Land Surface Modeling Summit 2022
(2022/9/12-15)

Treatment of water management processes in land models

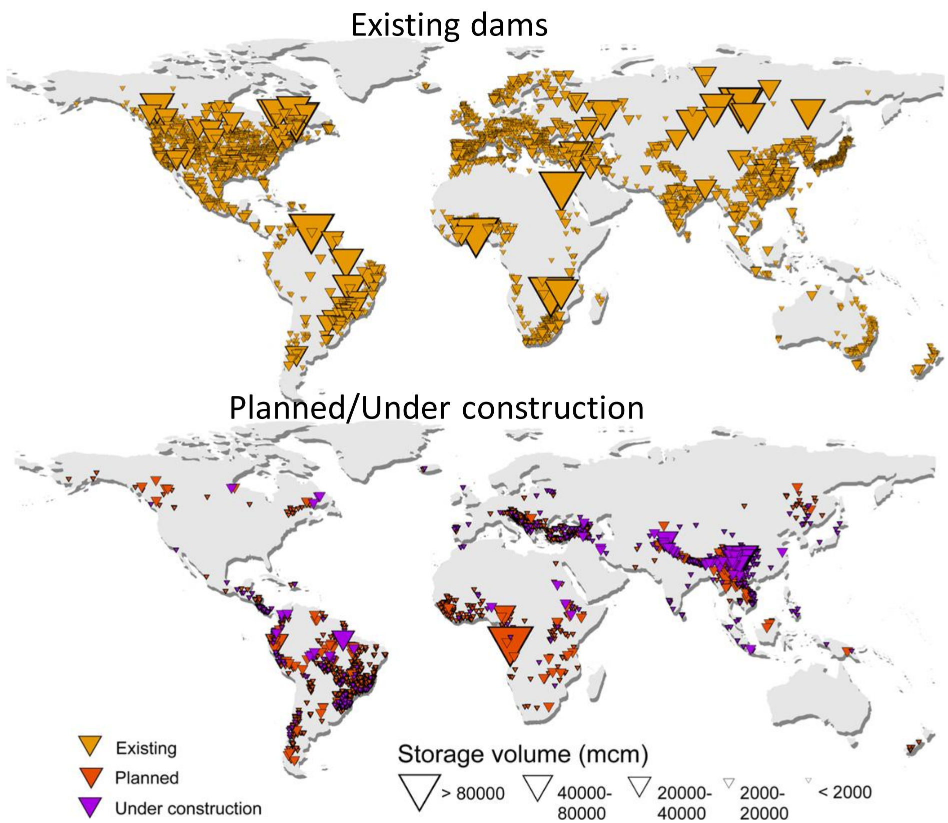
Kei Yoshimura (U Tokyo / JAXA)

Special acknowledgment to:
Naota Hanasaki, Inne Vanderkelen, Tokuta Yokohata, Risa Hanazaki, Tomoko Nitta, Daisuke Tokuda, Yosuke Miura & many others

Dams

Number	25,000+ (large dams), 16,700,000 (>0.1ha)
Volume	7200+km^3 (large dams) 8070km^3 (>0.1ha)~20% of global runoff

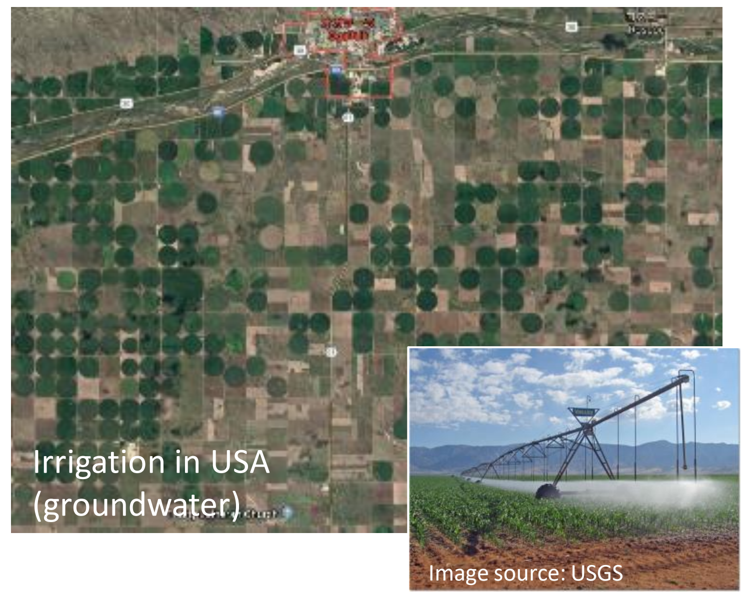
Data source: ICOLD 1998; Lehner et al. 2011;



Grill et al. 2015, Env Res. Lett

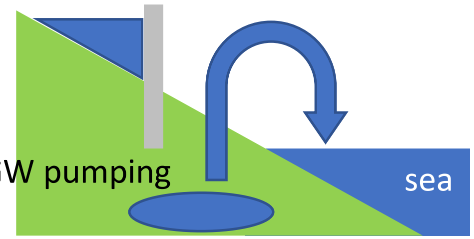
Irrigation

Area	2.7 million km^2 (~15% of cropland, ~2% of land)
Volume	2660 km^3/yr (~70% of total water withdrawal)
Source	Surface water & Groundwater



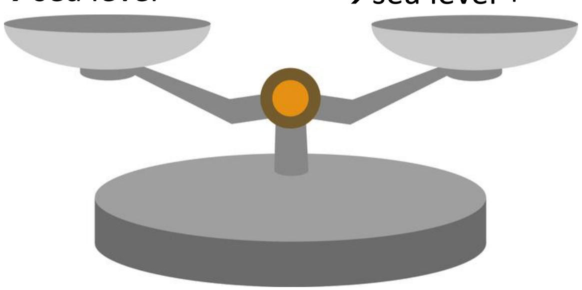
Impact on sea level rise

Dam storage

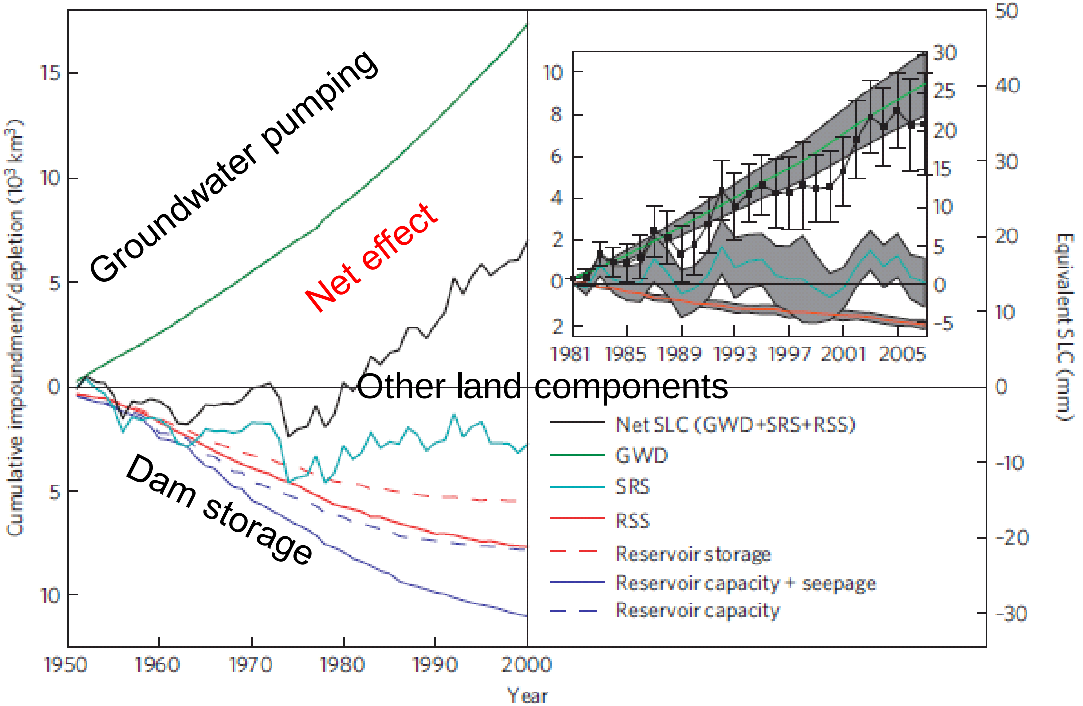


Dam storage
→sea level -

GW pumping
→sea level +



The terrestrial water storage contributions to sea-level change



NB: Likely groundwater pumping was overestimated in this study.

Pokhrel et al. 2012, Nature Geosci

Let’s get started with some history…

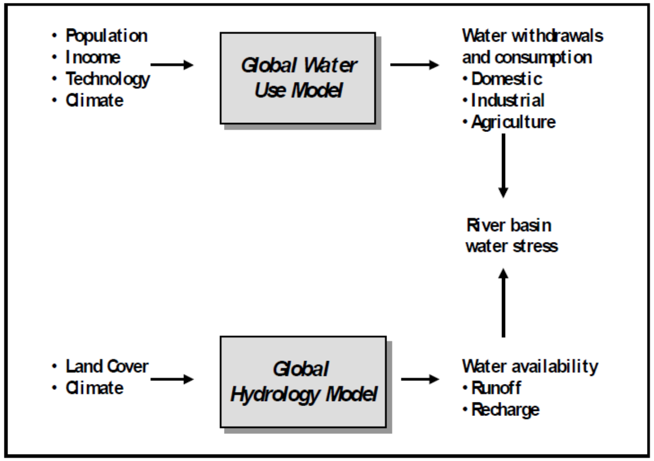
Zero-th generation

- Before global water resources model was available
- Based on nation-wise statistics.

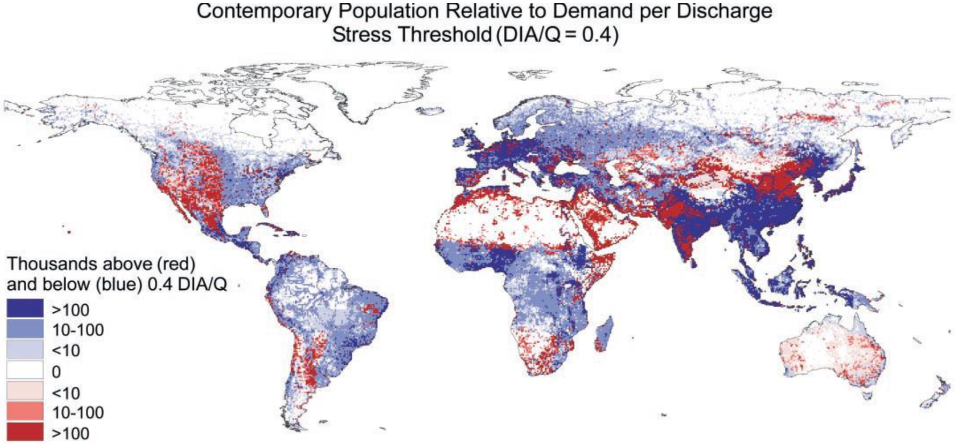
Raskin et al. 1997

First generation

- Estimate the spatial distribution of water use and availability separately
- Display simple water scarcity index (use/availability) at grid cells.



