Quantifying the Hydro-Economic Dependencies of US Cities:

Development of the National Water Economy Database

by

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ABSTRACT

Cities are, at once, a habitat for humans, a center of economic production, a direct consumer of natural resources in the local environment, and an indirect consumer of natural resources at regional, national, and global scales. These processes do not take place in isolation: rather they are nested within complex coupled natural-human (CNH) systems that have nearby and distant teleconnections. Infrastructure systems—roads, electrical grids, pipelines, damns, and aqueducts, to name a few—have been built to convey and store these resources from their point of origin to their point of consumption. Traditional hard infrastructure systems are complemented by soft infrastructure, such as governance, legal, economic, and social systems, which rely upon the conveyance of information and currency rather than a physical commodity, creating teleconnections that link multiple CNH systems. The underlying structure of these systems allows for the creation of novel network methodologies to study the interdependencies, feedbacks, and timescales between direct and indirect resource consumers and producers; to identify potential vulnerabilities within the system; and to model the configuration of ideal system states. Direct and indirect water consumption provides an ideal indicator for such study because water risk is highly location-based in terms of geography, climate, economics, and cultural norms and is manifest at multiple geographic scales. Taken together, the CNH formed by economic trade and indirect water exchange networks create hydro-economic networks. Given the importance of hydro-economic networks for human well-being and economic production, this dissertation answers the overarching research question: What information do we gain from analyzing virtual water trade at the systems level rather than the component city level? Three studies are presented with case studies pertaining to the State of Arizona. The first derives a robust methodology to disaggregate indirect water flows to subcounty geographies. The second creates city-level metrics of hydro-economic vulnerability and functional diversity. The third analyzes the physical, legal, and economic allocation of a shared river basin to identify vulnerable nodes in river basin hydro-economic networks. This dissertation contributes to the literature through the creation of novel metrics to measure hydro-economic network properties and to generate insight into potential US hydro-economic shocks.

DEDICATION

I would like to dedicate this dissertation to my family, friends, and loved ones whose support was vital throughout this journey.

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CHAPTER 1: INTRODUCTION

Cities are global hotspots of environmental change and economic consumption (Glaeser, Kolko, & Saiz, 2001; Grimm et al., 2008). Economic value production within cities takes place when firms enter into trade relationships based upon a perceived relative comparative advantage provided by local production factors and resource availability, such as land, labor, energy, and water. Historically, cities have relied upon hinterlands for a reliable supply of natural resources for millennia (Wolman, 1965), as hinterlands have become shared through global economic trade, cities now face systemic risks presented by this global coupled natural human system (Liu et al., 2007). Cities outsource water because of local constraints on resource and land availability, which has been studied thoroughly in the virtual water literature (Paterson et al., 2015). Numerous studies have utilized water footprinting methods and virtual water trade patterns to analyze national-level and economy-wide water consumption (Chapagain & Hoekstra, 2004; Daniels, Lenzen, & Kenway, 2011; Hoekstra & Chapagain, 2007; Hoekstra & Mekonnen, 2012; Konar, Dalin, Hanasaki, Rinaldo, & Rodriguez-Iturbe, 2012; Suweis et al., 2011).

Groups of colocated cities form metropolitan areas that contain varying types of land uses, ranging from preserved natural lands, to rural land uses, to highly urbanized forms that are major hubs in the world city network (Beaverstock, Smith, & Taylor, 2000; Sassen, 1991, 2011). Distinct land uses develop in metropolitan areas as a response to competitive pressures and market forces (Lo & Yang, 2002) that shape the regional economy and the available niches for economic production and income generation (Mills, 1967). As economic growth within the metropolitan area occurs, cities cooperate via trade, creating positive feedback loops that result in subregional growth and the formation of large, polynucleated conurbations (Batty, 2001). Taken as an aggregate unit, large metropolitan areas can be understood as networked economies that share local resources to create a competitive advantage in a valuable economic niche within regional, national and global economies.

Flows of indirect, or embedded, resources rely on shared critical infrastructure systems such as electric power, natural gas and petroleum production and distribution, telecommunications (information and communications), transportation, water supply, banking and finance, emergency and government services, and “locally” sourced agriculture (Rinaldi, Peerenboom, & Kelly, 2001). Critical infrastructure systems are crucial to sustaining human and economic welfare, and are also interdependent within the metropolitan area. Further, interdependences between critical infrastructures add complexity to the management of colocated cities within a metropolitan area (Pederson, Dudenhoeffer, Hartley, & Permann, 2006) resulting from a fundamental mismatch in scale between the city and the scale infrastructure within the metropolitan area. Discontinuities in governance, property rights, and infrastructure at municipal boundaries create niches and roles for distinct municipalities within the system, but also create technical and policy problems.

Therefore, embedded resources between cities are dependent on the functioning of multiple independently managed, yet interdependent and interconnected, infrastructure systems. Labor flows, or commuting, rely on shared roadways and public transit infrastructures to effectively, efficiently, and safely transport people and goods within metropolitan areas. Contiguous road networks connect entire regions, but may be managed by numerous governing bodies from federal to local agencies. For water resources in particular, an aquifer and watershed are frequently shared by many independent jurisdictions, municipalities, major self-supplied industries, and electric power utilities, which has led to the creation of regional water management systems and policies to govern shared water resources (Davis, 2007; Giordano & Wolf, 2003; Roberts, 1970). These water management plans result in some degree of coordination or cooperation between municipalities, industries, and electric power utilities, but in the absence of such regional plans, competition for water resources can occur within the framework of law governing the greater region. This competition may yield winners and losers, with more powerful and wealthy entities securing water rights and infrastructure for economic development, leaving the losers with water supply problems and constraints. Engineering, game theory, policy, and economic researchers have examined this problem from the perspective of managing the physical water resources and infrastructure and designing incentives for mutually beneficial cooperation (Herman, Zeff, Reed, & Characklis, 2014; Kasprzyk, Reed, Kirsch, & Characklis, 2009). However, this type of examination only reveals reliance on a rival and frequently nonexcludable (Ruddell, Adams, Rushforth, & Tidwell, 2014; Rushforth, Adams, & Ruddell, 2013) physical water resource, which is an input to the city's urban metabolism. Virtual water flows, an indirect input to the city, result from the consumption (input) and production (output) of economic goods and services, and, at the metropolitan area scale, the flow of labor (Baum-Snow, 2010). Previous city-level studies have focused on virtual water inflows arising from economic consumption by its residents (Dalin, Konar, Hanasaki, Rinaldo, & Rodriguez-Iturbe, 2012; Holger Hoff et al., 2014; Jenerette, Wu, Goldsmith, Marussich, & Roach, 2006; Suweis et al., 2011; Vanham & Bidoglio, 2014), but virtual water outflows resulting from economic production are equally important, and furthermore, they are directly proportionate to a city's need to invest in water supply infrastructure and water rights.

Recent city-level water footprint trade studies have provided insight into how cities outsource water to distant hinterlands. For Delhi, Berlin, and Lagos, city-level water footprinting found variations in blue and green water imports based on local diet, trade integration, and water availability in source regions (H. Hoff et al., 2013). An interregional input-output economic model developed to analyze the water footprint of Beijing, China, found that the primary sector had the largest water footprint among economic sectors, but the secondary economy sector was the most significant to the urban economy because economic activity at higher levels of the economy takes place in cities (Zhang, Yang, & Shi, 2011). City-level water footprint studies have underscored the important role that trade has in overcoming local water constraints and that through trade cities have access to new, indirect sources of water. These initial studies have sought to characterize the water footprint of the city, but to truly operationalize this information for the city water footprint, information must be coupled with hydrological information to characterize the vulnerability presented by a city's indirect water resources.

Therefore, the composition of the virtual water import network is different than from the virtual water export network for any given municipality. Some municipalities are net virtual water importers indirectly dependent on, and with water supply indirectly subsidized by, their metro area neighbors. Other municipalities are net virtual water exporters that indirectly subsidize their neighbors' water supplies through intrametropolitan trade that includes labor. This matters a great deal when two municipal water supply entities are rivals for access to a shared physical water resource and have strong intrametropolitan economic ties. This generally underappreciated interdependency is already a factor in both formal and informal relationships between municipalities, with impacts on urban planning and water supply policies. While direct water sharing agreements and water policies reflect formal long-term legal and political agreements, virtual water flows reflect short-term economic conditions such as competitive and locational advantages as well as trade dynamically negotiated by many private parties. Both the long-term legal agreements about "real" physical water resources, and the short-term trade agreements that implies virtual water cooperation, have large effects on the supply and demand of water in these communities. These impacts are present in all metropolitan areas owing to the added or avoided water infrastructure capital and operating costs implications. These impacts are even more important in metropolitan areas where physical water supplies are scarce and directly constrain economic growth; in this case, access to both physical and virtual water represents a strategic asset with long-term implications for the size and socioeconomic character of the municipalities.

To study the hydro-economic network created by economic trade and virtual water exchange in the United States, at the city scale, metropolitan-area scale, and river basin scale, a novel hydro-economic dataset, was created by synthesizing data from Oak Ridge National Laboratory's Freight Analysis Framework (FAF) dataset, the United States Geological Survey (USGS) Water Census, and economic characteristics from the

United States Census, United States Economic Census, and United States Department of Agriculture (USDA) National Agricultural Statistical Survey to calculate and disaggregate virtual water flows to the county level.

The resultant dataset, the National Water-Economy Database (NWED), was then used to study the US hydro-economy, to answer the following research questions:

- Q1: What information do we gain from analyzing virtual water trade at the systems level rather than the component city level?
- Q2: How and where do we outsource water, and does that expose us to indirect vulnerability that could disrupt the functioning of supply chains?
- Q3: How functionally diverse is the US hydro-economic network, and do network properties change with scale?
- Q4: What would be necessary to use this use systems-level virtual water trade information to better sense and anticipate the potential impact of future hydro-economic shocks to cities?

To answer these research questions, and restrict the scale of analysis to allow for the creation of targeted location-based water policies, the studies at each of these geographic scales have been focused on the state of Arizona and the Colorado River Basin, and are presented as chapters in this dissertation. Since each chapter is a standalone study using the NWED, there is some repetition between chapters.

<u>Developing the virtual water trade network</u>: [Chapter 2] Derive a robust and defensible methodology to disaggregate freight analysis zone flows to subcounty geographies featuring a case study of the Phoenix metropolitan area.

a) Formalize commodity flow methodology for city-level water footprint analysis.
b) Expand the commodity flow methodology to city clusters (metropolitan areas).
c) Perform first virtual water balance on virtual water flows between metropolitan area cities.
d) Develop methodology for virtual water flows of commuting; demonstrate municipal interdependence in a metropolitan area.

e) Develop metropolitan area city typology system.

Create city-level hydro-economic metric of vulnerability and functional diversity: [Chapter 3] Define and create methodology to determine hydro-economic leverage, vulnerability, and functional diversity of US cities with a case study of Flagstaff, Arizona.

f) Demonstrate Embedded Resources Accounting Framework virtual water balance calculation on a city.
g) Identify and characterize trade partner distributions in a city's virtual water trade network.
h) Create method to define a city's virtual water hinterland.
i) Develop an "Indirect Water Scarcity Index" to characterize a city's vulnerability to direct and indirect water resources.
j) Develop metric of functional diversity for a city in the US hydro-economic network.

Analyze river-basin level virtual water network: [Chapter 4] Create framework for analyzing the physical, legal, and economic allocation of a shared river, and develop method to identify the most important nodes within a river basin virtual water network with a case study of the Colorado River Basin.

k) Expand commodity flow methodology to states in a shared river basin.
l) Evaluate the variance between the direct allocation of water in a river basin through water rights and indirect water allocation through trade.

Methods, results, and discussions presented in Chapters 2, 3, and 4, are followed by a summary conclusion in Chapter 5, including an description of future work and research questions to be answered with future work. Appendix A contains supplemental information for Chapter 2, and Appendix B contains supplemental information for Chapter 3. Appendix C contains the Curriculum Vitae of the author. It is the author's hope that this dissertation leads to actionable information on how to identify and ameliorate future water conflicts through understanding how geographic areas indirectly share water resources.

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CHAPTER 2: THE HYDRO-ECONOMIC INTERDEPENDENCY OF CITIES: VIRTUAL WATER CONNECTIONS OF THE PHOENIX, ARIZONA, METROPOLITAN AREA*

2.0 Abstract: Water footprinting has revealed hydro-economic interdependencies between distant global geographies via trade, especially of agricultural and manufactured goods. However, for metropolitan areas, trade not only entails commodity flows at many scales from intramunicipal to global, but also substantial intrametropolitan flows of the skilled labor that is essential to a city's high-value economy. Virtual water flows between municipalities are directly relevant for municipal water supply policy and infrastructure investment because they quantify the hydro-economic dependency between neighboring municipalities. These municipalities share a physical water supply and also place demands on their neighbors' water supplies by outsourcing labor and commodity production outside the municipal and water supply system boundary to the metropolitan area. Metropolitan area communities span dense urban cores to fringe agricultural towns, spanning a wide range of the US hydro-economy. This study quantifies water footprints and virtual water flows of the complete economy of the Phoenix Metropolitan Area's municipalities. A novel approach utilized journey-to-work data to estimate virtual water flows embedded in labor. Commodities dominate virtual water flows at all scales of analysis; however, labor is shown to be important for intrametropolitan virtual water flows. This is the first detailed water footprint analysis of Phoenix, an important city in a water-scarce region. This study establishes a hydro-economic typology for communities

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to define several niche roles and decision making points of view. This study's findings can be used to classify communities with respect to their relative roles and to benchmark future improvements in water sustainability for all types of communities. More importantly, these findings motivate cooperative approaches to intrametropolitan water supply policy that recognize the hydro-economic interdependence of these municipalities and their shared interest in ensuring a sustainable and resilient hydro-economy for all members of the metropolitan area.

2.1 Introduction

Cities are hotspots of global environmental change and economic consumption (Glaeser, Kolko, & Saiz, 2001; Grimm et al., 2008). Groups of colocated cities form metropolitan areas containing varying types of land uses that range from preserved natural lands, to rural and agricultural land uses, to highly urbanized forms, which are major hubs in the world city network (Beaverstock, Smith, & Taylor, 2000; Sassen, 1991, 2011). Distinct land uses in metropolitan areas develop as a response to competitive pressures and market forces (Lo & Yang, 2002) that shape the regional economy and the available niches for economic production and value creation (Mills, 1967). As economic growth within metropolitan areas occurs, cities cooperate via trade, creating positive feedback loops that result in subregional growth and the formation of large, polynucleated conurbations (Batty, 2001). Taken as an aggregate unit, large metropolitan areas are networked economies that share local resources in order to create a competitive advantage and a valuable economic niche within regional, national, and global economies.

Resource flows within metropolitan areas rely on multiple independently managed, yet interconnected infrastructure systems such as electric power, telecommunications, transportation, water supply, law, banking and emergency services, and “locally” sourced agriculture (Pederson, Dudenhoeffer, Hartley, & Permann, 2006; Rinaldi, Peerenboom, & Kelly, 2001). However, because individual municipalities may manage only parts of shared infrastructure systems, there is a mismatch between the hydro-economic system’s boundaries and governance boundaries. For water resources in particular, many entities (municipalities, major self-supplied industries, and electric power utilities) may share an aquifer, water conveyance system, or watershed, thus necessitating the creation of regional water policies and plans to govern shared water resources (Davis, 2007; Giordano & Wolf, 2003; Roberts, 1970). While water management plans result in coordination and cooperation between stakeholders, in the absence of such regional plans, competition for water may yield winners and losers with more powerful and wealthy entities securing water rights and infrastructure for economic development, leaving the losers with water supply problems and constraints. Engineering, game theory, policy, and economic research have examined this problem from the perspective of managing the physical water resources and infrastructure, and designing incentives for mutually beneficial cooperation (Herman, Zeff, Reed, & Characklis, 2014; Kasprzyk, Reed, Kirsch, & Characklis, 2009). However, this type of examination only reveals reliance on rival and frequently nonexcludable (Ruddell, Adams, Rushforth, & Tidwell, 2014; Rushforth, Adams, & Ruddell, 2013) physical water resources, which are inputs to a city’s urban metabolism (Kennedy et al., 2015).

While direct water sharing agreements and water policies reflect formal long-term legal and political agreements, virtual water flows reflect short-term voluntary economic conditions, such as competitive and locational advantages. Both the long-term legal agreements about “real” physical water resources, and the short-term trade agreements that imply virtual water cooperation and virtual water transfers, have hydro-economic impacts on these communities such as added or avoided water infrastructure, investment, and operating costs, or economic opportunities. These virtual water dependencies become directly relevant in metropolitan areas where physical water supplies are scarce and constrain economic growth. In this case, access to locally sourced virtual water is considered alongside access to physical water as a strategically important consideration for hydro-economic sustainability and resilience, as well as the functional diversity of virtual water sources.

Virtual water is an indirect urban metabolism component that results from the consumption (input) and production (output) of goods and services and, at the metropolitan area scale, labor flows (Baum-Snow, 2010). Virtual water inflows are partially a result of population-dependent food and services consumption by the residential (R) sector while industrial and commercial (IC) consumption is related to the number of establishments of a particular industry and the size and composition of the labor force that works in each industry (Opie, Rowinski, & Spasovic, 2009). By contrast, IC and R virtual water outflows are related to economic size, structure, workforce population, and commuting patterns. Such factors create distinct cities that are an assemblage of IC, bedroom, and agricultural land uses that are served by one or several potable and nonpotable water supply systems. Therefore, some municipalities are net virtual water importers that indirectly augment water supplies through intrametropolitan trade, and others are net exports that indirectly augment their neighbor's water supply, which is highly relevant to urban planning and water supply policies when two municipal entities are rivals for access to shared physical water resource and have strong intrametropolitan economic ties.

In this study, virtual water flows were estimated for the Phoenix metropolitan area (PMA) at three scales. Previous city-level studies have focused on virtual water inflows arising from economic consumption by residents and at the national and global levels (Dalin, Konar, Hanasaki, Rinaldo, & Rodriguez-Iturbe, 2012; Hoff et al., 2014; Jenerette, Wu, Goldsmith, Marussich, & Roach, 2006; Suweis et al., 2011; Vanham & Bidoglio, 2014), but local and national virtual water outflows resulting from economic production are equally important, and furthermore, are directly proportionate to a city's need to invest in water supply infrastructure and water rights. Virtual water flow (1) into and (2) out of the PMA was calculated using a commodity flow approach, and (3) intrametropolitan area virtual water flows were calculated using commodity and labor flows. Both goods-producing and service economies are utilized to estimate the water footprint of PMA municipalities (Figure 1). The addition of intra-metropolitan flows and of the urban labor market are contributions by this paper to the virtual water literature and form the basis for estimation of submunicipal industrial, commercial, and residential footprints. The methods and data employed also allow us to identify regional and national virtual water flows for the PMA and its constituent municipalities. This paper is the first paper to comprehensively analyze water footprints and virtual water flows within a municipality in metropolitan area, intrametropolitan area, and national scale flows, simultaneously, thus contributing novel methods to the virtual water literature.

This paper documents urban water footprint balances for the Phoenix Metropolitan Area. In addition, this paper addressees several fundamental urban water footprint (Paterson et al., 2015) and teleconnection questions at the range of most relevant scales spanning the national to the local scale (Liu et al., 2015; Seto et al., 2012). At the national scale, we wish to understand which locations within the United States depend on the PMA's water resources and, conversely, on what water resources the PMA relies. Does the PMA primarily rely on in-state, regional, or national sources? We wish to understand which commodities are responsible for the bulk of the virtual water inflows and outflows from the metropolitan area. We wish to understand intra-PMA virtual water dependencies and distinguish between commodity and labor trade. How circular are the virtual water flows within the PMA and within each municipality, and what fraction of the total urban water footprint does the intrametropolitan virtual water flow represent? We wish to understand which municipalities are net importers and exporters of virtual water from their immediate neighbors and develop a typology for the hydro-economic role of each community within the hydro-economy. Finally, in order to inform cooperation at the municipal scale on water supply and infrastructure policy, we contextualize virtual water flows with respect to the size of each municipality's physical water supply infrastructure; in other words, we relate the virtual water flow to the urban water metabolism. This will demonstrate how much larger (or smaller) each municipality's physical infrastructure and water right would need to be if not for intrametropolitan virtual water connections with trading partners that share the local physical water supply.

2.2. Calculating Virtual Water Flows for the Phoenix Metropolitan Area

2.2.1. Study Area

The PMA was used for this study because it is as a major metropolitan area with substantial water infrastructure and water rights challenges (White, Withycombe Keeler, Wiek, & Larson, 2015). It is located in central Arizona and has a population of 4.19 million people (U.S. Census Bureau & Population Division, 2012). Due to the availability of utility-level water data, the study area was constrained to 25 municipalities[†] located in the conurbation surrounding the core municipality of Phoenix, which have a combined population of 3.69 million people (Figure 1). The urban "core" cities in the PMA are Phoenix, Mesa, Scottsdale, and Tempe (Zients, 2013). Although Phoenix is the central municipality, it is a suburban, low-density municipality that developed after World War II in the automotive era.

Due to the large population of the PMA and the local arid climate, the physical availability of water supplies and legal assurance of water rights are tight constraints on economic and residential growth. This problem is more acute for newer suburban municipalities that lack historic water rights, but also a challenge for older central municipalities with large aggregate water demand. Agricultural lands that surround the PMA face development pressures from expanding suburban municipalities. The major physical water resources for the PMA are the Colorado River via the Central Arizona

[†] For this paper, municipality is used to refer to a city and its management area, and the term city is used to refer to a nonspecific urban area.

Project (CAP); the Salt and Verde Rivers, via the Salt River Project (SRP); and substantial, but nonrenewable groundwater underlying the PMA. The core PMA municipalities have greater access to surface water (the CAP and SRP systems), while smaller municipalities on the outskirts of the PMA are more dependent on groundwater (Sampson, Escobar, Tschudi, Lant, & Gober, 2011). Scarce water resources coupled with precipitous growth has placed strains on the water supply system and created competition between PMA municipalities and economic sectors (industrial/commercial, residential, utilities, etc.) to secure water resources for future growth, making the PMA a suitable geography for hydro-economic studies.

2.2.2. Virtual Water Flow Calculation for Commodities at Municipal, County, and National Scales

Virtual water inflows and outflows were derived from commodity flows into and out of the PMA from the Freight Analysis Framework version 3 (FAF^3) database, which divides the United States into 123 domestic freight zones, referred to in this paper as FAF zones (Southworth, Davidson, Hwang, Peterson, & Chin, 2010). The database contains data on the FAF zone of origin (O) and destination (D) for 42 commodities. Commodities (C) are a more detailed categorization according to the Standard Classification of Transported Goods (SCTG), each of which fits underneath a water use category (i) corresponding to the United States Geological Survey (USGS) water use categories (Dang, Lin, & Konar, 2015; US Census Buearu, 2006). First, commodity production was summed by economic supercategory i and origin FAF zone O to arrive at total commodity production C for the FAF zone.

