

Water: Macro-scale process-based modeling of water

Steve Frolking
Richard B. Lammers
Danielle Grogan



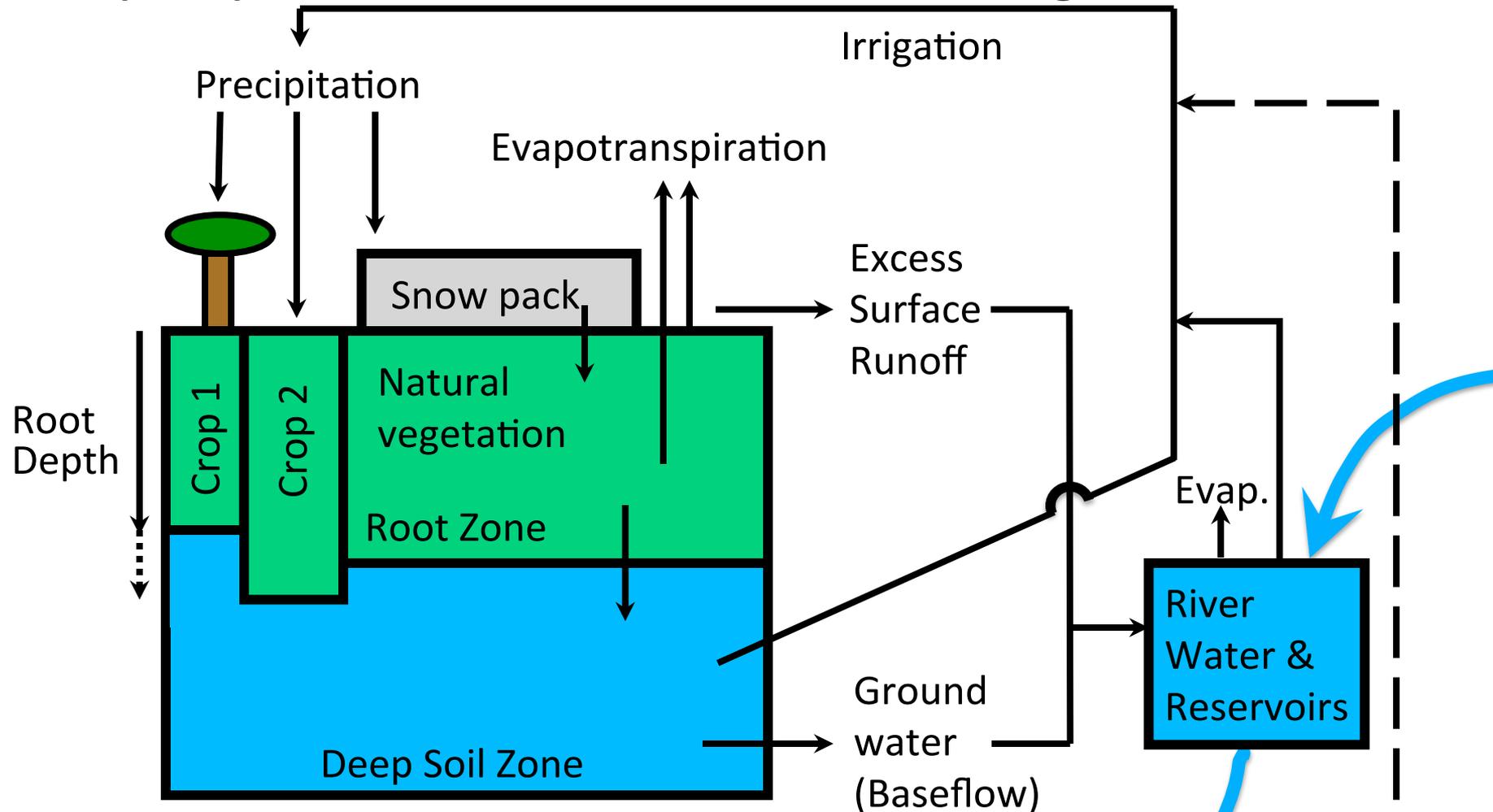
Water Systems Analysis Group
Earth Systems Research Center
University of New Hampshire
Durham, NH, USA

OUTLINE

1. Framework & methods
2. Context & questions
3. Some Outcomes
4. Relevance to IAMs

1. Framework & methods

(UNH) Water Balance Model Structure - Single Grid Cell



Irrigation: 31 crops/land cover (sub-grid fractions modeled separately)

Water Transport Model (WTM)

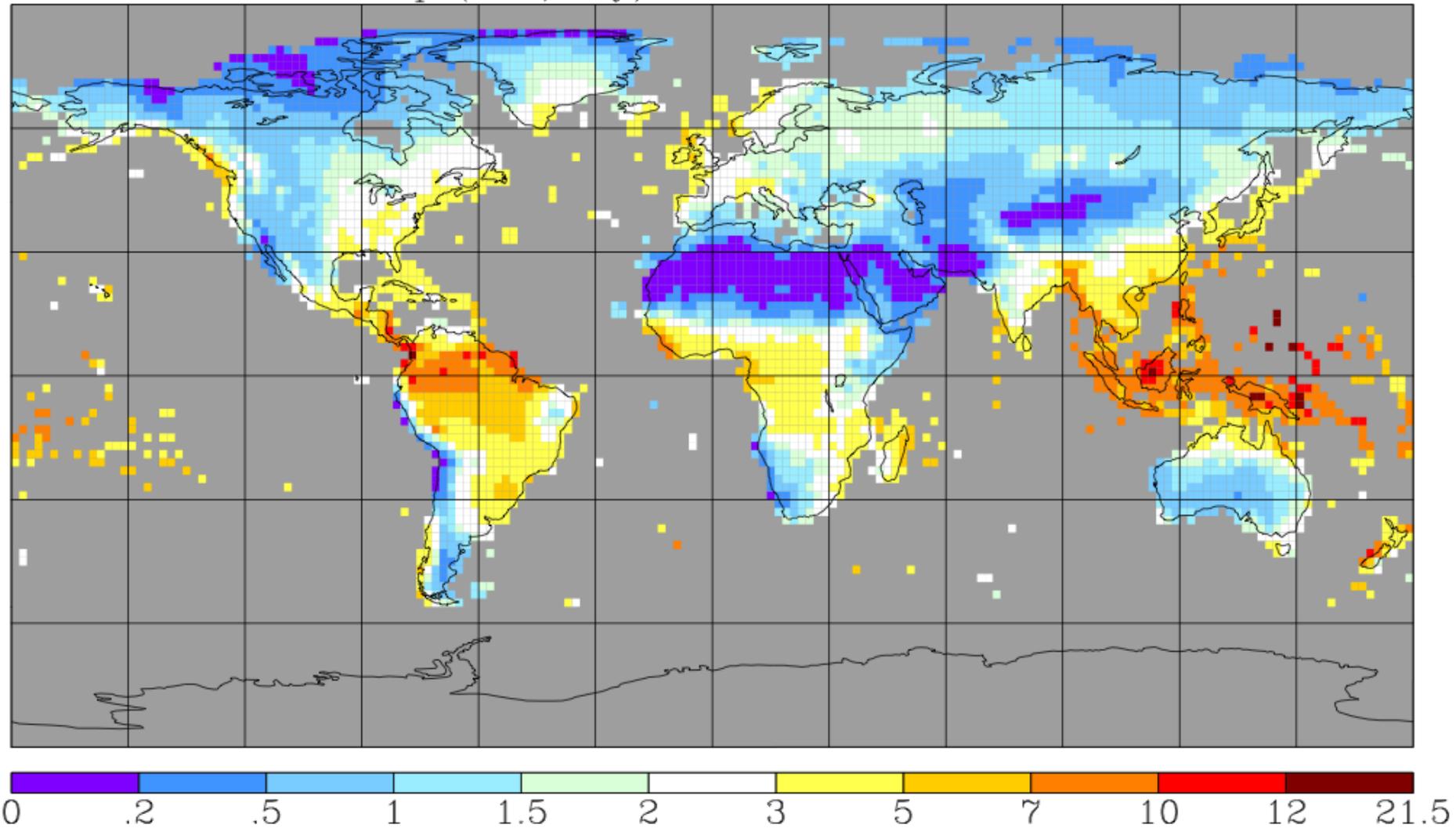
Unsustainable Irrigation (Fossil ground water)

1. Framework & methods

Precipitation Data (CRU TS 2.0)

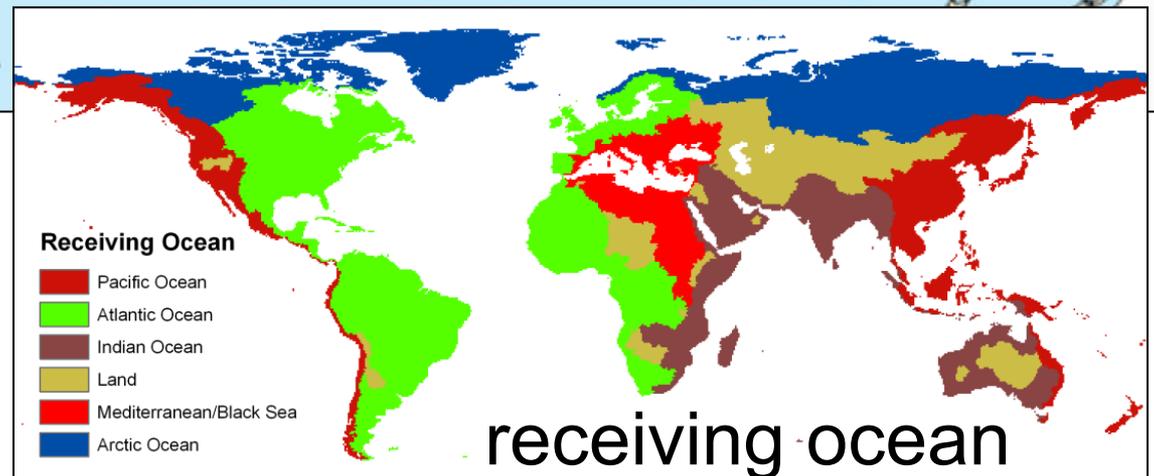
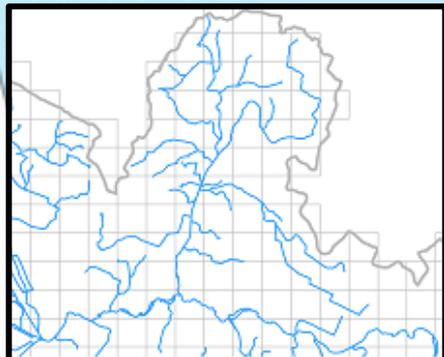
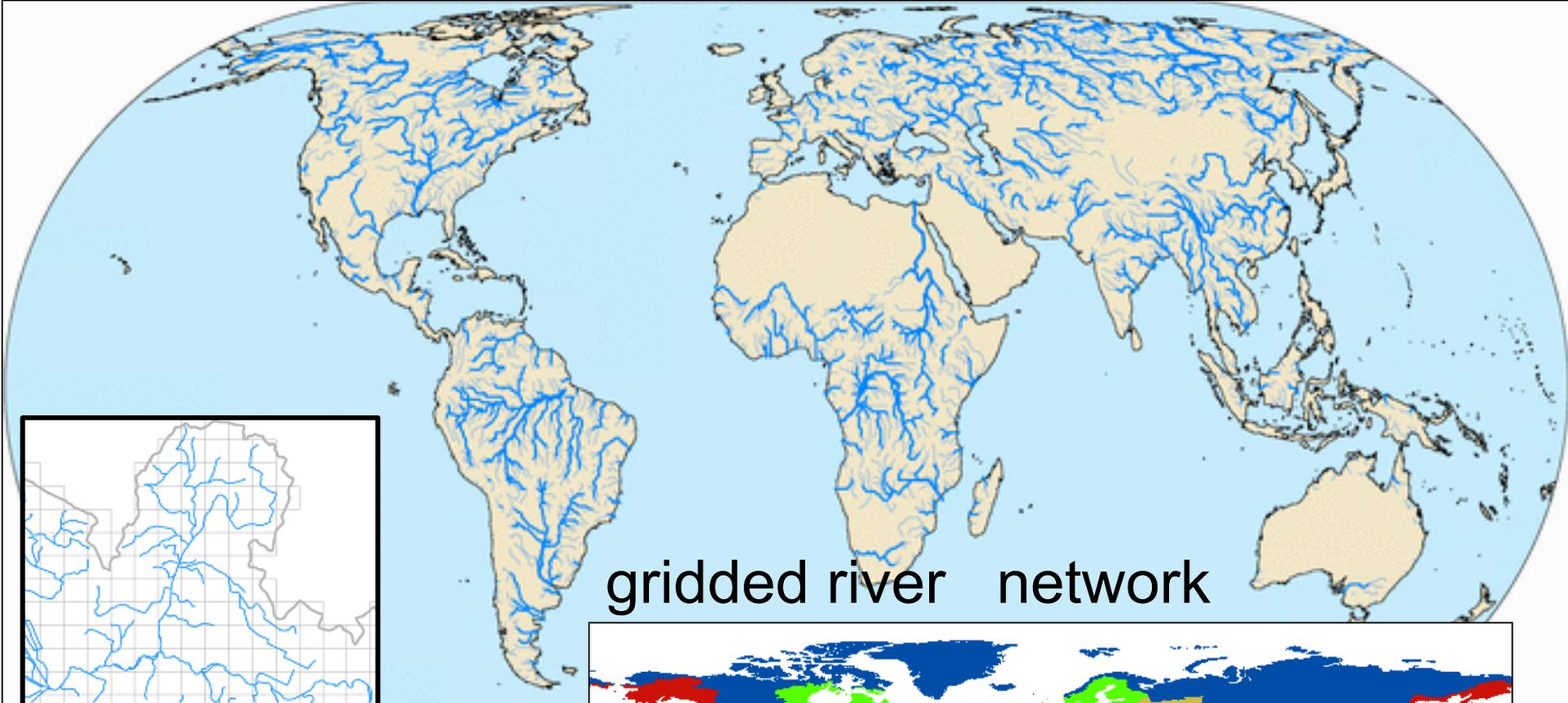
Ann 2000 Mean Precip (mm/day)

2.68



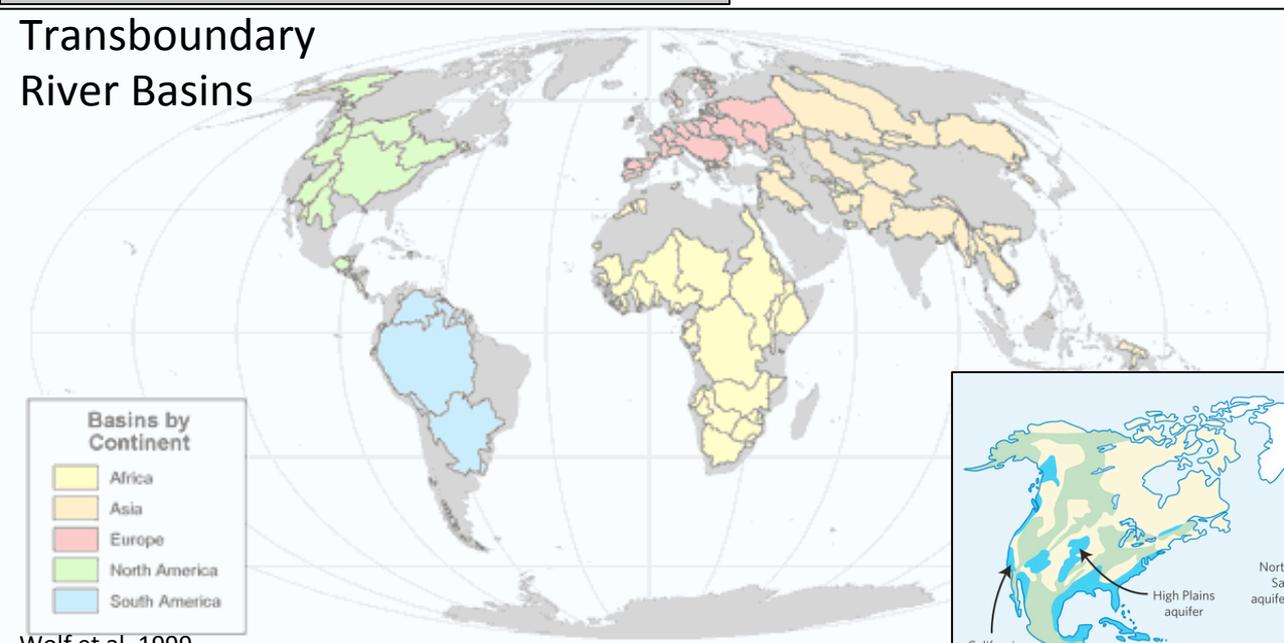
1. Framework & methods

Horizontal Water Transport



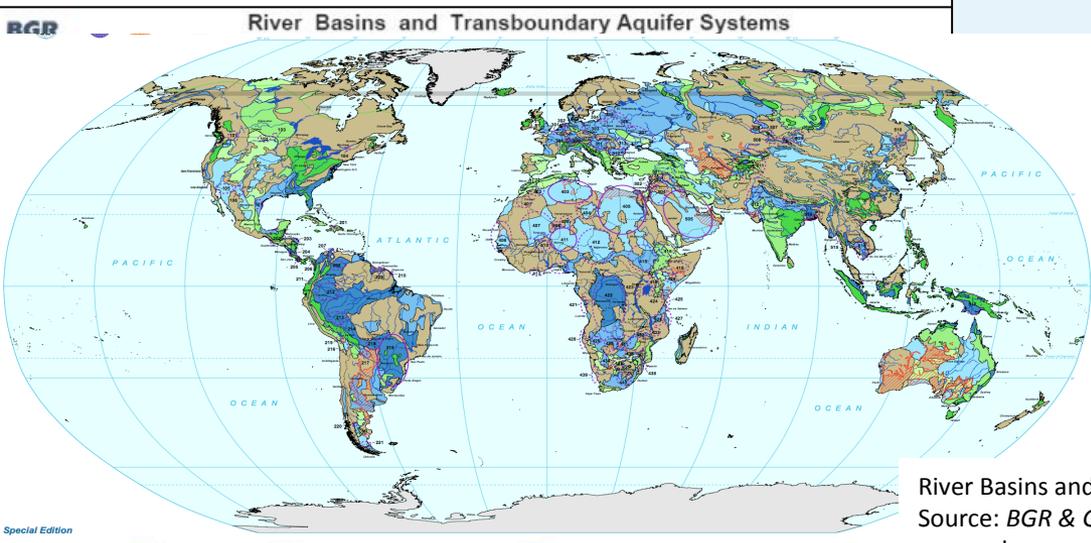
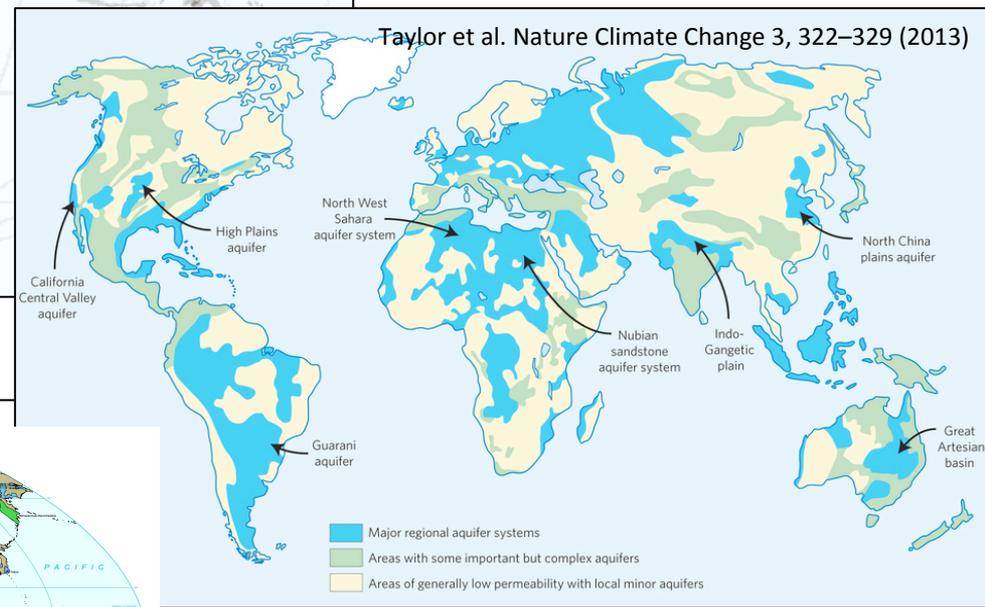
1. Framework & methods