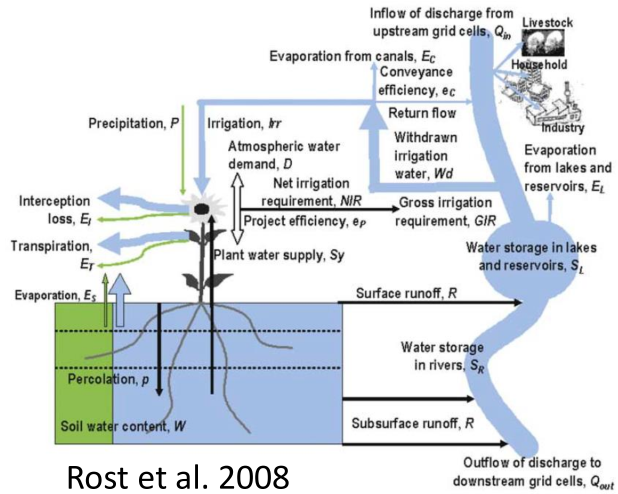
Alcamo et al. 2003



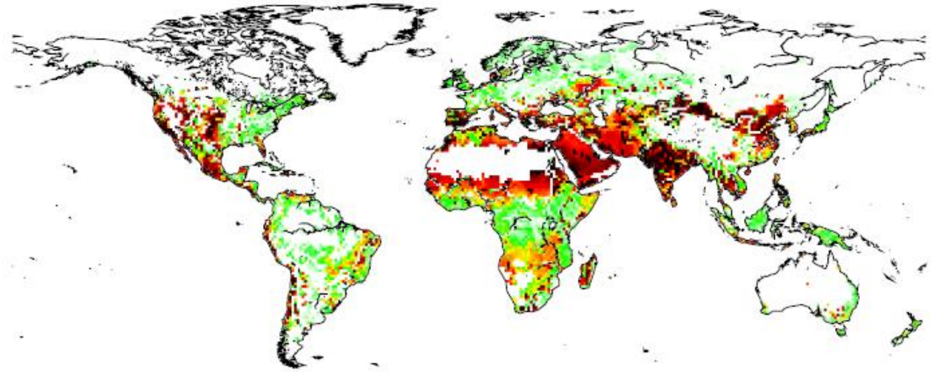
Vorosmarty et al. 2000

Second generation

- Integrate the hydrology and the water use models.
- Explicitly show the seasonality and the downstream effects using "new" indexes.



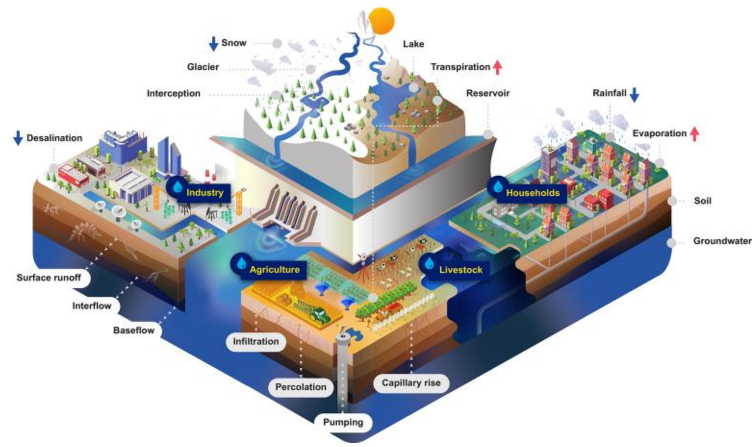
Rost et al. 2008



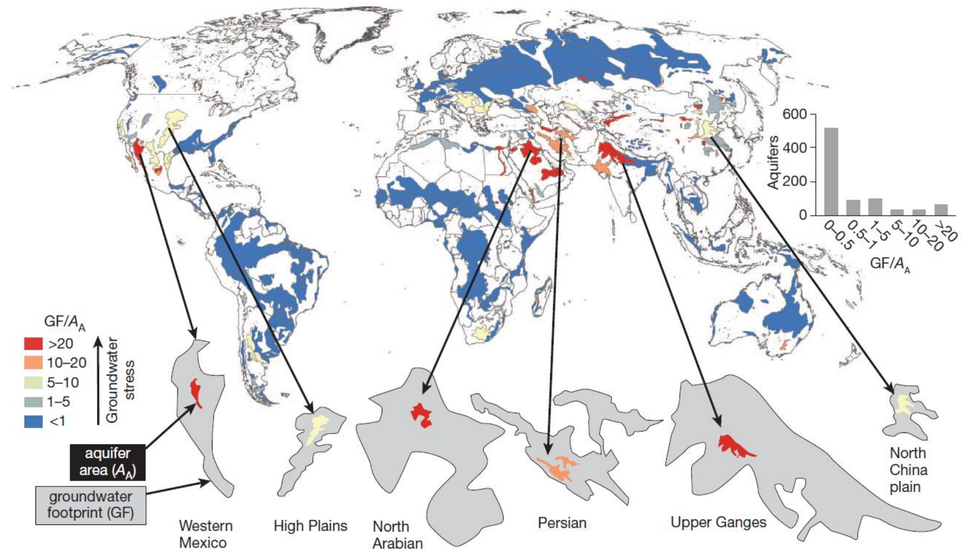
Hanasaki et al. 2008

Second generation +

- Separating water sources (surface and groundwater)
- Infrastructure (dams)
- High resolution (5 arcmin globally)
- Source code readability (Python)



Burek et al. 2020 (CWatM)

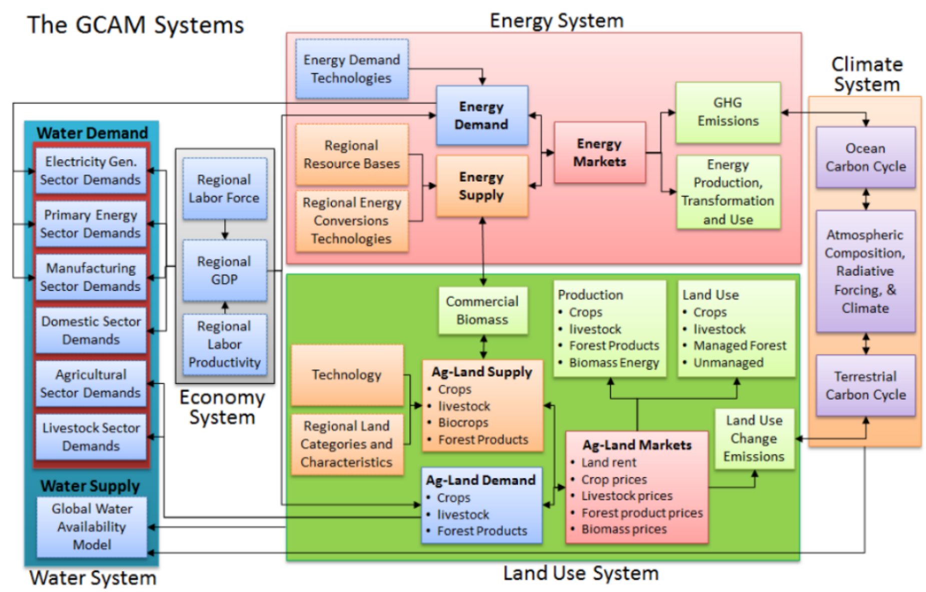


Gleeson et al. 2012

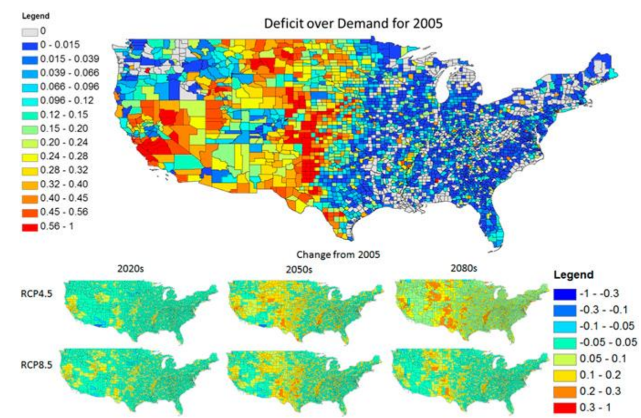
Other approaches

- Integrated Assessment Model (IAM)--"economics" as the principal rule of the world.

- Heavily constrained by socio-economic data, little available/useful at the grid level.