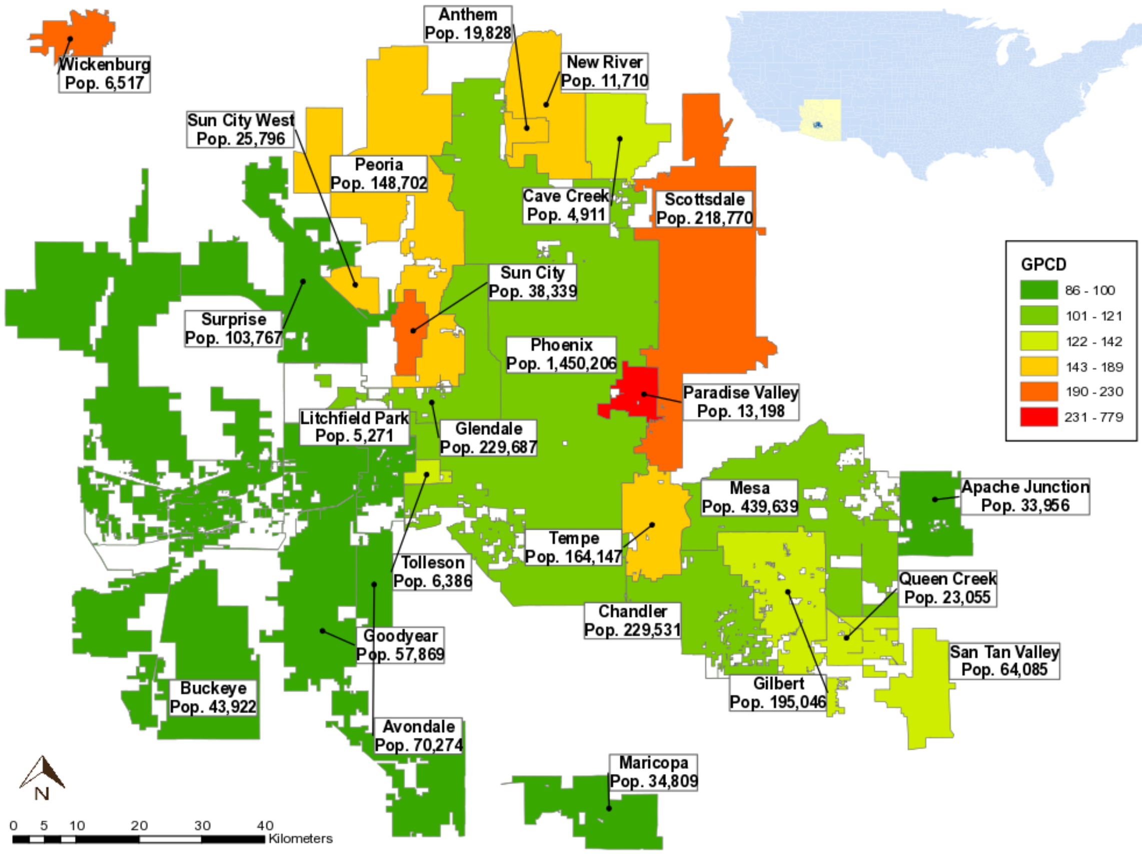

Figure 1. The map above shows the population of the PMA municipalities included in the system boundaries along with residential delivers in gallons per capita day (GPCD) for each municipality. Residential water consumption in the PMA is positively correlated with income. The inset in the upper right-hand corner shows the position of the PMA in Arizona within the United States.

$$C_{i,O} = \sum_{C,O} C_{i,C,O \to D} \text{ [tons]} \quad (1)$$

Next, the commodity production data per FAF origin zone was disaggregated to the county-level using production attraction criteria for each commodity (Equation 2). In this notation, we use *k* to denote an individual county, which is a portion of a corresponding FAF zone. Production and attraction criteria vary by commodity according to the factor inputs necessary for production (Mahmoudifard, Ko, & Mohammadian, 2014). Raw water use data at the county scale is aggregated to yield FAF zone water use data, or is disaggregated to municipalities using regional shares (RS) of employment (US Census Buearu), agriculture acreage estimates from the number of agricultural operations

(USDA NASS), and population (US Census Buearu, 2012) for each municipality within the county. A similar process is used to disaggregate economic data at the raw FAF zone scale to counties and municipalities. RS factors were checked so that $\sum_k RS_{O,k} = 1$ to ensure that mass is conserved. Disaggregation transforms the 123 FAF zones into 3,143 US counties, and then to 24 municipalities surrounding the city of Phoenix. The production of commodity category *C* within supercategory *i* by county *k* is apportioned relative to the county's fraction of the FAF zone's production of all commodities in supercategory *i*.

$$C_{i,k} = C_{i,O} \times RS_{i,O,k} \text{ [tons]} \quad (2)$$

To determine the average per ton blue water content for each economic sector at the county level, sector-level water consumption was divided by the result of Equation (2).

$$BWC_{i,k} = U_{i,k}/C_{i,k} \text{ [m}^3\text{/ton]} \quad (3)$$

Since each $BWC_{i,k}$ value is a county associated with its FAF zone, we can divide the county-level blue water content by the $RS_{i,O\rightarrow k}$ factor and sum by each FAF origin to arrive at the average per ton blue water content of commodity production at the FAF zone scale.

$$BWC_{i,O} = \sum_O BWC_{i,k}/RS_{i,O,k} \text{ [m}^3\text{/ton]} \quad (4)$$

After calculating the average blue water content of commodity production within each economic sector in each FAF zone, the virtual water flow between FAF zone origin and destinations are calculated from the original origin-destination commodity flow data.

$$VW_{i,O\to D} = C_{i,C,O\to D} \times BWC_{i,O} \text{ [m}^3\text{]} \quad (5)$$

These virtual water flows can be disaggregated to the more detailed commodity level *C*, from the more highly aggregated USGS water use database categories *i*. Alternatively, for virtual water flows associated with another type of good or service such as labor *L*, that subscript is substituted for *C*.

$$VW_{C,O\to D} = VW_{i,O\to D} \times \left(C_{i,C,O\to D} / \textstyle\sum_{i,O} C_{i,C,O\to D}\right) \text{ [m}^3\text{]} \quad (6)$$

FAF zone destinations were disaggregated to the county level using each county's relative proportion of the destination FAF zone's population *p* ($RS_{p,D,k}$) or the relative proportion of the origin FAF zone's commodity outflow in category *C* ($RS_{C,D,k}$). Again, RS factors were checked so that $\sum_D RS_{D,k} = 1$ to ensure that mass is conserved.

$$VW_{C,k\to D} = VW_{C,O\to D} \times RS_{C,O,k} \text{ [m}^3\text{]} \quad (7)$$

$$VW_{C,O\to k} = VW_{C,O\to D} \times RS_{p,D,k} \text{ [m}^3\text{]} \quad (8)$$

The virtual water flow from one county *k* to another county *l* is disaggregated from FAF zone commodity flows.

$$VW_{C,k\to l} = VW_{C,k\to D} \times RS_{p,D,k} \text{ [m}^3\text{]} \quad (9)$$

The flow between one municipality *m* and an FAF zone is an intermediary calculation required before computing flows between counties and municipalities.

$$VW_{C,m\to D} = VW_{C,O\to D} \times RS_{C,O,m} \text{ [m}^3\text{]} \quad (10)$$

$$VW_{C,O\to m} = VW_{C,O\to D} \times RS_{p,D,m} \text{ [m}^3\text{]} \quad (11)$$

The virtual water flow between one municipality *m* and a county *k* is a portion of the flow between the municipality and that county's FAF zone *O*.

$$VW_{C,m\rightarrow k} = VW_{C,m\rightarrow O} \times RS_{p,O,k} \text{ [m}^3\text{]} \quad (12)$$

$$VW_{C,k\rightarrow m} = VW_{C,O\rightarrow m} \times RS_{C,O,m} \text{ [m}^3\text{]} \quad (13)$$

The outflow (or equally, inflow) from one municipality *m* to another *n* within a FAF zone *O* is similar. Equation (14) also accommodates circular flows of commodities within a municipality.

$$VW_{C,m\rightarrow n} = VW_{C,m\rightarrow O} \times RS_{p,O,n} \text{ [m}^3\text{]} \quad (14)$$

This derivation yields origin-destination virtual water flows between FAF zones, counties, municipalities, and combinations of these scales by commodity category, from the source data concerning commodity trade and water use in each economic zone.

Notably, when this algorithm is applied all geographies within the FAF^3 database, total virtual flows are constrained by USGS water withdrawal data (Kenny et al., 2009), ensuring that virtual water is not over allocated beyond actual withdrawals. This is methodologically important because it highlights the large differences in per capita water footprint that are a function of geography and climate. This method therefore yields a true footprint that is accurate for both comparative benchmarking and also absolute hydrological and economic measurement purposes. Although there are many potential production and attraction factors (Bujanda, Villa, & Williams, 2014; De Jong, Gunn, & Walker, 2004; Harris et al., 2012; Viswanathan, Beagan, Mysore, & Srinivasan, 2008), this paper uses the regional shares of employment and agricultural acreage as production factors, and population as an attraction factor. Agricultural operations data, including livestock operations, are available at the zip code, which is associated with a municipality and county in the USDA National Agricultural Census.

2.2.3. Virtual Water Flow Calculation for Labor at Intrametropolitan Scales

Intrametropolitan area virtual water flows from the movement of labor were calculated on the basis of residential (per municipality, excluding industrial/commercial) GPCD. This method divides the population of each municipality into three groups: a nonworkforce population and two types of workforce population, workers that live and work in the same municipality, and workers that commute to other cities for employment. Virtual water flows from the movement of labor were used as a proxy for understanding the virtual water flows of the service economy because 71% of PMA employment is in the service sector (U.S. Census Bureau, 2014).

Within the study area, a worker living in one municipality could hypothetically work in any of the other 24 PMA municipalities. However, in actuality, the number of possible cities to which a worker could commute is constrained by time, distance, and the presence of jobs. Using these assumptions, and actual commute distance, travel time, journey to work statistics, and commuting flows between each municipality in the PMA, labor flows were estimated using a network-based commuting flow model that used the distance between cities as a deterrence to commuting (Supplementary Information, Table S1, Figure S1; (Maricopa County Air Quality Department, 2010; Thorsen & Gitlesen, 1998; U.S. Census Bureau, 2014; US Census Buearu, 2012, 2013). If cities shared borders, the commuting distance was assumed to be negligible. The flow of workers between PMA municipalities was constrained by daytime population change data, ensuring that estimated commuting flows followed observed data. Commuting flow results are presented in the Supplemental Information (Table S2, Figure S2). We recognize that there are a multitude of methods to estimate commuting flows and the approach taken in this paper could be substantiated or improved with real, observed commuting data from regional transit authorities.

After, the mobile population and commute destinations were determined for each municipality, intrametropolitan and intramunicipal virtual water flows were calculated using municipality-specific residential GPCD (Figure 1; (Arizona Department of Water Resources, 2011a, 2011b, 2011c, 2011d, 2011e, 2011f, 2011g, 2011h, 2011i, 2011j, 2011k, 2011l, 2011m, 2011n, 2011o, 2011p, 2011q, 2011r, 2011s, 2011t, 2011u, 2011v; Town of WIckenburg, 2012) and the commuting population between each PMA municipality, including inflows ($V_{L,n\rightarrow m}$), outflows ($V_{L,m\rightarrow n}$), and circular flows $V_{L,m\rightarrow m}$.

2.2.4. Disaggregation by Scale and Boundary of a Municipality's Water Footprint

Using the commodity (2.2) and labor (2.3) approaches to calculating virtual water flows, a net water footprint was calculated for each PMA municipality and for the metropolitan area using the Embedded Resources Accounting (ERA) framework (Ruddell et al., 2014; Rushforth et al., 2013). Used in this context, ERA is a minor variation on the standard Water Footprint Assessment (WFA; (Aldaya, Chapagain, Hoekstra, & Mekonnen, 2012) notation that accounts for a hierarchy of nested boundary conditions by disaggregating the internal water footprint term to reveal internal virtual water flows between entities inside a boundary. Multiple boundary conditions allow us to distinguish between the portion of the virtual water flow and water footprint accruing to different scales and locations; in this case (1) within a municipality (intramunicipal), (2) within the metropolitan area but outside the municipality (intrametropolitan), and (3) within the nation but outside the metropolitan area (intermetropolitan). In this study, we neglect international virtual water flows because they are small compared with intra/intermetropolitan flows, but the calculation of these flows is straightforward using the methods presented. Of particular importance is a methodological distinction between intrametropolitan or intramunicipal trade in virtual water, versus that derived from more distant water resources. This is because intrametropolitan virtual water trade represents a virtual reallocation between municipalities of a single shared physical water stock. This distinction also enables us to develop a general hydro-economic typology for communities within the system.

The general equation takes into consideration direct water consumption (U), as well as virtual water inflows (V_{In}) and outflows (V_{Out}) to arrive at scale-disaggregated net water footprint (E) for a municipality (subscript m). In WFA notation, $E = WF_{cons,nat}$ and $U = WF_{area,nat}$, virtual water is disaggregated into two types of virtual water flows: commodity (subscript C) and also labor flows (subscript L); there are multiple types of commodities but a single type of labor. U is the sum of all "blue" fresh water use within the municipal boundary, regardless of the geographical origin or mode of conveyance of that water; local and external direct water use U_l and U_x are combined into a single term U. In this case, there are three data sources and dominant water consumption categories, including potable deliveries to municipal Industrial and Commercial (IC) customers (U_{IC}), potable deliveries to municipal Residential (R) customers (U_R) and groundwater-supplied or canal-supplied deliveries to irrigated agriculture (U_{farm}). U is also known as the urban water metabolism. We assumed a consumptive use coefficient of 100% because there is relatively little water recycling in this metropolitan area or elsewhere in the

United States, so U is equal to total withdrawals for the purposes of this paper. This assumption causes a small overestimation in U and V. Virtual water inflows (V_{In}) are defined as the volume of water consumed outside the municipal boundary in the production of goods and services consumed inside the municipal boundary. Notably, virtual water inflows include circular flows within the municipality and therefore overlap partially with direct water consumption by the municipality. Outflows are defined as the volume of water used to produce within the municipality goods and services that are consumed outside the municipal boundary. Equation (15) shows the general ERA equation for a municipal water footprint.

$$E_m = U_m + V_{In,m} - V_{Out,m} \text{ [m}^3\text{]} \quad (15)$$

The direct water consumption of a municipality U_m is the sum of its water consuming processes.

$$U_m = U_R + U_{IC} + U_{farm} \text{ [m}^3\text{]} \quad (16)$$

Virtual water inflows happen at three scales: intramunicipal, intrametropolitan, and intermetropolitan with other counties or metropolitan areas, in this case limited to those within the United States. The commodity component of inflows and outflows is summed across all commodity categories at all three scales, but the labor component is of a single type and is negligible at the intrametropolitan scale.

$$V_{In,m} = \sum_{n,C} V_{C,n\to m} + \sum_{n} V_{L,n\to m} + \sum_{k,C} V_{C,k\to m} \text{ [m}^3\text{]} \quad (17)$$

Equation (18) gives the virtual water outflows from the municipality to all three scales.

$$V_{Out,m} = \sum_{n,C} V_{C,m\rightarrow k} + \sum_{n} V_{L,m\rightarrow n} + \sum_{k,C} V_{C,m\rightarrow k} \text{ [m}^3\text{]} \quad (18)$$

The net virtual water balances (*VWB*) for the PMA and each municipality is the net of inflows and outflows.

$$VWB_m = V_{In,m} - V_{Outm} \text{ [m}^3\text{]} \quad (19)$$

Circular virtual water flows (*CF)* are the volume of water used to produce a product or service that is consumed by another entity within the same boundary. In WFA notation, this is the internal water footprint of an area. The existence of a circular flow implies the existence of multiple entities within the boundary below the minimum scale of the water footprint analysis. The circular flow is not like WFA standard virtual water, because it does not cross a municipal boundary. This is an extension of the circular economy concept (Haas, Krausmann, Wiedenhofer, & Heinz, 2015). The volume of circular virtual water flow for a municipality is the difference between direct water use and virtual water outflows.

$$CF_m = V_{In,m\rightarrow m} = V_{Out,m\rightarrow m} = U_m - V_{Out,m} \text{ [m}^3\text{]} \quad (20)$$

The circular virtual water flows can be expressed as a ratio of virtual water outflows (exports) or inflows (imports) to all trading partners, in this case counties *k*. Labor and other categories follow this example.

$$CF_{C,m}^{export} = V_{C,m\rightarrow m} / \sum_{k} V_{C,m\rightarrow k} \text{ [m}^3\text{]} \quad (21)$$

$$CF_{C,m}^{import} = V_{C,m\rightarrow m} / \sum_{k} V_{C,k\rightarrow m} \text{ [m}^3\text{]} \quad (22)$$

The metropolitan area's (Subscript *a*) water footprint components are determined using a simple summation over the member municipalities' components *m*. An exception to this generality is the metropolitan area's circular flow, because it must account for an additional scale. The metropolitan area's circular virtual water flow is the sum of intramunicipal and intrametropolitan virtual water flows for all member municipalities.

$$CF_a = \sum_m CF_m + \sum_{m,n} V_{Out,m \to n} \text{ [m}^3\text{]} \tag{23}$$

Circular flows are implicitly included in the calculation of $V_{In,m}$ and $V_{Out,m}$ and do not need to be included in calculating because they are equal and opposite flows that canceled out in the calculation of the net water footprint (E_m) and virtual water balance of a municipality (VWB_m).

2.3. Results and Discussion

The PMA is a net importer of virtual water from the United States, or $\sum_{k,C} V_{C,k \to a} > \sum_{k,C} V_{C,a \to k}$. Virtual water imports from and exports to the rest of the world are negligible in relative terms. PMA virtual water inflows, including circular flows ($V_{In,a}$) totaled 4,125 Mm^3 and virtual water outflows, including circular flows ($V_{Out,a}$) totaled 2,584 Mm^3 (Table S3). The total virtual water flows associated with labor were 359 Mm^3. Phoenix and Scottsdale, core PMA municipalities, had the largest net virtual water inflows associated with labor, while Surprise and other suburban "bedroom" municipalities, had the largest net virtual water outflows associated with labor. On average, 36% of virtual water inflows embedded in the labor market resulted from intrametropolitan area flows; the remaining 64% resulted from circular virtual water flows within each municipality. Small "edge" municipalities tended to have higher relative intrametropolitan virtual water flows and large, "core" municipalities had relatively higher levels of circular flows.

2.3.1. Virtual Water Inflows from the Nation and the Metropolitan Area

Virtual water inflows were dominated by agricultural goods—processed foods, milled grain, animal feed, cereal grains. These results echo numerous virtual water studies that have identified the large role that food plays in the global virtual water trade network (Dalin et al., 2012; Hoff et al., 2014; Mekonnen & Hoekstra, 2011; Suweis et al., 2011; Vanham & Bidoglio, 2014). Virtual water related to the consumption of industrial goods, machinery, and electronics also result in large virtual water inflows. Though the magnitude of virtual water inflows varies by municipality population, virtual water flows associated with the trade of commodities averages 1,133 m^3 per capita for each PMA municipality due to using population as an attraction factor. Please refer to Tables S4 and S5 in the Supplemental Information for virtual water flows associated with commodities within the PMA and for virtual water flows by commodity.

Agricultural commodities originating from the western half of the United States are a large component of PMA virtual water inflows (Figure 2). In this region, irrigation is predominantly blue water, unlike the eastern half of the United States where rainfall is more abundant and provides a greater proportion, if not all, of crop water demand. The PMA's water footprint is more "blue" and less "green" than average for the United States.

Previous virtual water studies have reported a per capita blue water footprint of the United States of 239 m^3 per person (Mekonnen & Hoekstra, 2011), which is smaller than the 1,133 m^3 per capita blue water footprint calculated for the PMA. The deviation from previous work is because PMA relies heavily on "blue" surface water and groundwater abstractions, rather than "green" water virtual water supplies. The high level of circular virtual water flow within the PMA underscores this finding: 30% of a municipality's imported virtual water originates in the PMA, and much of the rest originates within the state (Arizona) and river basin (Colorado) where the PMA is located. Indirect or virtual water dependencies are concentrated within the same local hydrology and physical water supply upon which the PMA directly depends for its water supply, rather than being spatially distributed to hydrologically diversified regions. This large circular virtual water trade within the PMA and large dependency within the Southwestern US region and Colorado River Basin amplifies the community's hydro-economic exposure to scarcity and disruption of the local water resources (Ruddell et al., 2014; Rushforth et al., 2013).

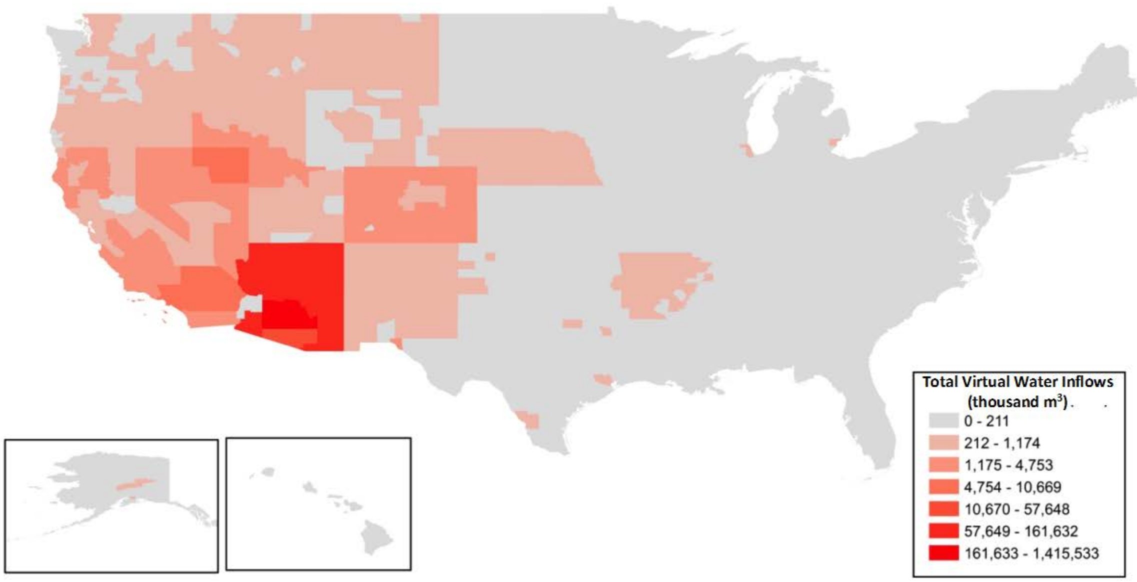

Figure 2: Virtual water inflows ($V_{C,k\rightarrow PMA}$) into the PMA are skewed to the dry (South) Western United States. Agricultural products dominate the virtual water inflow, especially from states such as Nebraska, Arkansas, and California. While the PMA does

not tend to import from distant rural areas, and imports little from eastern US metros, the PMA does trade with metropolitan areas across the United States.

2.3.2. Virtual Water Outflows to the Nation and the Metropolitan Area

Virtual water outflows per capita for the PMA follow a rough rank-order relationship from edge municipalities with high fractions of agricultural land (Buckeye) to residential/retirement communities (Sun City and Sun City West); ranging from 11,841 m^3 per capita in Buckeye to 3.0 m^3 per capita in Sun City West, which have the highest and lowest fractions of agricultural land use by area in the PMA. Virtual water outflows from the PMA to the rest of the United States are heavily weighted to the Southwest region, especially Arizona (Table 1), and all major national metropolitan areas (Figure 3), suggesting that the PMA is hydro-economically a regional city. Most of the Southwest is indirectly utilizing central Arizona water through economic interactions with the PMA. Nearly half of virtual water production ($CF_{C,PMA}^{export} = 48\%$) by the PMA's municipalities remains within the PMA. Comparing Figure 2 with Figure 3, virtual water outflows are more biased than inflows toward major national metropolitan area trading partners. However, both virtual water inflows and outflows are dominated by local trading partners: the PMA (first), Arizona (second), and Southern California (third) (Reimer, 2012).

Table 1: Virtual Water Exports from the PMA to Arizona (Commodities Only, Not Labor)

Virtual Water Outflow Destination	**Virtual Water Outflows ($V_{C,Out}$) (Thousand m^3)**	**% Total Virtual Water Export**
Tucson AZ MSA	132,579	5%
Remainder of Arizona	309,351	12%
Phoenix AZ MSA *	1,237,404	48%
Total Virtual Water Export to AZ	1,679,334	65%

Total Virtual Water Export	**2,583,530**	**100%**

* Includes Maricopa and Pinal County

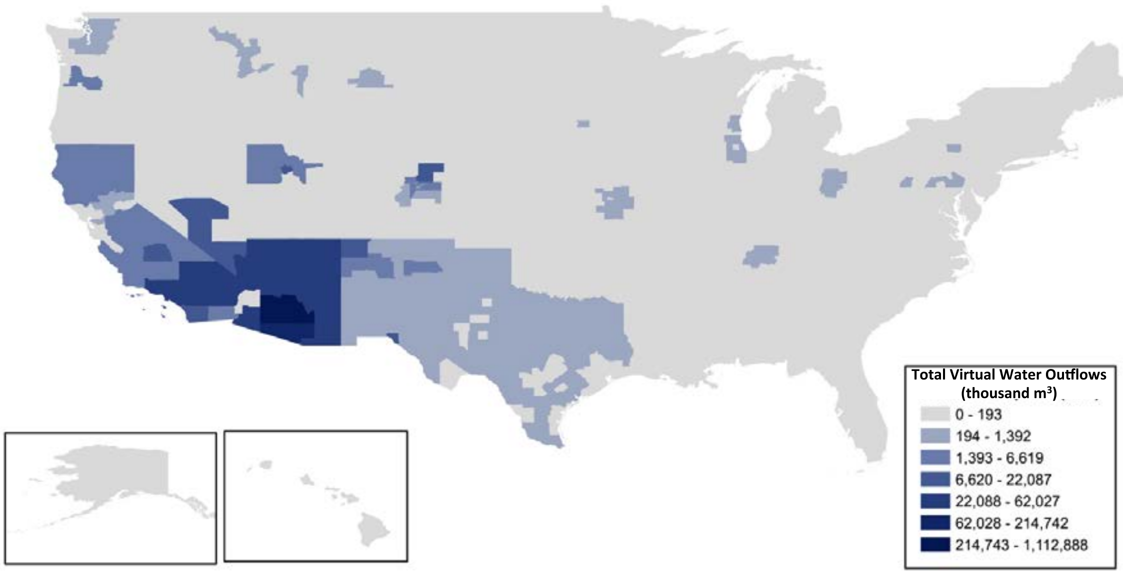

Figure 3: Virtual water outfows ($V_{C,PMA \rightarrow k}$) from the PMA are more concentrated in Arizona and regional neighbors, Nevada (Las Vegas), California, New Mexico, and Texas. Outflows are strongly correlated with the transportation route of the Interstate 10 highway and associated railways, which connects the PMA to markets in California, New Mexico and Texas. Virtual water outflows to areas outside of the Southwest United States are associated with other metropolitan areas, notably Salt Lake City, El Paso, Albuquerque, Denver, Boise, Seattle Portland, Kansas City, Milwaukee, Chicago, Columbus, Memphis, and Washington DC.

2.3.3. The Net Water Footprint of Commodities Consumed in the Metropolitan Area

Core cities are net virtual water importers from both their intra-PMA neighbors and from outside the PMA. Edge agricultural communities within the PMA are net exporters of virtual water to both core PMA municipalities and to the rest of the United States. These results corroborate the results of numerous water footprint and urban metabolism studies that found cities to be consumers of resources drawn from beyond local natural resource availability (Vanham & Bidoglio, 2014). However, disaggregating the national virtual water flows associated with commodities for the PMA reveals that many metropolitan areas and rural areas are net exporters to the PMA while other metropolitan areas and rural area are net importers from the PMA, which is a more nuanced view of subnational virtual water flows associated with a regional scale virtual water trade network (Figure 4).

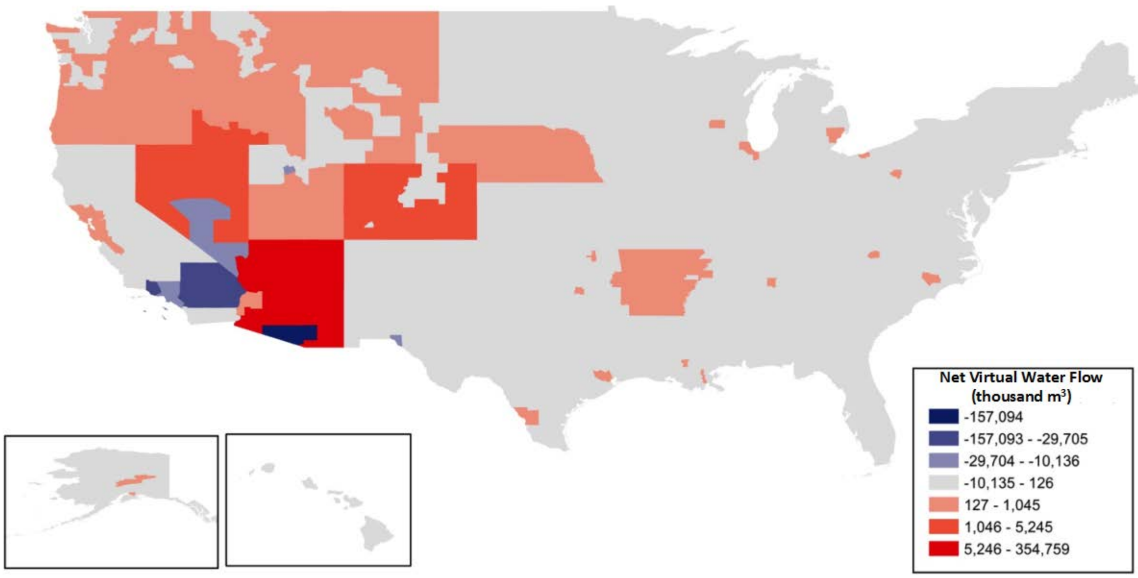

Figure 4: Net virtual water inflows for the PMA (VWB_{PMA}) are shown above. While virtual water inflows greater than outflows ($V_{in} > V_{Out}$), when disaggregated to the county-level it is evident that the PMA is both a net importer and exporter. The PMA is a net exporter of virtual water to regional metropolitan areas (LA, Las Vegas, Tucson, El Paso, and Salt Lake City) and imports from the remainder of the country.

