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Effects of irrigation on the water and energy balances of the Colorado and Mekong river basins

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Abstract

An irrigation scheme, based on simulated soil moisture deficit, has been included in the variable infiltration capacity macroscale hydrologic model. Water withdrawals are taken from the nearest river, or, in periods of water scarcity, from reservoirs. Alternatively, water can be assumed freely available. The irrigation scheme successfully simulates crop consumptive water use in large river basins. In general, irrigation leads to decreased streamflow and increased evapotranspiration. The locally significant increases in evapotranspiration (or latent heat) results in lower surface temperatures, and hence decreased sensible heat flux. Simulations performed for a 20-year period for the Colorado and Mekong river basins indicate irrigation water requirements of 10 and 13.4 km^3 year^{-1}, respectively, corresponding to streamflow decreases of 37 and 2.3%. The increase in latent heat flux is accompanied by a decrease in annual averaged surface temperatures of 0.04 °C for both river basins. The maximum simulated increase in latent heat flux averaged over the three peak irrigation months for one grid cell is 63 W m^{-2}, where surface temperature decreases 2.1 °C. Simulated actual water use is somewhat less than simulated irrigation water requirements; 8.3 and 12.4 km^3 year^{-1} for the Colorado and Mekong river basin, respectively.

Keywords: Irrigation; Reservoirs; Water resources; Evapotranspiration; Runoff

1. Introduction

The global water cycle reflects both natural and anthropogenic variability and changes on the land surface and in the atmosphere and oceans. Seasonal and long-term climate variability obviously impact runoff and evapotranspiration, and in the post-industrial era management of the world's rivers has changed the dynamics of the water cycle. Water intensive farming and irrigation increase evapotranspiration and reduce runoff. According to Shiklomanov (1996, 1997), 60–75% of global water withdrawals, now totaling 10–15% of current water supply (Vörösmarty and Sahagian, 2000), are used for irrigation. The effect of irrigation on the surface

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water balance is known to be locally and even regionally important. Jackson et al. (2001) estimated that about half of the water diverted for irrigation of crops is consumed through evapotranspiration. The increase in evapotranspiration, and hence reduction in streamflow, may well have second order effects via enhanced moisture recycling (Pielke, 2001). Of the more than 30,000 large dams (defined as being 15 m or higher) reported in the world register of dams (ICOLD, 2003), 35% are designed for irrigation purposes only, and hence irrigation impacts streamflow regimes indirectly as well. The fraction of water withdrawals compared to freshwater availability is expected to increase in the future, and the United Nations views freshwater scarcity as one of the most important environmental issues of the 21st century (United Nations Environmental Programme, 1999).

Most large-scale hydrological models, and the land surface schemes used in numerical weather prediction and climate models, ignore the effects of irrigation on surface water and energy fluxes. However, some recent studies have analyzed this effect and have shown its potential importance. Döll and Siebert (2002) computed global irrigation requirements under present-day climate, using a model of global water resources and water use. They found that annual net irrigation requirements (defined as the difference between potential evapotranspiration and precipitation available to the crop) can be more than 1000 mm year^{-1}, per unit irrigated area, in hot and semi-arid regions. Boucher et al. (2004), the first to represent irrigation in a general circulation model (GCM), incorporated the increase in evapotranspiration caused by irrigation in idealized climate simulations, and estimated a global mean radiative forcing up to 0.1 W m^{-2}, and a surface cooling of up to 0.8 K over irrigated areas. de Rosnay et al. (2003) developed an irrigation scheme for a land surface model, and found a mean increase in latent heat flux of 9.5% over the Indian Peninsula.

In this study we describe the development of an irrigation scheme based on simulated soil moisture and water available for irrigation. The main difference from the approach of de Rosnay et al. (2003), is that we take into account the effects of dams and reservoirs, and hence water can be stored for later use. The irrigation scheme is intended for use in a macroscale hydrological model that has previously been used for both regional and global applications. The objective of the study is to analyze the effects of irrigation on the water and energy balances of two large-scale basins with varying climate conditions; namely the Colorado and Mekong river basins. Comparisons are made between an ideal situation where water is assumed to be freely available and the more realistic situation where irrigation is constrained by water availability.

2. Model description

We have developed a modeling framework that represents the effect of irrigation on the water balance of large continental rivers. The centerpiece of the model structure is the variable infiltration capacity (VIC) macroscale hydrology model of Liang et al. (1994). We describe in this section modifications to the VIC model to include a sprinkle irrigation scheme based on a standardized method of irrigation scheduling and information about growing season and irrigation intensity given by the United Nations Food and Agriculture Organization's (FAO) database AQUASTAT (FAO, 2003), and the inclusion of a reservoir module in the Lohmann et al. (1998) routing model.

2.1. Variable infiltration capacity (VIC) macroscale hydrological model

The VIC macroscale hydrology model (Liang et al., 1994) solves the water and energy balance equations at the land surface. It is a grid-based model that usually is implemented at spatial scales from one-eighth to 2° latitude by longitude, and at hourly to daily temporal resolution. Land cover variability is represented through partitioning each grid cell into multiple vegetation types (and bare soil), and the soil column is divided into multiple (typically three) soil layers. Evapotranspiration is calculated using the Penman–Monteith equation (Shuttleworth, 1993). The saturation excess mechanism, which produces surface runoff, is parameterized through the Xinanjing variable infiltration curve (Zhao et al., 1980). Release of baseflow from the lowest soil layer is controlled through the non-linear Arno recession curve (Todini, 1996). Surface runoff and baseflow for each cell are routed to the basin outlet through a channel network as described by Lohmann et al. (1998), taking into account the fraction of each grid cell that flows into the basin being routed (Nijssen et al., 1997).