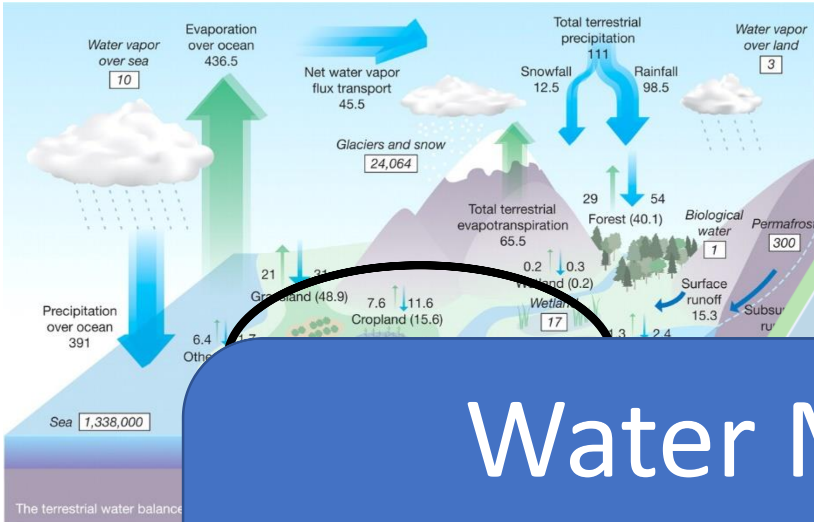


Hejazi et al. 2014

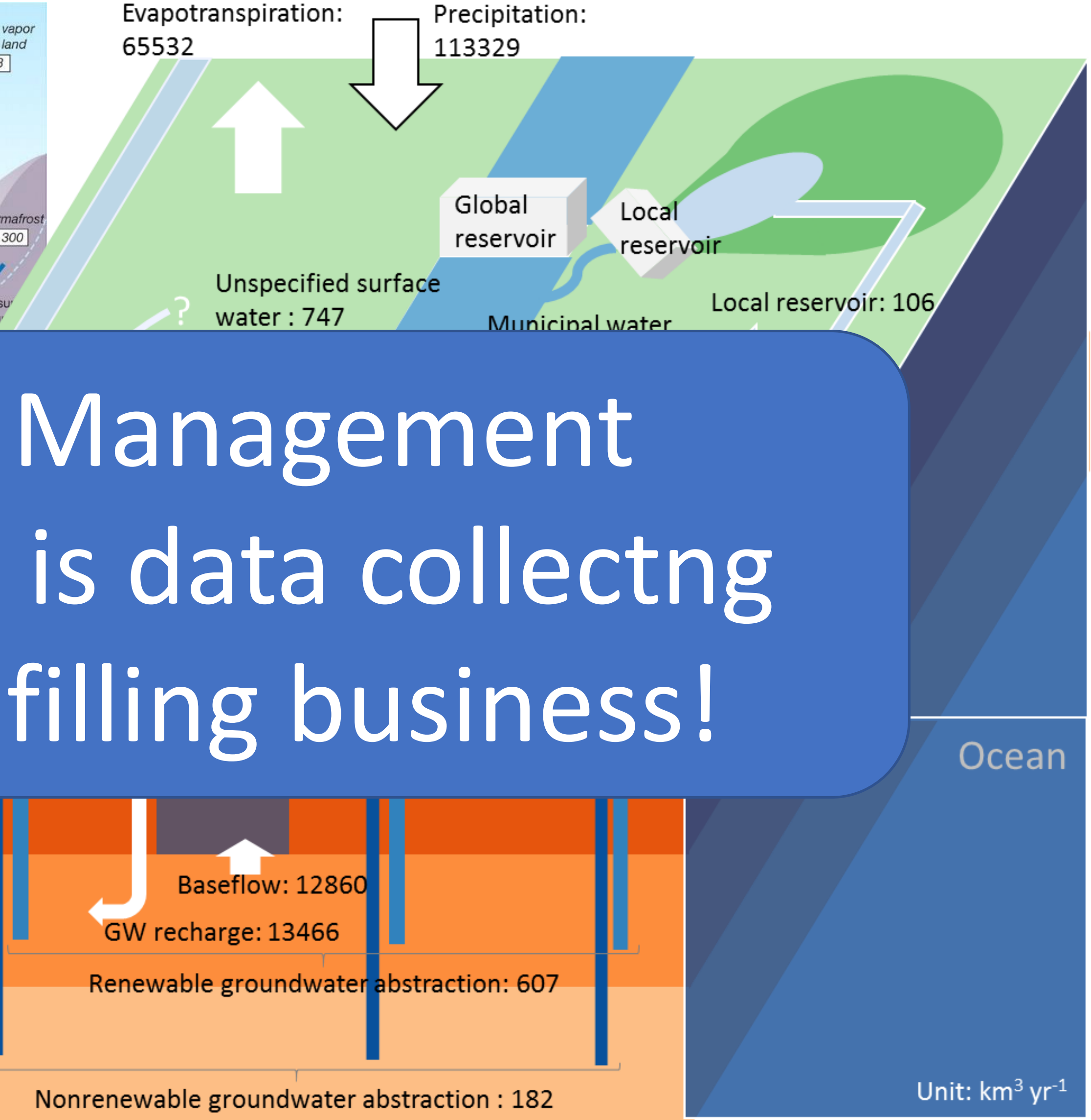


RCP4.5 could be more water stressed than RCP8.5.
Hejazi et al. 2015

As consequence…



Oki and Kan



Water Management Modeling is data collectng and gap filling business!

Hanasaki, 2017, AGU

Understanding has progressed. However, none of these water management models have been coupled with GCMs/ESMs.

Game changers emerge recently!

Dams and water management in CESM / CTSM / CLM5

Representing reservoirs in Earth system models

Look at dam parametrizations in global hydrological models

Impact models

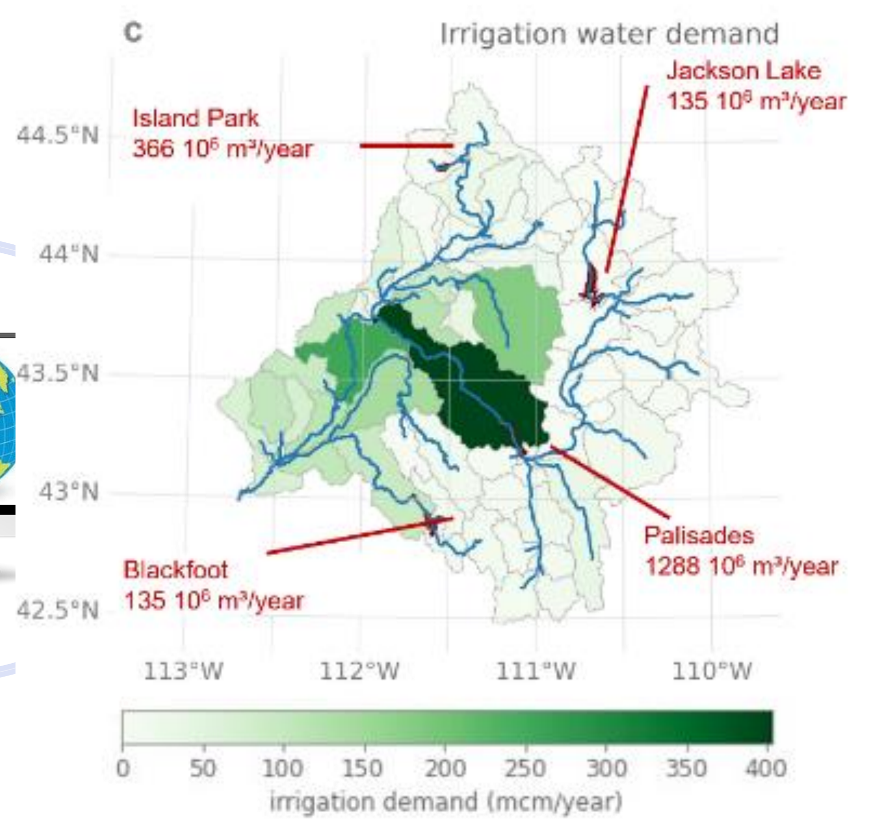
Detailed, specialized and process-based

Water management and catchment models

Observation-based storage and release policies

Global hydrological models

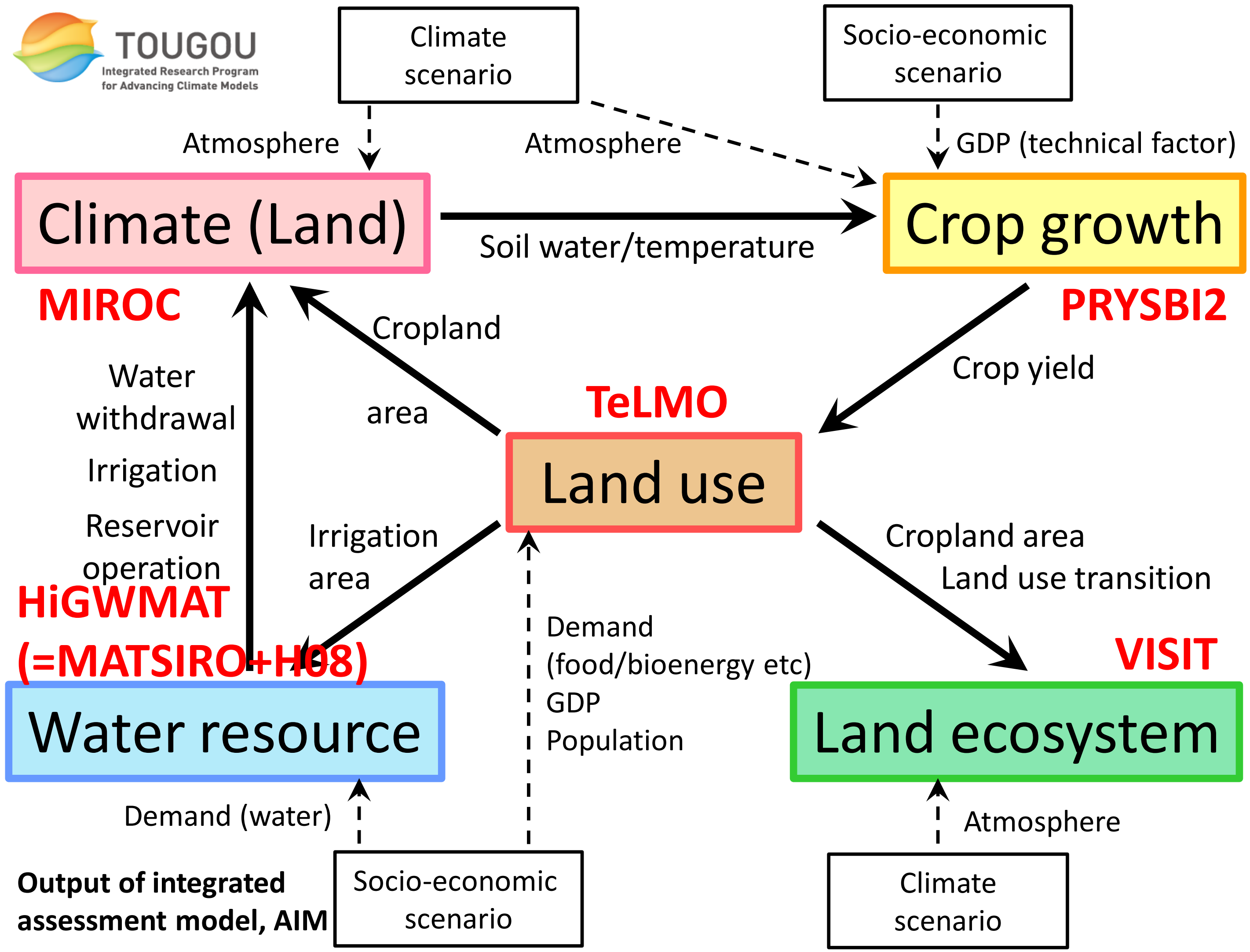
Generic dam parametrisations



Vanderkelen et al., 2021; 2022

Coutesy of I. Vanderkelen

Development of MIROC-INTEG-ES



MIROC-INTEG-LAND

Yokohata et al. 2020, Gesci Model Dev

We developed an integrated model, where **natural process** (land surface physics, ecosystems, water resource, crop growth) and **human process** (land use, water management, socio-economic) models are coupled and variables are exchanged

However, most of the connections are one-way and LAI/LU is annually updated. ➔ Dynamic communication is challenging

Courtesy of T. Yokohata

Integrated Land Simulator

Development of Integrated Land Simulator, ILS (Nitta et al., 2020)

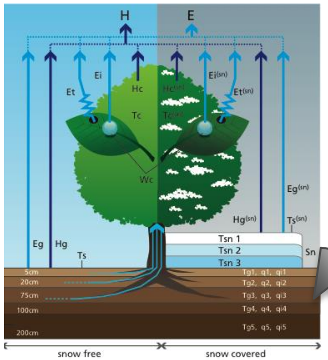
will contribute MIROC7/CMIP7

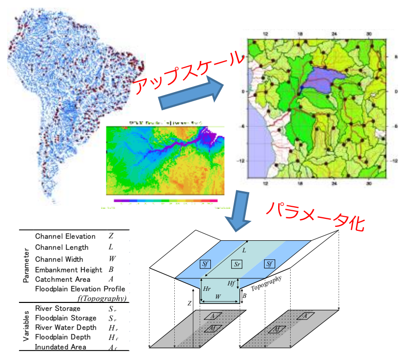
Basic concepts:

- Port the latest stand-alone models with smallest modification of the codes.
- Run the models with their preferred time steps and resolutions, and exchange necessary data with appropriate regridding by the coupler.

