Universiteit Utrecht

Deltares
Enabling Delta Life

Global scale water supply and demand:

impacts of climate and socio-economic change

Marc F.P. Bierkens[1,2], Inge E.M. de Graaf[1],
, Ludovicus P.H. (Rens) van Beek[1,]
Menno Straatsma, Edwin Sutanudjaja[1]
and Yoshihide Wada[1,2]

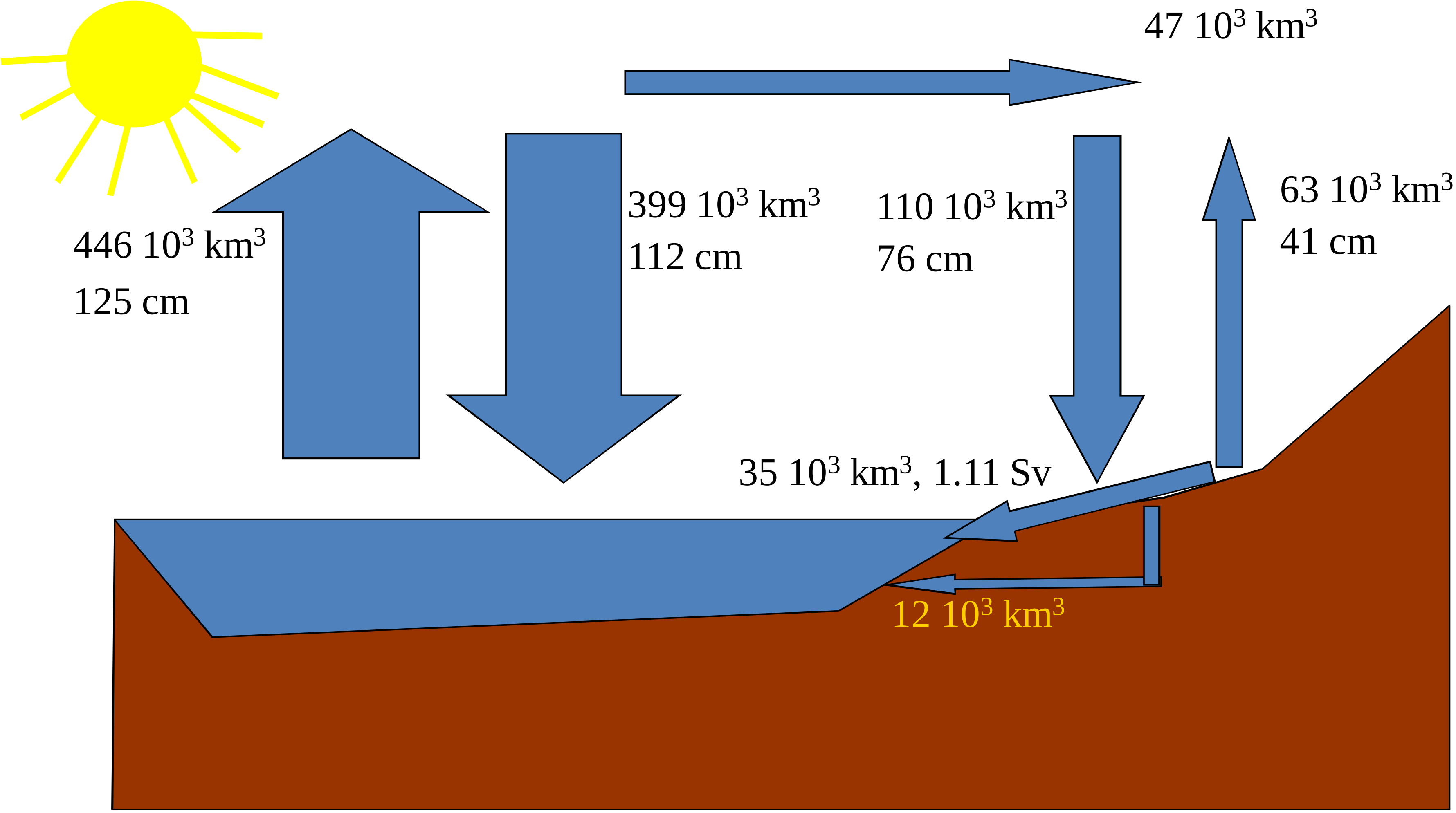
[1]Department of Physical Geography, Utrecht University, Utrecht, the Netherlands
[2]Deltares, Utrecht, the Netherlands
[3]NASA GISS, Columbia University Campus, USA

Content

- Water availability
- Water demand: local to global
- Global water stress
- Socio-economic and climate change
- Adverse effects of global water stress
- Adaptation and mitigation?

Water Availability

The global hydrological cycle (per year)



47 10^3 km^3

446 10^3 km^3
125 cm

399 10^3 km^3
112 cm

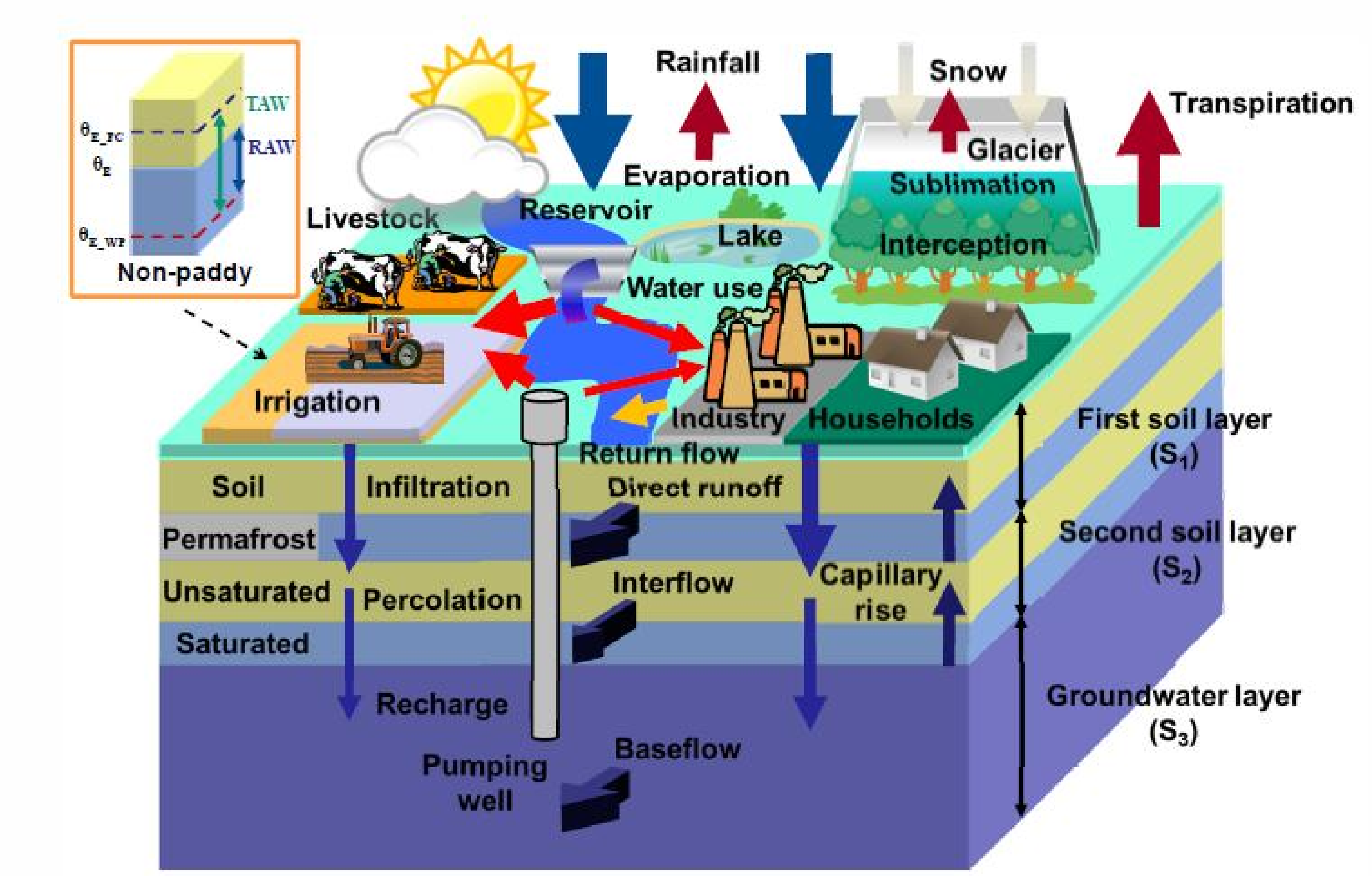
110 10^3 km^3
76 cm

63 10^3 km^3
41 cm

35 10^3 km^3, 1.11 Sv

12 10^3 km^3

simulation by integrated global hydrological models

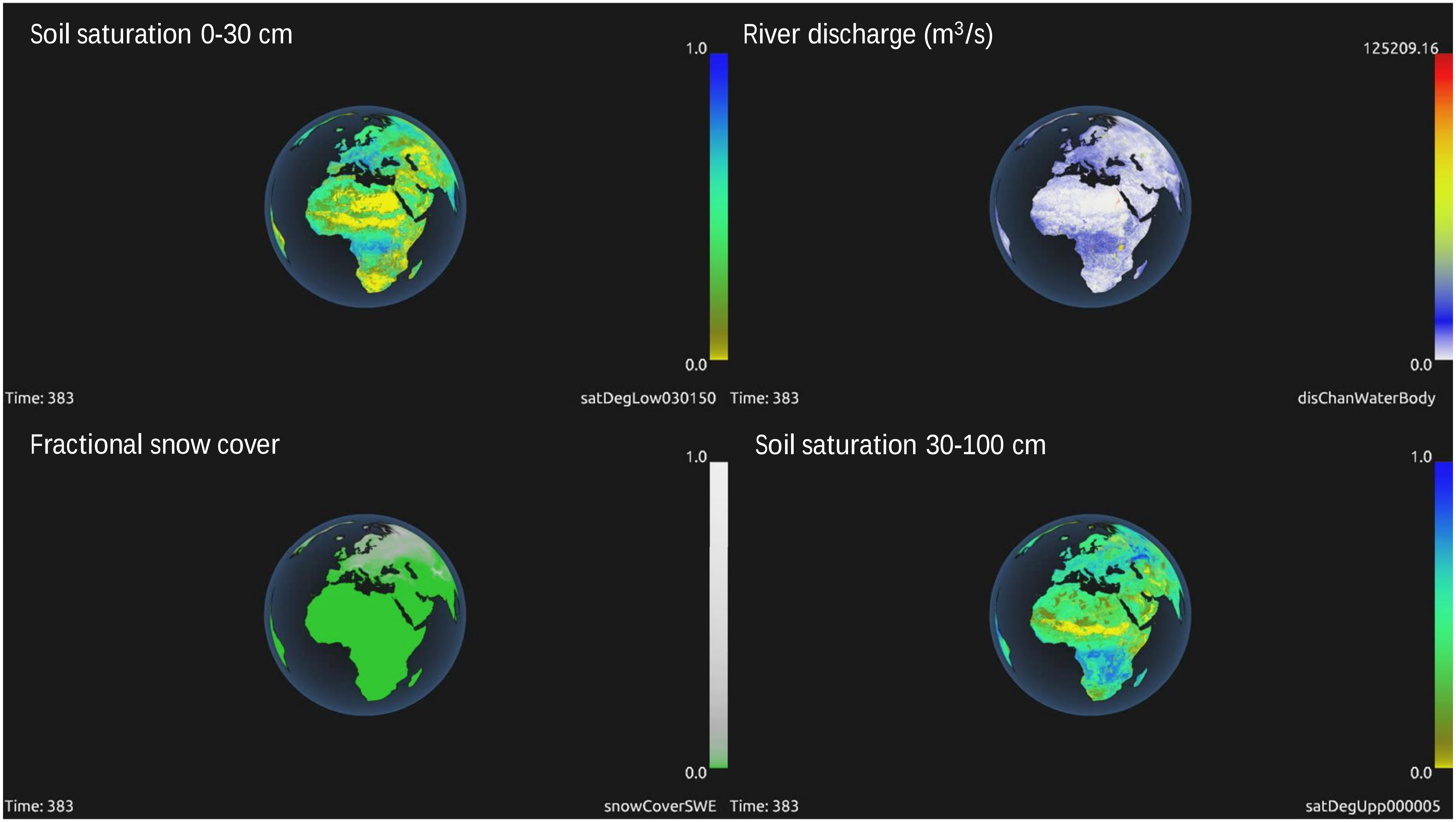


Wada et al., 2013 (ESD)

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

eWaterCycle



Continental runoff: comparison of studies

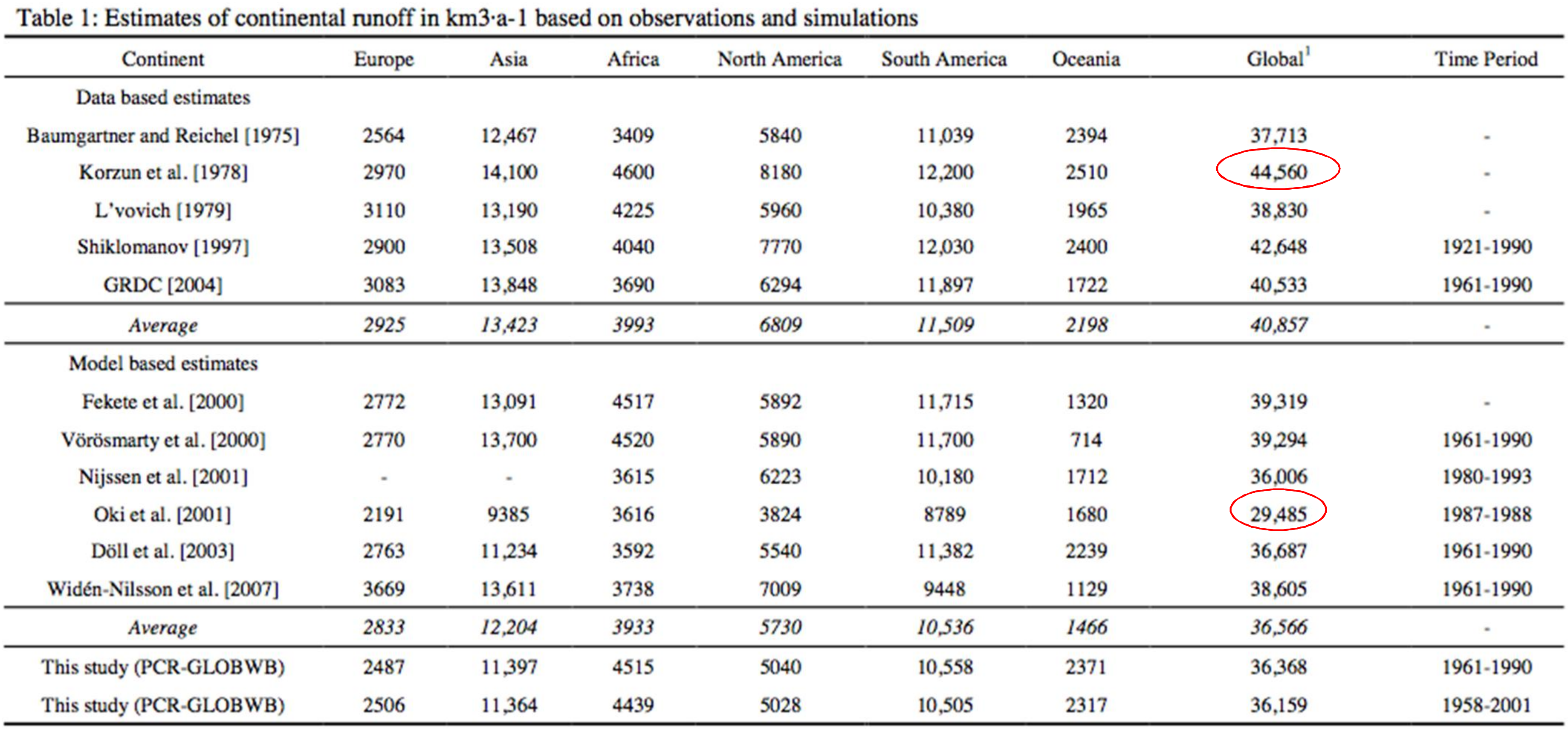
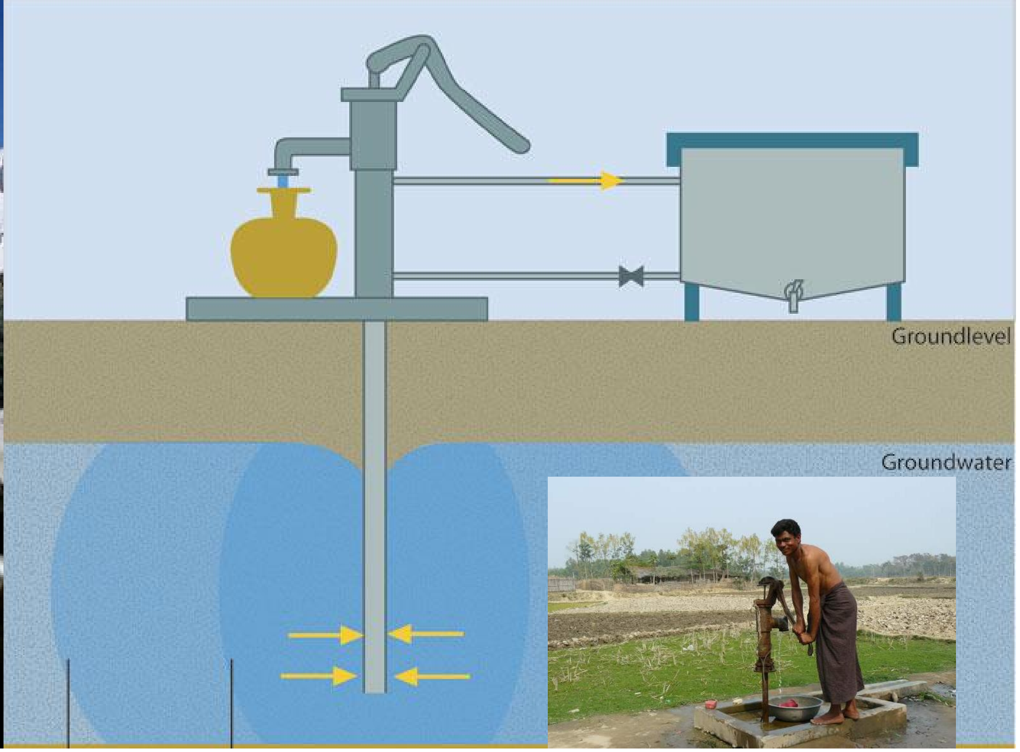
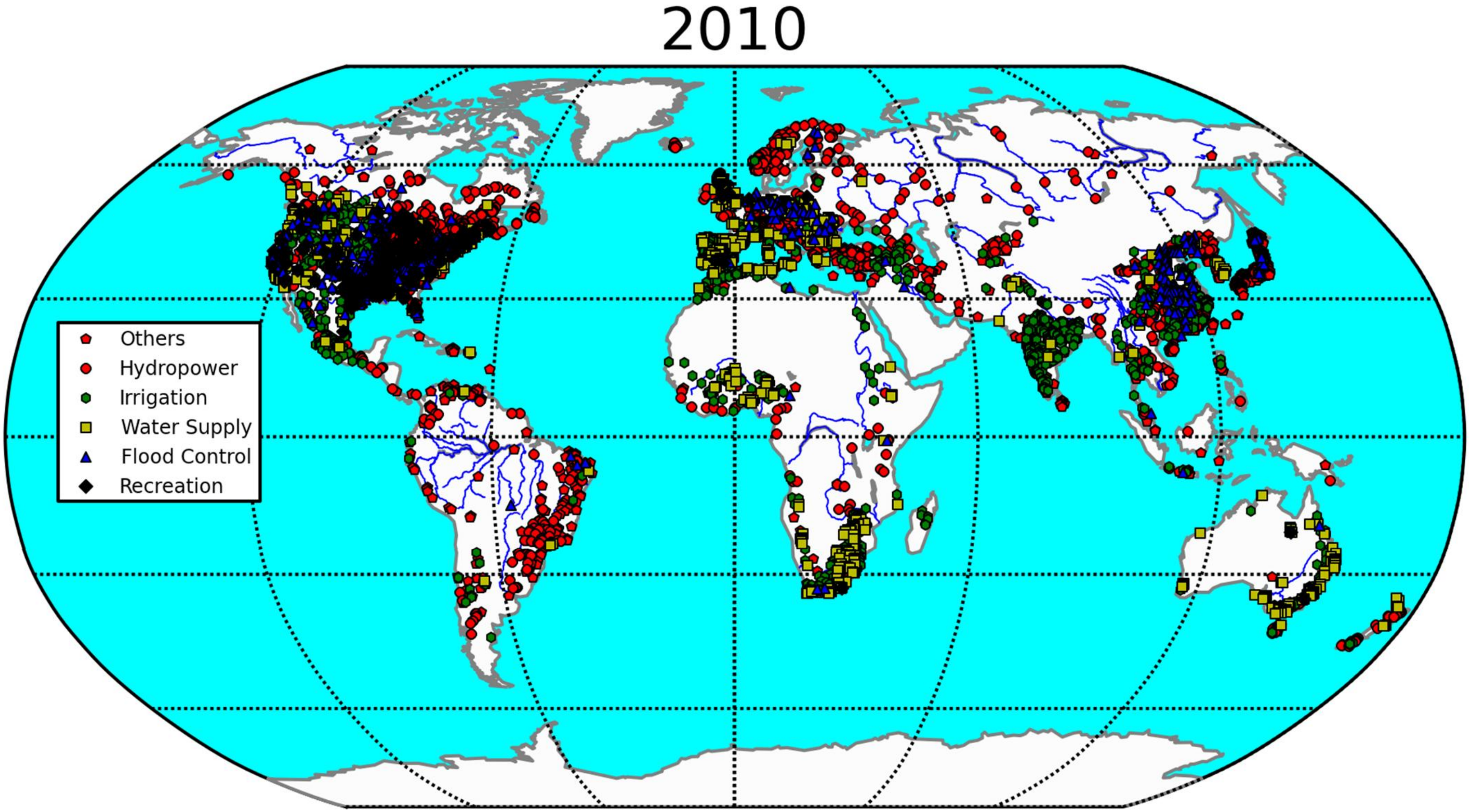