We utilized the energy balance mode of the VIC model, which means that the model iterates for the surface temperature that results in closure of the surface energy and water budgets at each time step. Minimum required input data to the model are daily precipitation, and maximum and minimum daily temperatures, which are partitioned to the model time step (3 h for this work). When radiation data and vapor pressure are not supplied to the model, VIC calculates these variables based on daily precipitation and daily minimum and maximum temperatures, using algorithms developed by Thornton and Running (1999), and Kimball et al. (1997) as described by Nijssen et al. (2001). If wind speed or atmospheric air pressure are not provided, the model uses default values (1.5 m s^{-1} and 95.5 kPa).

2.2. Model development: irrigation scheme and reservoir module.

The main purpose of irrigation is to avoid vegetation stress caused by limited soil moisture availability. The VIC model was therefore modified to allow for irrigation water use, based on the model's predicted soil moisture deficit. Irrigation starts when soil moisture drops below the level where transpiration becomes limited, and continues until soil moisture reaches field capacity. Grid cells in which irrigation occurs are partitioned into an irrigated and a non-irrigated part, based on Siebert et al.'s (2002) dataset on the fractional area irrigated within the cell. Crop characteristics are determined based on FAO's guidelines for computing crop evapotranspiration (FAO, 1998). Reference crop evapotranspiration is first calculated within each model grid cell based on the Penman–Monteith method (e.g. Shuttleworth, 1993). Crop coefficients and heights specified by FAO are thereafter used to calculate leaf area index values throughout the growing season. The crop coefficients used include soil evaporation as part of the water requirements. Crops with crop coefficients calculated in this way are assigned to the irrigated part of the grid cell, and the remaining vegetation is assigned to the non-irrigated part.

Storage reservoirs can affect streamflow significantly, and for this project a reservoir module was developed and included in the Lohmann et al. (1998) routing model. The operation of the dams is assumed to follow simple rule curves, which are constructed based on hydropower and/or irrigation water demand, or historical flow data. Run-of-the river dams are not considered, since they do not affect streamflow much.

Irrigation water can be extracted from river runoff locally, or, in periods of water scarcity, from reservoirs or any other prescribed point in the river basin. In this case, irrigation is restricted by water availability. Alternatively, irrigation water is assumed to be freely available, in which case the model simulates irrigation water requirements. In this case, irrigation is not restricted by water availability, and it is hence possible that more water is used for irrigation than is available in the river basin. The VIC model, like most land surface schemes, does not represent groundwater in a way suitable for modeling groundwater withdrawals, which hence is not taken into account in the model. Water withdrawals from reservoirs (or any other location if desired), are based on simple rules intended for implementation in any river basin. The elevation of the grid cell in need of water has to be lower than the elevation of the reservoir, and water is only extracted from the reservoir when there is not enough water available locally. Hence, the model imitates a water transport system based on gravity. Another generalization is that upstream locations are given priority on cost of the possible needs of downstream locations. The irrigation scheme is illustrated in Fig. 1.

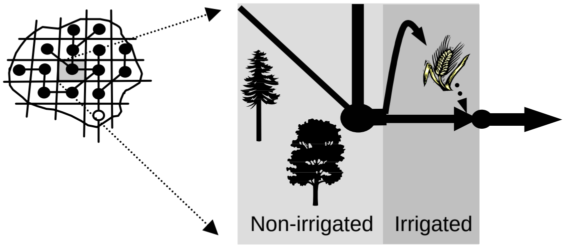

Fig. 1. Schematic representation of the VIC irrigation scheme. The model grids and routing network are shown to the left, and an example grid cell is shown to the right. Water is extracted from the river and applied to the irrigated part of the cell, and excess water returns to the river system.

3. Approach

3.1. Study areas

The algorithm described above was evaluated through application to two large river basins; the Colorado river basin in the Southwestern US, and the Mekong river basin in Southeast Asia. The Colorado river basin, which covers an area of 650,000 km^2, has the most complete allocation of its water resources of any river in the world and is also one of the most heavily regulated (USBR, 2000). Much of the Colorado river basin is arid, with naturalized annual streamflow (i.e. streamflow that would have occurred in the absence of water management) averaging only 40 mm year^{-1} over the drainage area. Aggregated reservoir storage in the basin is 74 billion m^3, or about four times the pre-development mean annual flow. Of the over 90 reservoirs on the river and its tributaries, by far the largest are Lake Mead (formed by Hoover dam) and Lake Powell (formed by Glen Canyon dam).

The Mekong river basin has a drainage area of 795,000 km^2, and a mean annual flow equivalent to a depth of 570 mm year^{-1} over the basin area (Mekong River Commission, 1998). Farmers in the Mekong basin produce enough rice to feed 300 million people, and 80–90% of all freshwater use in the Mekong region is devoted to growing food (Mekong River Commission, 2002). Though hydropower development plans in the Mekong basin were created in the 1950s (Bakker, 1999), political conflict over three decades in most of the riparian countries prevented their implementation. The locations of the river basins and the 0.5° VIC routing network, as well as the major reservoirs and gaging stations in each basin are shown in Fig. 2. Table 1 summarizes land cover in the two river basins.

