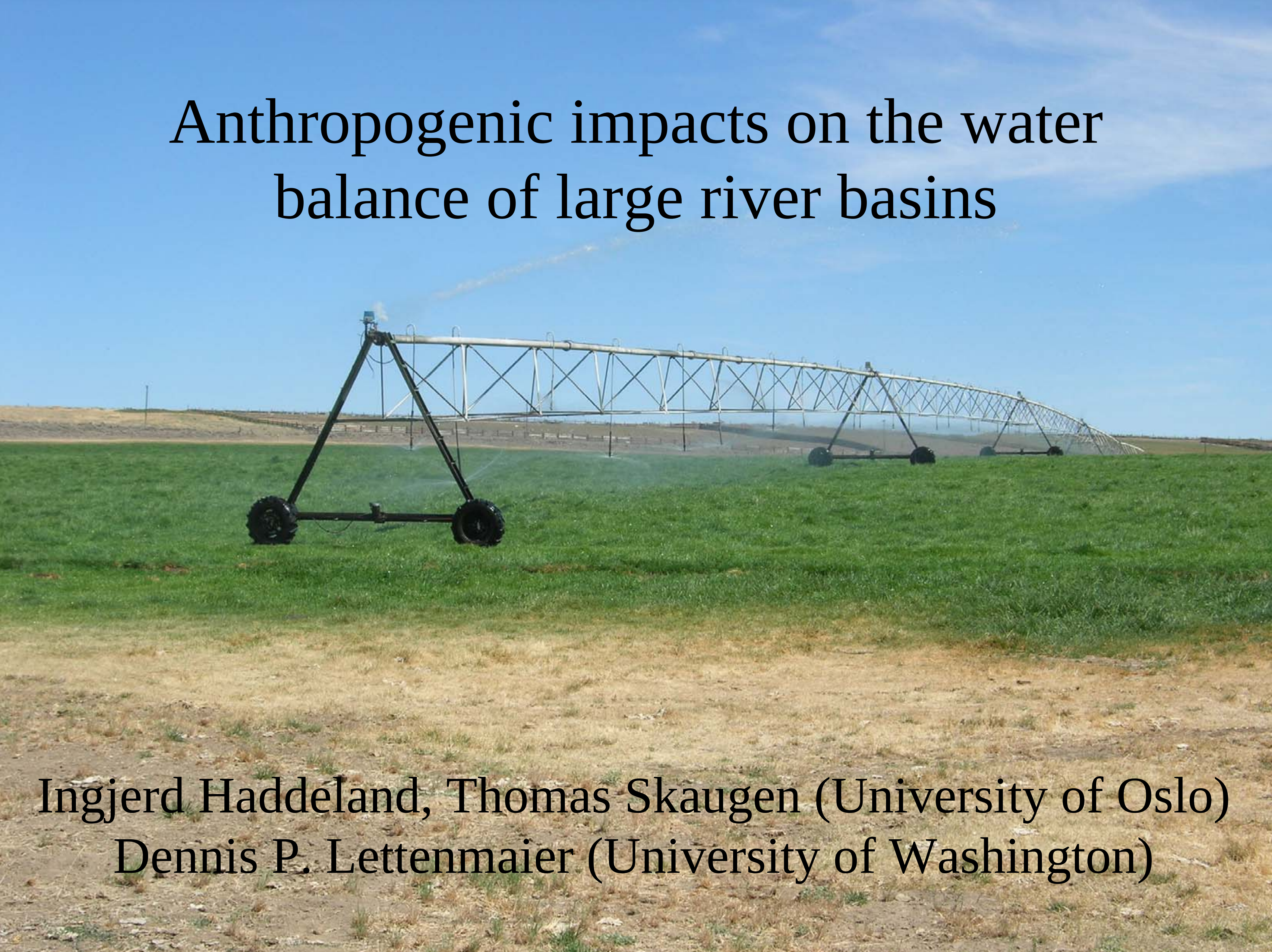
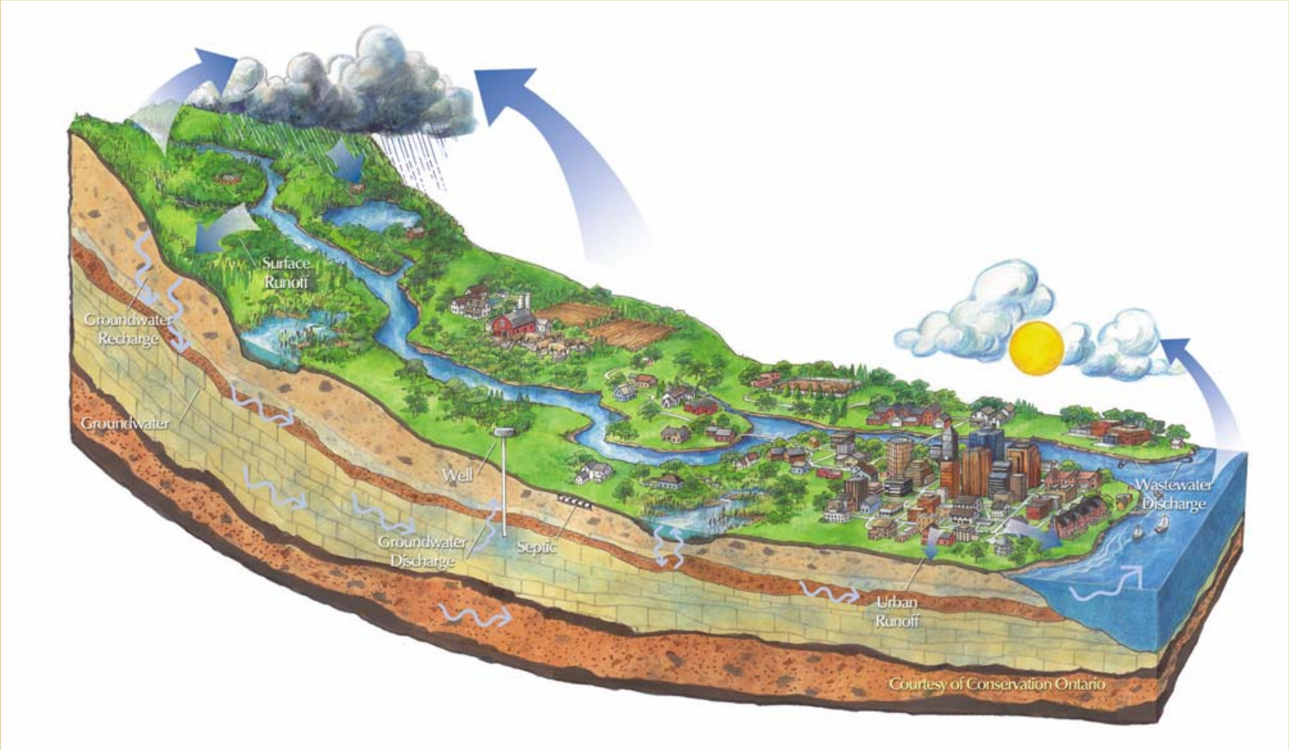


Anthropogenic impacts on the water balance of large river basins

Ingjerd Haddeland, Thomas Skaugen (University of Oslo)
Dennis P. Lettenmaier (University of Washington)