Table 1: Estimates of continental runoff in km3·a-1 based on observations and simulations

Continent	Europe	Asia	Africa	North America	South America	Oceania	Global[1]	Time Period
Data based estimates								
Baumgartner and Reichel [1975]	2564	12,467	3409	5840	11,039	2394	37,713	-
Korzun et al. [1978]	2970	14,100	4600	8180	12,200	2510	44,560	-
L'vovich [1979]	3110	13,190	4225	5960	10,380	1965	38,830	-
Shiklomanov [1997]	2900	13,508	4040	7770	12,030	2400	42,648	1921-1990
GRDC [2004]	3083	13,848	3690	6294	11,897	1722	40,533	1961-1990
Average	*2925*	*13,423*	*3993*	*6809*	*11,509*	*2198*	*40,857*	-
Model based estimates								
Fekete et al. [2000]	2772	13,091	4517	5892	11,715	1320	39,319	-
Vörösmarty et al. [2000]	2770	13,700	4520	5890	11,700	714	39,294	1961-1990
Nijssen et al. [2001]	-	-	3615	6223	10,180	1712	36,006	1980-1993
Oki et al. [2001]	2191	9385	3616	3824	8789	1680	29,485	1987-1988
Döll et al. [2003]	2763	11,234	3592	5540	11,382	2239	36,687	1961-1990
Widén-Nilsson et al. [2007]	3669	13,611	3738	7009	9448	1129	38,605	1961-1990
Average	*2833*	*12,204*	*3933*	*5730*	*10,536*	*1466*	*36,566*	-
This study (PCR-GLOBWB)	2487	11,397	4515	5040	10,558	2371	36,368	1961-1990
This study (PCR-GLOBWB)	2506	11,364	4439	5028	10,505	2317	36,159	1958-2001

Major fresh water stores on earth

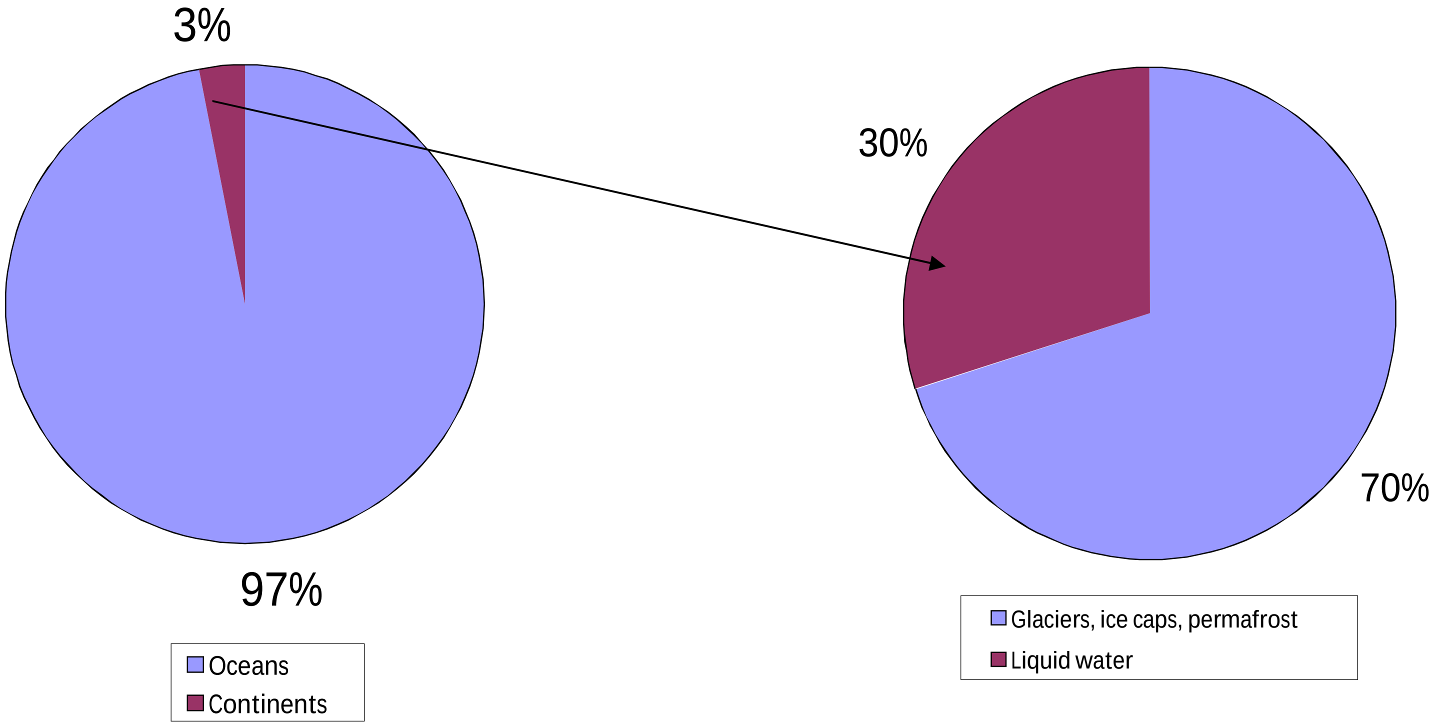




Large reservoirs from GRanD , Global Reservoirs and Dams Data base

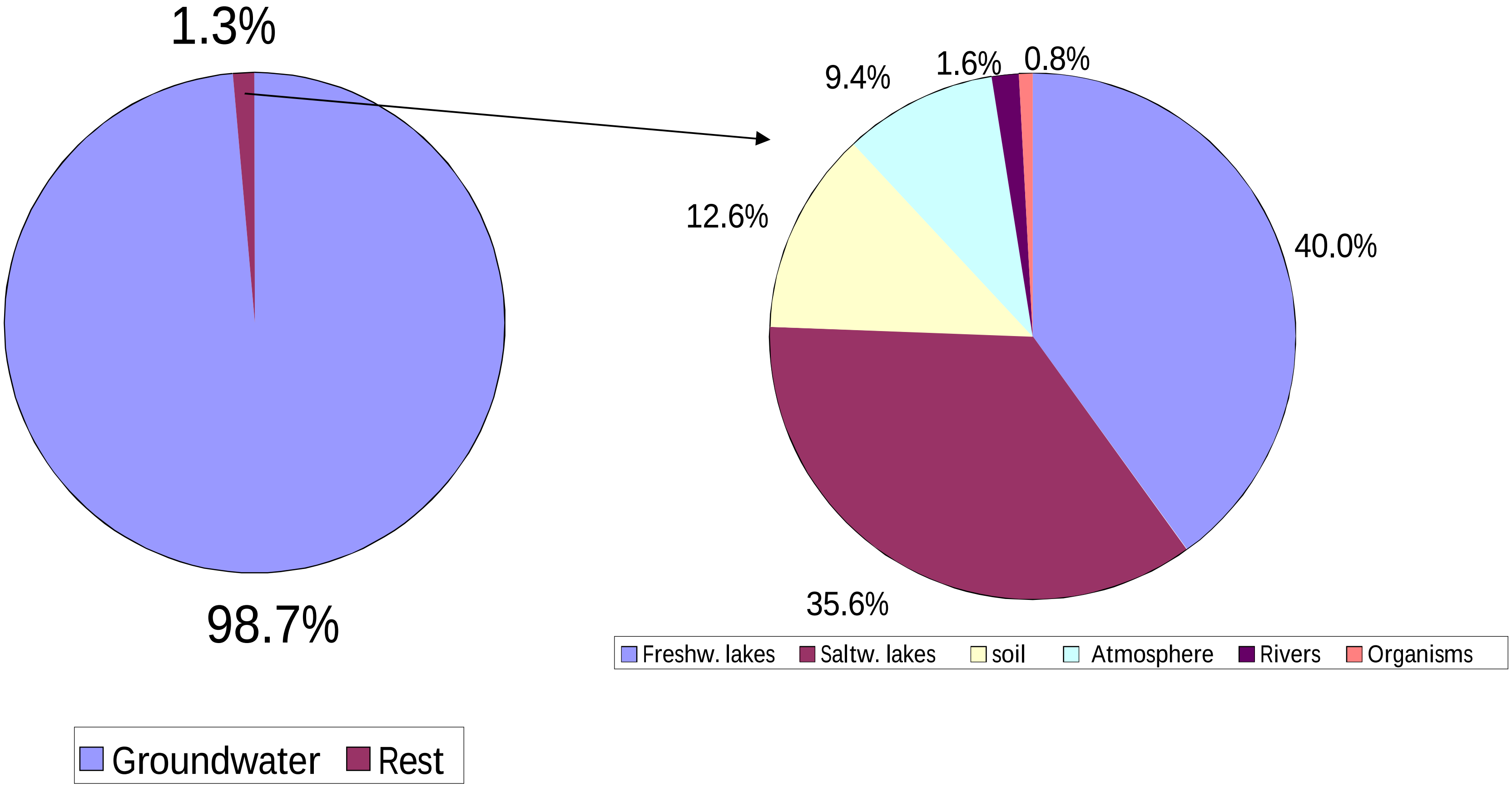
Reservoirs build since 1900:
10,000 km^3 (30 mm of sea-level rise) is stored behind dams

Global water stocks

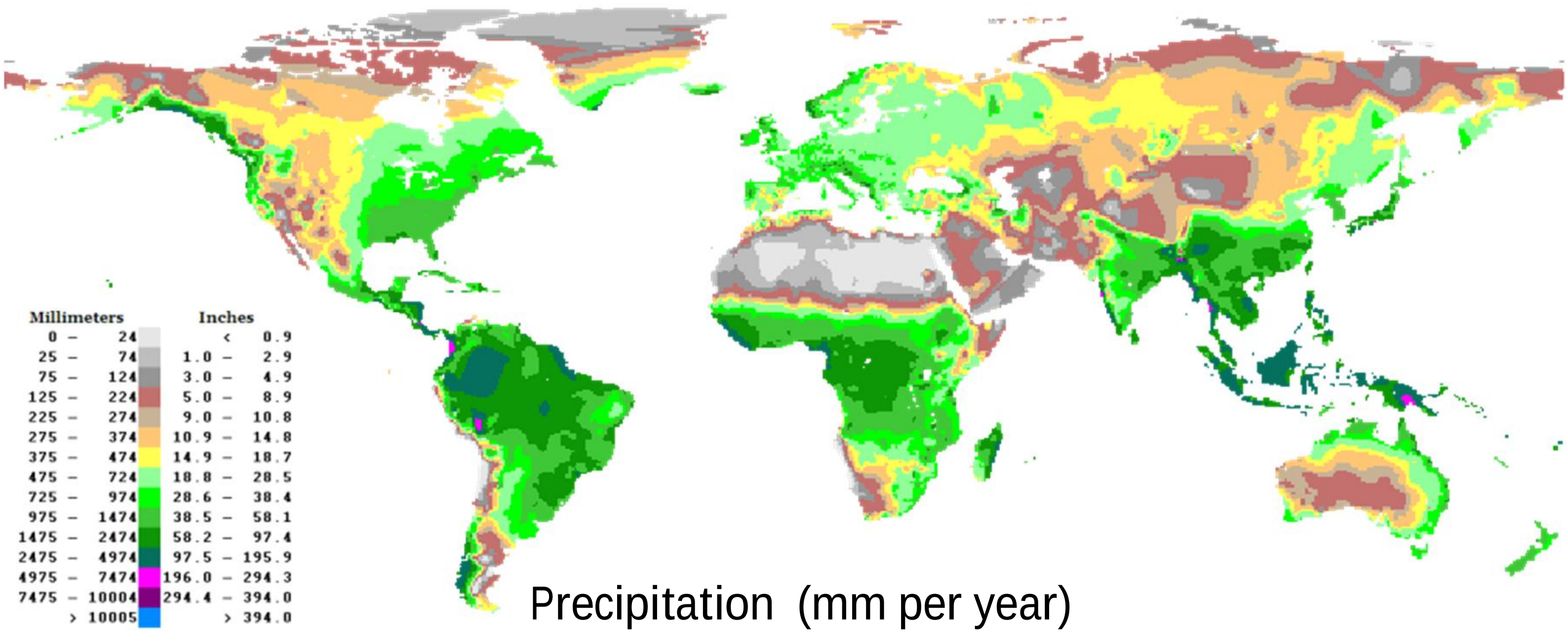


Total: $1360\ 10^6\ \mathrm{km}^3$ (=1 360 000 000 000 000 000 000 liter)