2.3.4. Virtual Water Flows Associated With Labor

Intramunicipal circular labor flows account for 64% of the virtual water of the labor market; the remaining 36% resulted from circular virtual water flows within each municipality. Agricultural edge municipalities and bedroom municipalities had high outflows of virtual water associated with labor, and core municipalities have high virtual water inflows associated with labor (Table S6 in the Supplementary Information). Approximately half of the virtual water flows of labor within the PMA were associated with inflows, outflows, and intramunicipal flows within the municipality of Phoenix; the remaining fraction of virtual water flows was suburban-to-suburban labor flows. These results echo previous studies on the changing patterns of metropolitan area commuting from purely suburban to central city commuting patterns to more decentralized and polynucleated commuting patterns around the metropolitan area (Baum-Snow, 2010). Larger municipalities have a higher percentage of circular flows.

2.3.5. Intra-Metropolitan Net Water Footprints

If all of a metropolitan area's municipalities share a common physical water resource, the net flows of virtual water within the metropolitan area are conceptually interchangeable with a proportionate physical reallocation of shared local water resources. The high degree of intra-PMA virtual water flows further underscores the role of shared physical water resources and local-scale virtual water dependencies within the PMA. These virtual water flows create hydro-economic interactions between independently managed municipal potable water infrastructures, and also the self-supplied and mostly agricultural water infrastructures in the area. The relative magnitude of the virtual reallocation of water is approximately estimated by the comparison between the direct water withdrawals (U) and the intrametropolitan net water footprint of each municipality (E_{PMA}; Figure 5). Core municipalities have a larger share of the area's shared physical water resources when virtual water flows within the metropolitan area are considered; the opposite is true for edge and bedroom municipalities. This affects per-capita water footprints, increasing them for core municipalities and decreasing them for edge municipalities (see Table S7 for the adjusted per-capita water footprints). Core municipalities depend disproportionately on their metropolitan area neighbors' water supplies, as opposed to more distant trading partners' water supplies. Figure 5 may also be understood as a downscaling to individual communities and economic sectors of the county-level aggregated virtual water flows and water footprints presented in Sections 2.3.1, 2.3.2, and 2.3.3.

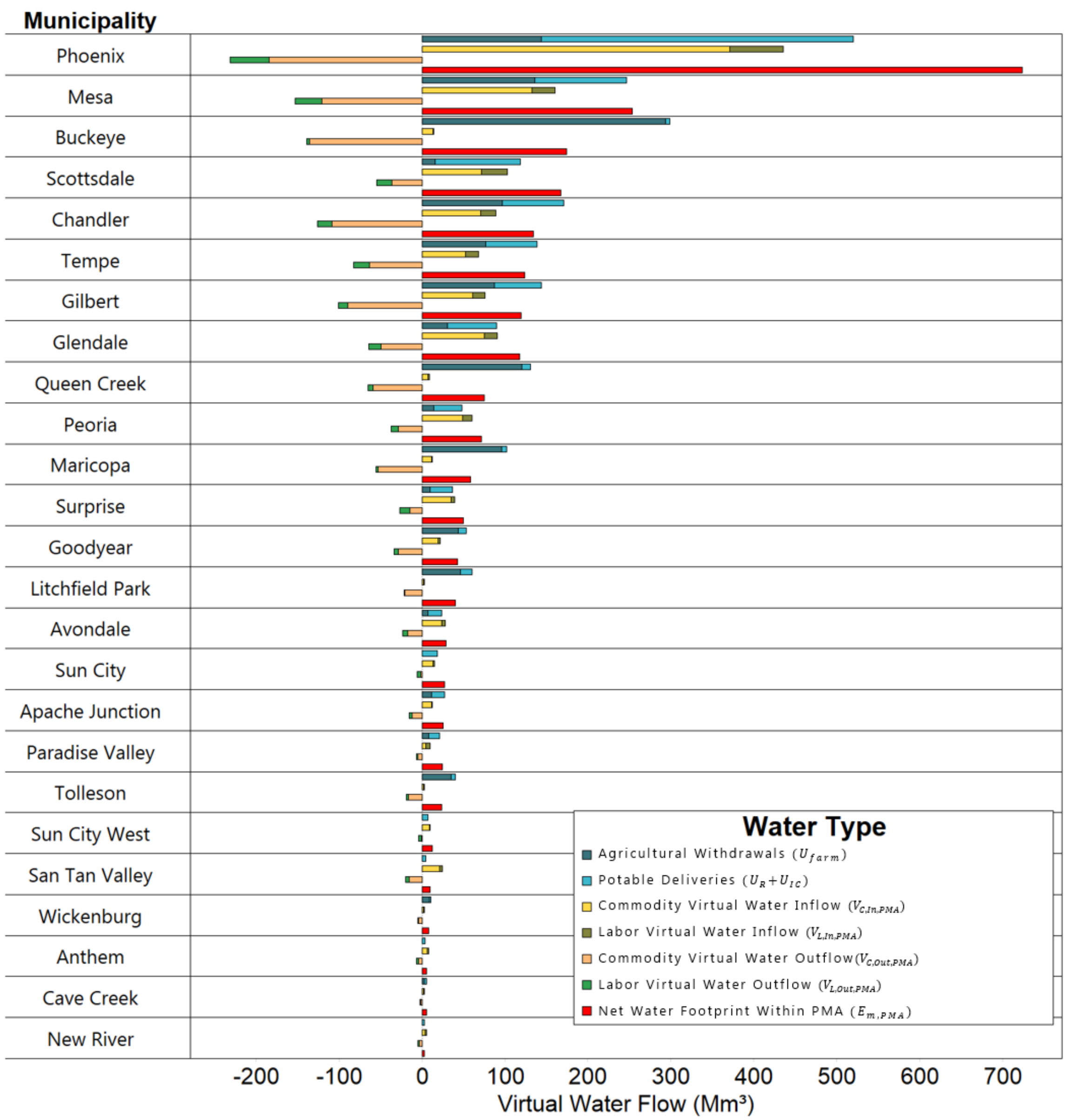

Figure 5: Components of the Intra-PMA Net Water Footprint of each municipality (a = PMA). Municipalities have different roles in the metropolitan economy: core municipalities tend to have virtual water inflows that are greater than outflows and also than potable system deliveries; bedroom municipalities have greater outflows of virtual water associated with labor than corresponding inflows. The net water footprint within the metropolitan area gives the complete impact of a municipality on the metropolitan

area's shared physical water resources, including indirect impacts via trade with metropolitan neighbors.

2.3.6. A Hydro-Economic Typology for Communities

The intrametropolitan scale net virtual water balance (VWB_m) is particularly important because it reveals how trade between neighboring municipalities affects the demand placed by each municipality on the shared physical water resource stock. Core municipalities are net importers of virtual water from the PMA in both labor and commodity trading categories, whereas agricultural or edge municipalities are net exporters in both categories (Figure 6). Many municipalities are net importers in one category and net exporters in the other. This example provides the basis for a general typology describing their relative roles.

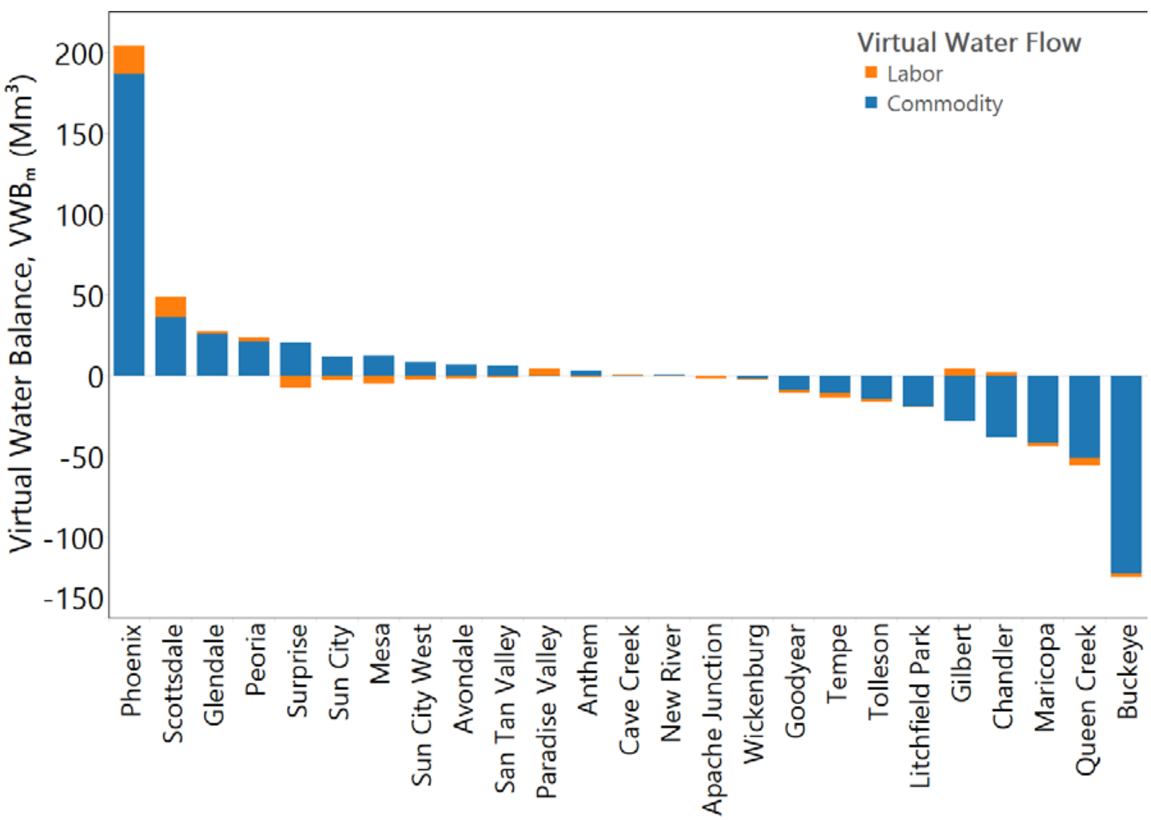

Figure 6: The core municipalities, chiefly Phoenix and Scottsdale, are net virtual water importers with respect to commodities and labor. Surrounding municipalities support the

core municipalities via the virtual water outflows in the form of labor (commuting) and commodities. A large fraction of the net commodity inflows and outflows is due to the virtual water associated with agricultural commodities, which fall outside of municipal water supply systems.

A generalized hydro-economic typology can be created based on the relative role of each community within the system boundary. Within the PMA, these roles have been simplified into the net trade in virtual water in the categories of commodities and labor. We use a Labor Flow Ratio (LFR), defined as $LFR = log(\sum_{n,C} V_{C,n\to m} \,/\, \sum_{n,C} V_{C,m\to n})$, and a Commodity Flow Ratio (CFR), defined as $CFR = log(\sum_{n} V_{L,n\to m} \,/\, \sum_{n} V_{L,m\to n})$. There are at least four qualitatively different hydro-economic types of communities (Figure 8): (1) “core” communities, which are high-value economic centers and job centers that are dependent on their neighbors for net virtual water inflows in both labor and commodities; (2) suburban “bedroom” communities, which are net virtual water exporters to core municipalities via labor flows, but net virtual water importers of commodities because of their relatively large residential populations (Kenessey, 1987); (3) “edge” communities, which are net virtual water exporters, especially of agricultural commodities but also of other commodities and labor; and (4) “transitional core” communities, which have become job centers and are therefore net importers of virtual water in labor, but are still net exporters of commodities, possibly due to economic specialization in an area such as manufacturing, or due to significant remaining agricultural activity. A “balanced” community is near the origin of the plot and is not a significant virtual water importer or exporter. This balance might be because the community has equal parts of each of the four types described above, or because the community is so small that it trades very little. Recall that the result in Figures 7 and 8 excludes virtual water flows across the municipal area’s system boundary, so the typology is relative to the chosen boundary. From a different point of view and using a more global boundary condition, all urban communities of substantial size are likely to be core-type communities.

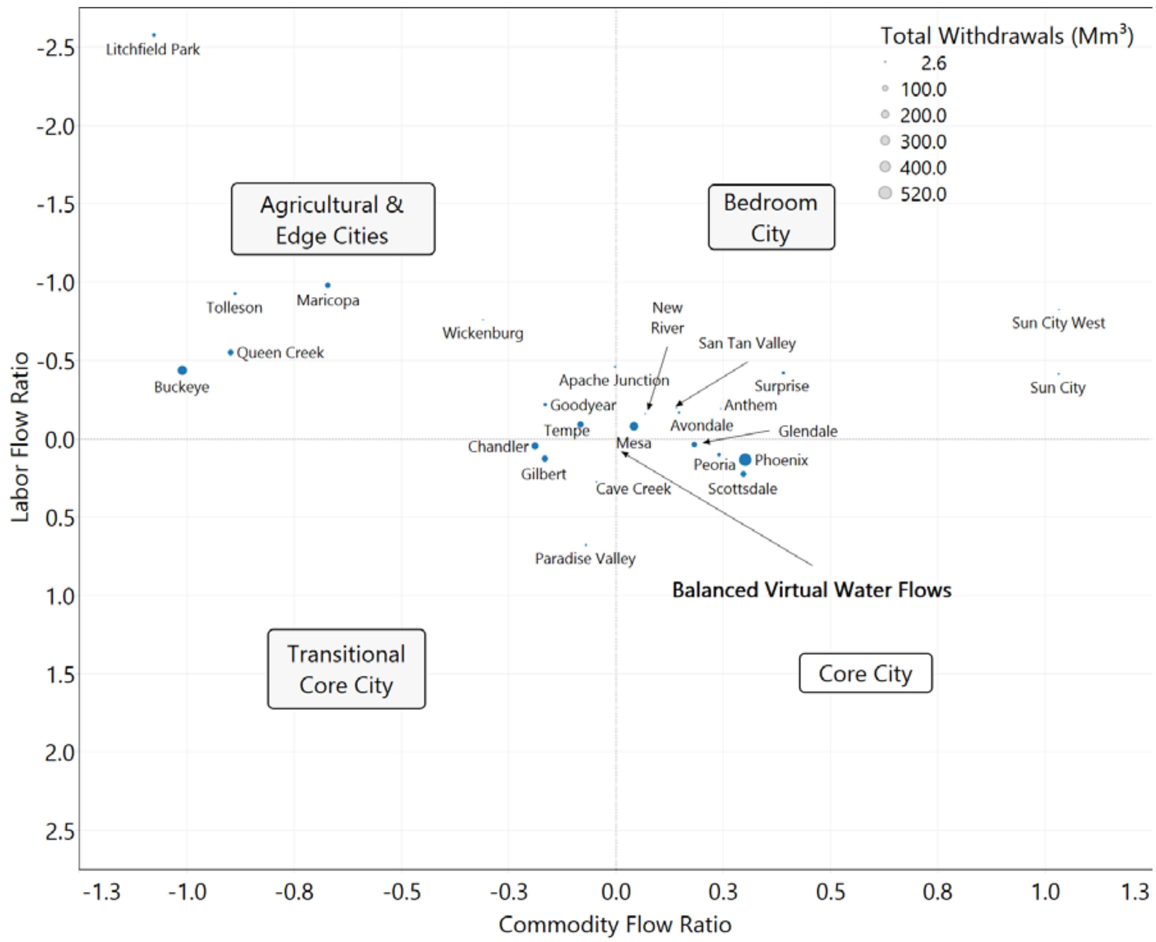

Figure 7: A two-dimensional hydro-economic typology for communities based on net virtual water flow ratios in the labor and commodity sectors of the economy. The PMA's leading municipalities, Phoenix and Scottsdale, typify the "core" community, and heavily agricultural communities such as Queen Creek and Buckeye typify the "edge" community. Chandler and Gilbert are "transitional core" communities that are developing to resemble Scottsdale but are currently part agricultural. Tempe and Mesa are "balanced" hydro-economies. This typology is based only on intrametropolitan virtual water flows,

and describes the relative hydro-economic role of each municipality within the metropolitan area.

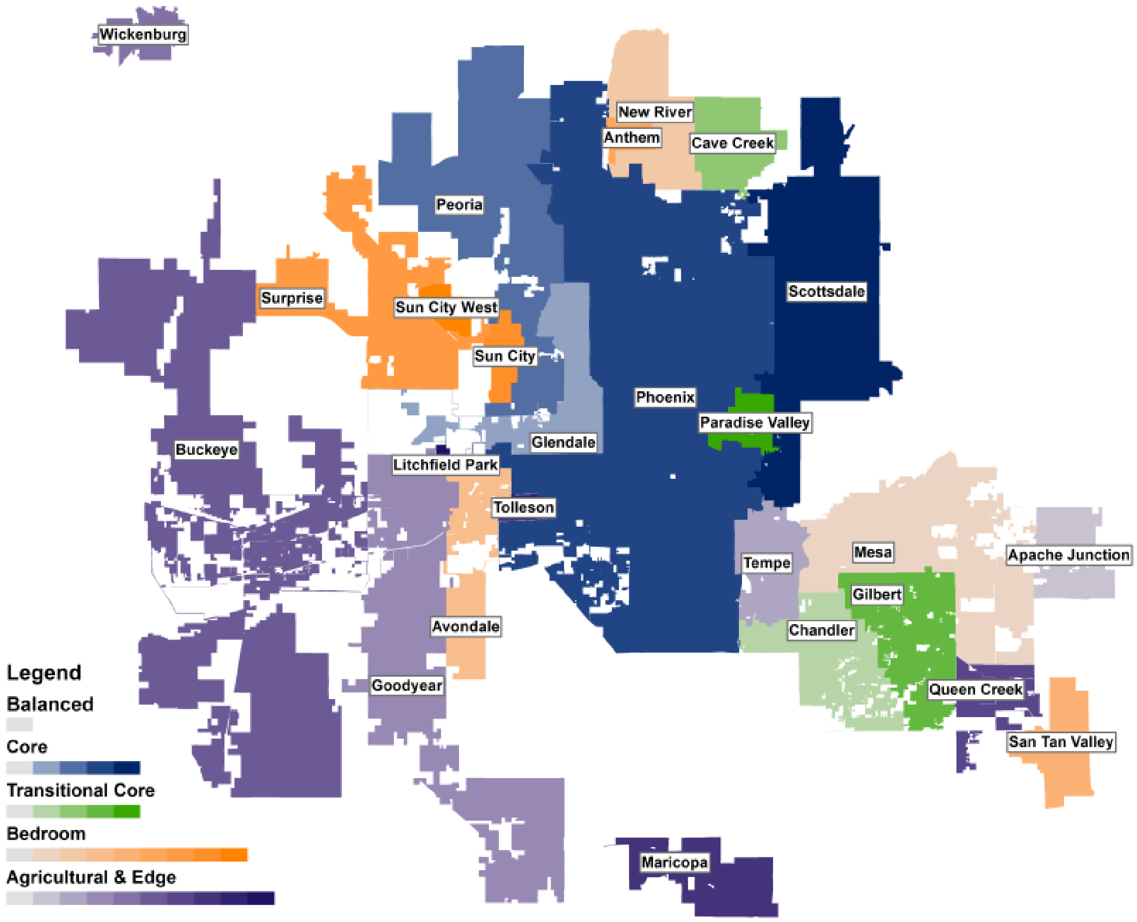

Figure 8: Mapping of the typology presented in Figure 7. PMA cities are mapped and shaded according to their city typology. Color intensity is proportional to a municipality's Euclidean distance from the origin, or balanced virtual water flows, and ranked within each typology.

2.4. Conclusions

2.4.1. Summary

This study has successfully quantified the water footprint balances of the Phoenix Metropolitan Area (PMA) at multiple scales, in a spatially explicit fashion. Thirty percent of the PMA's virtual water inflows are sourced "circularly" from within the PMA, and the majority of the rest is sourced within the state of Arizona, and to a lesser extent Southern California and other parts of the Lower Colorado River Basin. There is therefore a very strong indirect dependency of the PMA on the relatively scarce water resources of the Southwestern United States and especially the Lower Colorado River Basin and local Phoenix-area surface and groundwater supplies. This indirect dependency, measured by its virtual water inflow, is larger than the PMA's direct water consumption (or urban water metabolism). The PMA's per-capita water footprint is several times higher than the US national average, due to an increased reliance on water-intensive irrigated agriculture in the semiarid Southwest. Therefore, water shortage in the Colorado River Basin has the potential to impact the PMA not only through stress and potential shortage of physical supplies but also indirectly through stress on virtual water supplies throughout the basin.

Forty-eight percent of the PMA's virtual water production remains within the PMA ($CF_{C,m/(m\rightarrow n)}$ = 48%). The other 52% of virtual water outflows has a locational bias toward national metropolitan areas, especially those within the southwestern United States, including Southern California. The PMA still contains a prominent agricultural sector, which is responsible for much of the virtual water outflows. Even though this is a metropolitan area of more than four million people with relatively little agricultural land remaining inside the area, irrigated agriculture and agricultural water supplies, not potable supplies, are still the largest component of the PMA hydro-economy.

For these municipalities' urban water footprints, the metropolitan area scale contains the highest fraction of virtual water flows, followed by the state scale, the regional scale, and the national scale, in descending order, and with the flows dominated by the metropolitan scale and the state scale. Indirect water dependency is concentrated in the same physical location as the direct water supply, so the exposure of the PMA's hydro-economy and risk associated with the southern Arizona water supply is enhanced rather than mitigated by the highly circular structure of the hydro-economy. The indirect water supply chain of the PMA is concentrated in locations that are hydrologically, politically, and legally coincident with the direct water supplies of central Arizona.

There is a large and mobile skilled labor force that commutes between PMA municipalities, evidenced by the 22% of the PMA's potable water deliveries mobilized through intermunicipal labor flows within the PMA. While this is less than the virtual water trade in commodities, both commodities and labor are significant contributors to the intrametropolitan virtual water flows. There is a substantial difference between the patterns of virtual water trade sourced from potable urban water supplies versus agricultural and other self-supplied water users, and the two should be treated separately in this type of analysis. The PMA's municipalities are net virtual water importers from the entire nation, importing more virtual water than they export. However, within the PMA, communities take on different net virtual water flow balances with respect to commodity and labor flows. These differences yield four types of communities: "core," "transitional core," "bedroom," and "agricultural edge." Core communities such as Phoenix and Scottsdale are net virtual water importers in both commodities and labor, and are the most dependent on their neighbors' water supplies. The net intrametropolitan water footprint and the per-capita water consumption of core communities are larger than the direct water consumption alone indicates. Core communities are the net dependents and net beneficiaries of a hydro-economy that locates disproportionate water resource demands at the urban edge. The opposite is true for agricultural edge communities, such as Buckeye and Queen Creek, which hydro-economically subsidize the water demands of core communities. Transitional core and bedroom communities lie between core and edge communities on a spectrum.

2.4.2. Broader Implications

The high likelihood of drought in the Southwest (Cook, Ault, & Smerdon, 2015) poses potential challenges to both the PMA economy, the water resources system at multiple scales, and regional water resource management (Gober & Kirkwood, 2010). Each municipality within the PMA can plan for drought and long-term water scarcity, but the economic effectiveness of drought planning will most likely be manifest primarily at the scale of the metropolitan area and State of Arizona, not the individual municipality, due to the high degree of intrametropolitan and regional virtual water circularity revealed by our analysis. The impacts of any future potential water rationing, curtailment of water supply, or the failure of water infrastructure within one municipality will cascade throughout the metropolitan area's hydro-economy, affecting the nearest and strongest neighbors first. Core communities tend to have strong economic and water rights positions, and are much more insulated from the effects of drought than the bedroom and edge communities on which they are hydro-economically dependent. The core communities' high degree of hydro-economic dependency on their hydro-economically weaker bedroom communities may be a serious blind spot in the water resource sustainability and resilience strategies of the prominent core municipalities throughout the world.

One potential strategy for municipalities to enhance hydro-economic sustainability and resilience is to pursue public/private policies of a more spatially and hydrologically diversified indirect water supply chain, and one sourced to less droughtprone and less water-stressed geographies. This strategy adds an indirect supply chain component that complements the traditional approach to urban water supply policy, which emphasizes water efficiency and multiple redundant physical water sources. Another potential strategy is for core municipalities to more actively cooperate with bedroom and edge municipalities on issues of water rights, water infrastructure investment, and water allocation policy to ensure that the entire metropolitan area is hydro-economically secure. This paper shows that from a hydro-economic perspective, the 25 municipalities of the PMA function as an interdependent whole. In view of likely drought, it may benefit the municipalities to pursue infrastructure and policy that recognizes this fact.

Each type of community is likely to have a distinct point of view with respect to cooperative water policy and may follow its interests in choosing to acknowledge or discount the indirect component of the intrametropolitan water footprint. Core communities benefit the most from positive externalities and a lower apparent water footprint by neglecting the indirect dependency, and are less likely to see that cooperation with other communities on water infrastructure investment is in their best interest. Edge communities have the strongest interest in adopting a complete water footprint balance because they are important providers of water-derived goods and services, and have a net water footprint that is lower than is at first apparent. However, because edge communities are the most vulnerable to disruptions in water supply due to their junior water rights, limited economic and political power, and their relatively water-intensive economies, and because core communities depend on them, there is a shared interest in using this information to guide cooperative water policy and investment.

Intrametropolitan-scale virtual water flows are fundamentally different from international virtual water flows in that they are usually direct substitutes for physical water supplies (Gober & Kirkwood, 2010), in that the water involved could be physically reallocated to the other side of a municipal boundary if a different physical water infrastructure or water allocation were in place. The PMA's municipalities are dependent on shared physical water resources—the Colorado River, the Salt and Verde Rivers, and groundwater—that are divided among the municipalities by codified legal water rights. Intrametropolitan virtual water flows occur at hydrologically colocated scales, but the metropolitan region's physical water infrastructure and legal rights to water divide the physical water resource into multiple separate stocks. These multiple water stocks can suffer from different levels of stress, scarcity, or disruption that are created by differences in investment and water rights, rather than hydrological differences. These differences between municipalities' water stress, scarcity, and disruption risks are the direct result of water policy, law, and investment, and can therefore be solved by the same means.

Virtual water embedded in the labor market is unique because, unlike commodities, skilled labor tends to be relatively expensive and also a specific factor input (that is, an input without substitutes) associated with a metropolitan area's domain of specialization as a "cluster" of expertise and leadership in the service and high-value manufacturing sectors of the global economy (Samuelson, 1971). Virtual water in labor is the key linkage between the Industrial and Commercial (IC) and Residential (R) segments of the municipal water supply across municipalities. Commodities tend to be less expensive per unit of virtual water (e.g., a lower value intensity) and are more mobile, and can therefore be more readily outsourced to hydrologically diverse and distant suppliers that are not direct rivals for the city's direct local physical water resource. Cities can much more easily outsource their water-intensive agricultural commodity supply chain than the skilled labor underlying a city's economic competitive advantages in the global economy. Owing to this dynamic, it is predictable that intrametropolitan virtual water embedded in labor will tend to become more strategically important and impactful on water supply planning relative to agricultural commodities as cities grow. Therefore, in a future that holds the potential for water scarcity, bedroom communities will likely have an enhanced future strategic role and value within the metropolitan area's hydro-economy, and agricultural-type edge communities will likely have a diminished role if municipalities in the metropolitan area pursue agricultural-to-urban water transfers as a policy to free up local water supplies. However, while the relative importance of city types will likely change over time, the water sustainability of the PMA relies upon the coordination of water policies amongst municipality types because virtual water outsourcing at the intrametropolitan area scale is a direct substitute for physical water allocation.

