# Water Systems in Integrated Human-Earth System Models

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PLCY-798K

Integrated Human-Earth System Modeling and Policy Assessment

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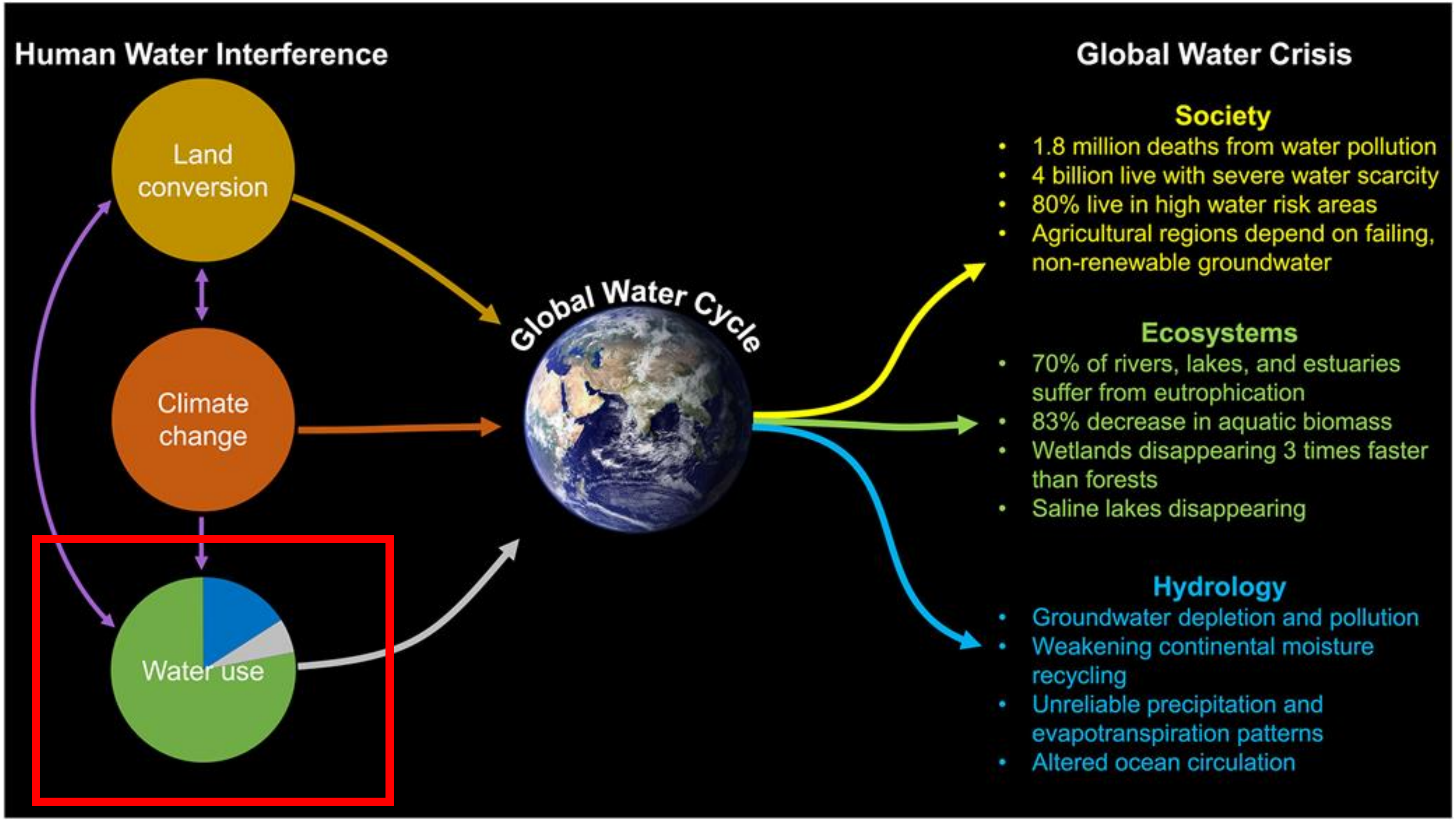
Credit to Tom Wild for slides

# Today’s Topics

- **Water Demand**
  - How much water do humans use, where, and for what purposes?
- **Water Supply**
  - How much water is sustainably available, where, and in what forms?
  - How will climate change affect this supply?
- **Approach to Representing Water in Integrated Models**
  - Why and how is water accounted for?
  - As an example, how does GCAM model water?
- **Exciting Science Questions Integrated Models are Exploring**
  - What key insights have emerged?
  - What questions remain unanswered?

# There is a Global Water Crisis, and Humans are Causing it




Source: Abbott et al. (2019)

# Water Demand

How much water do humans use, where, and for what purposes?

# First, Some Terminology

**Water withdrawal (i.e., usage, demand)**: amount of fresh water taken from a water body for purposes of satisfying some human purpose (energy, domestic, irrigation, etc.)

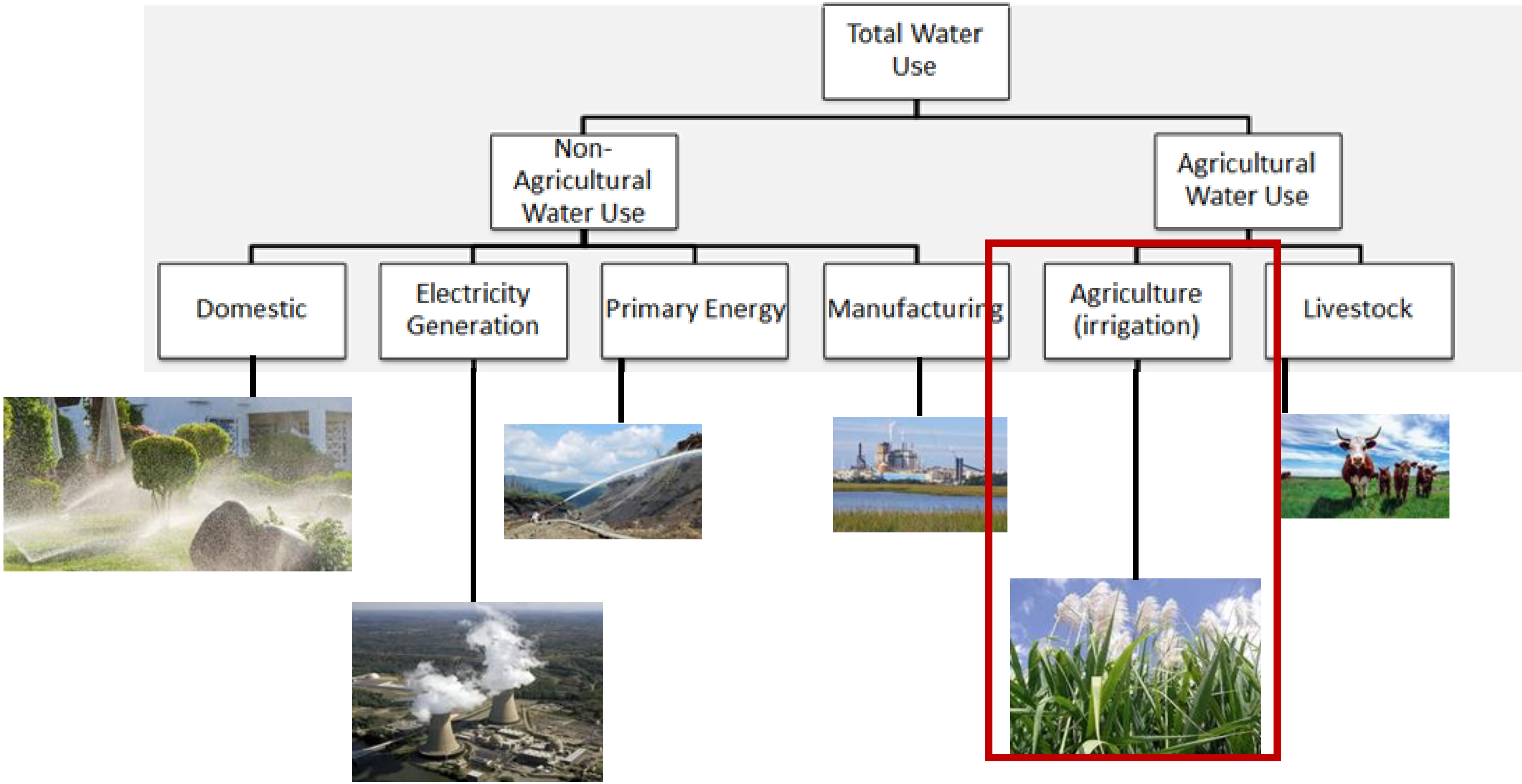
**Total Water Withdrawal:** sum of water *demands* across all sectors (agriculture, industry, municipal)

**Water consumption**: amount of water withdrawal that is not returned to the original source and is no longer available for reuse (e.g., consumed through evaporation or incorporated into products or waste materials)

**Water supply**: used loosely to mean a lot of different things. In modeling lingo, demand=supply to clear markets, the same as it does for energy or land. Can also be used to indicate "availability". Supply can come from surface water (lakes, river, reservoirs), groundwater (renewable or fossil), desalination, gray water "reuse", etc.

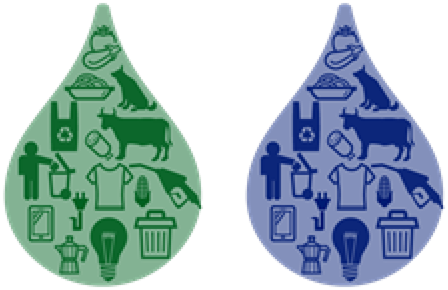
# So, how much water do countries use?

# Water is a Critical Input to the Agriculture, Domestic, and Industrial Sectors



# Future water usage in any region is complex to project, being tied to the evolution of future Ag. commodities trade dynamics

**Virtual Water**



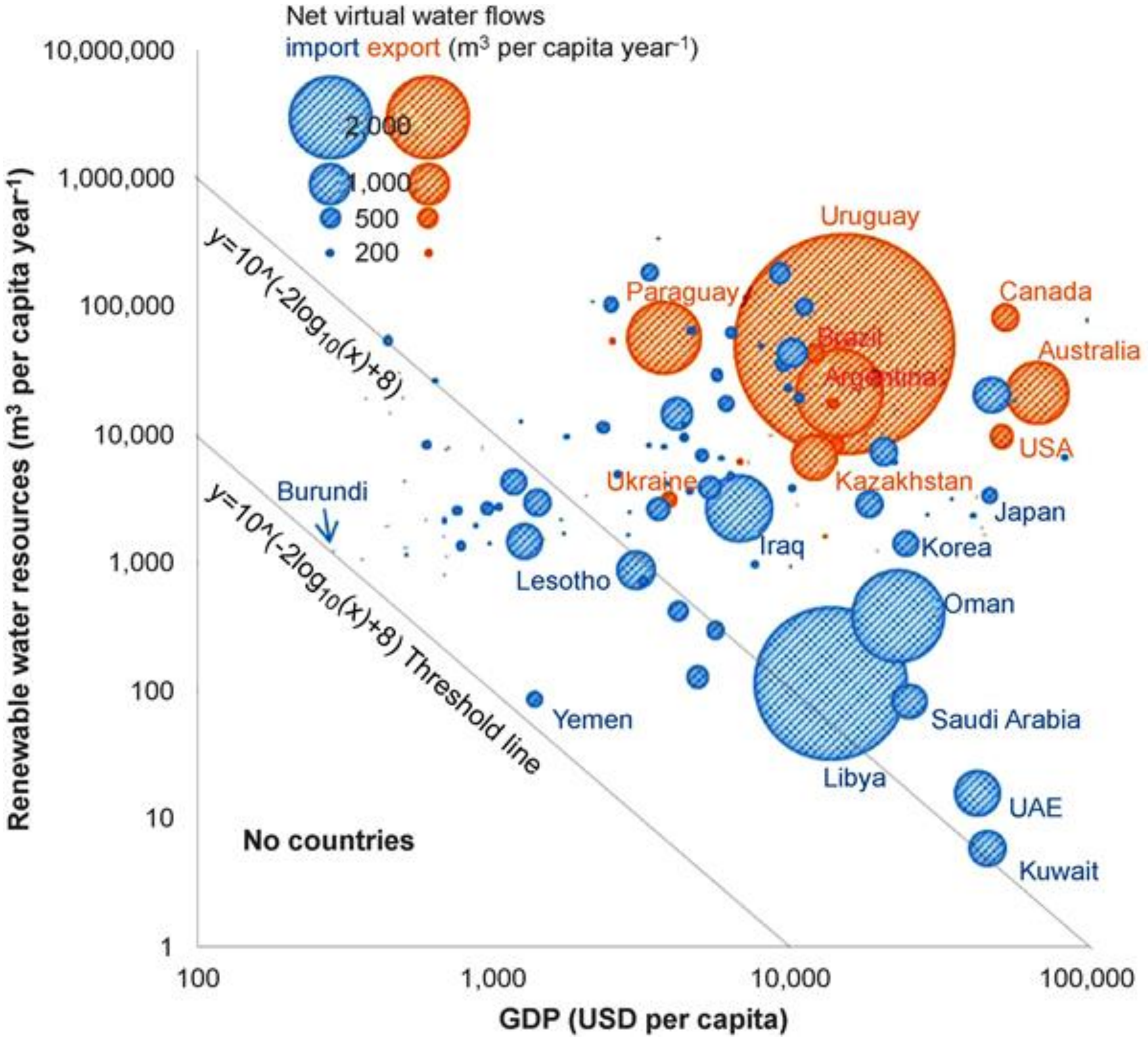
Adopted and modified from: *watercalculator.org*

Soil moisture and transpiration consumed in crop growth

Blue = fresh surface runoff and groundwater consumed in crop growth

- Virtual water trade – Amount of water embedded in commodity production that is then traded in the global market (Allen 1998)
- Importing is often driven by local unmet demands as a result of:
  - Insufficient water supply
  - Insufficient growing capacity (land or climate)
  - Cost

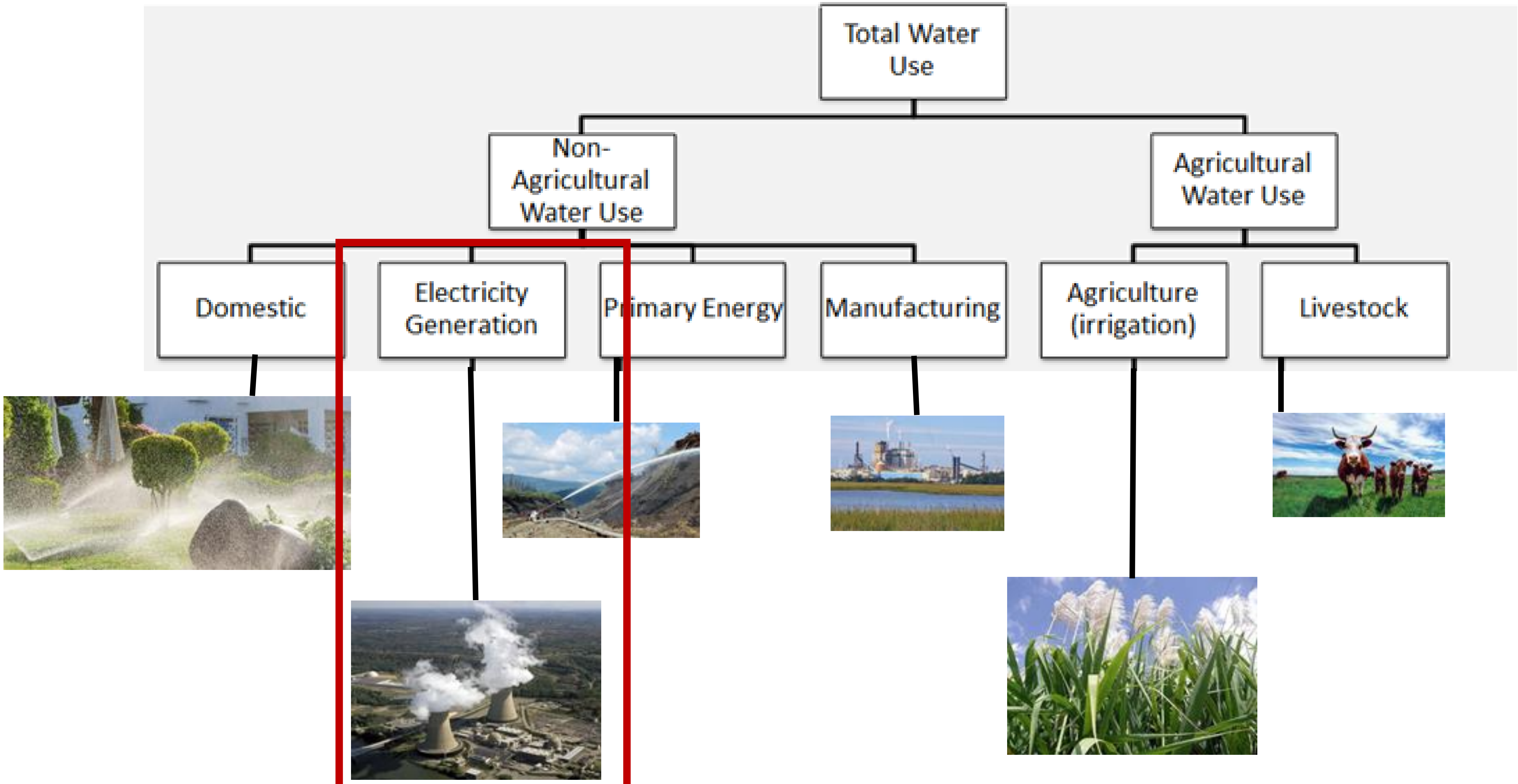
# Future water usage in any region is complex to project, being tied to the evolution of future Ag. commodities trade dynamics




*Integrated Human-Earth System Models like GCAM are uniquely positioned to deal with regional trade*

