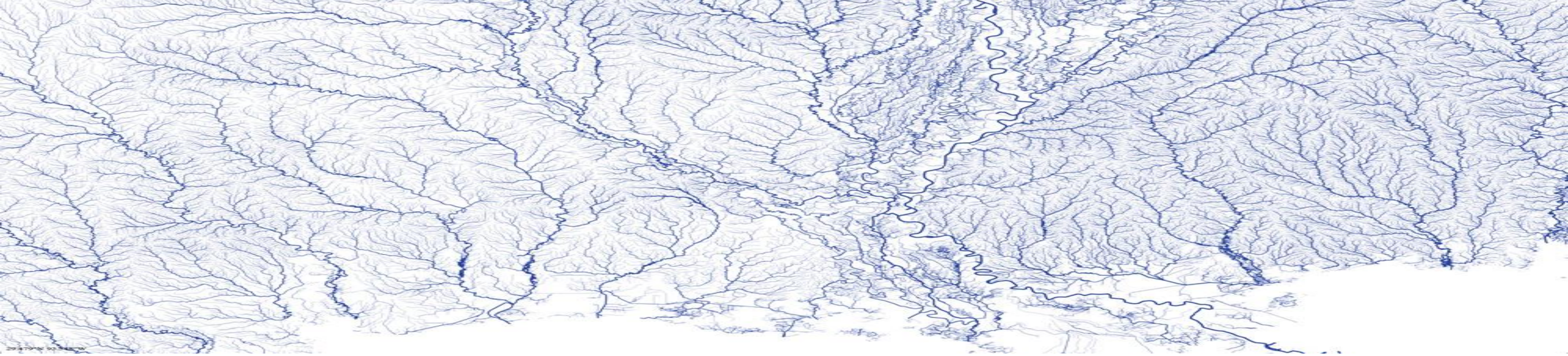

Global hydrology 2015: state, trends, and directions

Marc F. P. Bierkens

Department of Physical Geography, Utrecht University, Utrecht, Netherlands,
Deltares, Utrecht, Netherlands

Universiteit Utrecht

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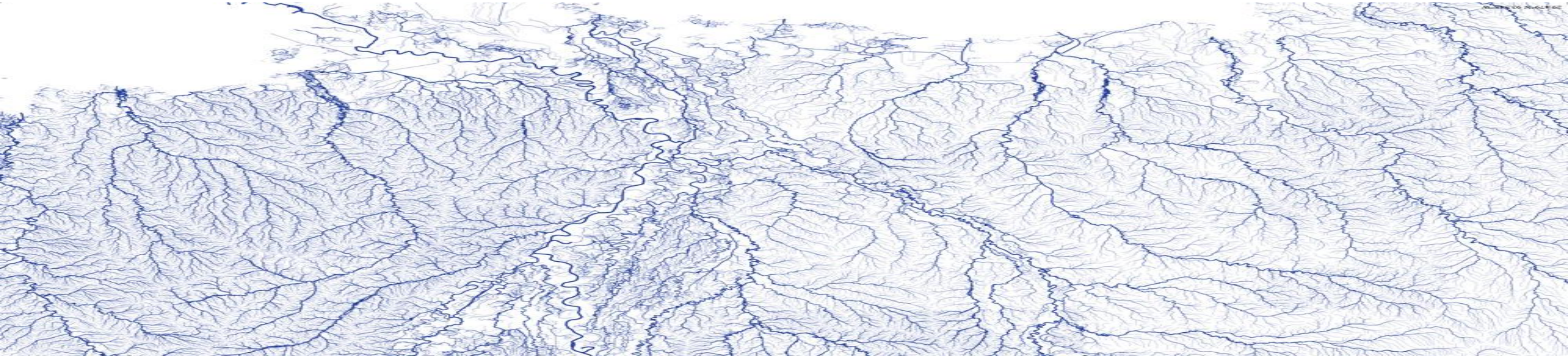
Enabling Delta Life



WATER RESOURCES RESEARCH, VOL. 22, NO. 9, PAGES 6S–14S, AUGUST 1986

The Emergence of Global-Scale Hydrology

PETER S. EAGLESON

Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge

- Hydrology is an *earth system science*: human impacts on the land surface surpass the catchment scale
- We need a *global hydrological models* to understand and tackle imminent environmental problems involving climate, agriculture and biodiversity where the hydrological cycle is central.
- We need the *data* to feed these models.
- We need to *educate young hydrologists* in global hydrology and its role in the earth system.

This talk:

1. What happened to global hydrology since 1986?
2. Taking stock.
3. Recent trends
4. What are the imminent challenges?
5. The future and beyond?

1. Development of global hydrology

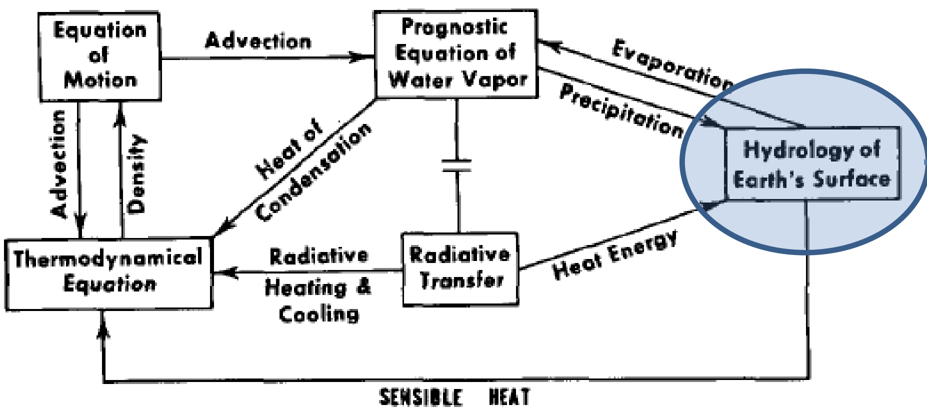
Field of development:

- Atmospheric science
- Hydrology and water resources
- Vegetation and Carbon

1. Development of global hydrology

Atmospheric science

First primitive land surface model:
Bucket model of Manabe (1969)



- Soil a single bucket with soil moisture W (in cm)
- Creating runoff when W > 15 cm
- $E = E_{pot}$ if W > 12.5 cm
- $E = E_{pot}*(W/12.5)$ if W <= 12.5 cm

MONTHLY WEATHER REVIEW
VOLUME 97, NUMBER 11
NOVEMBER 1969

UDC 551.513.13 : 556.013 : 556.1 : 551.511.33

CLIMATE AND THE OCEAN CIRCULATION[1]

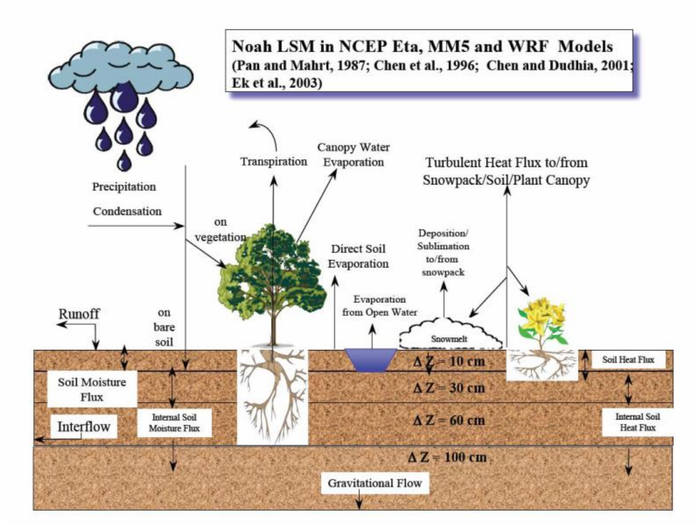
I. THE ATMOSPHERIC CIRCULATION AND THE HYDROLOGY OF THE EARTH'S SURFACE

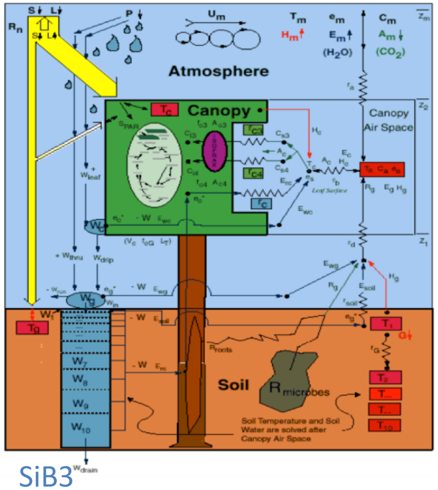
SYUKURO MANABE
Geophysical Fluid Dynamics Laboratory, ESSA, Princeton, N.J.

1. Development of global hydrology

Atmospheric science: LSMs

- Deardorf (1978): first complete LS-scheme: vegetation layer, soil heat flux, effective two-layer soil hydrology, and canopy interception.
- 1980s: First generation: OSU-LSM: BATS, SiB -> focus on sophisticated SVAT
- 1990s: Second generation: TESSEL, BATS2, MOSES, NOAH-LSM, VIC -> more sophisticated hydrology (Richard's Eq., Subgrid hydro)
- From year 2000 on: development into Land Earth System Models (LESM): CLM, JULES, Noah-MP, ORCHIDEE , LM3, (dynamic vegetation, routing)





SiB3

1. Development of global hydrology

Atmospheric science: LSMs

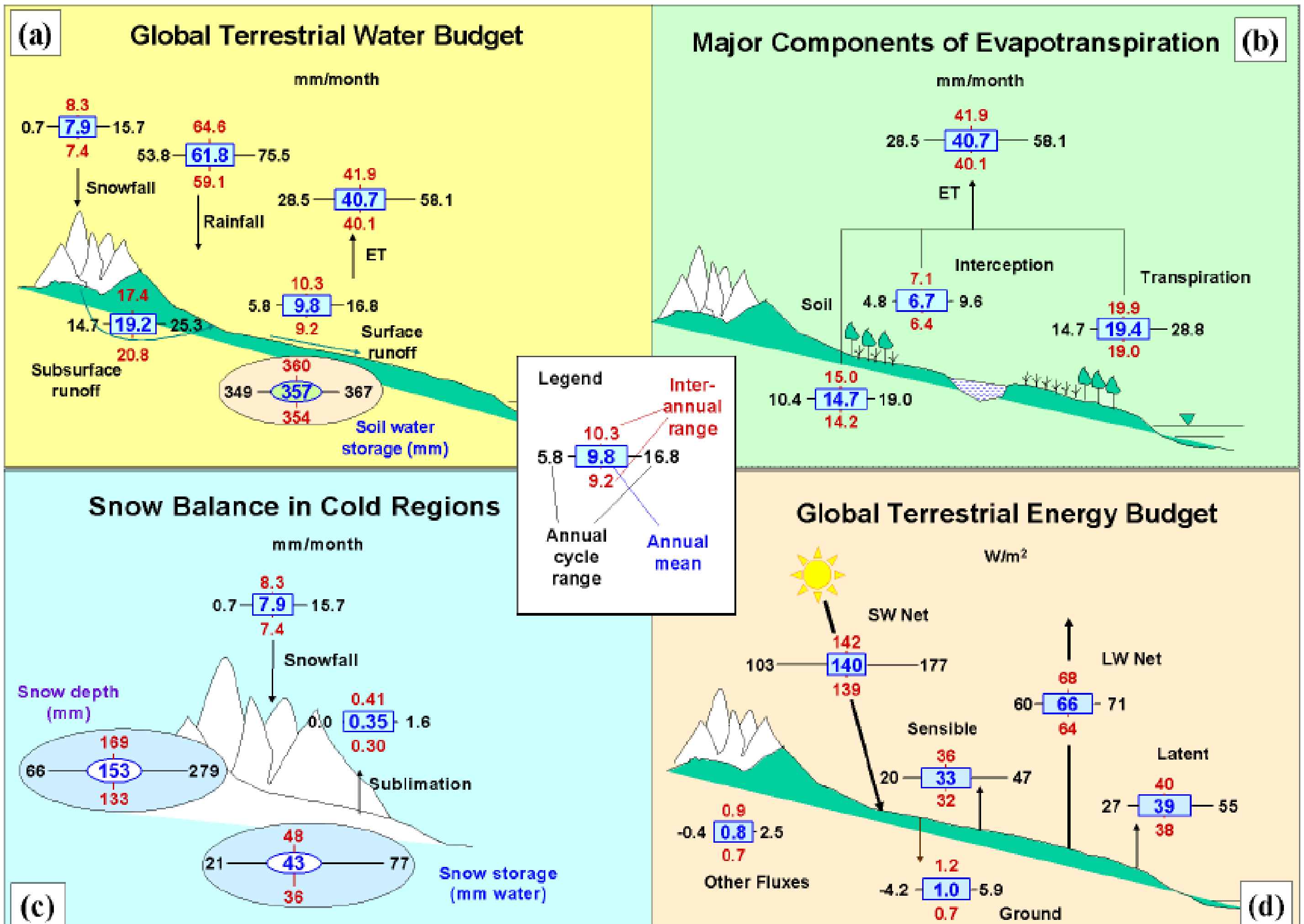
MIPs: Multi-model Inter-comparison Projects

