DOE Workshop on Community Modeling and Long-Term Predictions of the Integrated Water Cycle
Renaissance Washington DC Downtown Hotel
September 24 - 26, 2012

Modeling human-earth system interactions in the water cycle

Taikan OKI

Institute of Industrial Science, The University of Tokyo

special thanks to
Dr. Naota Hanasaki (NIES),
Dr. Yadu Pokhrel (Rutgers University),
Dr. Dai Yamazaki (University of Bristol),
and Ms. Cherry Mateo (IIS/The Univ. of Tokyo)

Why introduce complexities?

- "Real" water cycle on the Earth is not "natural" any more in the "Anthropocene (Crutzen, 2002)".
  - Realistic assessment how projected changes in hydrological cycles would change the damage risks by floods and droughts will become possible.
- Detailed land surface modeling may not improve the predictability of climate models, however,
  - Would provide new opportunities to validate the simulated results, e.g., snow fraction, flooded area, …
  - Connect "natural" climate system to *area of protection* (e.g., human health, bio diversity, …)

Impact of human activities on freshwater resources and their management, with climate change being only one of multiple stressors

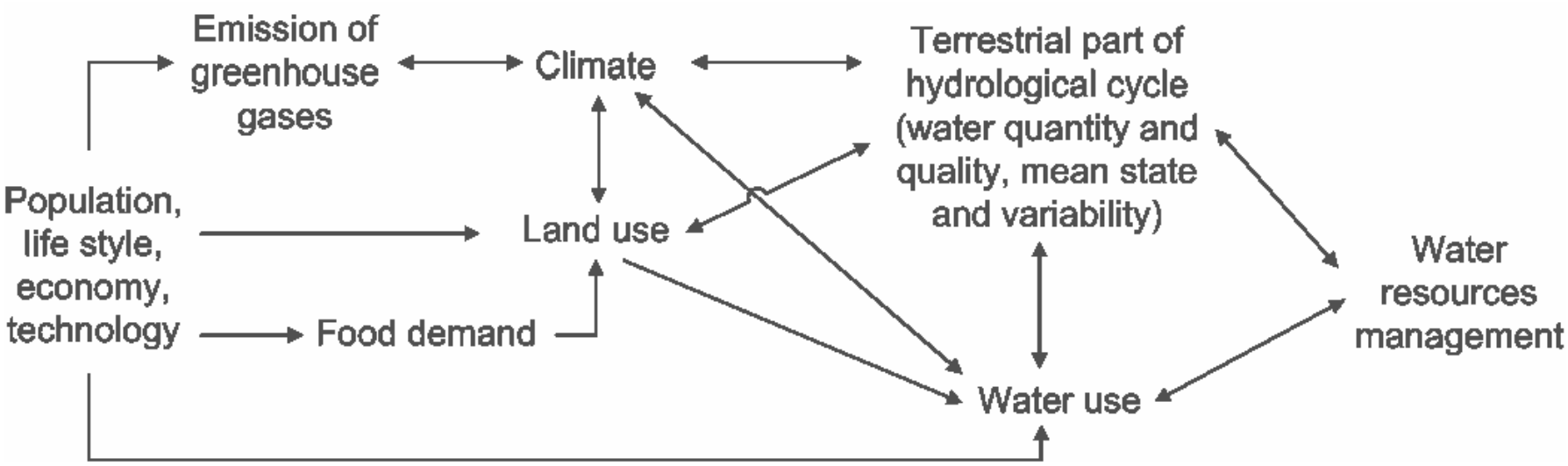
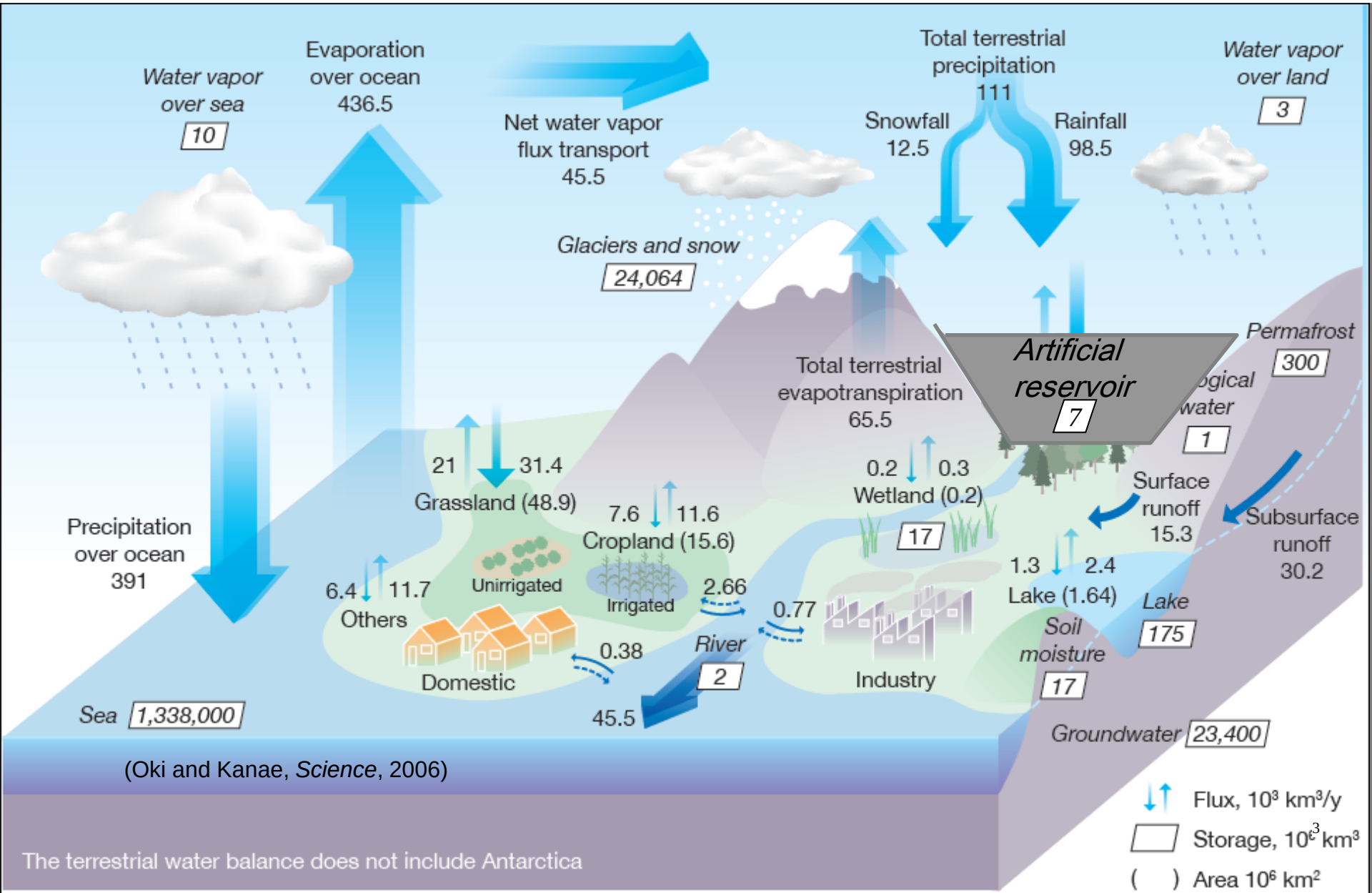


Figure 3.1: Impact of human activities on freshwater resources and their management, with climate change being only one of multiple pressures (modified after Oki (2005)).

Social change is as important as climate change.

(IPCC AR4, WGII, Chapter 3, "Freshwater Resources and their Management", 2006)

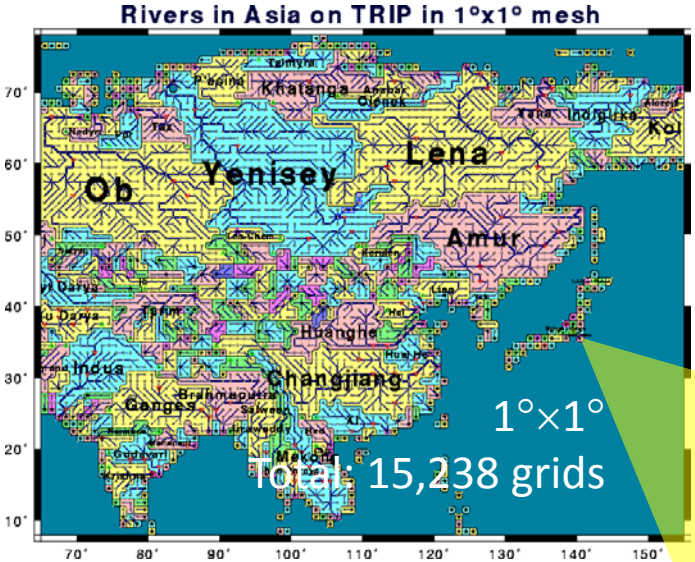
Synthesized Global Water Cycle

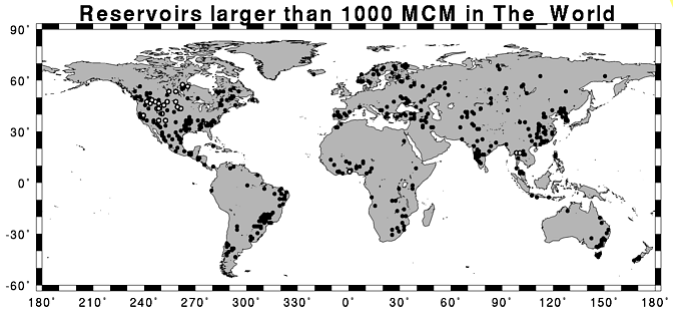


(Oki and Kanae, *Science*, 2006)