Global water stocks



There are huge amounts of water, but not distributed equally



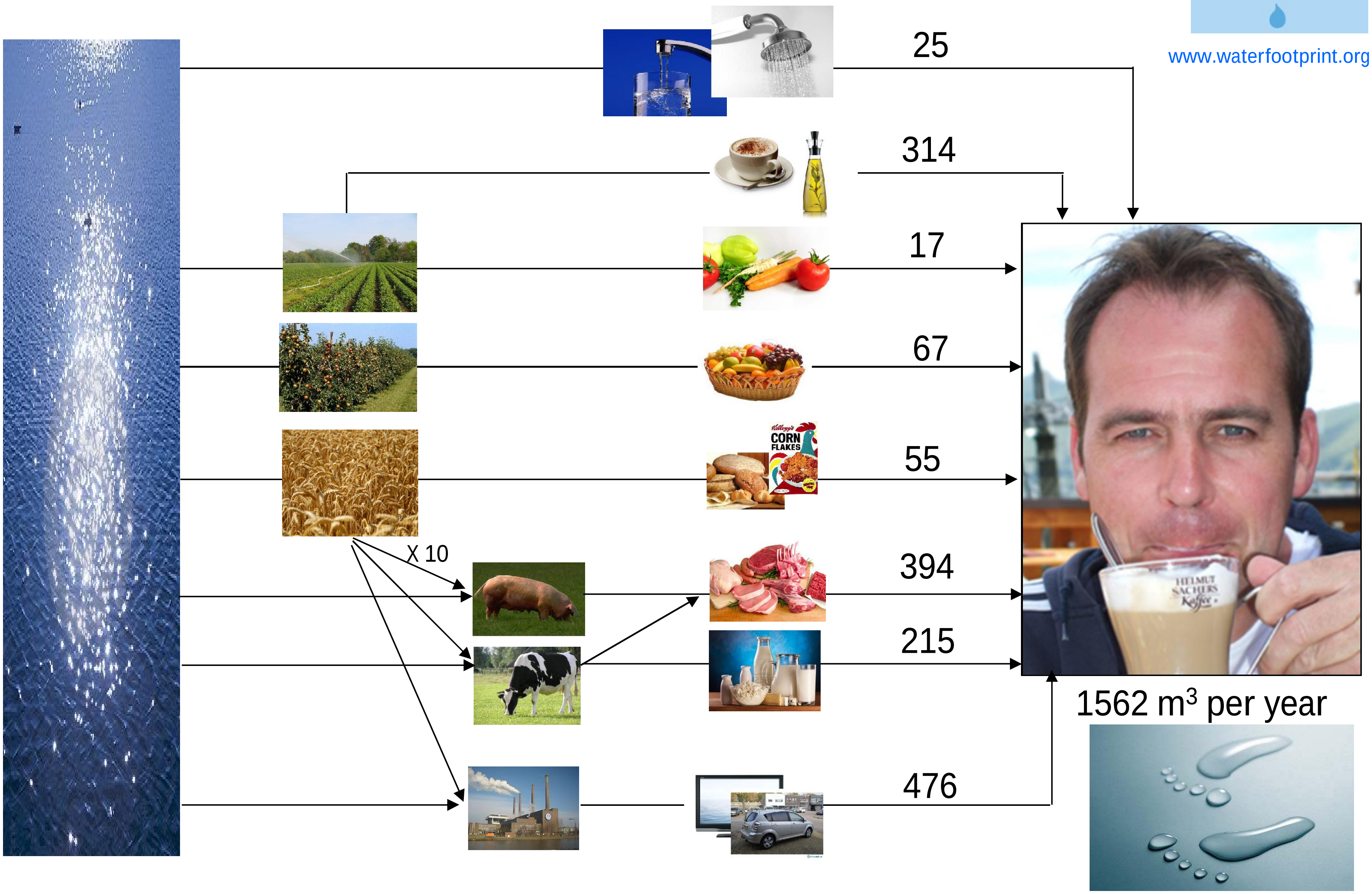
Precipitation (mm per year)

Population growth: people are moving into regions with little renewable water -> result is increasing water stress

Water Demand

Virtual water: How much water do we use as a person?

www.waterfootprint.org



Global net water demand (potential consumption)

aquastat

FAOSTAT

World Water Assessment Programme

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

CIESIN Columbia University

PBL Netherlands Environmental Assessment Agency

CRU

ECMWF

UNESCO

United Nations Educational, Scientific and Cultural Organization

UNEP

THE WORLD BANK

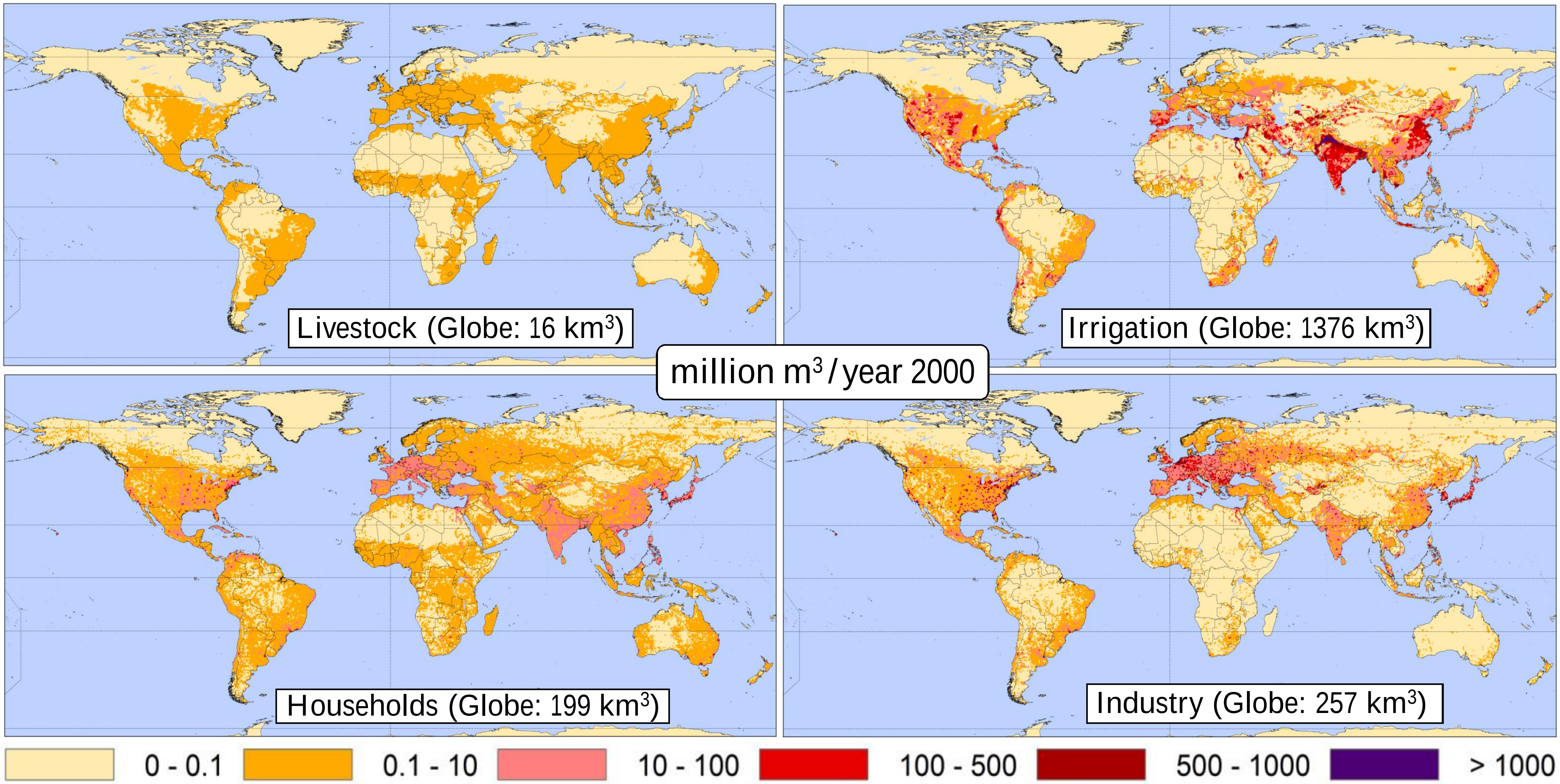
Working for a World Free of Poverty

iea International Energy Agency

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)

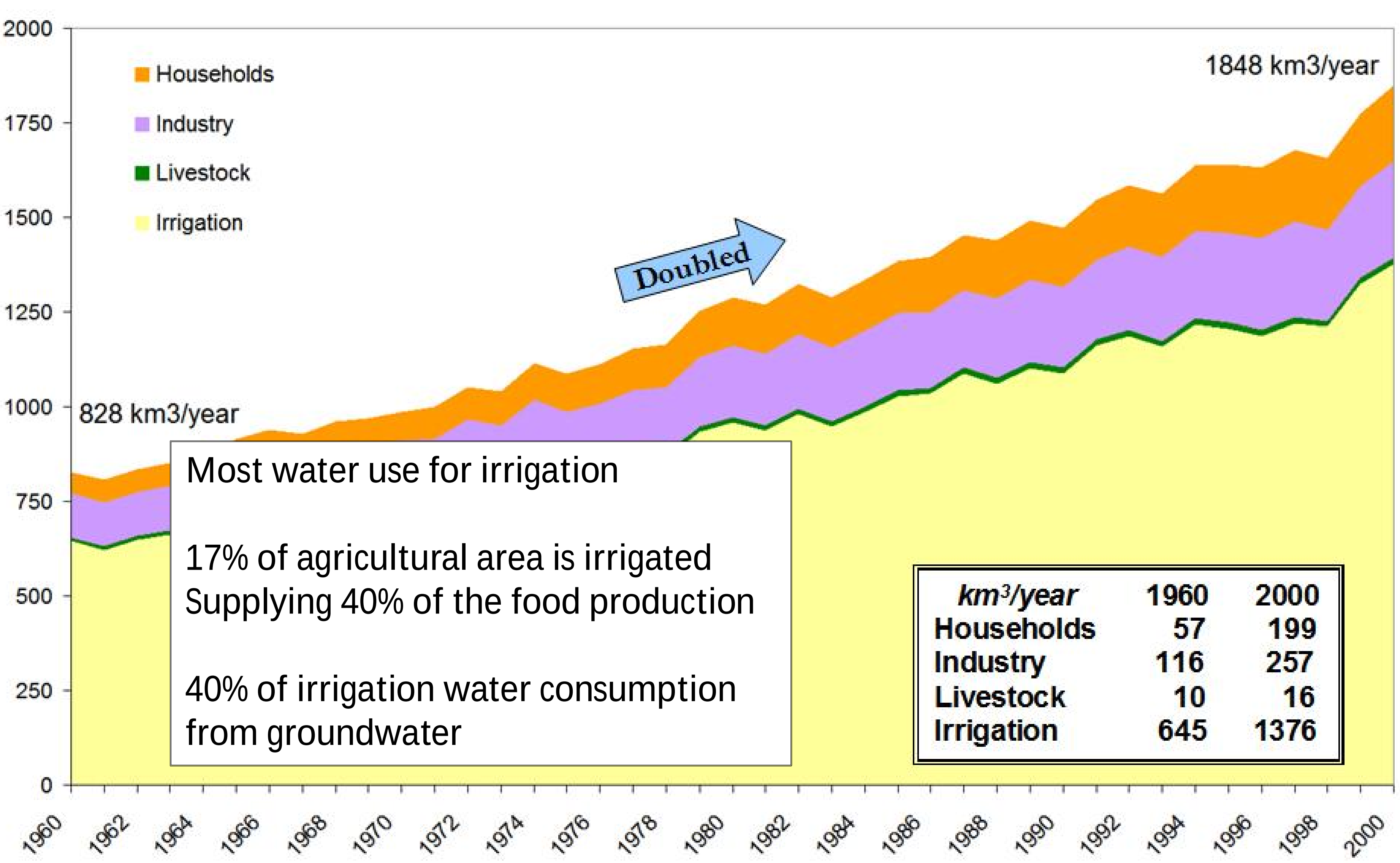
The human imprint: Global water consumption (potential abstraction – return flow)

Wada et al., HESS, 2011



Historical Trends

- **Global water demand more than doubled during the period 1960-2000**



Most water use for irrigation

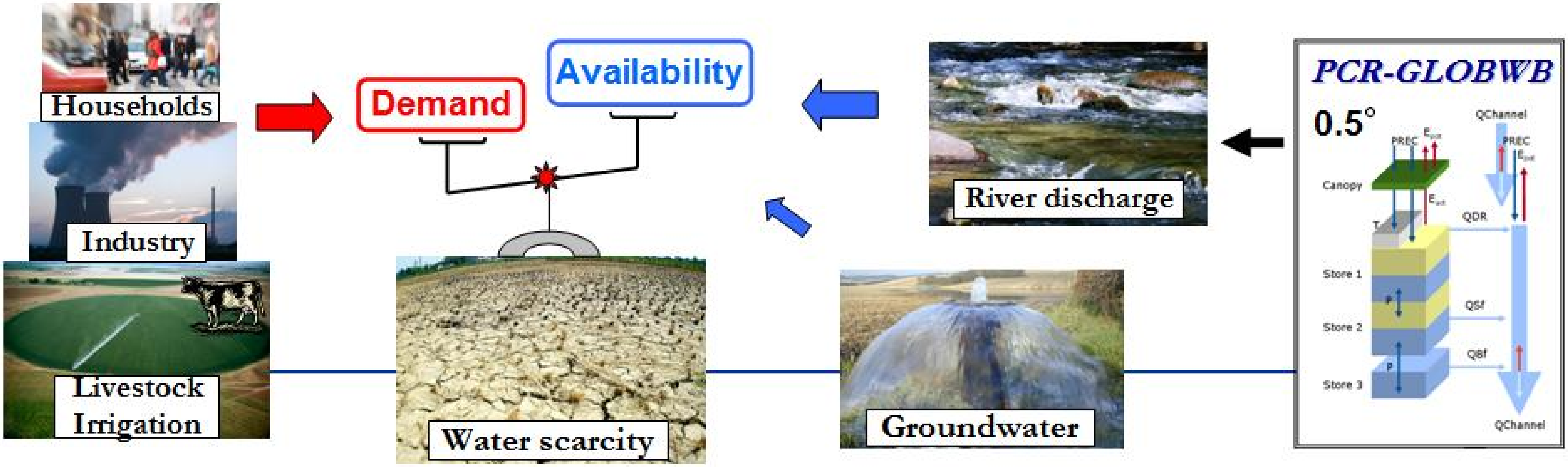
17% of agricultural area is irrigated
Supplying 40% of the food production

40% of irrigation water consumption
from groundwater

km³/year	1960	2000
Households	57	199
Industry	116	257
Livestock	10	16
Irrigation	645	1376

Water Stress

Calculating Water stress



Water stress ≈ Water Scarcity Index: $WSI = \dfrac{D}{A}$

D: Surface water demand
A: Water availability ≈ River discharge

Degrees of water stress	Per capita water availability ($m^3 \cdot capita^{-1} \cdot year^{-1}$)	Water Scarcity Index: WSI (-)	Definitions of degrees of water stress
No stress	> 1,700	$WSI < 0.1$	No water scarcity
Low stress	-	$0.1 \leqq WSI < 0.2$	Potential water scarcity
Moderate stress	1,700 - 1,000	$0.2 \leqq WSI < 0.4$	Looming water scarcity
High stress	1,000 - 500	$0.4 \leqq WSI < 0.8$	Experiencing water scarcity
Very high stress	< 500	$0.8 \leqq WSI$	Economic development is limited by water scarcity

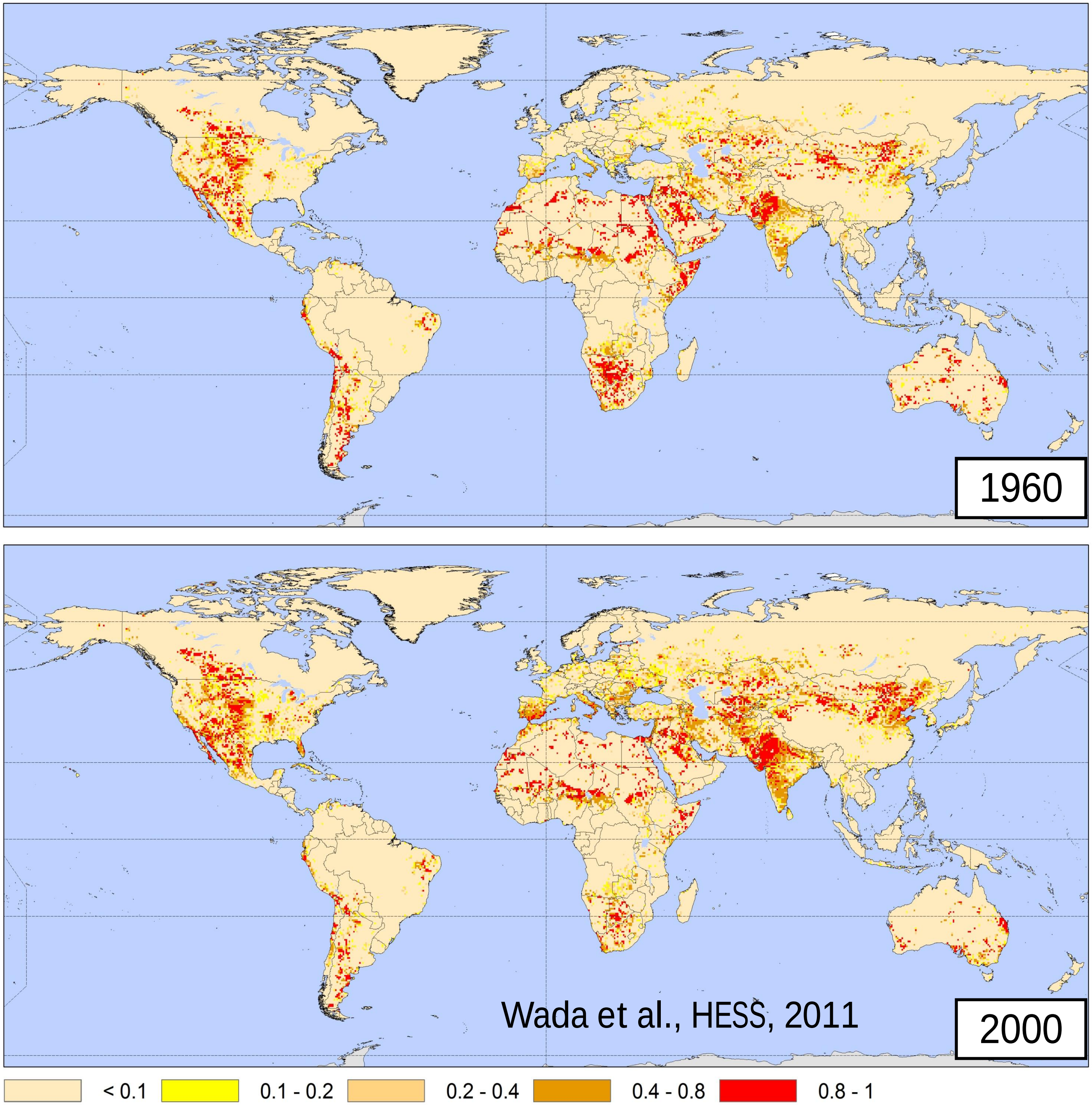
(Falkenmark et al., 1997)

