International Conference on Science and Technology for Sustainability
Building up Regional to Global Sustainability: Asia vision,
13-16 September 2011

Water Footprinting for Sustainable Development and Wise Management of Global Water

Taikan OKI

Institute of Industrial Science, The University of Tokyo

special thanks to
Drs. Naota Hanasaki (NIES) and Yadu Pokhrel

Introduction

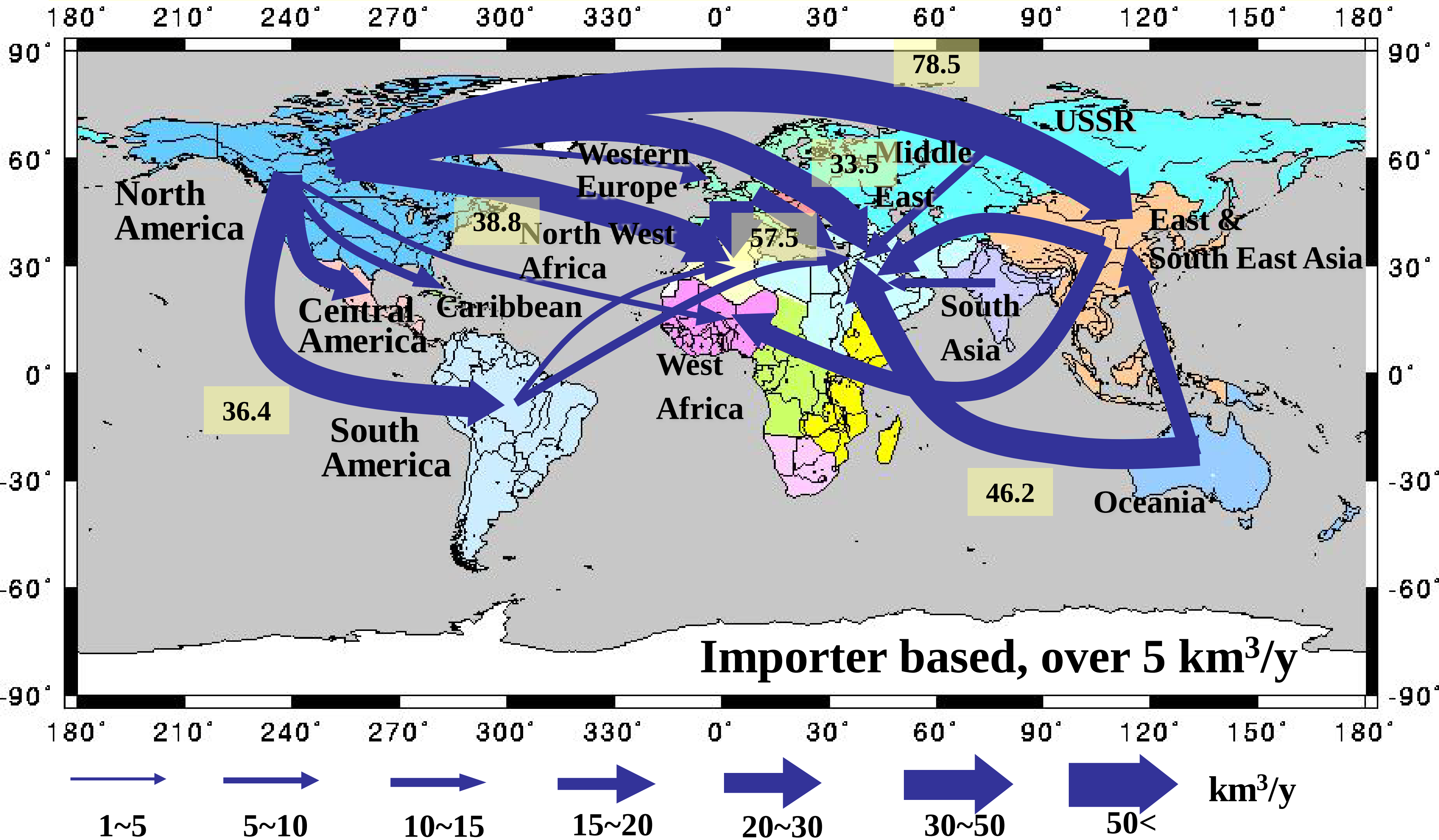
- **Worked for:**
  - **WCRP/GEWEX/GAME/GAME-Tropics**
  - **Research Institute for Humanity and Nature**
  - **Global Water System Project**
  - **LA for IPCC AR4/TP on Water/SREX, CA for MA**
  - **3rd Science and Technology Policy Plan, CSTP, Japan**
- **Currently working for:**
  - **IPCC AR5/WGII/Ch3 CLA**
  - **Task force for UNESCO IHP VIII**
  - **WCRP OSC Papers on Water/Land**
  - **ISO/TC207/SC5/WG8 “Water Footprint”**

Required Water for Fast Food

Beef Bowl	Hamburger Sandwich	Hamburger Sandwich	Buckwheat noodle	Pasta (Udon)
Regular JY280	2 regular Small Fries JY268	Teriyaki Burger Regular Fries JY430	With Egg JY300	Plain JY290
710kcal	745kcal	911kcal	377kcal	341kcal
1890L	2020L	530L	750L	120L

(M. Sato, 2003, Thesis, The Univ. of Tokyo.)

"Virtually Required Water" Trade between Regions in 2000 (cereals only)



(Oki, et. al, 2004)

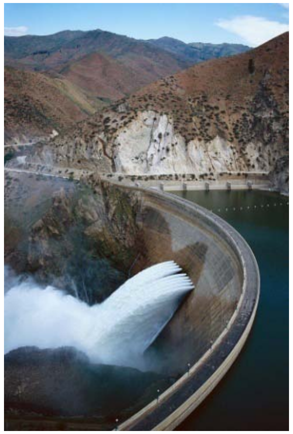
(Based on Statistics from FAO etc., for 2000)

Can we quantify water withdrawals by sources?

- The source of evapotranspiration
  - Precipitation
  - Irrigation water
    - Stream flow
    - Reservoirs and ponds
    - Renewable groundwater
    - Fossil groundwater

Low environmental impact
Sustainable
Low opportunity cost

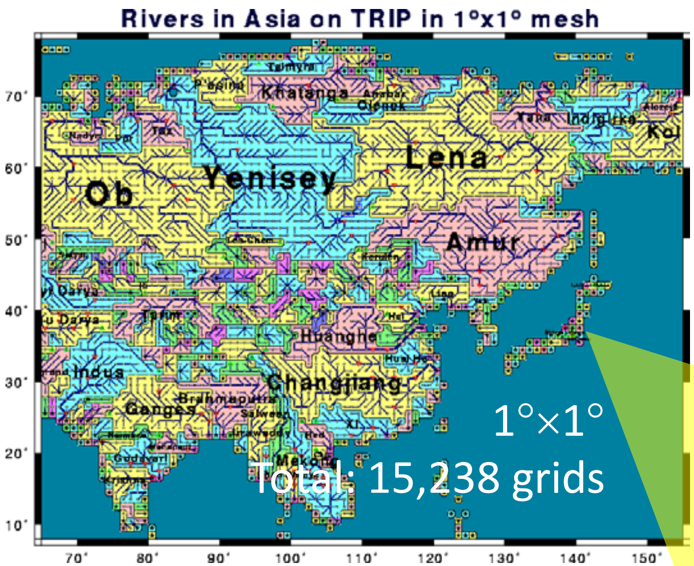
High environmental impact
Less-sustainable
High opportunity cost

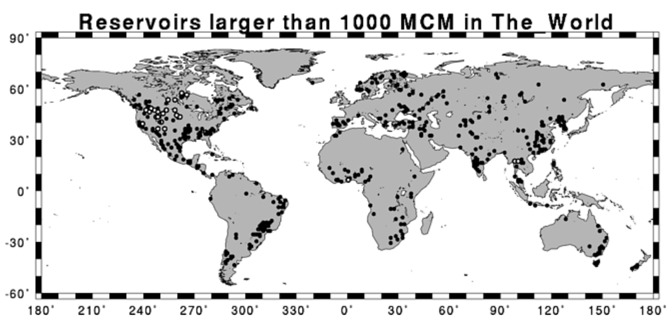


model

Step 1

Global water resources model H08

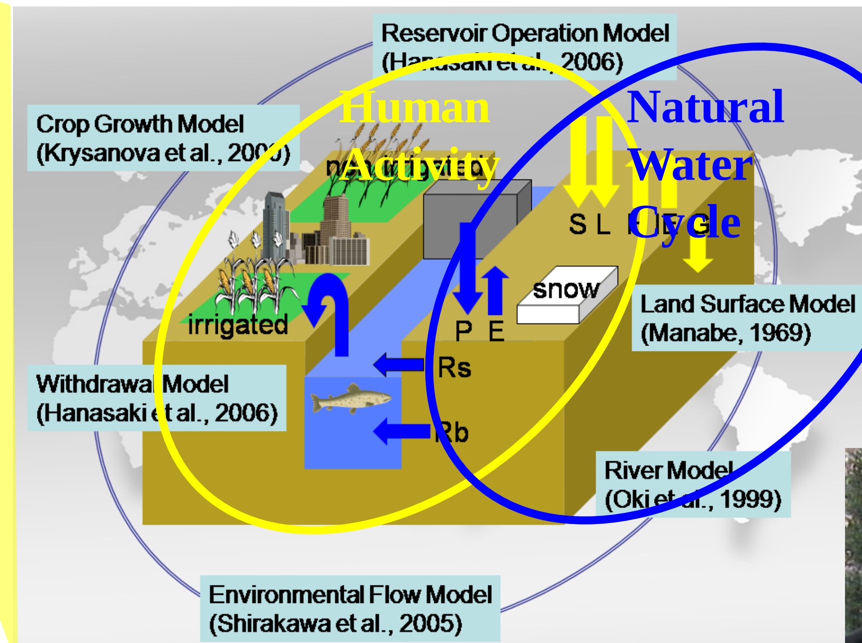




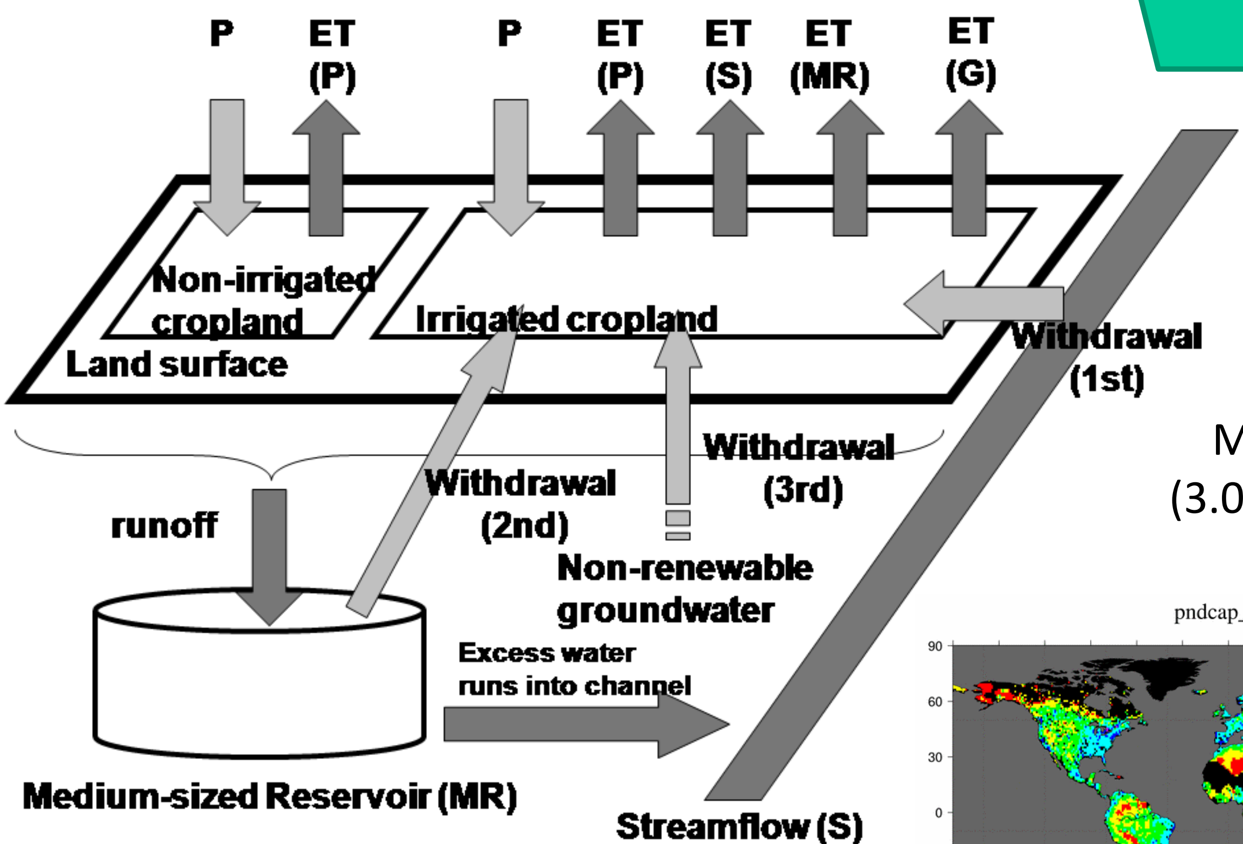
452 reservoirs, 4140 km^3

•Requirements

1. Simulate both water availability (streamflow) and water use at daily-basis
2. Deal with interaction between natural hydrological cycle and anthropogenic activities
3. Applicable for future climate change simulation

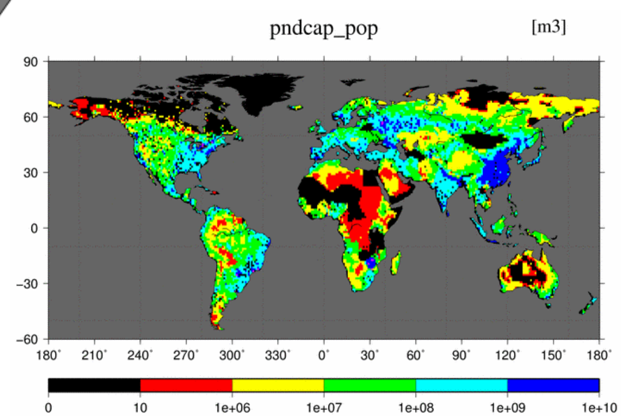


Enhancement of the H08 model



Large reservoirs
($1.0 \times 10^9 m^3 \leq S$)
$4140 km^3$

Medium-sized reservoirs
($3.0 \times 10^6 m^3 \leq S < 1.0 \times 10^9 m^3$)
$3280 km^3$



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

Results 1: Green water*

(*evapotranspiration originates from precipitation in cropland)