- Examples: PILPS [Henderson-Sellers et al., 1995] and the Global Soil Wetness projects I and II [Entin et al., 1999; Guo and Dirmeyer, 2006].
- Goals:
  - Model improvement
  - Global assessment of the hydrological cycle (fluxes)
  - Feedback studies
- Critique on MIPs:
  - They further model entanglement
  - Participating models is haphazard
  - Difficult to pinpoint where differences come from

1. Development of global hydrology

Atmospheric science: LSMs

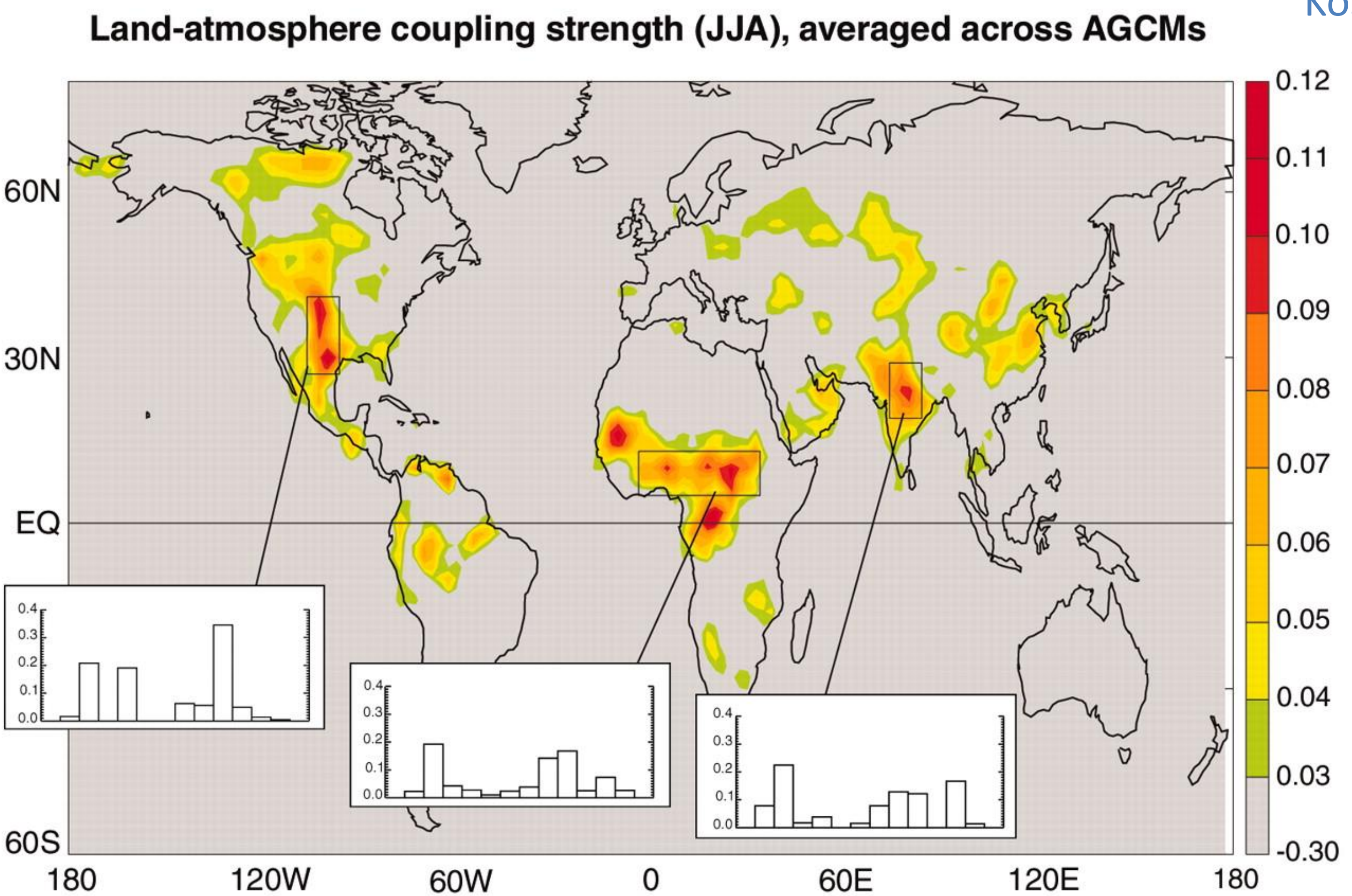
MIPs in global water resources assessments: GSWP II



1. Development of global hydrology

Atmospheric science: LSMs

MIPs in coupled model: e.g. GLACE Koster et al. (2006)

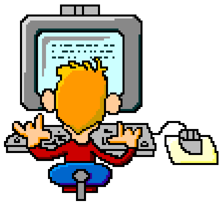


1. Development of global hydrology

Hydrology and water resources

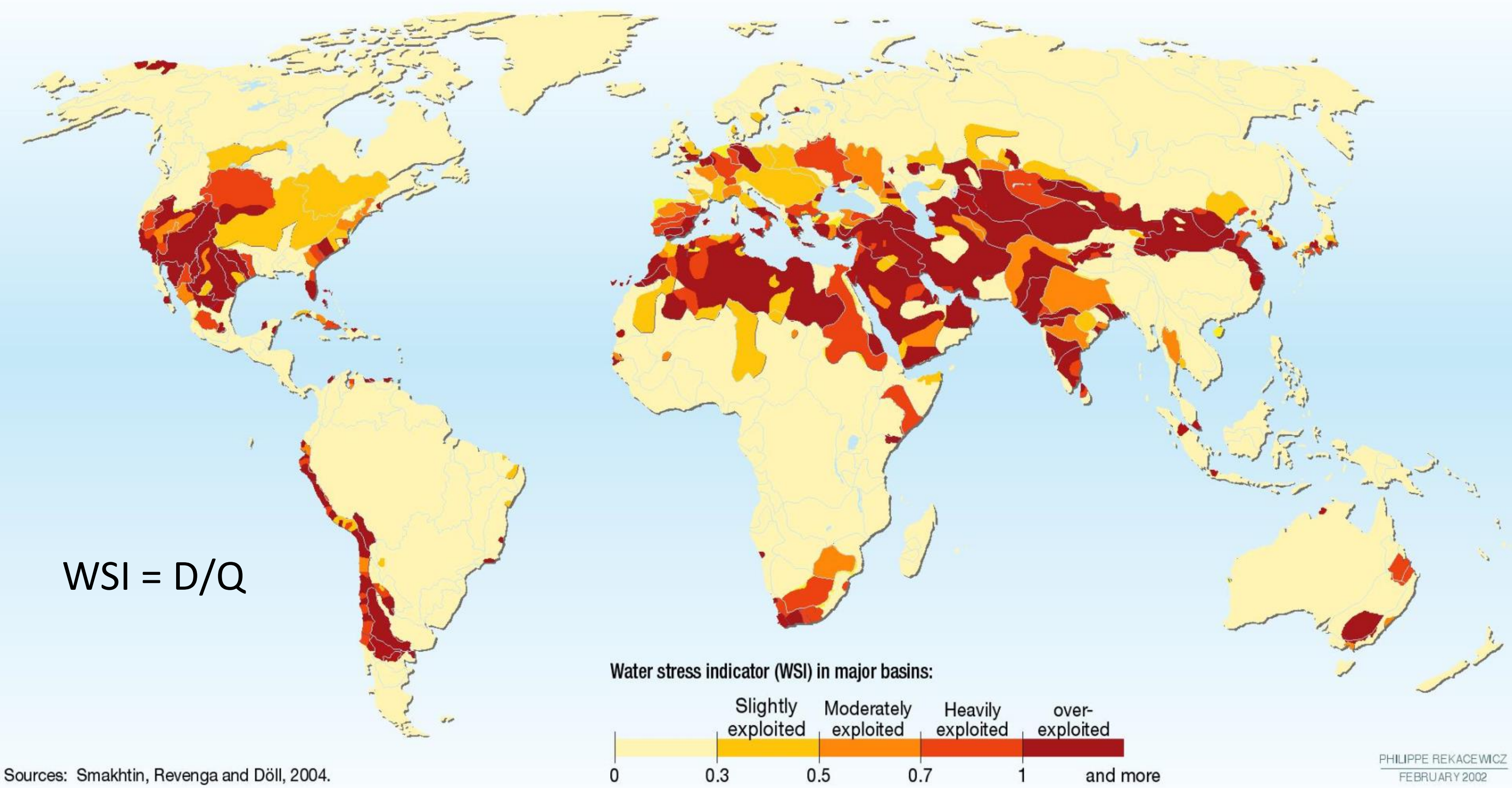
- Late 1980s and early 1990s: awareness of the shortage of global water resources (Falkenmark, 1989; Gleick, 1989, 1993)
- Late 1990: First detailed global water resources assessments comparing water availability with water use (Shiklomanov, 1997). mostly relied on statistics of water use (e.g., AQUASTAT) and observations of hydrology.
- Shortly thereafter: first Macroscale hydrological models (MHMs): WaterGap (1997), WBM (1998) and MacPDM (Arnell, 1999).
- **New features: modelling human water use (inspired by Integrated Assessment Models)**

Livestock densities, Irrigated areas, Population (Total, urban and rural), GDP, Electricity production, Energy and household consumption, Access to water (Total, urban and rural), Climate data (Temperature, radiation, cloud cover, wind speed, etc)



1. Development of global hydrology

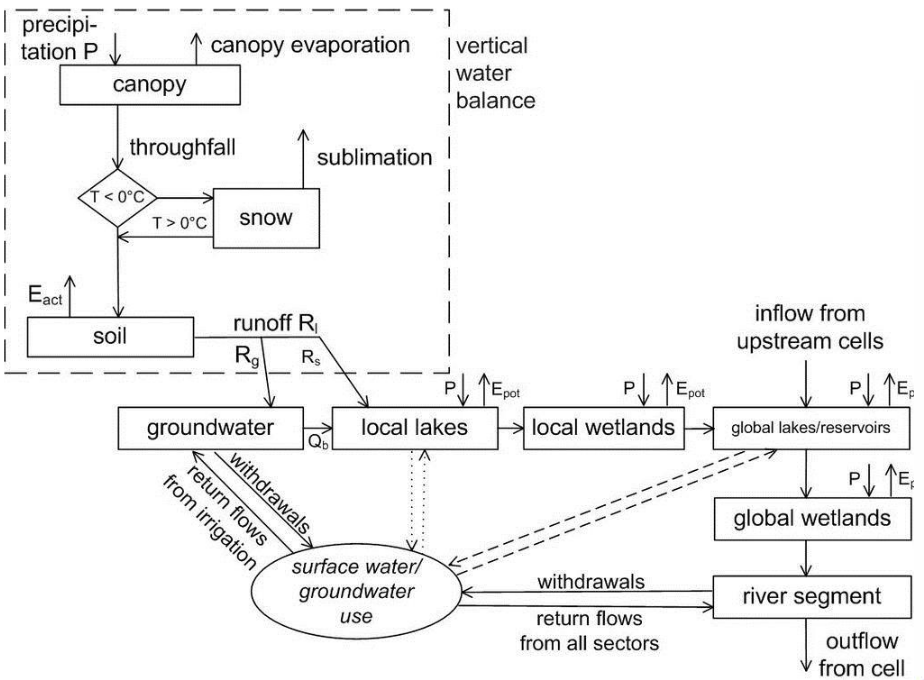
Hydrology and water resources



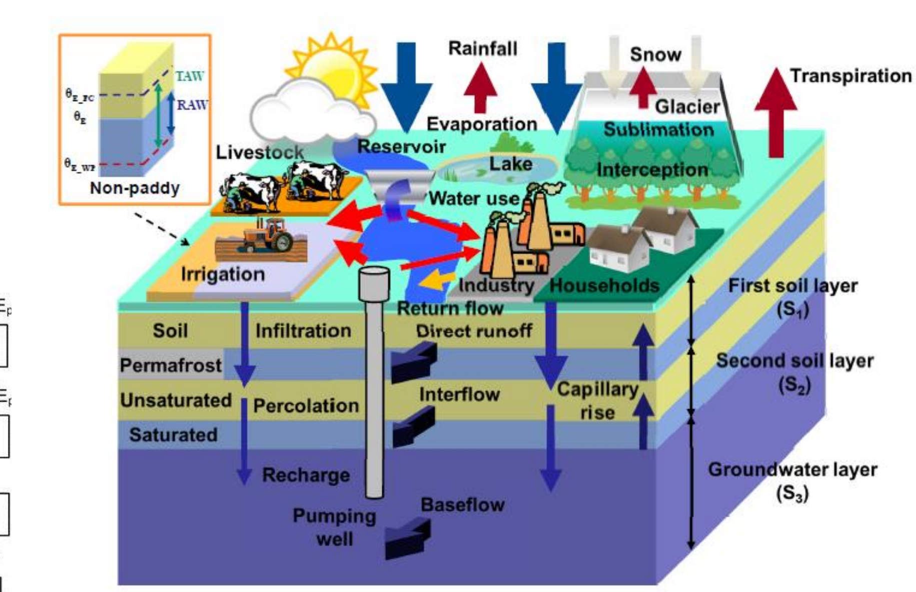
WSI = D/Q

1. Development of global hydrology

After 2010: Integrated hydrology and water resources modelling: reservoirs, water use and return flows, routing, monthly to daily analyses, 5 arcminute resolution (10x10 km)



