Modeling the impact of irrigation area changes and anthropogenic water regulation on terrestrial hydrological cycle

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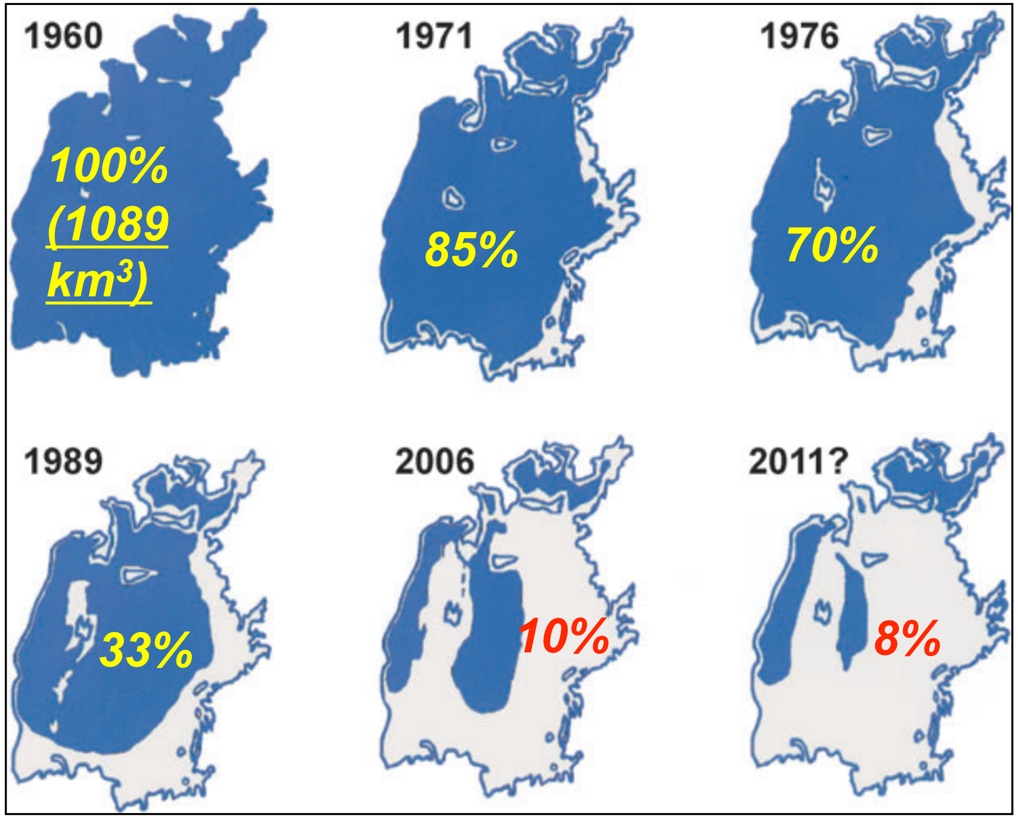
Pat J.F. Yeh (U. Tokyo)
Taikan Oki (U. Tokyo)
and more

What is happening in the world?

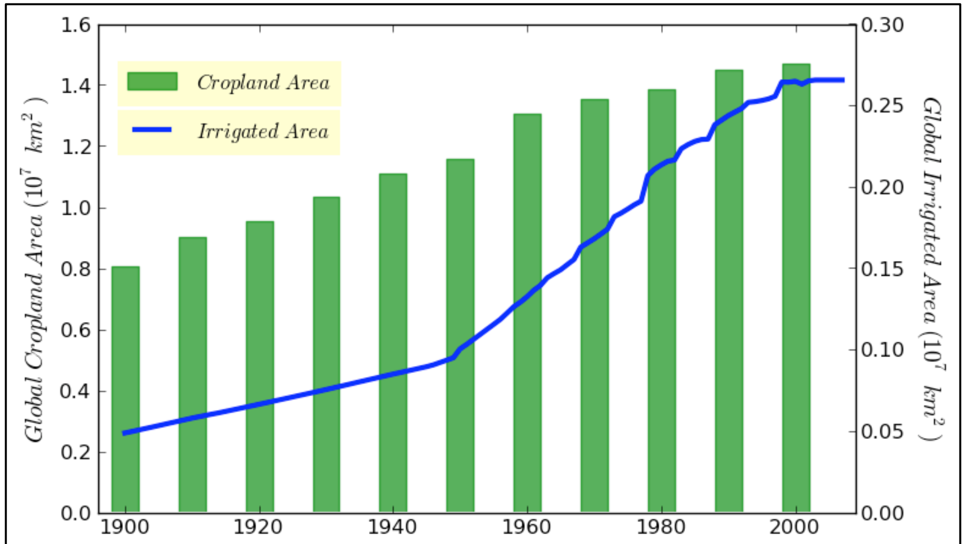
Disappearing the “Aral Sea” Lake



Micklin, 2007

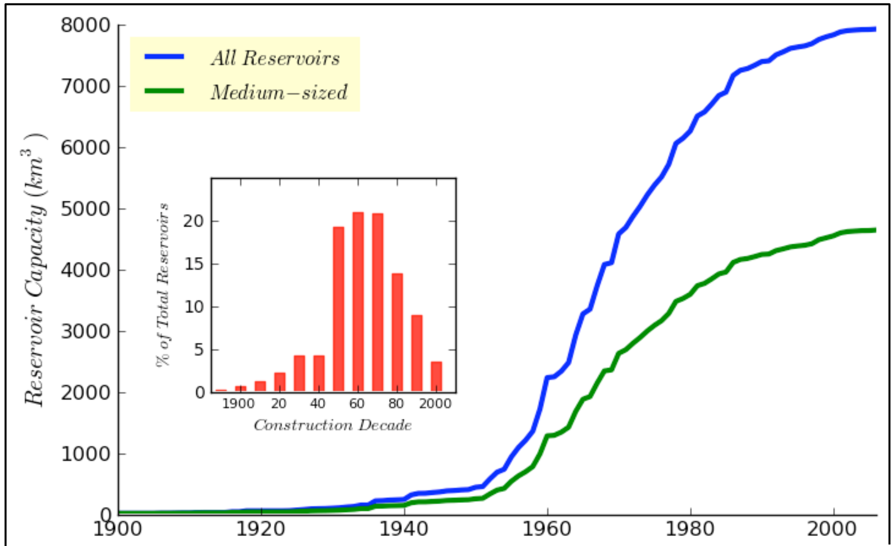
What is happening in the world?

Crop Area and Irrigation Area



1900 — 1950 — 2000

Reservoir Capacity (Total and Medium)



1900 — 1950 — 2000

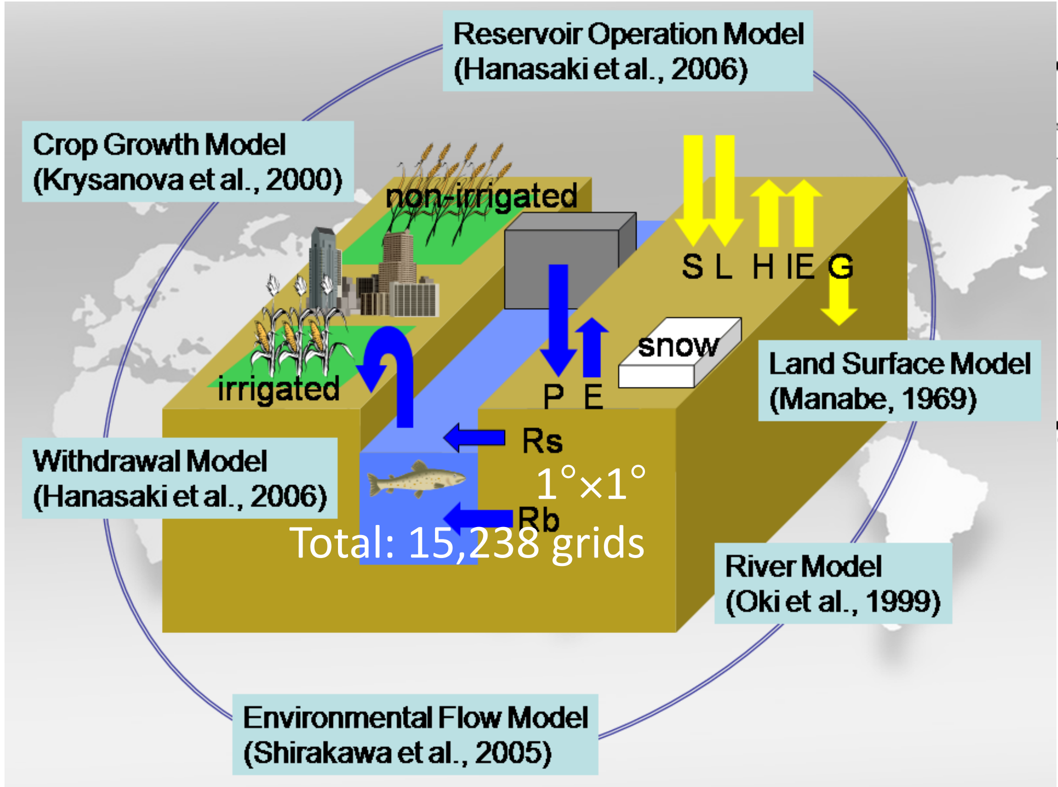
~70% of withdrawal, ~90% of withdrawal, is water for agriculture

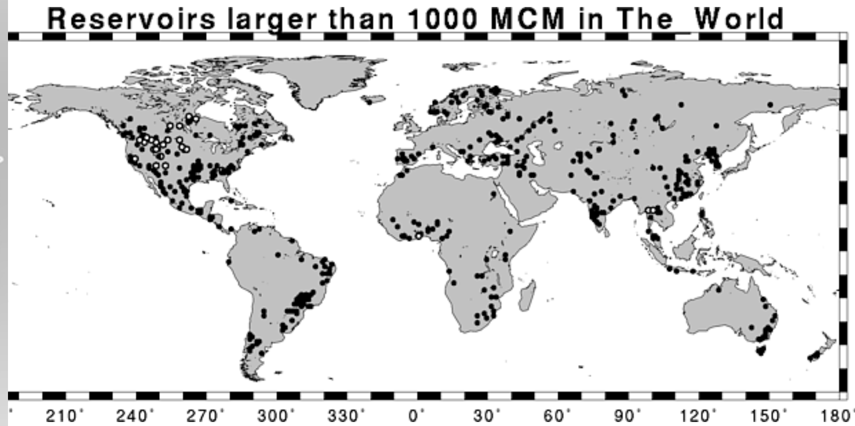
In order to address *Global Water Crisis* caused by human activities such as irrigation and reservoirs;

Two global models are introduced here.

Hanasaki et al., 2006, J. of Hydrol.
Hanasaki et al. ,2008a,b, Hydrol. Earth Sys. Sci.

Model 1: Global water resources model "H08"



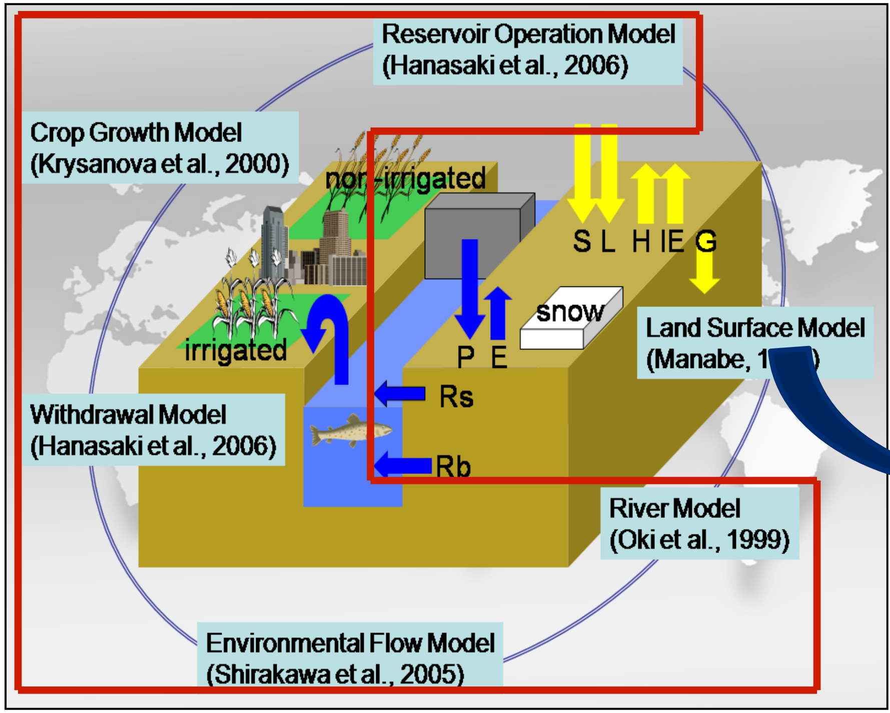


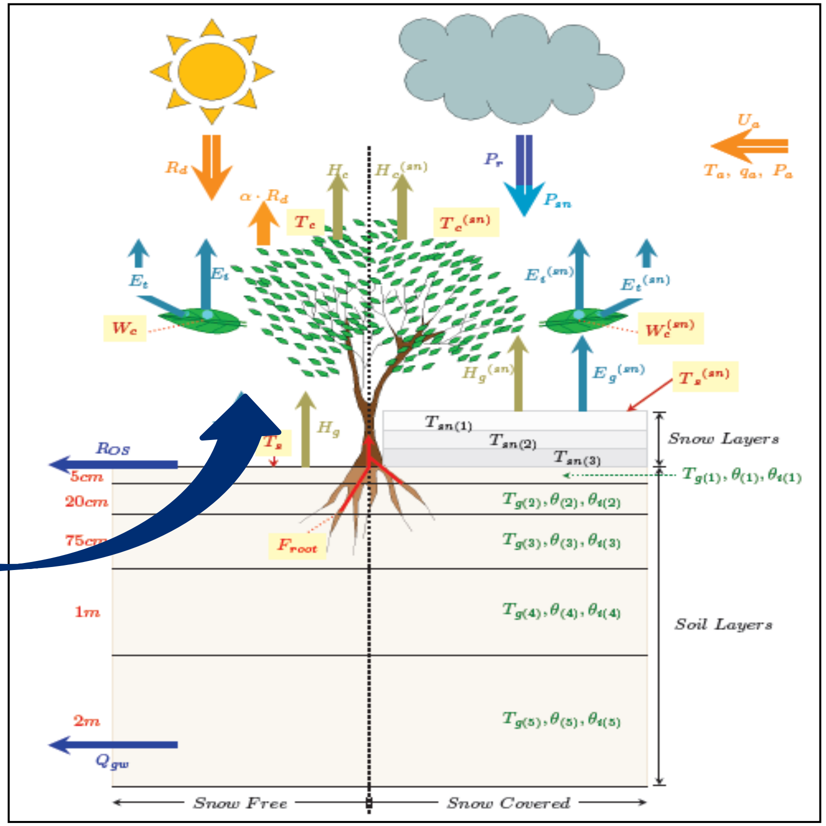
452 reservoirs, 4140 km^3
(nearly half of global total)

1. Energy balance and Water balance (≒Bucket)
2. Anthropogenic activities
   - Irrigation (and other water withdrawals)
   - Reservoir operations

Model 2: H08 + MATSIRO

Pokhrel et al., 2011, J. Hydrometeor..