Water Scarcity Index

$$WSI = \frac{D}{A}$$

Global population under high water stress (WSI > 0.4)

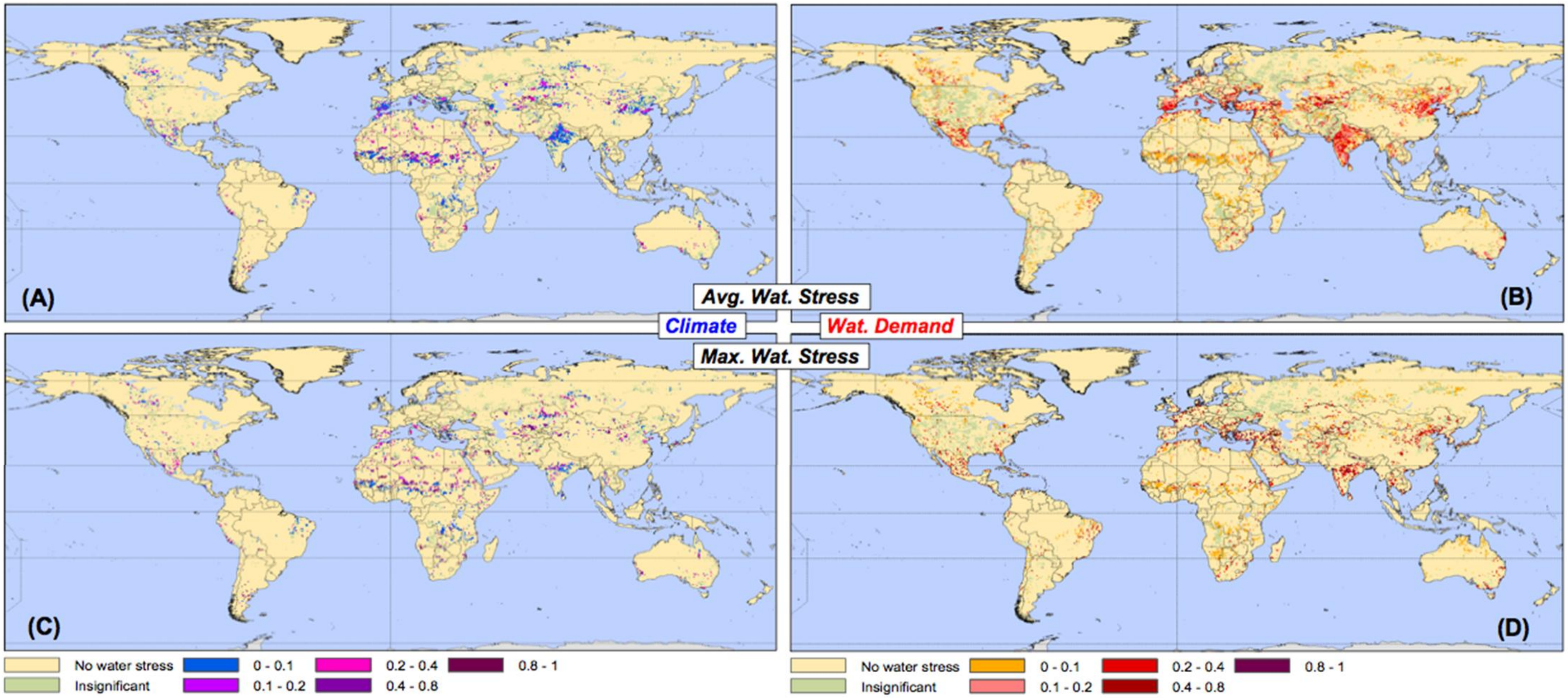
Year	Billions (% of total)
1960	0.5 (17%)
1970	0.7 (19%)
1980	1.0 (23%)
1990	1.2 (23%)
2000	1.8 (30%)



Wada et al., HESS, 2011

Socio-economic and climate change

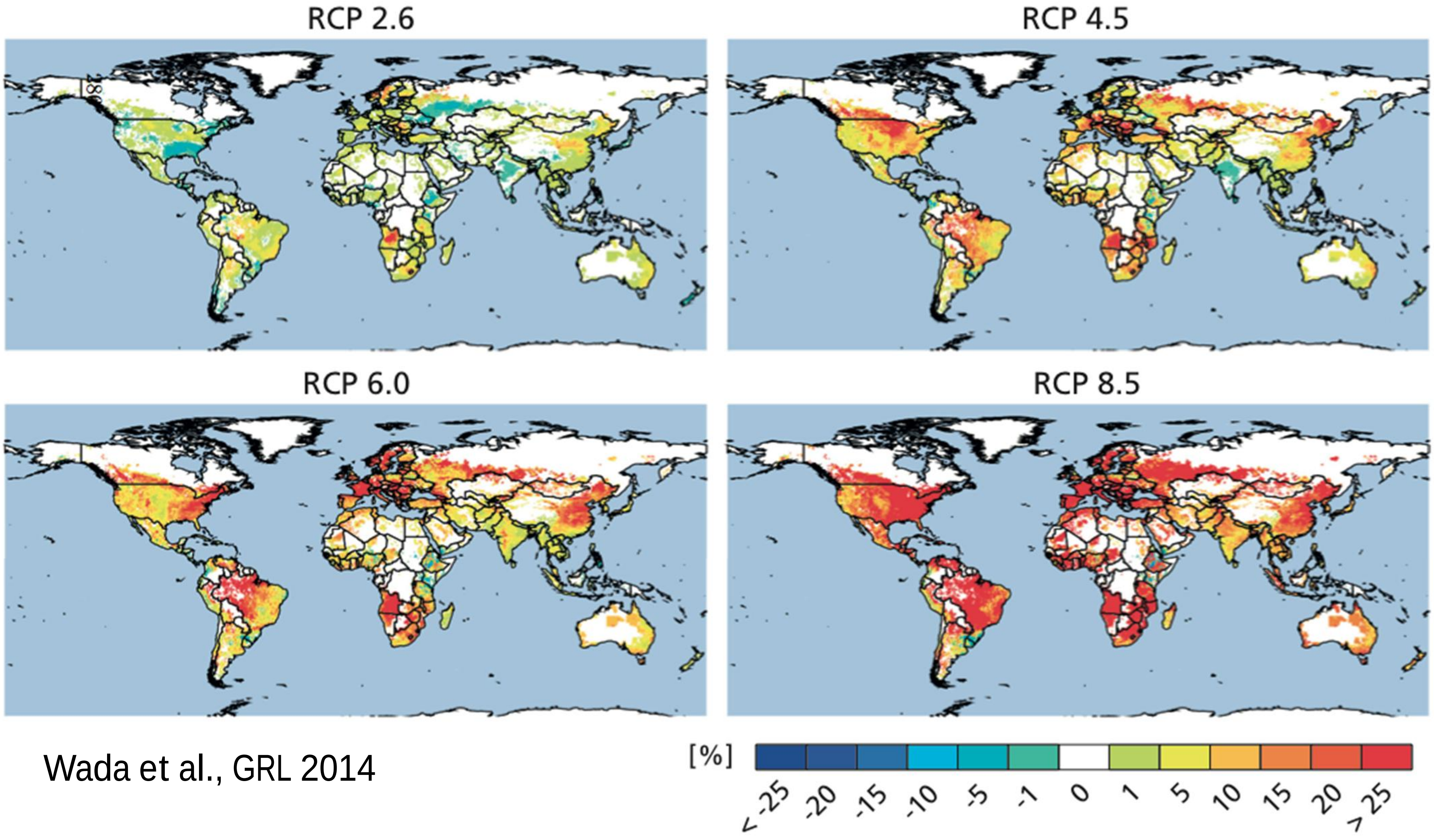
Climate versus socio-economic change



Wada et al., HESS 2011

Socio-economic change dominant in the last 50 years
Projections: climate change dominant factor

Irrigation water demand 2080: climate change only



RCP 2.6

RCP 4.5

RCP 6.0

RCP 8.5

Wada et al., GRL 2014

Adverse effects of water stress

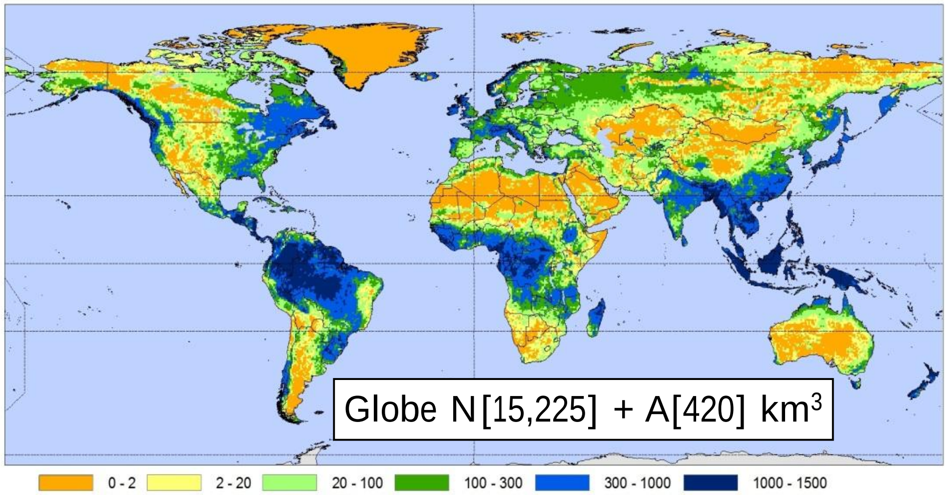
The adverse effects of water stress

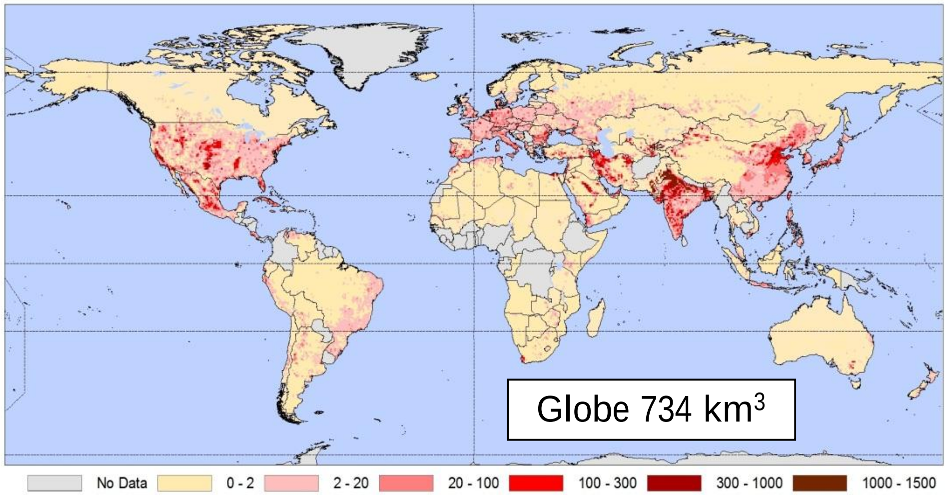
Failed harvests and hunger

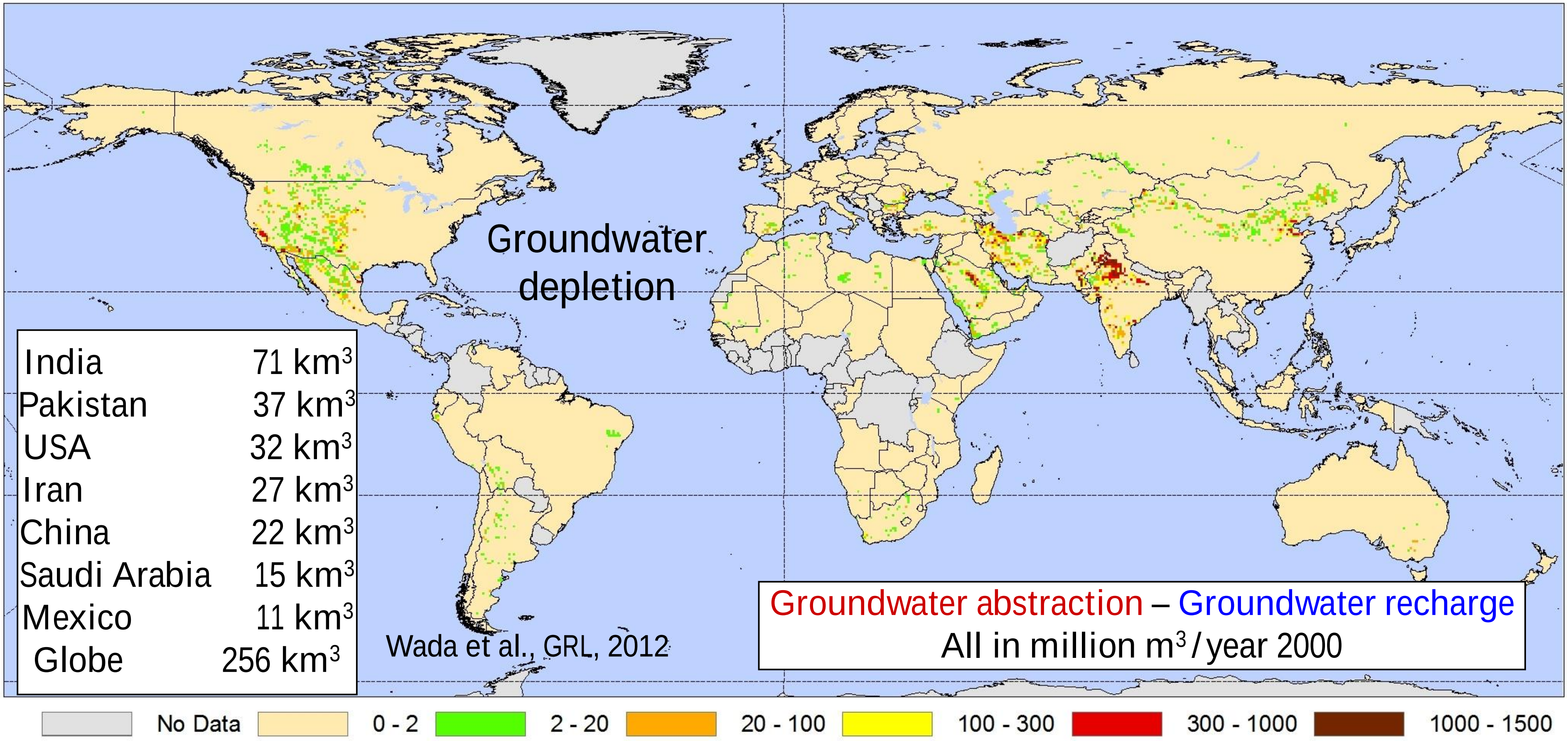
Drying rivers, lakes and reservoirs

Dessication of wetlands

Poor drinking water quality





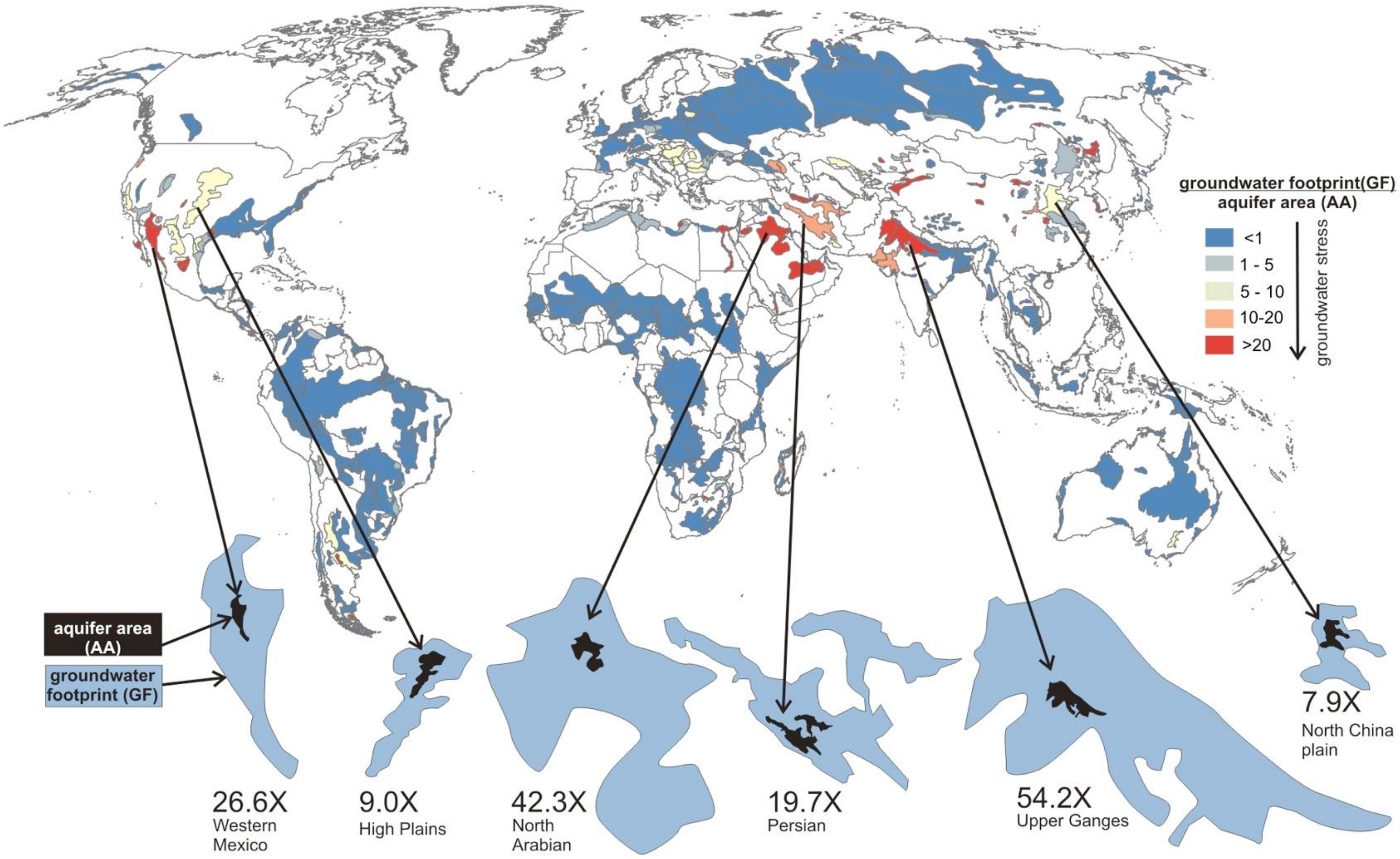


India	71 km^3
Pakistan	37 km^3
USA	32 km^3
Iran	27 km^3
China	22 km^3
Saudi Arabia	15 km^3
Mexico	11 km^3
Globe	256 km^3