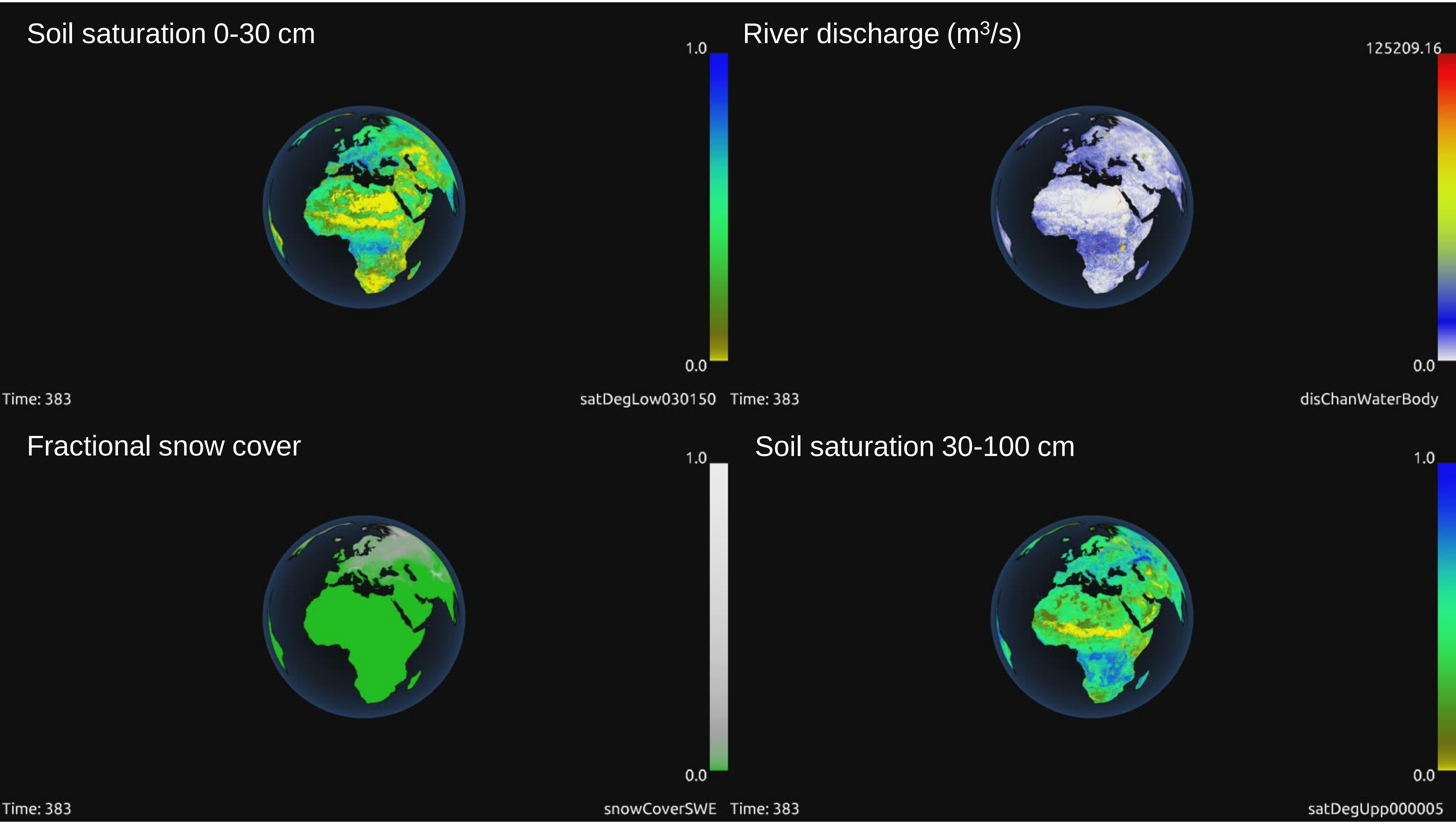
WaterGAP 3



PCR-GLOBWB 2.0

Simulation of global terrestrial water by the integrated global hydrological model PCR-GLOBWB

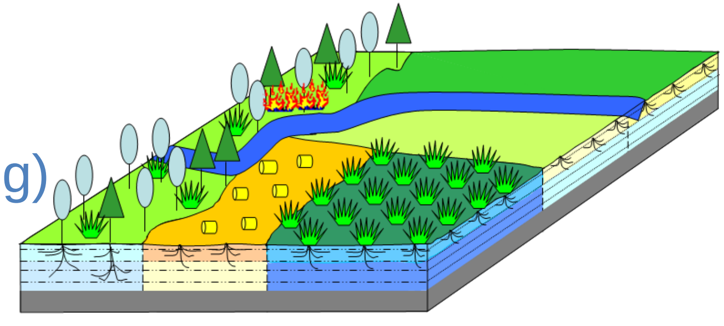
1980-2010 daily time step (time in months) at 5 minutes resolution



1. Development of global hydrology

Vegetation and carbon

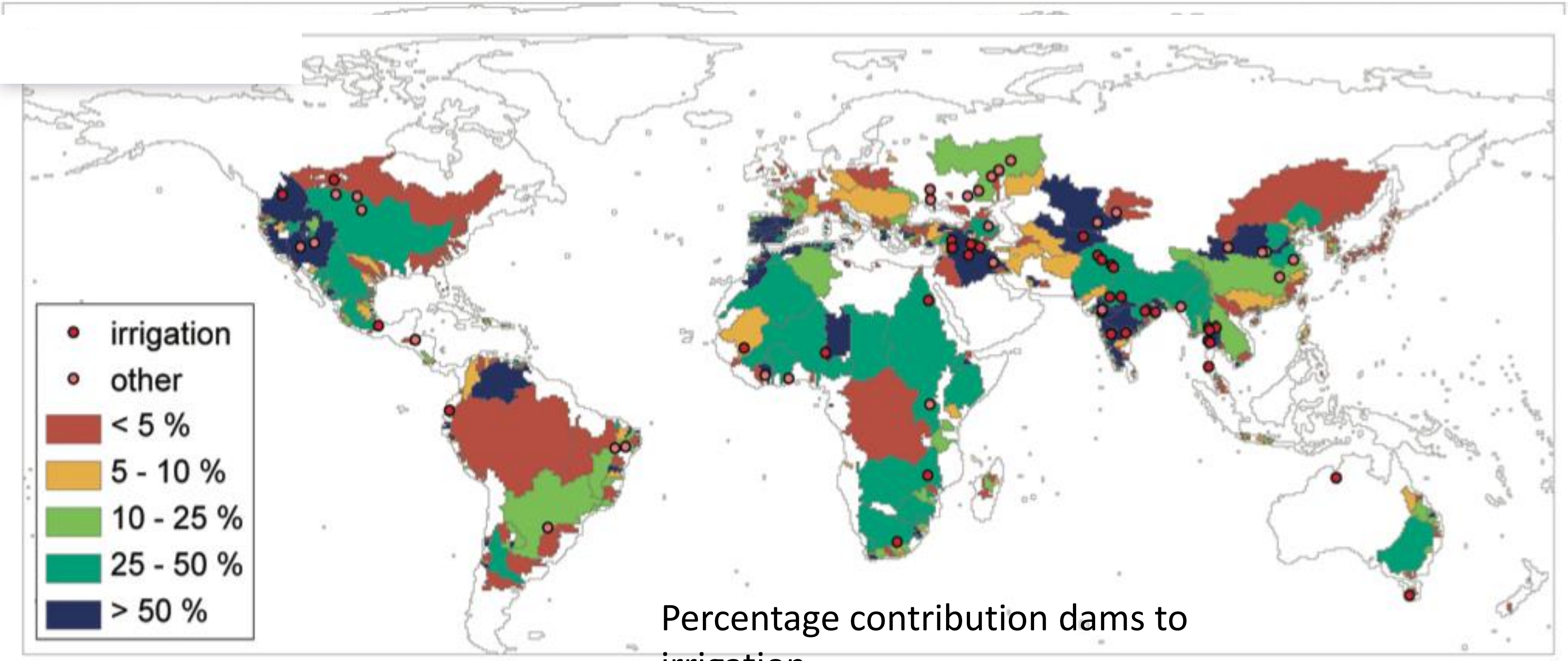
- Vegetation model: BIOME (Prentice et al., 1992): quasi-steady state; driven by monthly average hydroclimatology.
- LPJ (Sitch et al., 2003): dynamic vegetation model:
  - Plant physiology + stomatal response
  - Carbon-assimilation and transpiration and growth
  - Biogeochemistry including carbon
  - Simple soil hydrology only
- Two new tastes:
  - LPJ-Geuss: more complex vegation structure and species distribution
  - LPJml: agriculture and more complete hydrology (reservoirs, routing)



1. Development of global hydrology

Vegetation and carbon

Biemans et al. (2011): hydrology in LPJml – impact of reservoirs on irrigation



Percentage contribution dams to irrigation

Datasets !

Table 1. Some Important Data Sets Used in Global Modeling

Model Parameterization

GLCC land cover data: http://landcover.usgs.gov/landcoverdata.php

GLiM—Global surface lithology at 1 km: http://www.clisap.de/research/b:-climate-manifestations-and-impacts/crg-chemistry-of-natural-aqueous-solutions/global-lithological-map/ [*Hartmann and Moosdorf*, 2012]

GLHYMPS—Global HYdrogeology MaPS of permeability and porosity [*Gleeson et al.*, 2014]

Global map of irrigated areas: http://www.uni-frankfurt.de/45218039/Global_Irrigation_Map [*Döll and Siebert*, 2000]

SoilGrids1km—Global soils and soil properties at 1 km: http://soilgrids.org [*Hengl et al.*, 2014]

GRanD—Global reservoirs and dams database; contains 6862 records of reservoirs and their associated dams with a cumulative storage capacity of 6197 km^3 (>75% of the total volume of storage of reservoirs >0.01 km^3; http://sedac.ciesin.columbia.edu/data/set/grand-v1-dams-rev01)

HYDRO1k—1 km hydrological DEM and drainage network derived from GTOPO30: https://lta.cr.usgs.gov/HYDRO1K [*Verdin and Greenlee*, 1996]

HYDROSHEDS—Multiscale hydrological DEM and drainage network (finest resolution 90 m) as derived from the Shuttle Topography Mission. http://hydrosheds.cr.usgs.gov/index.php [*Lehner et al.*, 2008]

MIRCA2000—Global data set of monthly irrigated and rainfed crop areas around the year 2000. http://www.uni-frankfurt.de/45218023/MIRCA [*Portmann et al.*, 2010]

Meterological Forcing

CRU—Monthly meteorological forcing from observations 1901-current: http://www.cru.uea.ac.uk/cru/data/hrg/. TS V 1.0 [*New et al.*, 2000]; TS V 3.22 [*Harris et al.*, 2014]