1-D Land Model MATSIRO

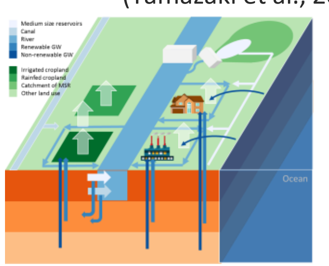
(Takata et al., 2003; Nitta et al., 2014; 2017)





River Model CaMa-Flood

(Yamazaki et al., 2011;)



Human Impact Model H08

(Hanasaki et al., 2008)

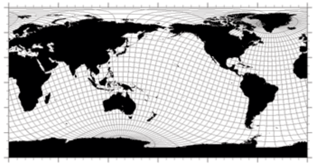
General purpose coupler Jcup (Arakawa et al., 2011)

Following models are developed and will be coupled:

- Dynamic sediment transport model (Hatono and Yoshimura, 2020)
- 3D ground water model (Miura and Yoshimura, 2020)
- River water temp. and quality transport model (Tokuda et al., 2019)
- Dam operation model (Hanazaki et al., in prep.), Etc.

AGCMs

MIROC (Tatebe et al., 2019)
NICAM (Sato et al., 2014) etc.



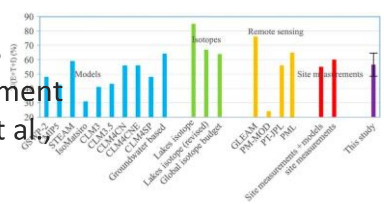
OGCMs

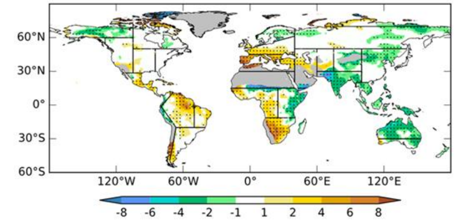
COCO (Hasumi, 2006) etc.

Key Achievements

- Global 90m DEM and hydrography data (Yamazaki et al., 2017; 2019)

- Global transpiration fraction on ET (Wei et al., 2017; 2016)
- Global aridity change by 1.5 degree agreement (Takeshima et al., 2020)

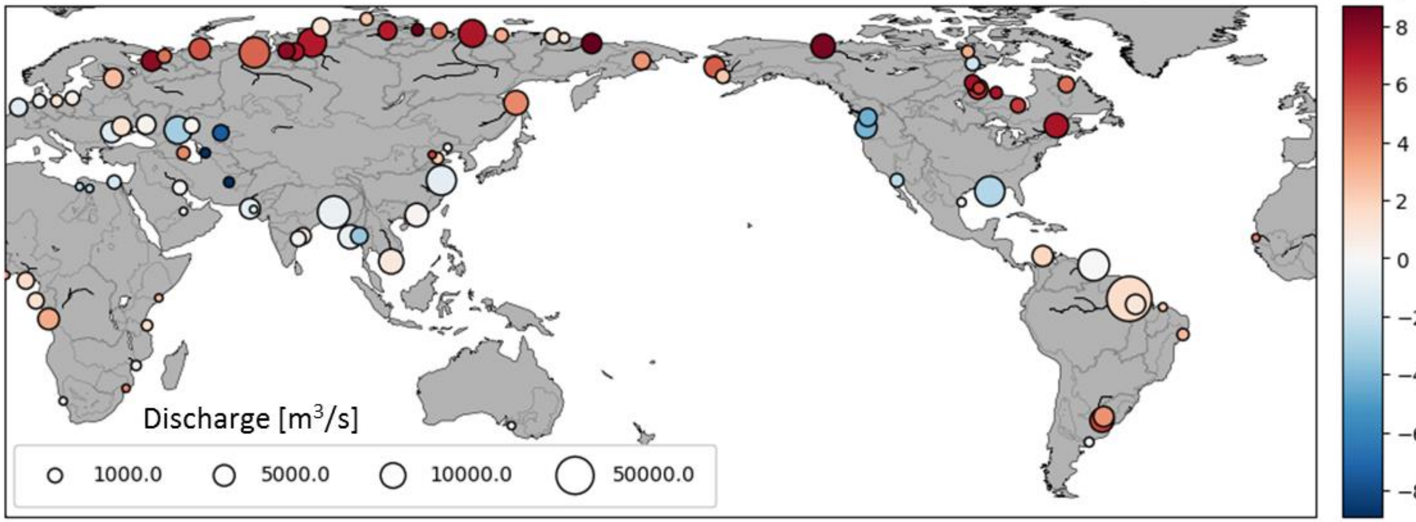




River water temperature & Surface Flux from Rivers/Lakes

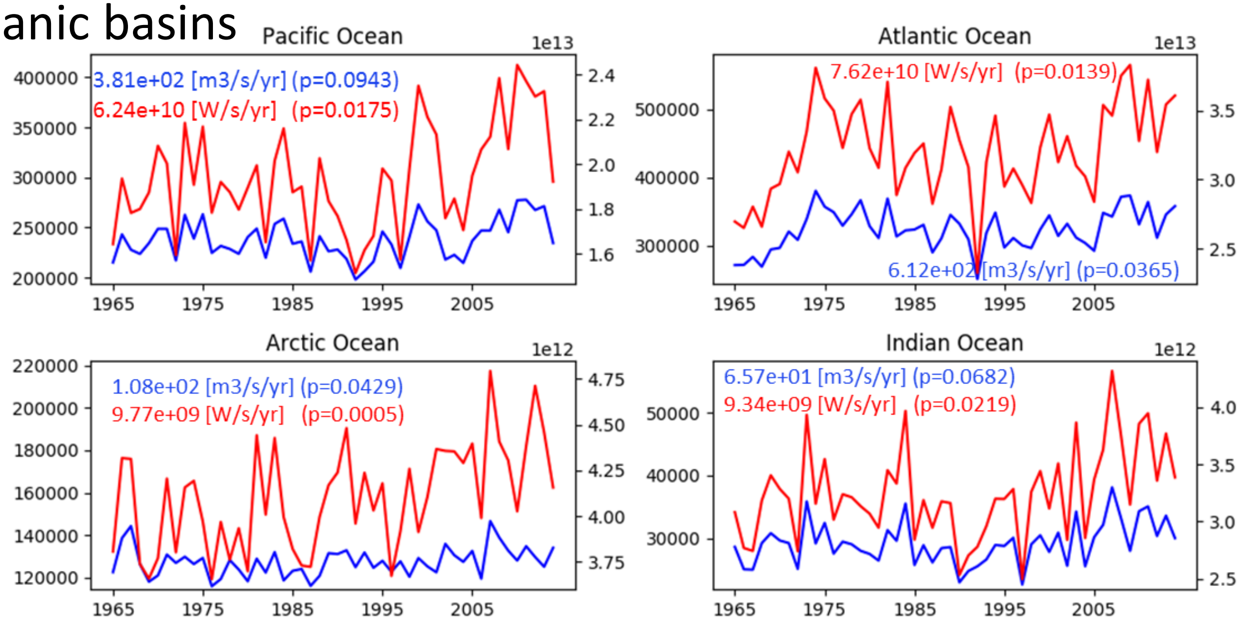
Arctic rivers effectively transports energy from warmer South to colder North region

Temperature difference between river water at mouth & the nearest coastal ocean [°C]



Long-term trend of Freshwater[m³/s] (left) and thermal discharge[W] (right) into oceanic basins

1965~2014 regression coefficient and p value



These estimation are conducted with global-scale river water temperature model [Tokuda et al., 2019]

Hanazaki et al., 2022

NEW dam operation parameterization

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RESEARCH ARTICLE

10.1029/2021MS002944

Key Points:

- Reservoir operation scheme for flood control was introduced into the global flood model
- Operational rules and parameters were identified to represent the actual flood control operation
- Developed reservoir operation scheme leads to improvement in discharge simulation during floods and significantly impacts flood mitigation

Development of a Reservoir Flood Control Scheme for Global Flood Models

Risa Hanazaki[1], Dai Yamazaki[1], and Kei Yoshimura[1]

[1]Institute of Industrial Science, The University of Tokyo, Tokyo, Japan

Abstract Integrating reservoir flood control operations in global flood forecasting systems is important for accurately estimating discharge and other variables. Because existing modeling operational rules and parameters do not reflect the actual variability due to a lack of associated data, globally applicable modeling of flood regulation needs to be studied further. In this study, we developed a flood control operation scheme with refined parameters and algorithms to tackle this problem. We used recently developed objective data sets of

Three Gorges Dam
https://www.jiji.com/jc/d4?p=mga001-5414087&d=004ent

Review of existing dam operation algorithms

1. Lake scheme

   Doll et al., 2003

2. Focused on primary purpose

   Based on inflow and downstream demand

   Hanasaki et al., 2006,

   Many studies based on H08

   Wisser et al., 2010a

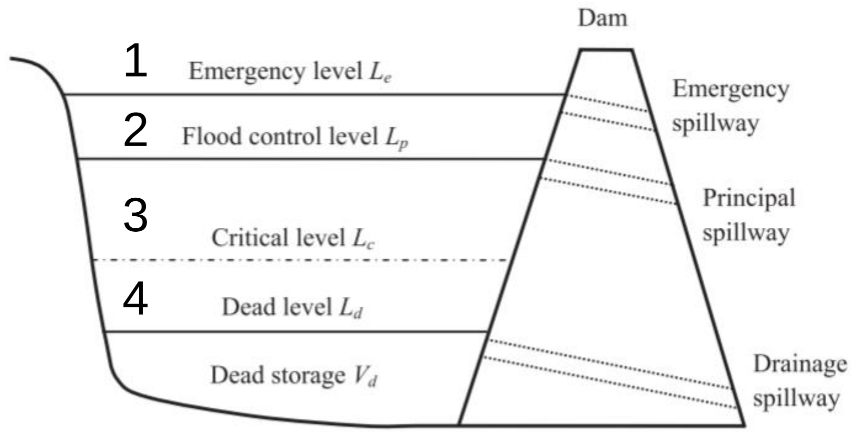


FIG. 1. Schematic of a multiyear and multipurpose reservoir (after Ward and Elliot 1995).