3.2. Input data

Daily atmospheric forcing data (maximum and minimum temperature, precipitation, and wind speed for the period 1979–1999) at 0.5° spatial resolution were obtained from Adam and Lettenmaier (2003) for the Mekong river basin, and from Maurer et al. (2002) for the Colorado river basin. Both datasets are gridded time series based on meteorological observations (see Adam and Lettenmaier (2003), and Maurer et al. (2002) for details). Topography and current land cover classification (elevation, vegetation, soil) were prepared for the Mekong river basin at 0.5° spatial resolution using the same data sources and methods as described in Nijssen et al. (2001), while the Maurer et al. (2002) land surface characteristics were used for the Colorado river basin. Information about fraction of area irrigated within each grid cell was obtained from Siebert et al. (2002). This dataset, originally at 5 min spatial resolution, was aggregated to 0.5° spatial

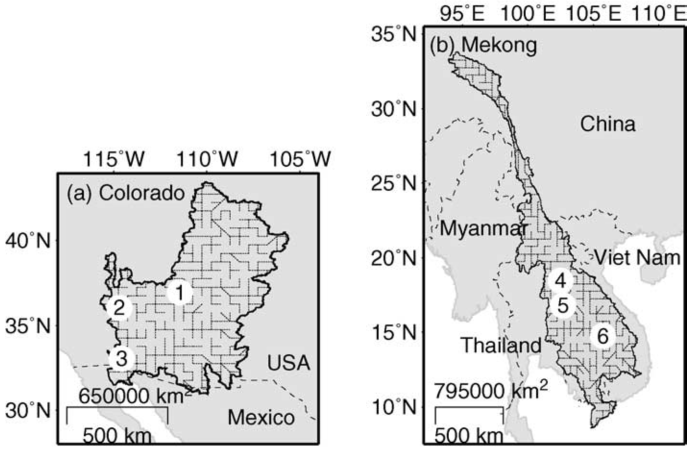

Fig. 2. Location of study basins with 0.5° VIC routing network, major system reservoirs and gaging stations. (1) Glen Canyon dam, (2) Hoover dam, (3) Imperial dam, (4) Nam Ngum dam, (5) Ubol Ratana dam, (6) Pakse gaging station.

Table 1
Vegetation cover in the Colorado and Mekong river basins

Vegetation type	Colorado (%)	Mekong (%)
Evergreens	4	19
Deciduous	1	4
Woodland	9	25
Wooded grassland/grassland	24	35
Shrubland	57	2
Cropland (not irrigated)	3	12
Cropland (irrigated)	2	3

resolution. Fig. 3 shows mean annual precipitation within each 0.5° cell, and also the percent irrigated area within the cells.

Two reservoirs, with operating rules based on historical observations, are represented in the routing model for the Colorado river basin. These are Lakes Mead and Powell, the combined storage capacity of which accounts for 85% (~63 billion m^3) of the basin total. Nam Ngum in Laos and Ubol Ratana in Thailand, the two dams represented in the Mekong river basin model, form reservoirs that have a combined storage capacity of about 10 billion m^3. The Nam Ngum dam is a hydropower dam; its operating policy is set to the installed power capacity (150 MW). Although the Nam Ngum dam was not completed until 1985, the model simulations treat it as if it had been in operation for the entire simulation period. The Ubol Ratana dam serves both as an irrigation and hydropower dam, and irrigation releases are given priority over power generation releases (Bogardi and Duckstein, 1992). It was assumed that there was no irrigation demand for the wet season, and 150 million m^3 per month during the dry season. The constant value per month during the wet season was chosen to match the mean annual irrigation release of the model of Bogardi and Duckstein (1992). Water is released for hydropower only during the wet season. For all dams, water releases are constrained by the reservoirs' storage requirement criteria.

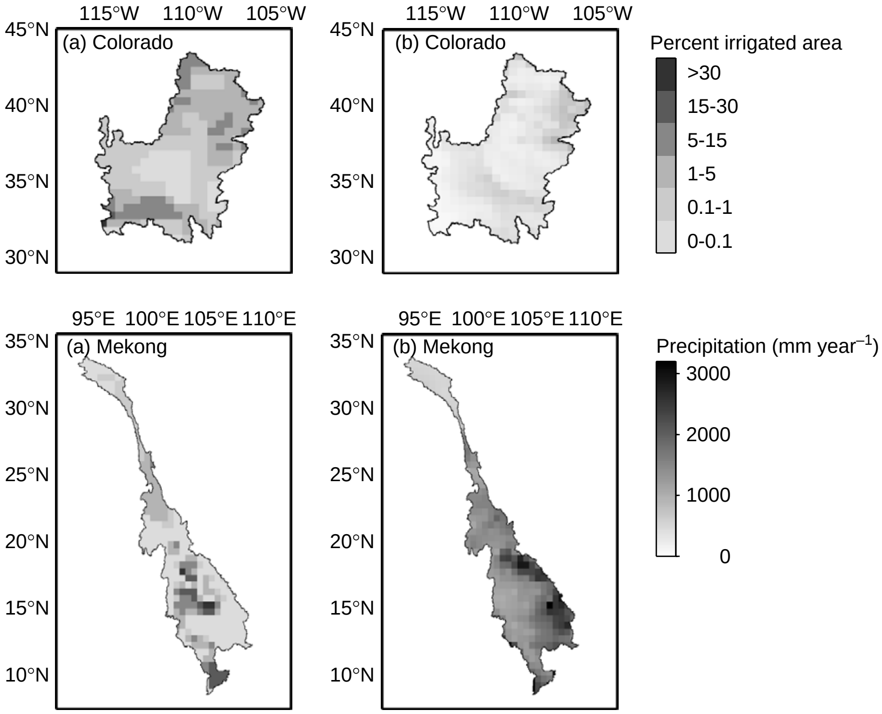

Fig. 3. (a) Percent irrigated area within each grid cell, and (b) mean annual precipitation in the Colorado and Mekong river basins.