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

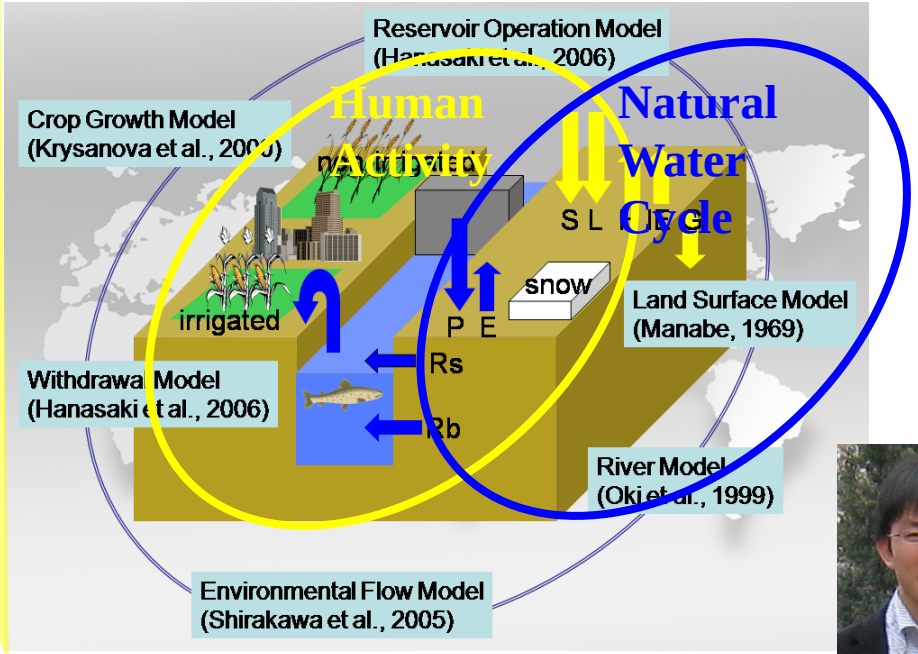
Global water resources model H08



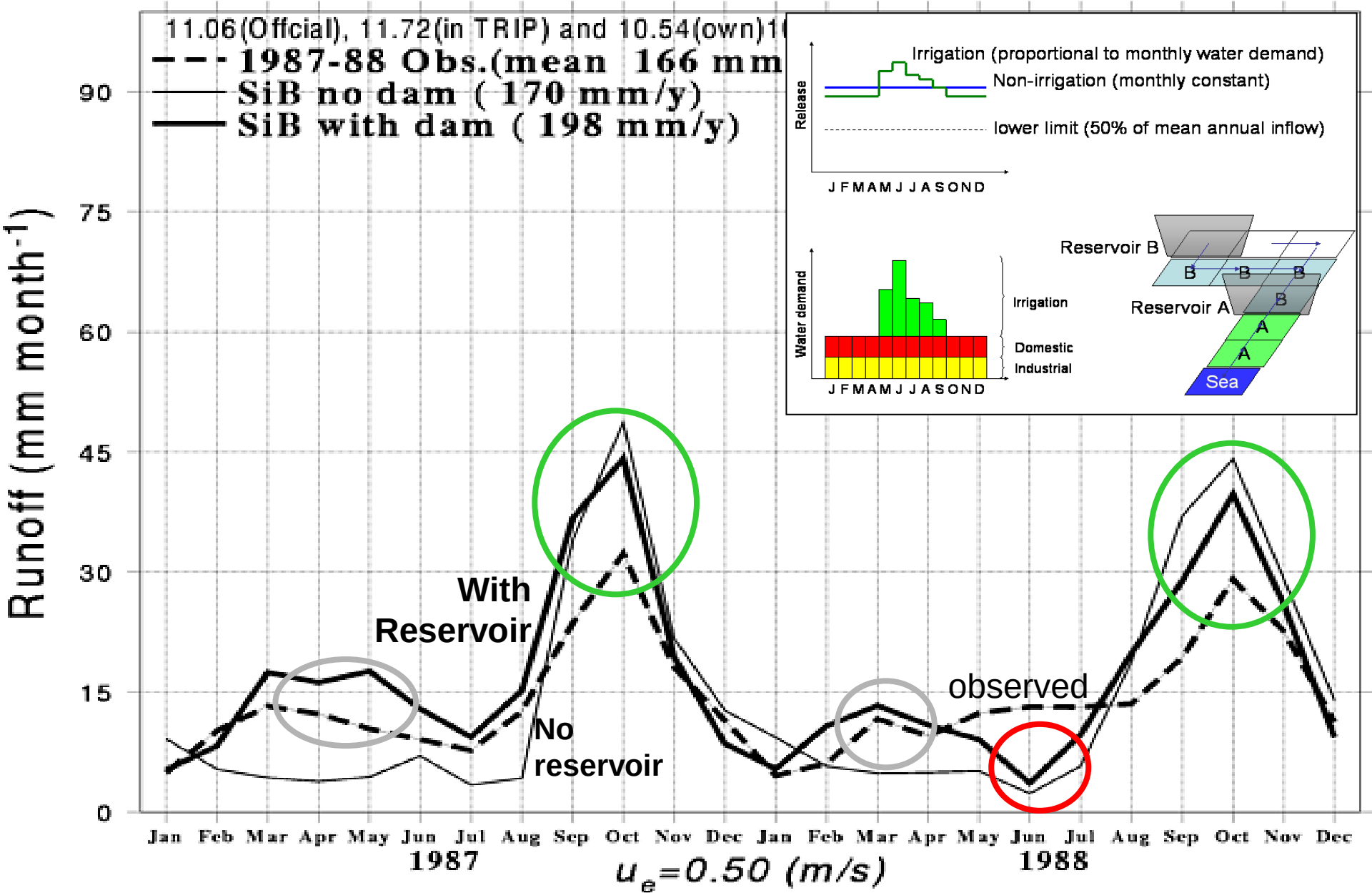


452 reservoirs, 4140 km^3

- **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**



Nakhon Sawan [100.5E16.5N] in Chao Phraya



Withdrawals by water sources

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

Sustainable

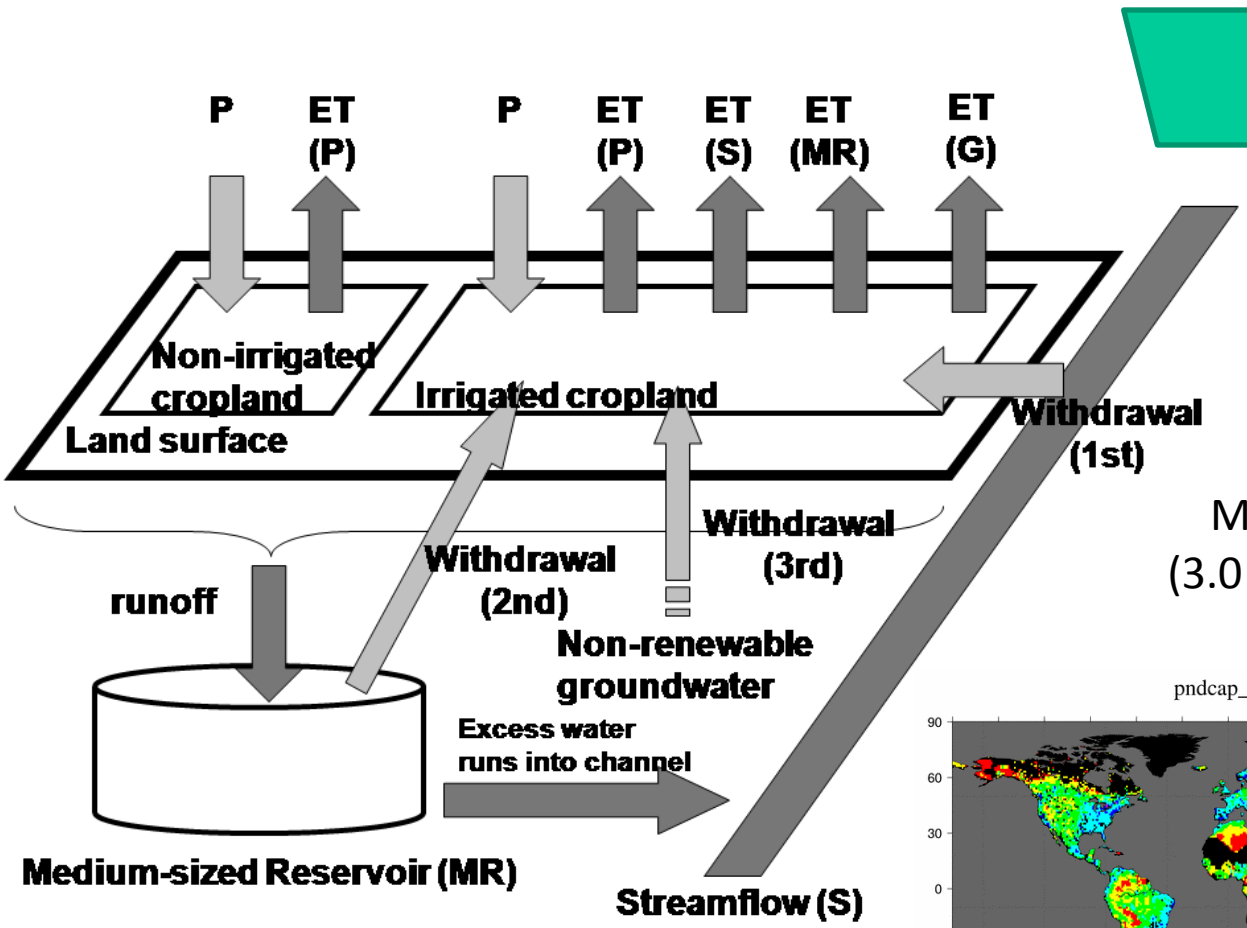
LOW

- Environmental Impacts
- Opportunity Cost

Non-Sustainable

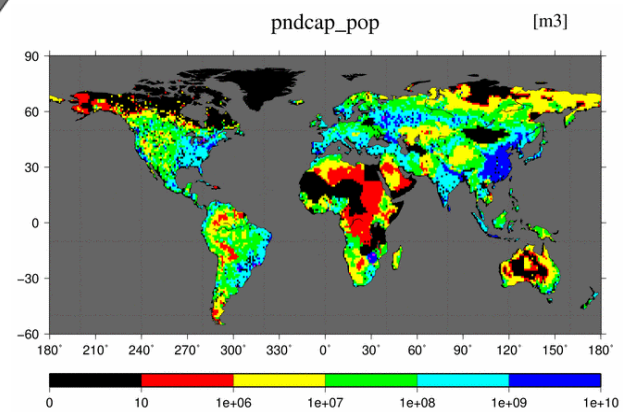
HIGH

Enhancement of the H08 model

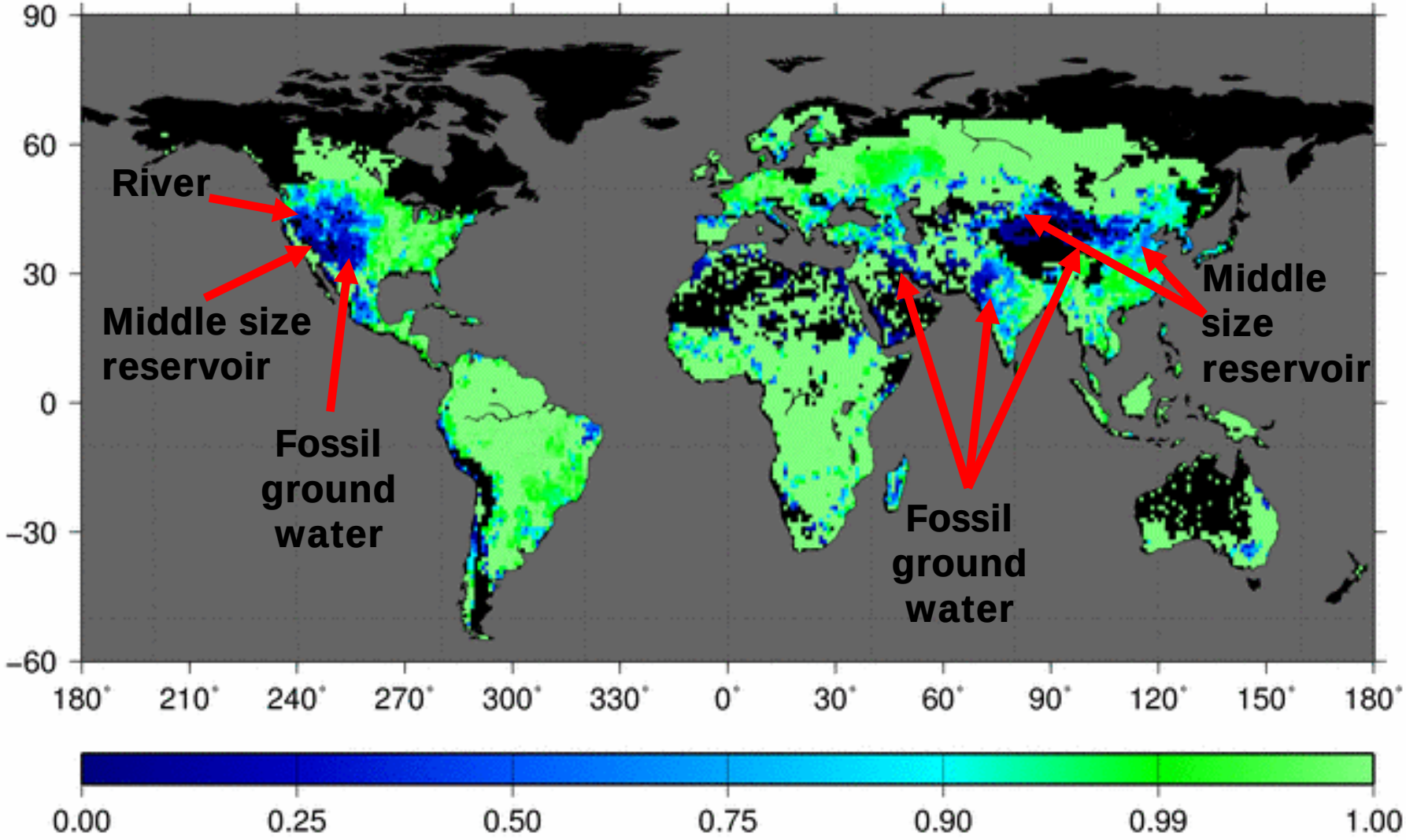


Large reservoirs
($1.0 \times 10^9 m^3 \leq S$)
$4140 km^3$

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

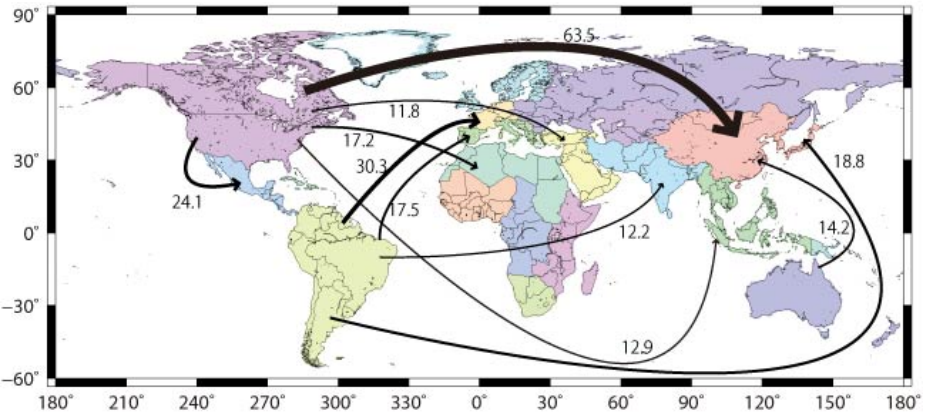


Share of precipitation (green water) in consumptive water use



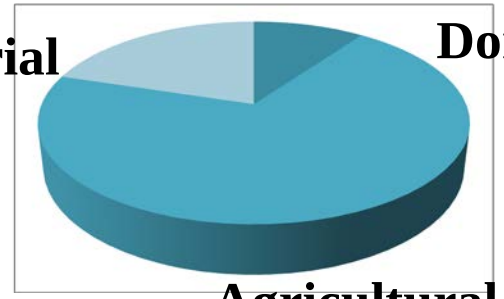
Global flows of virtual water export

Virtual water export (total)



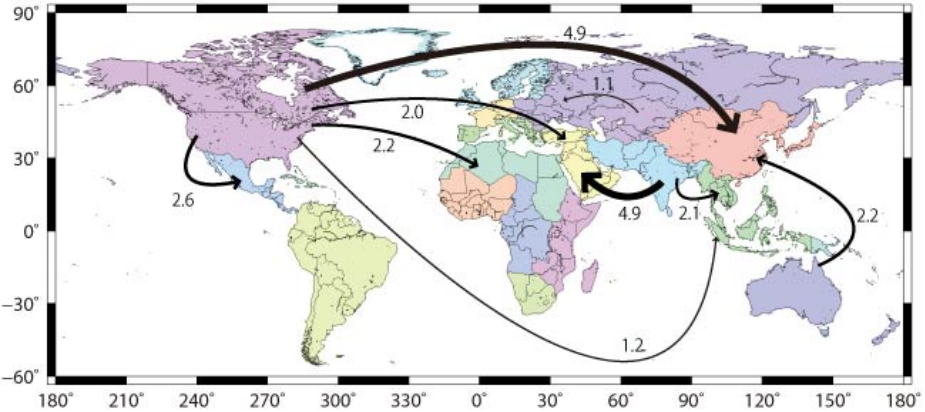
Total 545km^3 yr^{-1}

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



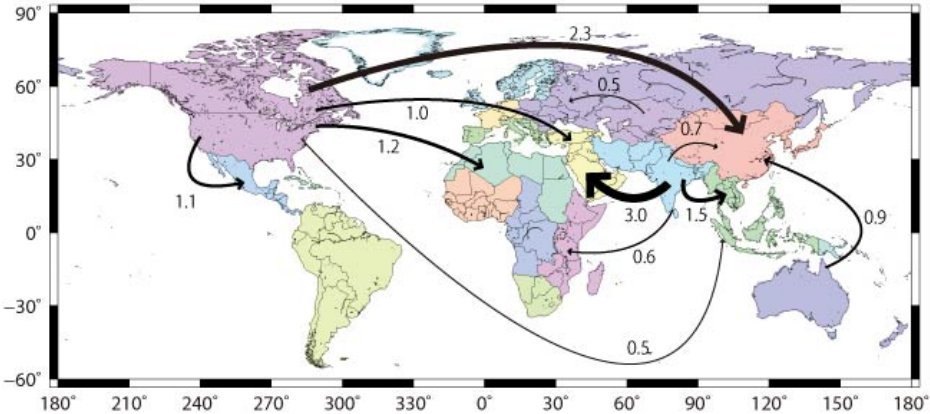
Shiklomanov, 2000

Virtual water export (irrigation)



Total 61km^3 yr^{-1}

Virtual water export (Nonlocal/Nonrenewable Blue Water)



Total 26km^3 yr^{-1}

Land surface models and Human Interventions

H08 (Hanasaki et al., 2008)
- Water & Energy Balance
- River Routing (TRIP)
- Reservoir Operation
- Water Withdrawals (DIA)
- Crop Growth
- Environmental Flow

