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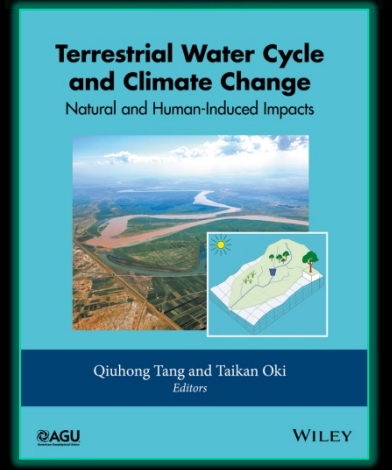
Estimating global groundwater withdrawal and depletion using an integrated hydrological model, GRACE, and in situ observations

Yadu N. Pokhrel

In the agenda:
"Impact of anthropogenic water usage on sea-level"

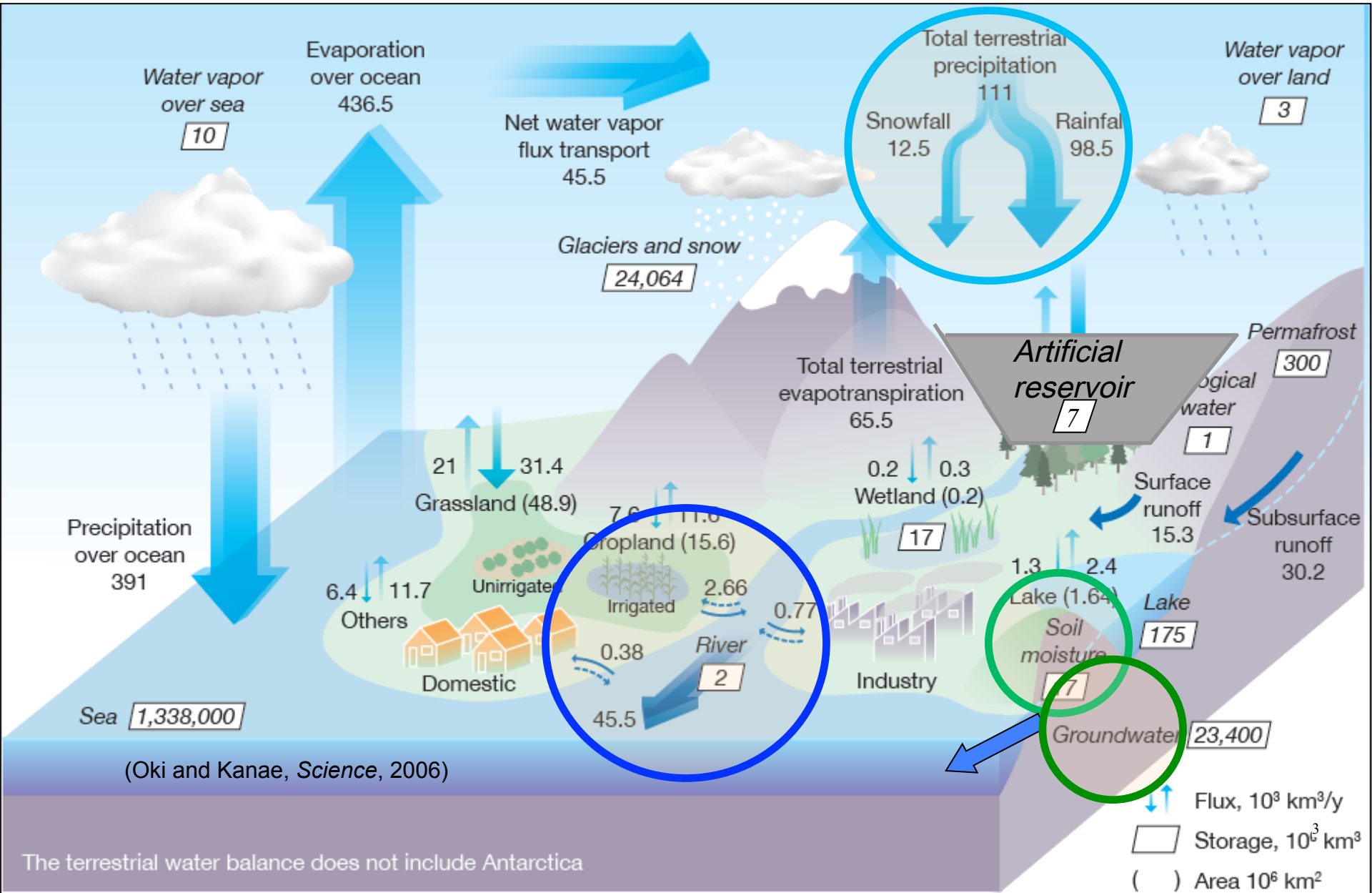
Taikan Oki

Institute of Industrial Science
The University of Tokyo



A workshop co-sponsored by GLASS and GHP "Including Water Management in Large Scale Models" Gif-sur-Yvette, France, 30 September 2016

Synthesized Global Water Cycle



Dam and Reservoirs

- **Human activity changes terrestrial water cycle:**
  - ✓ **Reservoir operation ⇔ operating rules unpublished**
  - ✓ **Irrigation intake ⇔ no high resolution data**

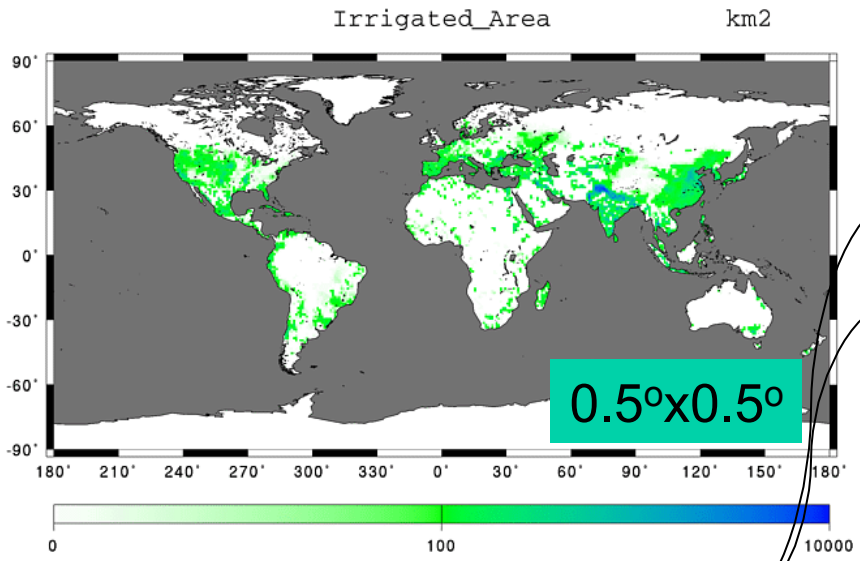
# of large dams in the world	45,000*
Their total storage capacity	7182 km^3*
Annual global river discharge	40000 km^3/year**
Global water withdrawal for irrigation	2504 km^3/year***
Annual global water withdrawal	3788 km^3/year***

∗ WRD, 1998, **Korzun, 1978, ***Shiklomanov, 2000

(Hanasaki et. al, *J. Hydrol.* , 2006)

Coupled Land-river-irrigation-reservoir model

(Hanasaki et. al, *J. Hydrol.* , 2006)



Meteorological condition

Crop calendar (estimation)

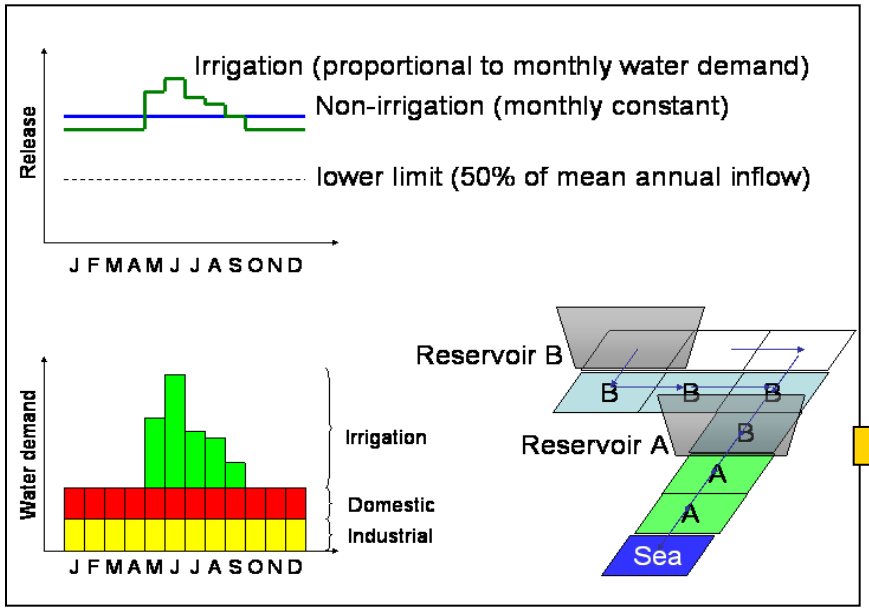
Irrigation condition

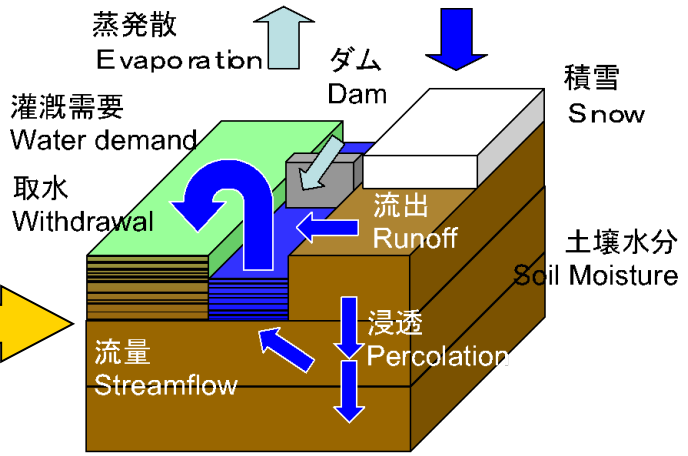
Crop water demand (per area)