Transboundary River Basins



Wolf et al. 1999
transboundarywaters.orst.edu/publications/atlas/atlas_html/interagree.html

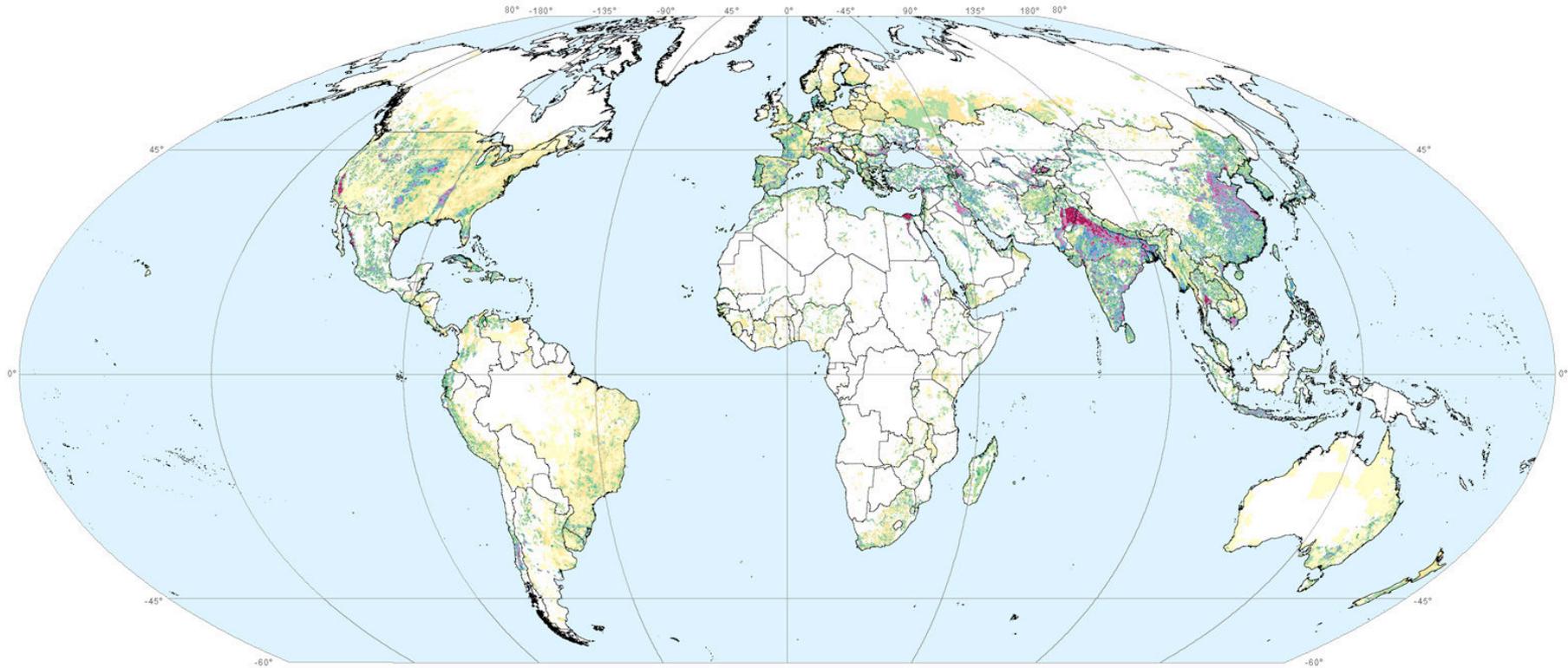
Global Aquifers (simplified)



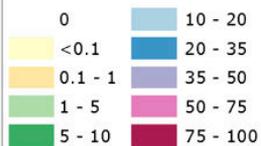
River Basins and Transboundary Aquifer Systems
 Source: BGR & GRDC
www.whymap.org/whymap/EN/Downloads/Global_maps/globalmaps_node_en.html

1. Framework & methods

The digital global map of irrigation areas February, 2007



**Area under irrigation in
percentage of land area**



The map depicts the area equipped for irrigation in percentage of cell area.
For the majority of countries the base year of statistics is in the period 1997 - 2002.

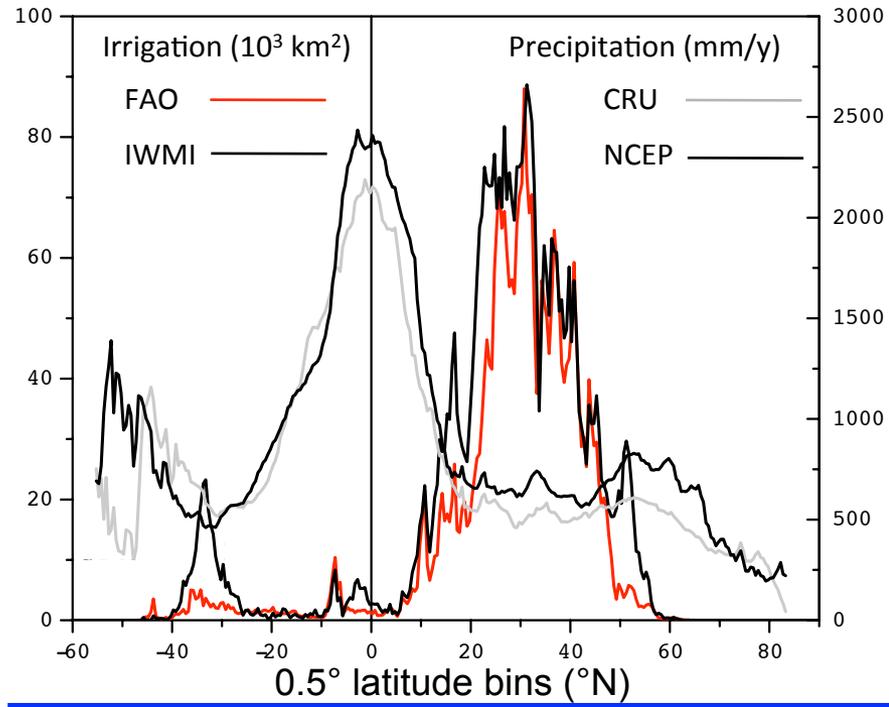
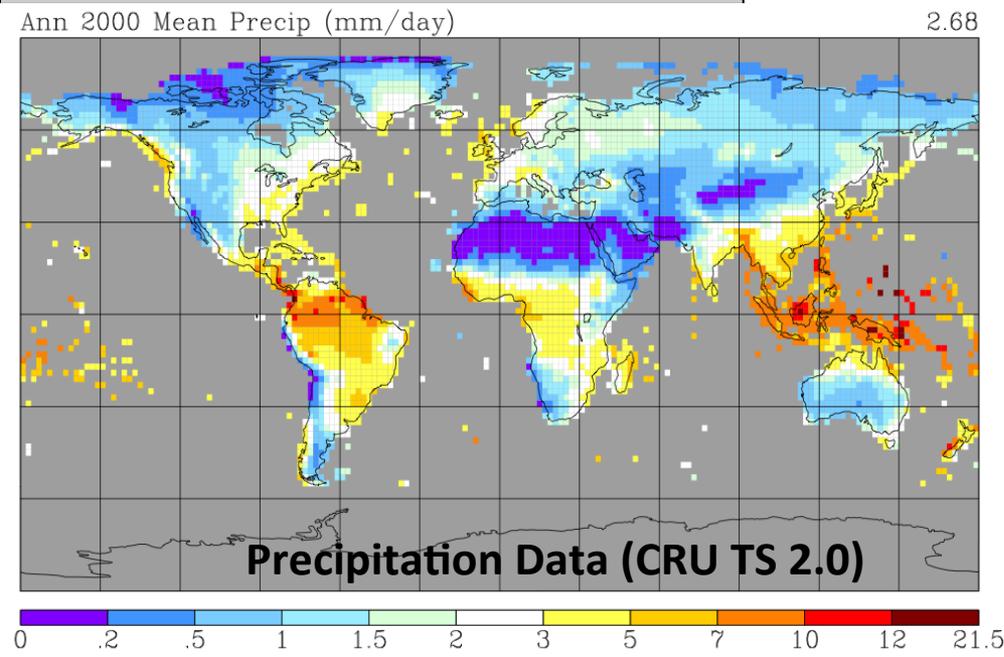
Projection: Mollweide

<http://www.fao.org/ag/agl/aglw/aquastat/irrigationmap/index.stm>

Stefan Siebert, Petra Döll, Sebastian Feick (Institute of Physical Geography, University of Frankfurt/M., Germany) and
Jippe Hoogeveen, Karen Frenken (Land and Water Development Division, Food and Agriculture Organization of the United Nations, Rome, Italy)

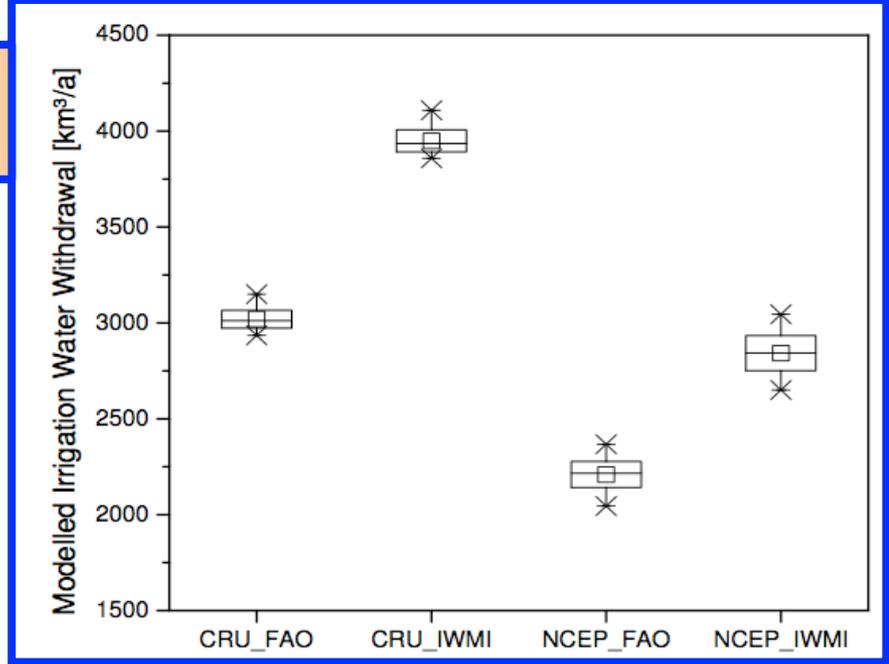
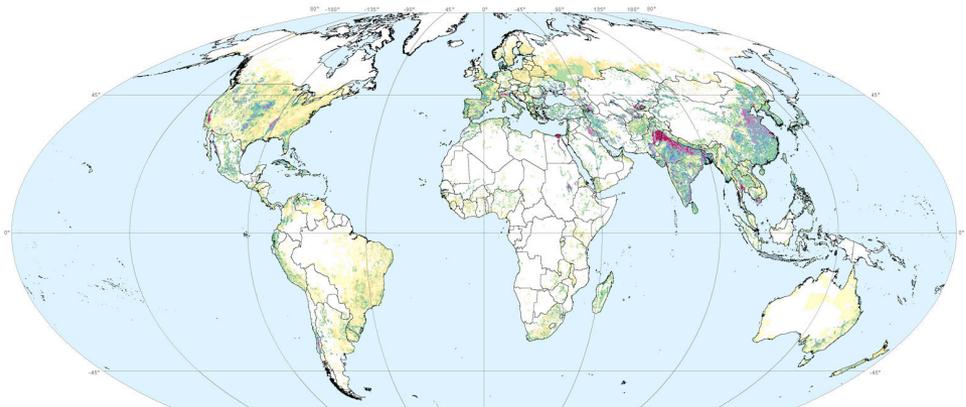


1. Framework & methods



variation in 2 input datasets led to $\sim 2000 \text{ km}^3/\text{y}$ range in modeled demand for irrigation water.

The digital global map of irrigation areas
February, 2007



1. Framework & methods

Small



- Supply ~40% of irrigated areas in India.
- Increasingly considered an important option to increase food security.
- Store local runoff: capacity ~1000 m³.
- Irrigated area: 5-50 ha.

Wisser et al. 2010.
J. Hydrology

Reservoirs

Large

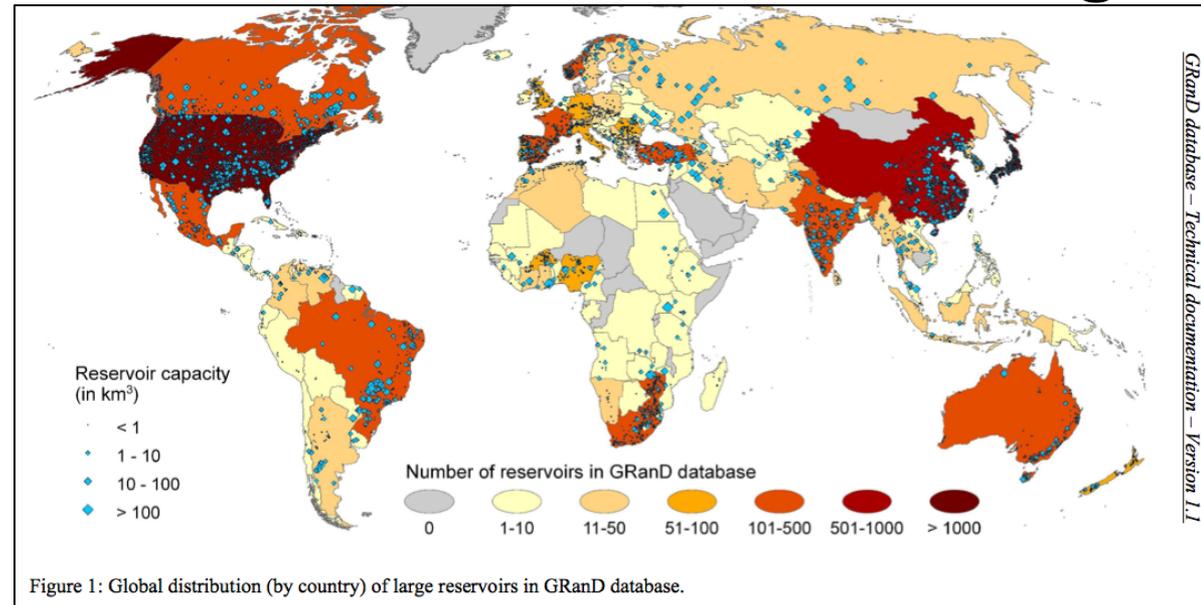
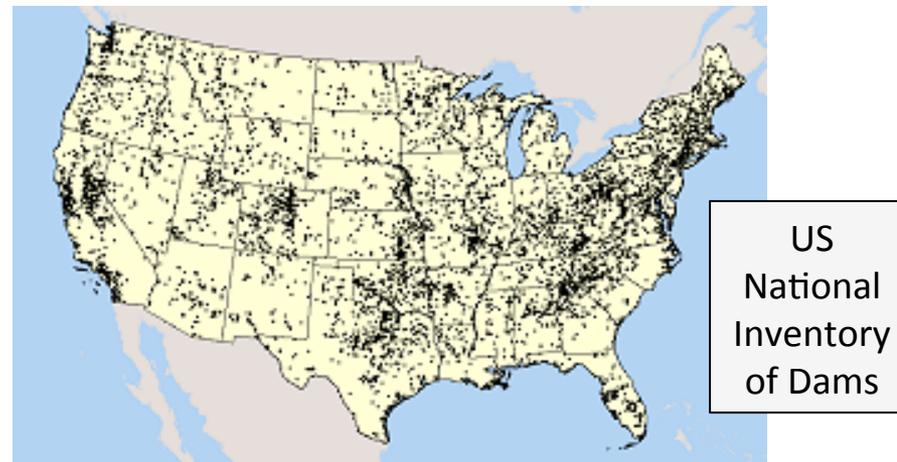


Figure 1: Global distribution (by country) of large reservoirs in GRanD database.

Large dam/reservoir database (GRanD; Lehner et al. 2011; $n \sim 6500$)
hydropower; flood control; irrigation; navigation
<http://www.gwsp.org/85.html>

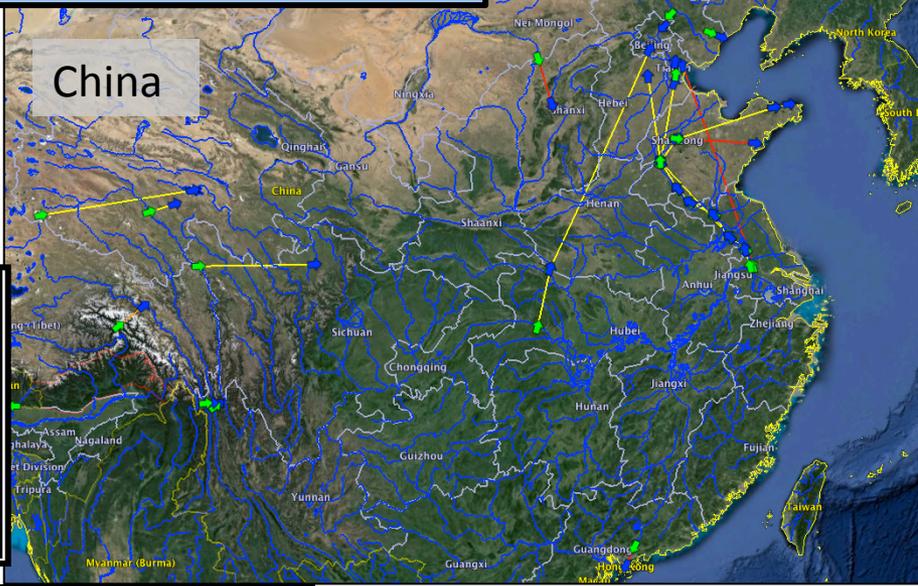


1. Framework & methods

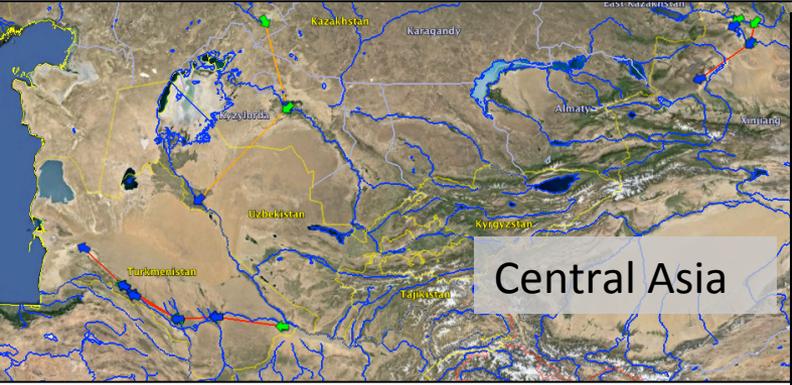
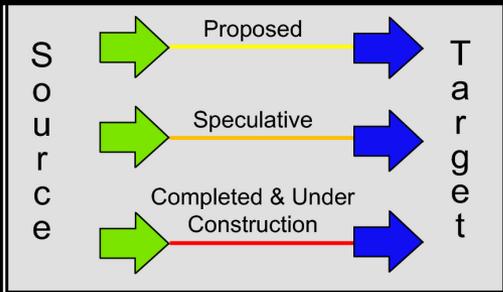
Inter-basin water transfers



North America

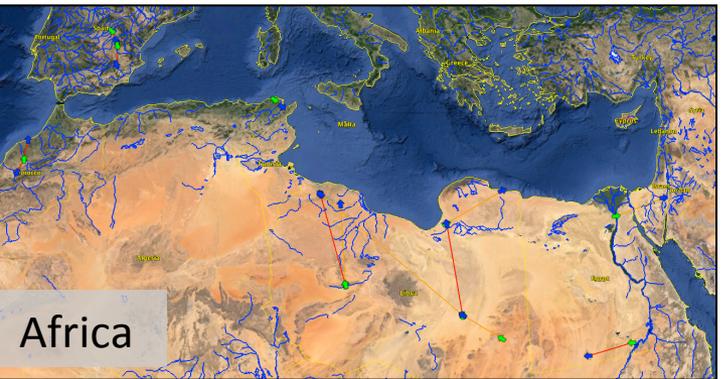


China



Central Asia

Continent	Count
Africa	13
Australia	3
Eurasia	80
North America	57
South America	11
Total	164



Africa

Status	Count
Completed	65
Under Construction	5
Proposed	21
Speculative	73
Total	164



South Asia

R Lammers (UNH) ms in prep.