FAO's database AQUASTAT (FAO, 2003) includes information about crop types, cropping periods and cropping intensity for 90 developing countries and countries in transition. In Southeast Asia, where rice is the dominant crop type, two cropping periods are common; May through September and October through February. For the Colorado river, information about crop types and cropping periods were obtained from the US Department of Agriculture (USDA, 1997; 1998). For both river basins, the crop information is merged into one crop type for each country or state.

4. Model validation and analyses

The model was tested for the two river basins for the period 1980–1999 (after initializing the model until equilibrium was reached at the onset of the simulation period). Model parameters obtained by Christensen et al. (2004) and Nijssen et al. (2001) when running the model at daily time steps in water balance mode, were adjusted for use at 3 h time steps in energy balance mode using the scheme presented in Haddeland et al. (in press). Initially the model was run without the irrigation and reservoir operations scheme implemented. Mean monthly simulated and naturalized (effects of reservoirs, diversions, and return flows removed) streamflow values below Imperial dam in the Colorado river basin are shown in Fig. 4. For the Mekong river basin, no naturalized streamflow data were available, and Fig. 4 shows mean monthly simulated and observed streamflow at Pakse in the Mekong river. Reservoir regulations do not affect monthly streamflow in the main-stem Mekong much (Goteti and Lettenmaier, 2001), and the irrigation water requirements in the area are small (see Table 2) compared to the mean annual runoff in the Mekong river basin (570 mm year^{-1}). Hence, it is reasonable to compare simulated and observed streamflow at Pakse. Although the summer streamflow is somewhat underestimated in the Colorado river basin, and the spring streamflow is overestimated in the Mekong river basin, the simulated streamflow in general matches the naturalized/observed streamflow in both cases.

FAO reports irrigation water requirements at the country level for developing countries and countries in transition. No data exist for the Mekong river basin alone. For validation purposes, VIC was therefore run for an area covering Myanmar, Thailand, Cambodia, Laos, Viet Nam and parts of Southern China; i.e. the Mekong river basin and adjacent areas. The model was run with the irrigation scheme implemented, and assuming that available water is not a limiting factor, which allows model-estimated irrigation water requirements to be compared to the numbers reported by FAO. USBR (1995, 2002, 2004) reports values for consumptive irrigation water use in the Colorado river basin, which may be smaller than the irrigation water requirements, depending on whether water scarcity limits irrigation or not. However, because no canals or aqueducts, which divert and transport water over large areas in the Colorado river basin, are represented in the model, the validation runs for the Colorado river basin were also done assuming freely available water for irrigation purposes.

In Table 2 the simulated and reported numbers for Southeast Asia and the Colorado river basin are presented. The reported numbers are for the year

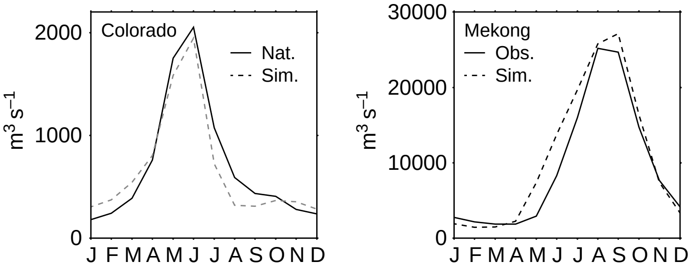

Fig. 4. Simulated and naturalized/observed streamflow in the Colorado river basin below Imperial dam, and at Pakse in the Mekong river basin.

Table 2
Simulated irrigation water requirements vs. reported numbers (km^3 year^{-1})

Area	Simulated	Reported
Myanmar	10.1	9.8
Thailand	26.7	24.8
Laos	2.3	0.8
Cambodia	1.5	1.2
Viet Nam	6.7	15.2
Colorado river basin	10.0	9.0

The reported number for the Colorado river basin includes only the US portion of the basin, and represents the average consumptive water use for the period 1980–1999. The reported numbers for southeast Asia are irrigation water requirements for the year 2000.

2000 for Southeast Asia (FAO, 2003), and the average number for the period 1980–1999 for the Colorado river basin (USBR, 1995, 2002, 2004), while the simulation results are averages for the 20-year simulation period (1980–1999). The discrepancy seen for Viet Nam can partly be explained by differences in reported area irrigated between FAO's database AQUASTAT, which reports that in Viet Nam a total area of 30,000 km^2 is irrigated, and the Siebert et al. (2002) dataset used in this project, which reports 19,000 km^2 irrigated area. The simulated irrigation water requirements for the Colorado river basin are 10 km^3 year^{-1}, which is a little more than the reported number for consumptive water use (9.0 km^3 year^{-1}) during the same period for the US portion of the basin (about 97% of total basin area). Given that water scarcity probably limits irrigation at times in the Colorado river basin, the model most likely estimates irrigation water requirements fairly accurate in this basin.