Irrigated areas

Crop water demand (per area)

Good observed data will improve the results

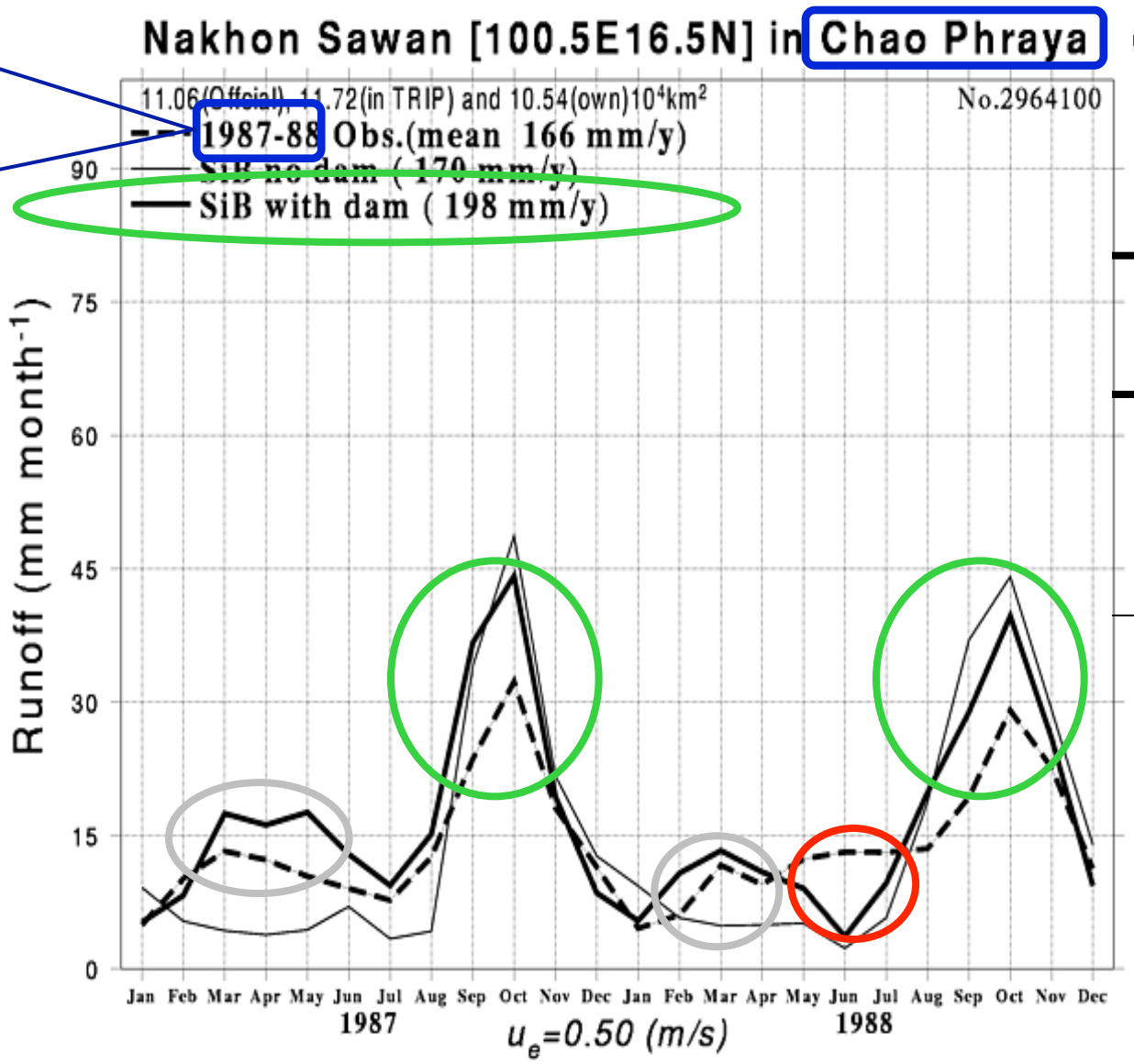




Discharge simulation is improved with reservoir operation rules

GSWP contributed reservoir scheme development

GAME-T contributed reservoir scheme development

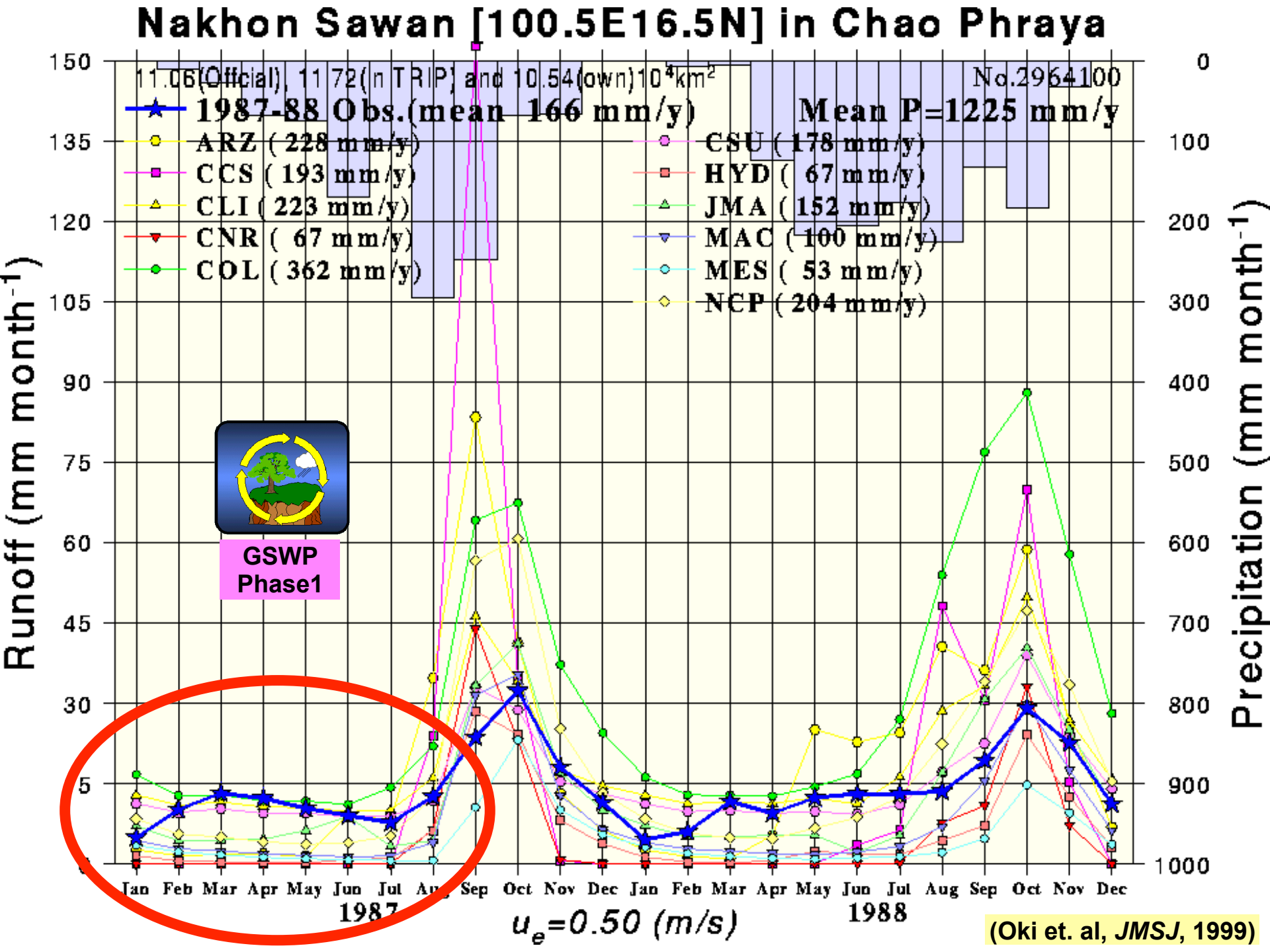


observed

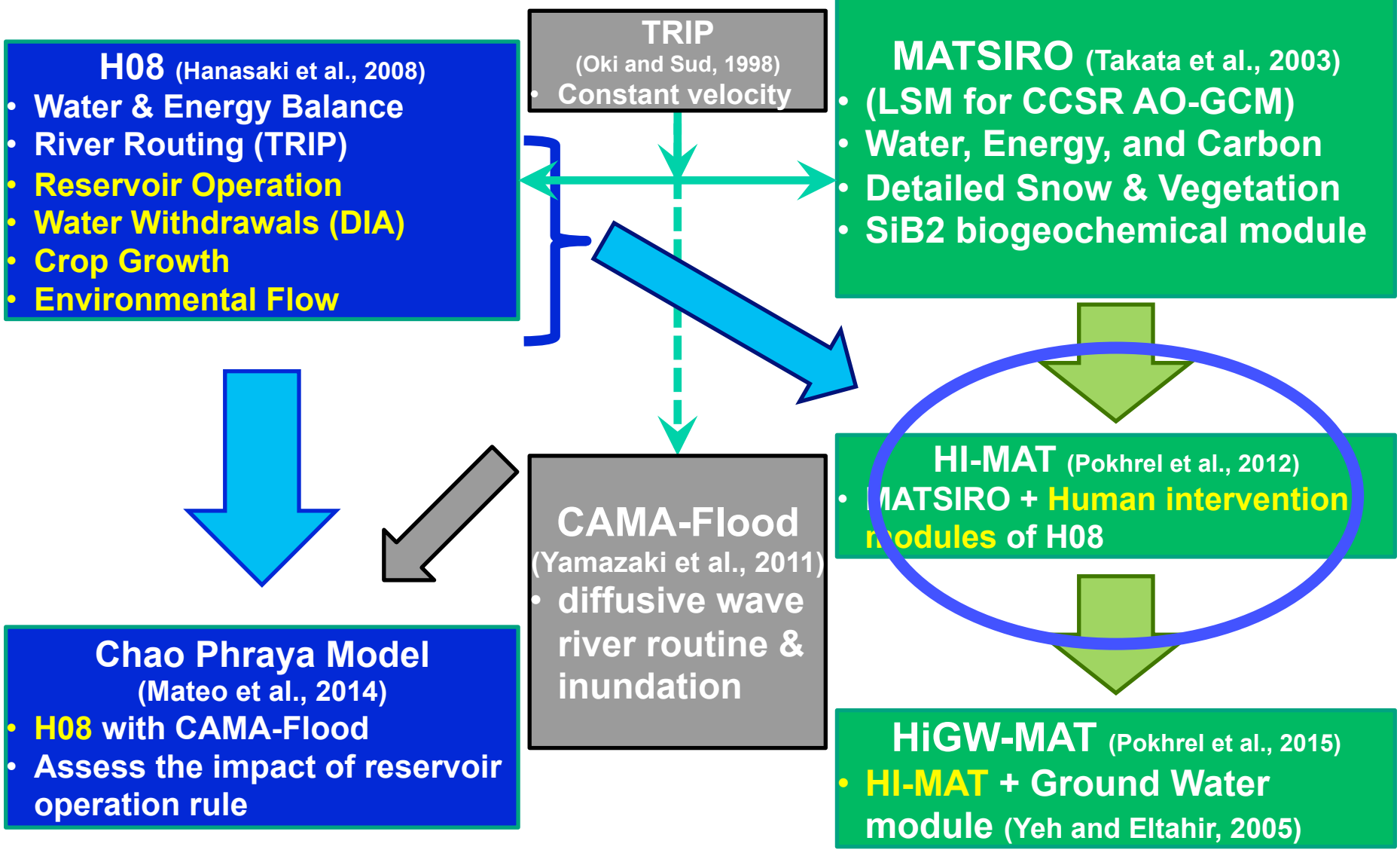
Simulation (with dam)

Simulation (no dam)

(Hanasaki et. al, *J. Hydrol.* , 2006)


Nakhon Sawan [100.5E16.5N] in Chao Phraya
11.06(Official), 11.72(in TRIP) and 10.54(own)10⁴km²
No.2964100
1987-88 Obs.(mean 166 mm/y)
Mean P=1225 mm/y
ARZ (228 mm/y)
CCS (193 mm/y)
CLI (223 mm/y)
CNR (67 mm/y)
COL (362 mm/y)
CSU (178 mm/y)
HYD (67 mm/y)
JMA (152 mm/y)
MAC (100 mm/y)
MES (53 mm/y)
NCP (204 mm/y)
GSWP Phase1
Runoff (mm month⁻¹)
Precipitation (mm month⁻¹)
150
135
120