2. Context & Questions

UNEP G-GRID ARENDAL CICERO Center for Klimaforskning Center for International Climate and Environmental Research - Oslo ICIMOD

HICIA FEASIBILITY STUDY 2007-2010 AND PROGRAMME 2011-2015

TOO MUCH TOO LITTLE WATER

ADAPTATION TO CLIMATE CHANGE IN THE HINDU KUSH HIMALAYAS AND CENTRAL ASIA

FAC WATER REPORTS 36

Climate change, water and food security

Irrawaddy Delta, Myanmar

Ice, Snow and Water: Impacts of Climate Change on California and Himalayan Asia

Workshop Report May 4 - 6, 2009 La Jolla, California

UC San Diego Sustainability Solutions Institute

UNEP - GRID

The fall of the water

Emerging threats to the water resources and biodiversity at the roof of the world to Asia's lowland from land-use changes associated with large-scale settlement and piecemeal development

Asia Society

Asia's Next Challenge: Securing the Region's Water Future

A report by the Leadership Group on Water Security in Asia

2. Context & Questions

March 4, 2014 | vol. 111 | no. 9 | 3197-3646

PNAS

Proceedings of the National Academy of Sciences of the United States of America www.pnas.org



The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP): Project framework

Lila Warszawski, Katja Frieler¹, Veronika Huber, Franziska Piontek, Olivia Serdeczny, and Jacob Schewe
Potsdam Institute for Climate Impact Research, 14412 Potsdam, Germany

Table 1. Participating impact models

Model (source)	Sector
LPJmL (15, 16)	Water/agriculture/ biomes
JULES (17, 18)	Water/biomes
VIC (19)	Water
H08 (20)	
WaterGAP (21)	
MacPDM.09 (22)	
WBM (23)	
MPI-HM (24)	
PCR-GLOBWB (25)	
MATSIRO (26)	
DBH (27)	
ORCHIDEE (28)	Biomes
Hybrid4 (29)	
SDGVM (30)	
JeDi (31)	
VISIT (32)	

Table 1. Participating impact models

Model (source)	Sector
VISIT (32)	
GEPIC (33)	Agriculture
EPIC (34)	
pDSSAT (35)	
PEGASUS (36)	
GAEZ-IMAGE (37)	
LPJ-GUESS (38)	
MARA (39)	Health (malaria)
Umea statistical model (40)	
LMM 205 (41)	
MIASMA (42)	
VECTRI (43)	
DIVA (44)	Coastal infrastructure
AIM (45)	(Agro-) economic effects
ENVISAGE (46)	
EPPA (47)	
GTEM (48)	
FARM (49)	
MAGNET (50)	
GCAM (51)	
GLOBIOM (51)	
IMPACT (53)	
MAGPIE (54)	

8 related research articles

2. Context & Questions

Are people more interested in how much water they will have in the next rainy season, or in predictions for 2100?

Response of snow-dependent hydrologic extremes to continued global warming

nature climate change

LETTERS

PUBLISHED ONLINE: 11 NOVEMBER 2012 | DOI:10.1038/NCLIMATE1732

Noah S. Diffenbaugh^{1*}, Martin Scherer¹ and Moetasim Ashfaq²

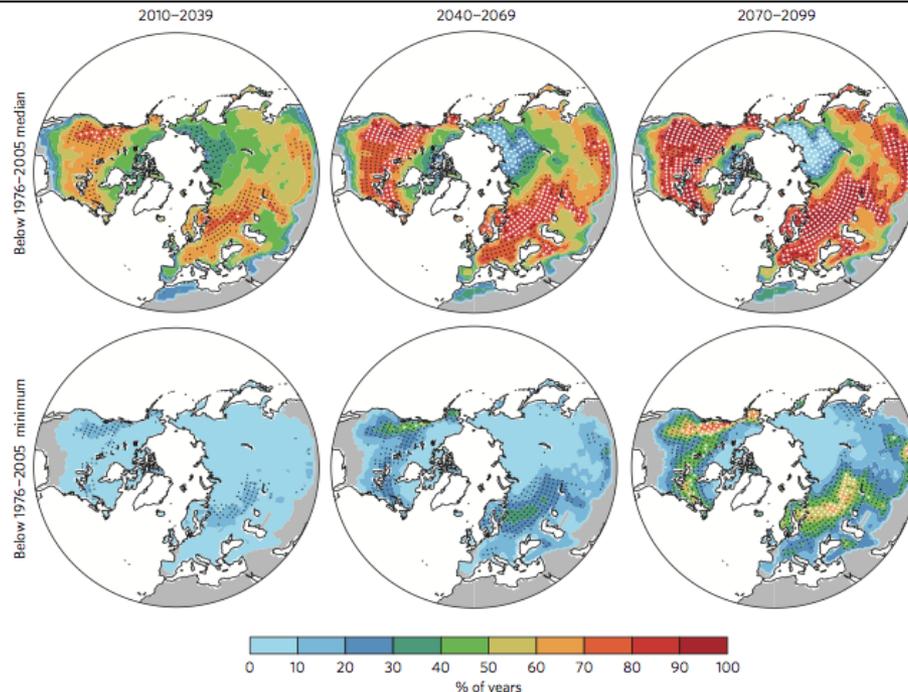


Figure 2 | Emergence of low and extremely low snow years in the twenty-first century. Percentage of years with accumulated March SWE below the simulated 1976–2005 median (top) or minimum (bottom) in three periods of RCP 8.5 (56 realizations from 26 models; Supplementary Table S1). Following ref. 21, stippling indicates areas where the magnitude of the multi-model ensemble mean occurrence divided by the multi-model standard deviation of occurrence exceeds 1.0 (black symbols) or 2.0 (white symbols). Grey denotes areas where at least half of the realizations have a median (top) or minimum (bottom) March SWE of zero in the 1976–2005 period.

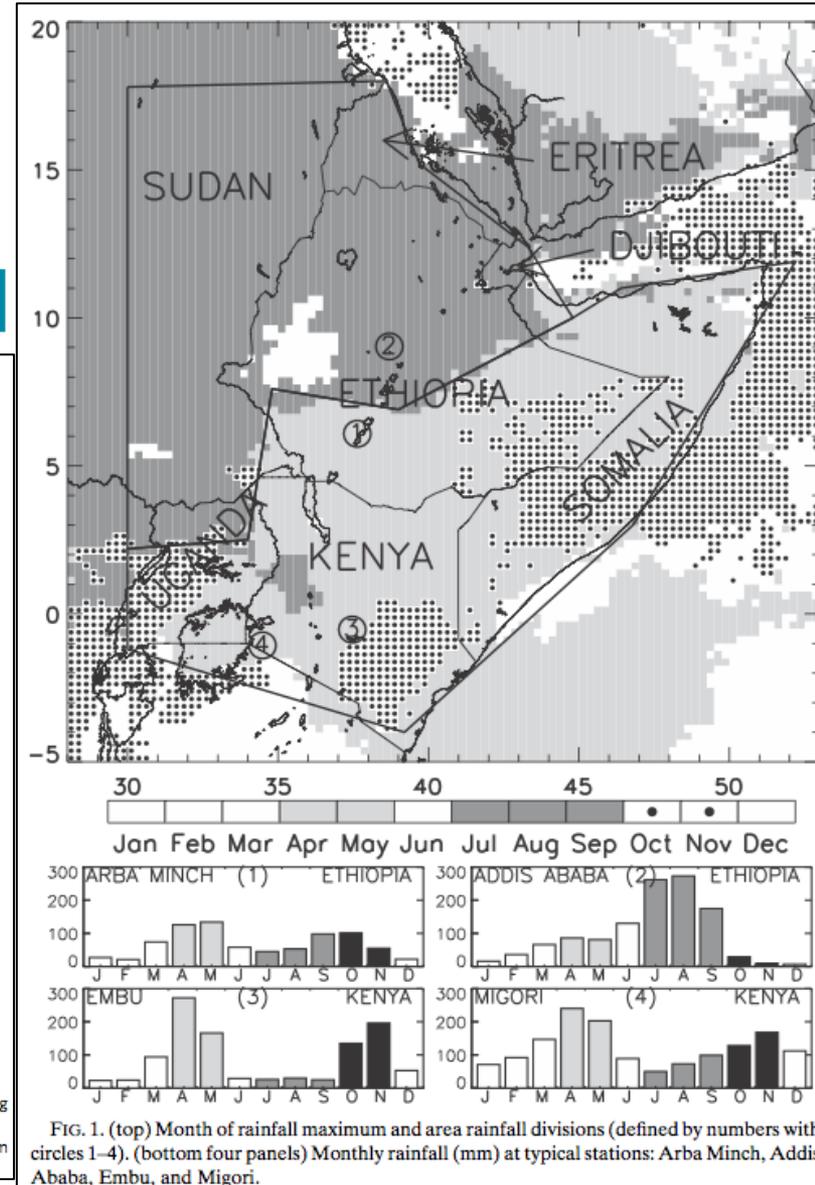


FIG. 1. (top) Month of rainfall maximum and area rainfall divisions (defined by numbers with circles 1–4). (bottom four panels) Monthly rainfall (mm) at typical stations: Arba Minch, Addis Ababa, Embu, and Migori.

2. Context & Questions

WATER RESOURCES RESEARCH, VOL. 47, W05301, doi:10.1029/2010WR010090, 2011

Hyperresolution global land surface modeling: Meeting a grand challenge for monitoring Earth's terrestrial water

Eric F. Wood,¹ Joshua K. Roundy,¹ Tara J. Troy,¹ L. P. H. van Beek,² Marc F. P. Bierkens,^{2,3} Eleanor Blyth,⁴ Ad de Roo,⁵ Petra Döll,⁶ Mike Ek,⁷ James Famiglietti,⁸ David Gochis,⁹ Nick van de Giesen,¹⁰ Paul Houser,¹¹ Peter R. Jaffé,¹ Stefan Kollet,¹² Bernhard Lehner,¹³ Dennis P. Lettenmaier,¹⁴ Christa Peters-Lidard,¹⁵ Murugesu Sivapalan,¹⁶ Justin Sheffield,¹ Andrew Wade,¹⁷ and Paul Whitehead¹⁸

The never-ending quest for higher spatial resolution.

i.e., global 1-km modeling

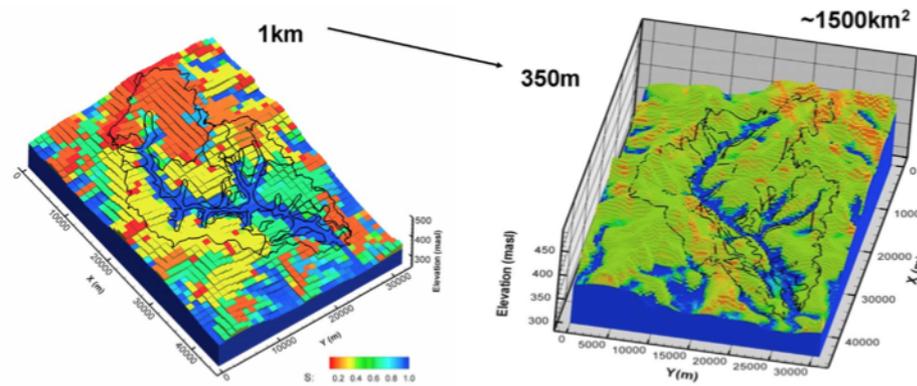


Figure 1. Higher-resolution modeling leads to better spatial representation of saturated and nonsaturated areas, with implications for runoff generation, biogeochemical cycling, and land-atmosphere interactions. Soil moisture simulations on the Little Washita showing the impact that the resolution has on its estimation

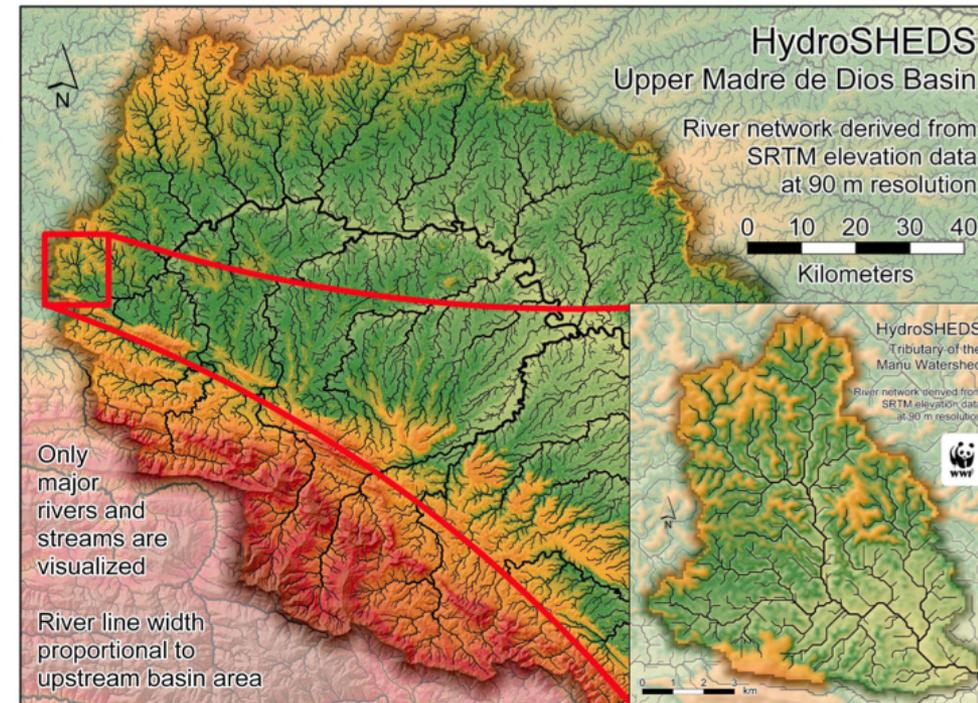
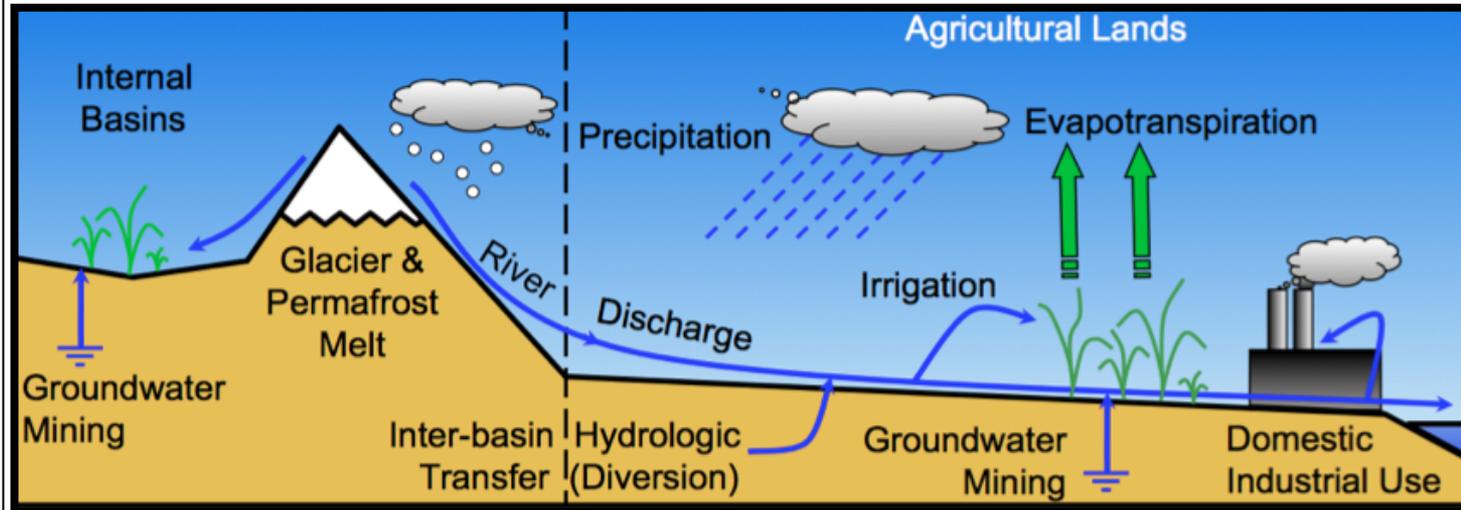


Figure 3. HydroSHEDS, an example of a global data set that will be needed for a hyperresolution hydrologic model. The data set consists of elevation, stream networks, watershed boundaries, drainage directions, and ancillary data layers such as flow accumulations, distances, and river topology at various resolutions from approximately 90 m to 10 km and is based on data from NASA's Shuttle Radar Topography Mission.

2. Context & Questions

Crops, climate, canals, and the cryosphere in Asia – changing water resources around the earth's third pole

- **Univ. New Hampshire**
Water balance and crop yield modeling
- **Boston University** –
Economic modeling; land use analysis and remote sensing
- **Penn State University**
Economic modeling
- **Univ. Alaska-Fairbanks**
Cryosphere modeling



1. Water and Climate: What are potential impacts of climate change on water supply in Asia?

2. Water and Food: What are present relative contributions of local surface water, upstream runoff, and deep groundwater to water resources for food production and how will these relative contributions evolve? What are potential impacts of major inter-basin transfers and improvements in irrigation and crop water use efficiency?