Wada et al., GRL, 2012

Groundwater abstraction – Groundwater recharge
All in million m^3/year 2000

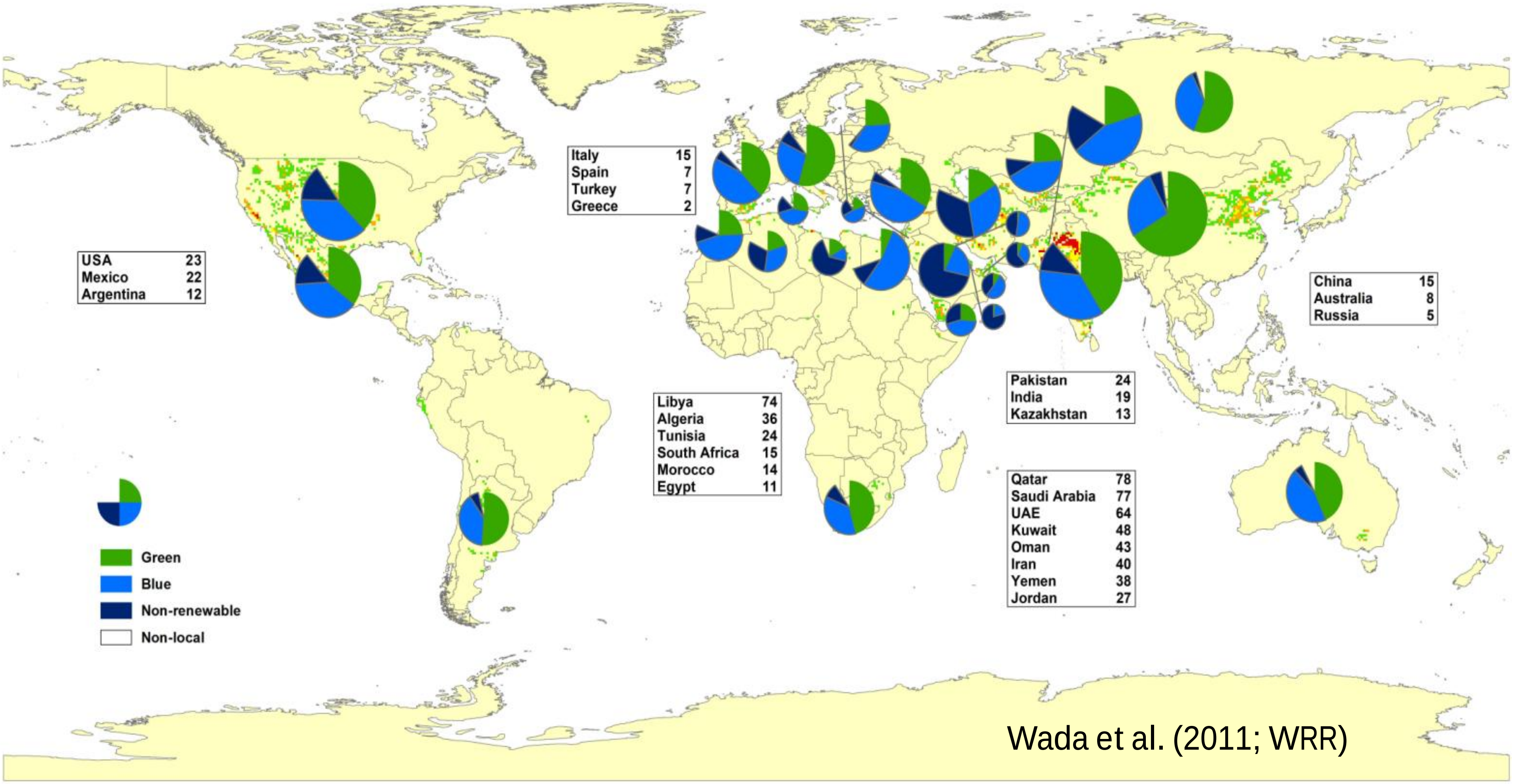
Sustainability view 1: The groundwater footprint



Gleeson, et al., Nature, 2012.

Global groundwater footprint = 3.5 times the global area of productive aquifers

Sustainability view 2: Contribution to food production



USA	23
Mexico	22
Argentina	12

Italy	15
Spain	7
Turkey	7
Greece	2

Libya	74
Algeria	36
Tunisia	24
South Africa	15
Morocco	14
Egypt	11

Pakistan	24
India	19
Kazakhstan	13

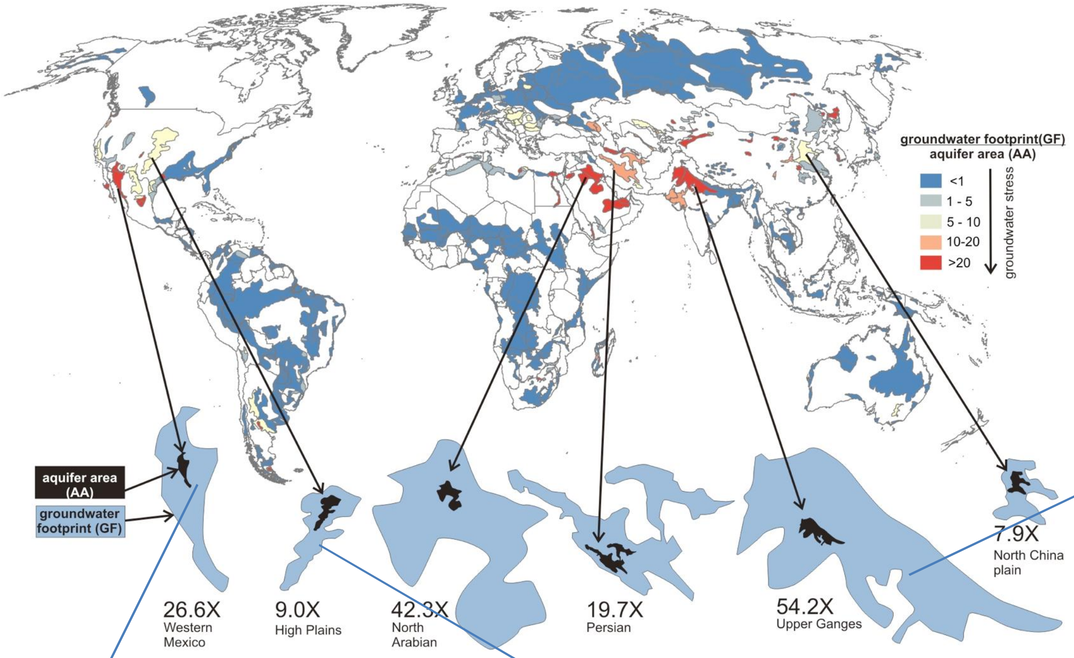
Qatar	78
Saudi Arabia	77
UAE	64
Kuwait	48
Oman	43
Iran	40
Yemen	38
Jordan	27

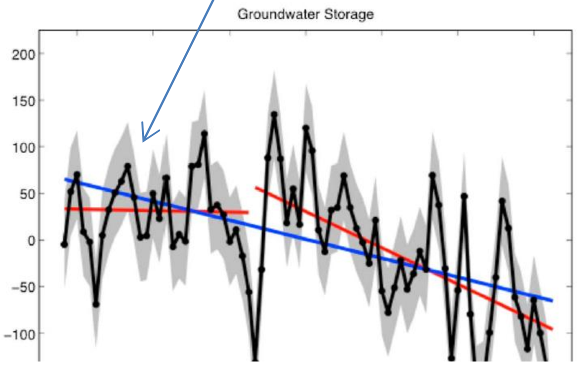
China	15
Australia	8
Russia	5

Wada et al. (2011; WRR)

20% of the global groundwater consumption for irrigation comes from non-renweable groundwater

GRACE and groundwater depletion

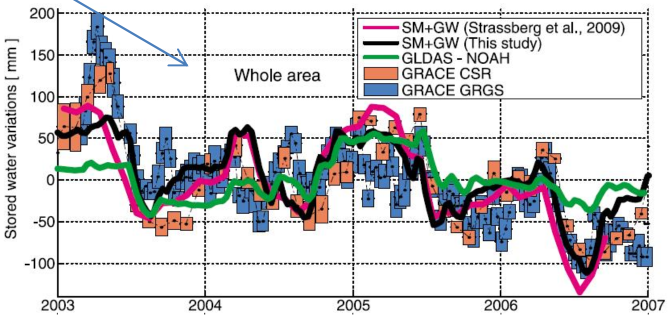




GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L03403, doi:10.1029/2010GL046442, 2011

Satellites measure recent rates of groundwater depletion in California's Central Valley

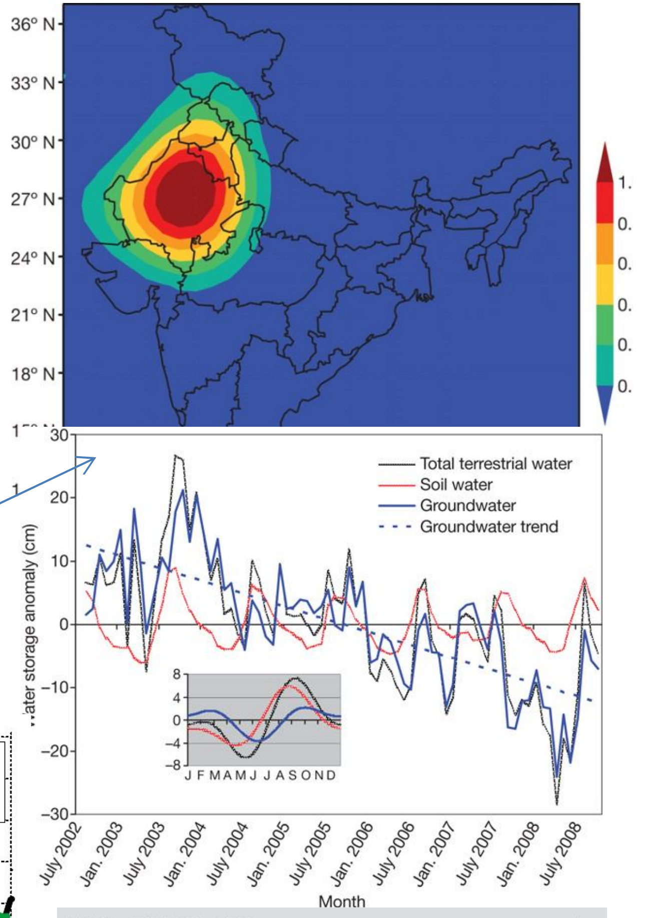
J. S. Famiglietti,[1,2] M. Lo,[1,2] S. L. Ho,[2,3] J. Bethune,[4] K. J. Anderson,[2] T. H. Syed,[2,5] S. C. Swenson,[6] C. R. de Linage,[2] and M. Rodell[7]



WATER RESOURCES RESEARCH, VOL. 46, W11517, doi:10.1029/2009WR008564, 2010

GRACE Hydrological estimates for small basins: Evaluating processing approaches on the High Plains Aquifer, USA

Laurent Longuevergne,[1,2] Bridget R. Scanlon,[1] and Clark R. Wilson[2]



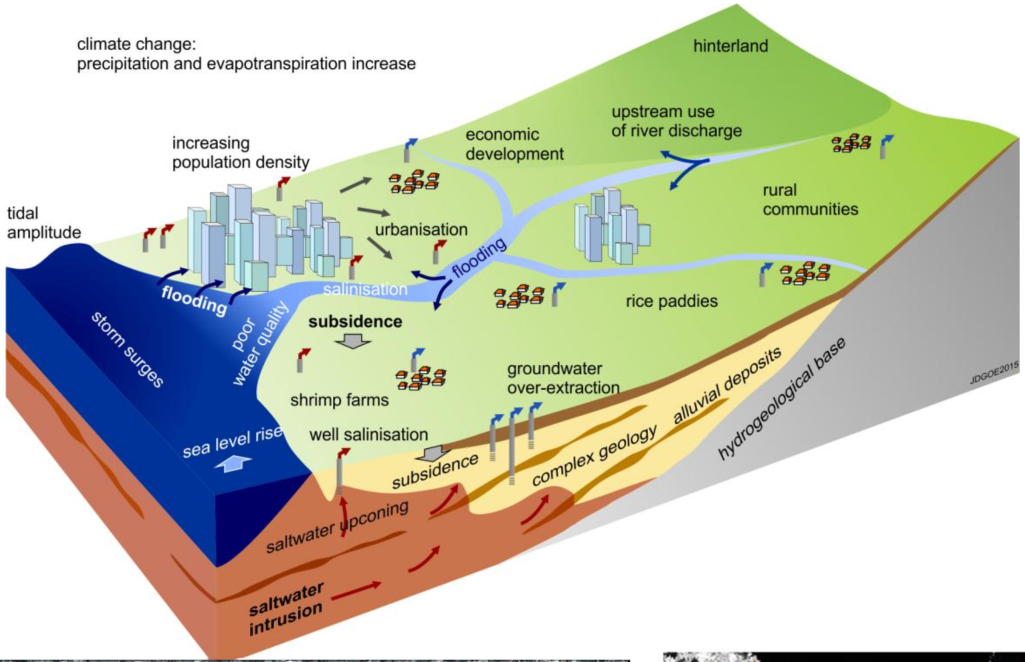
Vol 460 | 20 August 2009 | doi:10.1038/nature08238 nature

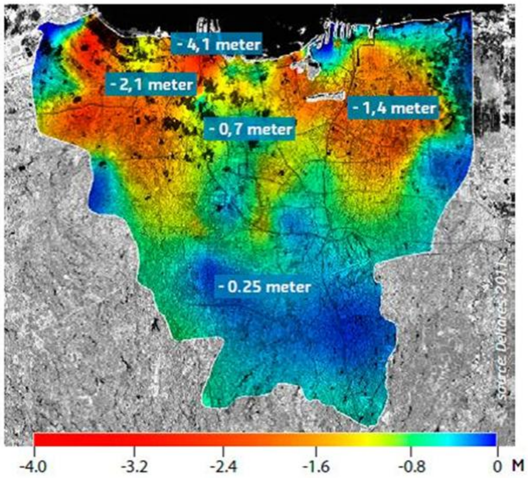
LETTERS

Satellite-based estimates of groundwater depletion in India

Matthew Rodell[1], Isabella Velicogna[2,3,4] & James S. Famiglietti[2]