Local water scarcity holds may restructure the local labor market and the greater, national commodity flow network. For example, drought in the US Southwest may increase the distance some commodities travel between their origin and destination in order to access virtual water outside of the Colorado River Basin, increasing transportation fuel consumption (which will increase the greenhouse gas intensity of domestic freight and other negative externalities that arise from freight movements, e.g., NO_x, SO_x, and $PM_{2.5}$ emissions), creating potential long-term, unintended negative externalities. Therefore, while drought is a local phenomenon, the full impact of water stress, in restructuring the labor and commodity network, will emerge at the national level, with impacts propagating through a hydro-economic network where metropolitan areas are the most critical hubs.

We have shown that municipalities and their potable water supply systems are highly interdependent via hydro-economic connections, and that information about urban water footprints and virtual water flows within a metropolitan area can be used to directly inform municipal water supply policy and infrastructure investment. While the purview of a municipal water manager is within the boundary of the municipality's potable water distribution system (Ruddell et al., 2014; Rushforth et al., 2013), economic development at the metropolitan area scale relies upon the strength of the region and thus the water management of all metropolitan area municipalities. A well-managed, sustainable, and resilient water supply system and water resources portfolio not only benefits the individual municipality, but also the entire metropolitan area.

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CHAPTER 3: THE VULNERABILITY AND FUNCTIONAL DIVERSITY OF A CITY'S WATER FOOTPRINT: THE CASE OF FLAGSTAFF, ARIZONA[3]

3.0 Abstract: Research has yet to operationalize water footprint information for urban water policy and planning to reduce vulnerability and increase functional diversity to water scarcity. Using a county-level database of the US hydro-economy, the National Water Economy Database (NWED), we spatially mapped and analyzed the Water Footprint of Flagstaff, Arizona, a small city. Virtual water inflow and outflow networks were developed using the flow of commodities into and out of the city. The power law distribution of virtual water trade volume between Flagstaff and its county trading partners broke at a spatial distance of roughly 2,000 km. Most large trading partners are within this geographical distance, and this distance is an objective definition for Flagstaff's zone of indirect hydro-economic influence—that is, its water resource hinterland. Metrics were developed to measure Flagstaff's reliance on virtual water resources, versus direct use of local physical water resources. Flagstaff's reliance on external water supplies via virtual water trade increases both its hydro-economic functional diversity and vulnerability to water scarcity. These methods empower city managers to operationalize the city's Water Footprint information to reduce vulnerability, increase functional diversity, and optimally balance the allocation of local physical water supplies with the outsourcing of some water uses via the virtual water supply chain.

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3.1 Introduction

Cities are crucibles of human behavior and, through specialized advantages in the service economy, value-producing nodes in the economic trade networks (Beaverstock, Smith, & Taylor, 2000; Gunasekaran, Lai, & Edwin Cheng, 2008; Malone & Laubacher, 1999) that lack the natural resources necessary for self-sufficiency, which creates dependencies on rural areas and, to a lesser extent, other cities. Through the lens of urban metabolism, cities are areas of high population density that create concentrated demands for resources—natural, agricultural, manufactured, or otherwise—that exceed local endowments (Kennedy, Cuddihy, & Engel-Yan, 2007; Kennedy, Pincetl, & Bunje, 2011). Resource consumption is consequently outsourced beyond its boundaries and into the hinterlands (Wolman, 1965). This process benefits the city by allowing it to specialize in valuable economic niches and provide new economic opportunities to its residents. However, technology has expanded the hinterlands to larger, more distant scales, creating an overlapping and teleconnected commons (Dietz, Ostrom, & Stern, 2003) and linking multiple cities via teleconnections (Liu et al., 2015; Seto et al., 2012). Stemming from this connectivity, cities now face systemic risks from distant problems via perturbations to the coupled natural human (CNH) system (Liu et al., 2007). Among these risks are shocks, such as drought, to water resources, which is becoming a more frequent phenomenon.

City-level virtual water trade studies have provided insight into how cities outsource water. For example, one study on Delhi, Berlin, and Lagos found that variations in local diet, trade integration, and water availability influence blue and green virtual water imports (Hoff et al., 2013). An interregional input-output economic model developed to study Beijing's water footprint found that the primary sector, which includes economic activities reliant on raw material extraction and agriculture, had the largest water footprint among all economic sectors and was concentrated in rural areas, while the secondary sector, manufacturing and other activities that transform primary sector products into finished goods, was the most significant direct water consumer in some urban areas (Zhang, Yang, & Shi, 2011). These city-level virtual water studies have highlighted the importance of trade in overcoming local water constraints: through trade cities have access to new, indirect sources of water (Zhao et al., 2015). However, for virtual water studies to inform city-level decision making, the boundaries and scale of analysis must match the highly localized scale of urban economies, decision making, and public policy development (Wichelns, 2010, 2011), and must consider spatial differences between water stocks.

One tactic to achieve this outcome is to expand the city-hinterland conceptualization to city-city interactions, so that studies encompass the entire range of city-level economic transactions, not just agricultural commodities and raw materials, but industrial and manufactured goods as well as the service economy. Another tactic is to spatially and economically disaggregate a city's virtual water trade network by location and by sector. Spatial disaggregation allows for the creation and calculation of hydro-economic network statistics and incorporates fine-scale hydrological information into managing a city's water footprint. Economic sectors provide a rubric to categorize a city into economic components and their factors of production (Kellerman & Krakover, 1986; Spellman, 2014) as well as the service sectors (Paterson et al., 2015). Expanding the analysis to encompass the urban-to-rural spectrum and disaggregating the network by spatial and economic characteristics creates a framework for analysis of a city's role within the complete hydro-economic system.

Analyzing city-to-city indirect virtual water interactions alongside direct use of physical water resources shifts the role of the city from solely a consumer of the hinterland's resources, which is emblematic of the urban metabolism and consumer water footprint view of the city, to a more accurate role as a concentrator of the services of water and a producer of value-added goods and services. A city balances direct physical water resource development against outsourcing of production of the goods and services of water. From this point of view, the city drives the flow of virtual water by outsourcing less valuable and more water-intensive water uses (R. Rushforth & Ruddell, 2015), and is the ultimate cause of the use of most water resources in the economy. Now the city takes its place in a continuum of hydro-economic actors, ranging from small towns and rural natural resource operations up to megacities. This approach opens new lines of inquiry relating water footprint characteristics to city characteristics—population and economic size, economic specialization, capitalization, geography, crime rates, and political stability—creating a direct linkage between water footprinting and the science of cities (Bettencourt, Lobo, Strumsky, & West, 2010; Krätke, 2007). Further, spatially and economically disaggregating a city's water footprint provides hydrological information at the scale necessary to characterize the city's hydro-economic leverage, vulnerability (Adger, 2006; Hashimoto, Stedinger, & Loucks, 1982; Vörösmarty, Green, Salisbury, & Lammers, 2000), resilience (Holling, 1973; Peterson, Allen, & Holling, 1998), and security (Kumar, 2015) of both physical and virtual water resources.

To operationalize virtual water information for prescriptive city-level decision making, virtual water analysis must be coupled with hydro-economic information and with the direct or local development of physical water resources. First, we utilize a previously published spatially and economically disaggregated hydro-economic database to delineate the water footprint of the city, including both virtual water inflows and outflows by all aspects of its economy, and we document the water productivity (Ruddell et al., 2014) of the direct and indirect water uses. Second, we develop a statistical method to define the geography of a city's hydro-economic hinterland based upon the observed statistical distribution characteristics of the virtual water flows. Next, we develop metrics of hydro-economic network leverage, vulnerability, and functional diversity (D'Odorico, Laio, & Ridolfi, 2010; Rockström et al., 2009; Suweis, Carr, Maritan, Rinaldo, & D'Odorico, 2015) to measure the security of a city's indirect virtual water hinterland and compare this with the security of the city's direct and local physical water resources. These metrics provide the foundation for benchmarking both the city's water footprint, and that footprint's economic values and security, and can provide the basis for a city to optimize its role in the hydro-economic system.

3.2 Methods

Flagstaff, Arizona, was used for this study because it is a developed, diversified regional economy that has a broad commerce network and is not within a metropolitan area city network. The exchange network is based upon actual flows of commodities and services into and out of Flagstaff. International trade is neglected because it only accounts for 2.6% of imports and 2.9% of exports for this city. Of the many ways to define a city's boundary (Buser, 2012; Harrison, 2010; Markusen, 1999), we use the water utility service boundary of the City of Flagstaff Utilities, creating a hydro-economic delineation between direct (physical or local) and indirect (virtual or nonlocal) water resources. Results are presented for virtual water inflows and outflows into and out of this boundary for the City of Flagstaff.

3.2.1 City-Level Water Footprint, Virtual Water Balance, and Boundaries

Virtual water inflows (V_{In}) and outflows (V_{Out}) were calculated using commodity flows (R. Rushforth & Ruddell, 2015) and disaggregated to the county level using regional shares (RS) of employment (US Census Buearu), agricultural establishments (USDA NASS), and population (US Census Buearu, 2012). Flagstaff's virtual water flows are a geographic extract from NWED. Our notation follows the Embedded Resources Accounting (ERA) Framework (Ruddell, Adams, Rushforth, & Tidwell, 2014; R. R. Rushforth, Adams, & Ruddell, 2013). As applied in this paper, ERA is a minor variant on the standard Water Footprint Assessment method (Aldaya, Chapagain, Hoekstra, & Mekonnen, 2012) that explicitly considers multiple boundary conditions and considers both virtual water flow and currency flow networks. ERA provides a formal basis for value intensity calculations, among other results.

Virtual water flows are indirect uses of water resources. Direct uses of physical water resources (U) may originate from within (U^l) and outside (U^x) the city's local boundary, where the sum of U^l and U^x is Flagstaff's urban water metabolism ($U_{urban} = U^l + U^x$). In this case, Flagstaff directly uses groundwater within the city's local boundary and also directly uses groundwater and surface water outside the system boundary via water conveyance infrastructure. Flagstaff's (F) net embedded water footprint (E_F) is shown with Equation 1.

$$E_F = U^x + U^l + V_{In,F} - V_{Out,F} \quad [m^3] \quad (1)$$

Since there are multiple external sources of direct or physical and indirect or "virtual" water, the U^x, V_{In} and V_{Out} terms are summed over all local direct water sources (*m*), external direct water sources (*n*), and all indirect water sources (*k*), for each commodity in the exchange database (*c*). The full ERA equation for Flagstaff's net water footprint is shown in Equation 2 where $V_{In} = \sum_{c,k} V_{c,k\rightarrow F}$ and $V_{Out} = \sum_{c,k} V_{c,F\rightarrow k}$.

$$E_F = \sum_n U_n^x + \sum_m U_m^x + \sum_{c,k} V_{c,k\rightarrow F} - \sum_{c,k} V_{c,F\rightarrow k} \quad [m^3] \quad (2)$$

Using commodity class definitions, Equation 2 can be grouped into agricultural, livestock, mining, and industrial economic sectors (*s*) (Equation 3).

$$E_F = \sum_n U_n^x + \sum_m U_m^x + \sum_{k,s} V_{s,k\rightarrow F} - \sum_{k,s} V_{s,F\rightarrow k} \quad [m^3] \quad (3)$$

No agricultural or livestock operations were within Flagstaff's local system boundary, and consequently there is no V_{Ou} associated with these activities. While there are agricultural and livestock operations associated with Flagstaff zip codes, these operations are located outside the system boundary.

The virtual water balance (VWB_F) is the difference between V_{In} and V_{Out} (Equation 4).

$$VWB_F = \sum_{c,k} V_{c,k\rightarrow F} - \sum_{c,k} V_{c,F\rightarrow k} \quad [m^3] \quad (4)$$

The circularity index (CI_F) of Flagstaff's net water footprint is the percentage of direct water withdrawals used as an indirect input within the city boundary; it is a self-sufficiency metric (Equation 5).

$$CI_F = \frac{\sum_c V_{c,F\rightarrow F}}{\sum_c V_{c,k\rightarrow F}} \quad [m^3] \quad (5)$$

Each flow of virtual water between Flagstaff and a trading partner has a reciprocal flow of value calculated simultaneously with V_{In} and V_{Out}. The value intensity (VI; Ruddell et al., 2014) of virtual water flows is calculated as the ratio between virtual water and currency flows for an aggregated sector of the city's economy (Equations 5 and 6). Value intensity is simply water productivity, assessed against either direct or indirect water uses.

$$VI_{k\rightarrow F} = \frac{\sum_c V_{c,k\rightarrow F}}{\sum_c USD_{c,F\rightarrow k}} \qquad [\text{USD/m}^3] \qquad (5)$$

$$VI_{F\rightarrow k} = \frac{\sum_c V_{c,F\rightarrow k}}{\sum_c USD_{c,k\rightarrow F}} \qquad [\text{USD/m}^3] \qquad (6)$$

Flagstaff's value intensity ratio (VIR_F) can then be defined as the ratio between $VI_{F\rightarrow k}$ to $VI_{F\rightarrow k}$.

$$VIR_F = \frac{VI_{F\rightarrow k}}{VI_{k\rightarrow F}} \qquad (7)$$

VIR_F measures leveraged water productivity and is an intensive hydro-economic property of Flagstaff, and it can be calculated for the city as a whole as well as specific economic sectors and commodity groups.

3.2.2 Scaling Properties of the Virtual Water Trade Network

Previous work has identified heavy-tailed, power law distributions in international virtual water trade with respect to the number of trading partners a country has, the number of commodities traded between countries, and the volume of virtual water traded by a country (M Konar, Dalin, Hanasaki, Rinaldo, & Rodriguez-Iturbe, 2012; M. Konar et al., 2011; Shi, Liu, & Pinter, 2014; Suweis et al., 2011). This current paper provides a spatially detailed, city-level domestic virtual water exchange network complement to the international-scale virtual water trade studies, albeit for only one node in the hydro-economic network. We tested the distribution of V_{In} and V_{Out} volumes by trading partner for power law (PL), exponential (Exp), stretched exponential (SE), lognormal (LN), and exponentially truncated power law (ETPL) distributions using published analytical methods (Alstott, Bullmore, & Plenz, 2014; Clauset, Shalizi, & Newman, 2009).

After fitting distributions to the datasets, the fit statistics (x_{min}) were used to investigate spatial differences in the virtual water exchange network. Using the distance of the x_{min} trading partner ($x_{min,dist}$) as a cut off, we tested whether trading partner distance from Flagstaff (k_{dist}) below a distance threshold differed from those above the distance threshold. Where a natural break is found in the scaling of virtual water transfer volumes versus distance, this distance is used to define the zone of indirect hydro-economic influence, and it yields an objective definition for Flagstaff's hydro-economic hinterland. This natural break defines x_{min}. Inside the hinterland, a relatively uniform set of economic patterns holds, and more water-intensive goods and services are sourced from shorter distance. Outside Flagstaff's hinterland, the relatively few and small trading relationships tend to represent exceptional cases where highly valuable and rare goods and services are obtained from whatever sources are available.

Network functional diversity calculations in this study are based on the functional diversity of suppliers. We therefore require an objective definition of the maximum possible functional distance from which virtual water flows could be sourced. Two logical choices for the hinterland boundary are based on the domestic and international trade networks. In this paper, we set the maximum functional distance at the hinterland boundary. The leverage, vulnerability, and functional diversity metrics are computed based only upon county trading partners that lie within Flagstaff's hinterland. The hinterland accounts for 95.7% of virtual water inflows and 99.9% of virtual water outflows, validating this assumption for practical purposes.

3.2.3 Measuring Hydro-Economic Leverage

Hydro-economic leverage (*HL*) is a measure of a city's relative reliance upon its virtual water exchange network for hydro-economic inputs. It is the ratio between virtual water inflows (V_{In}) and direct physical water use (U_{urban})—in this case, the municipality's withdrawals.

$$HL = V_{In}/U_{urban} \qquad (9)$$

While this is methodologically similar to the Water Footprint Network's water dependency metric, we use the term *leverage* because the city leverages its position as a creator of value-added goods in the economic network to access the hinterlands. *HL* > 1, indicates the city is more susceptible to exogenous water shocks (e.g. far-away drought) via the hydro-economic network, while *HL* < 1 indicates the city is more susceptible to endogenous shocks (e.g. a local drought) to local, physical water resources.

3.2.4 Measuring Systemic Hydro-Economic Vulnerability

An Indirect Water Stress Index (*IWSI*) was developed to quantify the vulnerability of Flagstaff's hydro-economic network based upon a previously published Water Stress Index (*WSI*) for US counties (Tidwell, Kobos, Malczynski, Klise, & Castillo, 2011) combined with virtual water flows. Water stress is analyzed at the county-level (*k*) with respect to the annual allocated fraction of sustainably available surface fresh water resources. The *WSI* ranges from 0 to 1, where $WSI = 1$ indicates total allocation of a county's water resources and, consequently, little capacity to withstand hydrologic shocks, (e.g., severe drought), which would cause water demands to exceed water availability. The county-level indirect vulnerability to a trading partner's water stress ($IWSI_{k\rightarrow F}$) is calculated as a trading partner's fractional contribution to Flagstaff's indirect vulnerability.

$$IWSI_k = \frac{V_{k\rightarrow F}}{\sum_{all\ k} V_{k\rightarrow F}} \times WSI_k \qquad (10)$$

Summing across all counties (*k*) yields the *IWSI* of the city's entire virtual water inflow network: $IWSI_F = \sum_k IWSI_k$. Since the city of Flagstaff is wholly within, and largely comprises, Coconino County, the direct water stress index (DWSI) for Flagstaff is set to the *WSI* of Coconino County, which is 0.29.

The ratio between the *IWSI* and *DWSI* gives a measure of systemic water resource risk (*SVWR*), where *SVWR = IWSI/DWSI*. *SVWR* is a measure of the performance of the hydro-economic network in reducing exposure to indirect water stress. A $SVWR \leq 1$ is considered optimal, especially when *DWSI* is high, because then indirect water use is not exacerbating systemic water stress, and a city could, in principle, increase outsourcing of water-intensive activities to its hydro-economic network to compensate for local water scarcity. The weighted averaged between *IWSI* and *DWSI* represents the city's systemic Hydro-Economic Network Vulnerability (*HNV*).

$$HNV_F = \left[\left(\frac{V_{In,F}}{U_F + V_{In,F}}\right) \times IWSI_F\right] + \left[\left(\frac{U_F}{U_F + V_{In,F}}\right) \times DWSI_F\right] \qquad (11)$$

The *WSI* employed by this paper does not consider artificial augmentation of surface water supplies by conveyances across county lines and only accounts for the long-term average surface water stress not seasonal stress. This is an appropriate choice because local renewable surface water is the only sustainable water source over the long term, and because conveyed water resources are subject to many additional political and technological problems and will generally be under greater stress during times of drought. Still, this assumption means we have overstated vulnerability to short-term drought to the extent that a county is the holder of senior water rights and the recipient of water transfers from other locations. Future work might utilize water stress metrics that account for surface water and groundwater stress as well as transbasin diversions, but this would require that the duration of a drought, rate of depletion, the volume of storage in groundwater aquifers, the capabilities of the water infrastructure, and the legal agreement surrounding a transbasin diversion be taken into account.

3.2.5 Measuring Systemic Hydro-Economic Functional Diversity

We adopt conceptual definitions drawn from ecological resilience (Holling, 1973; Peterson et al., 1998), and specifically the insurance hypothesis (McNaughton, 1977; Naeem & Li, 1997; B. Walker, Kinzig, & Langridge, 1999; B. H. Walker, 1992; Yachi & Loreau, 1999), to inform how we measure the functional diversity of a city's hydro-economic network. Merely within the US, this network can consist of more than 3,100 potential county-level trading partners. For any city, a few trading partners within the hinterland will contribute to the bulk of virtual water flow, while the majority and generally distant group of trading partners will contribute relatively small volumes of virtual water. If we apply the framework of Walker et al. (1999) and others to the US hydro-economic network, a city with a functionally diverse hydro-economic network should obtain virtual water from a large number of trading partners with a high degree of functional hydro-economic distance from the city and a high degree of functional diversity from each other. To operationalize this framework for a water footprint, we propose measures of hydro-economic functional distance and diversity.

To measure hydro-economic functional distance, we identified a basket of seven hydro-economic functional distance indicators (A^r, r = 1…7). The seven indicators we chose were a drought correlation indicator (DI); an urban classification indicator (UCI); an infrastructure connectivity indicator (ICI); a shared river basin indicator (SRBI); a physical distance indicator (PDI); a hydro-economic specialization indicator (HESI); and a shared water governance indicator (SWGI). These indicators are described in detail the Supplemental Information (Text S1).

For each indicator, a trading partner's normalized Euclidean distance ($A^r_{F,k}$) from Flagstaff was measured as,

$$A^r_{F,k} = \frac{|A^r_k - A^r_F|}{\max(A^r_{any\ k} - A^r_F)}. \tag{12}$$

This metric is normalized by the maximum observed distance in the network, so it implicitly assumes that the maximum observed distance is similar to the maximum possible distance. This assumption is approximately valid for such a large and diverse network as the US hydro-economic network, and it is valid by definition for our choice of the hinterland boundary x_{min} as the maximum distance. Counties that are hydro-economically similar to Flagstaff have $A^r_{F,k} = 0$, and completely dissimilar counties have $A^r_{F,k} = 1$.

To estimate functional diversity, we constructed a Shannon Diversity Index based on each distance indicator. The distances $A^r_{F,k}$ were binned into categories i (1…i…N) of similar distance (Figure 7). Then a normalized Shannon Diversity Index (SI^r) for each distance indicator was computed on the discrete probability distribution p of virtual water inflows V_{IN}, by distance category i, as,

$$SI^r = \frac{-\sum_i p(V_{IN}(i))\cdot \log p(V_{IN}(i))}{\log N}. \quad (13)$$

To integrate the basket of distance and functional diversity indicators, we construct a composite index as the weighted average of the basket of distance indicators A^r. The Relative Hydro-Economic Distance ($RHED_{F,k}$) is the weighted average of the basket of distance indicators, computed between Flagstaff and each of its trading partners. In this paper, we weighted each of the seven *A* distance indicators equally. As before for *A*'s, *RHED* distances were binned into categories of similar distance, then a normalized Shannon Diversity Index SI^{RHED} was computed from the distribution of virtual water inflows from each *RHED* distance category to create an integrated single measure of distance. To summarize, we developed a basket of seven hydro-economic functional distance indices A^r, one composite distance index *RHED* that integrates the basket, and for each distance index a corresponding functional diversity index *SI*. We also developed a vulnerability index *HNV* based on long-term renewable surface water stress.

3.3 Results

3.3.1 The City-Level Water Footprint

Flagstaff has an annual Net Blue Water Footprint E_F of 60.36 Mm^3 (921.78 m^3 per capita). Flagstaff's calculated V_{In} was 56.55 Mm^3 (836.60 m^3 per capita) and calculated V_{Out} was 7.15 Mm^3 (109.19 m^3 per capita), giving it a net Virtual Water Balance VWB_F of 49.40 Mm^3 (754.41 m^3 per capita). For the same year, the City of Flagstaff Utilities Division delivered (U_{urban}) 10.92 Mm^3 throughout the service territory. Flagstaff hydro-economy has a circularity index (CI_F) of 0.04, which indicates that

Flagstaff is heavily reliant upon nonlocal (outside the county) virtual water inputs into its hydro-economy. The VI of virtual water inflows ($VI_{k \to F}$) were $59 per m^3, while the VI of virtual water outflows ($VI_{F \to k}$) was $569 per m^3. Flagstaff's hydro-economy has a VIR_F of 9.64, increasing the value of its leveraged water resources by an order of magnitude by outsourcing less producing water uses and specializing more productive uses.

3.3.2 Virtual Water Import Source Characterization

For Flagstaff, 80% of its V_{In} originates within the state of Arizona and primarily from the Phoenix metropolitan area (PMA) and rural Arizona, see supplemental information (Table S1). While the Tucson metropolitan area is also a significant source of virtual water, it was an order of magnitude smaller than the PMA and rural Arizona (Table S1). Nebraska is Flagstaff's largest virtual water source outside of Arizona, followed by New Mexico. The Colorado River Basin states were large contributors of virtual water to the Flagstaff economy—California, Colorado, New Mexico, Utah, and Nevada ranked among the largest virtual water sources for Flagstaff. Spatial disaggregation and mapping of Flagstaff's water footprint shows that Flagstaff mostly outsources water use to the Southwestern United States (Figure 9).

Figure 9: Virtual water inflows into Flagstaff, AZ, originate mostly from the Southwestern US, specifically the Colorado River Basin, and are concentrated from rural Arizona and the Phoenix metropolitan statistical area. Nebraska and Northern California are the largest sources of virtual water outside of the Colorado River Basin. The 2,000 km band demarcates the approximate hydro-economic radius of Flagstaff's V_{In} trade network in the continental United States.

Agriculture was the largest component (76%) of Flagstaff's V_{In}. Previously reported findings indicated that agriculture represented 92% of the worldwide water footprint (Mekonnen & Hoekstra, 2011). Livestock is a small component of V_{In} (2.5%) because only water withdrawal by a livestock facility is attributed to the livestock sector; however, 26% of Flagstaff's V_{In} is attributable to animal feed. Flagstaff's annual per capita virtual water consumption is quadruple the reported blue water footprint of the United States of 239 m^3/capita/year (Mekonnen & Hoekstra, 2011). Rural areas and urban areas both figure prominently in Flagstaff's V_{In} exchange network. Over a third of

V_{In} is from metropolitan areas, underscoring the importance of city-city interactions in urban virtual water exchange (Figure 10). These results are influenced by trade with the PMA because it is an unusual metropolitan area that primarily exports agricultural virtual water and has a water intensity greater than the national average (R. Rushforth & Ruddell, 2015).

