A new detailed map of the U.S. hydro-economy: water footprints, teleconnections, and indirect vulnerability to drought

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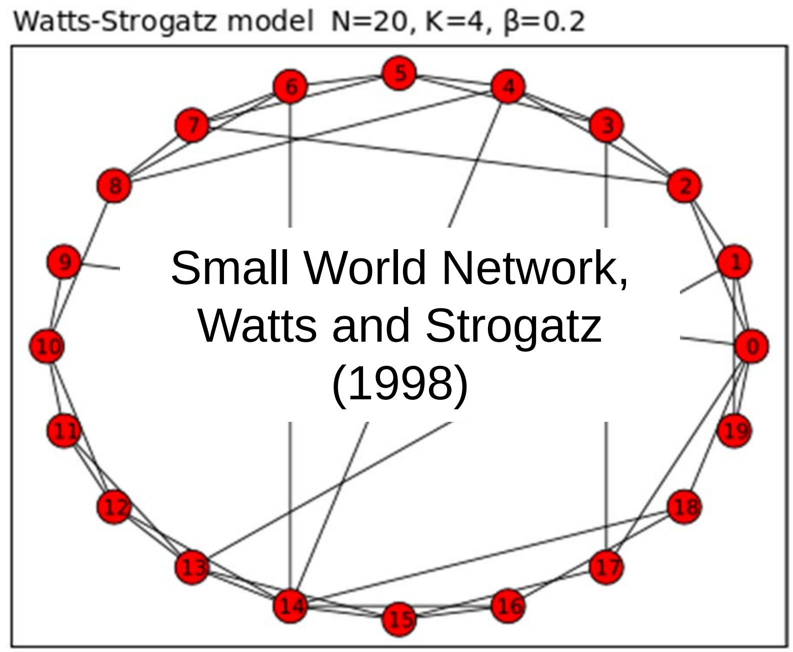
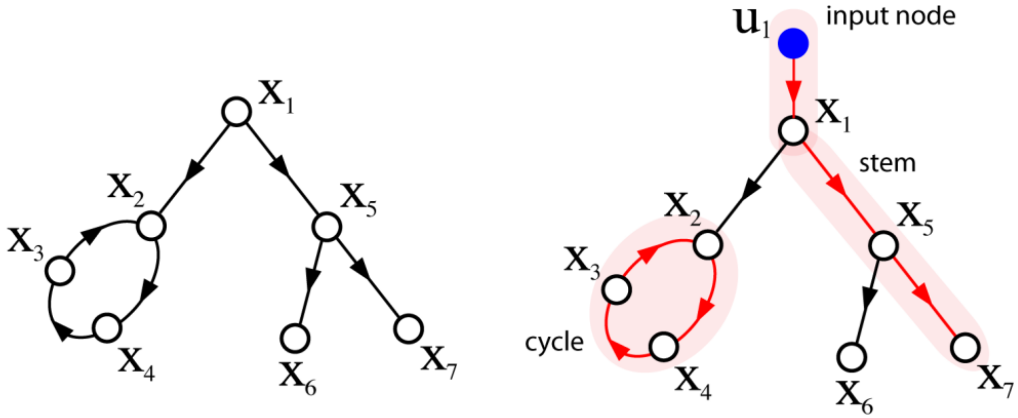
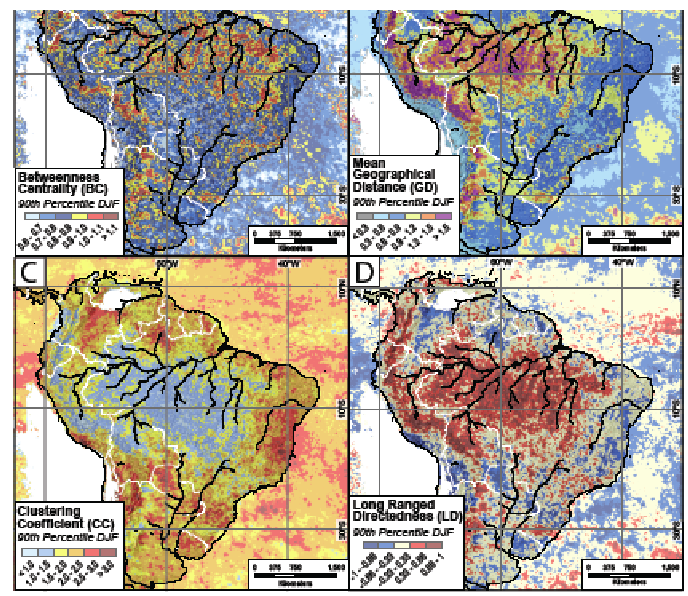
Classic Network Theory Applications



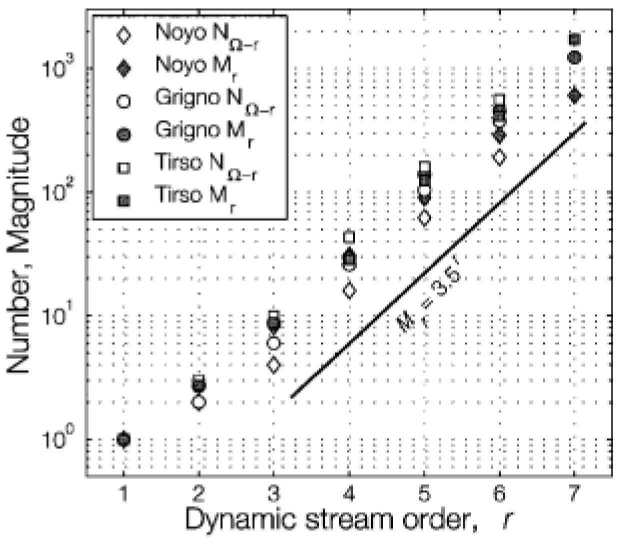
Control Centrality, Liu et al. (2012)

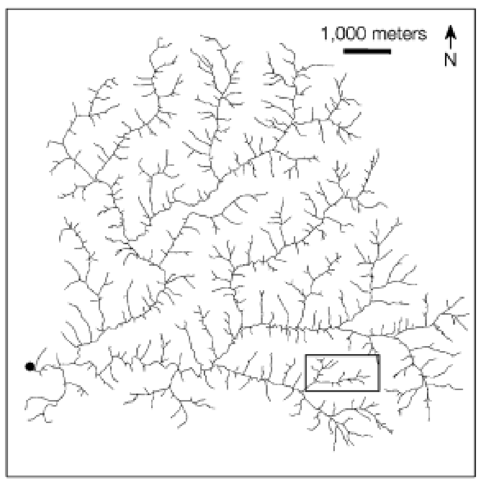


Betweenness Centrality for Amazon Rainfall, Boers et al. (2013)

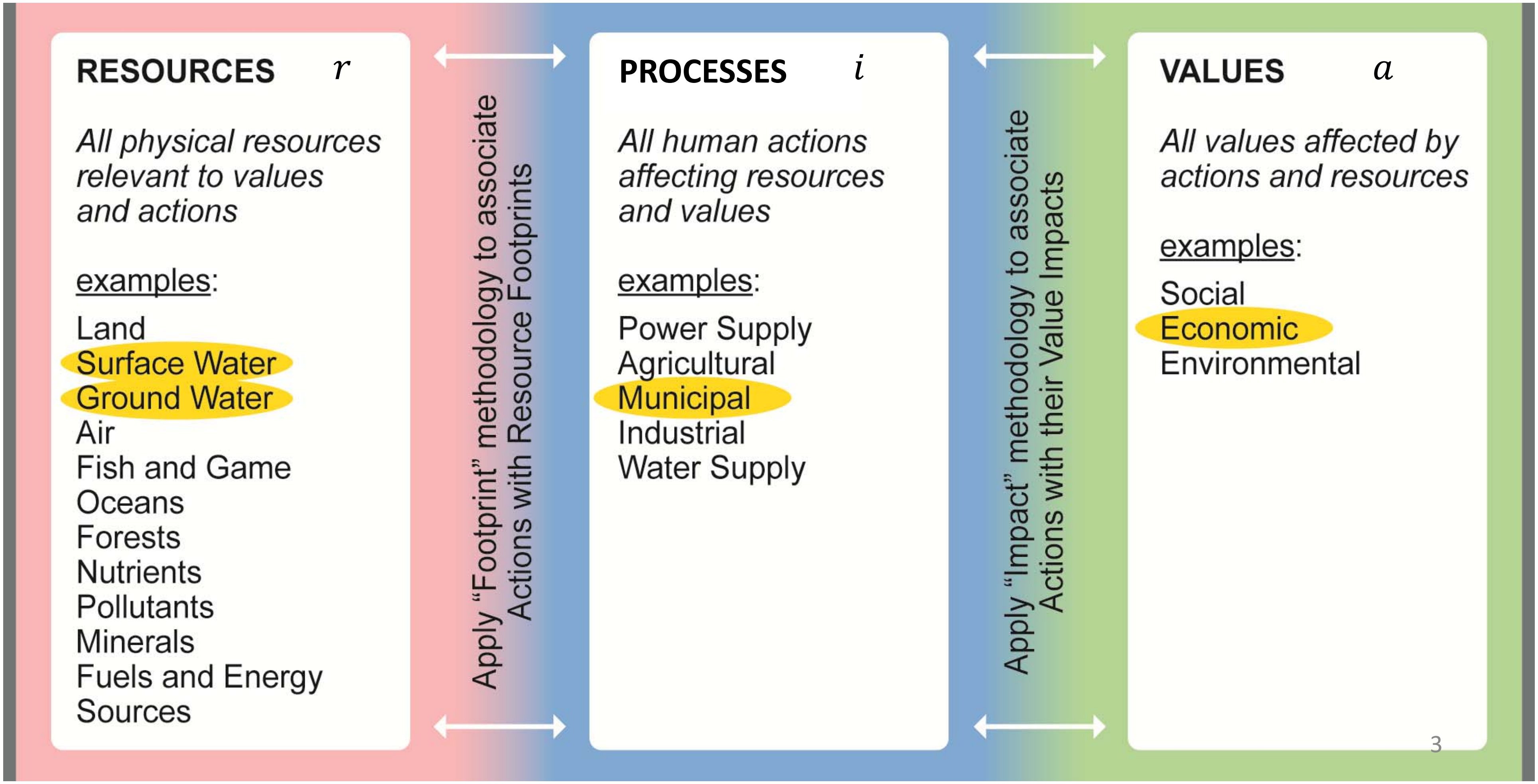


River Basin Power Law Scaling, Zaliapin et al. (2010)





Three types of networks intersect at a specific process node in a multitype Coupled Natural-Human System network:



Embedded Resource Impact Accounting (ERA):