Outline

- Background
- Approach
- Results
- Conclusions

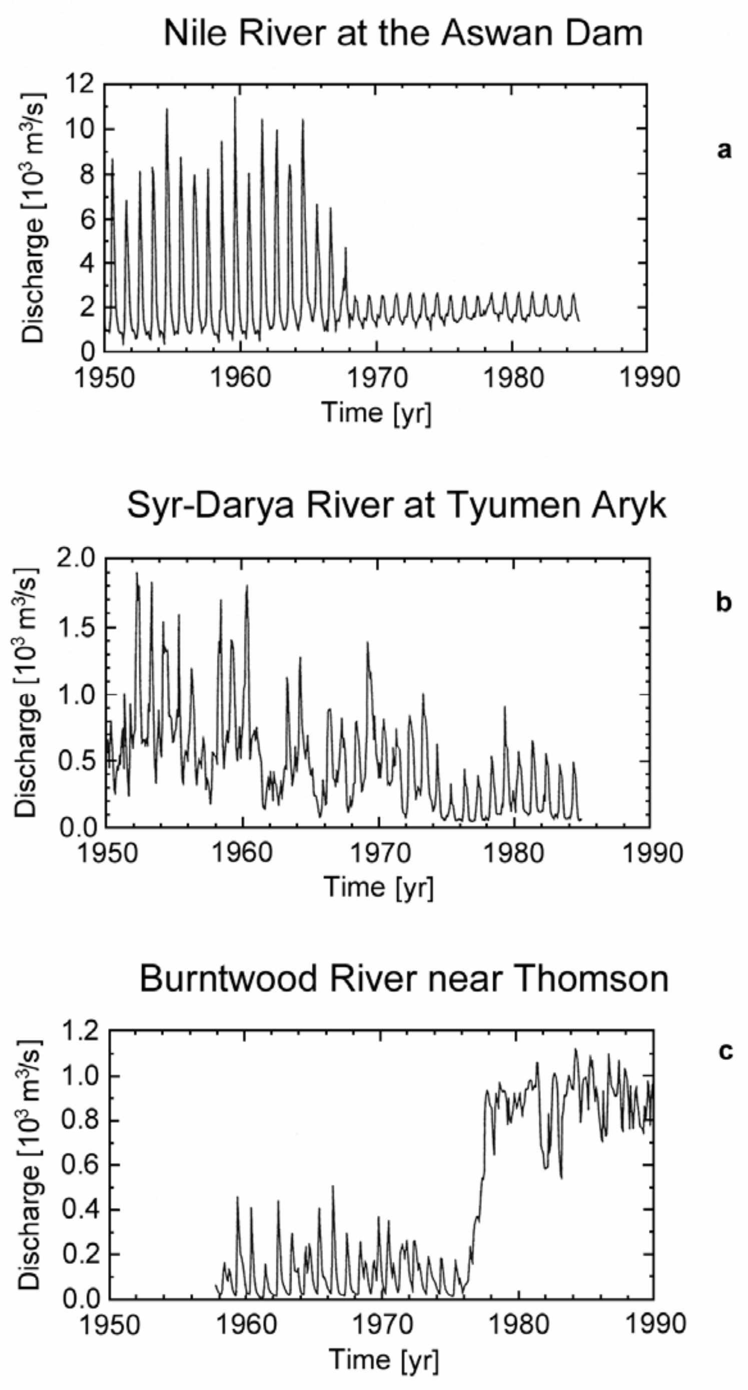


Introduction

- Irrigation:
  - 60-70 % of global water withdrawals *(Shiklomanov, 1997)*

- ICOLD: >30,000 large dams
  - 35 % built for irrigation purposes alone

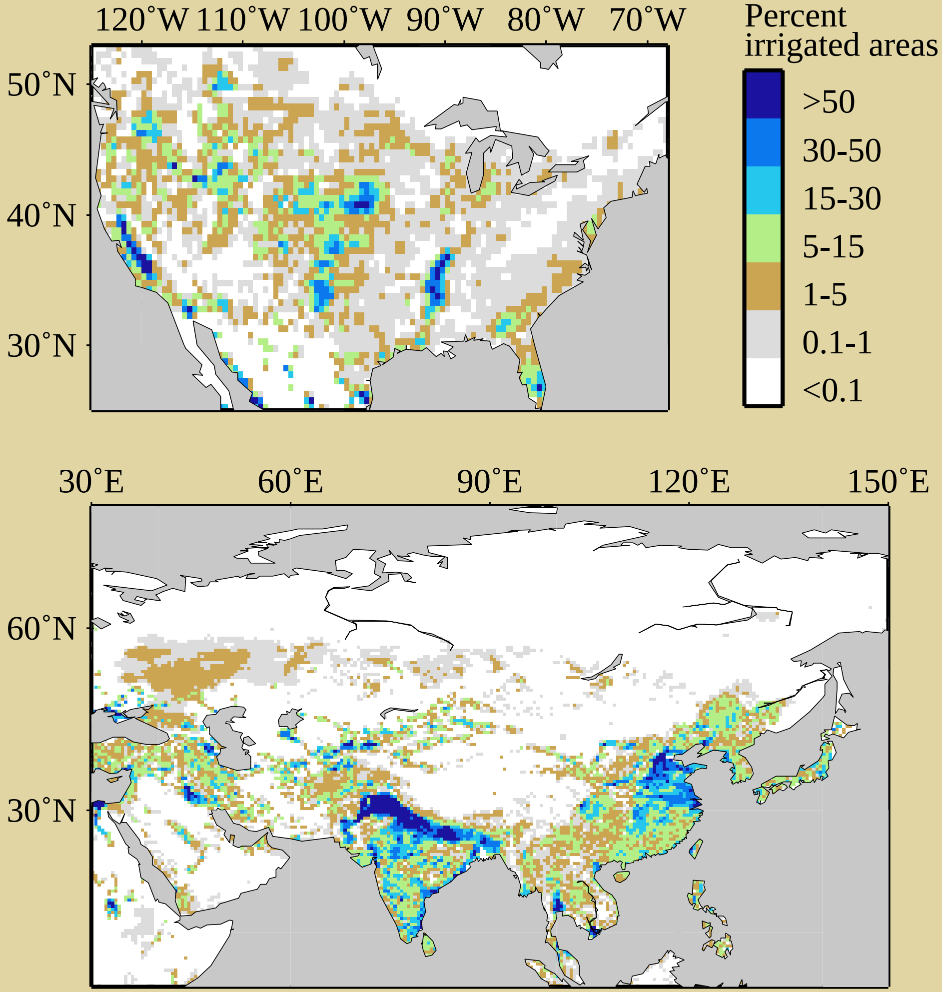
- Freshwater scarcity: one of the most important environmental issues of the 21st century *(UNEP, 1999)*



Vörösmarty and Sahagian, *Bioscience*, 2000.

Irrigated areas

Irrigated areas



- Irrigated areas, globally:
  - $2.5*10^6$ km^2
  - 1.7 % of global land area

- Location of irrigated areas:
  - Asia: 68%
  - America: 16%
  - China, India, USA: 47%

Stefan Siebert, Petra Döll, Sebastian Feick and Jippe Hoogeveen (2005), Global map of irrigated areas version 3, Institute of Physical Geography, University of Frankfurt, Germany / Food and Agriculture Organization of the United Nations, Rome, Italy

Irrigation: Definitions

- Irrigation water requirements:
  - Water required in addition to water from precipitation (soil moisture) for optimal plant growth during the growing season

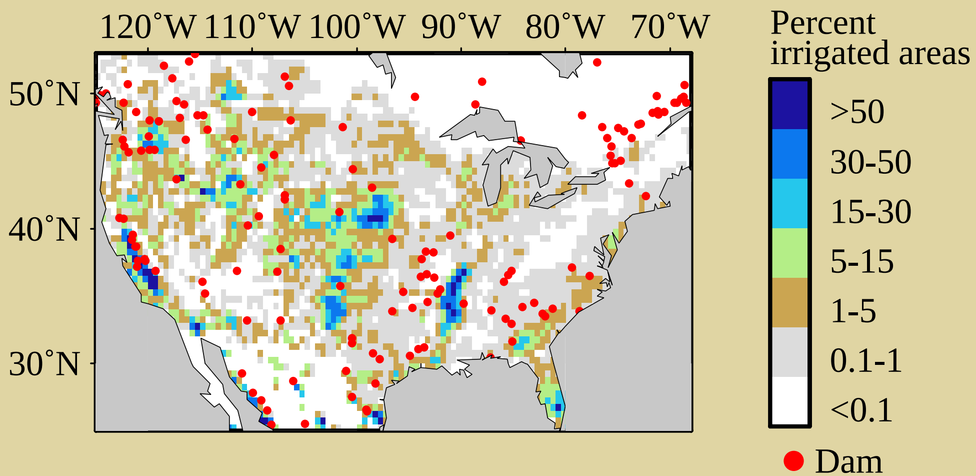
- (Consumptive) irrigation water use:
  - Water, in addition to water from precipitation, actually used by plants. Is equal to, or less, than irrigation water requirements.

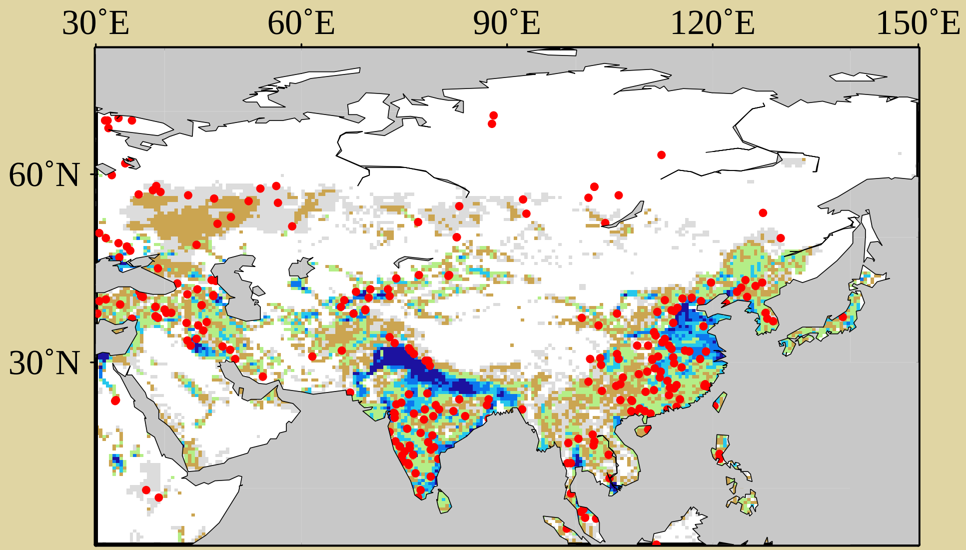
- Irrigation water deficits:

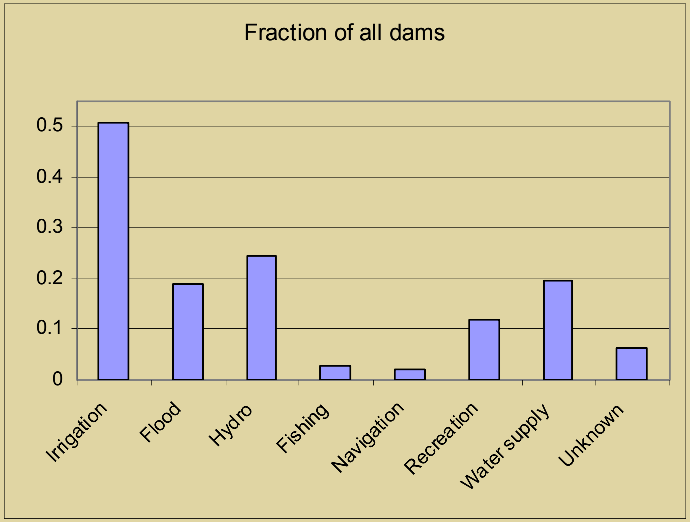
  Irrigation water requirements – Irrigation water use

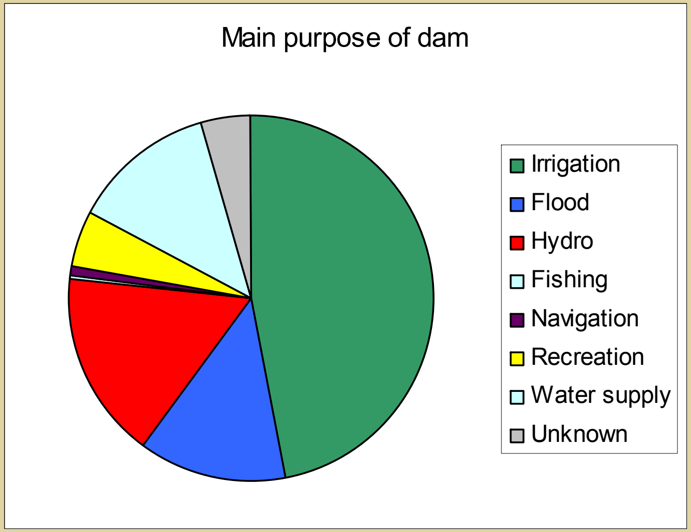
Reservoirs

Reservoirs









ICOLD, 2003. World Register of Dams 2003, International Commission on Large Dams (ICOLD), Paris, France.

Previous studies

- 20% of global mean annual runoff can be retained in reservoirs (Vörösmarty et al., *Ambio*, 1997)
- Reservoirs alters continental monthly river disharge by up to 34% (Hanasaki et al., *Journal of Hydrology*, 2006)
- Irrigation water requirements range from 1100 $km^3 year^{-1}$ (Döll and Siebert, *Water Resources Research*, 2002) to 2300 $km^3 year^{-1}$ (Shiklomanov, *United Nations*, 1997)
- Irrigation increases latent heat flux by 9.5% over the Indian Peninsaula (deRosnay et al., *Geophysical Research Letters*, 2003)
- Global mean radiative forcing is increased by up to 0.1 Wm^{-2}, temperatures decreases up to 0.8K over irrigated areas (Boucher et al., *Climate Dynamics*, 2004)

Measurements

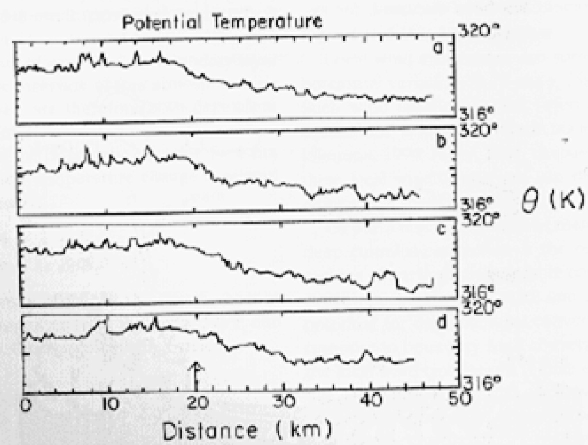


Figure 7. Measured potential temperature from Briggsdale to Windsor at the altitude of (a) 140 m, (b) 240 m, (c) 345 m, and (d) 440 m above the ground. The observed crop–dry land boundary is indicated by an arrow, with cropland to its right. Adapted from *Segal et al.* [1989] with permission from American Meteorological Society.

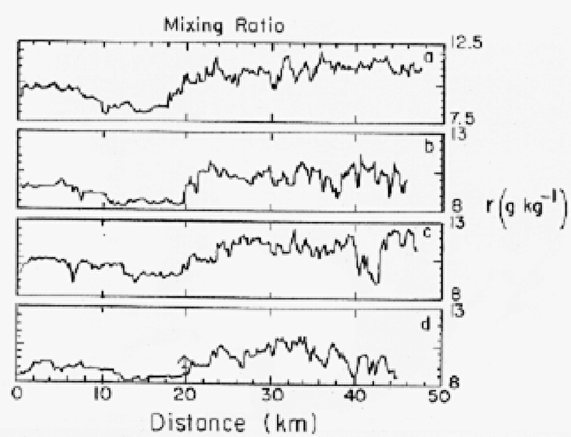


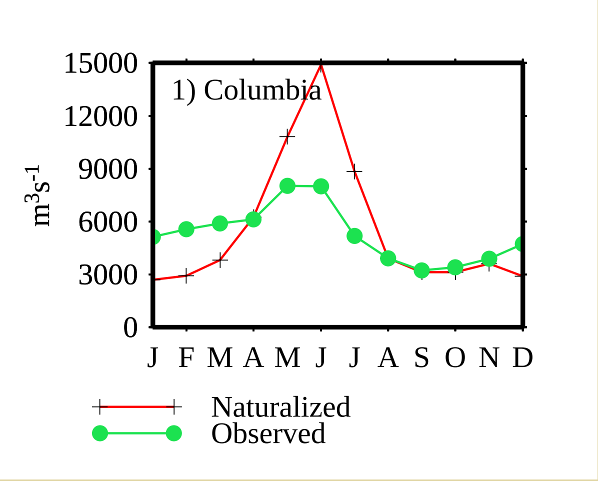
Figure 8. Same as Figure 7 except for moisture mixing ratio. Adapted from *Segal et al.* [1989] with permission from American Meteorological Society.