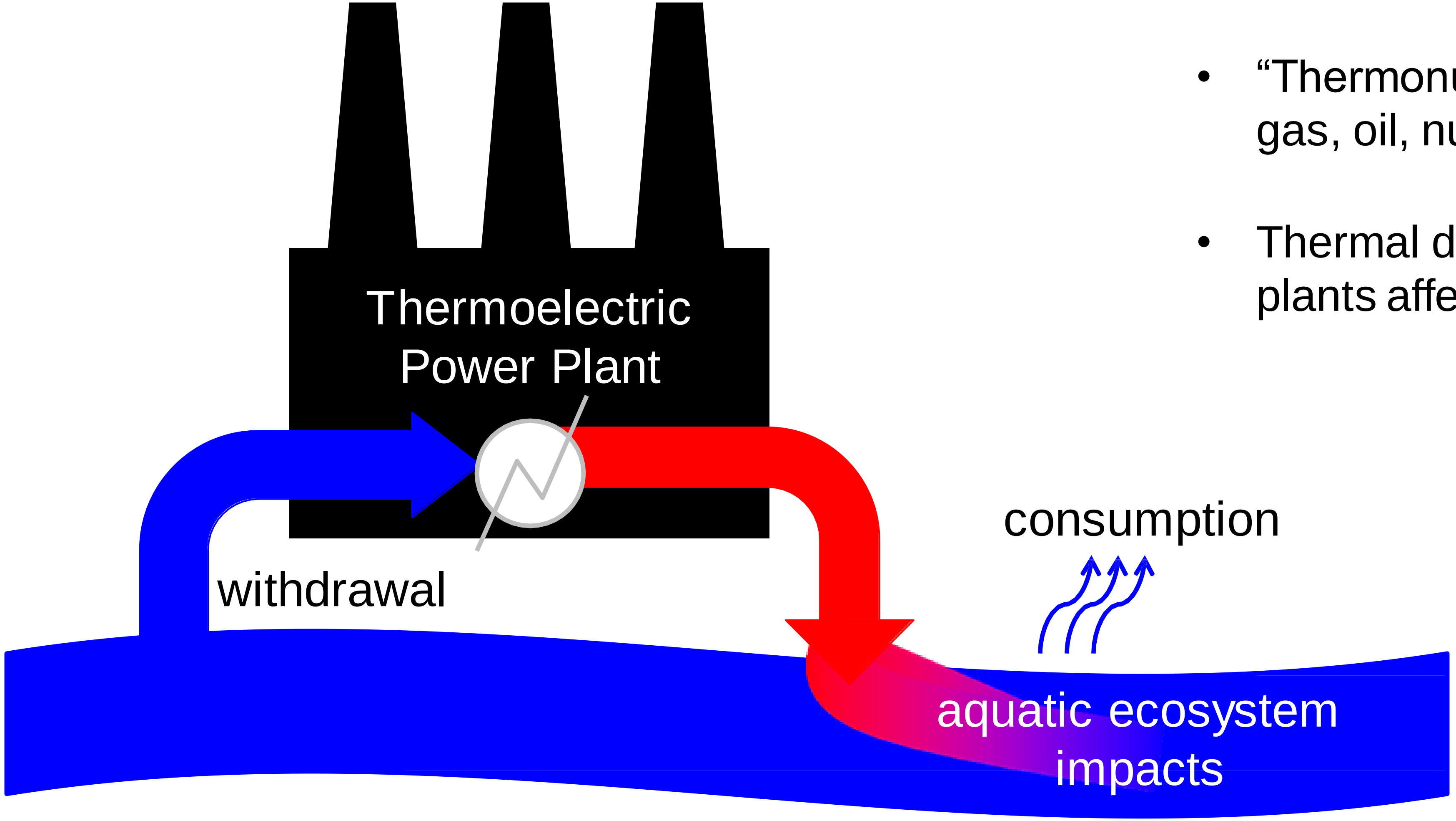
*Source: Oki et al 2017. Economic aspects of virtual water trade. ERL.*

# Water is a Critical Input to the Agriculture, Domestic, and Industrial Sectors



# Thermoelectric power plants require cooling

Once-through cooling technology requires a lot of water “withdrawal”, with some “consumption”

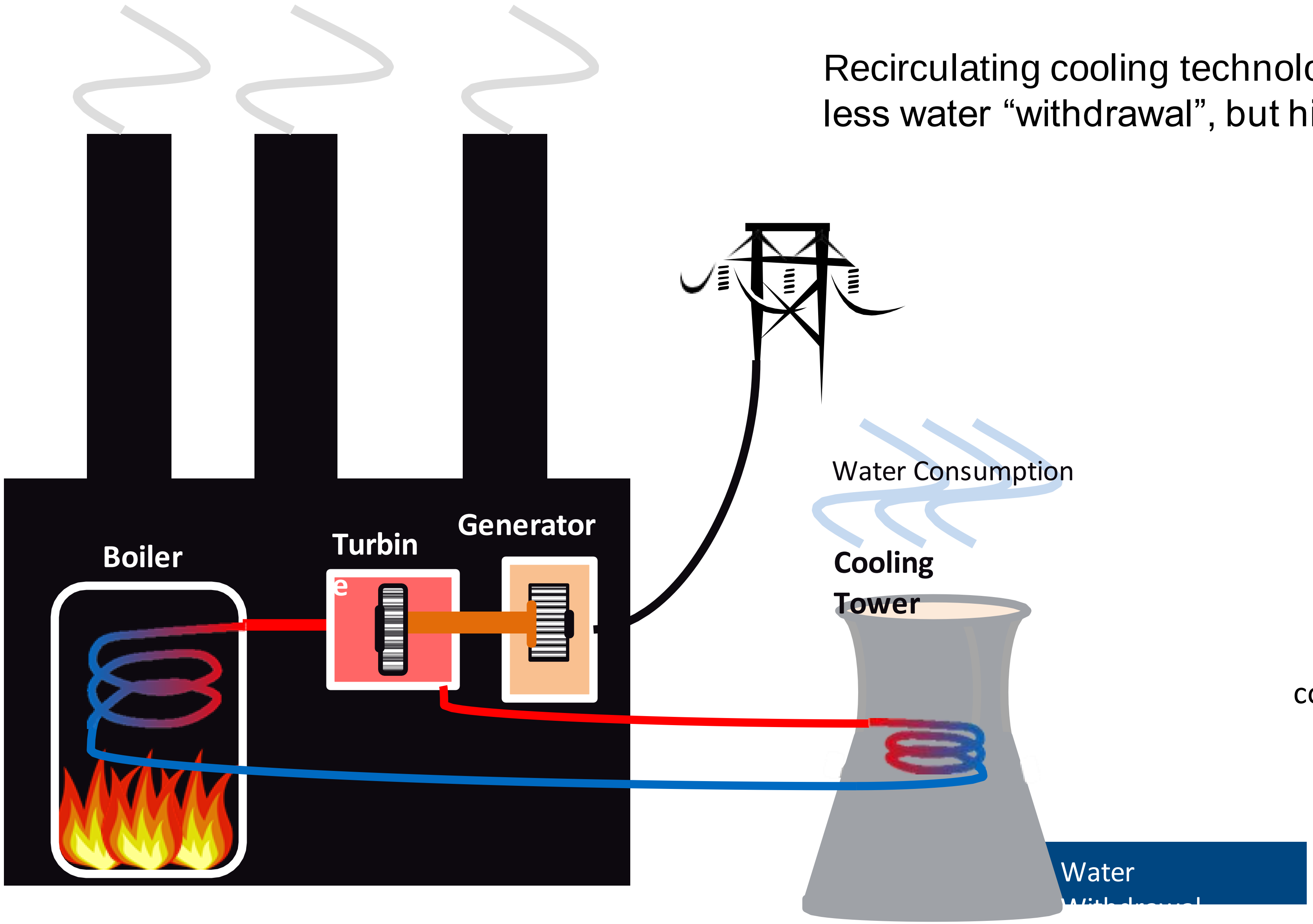



- “Thermonuclear” includes coal, gas, oil, nuclear, geothermal
- Thermal discharge from power plants affects aquatic ecosystems

courtesy of Ashlynn Stillwell, UIUC

# Thermoelectric power plants require cooling

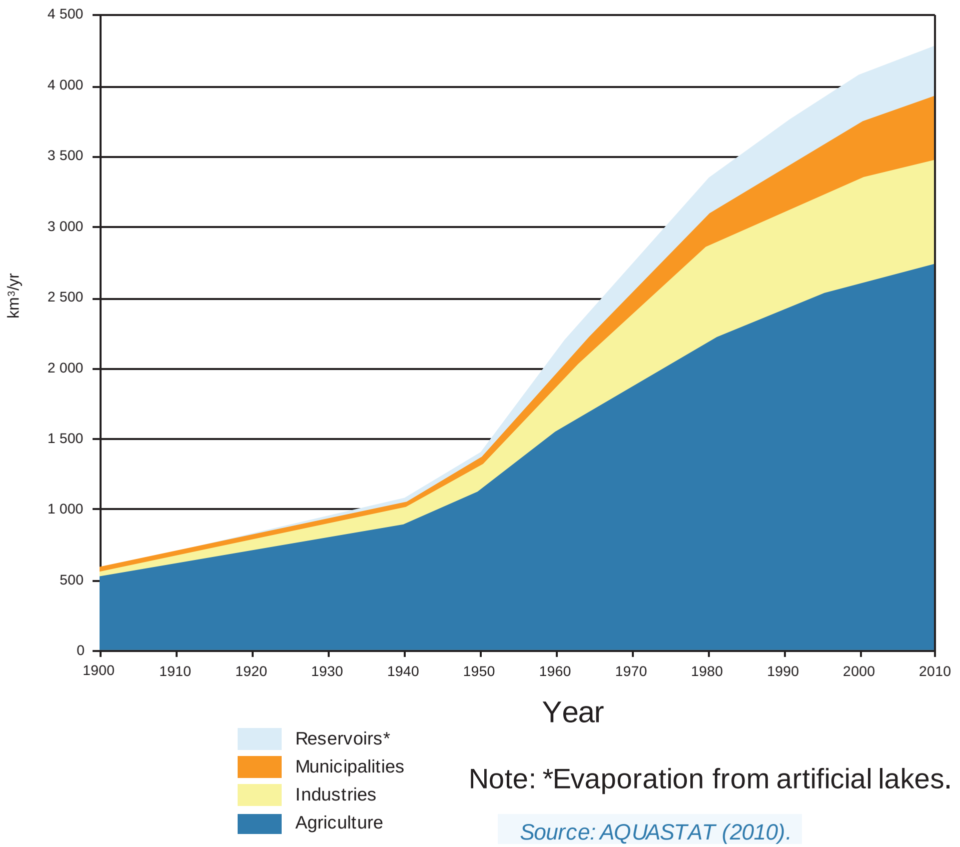
Recirculating cooling technology requires much less water “withdrawal”, but high “consumption”




courtesy of Ashlynn Stillwell, UIUC

# Agriculture Sector is the Dominant Water User Historically, with Largest Demands in developing economies

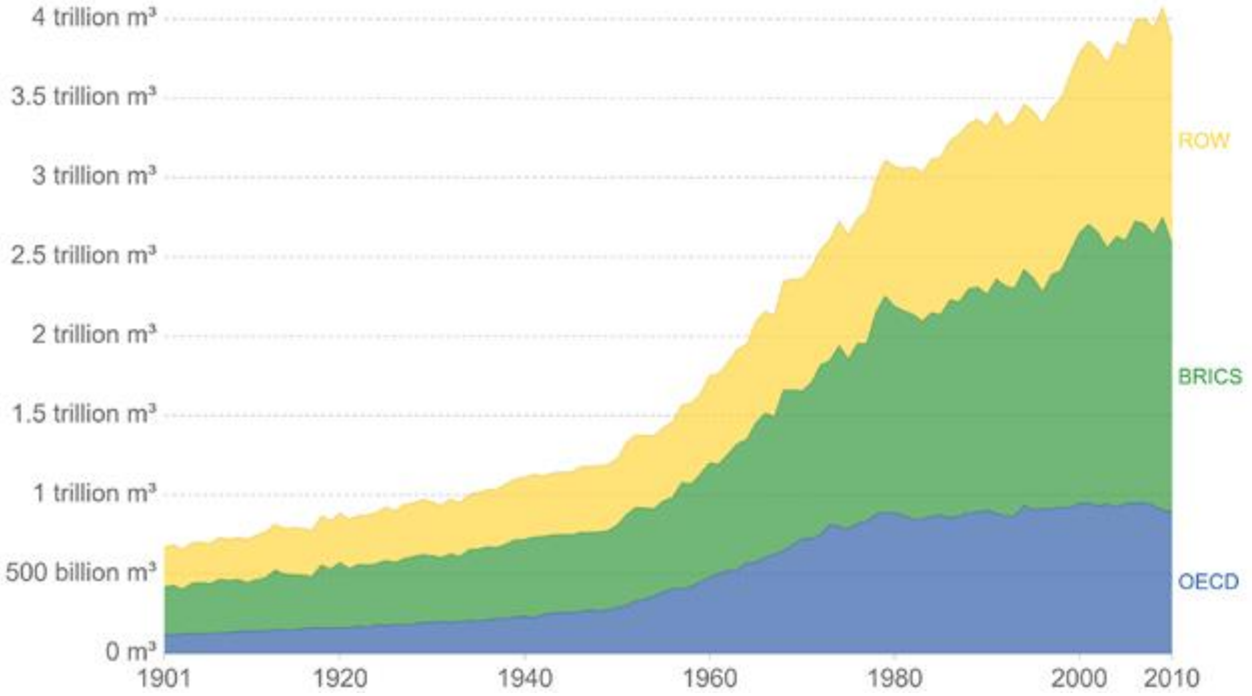
Global water withdrawals by sector




Note: *Evaporation from artificial lakes.

*Source: AQUASTAT (2010).*

Global water withdrawals by region




How will these demands evolve into the future? What sources of water will “supply” these demands in the future? Integrated Models like GCAM are useful for addressing such questions.

# How are humans modifying the water cycle via water use?


Source: Abbott et al. (2019)

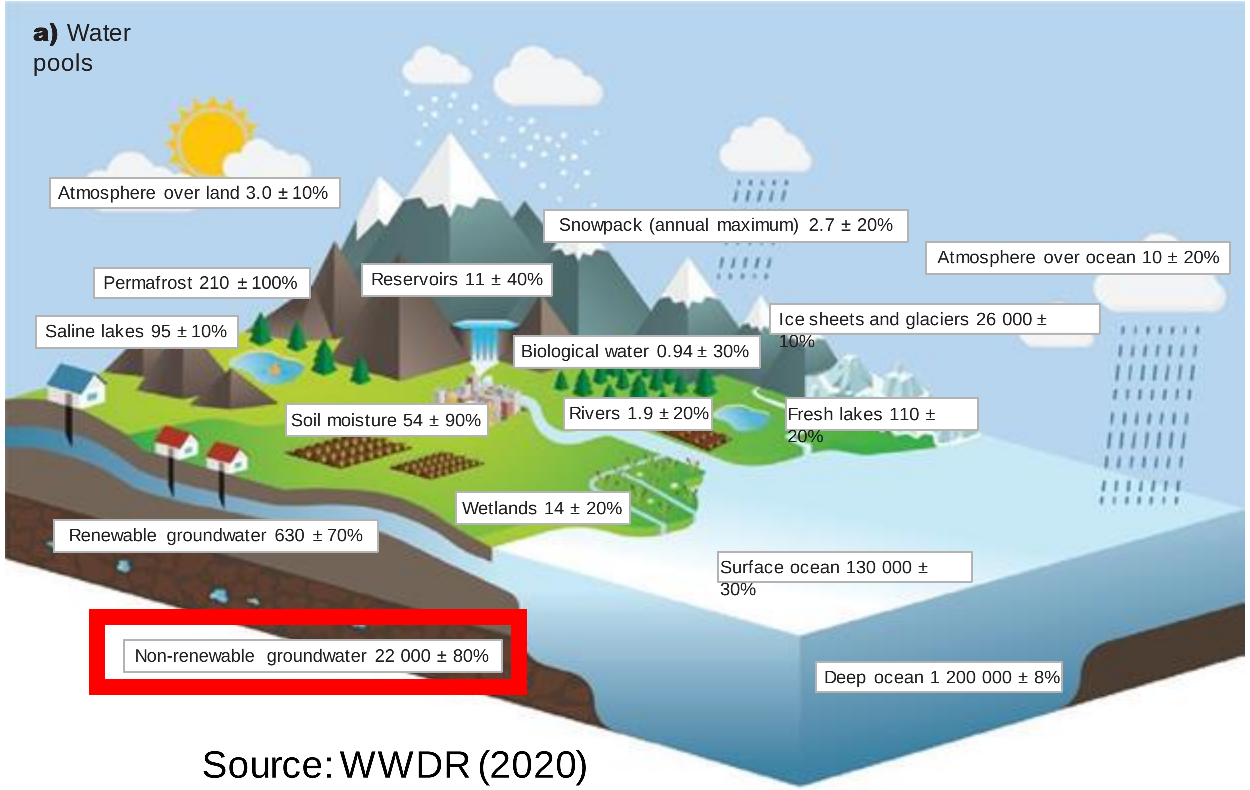
# Water Supply

How much water is (sustainably) available, where, and in what forms?

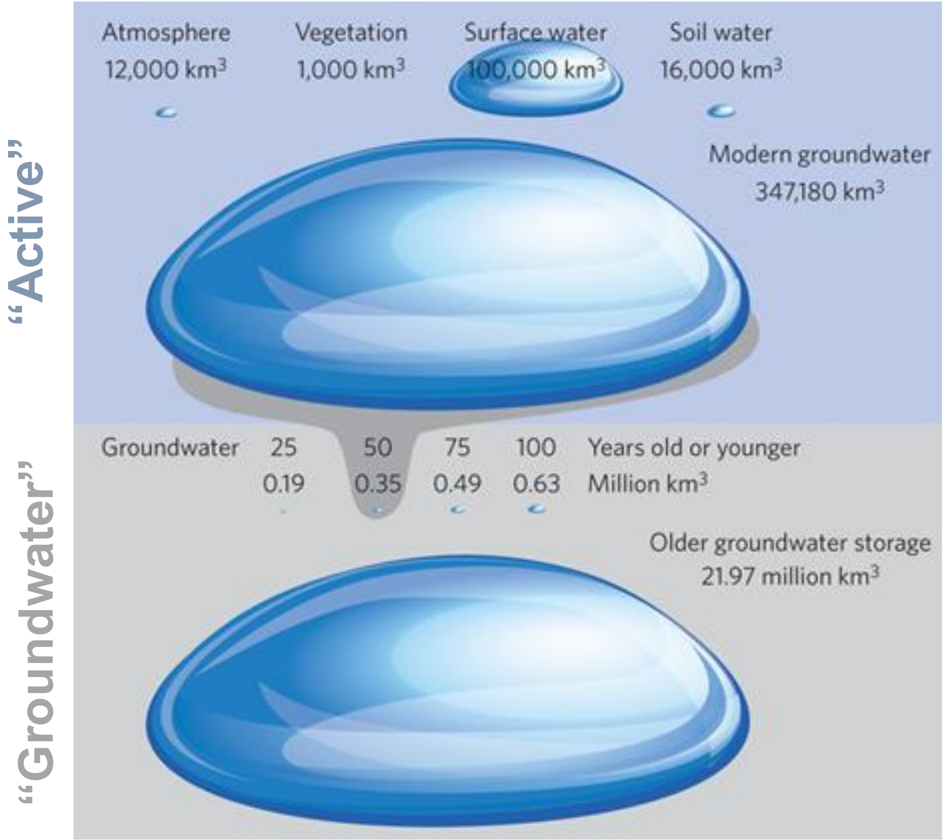
How will climate change affect this supply?

# The Global Water Cycle

Water Stocks (i.e., Pools)




Source: WWDR (2020)



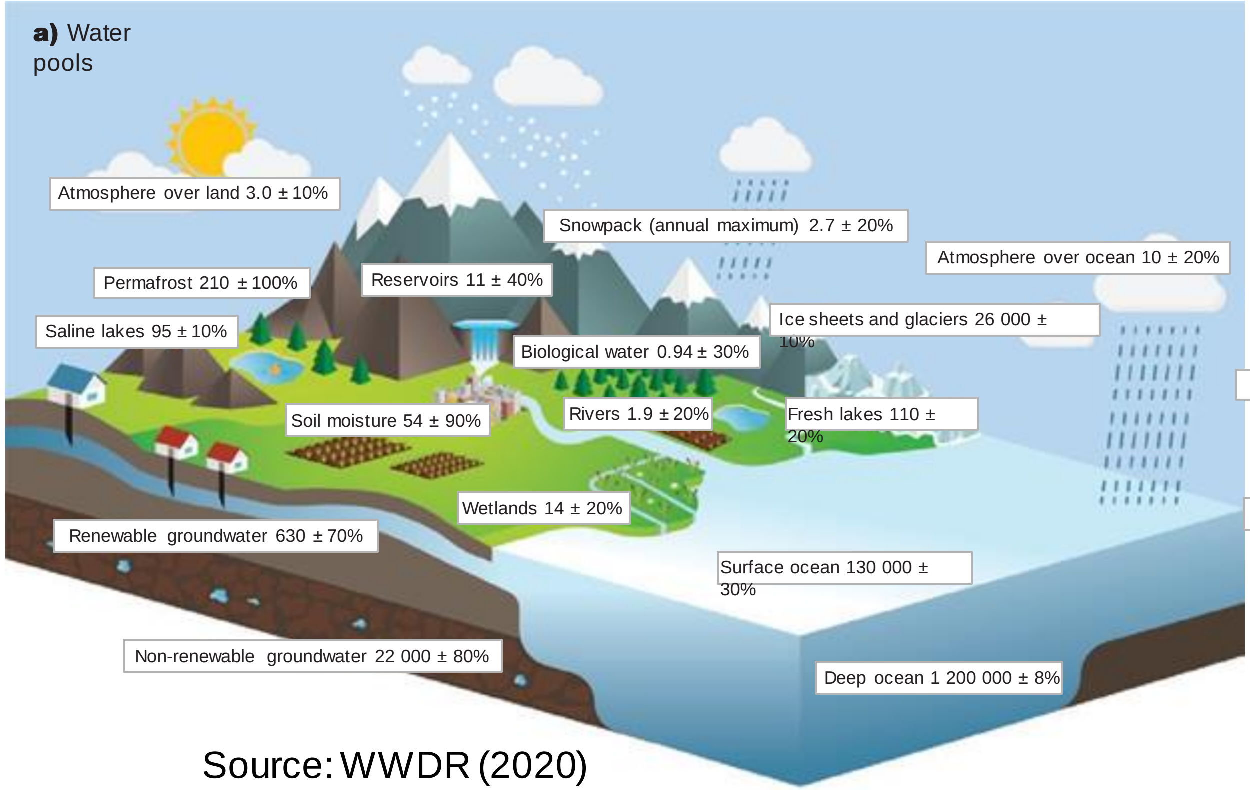

Source: Gleeson et al. (2016)

What are the largest stocks of available freshewater for human use?