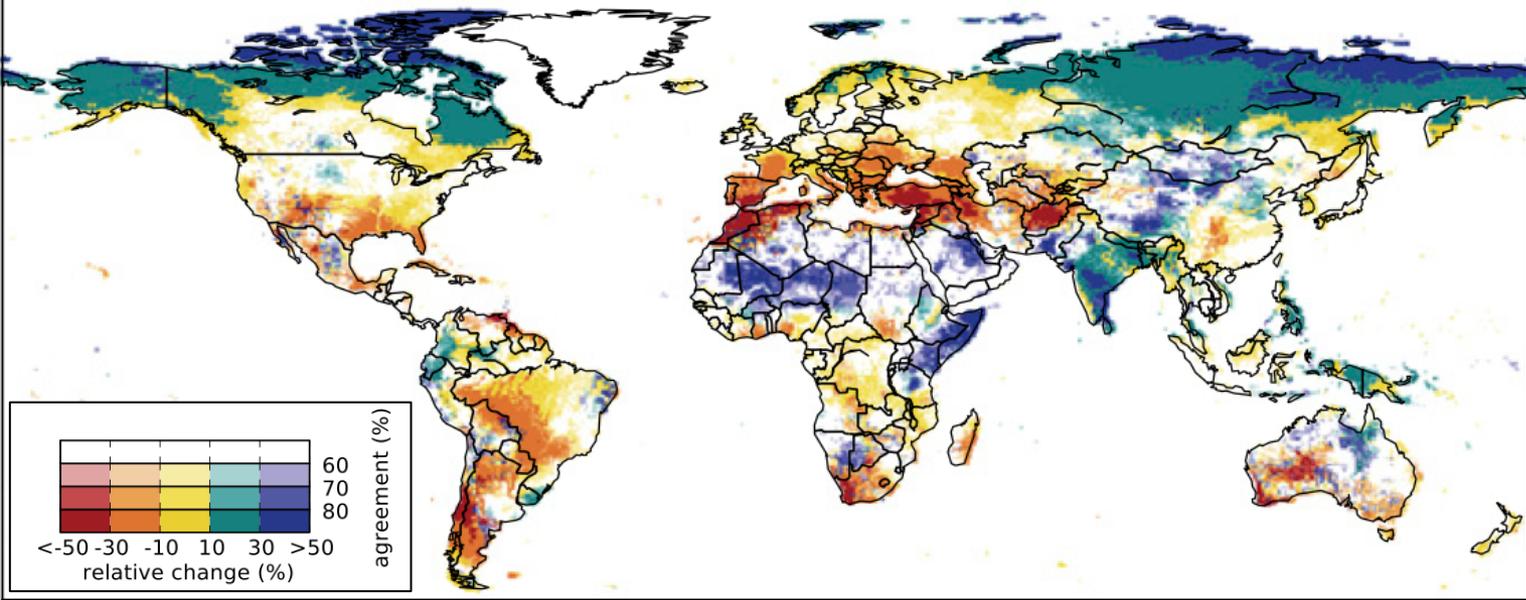
3. Water, Climate, and Sustainability: How will food and water pricing respond, and with what impacts on trade in food and virtual water, on water engineering efforts, on partitioning of water resources for agriculture, industrial, and municipal/domestic use, and on water resource policies?

3. Outcomes

Multimodel assessment of water scarcity under climate change PNAS, 2014, 111, 3245–3250

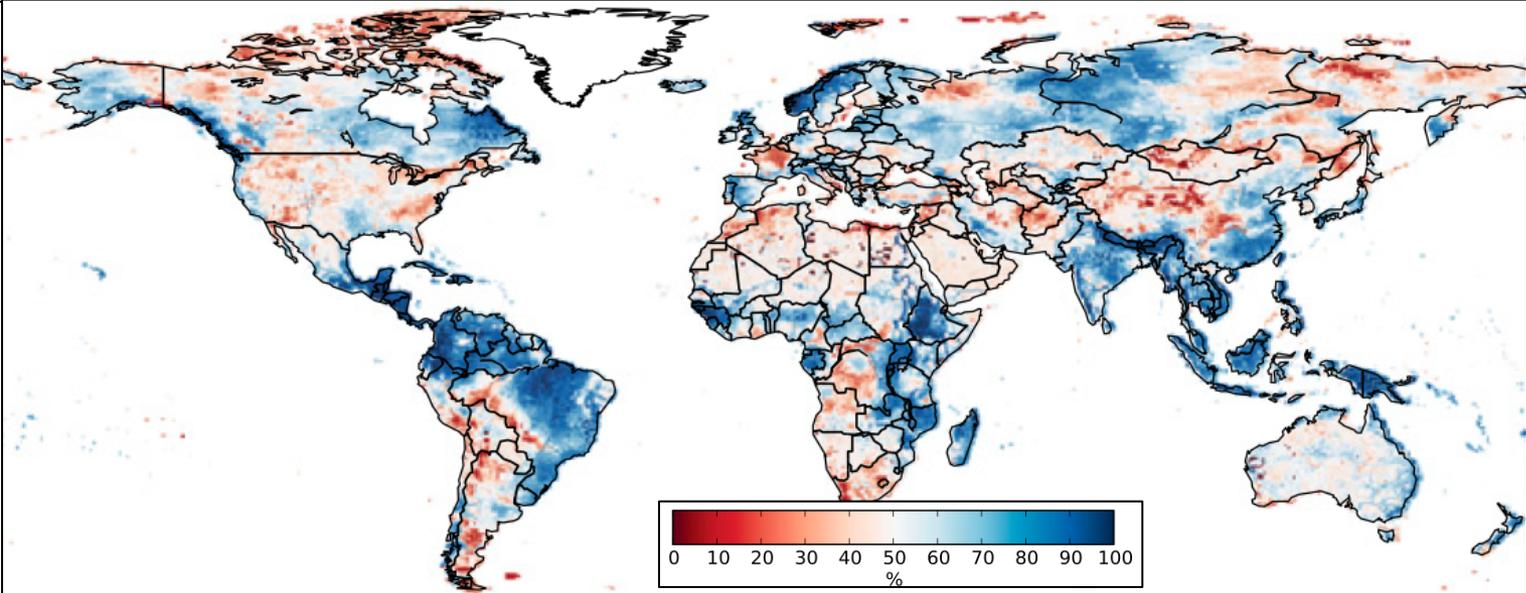
Jacob Schewe^{a,1}, Jens Heinke^{a,b}, Dieter Gerten^a, Ingjerd Haddeland^c, Nigel W. Arnell^d, Douglas B. Clark^e, Rutger Dankers^f, Stephanie Eisner^g, Balázs M. Fekete^h, Felipe J. Colón-Gonzálezⁱ, Simon N. Gosling^j, Hyungjun Kim^k, Xingcai Liu^l, Yoshimitsu Masaki^m, Felix T. Portmann^{n,o}, Yusuke Satoh^p, Tobias Stacke^q, Qihong Tang^r, Yoshihide Wada^f, Dominik Wisser^s, Torsten Albrecht^a, Katja Frieler^a, Franziska Piontek^a, Lila Warszawski^a, and Pavel Kabat^{t,u}

The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP)



Relative change (to present) in annual discharge at 2°C under RCP8.5.

Color hues show the multimodel mean change, and saturation shows the agreement on the sign of change across all GHM– GCM combinations

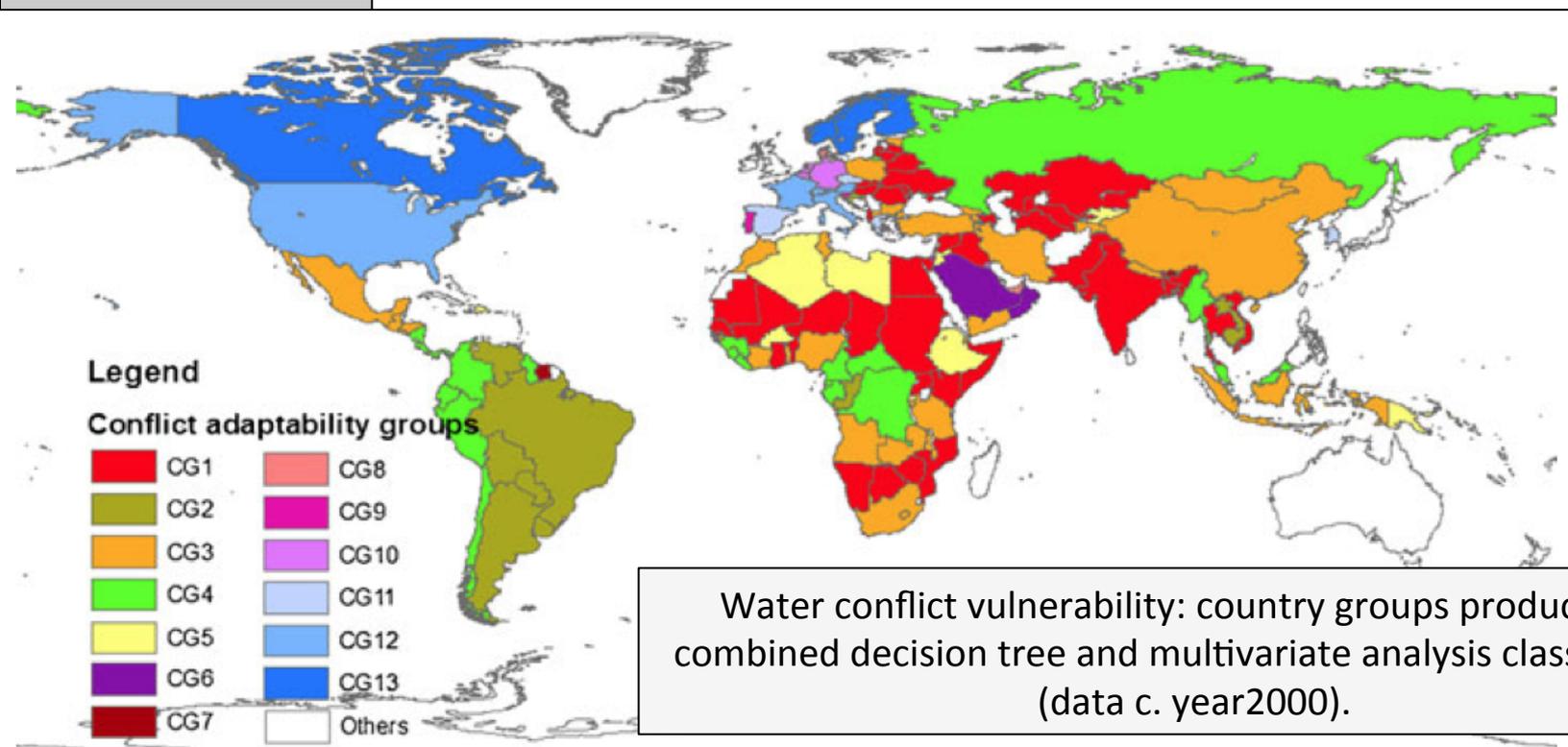


Ratio of GCM variance to total variance.

In red areas Global Hydrological Model variance predominates.

In blue areas Global Climate Model variance predominates.

3. Outcomes



Water conflict vulnerability: country groups produced by combined decision tree and multivariate analysis classification (data c. year2000).

group	groundwater dependency	external water dependency	water resources	income
1	low	HIGH	low	low
2	low	HIGH	HIGH	low
3	low	low	low	low
4	low	low	HIGH	low
5	HIGH	low	low	moderate
6	HIGH	low	low	moderate
7	HIGH	low	HIGH	low
8	HIGH	low	low	HIGH
9	low	HIGH	low	moderate
10	low	HIGH	low	HIGH
11	low	low	low	moderate
12	low	low	low	HIGH
13	low	low	HIGH	HIGH

Water Resour Manage (2014) 28:169–184
 DOI 10.1007/s11269-013-0478-x

Water Conflict Risk due to Water Resource Availability and Unequal Distribution

N. K. Gunasekara • S. Kazama • D. Yamazaki • T. Oki

3. Outcomes

OPEN ACCESS

IOP PUBLISHING

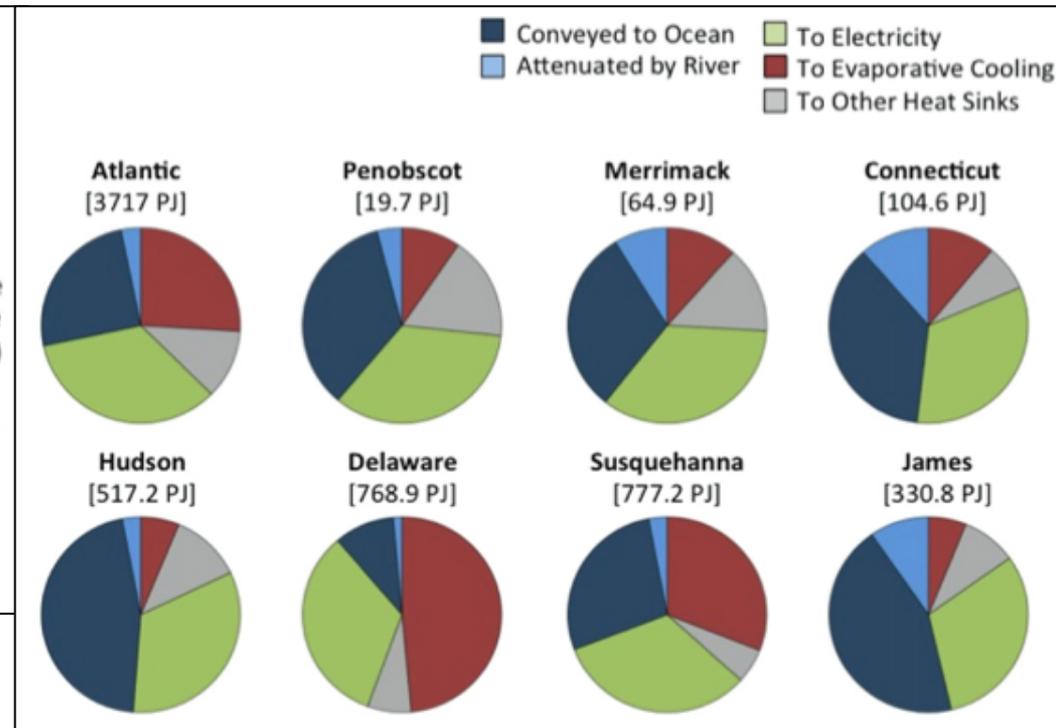
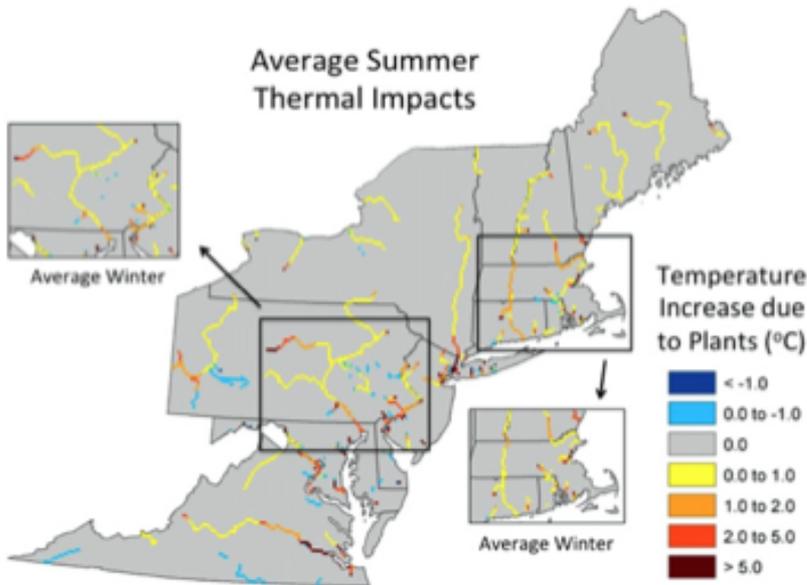
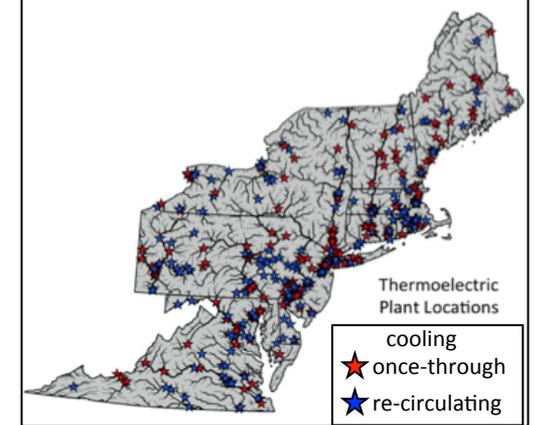
Environ. Res. Lett. 8 (2013) 025010 (10pp)

ENVIRONMENTAL RESEARCH LETTERS

doi:10.1088/1748-9326/8/2/025010

Horizontal cooling towers: riverine ecosystem services and the fate of thermoelectric heat in the contemporary Northeast US

Robert J Stewart¹, Wilfred M Wollheim^{1,2}, Ariel Miara³, Charles J Vörösmarty^{3,4}, Balazs Fekete^{3,4}, Richard B Lammers¹ and Bernice Rosenzweig³



Increase in average summer water temperatures (2000–2010) due to thermal pollution from power plants.

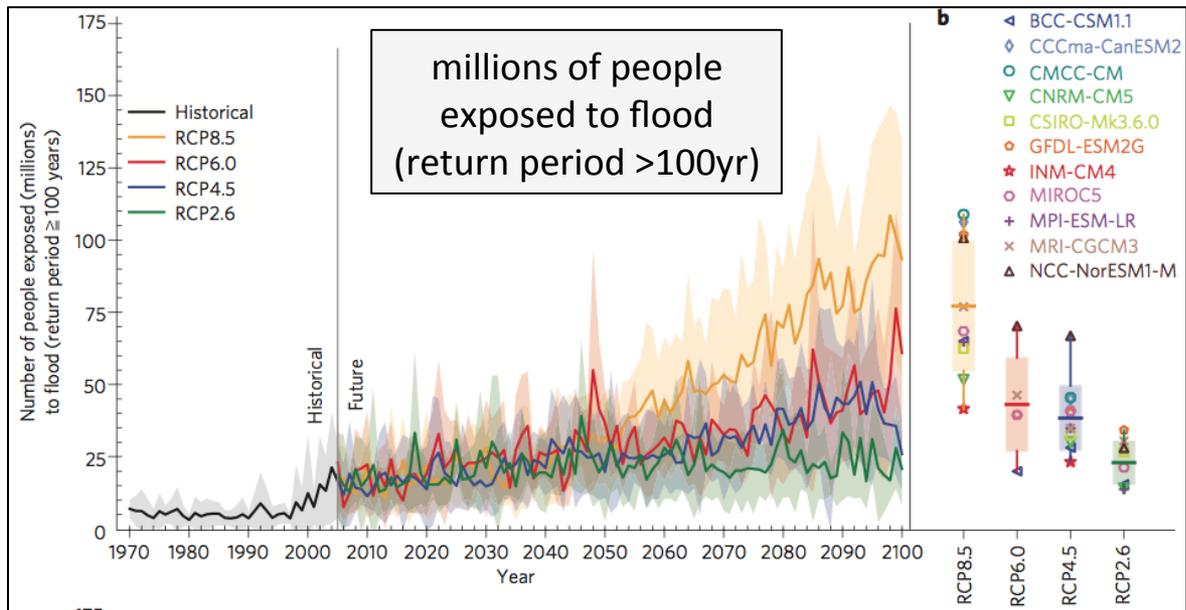
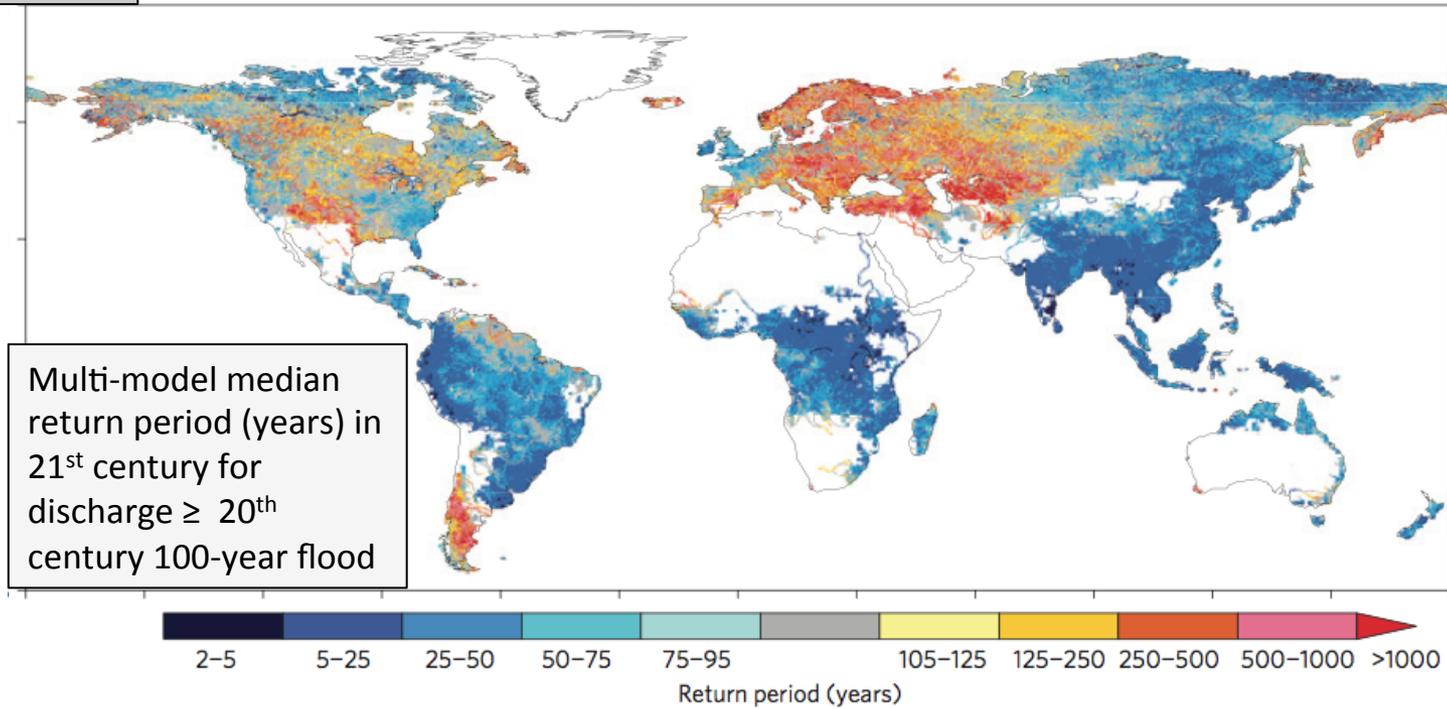
Callout boxes show results for average winter conditions in selected regions.