ERA-40 1.25° daily meteorological forcing from ECMRWF reanalysis 1958–2001: http://apps.ecmwf.int/datasets/data/era40_daily/ [*Uppula et al.*, 2005]

ERA-Interim 0.8° daily meteorological forcing from ECMRWF reanalysis 1979-current: http://data-portal.ecmwf.int/data/d/interim_daily/ [*Dee et al.*, 2011]

GPCP—Global precipitation climatology project: daily, monthly, and climatology data sets at 1° composed from combinations of multi-satellite data (microwave, infrared), 6000 gauges and sounding observations: http://www.gewex.org/gpcp.html [*Huffman et al.*, 2001]

MERRA—Daily meteorological forcing from the NASA Goddard Earth Observing System Data Assimilation System Version 5: http://gmao.gsfc.nasa.gov/research/merra/ [*Rienecker et al.*, 2011]

NCEP-CFSR 0.5° hourly reanalysis data from NCEP/NOAA for the period 1979–2011: http://nomads.ncdc.noaa.gov/ [*Saha et al.*, 2010]

WFD—Watch forcing data set: 0.5° 3/6 hourly meteorological forcing from ECMRWF reanalysis (ERA40) bias-corrected and extrapolated by CRU TS and GPCP (rainfall) and corrections for under catch. http://www.waterandclimatechange.eu/about/watch-forcing-data-20th-century [*Weedon et al.*, 2011]

Model Calibration and Validation

EWA-Friend European catchment data: http://www.bafg.de/GRDC/EN/04_spcldtbss/42_EWA/ewa_node.html

FLUXNET: Water vapor, energy, and CO_2 land-atmosphere fluxes from towers: http://fluxnet.ornl.gov/obtain-data

GRACE—Gravity recovery and climate experiment: http://grace.jpl.nasa.gov/

GRDC global runoff data: http://www.bafg.de/GRDC/EN/Home/homepage_node.html

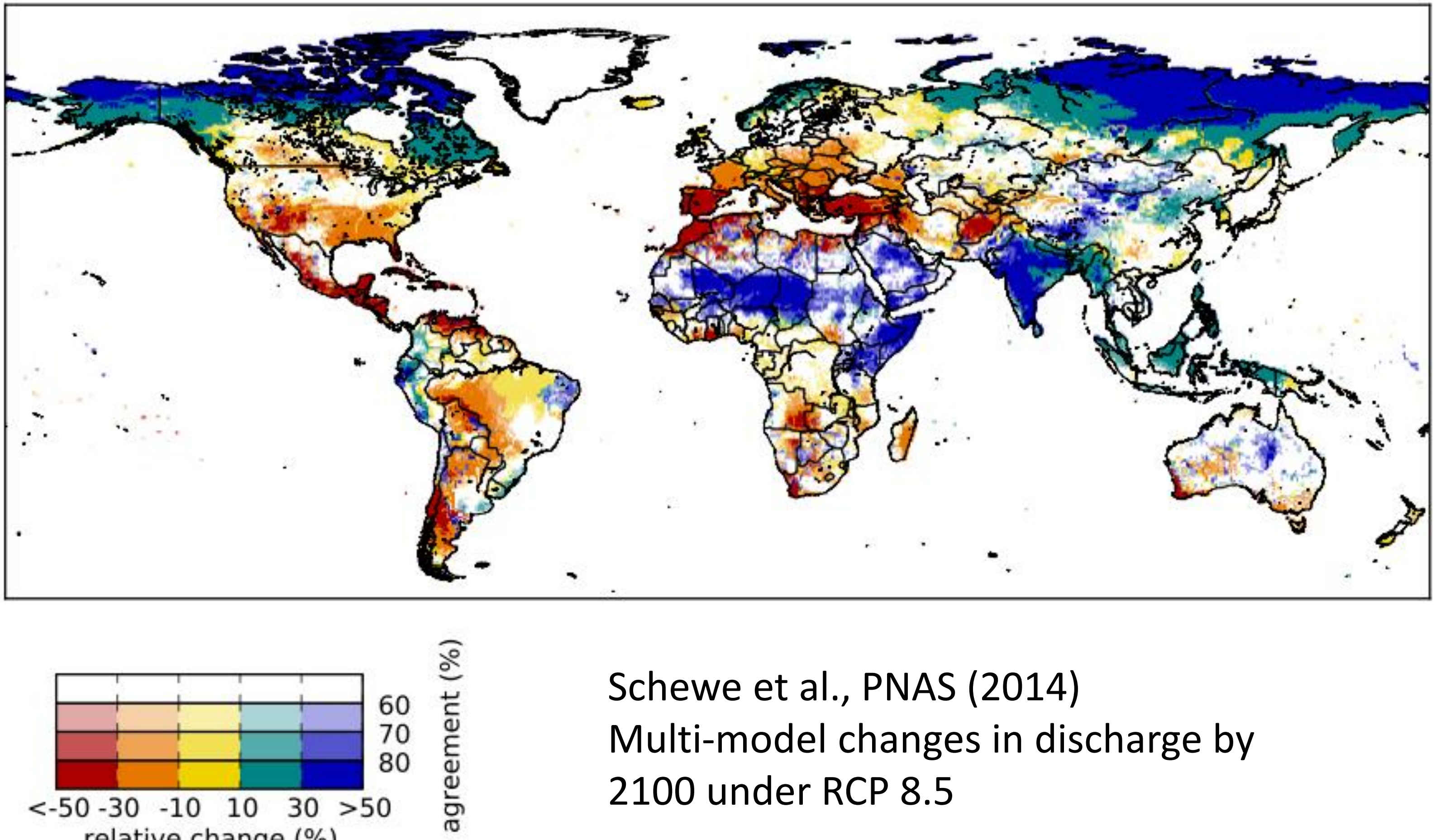
ISMN—Global network of soil moisture data: https://ismn.geo.tuwien.ac.at/ismn/ [*Dorigo et al.*, 2011]

MOPEX—US catchment data: ftp://hydrology.nws.noaa.gov/pub/gcip/mopex/US_Data/

RIVDIS—Global river discharge, 1807–1991, Version 1.1: http://www.daac.ornl.gov [*Vörösmarty et al.*, 1996]

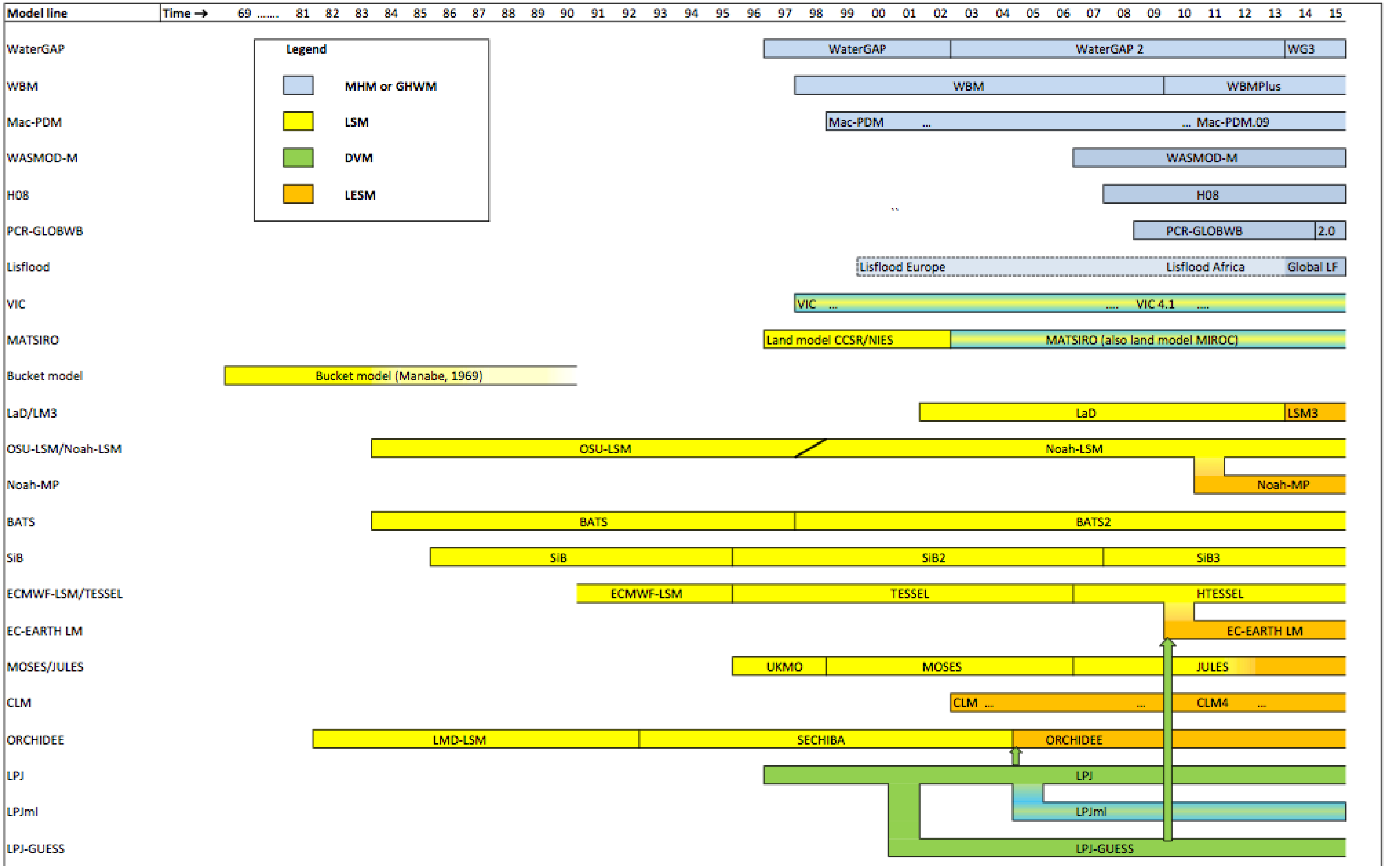
1. Development of global hydrology

Inter-Sectoral MIPs: ISI-MIP



Schewe et al., PNAS (2014)
Multi-model changes in discharge by 2100 under RCP 8.5

Genealogy of global hydrological models



2. Taking stock

Looking back at Eagleson (1986):

All things that Eagleson called for or wished for have come true

- Global hydrology is now a mature field of research: multiple disciplines
- Global hydrology is central to earth system science
- Large number of global datasets are readily available
- Students are growing up with global modelling skill