Groundwater (GW) provides a huge reserve. "Modern" groundwater = 3x SW; Fossil GW=220x SW. Though fossil GW is not "sustainable, can be expensive to pump, and is really of unknown quantity.

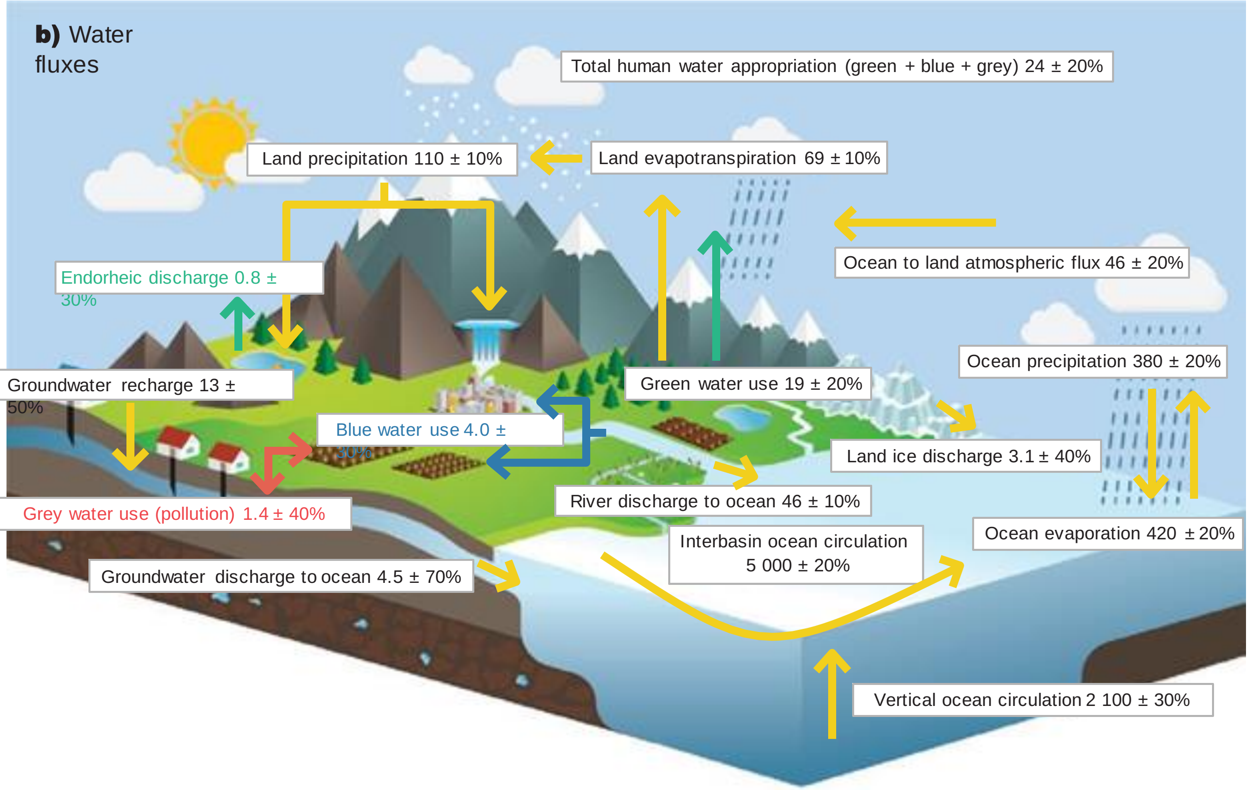
# The Global Water Cycle

## Water Stocks (i.e., Pools)




Source: WWDR (2020)

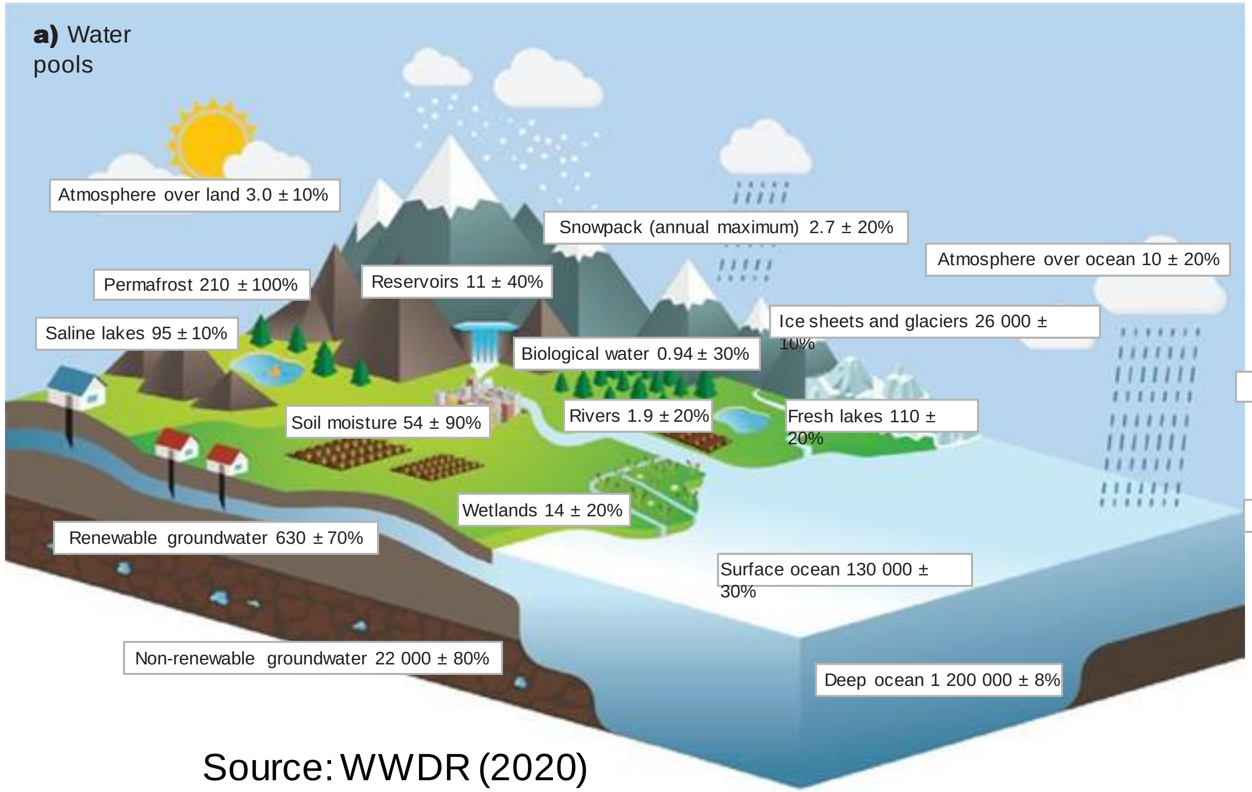
## Water Flows (i.e., Fluxes)

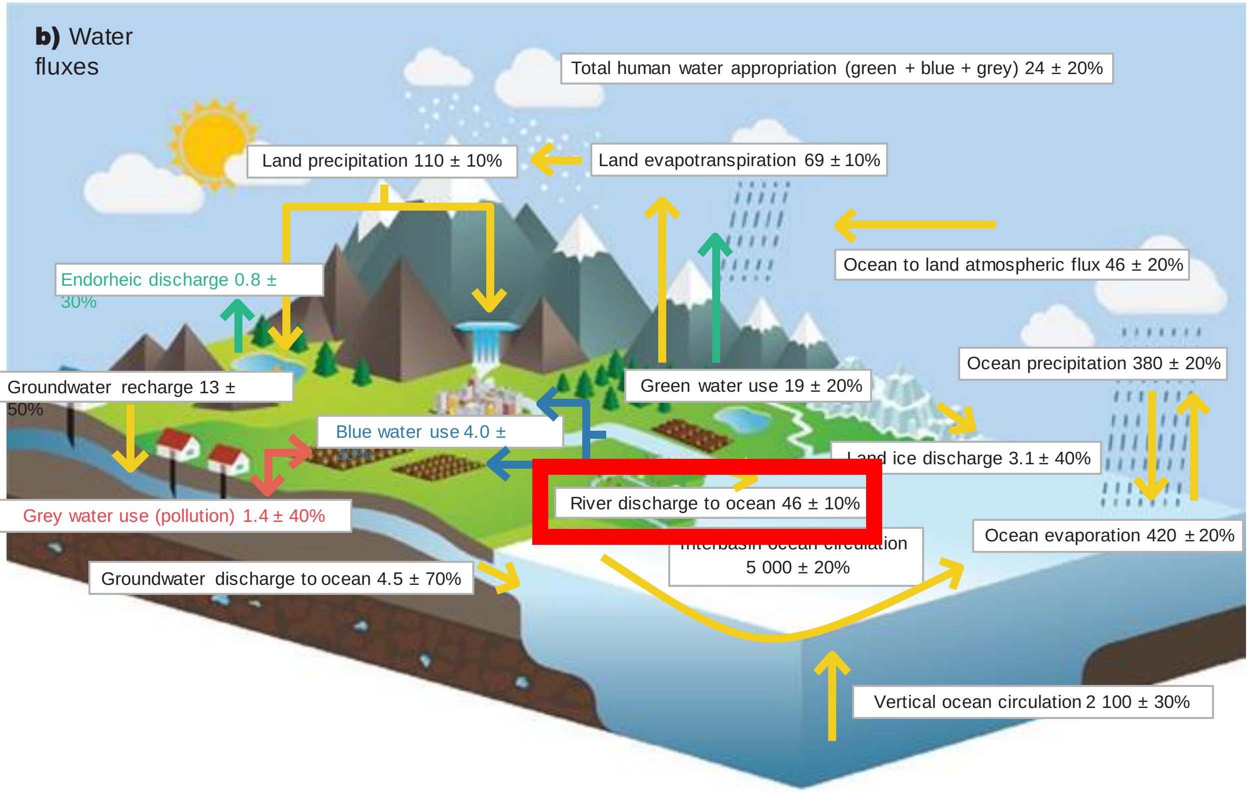



- It is no longer possible to understand the distribution of water quantity and quality on Earth without considering human activity.
- Human water use (fluxes) are separated into green (78%), blue (16%), and grey (6%) water use

# The Global Water Cycle

Water Stocks (i.e., Pools) | Water Flows (i.e., Fluxes)



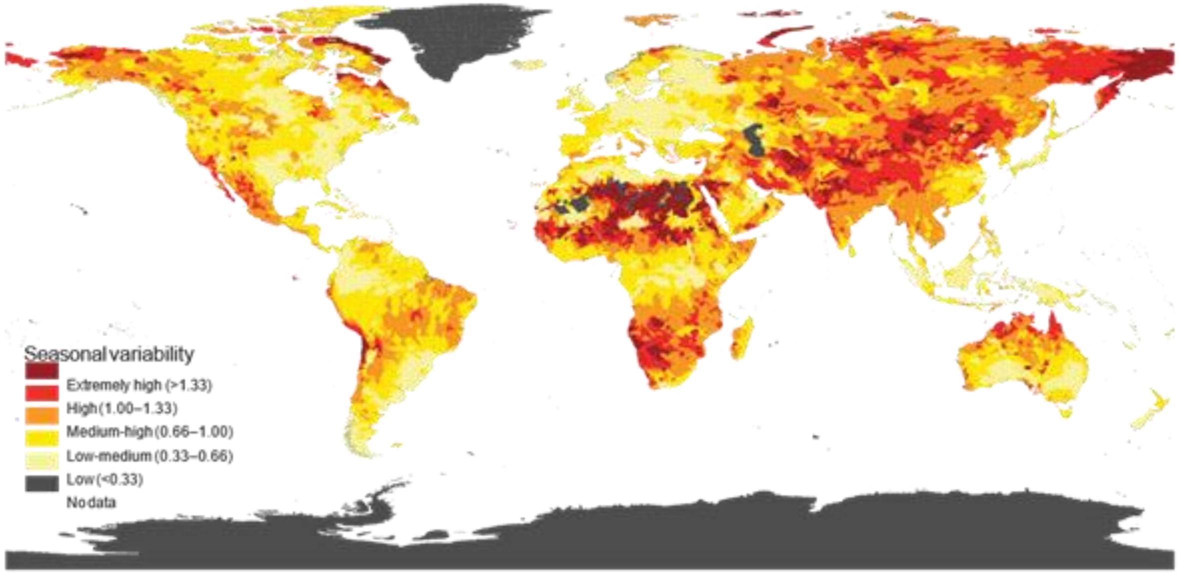




Source: WWDR (2020)

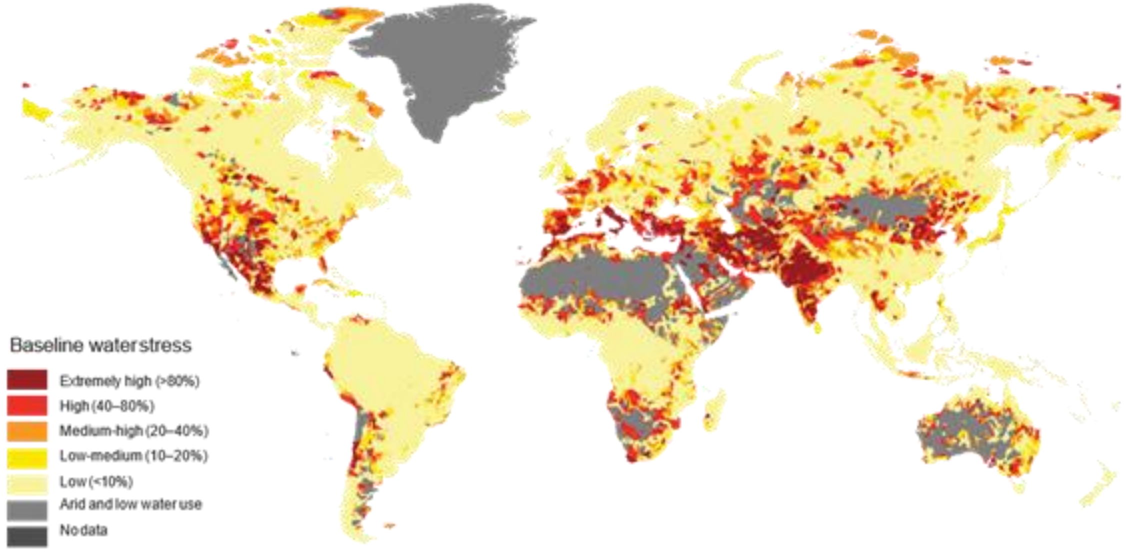
How much of this water can we sustainably use, and in which categories? 46 $10^3$ $km^3$/yr

# Spatiotemporal distribution of water supply and demand

**Seasonal Supply Variability**




**Water Stress**




Source: WRI (2019)

If we have 46000 km3/yr available, and we only use 4000 km3/yr, what's the problem? Uneven spatiotemporal distribution of water

# Dry Season: Vientiane, Laos

# Wet Season: Vientiane, Laos

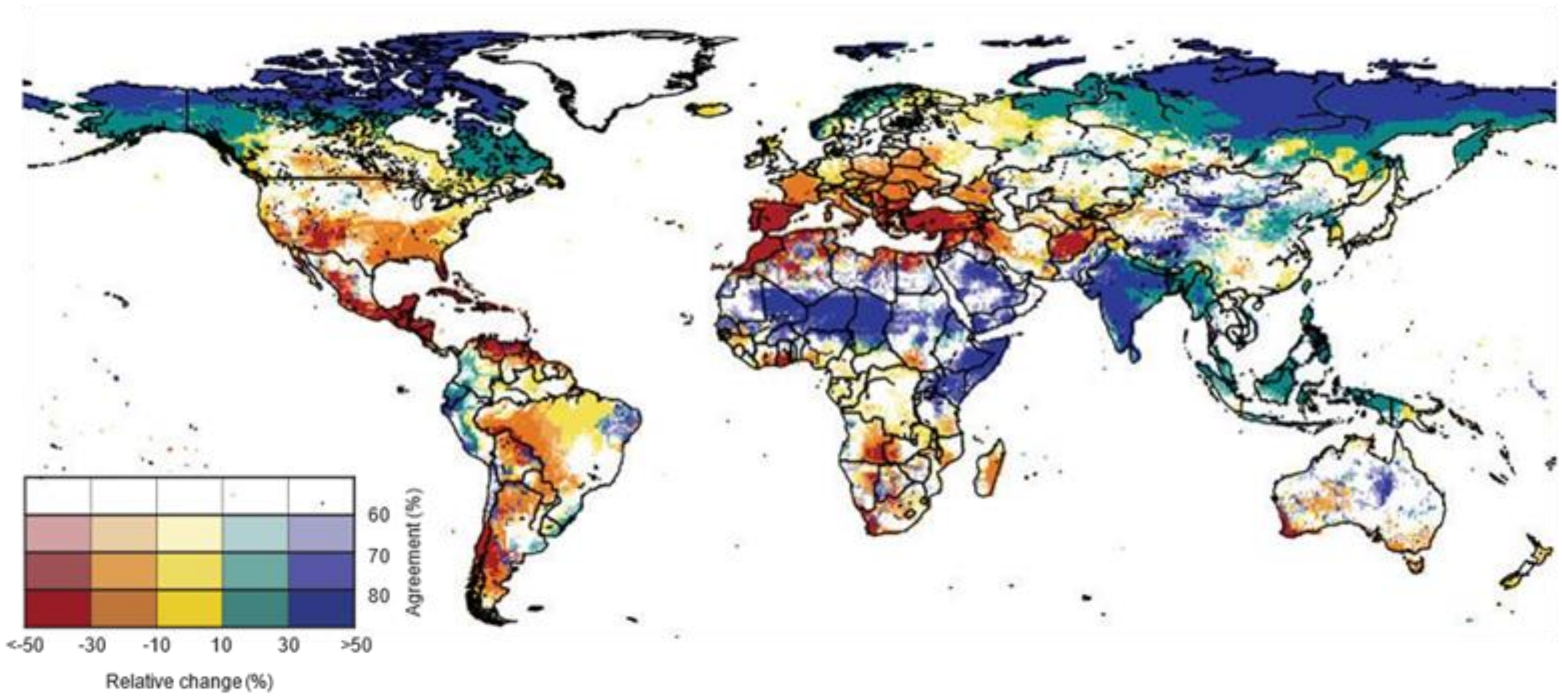
# How will Climate Change Impact Water Supply?