TRIP
(Oki and Sud, 1998)
- Constant velocity

MATSIRO (Takata et al., 2003)
- (LSM for CCSR AO-GCM)
- Water, Energy, and Carbon
- Detailed Snow & Vegetation
- SiB2 biogeochemical module

CAMA-Flood
(Yamazaki et al., 2011)
- diffusive wave river routine & inundation

HI-MAT (Pokhrel et al., 2012)
- MATSIRO + Human intervention modules of H08

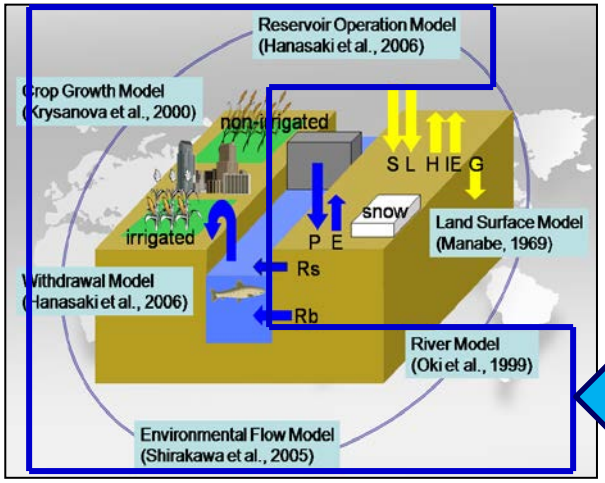
Chao Phraya Model
- H08 with CAMA-Flood
- Assess the impact of reservoir operation rule

HiGW-MAT
- HI-MAT + Ground Water module (Yeh and Eltahir, 2005)

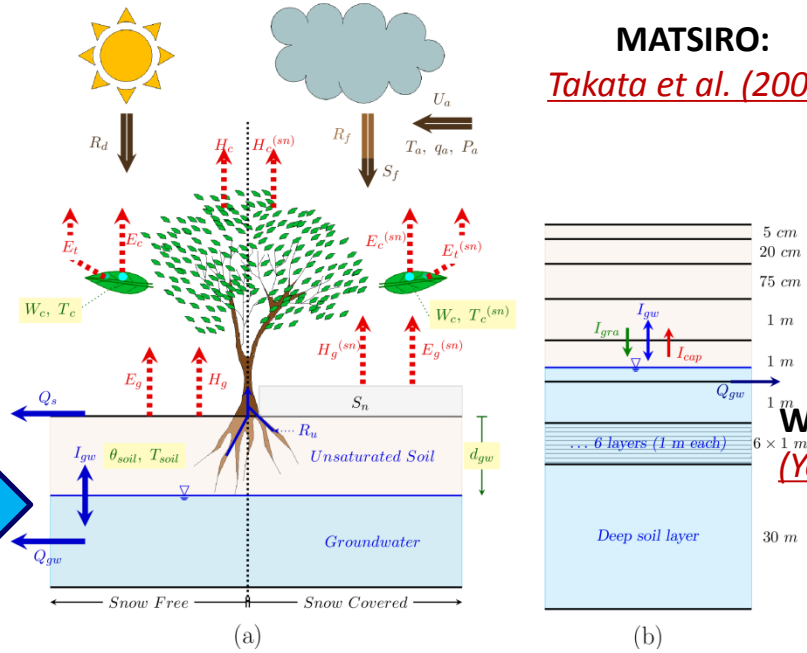
MODELS: MATSIRO & H08

- **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 cycles are not accounted.**

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



MATSIRO:
Takata et al. (2003)



Water table dynamics
(Yeh and Eltahir, 2005)

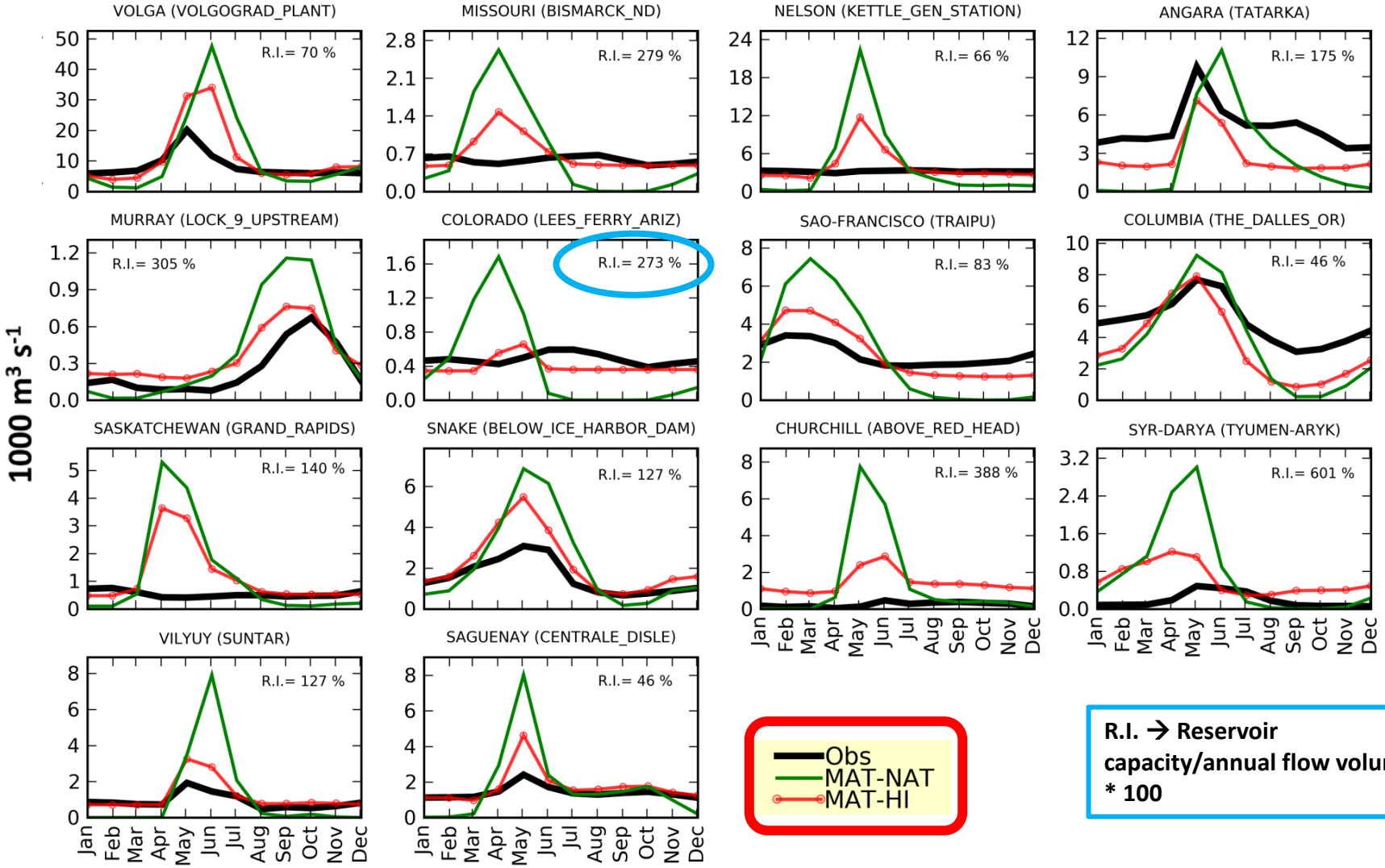
Pumping scheme
Koirala et al.

- ✓ 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**

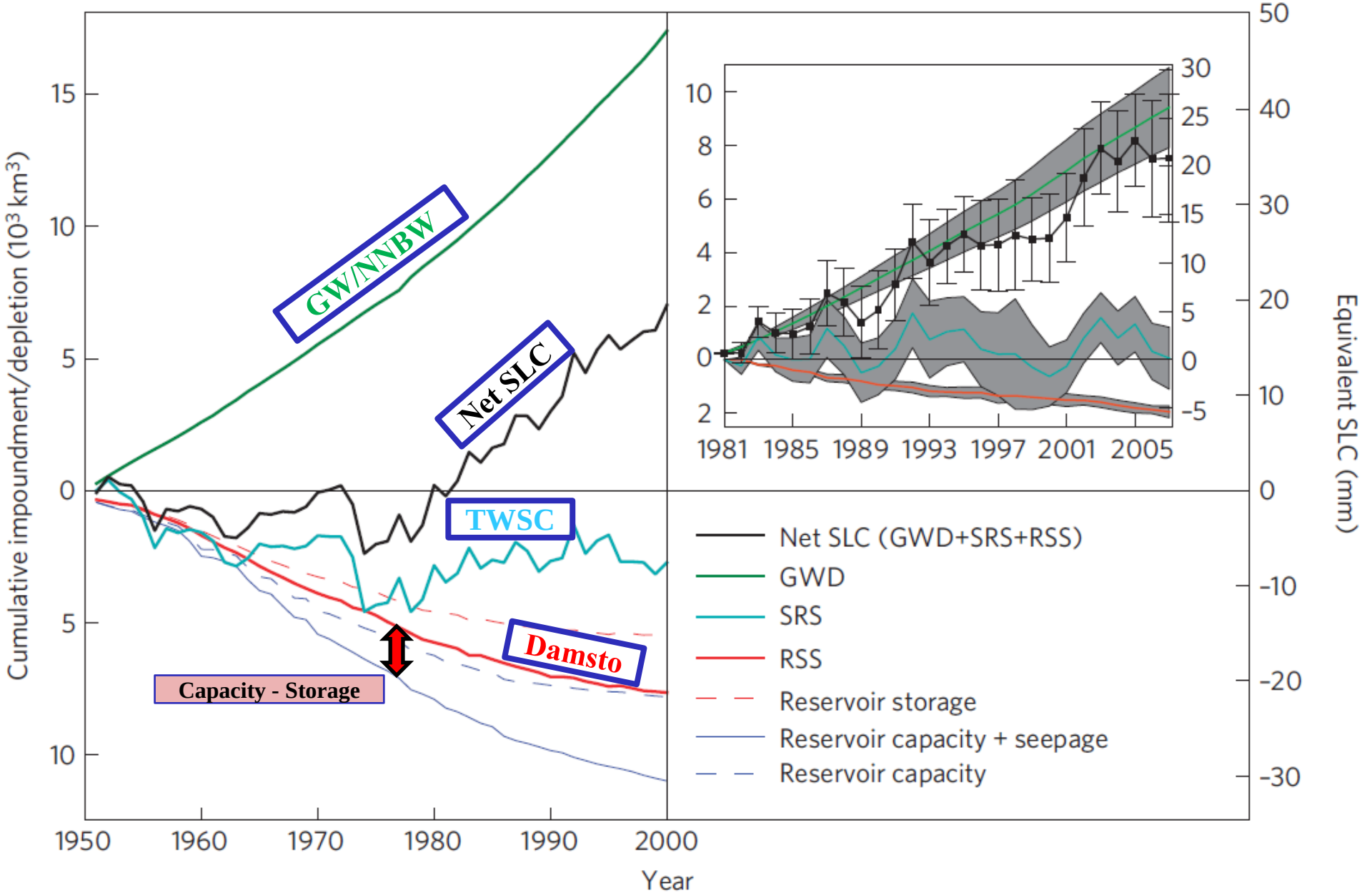
Simulated River Discharge (Highly Regulated Basins)

Seasonal variation improves significantly in many regulated basins.