105
90
75
60
45
30
5
0
100
200
300
400
500
600
700
800
900
1000
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
1987
1988
u_e=0.50 (m/s)
(Oki et. al, JMSJ, 1999)

Land surface models and Human Interventions

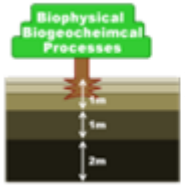


Land Surface Model with Anthropogenic Activities

HiGW-MAT

[Pokhrel 2012]

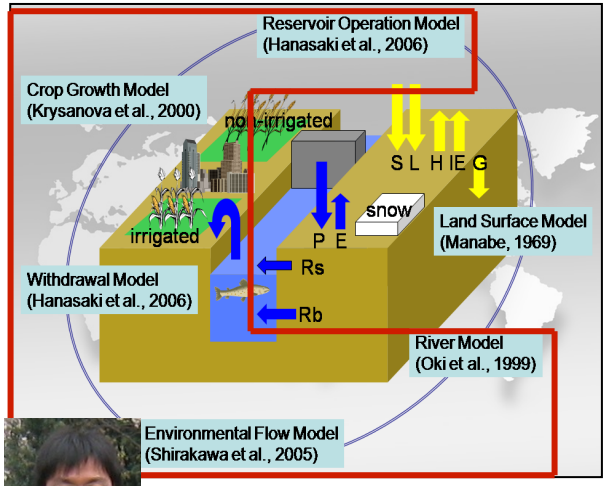
[Koirala 2013]



LSM MATSIRO

[Takata 2003]

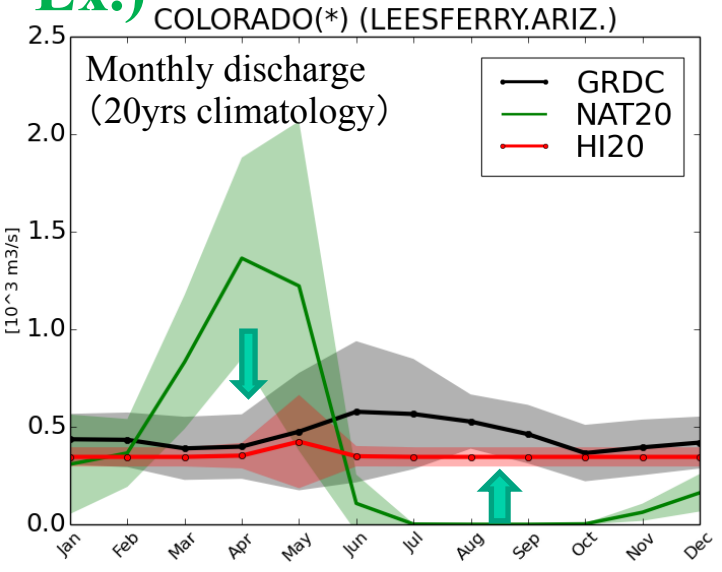
Type of Water regulation	Effects	
	on **River**	on **Landsurface**
Irrigation from **river water**	Expropriates water, then decrease river discharge ↓	Increases runoff ↑ and ET
Irrigation from **ground water**	Increases river discharge ↑	
Reservoir	Alleviates variation, then Increase low flow discharge ↑	None (possible indirect impacts)



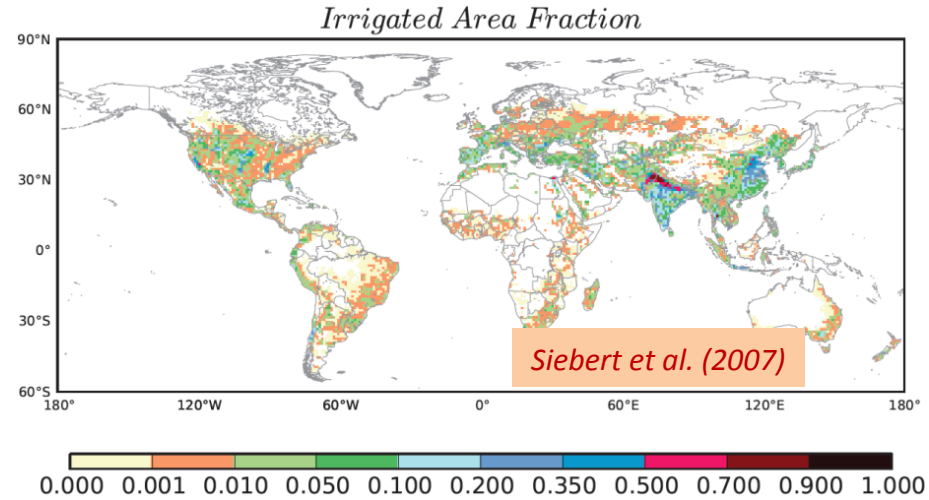
[Hanasaki 2008]