Unit：km³/yr	This study	Molden (2007)	Falkenmark and Rockström (2004)
ET from cropland	7650	7130	6800
ET from non-irrigated cropland (green)	5080	4910	5000
ET from irrigated cropland (green)	1220	650	
ET from irrigated cropland (blue)	1350	1570	1800

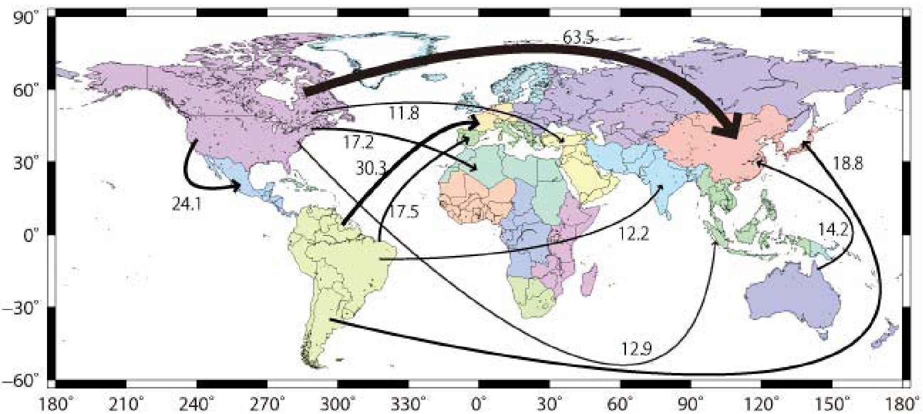
Direct simulation of ET

$$\frac{\text{Yield per area}}{\text{Water use efficiency}} = \text{ET}$$

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

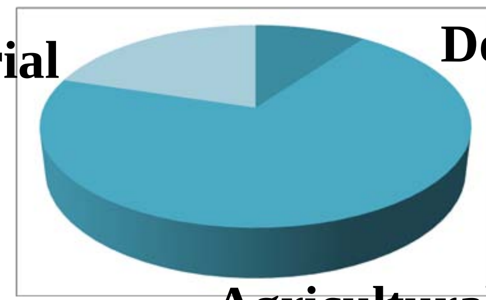
Global flows of virtual water export

Virtual water export (total)



Total 545km^3 yr^{-1}

Total water withdrawal：3,800km^{3}yr^{-1}



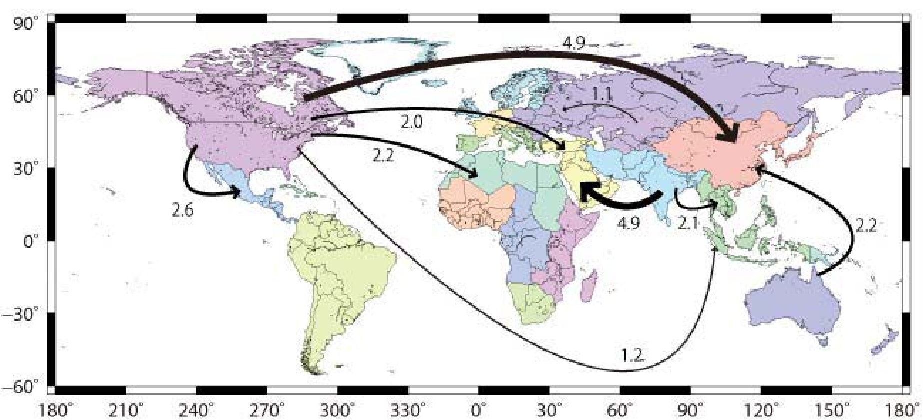
Industrial 770

Domestic 380

Agricultural 2,660

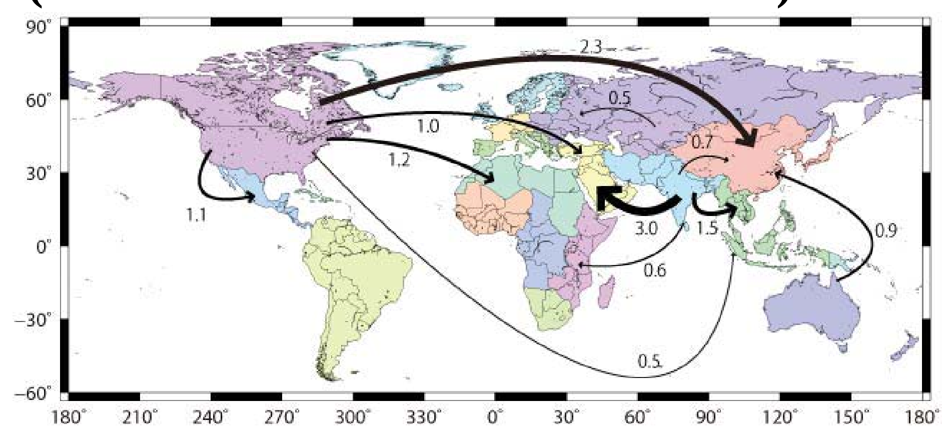
Shiklomanov, 2000

Virtual water export (irrigation)



Total 61km^3 yr^{-1}

Virtual water export (Nonlocal/Nonrenewable Blue Water)



Total 26km^3 yr^{-1}

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

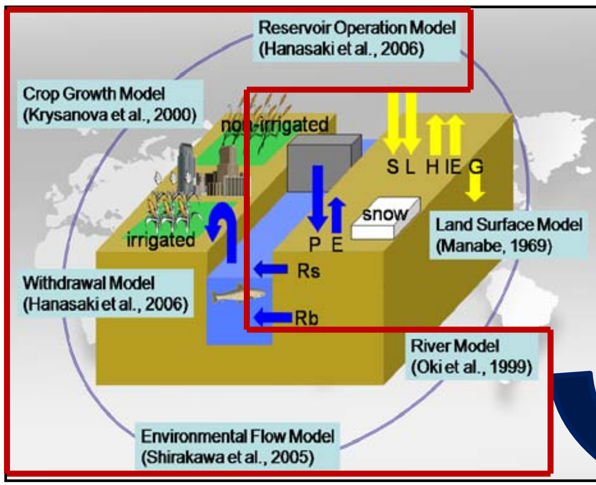
model

Step 2

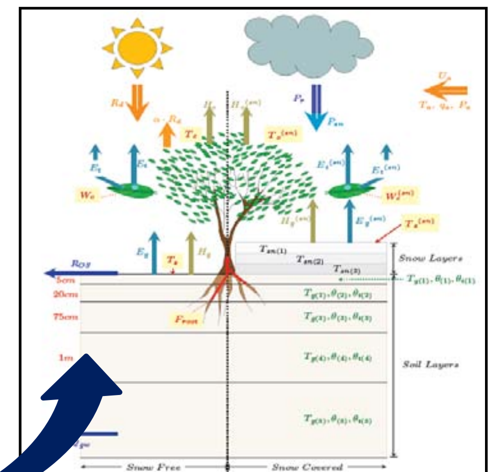
MODELS: MATSIRO & H08

- ☑ Land Surface Models (LSMs) are designed to be coupled with GCMs
  - **No Human Impacts (HI) representation**
- ☑ Numerous Global Hydrological Models (GHMs) with HI representation exist, but
  - Mostly designed for **offline simulations**
  - Simple ET parameterizations (**energy balance not considered**)
  - Vegetation dynamics/Carbon cycle not accounted

H08: *Hanasaki et al. (2008a, 2008b)*



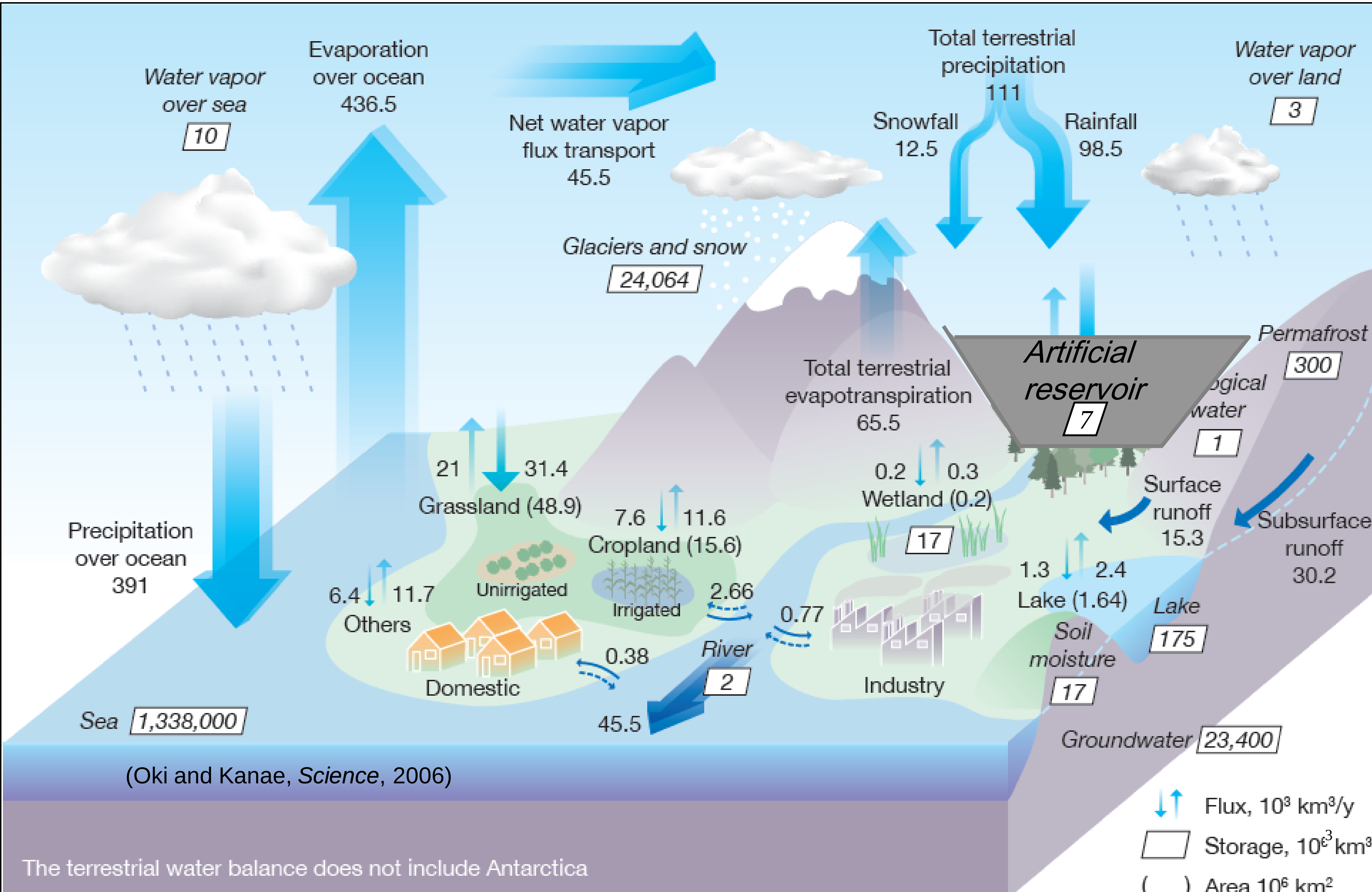
MATSIRO: *Takata et al. (20003)*



- ✓ Land surface hydrology scheme is a simple **Bucket Model**
- ✓ **Vegetation** : accounted implicitly

- ✓ **Further, new irrigation scheme for MATSIRO LSM is developed**
- ✓ **Water table dynamics and a newly developed pumping scheme**

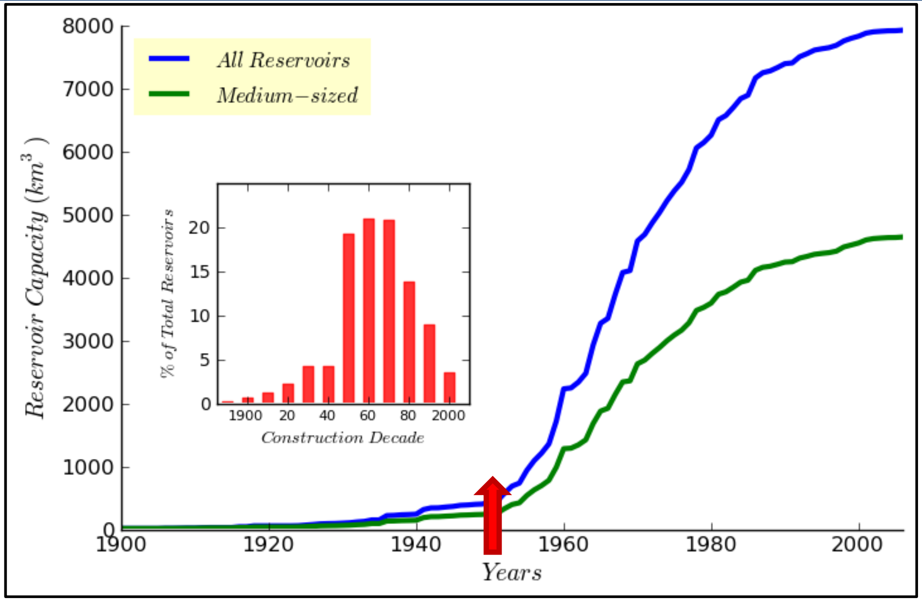
Synthesized Global Water Cycle

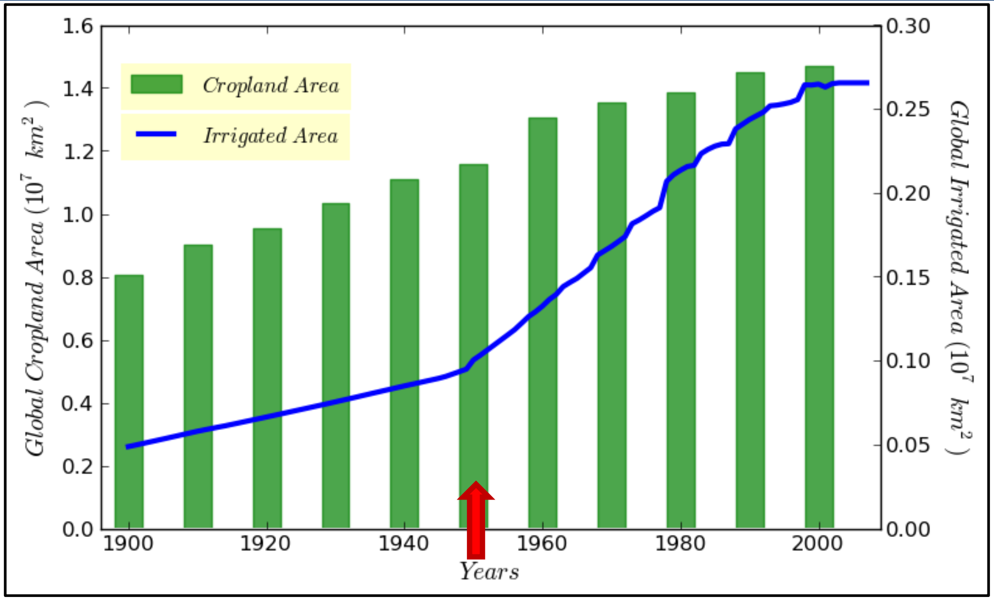


(Oki and Kanae, *Science*, 2006)