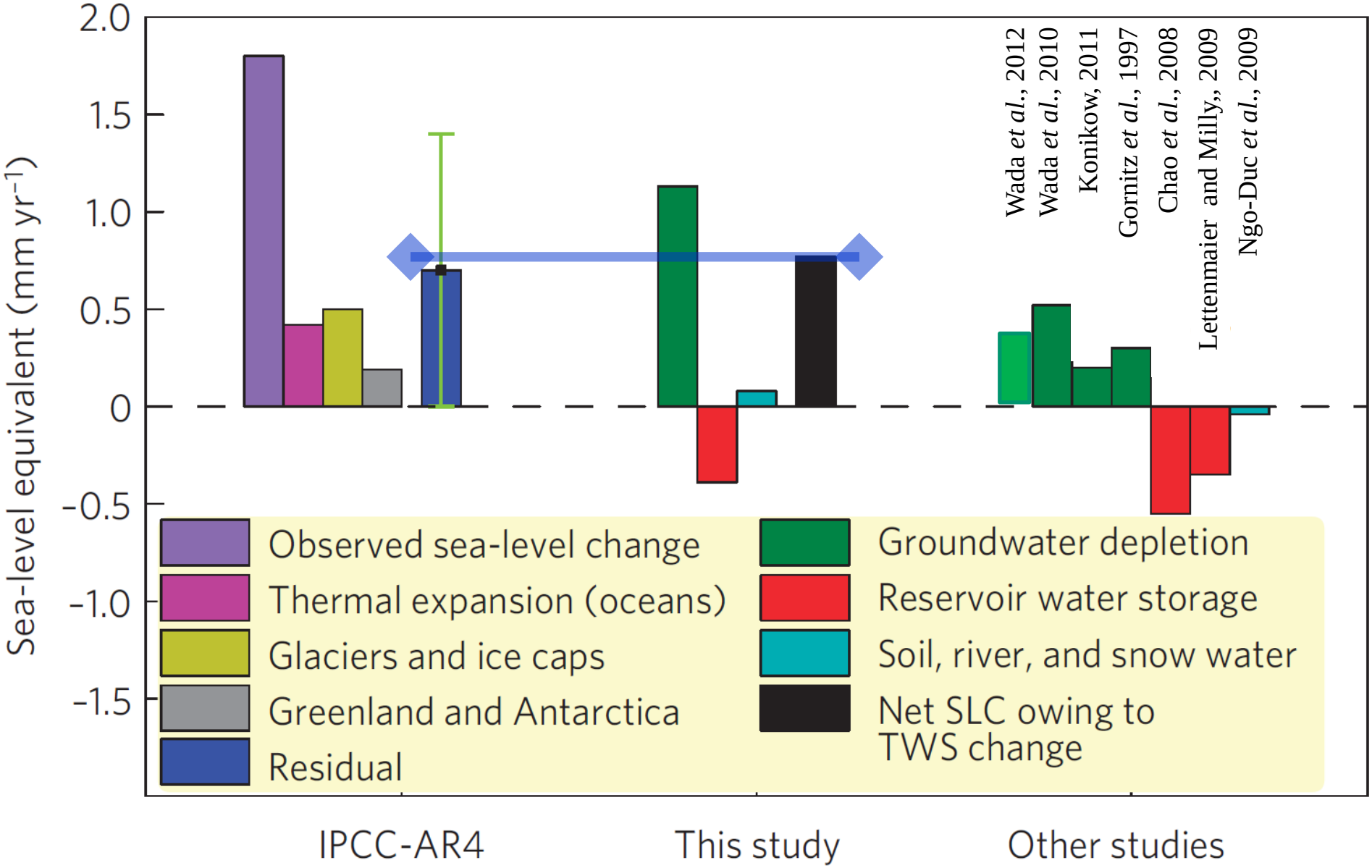


R.I. → Reservoir capacity/annual flow volume * 100

Sea Level Change: Anthropogenic TWS Contributions

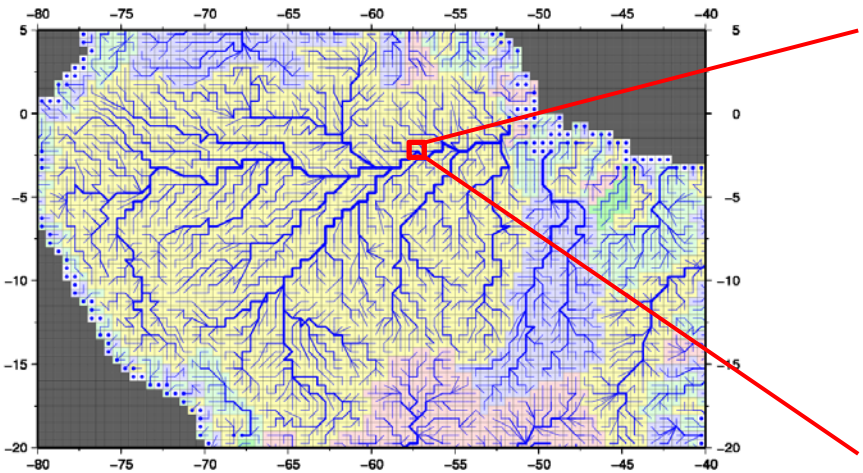


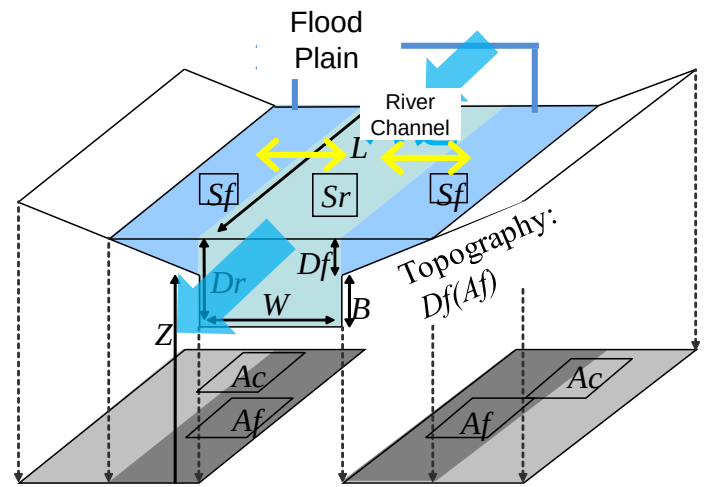
Contributions to Sea-level change in previous estimates



CaMa-Flood, Global River Model

Sub-grid topographic parameters for realistically representing storage-stage relationship and floodplain topography.





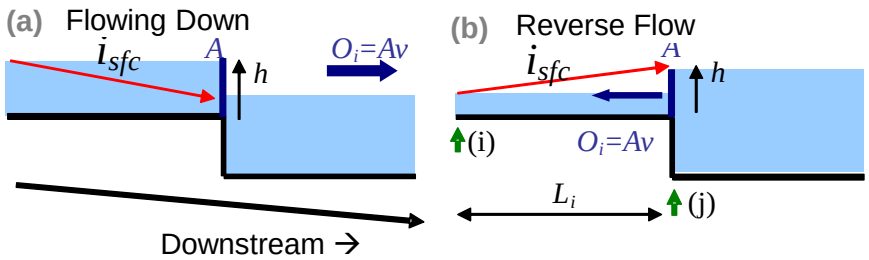
Global River Model

Sub-grid Topographic Parameters

Calculation of water surface elevation

⇒Diffusive Wave Equation

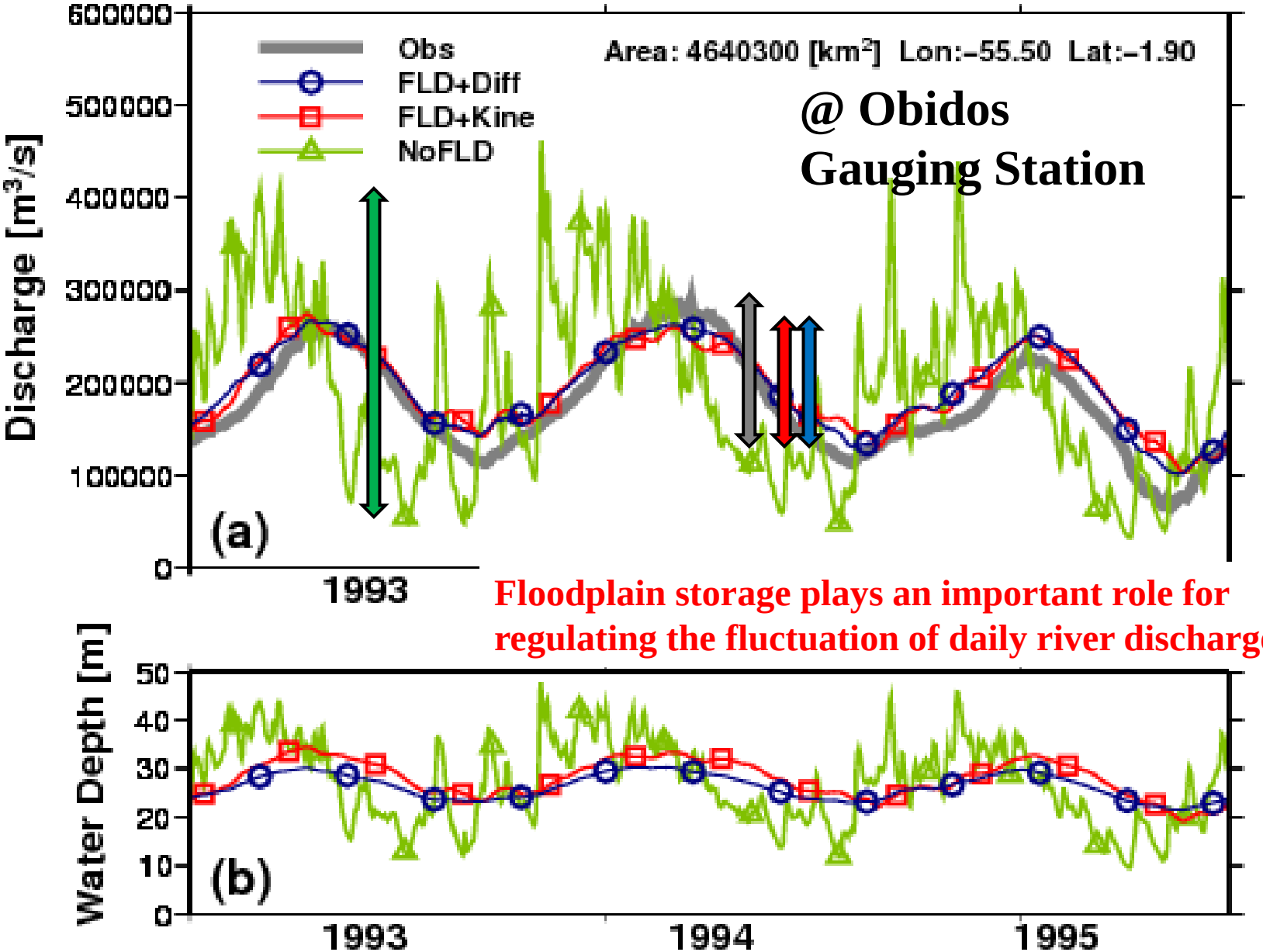
⇒ Physically-based estimation of river discharge



Discharge calculation based on water surface gradient

Also refer recent publication →Yamazaki, D., H. Lee, D. E. Alsdorf, E. Dutra, H. Kim, S. Kanae, and T. Oki, 2012: Analysis of the water level dynamics simulated by a global river model: A case study in the Amazon River, *Water Resour. Res.*, 48, W09508, doi:10.1029/2012WR011869.

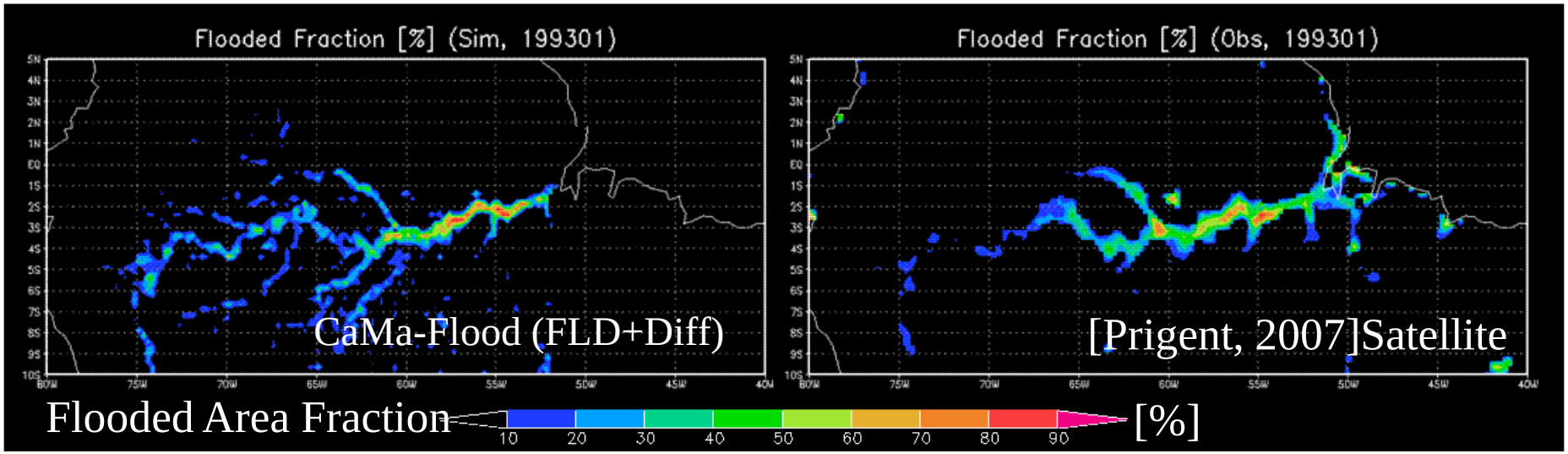
Results (Amazon River)

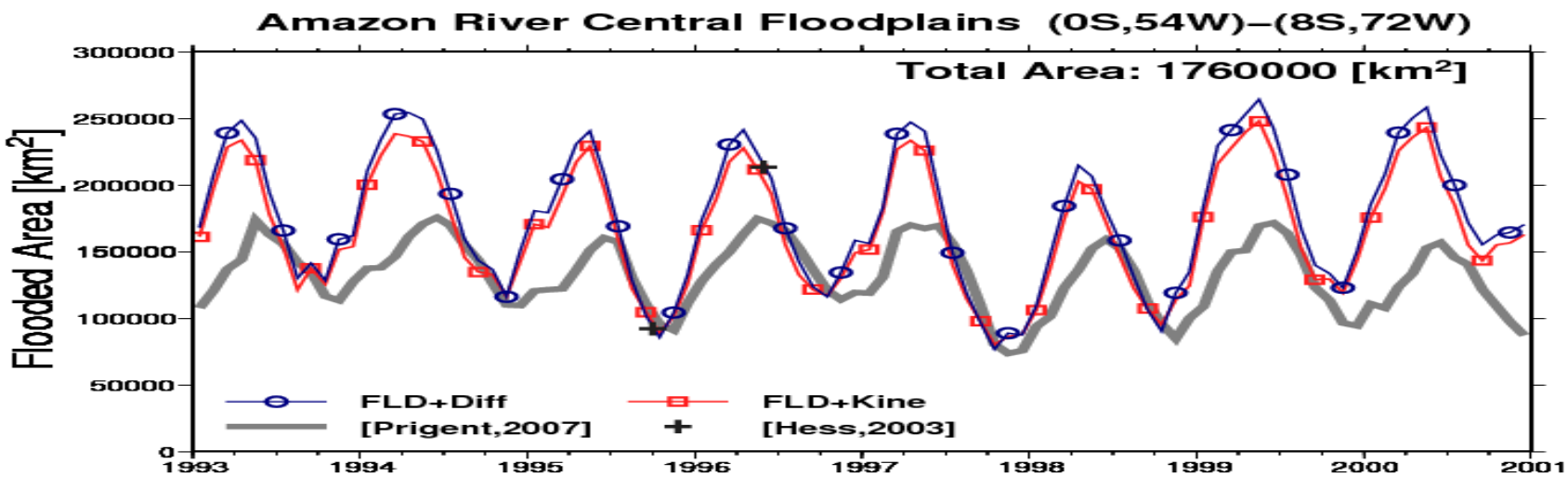


Floodplain storage plays an important role for regulating the fluctuation of daily river discharge