Additional model analyses were performed combining a variety of irrigation and reservoir operation options; (1) no irrigation, with and without the effect of reservoirs included in the model, (2) irrigation restricted based on water availability (i.e. river runoff) both with and without reservoirs, and (3) irrigation without any restrictions (i.e. water is assumed available). For all options, the same landcover and vegetation characteristics (e.g. height, leaf area index) were used. Wilting of plants is not taken into account in the model, which might have affected leaf are index somewhat in the simulations where irrigation is not taken into account.

5. Results and discussion

Table 3 summarizes the effects of irrigation on mean annual water balance components for the various analyses performed. In Fig. 5, the effect of irrigation on mean monthly simulated streamflow at the basin outlets is shown. The 'free irrigation' simulations do not take water scarcity into account, and the negative values in the Colorado river basin in Fig. 5(a) should be interpreted as basin averaged water deficits. These water deficits, although unrealistic, are presented as negative streamflow values for easier comparison to the other analyses. They clearly show that irrigation water demands in the Colorado river basin in the summer can not be met by surface water withdrawals alone in the absence of reservoirs. When reservoirs are included in the 'free irrigation' simulations, no restrictions are made on the allocation of surplus water within the basin. However, consumptive irrigation water use for the free irrigation simulations with and without reservoirs included in the model simulations is the same.

The reservoirs in the Mekong river basin have relatively little impact on streamflow at the outlet of the basin, as shown in Fig. 5. When irrigation water is assumed to be freely available, mean annual runoff decreases by 37 (standard deviation (σ) = 15) and 2.3 (σ = 0.4)%, for the Colorado and Mekong river basins respectively. When irrigation is restricted by available water, and reservoirs are excluded from the simulations, the corresponding numbers are 24 and 2.0%. Including the reservoirs, and restricting irrigation based on water availability, results in 29 and 2.1% streamflow reduction, compared to naturalized conditions (see also Fig. 5(b)). The percentage decrease in runoff calculated for the Colorado river basin is somewhat less than the observed decrease, despite a fairly close match between simulated and reported irrigation water consumption numbers. This can be explained by a slight overestimation (~5%) in the simulated naturalized runoff for the Colorado river basin. It should also be noted that observed current streamflow at the outlet of the Colorado river is much lower than shown in Fig. 5; the main reason for this is that diversions are not taken into account in the model simulations.

As noted above, groundwater withdrawals are not included in the modeling framework. In Southeast Asia, groundwater withdrawals for irrigation purposes are insignificant (FAO, 2003). In the Colorado river basin, groundwater withdrawals accounted for about 17% of total water withdrawals for irrigation purposes in 1995 (Solley et al., 1998), and the difference in evapotranspiration between the ‘free irrigation’ and ‘irrigation including reservoirs’ (1.7 $\mathrm{km}^3\ \mathrm{year}^{-1}$) analyses might have been somewhat smaller if groundwater withdrawals had been included in the model. However, for the Colorado river, which in reality is essentially dry at its mouth, it should also be noted that reservoir evaporation and diversions out of the basin (not presently modeled) account for about half of the water consumption in the basin, and about 4% of annual runoff is used for industrial or municipal purposes (USBR, 1995). Hence, increased surface water availability, especially in the lower Colorado river (where most of the groundwater withdrawals occur), more than cancels the effect of not taking groundwater withdrawals into account.

The simulation results indicate that the relative effects of irrigation on streamflow and evapotranspiration are much more significant in the Colorado river basin than in the Mekong river basin, although the total fraction irrigated area within the basin is less (2.0 vs. 3.0%) in the Colorado river basin. Given the much drier conditions in the Colorado river basin than in the Mekong river basin (see Fig. 2), this result is not surprising.

In Fig. 6, spatial differences between the simulations with and without irrigation are shown at 0.5° spatial resolution, i.e. the resolution at which the simulations are performed. The upper panel (a) shows the irrigation water requirements (mm year^{-1}) per unit grid cell area, while panel (b) shows the associated percentage increase in evapotranspiration for each cell, and panel (c) shows water shortages, i.e. the difference between irrigation water requirements and water withdrawals (reservoirs included), for each cell in the basins studied. If canals and aqueducts built for irrigation water transport had been included in the modeling scheme, the water shortage numbers would have been smaller, especially in southern Arizona and the Mekong delta where numerous canals transport

Table 3
Mean annual runoff, evapotranspiration, and consumptive water use uses in the Colorado and Mekong river basins for the various analyses performed

	Colorado				Mekong			
	No irrigation	Irrigation restricted		Free irrigation	No irrigation	Irrigation restricted		Free irrigation
		No reservoirs	Reservoirs included			No reservoirs	Reservoirs included	
Runoff (mm year^{-1})	42.3	32.2	30.0	26.5	734	719	718	716
Evapotranspiration (mm year^{-1})	335	346	348	350	812	827	827	828
Consumptive water use ($\mathrm{km}^3\ \mathrm{year}^{-1}$)	–	6.9 (0.3)	8.3 (0.5)	10.0 (0.7)	–	12.1 (0.2)	12.4 (0.2)	13.4 (0.2)

The numbers in parentheses are the standard deviation of the mean annual consumptive water use.