The terrestrial water balance does not include Antarctica

Historical Reservoir Storage & Irrigated Areas



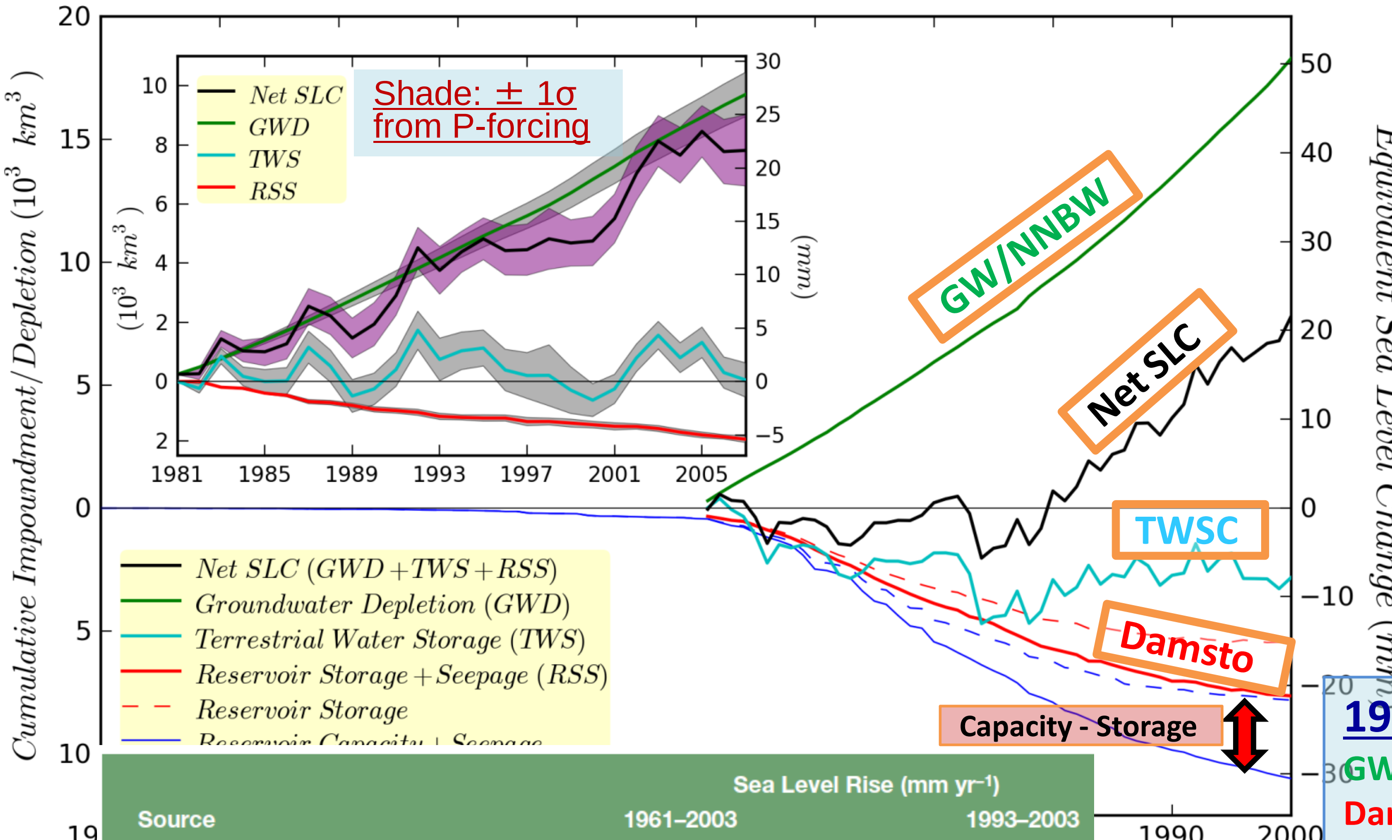


☑ Reservoir storage and irrigated areas largely increased from 1950s

☑ 1950—2000 simulation is conducted:

- Simulations: **MAT-NAT-NCC** (no HI), **MAT-HI-NCC** (with HI)
- Forcing data: **NCC** (Ngo-Duc et al., 2005)
- Historical Reservoirs/Land Use Change/Irrigated Areas Data:
  - ✓ Compiled from various sources: time-varying gridded datasets

Sea Level Change: Anthropogenic TWS Contributions



Source	Sea Level Rise (mm yr⁻¹) 1961–2003	1993–2003
Sum	1.1 ± 0.5	2.8 ± 0.7
Observed	1.8 ± 0.5	3.1 ± 0.7
Difference (Observed – Sum)	0.7 ± 0.7	0.3 ± 1.0

Seepage from reservoirs is accounted by using a simple **dynamic fluid diffusion** model: **seepage decrease with time as 1/√t**

1951-2007 SLC:
GW: +0.99 ± 0.07 mm/yr
Dam: -0.39 ± 0.02 mm/yr
TWS: -0.10 ± 0.05 mm/yr
IRR: +0.03 mm/yr
Net: +0.53 ± 0.08 mm/yr

1961-2003 SLC:
Net: +0.74 (IPCC:+0.7) mm/yr

1993-2003 SLC:
Net: +1.50 (IPCC:+0.3) mm/yr

Other factors that potentially affect sea level change:

- ✓ Land use change/deforestation: partly accounted by land use change data
- ✓ Wetland drainage, atmospheric water content change: relatively small
- ✓ Various factors are not fully independent: coupled land-atmosphere simulations

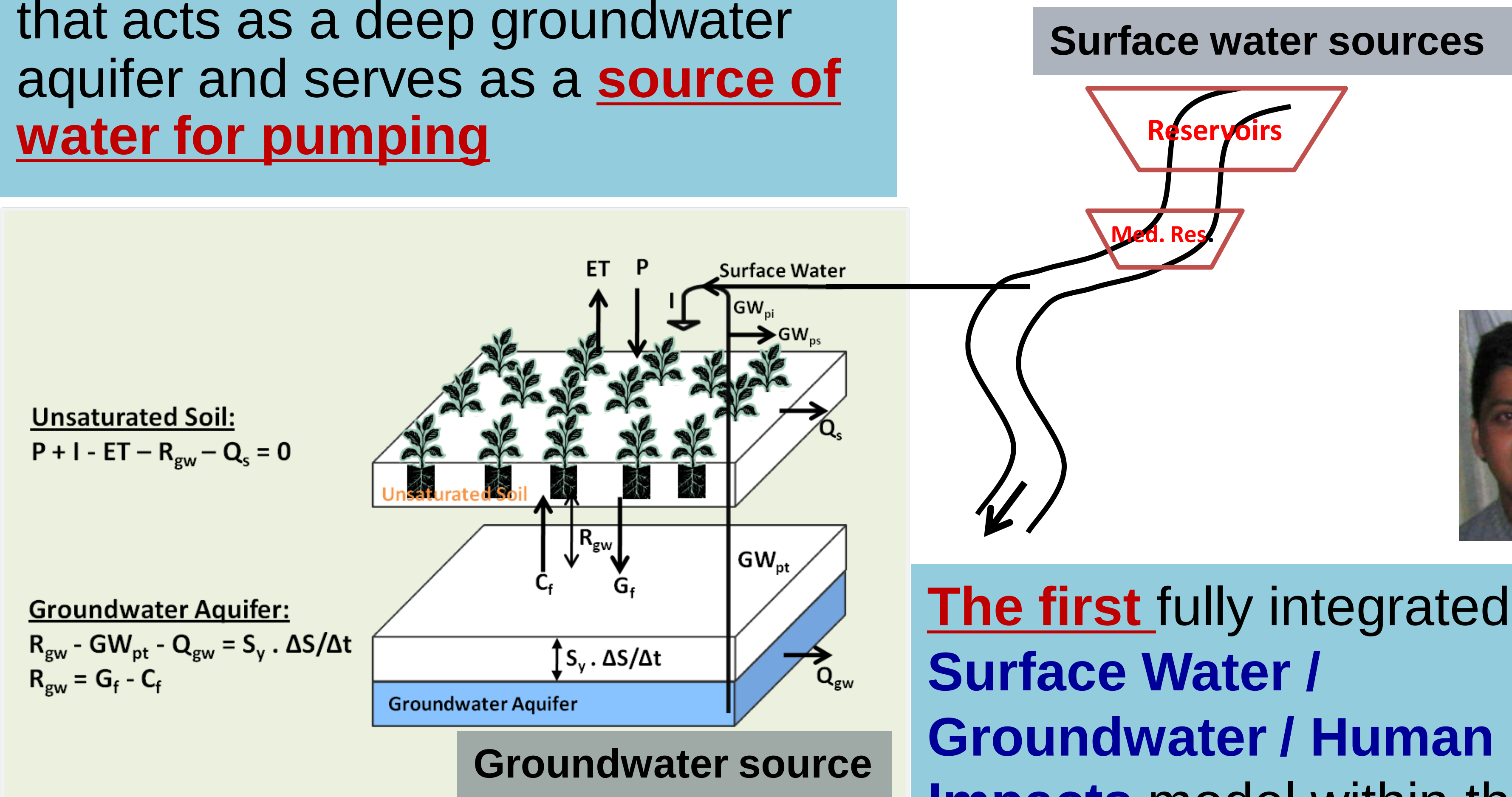
Pokhrel, Y., et al.: Anthropogenic terrestrial water storage contributions to global sea level change, *in Preparation*.

model

Step 3

Groundwater Pumping Scheme

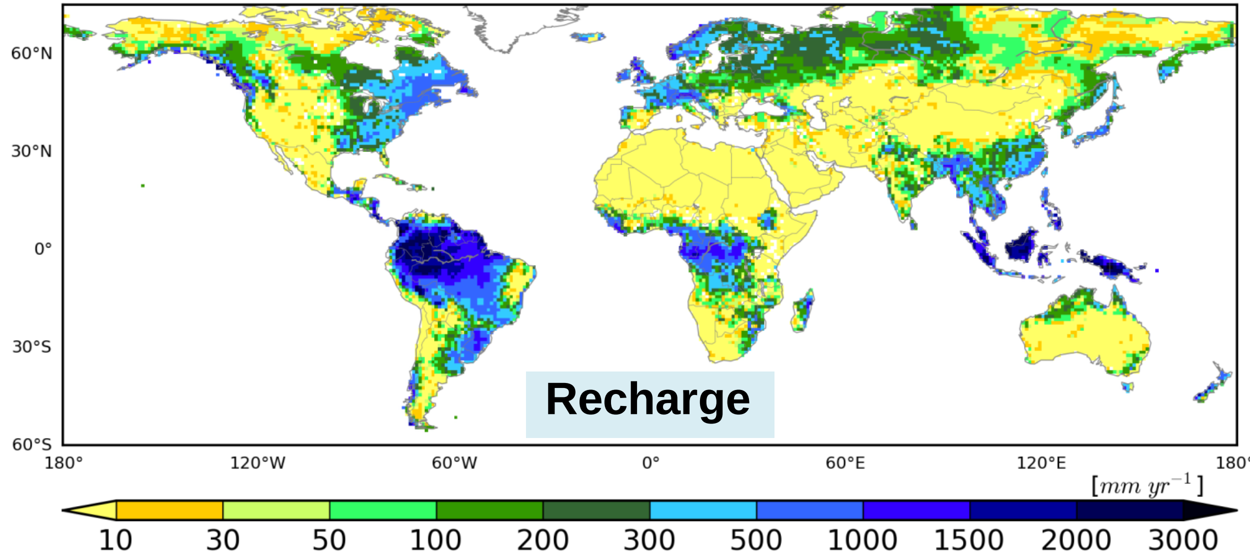
A thick bottom layer (90m) is added that acts as a deep groundwater aquifer and serves as a **source of water for pumping**

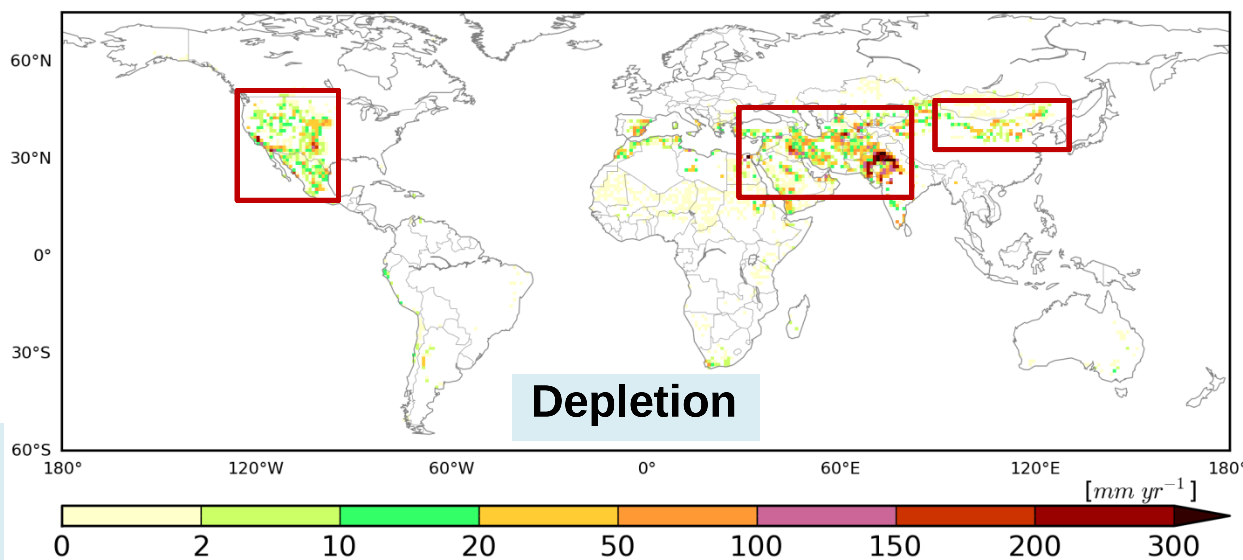


The first fully integrated **Surface Water / Groundwater / Human Impacts** model within the framework of **global LSM**

Global Groundwater Depletion

- ✓ Both **withdrawal** and **recharge** are simulated
- ✓ Groundwater **depletion** is estimated as the difference of **withdrawal and recharge**