Flooding in the Amazon

Spatial-temporal distribution of flooded area





Many thanks to Dr. Prigent and Dr. Hess for providing the satellite datasets

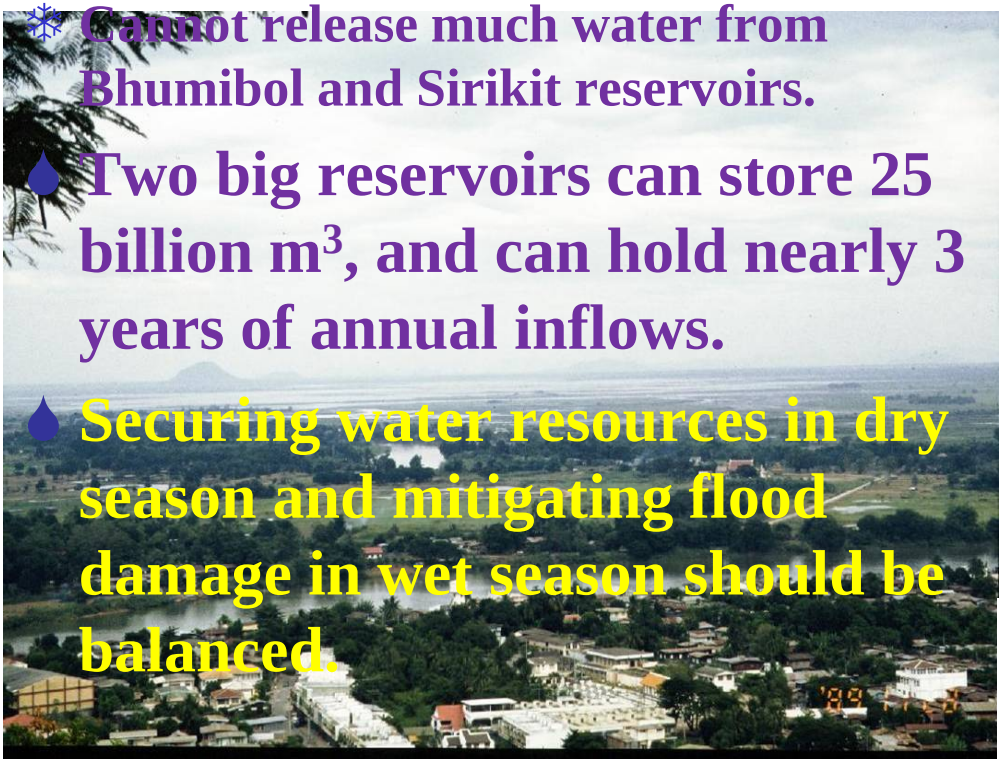
Rojana Industrial Park (9:27, Dec. 01, 2011)

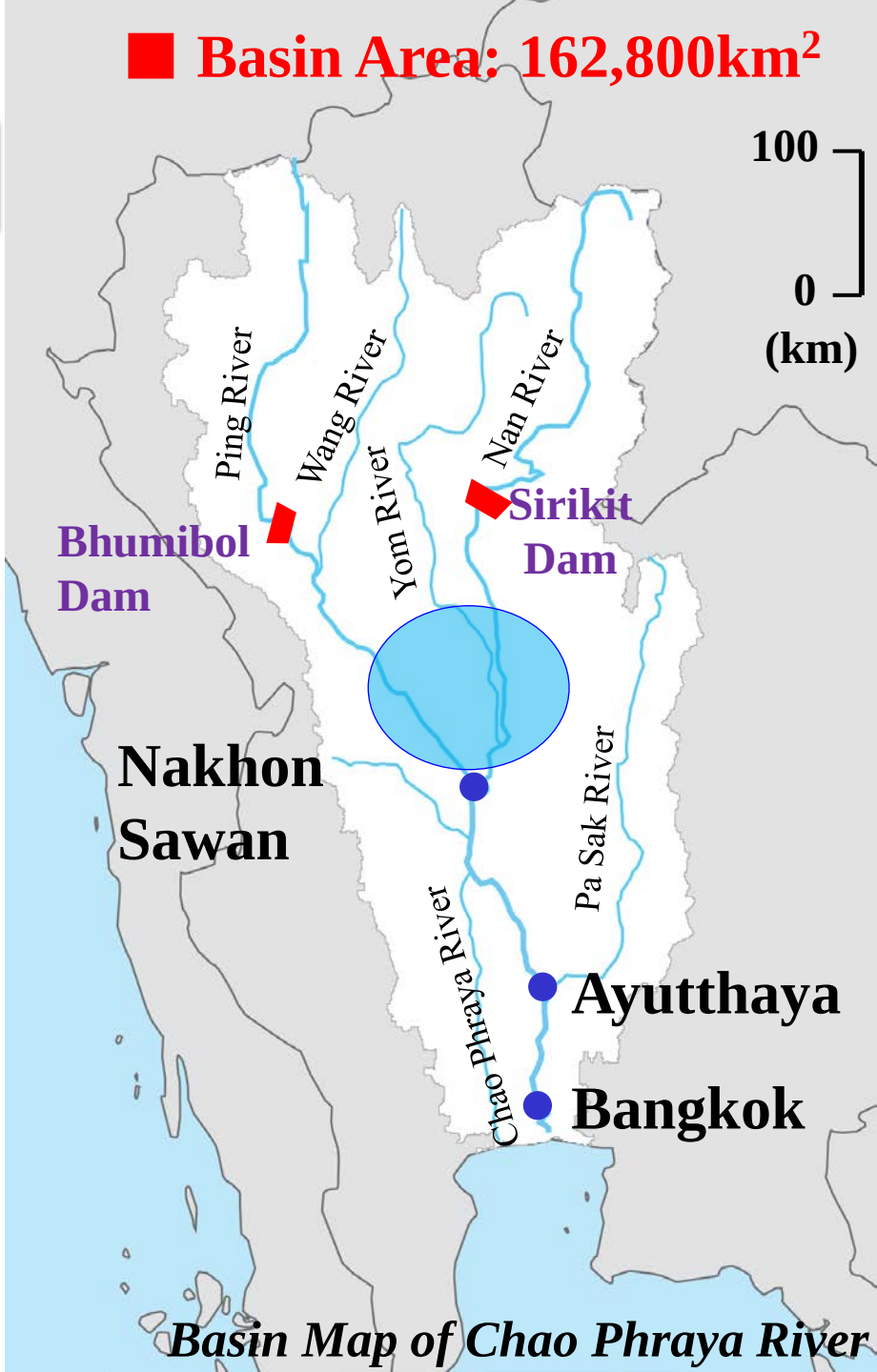
Flood in Thailand 2011

- Spilled and inundated more than 15 billion m^3 of water
- More than 800 death toll and missing
- 18,291 km^2 of damages in agricultural land
- Influenced more than 10 million people
- 804 factories in 7 industrial parks submerged
- Economic damage 1.36 trillion Bhat (=44 billion US$)
- Economic growth reduced to 0.1% (3.2/2.7/3.7/-9.0)
- More than 10 billion US$ of insurance payment
  - ✓ Larger than the payment because of the Earthquake in 2011
  - ✓ Record breaking economic damage by flooding in EM-DAT

Outline of Chao Phraya

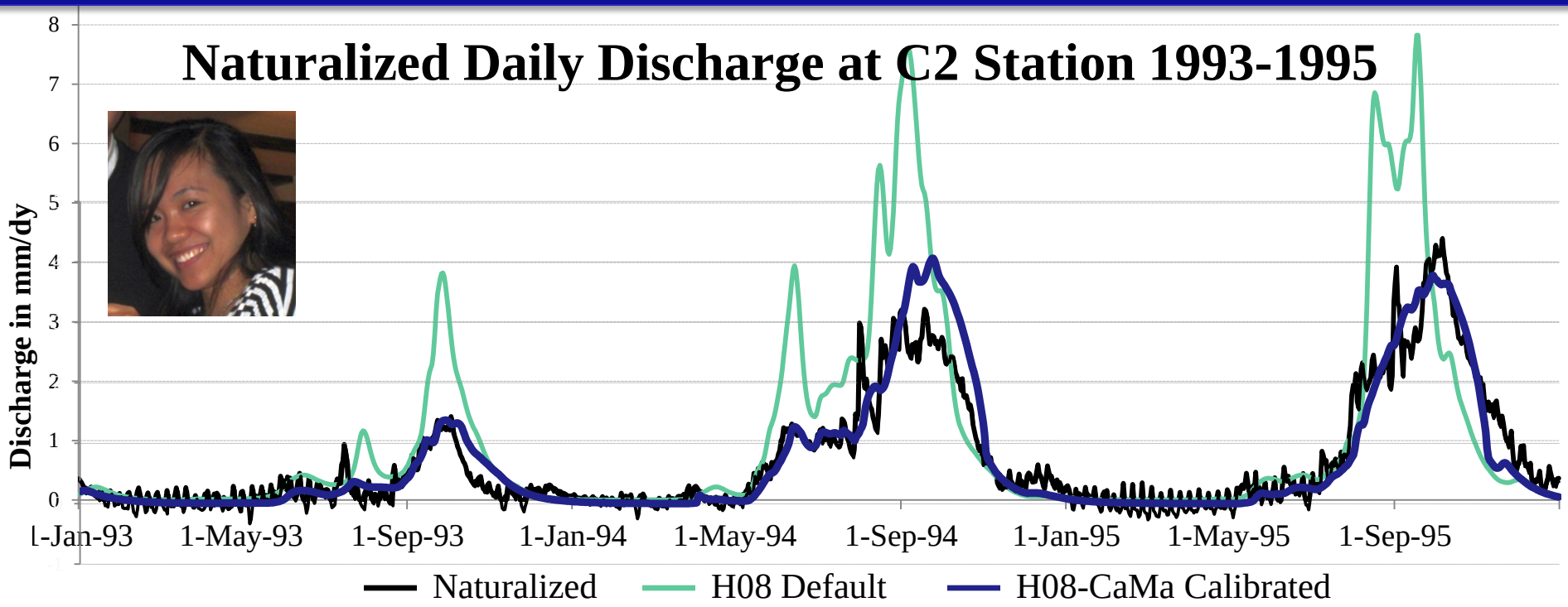
- Ping, Wang, Yom, and Nan river converge at Nakhon Sawan.
- There is no reservoir in Yom river, and the region frequently experiences floods in Aug.-Sep.
  - Cannot release much water from Bhumibol and Sirikit reservoirs.
- Two big reservoirs can store 25 billion m^3, and can hold nearly 3 years of annual inflows.
- Securing water resources in dry season and mitigating flood damage in wet season should be balanced.

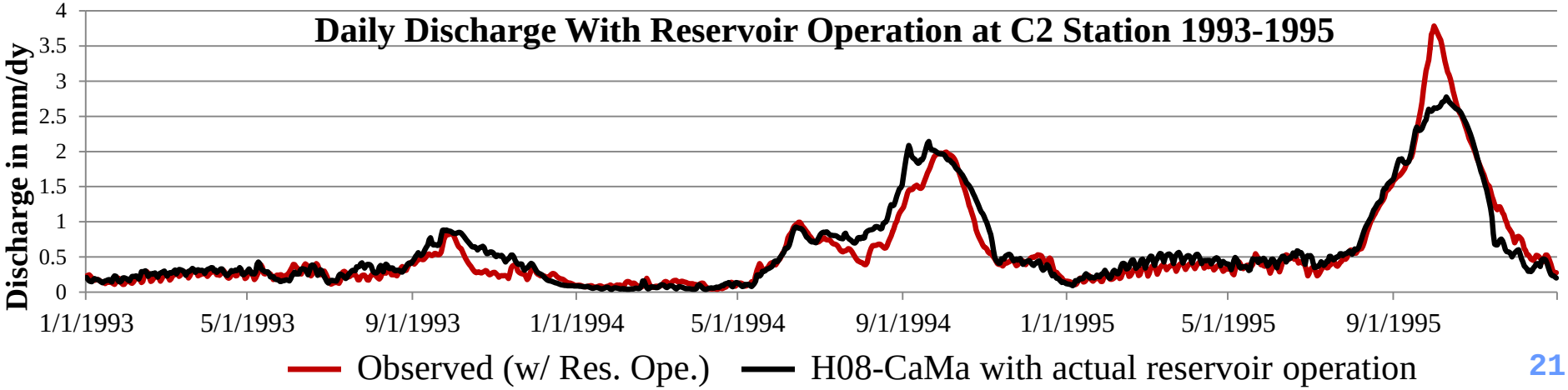




Basin Map of Chao Phraya River

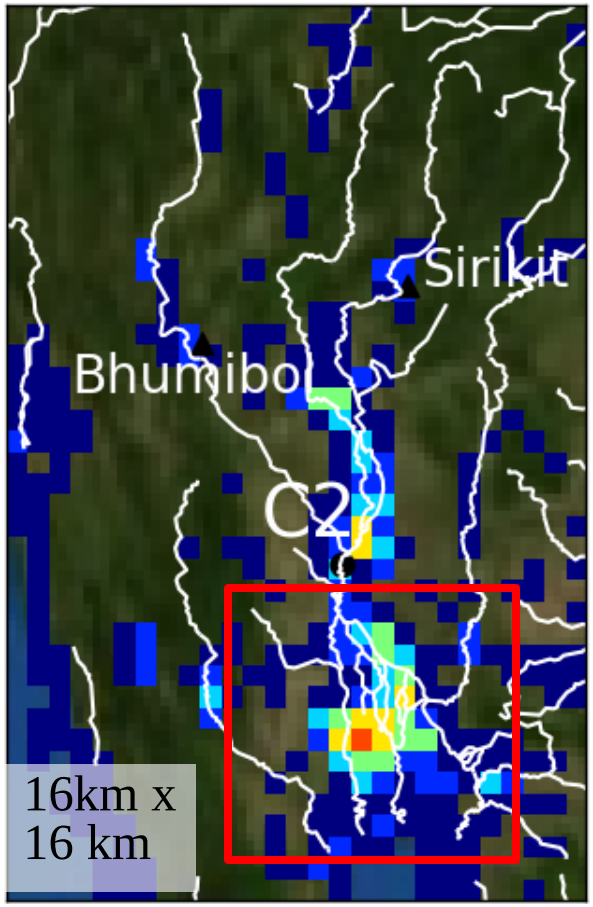
Parameters tuning is effective. Coupled H08-CaMa model gives excellent results.