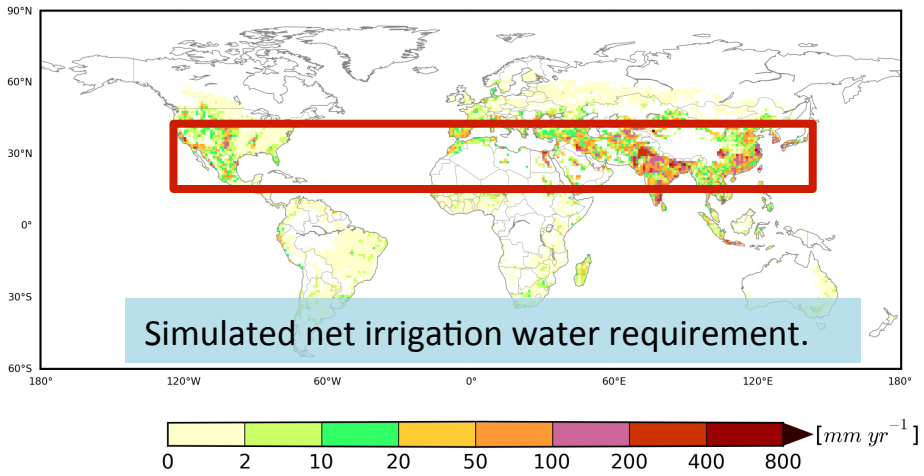
- **Crop growth and irrigation**
- **Human water withdrawals**
- **Reservoir operation**
- **Environmental flow**

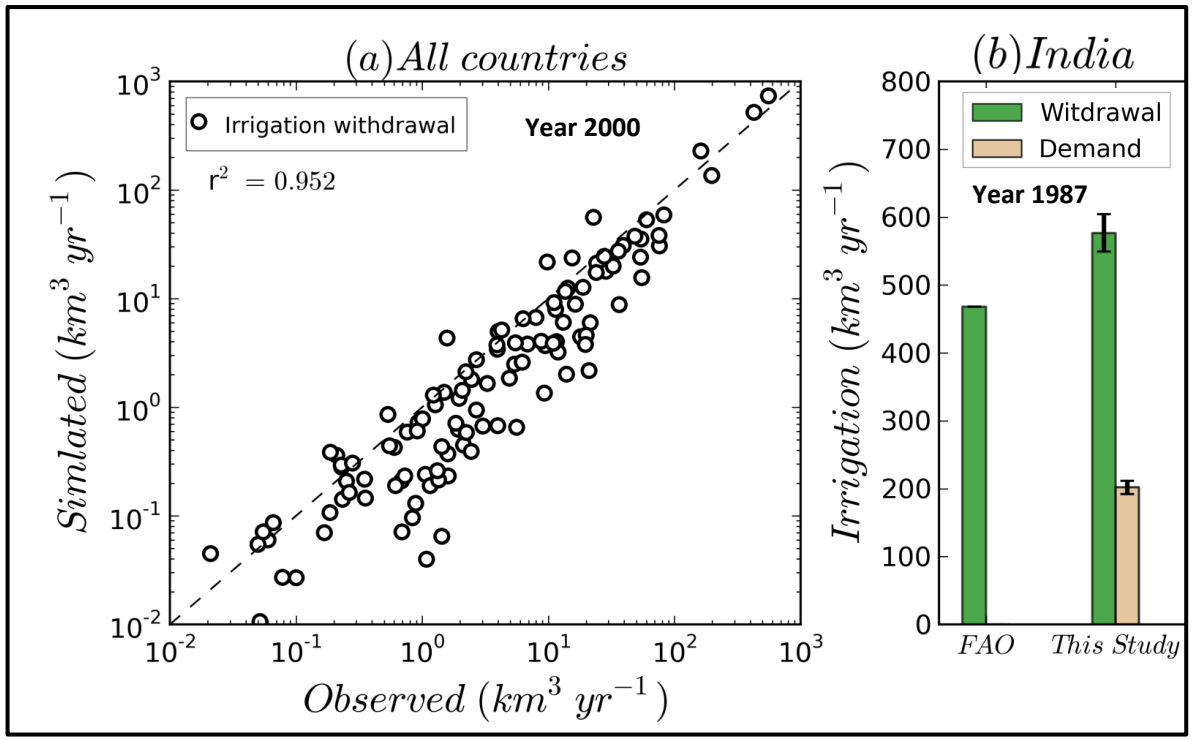
Ex.)



Global and Regional Irrigation Water Use







Country-scale irrigation water withdrawals are simulated well.

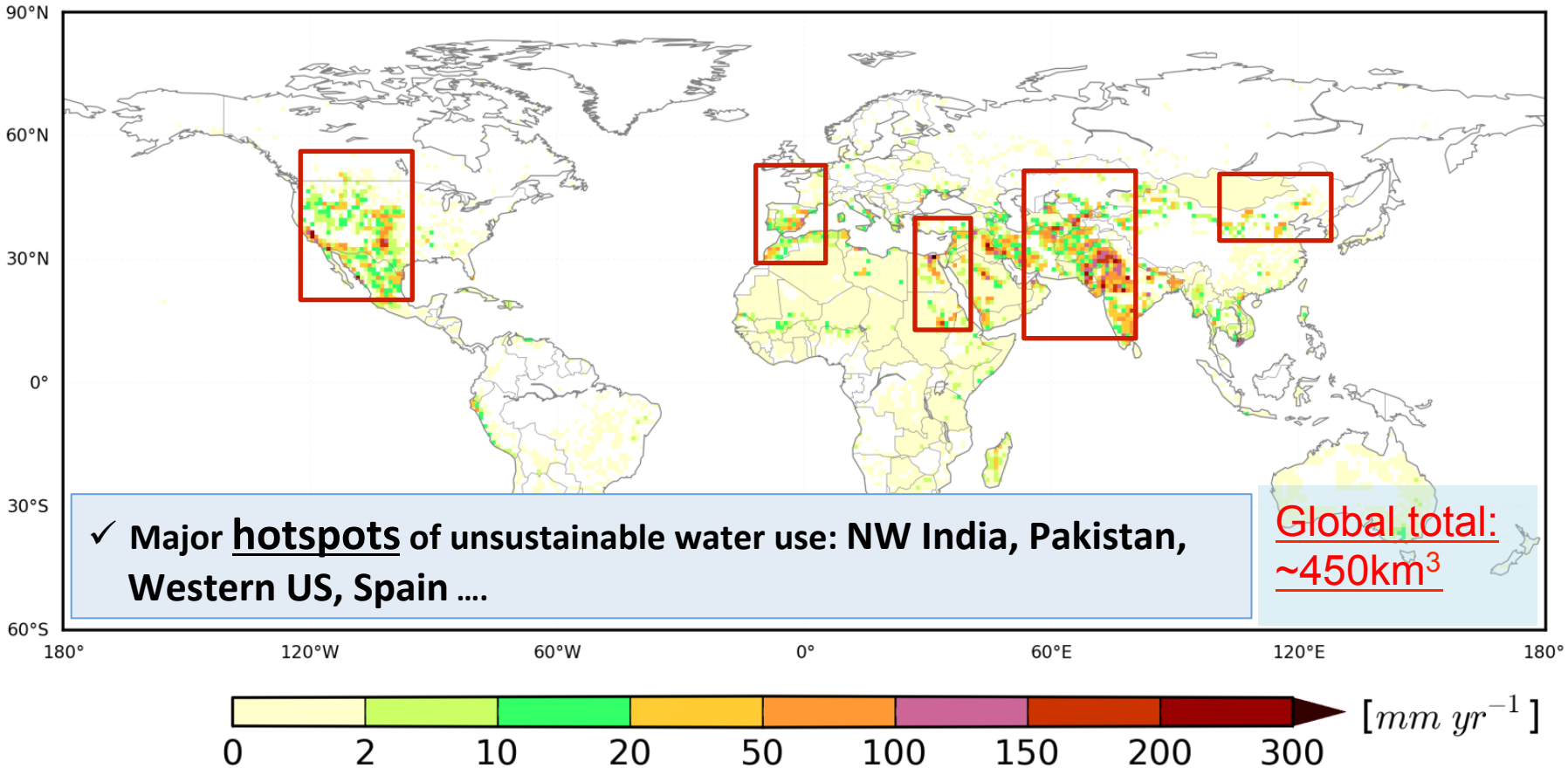
Observed data: FAO AQUASTAT, country statistics.

Pokhrel et al. (2012a)

Unsustainable Water Use (Non-local Non-renewable Blue Water)

➔Unsustainable groundwater (NNBW): **Demand – Supply**

➔Groundwater flow processes are accounted implicitly.