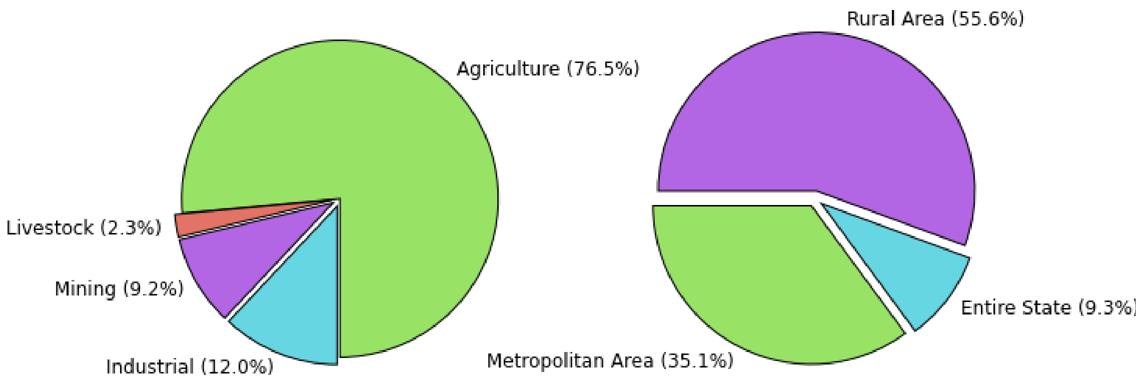


Figure 10: Virtual water inflows by economic sector and rural to urban geography type.

3.3.3 City-Level Virtual Water Production Characteristics

Flagstaff's virtual water outflow V_{Out} is 7.15 Mm^3. Rural Arizona area was the largest V_{Out} destination, followed by the Phoenix and Los Angeles metropolitan areas (Table S2). Over half (57%) of V_{Out} remained in Arizona and, given its CI_F, only 2.5% of V_{Out} remains within Flagstaff. Spatial disaggregation of the exchange network shows V_{Out} is concentrated in the Southwestern United States, especially Arizona, with a preferential flow to metropolitan areas and port cities (Figure 11). There were no agricultural or livestock operations found within the system boundaries, so V_{Out} consists of only industrial and mining commodities. V_{Out} from Flagstaff is primarily industrial goods, and the mining sector, including sand and gravel operations, has a smaller role in virtual water production (Figure 12).

Figure 11: Virtual water outflows from Flagstaff, AZ, are concentrated in the Southwestern United States, especially Arizona, but also reach national urban markets as well as Canada (via Detroit) and Mexico (via the Arizona border). Virtual water outflows to outside of the Southwest are to counties associated with metropolitan areas and port

cities. The 2,000 km band demarcates the approximate hydro-economic radius of Flagstaff's V_{Out} trade network in the continental United States.

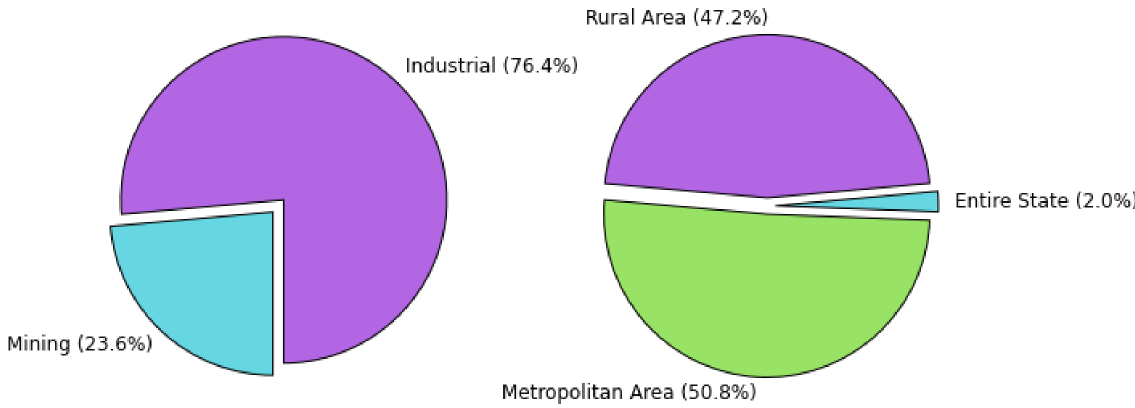


Figure 12: Flagstaff's virtual water outflows by economic sector and rural to urban geography type.

3.3.4 Value-Production in the US Hydro-Economic Network

The value intensity of goods varies by the economic sector (Table 2). Goods in the primary and secondary economic sectors that rely on the extraction of natural resources have lower value intensities than goods exchanged in higher sectors of the economy, such as industrial goods that are part of the tertiary sector. For Flagstaff, the measured $VI_{k \to F}$ of the livestock sector may be inflated due to the allocation of water used to produce animal feed to the agricultural sector (Table 3).

Table 2: Value Intensities and Value Intensity Ratios of Flagstaff's Hydro-Economic Sectors

Hydro-Economic Sector	$VI_{k \to F}$ **[USD/m^3]**	$VI_{F \to k}$ **[USD/m^3]**	VIR_F
Agriculture	3.72	0.00	0.00*
Livestock	48.10	0.00	0.00*
Mining	32.76	775.64	23.67
Industrial	435.44	498.68	1.15
All Sectors	59.41	568.34	9.57

**VIR_F is 0 due to lack of economic sector in Flagstaff.*

Table 3: V_{Out} Hydro-Economic Network Characteristics for Flow Percentiles and Distances

V_{Out} Flow Percentile	V_{Out} (Mm^3)	Mean V_{Out} Flow (Mm^3)	SD	Mean Distance (km)	SD	Cumulative V_{Out} (Mm^3)	% V_{Out}	% of Trading Partners
99th	0.24	0.17	0.23	1,193	1,112	5.44	76.1%	1%
95th	3.0×10^{-3}	0.04	0.12	2,098	1,219	6.45	90.2%	5%
90th	1.2×10^{-3}	0.02	0.09	2,277	1,131	6.74	94.3%	10%
~86th (x_{min})	7.8×10^{-4}	0.02	0.08	2,299*	1,090	6.84	95.7%	13%
52th	5.9×10^{-5}	4.5×10^{-3}	0.04	2,450	923	7.11	99.6%	48%

**Distance corresponds with the $x_{min,dist}$ of the V_{Out} hydro-economic network.*

SD – Standard Deviation

The value intensity of virtual water inflows ($VI_{k\rightarrow F}$) is less than the value intensity of virtual water outflows ($VI_{F\rightarrow k}$). This holds true for each sector of the economy in which Flagstaff participates, resulting in a VIR_F greater than 1. However, since Flagstaff does not produce goods in the agriculture and livestock sectors of the economy, the resulting VIR_F value is 0. Flagstaff's VIR_F is especially pronounced in the mining sector, indicating a relative comparative advantage in the mined goods it produces relative to the areas from which it sources mining sector products. Flagstaff's economy has a total VIR_F greater than 1, which indicates that the city is a value-producing node in the US hydro-economic network.

3.3.5 A Heavy-Tailed Power Law Distribution Describes Virtual Water Flows

Previous virtual water trade studies have found volumes of virtual water flows by country to follow PL and other "heavy-tailed" distributions relating virtual water trade volume to distance (Dalin, Konar, Hanasaki, Rinaldo, & Rodriguez-Iturbe, 2012; M. Konar et al., 2011; Suweis et al., 2011). The distribution of virtual water flows by trading partner could fit one of several candidate heavy-tailed distributions—PL, SE, LN, and ETPL distributions—so candidate distributions were fit to the datasets and compared using a log-likelihood test to determine the best candidate distribution (Figure 13). Log-likelihood test results show that the LN, SE, and ETPL distributions fit V_{In} by trading partner equally well, while a PL distribution is the best candidate distribution for V_{Out} by trading partner (Table S3). Across all distributions, the x_{min} parameter remained constant for both V_{In} (x_{min} = 1.4x10^{-4} Mm^3) and V_{Out} (x_{min} = 7.8x10^{-4} Mm^3) exchange networks.

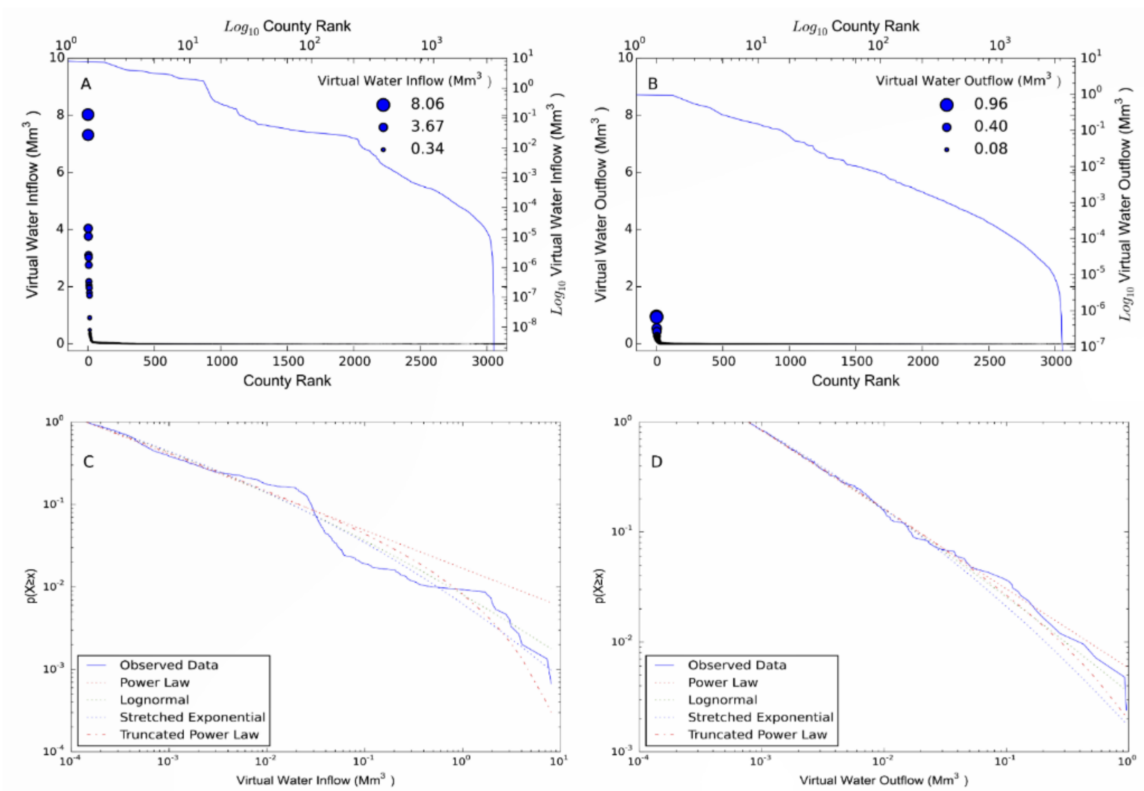


Figure 13: (A&B) Virtual water inflows and outflows for Flagstaff, AZ presented by rank. (C&D) The complementary cumulative distribution function (CCDF) of the heavy-tailed distributions are shown for the scaling range above x_{min}. Analysis revealed no significance difference in fit between the SE and TPL fits for inflows and no statistical difference between distributions for outflows. Only a handful of the trading partner counties account for the "heavy tail" and nearly all of the virtual water flows.

For the V_{In} and V_{Out} networks, 99.0% and 95.7%, respectively, of virtual water transferred is with trading partners closer than x_{min}, which only includes 48% and 13%, respectively, of the total trading partners. The x_{min} value separating the high-volume, heavy-tailed trading partners from the rest of the trading partners is associated with a specific distance, $x_{min,dist}$. For Flagstaff, the $x_{min,dist}$ for both V_{In} and V_{Out} is roughly 2,000 km, which corresponds roughly to the Southwestern US region and encompasses major trading partners such as Phoenix, Las Vegas, Southern California, Tucson, El Paso, Denver, Salt Lake City, Seattle, Portland, Dallas, Houston, and the western Great Plains. $x_{min,dist}$ is the effective radial dimension of Flagstaff's hydro-economic zone of influence and hinterland boundary.

In Flagstaff's relatively simple hydro-economic network, the large heavy-tailed trading partners were on average geographically closer to Flagstaff than other trading partners (V_{Out} Table 3; V_{In} Table 4). These results underscore that geographical distance is a primary factor determining a city's hydro-economic network structure. Flagstaff has its strongest economic relationships with its closest neighbors. Flagstaff is exceptionally vulnerable to exogenous hydrologic shocks (e.g., droughts) affecting its high-volume, heavy-tailed trading partners. These major partners mostly share a similar hydro-geography with Flagstaff and have similar or higher levels of water stress.

Table 4: V_{In} Hydro-Economic Network Characteristics for Flow Percentiles and Distances

V_{In} Flow Percentile	V_{In} (Mm^3)	Mean V_{In} Flow (Mm^3)	SD	Mean Distance (km)	SD	Cumulative V_{In} (Mm^3)	% V_{in}	% of Trading Partners
99th	0.81	1.51	2.02	1,246	537	48.29	85.1%	1%
95th	0.28	0.34	1.08	1,402	630	53.01	93.4%	5%
90th	6.3×10^{-3}	0.18	0.78	1,638	845	55.69	98.1%	10%
85th	1.6×10^{-3}	0.12	0.64	1,800	880	56.18	99.0%	15%
~52nd (x_{min})	1.4×10^{-4}	0.04	0.36	2,182*	877	56.69	99.9%	48%

**Distance corresponds with the $x_{min,dist}$ of the V_{In} hydro-economic network.*

SD – Standard Deviation

Less virtual water is imported from longer distances because the costs associated with moving goods to Flagstaff increases with distance and because water-intensive commodities such as agricultural products and raw materials are relatively massive and expensive to transport. There is an inverse relationship between V_{In} volume and county trading partner distance that is statistically significant at the p<0.05 level (Figure S1).

However, cross-country and long-distance virtual water transfers are observed in the data, and some of these distant trading partners are also high-volume partners. This expensive long-distance virtual water transfer must have a counterbalancing beneficial factor that can overcome the cost barrier. There is a significant, direct relationship (p<0.05) between $VI_{k \to F}$ and the trading partner's distance (Figure S2). This means that, for Flagstaff, more valuable and less water-intensive commodities are imported from longer distances, which is a pattern not seen in international virtual water trade where low-value, water intensive commodities and crops such as wheat and alfalfa are transported long distances.

In contrast to inflows, distance does not significantly influence the volume of virtual water outflows to a trading partner, but trading partner size (population) does. Flagstaff supplies more virtual water to more populous and urban trading partners ($p<0.05$; Figure S1). At the county level, 77% of virtual water outflow is to trading partners that have a larger population than Flagstaff, whereas only 53% of virtual water inflows originate from larger trading partners. This places Flagstaff roughly in the center of the spectrum of US communities on the nation's hydro-economic value chain and typology (R. Rushforth & Ruddell, 2015), trading in similar proportion with both larger metropolitan areas and smaller rural communities.

In summary, the structure of V_{In} hydro-economic network of this city is influenced more by distance and transportation cost of the trading partner, but the V_{Out} hydro-economic network of this city is influenced more by the population and market size of the trading partner. This difference in organizing principles originates in the highly specialized value-added economy of a city. Flagstaff is different from some cities in the literature (Shi et al., 2014) in at least two respects: (1) it is a regional city without much global or port trade; and (2) it has abundant regional raw material and agricultural trading partners. A typical city imports and consumes more energy, raw materials, and agricultural products than it produces, and produces and exports more industrial products and services than it consumes. The imports tend to have a lower *VI*, and to be more massive and expensive to transport, than the exports. As a result, a city's virtual water supply chain will tend to be skewed toward nearby suppliers with low transport costs, but its export network is less sensitive to transport cost and seeks high demand wherever it is located.

3.3.6 Flagstaff's Hydro-Economic Leverage, Vulnerability, and Functional Diversity

Flagstaff's hydro-economic network is highly leveraged upon virtual water resources (*HL = 5.17*). The high *HL* indicates that the V_{In} exchange network represents a potential vulnerability for Flagstaff. This will be true for most cities, because virtual water imports tend to be a large fraction of the city's water footprint. Flagstaff (Coconino County, Figure 6) has a Direct Water Stress Index (*DWSI)* of 0.29. However, its V_{In} exchange network has an Indirect Water Stress Index (*IWSI)* of 0.71. Flagstaff's virtual water resources are nearly 2.5 times more vulnerable to water scarcity than local resources, as indicated by the Systemic Virtual Water Risk (*SVWR)* of 2.45. The increased vulnerability of virtual water resources gives a Hydro-Economic Network Vulnerability (*HNV)* of 0.66, indicating that Flagstaff outsources water consumption to regions with greater water stress than local water resources, and this is likely due to the large role of the PMA and rural Arizona in Flagstaff's water supply chain. Significant indirect water vulnerabilities are also presented by the Central Valley in California, Southern California, the Denver metropolitan area, and northern New Mexico (Figure 14).

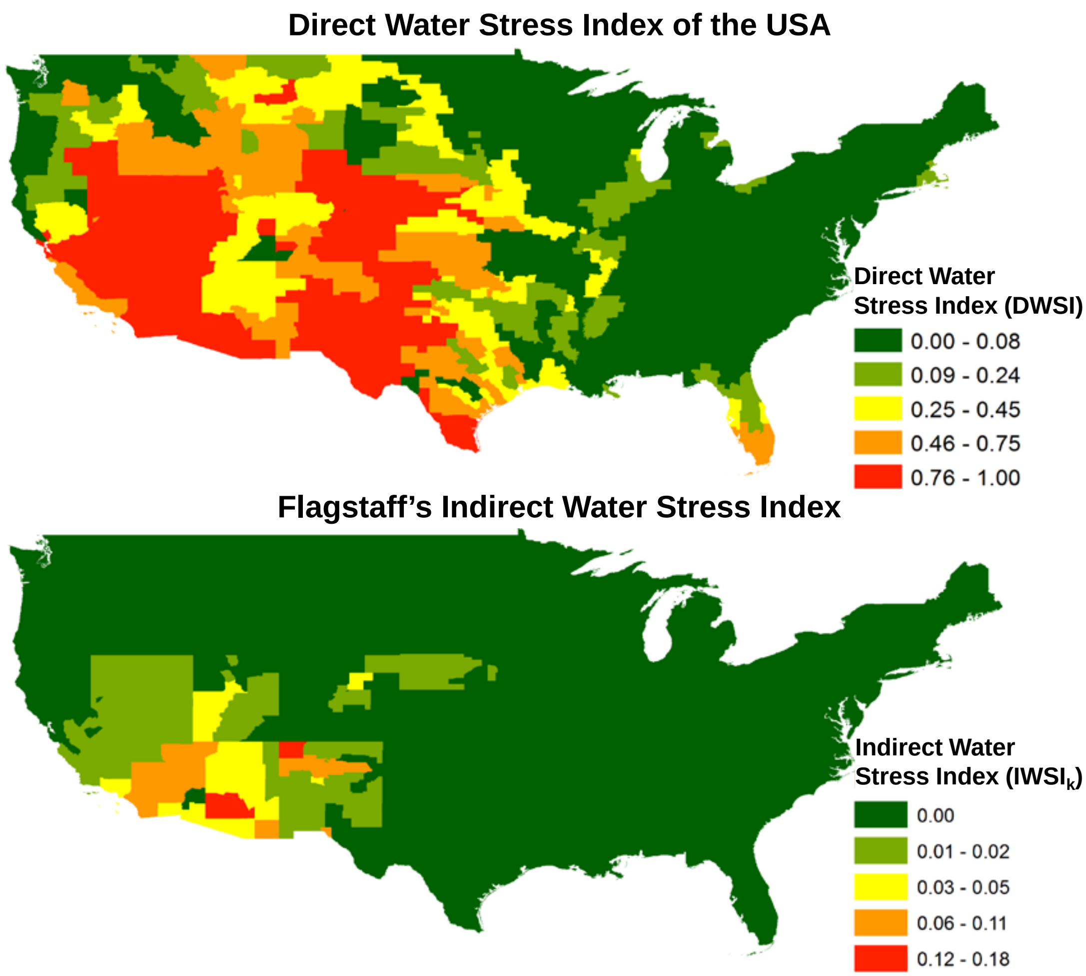
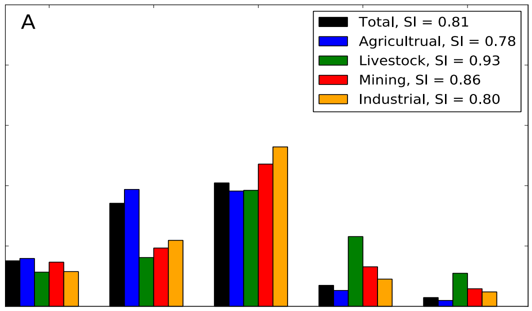


Figure 14: (Top) The Direct Water Stress Index (*DWSI*) for each county in the United States; this is the ratio of annual surface water withdrawals to available flows. (Bottom) Flagstaff's vulnerability to water stress, mapped as the Indirect Water Stress Index of each county in the United States with respect to Flagstaff's economy [$IWSI_k$; Equation 10]. The major areas of water stress in Flagstaff's virtual water trade network (inflows) are Maricopa County, Arizona and Pima and Cochise Counties in Arizona. The Central Valley in California and the Denver Metropolitan Area also areas of vulnerability to Flagstaff's economy.

The functional diversity of Flagstaff's virtual water inflows measured the virtual water volume weighted with respect to the *RHED* Index, a composite index of functional hydro-economic distance indicators. An *RHED* of 1 indicates a maximum ability to respond to hydro-economic shocks, and an *RHED* of 0 indicates the inability to respond to hydro-economic shocks. Flagstaff sources virtual water from a diverse array of geographic areas, but due to the heavy-tailed distribution of the V_{In} exchange network, the majority (>95%) of its virtual water originates from sources that are physically closer to Flagstaff, specifically within Arizona and the Colorado River Basin. Hydrological water scarcity in these areas is moderately (DI = 3) to highly (DI = 1) correlated to water scarcity in Flagstaff (Figure 15). One way for Flagstaff to create a more resilient V_{In} hydro-economic network is diversifying the network with respect to water scarcity by seeking suppliers in regions where water scarcity is uncorrelated to water scarcity in Flagstaff. This will also increase diversity with respect to the Physical Distance Indicator (*PDI*), the Shared River Basin Indicator (*SRBI*), and the Shared Water Governance Indicator (*SWGI*).



dustrial, SI = 0.74

Figure 15: The relative proportion of virtual water flows for each distance indicator category (A and RHED). Virtual water flows are evenly distributed across some diversity indicators (panel B), while there are others concentrated to a few scores (panel D, E, G), and the remainder fall in between (panel A, C). Overall (panel H, RHED), Flagstaff's virtual water flows tend to be sourced from counties that are somewhat similar but not identical to local hydro-economic conditions, probably because those suppliers are

physically close to Flagstaff. The labels along the x-axis are the bins used to group the discrete probability distribution along the y-axis [see Equation 12].

Shannon Diversity Indices (*SI*) were calculated for Flagstaff's V_{In} exchange network to characterize the diversity of agricultural, industrial, mining, and livestock virtual water flows and total virtual water flows. The overall functional diversity of Flagstaff's V_{In} exchange network is measured by the *SI* of the *RHED* index. The indicators developed for the *RHED* index do not comprise an exhaustive list, may vary by application and developmental needs, and can include other indicators of diversity, such as alternative transportation systems, financial systems, municipal bond ratings, and debt risk. Flagstaff's *HL*, *SVWR*, and *HNV* indicate that Flagstaff increases its exposure to water stress through commerce because it is highly leveraged upon virtual water trading partners that have a higher average water stress than Flagstaff, mostly in central and southern Arizona. However, increased vulnerability of the hydro-economic network to water stress accompanies increased functional diversity of the V_{In} exchange network. In summary, while Flagstaff's external water footprint and hydro-economic network structure increases Flagstaff's vulnerability to water stress, it also reduces Flagstaff's exposure to water stress (Figure 16).

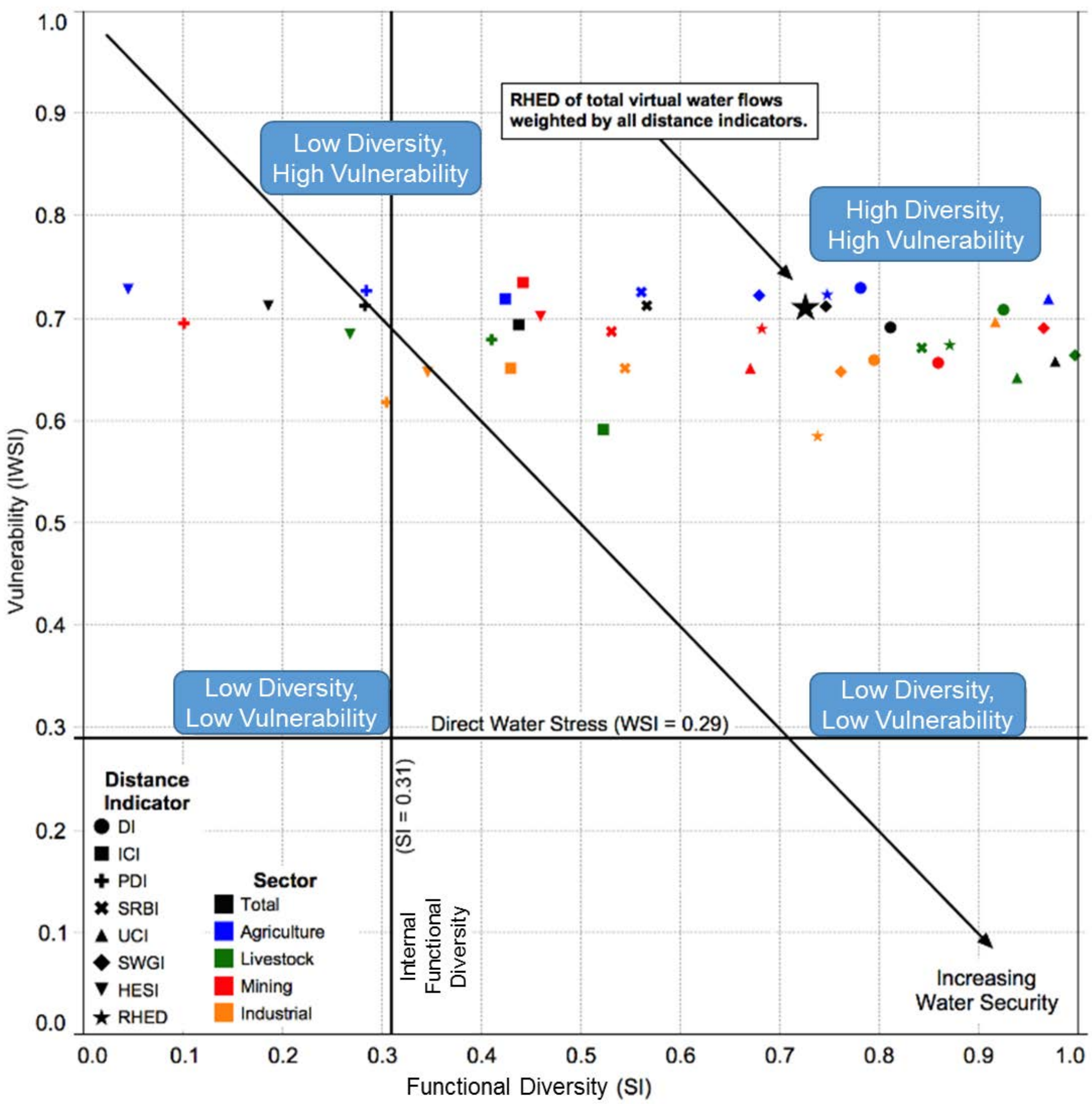


Figure 16: Flagstaff sources virtual water from a hydro-economically diverse set of counties in the United States and as a result is relatively resilient, but these counties are even more water-stressed than Flagstaff, yielding a relatively high hydro-economic vulnerability. Flagstaff could improve its water security by managing the hydro-economic network to reduce vulnerability to drought, but this should not come at the cost of its functional diversity. Flagstaff's internal functional diversity is measured with the SI^{RHED} metric. The two thresholds labeled in this figure show the Direct Water Stress Index of Flagstaff and Internal Functional Diverstiy of Flagstaff's Hydro-Economy (calculated with *Equation 8)*; water security increases as Flagstaff sources from virtual water come from more diverse and less water stressed geographic areas.