Anthropogenic activities
- Irrigation (and other)
- Reservoir operations

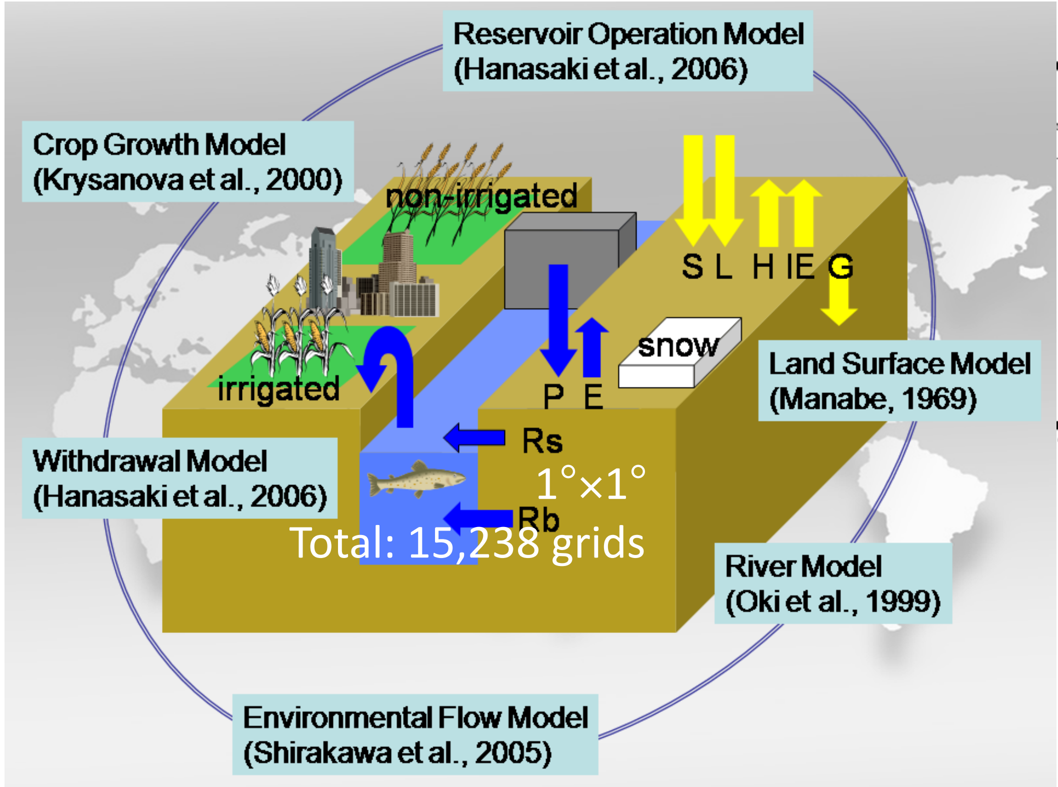
+

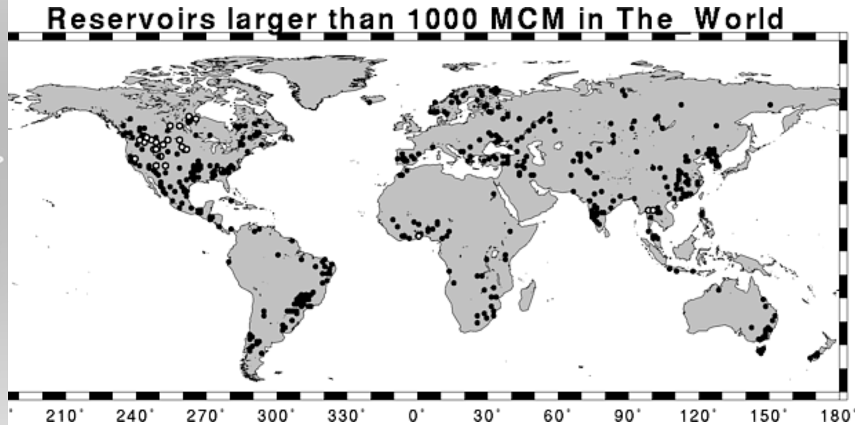
MATSIRO
- SiB2 type land surface model
- Land surface of MIROC GCM

Numerical Model 1

Hanasaki et al., 2006, J. of Hydrol.
Hanasaki et al. ,2008a,b, Hydrol. Earth Sys. Sci.

Model 1: Global water resources model "H08"





452 reservoirs, 4140 km^3

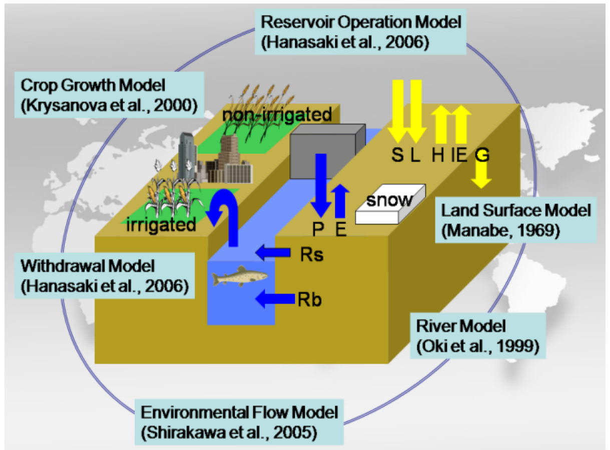
1. Energy balance and Water balance (≒Bucket)
2. Anthropogenic activities
   - Irrigation (and other water withdrawals)
   - Reservoir operations

Further development to Model 1

- The sources of water for agriculture
  - Precipitation
  - Irrigation water
    - Streamflow
    - Reservoirs and ponds
    - Deep groundwater

Renewable, Sustainable

Non-renewable, Non-sustainable



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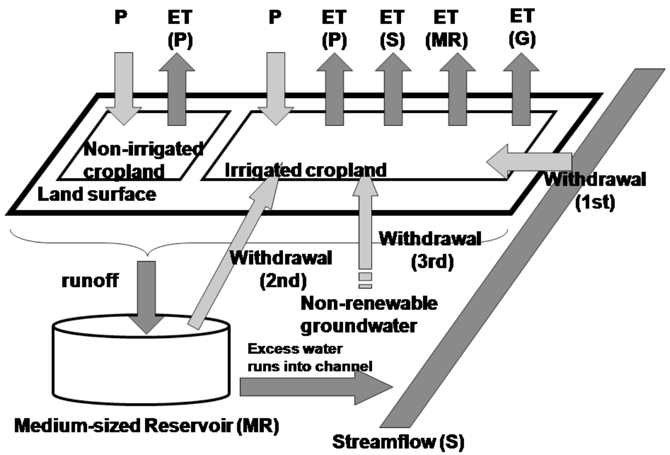
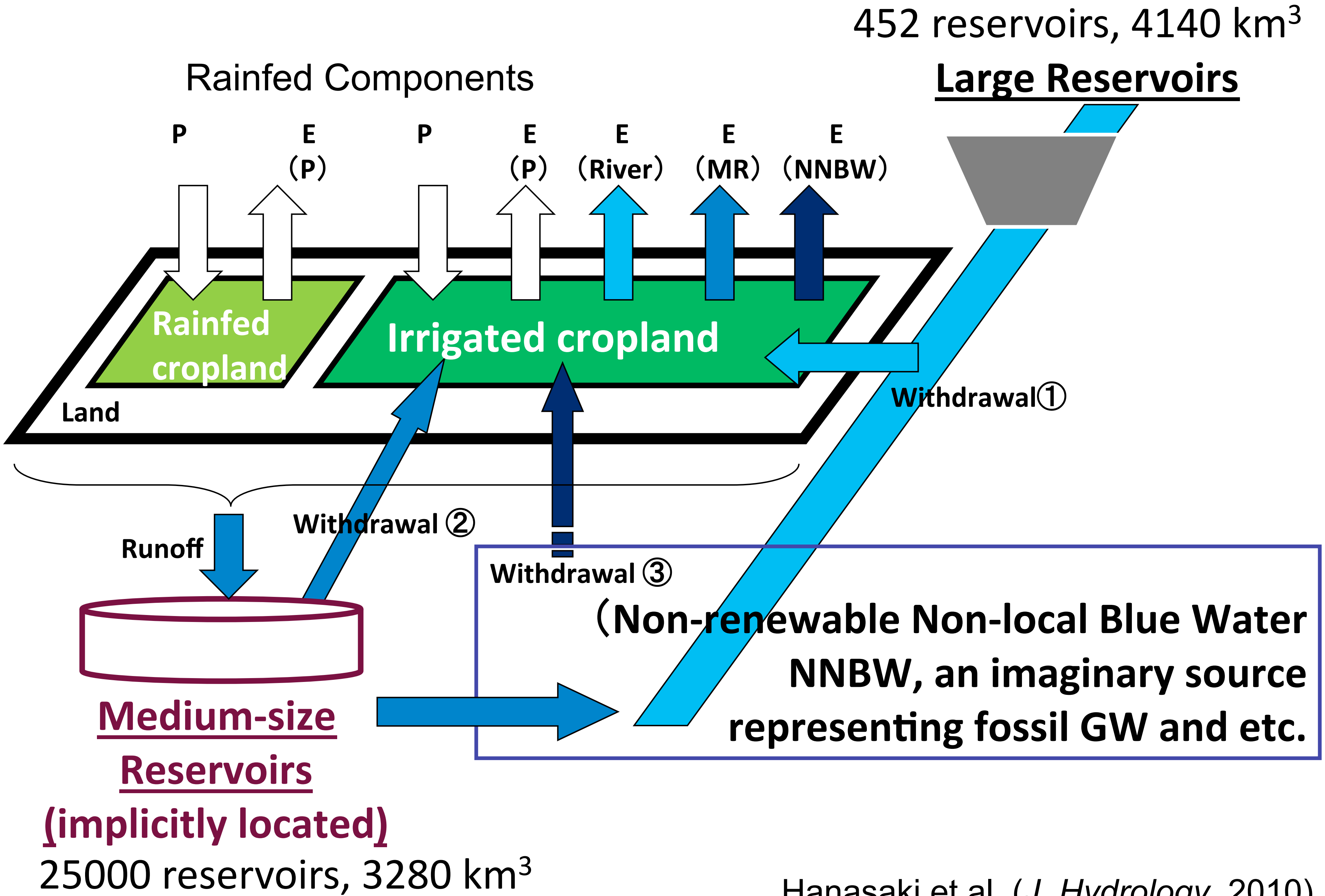
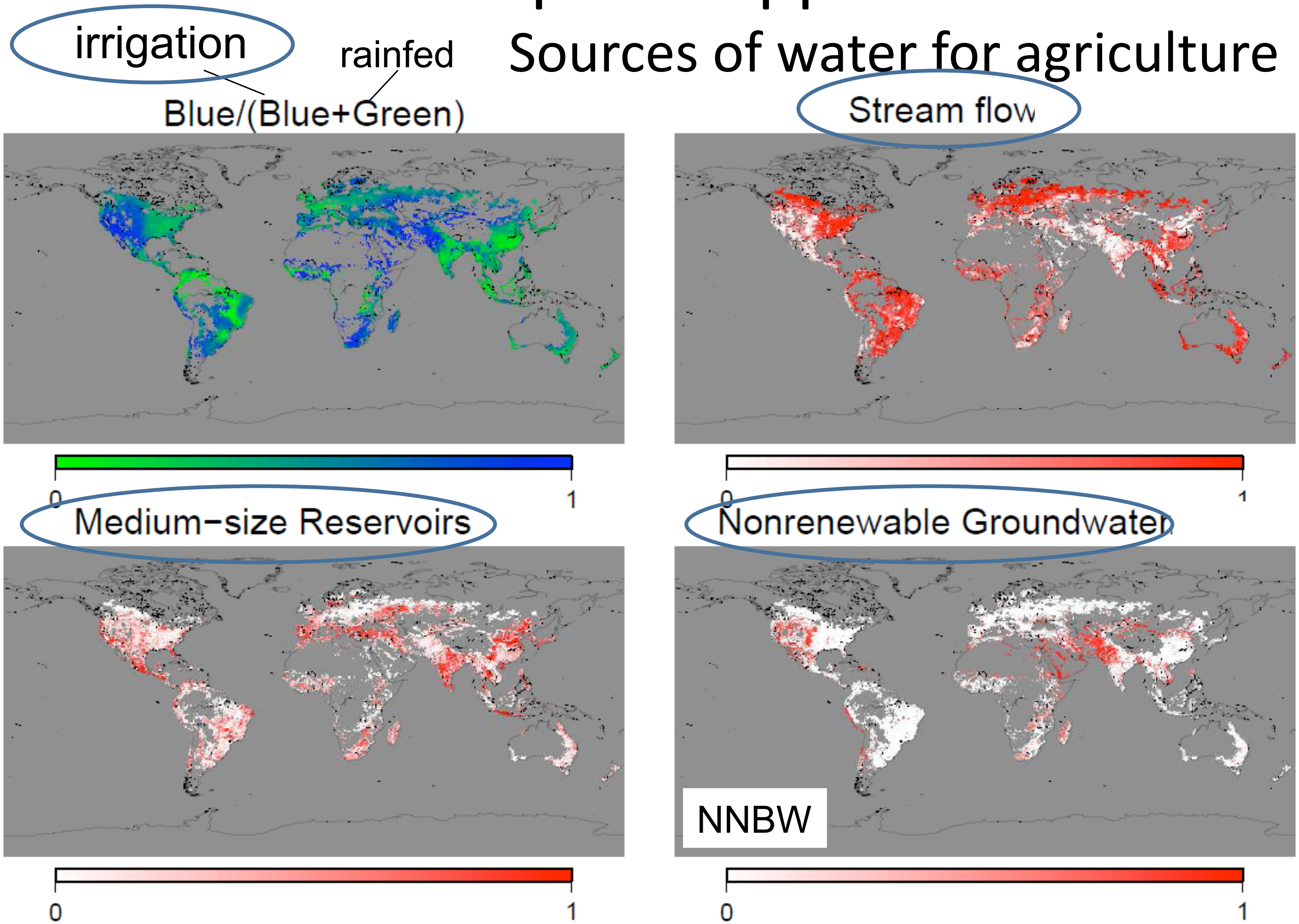