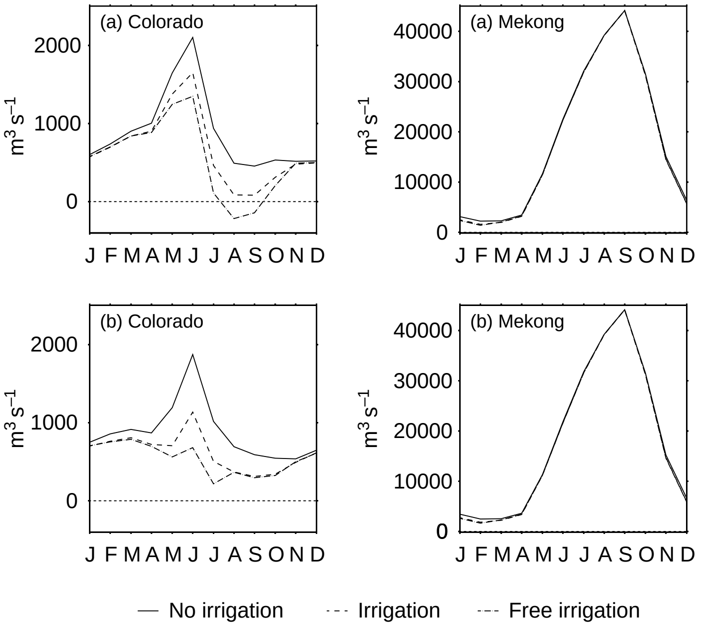

Fig. 5. (a) Effects of irrigation on mean monthly streamflow (no reservoirs included in the model), and (b) Effects of irrigation on mean monthly streamflow in the Colorado river basin when reservoirs are included in the simulations.

water for irrigation. It should be noted that all numbers reported in Fig. 6 are averaged over grid cells, and that the numbers would have been much higher if reported per unit irrigated area. Within the 20 year simulation period, irrigation water requirements for the Colorado river basin range from 8.3 to 11.5 $\mathrm{km}^3\ \mathrm{year}^{-1}$, and from 11.5 to 15.4 $\mathrm{km}^3\ \mathrm{year}^{-1}$ for the Mekong river basin. Beside these annual mean basin scale values, larger temporal variability is observed at finer spatial scale. Irrigation water requirements per unit irrigated area were calculated for each cell and year in the simulation period, and based on this 20-year time series the coefficient of variation of irrigation water requirements for each cell was calculated. Fig. 7 shows that for the driest areas, i.e. those with the highest irrigation water requirements, the inter-annual variability is lowest. This is because for the driest areas, rainfall provides little of the water requirement, and hence its variability is effectively filtered out.

In practice, farmers might anticipate the need to irrigate based on forecasted precipitation. The irrigation scheme implemented in VIC, which is not intended for operational use, does not take precipitation forecasts into account. In periods of water scarcity, and when water withdrawals are restricted by available river runoff, the scheme does not evaluate whether the available water will increase soil moisture sufficiently, but rather extracts whatever water is available. This can lead to somewhat inefficient use of water, because frequent and less than optimal water withdrawals will result in increased water loss through canopy evaporation. This is reflected in the results for the Colorado river basin, where the increase in canopy evaporation caused by irrigation is less than 1 mm (128.0 mm as opposed to the original 127.5 mm) when water is assumed freely available, and 3.5 mm when water withdrawals are restricted by available water (no reservoirs). On the other hand, the irrigation scheme should be very efficient in periods of water abundance, since it always keeps track of soil moisture and hence has the opportunity of irrigating at the exact time recommended, i.e. when soil moisture drops below the level where crop transpiration becomes limited by moisture. It should also be noted that the scheme always gives priority to upstream areas. That is, if irrigation water is needed at several locations along the river, the upstream areas extract water without considering the needs of downstream areas. Clearly, this is contrary to water