3.4. Discussion

3.4.1 Using the City's Water Footprint to Improve Policy

Consumption- and production-based water footprints for cities have the potential to be valuable management tools for cities because they are hubs of economic production as well as consumption (Sassen, 2011). While cities are centers of population and food demand, some metropolitan areas are also large exporters of food due to the colocation of farms at the urban fringe. Further, most cities have substantial virtual water demand in nonagricultural sectors of the economy, such as industrial and mining sectors. Our results underscore the important role that cities and urban areas have in the US domestic hydro-economic network—not just as consumers but also as significant exporters of virtual water and the value-added production hubs of the hydro-economy. Therefore, city-level virtual water analyses ought to account for both unidirectional and bidirectional virtual water exchange between all types of city and rural trading partners, instead of focusing solely on the city being solely a center of demand. This analysis should encompass at least a regional scope covering the city's complete hinterland, but should also possibly attend to more distant teleconnections where they are found to be substantial.

Water footprint accounting has previously been used as an awareness and informational tool. However, with further analysis, and only after spatial and economic disaggregation, consumption-based virtual water accounting can yield quantitative insight into the functional diversity of and potential vulnerabilities in the US hydro-economic network. Mapping the geographic origin of a city's or region's indirect water sources can potentially help municipal managers understand the indirect impact of drought, or other hydrologic shocks, to the functioning of a city's economy. While the municipal water manager does not have control over indirect (virtual) water resources, economic policy enacted at the municipality level and the purchasing decisions made by private-sector supply chain managers can potentially increase the functional diversity of hydro-economic networks and minimize the extent to which a city exposes itself to indirect water vulnerability in the supply chain. Mapping the indirect water stress of virtual water sources creates the knowledge necessary to detect early warning signs of potential disruptions (Suweis & D'Odorico, 2014).

This is a new type of policy based on benchmarking water footprints and the associated vulnerability and functional diversity impacts of those water footprints on a city's water security. Public policymakers and businesses need to measure and benchmark the water footprint before they can act on the information. This measurement and benchmarking should now take place, so that management can follow.

3.4.2 Determinants of a City's Virtual Water Network Structure

Flagstaff exchanges the bulk of its virtual water from very few trading partners that tend to be within a 2,000-km radius encompassing the Southwestern United States. This behavior creates a heavy-tailed power law distribution with respect to V_{In} and V_{Out} exchange volumes by trading partner. For both V_{In} and V_{Out} exchange networks, the trading partners within the heavy tail were geographically closer to Flagstaff than other trading partners. The negative scaling exponent found for the PL and ETPL distributions relating V_{In} and V_{Out} exchange volumes to distance indicates a hydro-economic preference for closer, and presumably less transport-intensive, trading partners. The structure of this city's virtual hydro-economic network shows no evidence of reacting water price signals; it is not based upon minimizing water withdrawals or minimizing vulnerability to water stress. Rather, minimizing distance (cost) between trading partners appears to organize the virtual water network more for inflows of transport-intensive agricultural and energy commodities than for outflows of more valuable and less transport-intensive services and manufactured goods, which are biased toward large, populous markets.

Statistical analysis of Flagstaff's trade network has identified an objective definition for the hydro-economic hinterland boundary, or zone of influence and dependency, of this city, and determined that the geographical distance radius of Flagstaff's hinterland is roughly 2,000 km, based on the $x_{min,dist}$ of Flagstaff's hydro-economic network, encompassing the Southwestern United States. Flagstaff's hydro-economic hinterland substantially overlaps with that of dozens of other metropolitan areas of the western United States as well as the Central Valley, High Plains, and Mississippi Embayment aquifers, which have been previously identified as critical to the US virtual water exchange network (Dang, Lin, & Konar, 2015; Marston, Konar, Cai, & Troy, 2015). However, the most important teleconnections exist within the state of Arizona, owing to Flagstaff's role as a regional city. Any rural county therefore potentially belongs to the hinterland of several different cities, and cities can themselves be a part of each other's hinterlands. Whereas the political entity of Flagstaff is a small contiguous geographical boundary subsumed within Coconino County, the hydro-economic entity of Flagstaff is a spatially diffuse and networked entity sprawling across the western United States. The city's hydro-economy can therefore be conceptualized and managed as such.

3.4.3 Optimizing a City's Hydro-Economic Security

Foundational works identified virtual water as a means to overcome local drought by gaining access via commerce with areas with more abundant water resources (Allan, 1998). However, for Flagstaff, this may not be the case: commerce increases exposure to water stress by several multiples (*SVWR = 2.45*) because Flagstaff's virtual water originates predominantly from southern Arizona and California sources with high water stress. Ninety-two percent of virtual water inflows to Flagstaff originate from within the Colorado River Basin's states (Figure 5). Continued drought in the Colorado River Basin may potentially disrupt Flagstaff's economy and damage water security via both its direct physical and indirect "virtual" water resources. While Flagstaff's indirect water footprint is both bigger and may potentially be more vulnerable than its direct water footprint, the geographic source of virtual water resources can be shifted more easily than sourcing and developing a diverse and resilient set of new physical water resources within Coconino County. Flagstaff's indirect water footprint is relatively large. It is diverse and therefore it can be used to respond to drought in and around the Colorado River Basin.

Optimizing Flagstaff's hydro-economic network entails increasing the functional diversity (diversifying A^r's and maximizing *SI*'s), while reducing vulnerability to water stress or minimizing *HNV* (It should be noted that the current *IWSI* should not be taken as a predictor of future *IWSI*.). This optimization involves selection of trading partners and also management of the relative dependency of the city on local versus indirect water supplies (leverage *HL*). Under these optimization criteria, systemic vulnerability to water stress is minimized, and if any specific part of the water supply chain were impacted by water stress, it would be as easy as possible to replace that source without hindering the functionality of the network. This functional diversity gives the network the ability to persist and reorganize in response to endogenous and exogenous shocks (Folke, Colding, & Berkes, 2003). It appears in this case that vulnerability and functional diversity are in tension, making this an ideal application for multiobjective Pareto optimization techniques. It is however outside the scope of this paper to apply an optimization technique to Flagstaff's hydro-economic network. Analysis of this type would depend on pricing, supply chain flexibility, the wealth of the node of interest within the hydro-economic network, and the county-level water stress at the time of the outsourcing decision. A city's hydro-economic security involves the minimization of hydro-economic network vulnerability and the maximization of hydro-economic network functional diversity, among other more conventional considerations of reliability, affordability, and quality of the physical water supply. This could be accomplished, for example, by shifting some of the agricultural supply chain away from southern Arizona to a less water-stressed supplier in a distant location. For a city in a water-scarce region, sourcing more water-intensive goods from distant and water-abundant locations like the Pacific Northwest or the Great Lakes (*The Economist*, 2015) would potentially decrease water vulnerability and enhance water sustainability. Of course, this policy would come at a cost and might potentially require building an even more highly leveraged and highly specialized hydro-economy to generate the additional revenue needed to support higher costs.

Flagstaff has little economic diversity and little to no hydro-economic functional diversity within its own local county boundaries, with respect to the functional distance metrics we defined. Flagstaff has dramatically increased the functional diversity of its hydro-economic network by trading, because it has access to a larger hydro-economic diversity of suppliers than it would otherwise. Flagstaff specializes in manufacturing and services, and appears to neglect the primary or natural resource economy, including agriculture. An operational policy should attempt to optimize the hydro-economic network so as to reduce vulnerability without reducing functional diversity.

These findings may have direct implications for the movement to source urban food and goods "locally." While it is true that locally sourced goods and services generally keep money within the local economy and reduce carbon emissions associated with transport, locally sourced water may not always be the best choice for water sustainability and security. "Net zero" water and "local" water cannot be assumed to be better solutions than outsourcing to distant suppliers who utilize abundant water sources. There is no single answer for what is the most sustainable and secure choice. Each city's optimal solution will depend on its detailed hydro-economic context, and this context must be assessed in detail before developing solutions. Managing the city's water footprint is nothing like managing the city's carbon footprint. A smaller water footprint may not necessarily better. Instead, a more diverse water footprint sourced from less water-stressed locations is better. Of course, reducing water use can reduce water stress, so water conservation and efficiency programs also serve this end. The goals for a city's water sustainability and security should be to take pressure off stressed water supplies in specific locations to improve the vulnerability and functional diversity profiles of the city's direct and indirect water supplies. This can be accomplished by managing the water footprint and reshaping the hydro-economic network through managing the water supply chain.

Flagstaff's hydro-economic network is concentrated in the Southwestern United States and, specifically, the Lower Colorado River Basin. Given the current projections for drought in the region (Seager et al., 2007) and the ongoing historically significant drought and water loss in California (Castle et al., 2014; Diffenbaugh, Swain, & Touma, 2015; Mann & Gleick, 2015), the *HNV* provides potential insight into the vulnerability of Flagstaff's indirect water resources to hydrological and meteorological shocks. Due to the heavy-tailed distribution of virtual water inflows in the V_{In} exchange network, shocks to only a few locations could significantly impact Flagstaff's economy. To overcome these risks, firms should evaluate their water supply chains and diversify to less hydrologically stressed areas. By measuring and managing the water footprint, cities could potentially increase hydro-economic functional diversity, decrease vulnerability drought, and boost water security.

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CHAPTER 4: THE THREE COLORADO RIVERS: THE HYDROLOGIC, LEGAL, AND ECONOMIC ALLOCATIONS OF THE WATER IN A SHARED RIVER BASIN

4.0 Abstract: The reallocation of surface water rights is not easily revisited because the political capital to reallocate water rights often cannot be recovered. Take the Colorado River Compact: it was signed in 1922 and has remained in place for nearly a century. Since its signing, the population of the Colorado River Basin states have increased tenfold, while average flows have decreased due to environmental and climatic threats unforeseeable to the Compact signers. While legal doctrines govern the physical flow of water, as economies have become more integrated, water has become increasingly shared through the economic trade in addition to physical infrastructure. Thus, the Colorado River is at once three rivers operating at differing timescales: a physical river operating at a geologic timescale, a legally allocated river operating at the generational timescale, and an economically reallocated river through virtual water transfers operating at a short-term, transactional timescale. This study presents findings of the virtual water complement to the Colorado River Compact. The goal of this study is to determine how the legal allocation of physical water flows compares to the virtual water allocation in a shared river basin. We find that California is the major recipient of the virtual allocation of the Colorado River, while Arizona is the most important node according to virtual water transfer network statistics.

4.1 Introduction

The Colorado River Basin (CRB) is no longer composed of frontier states. The seven CRB states—Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming—contribute 19% of the US GDP (U.S. Bureau of Economic Analysis, 2014), and if these states were a country, the combined GDP would be the fifth largest economy in the world (U.S. Bureau of Economic Analysis, 2014; World Bank, 2015). However, potentially constraining economic growth is decades of drought in the Colorado River Basin that has strained basin-wide water management policies. The elevation of Lake Mead is approaching levels that, if reached, would put in motion a set of emergency water management plans to curtail water deliveries to junior water rights holders in the CRB (Glennon & Pearce, 2007). While a shortage declaration will impact water deliveries to high volume, low value water-using activities first, such as agriculture in central Arizona, southern Nevada, and the Upper Basin (MacDonnell, Getches, & Hugenberg, 1995), the unprecedented declaration of a shortage on the Colorado River, will have unknown social, hydrologic, and economic impacts at the regional, national, and global scale. This paper focuses on the regional implications of drought and a shortage declaration using virtual water transfers and network statistics to identify critical nodes in the Colorado River hydro-economic network.

This historical water management precipice in the Southwest United States is a result of the confluence of ongoing drought, exacerbated by climate change (Niklas S Christensen, Wood, Voisin, Lettenmaier, & Palmer, 2004; Mann & Gleick, 2015; Seager et al., 2007), demographics, and political and economic negotiations dating back to the first formal agreement of water sharing between the seven CRB states. Signed in 1922, the Colorado River Compact (the Compact), apportioned 16.5 million acre feet (MAF) between the Upper Basin (Colorado, New Mexico, Utah, and Wyoming) and Lower Basin (Arizona, California, and Nevada), which were allocated 7.5 MAF each, and Mexico (United States Bureau of Reclamation, 2008), which was allocated 1.5 MAF, specifically for agriculture, in the Colorado River Delta region (Christensen & Lettenmaier, 2007). Apportioning the river in the Upper and Lower Basin took different paths: where the Upper Basin allocated water by the proportion of flow each state contributed to the River, the Lower Basin allocated the river by the population of each state at the Compact's signing. Under this sharing agreement, California received the majority of the Lower Basin's allotment, and most overall of any state, because the young states of Arizona and Nevada were yet to undergo major population growth (MacDonald, 2010; Ross, 2011).

Meticulous record keeping and paleohydrological work reconstructing Colorado River flows have revealed a fundamental mismatch between the sociopolitical/legal system that governs the river and the hydrologic and economic reality of the river. The moving average of the Colorado River flow used as the basis for the Compact was based upon an anomalous wet period (Woodhouse, Gray & Meko, 2006). The population of the Colorado River Basin has increased tenfold since the signing of the Compact, and all seven CRB states have created, or are constructing, large-scale water infrastructure to utilize their full Colorado River water right, exacerbating the mismatch between the volume of Colorado River water legally allocated and physical available.

Infrastructure projects in the CRB provide basin states the ability to divert the Colorado River to major population centers and irrigation districts outside the physical catchment boundary. For example, Colorado's Big Thompson project diverts over 200,000 acre-feet of Colorado River water across the Continental Divide and into the Big Thompson River for delivery by the Northern Colorado Water Conservancy District (Howe, 1987); the Central Utah Project, once completed, will provide the Salt Lake City metropolitan area access to Colorado River water (Booker & Young, 1994); New Mexico diverts their share of the Colorado River from the San Juan River, a tributary, over the continental divide and into the Rio Grande for use by Albuquerque (Meyers, 1966); and 4.4 MAF is diverted away from the Colorado River watershed to Southern California (Robison & Kenney, 2012). These infrastructure projects and the future planning areas create an actual sociohydrological watershed that is 45% larger in area than the actual physical watershed and a flow allocation that is 11%–22% greater than long-term flows (Niklas S Christensen et al., 2004); Figure 1). In negotiation for US federal funds to build the Central Arizona Project (CAP), which conveys water through the Sonoran Desert to thousands of acres of farmland and the Phoenix and Tucson metropolitan areas, Arizona accepted that the CAP would have junior water rights status on the river (Glennon & Pearce, 2007). Therefore, if a shortage were to be called on the Colorado River, Arizona would be the first to lose a portion of its water rights so that senior water rights holders would not be impaired by the shortage on the river.

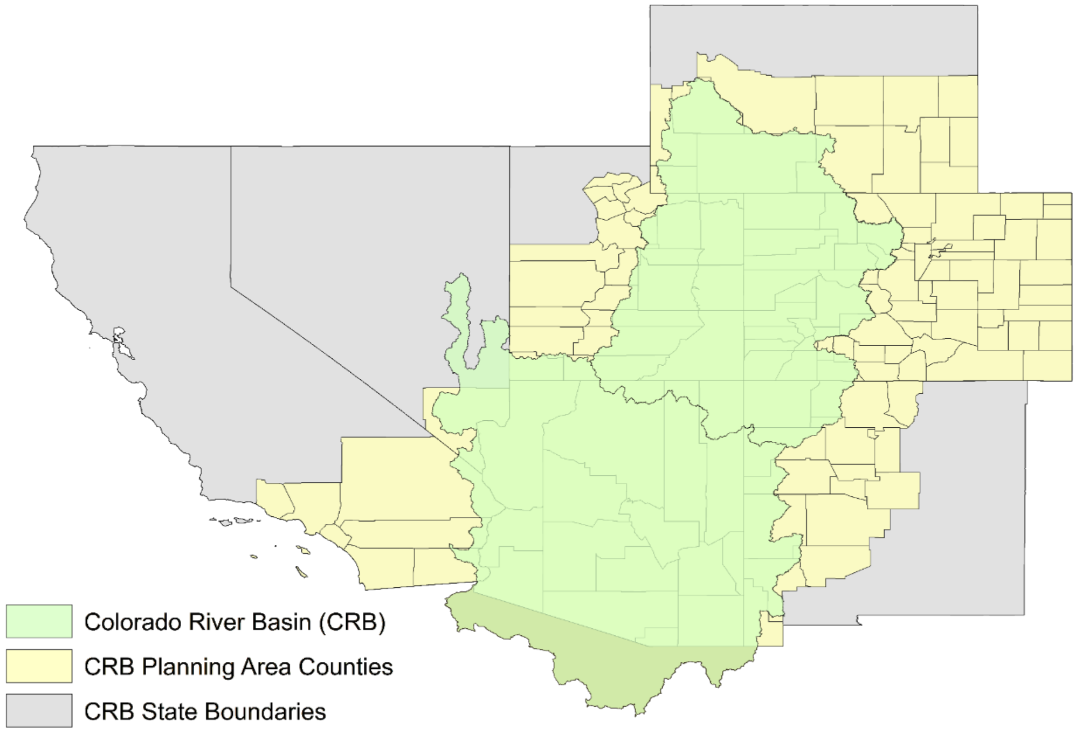

Figure 17: The nested geographies of the Colorado River Basin. The outline in grey shows the full extent of the Colorado River Basin States. The yellow area shows the counties that are included in the Colorado River Basin planning area; areas of current and future Colorado River water use. The area in blue is the physical watershed boundary for the Colorado River.

Because the ramifications of a shortage call on the Colorado River are high, methods must be developed to evaluate how such a decision would propagate through the Colorado River Basin hydro-economic impacts through coupled-natural human (CNH) systems (Liu et al., 2007; Liu et al., 2015). Virtual water can be employed to measure hydro-economic connectivity within the water supply chain. Following from this, we propose using intrabasin virtual water flows as a method to measure hydro-economic connectivity among Colorado River Basin states to develop a framework to describe the three Colorado Rivers—the physical, legal, and economic rivers. The physical Colorado

River is the natural flow regime of the river operating over geologic timescales. The legal river allocates the physical river according to socioeconomic and sociohydrologic interests, facilitating the distribution of the physical river through infrastructure over generational timescales. The distribution of the physical river can occur within the basin, contra to the natural flow of the river and to areas outside of the river basin. This extends the physical watershed boundaries to a sociohydrological boundary, which includes the social component of the river in addition to the physical watershed (Lane, 2014). For the CRB, this expands the watershed to include areas outside the physical watershed that receives Colorado River water (Figure 1). The economic river then reallocates the legal river through the withdrawal and use of water to produce goods and services. The mechanism of this reallocation is virtual water transfers within and outside the basin, and occurs at short-term transactional timescales. The complex interactions between the three river systems governing the Colorado River are an example of hydro-complexity (Kumar, 2015). We employ this framework to evaluate the direct and indirect impacts of shortage on the river using state-to-state and county-to-county virtual water and economic flows.

4.2 Virtual Water Flow Characteristics of the CRB States

Previous virtual water studies of the United States, including the western United States and the CRB, have highlighted the large volumes of water that are mobilized via agriculture and power generation. At the national level, the total state-to-state agricultural virtual water flow within the United States was estimated to be 158 million acre-feet, with California having the largest water footprint (Mubako & Lant, 2013). At the metropolitan area scale, studies have found the Phoenix metropolitan area hydro-economy to be highly regionalized and concentrated in the Southwest United States (R.

Rushforth & Ruddell, 2015). Wyoming and Arizona are the largest virtual water exporters within the Western Electricity Coordinating Council (WECC) grid and California was the largest importer of virtual water via electricity in the western United States (B. L. Ruddell, Adams, Rushforth, & Tidwell, 2014). Across the Colorado River Basin, electricity consumed 330,313 acre-feet of water and exported nearly half—159,068 acre-feet—to demand located outside of the river basin (Kelley & Pasqualetti, 2013). Beyond quantifying flows, virtual water studies illustrate the strategic importance that the Colorado River Basin plays as a domestic source of virtual water for the United States.

For the CRB basin states, the water flowing in the Colorado River is a shared natural resource that is stored in central reservoirs and distributed through hundreds of kilometers of aqueducts via large-scale diversion projects. Since the large-scale diversion projects remove water from the main stem of the Colorado River to geographic areas that are either outside of the river basin—which is the case in California, Colorado, New Mexico, Utah, and Wyoming—or against the flow of the basin—which is the case in Arizona and Nevada—the Colorado River provides a rivalrous water resource. Use of the Colorado River's water resources necessarily precludes use by other states unless there is a return flow into the river or sharing agreement in place. Therefore, rivalry increases along the Colorado River as it flows from its headwaters to the US border, and eventually the Colorado River Delta, as the total number of potential users governed by a "use it or lose it" water doctrine increases. Due to this, at the basin-scale, virtual water transfers represent a strategic trade-off between local consumption and in-basin outsourcing. The importance of virtual water, and its productivity, necessarily increases further down the watershed as it can be used as leverage to ensure that water remains in the river long enough to reach downstream users.

Through virtual water, basin states can access a greater percentage of the river's flow than the legally defined allocations, which results in a hydro-economic reallocation of the original physical allocation of water. This rivalry can have several implications on the availability of Colorado River water. First, if a water-using activity is outsourced to a neighboring state because it is cheaper to produce that good in that state, there may be an overall change in efficiency that results in more or less water consumption than if no intra-basin trade occurred, and this could decrease or increase physical flows available to states consuming virtual water during a shortage. Secondly, if the virtual water sources within the river basin are junior water rights holders, the strategically outsourced good is subject to regulatory and legal water allocation risk in addition to the hydrological risk present within the basin. Third, if the water rights of virtual water consumers are greater than water rights of virtual water producers, a shortage could impact the water supply chain of consumers and drive. This is the first study to assess virtual water allocation at the river basin level and analyze the implications of a shortage call on basin-level virtual water balances and compare with the physical and hydrological 4.3 Methodology.

4.3.1 Study Area

Due to the large-scale diversion projects that physically export Colorado River water outside the river basin boundaries, the boundaries for this study were expanded to include all of the areas in the US Bureau of Reclamation Colorado River Water Demand and Supply Study. Therefore, the boundaries of this study are the broader sociohydrological boundaries, rather than the physical catchment boundaries (Figure 1), which includes parts of Southern California, the Great Basin, Missouri River watershed, Rio Grande watershed, and Arkansas River watershed. Arizona is the only Colorado River Basin state that is almost wholly within the physical boundaries of the Colorado River Basin. The socio-hydrolgoical boundaries of the Colorado River provide a richer context for this study because these boundaries capture the full extent of current and future Colorado River water utilization by basin states.

4.3.2 County, State, and River Basin-Level Virtual Water Flows

Virtual water flows are indirect uses of water resources. Virtual water inflows (V_{In}) and outflows (V_{Out}) were derived from national commodity flow data (R. Rushforth & Ruddell, 2015) and disaggregated to the county level using employment data (US Census Buearu), agricultural establishment data (Boryan, Yang, Mueller, & Craig, 2011; USDA National Agricultural Statistics Survey), and population data (US Census Buearu, 2012). Virtual water flows from each CRB county are geographic extracts from the National Water Economy Database (NWED), which is part of the larger National Water-Economy Project (NWEP;(B. Ruddell & Rushforth, 2015; R. Rushforth & Ruddell, 2015) . Virtual water flows were analyzed with the Embedded Resources Accounting (ERA) Framework (B. L. Ruddell et al., 2014; R. R. Rushforth, Adams, & Ruddell, 2013), which are a minor variant on the standard Water Footprint Assessment method (Aldaya, Chapagain, Hoekstra, & Mekonnen, 2012) that explicitly considers multiple boundary conditions—in this case, county, state, physical, and sociopolitical river basin boundaries—and both virtual water flow and currency flow networks.