- An accelerated water cycle will increase rainfall and thus renewable freshwater flux. But there will be winners and losers. Some regions will see more and some less water on average.

- There is huge uncertainty—Earth System Models (ESMs) only agree for about 1/3 of land area.

- This is a big challenge for IAMs, because they have not been built to consider extreme events

**Figure 8** Climate change scenario trends in water availability




Note: This figure depicts the relative change in annual discharge at 2°C temperature increase compared with present day, under RCP8.5.

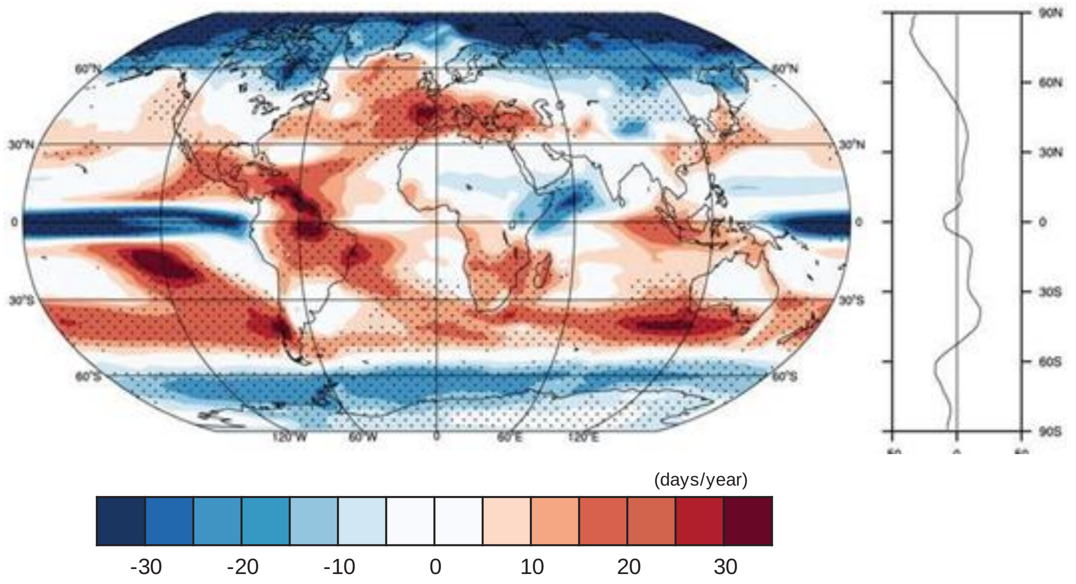
*Source: Schewe et al. (2014, fig. 1, p. 3246). The Attribution Share-Alike 3.0 IGO (CC BY-SA 3.0 IGO) licence does not apply to this figure.*

# How will Climate Change Impact Water Supply?

- One thing ESMs do agree on is projected increasing frequency and magnitude of *extreme events* such as heatwaves, droughts, unprecedented rainfalls, thunderstorms and storm surge events.

- This modeling requires assumptions about emissions that come from models like GCAM, but is otherwise typically *disconnected* from these models, in the sense that Integrated Human-Earth System Models have not traditionally explicitly considered climate feedbacks.

**Figure 6** CMIP5 multi-model ensemble average mean change in frequency of dry days (days/year) by 2060–2089, relative to the historical period 1960–1989, using the RCP8.5 forcing scenario




Note: Stippling indicates areas where at least 70% of the models agree on the sign of the change. Graph to the right: zonal mean values.

*Source: Polade et al. (2014, fig. 2).*

# How are humans modifying the water cycle via climate change?


Source: Abbott et al. (2019)

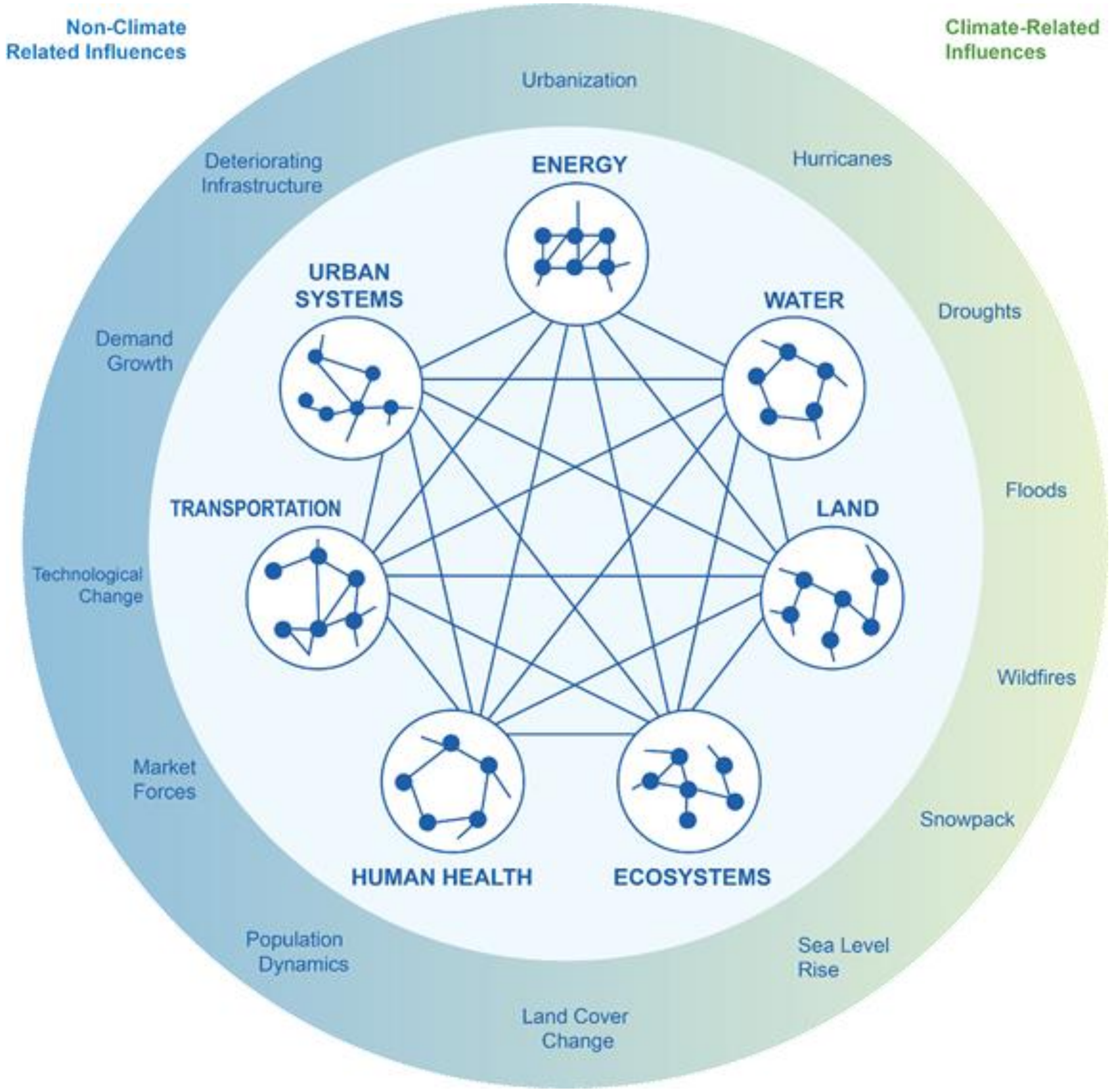
# Approach to Representing Water in Integrated Human-Earth System Models

Why and How is Water Accounted for?

As an example, how does GCAM model water?

# Why do we include water?

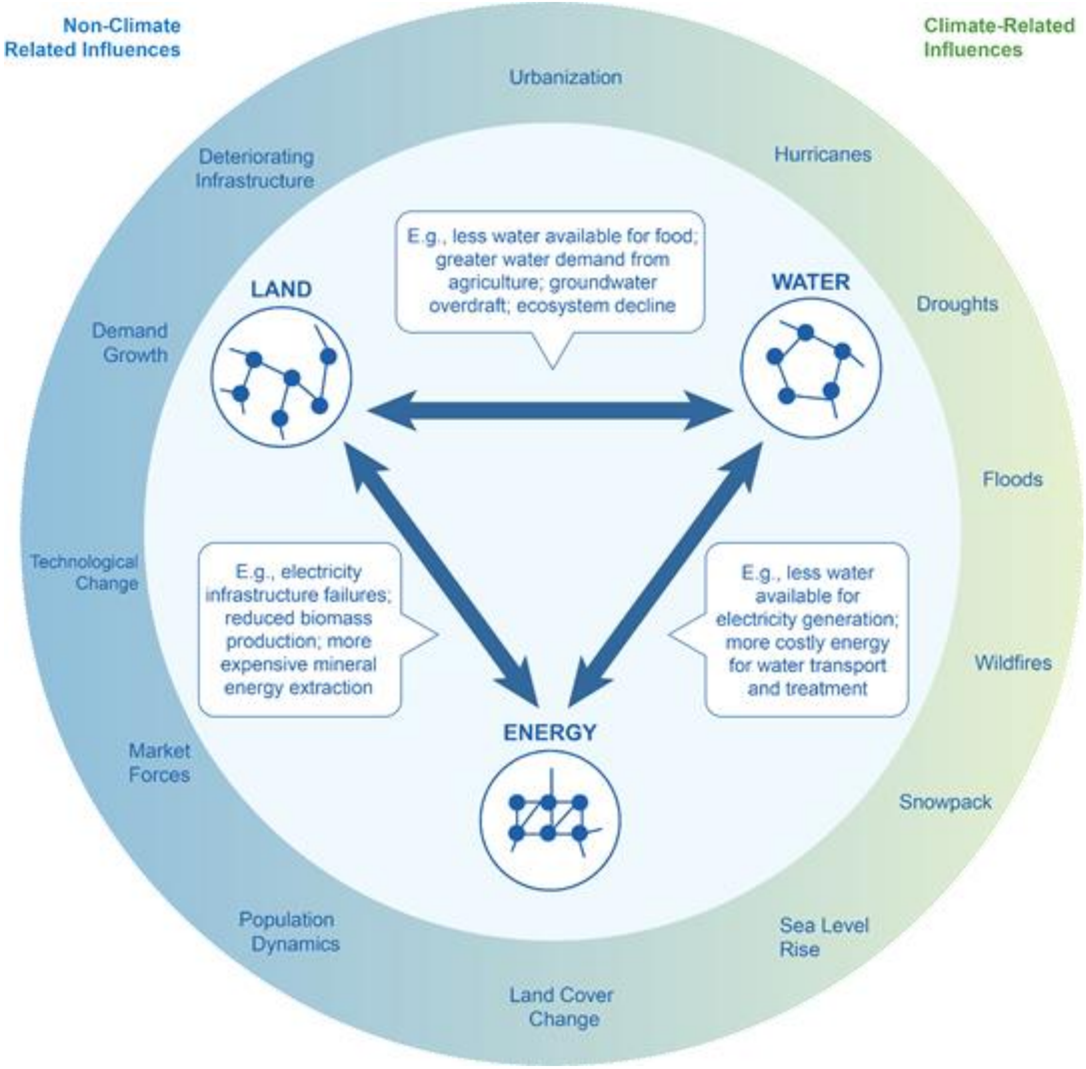
- The world we live in is a complex web of natural, built, and social systems (i.e., coupled human-earth systems)
- Energy, water, land and other system elements are *highly* interconnected
- Multiple climate and non-climate factors influence the way these systems behave and interact with one another
- The evolution of energy, water, and land in turn influence climate




Source: Clarke et al. (2018)

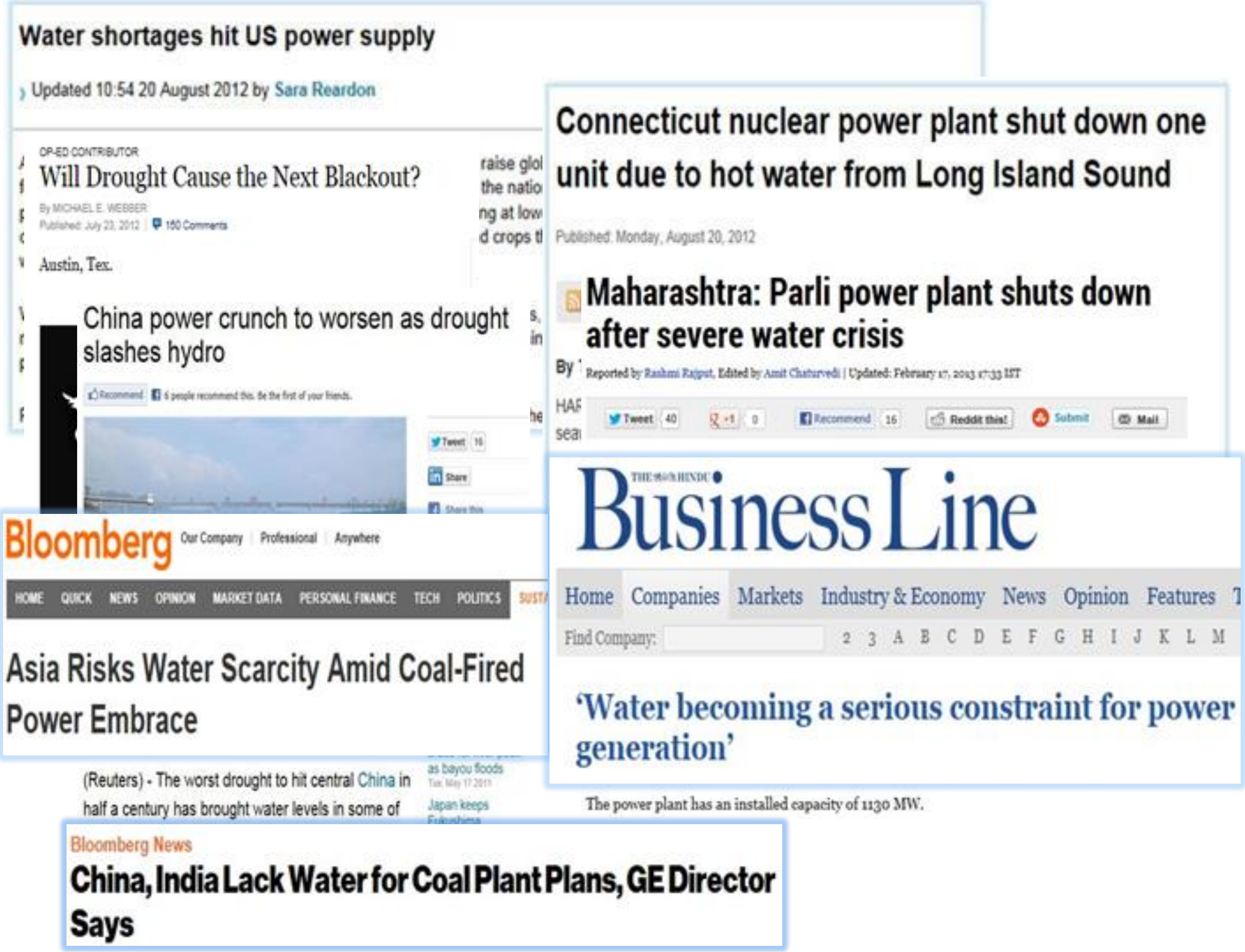
# Some Examples of Complex Sectoral Interactions Involving Water

- Population grows, demanding more energy, land for food, and water for the food and energy
- Humans produce more emissions, which alter climate, resulting in altered water availability and increasing energy system requirements
- Tensions across water users (agriculture and energy) occur, requiring coordinated planning




Source: Clarke et al. (2018)

# The water scarcity challenge is already present and very real



Water shortages hit US power supply

Updated 10:54 20 August 2012 by Sara Reardon

OP-ED CONTRIBUTOR

Will Drought Cause the Next Blackout?

By MICHAEL E. WEBBER

Published: July 23, 2012 | 150 Comments

Austin, Tex.

China power crunch to worsen as drought slashes hydro

(Reuters) - The worst drought to hit central China in half a century has brought water levels in some of

Connecticut nuclear power plant shut down one unit due to hot water from Long Island Sound

Published: Monday, August 20, 2012

Maharashtra: Parli power plant shuts down after severe water crisis

Bloomberg

Asia Risks Water Scarcity Amid Coal-Fired Power Embrace

THE HINDU Business Line

Home Companies Markets Industry & Economy News Opinion Features

'Water becoming a serious constraint for power generation'

The power plant has an installed capacity of 1130 MW.

Bloomberg News

China, India Lack Water for Coal Plant Plans, GE Director Says

# How and Why do models include water?

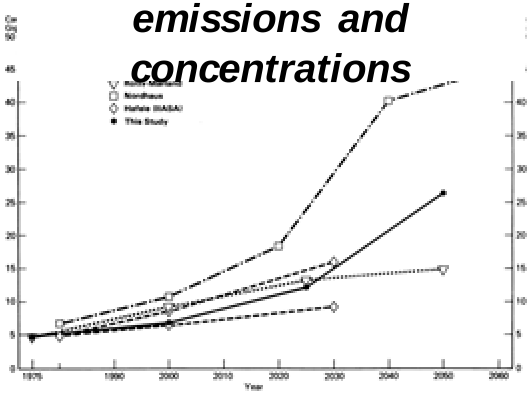
- Water is a potential constraint to economy, energy, and land growth
- Many models (e.g., GCAM) only included water within the last 5-10 years or so
- Water demand/supply/allocation vary across models
- Water supplies and demands are represented in economic terms
- Water supply (stocks, flows, costs) is handled via existing, detailed global surface and groundwater hydrology models that provide external (exogenous) inputs
- Water demand is handled internally, being linked to economic factors

| Model | Home Institution | Hydrologic model |
|---|---|---|
| AIM<br>Asia Integrated Model | National Institutes for Environmental Studies, Tsukuba Japan | **H08** |
| GCAM<br>Global Change Analysis Model | Joint Global Change Research Institute, PNNL, College Park, MD | **Xanthos** |
| IGSM<br>Integrated Global System Model | Joint Program, MIT, Cambridge, MA | **CLM-WSM** |
| IMAGE<br>The Integrated Model to Assess the Global Environment | PBL Netherlands Environmental Assessment Agency, Bildhoven, The Netherlands | **LPJmL** |
| MESSAGE<br>Model for Energy Supply Strategy Alternatives and their General Environmental Impact | International Institute for Applied Systems Analysis; Laxenburg, Austria | **GLOBIOM** |
| REMIND<br>Regionalized Model of Investments and Technological Development | Potsdam Institute for Climate Impacts Research; Potsdam, Germany | **LPJmL** |

# The Evolution of GCAM Research

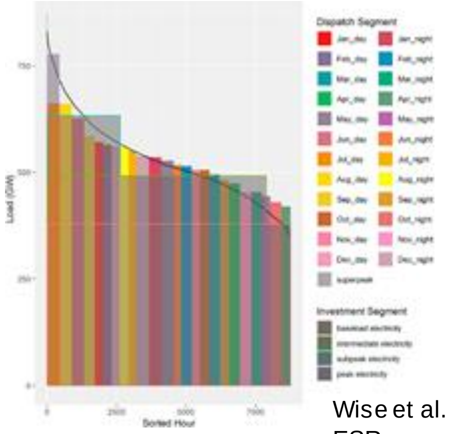
Understanding the complex interactions among energy, water, land, climate, socioeconomics, and other important human and natural systems at regional to global scales

## 1980s
***Projections of emissions and concentrations***



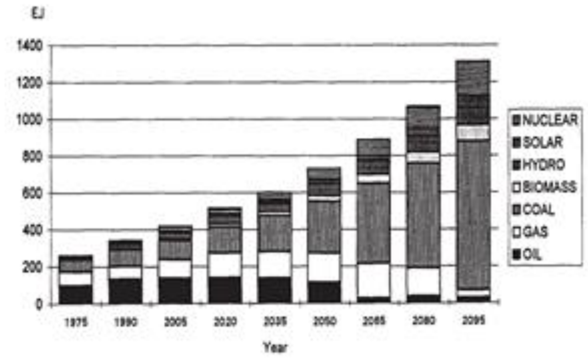
Edmonds and Reilly (1983). *The Energy Journal.*

## 2015–Present
***Integrating impacts***




Wise et al. (2019). ESR

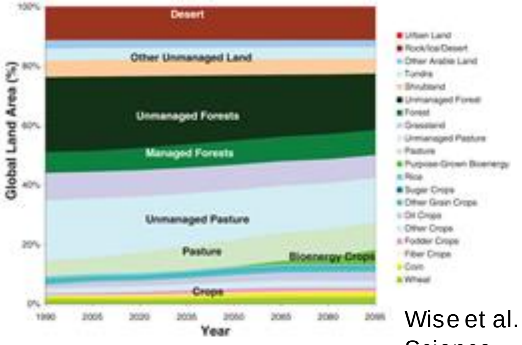
## 1990s
***Energy and***




Edmonds et al. (1995). Energy Policy.