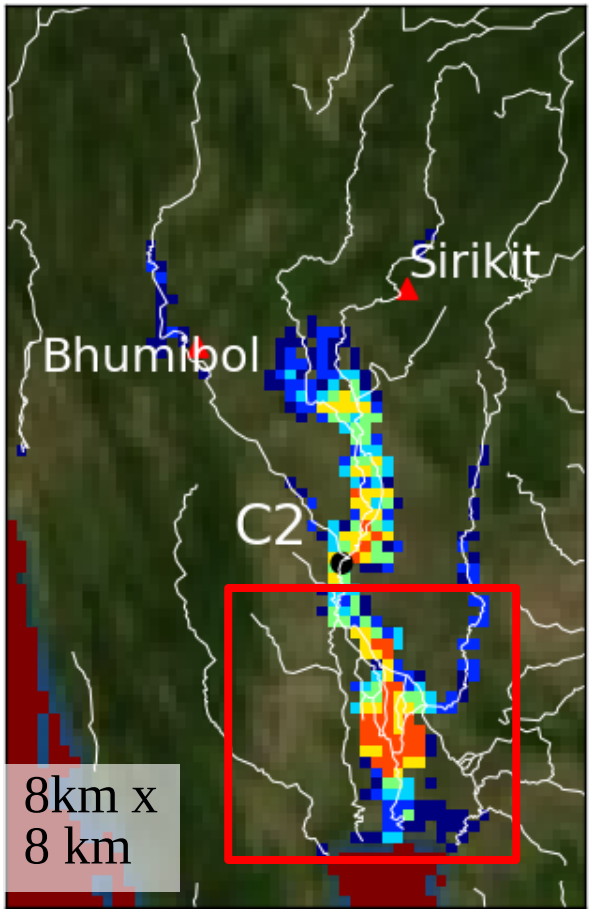


Shape of inundation was simulated well

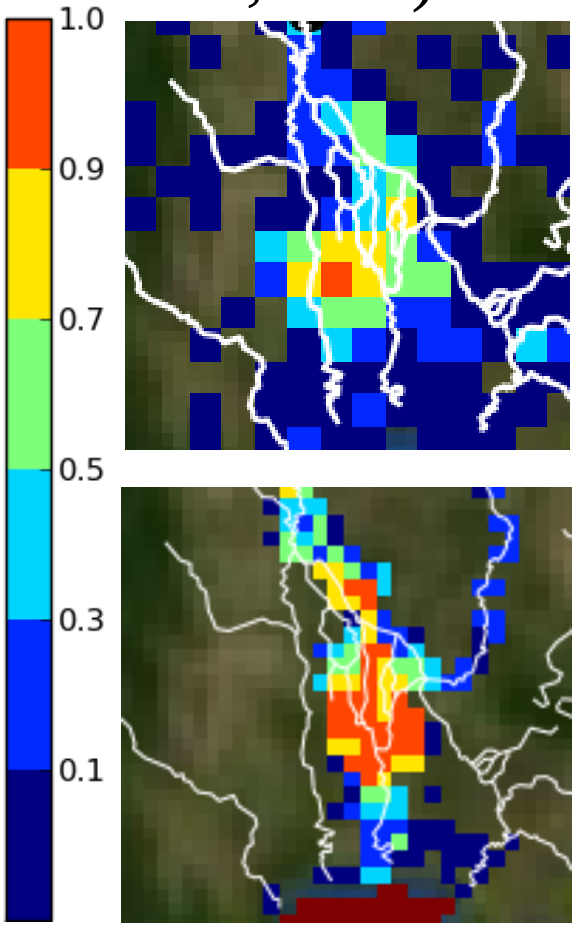
Percent of area that is inundated (October 15,2011)



MODIS & AMSR-E Obs.
[Takeuchi, K. Oki, H. Kim, 2012]

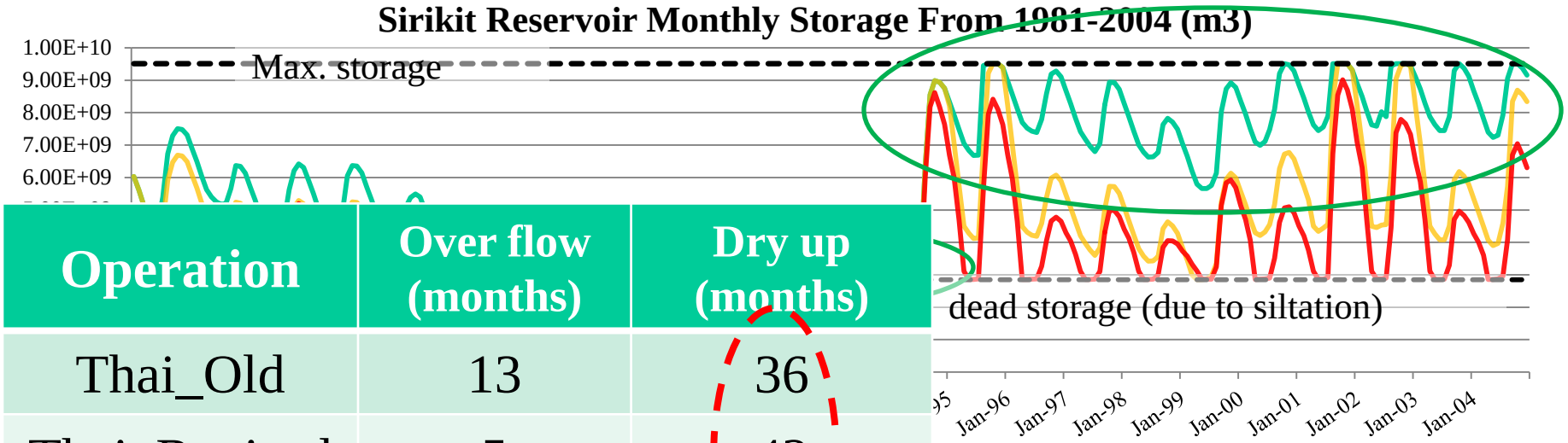


Simulation H08-CaMa

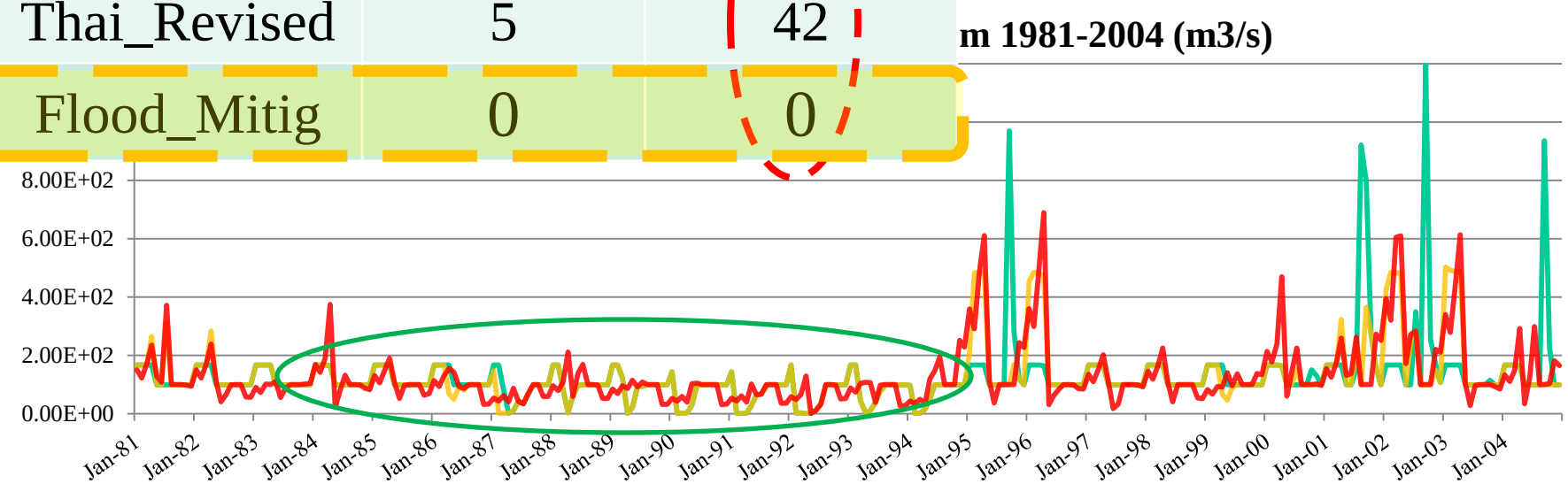


Zoomed in images

Water management is much better in the proposed reservoir operation scheme.

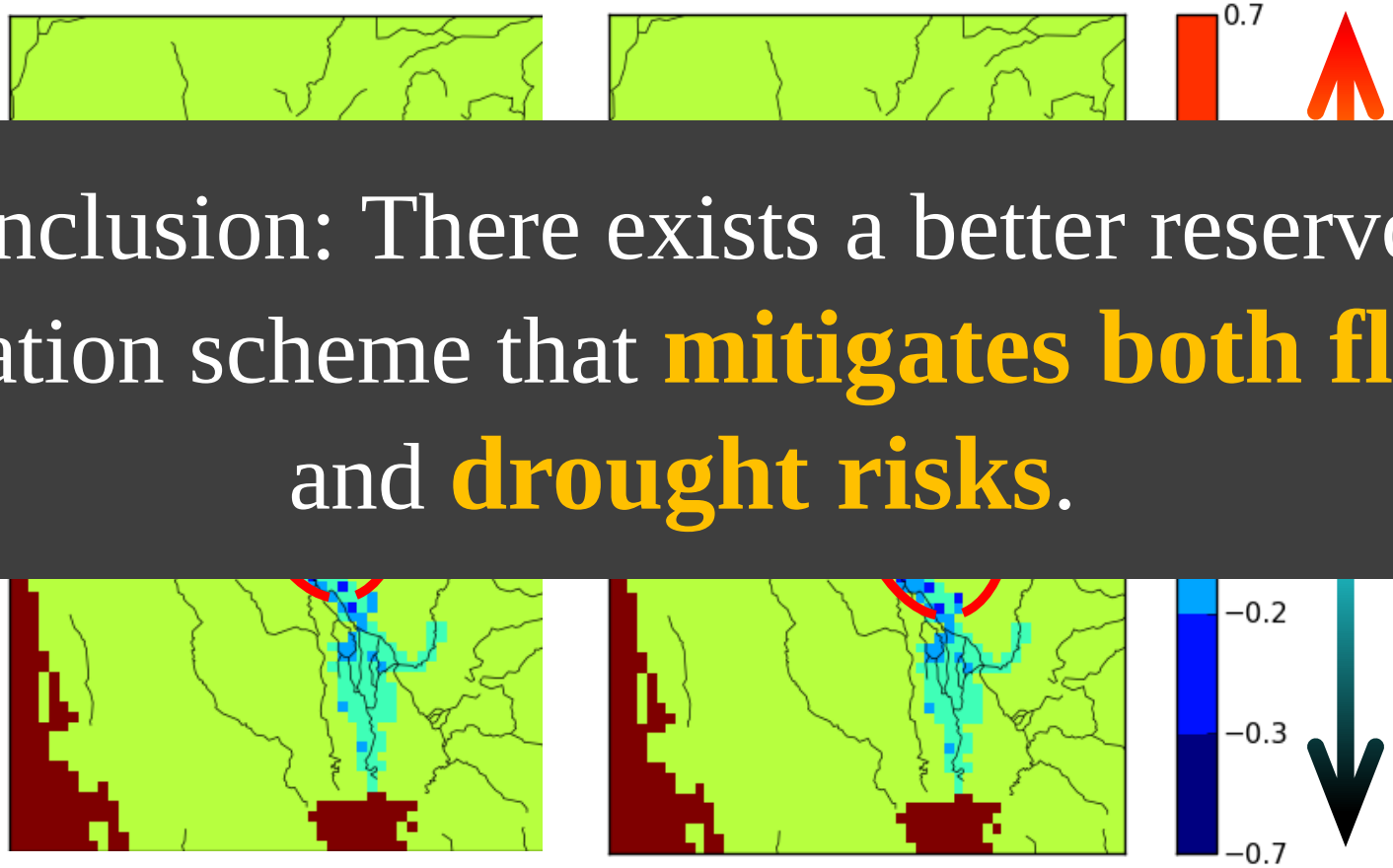


Operation	Over flow (months)	Dry up (months)
Thai_Old	13	36
Thai_Revised	5	42
Flood_Mitig	0	0



Flood mitigation reservoir scheme shows greatest flooded area reduction

Reduction* on percent of area that is inundated (Oct. 15,2011)

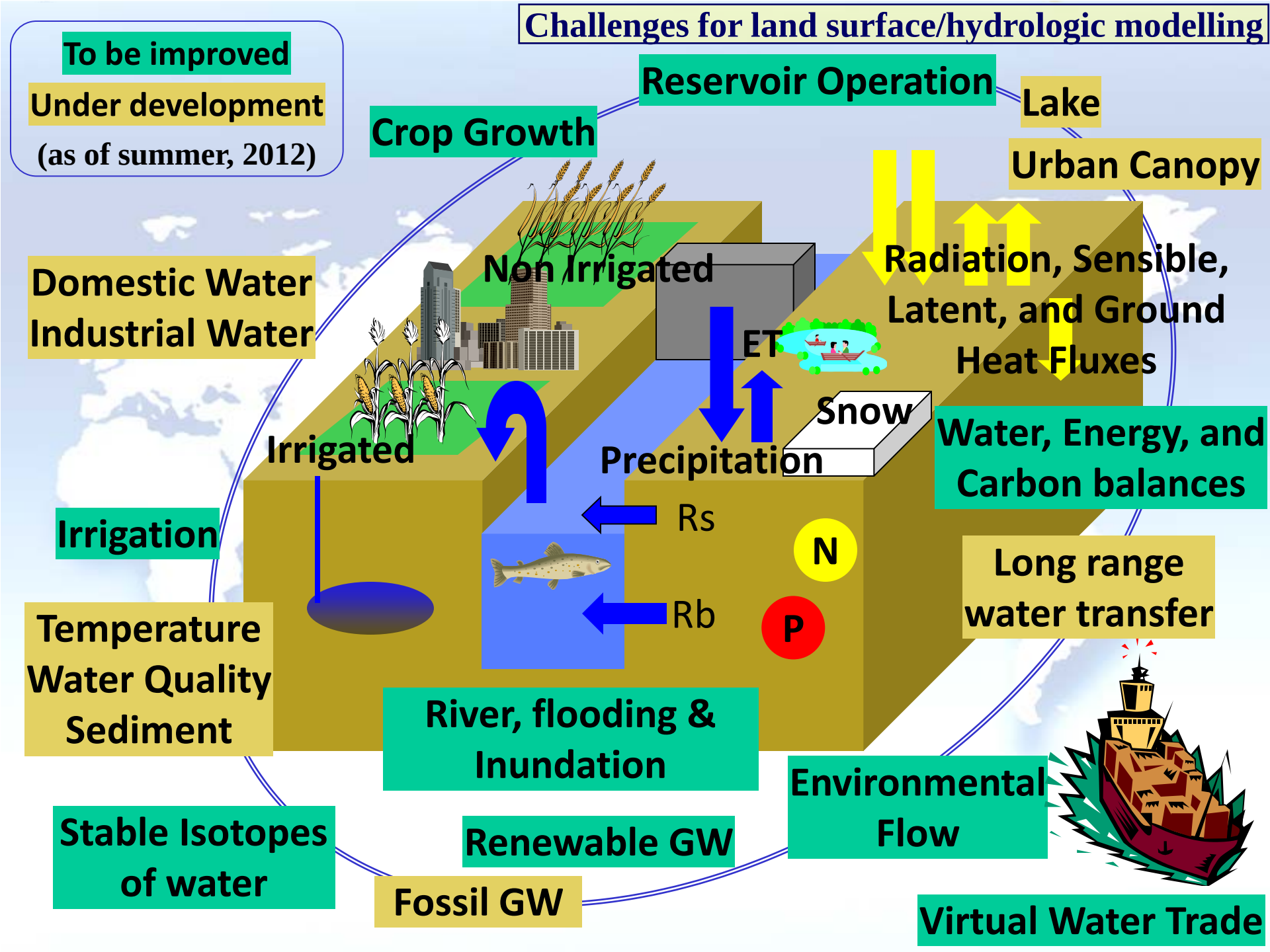


Conclusion: There exists a better reservoir operation scheme that **mitigates both flood** and **drought risks**.