For a geographic area in the Colorado River Basin, the water footprint was calculated on the basis of direct uses of "wet" water resources (*U*) that may originate from within (U^l) and outside (U^x) a geographic boundary and virtual water inflows (V_{In}) and outflows (V_{Out}) (Equation 1). The water footprint then constitutes flows from the three rivers, where U^l are flows from the hydrologic river; U^x are flows from the legal river; and V_{In} and outflows V_{Out} are flows from the economic river.

$$F = U^l + U^x + V_{In} - V_{Out} \qquad [m^3] \qquad (1)$$

Since there are multiple external sources of direct or "wet" and indirect or "virtual" water, the U^x, V_{In}, and V_{Out} terms are summed over all external direct water sources (n) and all indirect water sources (k), for each commodity in the trade database (c). The full ERA equation for the county's net water footprint (K) is shown Equation 2 where $V_{In} = \sum_{c,k} V_{c,K \to k}$ and $V_{Out} = \sum_{c,k} V_{c,K \to k}$.

$$F = \sum_n U_n + \sum_{c,k} V_{c,K \to k} - \sum_{c,k} V_{c,k \to K} \qquad [m^3] \qquad (2)$$

Using commodity class definitions, Equation 2 can be grouped into agricultural, livestock, mining, and industrial economic sectors (s) (Equation 3).

$$F = \sum_n U_n + \sum_{k,s} V_{s,k \to K} - \sum_{k,s} V_{s,K \to k} \qquad [m^3] \qquad (3)$$

A CRB state's virtual water balance (VWB_S) is the difference between V_{In} and V_{Out} (Equation 4).

$$VWB_S = \sum_{c,k} V_{c,k \to K} - \sum_{c,k} V_{c,K \to k} \qquad [m^3] \qquad (4)$$

Each flow of virtual water between trading partners has a reciprocal flow of value calculated simultaneously with V_{In} and V_{Out}. The value intensity (VI; Ruddell et al., 2014) of virtual water flows is calculated as the ratio between virtual water and currency flows for an aggregated sector of the city's economy (Equations 5 and 6). Value intensity is simply water productivity, assessed against either direct or indirect water uses.

$$VI_{k \to K} = \frac{\sum_{c,k} V_{c,k \to K}}{\sum_{c,k} USD_{c,K \to k}} \quad \text{[USD/m}^3\text{]} \quad (5)$$

$$VI_{K \to k} = \frac{\sum_{c,k} V_{c,K \to k}}{\sum_{c,k} USD_{c,k \to K}} \quad \text{[USD/m}^3\text{]} \quad (6)$$

A county's value intensity ratio (*VIR*) can then be defined as the ratio between $VI_{K \to k}$ to $VI_{k \to K}$.

$$VIR = \frac{VI_{K \to k}}{VI_{k \to K}} \quad (7)$$

Finally, the fraction of a county's virtual water that stays within its state (*S*) relative to the CRB planning area (*CRB*) and the CRB relative to the United States (US) was calculated to understand if a county had a greater presence within the regional or national hydro-economic network.

$$Fraction_{Within\ State} = \frac{\sum_{c,K} V_{c,k \to S}}{\sum_{c,k} V_{c,k \to US}} \quad (8)$$

$$Fraction_{Within\ Basin} = \frac{\sum_{c,K} V_{c,k \to CRB}}{\sum_{c,k} V_{c,k \to US}} \quad (9)$$

Because each state contains a specific set of counties, aggregating county-level virtual water flows to the corresponding state level allows for the calculation a VWB-adjusted CRB allocation (CRB_{VWB}), which is a measure of a state's true impact on the Colorado River.

$$CRB_{VWB,S} = U_S + V_{S,In} - V_{S,Out} \quad \text{[m}^3\text{]} \quad (10)$$

In Equation 10, U_S is equal to a state's legally allotted CRB allocation set in the Law of the River.

4.3.3 Three Rivers Framework (TRF)

Using the TRF, the hydrologic river (HR_S) is the volume of natural flow contributed by each state to the overall river flow. The legal river (LR_S) is the volume of river water allocated to each state. Given these, the socio-hydrological endowment (SHE_S) of a CRB state is the volume of water in excess of or less than the natural flow.

$$SHE_S = LR_S - HR_S \qquad [m^3] \qquad (11)$$

The socio-hydrological impact of a CRB state (SHI_S) is that the Colorado River is then taken as the sum of the state SHE_S plus its virtual water balance (VWB_S).

$$SHI_{S,CRB} = SHE_{S,CRB} + VWB_S \qquad [m^3] \qquad (11)$$

The SHI_S is a measurement of a CRB state's combined hydrologic, legal, and economic impact on a river.

4.4 Results

4.4.1 County-Level Virtual Water Flow

State-level virtual water flow volumes obscure much of the nuance of the virtual water trade network. Variations between virtual water import and export are highly dependent on population, hydro-economic specialization, and urban form. Typically, rural agricultural counties tend to be virtual water exporters, while highly urbanized counties tend to be importers of virtual water (Figure 18).

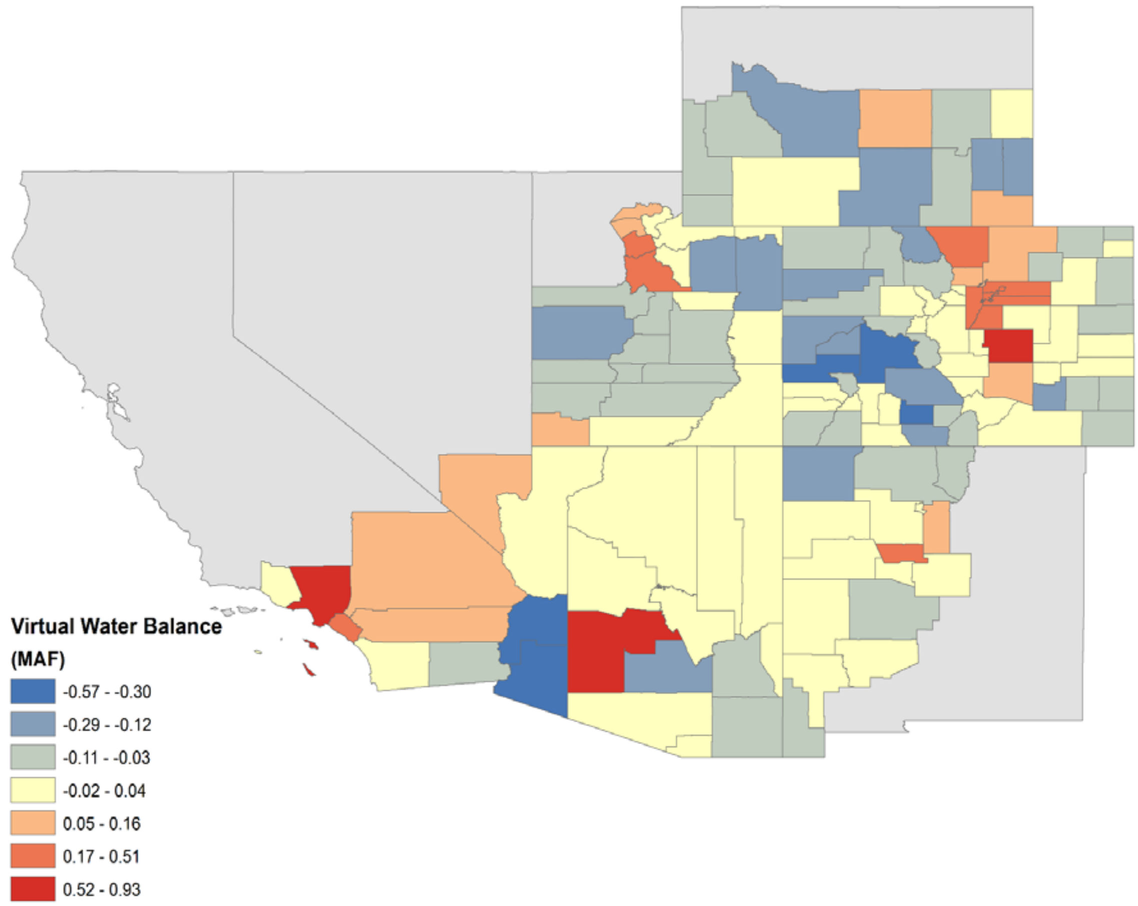

Figure 18: Virtual water balances at the county level reveal nuances masked at the state level. Counties associated with densely populated urban areas tend to have positive virtual water balances and are therefore net imports of water within the Colorado River Basin. Rural, agricultural counties are typically virtual water exports with negative virtual water balances. Arizona contains both large virtual water importing and exporting counties.

Exceptions to this pattern are highly urbanized counties with large metropolitan areas that still have significant acreage under irrigated agriculture, (e.g., Maricopa County, AZ, as well as Riverside and San Bernardino County, CA). Though these counties have a significantly positive virtual water balance, virtual outflows are still large relative to other counties in the CRB. The most significant exporting regions within the Colorado River Basin are along the Colorado River in Arizona (La Paz and Yuma Counties), western Colorado, and central and western Utah.

The hydro-economic importance of virtual water exporting counties within the Colorado River Basin can also be estimated by measuring how much of total virtual water export stays within the CRB. These counties have a large portion of their virtual water network concentrated within the CRB. Therefore, shocks that affect their water supplies in turn affect the hydro-economic performance of other CRB counties, inadvertently affecting both legal and economic components of water allocation in the hydro-economic network (Figure 19, Table 5).

Table 5: US-Level and CRB-Level Virtual Water Flows

State	US-Level Virtual Water Flows, Mm^3			CRB-Level Virtual Water Flows, Mm^3		
	Inflows	Outflows	Balance	Inflows	Outflows	Balance
AZ	4.36	5.43	*-1.08*	0.90	0.76	0.15
CA	8.98	4.48	4.50	1.41	0.61	0.79
CO	2.69	10.87	*-8.18*	0.57	1.36	*-0.79*
NM	1.16	1.36	*-0.20*	0.21	0.19	0.02
NV	0.91	0.27	0.64	0.19	0.04	0.15
UT	1.99	3.17	*-1.18*	0.38	0.45	*-0.06*
WY	0.63	3.48	*-2.84*	0.16	0.41	*-0.25*
Total	**20.73**	**29.06**	***-8.33***	**3.81**	**3.81**	**0.00**

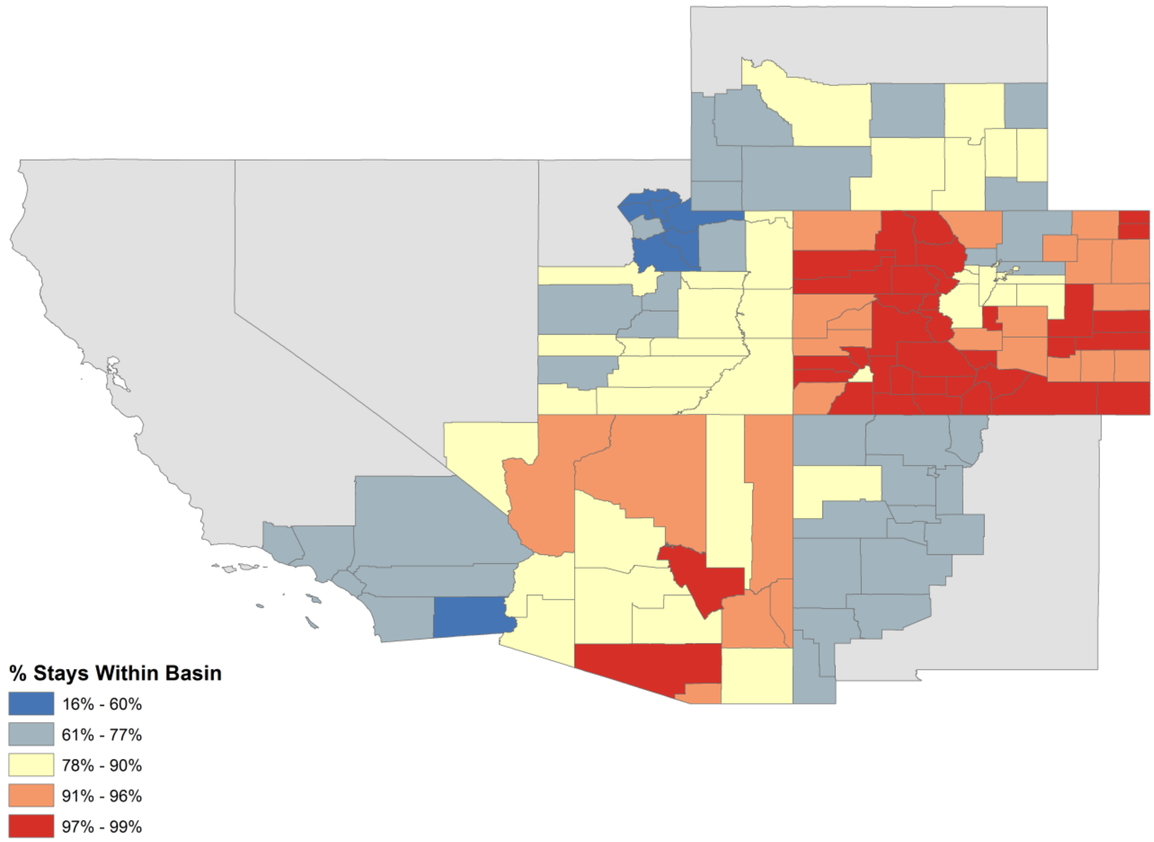

Figure 19: County-level trade patterns vary with respect to the percentage of water that stays within the Colorado River Basin. Virtual water flows from Colorado counties tend to stay within the basin due the large fraction of virtual water that stays within the state. Arizona also has a large fraction of counties that trade almost primarily within the Colorado River Basin. Virtual water from Southern California and the Salt Lake City metropotlian area tends to leave the Colorado River Basin.

4.4.2 State-Level Virtual Water Flows

Virtual water flows in the Colorado River Basin result in the interstate mobilization of 12.87 MAF, which is roughly 78% of the total flow legally allocated by the Colorado River. Virtual water flow includes surface water and groundwater, therefore the virtual water transfers can exceed the mean annual flow of the Colorado River. The lowest three-year running average of flow in the Colorado River and Lee's Ferry was 5.4 MAF, less than half the volume of water transferred via virtual water trade. Total virtual water flow within the Colorado River Basin points to how effectively the hydro-economic networks reallocate water between geographies.

The Lower Basin, which contains Southern California, the largest population center and recipient of Colorado River water, as well as Arizona, and southern Nevada dominates virtual water flow. California is the largest importer of virtual water in the CRB, followed by Colorado and Arizona, while Colorado is the largest exporter, followed by Arizona and Wyoming (Table 6). The largest state-to-state virtual water transfer is from Colorado (Upper Basin) to California (Lower Basin), and Arizona (Lower Basin) to California. Virtual water trade in the Colorado River exhibits a home bias effect that is also observed in intrastate and national scales hydro-economic networks (Reimer, 2014; R. Rushforth & Ruddell, 2015).

Table 6: Virtual Water Inflows and Outflows by Colorado River Basin State

	Inflows			**Outflows**			**Circular Flows**			**Balance**	
State	*VW (MAF)*	*VF (B$)*	*VI ($/gal)*	*VW (MAF)*	*VF (B$)*	*VI ($/gal)*	*VW (MAF)*	*VF (B$)*	*VI ($/gal)*	*VW (MAF)*	*VF (B$)*
AZ	0.63	70	2.93	0.48	35	4.47	0.27	121	0.74	0.15	35
CA	1.05	127	2.7	0.26	43	1.96	0.36	412	0.28	0.79	84
CO	0.31	80	1.28	1.11	125	2.88	0.25	1194	0.07	-0.79	-45
NM	0.19	21	2.99	0.17	31	1.81	0.02	129	0.04	0.02	-10
NV	0.18	26	2.28	0.03	1	8.98	0.01	10	0.2	0.15	25
UT	0.32	44	2.33	0.38	85	1.45	0.07	179	0.12	-0.06	-41
WY	0.1	14	2.4	0.36	61	1.92	0.05	75	0.23	-0.25	-47
Total	**2.79**	**382**	**2.38**	**2.79**	**382**	**2.38**	**1.02**	**2120**	**0.16**	**0**	**0**

Virtual water flow (VW); Value flow (VF); Value Intensity (VI)

4.4.3 A Virtual Water–Adjusted Colorado River Allocation

Hydro-economic connectivity within the Colorado River Basin results in virtual water transfers between the Upper and Lower Basin (Table 7). The largest state-to-state virtual water connection transfers water from Wyoming into Colorado; Colorado into Southern California; Arizona into California; and Colorado into Arizona. Interstate virtual water trade results in the Upper Basin, of which Arizona is also a small fraction, subsidizing water consumption in the Lower Basin via virtual water transfers. While developing water storage and conservation efforts in the Upper Basin are potential mechanisms to free up more direct "wet" water resources for the Lower Basin, the significant volume of water that flows from the Upper Basin to the Lower Basin indirectly through economic trade is also a significant source of water security for the Lower Basin.

Table 7: Virtual Water Transfers Betwwen Upper and Lower Colorado River Basins

Source Basin	**Destination Basin**	**VW (MAF)**	**VF (M$)**	**VI ($/gallon)**
Lower Basin	Lower Basin	0.42	59	2.33
Lower Basin	Upper Basin	0.35	20	5.65
Upper Basin	Lower Basin	1.44	163	2.87
Upper Basin	Upper Basin	0.58	139	1.36

Virtual Water Flow (VW); Value Flow (VF); Value Intensity (VI)

Though interstate virtual water is a large politically significant transfer of water at the basin scale, intrastate virtual water transfers are the most significant virtual water transfers in the CRB in terms of the volume of water traded (Figure 20).

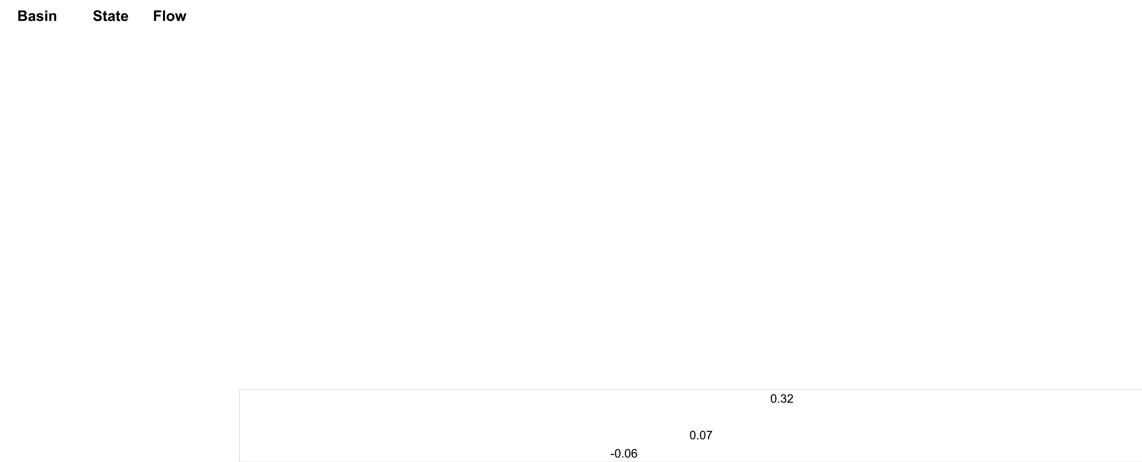

Figure 20: The Colorado River Basin states vary in their hydro-economic role within the basin. Colorado, Wyoming, and Arizona are large virtual water exports, while California and Nevada are virtua water importers. Even though Colorado is a large virtual water importer, it has a net virtual water impact on the Colorado River Basin close to zero. For many states, circular virtual water flows are larger than both virutal water imports and exports.

For Arizona, Colorado, New Mexico, and Utah, circular flows are the most significant flows of virtual water. In these states, virtual water trade transforms direct water resources in rural areas into indirect virtual water resources for urban areas. In these states, virtual water trade follows a home bias trade pattern. Wyoming exports more virtual water to Colorado River Basin states than it imports, making it a virtual water exporter at the CRB scale. Only Utah has no net impact on the Colorado River Basin (Table 8). This is likely due to the current underutilization of the state's Colorado River allocation. However, for California and Nevada the volume of virtual water inflows are greater than circular flows, indicating that (1) these states do not have a home bias for virtual water trade at the scale of the Colorado River Basin, and (2) these states are highly dependent on other Colorado River Basin states as nearby sources of virtual water.

California and Nevada heavily rely upon Colorado and Arizona for virtual water inputs and, therefore, disruptions to water supply in these two states has the potential to disrupt the hydro-economic network at the Colorado River Basin scale. However, while Colorado has more secure water rights to Colorado River water, Arizona, with its junior water rights, is both the most vulnerable node within the CRB hydro-economic network and has the potential to disrupt the function of the hydro-economic network.

Table 8: Colorado River Allocation Compared to Virtual-Water Adjusted Water Footprint

State	**HR_S* (MAF)**	**LR_S** (MAF)**	**Economic River**			**SHE_S (MAF)**	**SHI_S (MAF)**
			V_{Out} (MAF)	**V_{In} (MAF)**	**VWB_S (MAF)**		
AZ	1.05	2.85	0.90	0.76	0.15	1.80	1.95
CA	0.00	4.40	1.41	0.61	0.79	4.40	5.19
CO	9.60	3.86	0.57	1.36	*-0.79*	-5.74	-6.53
NM	0.60	0.84	0.21	0.19	0.02	0.24	0.26
NV	0.15	0.30	0.19	0.04	0.15	0.15	0.30
UT	1.80	1.71	0.38	0.45	*-0.06*	-0.09	-0.15
WY	1.80	1.04	0.16	0.41	*-0.25*	-0.76	-1.01
Total	15.00	15.00	3.81	3.81	0.00	0.00	0.00

*The HR_S is the estimated natural flow contribution of each state.
**The LR_S is the 1922 Colorado River Allocation.

4.4.4 Hydro-Economic Implications of Basin-Wide Shortage

As the Colorado River Basin stands on the precipice of its first ever call on the River, there is still little that is known about the hydro-economic repercussions of mandated water reductions at the state level. Using the virtual water trade network developed for this study, a simple flow network was created to plot each CRB state's top two virtual water sources. At this level of network connectivity, Arizona, California, and Colorado have the highest calculated betweeness centrality, indicating that these two states are the most central to the functioning of the Basin-scale hydro-economic network (Table 9). Further, the simple flow diagram shows a stark partition between the Upper and Lower Basin, indicating the virtual water trade within the basin is also distance dependent: states tend to trade with their neighbors (as is the case with Arizona), but few states trade across the Basin, making Colorado an outlier within the CRB.

Table 9: Network Statistics of the Three Colorado Rivers

Node	**In Degree**	**Out Degree**	**Degree**	**Closeness Centrality**	**Harmonic Closeness Centrality**	**Betweeness Centrality**	**Eigenvector Centrality**
Colorado River	7	8	15	**1.00**	**1.00**	**17.12**	0.83
CO	7	**9**	**16**	0.89	0.94	1.95	0.86
AZ	**8**	8	**16**	0.80	0.88	1.62	**1.00**
CA	**8**	7	15	0.73	0.81	0.87	**1.00**
UT	7	8	15	0.80	0.88	0.45	0.86
NM	6	4	10	0.62	0.69	0.00	0.79
NV	6	2	8	0.53	0.56	0.00	0.69
WY	4	8	12	0.80	0.88	0.00	0.37
Mexico	1	0	1	0.00	0.00	0.00	0.12

A shortage call on the river will set in motion a series of mandated water curtailment polices in Arizona. While other Basin states may feel relief that they do not have the junior rights on the river, they will not be unaffected by Arizona's junior status. California, Nevada, Utah, and New Mexico rely heavily on Arizona's virtual water output as inputs into their economies. Much of this virtual water output is in the form of low-value, highly consumptive irrigated agriculture, which will have to be sourced from elsewhere in the United States and global hydro-economic networks. While substitutes may be easy to find, since Arizona is adjacent to these states, or at least within close proximity, there will be an implicit tradeoff between water security and trade distance, which will in turn increase the cost of inputs and negative externalities that result from increased freight hauling distances (air emissions, carbon pollution).

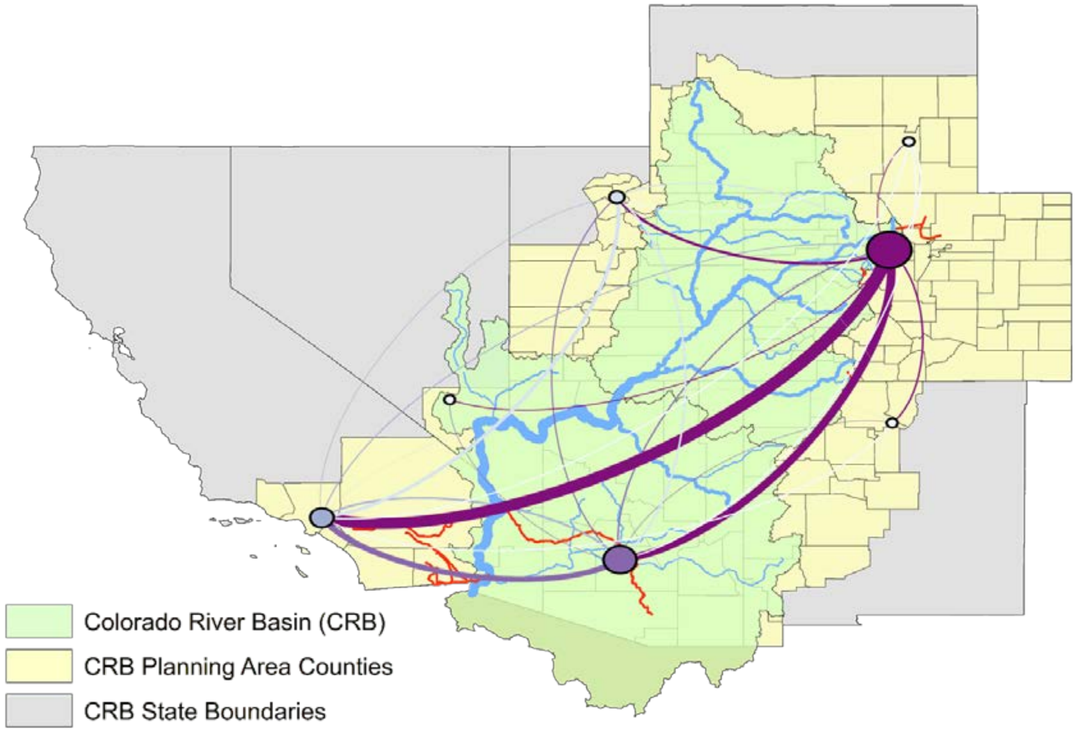

Figure 21: Network analysis provides insight into which states are the most important virtual water exports within the Colorado River Basin. Because each state trades with every other state within the CRB, the network was simplified to show just the top two inflows and outflows. At this level of trade connections, Colorado and Arizona are the most important virtual water sources within the Colorado River Basin.

4.5 Discussion

With the ongoing drought in the Colorado River Basin and the potential reduction to states with junior water rights, hydro-economic analyses must be conducted to understand the full implication of existing water policy regimes and to potentially craft new basin-level water policies that reflect the reality of how water is reallocated within the basin via economic activity.

The predominant flow of water, both physically and virtually, within the CRB is from the Upper Basin to the Lower Basin. Rationing of water for irrigated agriculture within the Upper Basin to provide for urban consumption in the Lower Basin will have the indirect effect of reducing the volume of water available to be outsourced by highly water consumptive economic goods, chiefly agriculture. Excluding circular water flows that originate and terminate within a state, Colorado is the most hydro-economically important source of virtual water within the CRB. Colorado is one of the top two largest sources of virtual water for California, Arizona, New Mexico, Utah, and Wyoming. Secure physical water resources for virtual water producing economic activities in Colorado is key to maintaining the functioning of the CRB virtual water trade network in its current state. Therefore, hydrological or legal disruption to physical water resources in Colorado has the potential to disrupt the CRB virtual water trade network. The CRB hydro-economic network may have to reorganize and source new virtual water resources for different geographic areas. Given the long-term regional drought, new virtual water resources will likely have to originate from less water stressed regions, which necessarily increases the trade distance of the CRB hydro-economic network, and therefore, the cost of doing business for CRB establishments.