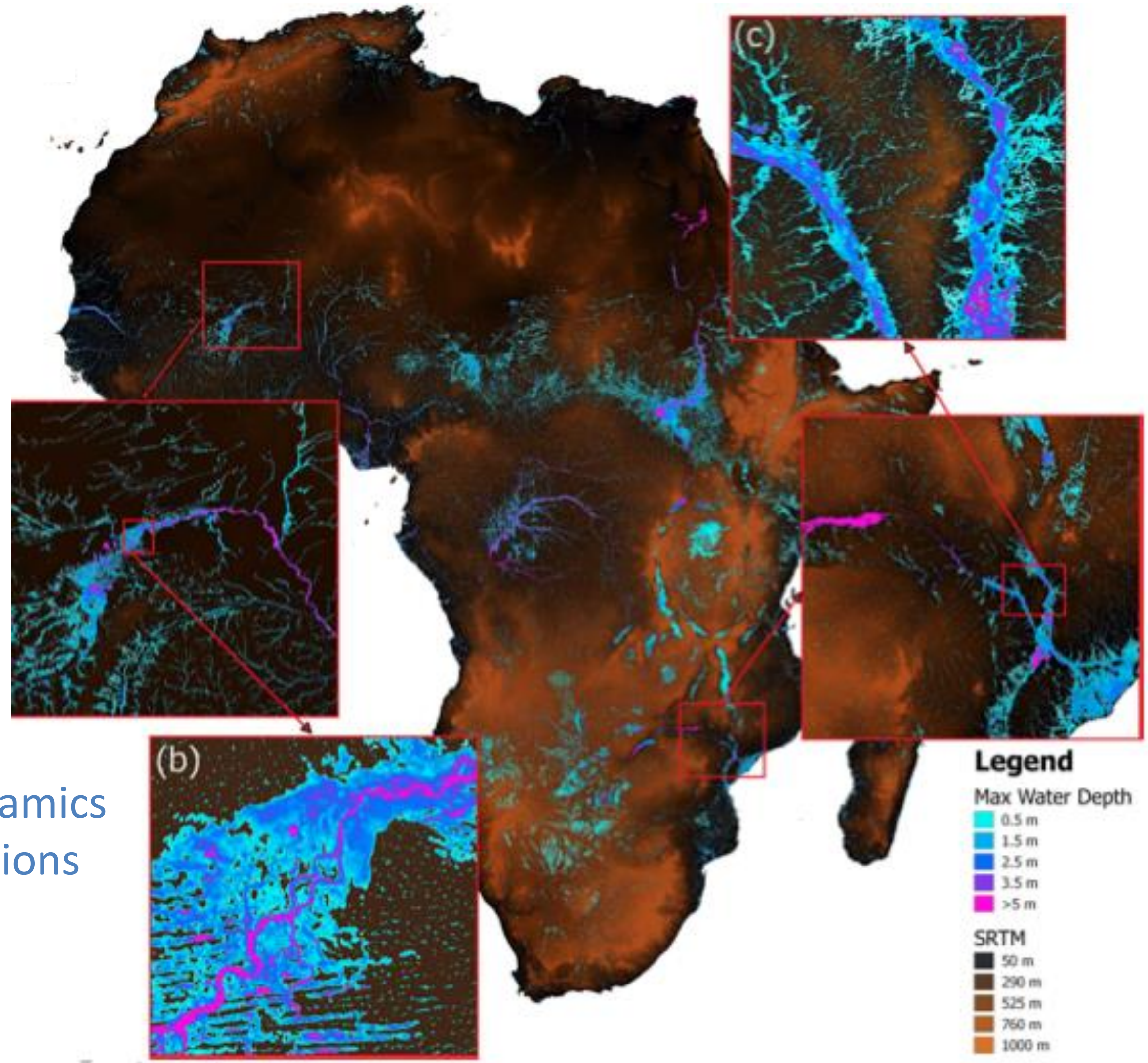
Missed opportunities

- Connecting with catchment hydrology to improve runoff representation
- Adopting better regularization and calibration procedures

3. Recent trends

3a. Technological advances: global flood (risk) modelling

1. Bates et al. (2010), Samson et al. (2015)
2. Yamazaki et al. (2011), Hirabayashi, et al. (2013)
3. Winsemius et al. (2013), Ward et al. (2014)

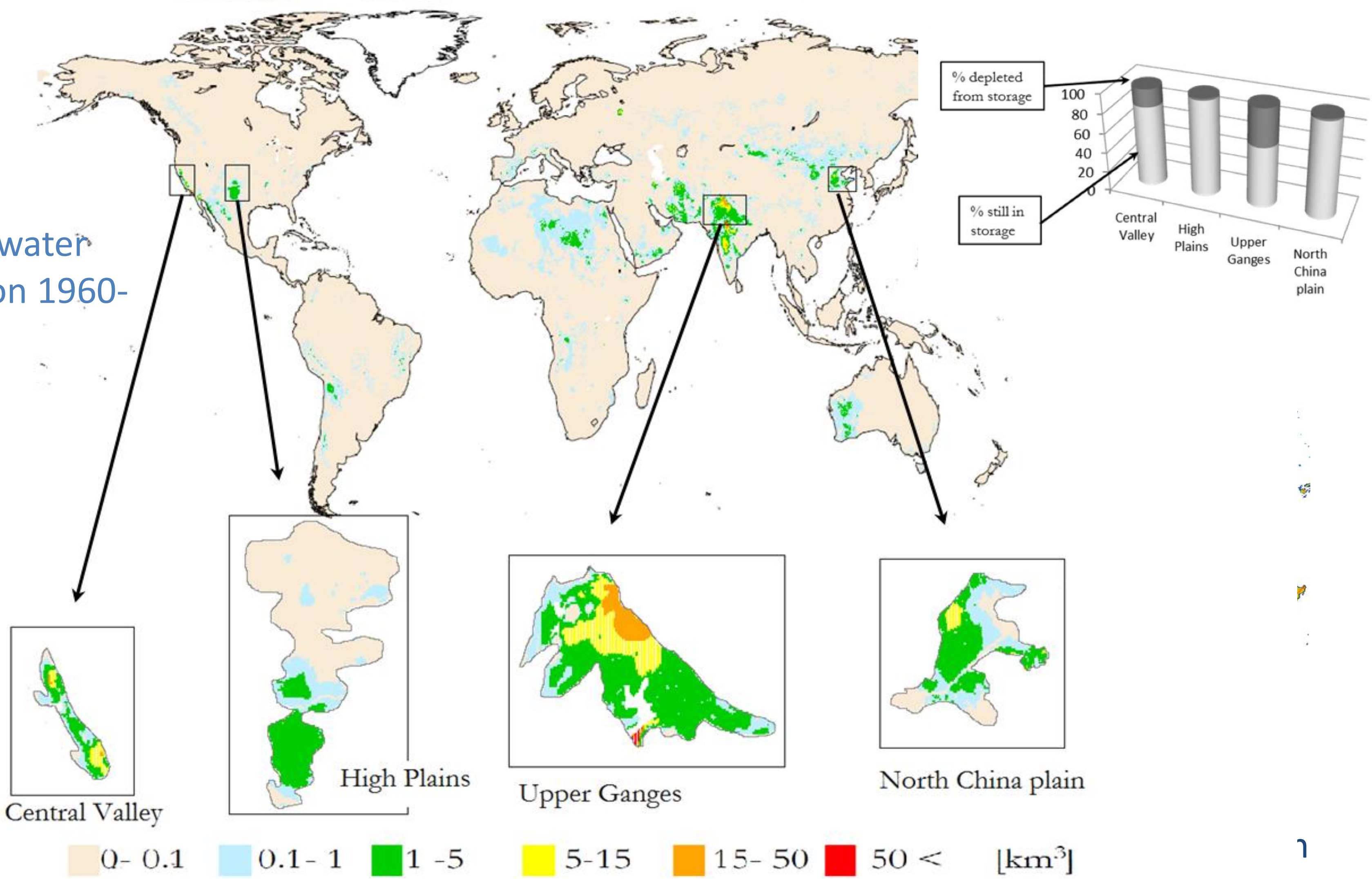


- Overbank redistribution
- 2D diffusive wave hydrodynamics
- Full 2D shallow water equations

3. Recent trends

3a. Technological advances: global groundwater modelling

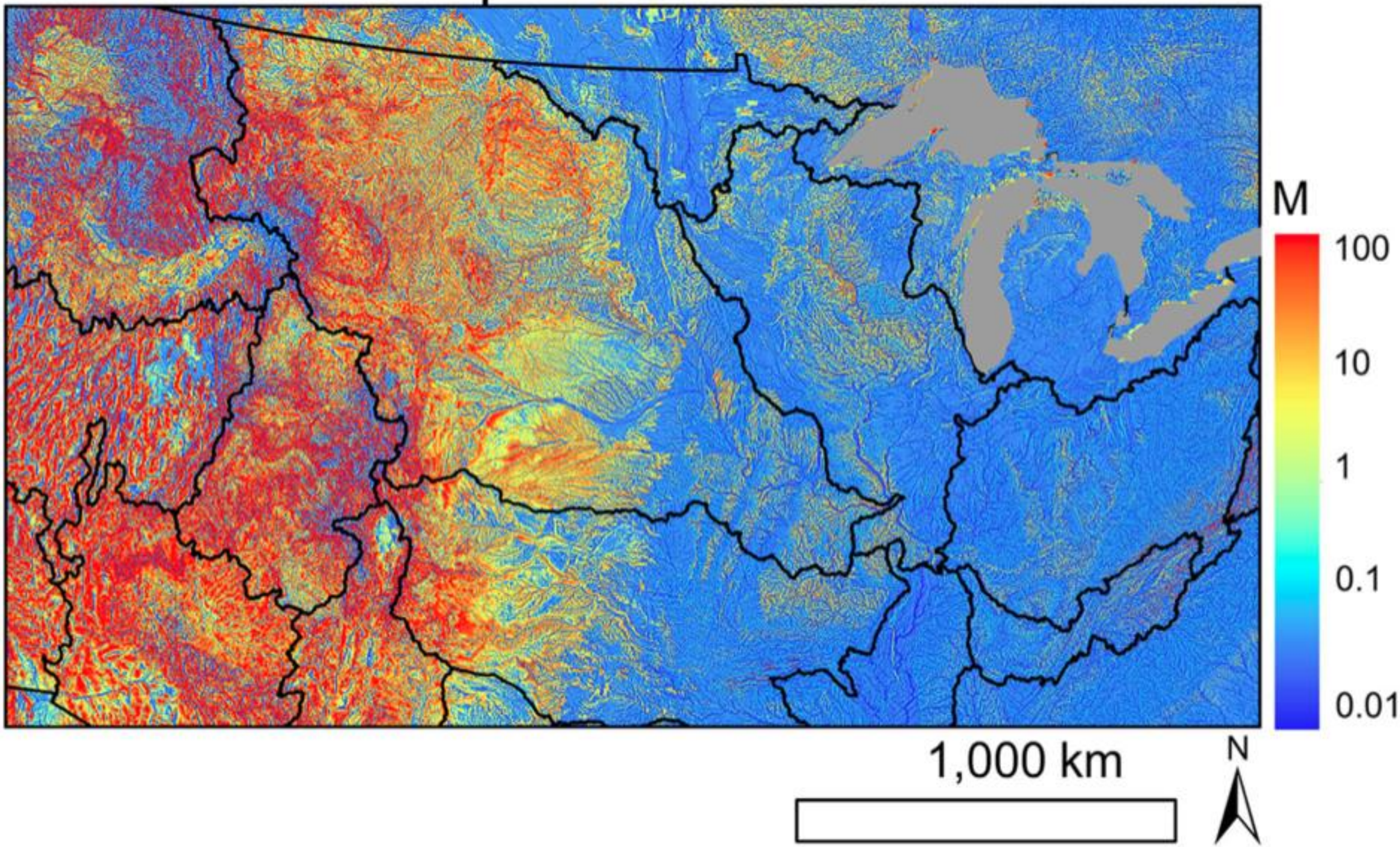
Groundwater depletion 1960-2010



3. Recent trends

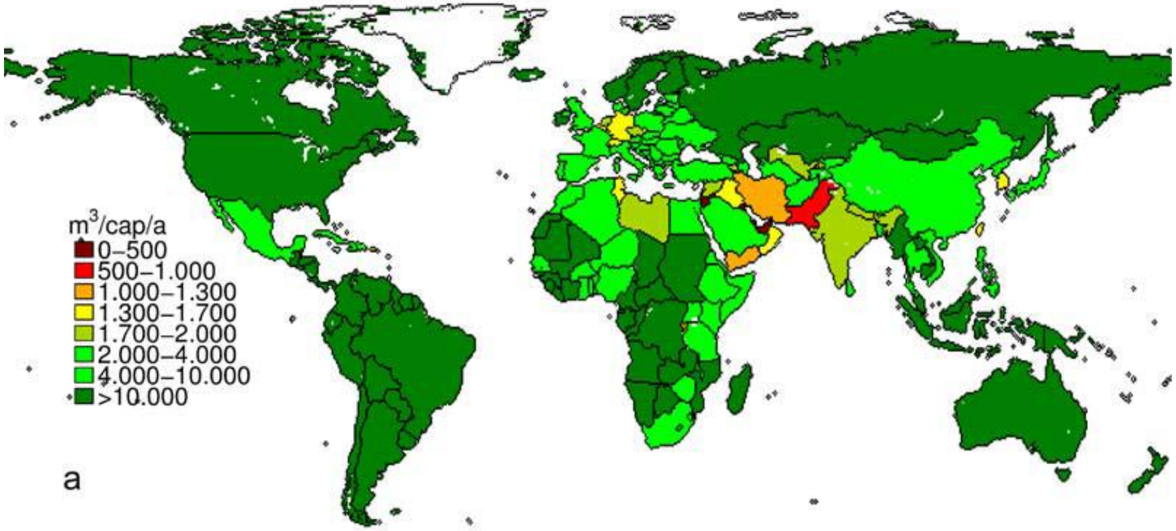
Laura Condon and Reed Maxwell, WRR (2015)