Hanasaki et al. (*J. Hydrology*, 2010)

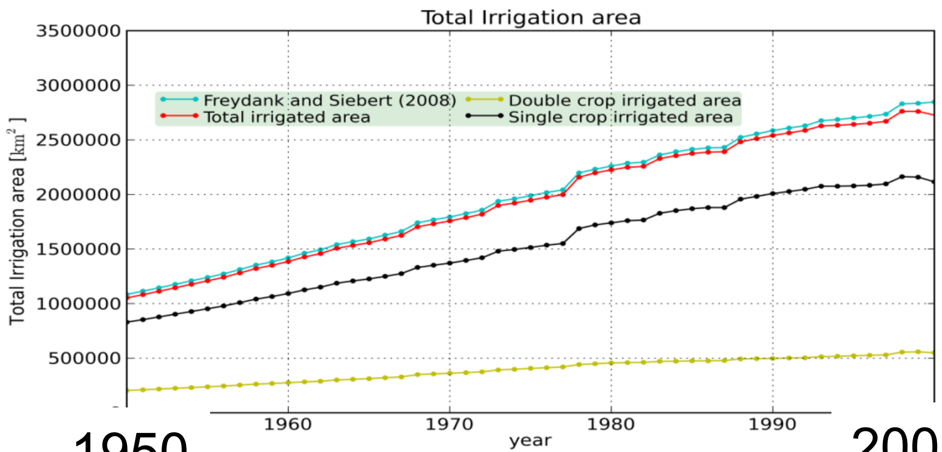
An example of application of H08

Sources of water for agriculture



A hindcast 1950-2000 with Numerical Model 1

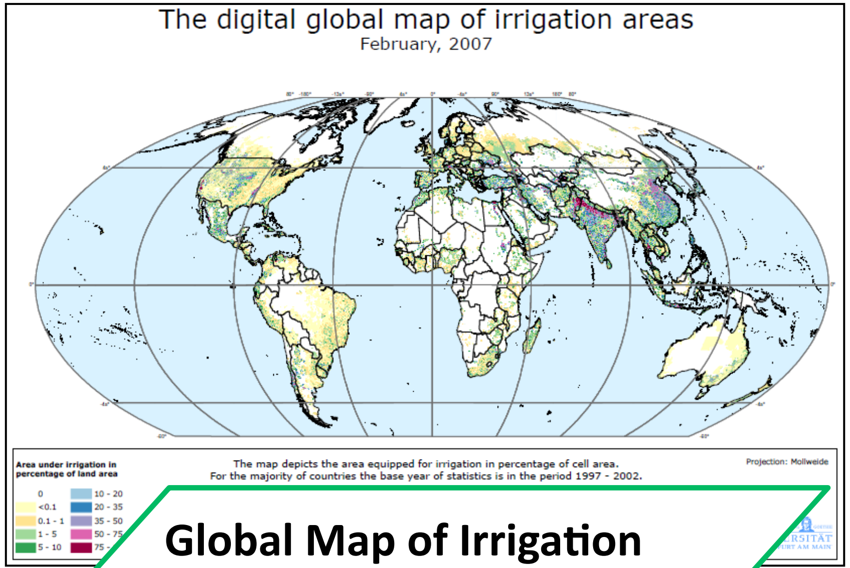
◎Irrigation Map for 1950-2000



1950 2000

Country Statistics 1950-2000

(Freydank and Siebert, 2008)



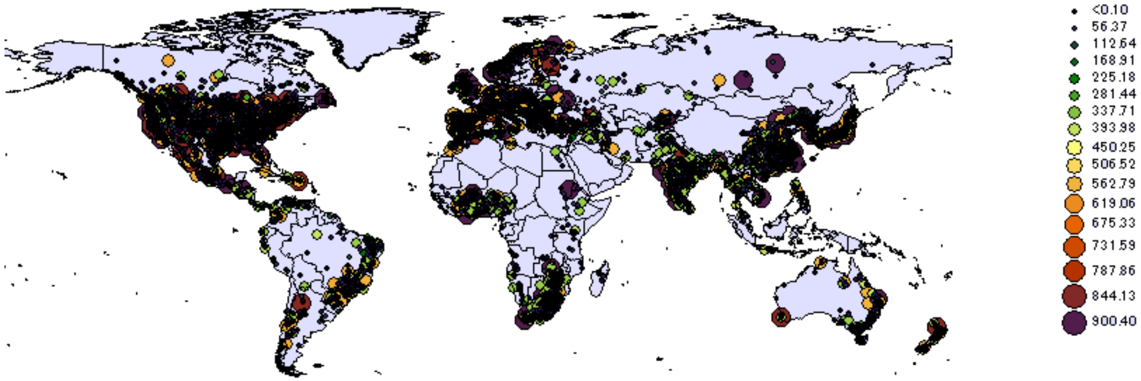
Global Map of Irrigation Areas at the year 2000

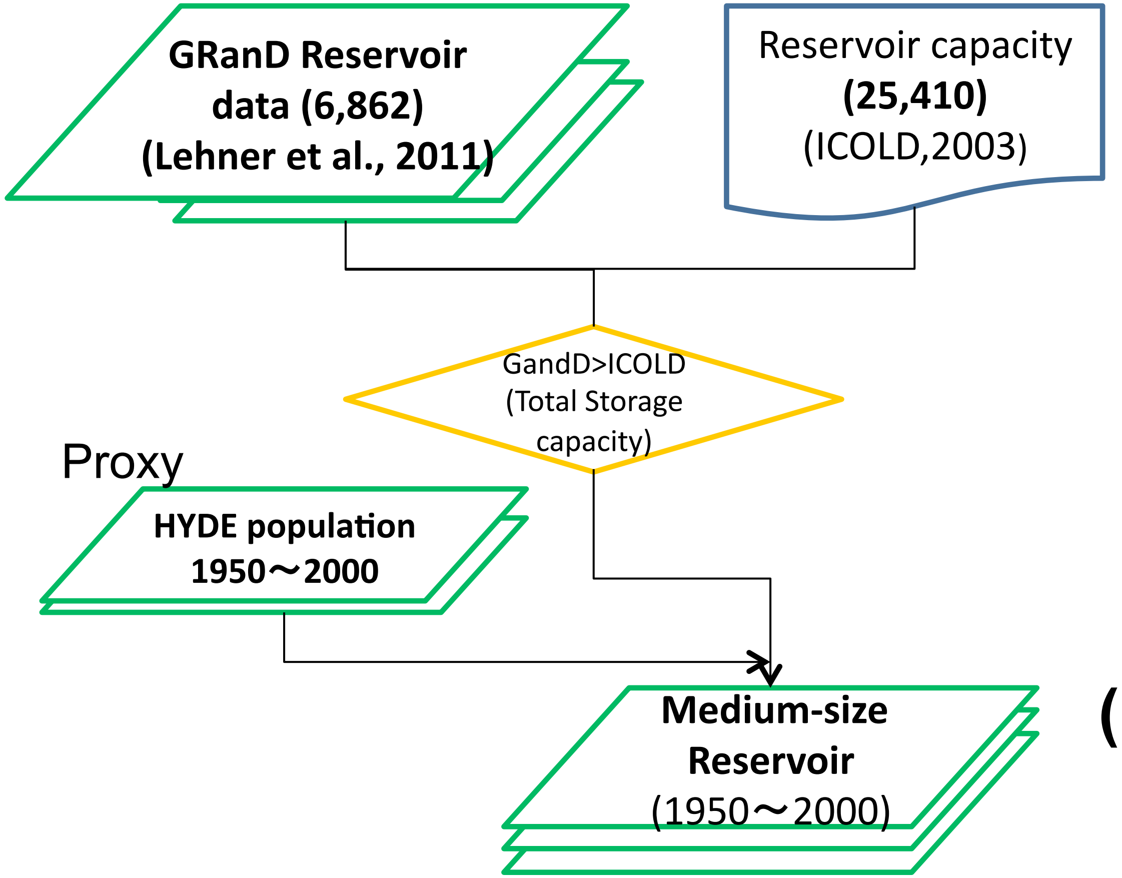
(Siebert et al., 2005)

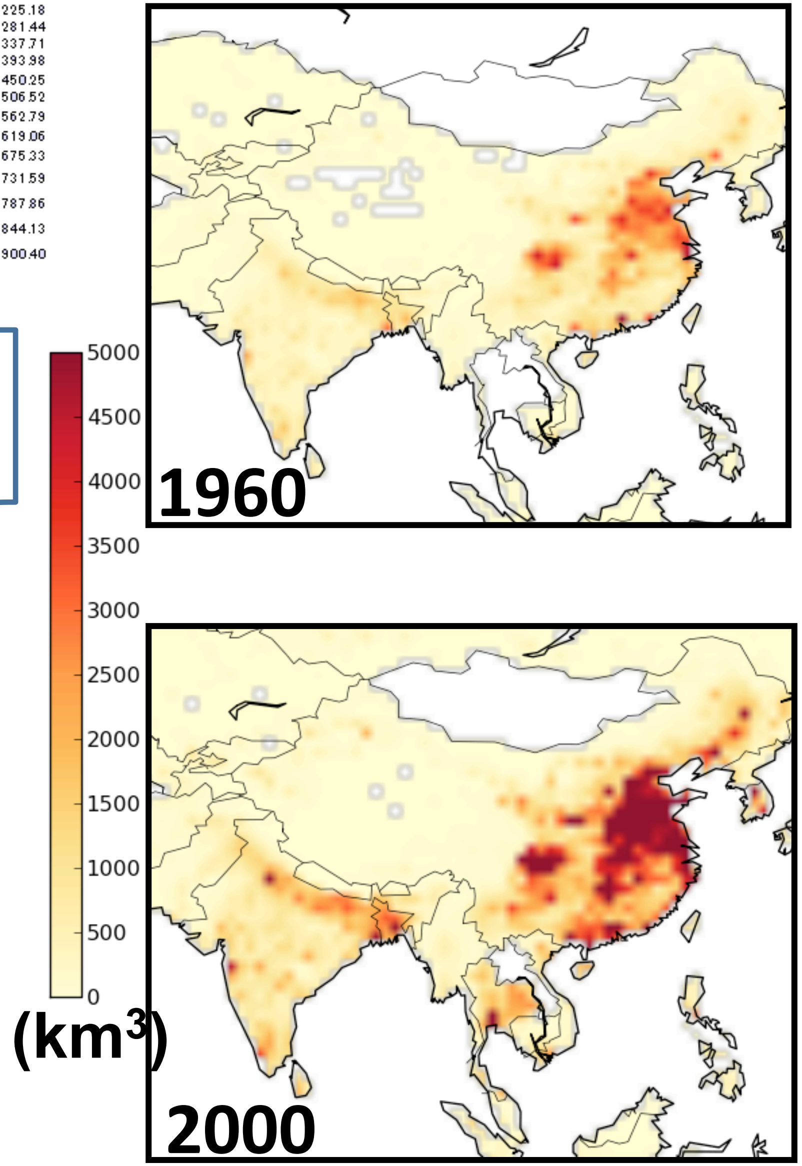
Historical Irrigation Area Map

(1950-2000)

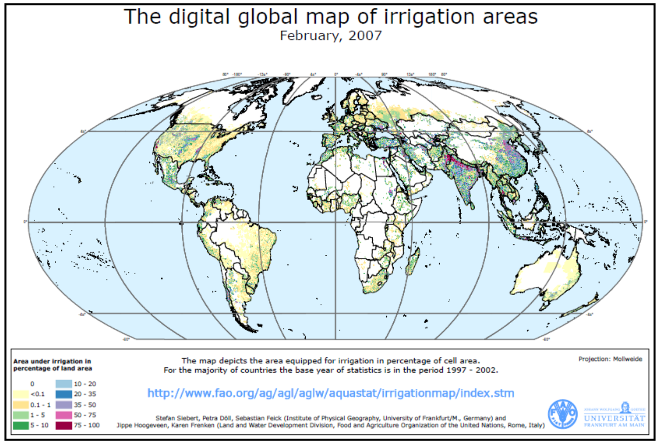
◎Medium-sized Reservoir Capacity 1950-2000



