Green, blue, and grey water:

Understanding the contemporary water cycle

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https://earthdata.nasa.gov/sites/image from photos.com

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Basic questions in water resource assessment and management:

1) How much freshwater is *available* in a given location of interest?

2) *How* is it available?

3) How can this water be managed *sustainably*?

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The thesis of this talk:

1) Water is available from two coupled natural systems—the green and blue water systems—and one human source: grey water, broadly defined.

2) Sustainable water management practices are those best fitted to the opportunities and constraints (hydroclimatic, ecological, engineering) of the location of interest.

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Topics:

- Definitions
  - Green water
  - Blue water
  - Grey water
  - Hydroclimatic regimes
- Sustainable water management
- Rethinking the contemporary water cycle

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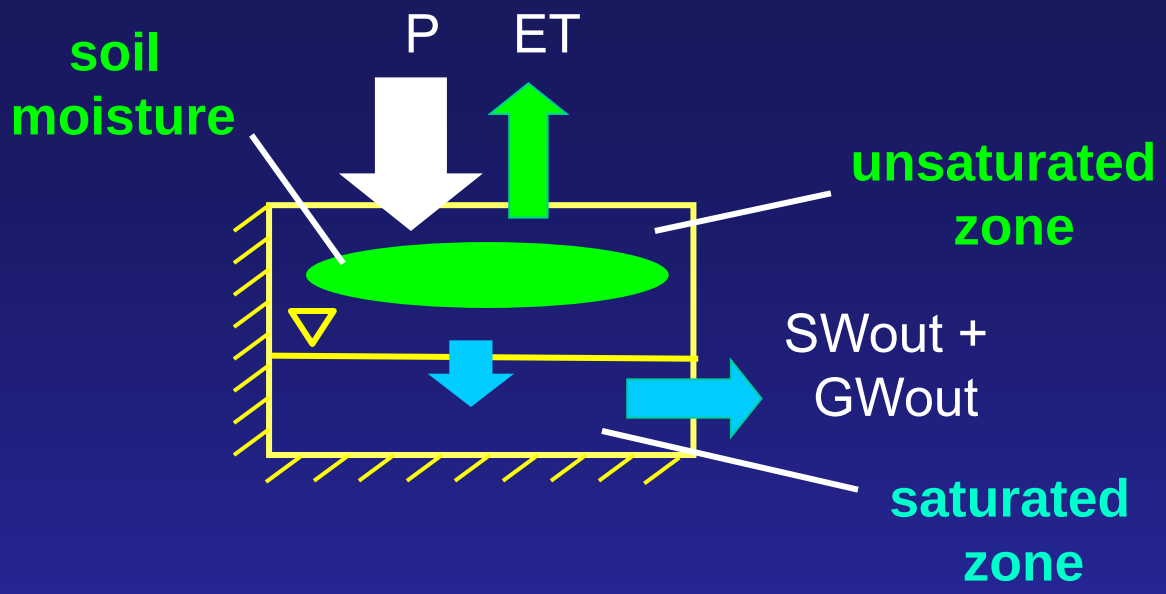
Green water

watershed
spatial framework



- Soil moisture in unsaturated zone (green reservoir)

- Evapotranspiration (ET) flux to the atmosphere (green flux) from the partition of undifferentiated precipitation (P) influx.

Green-blue terminology introduced by
Falkenmark & Rockström (2004).

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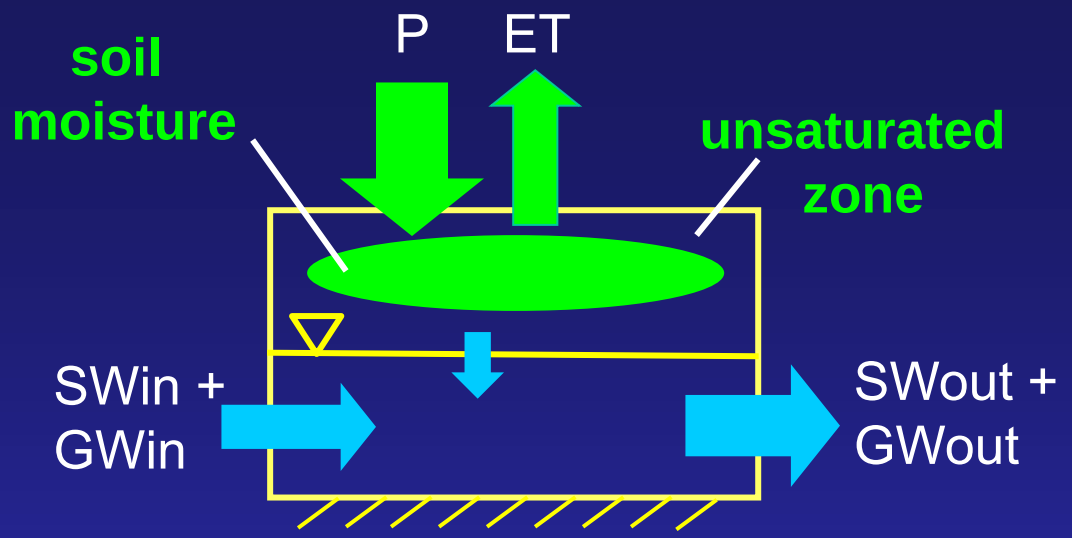
Green water

open-system
spatial framework



- Soil moisture in unsaturated zone (green reservoir)
- Land-atmosphere fluxes of the hydrologic cycle (P, ET); (green fluxes)

Green terminology re-interpreted for open-system framework by Weiskel et al., 2014.

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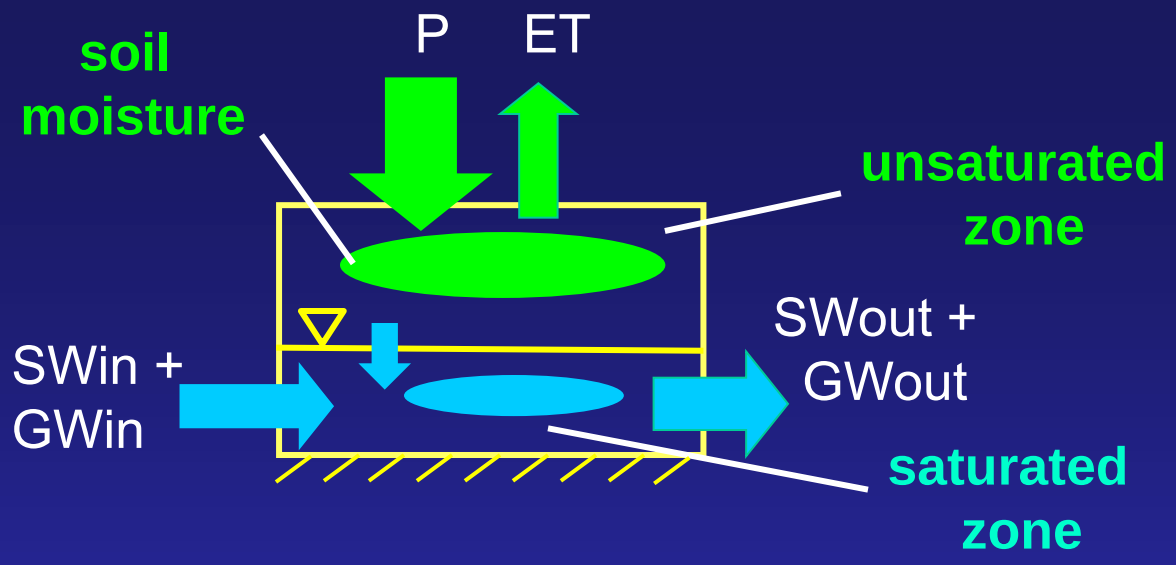
Blue water



- Saturated storage in streams, lakes, groundwater, wetlands, glaciers, and snowpack (blue reservoir).