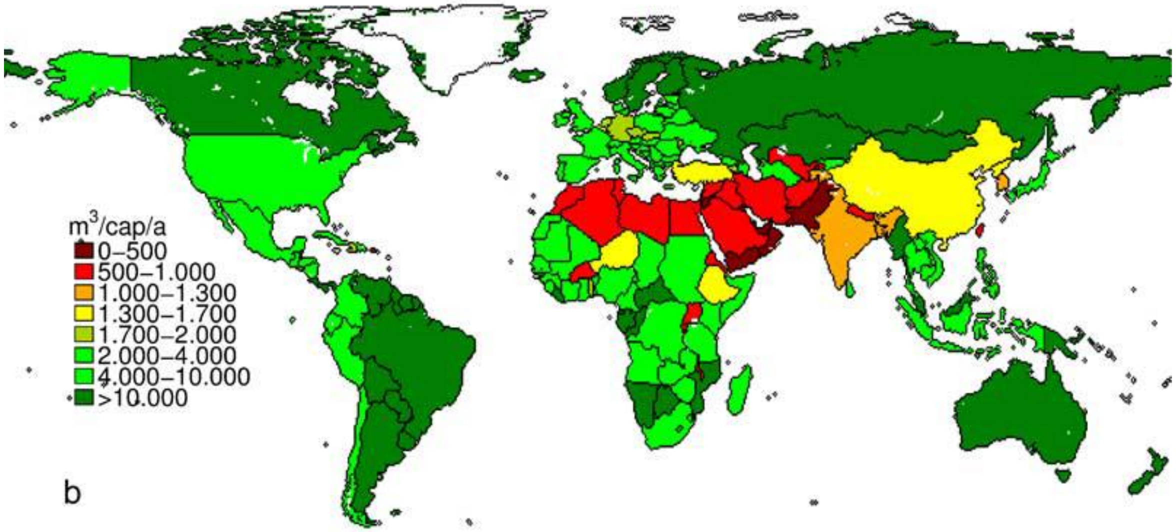
b. Water Table Depth



3. Recent trends

3b. New domains of application





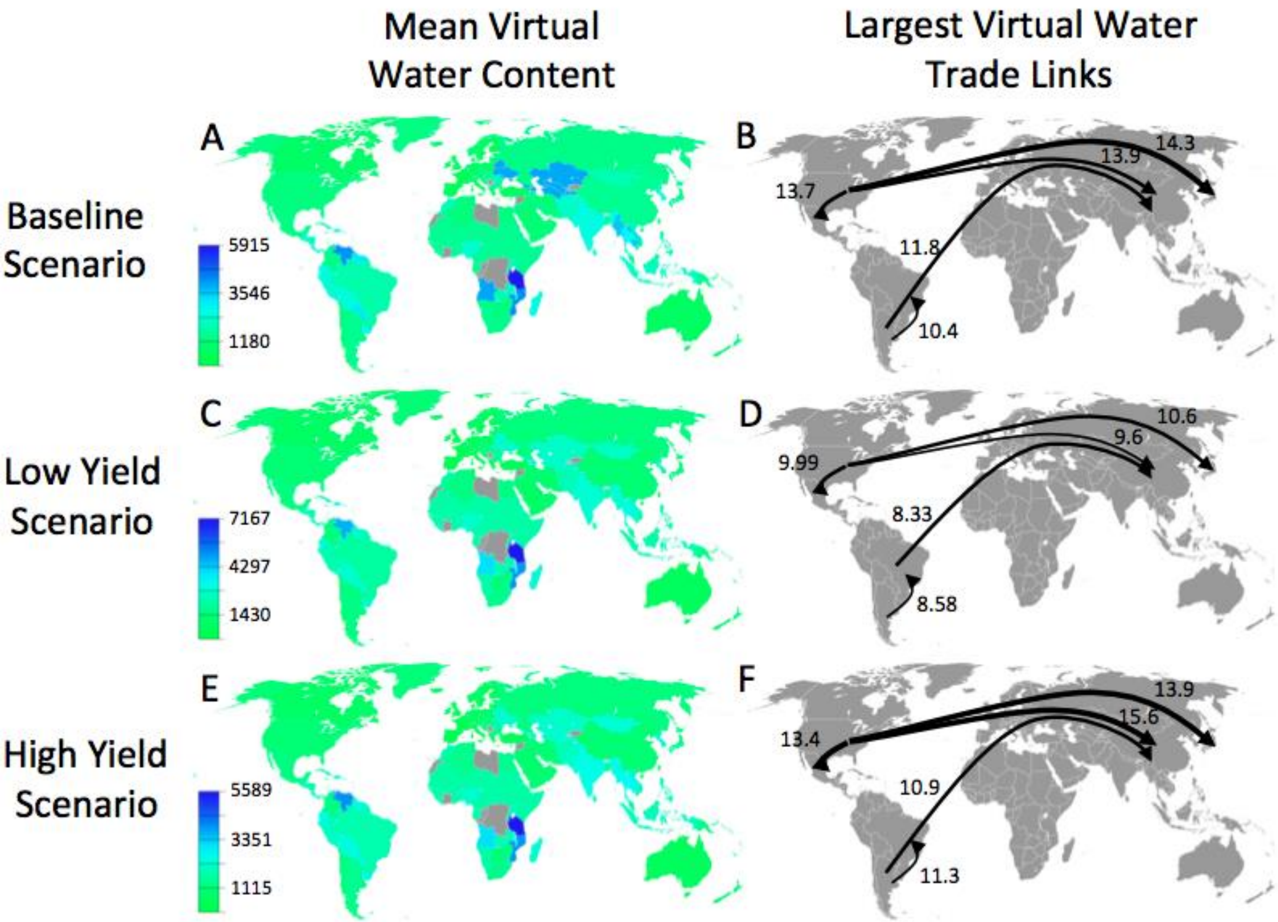
Food security

Change in green + blue water per capita by 2050 based on LPJml (Rockstrõm et al., WRR (2009)

3. Recent trends

3b. New domains of application

Hydro-economics

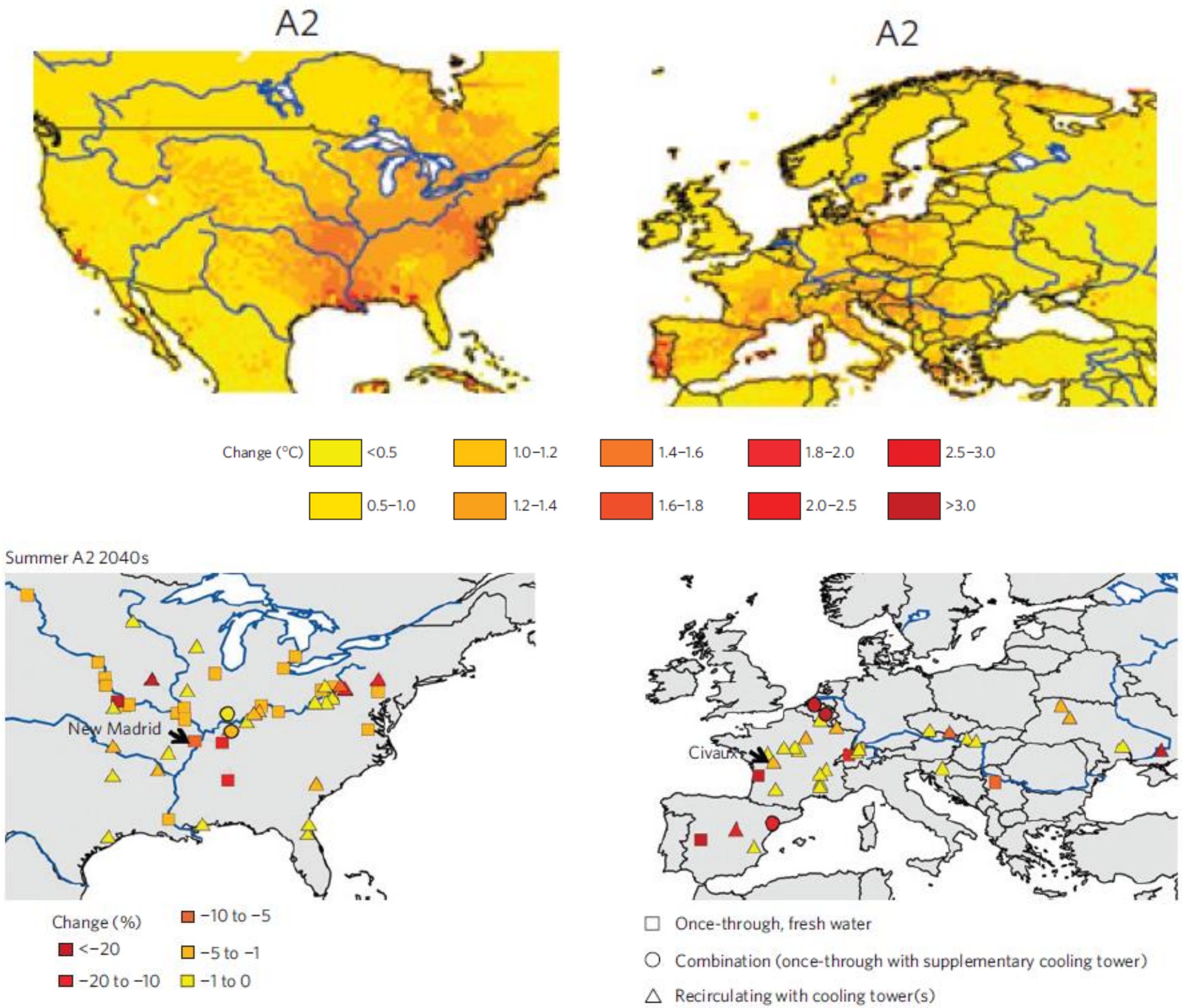


Climate change and socio-economic change on VWC (ET/Yield) per country and the effect on current food trade (trade links and future changes in trade volumes based on GTAP)

Konar et al.. HESS (2013)

3. Recent trends

3b. New domains of application



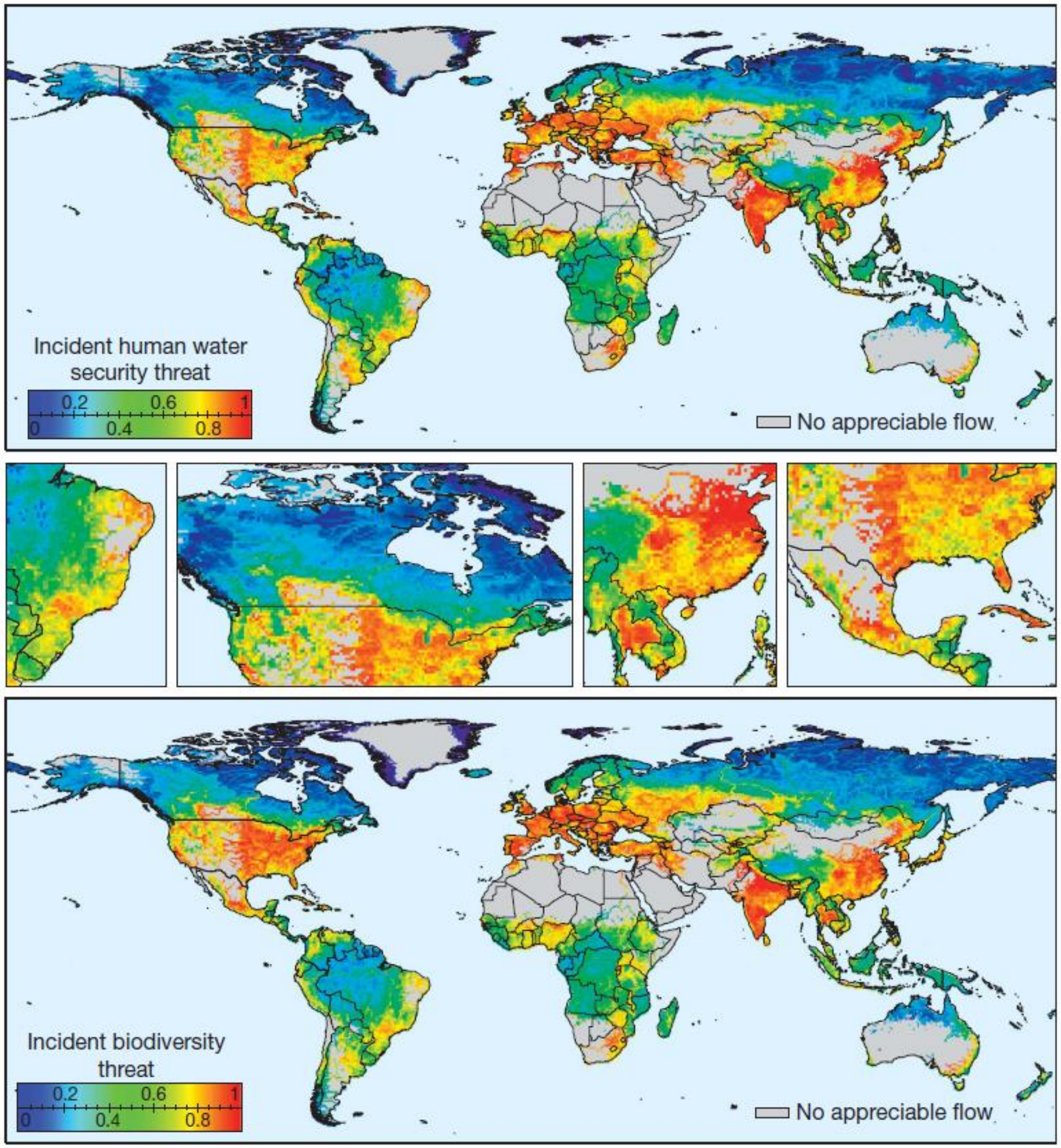
Energy

Effect of climate change on river water temperature (through dT and dQ) and the effect on power plant cooling capacity