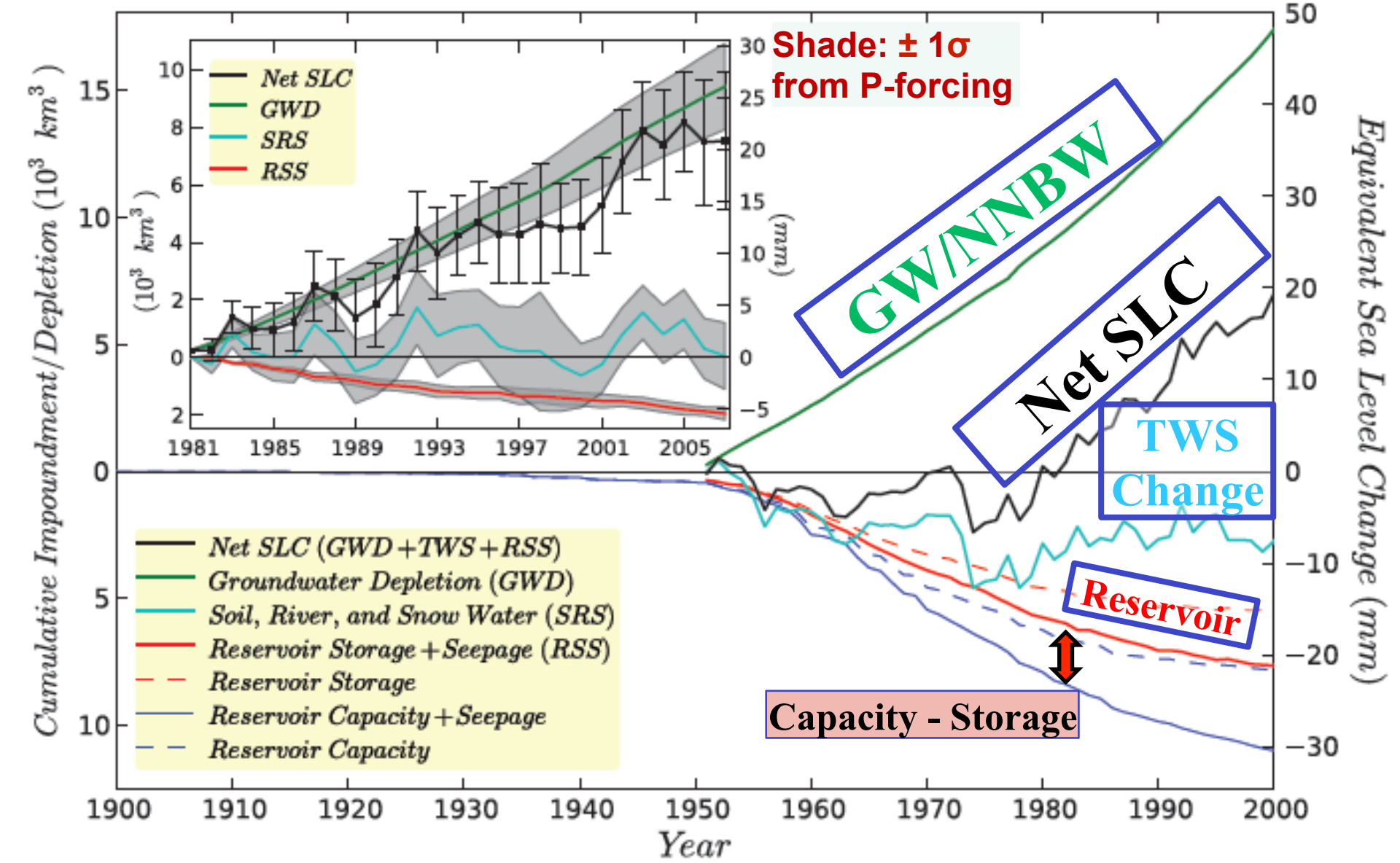


✓ Major **hotspots** of unsustainable water use: **NW India, Pakistan, Western US, Spain ….**

Global total: ~450km^3

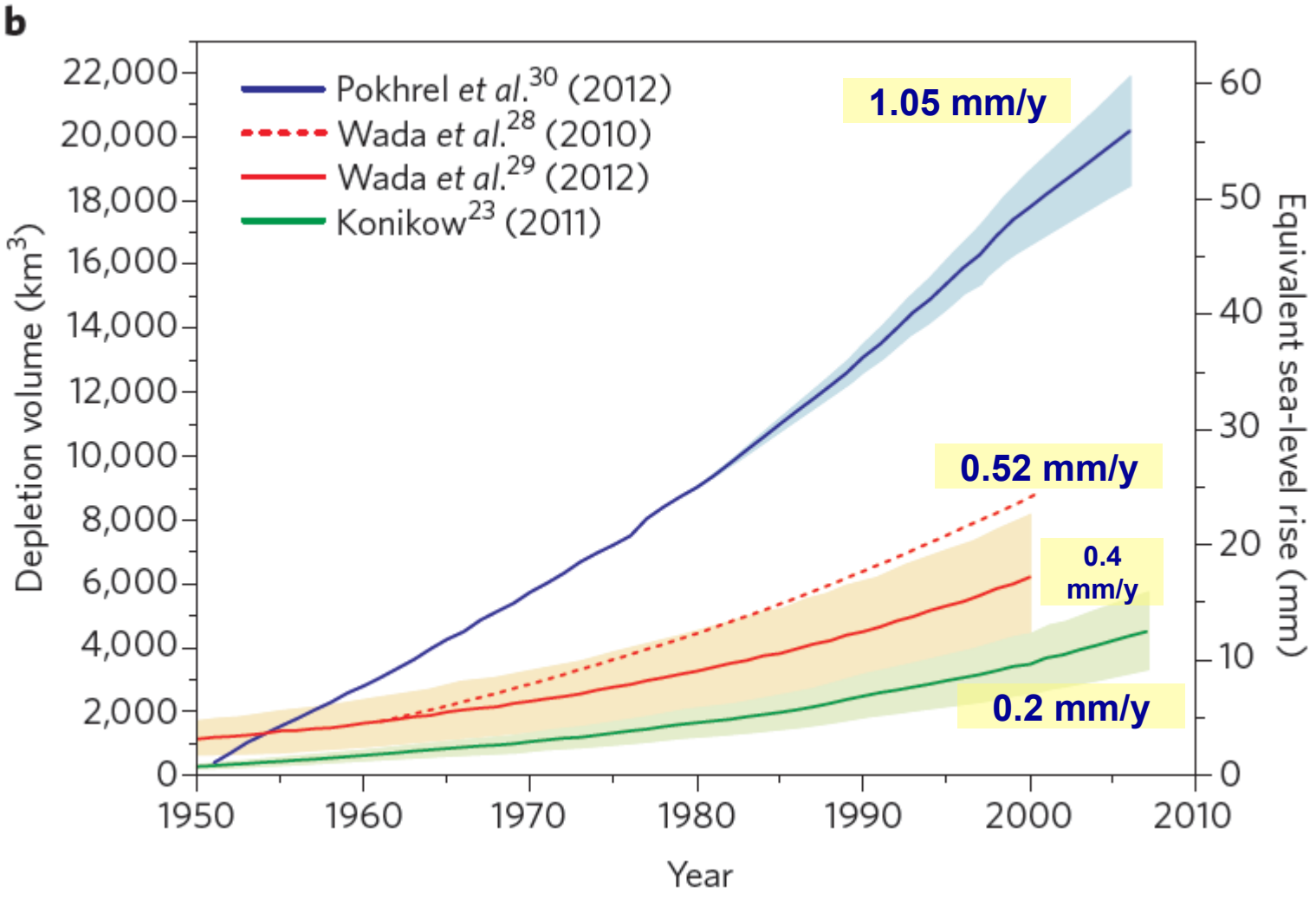
Pokhrel et al. (2012a)