- SW and GW fluxes in and out of a landscape hydrologic unit (blue fluxes)

Terms introduced by Falkenmark and Rockström (2004)

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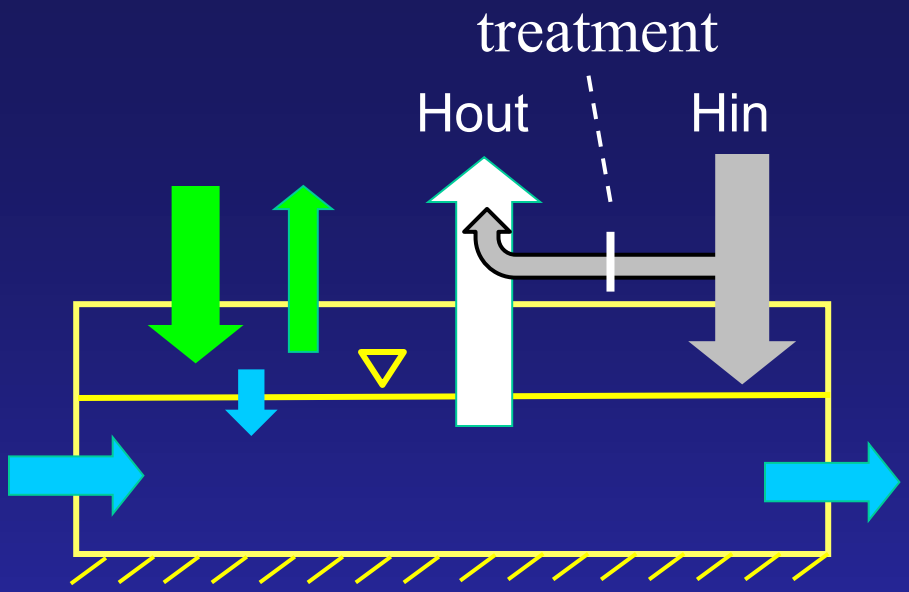
Grey water
(narrowly defined)



Wastewater generated from domestic activities such as laundry, dishwashing, and bathing, which can be recycled for uses such as irrigation. Excludes sewage (also known as black water).

http://en.wikipedia.org/wiki/Permaculture

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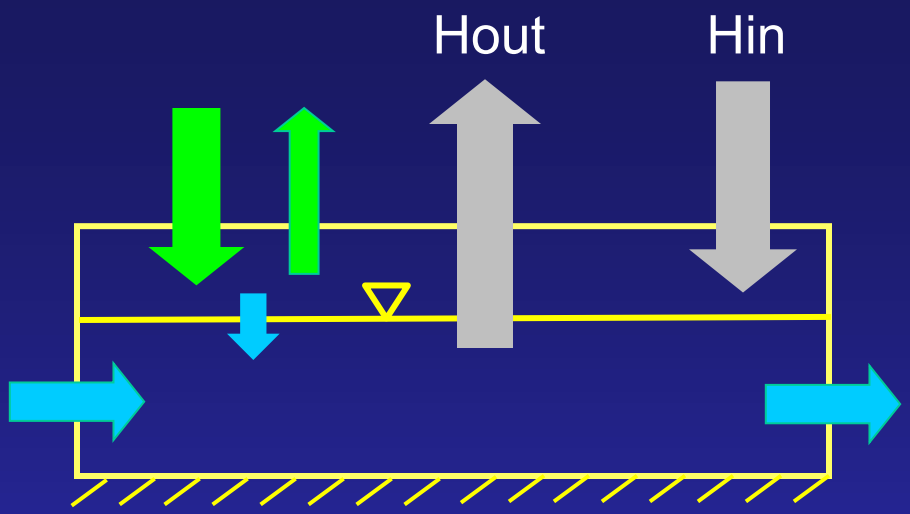
Grey water
(broadly defined)



Water stored in, or flowing through, human water infrastructure.

-- Weiskel et al., in prep.

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Hydroclimatic regime…

- The particular combination of green and blue inflows and outflows that characterizes the baseline, pre-development water balance of a landscape hydrologic unit.

- The regime is a function of the (1) local climate (ET, P), and the (2) hydrologic position of the unit in landscape, (P / [P + GWin + SWin]).

- Weiskel et al., 2014

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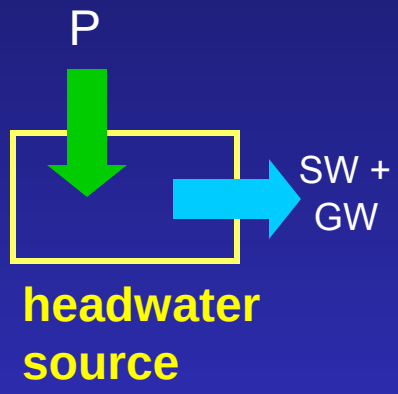
The hydroclimatic regime…

controls *how* water is available, and its dominant flowpath through a landscape unit.



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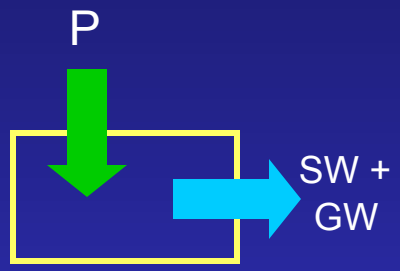
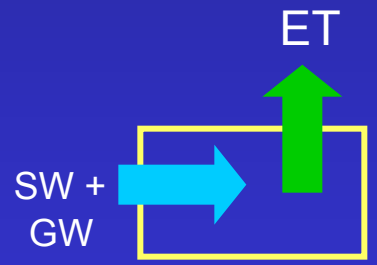


headwater source



terminal sink

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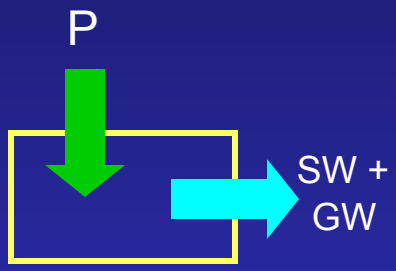

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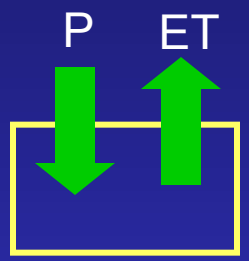
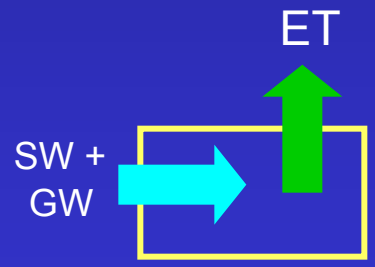


headwater no-flow



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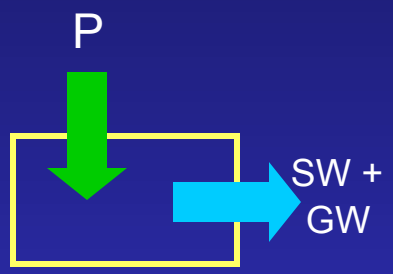

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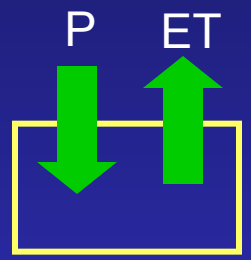

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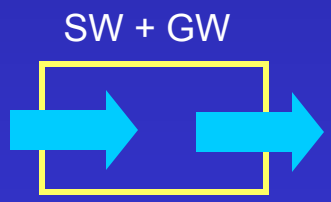
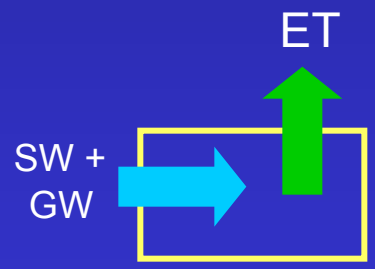


terminal flow-through



terminal sink

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Sustainability—What is it?