Temperature increases due to plants are more widespread in the summer because waste heat inputs are dissipated more quickly in the winter.

Allocation of total heat (in petajoules) generated in freshwater thermoelectric power plants during electricity production at selected basins.

3. Outcomes

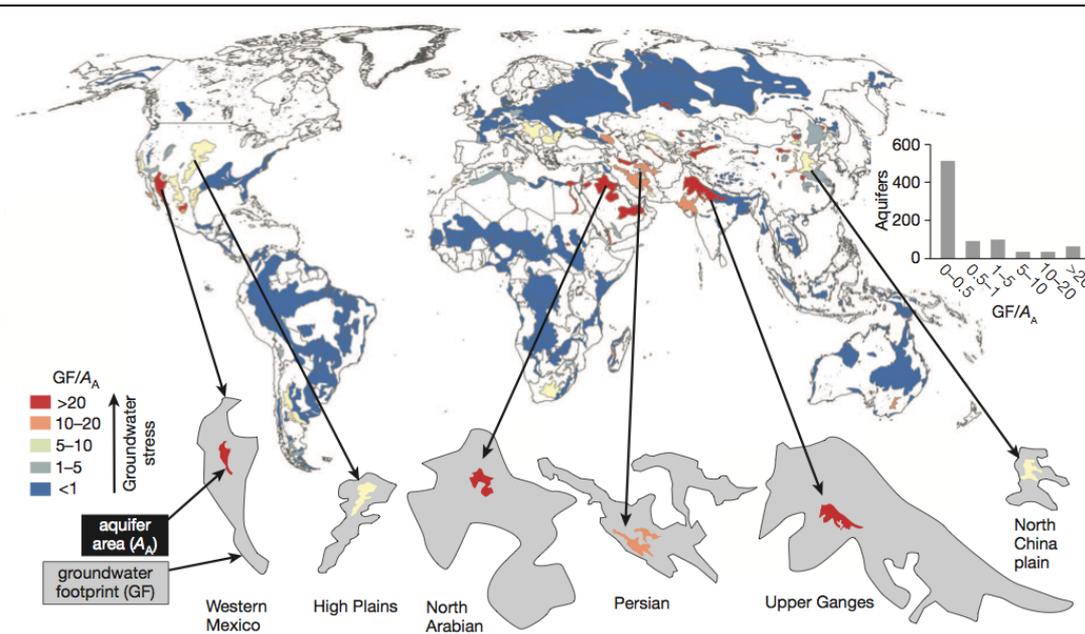
Hirabayashi *et al* (2013) Global flood risk under climate change, *Nature Climate Change*



3. Outcomes

Water balance of global aquifers revealed by groundwater footprint

Tom Gleeson¹, Yoshihide Wada², Marc F. P. Bierkens^{2,3} & Ludovicus P. H. van Beek²



Groundwater footprints of aquifers that are important to agriculture are significantly larger than their geographic areas. Aquifers are major groundwater basins with recharge of >2 mm yr. At the bottom of the figure, the areas of the six aquifers (Western Mexico, High Plains, North Arabian, Persian, Upper Ganges and North China plain) are shown at the same scale as the global map; the surrounding grey areas indicate the groundwater footprint proportionally at the same scale. The ratio GF/AA indicates widespread stress of groundwater resources and/or groundwater-dependent ecosystems. Inset, histogram showing that GF is less than AA for most aquifers.

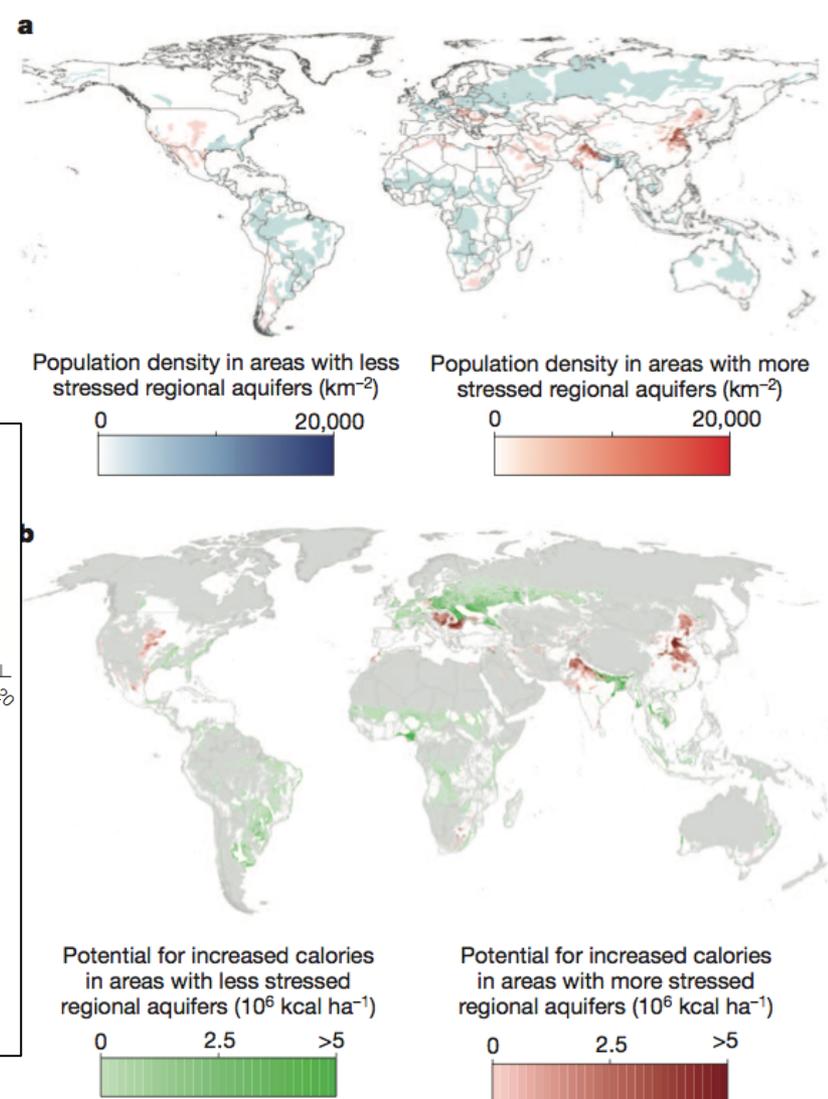
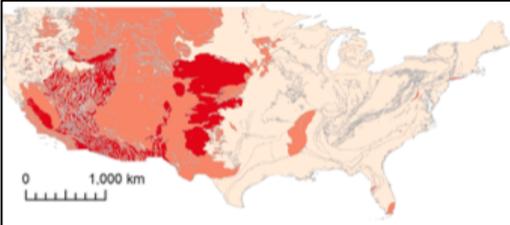
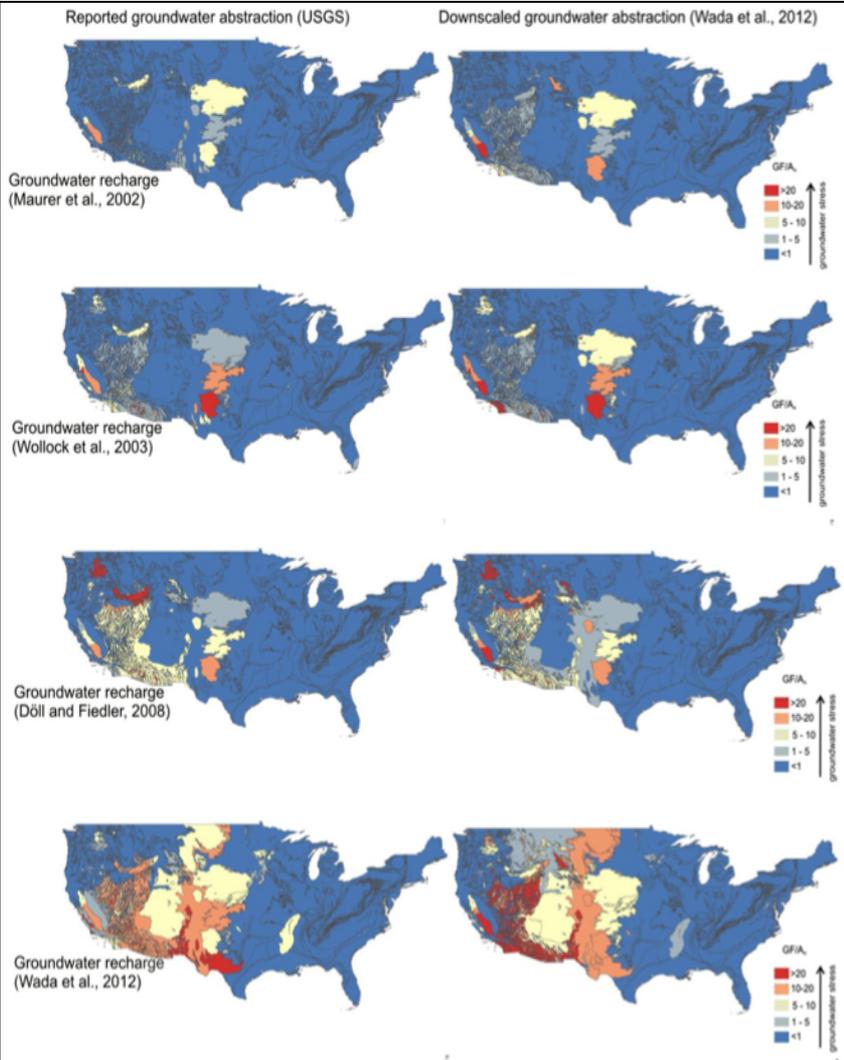


Figure 2 | Groundwater stress may be affecting ~1.7 billion people and could limit the potential to increase agricultural production. The ratio GF/A_A is used to differentiate areas with less groundwater stress ($GF/A_A < 1$) and more groundwater stress ($GF/A_A > 1$). **a**, Population densities, derived from the gridded population of the world for year 2000 (ref. 29). Areas that do not have underlying regional aquifers, or that have very low population density are shown in white. **b**, Potential for increased calories (see main text). Some areas with potential new calories¹⁵ coincide with stressed aquifers and some areas coincide with aquifers that are less stressed. Areas with potential new calories that are not underlain by a regional aquifer are shown in white.

3. Outcomes

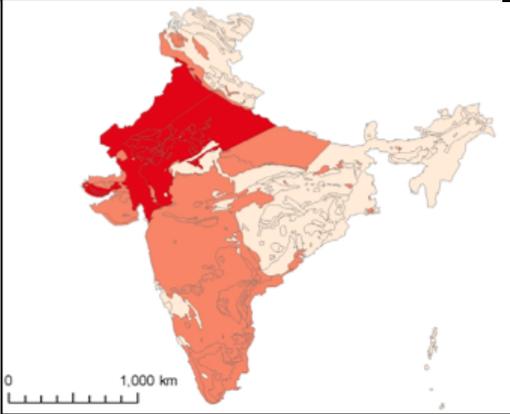
Gleeson & Wada, *ERL* 2013

Assessing regional groundwater stress for nations using multiple data sources with the groundwater footprint



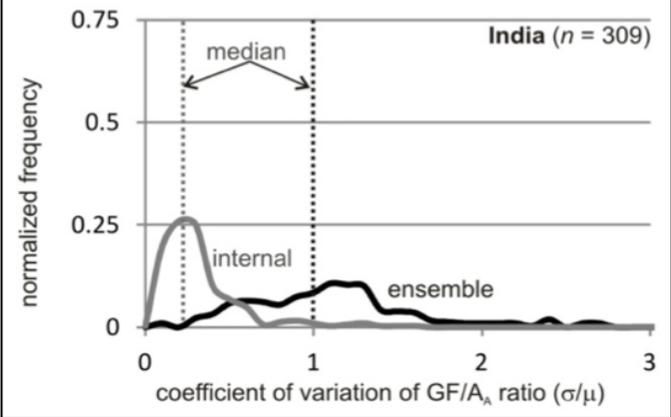
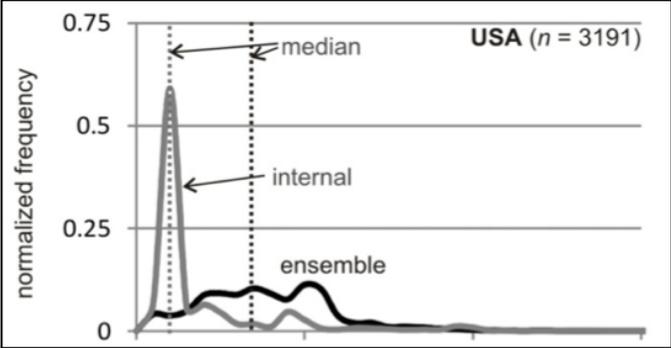
$$GF \text{ (groundwater footprint)} = \frac{\text{gw withdrawal}}{\text{gw net recharge}} \cdot \text{Area}$$

A_A = aquifer known area



Aquifer stressed ($GF/A_A > 1$) for:

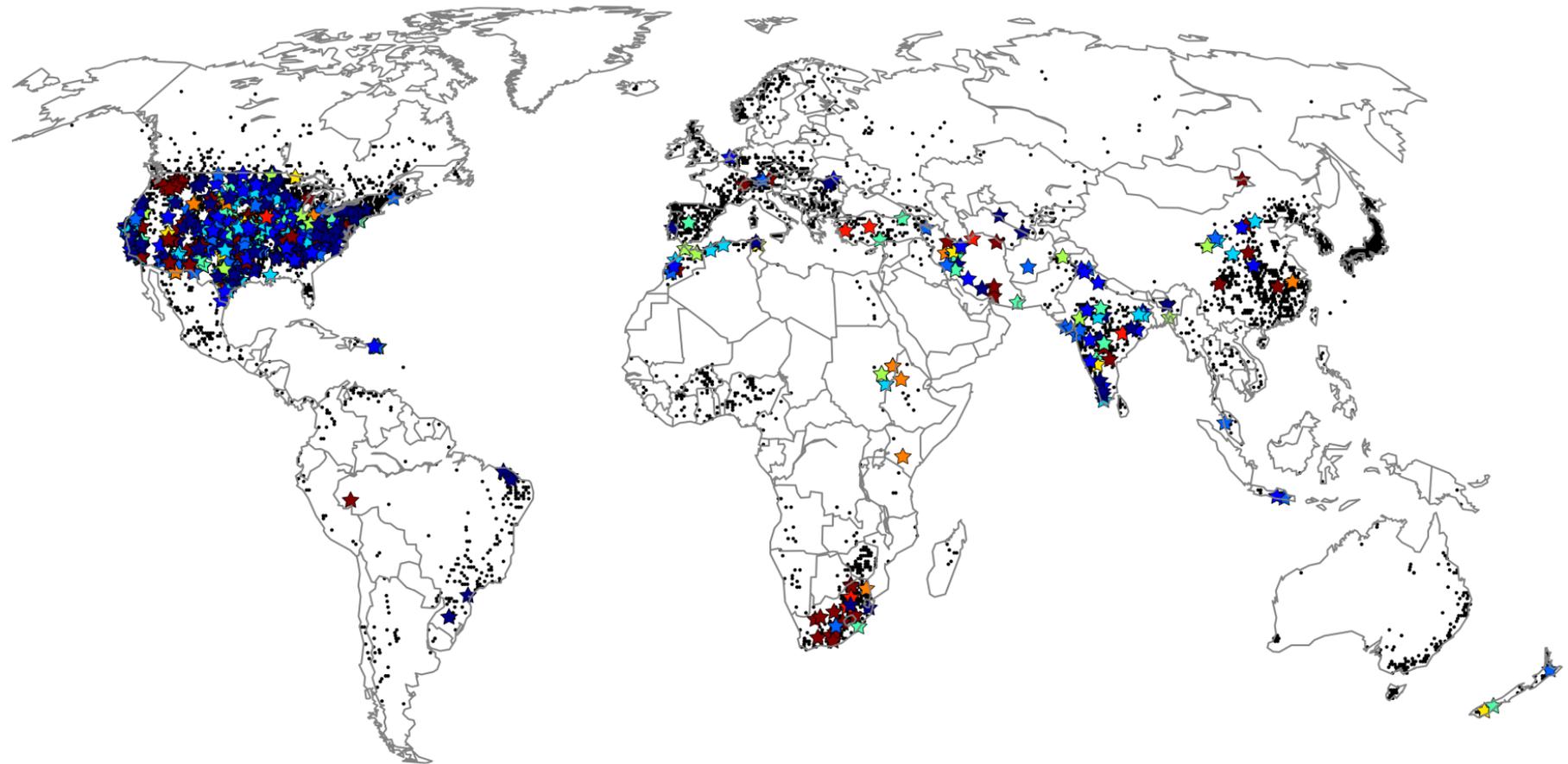
- ALL combinations of input data
- SOME combinations of input data
- NO combinations of input data



ensemble
uncertainty
2-5x
internal
uncertainty

3. Outcomes

Dwindling Storage in Reservoirs



- Reservoirs in GRanD database
- ★ Reported reservoir capacity loss rates due to sedimentation