A mulittype network theory for complex Coupled Natural Human Systems

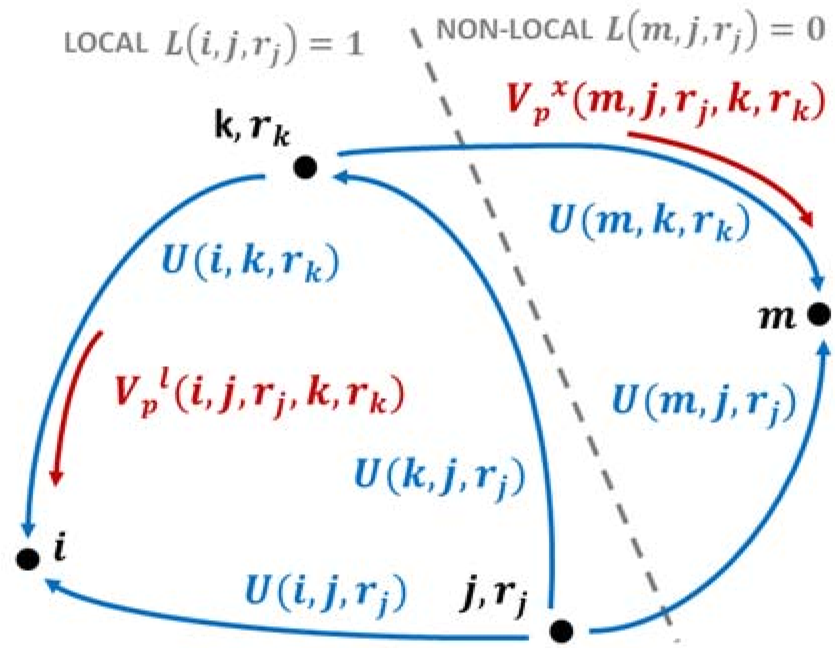
Net Systemic Impact (footprint) of a Process, E: the sum of the Direct (U) and indirect (V) network impacts of a process on a stock of interest, conditioned on a local/external (*l/x*) boundary (Q=0 case)

$$E = U^{l} + U^{x} + V_{IN}^{l} - V_{OUT}^{l} + V_{IN}^{x} - V_{OUT}^{x}$$

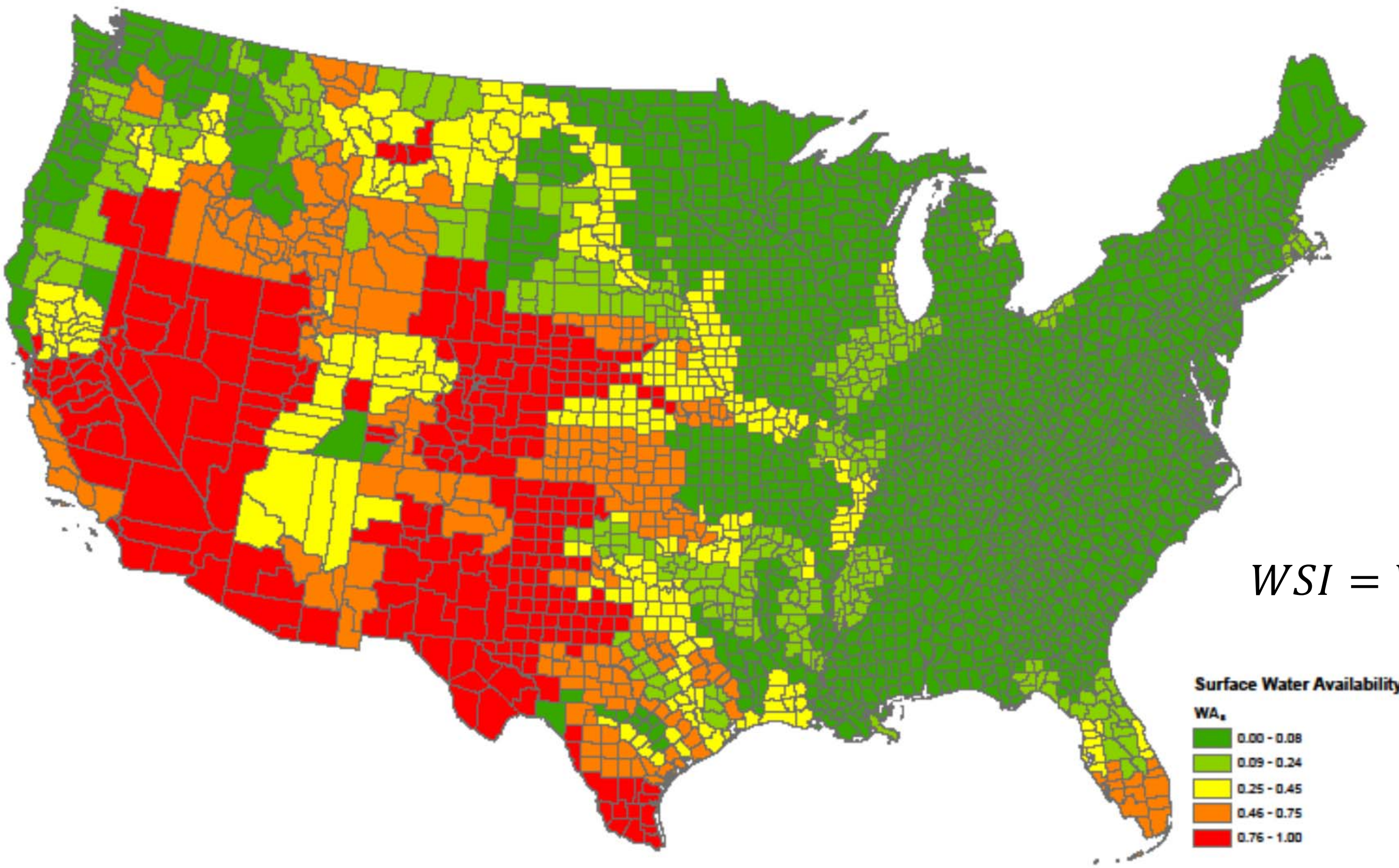
"Virtual Water" (Allan, 1993) is a special single-type network case of ERA. ERA is itself a special case of I/O and LCA, which are also network concepts.

The foundation of ERA is the *partial embedded resource impact V_p*; the sum across intermediaries *k* and r_k is the net indirect impact *V*

$$V_p(i,j,r_j,k,r_k) = \frac{U(i,k,r_k)}{\sum_n U(n,k,r_k)} * U(k,j,r_j)$$



A CNH Problem: Water Scarcity



$$WSI = WA_s = \frac{P}{Q + P}$$

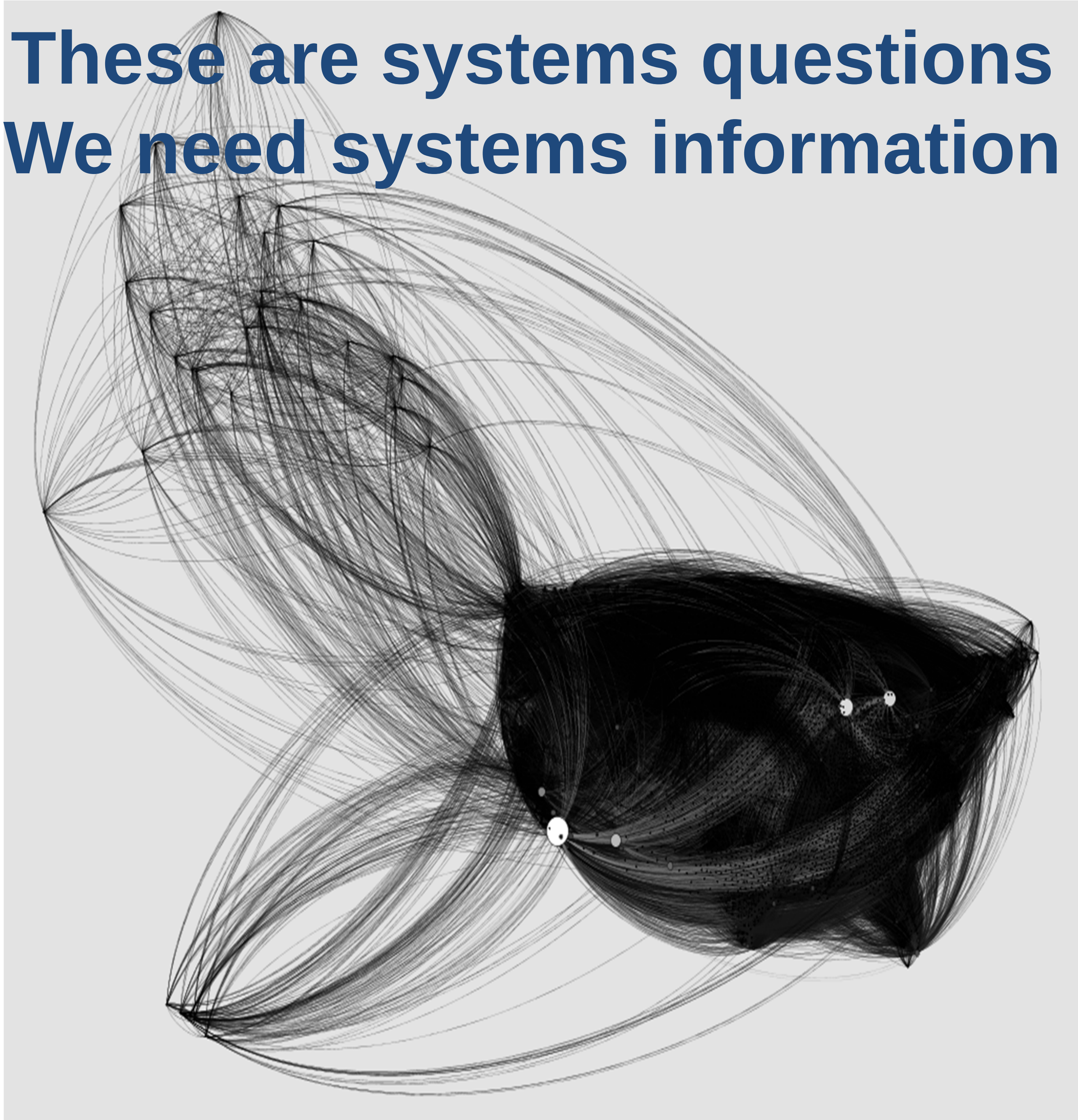
V. C. Tidwell, P. H. Kobos, L. A. Malczynski, G. Klise, C. R. Castillo, Exploring the water-thermoelectric power Nexus. *Journal of Water Resources Planning and Management* **138**, 491-501 (2012).

How to cope with Water Scarcity?

1. Technology, efficiency, and reuse (expensive)?
2. Curtail economic growth (too expensive)?
3. Political reallocation of water from less valuable (energy, food) to more valuable uses (who decides)?
4. Economic reallocation of water resources using prices and water rights (political barriers and high transaction costs)?
5. Compromise our social, environmental, or economic values?
6. **Outsource largest and least valuable water uses using the economic network to connect to distant water supply?**

These are systems-level questions
We need systems-level information

These are systems questions
We need systems information

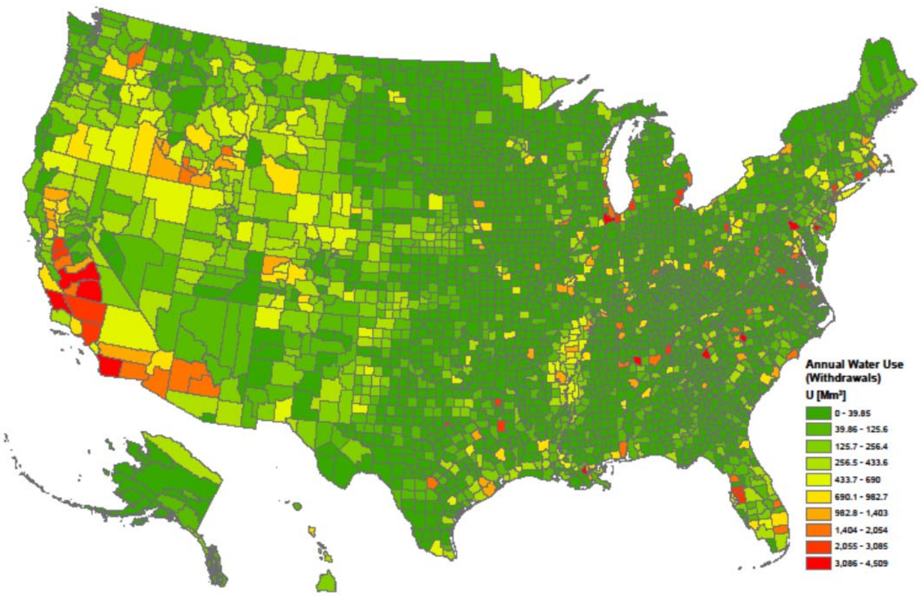


The National Water-Economy Database 1.0 (NWED)

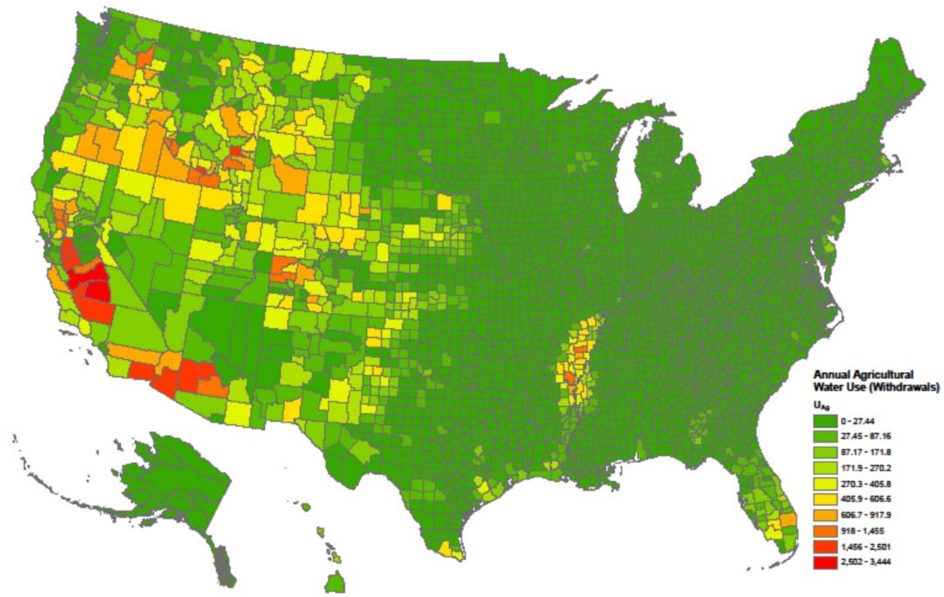
- A complete map of the US water footprint
- A hydro-economic map of the water supply chain, including precise teleconnections to drought-prone locations
- A map of the "water-everything" nexus: food, energy, services, manufacturing, etc.
- Detailed enough for policy assessment and decision making at the crucial city and watershed scales
- Provides the systems level information needed to evaluate local water problems in context
- Provides complete water productivity benchmarking ($/gal)
- <u>This is basic data we need to answer Food-Energy-Water (FEW) and other complex water resource system questions!</u>