…The "development and use [of water by humans] in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences."

- William Alley et al., 1999

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One approach to sustainability…

- Define the water balance (hydroclimatic regime) of your landscape unit of interest.
- Identify the dominant "flowpath" through your landscape unit (inflow-outflow combination).
- Apply water management practices that "tap into" the dominant flowpath, in preference to lesser flowpaths.

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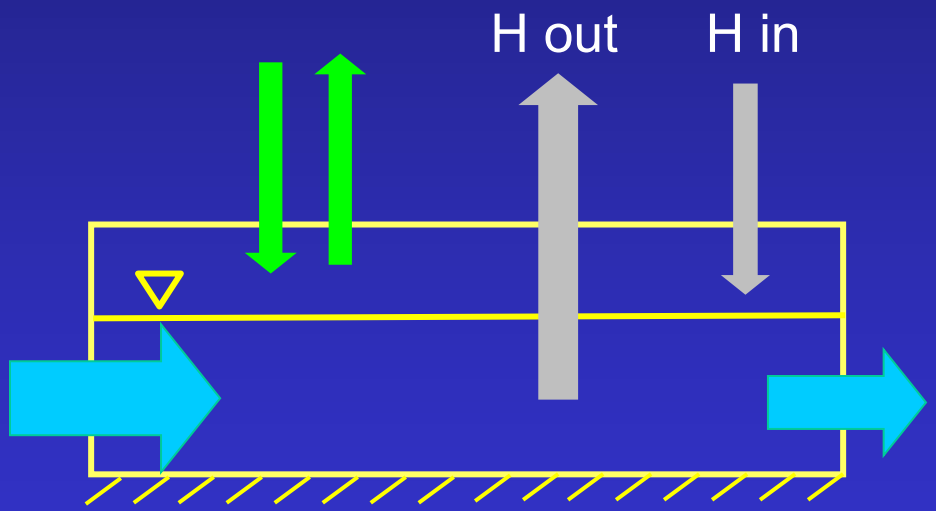
For example,

- Stream-corridor, flow-through regimes dominated by blue water inflows and outflows—are often well-suited for human withdrawals and return flows (Hout, Hin).



…*insofar as* flow and storage alterations (depletion, surcharging) are kept within acceptable limits…

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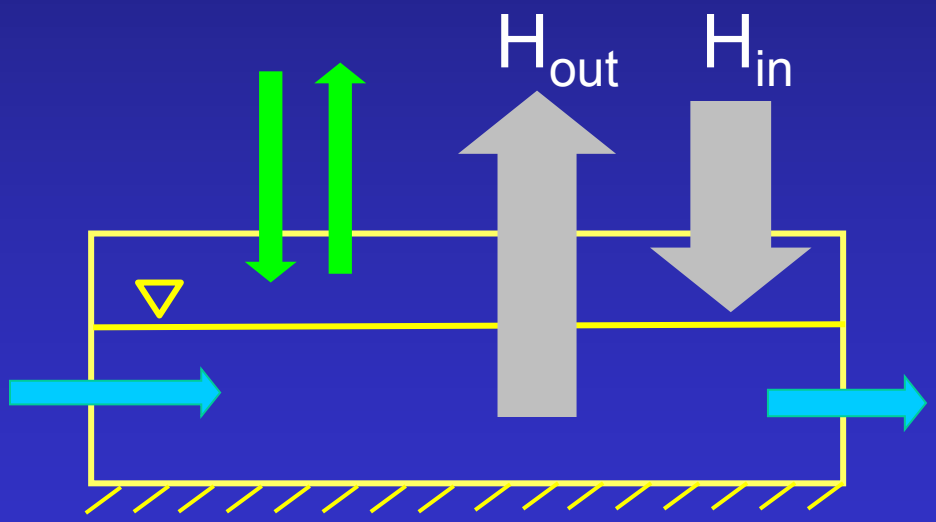
And…

- if human water flows (grey flows, in broad sense) are not too large relative to blue flows…



…causing a human-flow-dominated ("churned") condition.

--Weiskel et al., 2007

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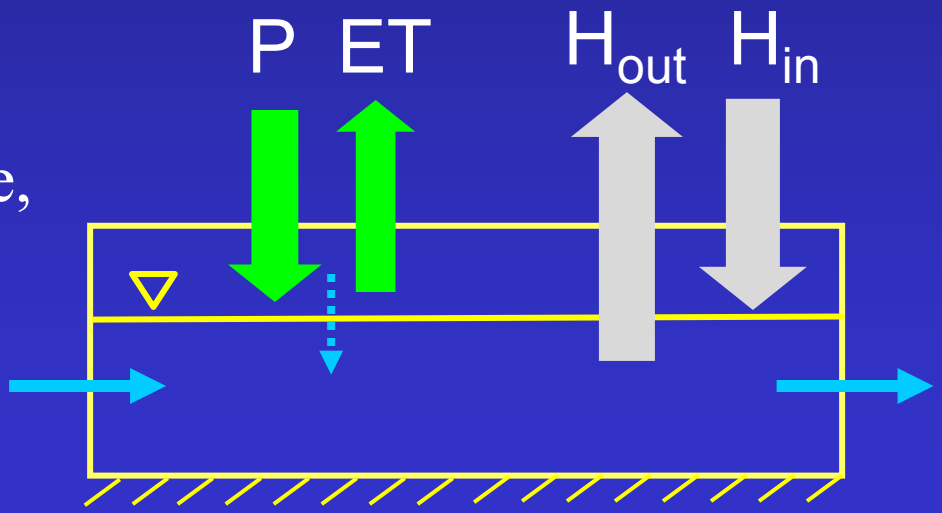
However,

- Half of the world's lands are *drylands*… (dry-subhumid, semi-arid, or arid; P ~ ET, with very low runoff and recharge rates.)

- P → ET is the dominant dryland flowpath; Hout and Hin tend to deplete, surcharge, or churn natural systems in this hydroclimatic regime.



For example….

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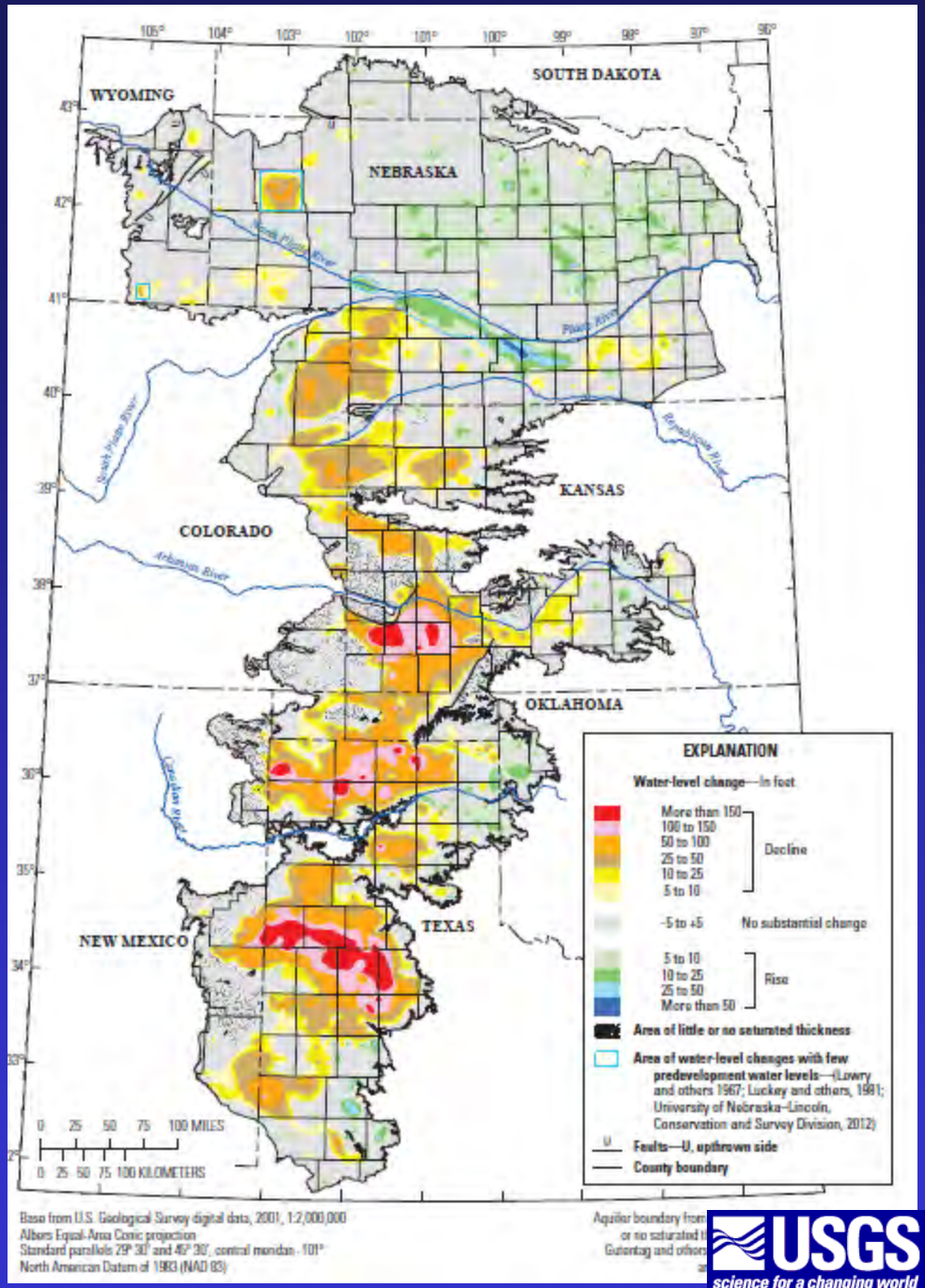
Example:

High Plains Aquifer

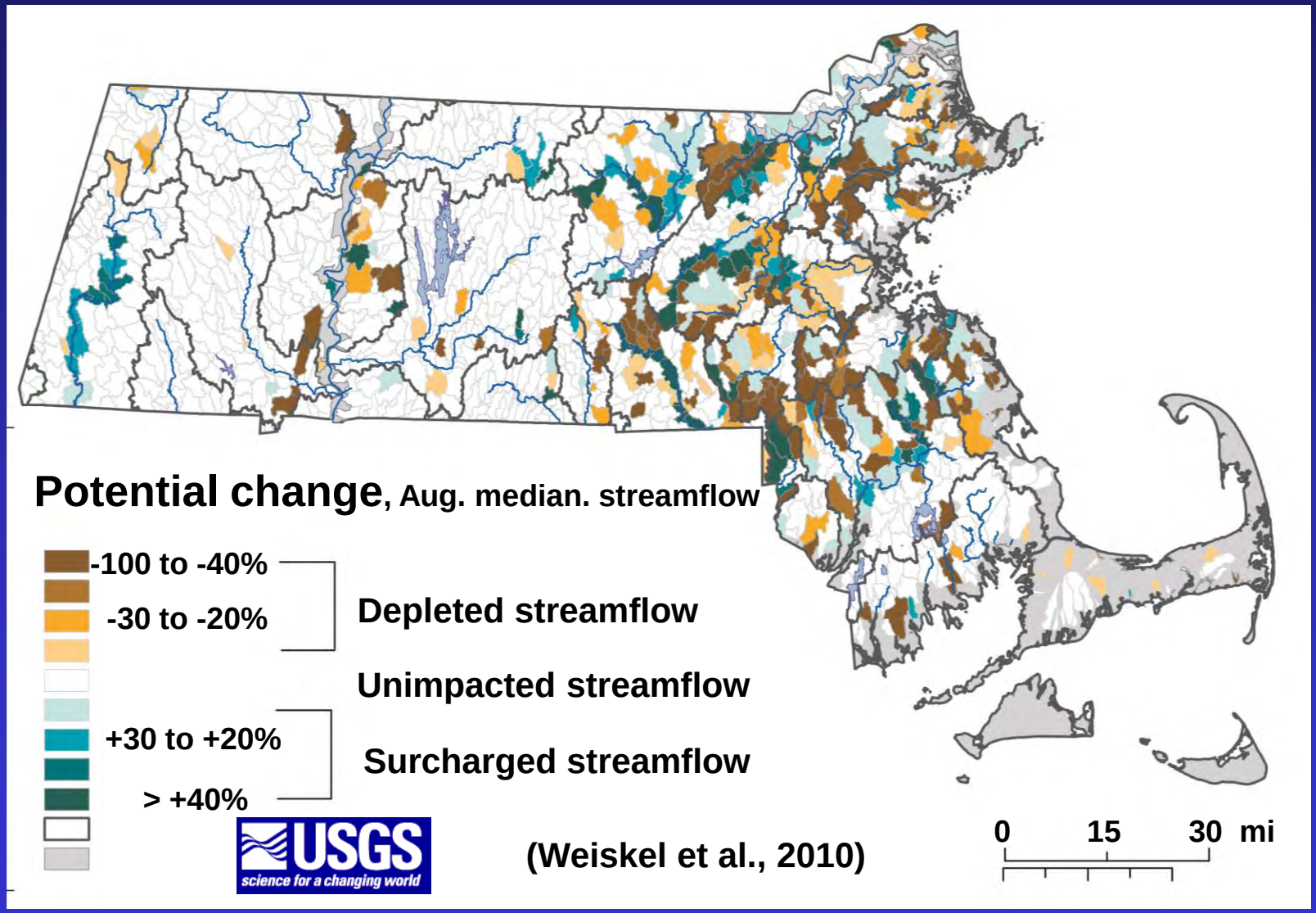
depletion (south),
surcharging (north)

from large GW pumping (south) & SW diversions to aquifer (north), relative to aquifer recharge.

(McGuire, 2013)



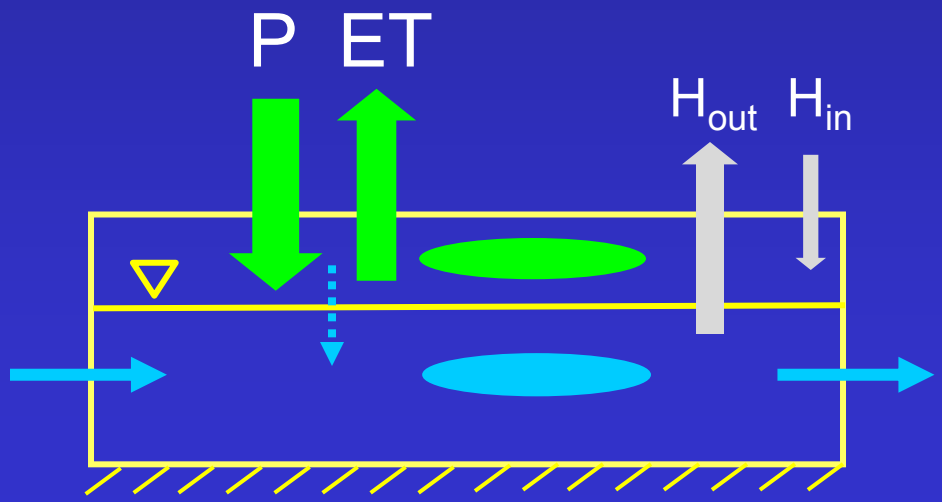
Also, streamflow depletion, surcharging, even in a humid region, like Massachusetts



One approach to mitigate impacts

High-efficiency irrigation

- Center pivot and drip irrigation can reduce Hout and Hin impacts on aquifer storage, relative to other methods.
- However, Hin (irrigation return flow) should not be entirely eliminated, or else soil salinization may occur.