Objective of this study

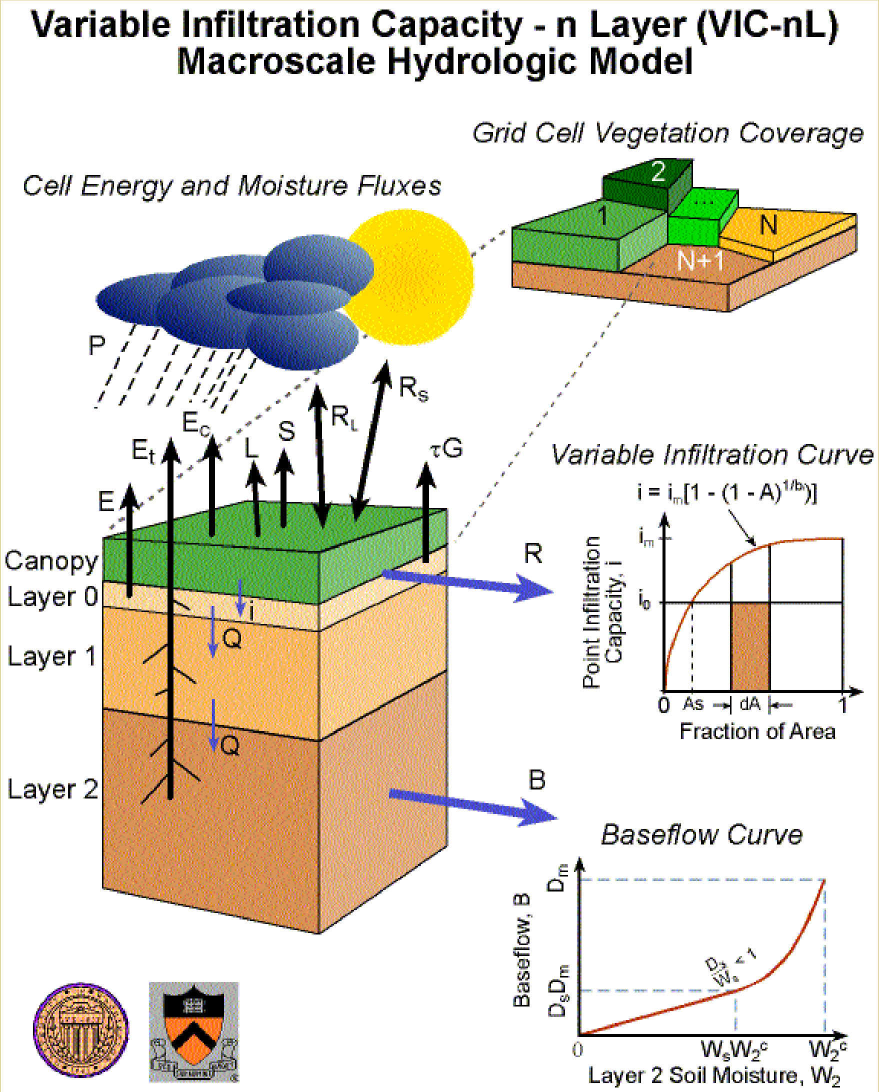
- “The effects of irrigation and large reservoirs on the water balance are studied with the objective of obtaining plausible reproductions of observed flows at the outlets of large river basins, with a special emphasis on river basins affected by irrigation.”

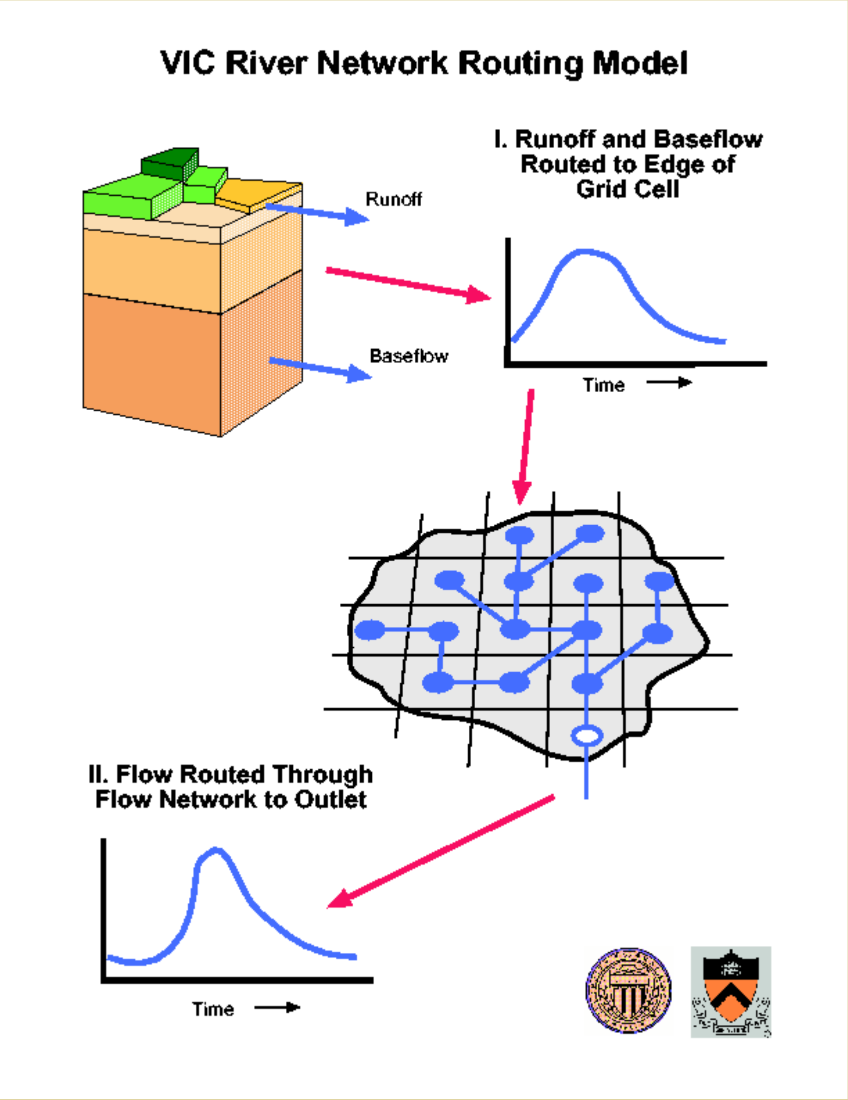
- ”Traditional” macroscale models:
  – Simulates naturalized streamflow

- Model development:
  – Generic reservoir model
  – Irrigation scheme



Variable Infiltration Capacity model

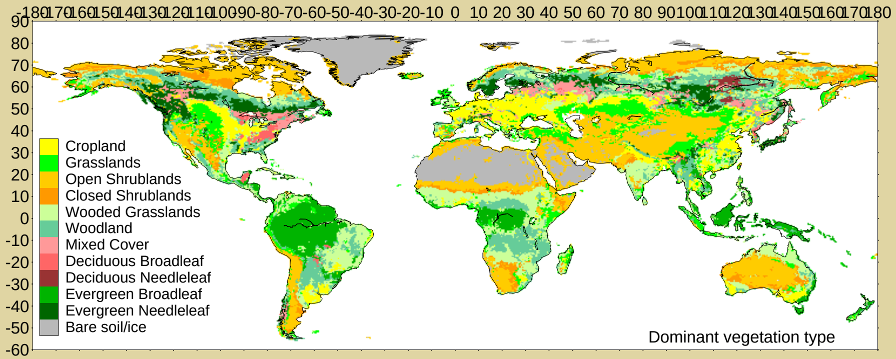


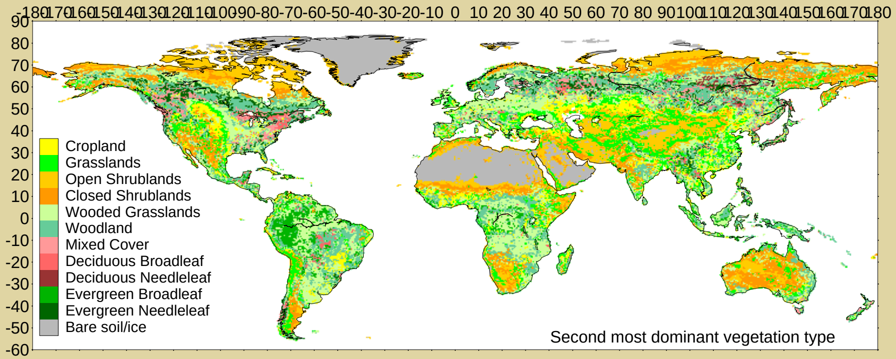


Approach

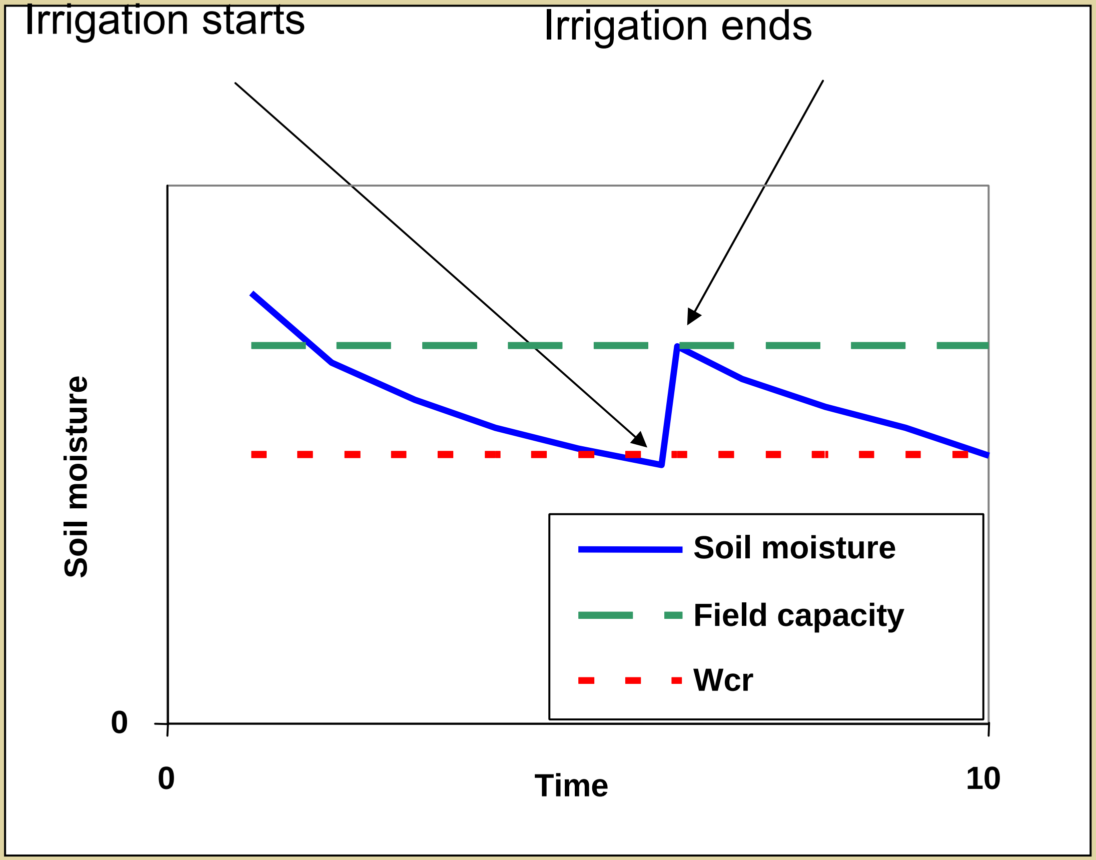
- Macroscale hydrologic model: VIC
- Resolution
  - Spatial: 0.5 degrees
  - Temporal: Daily
- Input data
  - Precipitation, max/min temperature, wind
  - Land cover data (vegetation, soil properties, topography)
- Time period: 1980 – 1999