3. **Multi-purpose operation**

   Based on reservoir zoning

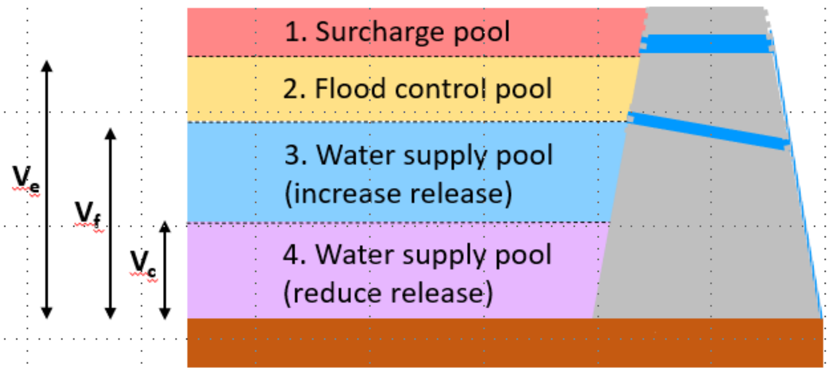
   (Haddeland et al. 2006; Wu and Chen, 2012; Wang et al., 2019; Zajac et al., 2017; Dong et al., 2019)

zone	Operational purpose	example operational rules in Zajac et al., 2017
1	Prevent overtopping	$Q = \max\left(\frac{V - V_e}{\Delta t}, Q_f\right)$
2	Flood control	$Q = Q_n + \frac{V - V_c}{V_e - V_c} \times \max(I - Q_n, Q_f - Q_n)$
3	Supply for hydropower, irrigation, domestic use, …	$Q = Q_n + \frac{V - V_c}{V_e - V_c} \times \max(I - Q_n, Q_f - Q_n)$
4	impoundment	$Q = Q_{min} + (Q_n - Q_{min}) \times (V - V_d)/(V_c - V_d)$

Q: outflow, I: inflow, V: storage

Q_f: flood discharge (non-damaging discharge), Q_n: normal discharge

Implementation of New Dam Operation Algorithm



Q: outflow, I: inflow, V: storage volume

Parameters

Q_f: flood discharge (non-damaging discharge)

Q_n: normal discharge

r: $(V_e - V_f)$ / drainage area

zone	Operational purpose	I >= Qf	I < Qf
1	Prevent overtopping	$Q = I$	$Q = Q_f$
2	Flood control	$Q = Q_f + \max\left(1 - \frac{r}{0.2}, 0\right) \times \frac{V - V_f}{V_e - V_f} \times (I - Q_f)$	$Q = Q_n \times 0.5 + \left(\frac{V - V_c}{V_e - V_f}\right)^2 (Q_f - Q_n)$
3	Supply for hydropower, irrigation, domestic use, …	$Q = Q_n \times 0.5 + \left(\frac{V - V_c}{V_f - V_c}\right)(Q_f - Q_n)$	$Q = Q_n \times 0.5 + \left(\frac{V - V_c}{V_e - V_c}\right)^2 (Q_f - Q_n)$
4	impoundment	$Q = Q_n \times \left(\frac{V}{V_f}\right)$	$Q = Q_n \times \left(\frac{V}{V_f}\right)$

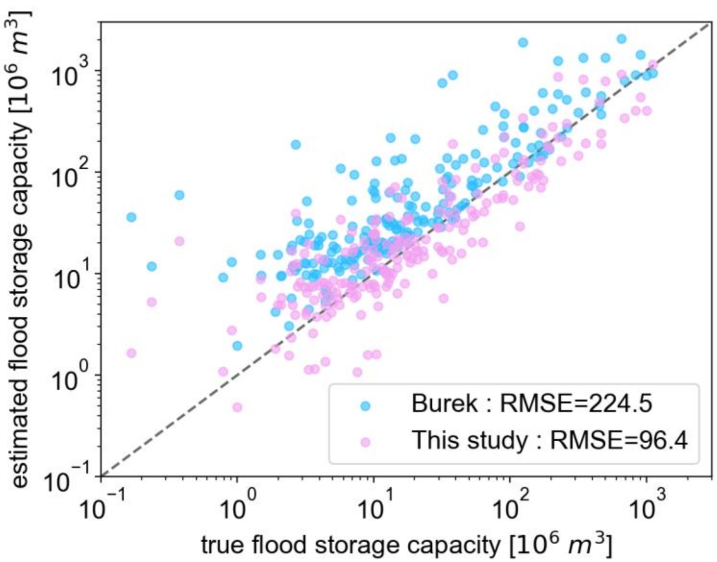
1. Outflow is kept low due to small storage in initial phase of large flood
2. Outflow is a function of storage and inflow, considering flood control storage capacity
3. Operation during small flood and wet seasons

Reservoir outflow is formulated to represent flood control operation and storage variation in non-flood period

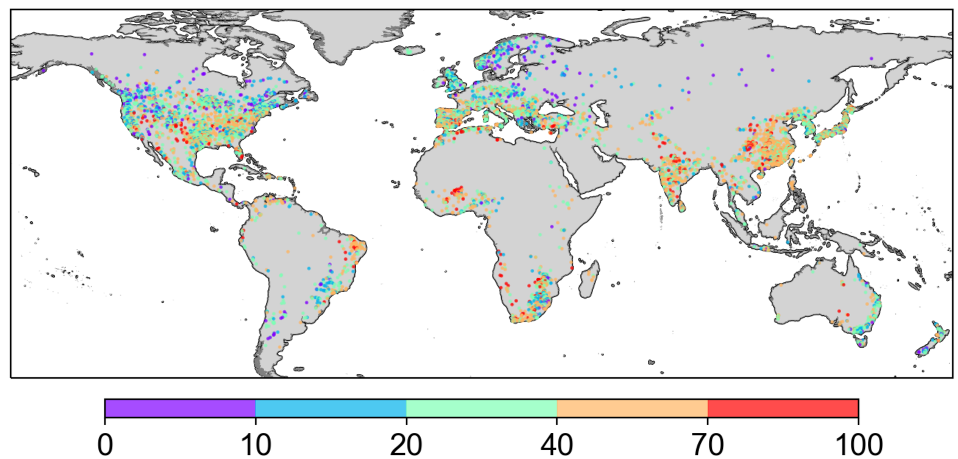
Estimation and validation of flood storage capacity (FSC)

	Estimation of FSC	Global applicability	Characteristic of operation
Burek et al., 2013	70% of total storage (Vmax)	○	×
Yassin et al., 2019	45%-ile of observed volume	×	○
This Study	75%-ile of GRSAD* is converted to volume using ReGeom**	○	○

*Global Reservoir Surface Area Dataset: Zhao and Gao, 2018
**Global Reservoir Geometry Database: Yigzaw et al., 2018



Validation of FSC at 212 dam reservoirs



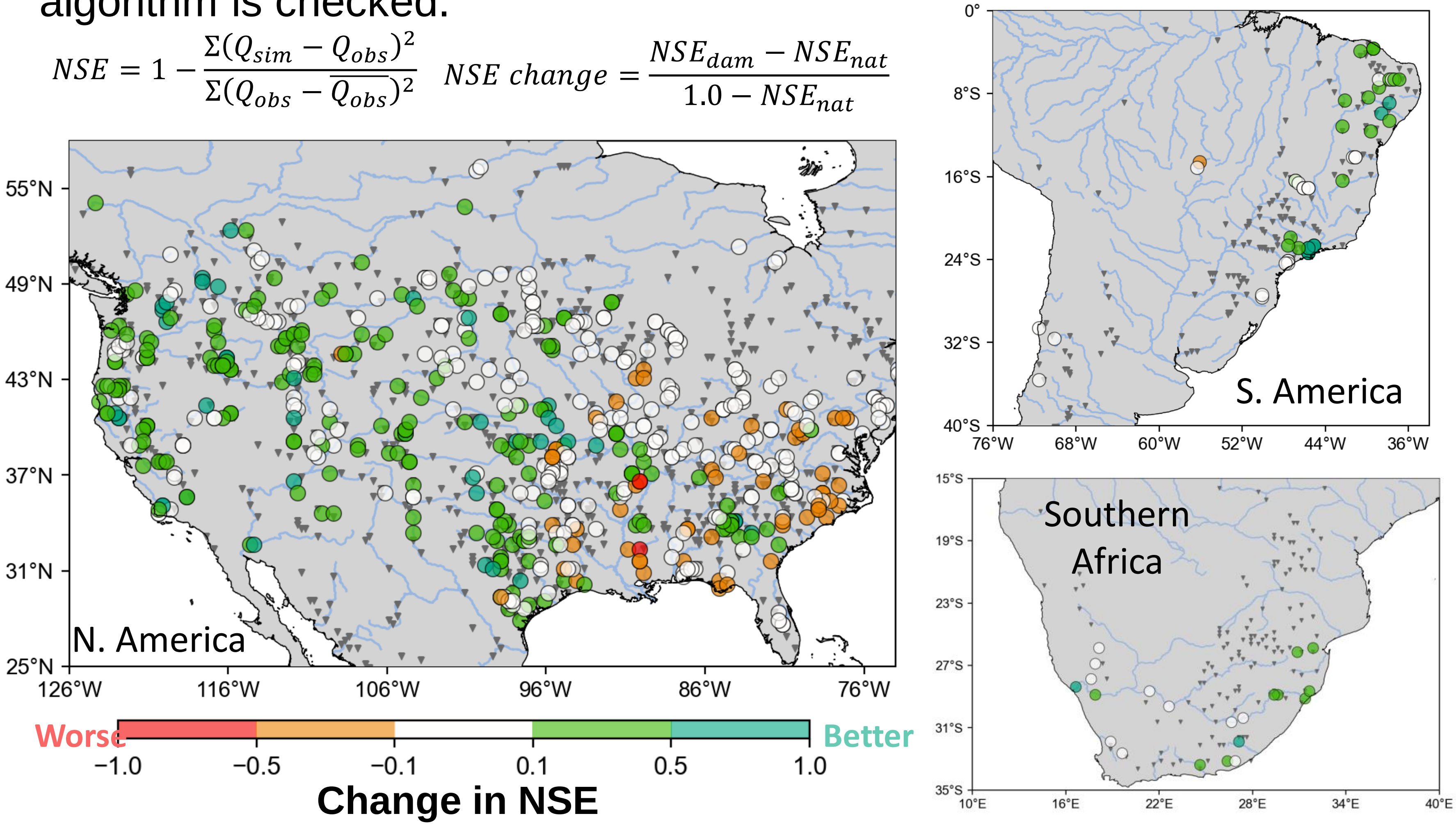
Distribution of FSC ratio at 6862 dams [%]