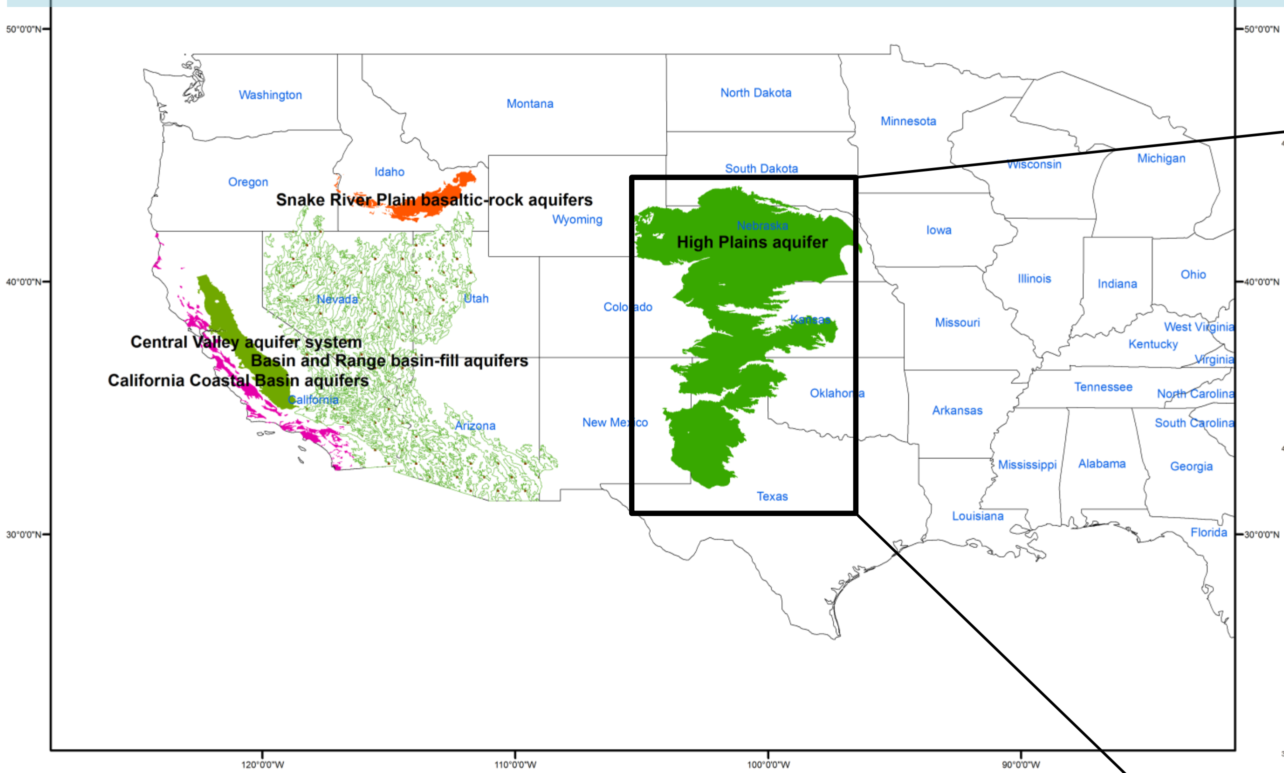


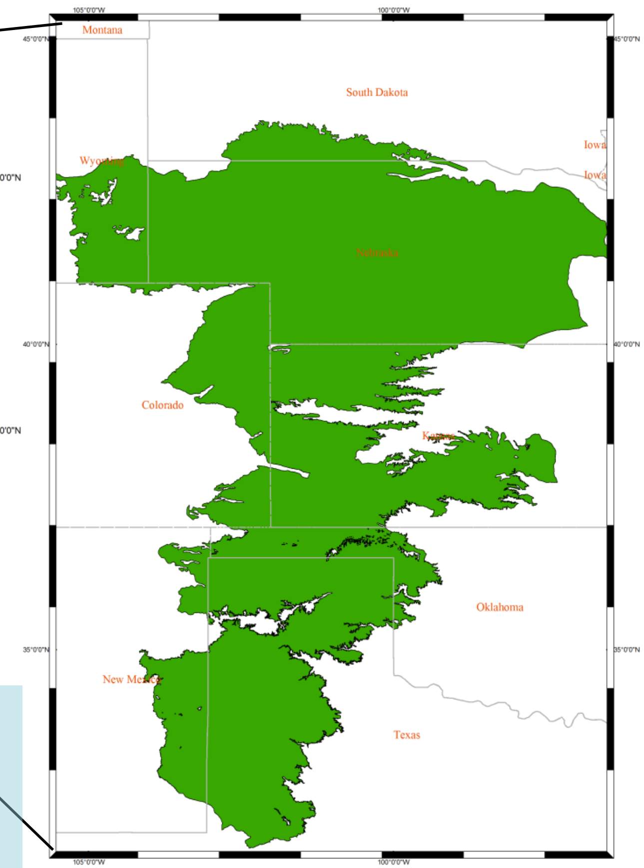
Global total
~370 km^3

Wada et al, 2010:
~290 km^3

Groundwater Use: Validation in US Aquifers

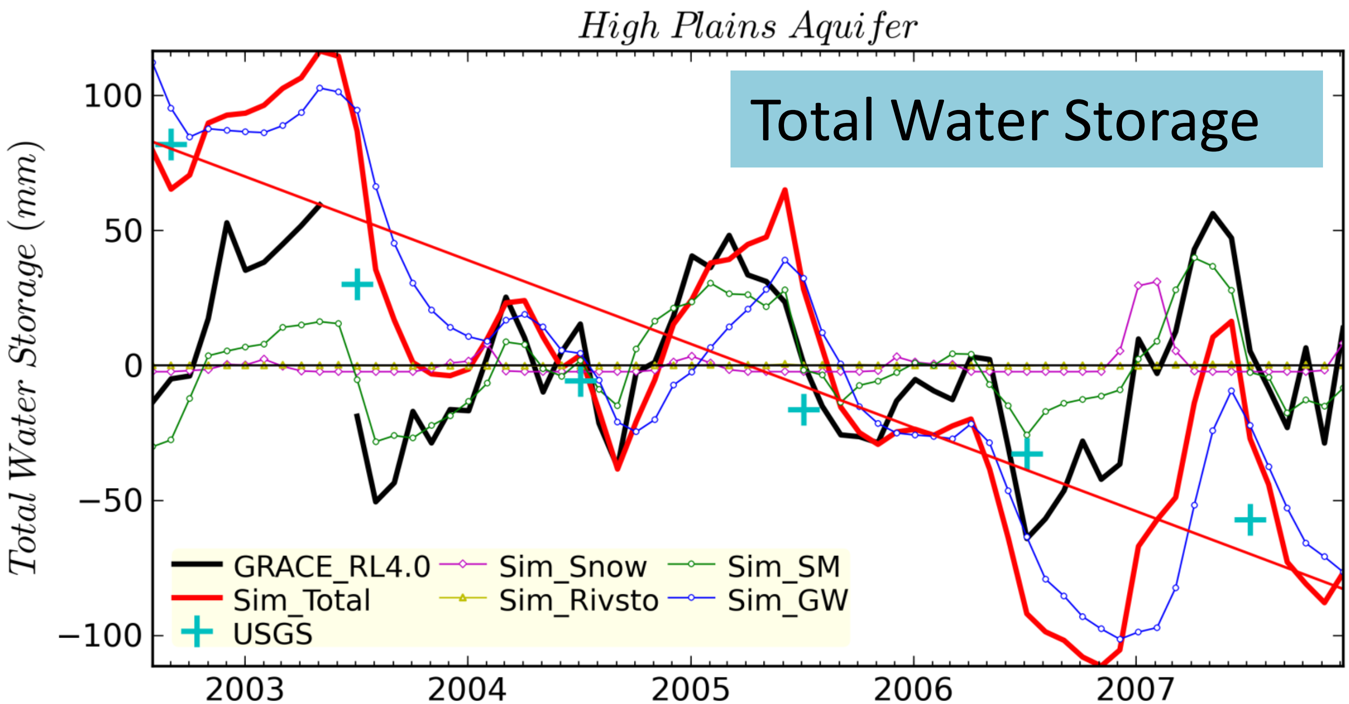
Almost 30% of GW withdrawals for irrigation in the US.
~97% of GW withdrawals from the aquifer are used for irrigation.





Groundwater levels have significantly **declined** since extensive GW **irrigation** started during 1950s.

Groundwater Depletion (High Plains Aquifer)



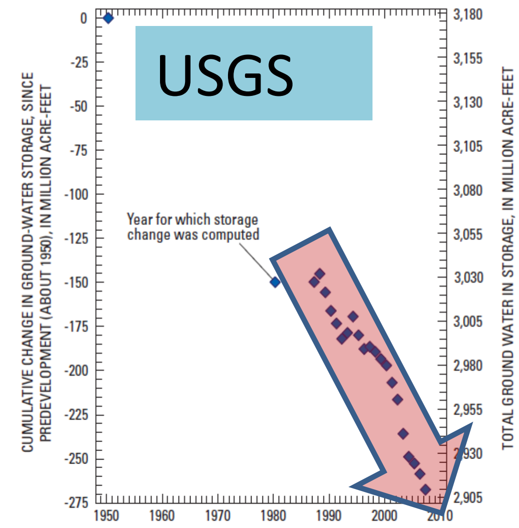
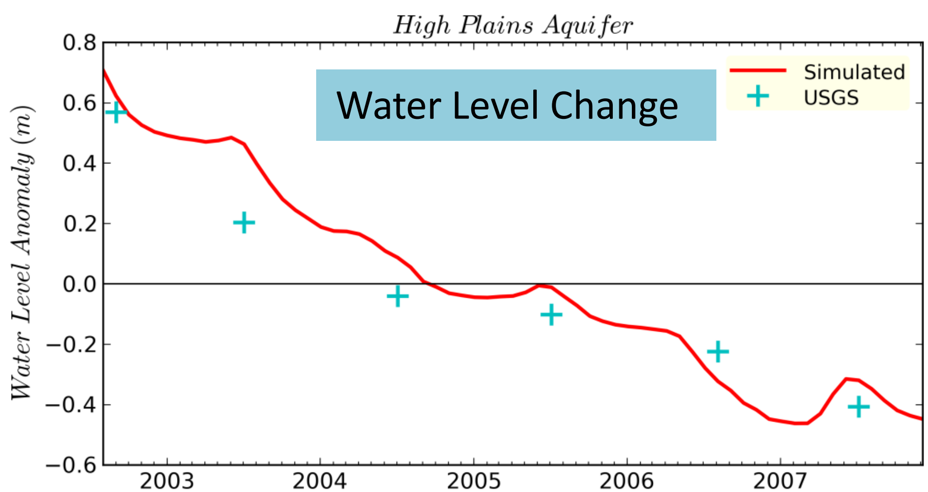


Figure 2. Cumulative change and total ground water in storage in the High Plains aquifer, predevelopment to 2007 (modified from McGuire, 2006).



USGS reports considerable decline in groundwater storage/levels in recent years.

Remarks

- Integrated model of natural hydrology & anthropogenic activities is under development.
  - Capable of assessing the source and path of water withdrawals for agricultural productions
  - Monitor the non-local/non-renewable water usages
- Human activities are changing the hydrological cycles even on global scale:
  - Storing in artificial reservoirs, exploiting fossil ground water, and the changes terrestrial water storages are changing the sea level.

IPCC AR5 WGII Ch3 “Freshwater”, 1st Lead Author Meeting, Tsukuba, Japan, Jan.2011

Working Group II calendar

- LAM1: January 2011
- Informal Peer Review: (ZOD ↓) July - September 2011
- LAM2: December 2011
- Expert Review: (FOD ↓) June - August 2012
- LAM3: October 2012
- Government & Expert Review: (SOD ↓) March - May 2013
- LAM4: July 2013
  Literature cutoff (in press)
- Final Government Distribution: (FGD ↓) October - December 2013
- Plenary: March 2014

AR5/WGII Chapter 3 "Freshwater Resources"
Taikan Oki (taikan@iis.u-tokyo.ac.jp), CLA

Announcement

- **Domestic meeting preparing for the Belmont forum/Grand Challenge WS on Water Security**
  - **with delegates from MEXT**
- **Date: Friday, October 21st, 2011**
  - **Time: 11:00-17:00**
- **Place: Institute of Industrial Science**
  - **Komaba II Research Campus, The U of Tokyo**
- **Contacts:**
  - **Taikan Oki (taikan@iis.u-tokyo.ac.jp)**
  - **Makoto Taniguchi (makoto@chikyu.ac.jp)**

飲水思源

When you drink water, think its origin.

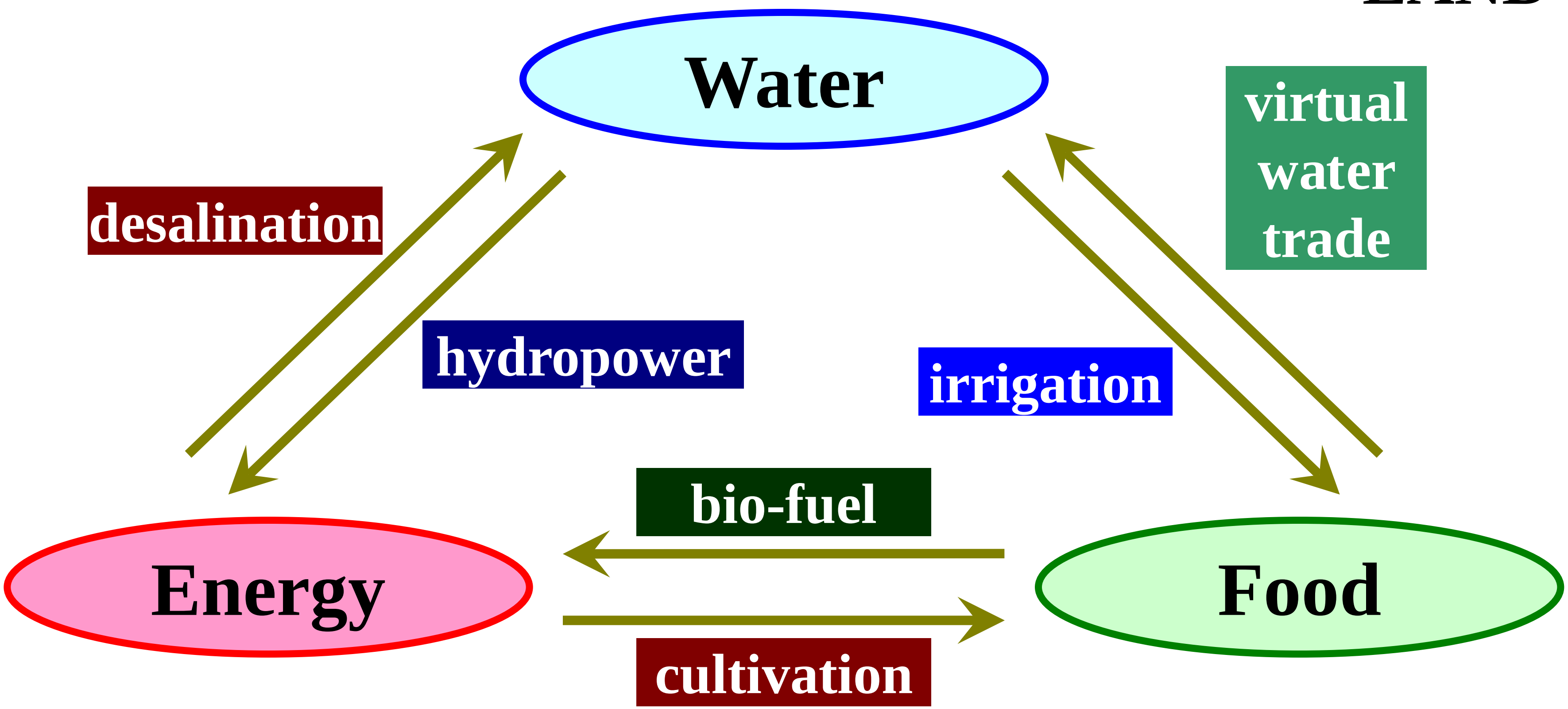
飲食思水

When you eat, think about water.