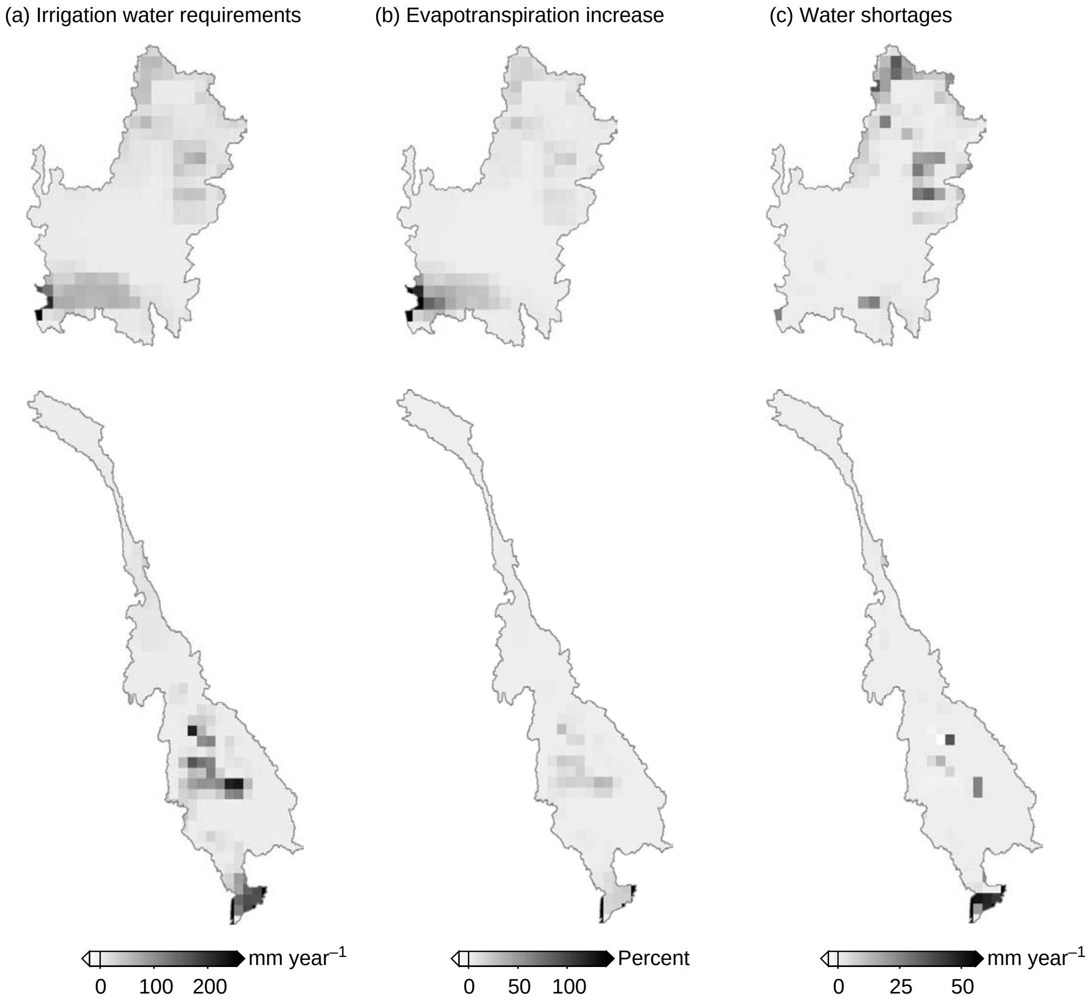

Fig. 6. Spatial effects of irrigation on water balance components.

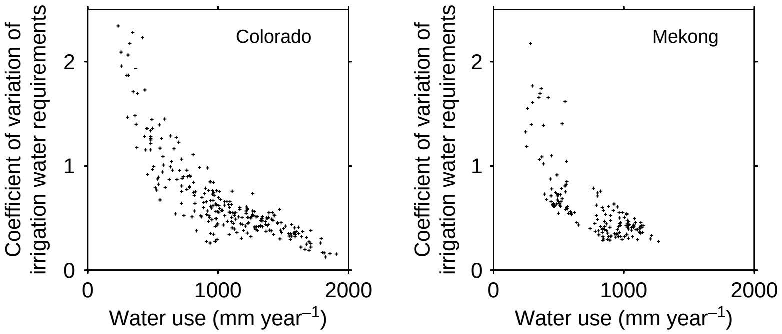

Fig. 7. Mean annual irrigation water requirements per unit irrigated area within each cell, compared to the coefficient of variation for the 20-year simulation period.

law in the Colorado river basin, which is based on seniority of water rights. In terms of large scale behavior of the system, however, it gives a reasonable approximation to the overall impact of irrigation.

Averaged over the years and basins, the surface energy balance is not changed much by irrigation. For example, the basin averaged increase in latent heat flux over the Colorado and Mekong river basins, when assuming irrigation water is freely available, is 1.2 and 1.3 $\mathrm{W m^{-2}}$, or 4.7 and 2.1%, respectively. However, locally and seasonally significant increases in evapotranspiration (or latent heat) result in lower surface temperatures, and hence decreased sensible heat flux and increased net radiation. Fig. 8 shows peak irrigation season changes (June through August for the Colorado river basin, and December through February for the Mekong river basin) in latent heat, sensible heat, and surface temperature for each grid cell. Again, the largest effects can be seen in cells where the percentage irrigated area is high, i.e. the southwestern Colorado river basin, and central and southern Mekong river basin. The maximum changes in surface fluxes can be found in the cell centered at latitude 32.25 and longitude −115.75 (Colorado river basin), where fraction