Thai_Revised **Flood_Mitig.**

*Reduction = (Current scheme – Thai_Old)/grid area

Challenges for land surface/hydrologic modelling



Sources of Uncertainties

Environmental Info.
Precip., radiation, temp., humidity, wind,…
(Atmospheric Forcing)

Regional Info.
Soil, Vegetation, Topography, Basin area, …
(parameters)

Initial/Boundary Conditions

Specific Temporal and Spatial Scales

Theory, Equation, or Model

Runoff:
- annual mean
- low flow
- 100 year flood

Solutes:
- quality
- sediment
- isotopic ratio

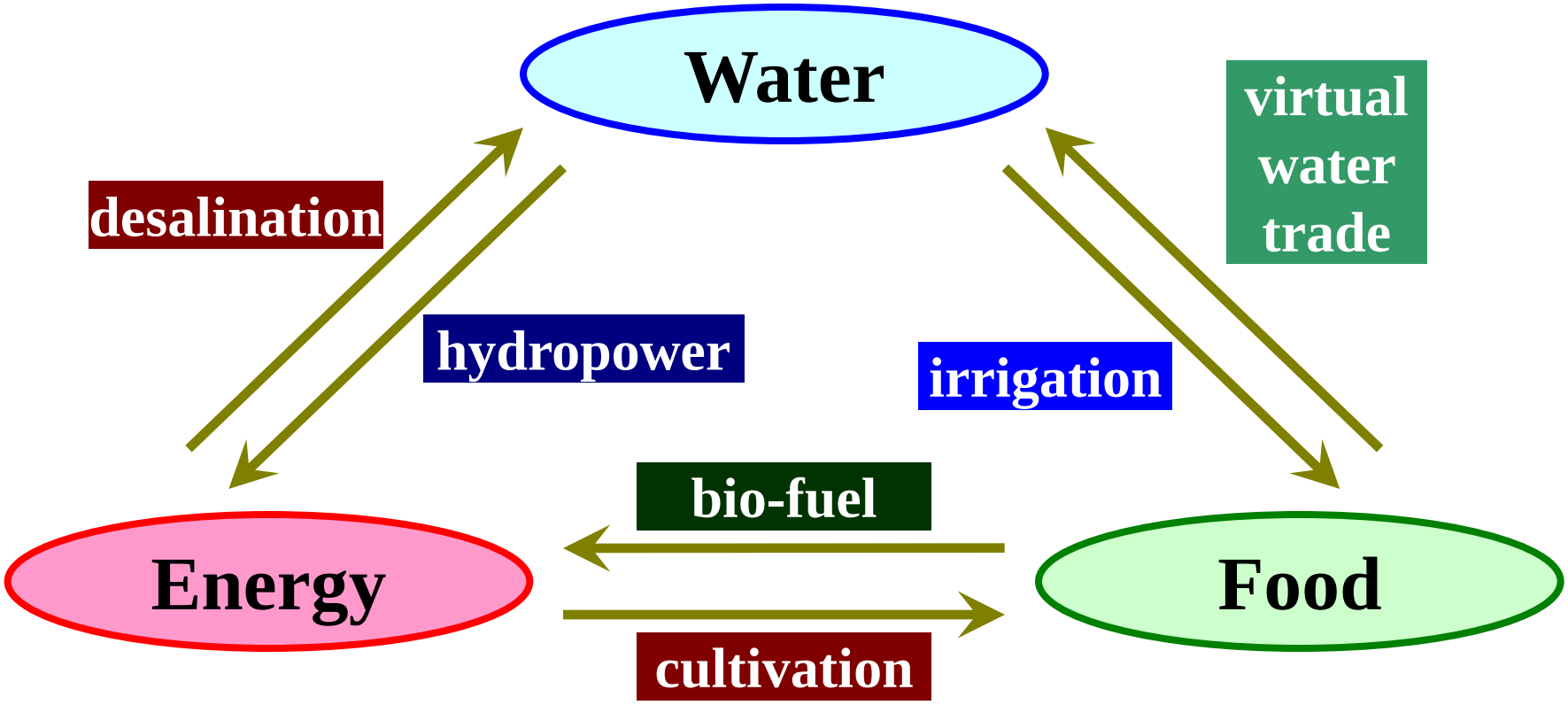
Applicability/Accuracy may differ region by region.

Remarks

- **Human interferences on water cycles are changing the sea level (in addition to CC)**
  - **Critical information: extraction from renewable or non-renewable ground water, distribution of irrigated cropland, irrigation efficiency, …**
- **Integrated model is not perfect but promising:**
  - **Estimate the source and path of water withdrawals for agricultural productions ➔ sustainability**
  - **Propose better reservoir operation rules**
- **Better seasonal prediction of precipitation will supports better reservoir operation.**

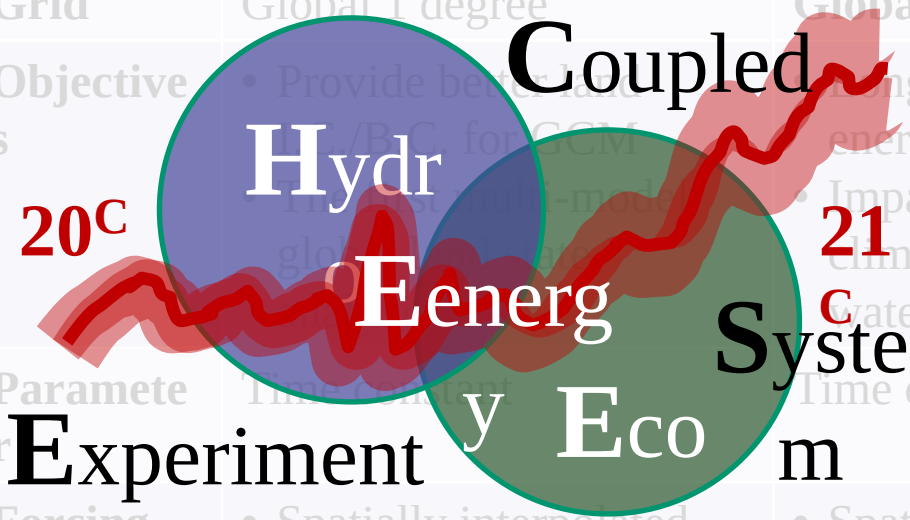
Support developing sustainability in a society

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



GEWEX/GLASS/GSWP3

	GSWP1, 2	Water-MIP, ISI-MIP	GSWP3
Timespan	2 years (1987-1988), 10 years (1986-1995)	**20c, 21c**	**EXP1: 20c (1901-2010)** **EXP2: 21c** **EXP3: 1979 – present**
Grid	Global 1 degree	**Global 0**	
Objectives	• Provide better land BC/B.C. for GCM • The first multi-model global [illegible]	• Long t energy • Impact assessment of climate water a	carbon cycles
Parameter	Time constant	Time constant	**Time varying** for C cycle
Forcing	• Spatially interpolated • Monthly filed constraint using Obs.	• Spatially interpolated • Monthly field constraint using Obs. • Internally inconsistent	• **Dynamically downscaled** • **Daily** and Monthly field constraint using Obs.



Coupled Hydro-Energy-Eco System Experiment

Century long timespan (EXP1: 1901-2010)

Time varying LUCC / CO^2

GSWP3 Kick-off meeting @ Tokyo (5-6 Nov.)

http://hydro.iis.u-tokyo.ac.jp/GSWP3

東京大学 THE UNIVERSITY OF TOKYO

COLA Center for Ocean-Land-Atmosphere Studies

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

UCCHM

Working Group II calendar

- **LAM1:** **January 2011**
- **Informal Peer Review:** **July - September 2011**
- **LAM2:** **December 2011**
- **Expert Review:** *We are here.* **June - August 2012**
- **LAM3:** **October 22-26, 2012**
- ***Literature cut-off date for "submitted" papers: Jan 31, 2013***
- **Government & Expert Review:** **March - May 2013**
- **LAM4:** **July 2013**
- ***Literature cut-off date for "accepted" papers: Aug 31, 2013***
- **Final Government Distribution:** **October - December 2013**
- **Plenary:** **March 17-21, 2014 in Japan.**

ZOD

FOD

SOD

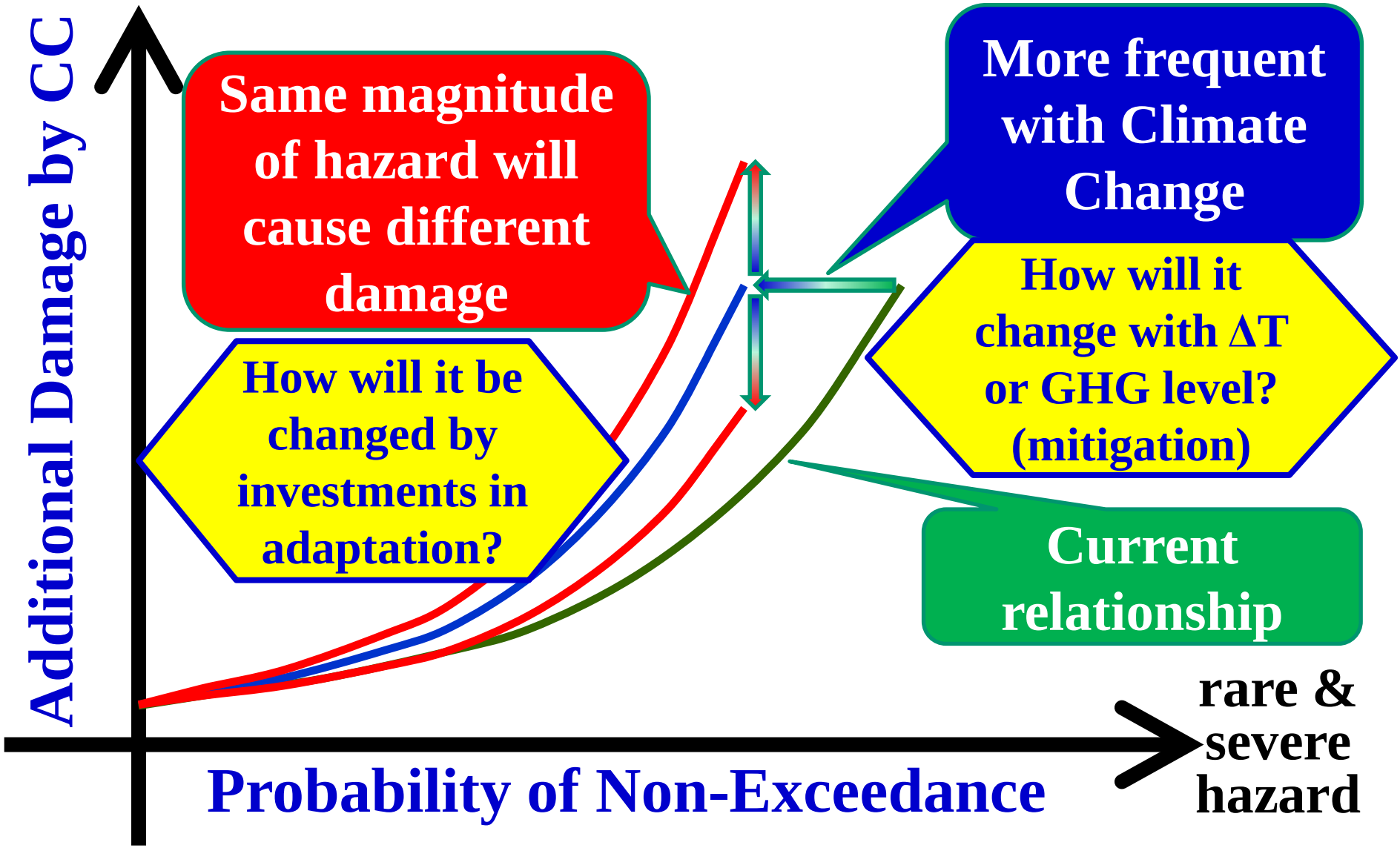
Literature cutoff (in press) FGD

IPCC AR5

- **Move from "it's real" to "here is the information you need to make good decisions for your stakeholders"**
  - **Risk management framing**
  - **Multiple stresses framing**
  - **Full partnership for adaptation**