Thank You!

Support developing sustainability in a society

- Water should not be dealt alone separated from food and energy. ←Limited Resources = "LAND"



Sea Level Change: Anthropogenic TWS Contributions

Source	Sea Level Rise (mm yr⁻¹) 1961–2003	1993–2003
Thermal Expansion	0.42 ± 0.12	1.6 ± 0.5
Glaciers and Ice Caps	0.50 ± 0.18	0.77 ± 0.22
Greenland Ice Sheet	0.05 ± 0.12	0.21 ± 0.07
Antarctic Ice Sheet	0.14 ± 0.41	0.21 ± 0.35
Sum	1.1 ± 0.5	2.8 ± 0.7
Observed	1.8 ± 0.5	
		3.1 ± 0.7
Difference (Observed –Sum)	0.7 ± 0.7	0.3 ± 1.0

IPCC-AR4: "We conclude that the budget of sea level has not yet been closed satisfactorily closed … anthropogenic contributions from terrestrial water storage are poorly known and are omitted in the current assessment…"

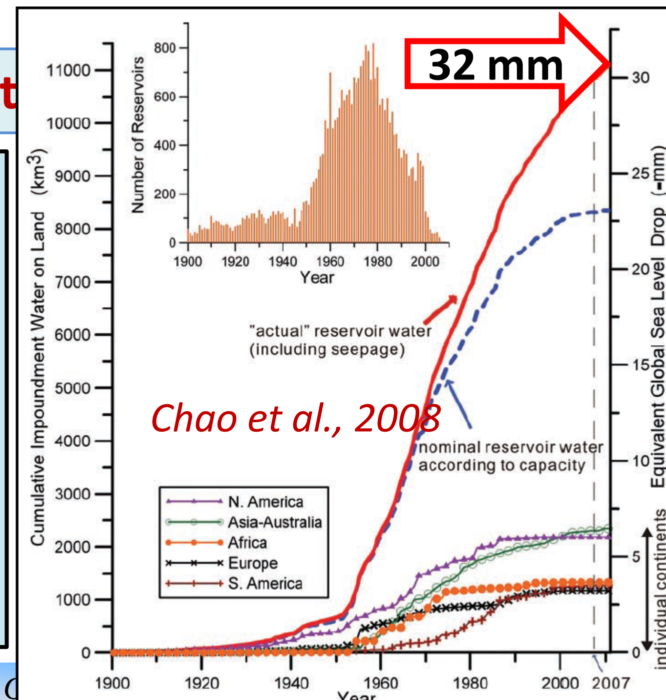
Can this gap be partly filled by anthropogenic TWS cont

Very few studies exist:

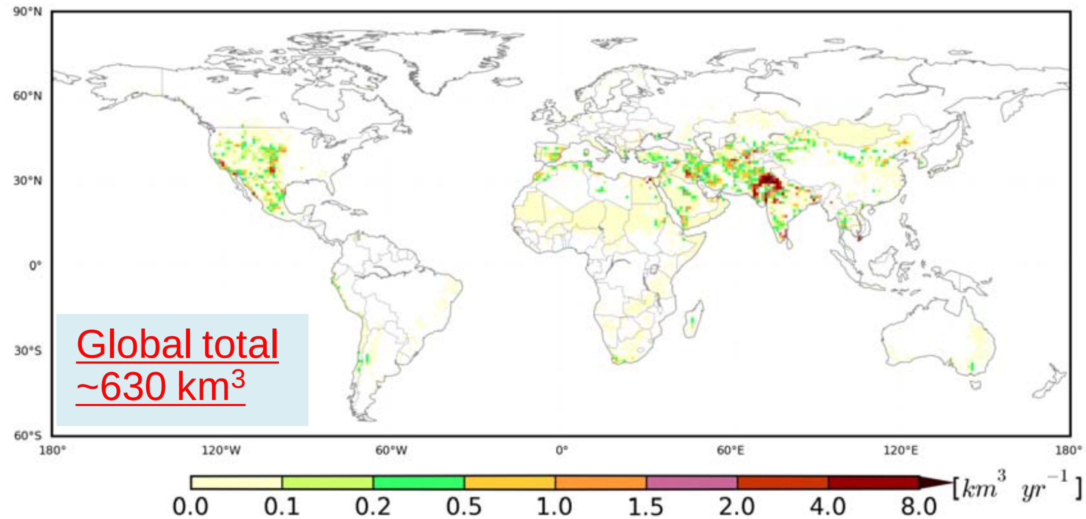
✓ Chao et al. (2008) estimated reservoir impoundment contributions to sea level change, but the maximum capacity of reservoirs was considered

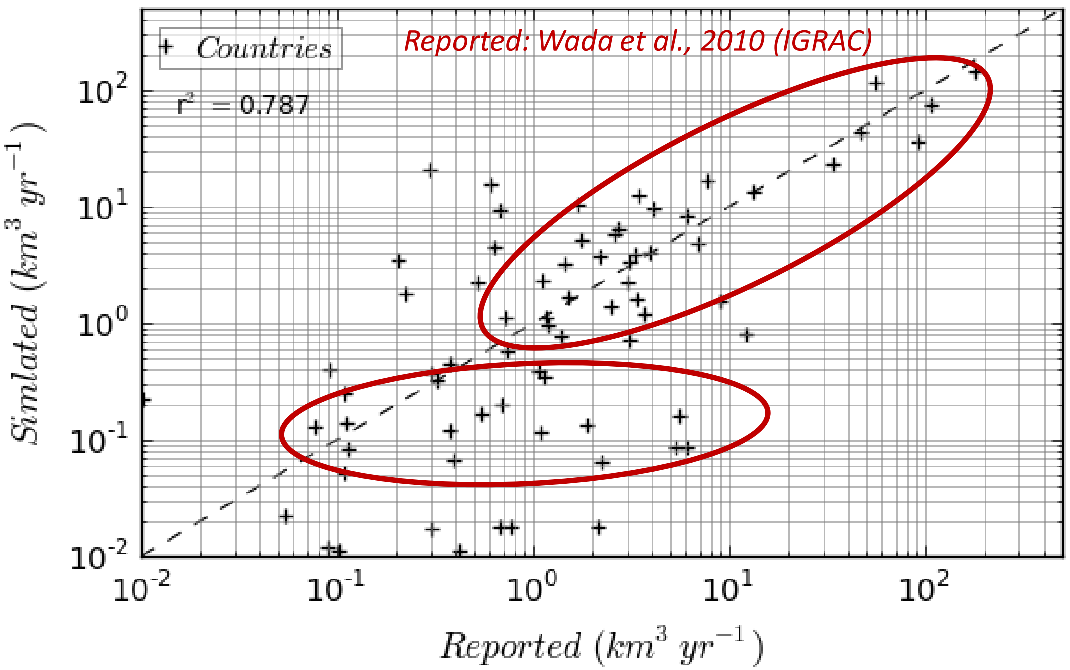
✓ Actual reservoir storage = ??

✓ Comprehensive estimation of direct anthropogenic TWS contributions to SLC is not available



Global Groundwater Withdrawal





- ✓Large withdrawals in <u>North India, Western US, Middle East, Spain</u>
- ✓More than 90% is used for **<u>irrigation</u>**

- ✓Results agree **<u>fairly well</u>** for many countries
- ✓Even the reported values may have significant **<u>uncertainties</u>** as they are **<u>reconstructed</u>** based on population distribution

Groundwater withdrawal

Groundwater withdrawal in major countries

Unit: km^3/yr	This study	WRI (2007)
India	129.3	169.1
USA	78.8	68.4
Pakistan	47.3	54.0
Mexico	12.3	16.0
Bangladesh	6.6	9.4
Saudi Arabia	6.0	13.0

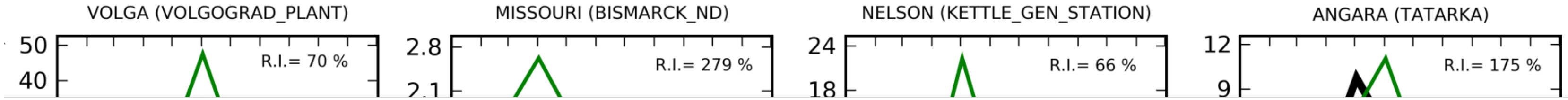
Ground water withdrawal in the Ogallala aquifer

Unit: mm/yr	This study	USDA (2002)	Area km^2
Maize	369	331	36.02
Wheat	408	247	6.33
Cotton	434	255	5.55

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

Simulated River Discharge (Highly Regulated Basins)

Seasonal variation improves significantly in many regulated basins.

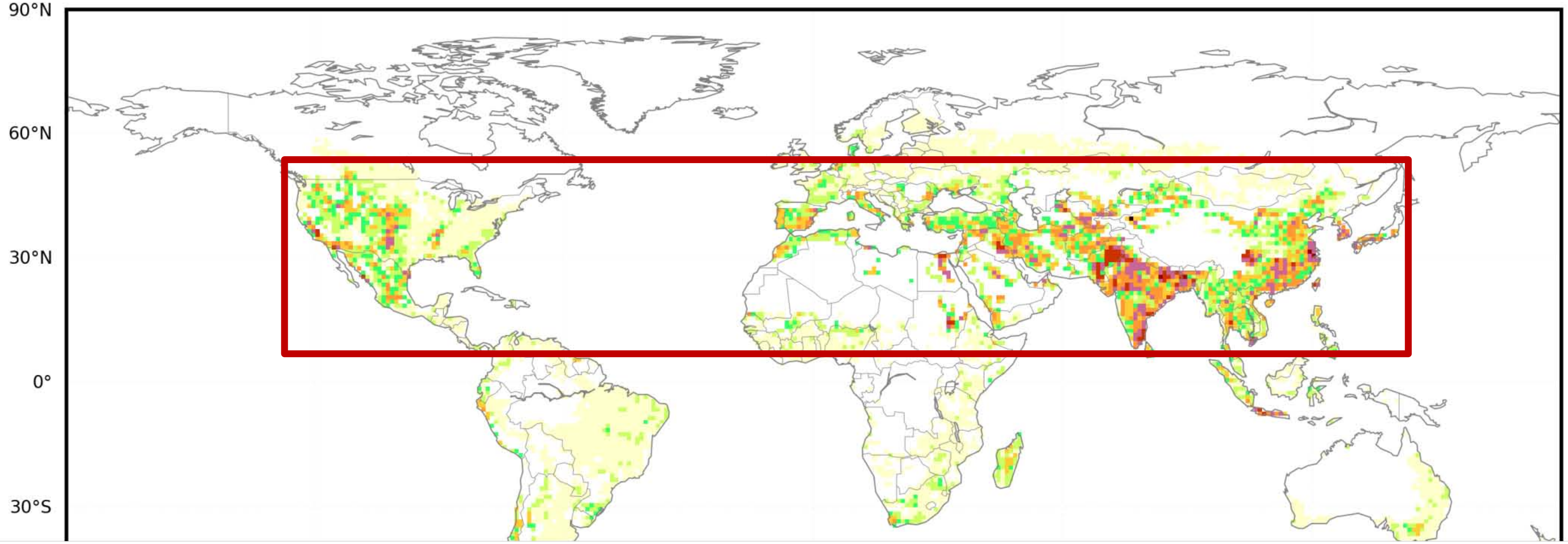


1000 $m^3 s^{-1}$

R.I. → Reservoir capacity/annual flow volume * 100

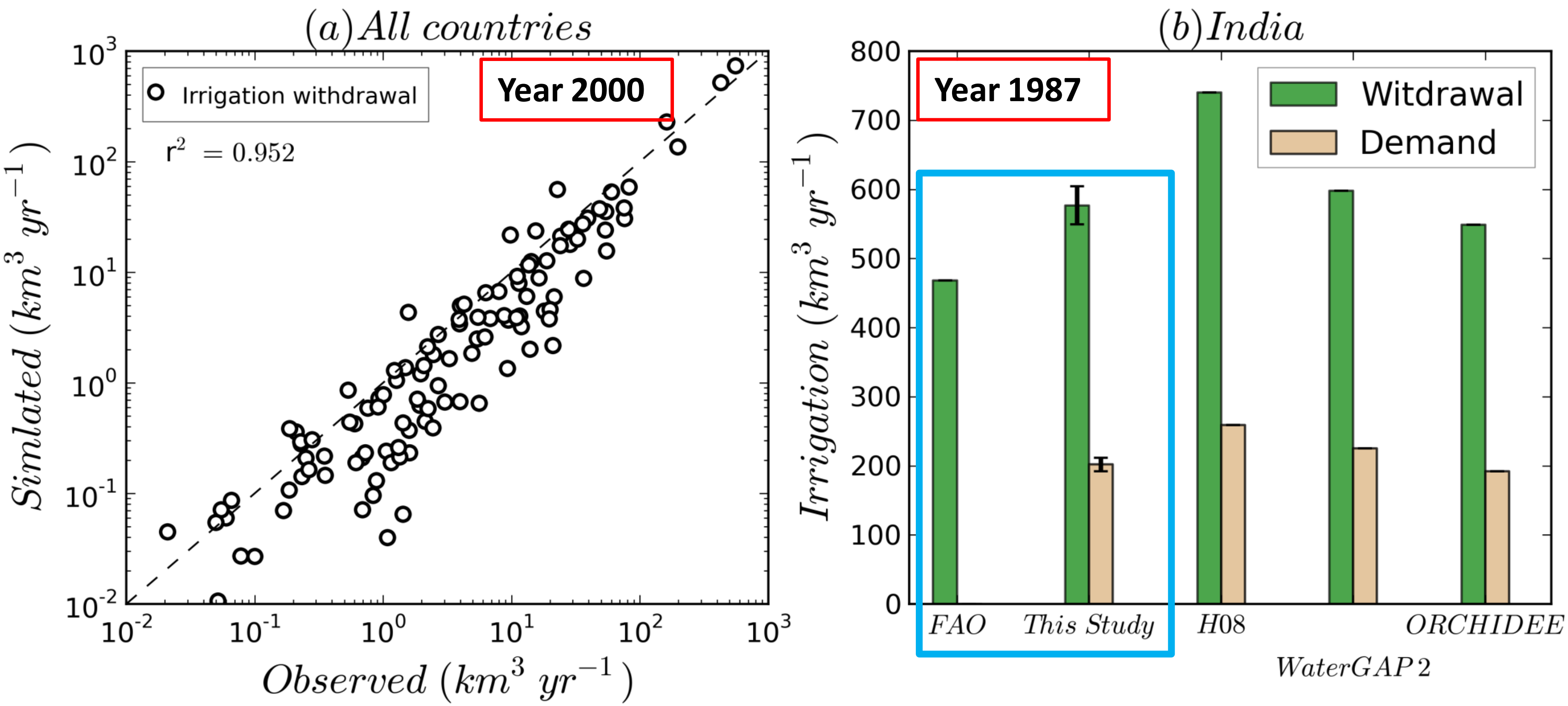
Global Irrigation Water Requirements

Simulated net irrigation water requirement: grid averaged values.