- Irrigation scheme
  - VIC. Surface water withdrawals only
- Reservoir module
  - Routing model





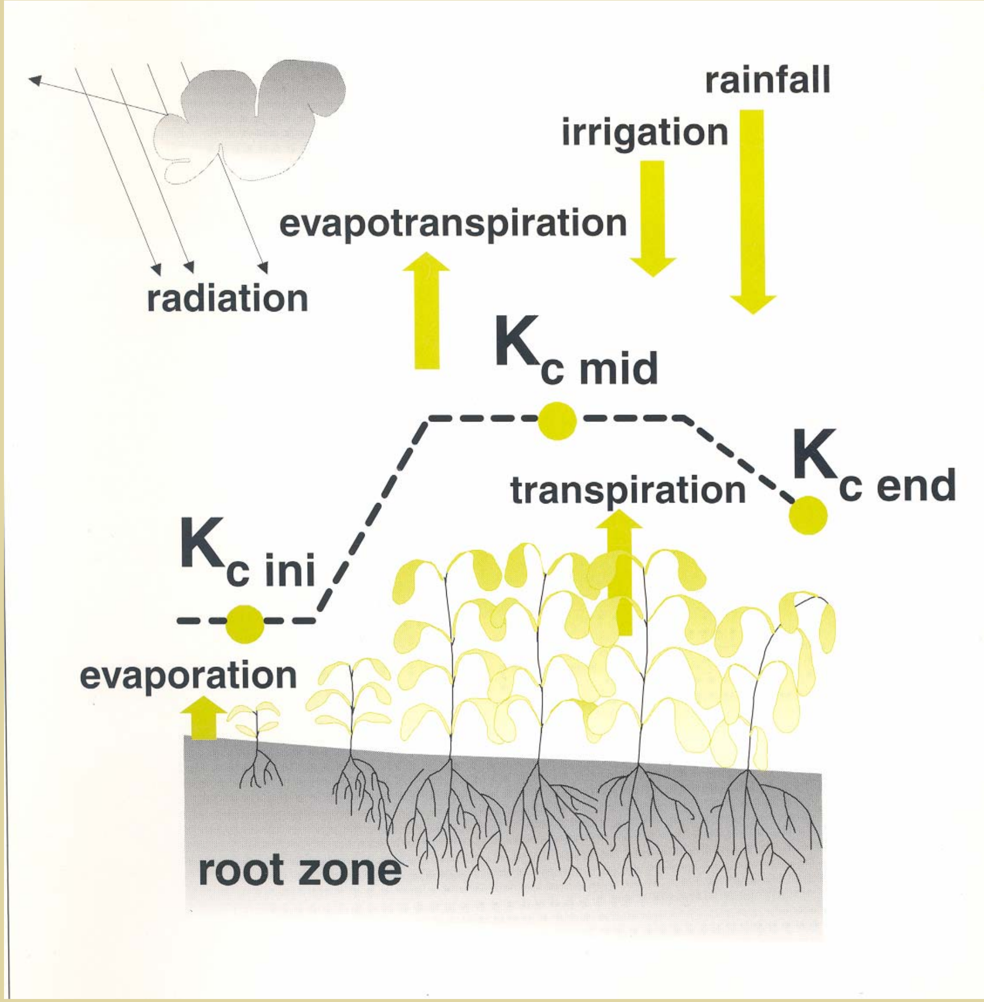
Irrigation scheme



Irrigation scheme

	Irrigated area (1000 ha)	Crop area as percentage of the total area equipped for irrigation by month											
		J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
VIETNAM													
Rice	4500												
Rice-one						75	75	75	75	75			
Rice-two		75	75								75	75	75
Maize	110	4	4								4	4	4
Sweet potatoes	16	1	1								1	1	1
Sugarcane	168	6	6	6	6	6	6	6	6	6	6	6	6
Vegetables	276	9	9								9	9	9
Bananas	23	1	1	1	1	1	1	1	1	1	1	1	1
Citrus	35	1	1	1	1	1	1	1	1	1	1	1	1
All irrigated crops	5128	96	96	8	8	83	83	83	83	83	96	96	96
Equipped for irrigation	3000												
Cropping intensity	171												