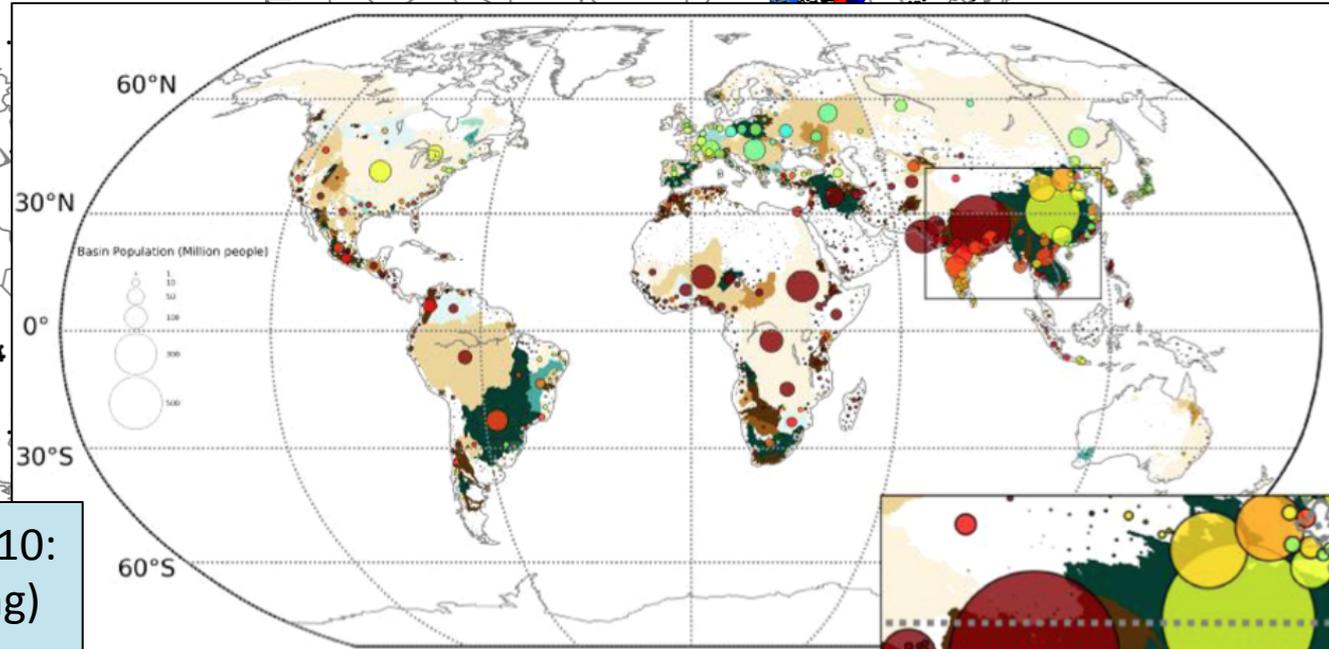
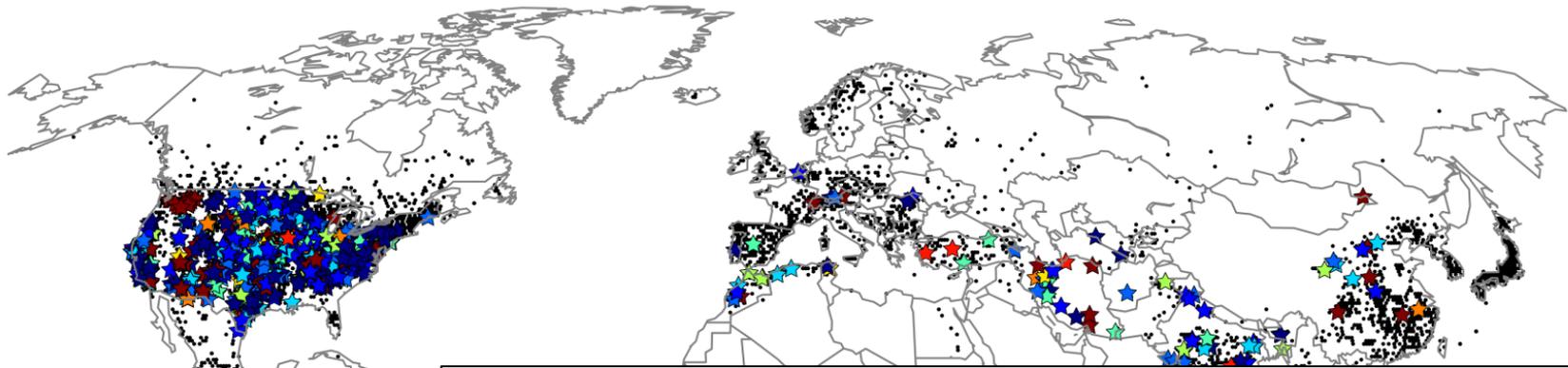


Loss Rate [% per year]

(from Dominik Wisser, Bonn U)

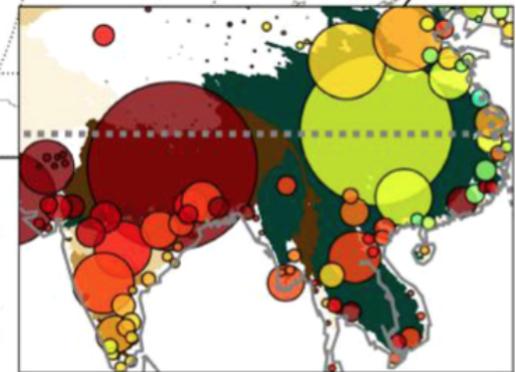
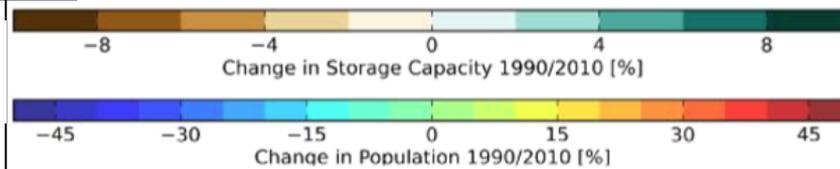
3. Outcomes

Dwindling Storage in Reservoirs



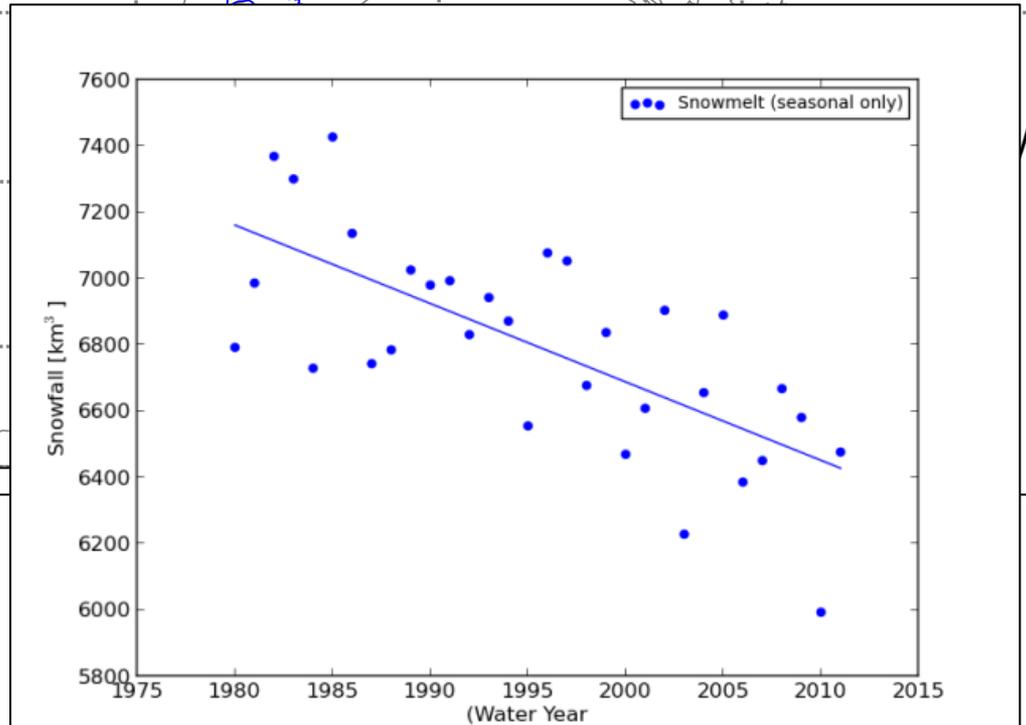
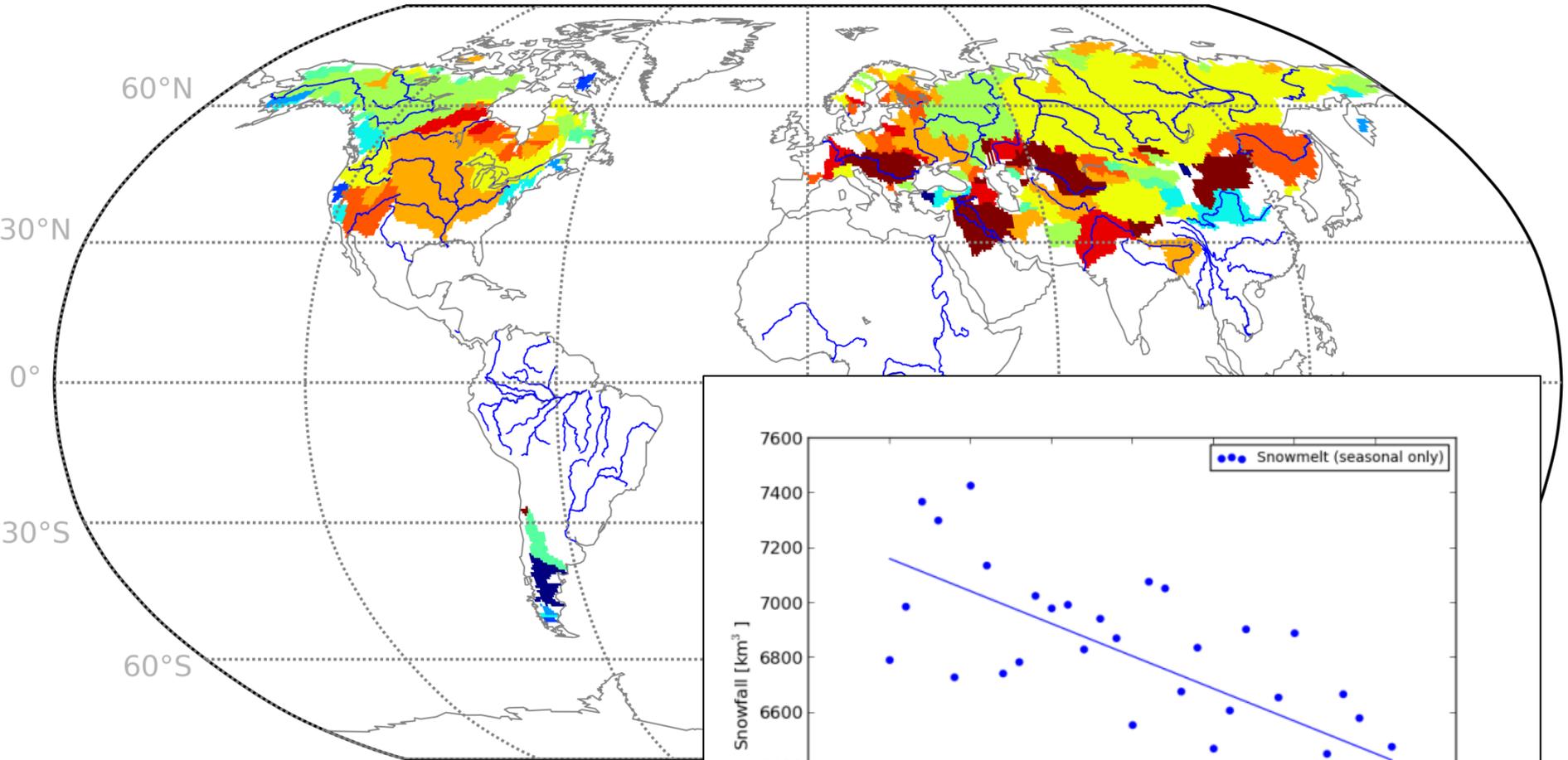
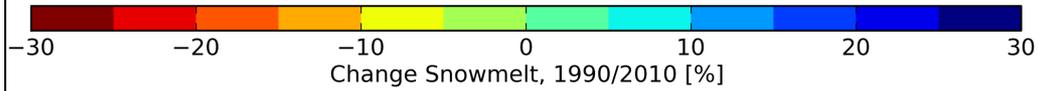
river basin change 1990-2010:
• reservoir capacity (shading)
• population (filled circles)

Wisser et al. 2013 *WRR*



3. Outcomes

Dwindling Storage in Snow



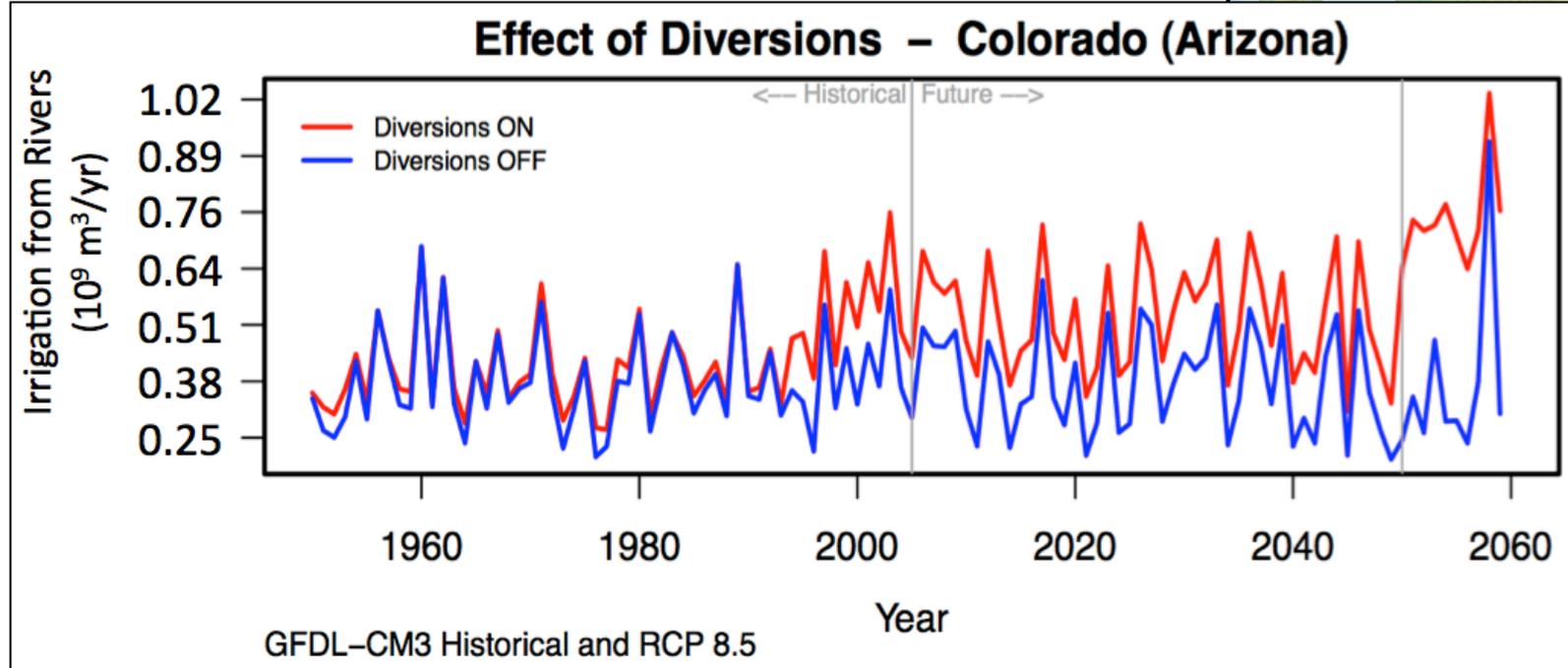
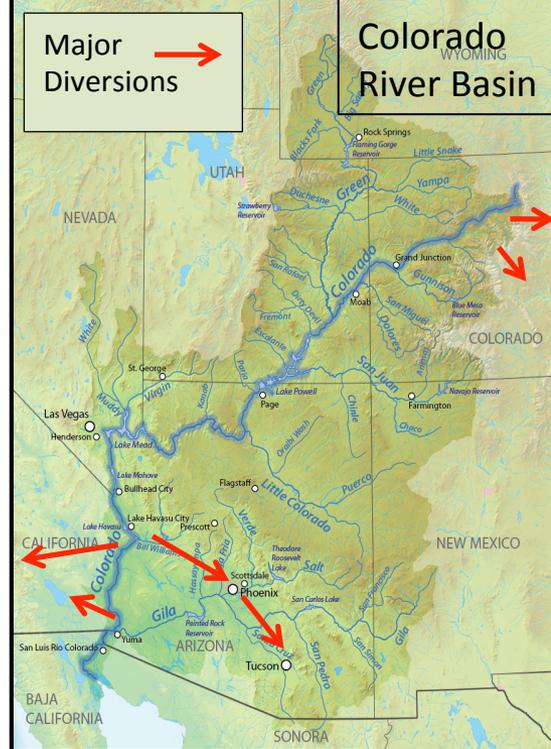
(from Dominik Wisser, Bonn U)

3. Outcomes Interbasin Water Transfers

Includes: Reservoirs and Irrigation. Irrigation water applied with 100% efficiency (no loss back to system).

With and Without Inter-basin Transfers (Diversions).

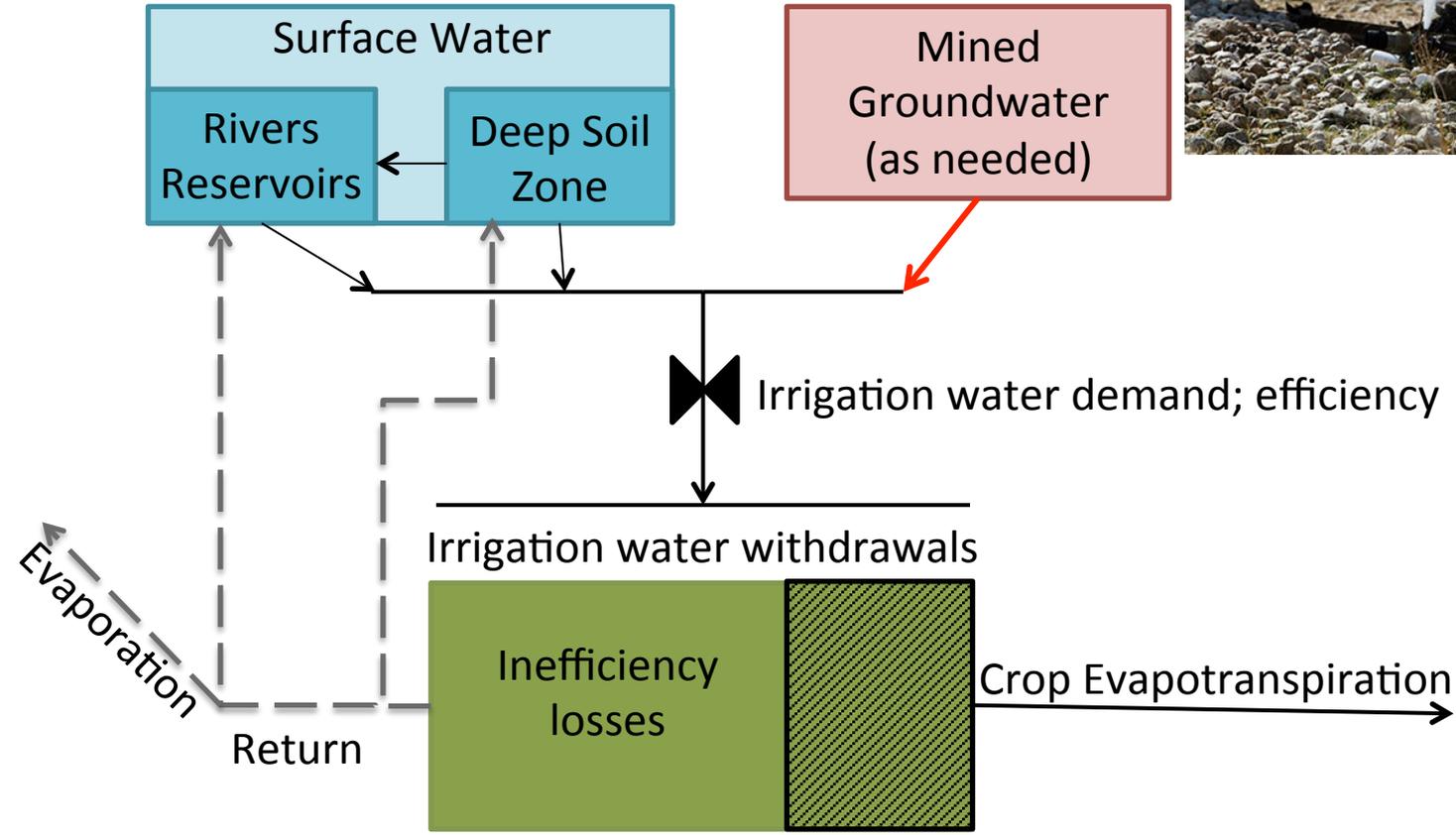
When Diversions turned on (red line) more water is abstracted from rivers for irrigation.