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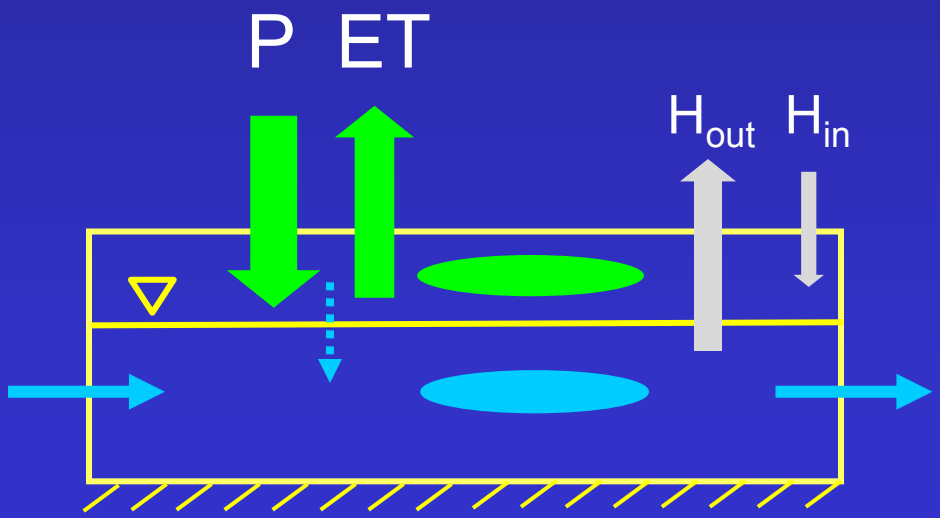
Alternatively,

Green water management practices can be used:

(1) To protect or restore the green water reservoir (soil moisture), and

(2) To carefully manage green water fluxes (P and ET)



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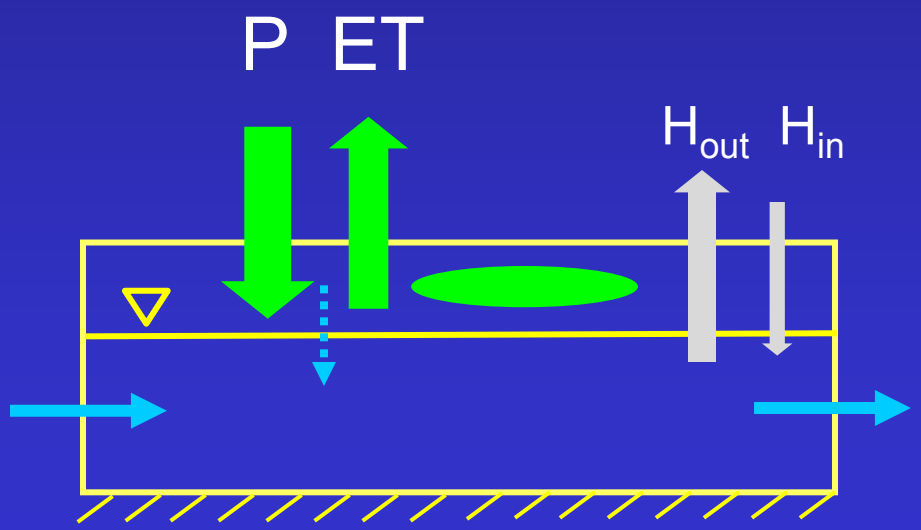
1) Practices that improve…

soil structure, water-holding capacity, thus enhancing the green water reservoir

- Reduced tillage and no-till farming
- Use of cover crops and perennial grain crops
- Organic matter amendments (manure and compost)



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No-till farming… is becoming very popular in U.S.

Soybeans grown into corn stalks, Union County, Iowa

http://www.washingtonpost.com/blogs/wonkblog/wp/2013/11/09/

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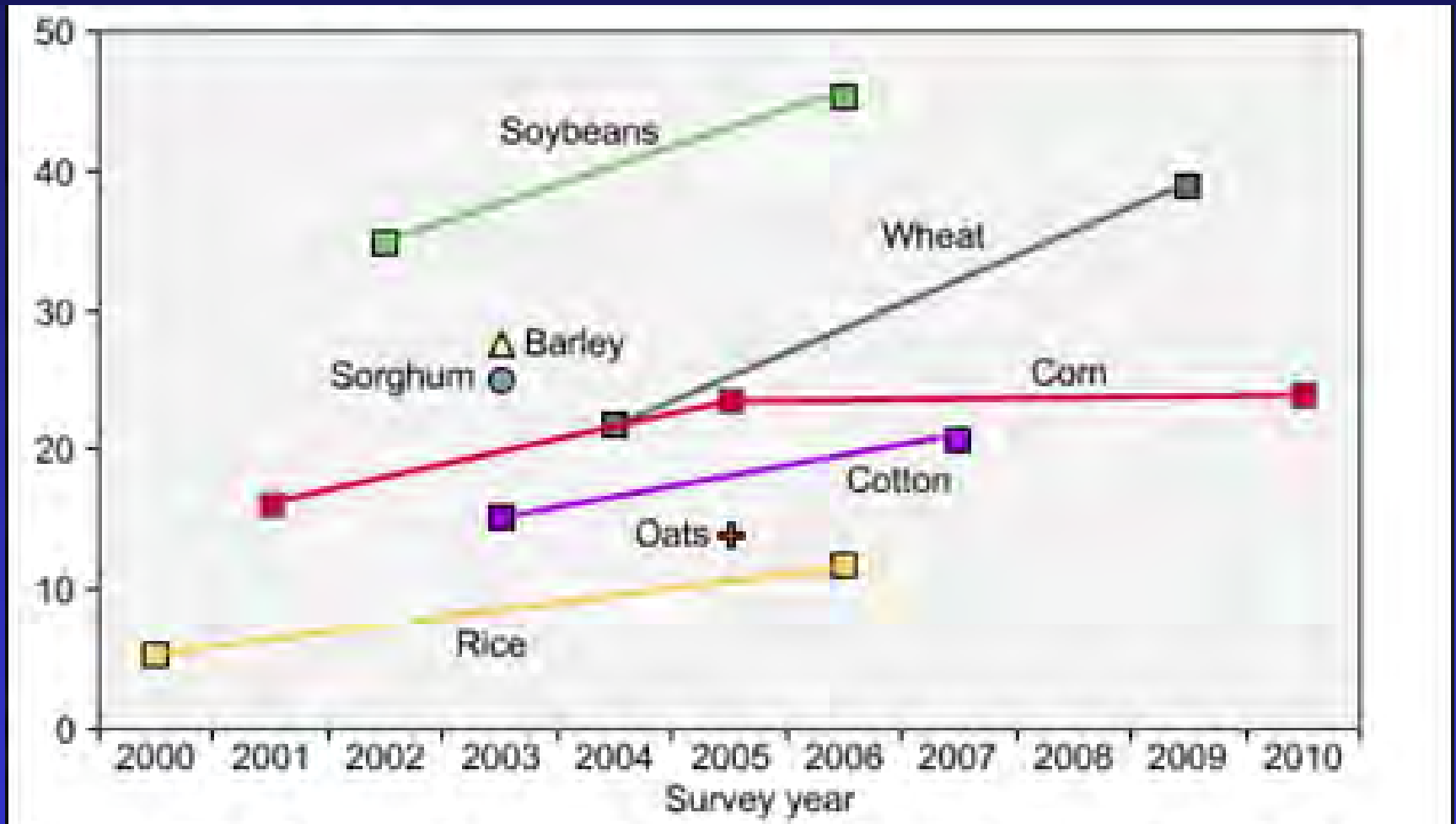
Percent of U.S. crop acreage under no-till practices 2000-2010



Source: USDA, Economic Research Service and USDA, National Agricultural Statistics Service, Agricultural Resource Management Survey, Phase 2, 2000-2010.