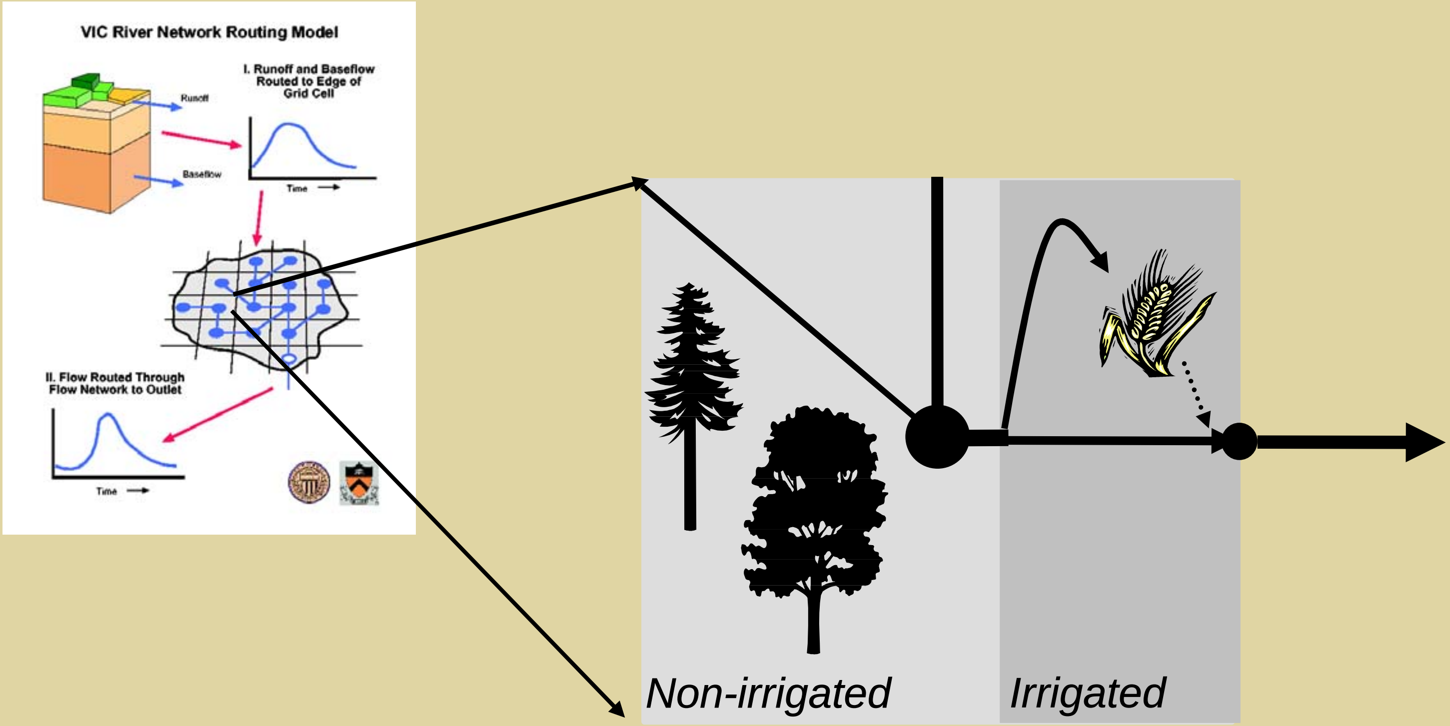
Irrigation scheme



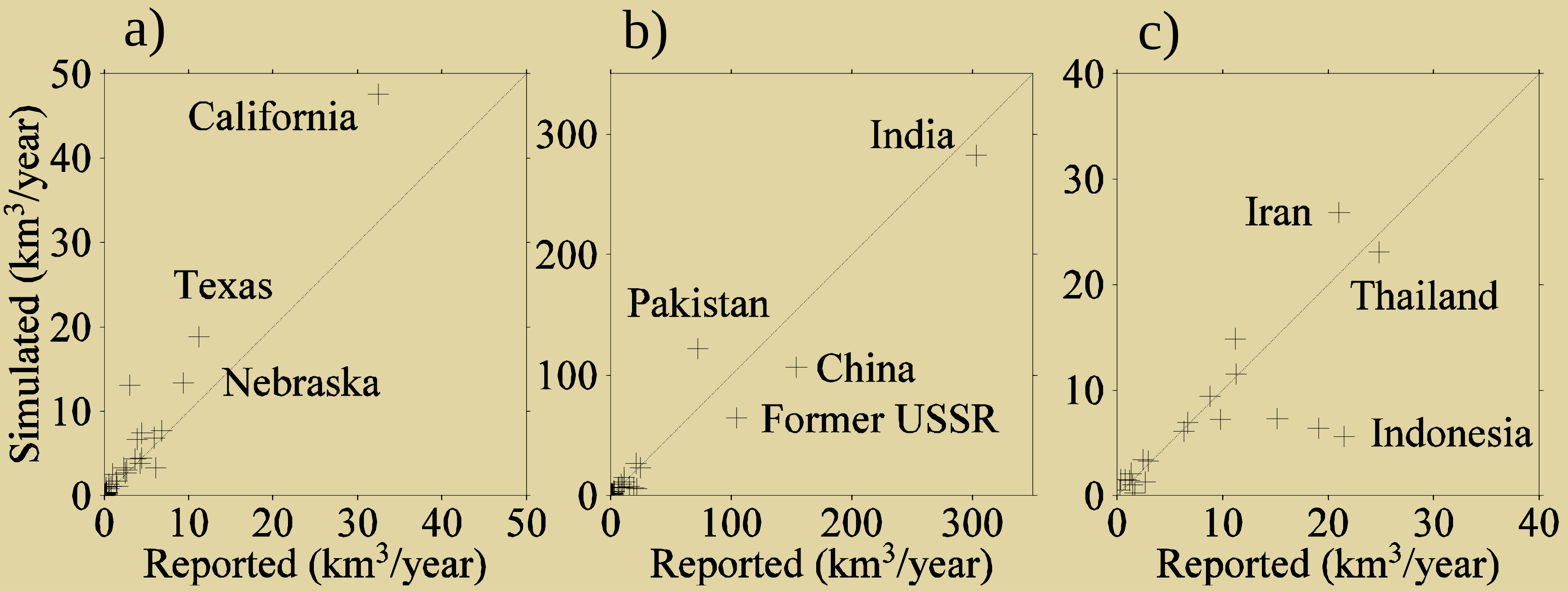
ET = K_c * ET_o

ET_o: Reference crop evapotranspiration

Irrigation scheme

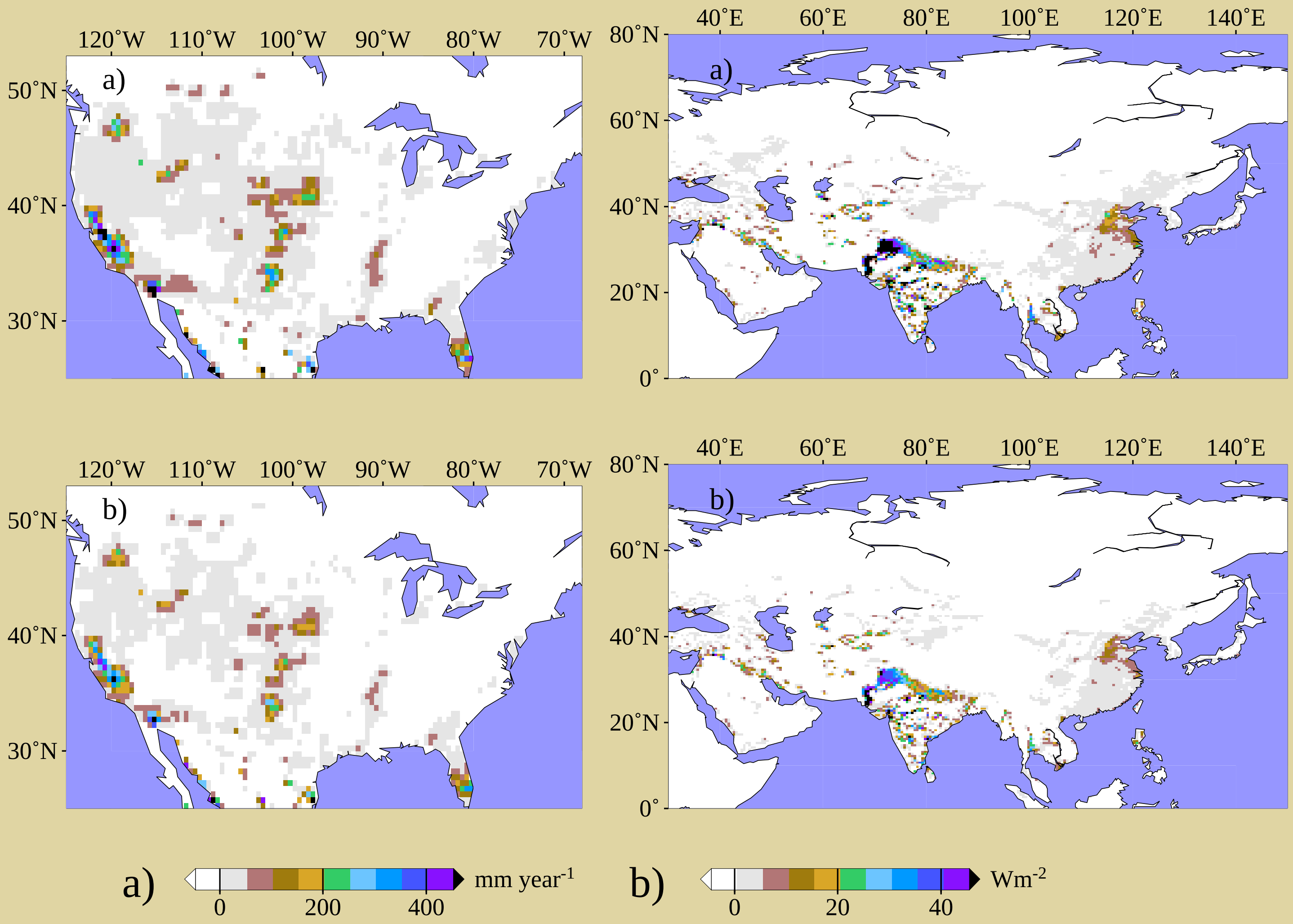


Irrigation scheme: Validation



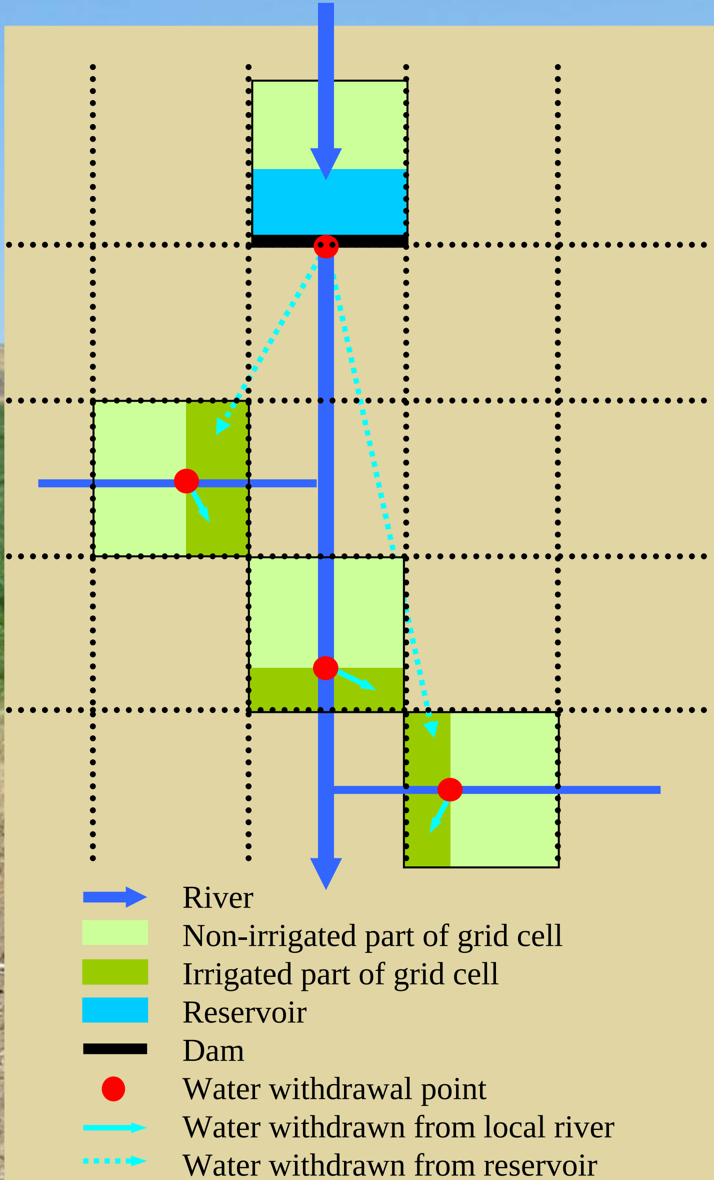
a) Mean annual simulated irrigation water requirements compared to irrigation water use in USA. b) Mean annual simulated and reported irrigation water requirements for countries in Asia. c) The lower values shown in b).

Irrigation water requirements



a) Irrigation water requirements. b) Corresponding increases in latent heat fluxes

Reservoir model



1st priority: Irrigation water demand

2nd priority: Flood control

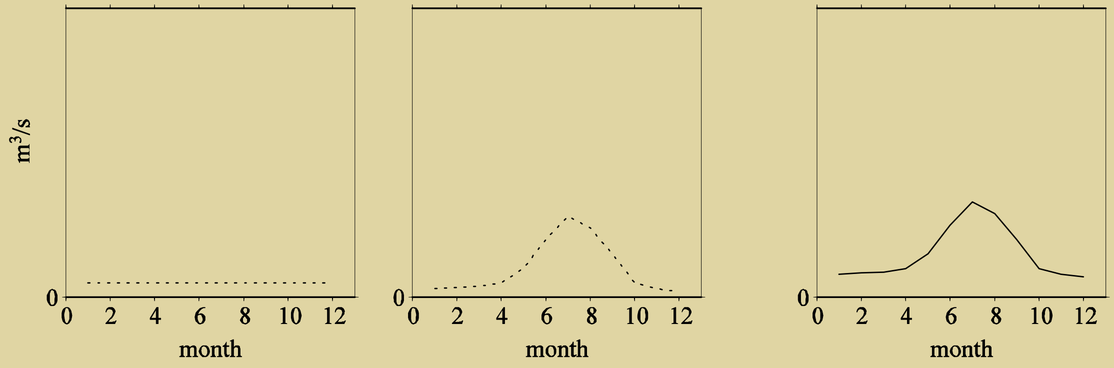
3rd priority: Hydropower production

If no flood, no hydropower:

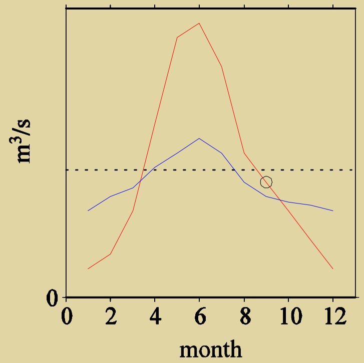
Make streamflow as constant as possible

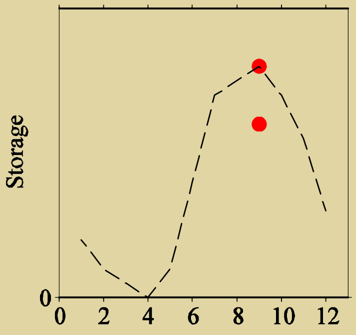
Reservoir model

7q10
+
irrigation water requirements:



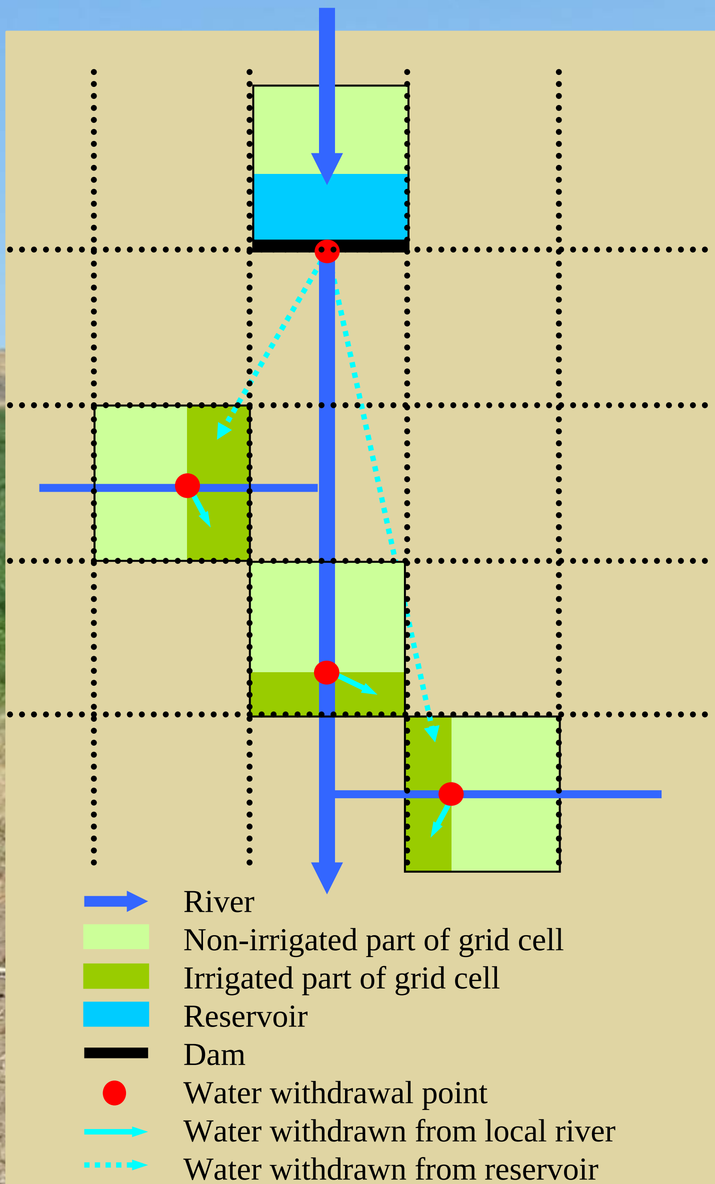
"Naturalized" inflow
Simulated inflow
Operational year
Storage settings





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

Reservoir model



1st priority: Irrigation water demand
2nd priority: Flood control
3rd priority: Hydropower production

If no flood, no hydropower:
Make streamflow as constant as possible

Objective functions used to optimize Q:

Irrigation: $\min \sum_{i=1}^{365} \left(Q_{d_i} - Q_{r_i} \right), Q_d > Q_r$

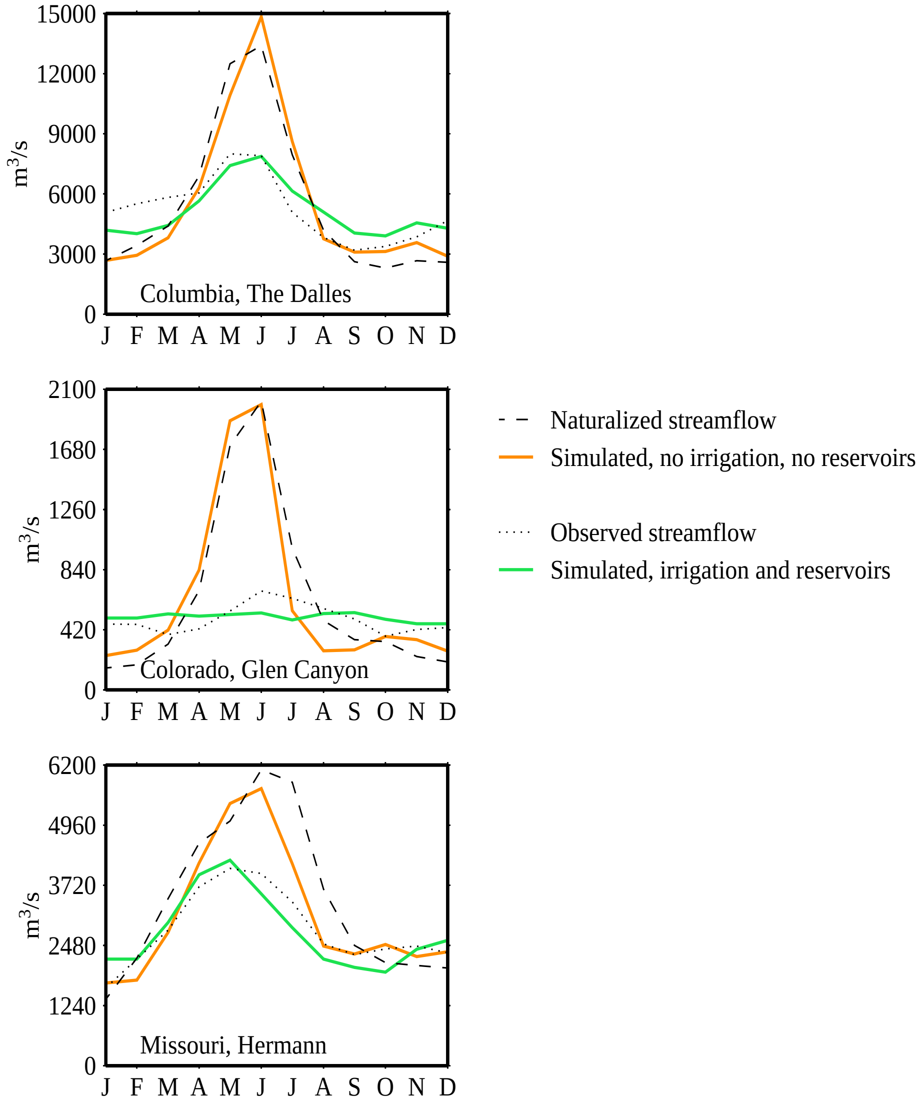
Flood protection: $\min \sum_{i=1}^{365} \left(Q_{r_i} - Q_{flood} \right)^2, Q_r > Q_{flood}$

Hydropower: $\min \sum_{i=1}^{365} \frac{1}{Q_{r_i} \rho \eta h g}$

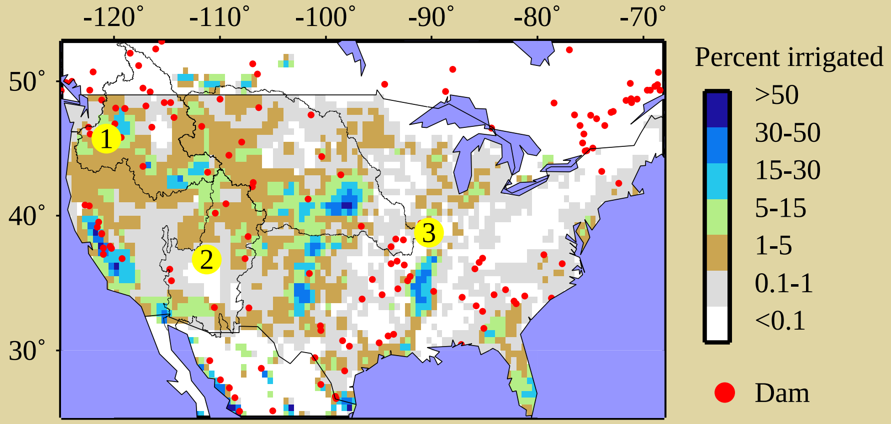
Water supply, navigation: $\min \sum_{i=1}^{365} \left| \left(Q_{r_i} - Q_{mean} \right) \right|$

Optimization scheme: SCEM-UA algorithm of Vrugt et al. (*Water Resources Research*, 2003)

Reservoir model: Evaluation

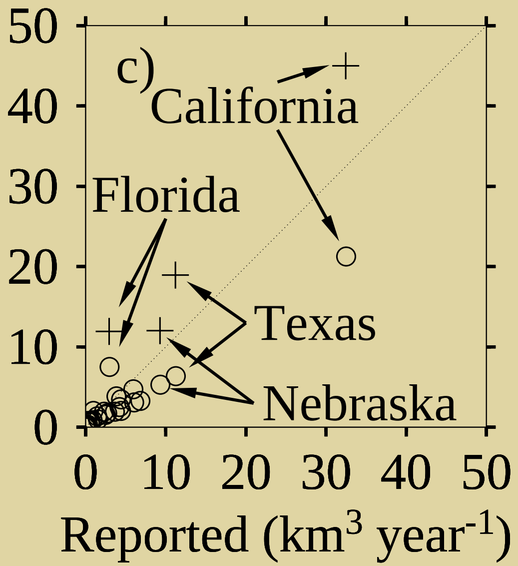


Model evaluation:
1) Columbia, 2) Colorado, and 3) Missouri River basins



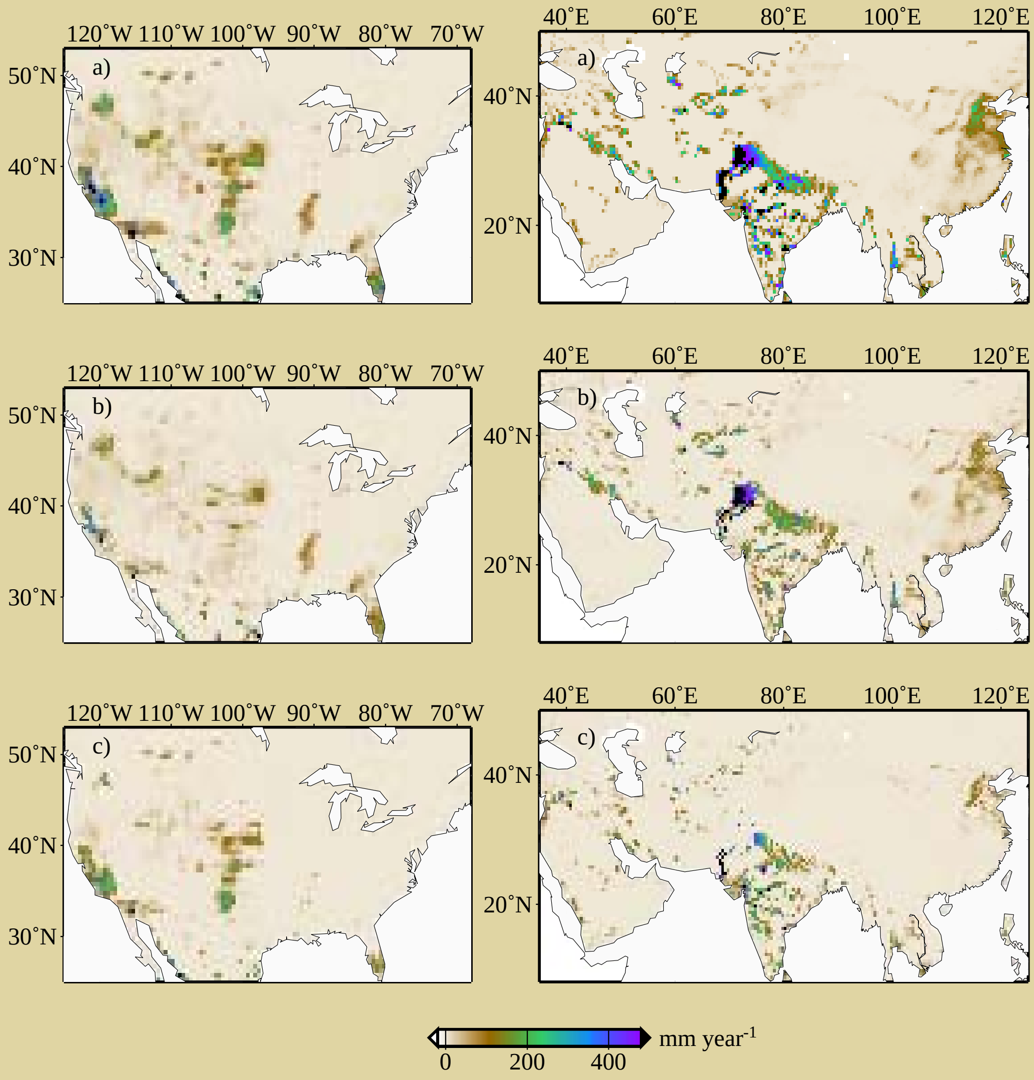
Irrigation water use: Validation

- Mean annual simulated and reported irrigation water use (o) and simulated irrigation water requirements (+) in the conterminous USA.



- Groundwater withdrawals
- Diversions

Results: Irrigation water



a) Irrigation water requirements
b) Irrigation water uses
c) Irrigation water deficits