3. Outcomes

Improving irrigation efficiency

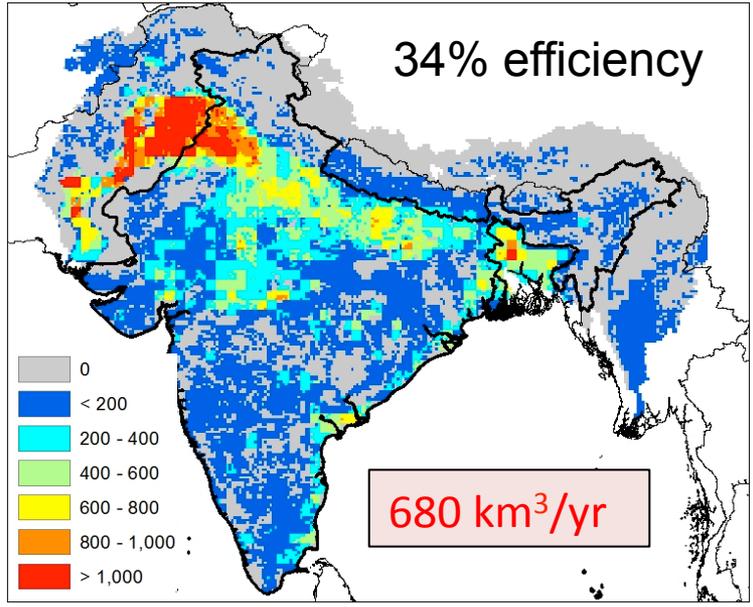
India's irrigation efficiency (FAO) = 0.34
Irrigation water withdrawal = demand ÷ 0.34



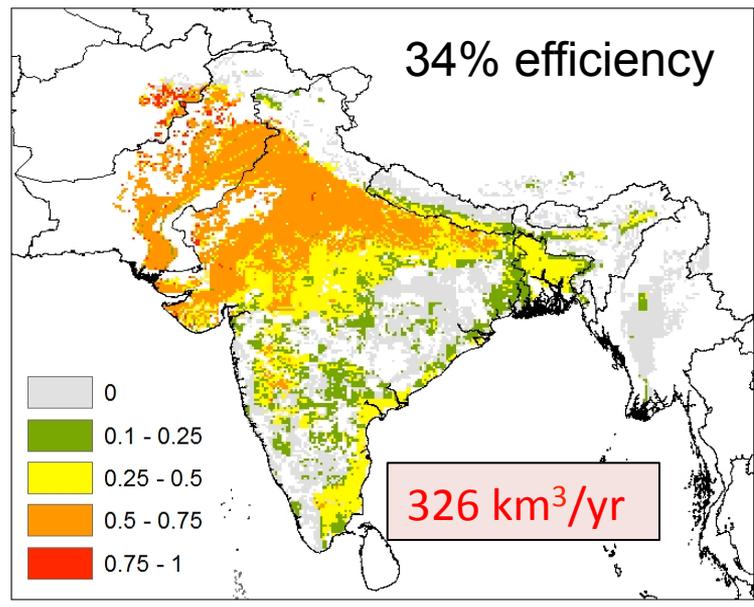
3. Outcomes

Irrigation, mined groundwater fraction of demand (c.2000)

irrigation water demand (mm/y)



Mined groundwater (MGW) fraction of demand

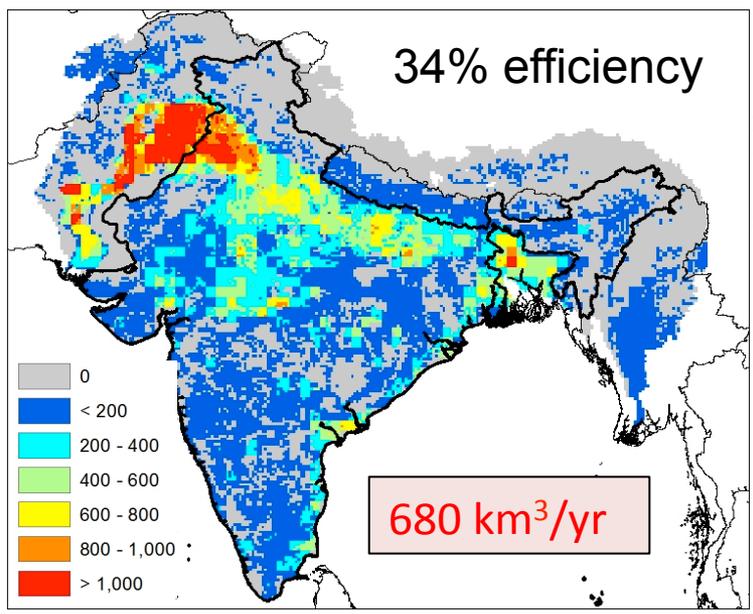


MGW = 48% of demand

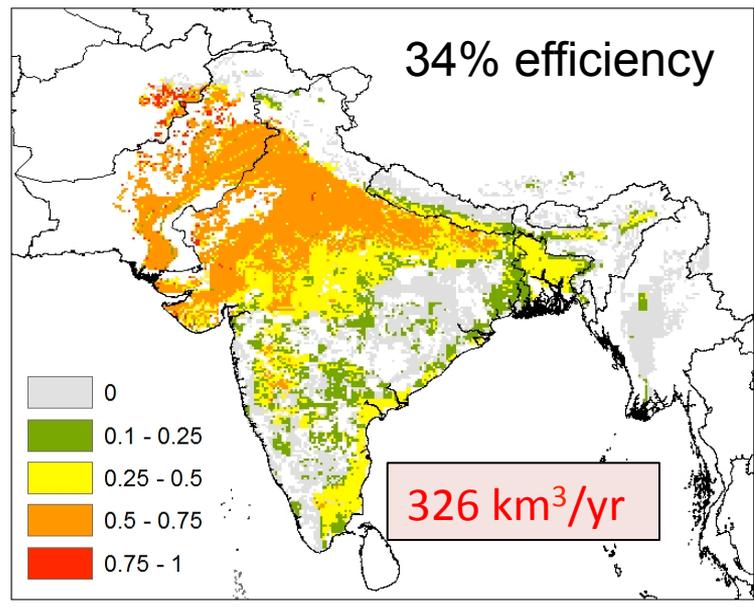
3. Outcomes

Irrigation, mined groundwater fraction of demand (c.2000)

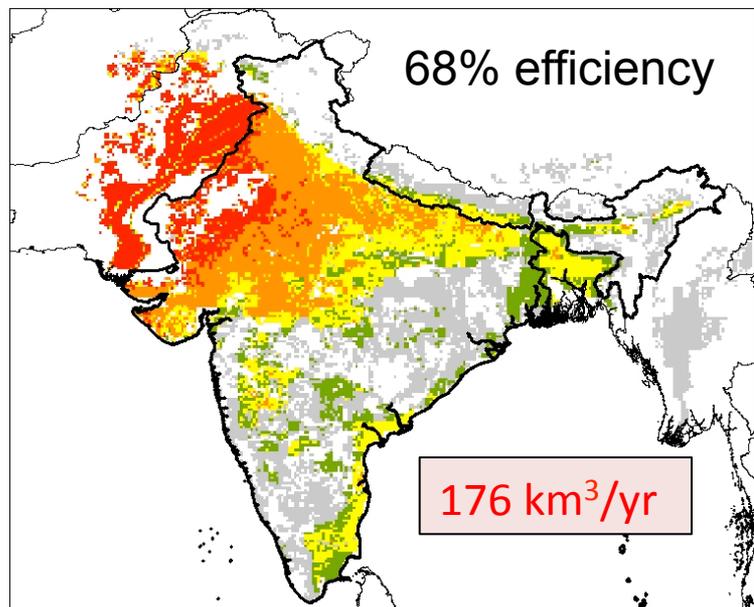
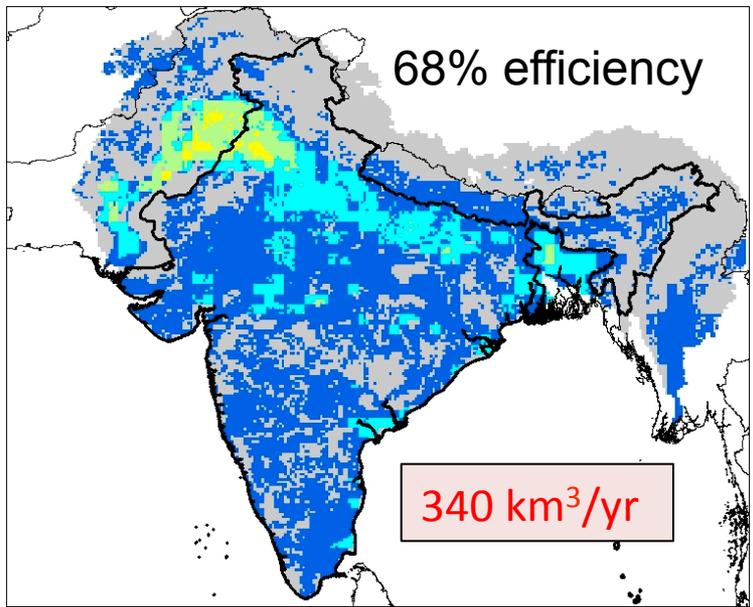
irrigation water demand (mm/y)



Mined groundwater (MGW) fraction of demand



MGW = 48% of demand

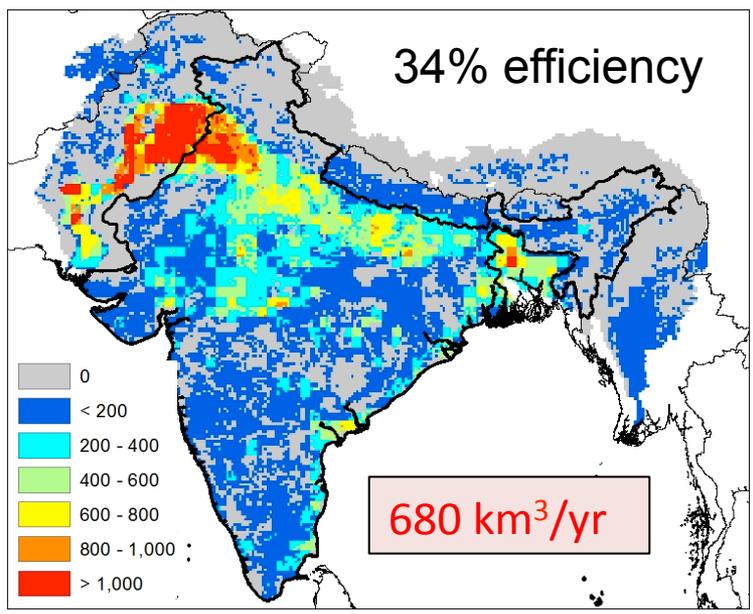


MGW = 52% of demand

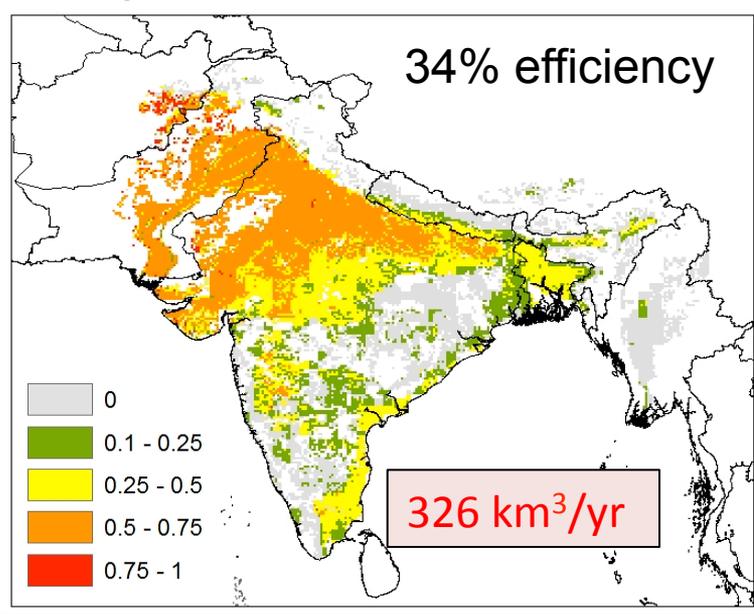
3. Outcomes

Irrigation, mined groundwater fraction of demand (c.2000)

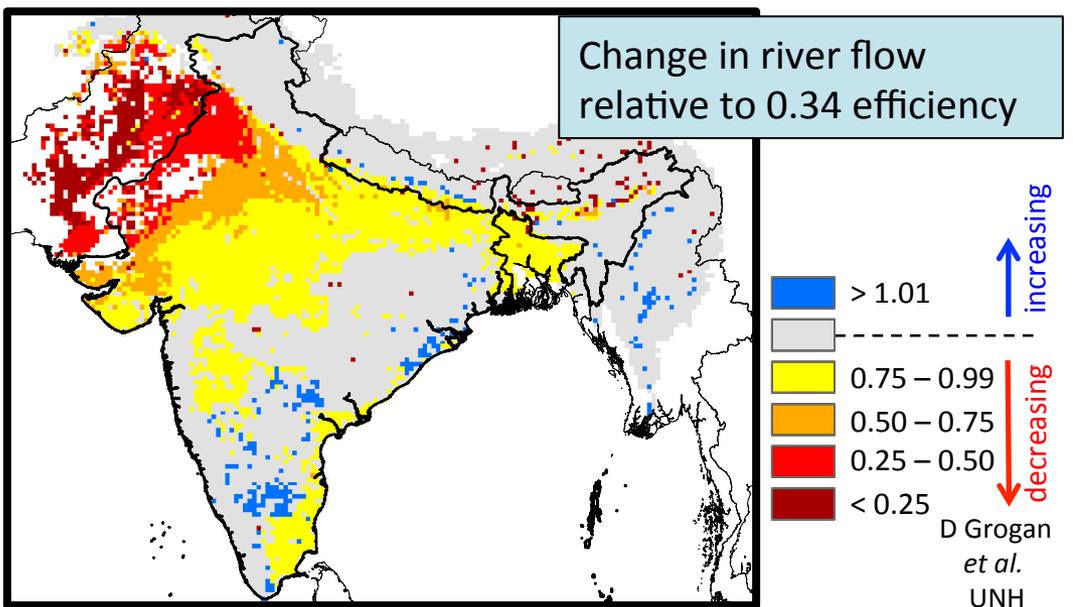
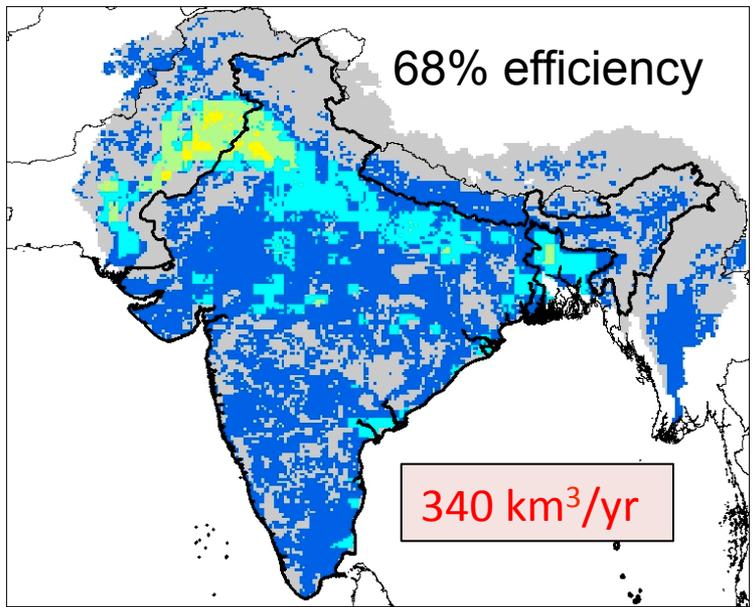
irrigation water demand (mm/y)



Mined groundwater (MGW) fraction of demand



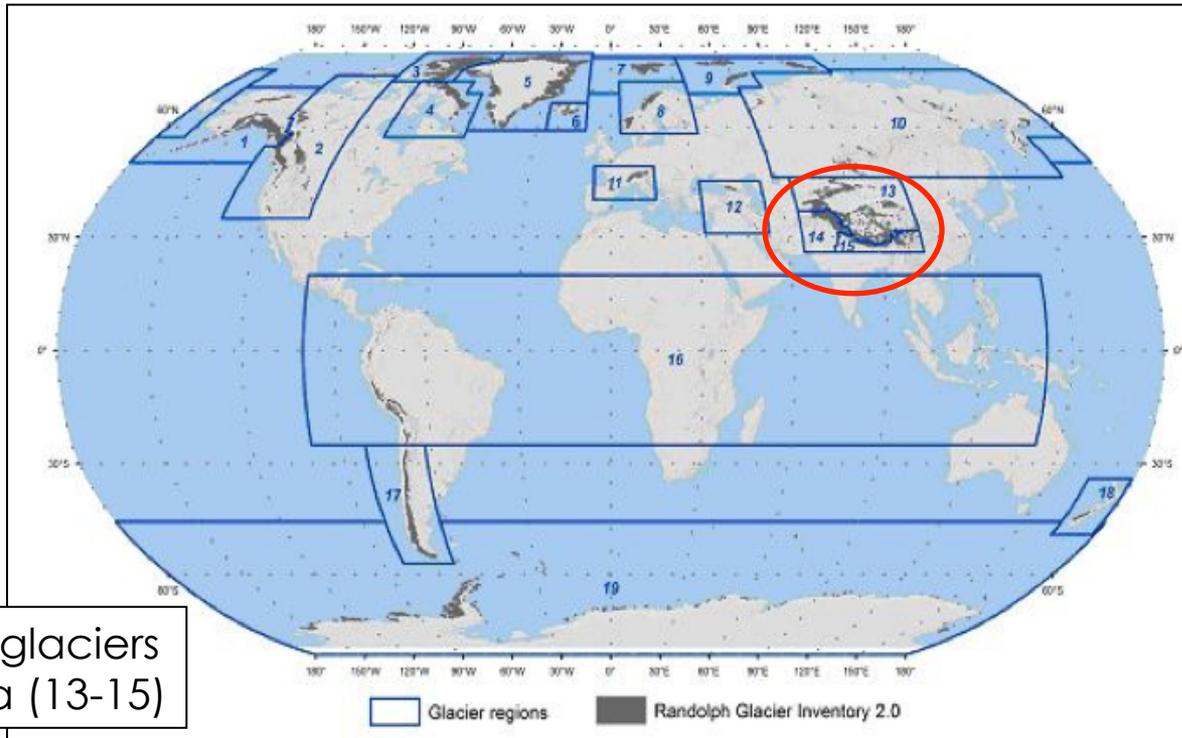
MGW = 48% of demand



3. Outcomes

Coupling WBM & Glacier Mass Balance Modeling

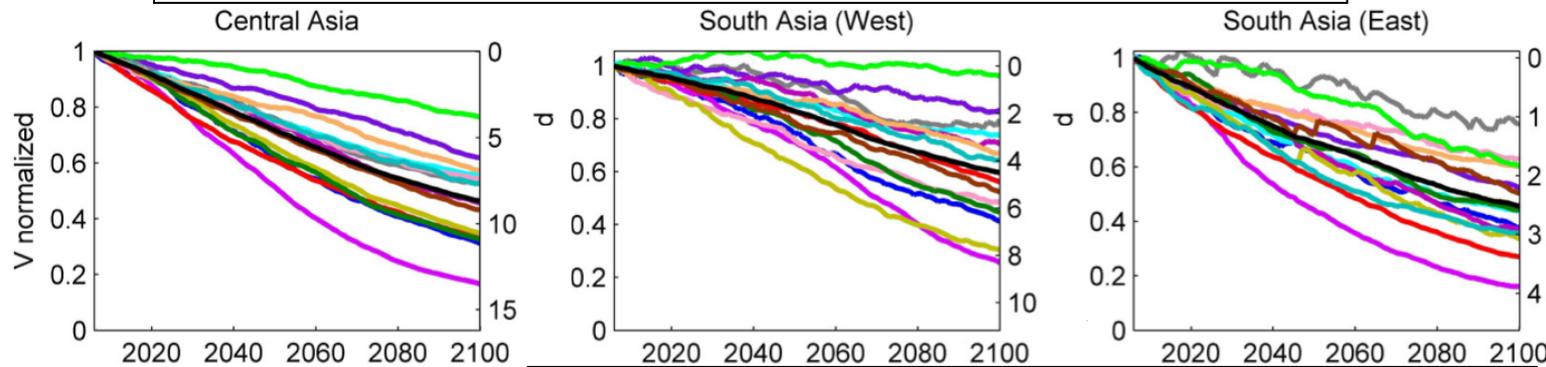
Radic et al. (*Climate Dynamics*, 2013)