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2) Practices to better manage green water fluxes (P and ET)

Increasing water productivity, or the amount of "crop per drop", by:

-- Maximizing rainfall infiltration into soil, and

-- Minimizing unproductive green-water losses from evaporation…

-- Rainwater harvesting

- Falkenmark and Rockström (2004)

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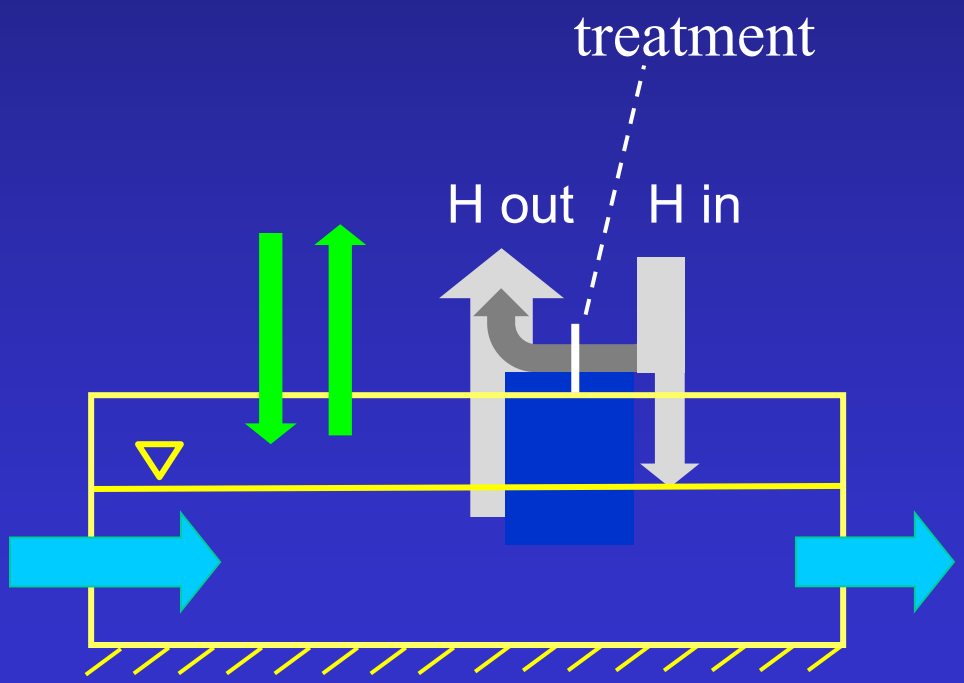
Finally, the role of water re-use…

…Treatment and re-use of grey water (narrow sense) mitigates environmental footprint of water use by reducing both withdrawal and return-flow volumes.



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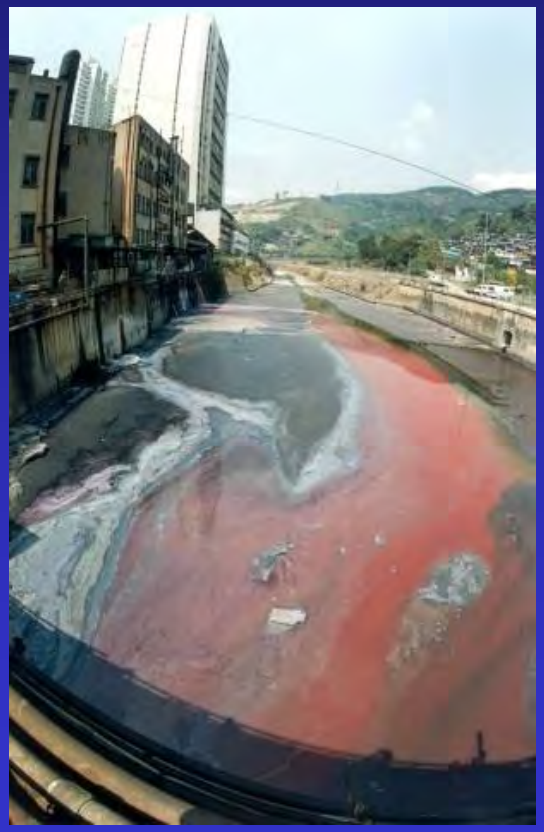
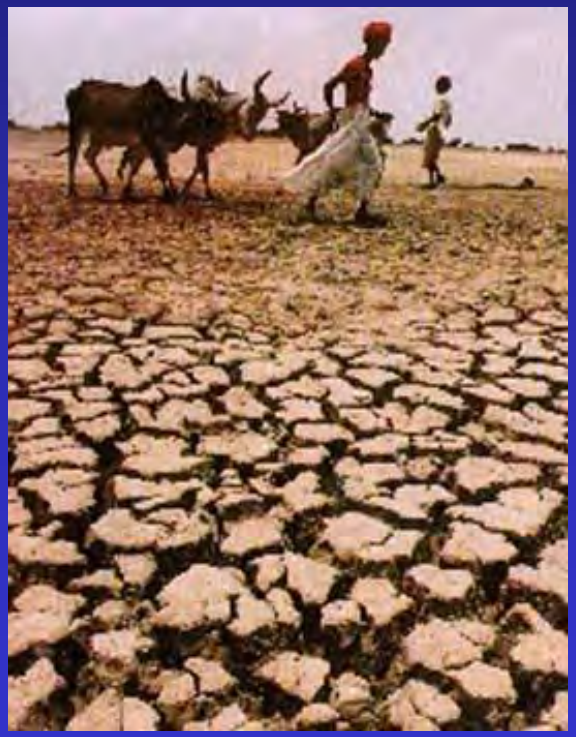
Implications: Understanding the contemporary water cycle