US Water Use

Annual Total Withdrawals (U, Mm^3)



Annual Agricultural Withdrawals (U_{ag}, Mm^3)

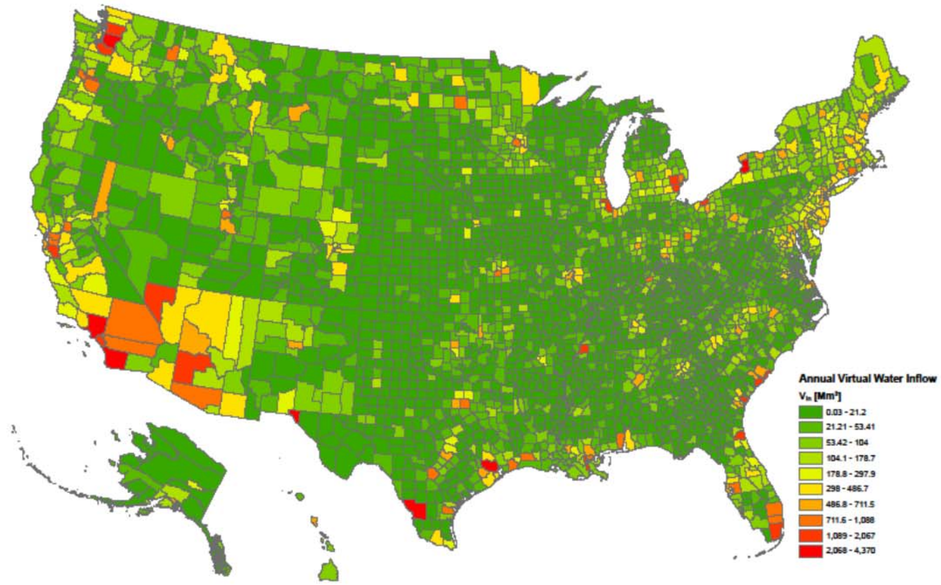


Also see: M. A. Maupin *et al.*, "Estimated use of water in the United States in 2010," (US Geological Survey, 2014).

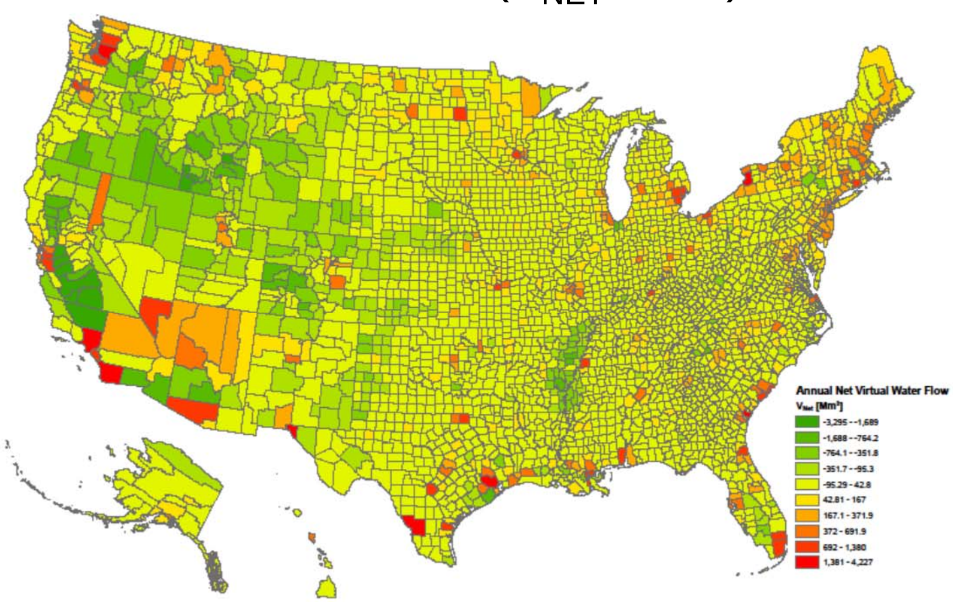
Preliminary Data – Not for Publication

Virtual Water

Virtual Water Inflow (V_{IN}, Mm^3)

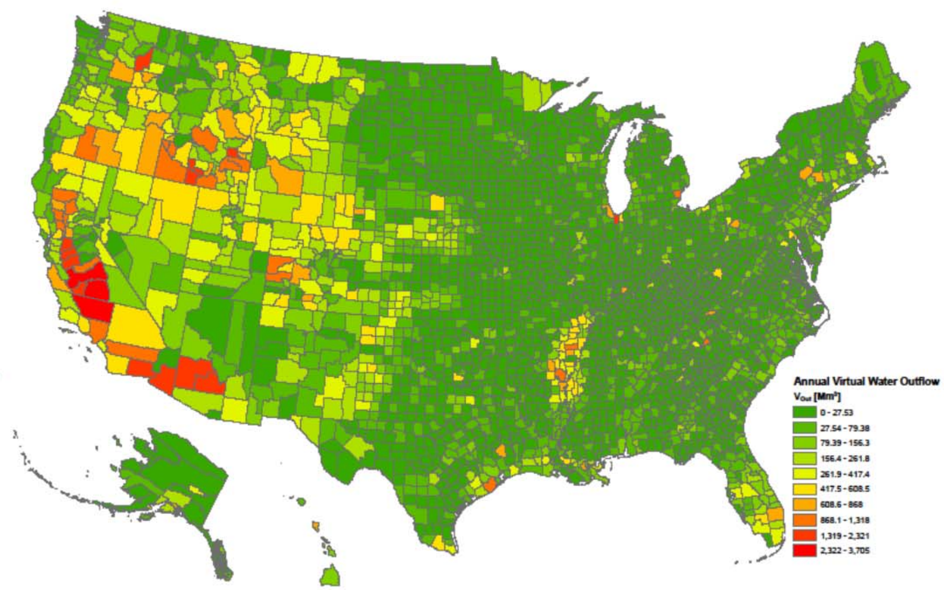


Net Virtual Water (V_{NET}, Mm^3)

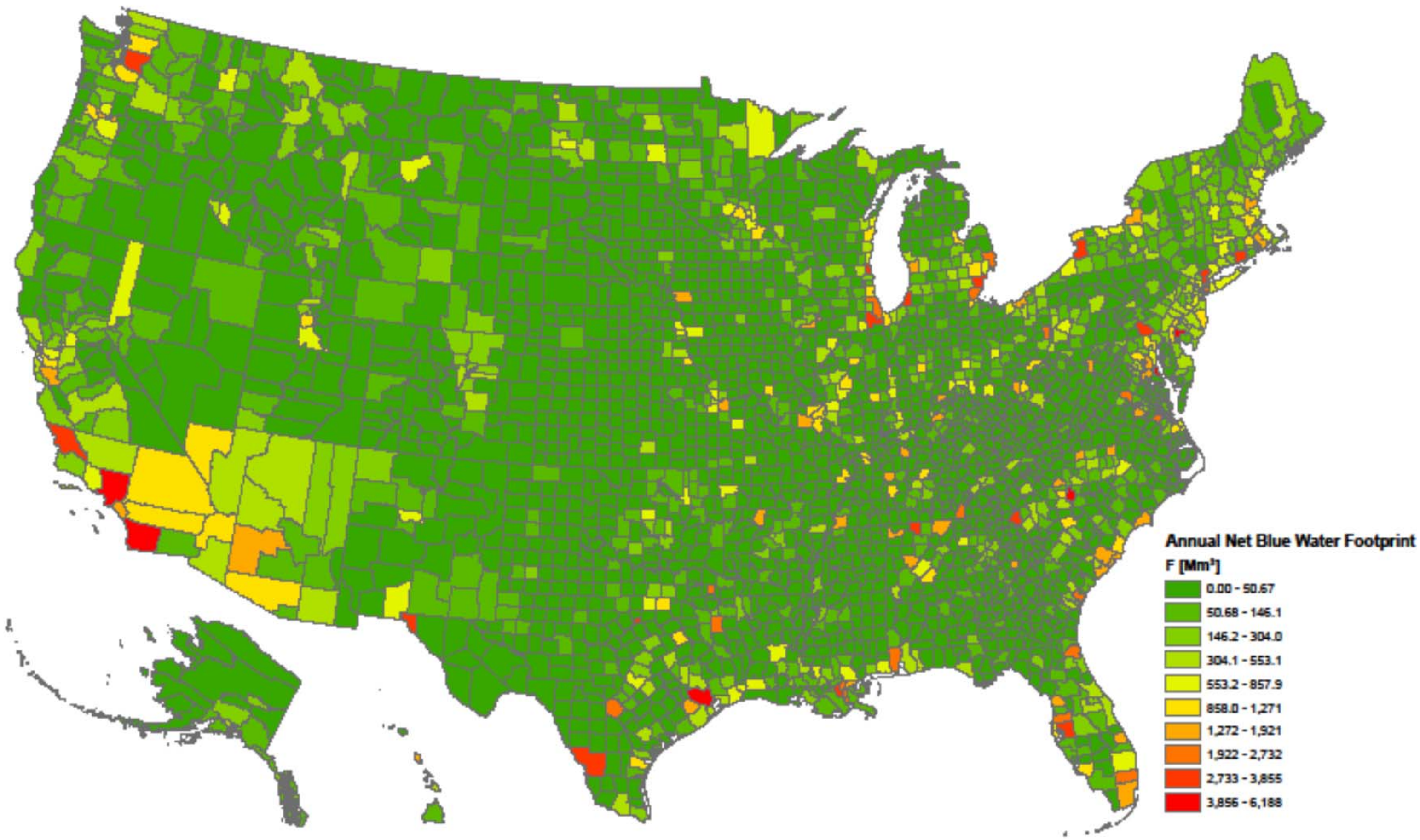


(green is net outflow, negative)