Anthropogenic TWS Contributions for Sea Level Change



Contributions to Sea-level change in previous estimates

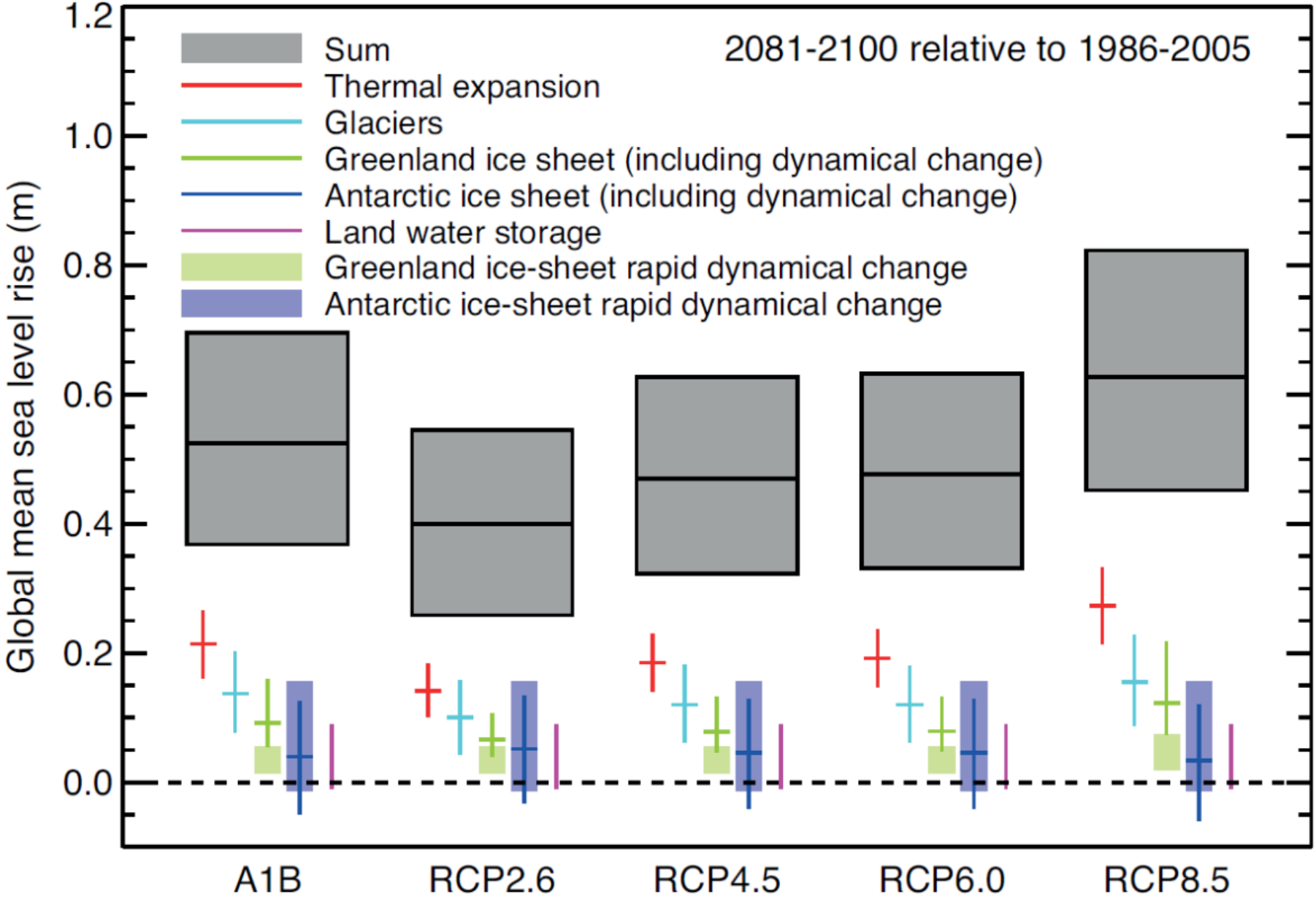
… our estimate is a minority



(Aeschbach-Hertig and Gleeson, *Nature Geoscience*, 2012)

Source	1993–2010
Observed contributions to global mean sea level (GMSL) rise	**(mm/y)**
Thermal expansion	1.1 [0.8 to 1.4]
Glaciers except in Greenland and Antarctica[a]	0.76 [0.39 to 1.13]
Glaciers in Greenland[a]	0.10 [0.07 to 0.13][b]
Greenland ice sheet	0.33 [0.25 to 0.41]
Antarctic ice sheet	0.27 [0.16 to 0.38]
Land water storage	0.38 [0.26 to 0.49]
Total of contributions	**2.8 [2.3 to 3.4]**
Observed GMSL rise	**3.2 [2.8 to 3.6]**
Modelled contributions to GMSL rise	
Thermal expansion	1.49 [0.97 to 2.02]
Glaciers except in Greenland and Antarctica	0.78 [0.43 to 1.13]
Glaciers in Greenland	0.14 [0.06 to 0.23]
Total including land water storage	**2.8 [2.1 to 3.5]**
Residual[c]	**0.4 [–0.4 to 1.2]**

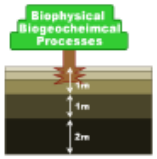
(Adopted from Table 13.1 of IPCC AR5, 2013)



(Figure 13.10 of IPCC AR5, 2013)

Fully Coupled Model (HiGW-MAT)

Natural Flow of Water + **Human Impacts** + **GW-Pumping**



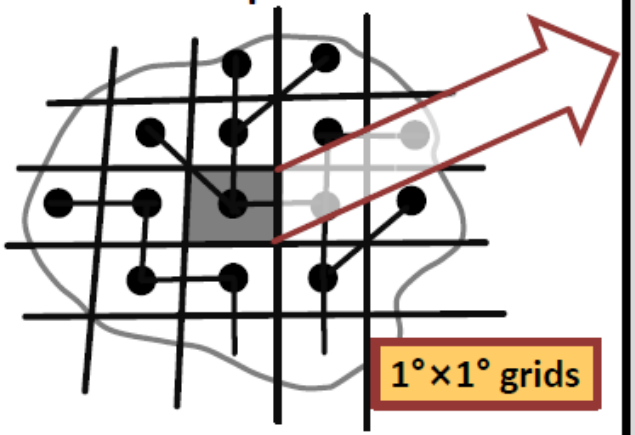
MATSIRO

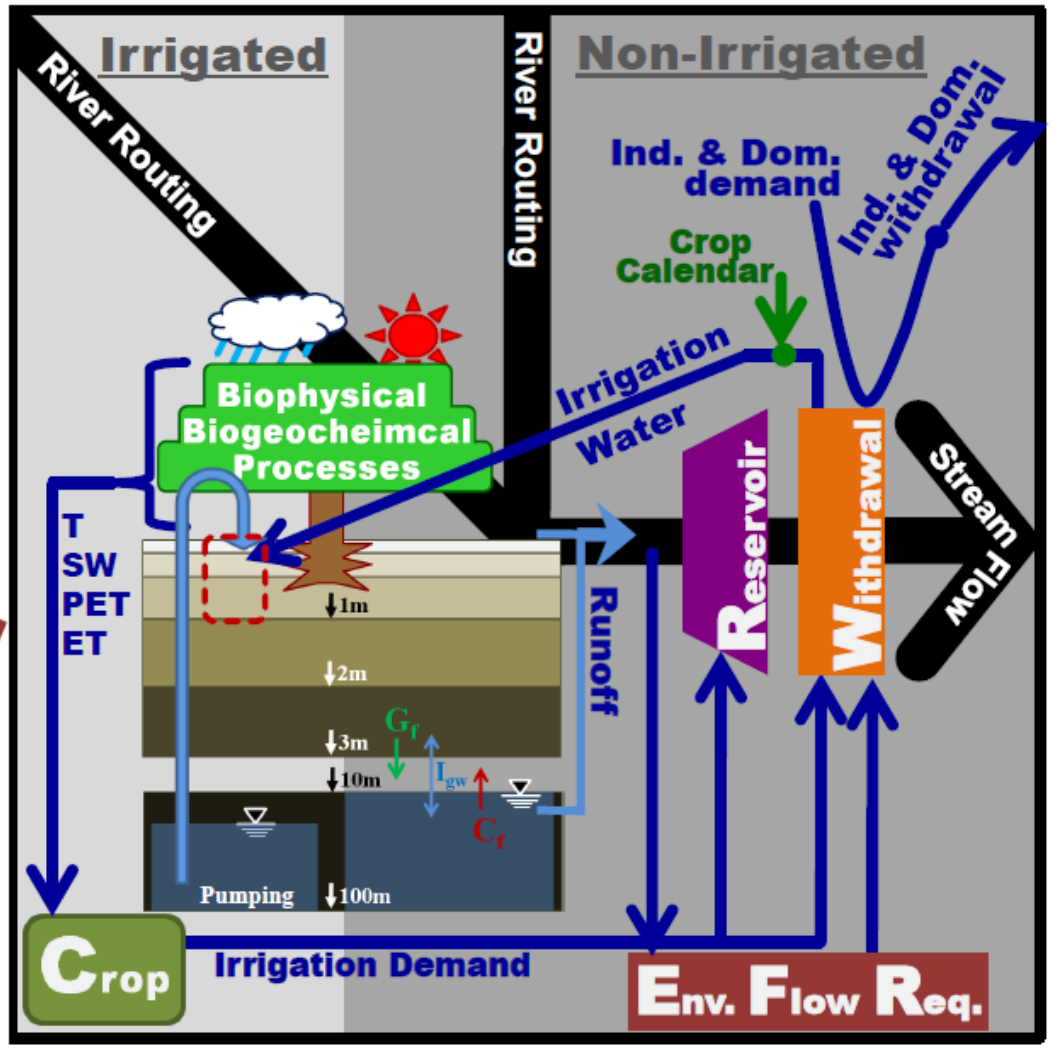
Crop — Crop growth & irrigation module

Withdrawal — Human water withdrawal module

Reservoir — Reservoir operation module

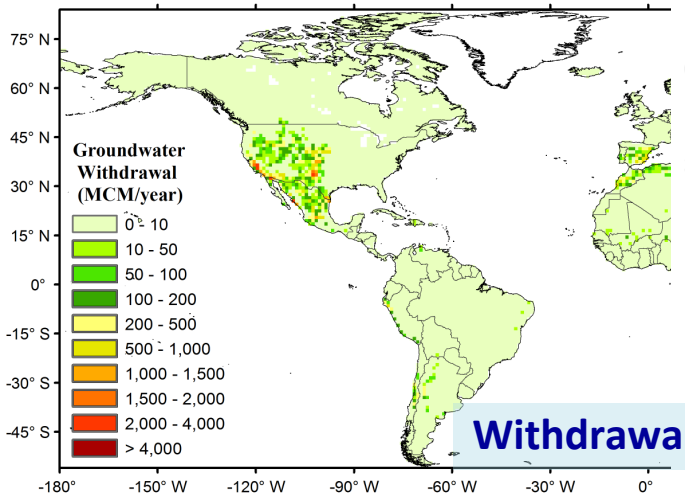
Env. Flow Req. — Environmental flow requirement module