Improved accuracy of FSC estimation by utilizing time-series of observed reservoir surface area that reflects the impact of actual dam operations

Reproducibility of river discharge at downstream of dams

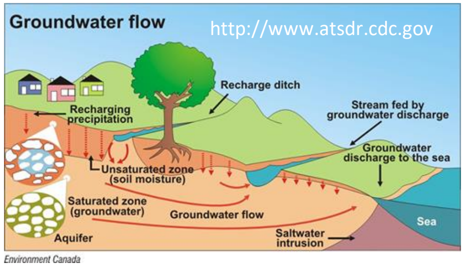
- Change of Nash Sutcriffe Efficiency (NSE) by adding the dam operation algorithm is checked.

$$NSE = 1 - \frac{\Sigma(Q_{sim} - Q_{obs})^2}{\Sigma(Q_{obs} - \overline{Q_{obs}})^2} \quad NSE\ change = \frac{NSE_{dam} - NSE_{nat}}{1.0 - NSE_{nat}}$$



NSE significantly improved at 283 out of 687 discharge sites

Challenges of water management implementation



1. Groundwater process
   - GW is a fundamental hydrological process
   - Availability: Global models on groundwater recharge
     Doll and Fiedler (2008), Wada et al. (2010), Pokhrel et al. (2015)

2. Groundwater abstraction
   - GW accounts for +15% of total water withdrawal
   - Availability: Global models on groundwater abstraction
     Wada et al. (2010), Doll et al. (2014), Pokhrel et al. (2015)

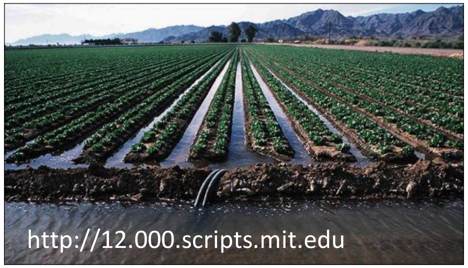
3. **Aqueduct water transfer**
   - River water is transferred at a distance.
   - Availability: Simple models on inter-cell water transfer
     Haddeland et al. (2006)

Courtesy of N. Hanasaki

Challenges of water management implementation

4. Minor reservoirs
   - Not located on the main stems of river network
   - Availability: Some simple treatments
     Hanasaki et al. 2010; Wisser et al. 2010

5. Seawater desalination
   - More than 20km^3/year of production capacity
   - Availability: Stand alone model:
     Hanasaki et al. (2016)

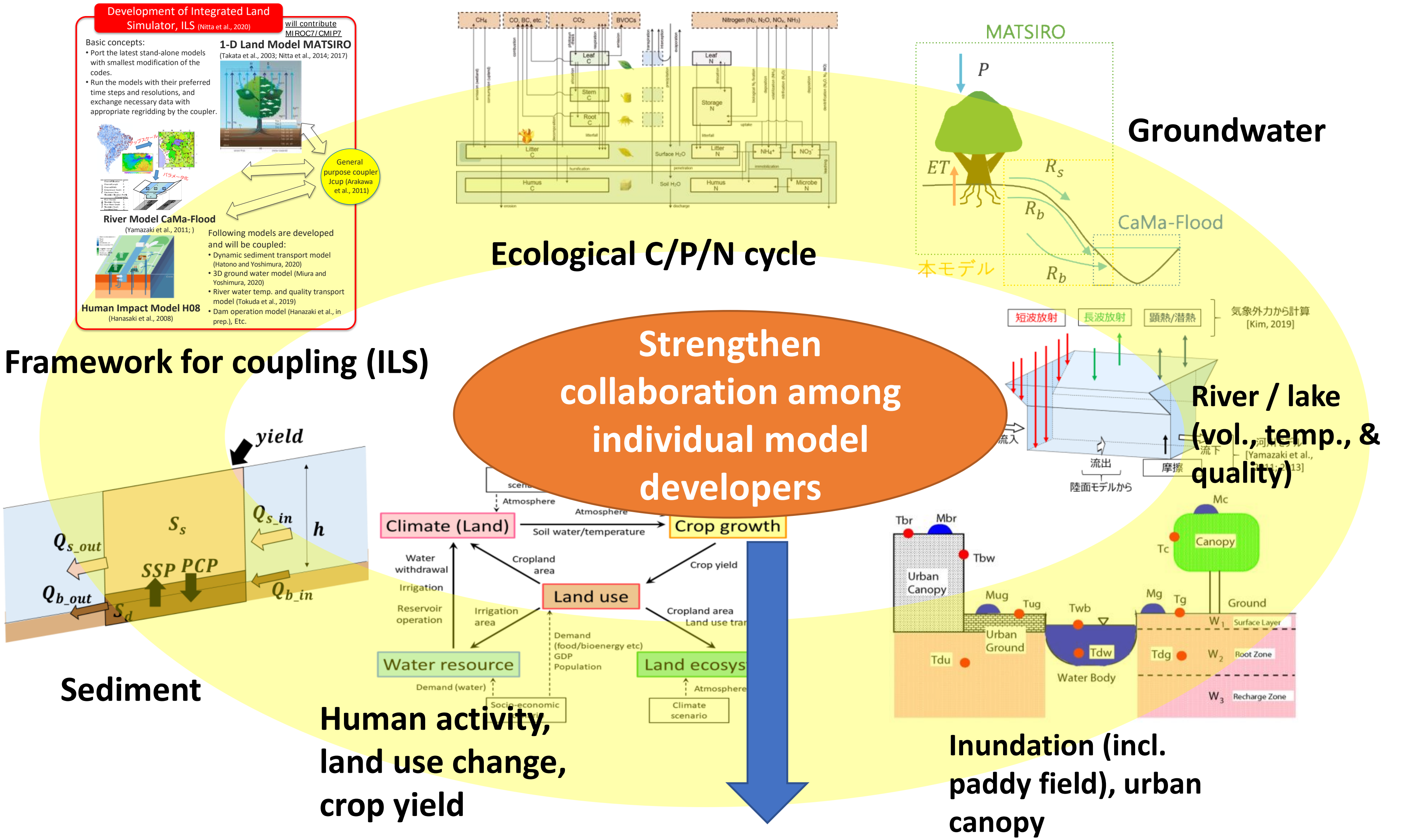


6. Return flow and delivery loss
   - These two exceed water consumption!
   - Availability: Simple models:
     Rost et al. (2008)

7. Maintaining traceability of water sources

Courtesy of N. Hanasaki

Community Effort of Land Model Development



Construction of a platform model consisting of a group of stand-alone models and maintenance of various peripheral softwares incl. regridding and coupling.

Coupling to Weather, Climate, and Earth System Models

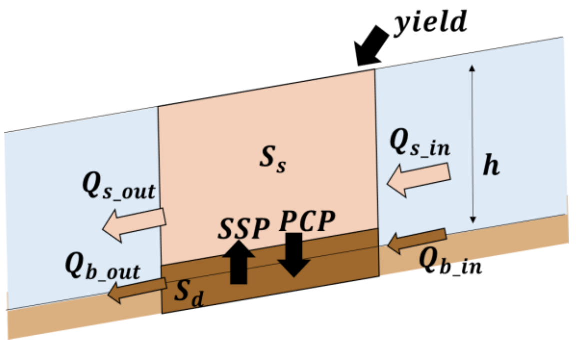
Thank you for listening!

Any comment/question?

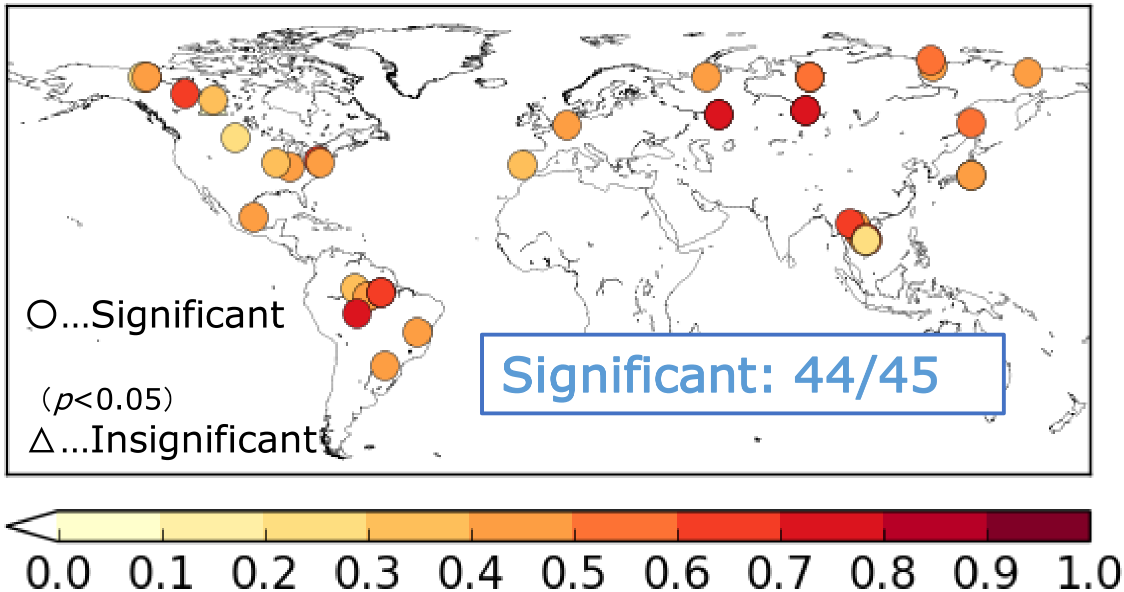
Misako Hatono@Tohoku U.