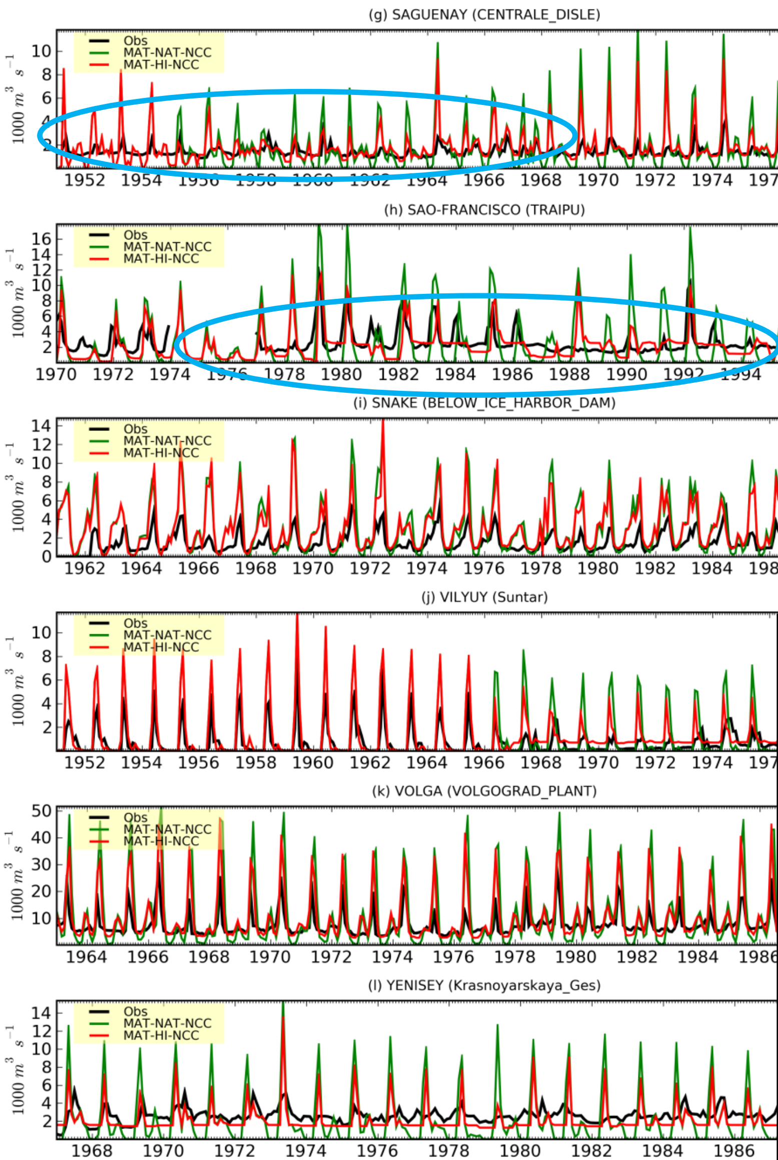
Observed data: FAO AQUASTAT (country statistics), 1998~2002

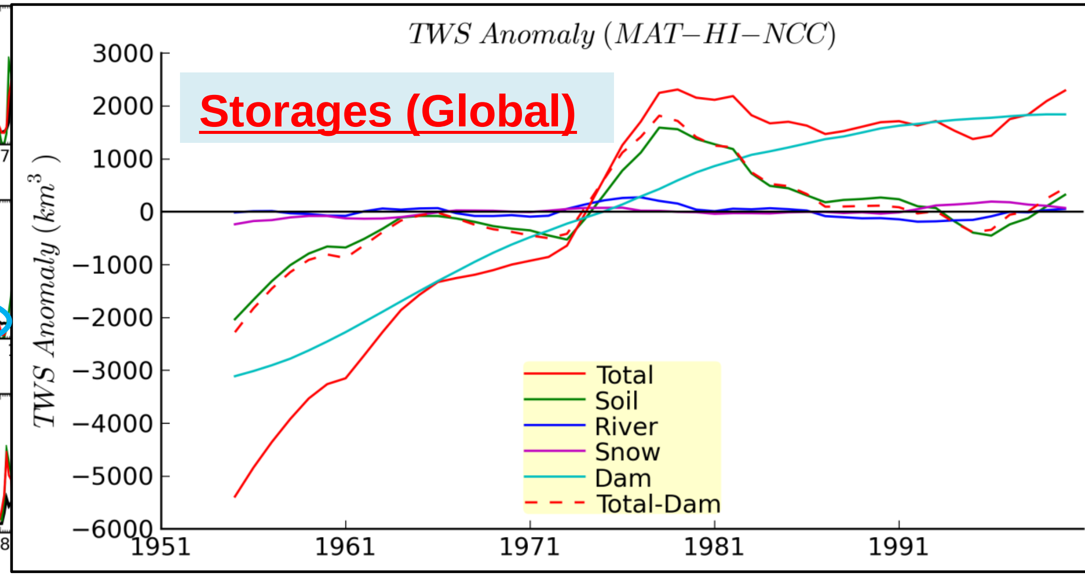
Water use efficiency: Doll & Siebert (2002)

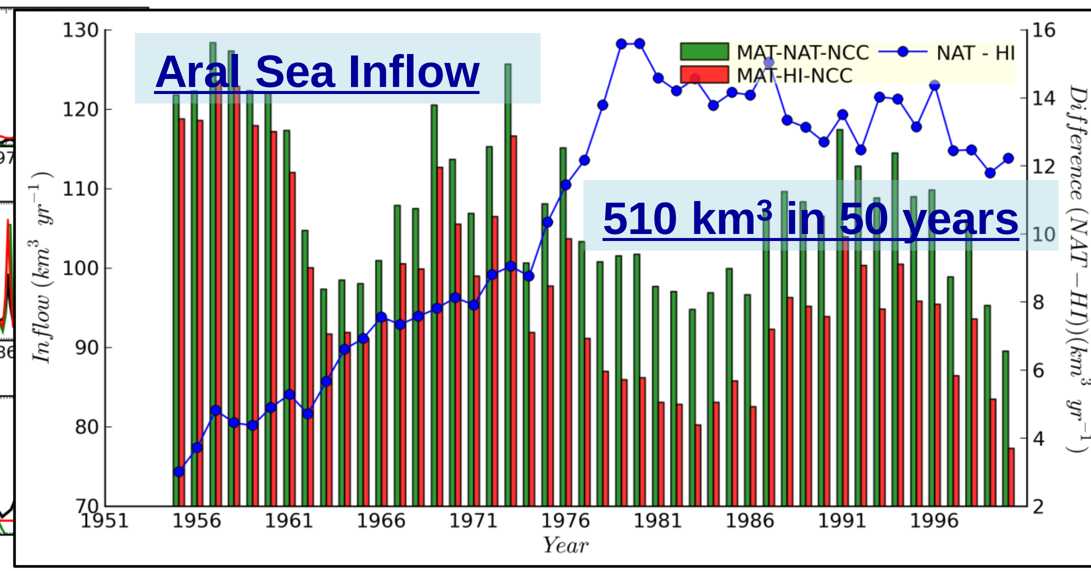


The model estimates of irrigation water withdrawals agree well with the observations. Error bars: **uncertainty due to precipitation** data.

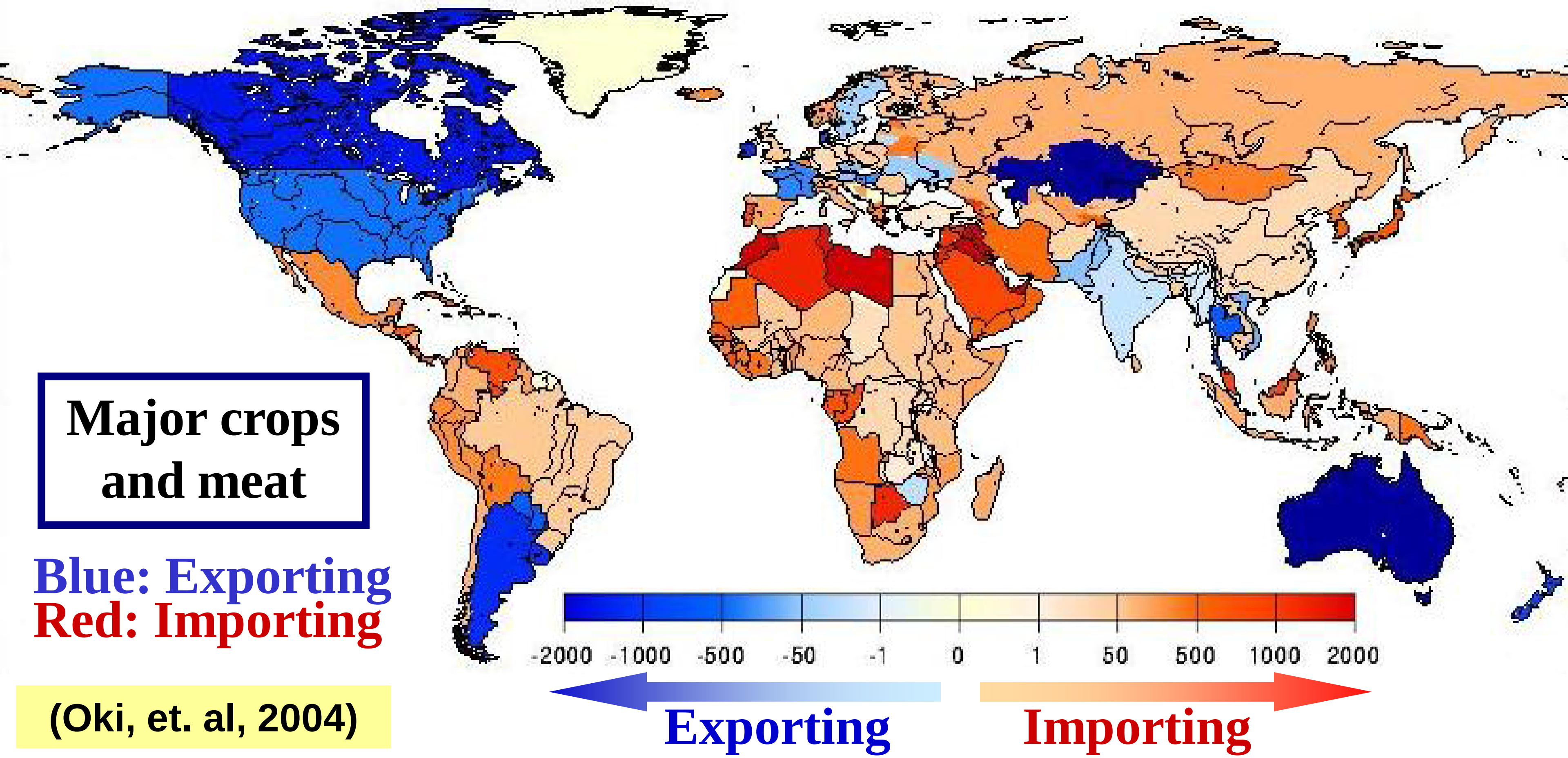
Human Impacts: River Discharge and TWS







Virtual Water Balance in Countries ($m^3/c/y$) in 2000



Major crops and meat

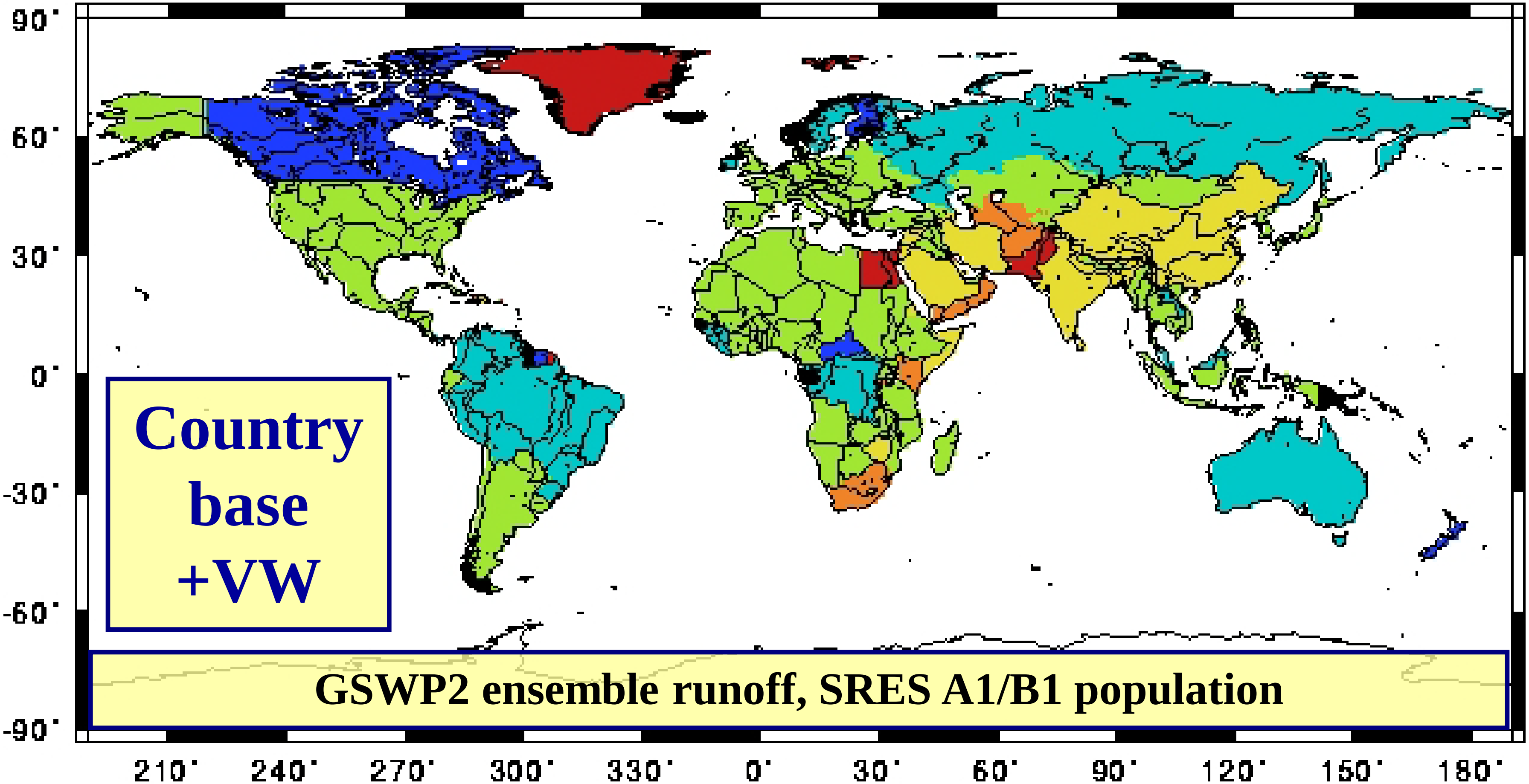
Blue: Exporting
Red: Importing

(Oki, et. al, 2004)