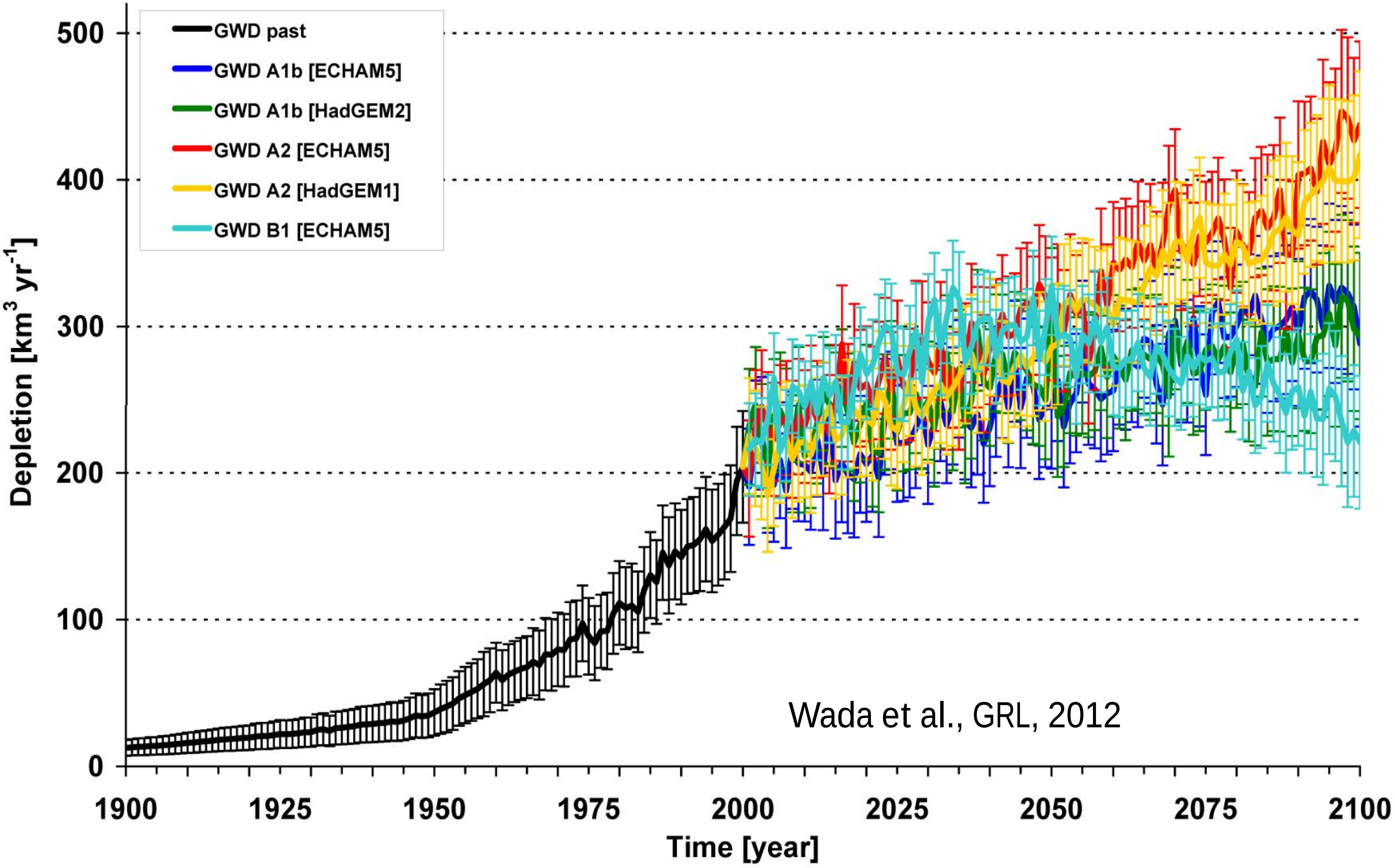
Detrimental effect:
salinisation and subsidence





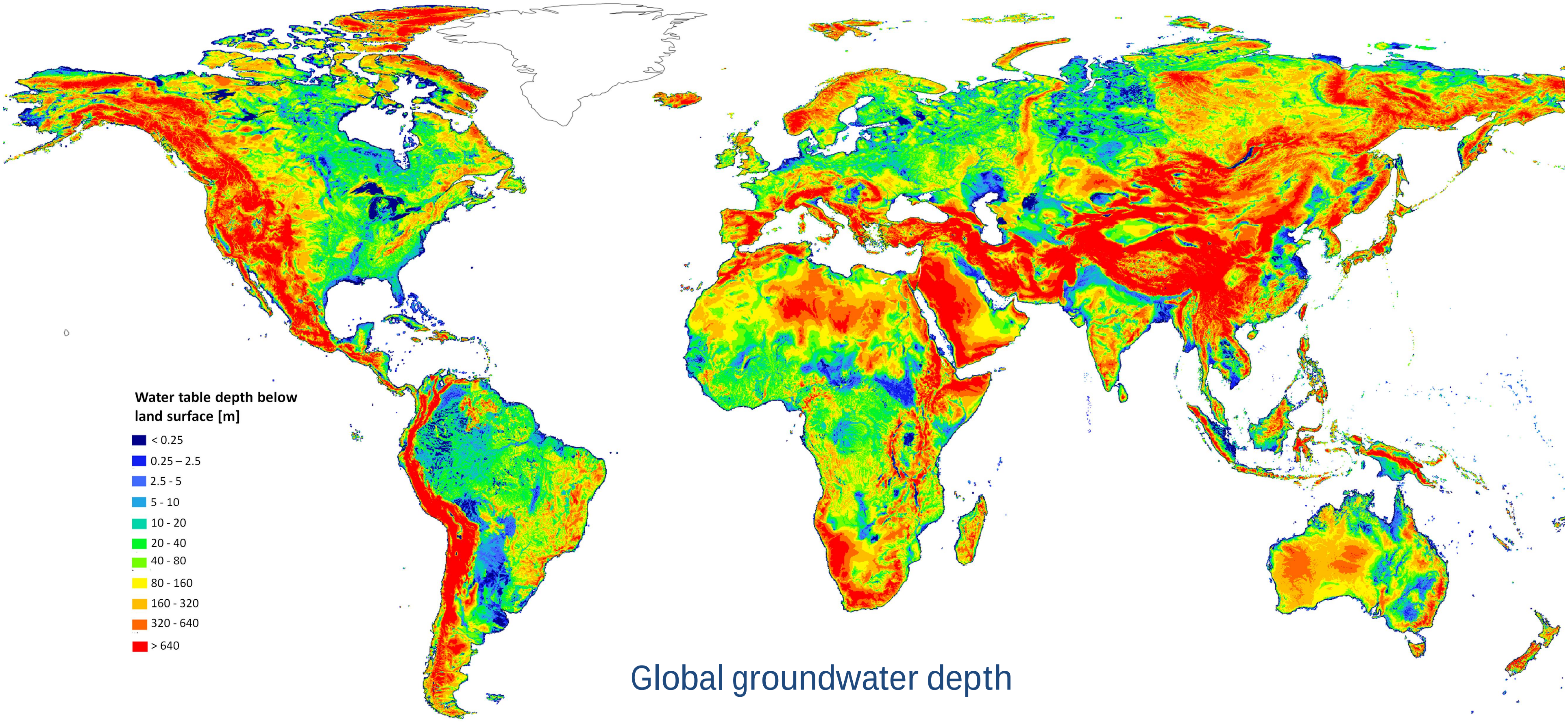
Land subsidence in Jakarta in period 1974-2010

Past reconstruction and future projections: 1900-2100



Wada et al., GRL, 2012

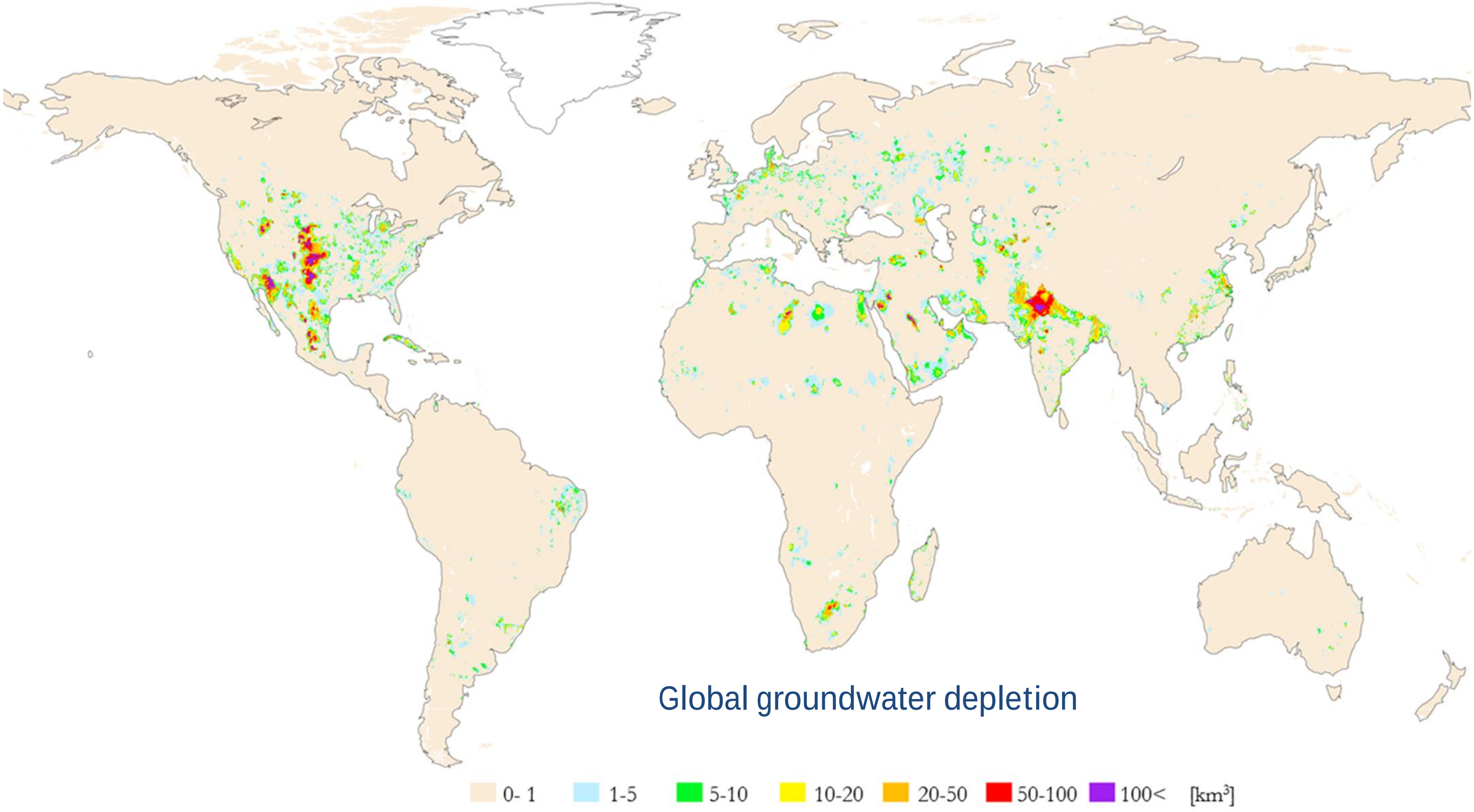
Next step: Global groundwater modelling



Global groundwater depth

De Graaf et al. (to be submitted to WRR);
objective: analysing global groundwater over-exploitation

Next step: Global groundwater modelling



Global groundwater depletion

Cumulative Groundwater depletion (1960-2010)

De Graaf et al. (to be submitted to WRR);
objective: analysing global groundwater over-exploitation

Adaptation and mitigation

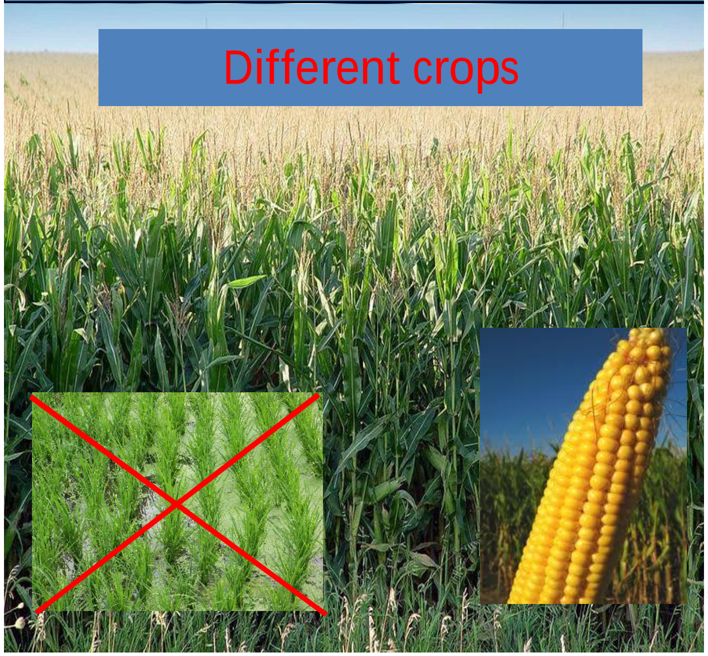
Local solutions: Adaptation

Become a veggie!

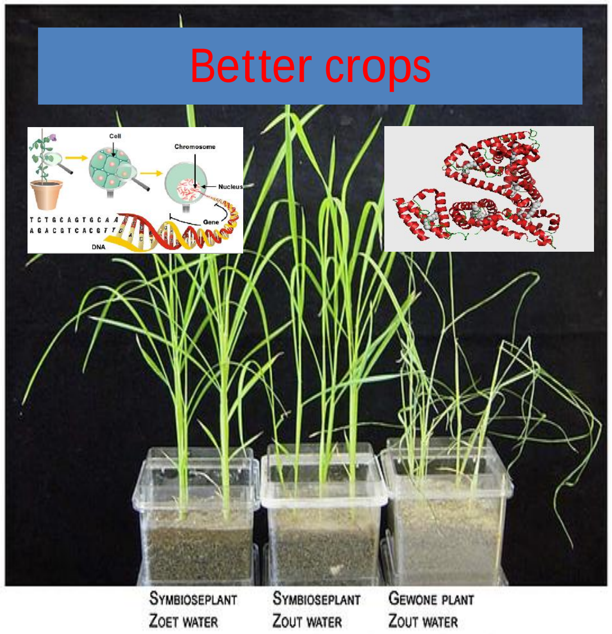
1562 becomes 1292 m^3 per year

More dams

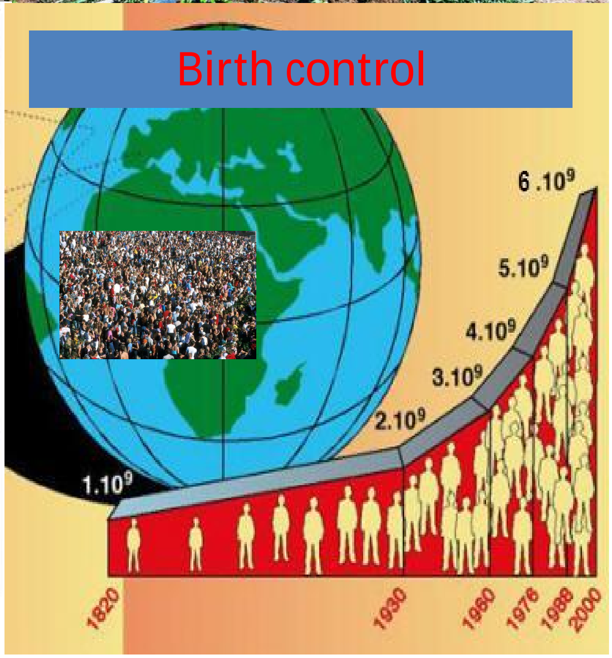
Improve irrigation



Different crops



Better crops



Birth control

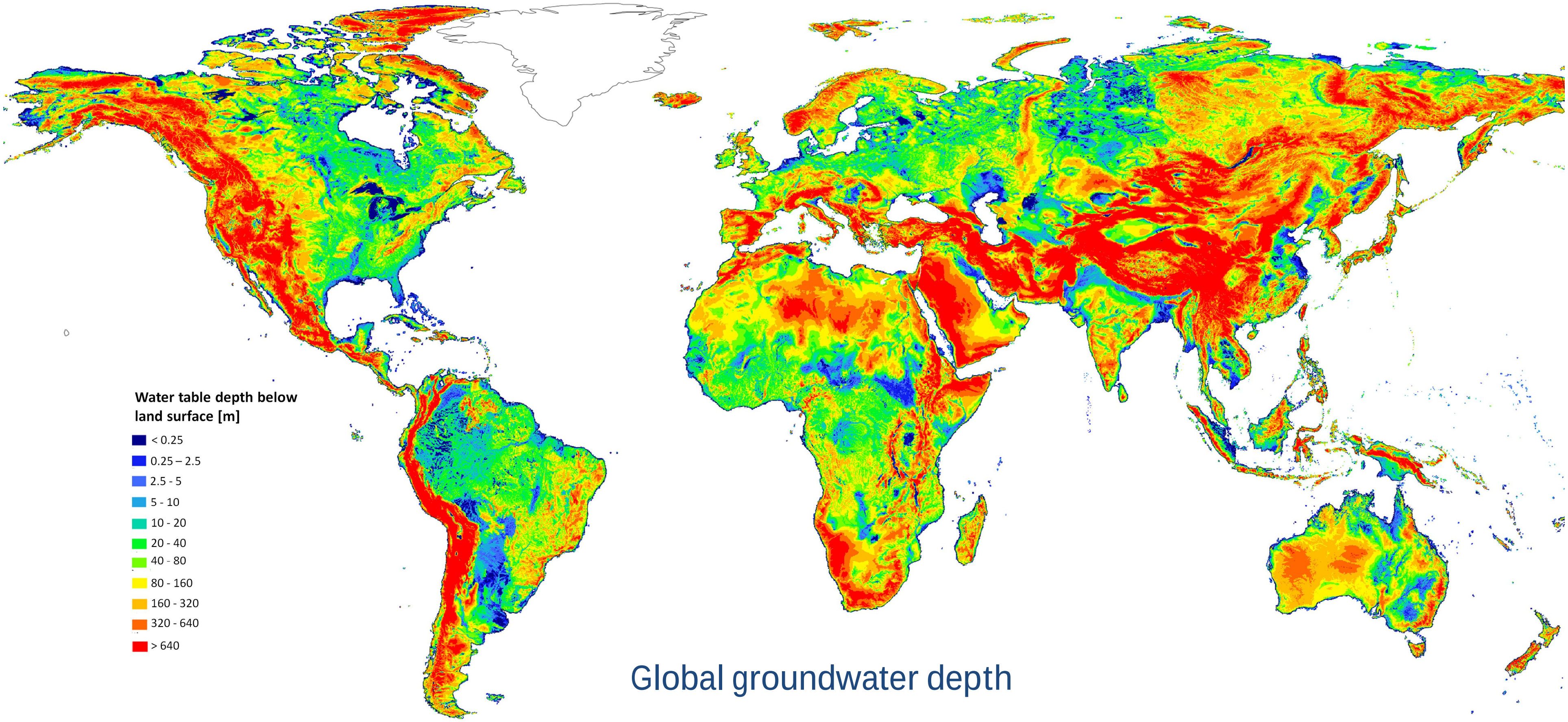
Local adaptation:
Water management and water technology