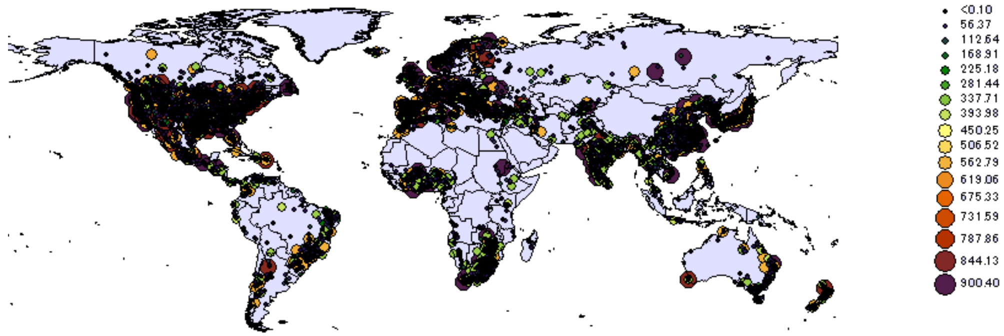




Hindcast 1950-2000

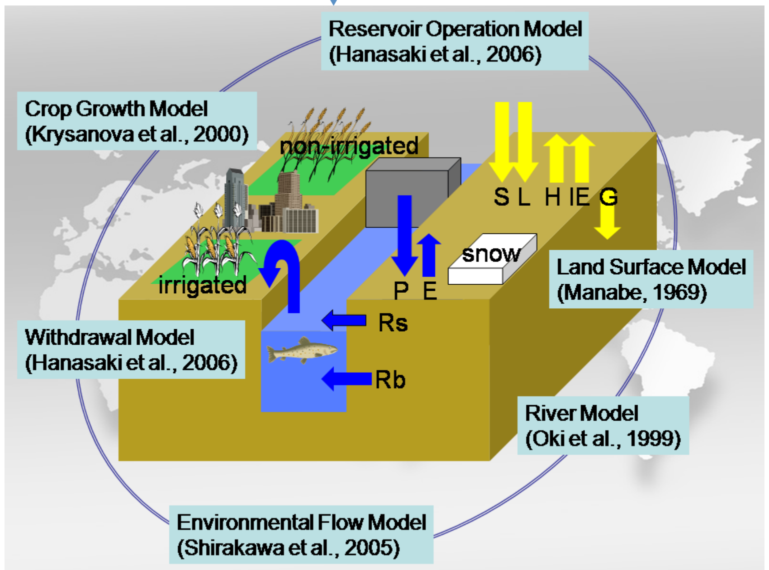


Irrigation Area

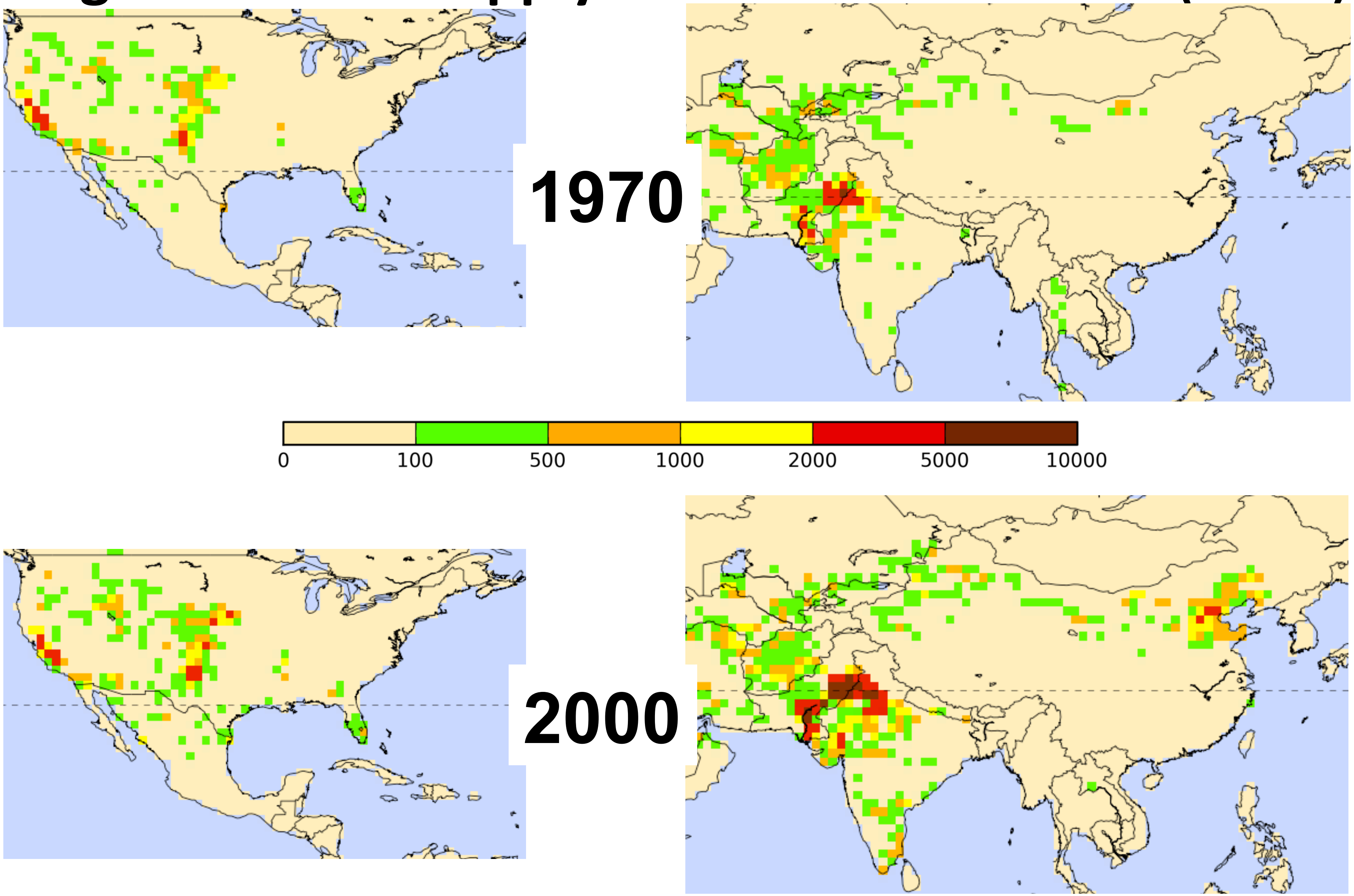


Reservoirs

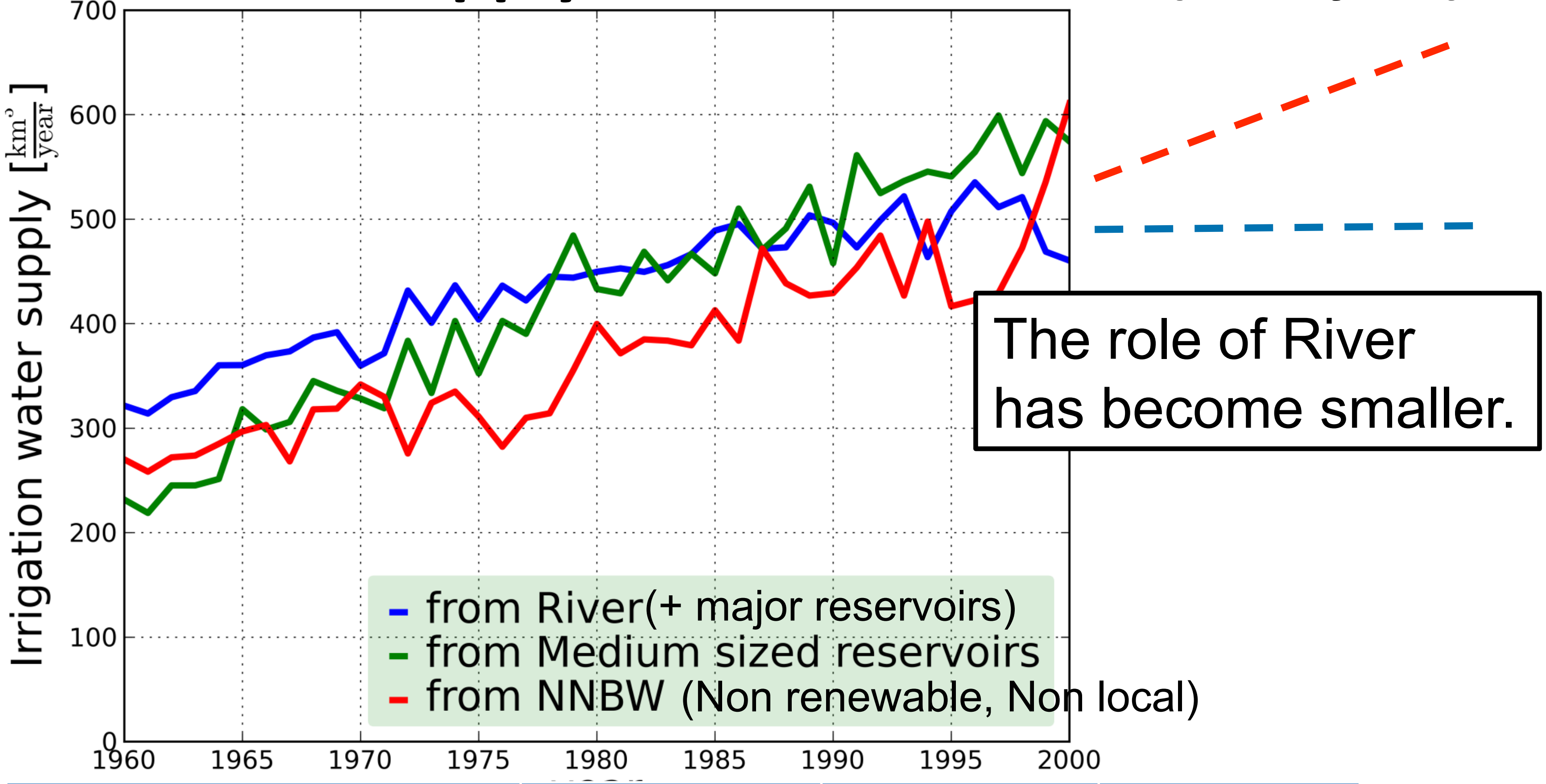
Climate Data



Result of Simulation 1950-2000: Irrigation water supply from Non-renewable (Mkm³)

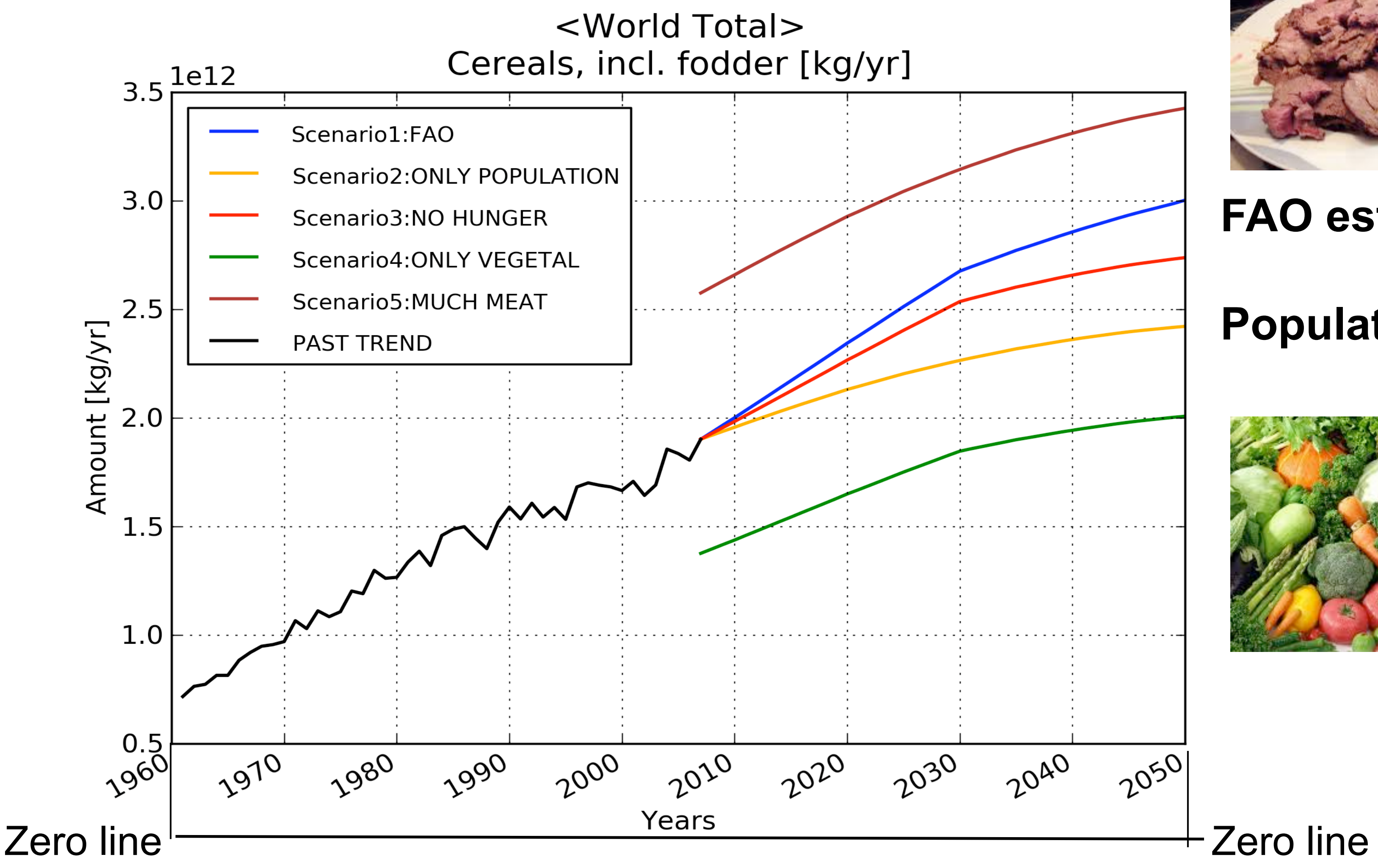


Result of Simulation:
Irrigation water supply from each source (km³/year)



Decade average	(a) 1960's	(b) 1990's	(b)/(a)
Irrigation area (km^2)	1,551,771	2,644,001	1.7
Medium-sized reservoirs (km^3)	1449	2967	2.0
Total water demand (km^3)	920	1504	1.6
Water supply from NNBW (km^3)	280(30.4%)	455(30.2%)	**1.6**

How much food do we need?