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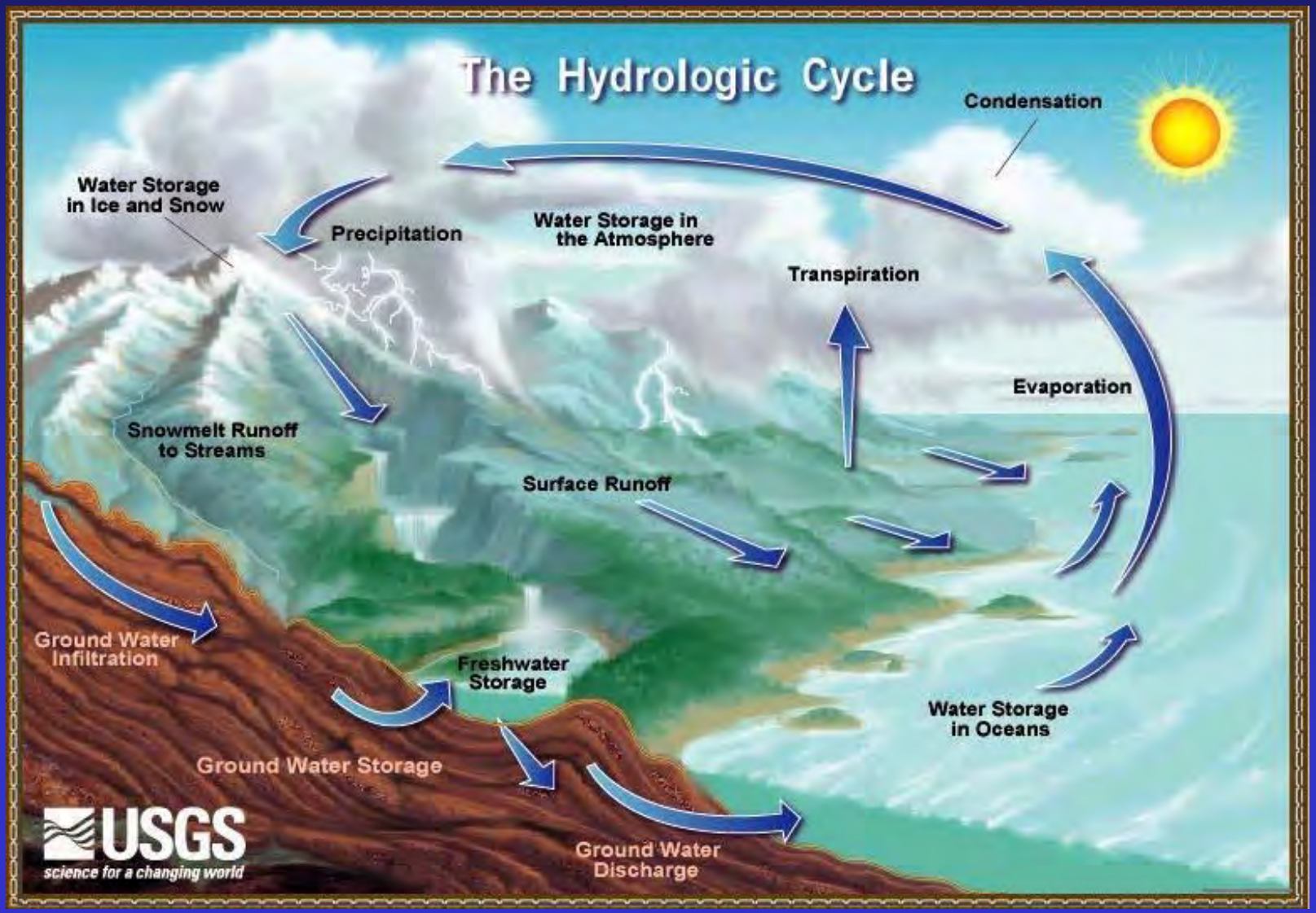
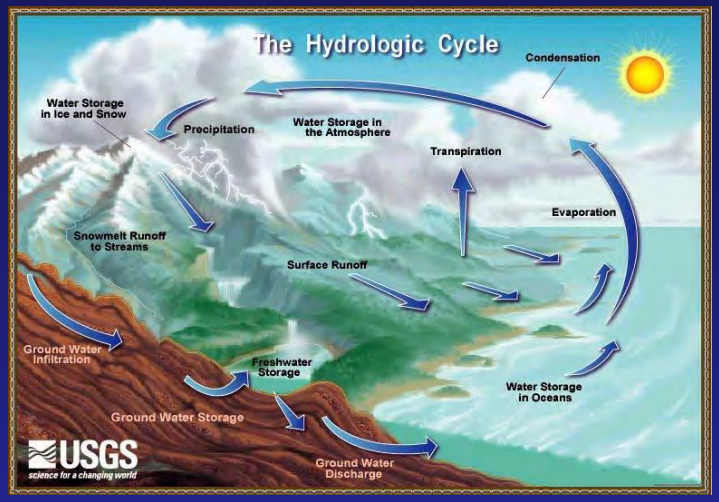
Traditional image of the water cycle:

Google “water cycle”, and you get this image…



A highly useful model for certain regions especially…



- Humid, mountain-source regions, which meet the blue-water needs of ~20% of world's population.

- Himalayas, East African and Turkish Highlands, Alps, Rockies, Sierra Nevada, Cascades, Andes.

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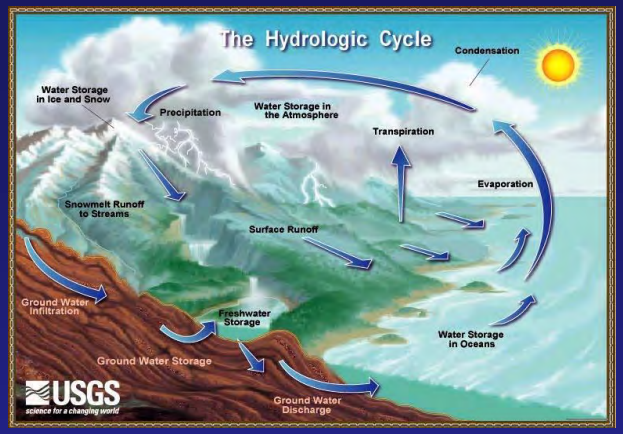
However, this model has important limitations ...



- Humid bias: Neglects half of the world's land area (i.e., drylands—zero-runoff and runoff consuming lands, where $P \leq ET$).

- Blue-water bias: Management of P, ET, and the soil moisture reservoir are often neglected.

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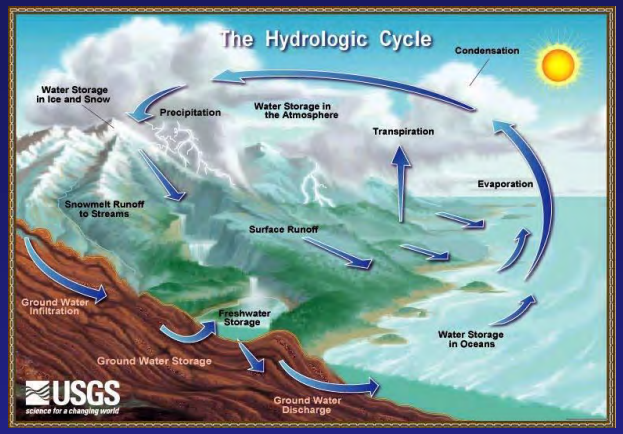
Limitations (continued...)



- Spatial bias: Unitary cycle concept obscures the large hydrologic diversity within watersheds.

- Neglect of human role: Integral role of humans is is not represented.

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One approach to correct these biases…

- Place the open-system, "hydrologic landscape" concept of Tom Winter (2001) at the center of our thinking.

- Use new datasets (climate, hydrography) and water balance models, constrained by data, to discretize the water cycle into local landscape units, link the units into continental networks (10^4 – 10^6 units), and estimate both the total (green + blue) and net (blue) water balance of each unit.

- Integrate human (grey) components of the water cycle.

- Develop and map both traditional and new indicators of water availability and use at the continental scale.

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Examples of traditional (and new) indicators,

derived from the hydrologic unit water-balance equation:

$$P + Lin + Hin = ET + Lout + Hout + dS/dt$$

where Lin, out = (GW + SW) in, out,
and assume Hin, Hout, and dS/dt = 0 for present.

Local runoff (traditional) = P – ET

Hydro-unit ET ratio = ET/P

Green-blue index = (P+ET)/(P+ET+Lin+Lout)

Hydrologic position = P/(P+Lin)

Total water availability (new) = (P+Lin)