- Rainwater harvesting
- Enhanced and/or artificial recharge
- Artificial recharge and recovery
- Conjunctive groundwater and surface water use
- Re-use, cascading and re-circulation

National and international economic measures

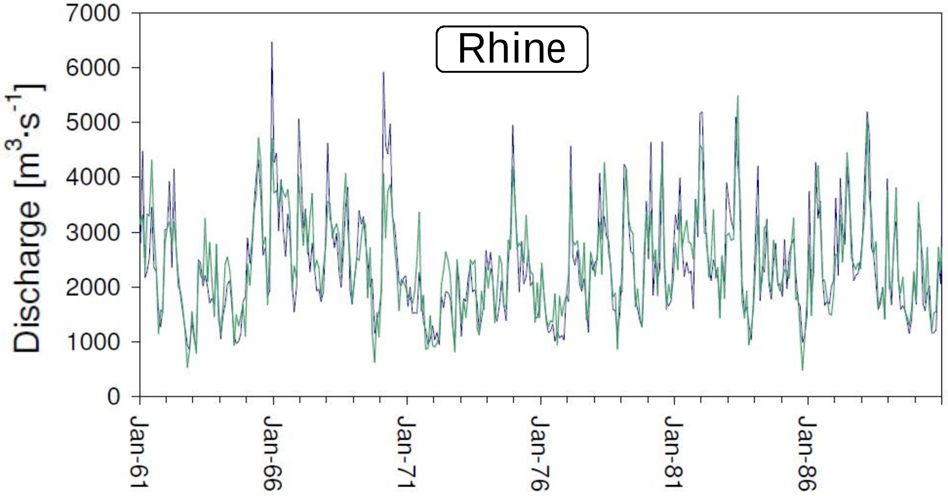
- Water pricing
- Subsidies
- Investment: financial arrangements (e.g. ppp)
- Investment: tax arrangements

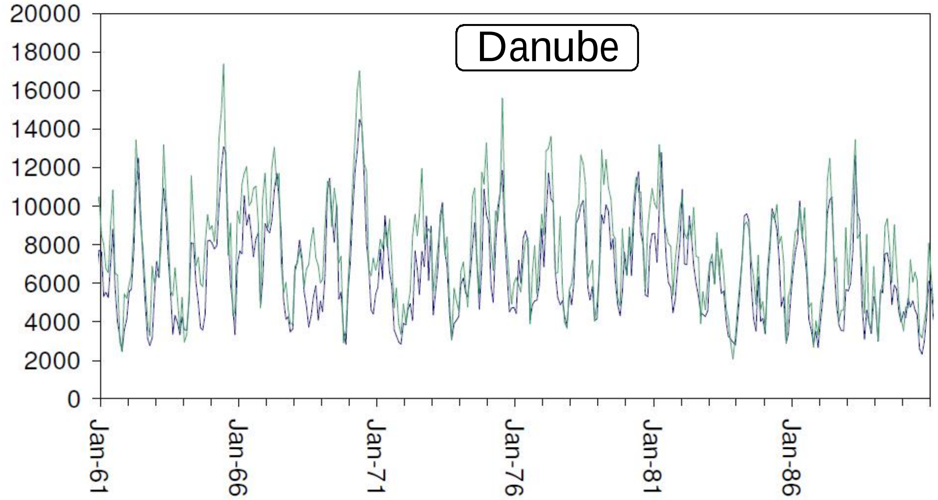
Questions?

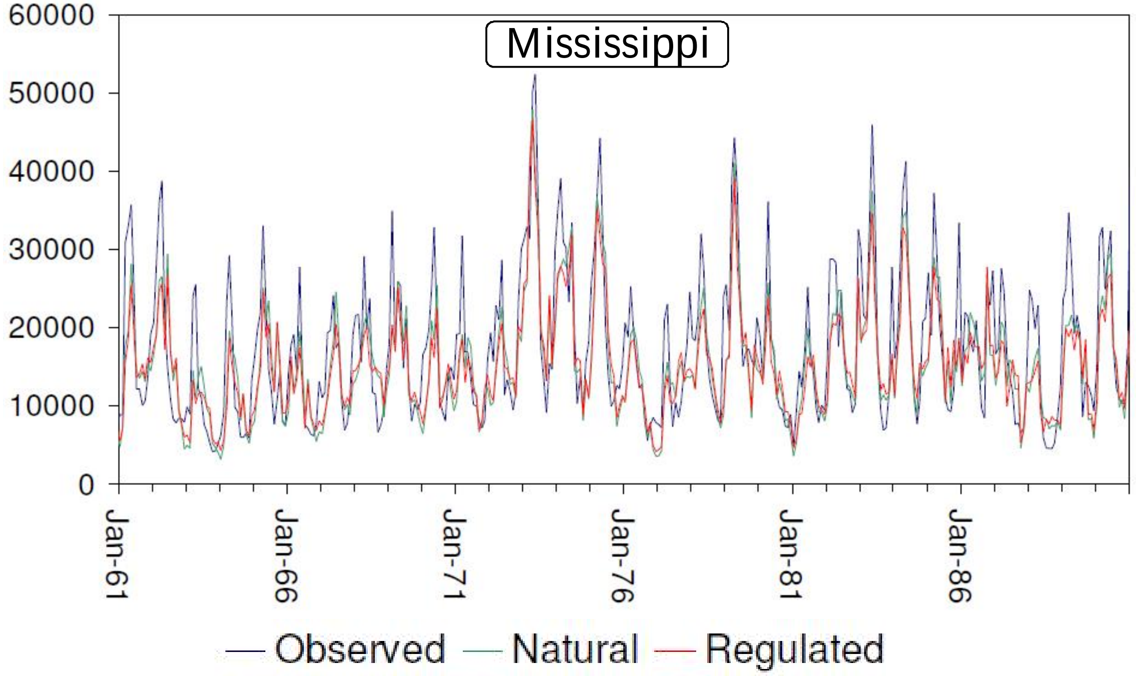


Global groundwater depth

Validation streamflow







Comparisons with GRDC stations (N= 1978) in monthly discharge (m^3/s)

	R^2
Minimum	0.855
Mean	0.909
Maximum	0.775

Verification

FAO AQUASTAT								
Sector		**1970**	**1975**	**1980**	**1985**	**1990**	**1995**	**2000**
Agriculture	R^2	0.98	0.98	0.96	0.97	0.97	0.99	0.98
	α	1.12	1.08	0.96	0.92	0.99	0.90	1.01
Industry	R^2	0.98	0.99	0.98	0.97	0.97	0.92	0.98
	α	1.03	1.06	1.20	0.99	0.99	1.20	1.10
Domestic	R^2	0.97	0.98	0.95	0.97	0.98	0.96	0.95
	α	0.85	0.98	0.95	0.88	0.90	1.10	0.92
Total	R^2	0.96	0.98	0.99	0.96	0.96	0.98	0.96
	α	0.85	1.09	0.89	0.95	0.99	0.91	0.99

R^2: Coefficient of determination

α: Slope

Large deviations

≥ +50%

Greece

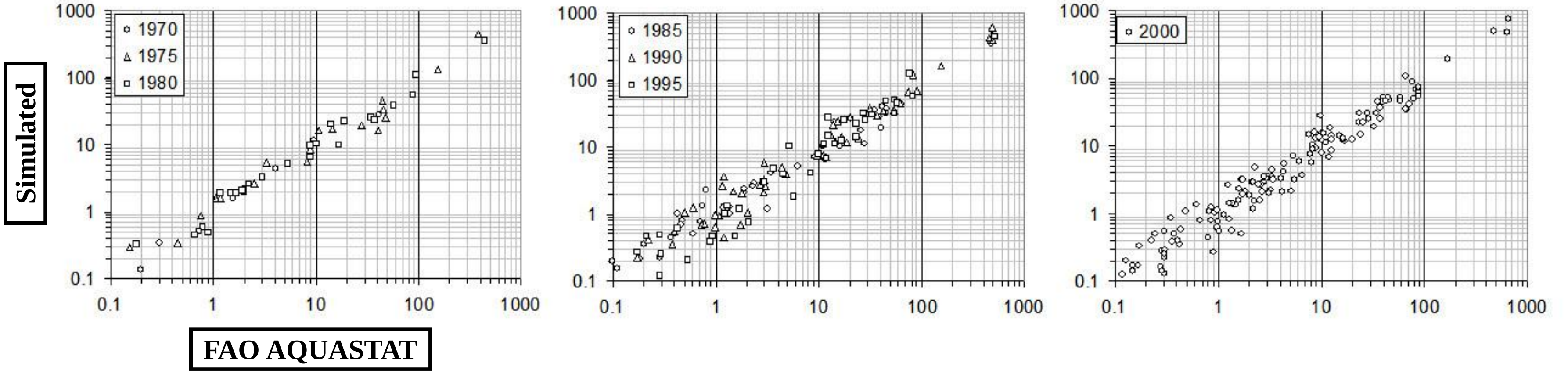
Iraq

≤ -50%

Mali

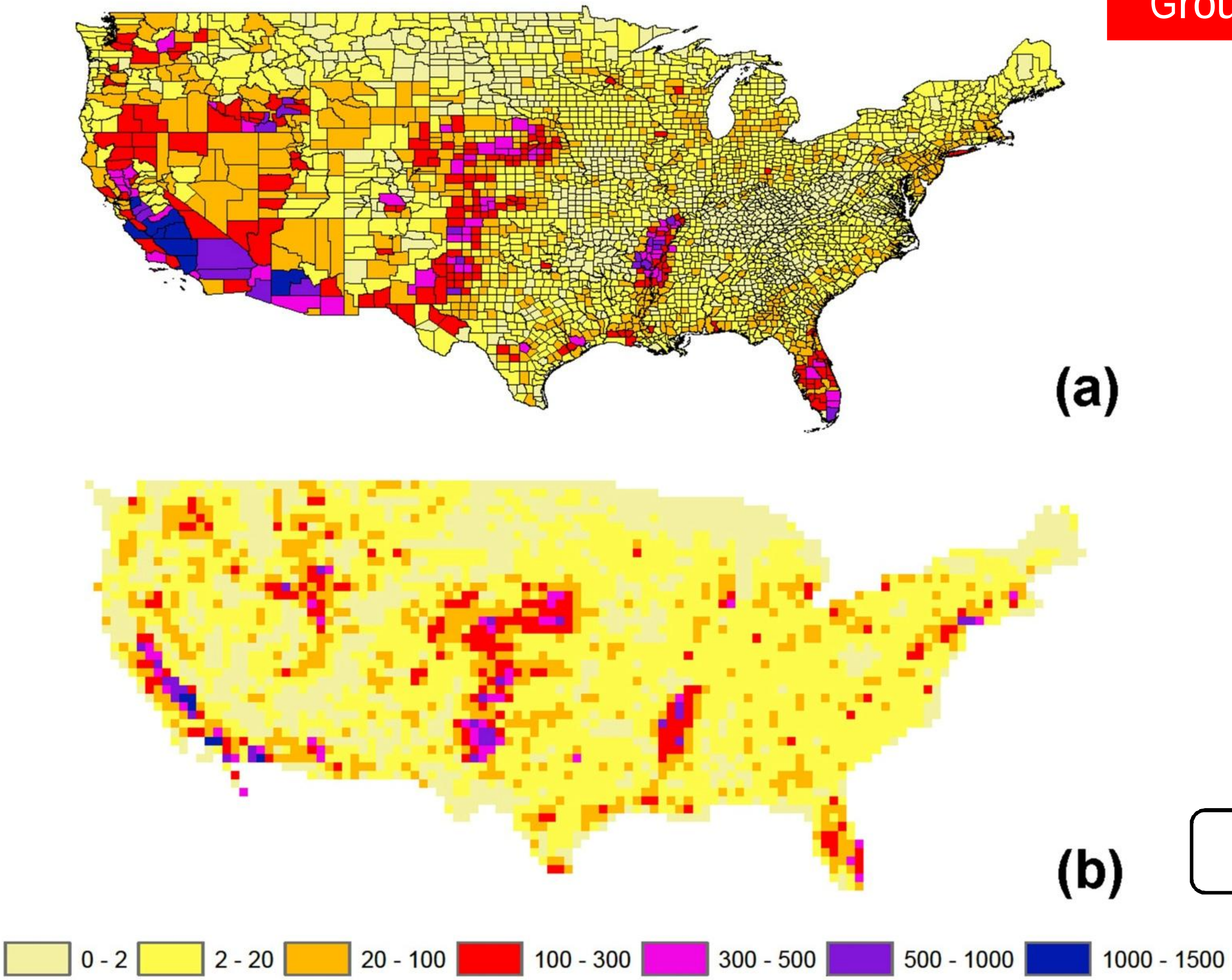
Turkmenistan

Total water demand



Validation

Groundwater abstraction



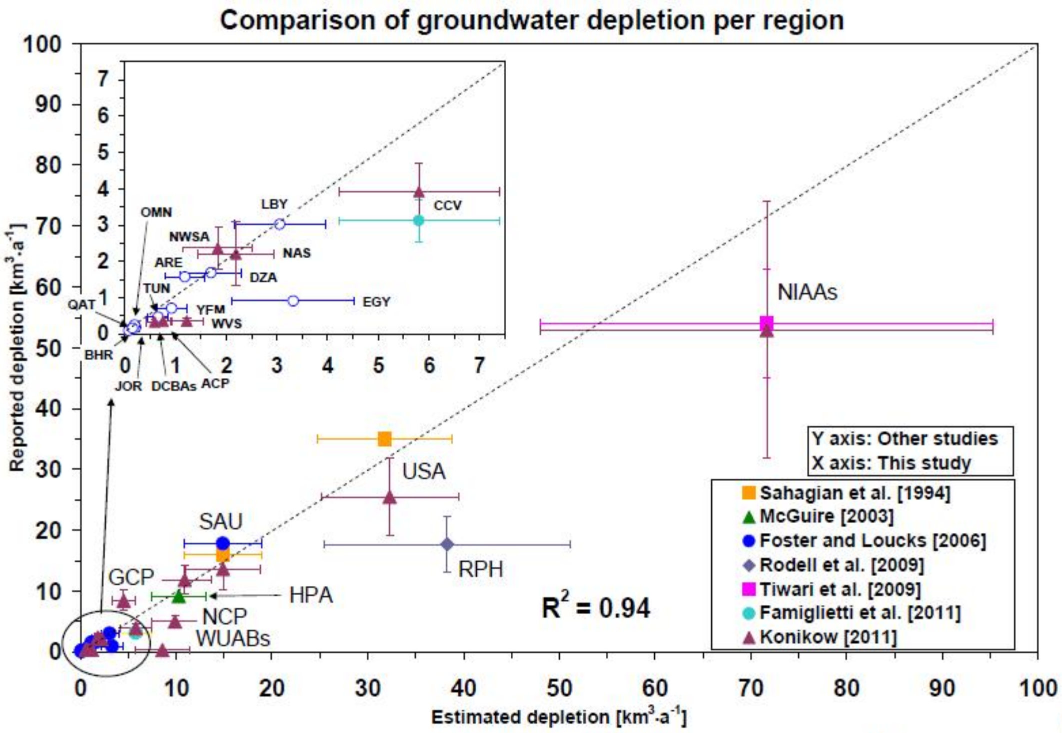
USGS

[Per county]

This study

[0.5°]

million m^3/year 2000



Validation

Compare to independent, mostly volume-based, estimates

Correction

Our estimates tend to overestimate depletion in non-arid regions

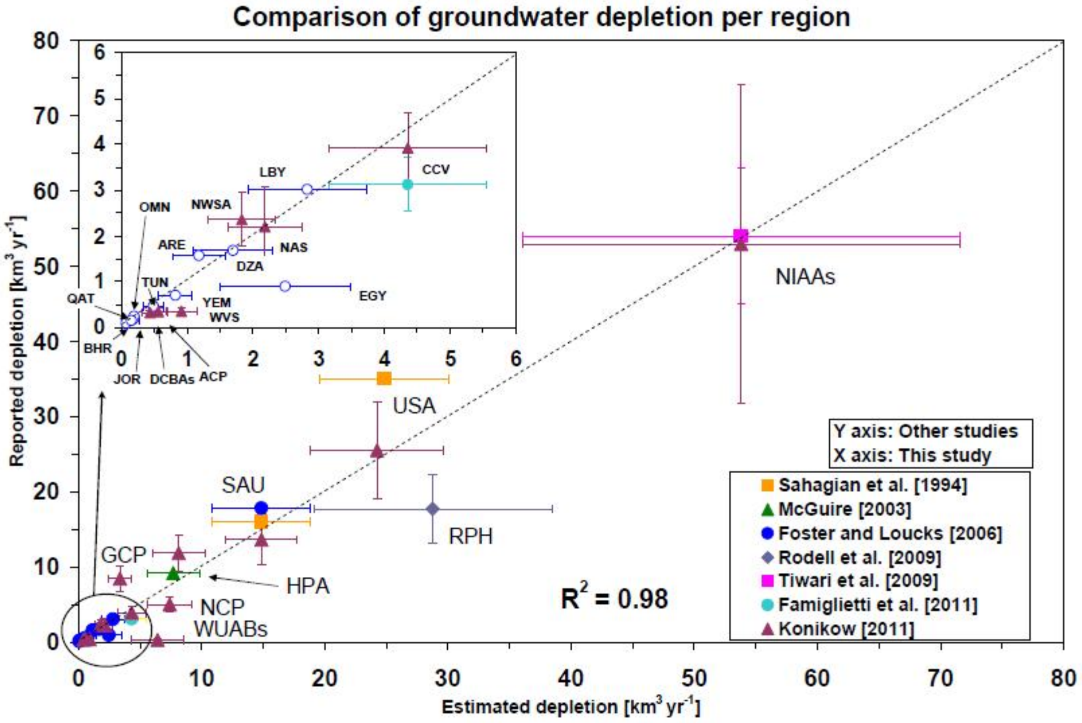
Global total (year 2000)