FAO estimates

Population only

Numerical Model 2

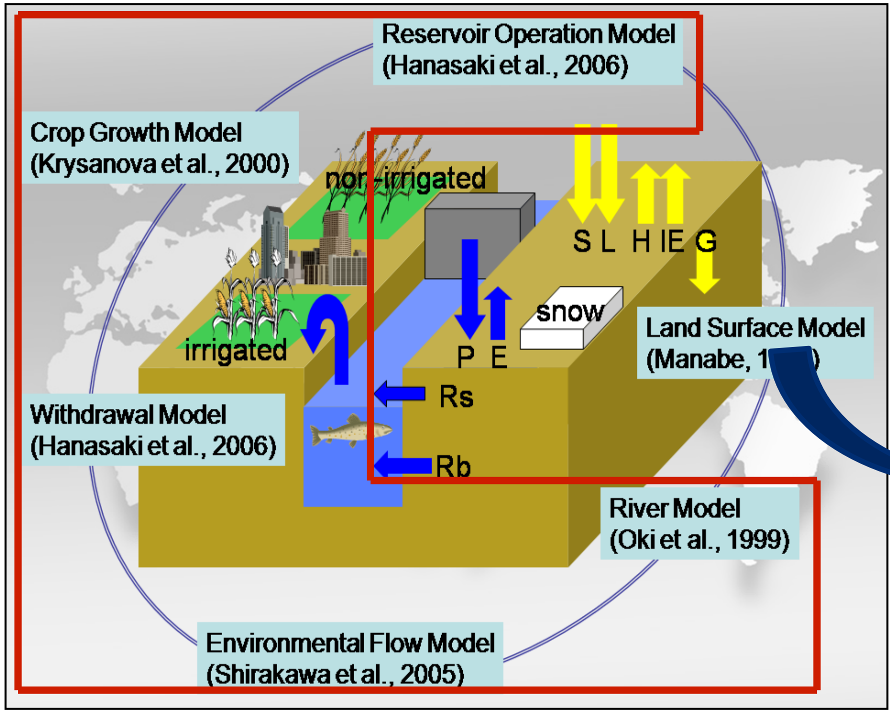
Replacing a Bucket model of Model 1
with a *state-of-the-art* Land Surface Model

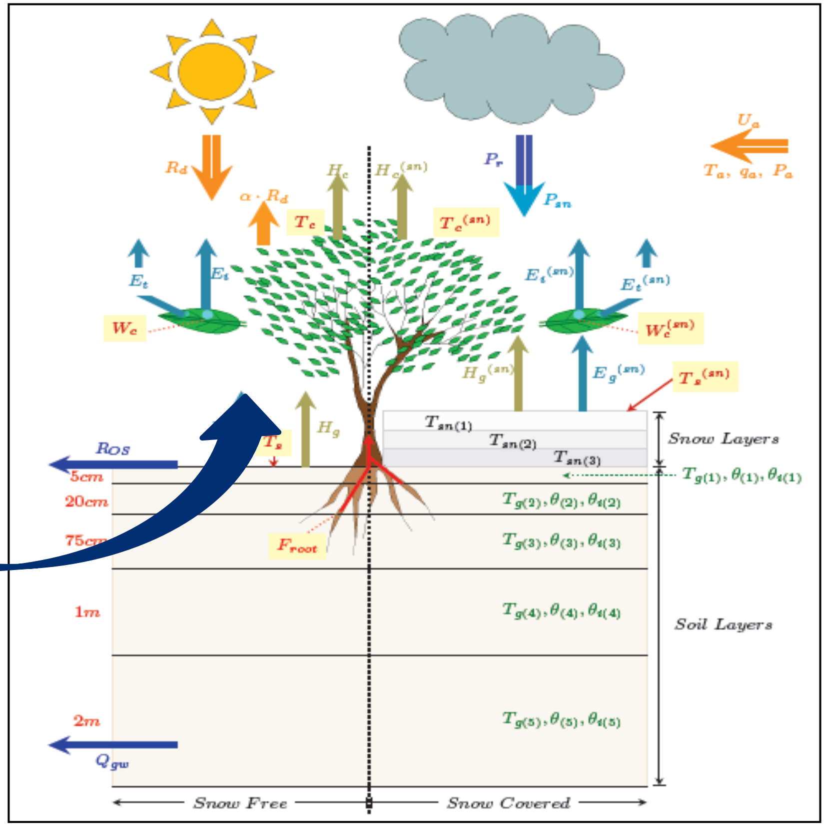
→ Water budget in dry areas/seasons has become better.

Snowmelt has become better.

Model 2: H08 + MATSIRO

Pokhrel et al., 2011, J. Hydrometeor..





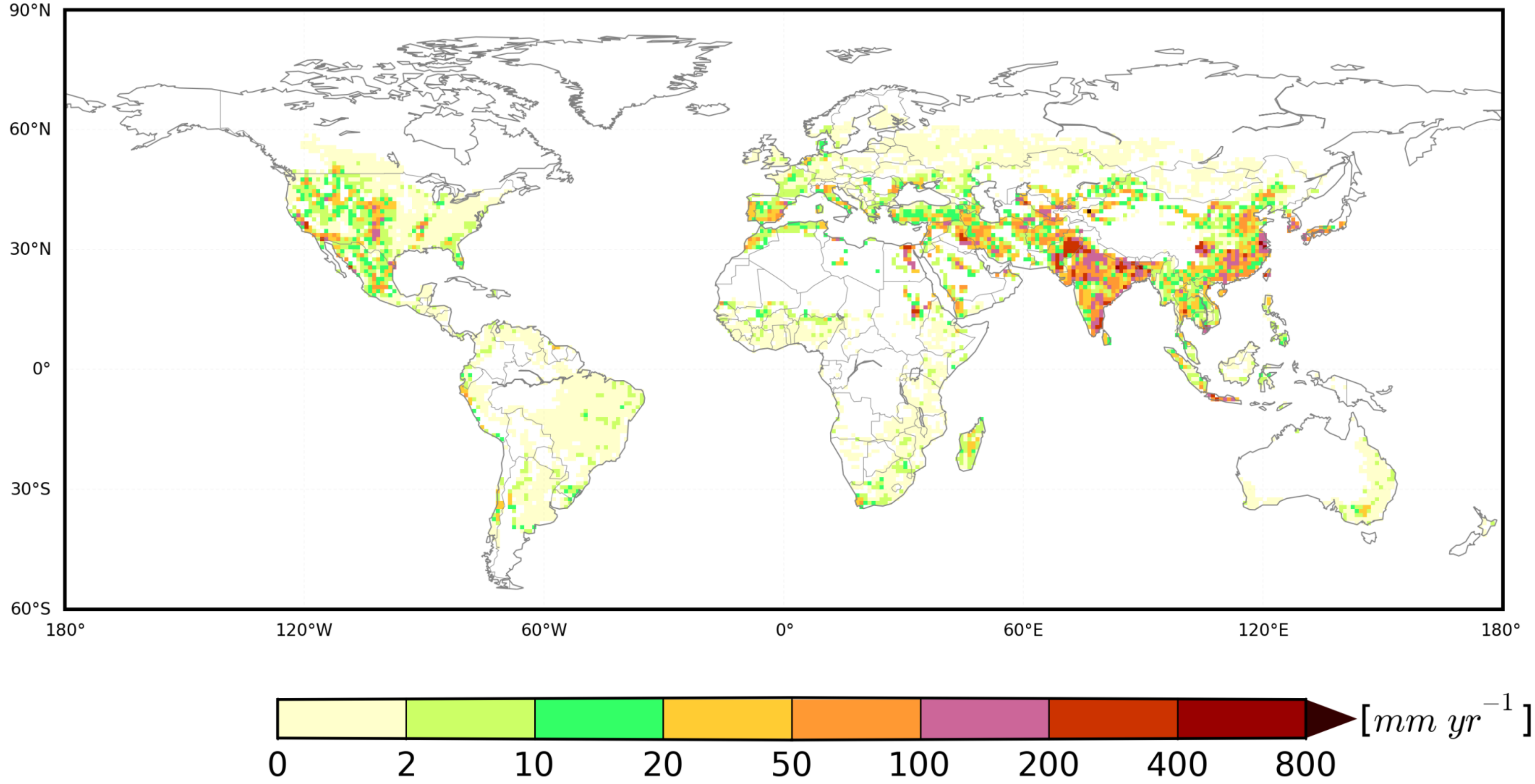
Anthropogenic activities
- Irrigation (and other)
- Reservoir operations