Sediment dynamics modeling

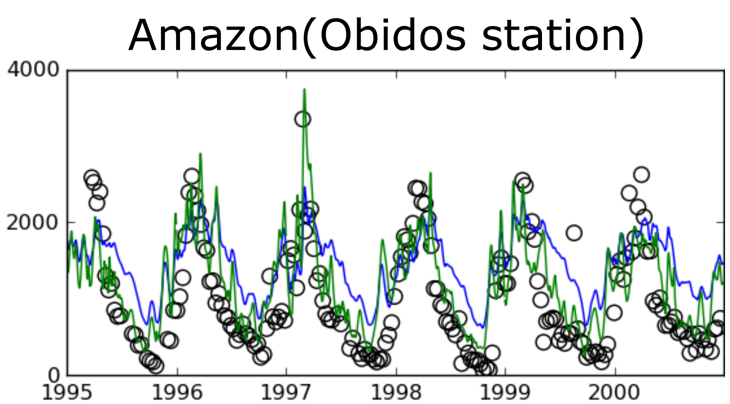
- Incorporated sediment dynamics into CaMa-Flood within the framework of ILS
  - ✓ Considers suspended sediment and bedload
  - ✓ Seasonal variation is well represented. Regional calibration improves accuracy in peak values



Schematic of sediment model



Correlation coefficient of suspended sediment



Suspended sediment[10^3ton/yr]

Obs. CTL Calibrated

Variably Saturated Groundwater Model

Miura and Yoshimura, 2020

Governing equation

$$\frac{\partial\theta(\varphi)}{\partial t}+S_sS_w(\varphi)\frac{\partial\varphi}{\partial t}=\nabla\cdot[K(\varphi)\cdot\nabla(\varphi+Z)]+q$$

One dimensional
S_s ---> 0
q ---> exclude

θ ---> 0
$S_w(\varphi)$---> 1
$h=\varphi+Z$

Richards equation

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial\varphi}{\partial z}+1\right)\right]$$

Groundwater equation

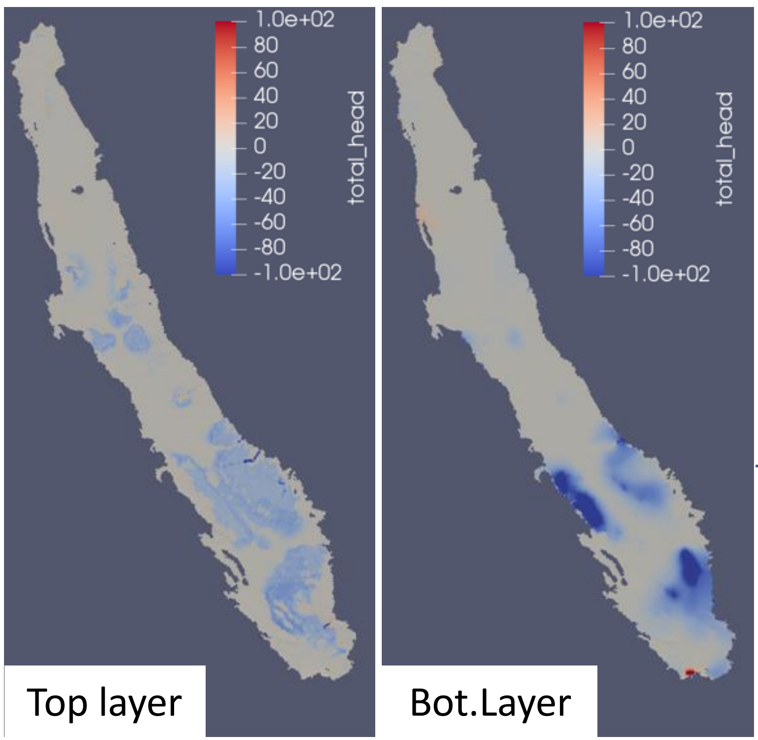
$$S_s\frac{\partial h}{\partial t}=\nabla\cdot[K\cdot\nabla(h)]+q$$

θ : water content
φ : pressure head
S_s: specific storage
S_w: saturation ratio
K : hydraulic conductivity
q : source/sink term

with GW pumping parameterization

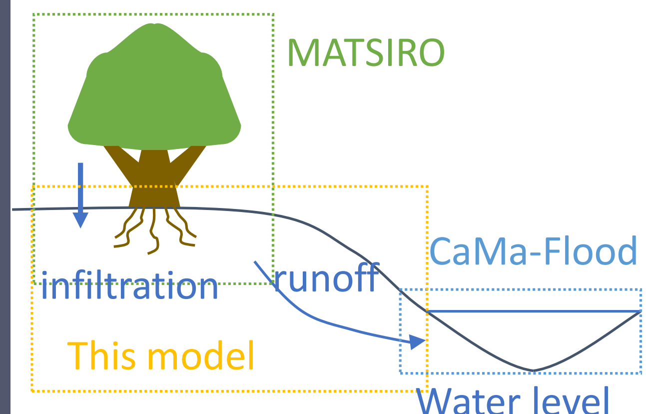
Unknown value	
Primary	Pressure head (φ)
Secondary	Water content (θ) Saturation ratio (S_w)
Primary to Secondary	Water retention (e.g. Van Genuchten model)

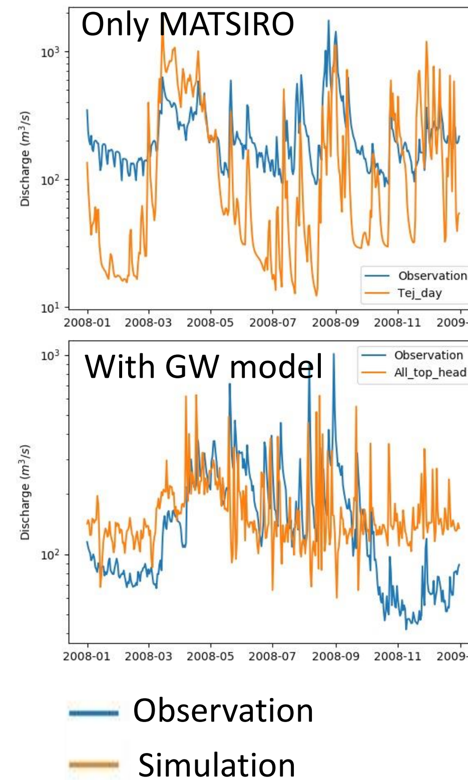
Model output
Groundwater level (Hydraulic head) Groundwater table
Flow velocity
Water balance



GW table drop after 100 years

Modulate this model in ILS and coupled with MATSIRO and CaMa-Flood.





➔ Better reproducibility in low flow.

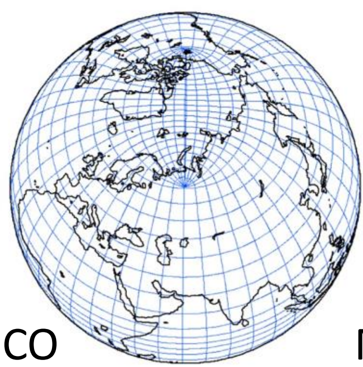
http://hydro.iis.u-tokyo.ac.jp/~akira/page/Works/contents/SPRING/

Courtesy of A. Takeshima

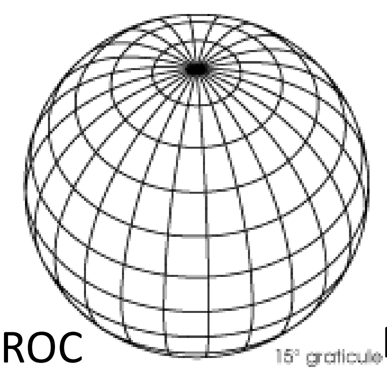
Development of a regridding tool SPRING

- Correspondence table of lattices used to exchange physical quantities between models of different lattice systems
- Distributes physical quantities according to the percentage of overlapped area between lattices
- Used not only for exchanging variables between models via JCup, but also for making boundary conditions, etc, by changing resolution (upscaling).

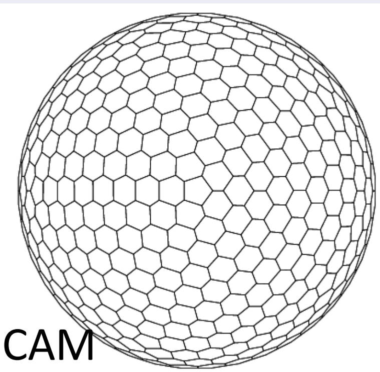
	Model	Coordinate	Grid # (lat*lon)
Ocn	COCO [Hasumi et al., 2000]	Tri-polar grid	256*360
Atm	MIROC [Watanabe et al., 2011] NICAM [Satoh et al., 2008]	T85 Pentagon/Hexagon	128*256 32*32*10
Lnd	MATSIRO [Takata et al., 2003]	0.5˚*0.5˚ Rectangle	360*720
Riv	CaMa-Flood [Yamazaki et al., 2011]	Unique grid	360*720