ENERGY-ECONOMY-CLIMATE

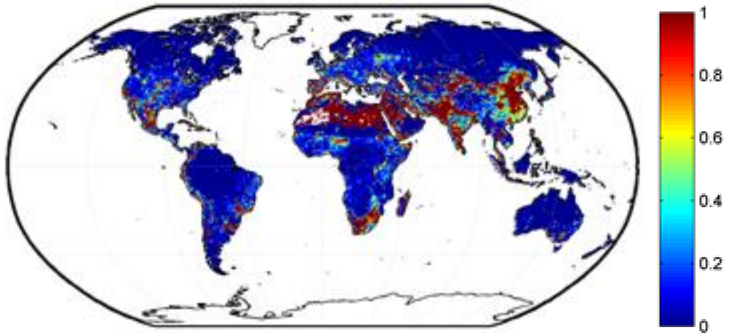
## 2000s
***Land use system***




Wise et al. (2009). Science.

ENERGY-ECONOMY-LAND-CLIMATE

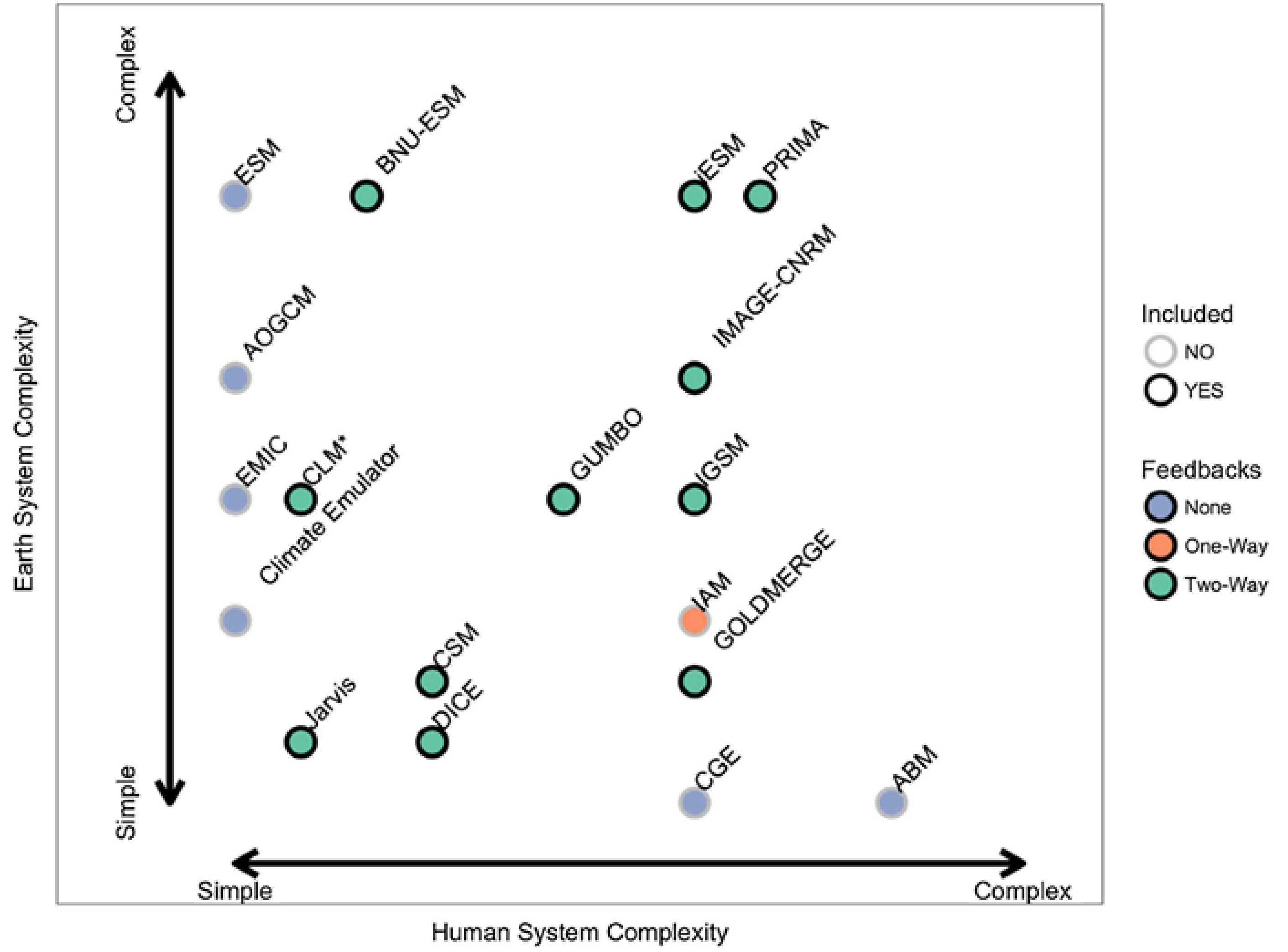
## 2010s
***Water system***




Hejazi et al. (2014). HESS.

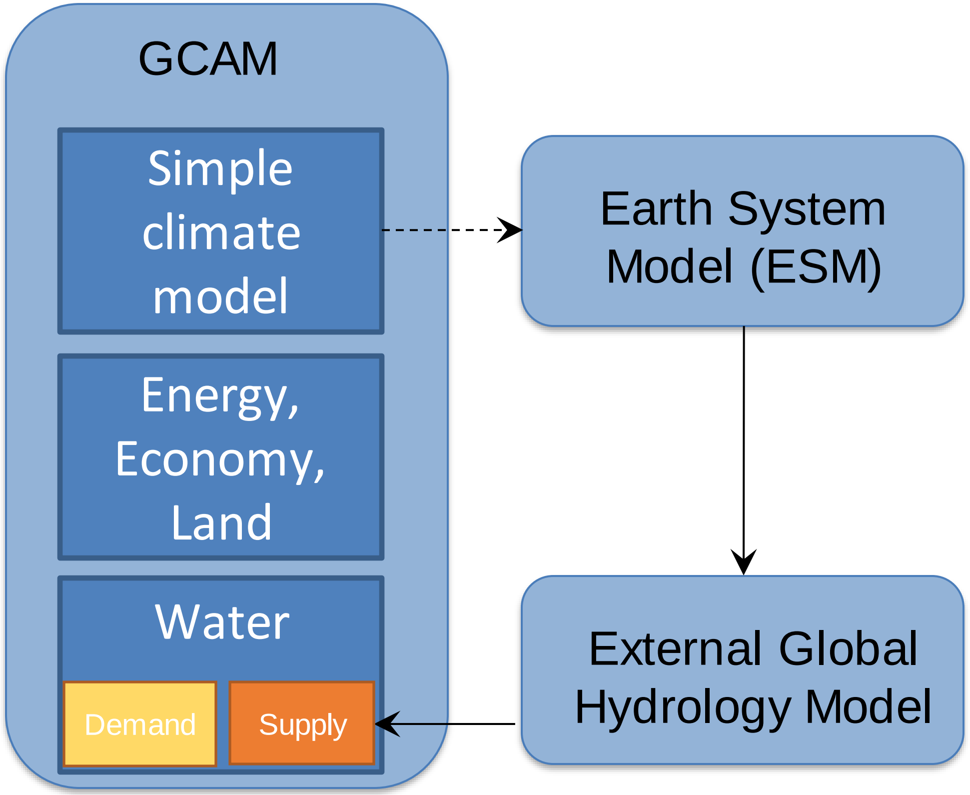
ENERGY-ECONOMY-LAND-WATER-CLIMATE

# We do not typically account for two-way feedbacks. Instead, we feed climate impacts on water supply one-way.




Calvin and Bond Lamberty (2018), *ERL*

GCAM Approach to Climate Impacts on Water Supply



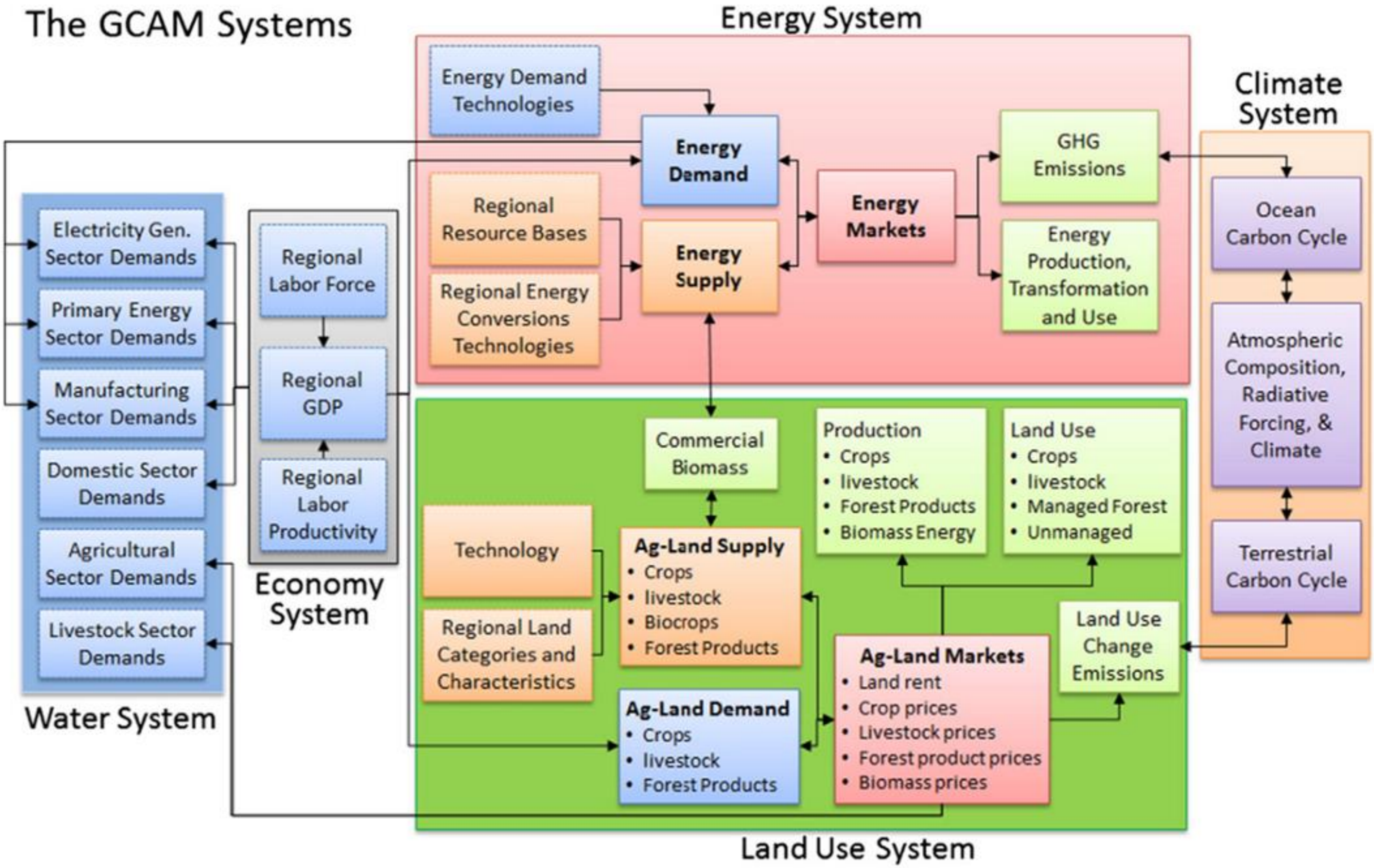
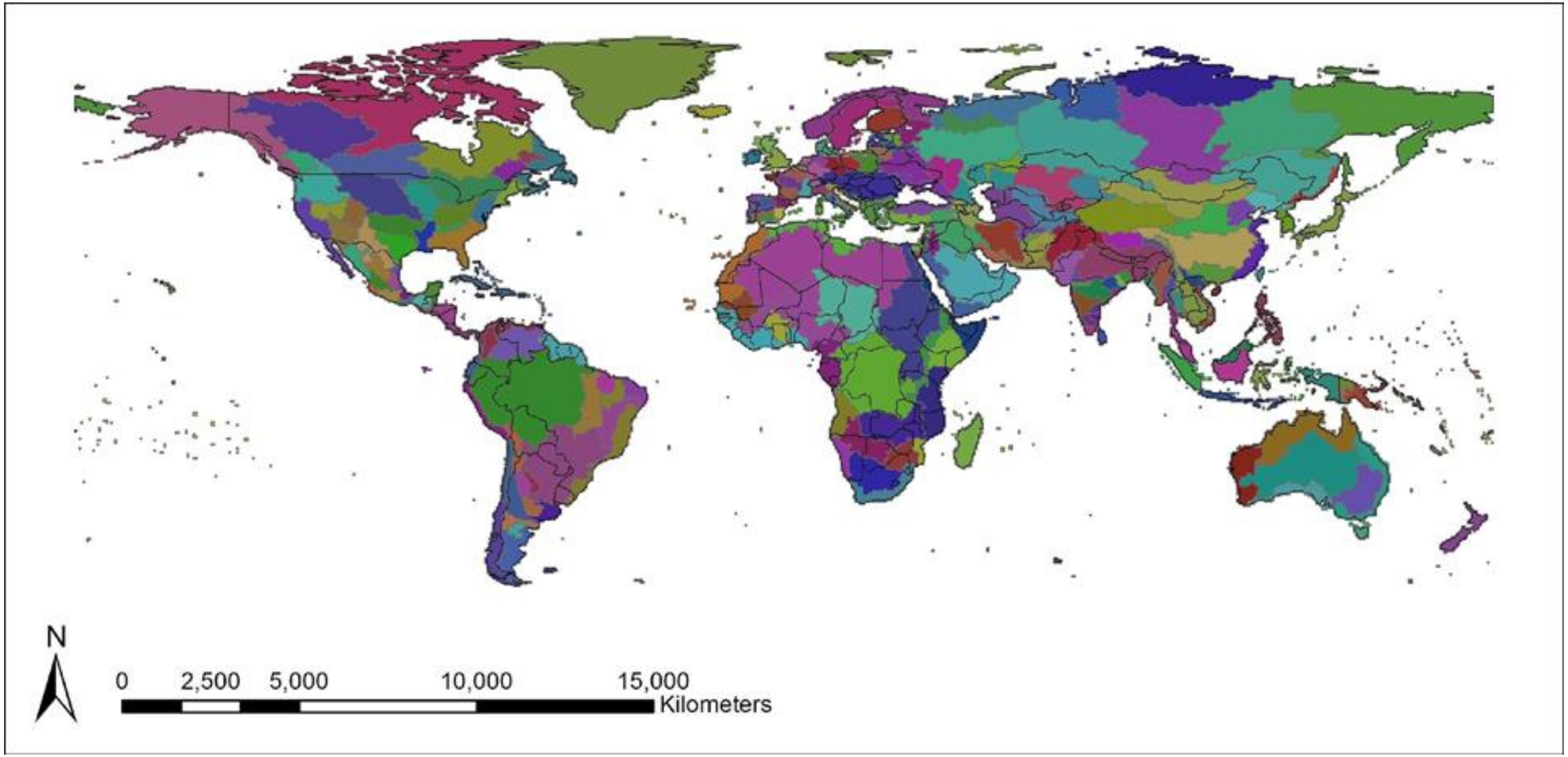