\+

MATSIRO
- SiB2 type land surface model
- Land surface of MIROC GCM

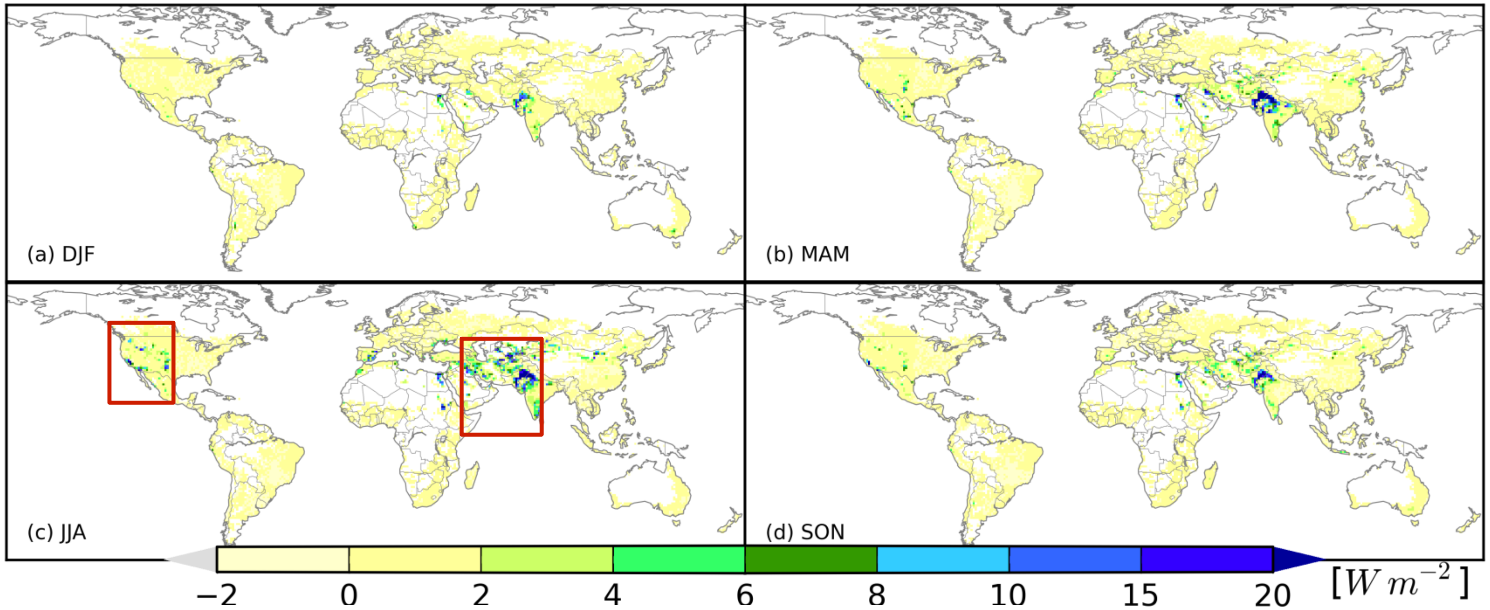
Example of simulated results

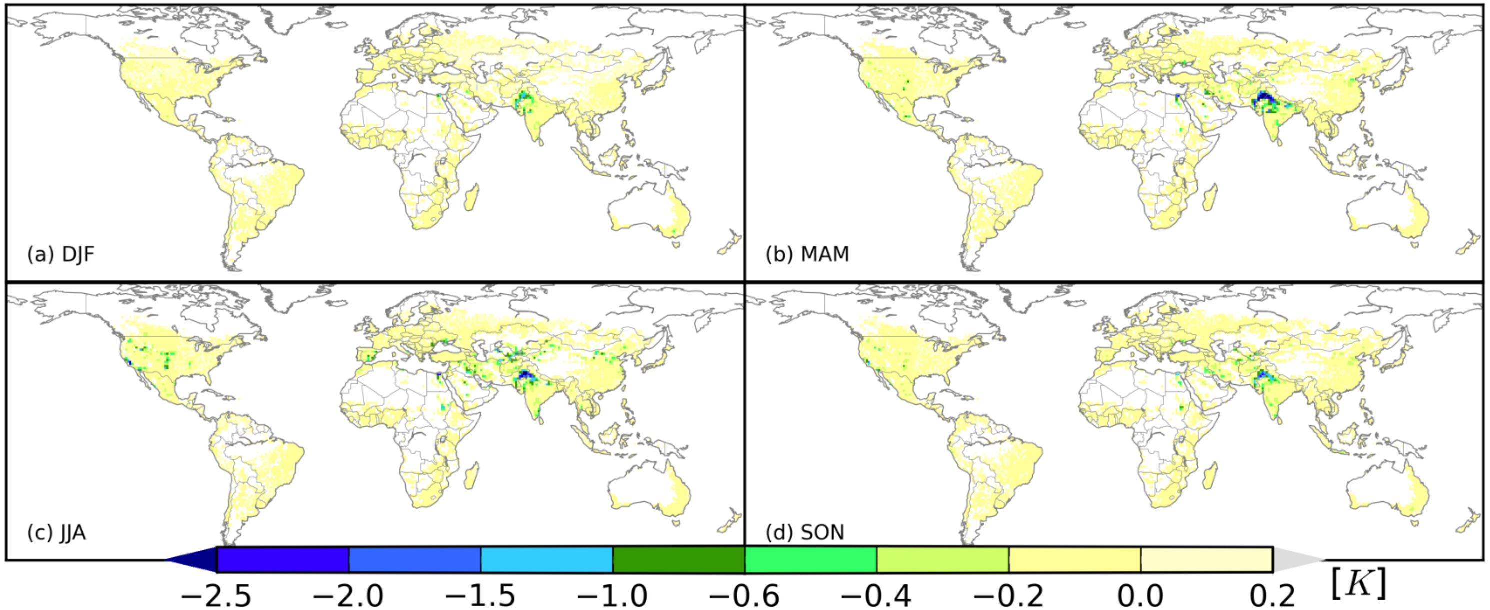
Net Irrigation Water Requirement



Another example: Changes in Heat Balance

Change in seasonal latent heat flux



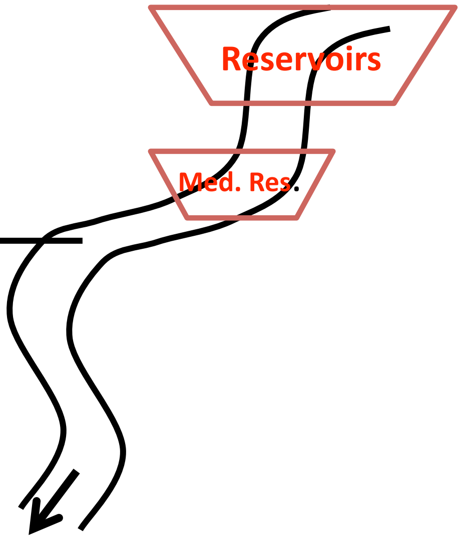


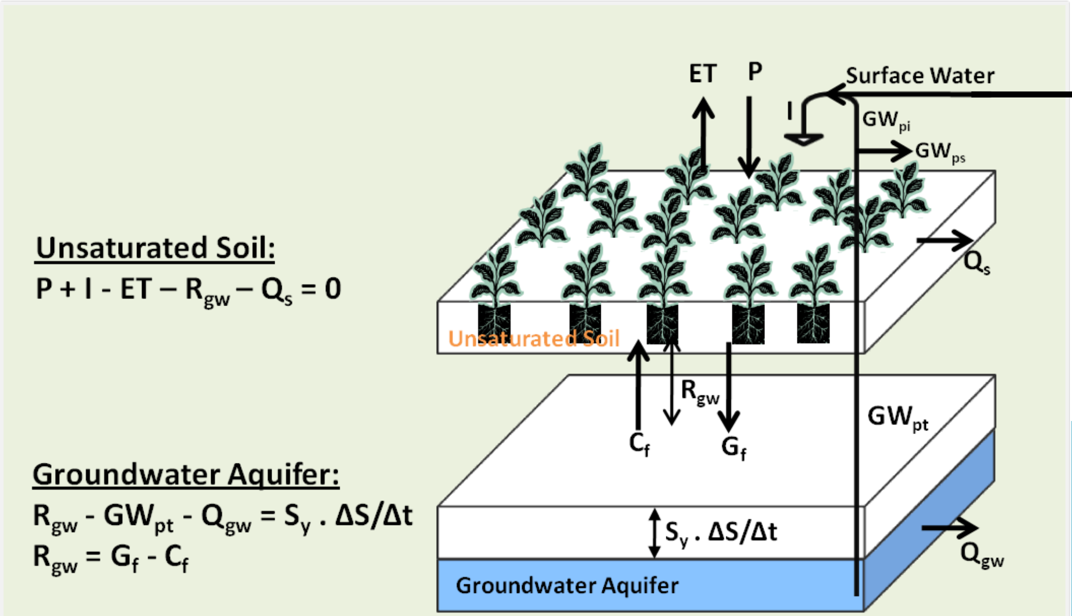
Change in seasonal surface temperature

Further Development: Groundwater Pumping

A thick bottom layer (90m) is added that acts as a deep groundwater aquifer and serves as a **source of water for pumping**

Surface water sources



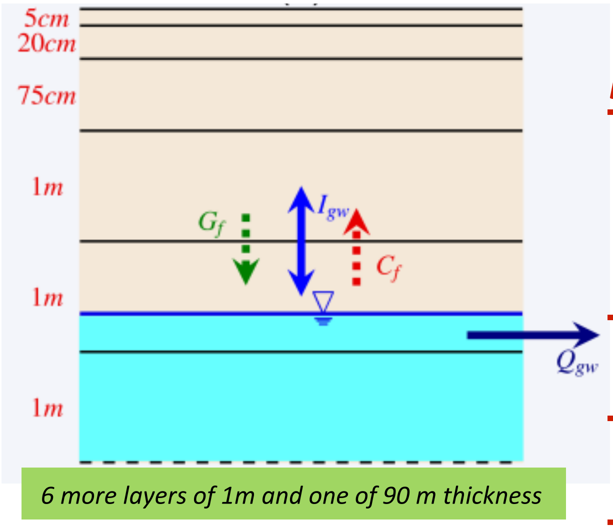


Groundwater source

For more details, Poster by *Pokhrel* in C43

First(!?) fully integrated **Surface Water / Energy B. Groundwater / Human activities** model within the framework of a **global LSM**

Groundwater Representation



Koirala (2011)

Presentation In this session Later.

- Water Balance of GW reservoir:

$$S_y \frac{\Delta d_{gw}}{\Delta t} = I_{gw} - Q_{gw}$$

- Baseflow initiates when WTD is shallower than threshold value:

$$Q_{gw} = K\left(d_0 - d_{gw}\right) \quad if\ 0 \le d_{gw} \le d_0$$
$$Q_{gw} = 0 \quad if\ d_{gw} \ge d_0$$

- Based on ***Yeh and Eltahir (2005a,b)***
- Soil Column has **explicit saturated and unsaturated** soil zones.
  - Interacting through **exchange of moisture flux** (GW recharge)
- GW Recharge is estimated based on Richards' equation:

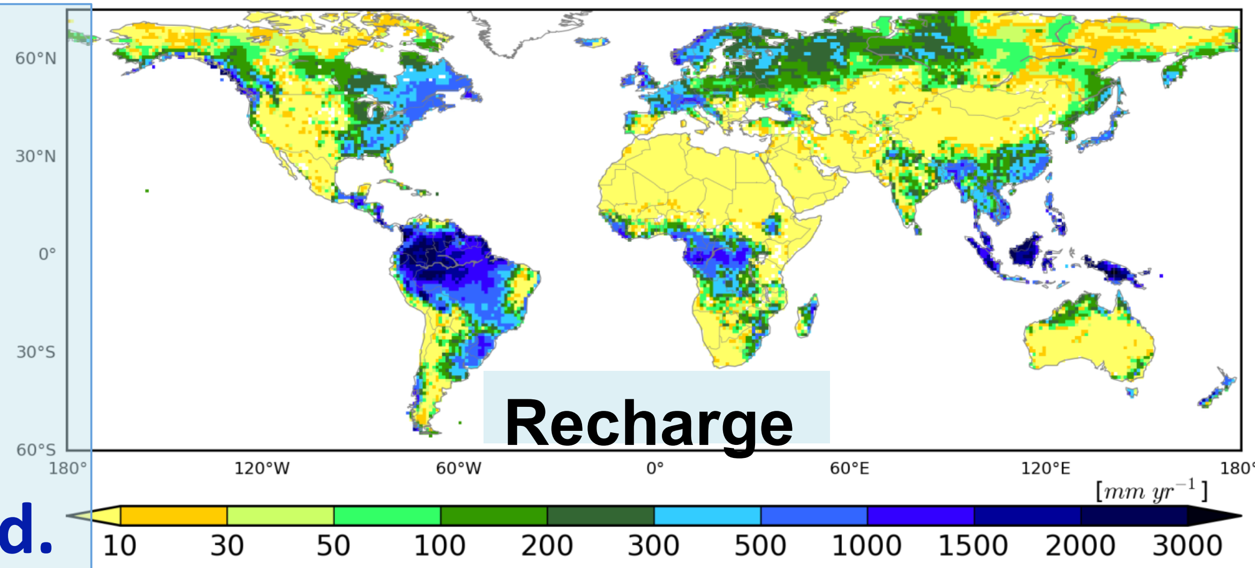
$$I_{gw} = k\left(\frac{d\psi}{dz} - 1\right)$$

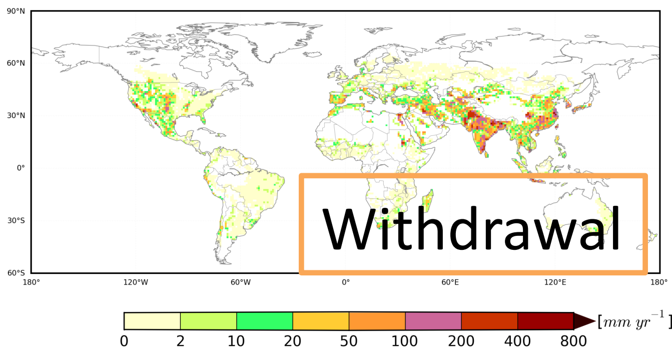
- Lateral flow between grid cells is not considered

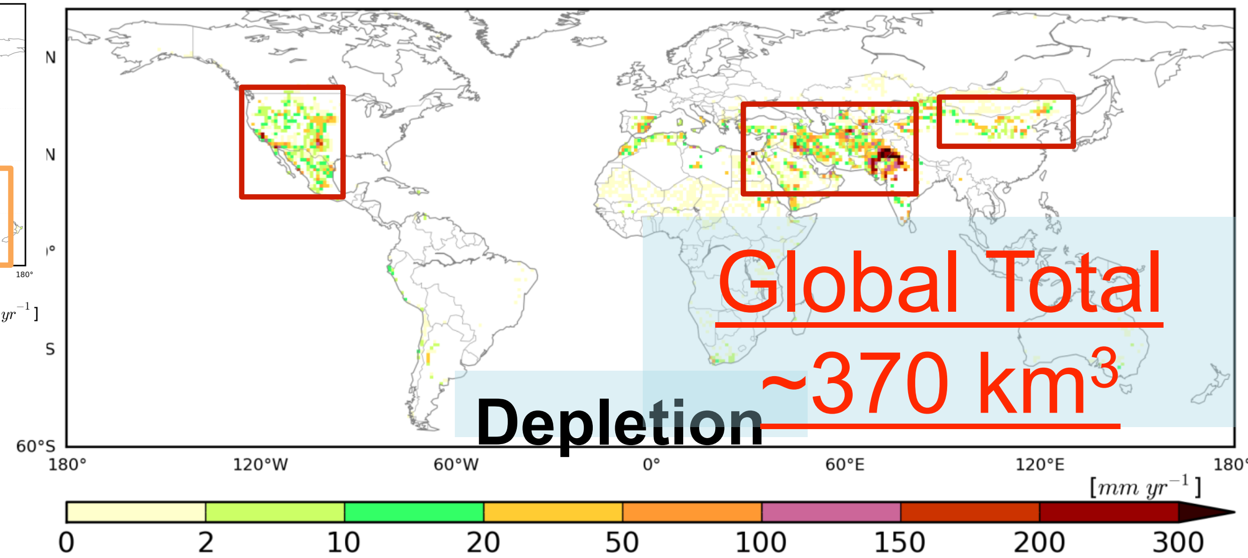
S_y: Specific yield, I_{gw}- recharge, Q_{gw} is baseflow, d_{gw}- water table depth (WTD), d_0- threshold WTD, K-outflow constant.

Global Groundwater Recharge and Depletion

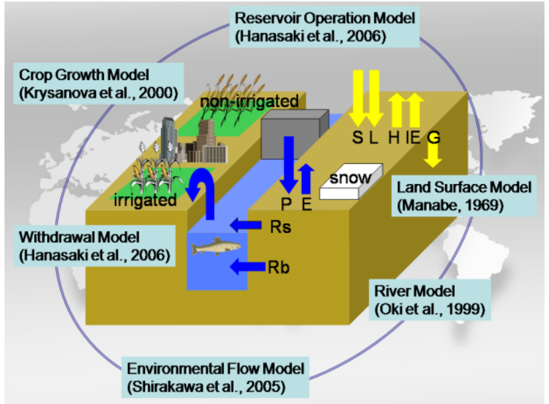
- ✓ Both withdrawal and recharge are simulated
- ✓ As a result, Depletion is explicitly simulated.