This study: 204 km^3/year

= 0.57 mm/year

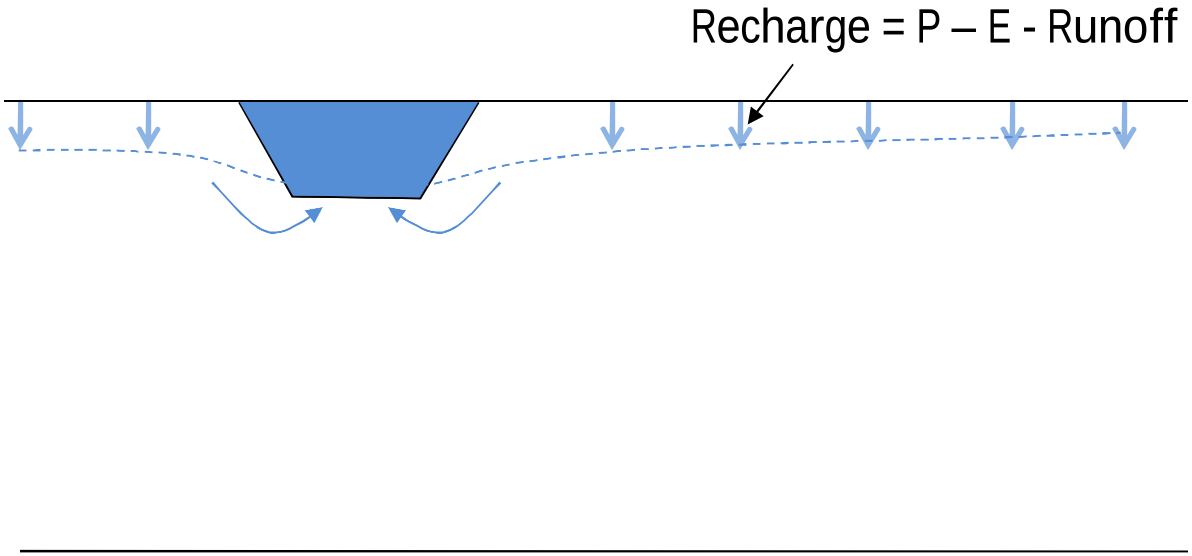
Konikow (2011): 145 km^3/year

= 0.40 mm/year



Mechanism of GWD

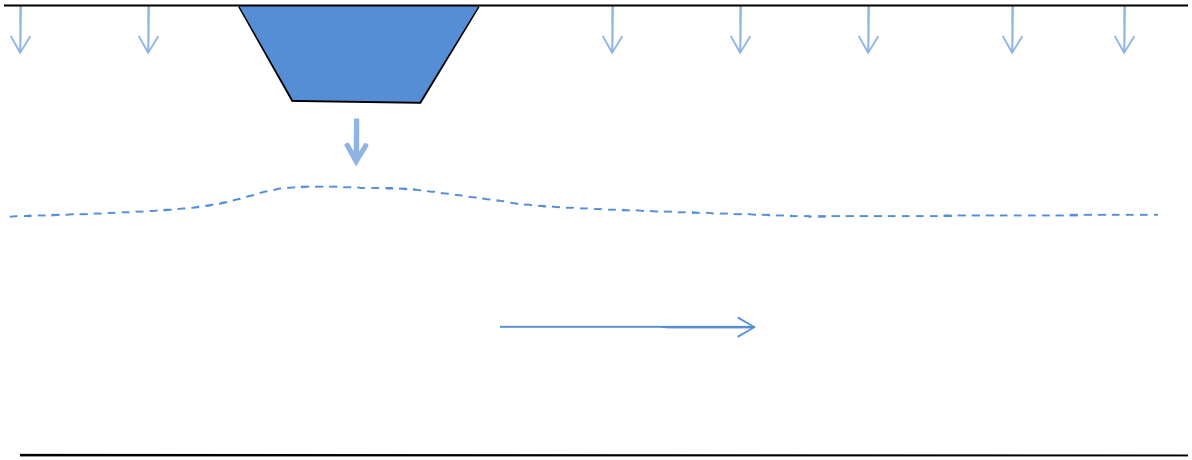
Natural situation: $P > E_{pot}$



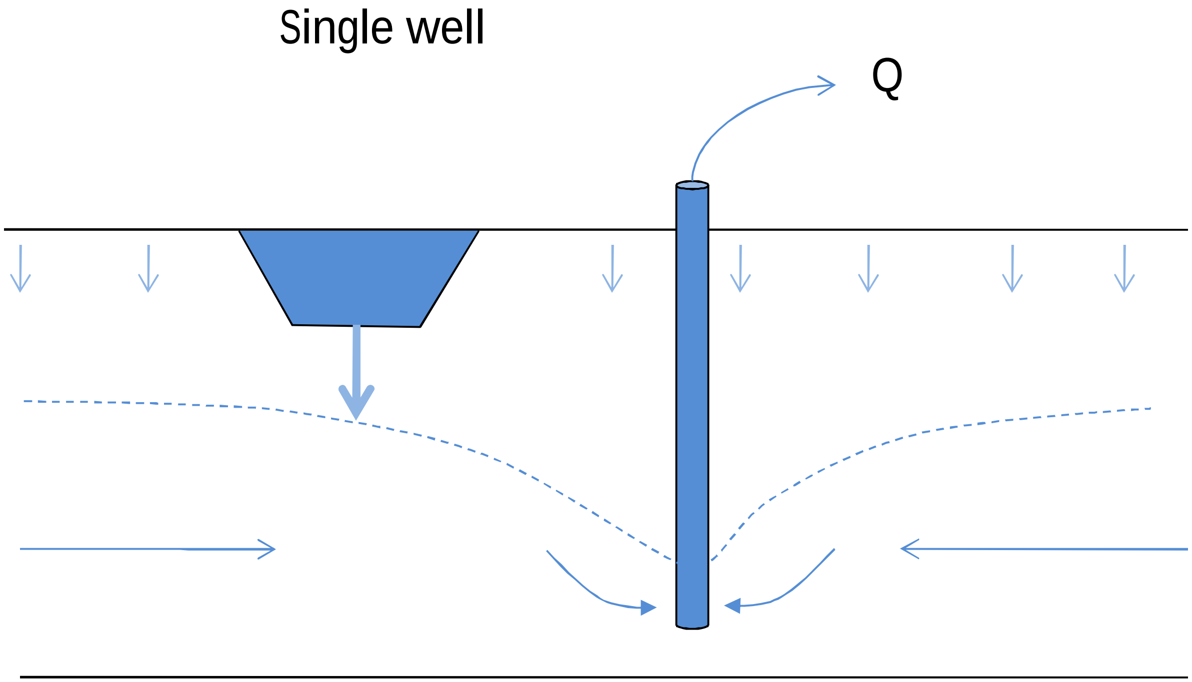
Recharge = P – E - Runoff

Mechanism of GWD

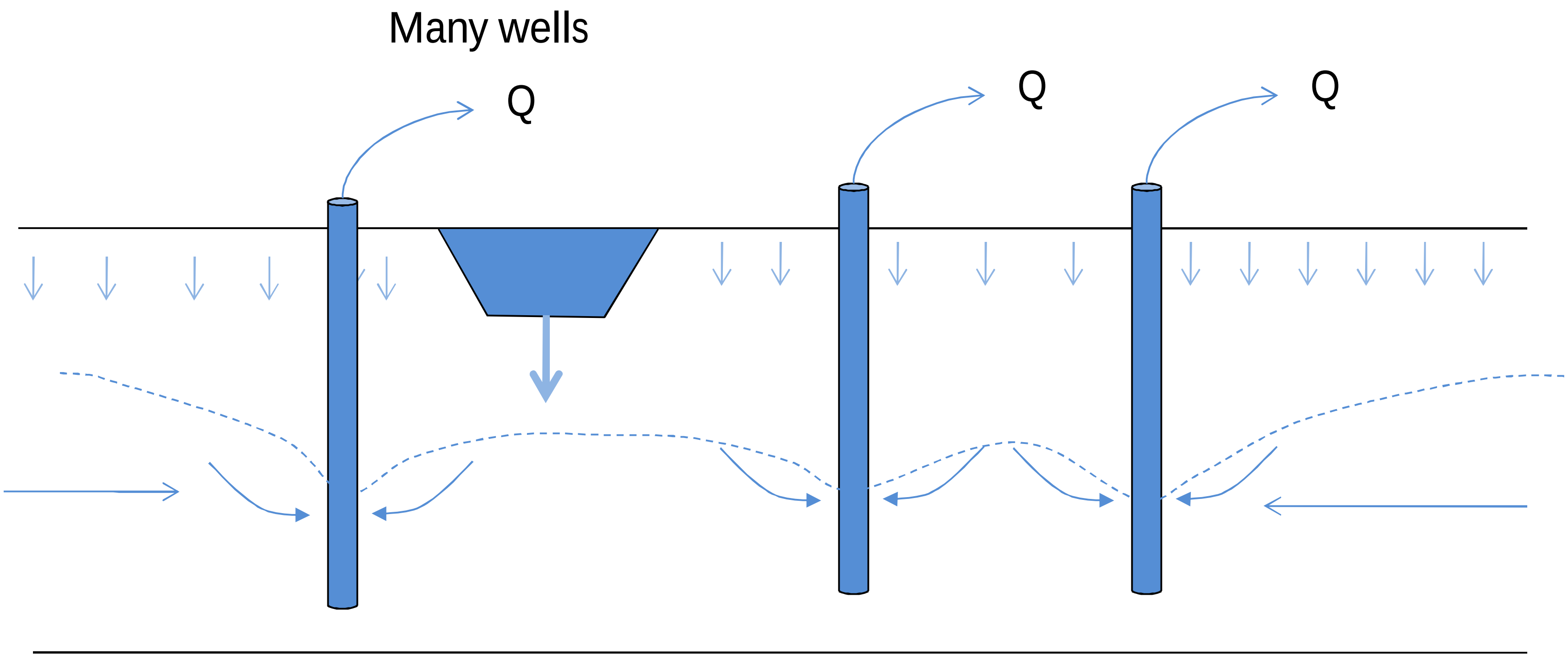
Natural situation: $P < E_{pot}$



Mechanism of GWD

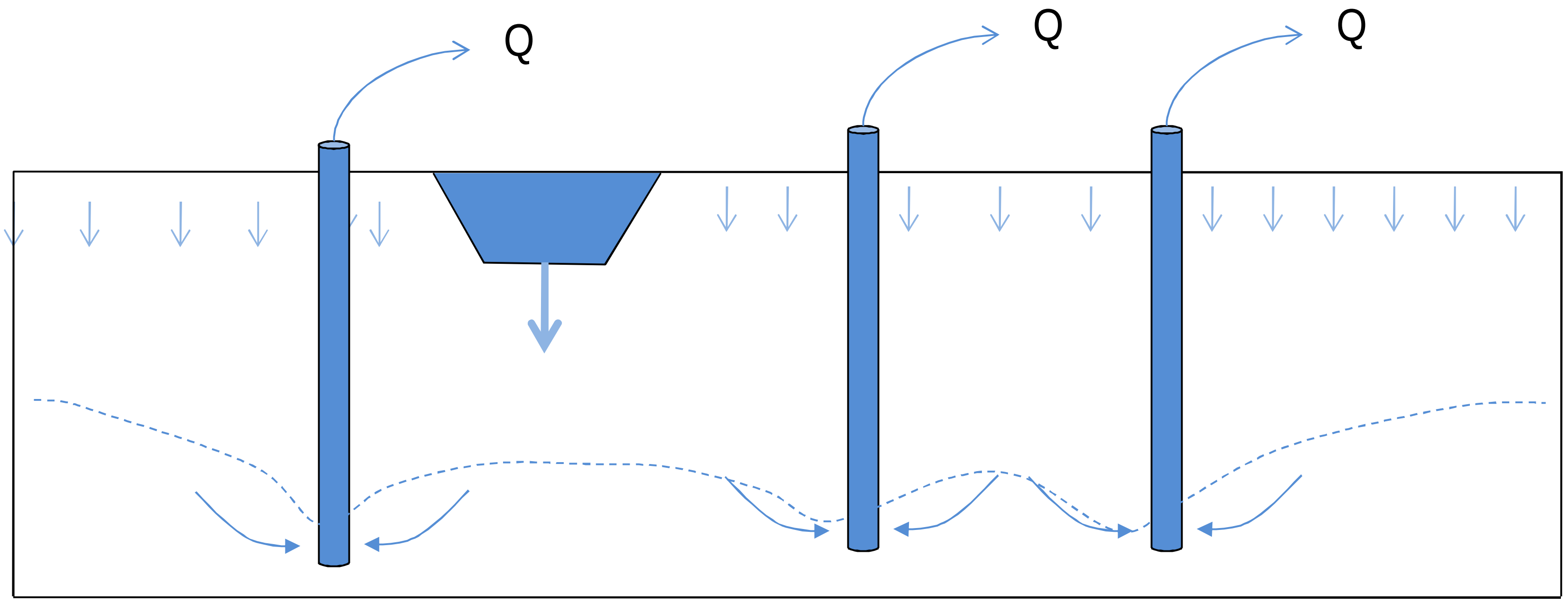


Mechanism of GWD

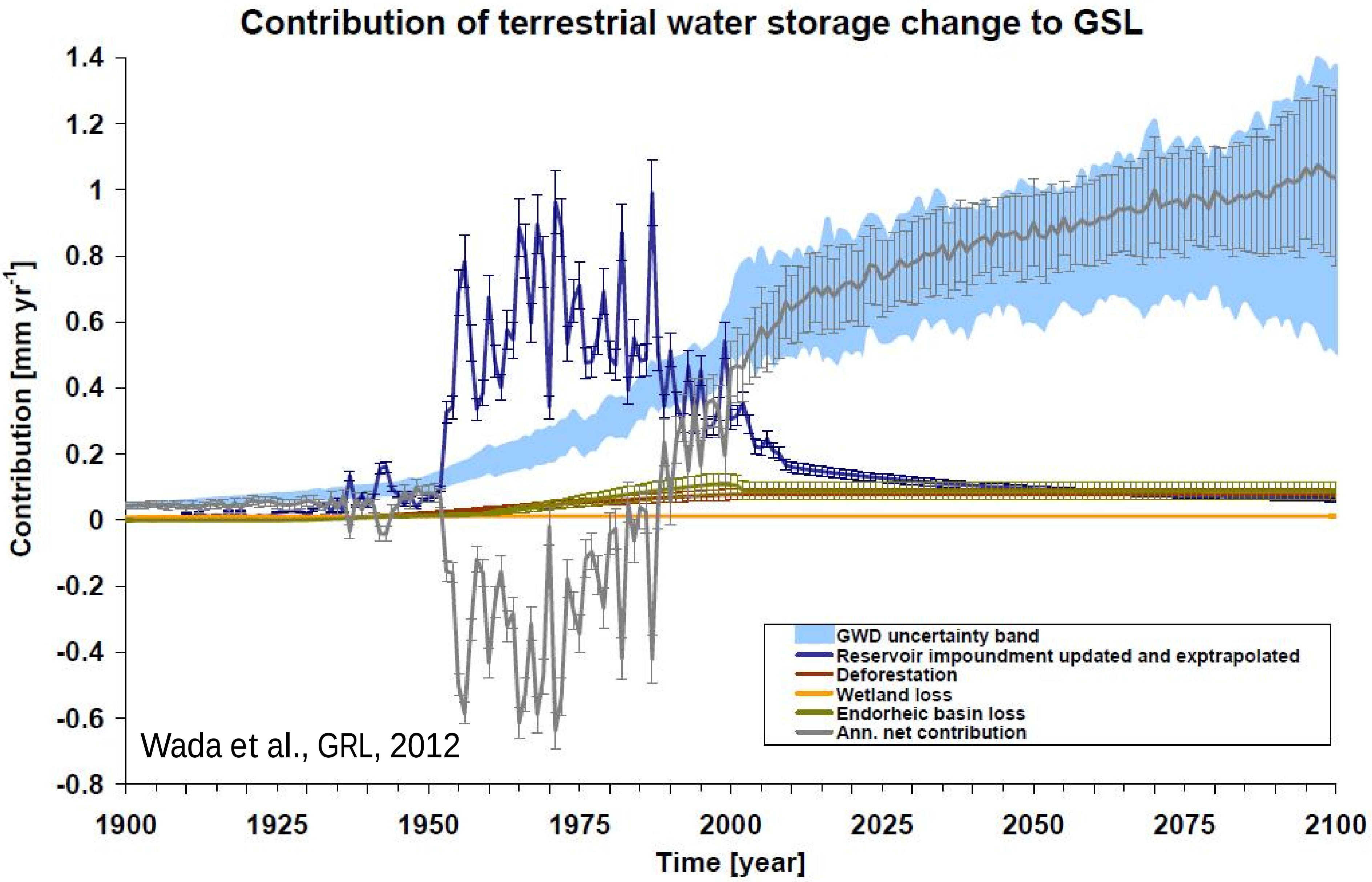


Mechanism of GWD

Many wells: finite aquifer



Net Contribution from TWS Change to Sea Level 1900-2100



Wada et al., GRL, 2012