Van Vliet et al. Nature Climate Change (2012)

3. Recent trends

3b. New domains of application



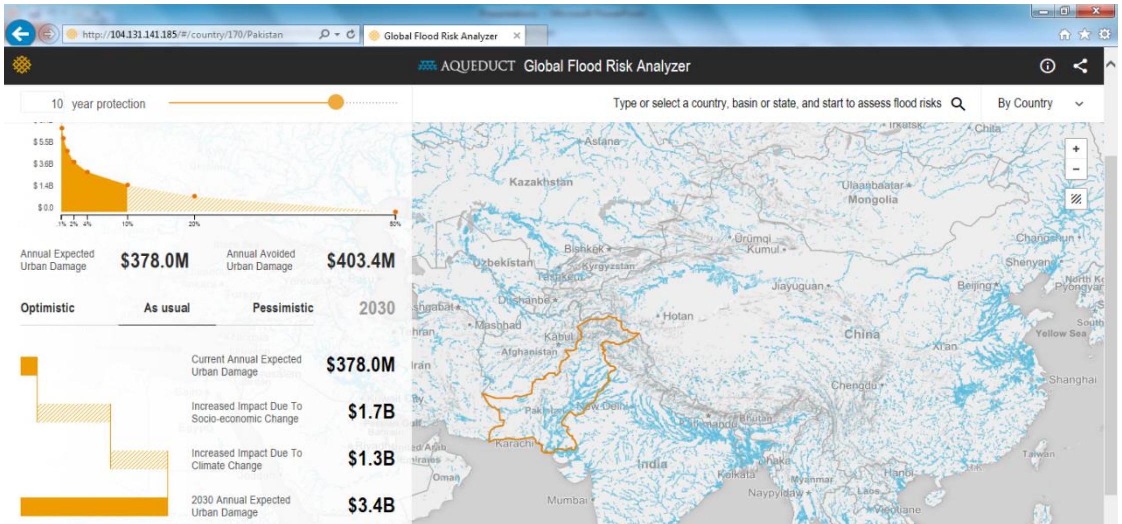
Biodiversity

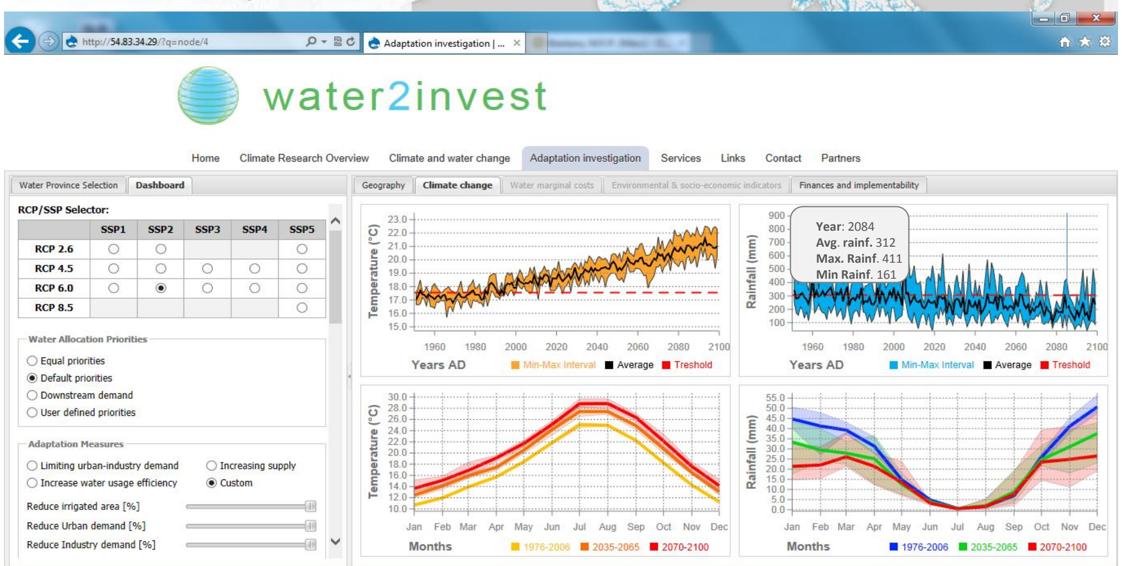
Human (blue) water security and (mostly aquatic) biodiversity are tightly connected.

Global hydrological data and the global hydrological model WBM are central to the analysis. Vörösmarty et al, Nature (2010)

3. Recent trends

3b. New domains of application





Hydro-climate services

- Flood frequency
- Flood and drought forecasting
- Climate adaptation

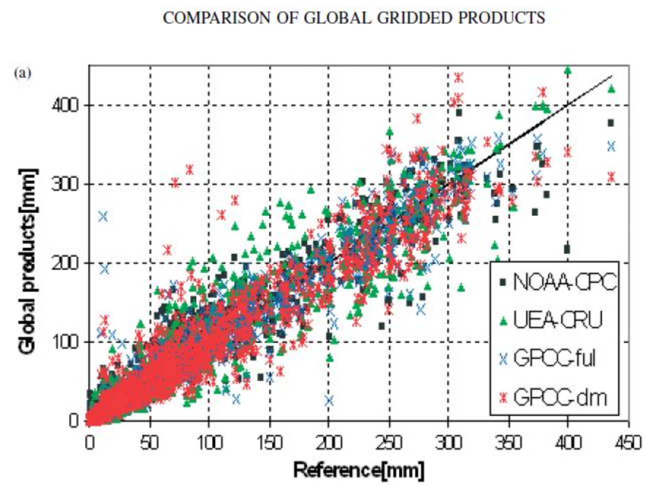
http://floods.wri.org

http://forecast.ewatercycle.org/

4. Imminent challenges

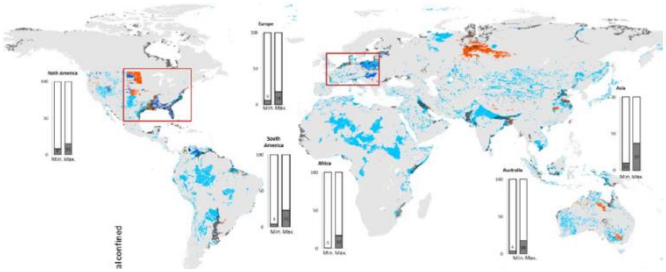
1. Long outstanding issues

- Relatively poor performance GHMs
- Accuracy rainfall products
- Runoff representations in GHMs



2. Missing data links

- Global river geometry and bathymetry
- River diversions
- Local redistribution networks
- Global hydrogeological data



4. Imminent challenges

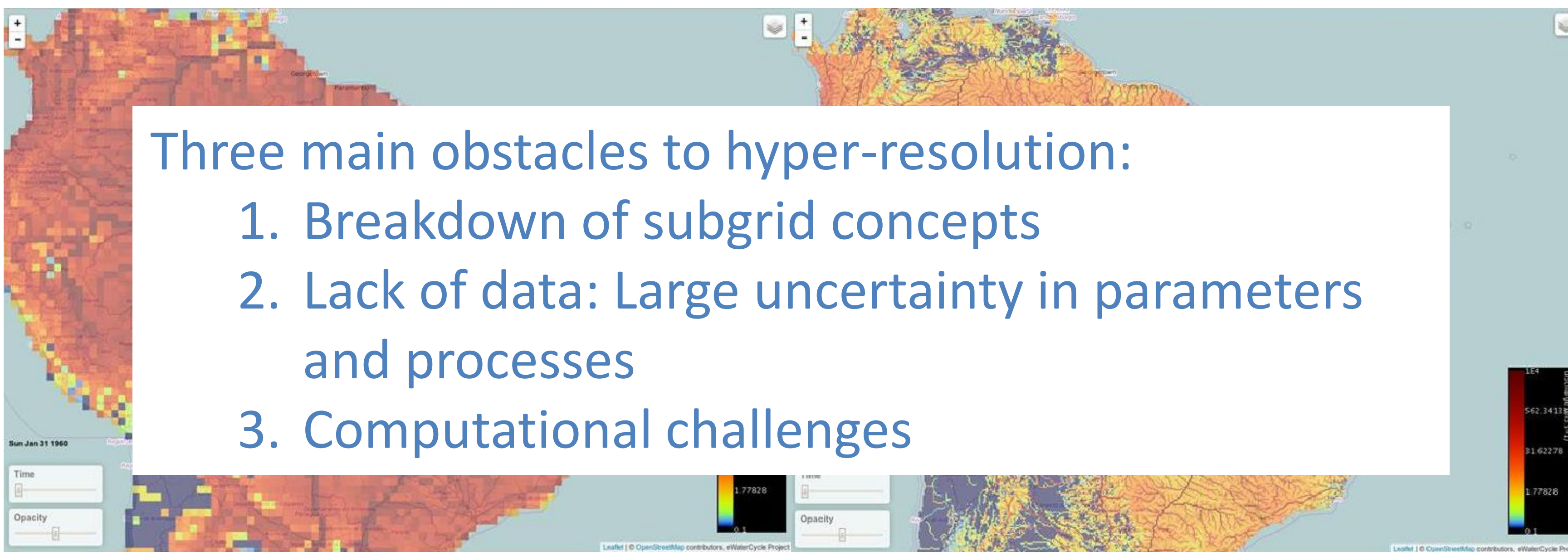
3. Hyper-resolution modelling

INVITED COMMENTARY

HP TODAY

HYDROLOGICAL PROCESSES
Hydrol. Process. (2014)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/hyp.10391

Hyper-resolution global hydrological modelling: what is next?
"Everywhere and locally relevant"