About 80,000 glaciers in Central Asia (13-15)

glacier annual volume

glacier melt sea-level equiv. (mm)

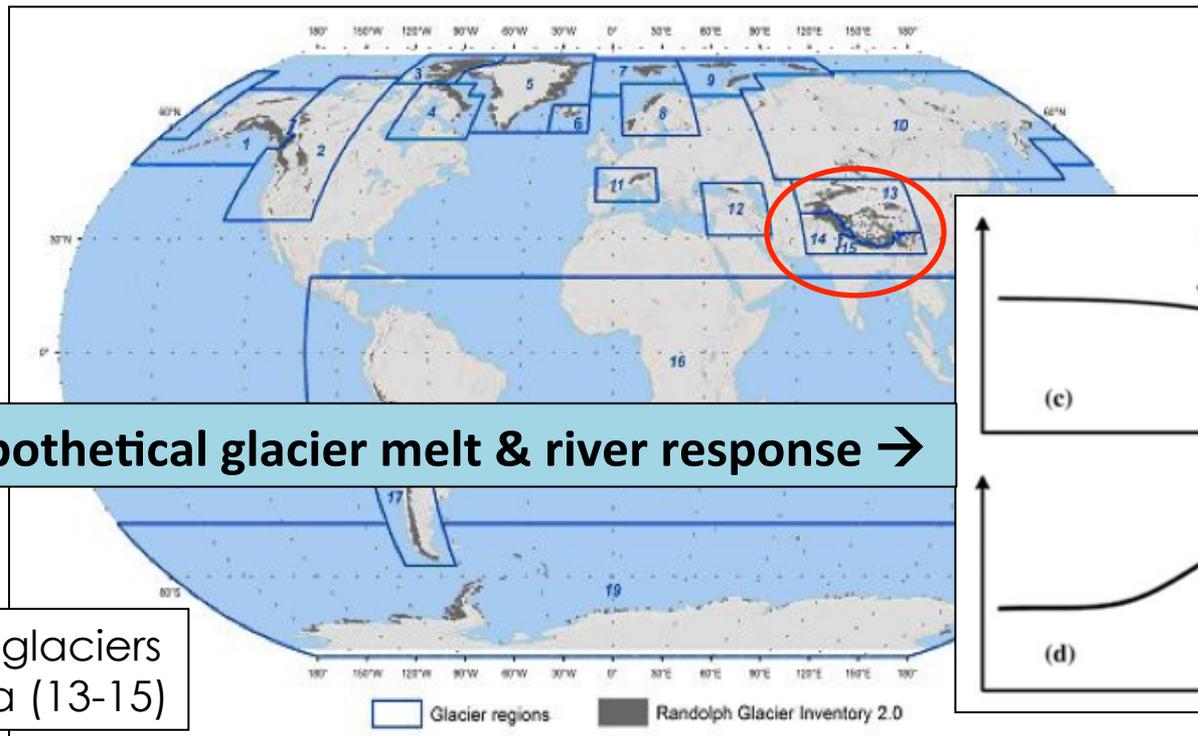


- BCC-CSM1-1
- CNRM-CM5
- GISS-E2-R
- IPSL-CM5A-LR
- MRI-CGCM3
- CanESM2
- CSIRO-Mk3-6-0
- HadGEM2-ES
- MIROC-ESM
- NorESM1-M
- CCSM4
- GFDL-CM3
- INM-CM4
- MPI-ESM-LR
- model mean

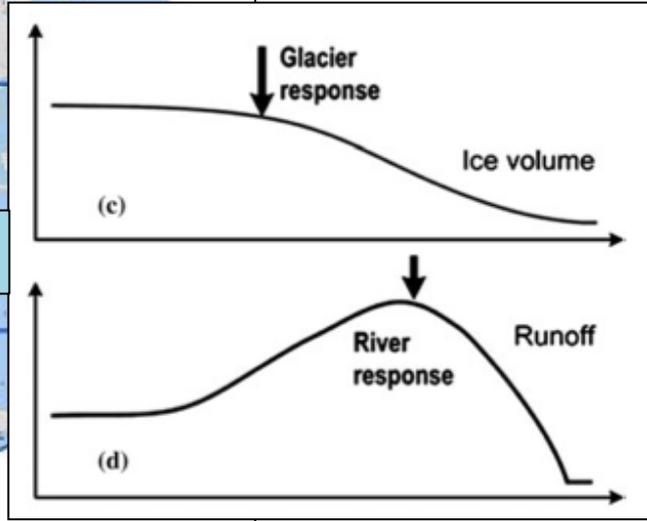
IPCC AR5 RCP4.5 scenario

3. Outcomes Coupling WBM & Glacier Mass Balance Modeling

Radic et al. (*Climate Dynamics*, 2013)



Hypothetical glacier melt & river response →

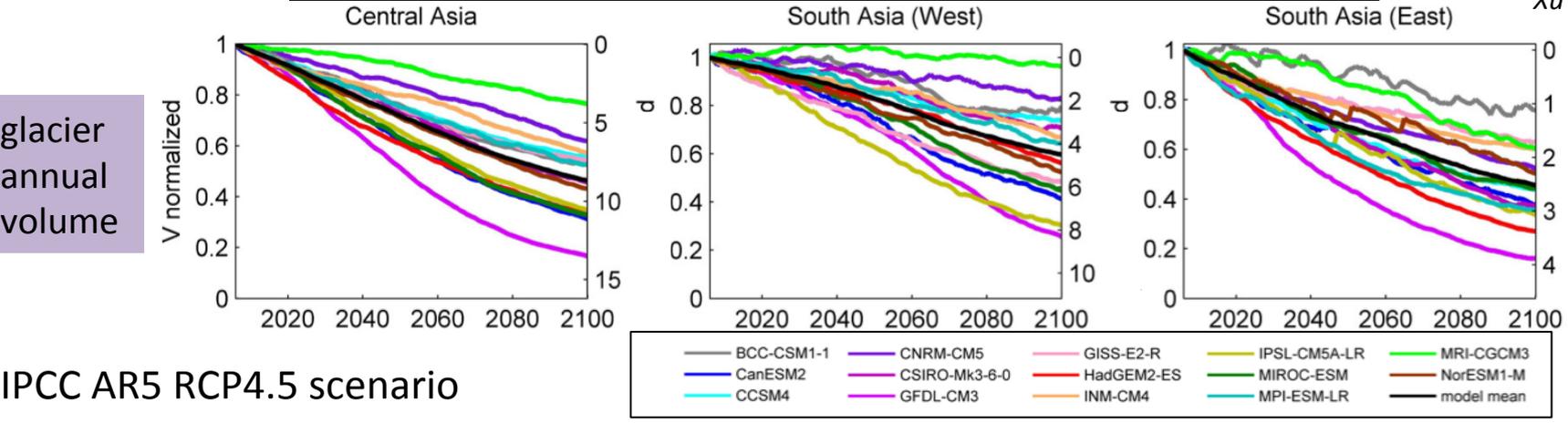


About 80,000 glaciers in Central Asia (13-15)

Xu et al. (2009)

glacier annual volume

glacier melt sea-level equiv. (mm)



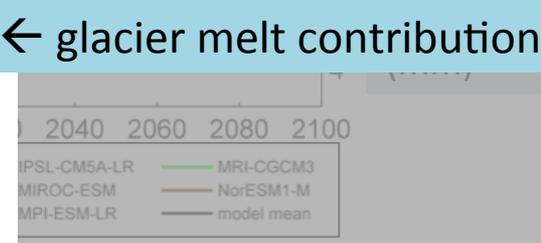
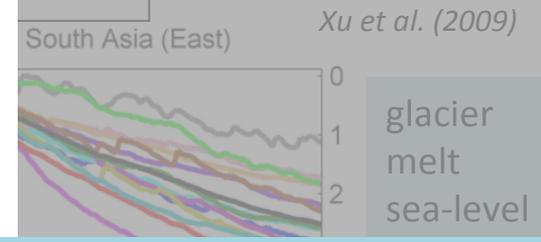
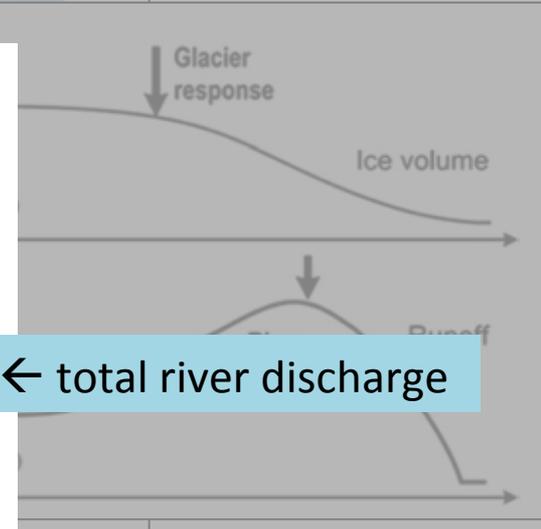
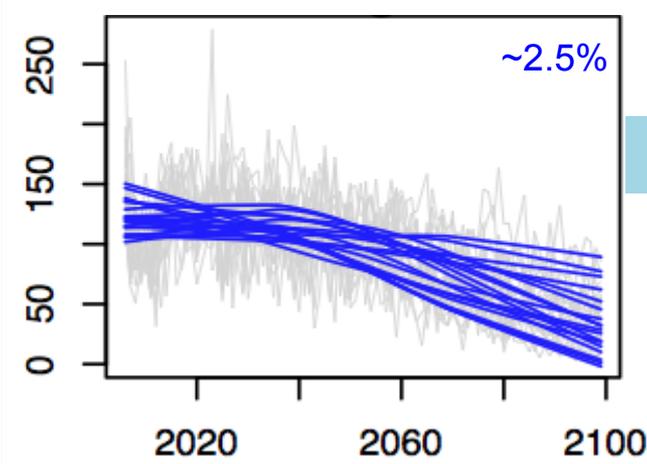
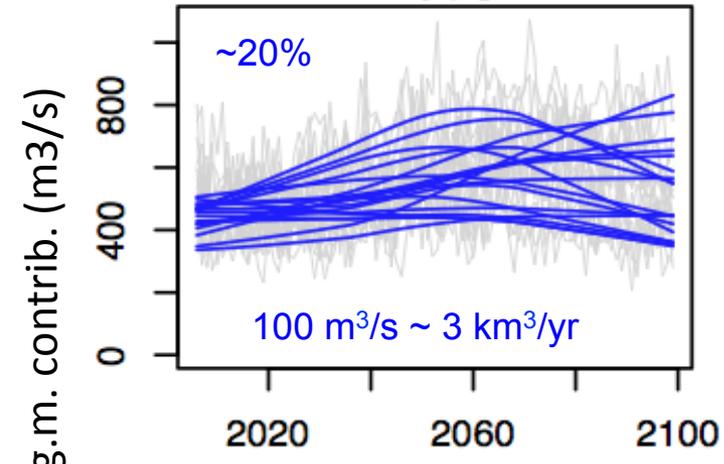
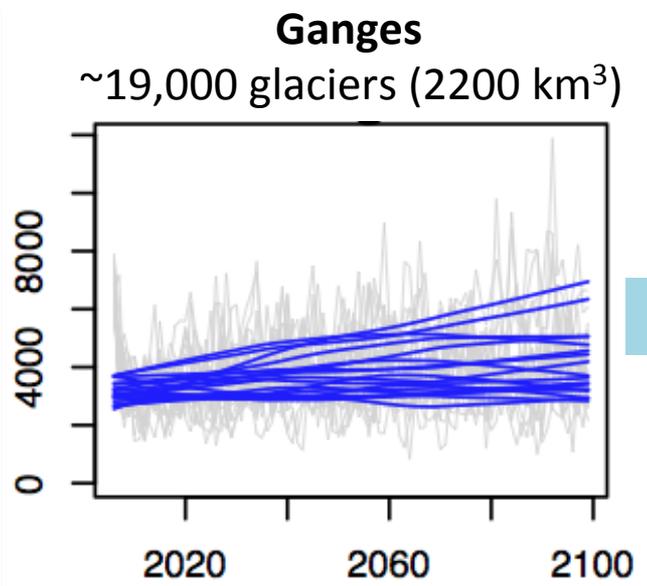
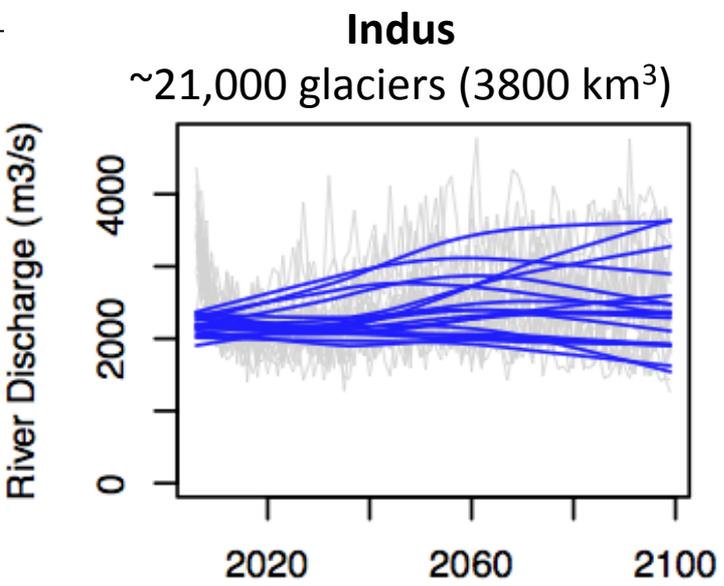
IPCC AR5 RCP4.5 scenario

3. Outcomes Coupling WBM & Glacier Mass Balance Modeling

— annual discharge for 9 GCMs and 2 scenarios (RCP 4.5 & 8.5)
— smoothed annual discharge



Radic et al. (*Climate Dynamics*, 2013)



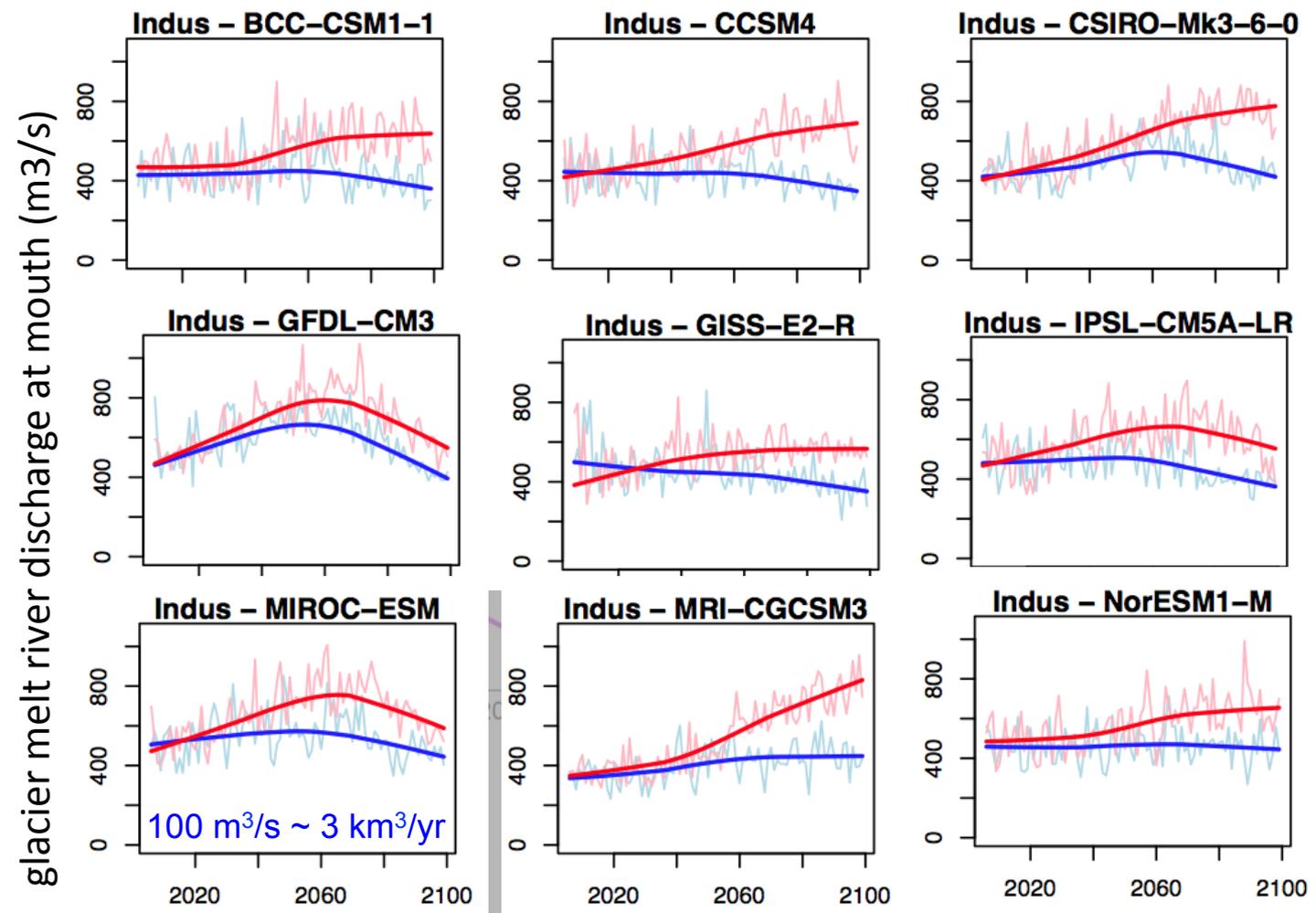
3. Outcomes Coupling WBM & Glacier Mass Balance Modeling

— **Indus River** annual discharge for 9 GCMs and 2 scenarios (RCP 4.5 & 8.5)
— smoothed annual discharge (RCP 4.5 & 8.5)

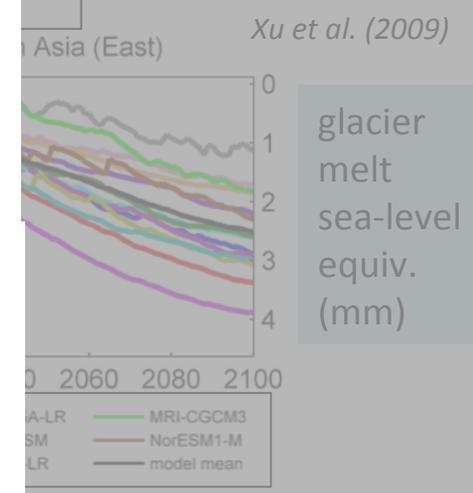


Radic et al. (*Climate Dynamics*, 2013)

glacier melt contribution



Indus
 ~21,000 glaciers
 (3800 km³)
 ~20% of discharge



Xu et al. (2009)

glacier melt sea-level equiv. (mm)

4. Relevance to IAMs

How can 'technologies' improve water supply & crop yield?