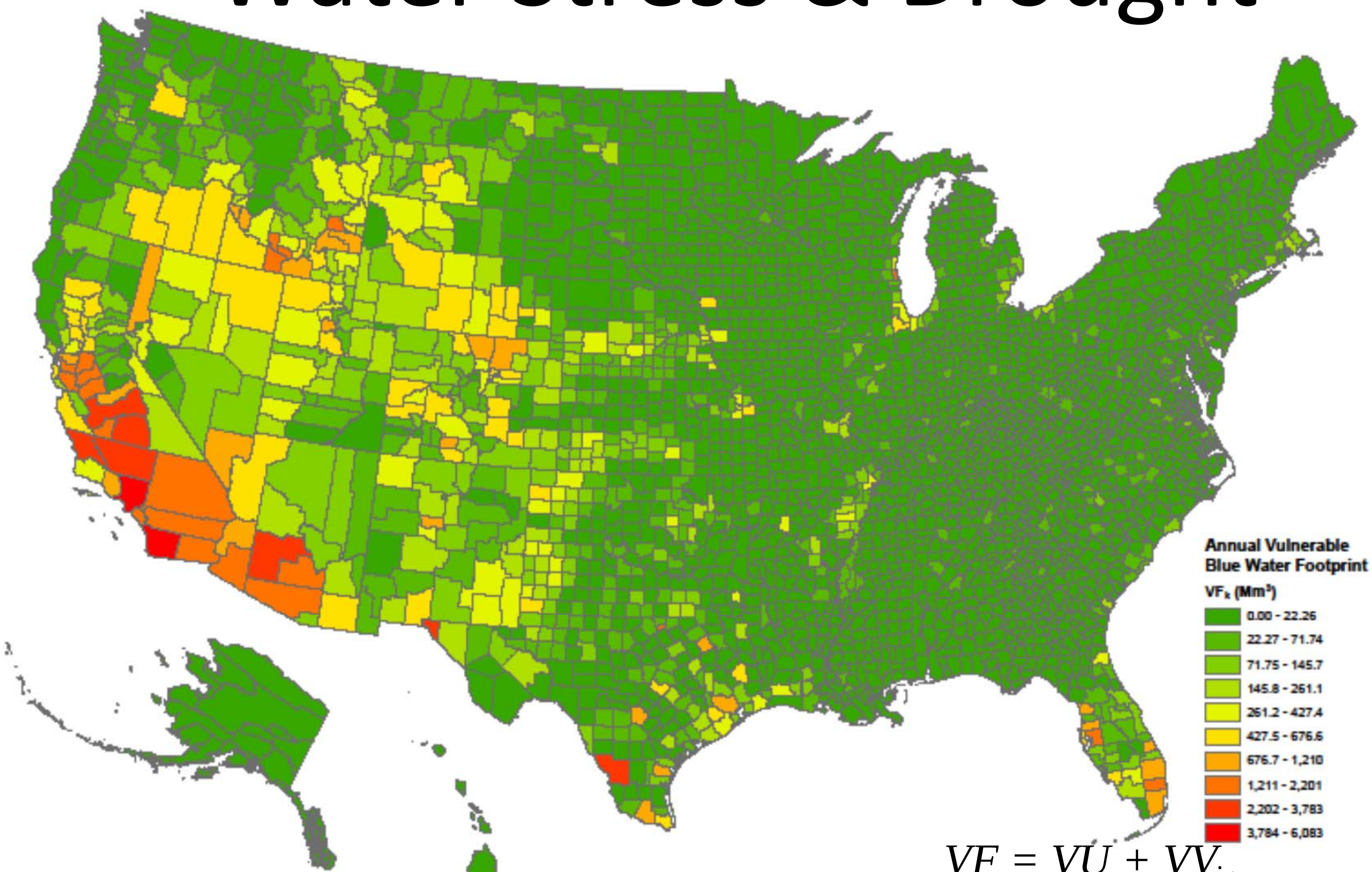
Virtual Water Outflow (V_{OUT}, Mm^3)



The US Net Blue Water Footprint



Vulnerability of the Footprint to Water Stress & Drought



$$VF = VU + VV_{in}$$

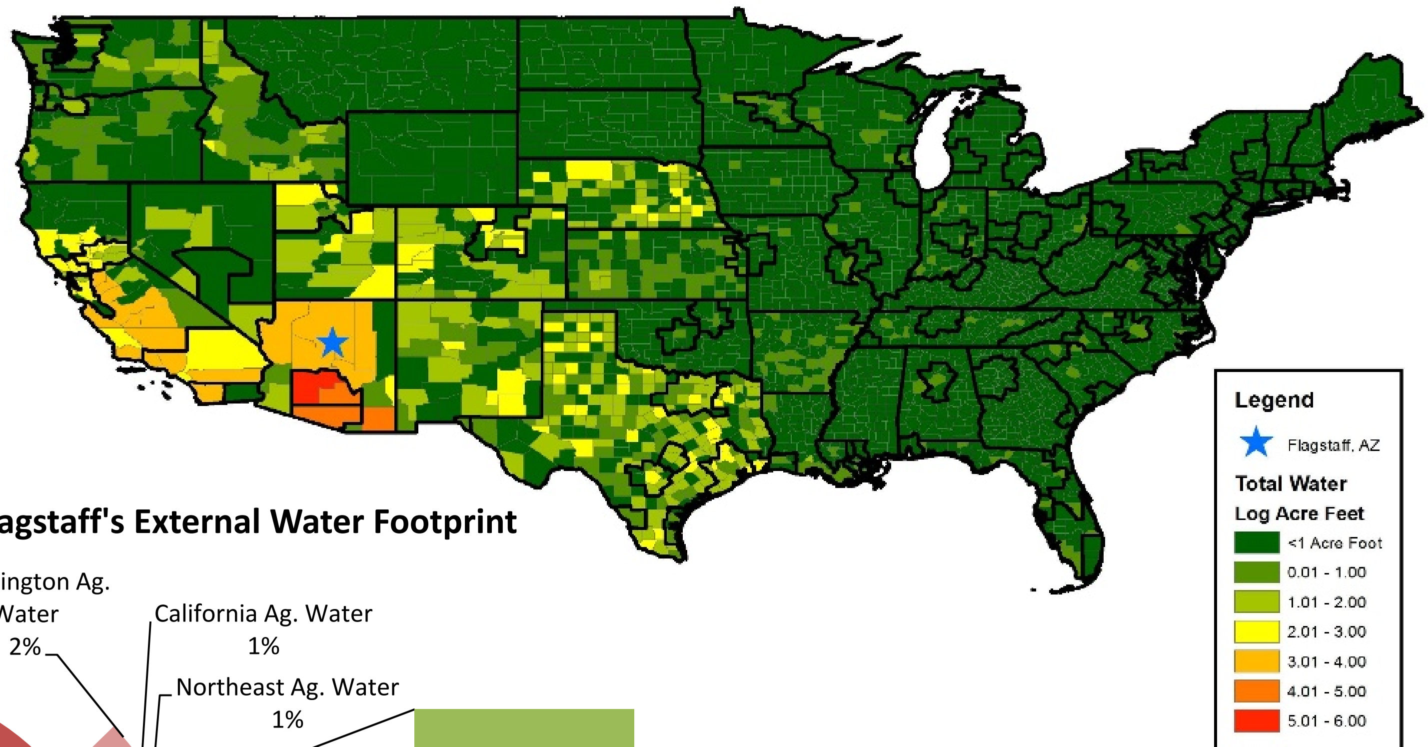
$$VV_{in,K} = \sum_{all\ k} V_{k \to K} \times WSI_k$$

$$VU_K = U_K \times WSI_K$$

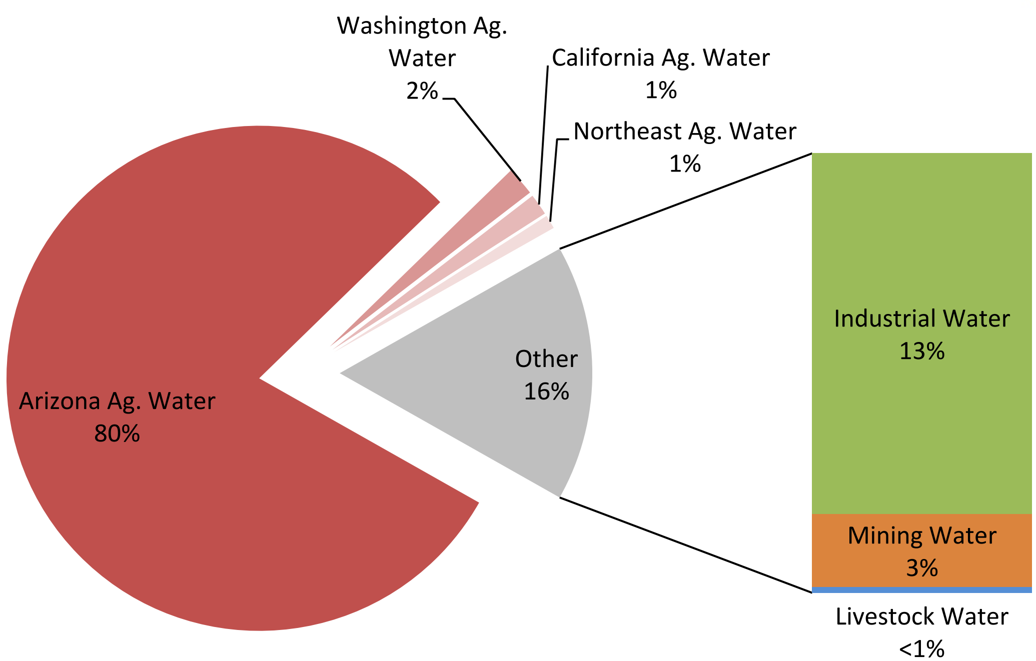
WSI from: V. C. Tidwell, P. H. Kobos, L. A. Malczynski, G. Klise, C. R. Castillo, Exploring the water-thermoelectric power Nexus. *Journal of Water Resources Planning and Management* **138**, 491-501 (2012).