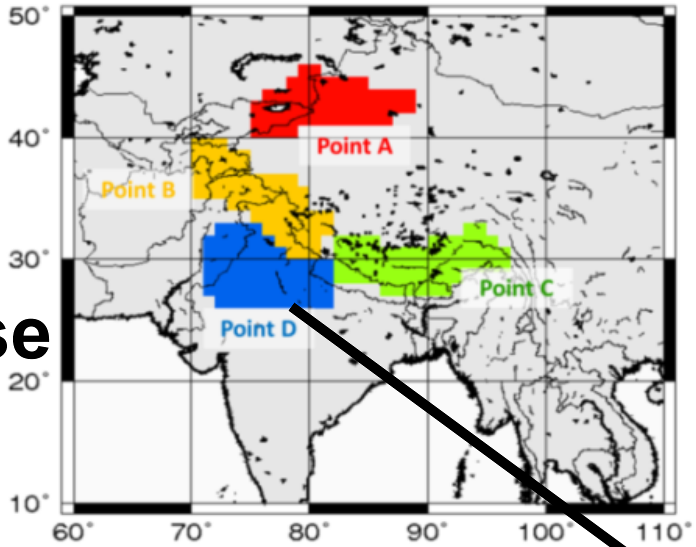




A potential excercise for a hotspot



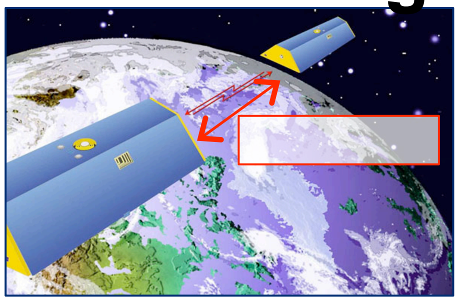
Human Wateruse

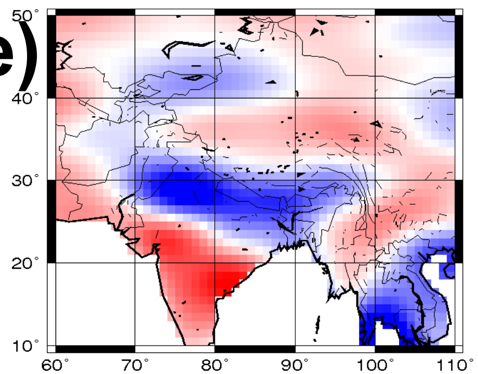


Global distributed Glacier model (C40) (Hirabayashi et al., J. *Hydrology*, 2010)

GSWP-type Global land water budget (Kim et al.,*GRL*, 2009)

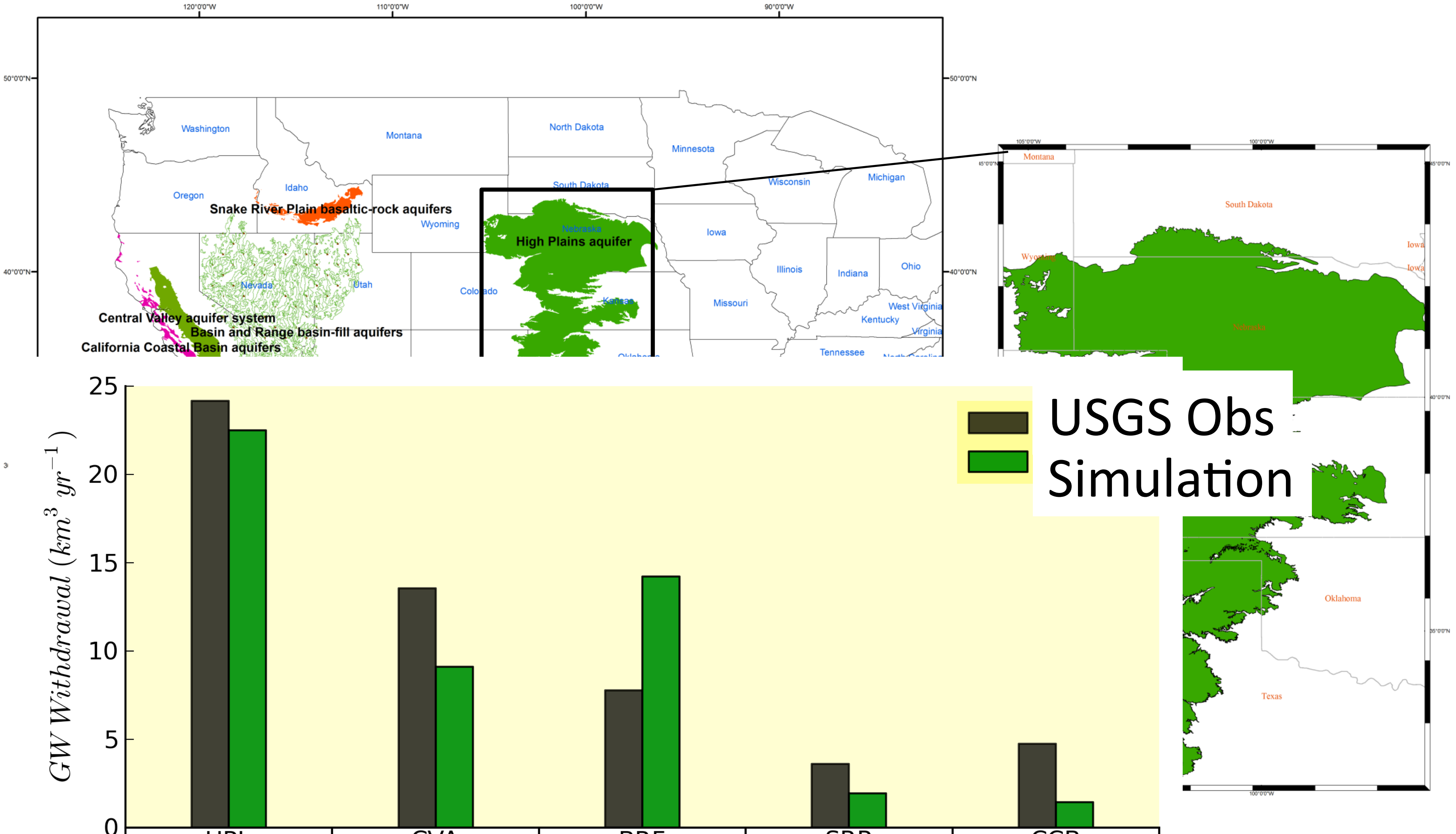
GRACE Satellite (water storage)





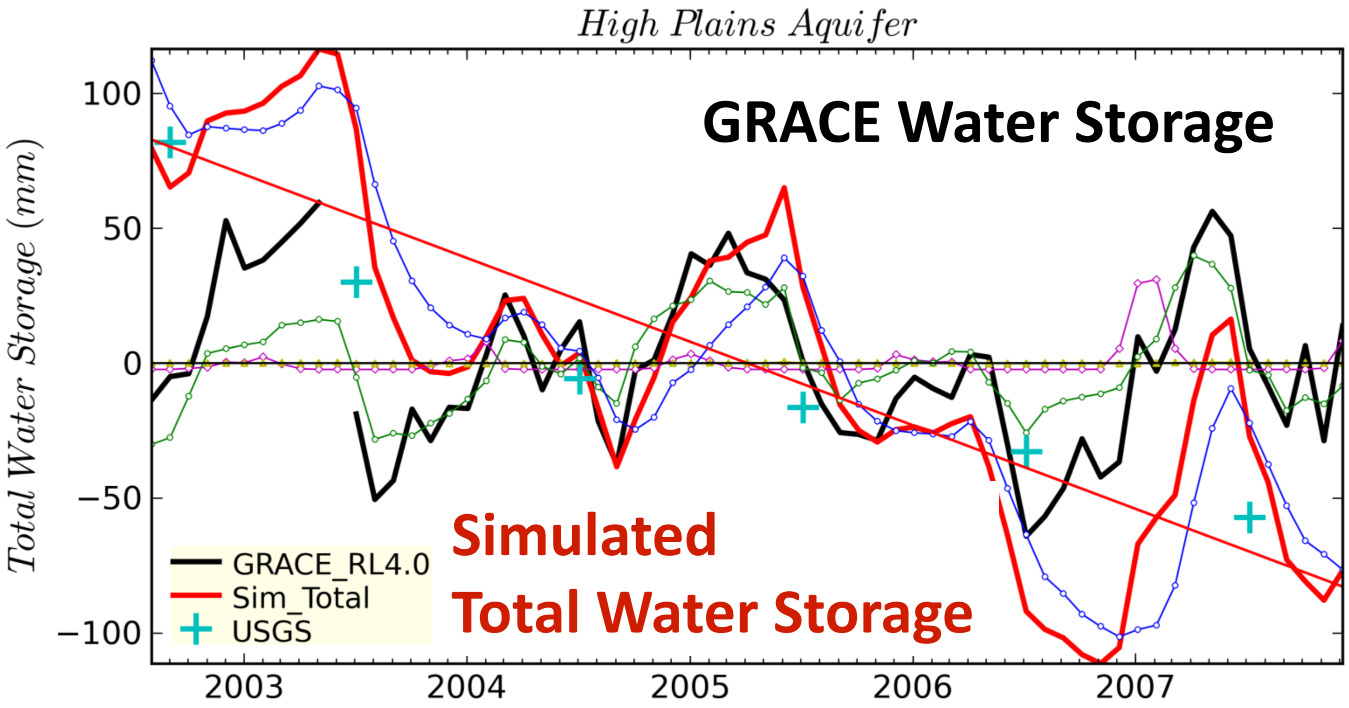
X% Groundwater
Y% Glacier
Z% Soil Moisture
W% Reservoir

Validation in the major US aquifer



	HPL	CVA	BRF	SRP	CCB
Agr(%)	100.0	99.4	86.5	100.0	65.6
Ind(%)	0.0	0.4	9.6	0.0	24.2
Dom(%)	0.0	0.2	3.9	0.0	10.1

High Plains: Simulation v.s. GRACE



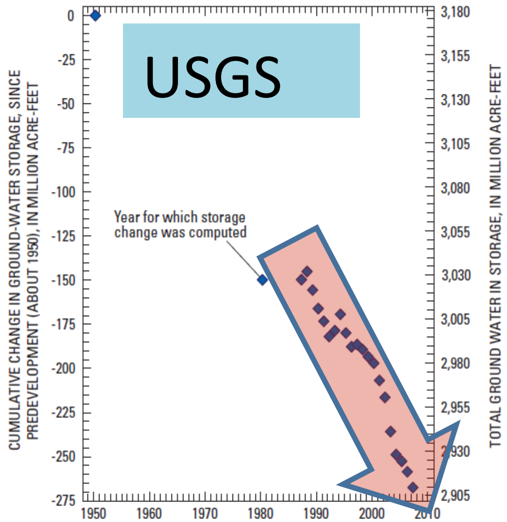
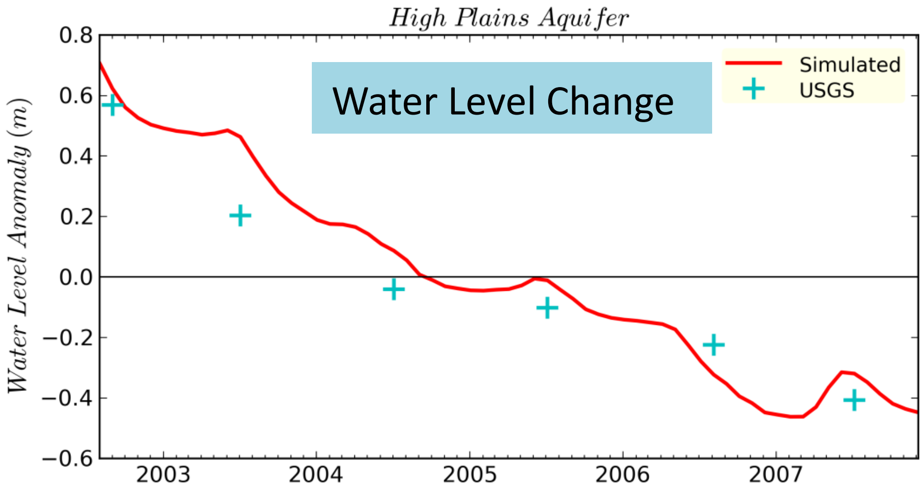


Figure 2. Cumulative change and total ground water in storage in the High Plains aquifer, predevelopment to 2007 (modified from McGuire, 2006).

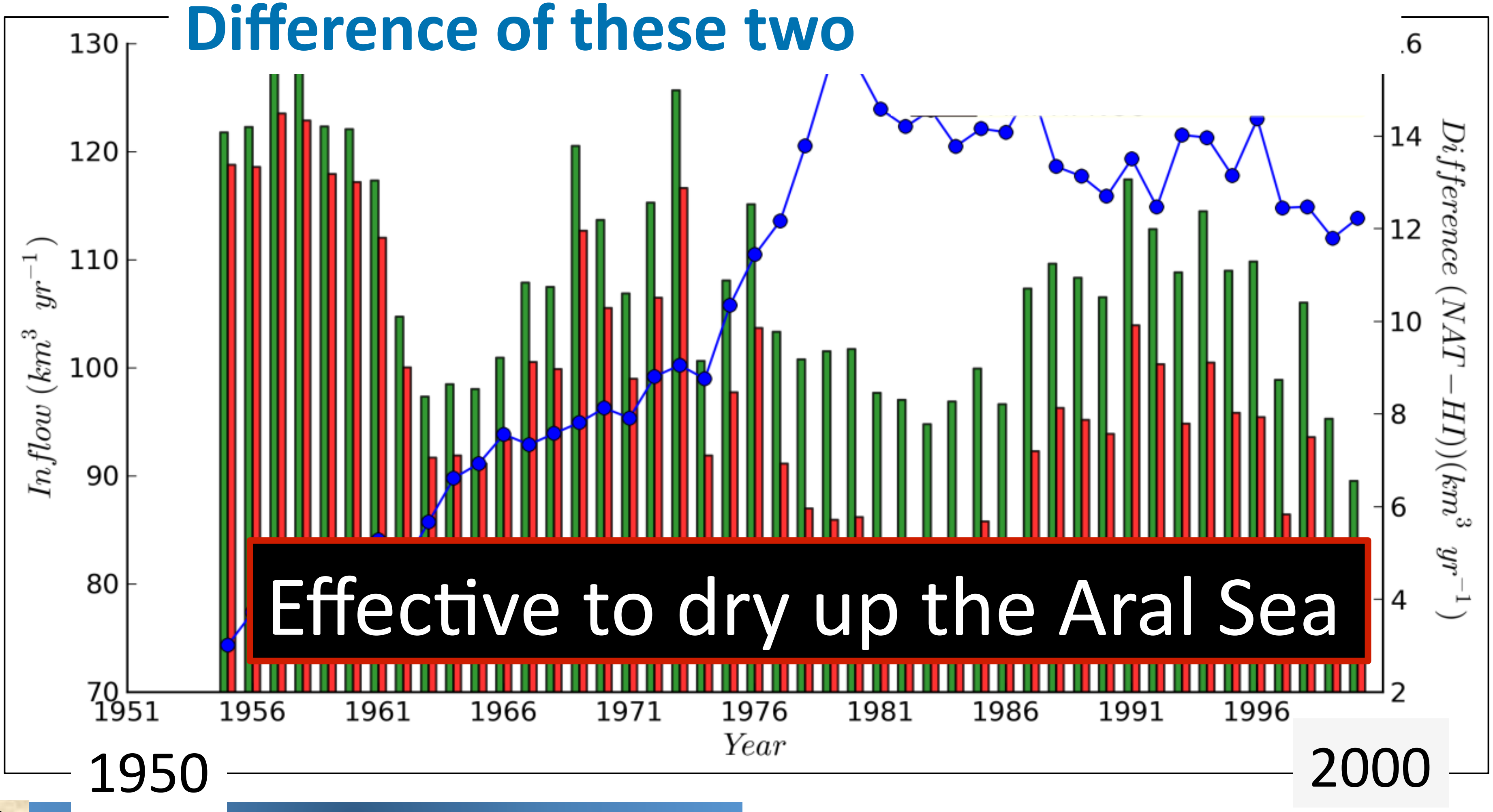


“Aral Sea” Inflow

Natural Inflow (without human activities)