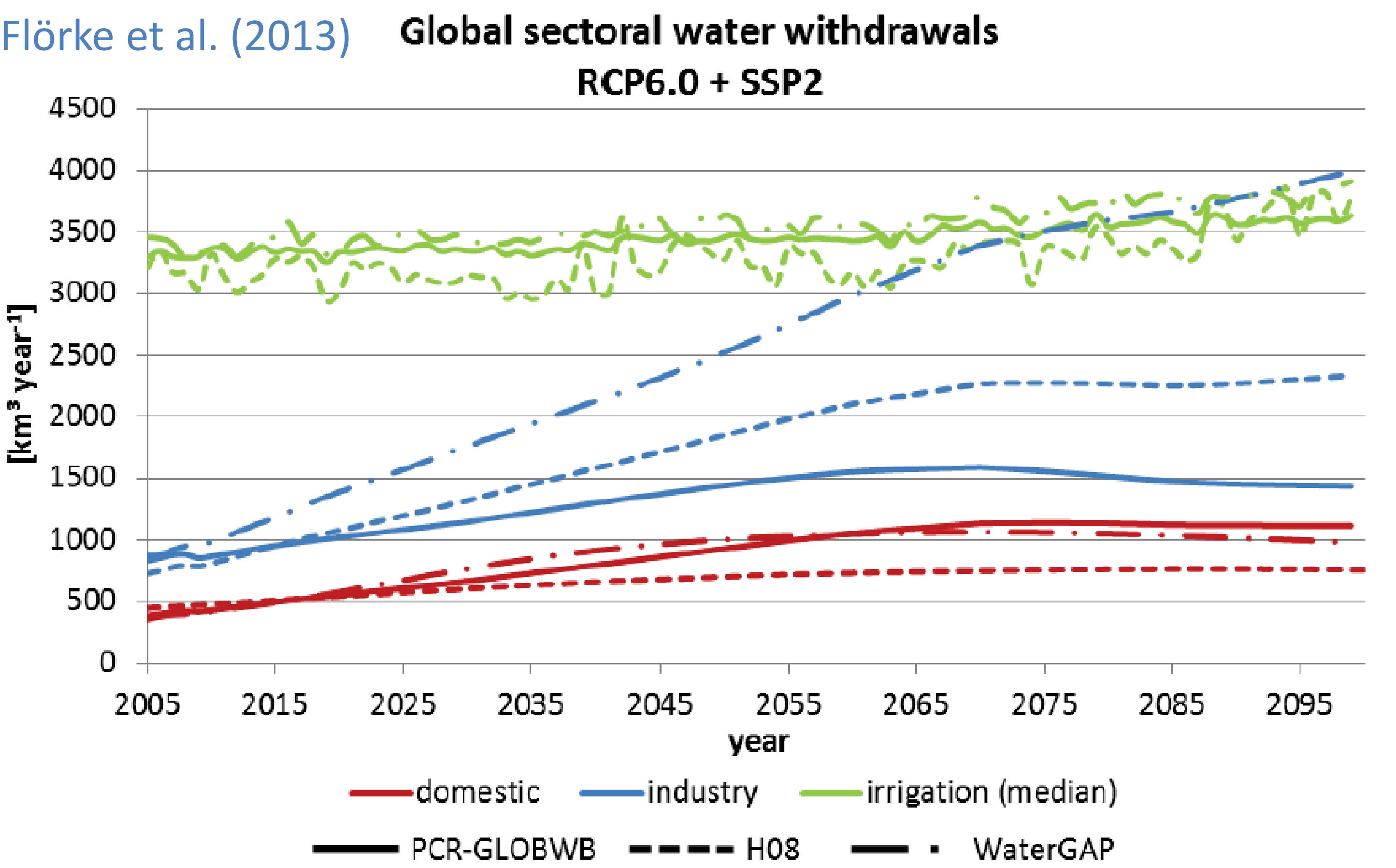
Three main obstacles to hyper-resolution:

1. Breakdown of subgrid concepts
2. Lack of data: Large uncertainty in parameters and processes
3. Computational challenges

4. Imminent challenges

4. The human factor

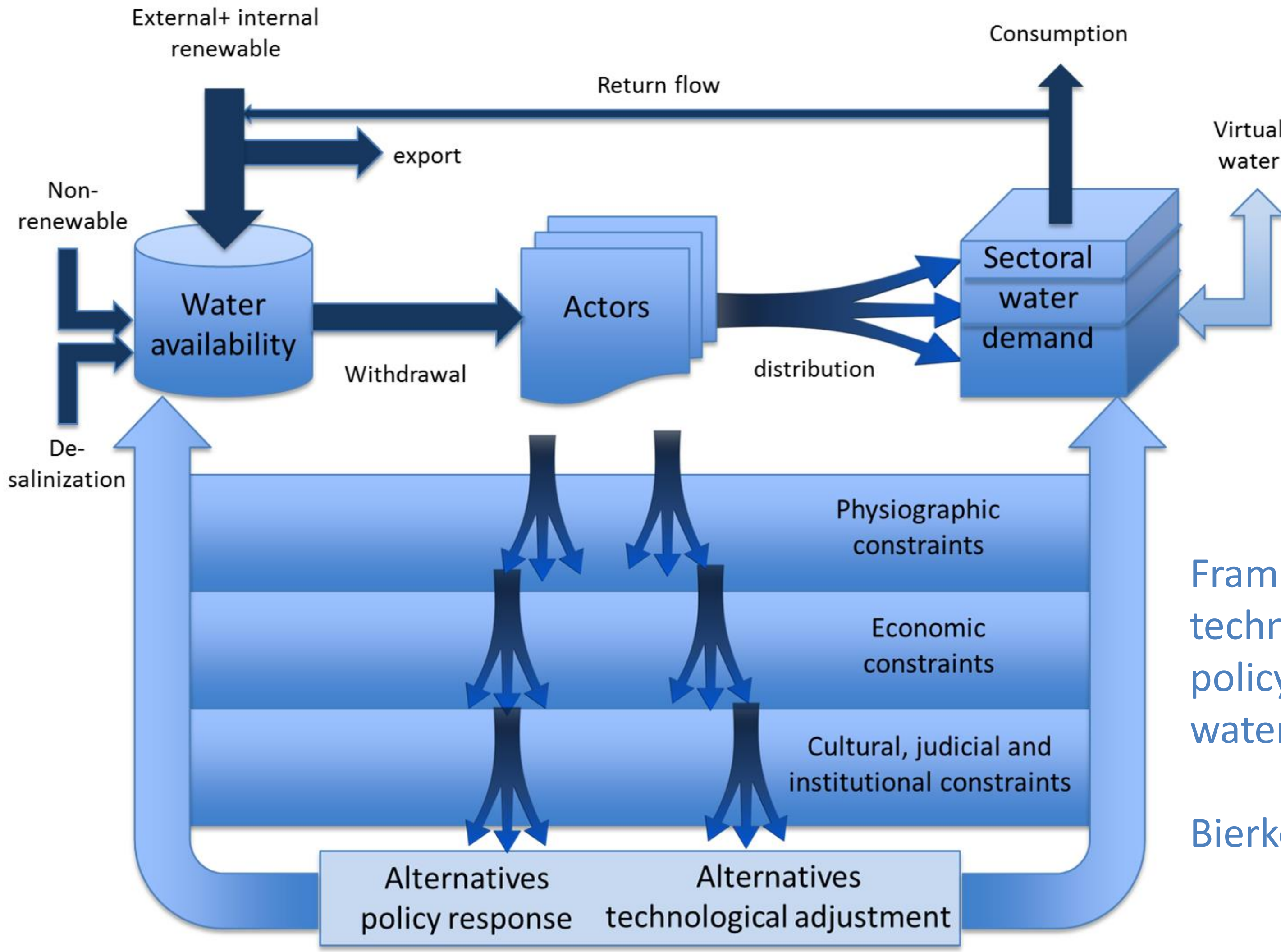
Flörke et al. (2013)



Projections from three global hydrology and water resources models

4. Imminent challenges

4. The human factor: Enter Socio-hydrology



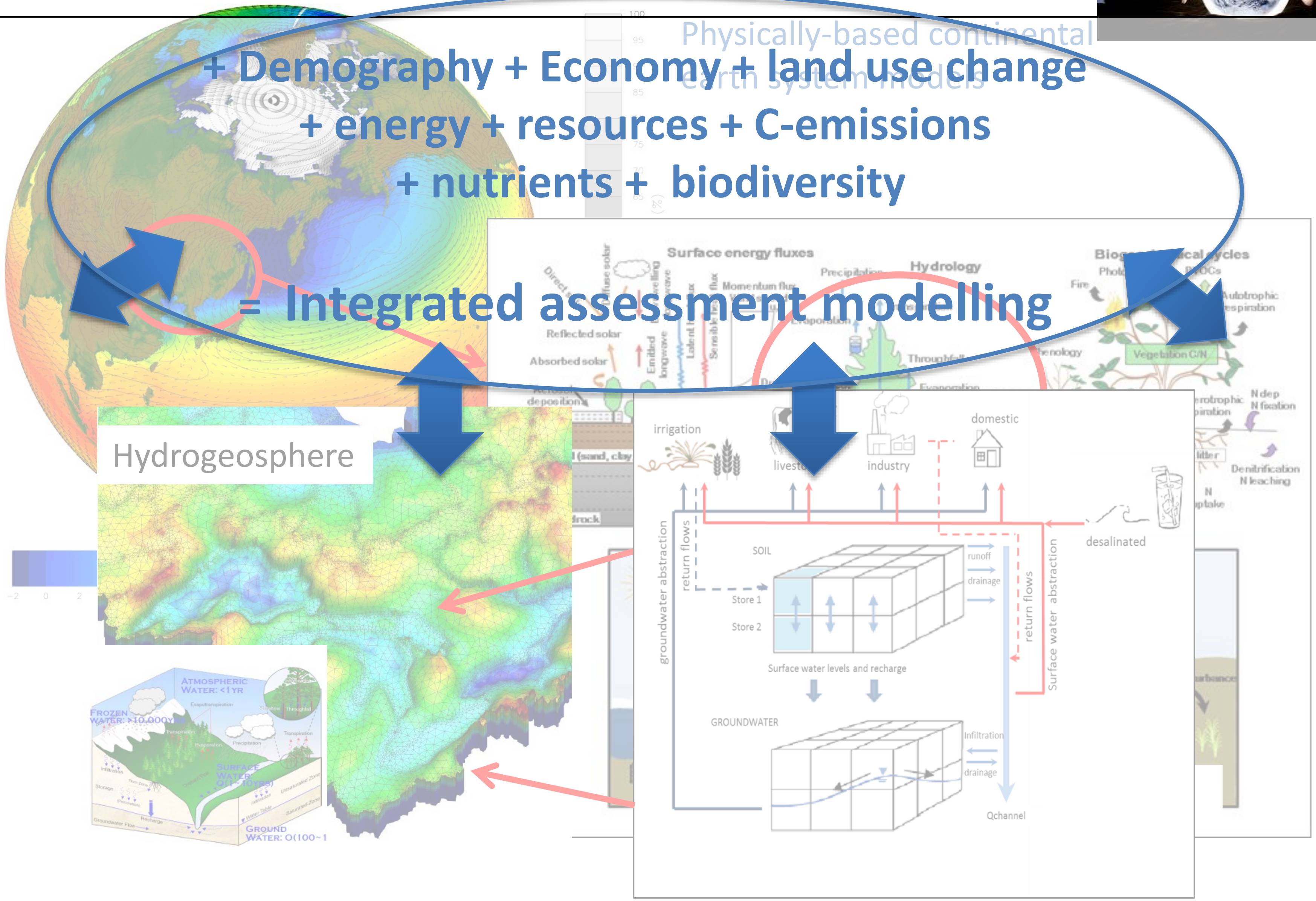
Framework for technological and policy response to water scarcity.

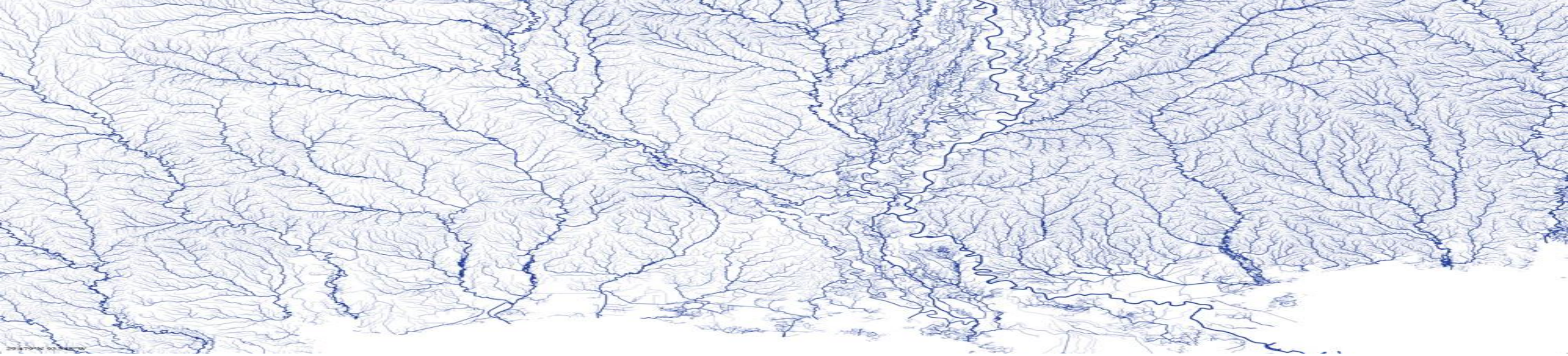
Bierkens, WRR (2015)

5. The future and beyond

+ Demography + Economy + land use change
+ energy + resources + C-emissions
+ nutrients + biodiversity

= Integrated assessment modelling





Questions?

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Water Resources Research

REVIEW ARTICLE

10.1002/2015WR017173

Special Section:
The 50th Anniversary of Water Resources Research

Global hydrology 2015: State, trends, and directions

Marc F. P. Bierkens[1,2]

[1]Department of Physical Geography, Utrecht University, Utrecht, Netherlands, [2]Deltares, Utrecht, Netherlands