Preliminary Data – Not for Publication

Flagstaff’s Water Footprint

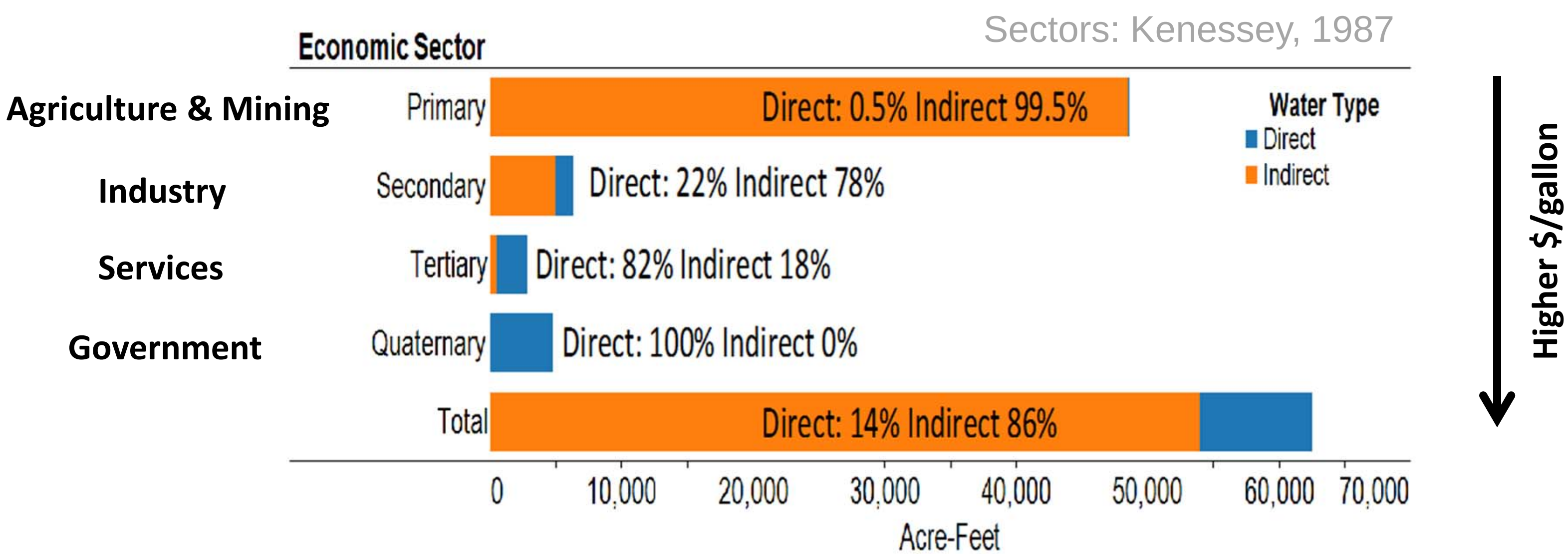


Breakdown of Flagstaff's External Water Footprint



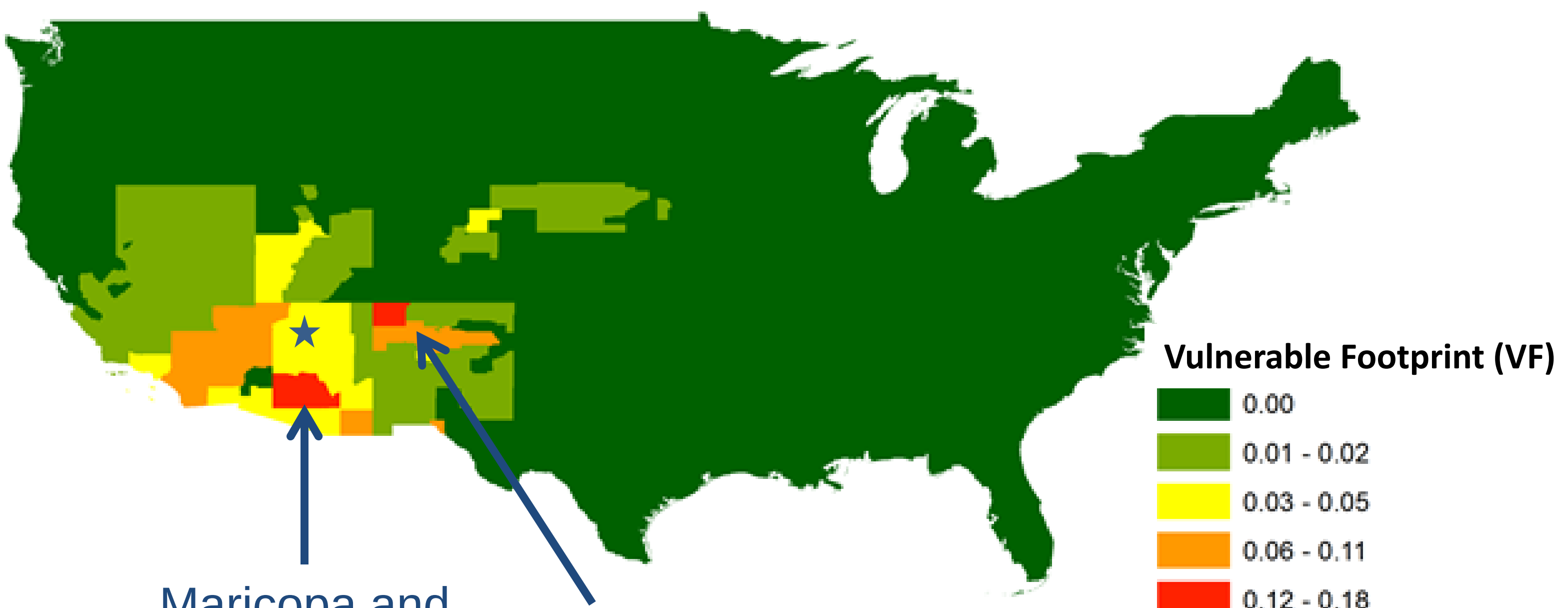
Preliminary Data – Not for Publication

Water Productivity Explains Flagstaff's Water Outsourcing



Preliminary Data – Not for Publication

Flagstaff's Indirect Vulnerability to Water Stress & Drought



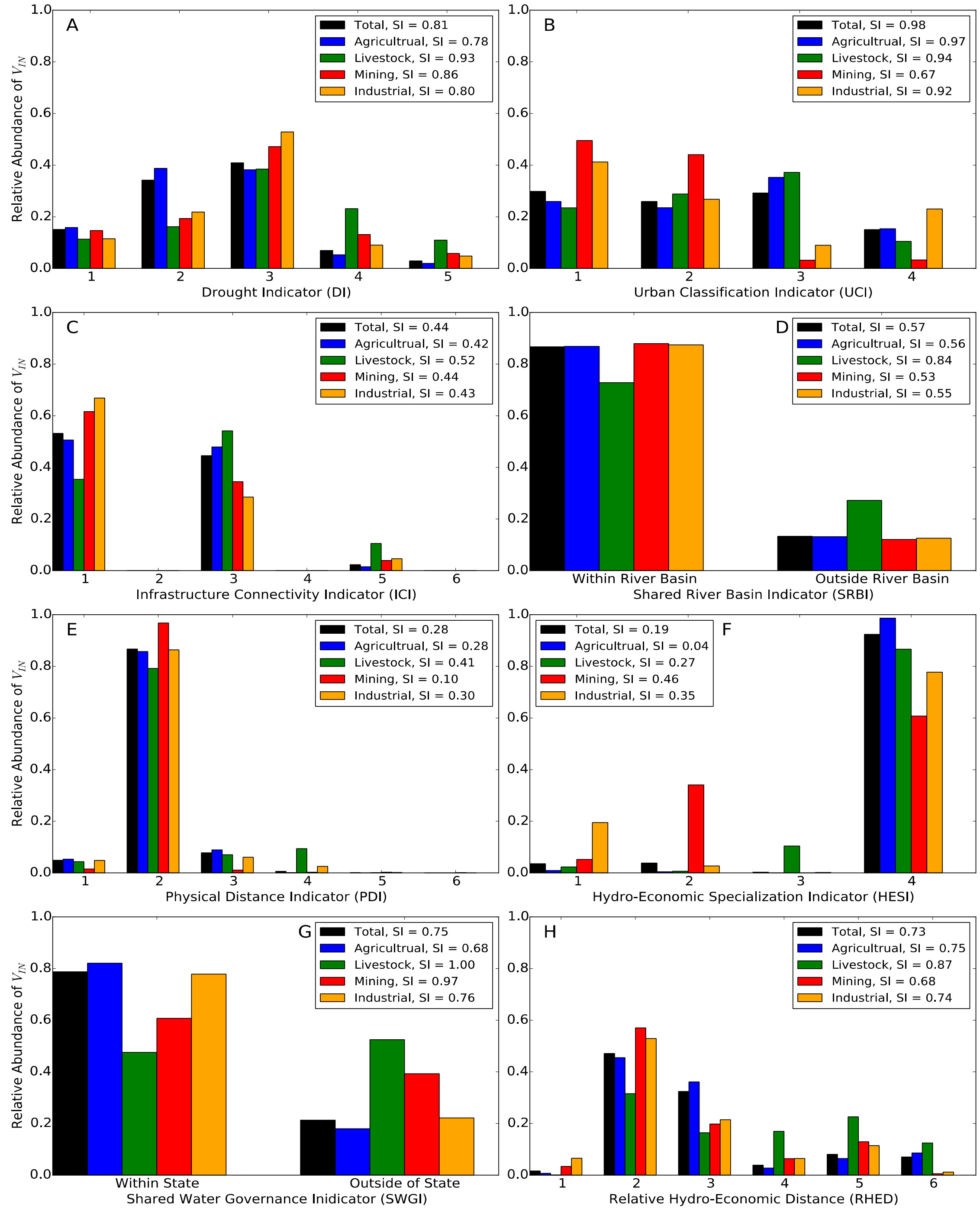
Maricopa and Pinal Counties (Phoenix & Farms)

Neighboring Farmington (energy), Gallup, Albuquerque

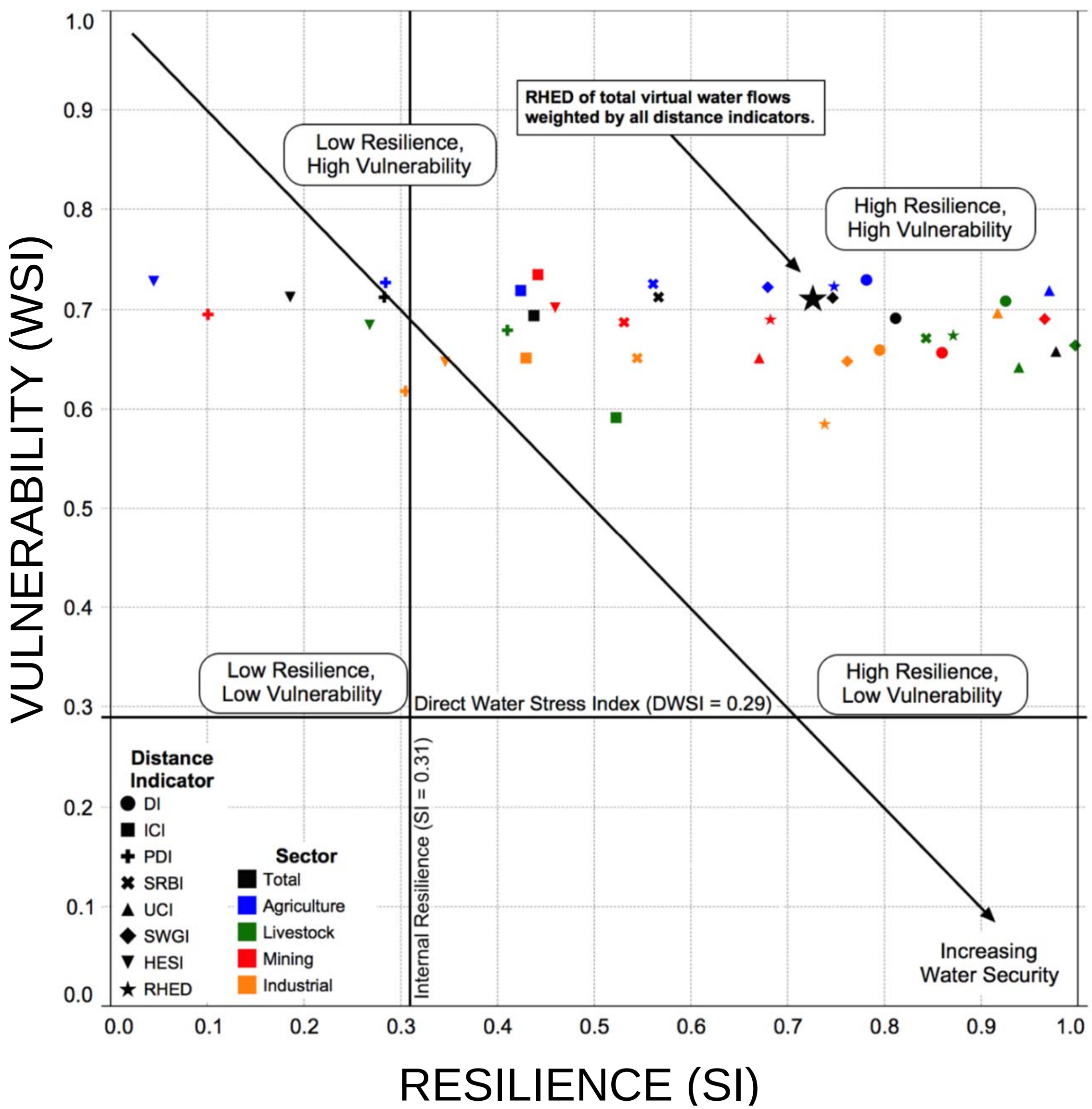
Preliminary Data – Not for Publication

NWEP
NATIONAL WATER ECONOMY PROJECT

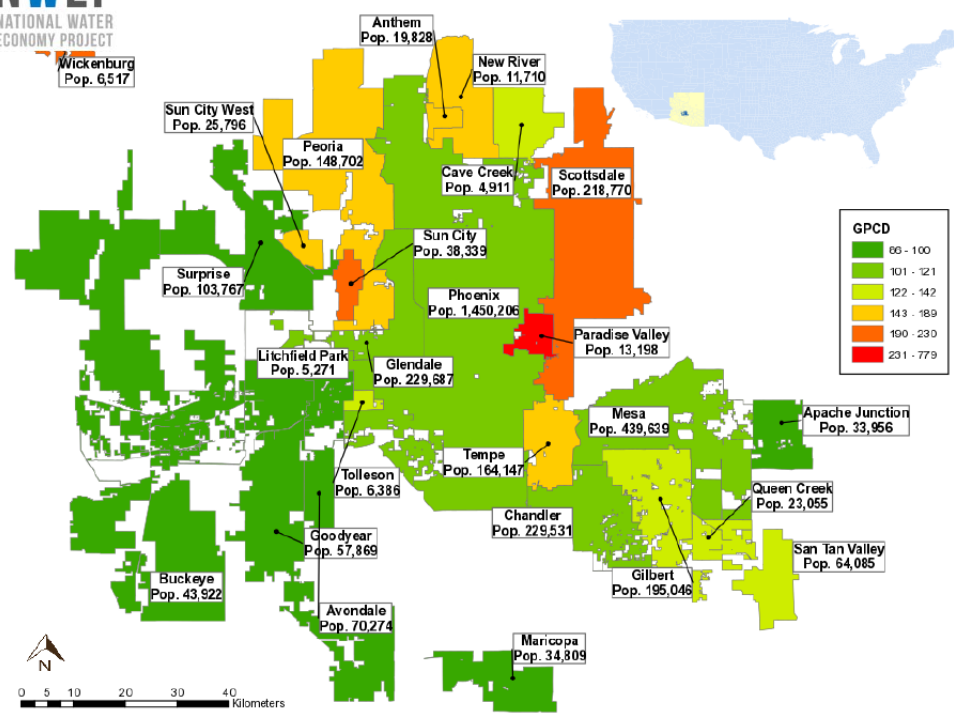
Footprint Diversity Indicators Inform Flagstaff's Potential Resilience to Drought