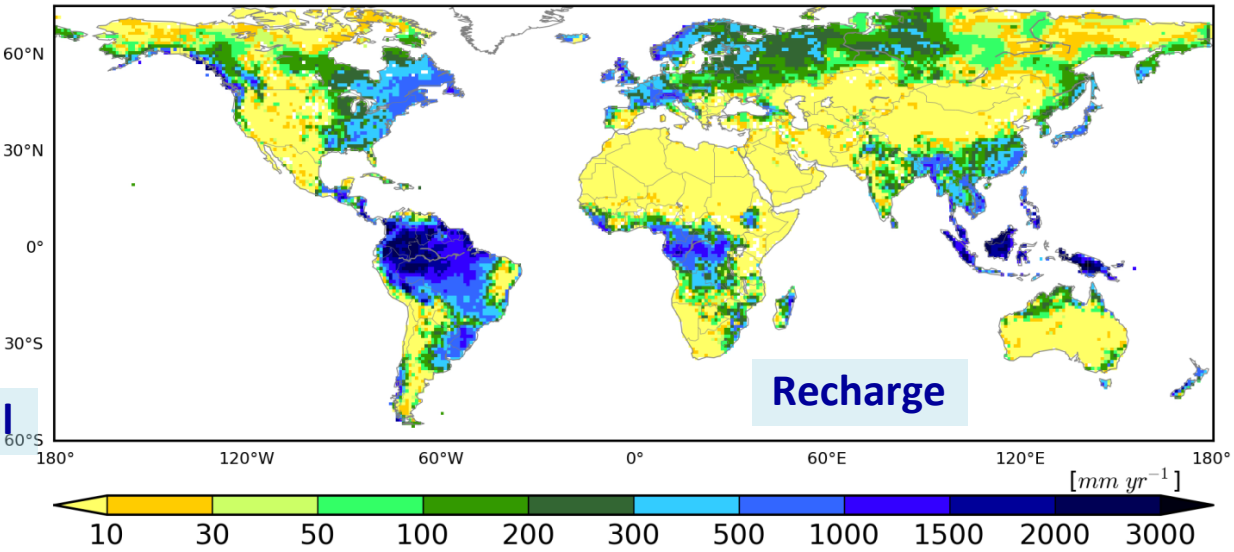


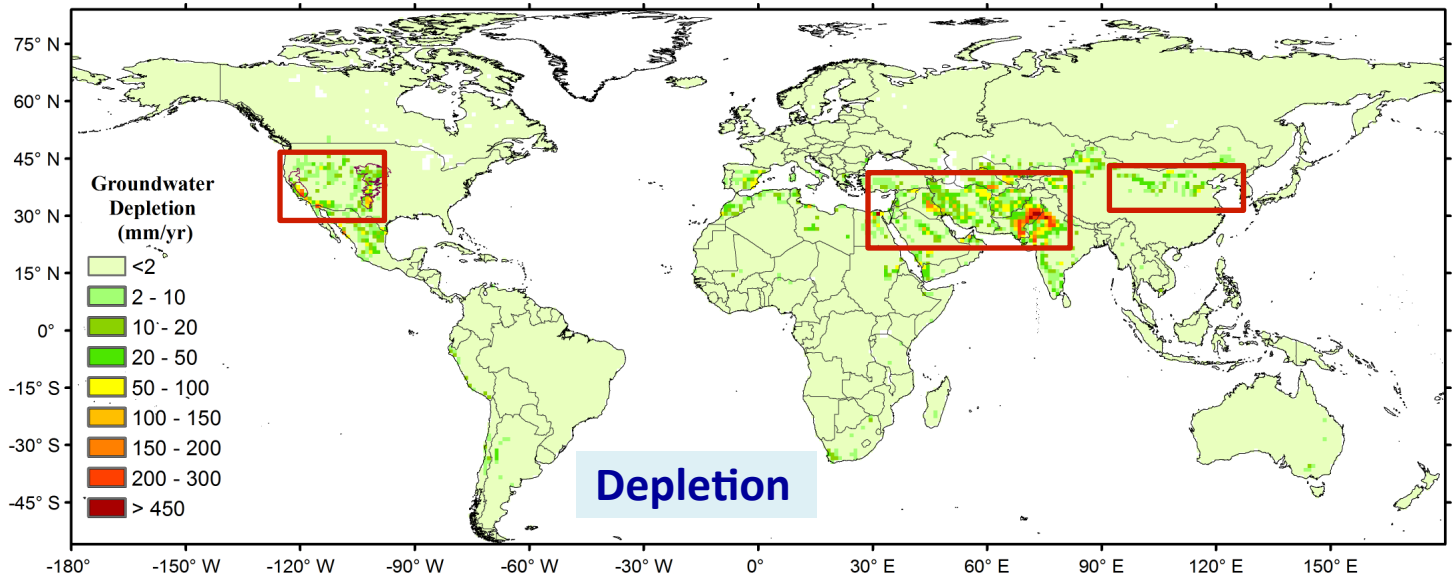


Pokhrel et al. (2015, WRR)

Global Groundwater Withdrawal & Depletion





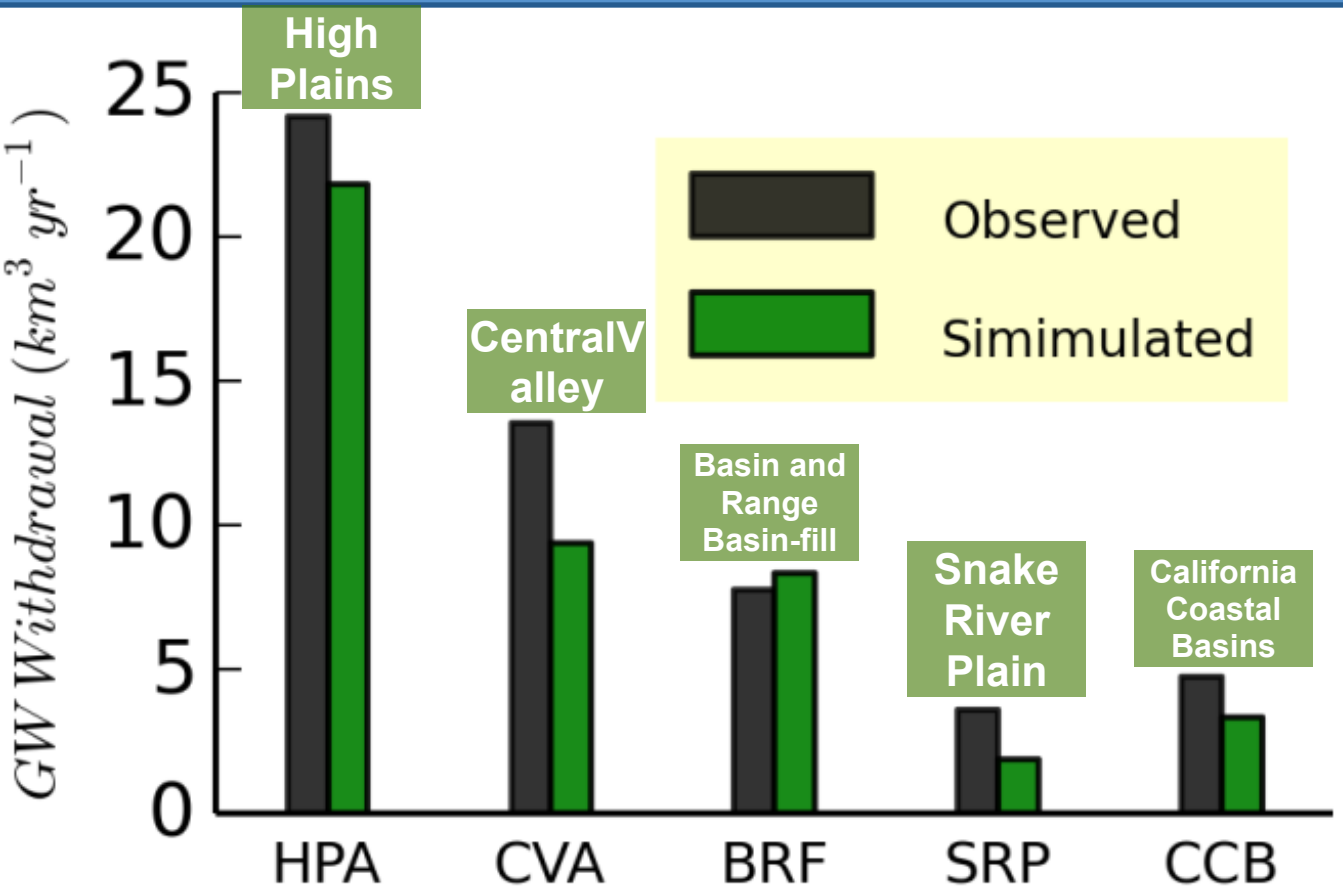


Global total depletion (annual):