Inflow with human activities

Difference of these two

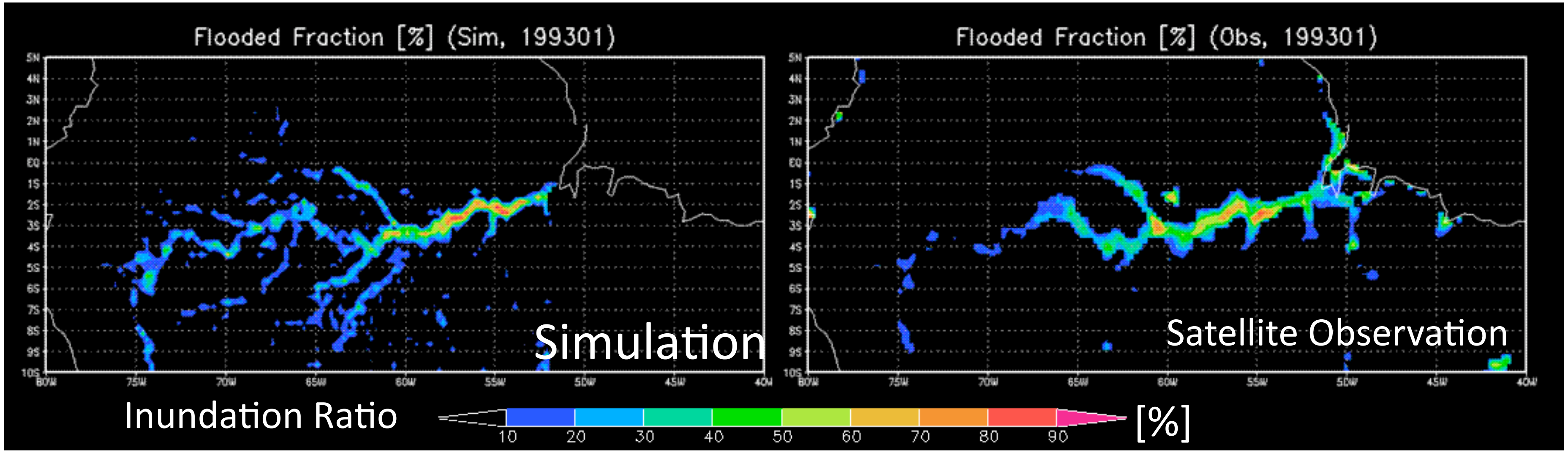


Almost finally,
importance of another kinds of land data:
Topography and River channel parameters.

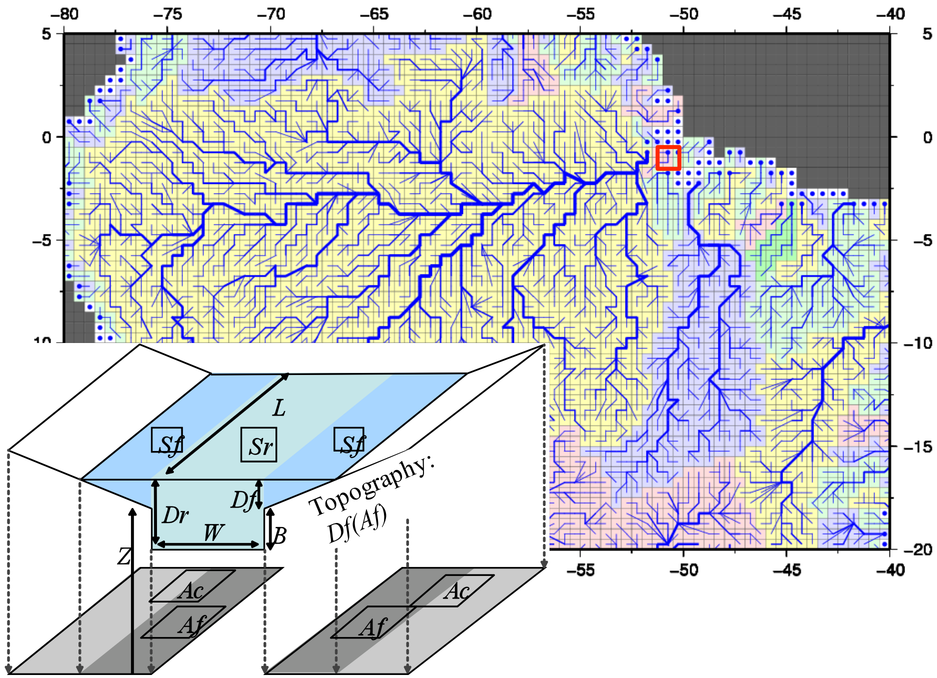
for inundation (natural irrigation) simulation.

Flood in Bangkok, Now

Inundation (Natural Irrigation) of Amazon River



Yamazaki et al. (*WRR*, 2011)

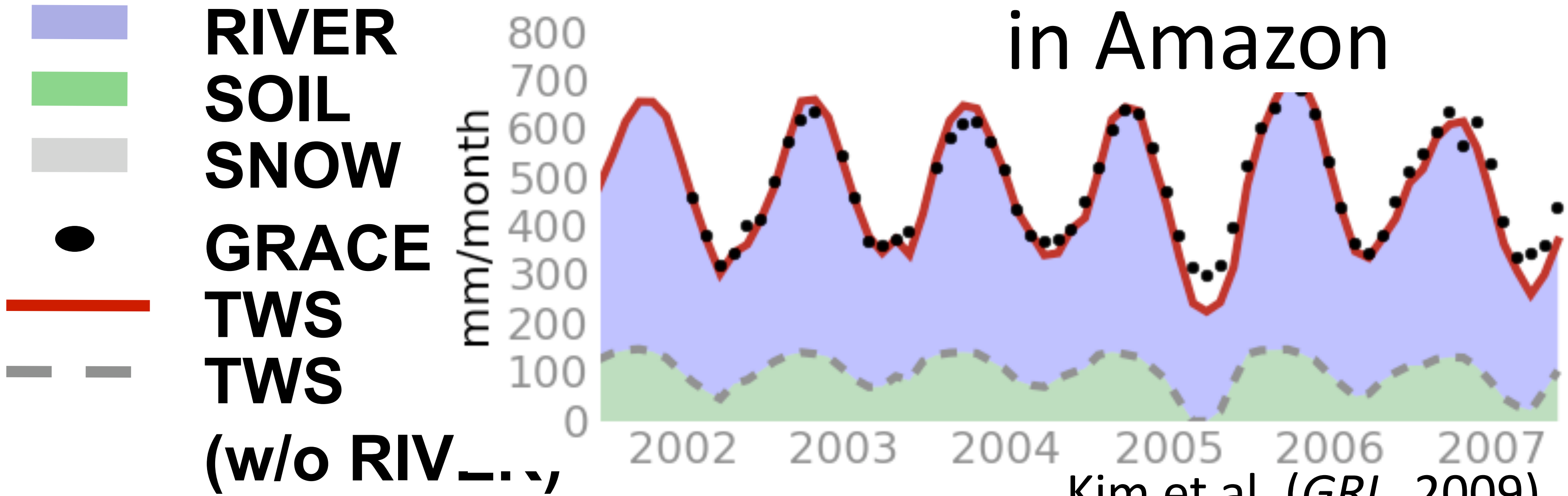


Many people live in flood plains.

Adequate inundation simulation is necessary for the assessment of human-water interaction.

Topography and river channel parameters are crucial.

Inundation model is important from the viewpoint of validating water storage in Amazon



Kim et al. (*GRL*, 2009)

Now, it has become possible to separate

- Surface inundated water
- Soil moisture
- Shallow Groundwater
- River water

Discussion and Conclusion 1

- A *state-of-the-art* Land Surface Model with anthropogenic activities is realized.
- The model can be used for assessing the past, current, and future status of *global water crisis*.
- The model/simulation is very much ***data-driven***. (irrigation area, reservoir capacity, groundwater depletion, river channel parameters, …)

Discussion and Conclusion 2

- I hope **WCRP/GEWEX** plays a key role, because this topic is a physical aspect of global water cycle, and is important for society. (particularly in dataset development/assessment)
- I also hope WCRP/GEWEX plays a key role in the application:
  in the assessment of *water crisis, and*
  in showing a pathway to overcome the *crisis*.

Major sources of this presentation

- Pokhrel, Y., N. Hanasaki, S. Koirala, J. Cho, P. J.-F. Yeh, H. Kim, S. Kanae, T. Oki:
  J. Hydrometeorology, in press, 2011.

- Hanasaki, N., T. Inuzuka, S. Kanae, T. Oki:
  J. Hydrology, 384, 232-244, 2010.

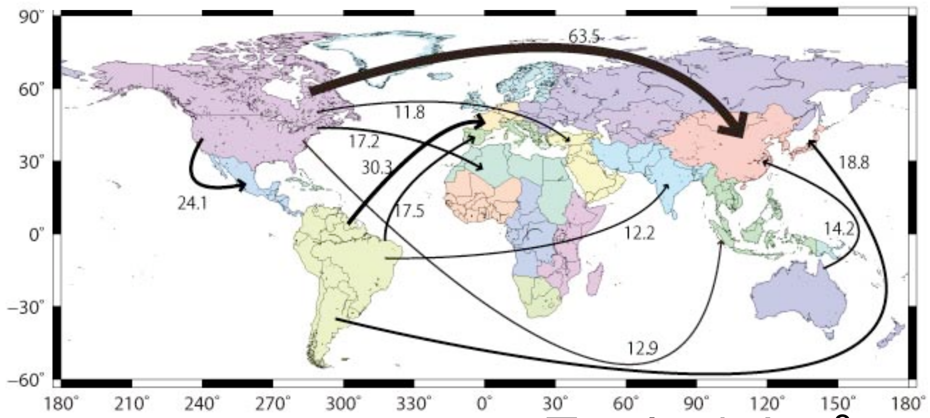
- and several more:
  Yamazaki et al. (*WRR*, 2011), Pokhrel et al. (*submitted*)
  Kim et al. (*GRL*, 2009) Sujan et al. (*submitted*)
  Hirabayashi et al. (*J. Hydrol*, 2010)
  Hanasaki et al. (*J. Hydrol*, 2010)

Thank you very much.

Let’s look forward to
GSWP3
which will produce interesting
outcomes in this topic.

Another example of application: Global flows of Virtual Water

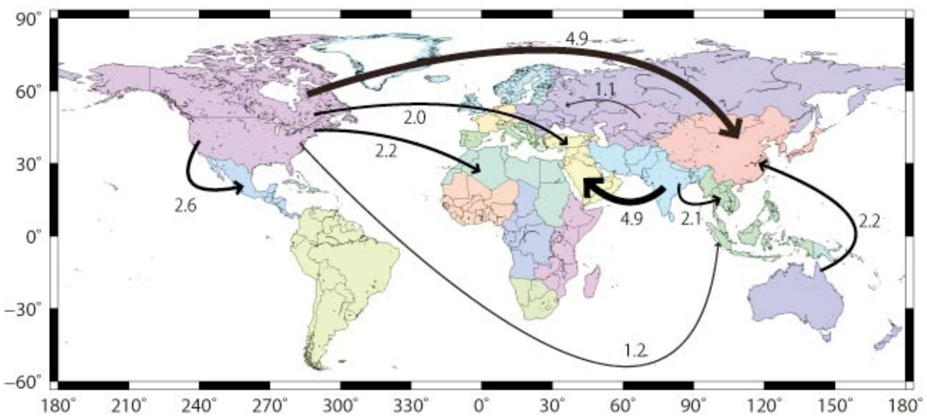
Virtual water export (total)



Total 545km^3 yr^{-1}

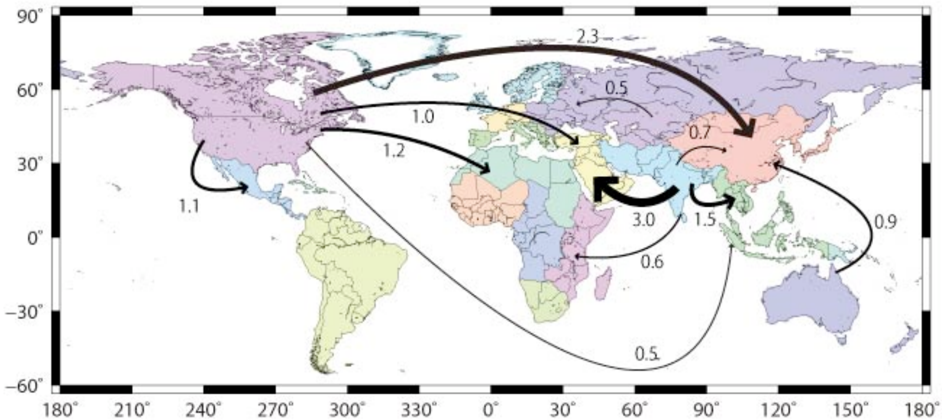
Virtual Water refers to the water used in the production of a good or service, in the context of trade. (wikipedia)

Virtual water export (irrigation)



Total 61km^3 yr^{-1}

Virtual water export (Nonrenewable Water)



Total 26km^3 yr^{-1}