Irrigation water requirements

NLDAS: 18 mm year^{-1}

Asia: 16 mm year^{-1}

Irrigation water uses

NLDAS: 10 mm year-1

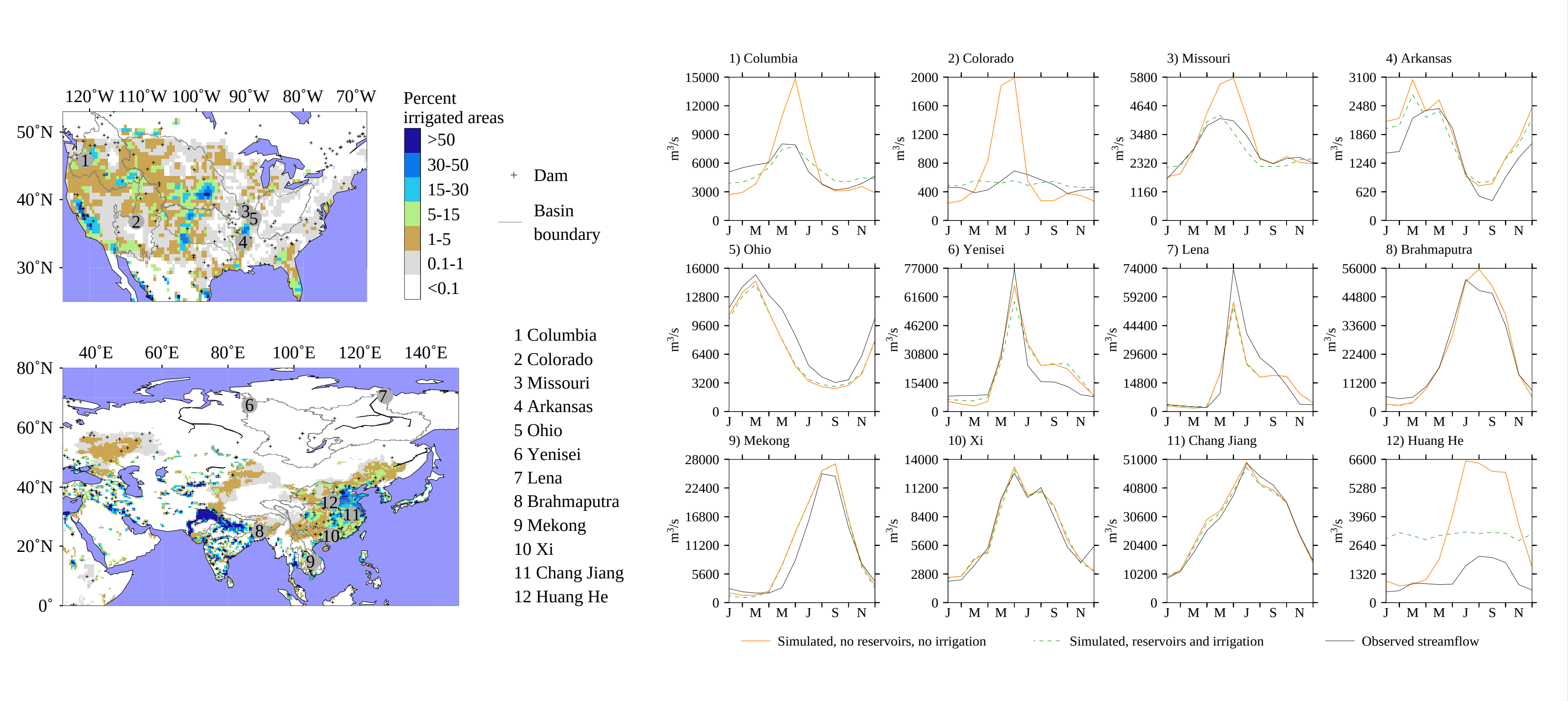
Asia: 10 mm year-1

Global terrestrial

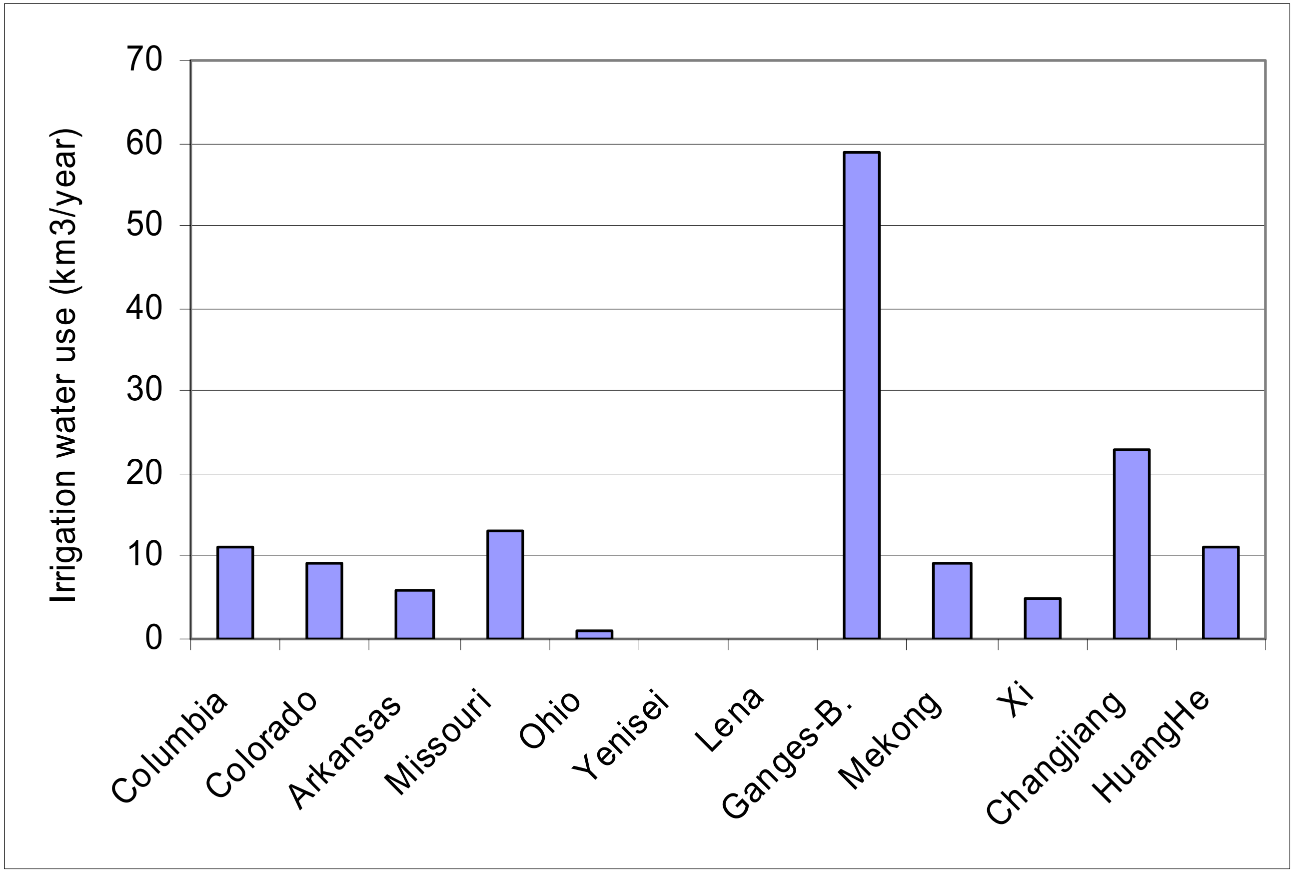
- precipitation: 800 mm year^{-1}
- evapotr.: 400 mm year^{-1}

Haddeland, I., T. Skaugen, and D.P. Lettenmaier, 2006, Continental-scale water resources modeling, Nordic Hydrological Conference