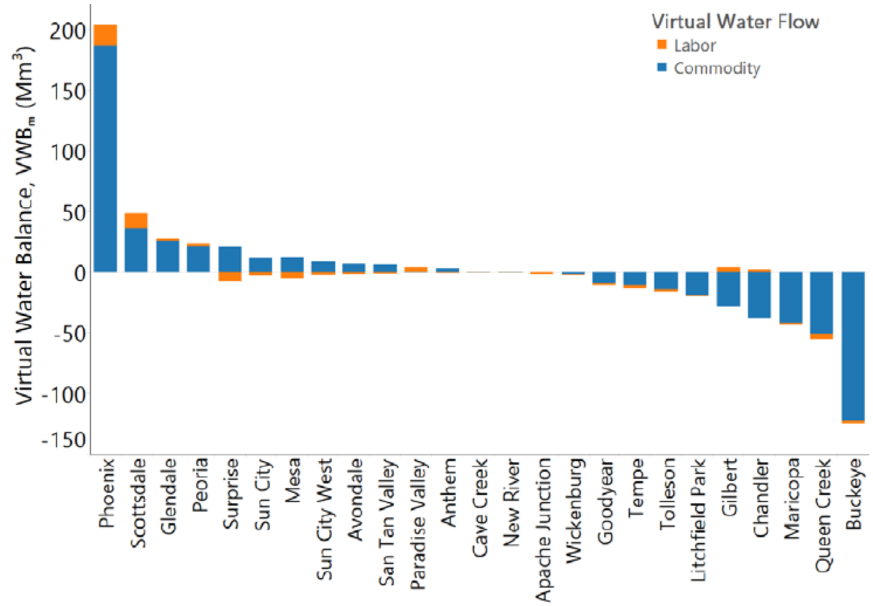


Flagstaff: Vulnerable but also Potentially Resilient to Drought

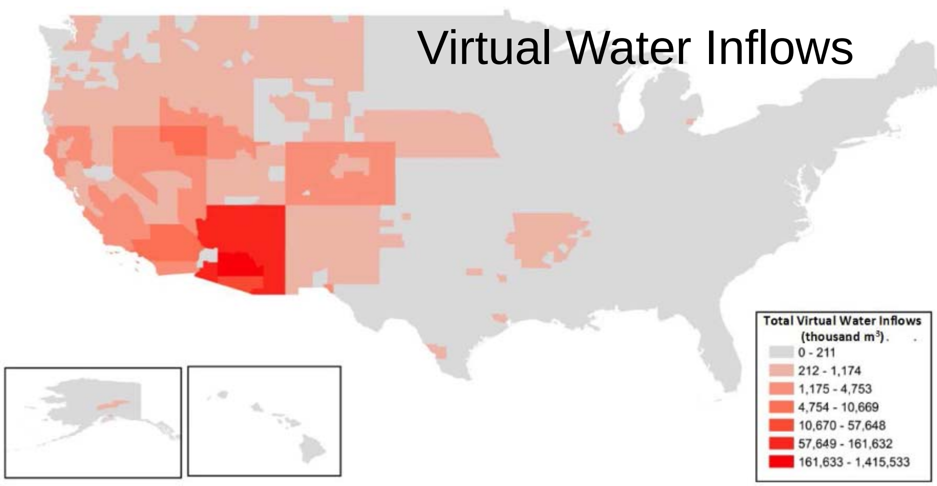


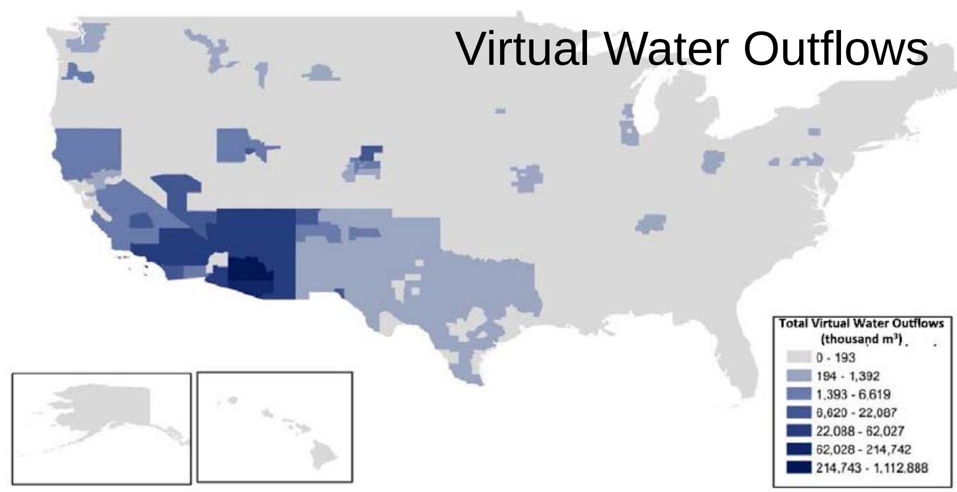
Phoenix Metro Virtual Water Flows



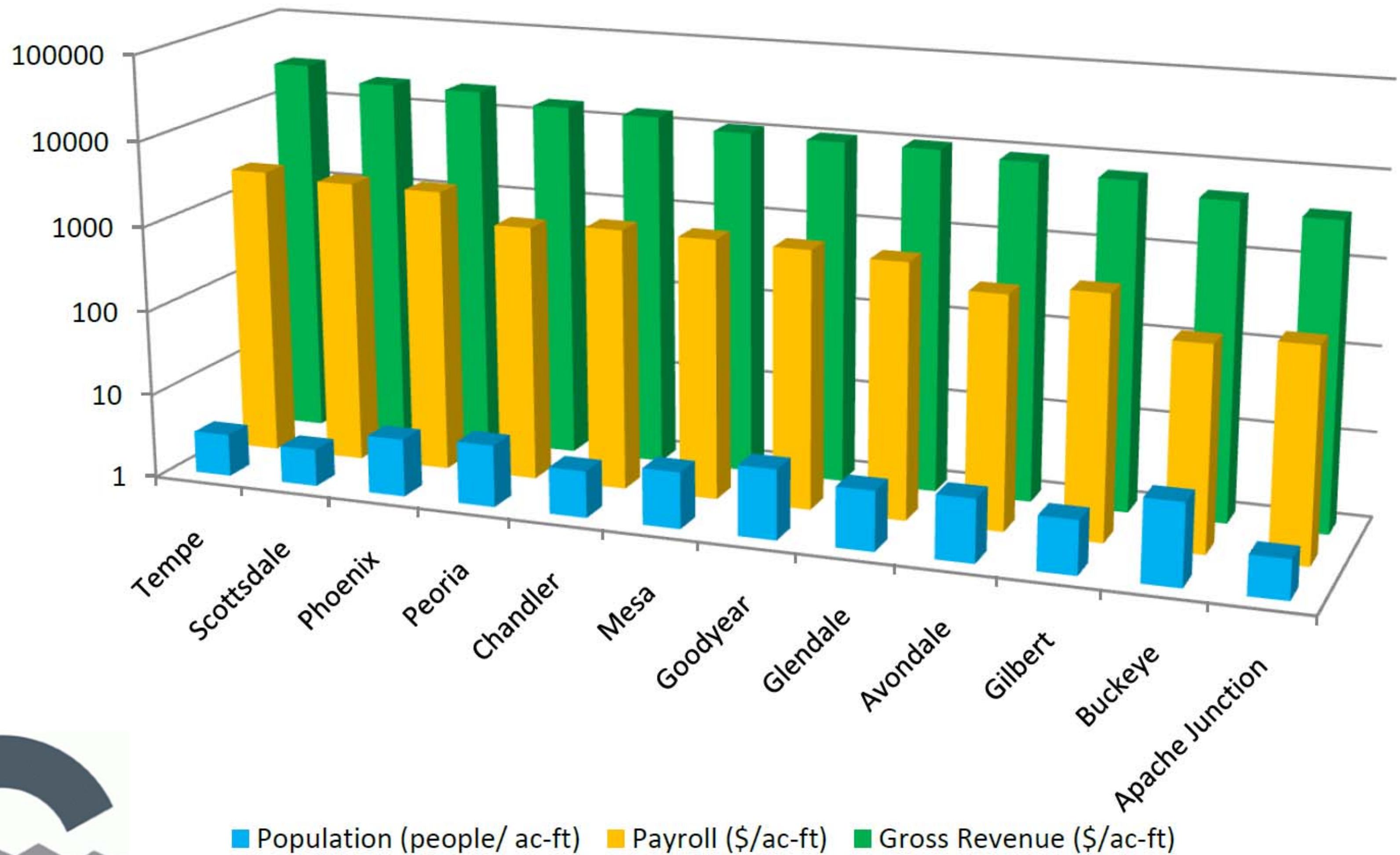


R. Rushforth, B. Ruddell, The Hydro-Economic Interdependency of Cities: Virtual Water Connections of the Phoenix, Arizona Metropolitan Area. *Sustainability* **7**, 8522 (2015).





Water Productivity Benchmarking for Phoenix Area Cities



Ruddell, B.L. (2012), Embedded Values Assessment of Water Value Intensities for Phoenix MSA Cities, City of Chandler, Arizona, September, 2012.

Summary

- The new National Water-Economy Database (NWED) provides a complete county/city/sector water footprint for the US.
- Local and Regional connections dominate (re: Vörösmarty et al., Science 2015, "What scale for water governance?")
- Long range teleconnections create vulnerability for major cities; cities are the hubs of the US hydro-economic network
- This is basic data needed for FEW work (Food-Energy-Water), including data-driven modeling of water & the economy
- Embedded Resource Accounting (ERA) and related Footprint-family metrics can identify connections, efficiency, productivity, vulnerability, and resilience on the multitype socio-economic network coupling Food, Energy, and Water

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*The views expressed are those of the authors, and not necessarily the Sponsors

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Manu Lall and the America's Water Team
Water Footprint Network
City of Flagstaff
City of Chandler

Decision Boundaries and Worldview Determine the Perceived CNH

		Include Indirect (Embedded/Virtual)?	
		No	Yes
Include External?	No	Narrowly self-interested Manager in typical command and control style. Ex.: Hydraulic mission style or property rights style of development and resource management [57, 58].	Narrowly self-interested Manager wishing to utilize indirect market pressure, trading, and offsets as an efficient and adaptive policy tool to augment typical command and control style. Ex.: Water Footprint, Carbon Footprint Manager [29, 59], National cap and trade and offset plans.
	Yes	Socially/Environmentally activist manager causing positive or negative external direct resource stock impacts but voluntarily or by regulation counting them in management decisions. Ex.: Company purchasing land in foreign countries for direct resource use [60]	Socially/Environmentally activist manager voluntarily or by regulation counting external direct impacts and also voluntarily or by regulation participating in external indirect offsets, or landowner receiving compensation for selling external offsets. Ex.: Global EF offsets [59, 61].

Perceived and accounted impacts depend on Point of View

Perform accounting against boundaries, or infer the location of the boundaries!