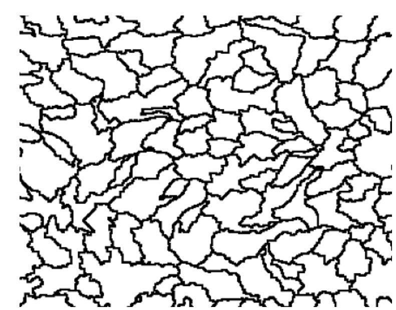
COCO



MIROC



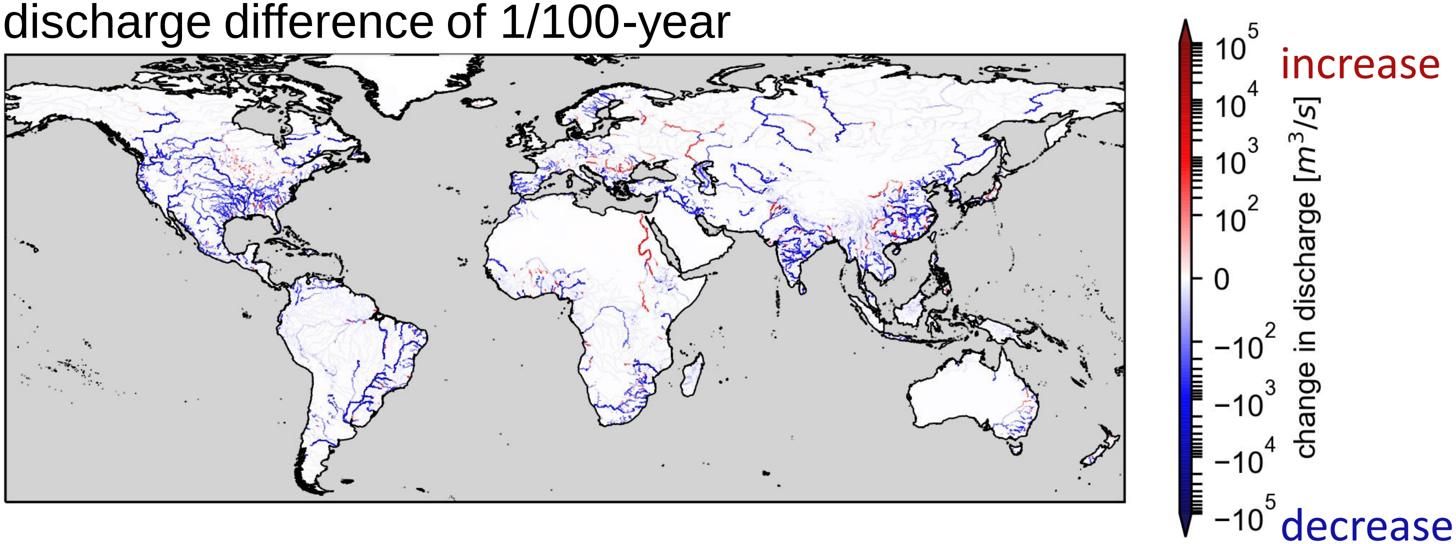
NICAM



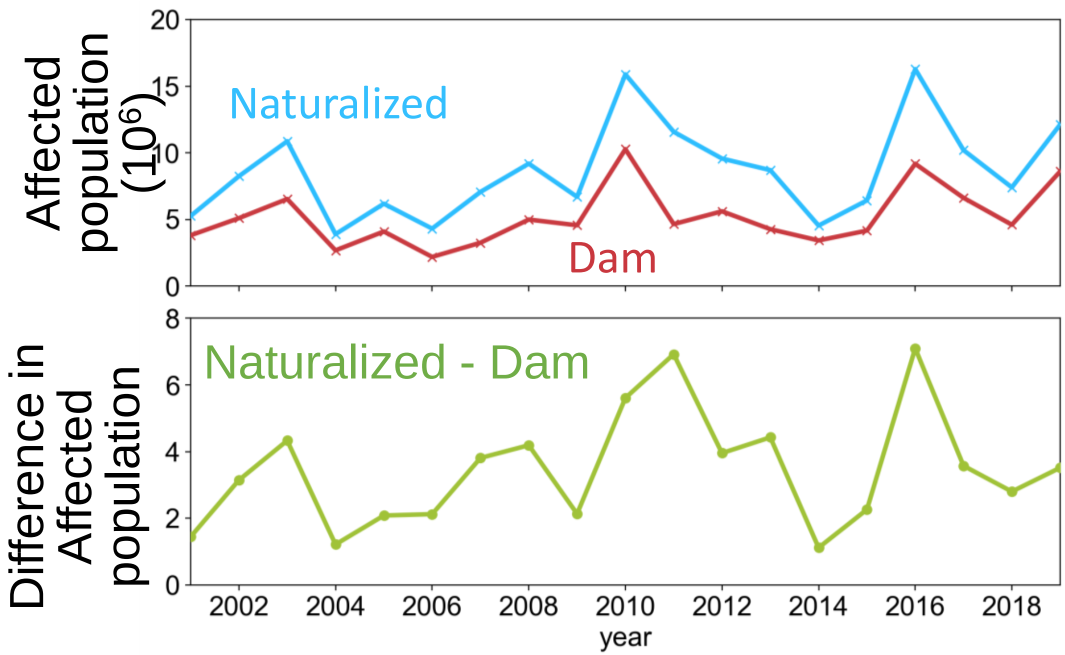
CaMa-Flood

Impact of the New Dam Operation on Flood Damage

discharge difference of 1/100-year



Affected population by 1/100-year Floods

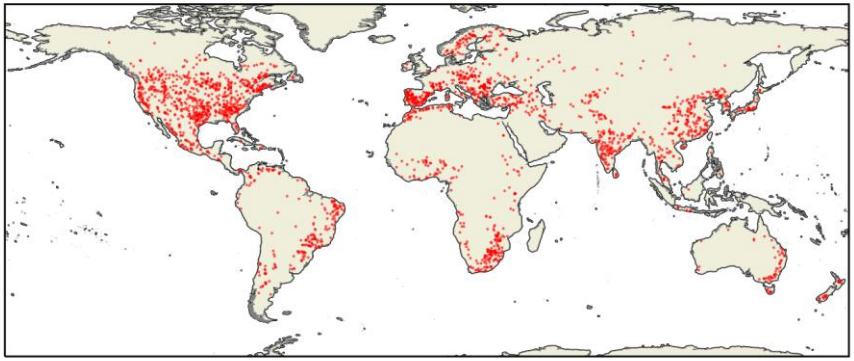


Affected population estimation method: Boulange et al. (2021)

By implemented dam operation, extreme discharge was dropped, and affected numbers of people were significantly decreased.

Estimation of necessary parameters for dams

- 2169 dams are identified in the river routing map.
  - Global Reservoir and Dam is used (Lehner et al., 2011)
  - Catchment area >1000km^2
  - 1/4 degree gridding



- For those dams, these parameters are estimated by using available datasets and validated in Japan / US where the parameters are explicitly open public.

Parameters	Japan	Global
Vmax, Vf, Ve, Vc	Given	Next Page
flood discharge Q_f	Given	$Q_{100} \times 0.3$ (Q_{100} : 1/100year discharge)
normal discharge Q_n	Given	Climatological Averaged Discharge
Release coefficient k	Given	$\max\left(1 - \frac{V_e - V_f}{A} \times \frac{1}{0.2}, 0\right)$

Previous research

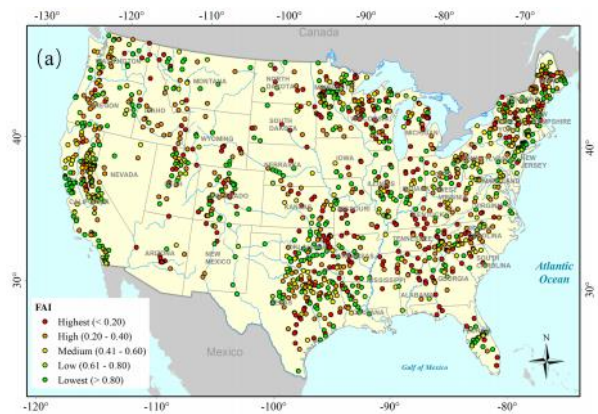
- Many studies have been done to implement reservoir operation into large scale models (ex. Hanasaki et al., 2008; Wisser et al., 2010)
  - Recent studies assessed the impact on floods (Zajac et al., 2017; Rouge et al, 2019; Gutenson et al., 2019; Fleischmann et al., 2019)

1. Uncertainty in modeling reservoir operation (Zajac et al., 2017)

Limited information & variability in reservoir operation

→Generalized approach to estimate reservoir outflow is required

Reservoir parameters have a pronounced effect (Zajac et al., 2017)
ex. conservative / flood control storage capacity,
normal / non-damaging outflow



Peak outflow / peak inflow at dams

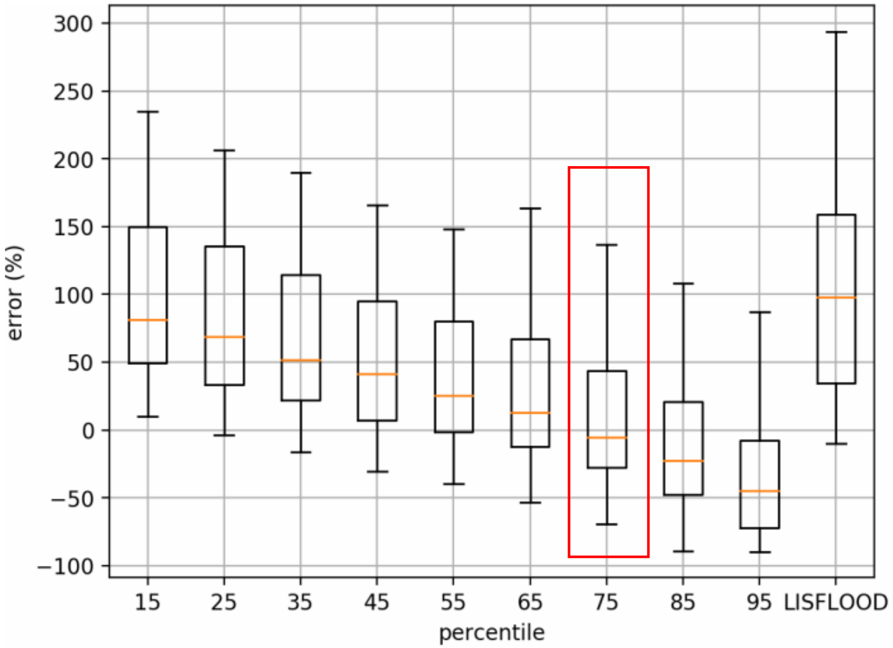
However, there is still no consensus on the best approach (Gutenson et al., 2019)

2. Few studies are globally applicable & able to simulate detailed hydrodynamics

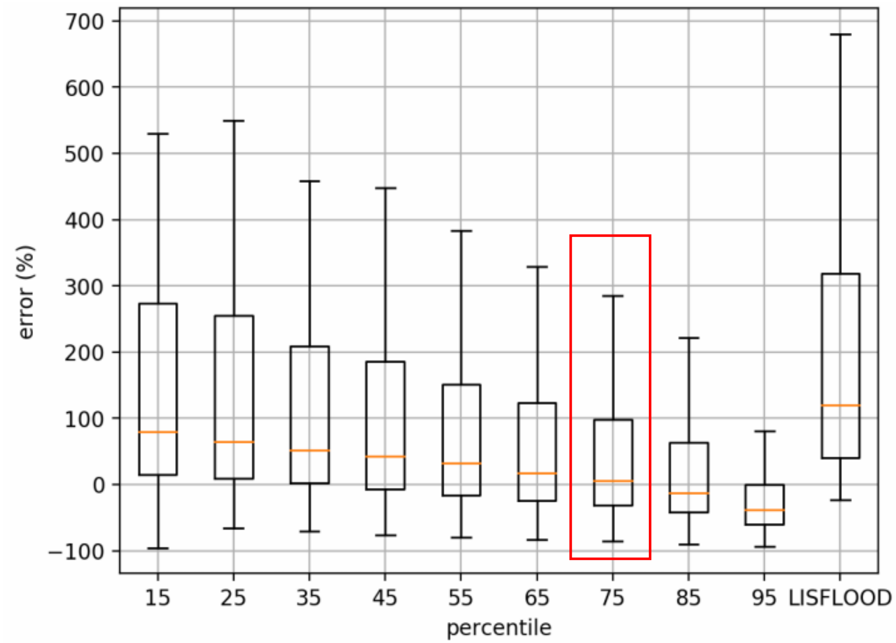
- Large scale, but river routing without detailed hydrodynamics (ex. Zajac et al., 2017)
- River models with backwater effect, but not applicable globally (Mateo et al., 2014) or not focused on flood control (Shin et al., 2019)

Estimation of flood storage capacity

- Validation of flood storage capacity
  - Validation and comparison with Zajac et al., 2013 (LISFLOOD) method



Error in flood storage capacity of **30 reservoirs in Japan**



Error in flood storage capacity of **181 reservoirs in US**

✓ **Flood storage capacity is estimated better** both in Japan and US than Zajac method

✓ Assuming **75 percentile** of GRSAD as conservative storage is the best

Experiment setting & validation data

- Experiment setting
  - Simulation period: 2001~2019
  - Spatial resolution: 0.25degree
  - Runoff forcing: ERA5-Land (0.1degree)
  - Initial condition
    - Initial value of reservoir storage is normal storage

- Validation data
  - River discharge (687 gauges)
    - GRDC
    - Data from Hylkebeck
    - Japan
  - Reservoir inflow, outflow, storage
    - Downloaded from reservoir managers' website in US
    - SWAT Plus database (only outflow in US)

History of Japanese projects on climate change and its prediction