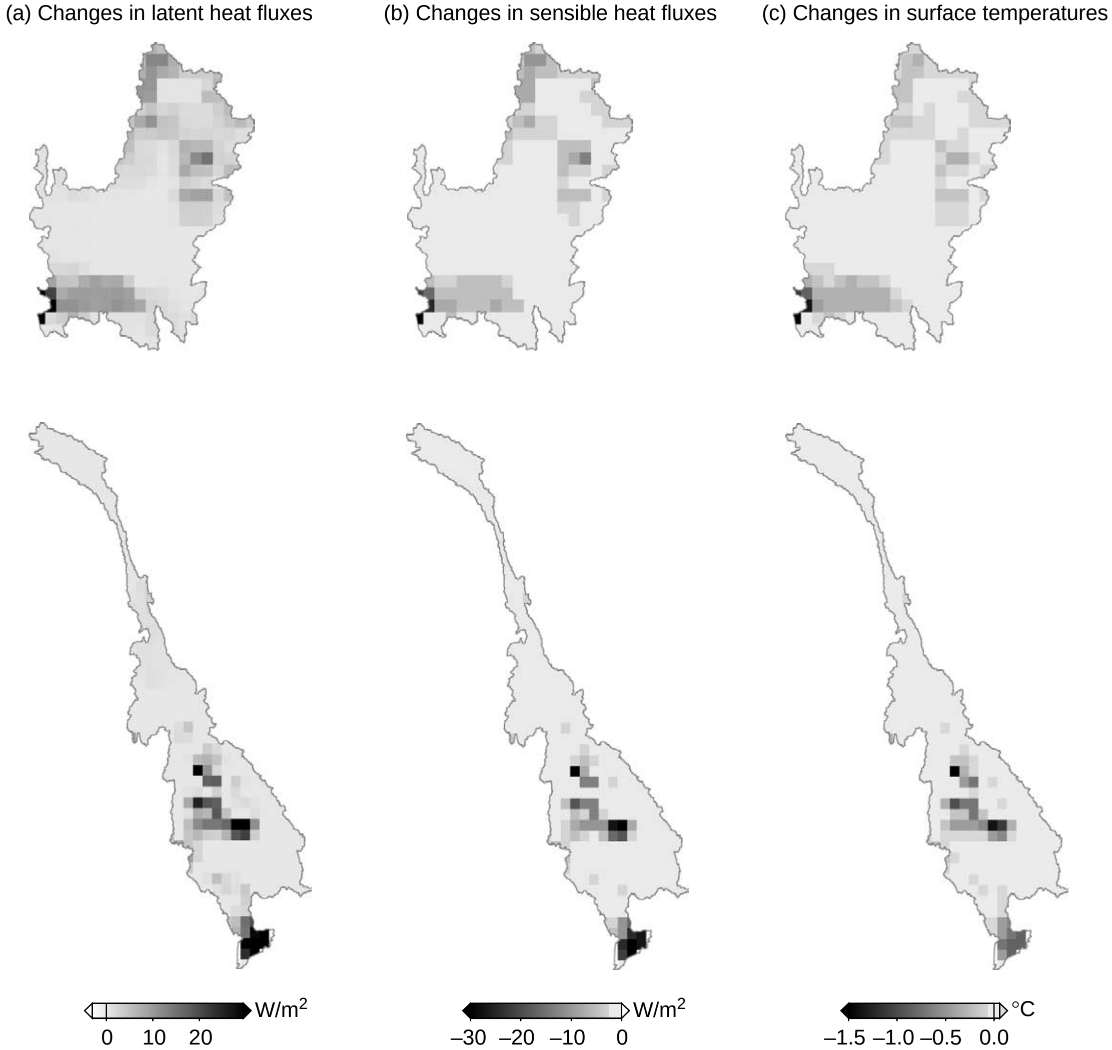

Fig. 8. Spatial effects of irrigation on energy balance components.

irrigated area is 46%. Averaged over this cell, irrigation causes evapotranspiration to increase from 24 to 231 mm during the 3-month period in question, latent heat increases by 63 Wm^{-2}, and the daily averaged surface temperature decreases 2.1 °C. On the other hand, on an annual average, and averaged over the basins, the decreases in surface temperatures are very small—0.04 °C for both river basins.

The lower surface temperatures and increased evapotranspiration resulting from irrigation indicate that the near-surface atmosphere will be somewhat cooler and moister over irrigated areas than over non-irrigated areas, and hence a reduction in the difference between air temperature and dew point temperature is likely. Crook (1996) discusses the impact changes in dew point temperatures have on rainfall, and it is also shown that smaller Bowen ratios increases the thermodynamic potential for deep cumulus convection (Segal et al., 1995). Irrigation obviously impacts soil moisture levels, which is also shown to impact rainfall (e.g. Marshall et al., 2004). The importance of taking the effect of irrigation into account in land surface models used in atmospheric models has also been shown by Adegoke et al. (2003), who found significant differences in midsummer turbulent heat fluxes and surface temperatures between irrigated (topsoil saturated each day) and dry (soil allowed to dry out) simulations for Nebraska. The work presented in this study provides a basis for simulating the coupled atmospheric-hydrologic effects of irrigation, based on a physical representation of the relation between evaporative demand, soil moisture deficit, and water availability.

6. Conclusions

Crop irrigation water use has the potential of altering the natural hydrologic water balance of river basins. In this study, an irrigation scheme based on simulated soil moisture deficit has successfully been implemented in the VIC model. The irrigation scheme withdraws water from the nearest (major) river, but can also make use of water from more distant locations, like reservoirs. The irrigation scheme is capable of simulating irrigation water requirements (i.e. water is assumed freely available), and actual water withdrawals (i.e. irrigation is restricted on available water). Validation runs for the Colorado river basin and Southeast Asia show that the model is able to capture the main hydrologic effects of irrigation, and simulated irrigation water requirements are close to the reported ones.

Simulations performed for a 20-year period for the Colorado and Mekong river basins indicate irrigation water requirements of 10 and 13.4 $\mathrm{km}^3\ \mathrm{year}^{-1}$, respectively. The numbers correspond to mean annual streamflow decreases at the outlet of the basins of 37 and 2.3%. Simulated actual water use is somewhat less, resulting in streamflow decreases of 29 and 2.1%.

Averaged over the years and basins, and assuming water is freely available, latent heat flux increases by 4.7 and 2.1% (1.2 and 1.3 Wm^{-2}) for the Colorado and Mekong river basins, respectively. The increase in latent heat flux is accompanied by a decrease in surface temperatures of 0.04 °C (yearly average) for both river basins. The changes are logically the greatest in grid cells where a large fraction is equipped for irrigation. The maximum simulated increase in latent heat flux during the three peak irrigation months for one grid cell (located in the southwestern part of the Colorado river basin) is 63 Wm^{-2}, where surface temperature decreases 2.1 °C.

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