The National Water-Economy Database 1.0 (NWED)

Water footprint methods giving county-to-county virtual water flows for the United States

- Blue Water, no green (yet), withdrawal-based
- 43 Commodity Types incl. ag, energy, manuf., etc. Aggregated to 5 Economic Sectors: Agriculture, Industry, Livestock, Mining/Energy, and misc. Urban
- (dis)Aggregated to individual municipalities and MSA's
- Complete US water use and economic production are in the water footprint
- Missing from version 1.0 are inter-county service sector and electric trades, and also the virtual water content of foreign-origin commodities (relatively small)

Annual average County Level and Economic Sector data; not seasonal or establishment

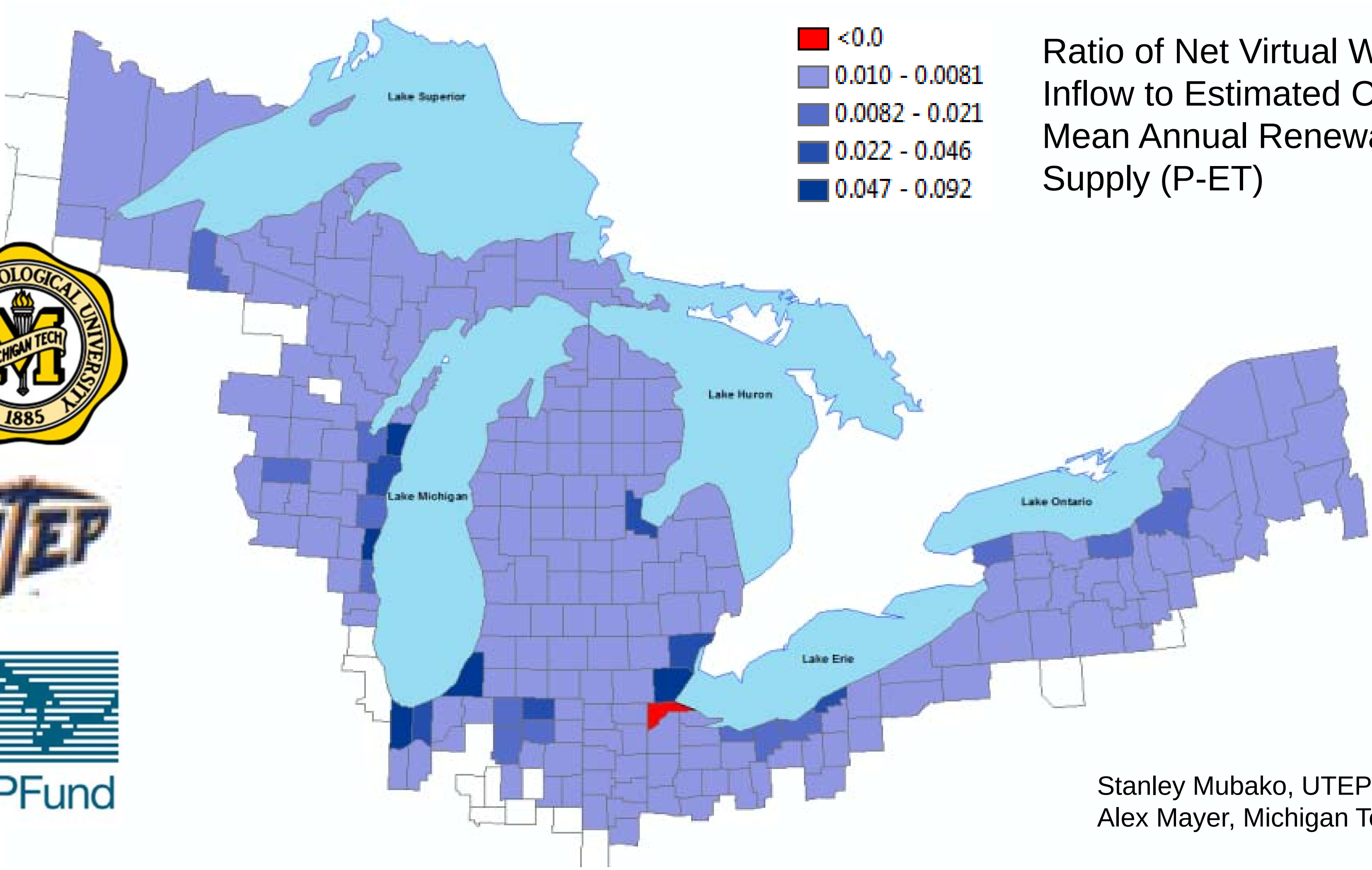
- US Commodity Flows – Freight Analysis Framework (FAF3) from Oak Ridge National Labs
- US Water Census- USGS Water Use of the Nation
- US Economic Census
- USDA National Agricultural Statistics Survey

$$F = U + V_{IN} - V_{OUT}$$

U = Water Use
V_{IN} = Virtual Water Inflow
V_{OUT} = Virtual Water Outflow

Preliminary Data – Not for Publication

Impact of Virtual Water Trade on Aquatic Ecosystem Water Balances

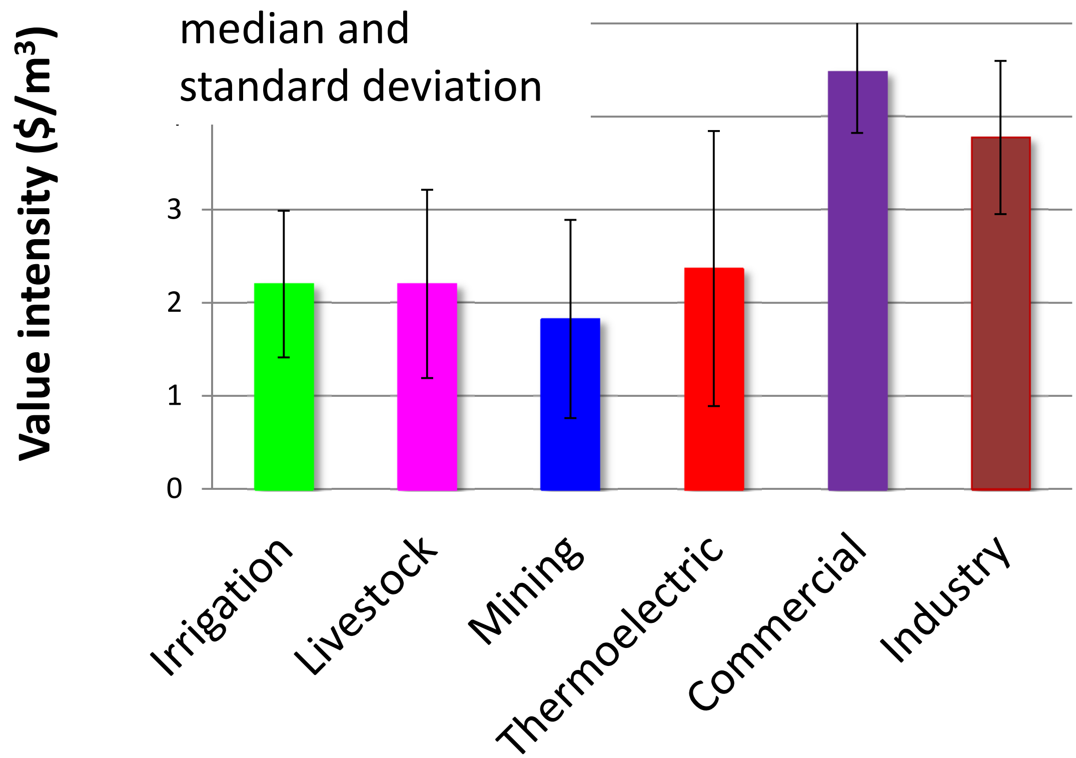


Ratio of Net Virtual Water Inflow to Estimated County Mean Annual Renewable Supply (P-ET)