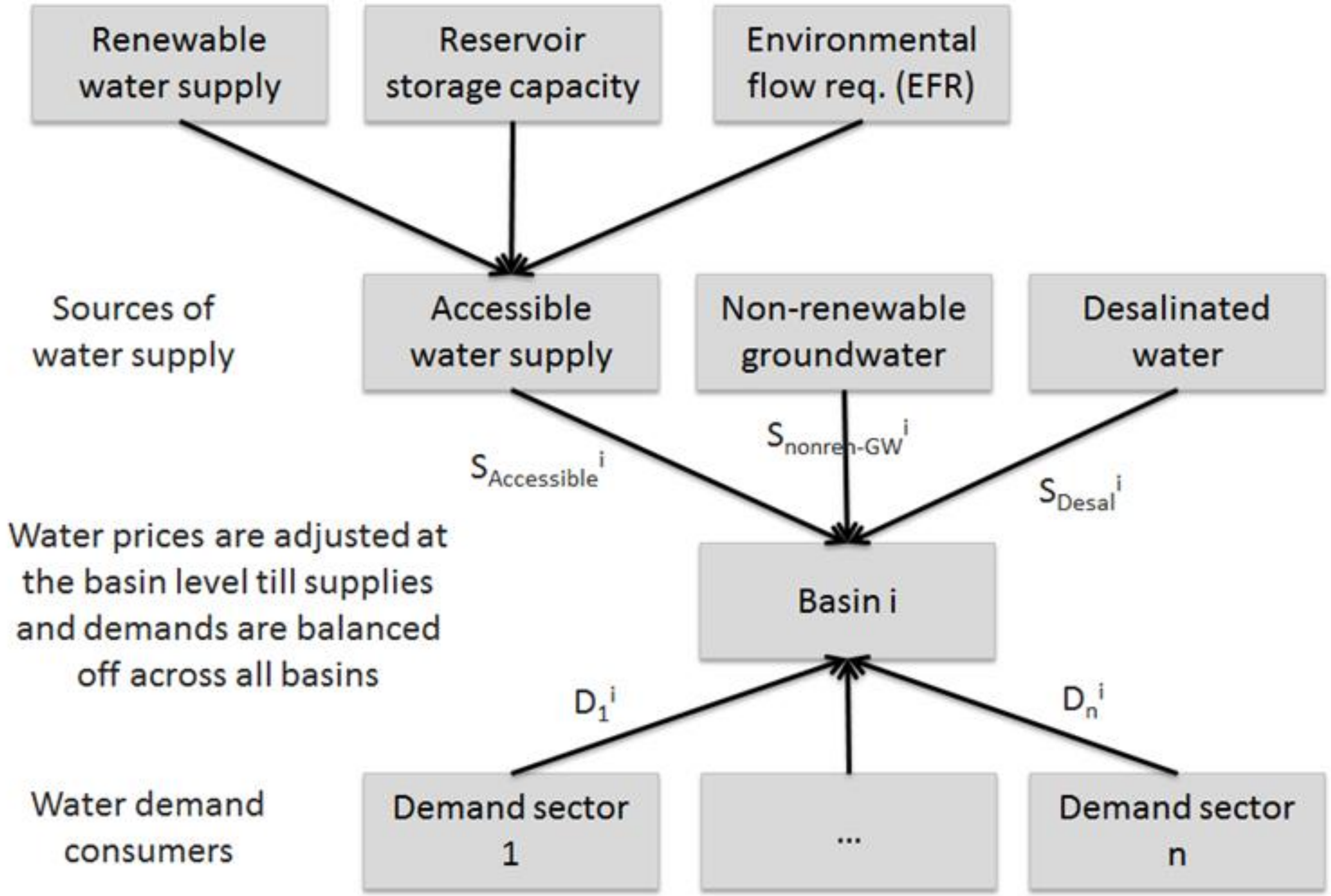

**Fig. 1.** Schematic of the GCAM systems with links to the water system.

# GCAM hydrological regions in the GCAM Core

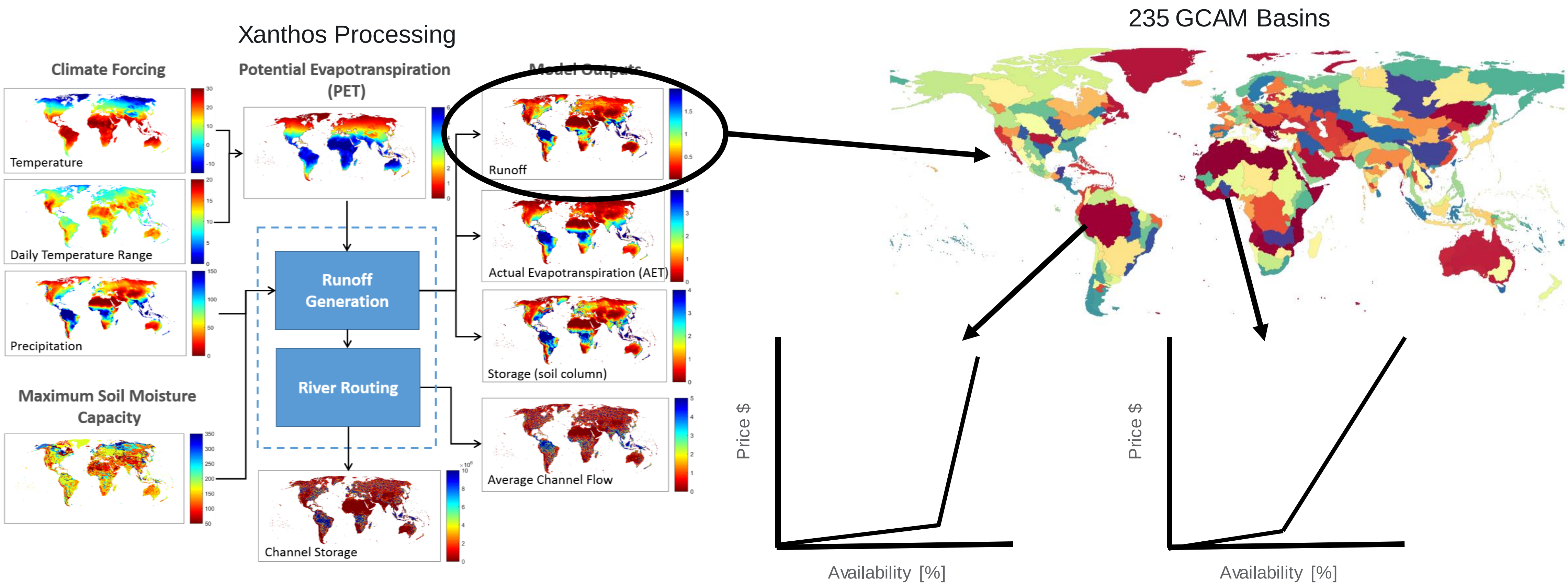
Core GCAM tracks balances water supply and demand in 235 hydrological regions (not exactly basins)



# Schematic of the water allocation mechanism at the basin scale in GCAM



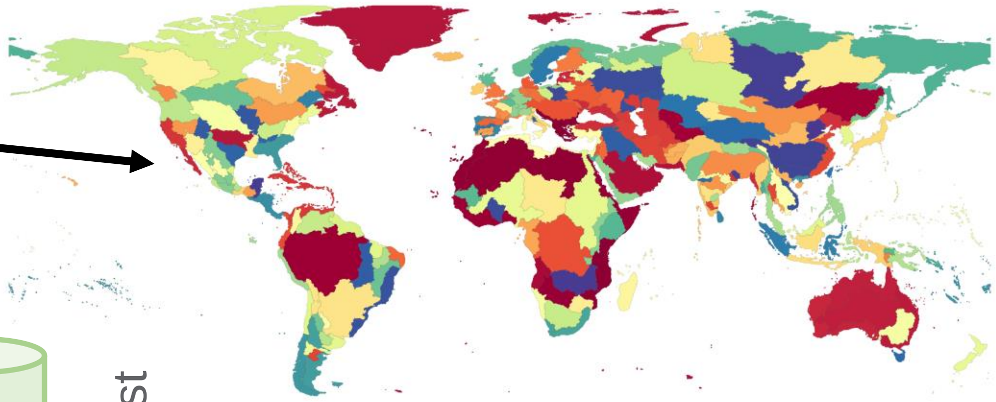
# Surface water supply and cost curves in GCAM

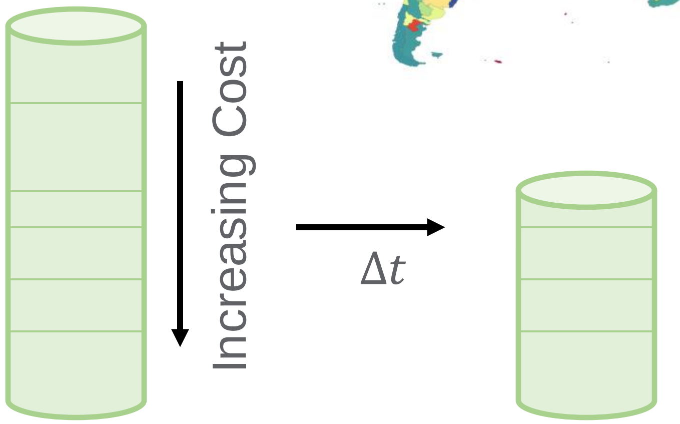


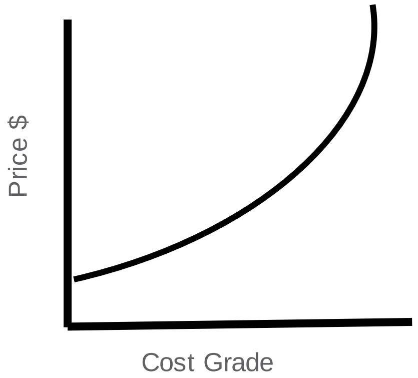

1. Calculate maximum runoff and accessible water* for each year using Xanthos and 1970-2015 WATCH data
2. Aggregate 0.5º gridded data to 5-year moving averages at GCAM basin scale.
3A. For basins with no historical nonrenewable groundwater depletion find the accessible percentage of maximum runoff (accessible/runoff) ***cost curve inflection point***
3B. For basins with historical nonrenewable groundwater extraction, back calculate accessible portion by $\frac{(Demands - Depletion)}{runoff}$ averaged over historical years ***cost curve inflection point***
4. Set initial supply grades (0%, accessible percent, 100%) and cost grades (~0, 0.001, 10), then interpolate for 20 total grades

# Groundwater supply and cost curves in GCAM

- Derived unit cost of groundwater extraction over time at 50km grid cells
- Estimates of groundwater availability from previous studies on porosity, depth-to-groundwater, and aquifer thickness in addition to WHYMAP
- Constrained to only allow for 25% use of all physical water estimated in aquifer
- Calculations within require an assumption of confined aquifer, however results assumed to be from unconfined aquifer



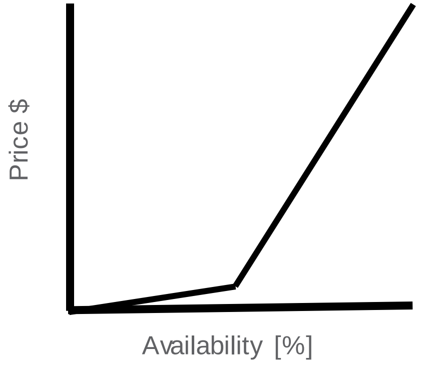


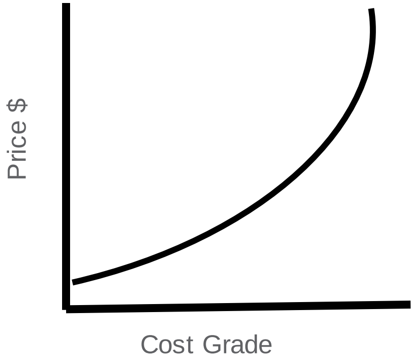

1. Aggregate unit costs at 50km grid to GCAM basin scale and transform into 24 unique cost grades
2. Historical groundwater depletion from WaterGap is placed into grade_hist which is pulled during historical calibration
3. Added to GCAM as a subresource with price interactions with renewable water cost curves.

# Surface water and Groundwater price interaction

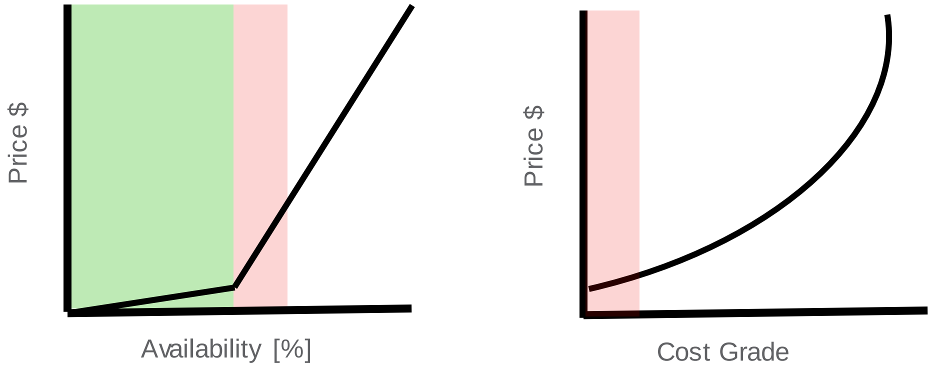
Renewable cost curve
Basin A




Groundwater cost curve
Basin A



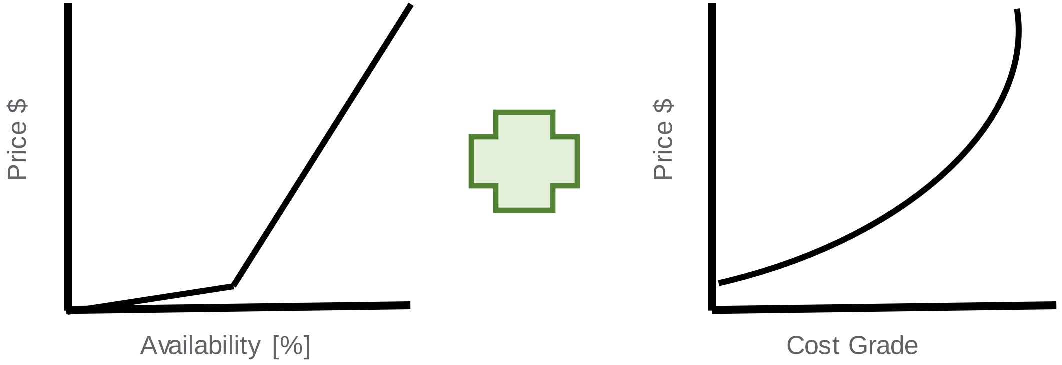

1. Water withdrawals come from cheap renewable sources first.
2. If demands exceed the accessible portion in any given timestep, a price interaction between groundwater and renewable water occurs where water is drawn from the cheaper source first.

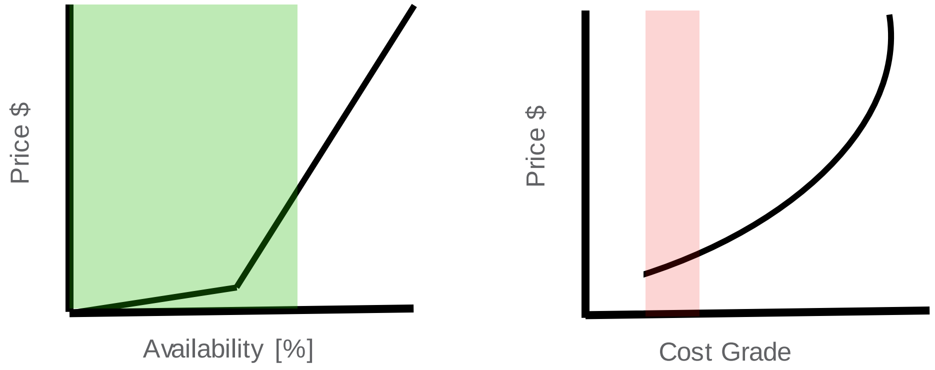


# Surface water and Groundwater price interaction

Renewable cost curve
Basin A

Groundwater cost curve
Basin A




1. Water withdrawals come from cheap renewable sources first.
2. If demands exceed the accessible portion in any given timestep, a price interaction between groundwater and renewable water occurs where water is drawn from the cheaper source first.
3. As groundwater is exhausted in low-cost grades, the point of interaction between renewable and groundwater is pushed to higher prices
4. More water than is deemed accessible must be pulled in order to start the price interaction with groundwater

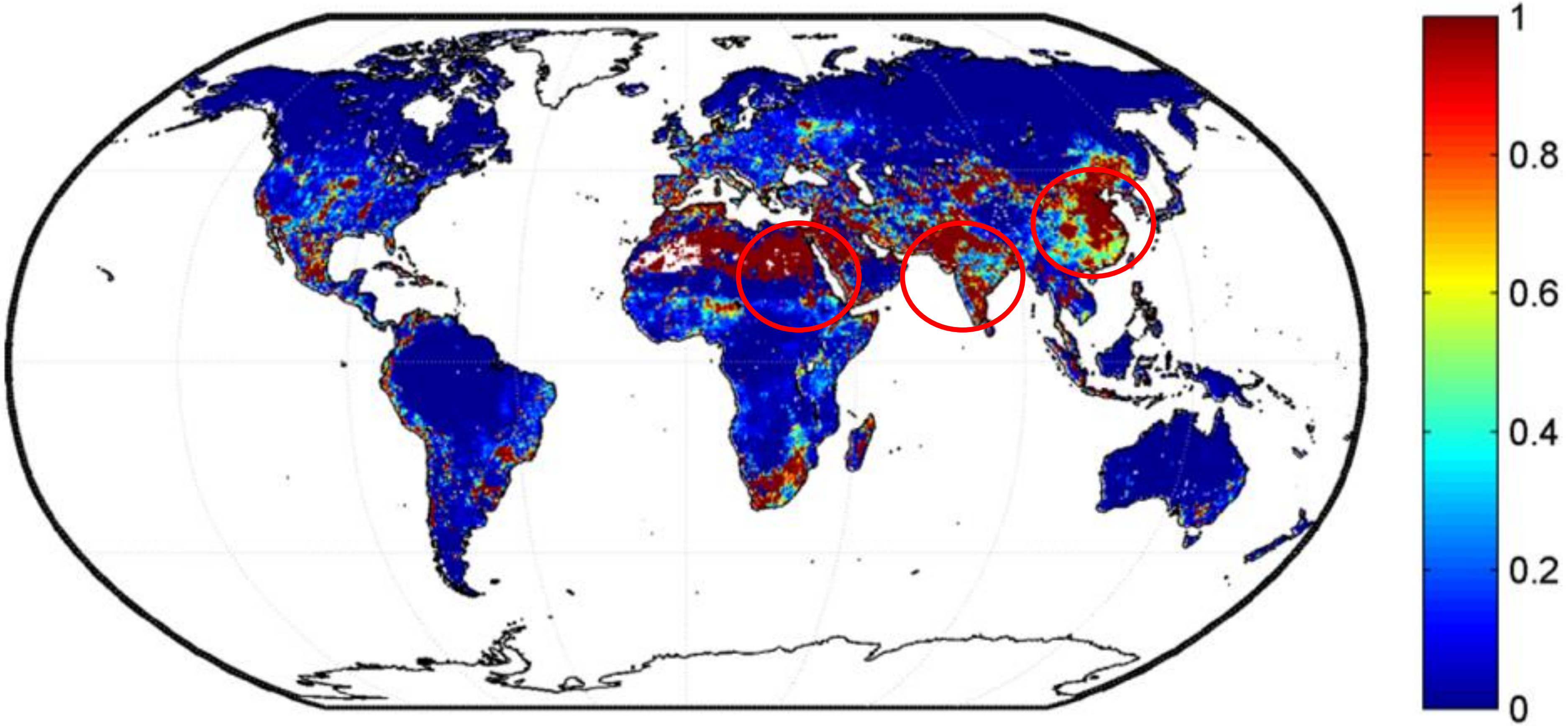
# Exciting (Water-Related) Science Questions IAMs are Exploring

What key insights have emerged from IAMs?

What questions remain unanswered?

# Where will future water scarcity occur and worsen?

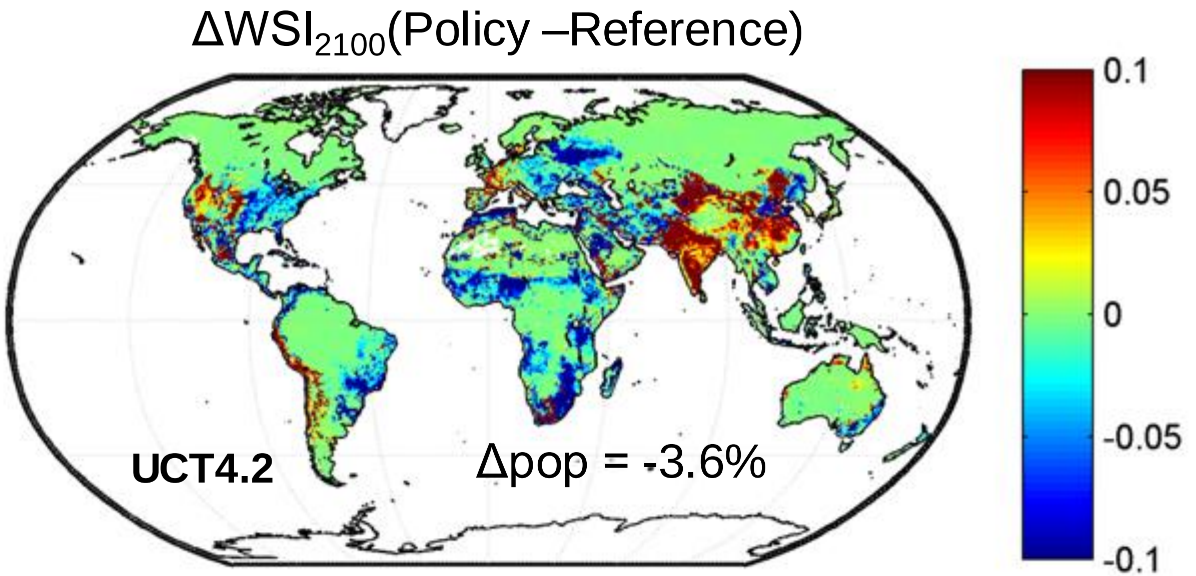
- Hotspots with exacerbating water scarcity conditions in year 2100
- Water scarce regions will face worsening conditions

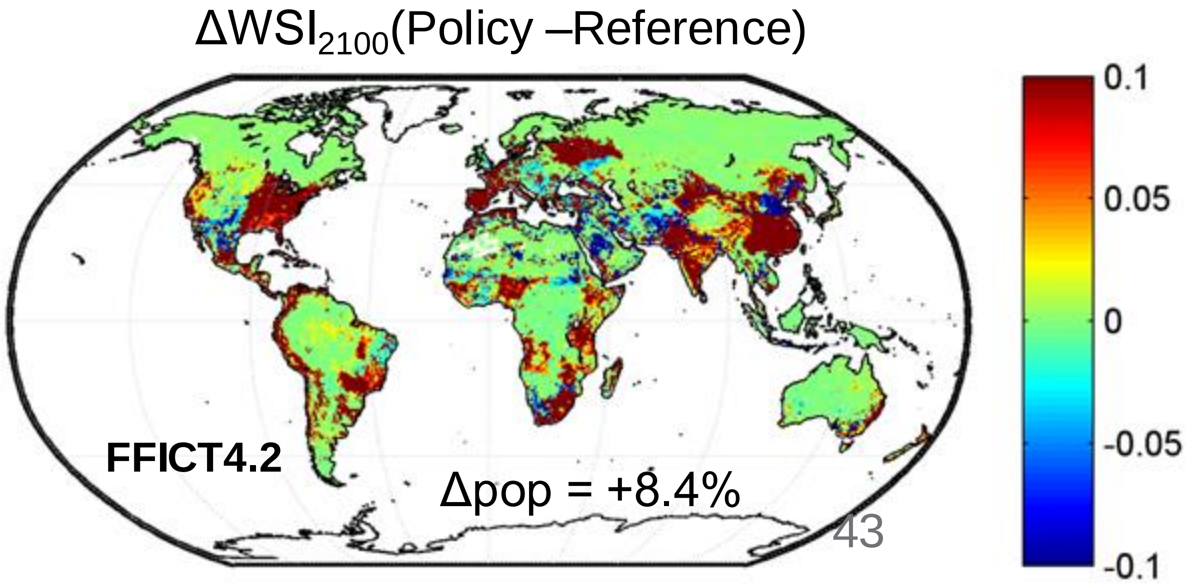



Hejazi M, J Edmonds, L Clarke, P Kyle, E Davies, V Chaturvedi, M Wise, P Patel, J Eom, K Calvin. 2014. "Integrated assessment of global water scarcity over the 21st century under multiple climate change mitigation policies." Hydrology and Earth System Sciences 18:2859-2883. DOI:10.5194/hess-18-2859-2014.