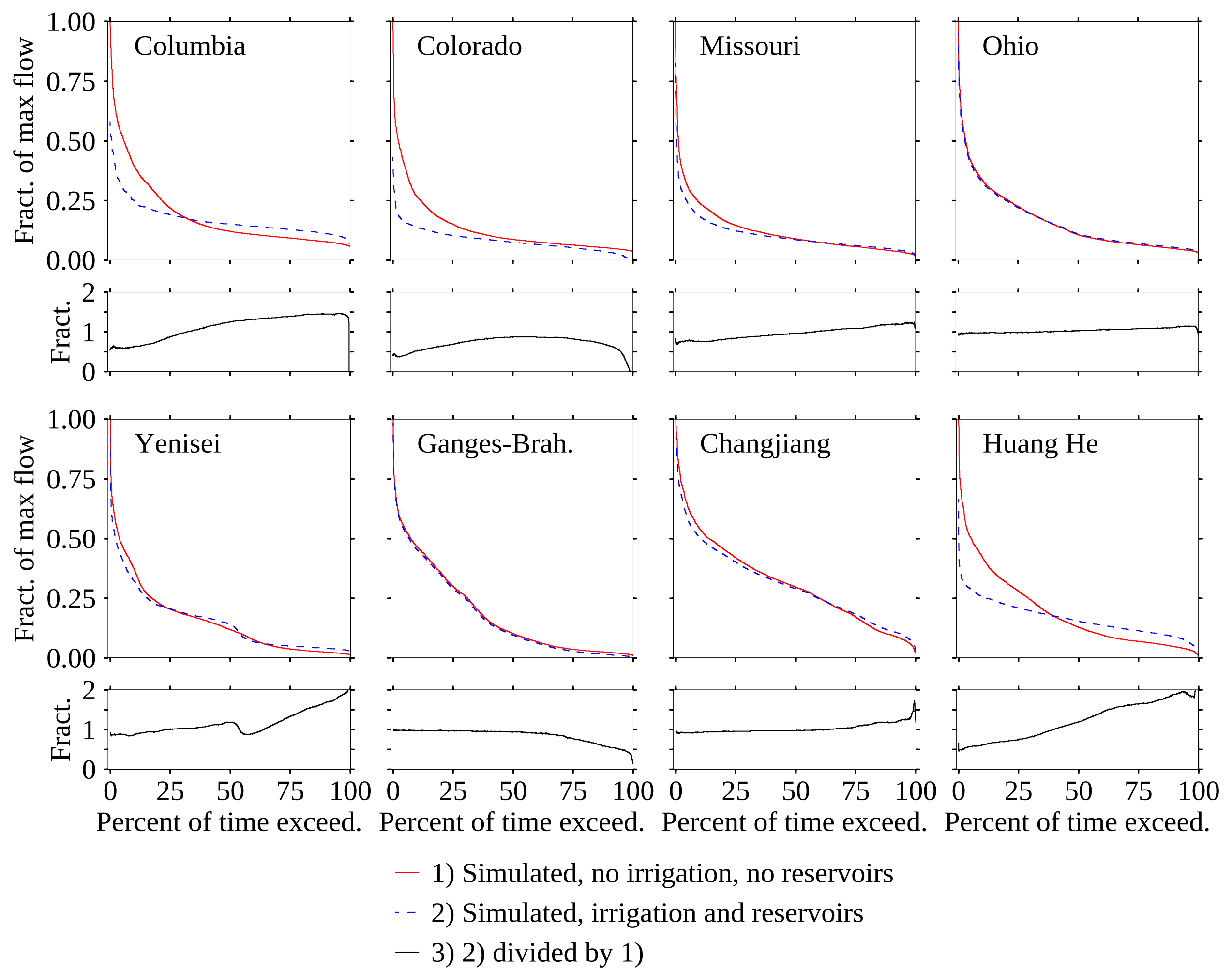
Results: Streamflow



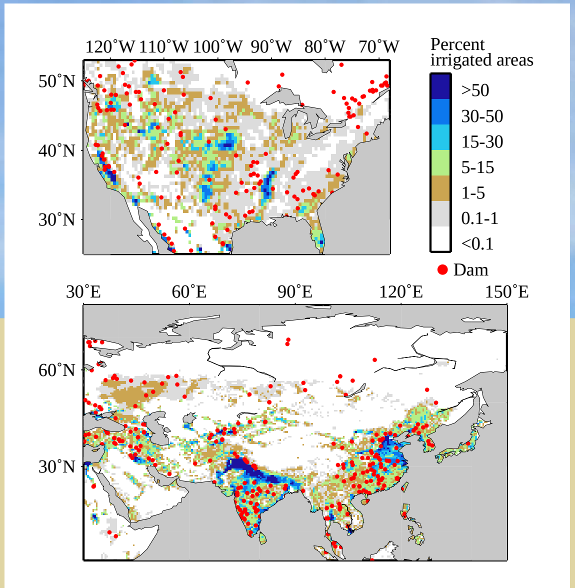
Results: Irrigation water use

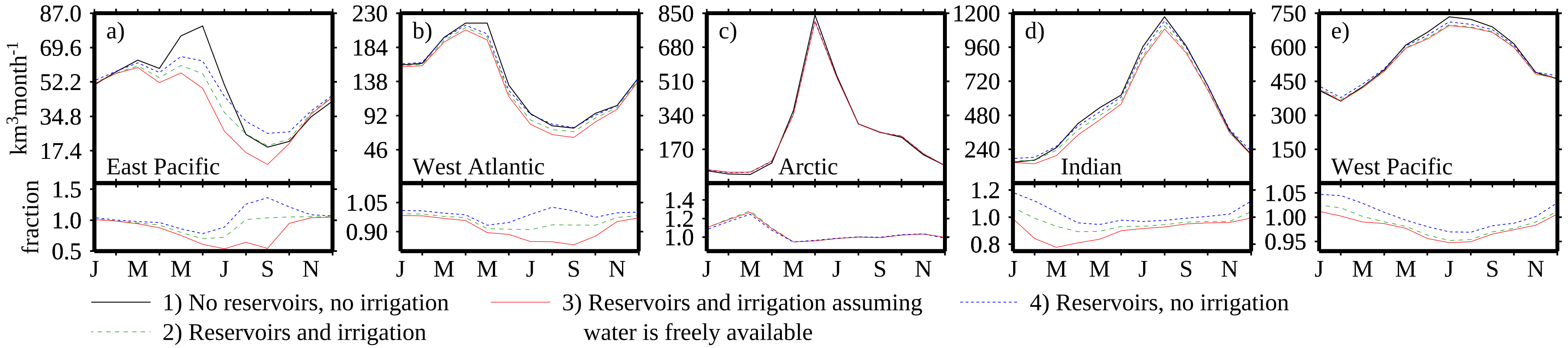


Results: Flow duration curves



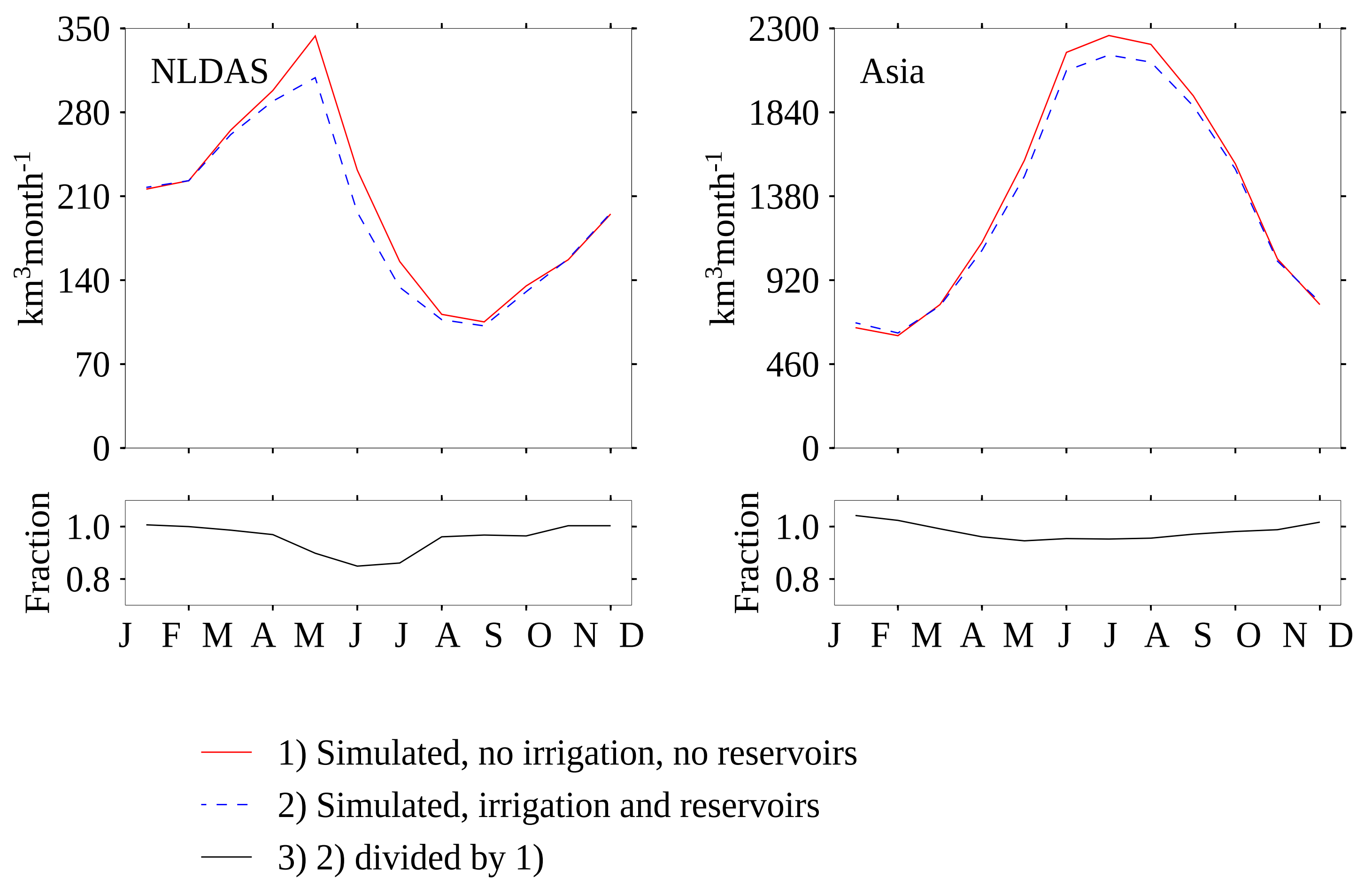
Results: Streamflow



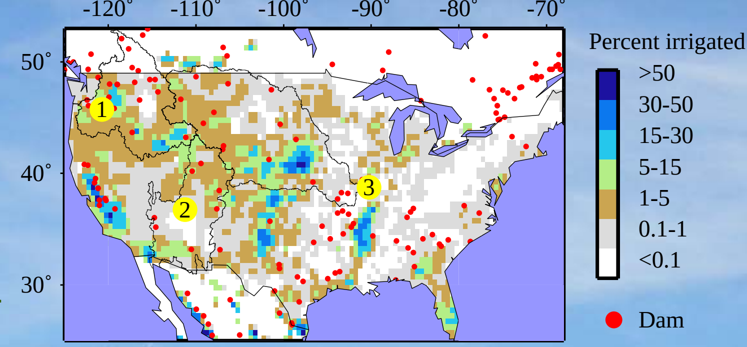


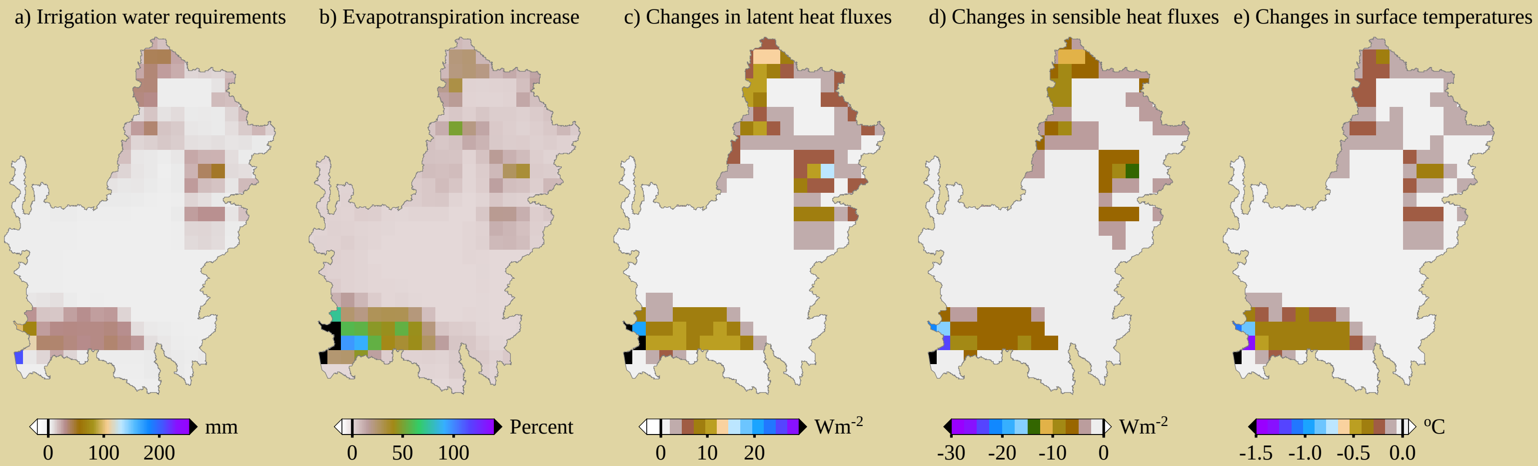
Effects on freshwater fluxes reaching the oceans. a) and b) represent rivers draining the NLDAS region to the Pacific and Atlantic Oceans, respectively. c) represents rivers draining northwards to the Arctic Ocean in the Asian region, while d) and e) represent river draining Asia to the Indian and Pacific Oceans, respectively. The lower panels show the results of simulations 2 through 4 divided by simulation 1.

Results: Continental streamflow



The Colorado River basin





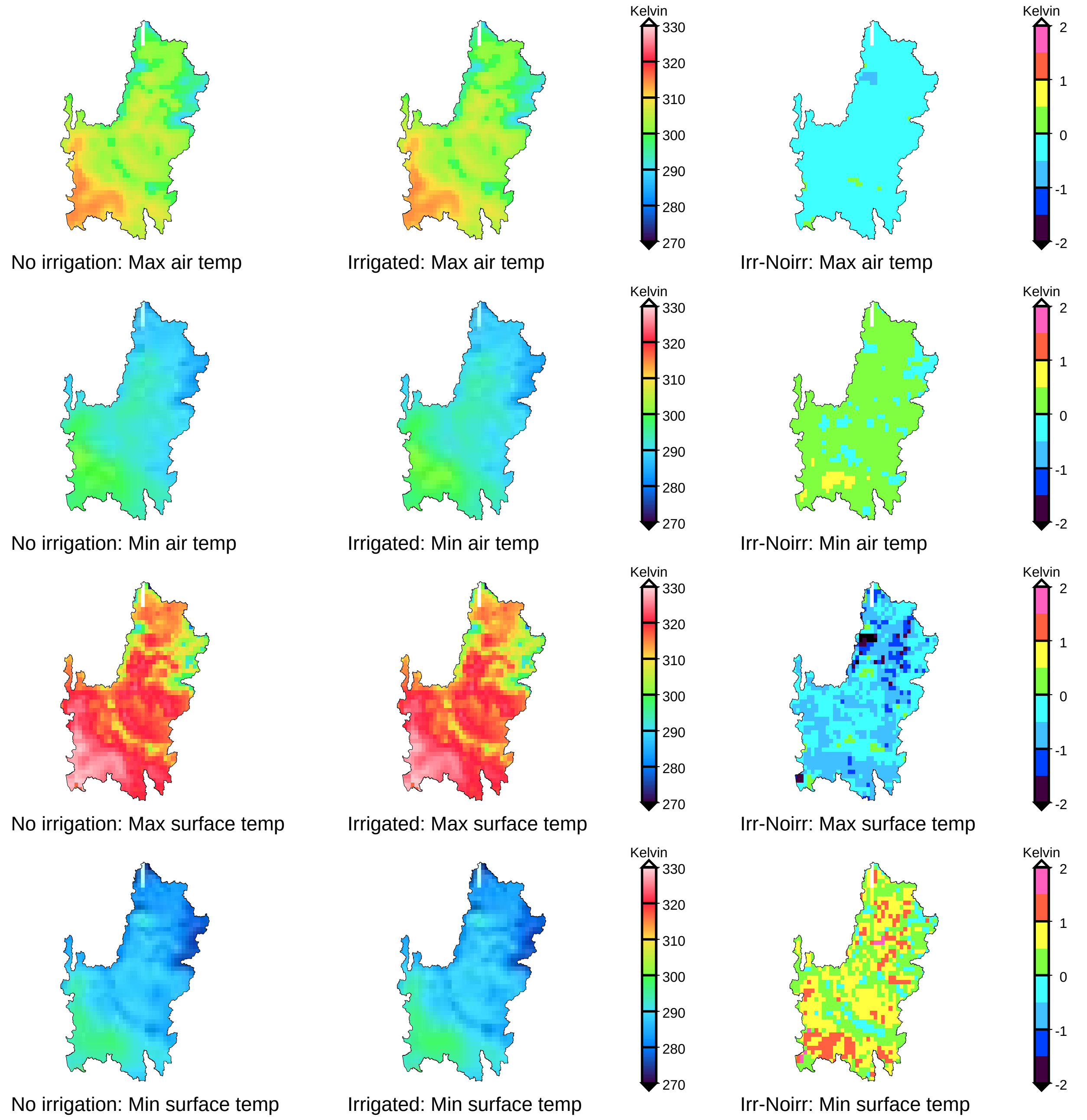
- Naturalized:
  - Q: 42.3 mm year^{-1}
  - ET: 335 mm year^{-1}
- Irrigation included:
  - Q: 26.5 mm year^{-1}
  - ET: 350 mm year^{-1}

RCM-VIC

Effects of irrigation on air and surface temperatures

Colorado River basin

Mean results, July 2003



Conclusions

- The model does a reasonable job of reproducing the effects of management on selected large rivers.
- Reservoirs and crop irrigation water use has the potential of altering the natural hydrologic water balance of river basins.
- 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.
- Averaged over larger regions, the changes in heat fluxes and surface temperature are small, but locally the changes can be significant.

References

Haddeland, I., D.P. Lettenmaier, and T. Skaugen, 2006, Effects of irrigation on the water and energy balances of the Colorado and Mekong River basins, *Journal of Hydrology* (in press)

Haddeland, I., T. Skaugen, and D.P. Lettenmaier, 2006, Anthropogenic impacts on continental surface water fluxes, *Geophysical Research Letters* (in press)