--Weiskel et al., 2014

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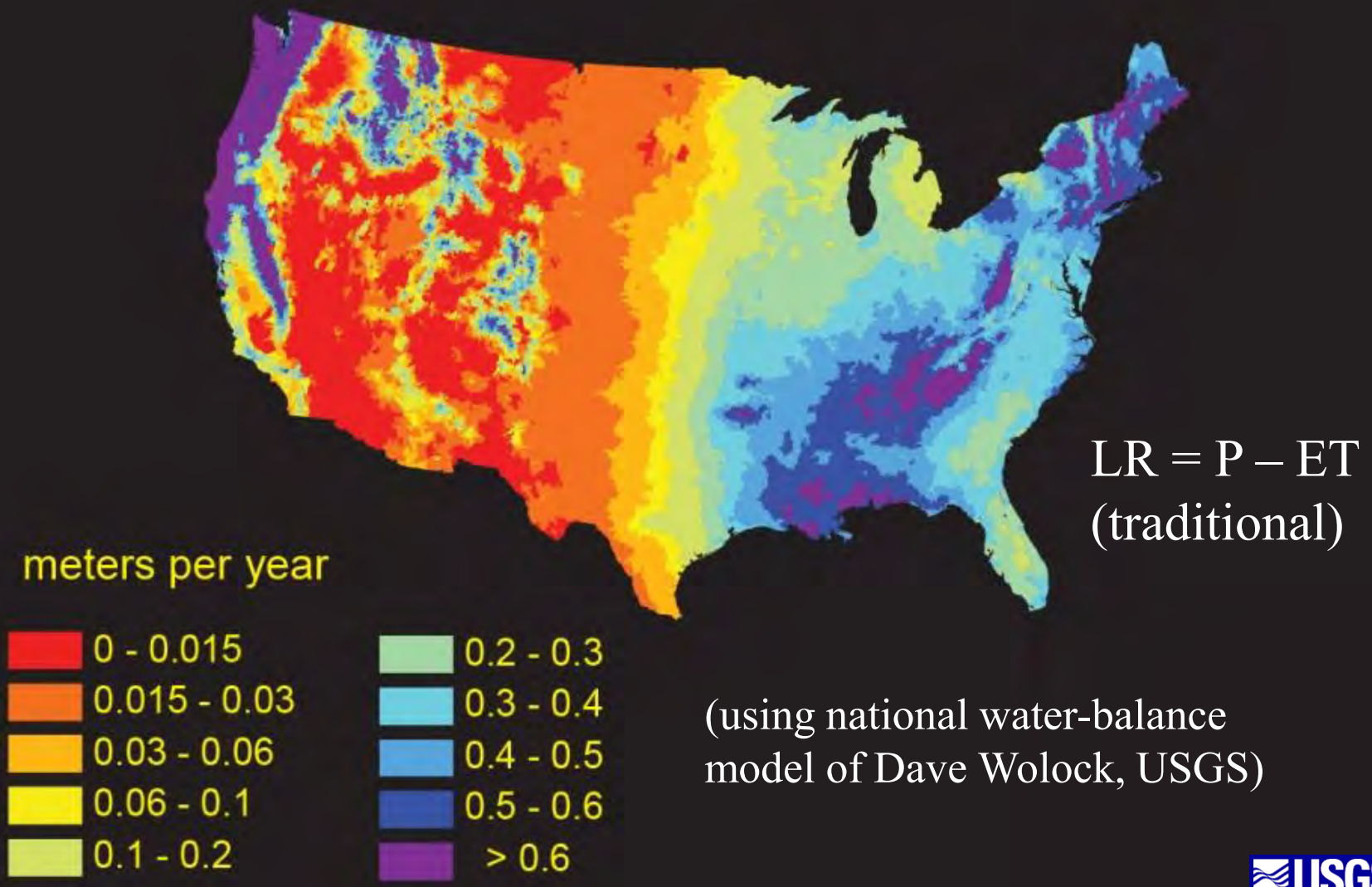
Local runoff:

53,400 U.S. hydrologic units (mean-annual, 1896-2006)



LR = P – ET
(traditional)

(using national water-balance model of Dave Wolock, USGS)

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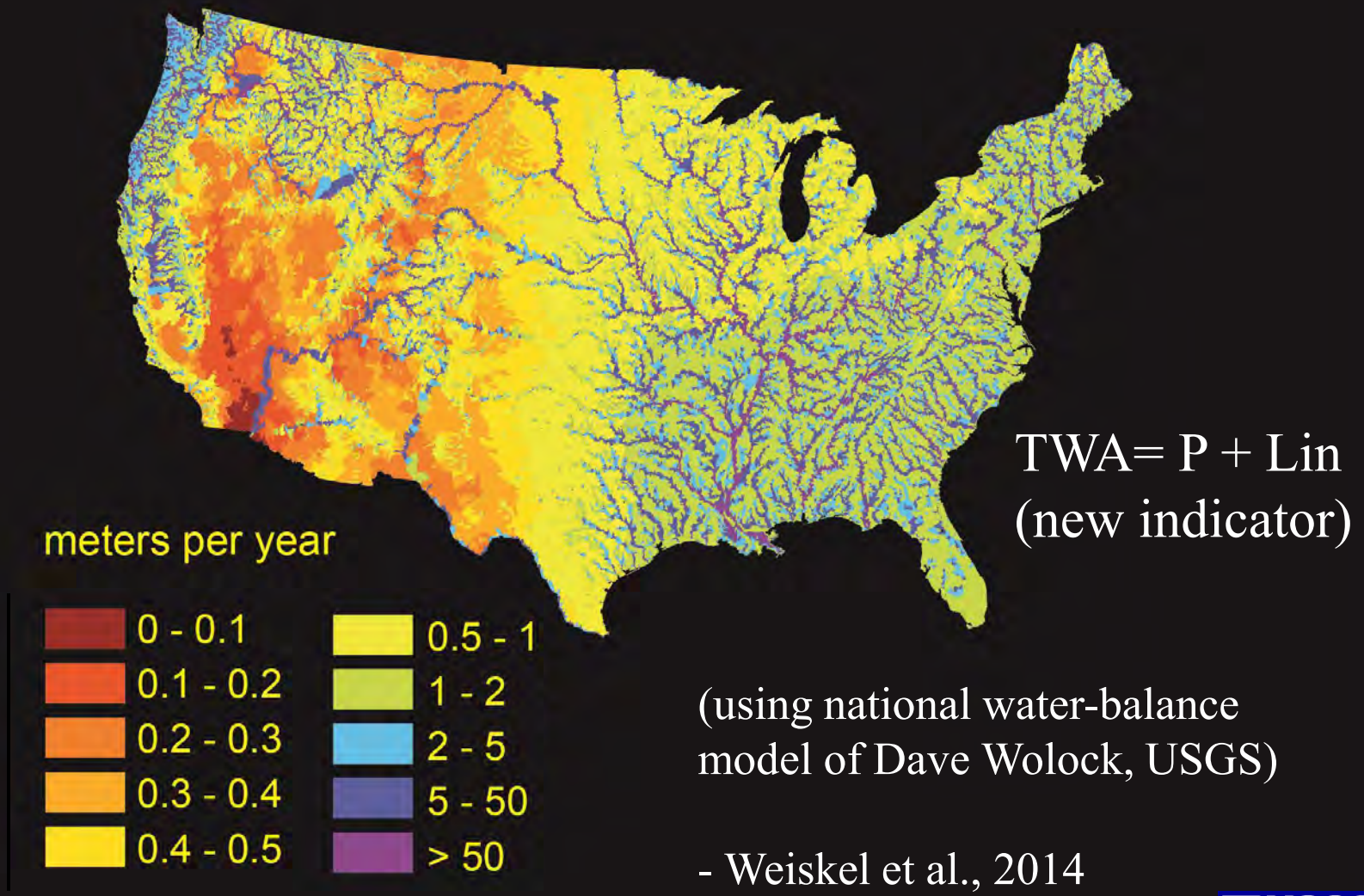
Total Water Availability

53,400 hydrologic units (mean-annual, 1896-2006)



TWA= P + Lin
(new indicator)

(using national water-balance model of Dave Wolock, USGS)

- Weiskel et al., 2014

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Summary:

- Green water—unsaturated water storage (soil moisture), and P and ET fluxes (open system definition).

- Blue water—saturated storage, and ground-water and surface water fluxes.

- Grey water– non-sewage wastewater, suitable for re-use after treatment (narrow definition).

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Summary (continued…)

- Grey water– water in human water infrastructure (broad definition).

- Hydroclimatic regime—the combination of green and blue inflows and outflows characterizing baseline hydrology of a landscape hydrologic unit.

- Sustainable water management—management practices that tap into, where feasible, the dominant flowpath of a hydrologic unit.

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And— a re-thinking of the water cycle as…

- discretized
- networked
- variable (in time and space)
- integrated with humans
  (via direct and indirect interactions)

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Thank you very much….

I would also like to thank:

- Malin Falkenmark, Johann Rockström , and Charles Vörösmarty, for their seminal work in global hydrology.

- Rich Vogel, for his insight, enthusiasm, and receptiveness.

- Bill Alley, Bob Hirsch, Eric Evenson, Keith Robinson, Tom Winter, Dave Wolock, Phil Zarriello, Sara Levin, Bob Lent, Leslie DeSimone, Kernell Ries, Pete Steeves, Stacey Archfield and Dave Armstrong for insights and support.

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