# How will climate mitigation affect water scarcity?

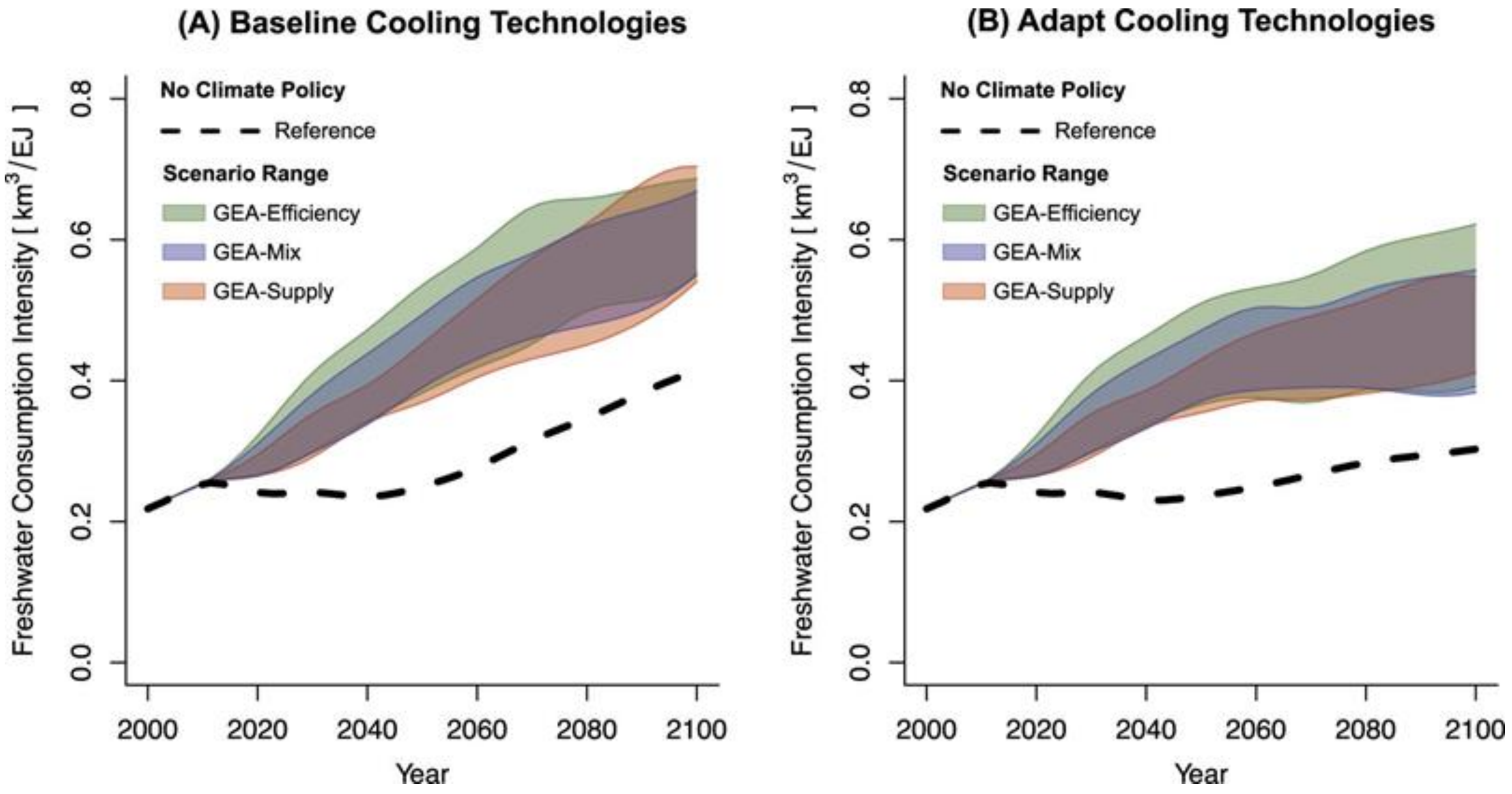
- Climate mitigation will affect water scarcity
- The type of climate policy and stringency of target matter
- Climate mitigation will generally alleviate water scarcity. But, policies favoring bio-energy will exacerbate water scarcity
- Location matters – there are winners and losers




Hejazi et al. 2014. "Integrated assessment of global water scarcity over the 21st century under multiple climate change mitigation policies." Hydrology & Earth Sys. Sc. 18:2859-2883.

# What are the water sector implications of the energy transitions required to implement climate policy (e.g., 2°C)?

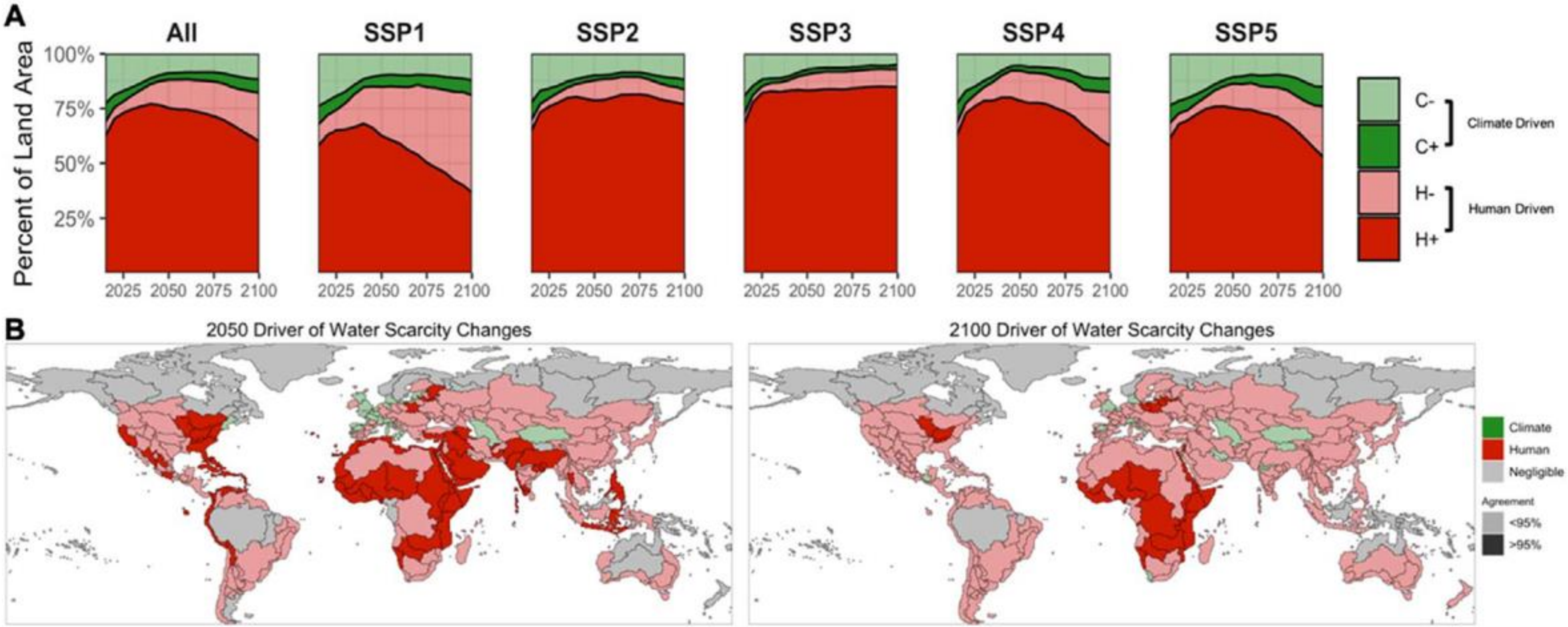



Fricko et al. (2018), ERL

- Achieving 2 °C will require increased cooling water usage (relative to Reference scenario) due to increasing electricity demand
- Adapting cooling technologies can help reduce demands
- Reducing *energy demands*, emerges as a key strategy to limit water usage, which underscores the importance of an *integrated* (i.e., IAM) approach

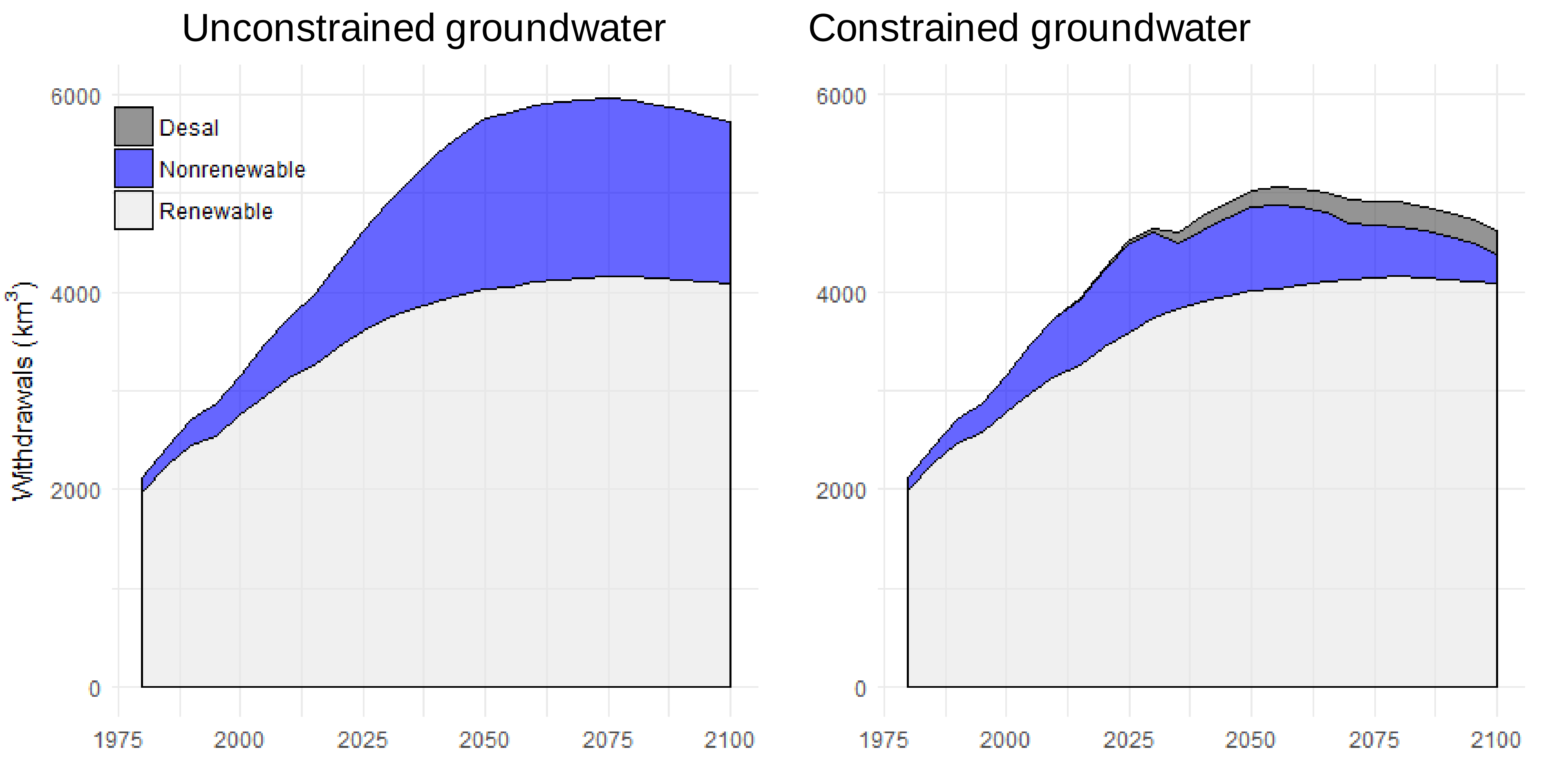
# Will human activities (water demands) or climate change impacts be the key driver of changes in water scarcity?

Humans Drive Future Water Scarcity Changes Across all Shared Socioeconomic Pathways



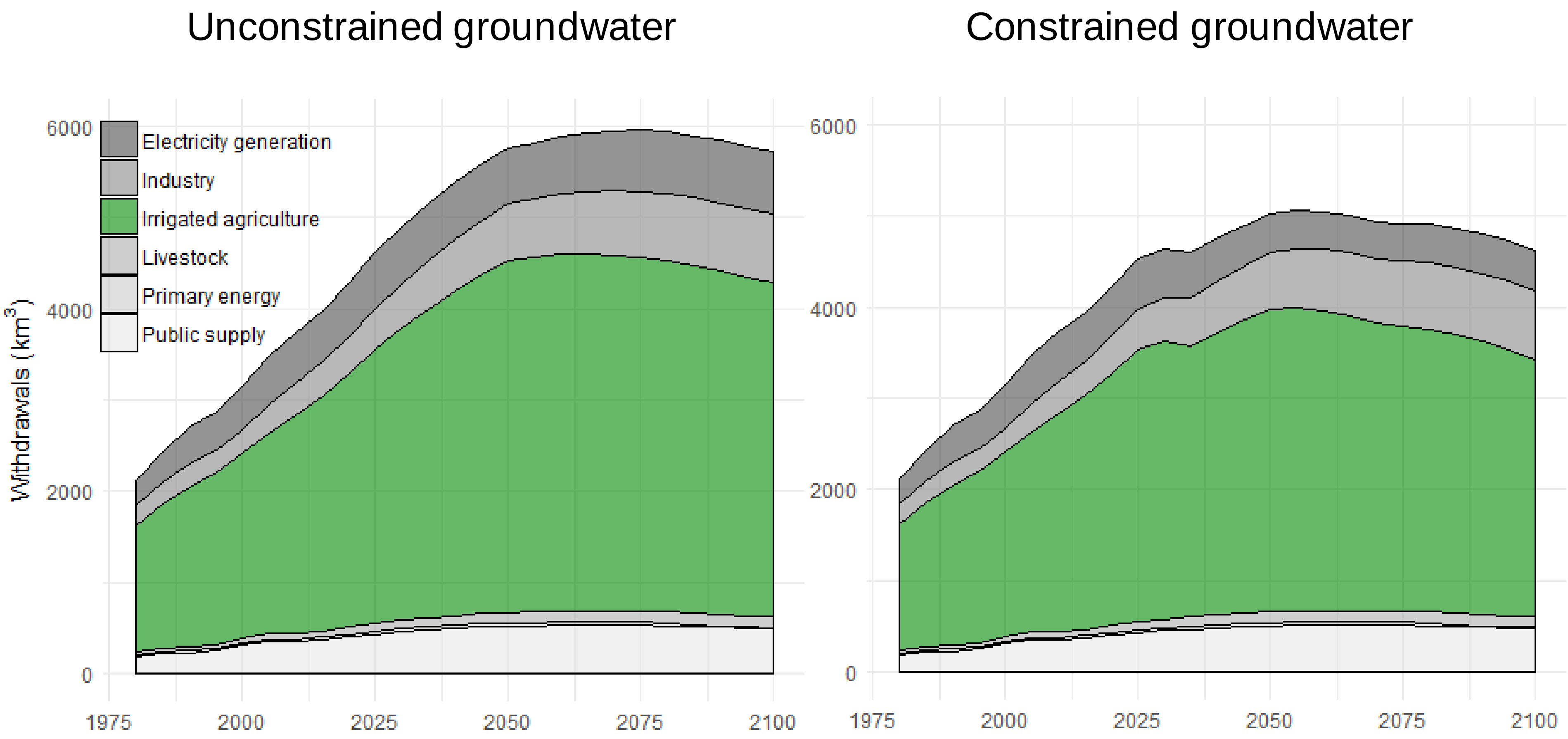

Graham et al. (2020), ERL

# Groundwater constraints reduce total consumption and hasten peak withdrawal



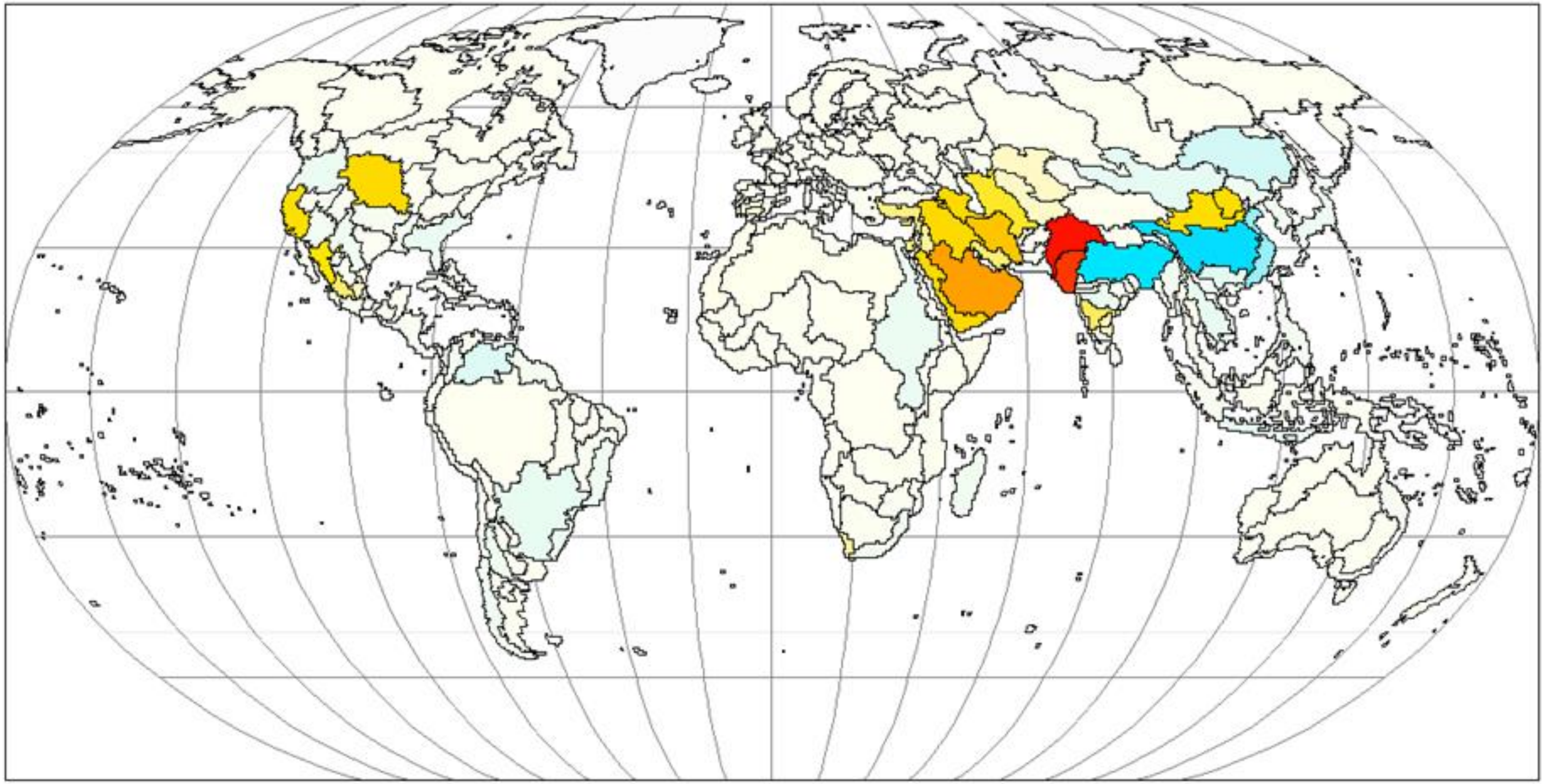

Turner, S. W., *et al.* (2019). Influence of groundwater extraction costs and resource depletion limits on simulated global nonrenewable water withdrawals over the twenty-first century. *Earth's Future*, *7*(2), 123-135.