- ✓ **This study**: ~330 km^3
- ✓ Wada et al. (2010): ~290 km^3
- ✓ Doll et al. (2012): ~250 km^3
- ✓ Konikow et al. (2011): ~145 km^3

Pokhrel et al. (2015, WRR)

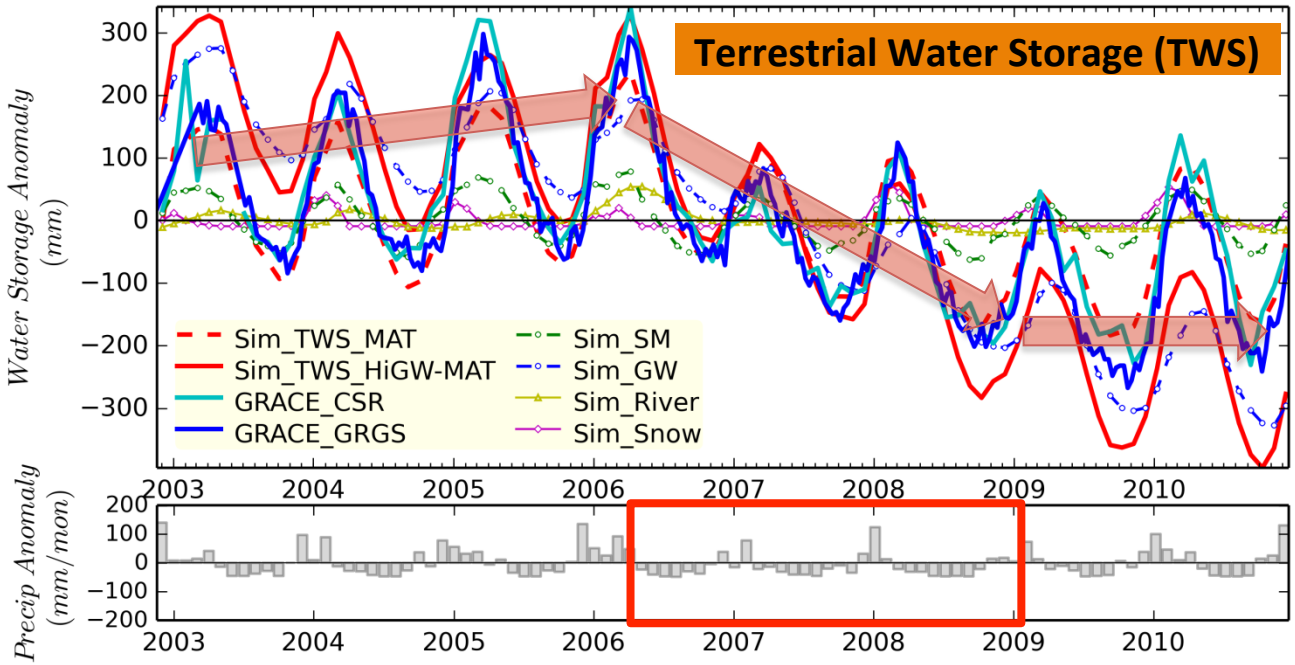
Groundwater Withdrawal (US Aquifers)

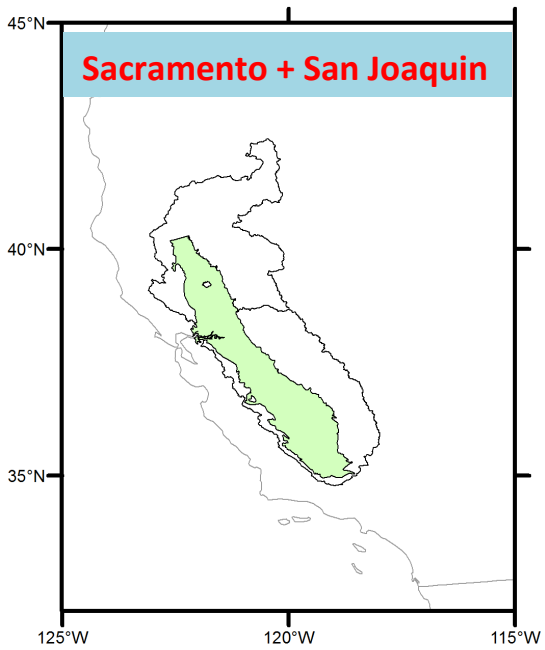


- ✓ Simulated withdrawals compare well with USGS observations.
- ✓ Groundwater is mainly used for irrigation in most aquifers.

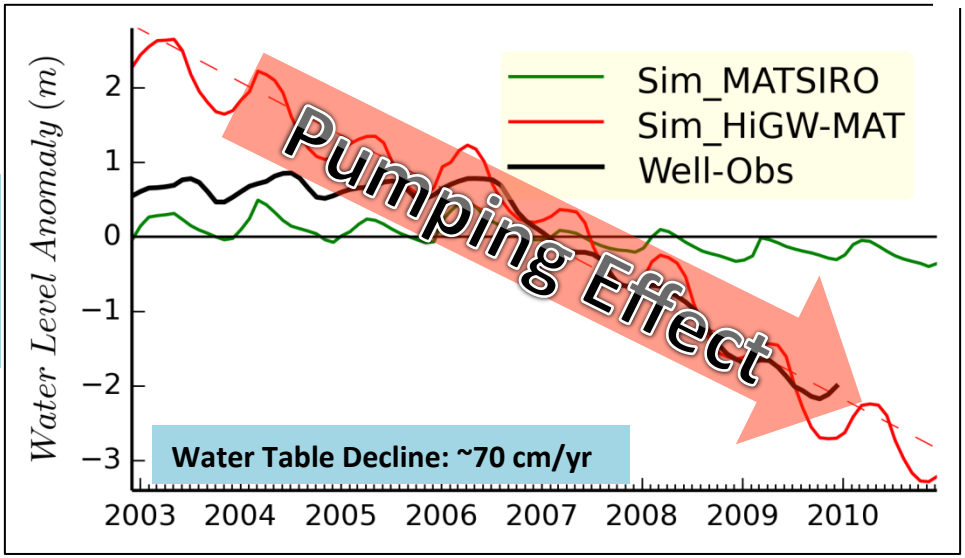
Pokhrel et al. (2015, WRR)

TWS & Groundwater Depletion (Central Valley)





Water Table Depth
- Green – Natural
- Red – Pumping



Pokhrel et al. (2015, WRR)

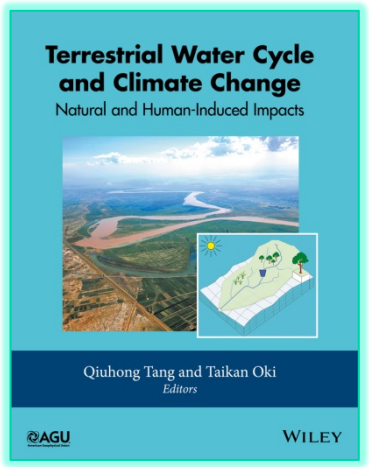
Remarks

- Human interventions on local hydrological cycles should have been triggering unintended consequences:
  - Enhancing global mean sea level rise (GMSLR) by ground water pumping for irrigation (~300 km^3/y ?)
  - Suppressing GMSLR by storing water in artificial reservoirs (~8,000 km^3 of total capacity)
- Fully coupled terrestrial model for both offline and coupled simulations should be promising:
  - Energy-water-carbon, natural and human, hill slope-river-flood plain, surface/subsurface/groundwater, …

http://hydro.iis.u-tokyo.ac.jp/

Terrestrial Water Cycle and Climate Change: Natural and Human-Induced Impacts

Qiuhong Tang and Taikan Oki



- Overview of the changes in the terrestrial water cycle
- Human alterations of the terrestrial water cycle
- Recent advances in hydrological measurement and observation
- Integrated modeling of the terrestrial water cycle
- ***The Terrestrial Water Cycle: Natural and Human-Induced Changes*** will be a valuable resource for students and professionals in the fields of hydrology, water resources, climate change, ecology, geophysics, and geographic sciences.
- The book will also be attractive to those who have general interests in the terrestrial water cycle, including how and why the cycle changes.

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