- **7 out of top 10 importing countries are seriously poor in water resources.**
- **7 out of top 10 exporting countries are rich in water resources.**
- **Denmark (10) and India (18) are water stressed but exporting *RW* in net.**

World Water Resources Considering Virtual Water Trade

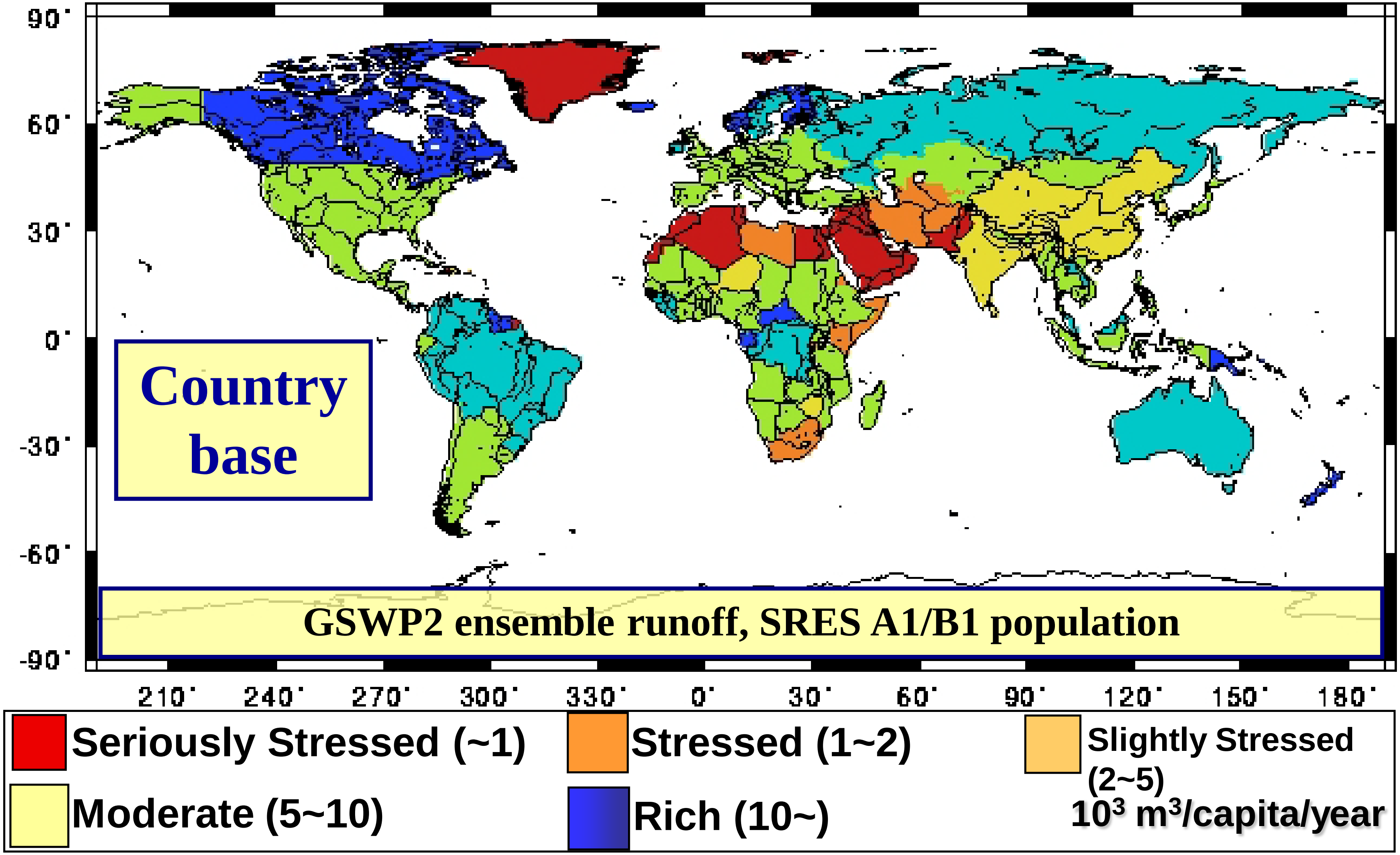
Potentially Available Water Resources per Capita in 2000



Seriously Stressed (~1)
Stressed (1~2)
Slightly Stressed (2~5)
Moderate (5~10)
Rich (10~)
10^3 m^3/capita/year

Conventional Water Resources Assessment

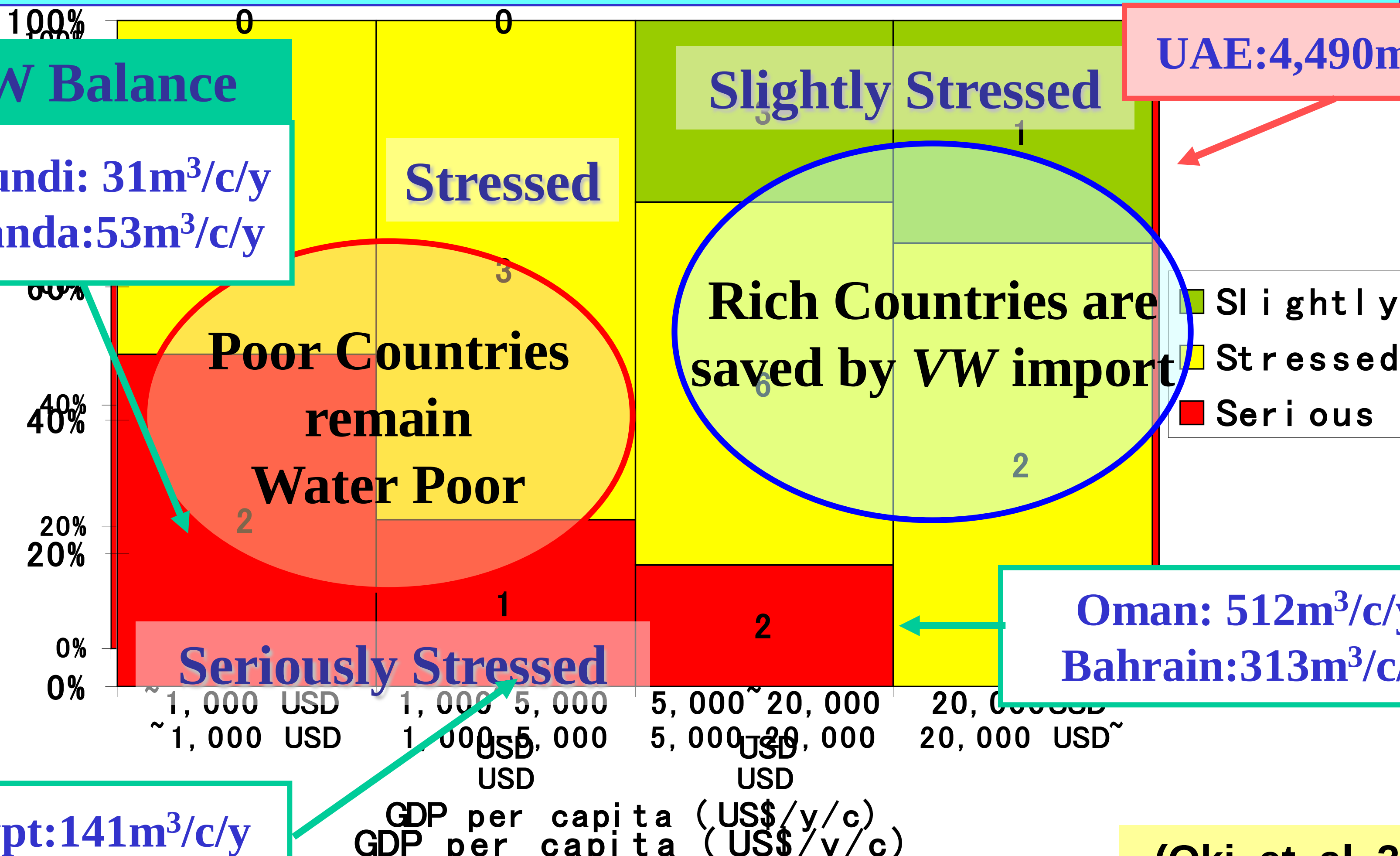
Potentially Available Water Resources per Capita in 2000



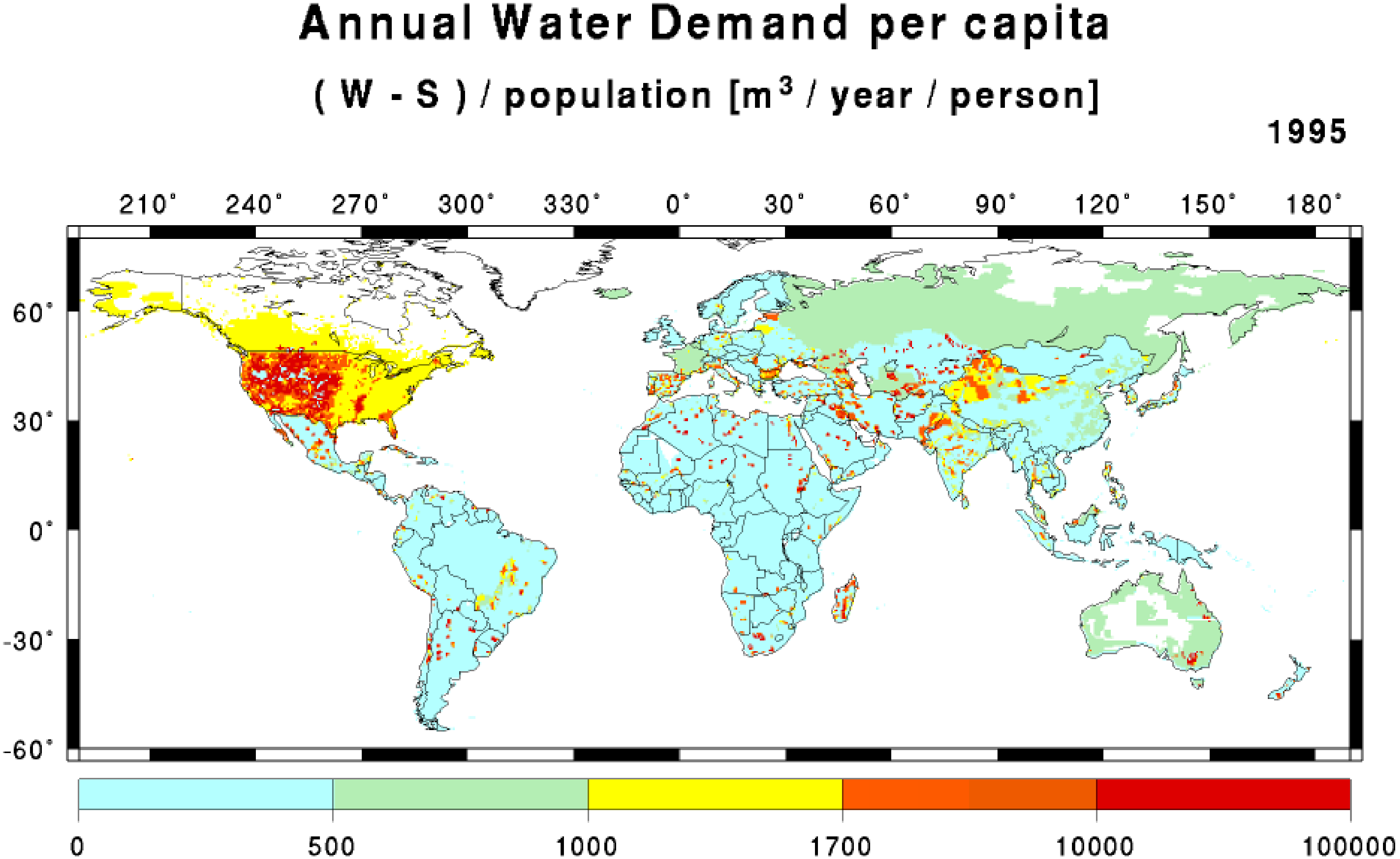
Water Resources Assesment Considering VW trade