# Biggest impacts on irrigated agriculture and electricity generation

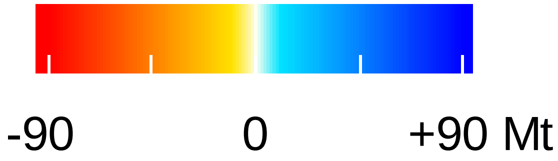



Turner, S. W., *et al.* (2019). Influence of groundwater extraction costs and resource depletion limits on simulated global nonrenewable water withdrawals over the twenty-first century. *Earth's Future*, *7*(2), 123-135.

# Production of irrigated crops moves elsewhere…

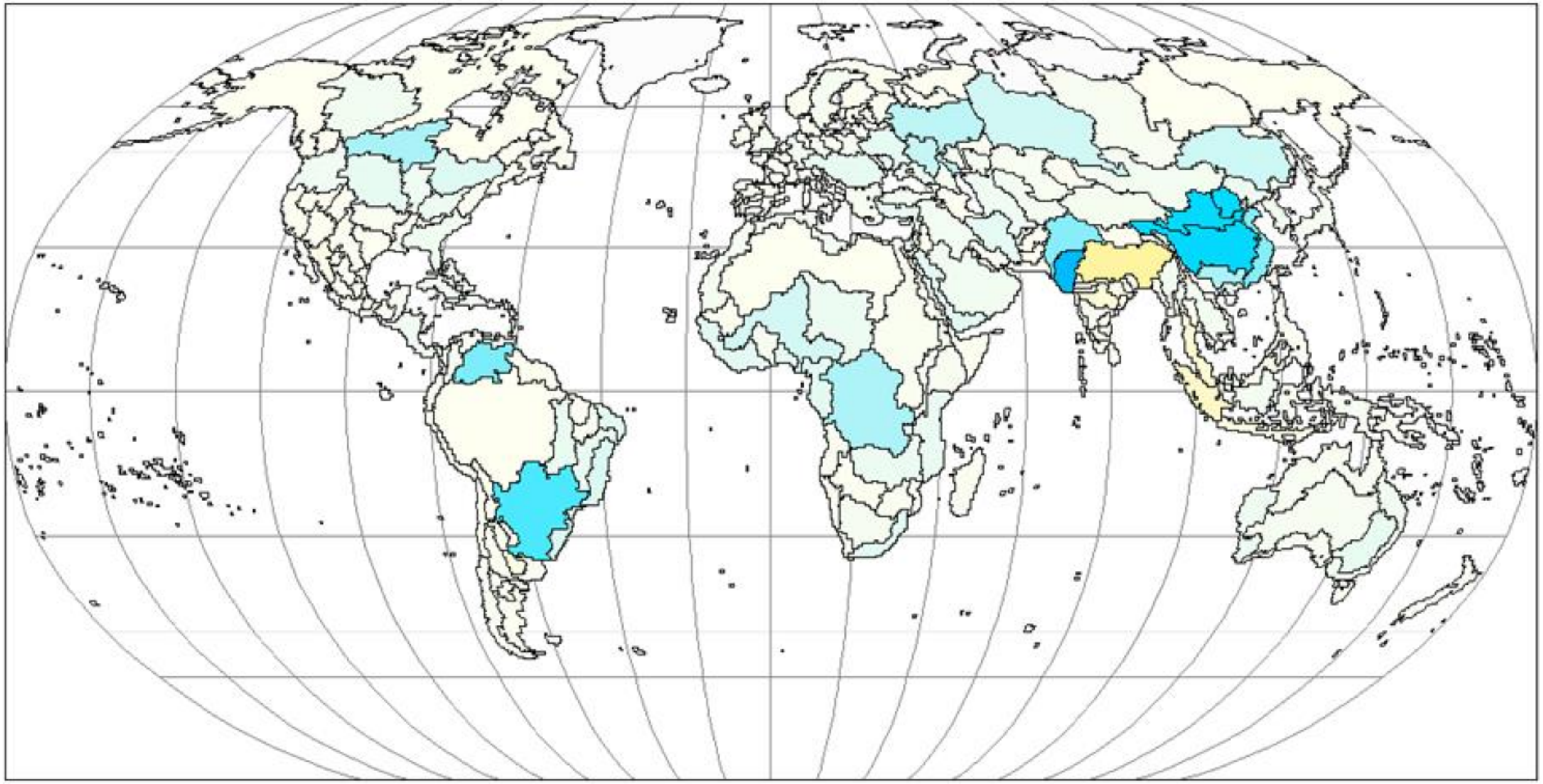


Impact of groundwater constraints (year 2100)

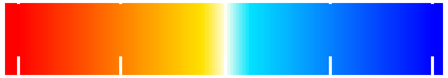



Turner, S. W., *et al.* (2019). A pathway of global food supply adaptation in a world with increasingly constrained groundwater. *Sci. Tot. Env.*, *673*, 165-176.

# … and rain fed crops comprise a larger share of production

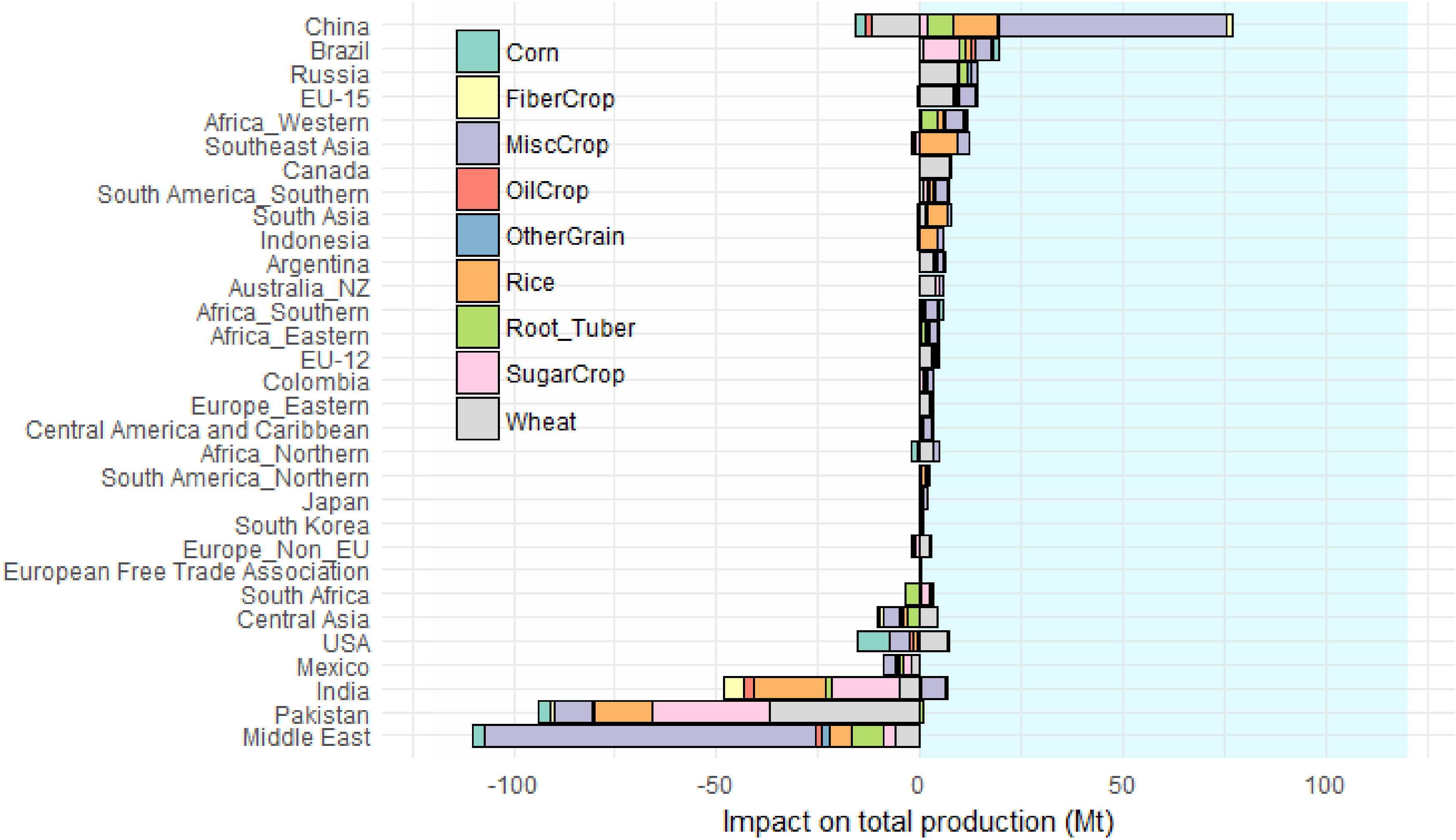


Impact of groundwater constraints (year 2100)




Turner, S. W., *et al.* (2019). A pathway of global food supply adaptation in a world with increasingly constrained groundwater. *Sci. Tot. Env.*, *673*, 165-176.

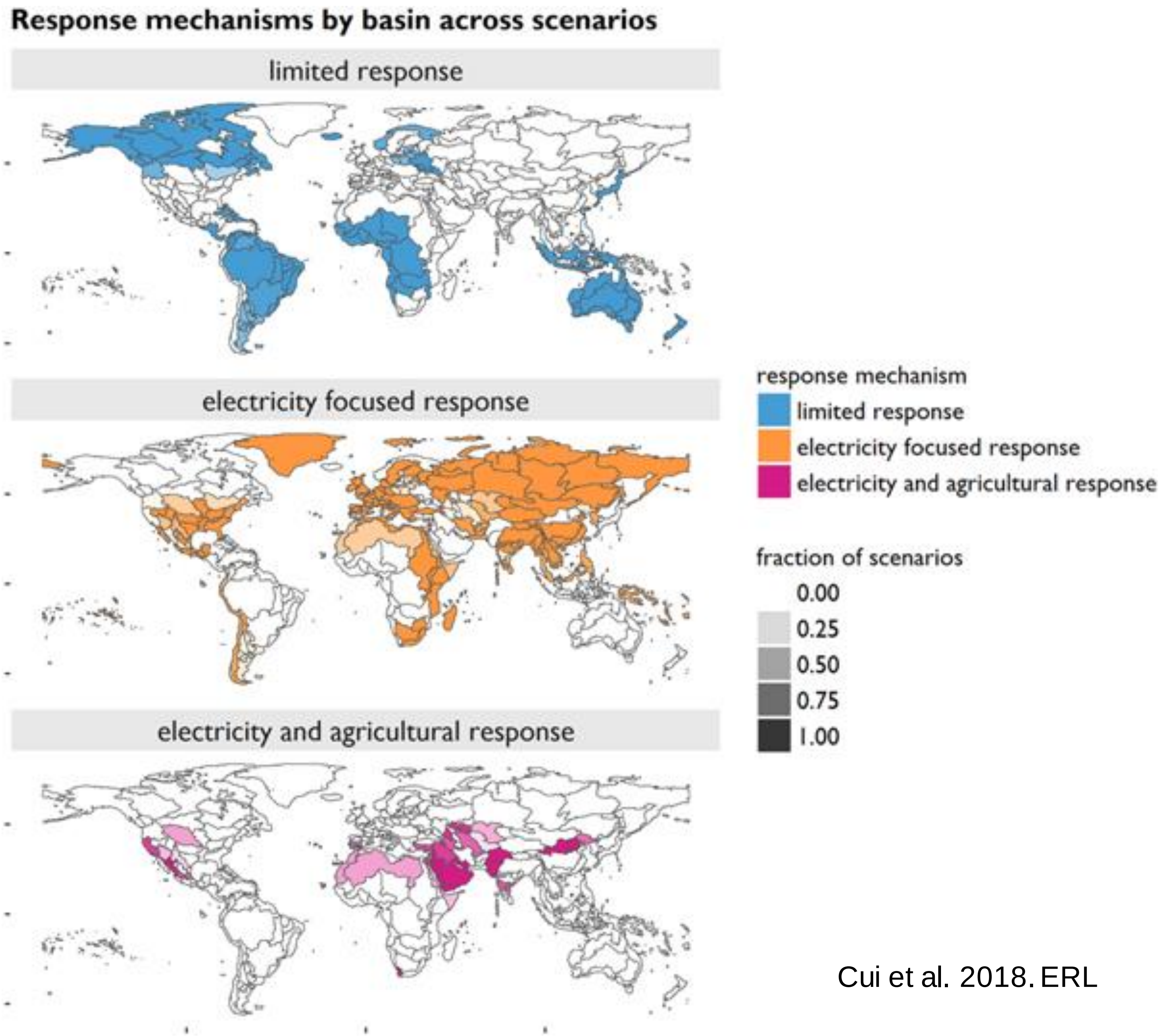
# Middle East, India, Pakistan lose out, while US sees net production loss




Turner, S. W., *et al.* (2019). A pathway of global food supply adaptation in a world with increasingly constrained groundwater. *Sci. Tot. Env.*, *673*, 165-176.

# Responses to constraints often occur across different systems

Different strategies are taken in response to water constraints, which is robust across alternate scenarios




Cui et al. 2018. ERL

# Summary

- Water is a key input (and potential constraint) to agricultural and industry and thus their emissions, which is a key reason Integrated Human-Earth System Models include water

- Humans have altered the water cycle through water usage, climate change, and land use change

- In turn, climate change is likely to increase extreme events, which Integrated Models have trouble handling

- Humans (i.e., demands) will play a critical role in the future of water withdrawals and scarcity

- Integrated Human-Earth System Models have addressed questions about the *future*, such as:
  - How will future water scarcity evolve in the future?
  - What does climate policy mean for water?
  - Can the human system adapt to water shortages via agricultural trade and transformed cooling options?
  - What will be the relative usage of groundwater vs. surface water vs. desal in meeting future demands?

# Future Challenges to Address in Modeling Water in IAMs

Model evaluation over history (e.g., 1975-2010) is a prerequisite to publish water modeling results

Water use at sub-annual scale or even at annual scale is hardly available

Mapping between geopolitical regions, AEZs, and river basins

Time period in IAMs is too coarse to capture the inter- & intra-variability in water

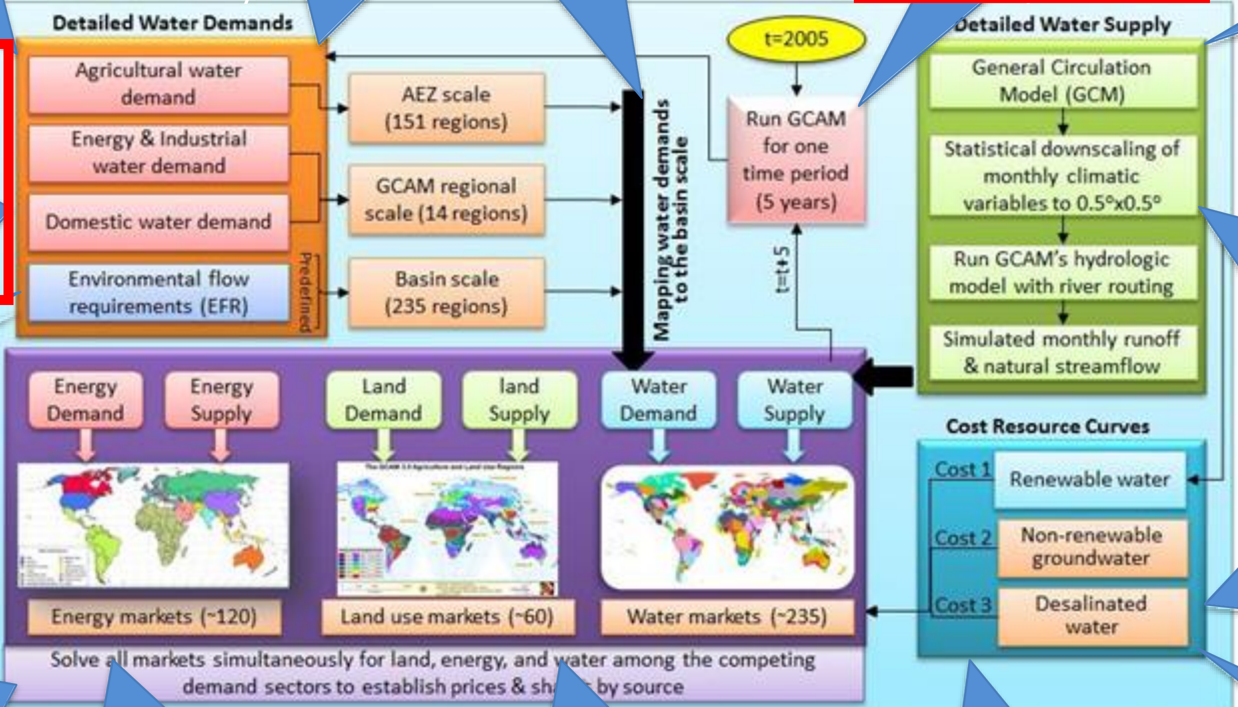
Limited to the 4 RCPs for which there exists GCM simulations

The ability to store water (reservoirs) and reuse water

GCM outputs come at various spatial units and require downscaling and bias-correction

The impact of climate changes on water demands, and hydropower

Developing resource curves for the various sources of water and their historical use




The role of adaptation (irrig., cooling tech). How quickly can adaptation come in the future?

Water regulations are heterogeneous and water allocation are often not based on markets

Water is heavily subsidized in many regions and different sectors face different water

How much gw water is available and how much has already been

Energy use associated with extraction and treatment of water 3