Stanley Mubako, UTEP
Alex Mayer, Michigan Tech

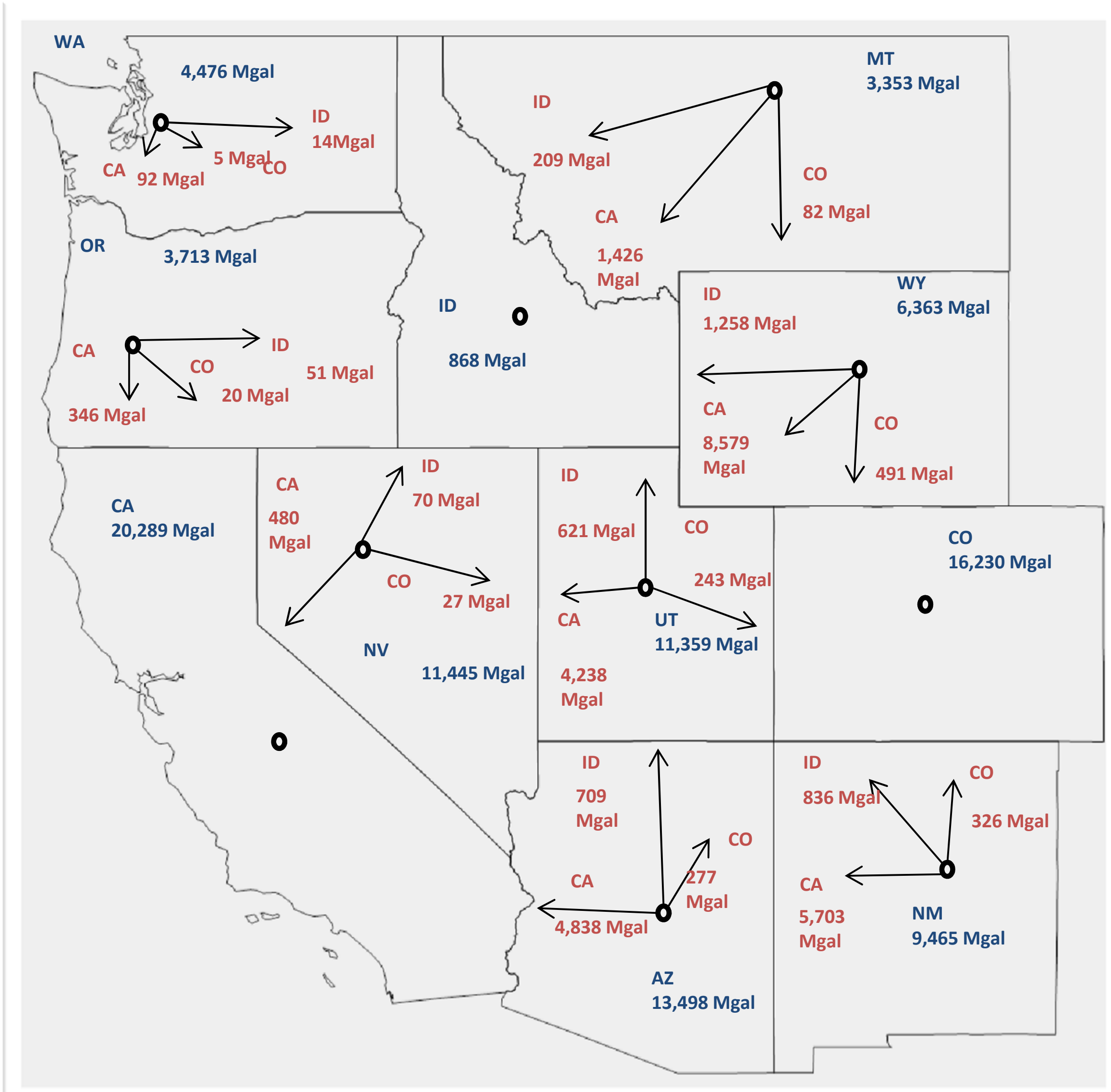
Preliminary Data – Not for Publication

Water Productivity Benchmarking for Great Lakes Industries



Stanley Mubako, UTEP
Alex Mayer, Michigan Tech

Water-in-Electricity Analysis



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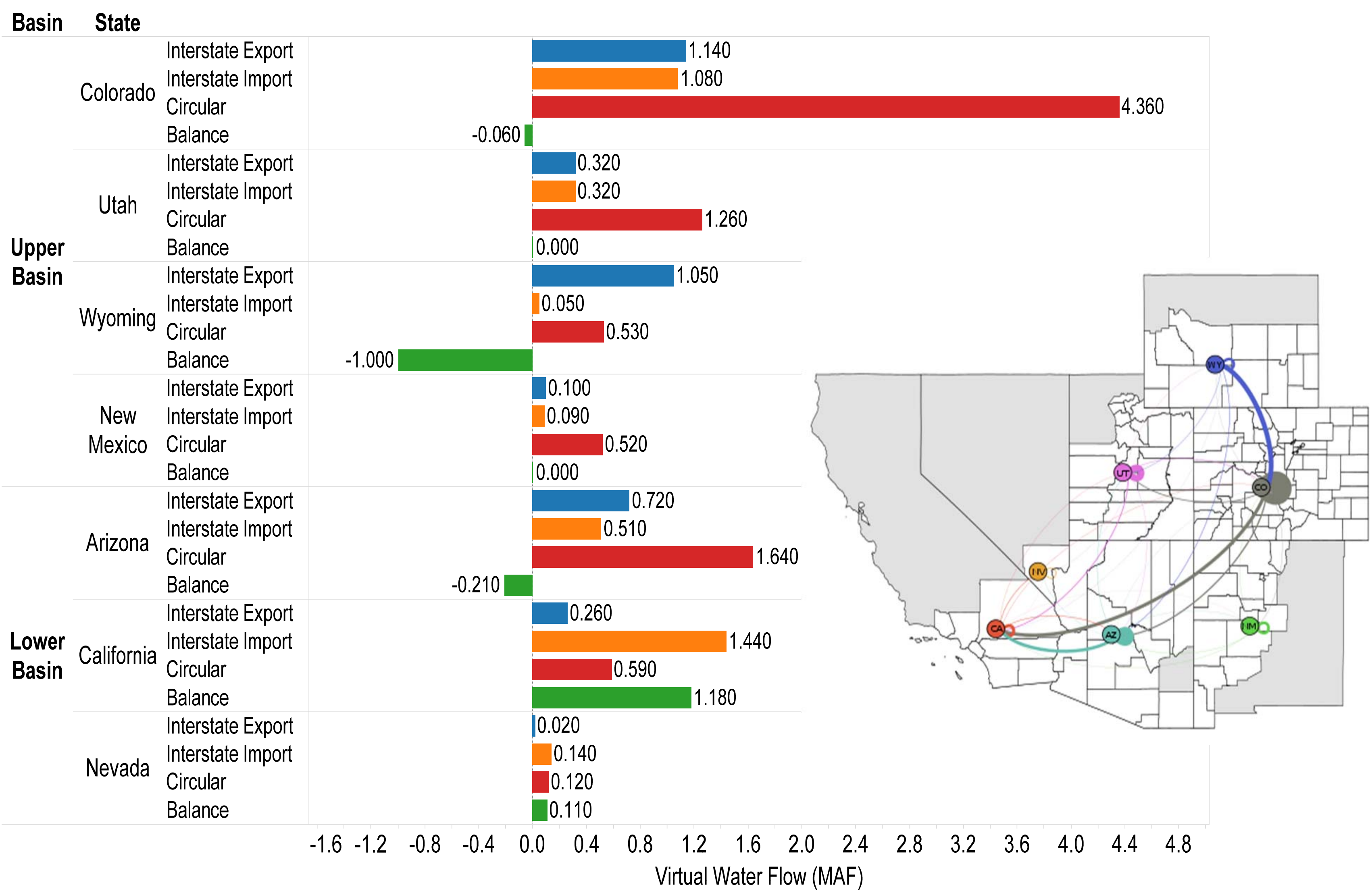
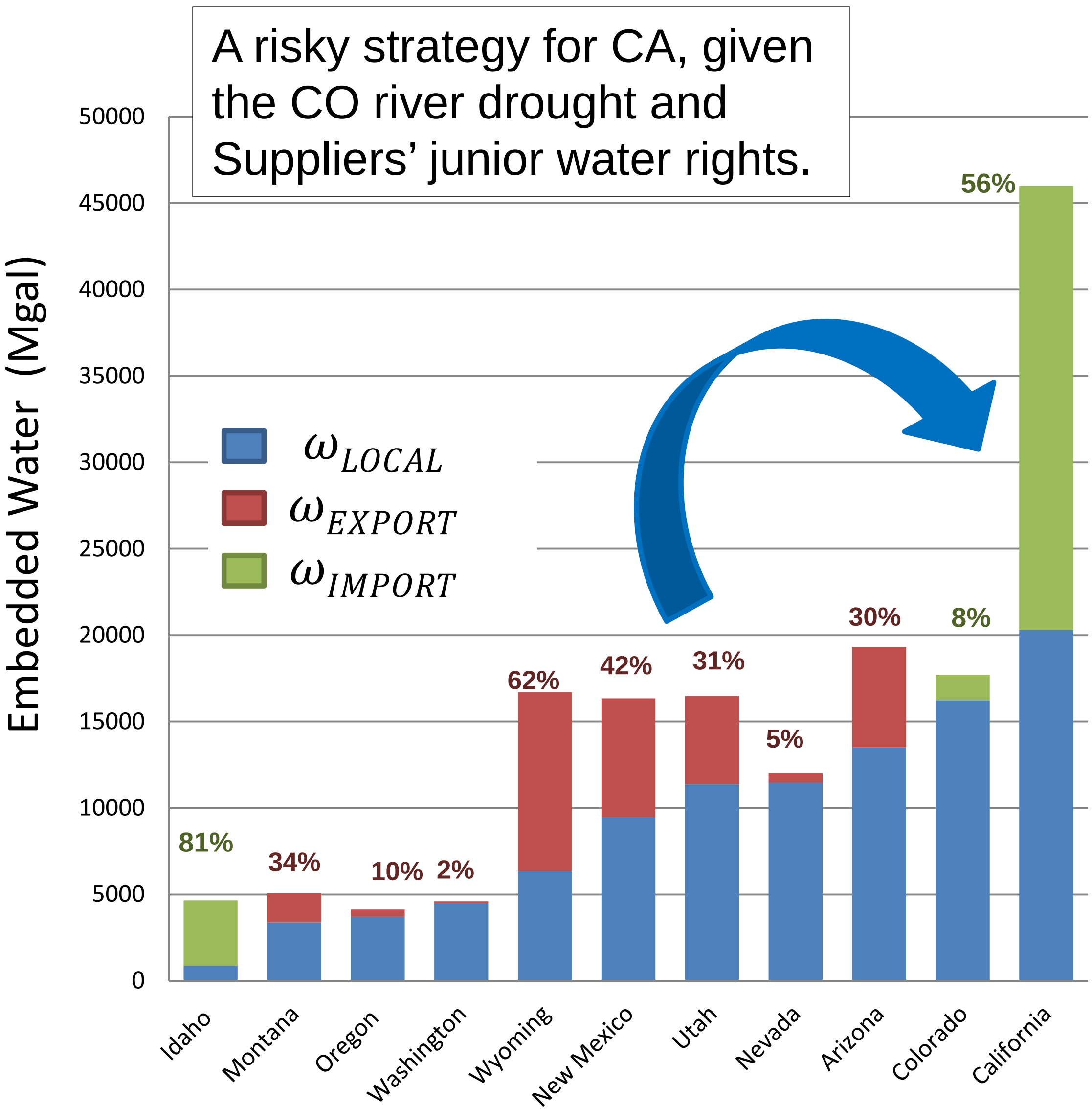
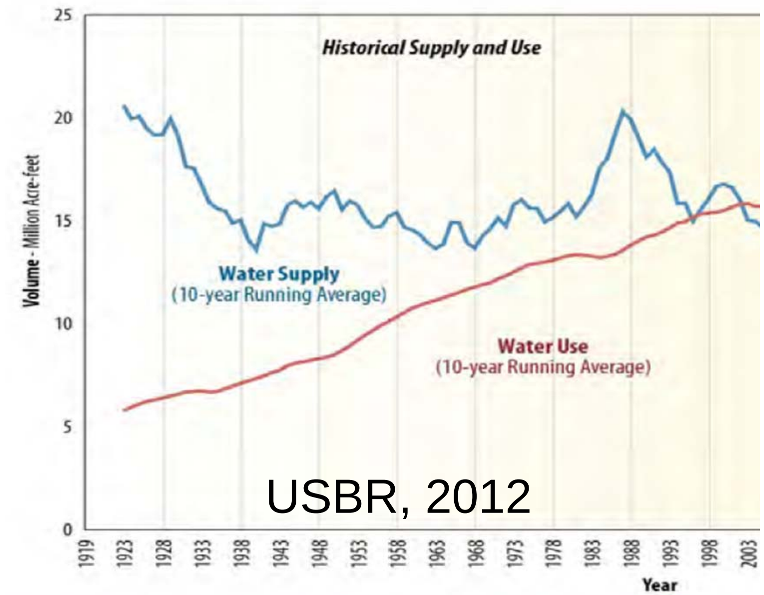
Virtual Water Colorado River Basin Reallocation



A systematic shift of water impacts (and carbon emissions) from California to energy exporters like Wyoming



Martin and Ruddell [2012]



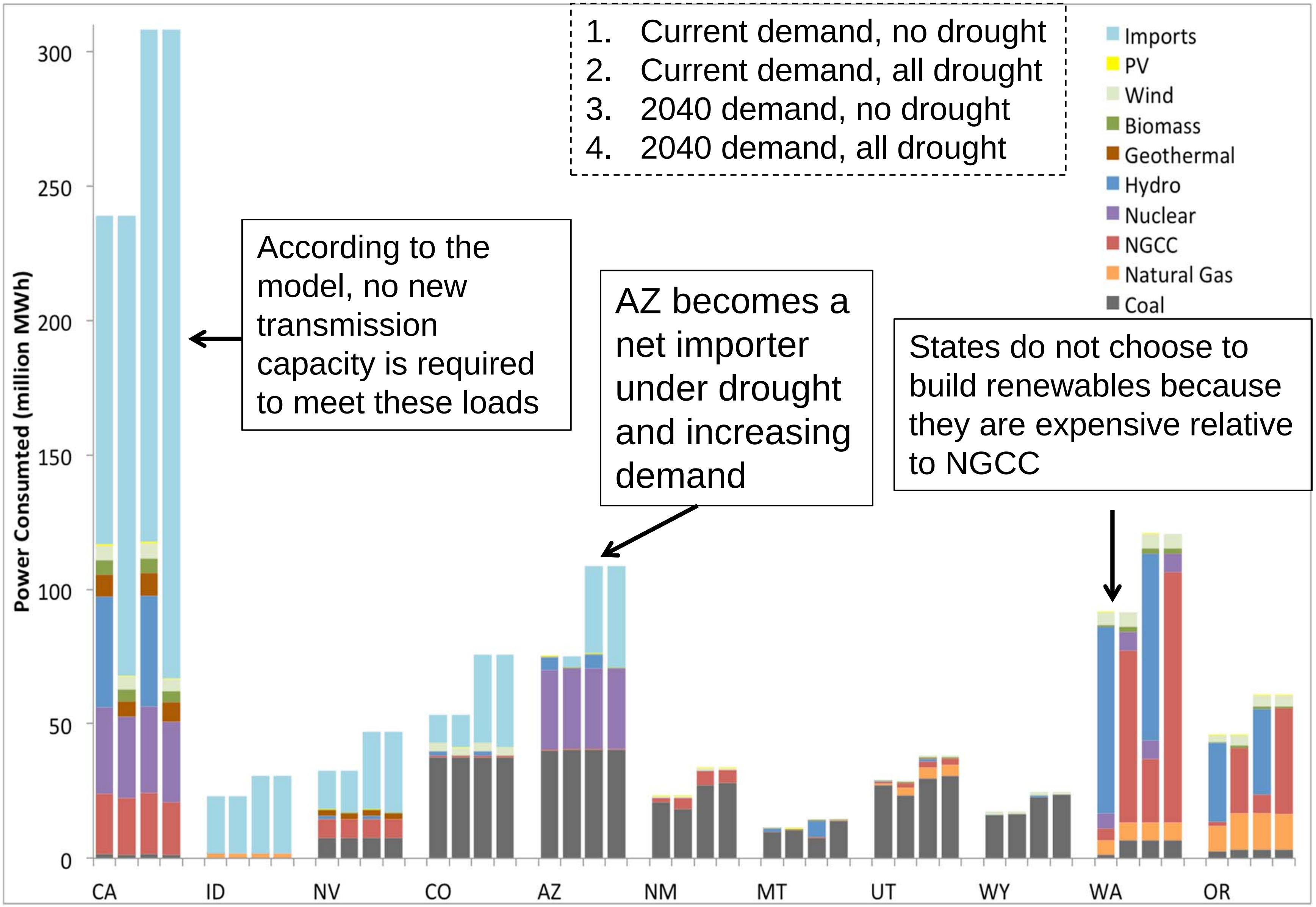
15% increase in water consumption through trade in electricity on the Western U.S. power grid

	U (Mgal)	V (Mgal)	E (Mgal)	U' (Mgal)	RS (Mgal)	RS (%)
	Actual	**Actual**	**U + V**	**If-local**	**U' - E**	**RS/U'**
Arizona	19322	-5824	13498	13498	0	0
California	20289	25703	45992	31200	-14792	-47%
Colorado	16230	1471	17701	17928	227	1%
Idaho	868	3768	4636	1896	-2740	-145%
Montana	5070	-1717	3353	3353	0	0
New	16330	-6865	9465	9465	0	0
Nevada	12023	-578	11445	11445	0	0
Oregon	4129	-417	3713	3713	0	0
Utah	16461	-5102	11359	11359	0	0
Washington	4587	-111	4476	4476	0	0
Wyoming	16690	-10328	6363	6363	0	0
System	**132000**	**0**	**132000**	**114695**	**-17304**	**-15%**

Savings are negative, because of outsourcing to inefficient producers. Note, however, this is not 'unsustainable'. It probably means water is less valuable/scarce in those places.

Martin and Ruddell [2012]

Model Results: Consumption



NGCC or importing always most cost-effective options, regardless of scenario

In the future, regional water savings via Trade