22 Countries were classified into "seriously stressed" in 2000 by conventional water resources assessment.

➔ +Virtual Water Import

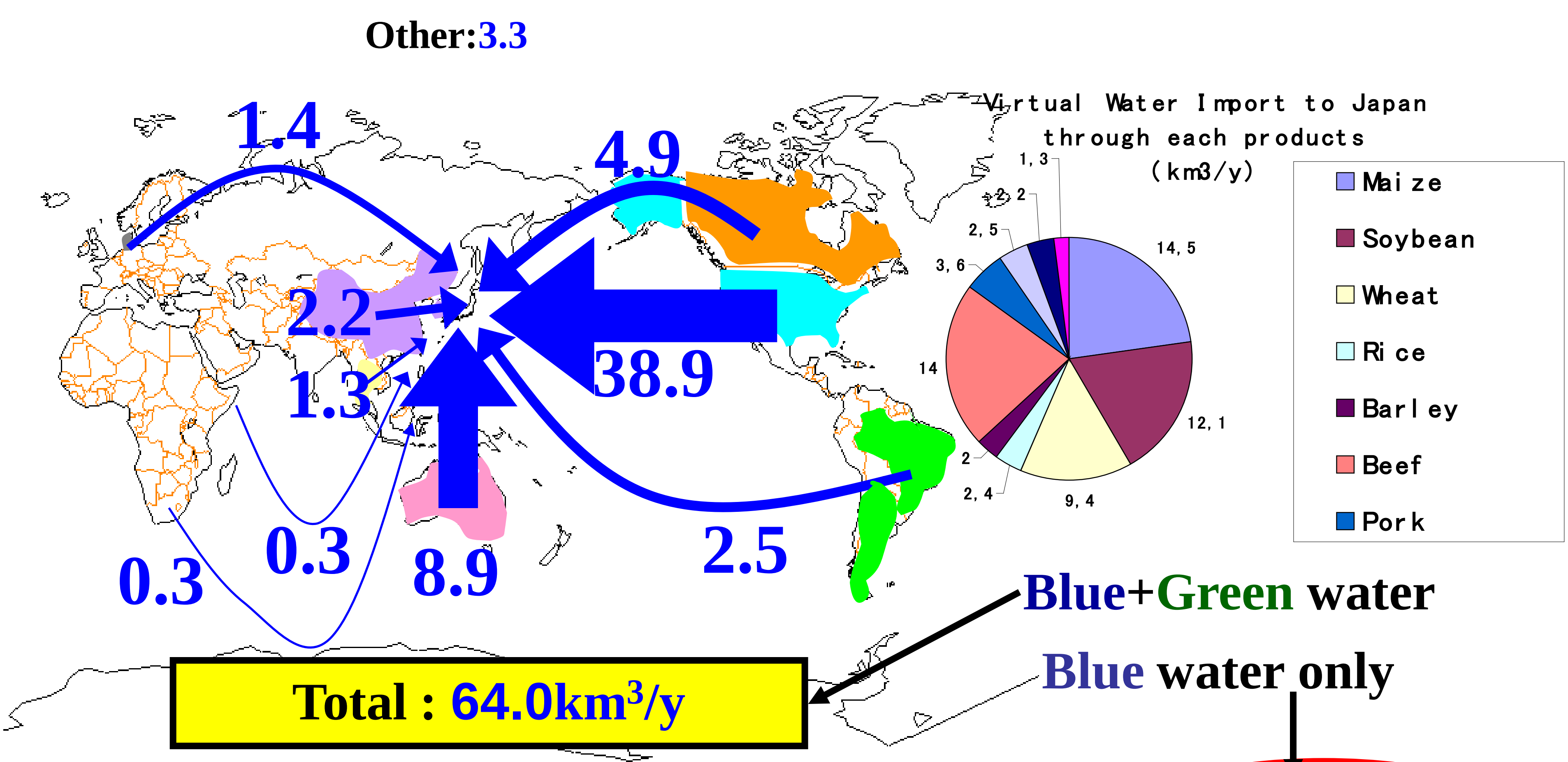


(Oki, et. al, 2004)



R_{ws}= *(W-S)/Q* and A_{wc}= *Q/C(m³/y/c)* have similar global distribution → Is *(W-S)/C* globally uniform?

Virtual Water Import to Japan

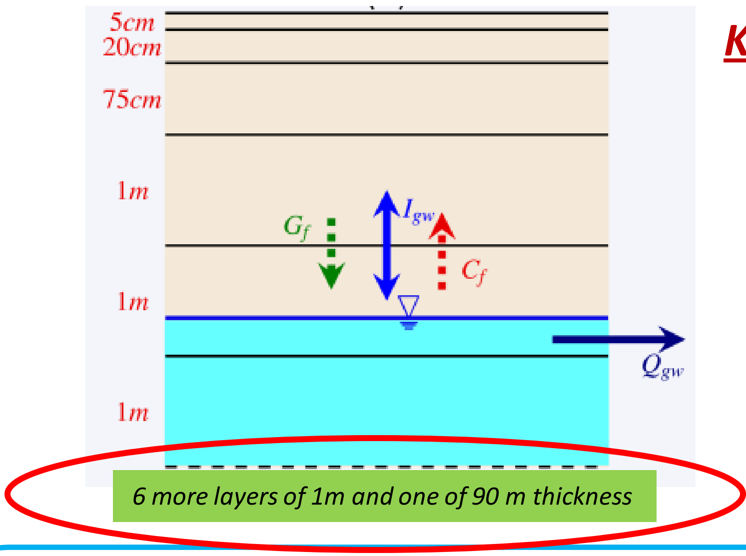


(for JFY in 2000)

Domestic Withdrawals in Japan: 89 km³/y
Domestic Blue Water in Japan: 400 km³/y
Domestic Green Water in Japan: 30 km³/y

(Oki, et. al, 2002, IHE-UNESCO)

Groundwater Representation



Koirala (2010)

- 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

- Water Balance of GW reservoir:

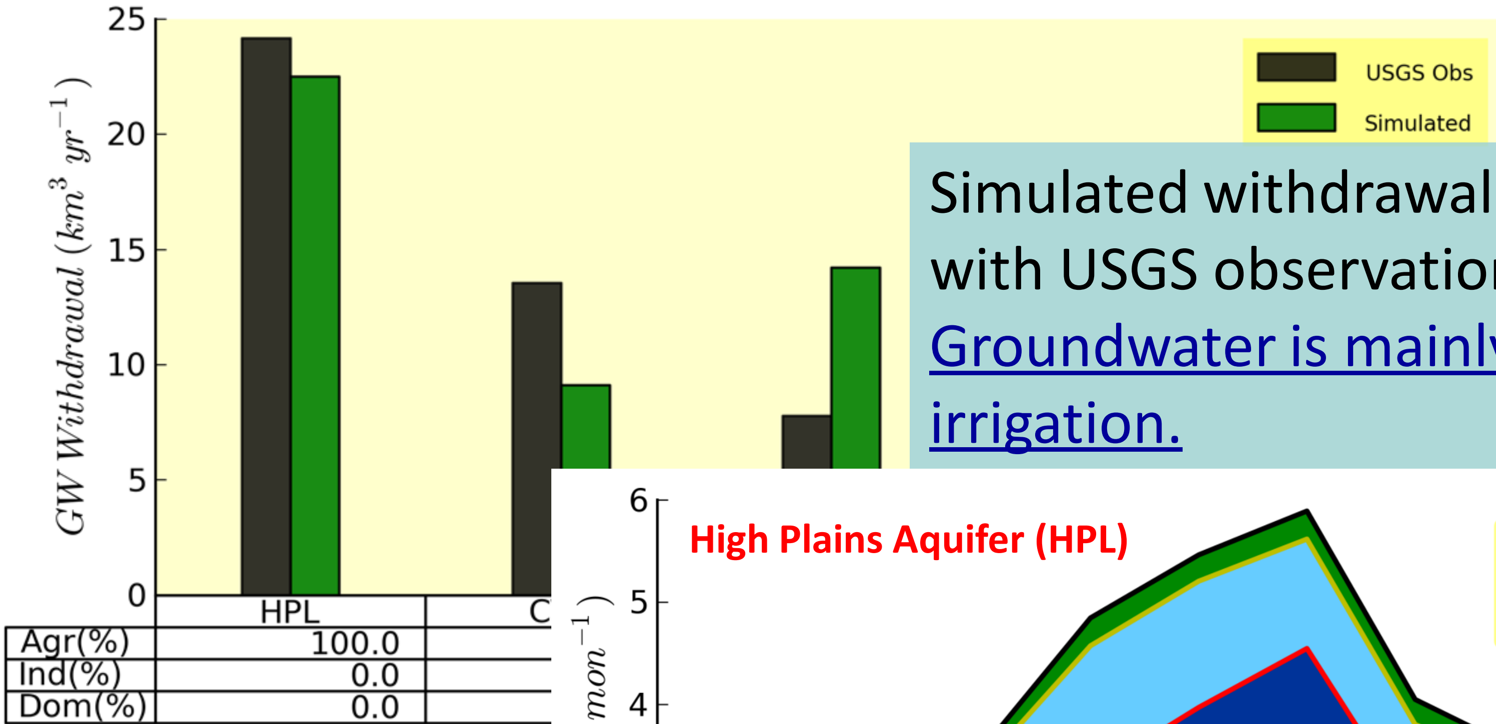
$$S_y \frac{\Delta d_{gw}}{\Delta t} = I_{gw} - Q_{gw}$$

- Baseflow initiates when WTD is shallower than threshold value:

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

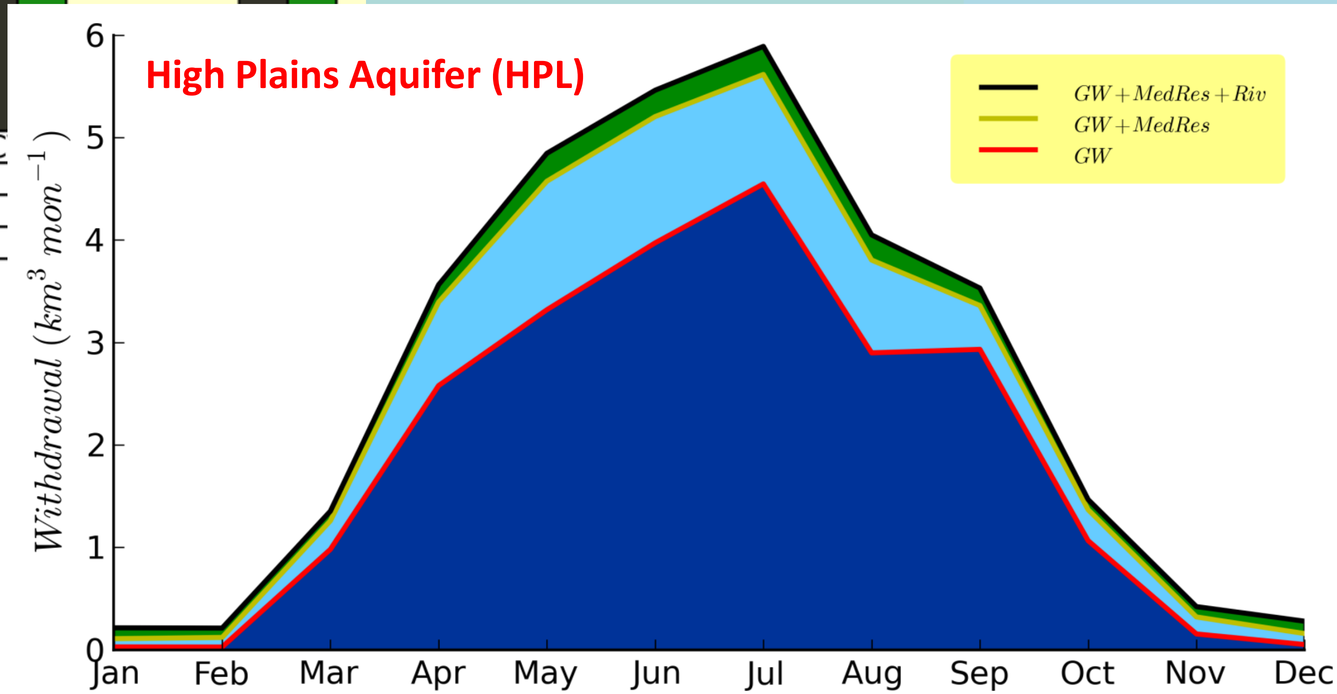
S_y: Specific yield, I_{gw}- recharge, Q_{gw} is baseflow, d_{gw}- water table depth (WTD), d_0- threshold WTD, K-outflow constant.

Groundwater Withdrawal (US Aquifers)

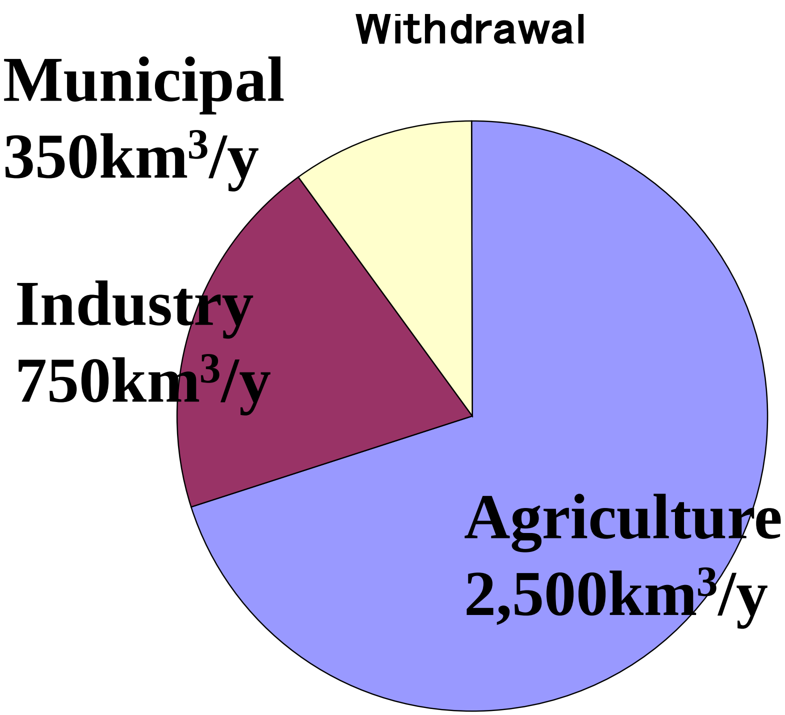


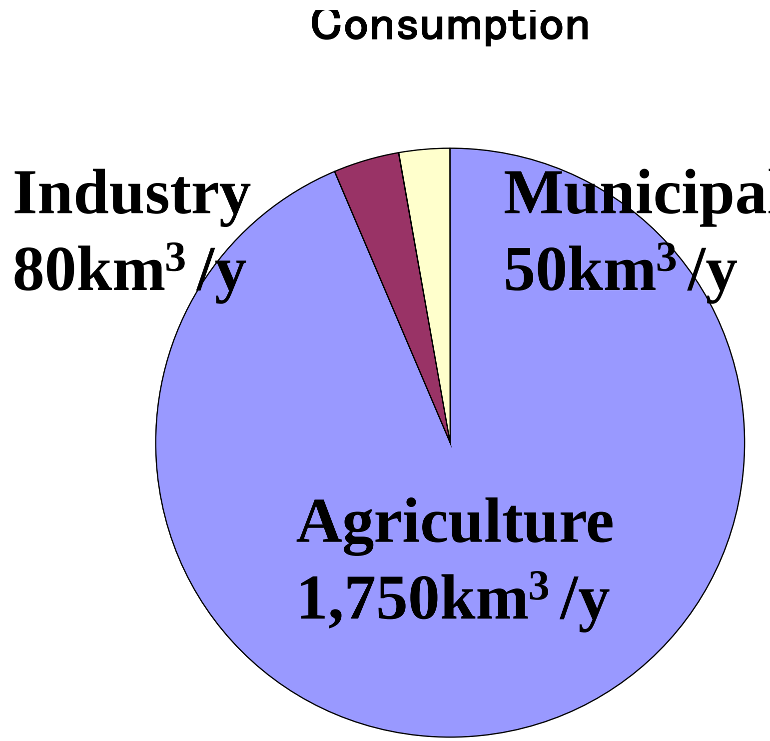
Simulated withdrawals compare well with USGS observations.
Groundwater is mainly used for irrigation.

Groundwater contributes ~75% of all water uses in areas overlying the HPL.



How water is used in the world?





$3{,}800km^3km^3/y$ $2{,}100km^3/y$

(Evaporation from reservoir 200 km^3/y)

(for 1995, from I. A. Shiklomanov, 1999)