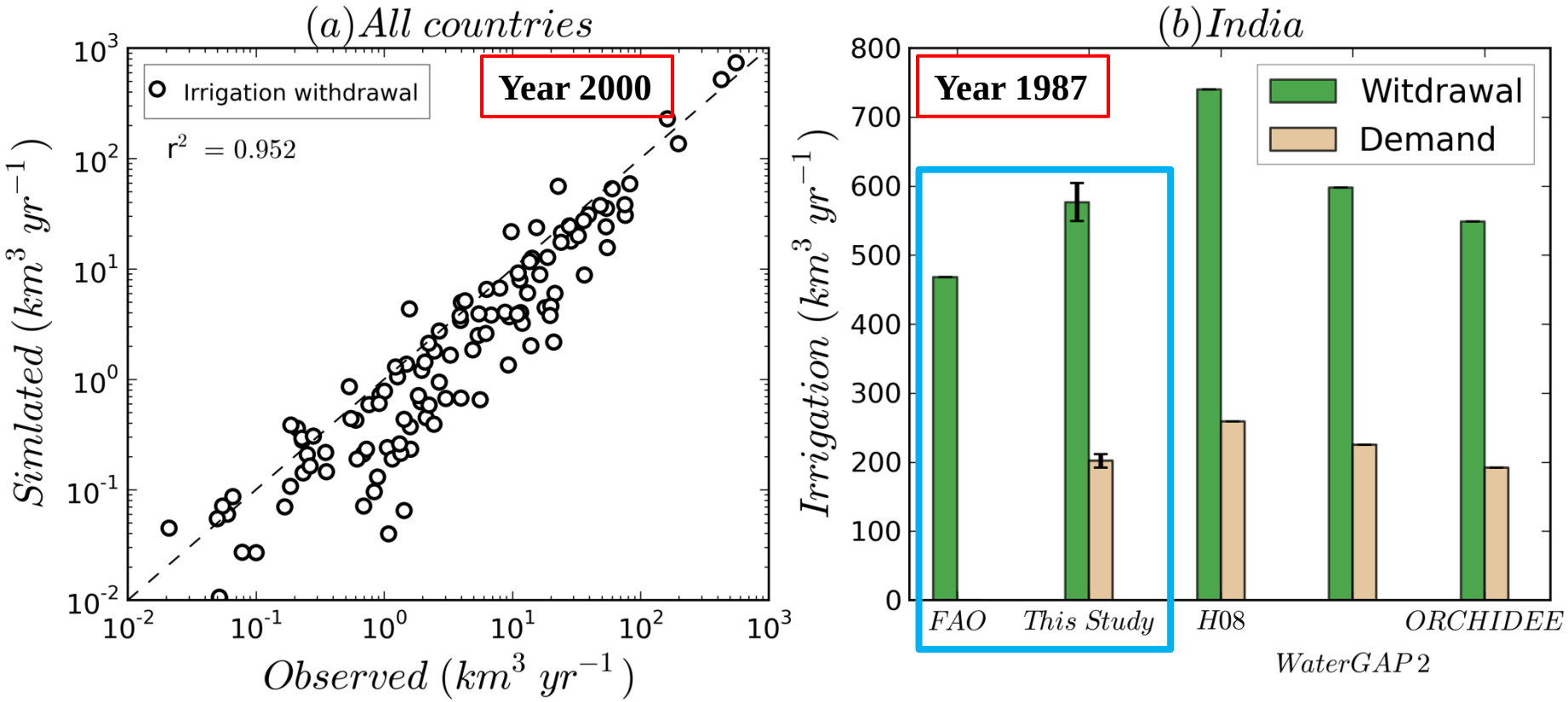
(Source: Chris Field, 2010)

Impact Assessments with CC and SC



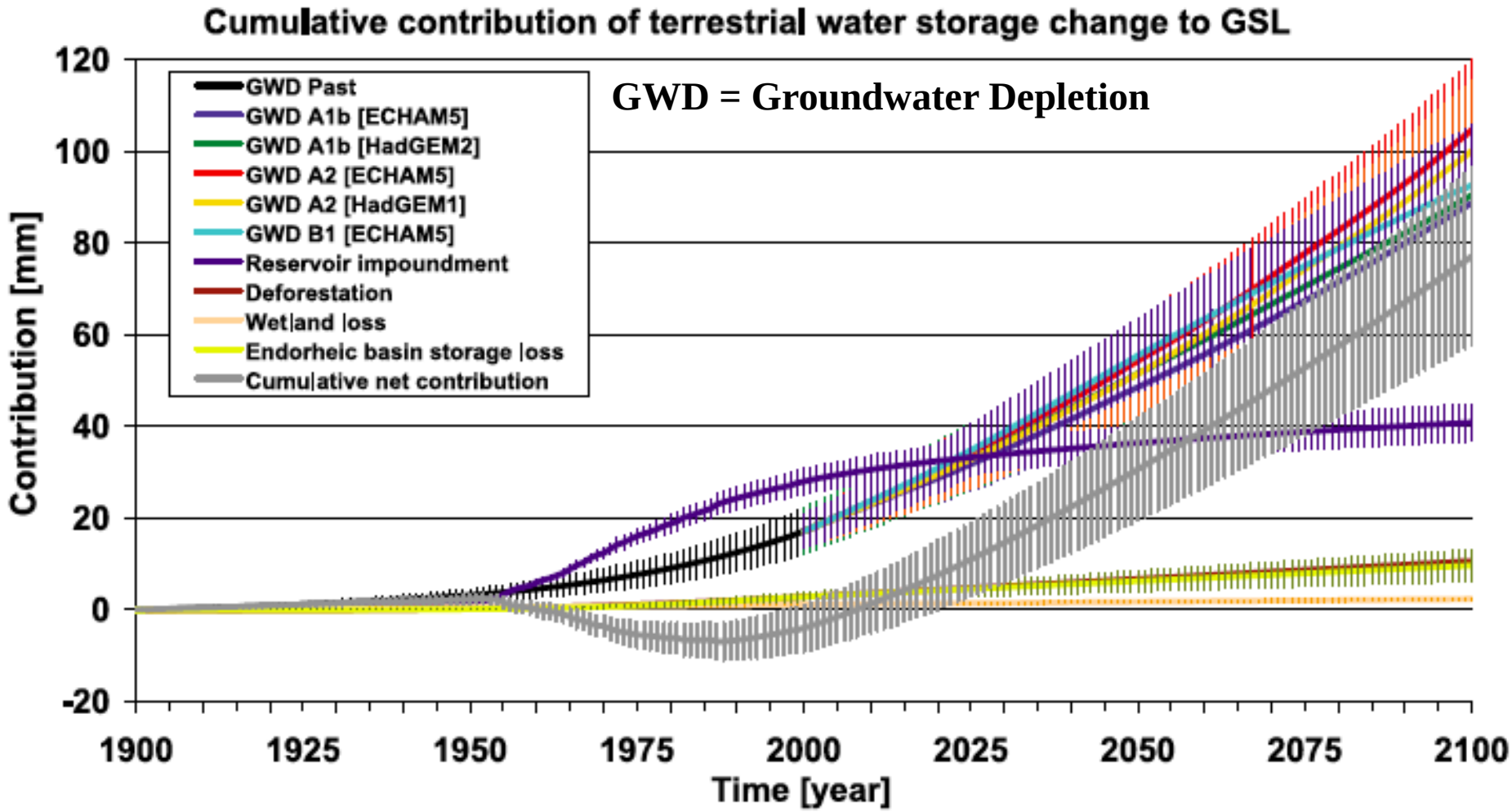
Validation of Irrigation Water Use

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.

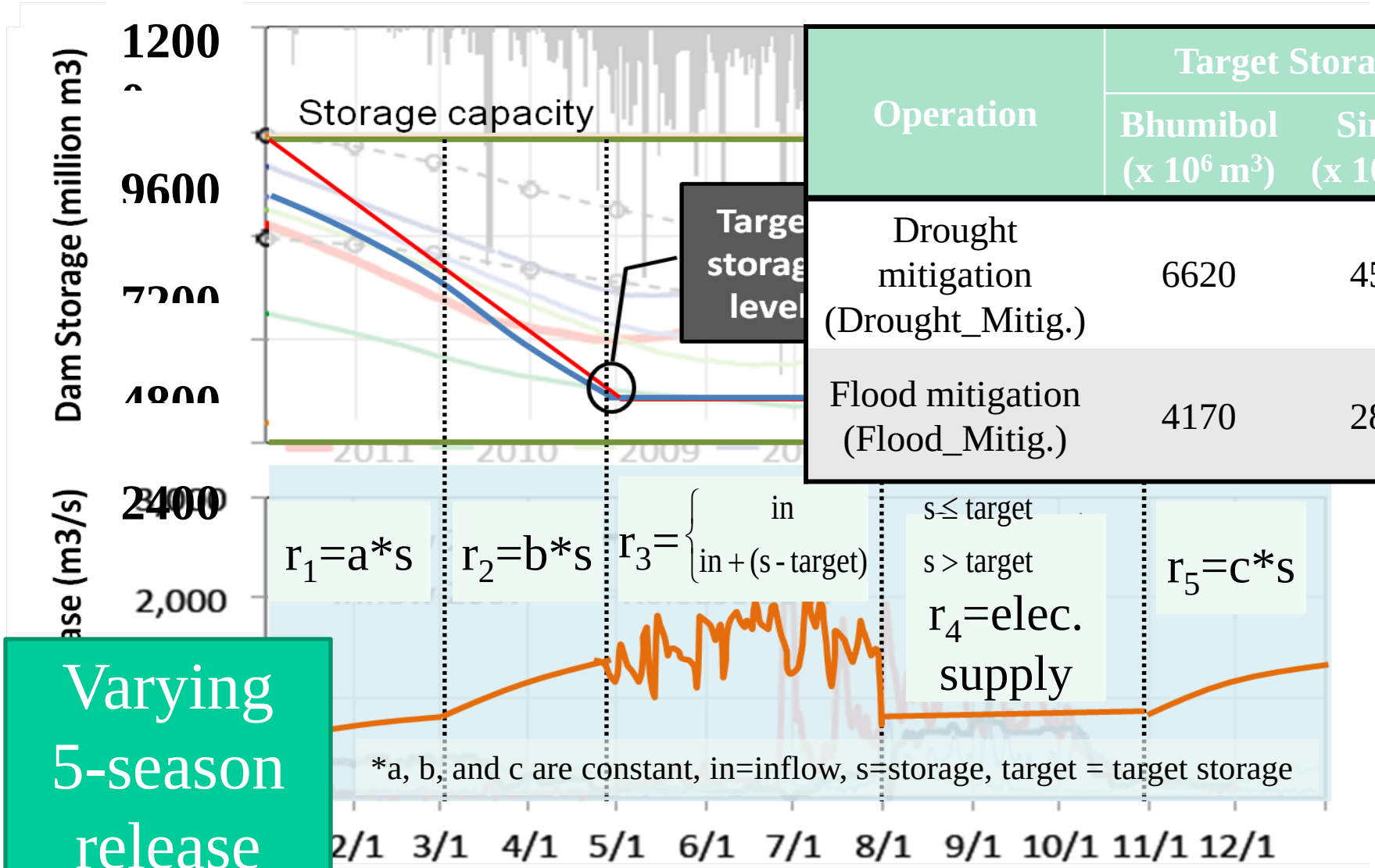
Sea Level Change due to TWS: Past and Future



Pathum Thani (9:59, Dec. 01, 2011)

(11:50, Nov. 21, 2011)

Reservoir operation scheme with release as a function of storage is developed



Operation	Target Storage	
	Bhumibol ($x\ 10^6\ m^3$)	Sirikit ($x\ 10^6\ m^3$)
Drought mitigation (Drought_Mitig.)	6620	4585
Flood mitigation (Flood_Mitig.)	4170	2855

$r_1 = a*s$

$r_2 = b*s$

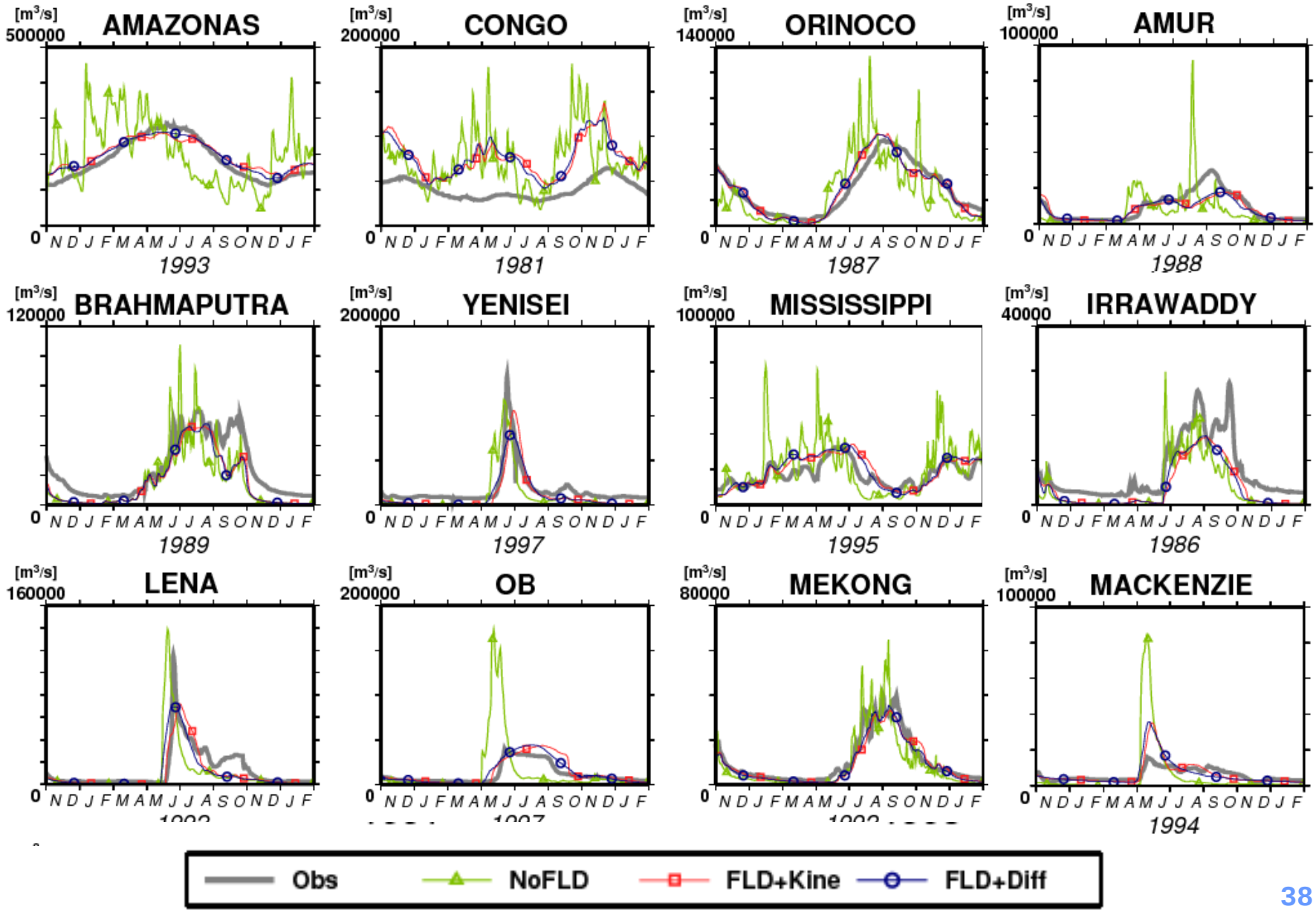
$r_3 = \begin{cases} in & s \le target \\ in + (s - target) & s > target \end{cases}$

r_4=elec. supply

$r_5 = c*s$

*a, b, and c are constant, in=inflow, s=storage, target = target storage

Varying 5-season release

Results (World major rivers)

Daily River Discharge