For the Lower Basin states—California, Arizona, and Nevada—legally mandated water rationing is a near-term hydro-economic vulnerability (Vörösmarty, Green, Salisbury & Lammers, 2000). Arizona is the second most import virtual water source within the Colorado River and the most import source of virtual water for Nevada and second most for California. Further, Utah and New Mexico also rely on Arizona as a virtual water source. Virtual water outflows originated from Arizona result largely from low-value agriculture, which is the first economic sector targeted by mandatory water curtailments in the case of water shortage on the Colorado River. Agricultural exports from Arizona, specifically from central and southern Arizona counties like Pinal County, are both a major component of the CRB hydro-economic network and the most legally and hydrologically vulnerable (Tidwell, Kobos, Malczynski, Klise & Castillo, 2011). Therefore, a fundament schism exists between the established water policy and the geographic location of economic activities.

A shortage call on the Colorado River may have both direct and indirect hydro-economic impacts on the Colorado River Basin states. Arizona agriculture, especially farms located in central and southern Arizona, will most likely be the first to feel the impacts through the loss of renewable surface water supplies from the central Arizona project. Impacts to Arizona's economy may be the most proximate indirect hydro-economic impacts—whether through the direct loss of agricultural jobs or the indirect economic impacts of industries that rely on inputs from local agriculture. Outside of Arizona, Nevada will most likely be impacted by mandatory reductions to Arizona's water allocation. Our analysis has shown that Arizona is the single largest source of virtual water for southern Nevada and the bulk of this water flow and the economic trade network of southern Nevada may have to reorganize in response to water rationing in Arizona.

4.6 Conclusions

Long-term drought in the Colorado River Basin has the potential to disrupt the basin-level hydro-economic network by reducing both the availability of physical water resources and by disrupting the basin-level virtual water trade network. Virtual water flow in the Colorado River Basin largely follows the flow of the river—the Upper Basin exports virtual water to the Lower Basin. Within the Lower Basin, a shortage call on the river would legally mandate the reduction of Colorado River use by Arizona. However, Arizona is the second most important virtual water exporter within the CRB, and therefore, a legal reduction to Arizona's Colorado River allocation holds the potential to have both a direct impact to Arizona's economy and an indirect effect at the basin-level by disrupting virtual water exporting activities, specifically to the Lower Basin states of Nevada and California and to a lesser extent the Upper Basin states of Utah and New Mexico.

If there is a shortage call on the Colorado River, the CRB states are potentially on the precipice of a new water management regime with unknown economic consequences for the seven basin states. Studying the hydro-economic connectivity of the Colorado River Basin states through a virtual water trade network holds the potential to give water managers the ability to sense potential disruptions to the basin-level hydro-economy. Further studies on this topic should focus on how to anticipate, adapt, and learn from basin-level hydro-economic shocks in order to build a resilient Colorado River Basin hydro-economy.

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CHAPTER 5: CONCLUSION

The overarching goal of this work was to determine what information is gained from analyzing virtual water trade at the systems level rather than the component city level. The complete US hydro-economic network was developed from numerous primary data sources and compiled as the National Water-Economy Database (NWED) to answer this question. This dissertation has explored US hydro-economic networks disaggregated to the county-level in the NWED at three geographic scales pertaining to the state of Arizona: the individual city, a conurbation of cities within a metropolitan area, and the county and state level for a river basin. At each scale, the networked interdependencies on shared water resources were revealed and shown how they will impact water policy.

Analysis of the hydro-economic network for the Phoenix metropolitan area, the city of Flagstaff, and the Colorado River Basin has yielded new information [Q1] typologies of cities within metropolitan areas based upon indirect water consumption patterns [Chapter 2]; metrics of hydro-economic leverage, vulnerability, and functional diversity [Chapter 3]; and identification of potential conflicts between hydrologic, legal, and economic allocations of the Colorado River Basin [Chapter 4]. This new information using extracts of the US hydro-economic network disaggregated to the county level and the county-level data were analyzed and mapped [Q2].

Chapter 2 explored the hydro-economic network of the Phoenix metropolitan area at multiple scales: first, within the Phoenix metropolitan area (PMA) via commodities and labor, and second, between PMA cities and the remainder of the United States. It was shown that with the PMA, communities have one of four roles based on their virtual water balances and economic roles within the metropolitan area:

(1) “core” communities, which are high-value economic centers and job centers that are dependent on their neighbors for net virtual water inflows in both labor and commodities; (2) suburban “bedroom” communities, which are net virtual water exporters to core municipalities via labor flows but net virtual water importers of commodities because of their relatively large residential populations; (3) “edge” communities, which are net virtual water exporters, especially of agricultural commodities but also of other commodities and labor; and (4) “transitional core” communities, which have become job centers and are therefore net importers of virtual water in labor but are still net exporters of commodities, possibly due to economic specialization in an area such as manufacturing, or due to significant remaining agricultural activity [Chapter 3].

Within the metropolitan area, water is shared directly and indirectly through commodities and labor, and an adjusted per-capita consumption can be calculated for each city within a metropolitan area to estimate its true impact on local water resources shared by adjacent cities. The role that each city has within the metropolitan area hydro-economic network can influence metropolitan area water strategy and either acknowledges or discounts the indirect component of the intra-metropolitan water footprint.

The study of the hydro-economic network of a single city was explored in Chapter 4 with the goal of operationalizing water footprint information for the development of policies on hydro-economic vulnerability and functional diversity [Q2 and Q3]. The analysis in Chapter 4 showed that spatial and economic disaggregation, as well as consumption-based virtual water accounting, are requisites to develop quantitative insight into the functional diversity of and potential vulnerabilities in the US hydro-economic network. The geographic origin of a city’s or region’s indirect water sources can be mapped to help municipal managers understand the potential indirect impact of drought, or other hydrologic shocks, to the functioning of a city’s economy.

While the municipal water manager does not have control over indirect (virtual) water resources, economic policy enacted at the municipality level and the purchasing decisions made by private-sector supply chain managers can increase

> the functional diversity of hydro-economic networks and minimize the extent to which a city exposes itself to indirect water vulnerability in the supply chain [Chapter 4].

This is a new type of policy based on benchmarking water footprints, and the associated vulnerability and functional diversity affects a city's or businesses' indirect water security and can be directly applied by city purchasing officers and the private sector to develop nuanced sustainability purchasing plans that target more than just reduced supply chain water consumption, but also reduced supply chain water vulnerability.

Chapter 5 explored the functioning of a hydro-economic network within a shared Colorado River Basin. This chapter presents a highly timely study due to the ongoing drought in the Colorado River Basin, record low elevation levels in Lake Mead, and the looming threat of reducing allocations to states with junior water rights. Hydro-economic analyses are required to understand the full implication of existing water policy regimes and to potentially craft new basin-level water policies that reflect the reality of how water is reallocated within the basin via economic activity [Q4]. For example, the rationing of water for irrigated agriculture within the Upper Basin to provide for urban consumption in the Lower Basin will have the indirect effect of reducing the volume of water available to be outsourced by highly water consumptive economic goods, chiefly agriculture [Chapter 5].

Of the seven Colorado River Basin states, Colorado is the most hydro-economically important source of virtual water within the CRB, and therefore: "Secure physical water resources for virtual water producing economic activities in Colorado is key to maintaining the functioning of the CRB virtual water trade network in its current state" [Chapter 5]. However, Arizona is the second most important state within the

Colorado River hydro-economic network and a large source of virtual water for Nevada and California. These virtual water outflows result largely from low-value agriculture, which will likely be the first economic sector targeted by mandatory water curtailments in the case of water shortage on the Colorado River. Agricultural exports from Arizona, specifically from central and southern Arizona counties like Pinal County, are a major component of the CRB hydro-economic network. A shortage call on the Colorado River may have both direct and indirect hydro-economic impacts on the Colorado River Basin states. Impacts to Arizona's economy will likely be the most proximate indirect hydro-economic impacts—whether through the direct loss of agricultural jobs or the indirect economic impacts of industries that rely on inputs from local agriculture. Outside of Arizona, Nevada will like be the next state impacted by mandatory reductions to Arizona's water allocation.

5.1 In Summary

Cities are complex, coupled natural human systems that contain interacting and overlapping social, economic, and environmental processes. For many water managers, the top management priority is to secure a safe and reliable water supply. Water provided by municipal providers is not just vital to human health and well-being, but also economic and environmental health and well-being. Tools such as the water footprint provide cities information about the volume of water required to sustain economic output and growth, but lack information regarding the vulnerability and functional diversity of water footprint components.

A city's total water footprint contains two distinct components: it's internal and external water footprint. Managing the internal water footprint has traditionally been the mission of municipal water manager, while a city's external footprint has been ignored because these impacts occur outside the water management area. However, the volume of water outsourced outside of a city's water management area is several times larger than its internal water footprint and is used to produce vital inputs to a city's economy, making it integral to the economic success of a city. By geographically disaggregating a city's external water footprint, city managers can begin to understand the water-related risks and vulnerabilities of its supply chain and create strategic partnerships to bolster the functional diversity of its outsourced water supplies. Therefore, the goal of this study is to measure, city-level water footprint vulnerability and functional diversity in the United States.

Through trade, a city accesses more water than it physical has access to, but the virtual water sources can expose a city to external hydrological risks and vulnerabilities that can affect local economic processes. Risks that are present in outsourced, virtual water supplies are particularly relevant to cities where the majority of water consumed by economic processes within a city are outsourced to nonlocal water sources, which each have their own set of hydrologic and regulatory risks and vulnerabilities. For smaller cities, where trade is predominantly regional, local water stress may be exacerbated by regional conditions and heavy dependence on the closest, biggest city. For these small cities, a more resilient economic system may be built by diversifying their hydro-economic trade networks and considering the indirect stress of virtual water sources.

For large cities, where trade takes places at the global scale, have more diverse trade networks and less vulnerable hydro-economic network may create additional negative externalities resulting from accessing virtual water from more distant domestic and global trading partners.

In recent years, the dominant foreign policy narrative has become, “foreign policy is domestic policy.” The same soon may be true for the US hydro-economic network: hydrological risks and vulnerabilities within a city’s trade network present a unique set of challenges to a city that need to be considered along with the management of local water sources. By geographically disaggregating a city’s water footprint, decision makers can potentially incorporate water outsourcing strategies into municipal and corporate planning. Looking into the future, as cities undergo water stress from prolonged drought or changing climatic patterns, interdependencies in a city’s virtual water trade network present potential opportunities for collaboration, which may potentially create a more resilient hydro-economic system.

5.2 Future Work

The most immediate future work after this dissertation is to expand the scale of analysis to the entire US hydro-economy. Taking from Chapter 4, the first task will be to measure the vulnerability and functional diversity of the United States domestic hydro-economy. The goal of this work is threefold: (1) to define the virtual water hinterland of the United States; (2) to calculate hydro-economic leverage, vulnerability, and functional diversity of each county in the United States; and (3) to identify shared water resources that present the highest amount of indirect water stress to the US hydro-economic network. This work will also develop a national hydro-economic classification system to enable the creation of targeted indirect water policies, such as sustainability purchasing plans, based upon the specific hydro-economic roles that are present in the United States.

Further, there will be future work to further refine the National Water Economic Database and publish a second version of the database. The commodity flow data underlying the NWED is the Freight Analysis Framework version 3.5. Since writing this dissertation, Oak Ridge National Laboratory has published the Freight Analysis Framework version 4.0, which contains commodity flow data for 2012. With this update to NWED, the database will be expanded to include import and export flows, in addition to the domestic flows already included in NWED, and expand embedded resource flows to carbon and phosphorus in order to expand multitype network analysis. The second version of the database will utilize input-output tables to allocate virtual water flows associated with commodity groups to industry classes in addition to estimating virtual water storage at node within the US hydro-economy. This update will allow for the calculation of industry-specific hydro-economic statistics of leverage, vulnerability, and functional diversity as well as a finer disaggregation of commodity flows and associated virtual water flows, embedded carbon flows, and other embedded resource flows.

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APPENDIX A

SUPPLEMENTARY TABLES AND GRAPHS FOR THE HYDRO-ECONOMIC INTERDEPENDENCY OF CITIES: VIRTUAL WATER CONNECTIONS OF THE PHOENIX, ARIZONA, METROPOLITAN AREA

Table A1. Distances Between PMA Municipalities (km)

City	Anthem	Apache Junction	Avondale	Buckeye	Cave Creek	Chandler	Gilbert	Glendale	Goodyear	Litchfield Park	Maricopa	Mesa	New River	Paradise Valley	Peoria	Phoenix	Queen Creek	San Tan Valley	Scottsdale	Sun City	Sun City West	Surprise	Tempe	Tolleson	Wickenburg
Anthem	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Apache Junction	105	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Avondale	67	86	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Buckeye	90	114	24	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Cave Creek	28	91	72	101	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Chandler	87	42	64	93	69	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Gilbert	85	29	64	93	67	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Glendale	44	72	27	54	50	51	51	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Goodyear	68	86	0	24	74	66	66	29	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Litchfield Park	62	88	8	30	67	67	67	24	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Maricopa	105	78	85	112	99	40	51	72	85	88	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mesa	77	32	56	85	58	13	11	45	58	59	56	-	-	-	-	-	-	-	-	-	-	-	-	-	-
New River	10	114	74	90	35	93	91	51	75	69	112	82	-	-	-	-	-	-	-	-	-	-	-	-	-
Paradise Valley	55	56	50	78	37	35	35	24	51	53	62	24	62	-	-	-	-	-	-	-	-	-	-	-	-
Peoria	44	78	26	54	50	58	58	6	27	21	78	50	51	51	-	-	-	-	-	-	-	-	-	-	-
Phoenix	8	56	29	58	51	35	35	16	30	32	56	30	58	58	22	-	-	-	-	-	-	-	-	-	-
Queen Creek	111	32	82	109	85	18	16	69	82	85	48	29	109	109	74	53	-	-	-	-	-	-	-	-	-
San Tan Valley	122	30	101	130	106	35	38	90	102	104	61	48	130	130	94	72	21	-	-	-	-	-	-	-	-
Scottsdale	65	48	45	74	46	29	29	34	46	48	58	18	72	8	38	21	46	67	-	-	-	-	-	-	-
Sun City	43	93	26	54	48	72	70	11	27	22	91	62	50	50	3	35	88	110	53	-	-	-	-	-	-
Sun City West	42	106	27	51	54	85	83	24	29	22	104	80	42	42	18	50	101	123	69	13	-	-	-	-	-
Surprise	53	102	22	46	54	82	82	21	22	16	101	72	48	48	14	46	98	120	69	10	8	-	-	-	-
Tempe	64	43	43	70	54	22	22	30	45	46	48	11	70	70	37	18	38	61	10	50	62	61	-	-	-
Tolleson	60	77	10	34	66	56	54	18	11	16	75	46	67	67	19	21	72	94	37	19	32	30	34	-	-
Wickenburg	72	160	80	93	85	139	139	72	78	72	160	130	72	72	64	104	155	178	122	61	53	54	117	86	-

Table A2: Virtual Water Flow Associated With Labor Between Cities ($\boldsymbol{V_{L,n\rightarrow m}}$) (Million Cubic Meters, Mm^3)

City	Anthem	Apache Junction	Avondale	Buckeye	Cave Creek	Chandler	Gilbert	Glendale	Goodyear	Litchfield Park	Maricopa	Mesa	New River	Paradise Valley	Peoria	Phoenix	Queen Creek	San Tan Valley	Scottsdale	Sun City	Sun City West	Surprise	Tempe	Tolleson	Wickenburg
Anthem	256	1	6	1	6	37	31	32	5	0	1	68	768	10	461	543	1	3	125	79	10	8	57	1	0
Apache Junction	3	310	10	1	1	360	262	60	8	0	2	303	1	17	25	906	18	555	230	3	0	14	123	1	1
Avondale	5	4	520	190	2	130	107	434	301	0	3	240	2	36	624	1907	4	9	490	107	34	318	262	4	1
Buckeye	4	3	52	261	1	87	72	85	201	0	2	160	2	24	35	1286	3	6	294	5	1	460	134	0	1
Cave Creek	2	0	1	0	89	9	7	8	1	0	0	16	24	1	3	125	0	1	32	0	0	2	13	0	0
Chandler	17	27	65	7	5	5138	1859	393	51	0	88	1995	8	33	163	5908	226	288	1917	21	3	92	479	7	3
Gilbert	15	149	57	6	4	747	3152	347	45	0	9	1761	7	29	144	871	637	254	1692	19	3	81	2344	6	3
Glendale	38	12	233	7	5	387	319	3386	69	0	10	1241	7	519	577	5672	13	27	200	332	62	944	1598	25	3
Goodyear	5	3	78	251	1	111	92	372	613	0	3	206	2	31	535	1554	4	8	419	92	29	272	224	47	1
Litchfield Park	0	0	7	21	0	9	8	14	22	0	0	17	0	3	251	23	0	1	32	129	1	23	19	0	0
Maricopa	3	2	12	1	1	437	61	72	9	0	271	137	1	20	30	1099	2	5	251	4	1	17	114	1	1
Mesa	31	923	120	13	9	1573	3457	645	96	0	19	10892	14	793	304	10449	216	52	5212	39	6	171	2700	12	0
New River	735	1	4	0	0	26	21	25	3	0	1	47	240	7	10	378	1	2	86	1	7	3	39	0	0
Paradise Valley	1	1	4	0	0	7	10	73	3	0	1	269	0	650	9	321	1	2	99	7	6	3	34	0	0
Peoria	25	8	158	5	3	263	217	389	47	0	7	486	5	73	1869	3855	9	18	136	205	42	1393	62	17	2
Phoenix	521	77	1738	44	395	5178	1092	3654	441	0	64	4505	47	1842	3681	56212	80	171	11143	102	19	325	2934	71	21
Queen Creek	2	19	7	1	1	2887	208	44	6	0	1	82	1	12	18	667	256	799	169	2	0	10	11	1	0
San Tan Valley	6	58	22	2	2	48	61	135	18	0	4	256	3	38	56	2056	78	523	470	7	1	32	213	2	1
Scottsdale	15	25	102	7	23	2041	1590	120	81	0	10	4565	7	277	80	5439	74	26	12980	19	3	85	441	2	1
Sun City	6	2	38	1	1	64	53	2743	11	0	2	118	1	26	95	157	2	4	217	405	47	339	98	4	1
Sun City West	4	1	25	1	0	42	34	416	7	0	1	77	11	35	1123	620	1	3	142	33	182	222	64	0	0
Surprise	8	6	661	452	2	201	165	1993	524	0	5	371	55	168	299	4123	7	14	679	156	146	1574	308	29	2
Tempe	12	19	76	5	3	579	2613	921	60	0	7	5300	5	76	59	4046	19	19	1247	14	2	63	5132	1	2
Tolleson	0	0	8	4	0	11	9	111	570	0	0	36	0	3	300	164	0	1	6	154	0	802	3	37	0
Wickenburg	0	0	2	0	0	11	9	11	1	0	0	20	0	3	4	161	0	1	37	1	0	2	17	0	457

Table A3: Commodity Virtual Water Flows by City Presented by ERA Component (Million Cubic Meters, Mm^3

Municipality	E	U		V_{In}				V_{Out}			
	E_m	U_{urban}	U_{farm}	$CF_{C,m}^{import}$	$\sum_{n,C} V_{C,n\to m}$	$\sum_{k,C} V_{C,k\to m}$	$V_{In,m}$	$CF_{C,m}^{export}$	$\sum_{n,C} V_{C,m\to n}$	$\sum_{k,C} V_{C,m\to k}$	$V_{Out,m}$
	Net Water Footprint	Potable Deliveries	Agricultural Withdrawals	Circular (%)	Intra'PMA (%)	US (%)	**Sum**	Circular (%)	Intra'PMA (%)	US (%)	**Sum**
						Mm^3					
Anthem	17	3.5	0	0.3 (1%)	8.5 (38%)	13.6 (60%)	**23**	0.3 (3%)	6.6 (74%)	2 (22%)	**8.9**
Apache Junction	42	16	12	0.4 (1%)	12.7 (33%)	25.4 (66%)	**39**	0.4 (2%)	15.1 (62%)	8.9 (37%)	**24**
Avondale	66	16	7.5	1 (1%)	27.9 (35%)	50.8 (64%)	**80**	1 (3%)	23.1 (61%)	13.9 (37%)	**38**
Buckeye	95	5.3	294	2 (4%)	14.5 (29%)	33.3 (67%)	**50**	2 (1%)	139.3 (55%)	112.6 (44%)	**254**
Cave Creek	7.1	2.1	3.1	0.1 (2%)	2.2 (39%)	3.2 (57%)	**5.6**	0.1 (3%)	2.2 (61%)	1.3 (36%)	**3.6**
Chandler	183	73	97	13.7 (5%)	89.5 (34%)	157 (60%)	**260**	13.7 (6%)	125.6 (51%)	108.4 (44%)	**248**
Gilbert	165	57	87	9 (4%)	76.5 (35%)	135.6 (61%)	**221**	9 (5%)	100.8 (50%)	90.2 (45%)	**200**
Glendale	236	59	31	7.5 (3%)	90.9 (35%)	161.9 (62%)	**260**	7.5 (7%)	63.8 (56%)	43 (38%)	**114**
Goodyear	63	10	44	1.2 (2%)	22.4 (34%)	42 (64%)	**66**	1.2 (2%)	33.2 (59%)	21.9 (39%)	**56**
Litchfield Park	28	14	46	0 (0%)	1.8 (30%)	4.2 (70%)	**6**	0 (0)	21.7 (56%)	16.8 (44%)	**39**
Maricopa	39	6.6	96	0.8 (2%)	11.6 (29%)	27 (68%)	**40**	0.8 (1%)	55.7 (54%)	46.1 (45%)	**103**
Mesa	457	111	136	30 (6%)	160.4 (32%)	307.9 (62%)	**498**	30 (10%)	153.3 (53%)	104.4 (36%)	**288**
New River	8	2.6	0	0.3 (2%)	5.2 (39%)	7.8 (59%)	**13**	0.3 (4%)	5.1 (65%)	2.5 (32%)	**7.9**
Paradise Valley	26	13	8.2	0.8 (5%)	9.5 (63%)	4.6 (31%)	**15**	0.8 (8%)	6.3 (61%)	3.3 (32%)	**10**
Peoria	151	34	14	3.5 (2%)	60.3 (36%)	104.7 (62%)	**169**	3.5 (5%)	37 (57%)	24.8 (38%)	**65**
Phoenix	1485	376	144	191.5 (12%)	435.4 (26%)	1016.8 (62%)	**1644**	191.5 (28%)	231.4 (34%)	255.9 (38%)	**679**
Queen Creek	46	10	120	0.7 (3%)	9.2 (35%)	16.3 (62%)	**26**	0.7 (1%)	64.9 (59%)	45 (41%)	**111**
San Tan Valley	41	5.1	0	0.9 (1%)	24.3 (33%)	47.4 (65%)	**73**	0.9 (2%)	19.9 (55%)	15.7 (43%)	**37**
Scottsdale	281	103	16	18.3 (7%)	103.3 (42%)	126.3 (51%)	**248**	18.3 (21%)	54.8 (64%)	12.8 (15%)	**86**
Sun City	59	18	0.3	0.5 (1%)	14.9 (34%)	28 (64%)	**44**	0.5 (18%)	6.1 (218%)	−3.8 (−136%)	**2.8**
Sun City West	35	7.7	0	0.2 (1%)	9.3 (32%)	19.7 (67%)	**29**	0.2 (11%)	4.3 (226%)	−2.6 (−137%)	**1.9**
Surprise	123	28	9.5	1.8 (2%)	39.7 (34%)	76.1 (65%)	**118**	1.8 (6%)	26.9 (85%)	2.9 (9%)	**32**
Tempe	187	61	77	9.3 (5%)	68 (37%)	108.8 (58%)	**186**	9.3 (7%)	82.2 (60%)	45.7 (33%)	**137**
Tolleson	17	5	35	0.1 (1%)	2.4 (33%)	4.7 (65%)	**7.2**	0.1 (0)	18.9 (62%)	11.6 (38%)	**31**
Wickenburg	9.8	2	8.8	0.6 (8%)	2.3 (31%)	4.5 (61%)	**7.4**	0.6 (7%)	4.8 (56%)	3 (35%)	**8.5**
Total Flow	**3868**	**1040**	**1286**	**295**	**1303**	**2528**	**4125**	**295**	**1303**	**986**	**2584**

Table A4: Virtual Water Imports, Exports, and Net Flows Associated with PMA Commodity Flow (n = PMA)

Municipality	**Metropolitan Area Flow**				**Net Metropolitan Area Flow**		
	V_{In}	$V_{C,In,\ PMA}$ (% of V_{In})	V_{Out}	$V_{C,Out,\ PMA}$ (% of V_{Out})	E_m (V_{In}/V_{Out})	$E_{m,PMA}$	U_m^{urban}
	Thousand m^3						
Anthem	22,475	6721 (30%)	8901	3821 (43%)	13,574 (2.5)	2900	3518
Apache Junction	38,489	11,437 (30%)	24,301	11,480 (47%)	14,188 (1.6)	−43	16,014
Avondale	79,655	23,563 (30%)	37,969	16,770 (44%)	41,686 (2.1)	6,793	16,371
Buckeye	49,785	13,274 (27%)	253,893	135,873 (54%)	204,107 (0.2)	−122,599	5274
Cave Creek	5567	1667 (30%)	3612	1847 (51%)	1955 (1.5)	−180	2128
Chandler	260,173	70,715 (27%)	247,697	108,836 (44%)	12,476 (1.1)	−38,121	73,272
Gilbert	221,084	61,247 (28%)	199,937	89,509 (45%)	21,147 (1.1)	−28,262	57,013
Glendale	260,350	74,795 (29%)	114,282	48,971 (43%)	146,068 (2.3)	25,824	59,348
Goodyear	65,594	19,223 (29%)	56,327	28,000 (50%)	9267 (1.2)	−8,777	10,220
Litchfield Park	5975	1762 (29%)	38,470	20,973 (55%)	32,495 (0.2)	−19,211	14,271
Maricopa	39,456	11,324 (29%)	102,632	52,909 (52%)	63,176 (0.4)	−41,585	6566
Mesa	498,330	132,920 (27%)	287,654	120,506 (42%)	210,675 (1.7)	12,414	110,839
New River	13,273	3970 (30%)	7877	3389 (43%)	5396 (1.7)	581	2554
Paradise Valley	14,960	4468 (30%)	10,380	5237 (50%)	4580 (1.4)	−769	12,966
Peoria	168,553	49,352 (29%)	65,266	28,322 (43%)	103,287 (2.6)	21,030	33,769
Phoenix	1,643,805	370,888 (23%)	678,790	184,446 (27%)	965,015 (2.4)	186,442	376,218
Queen Creek	26,133	7464 (29%)	110,529	58,783 (53%)	−84,397 (0.2)	−51,319	10,186
San Tan Valley	72,640	21,511 (30%)	36,538	15,493 (42%)	36,103 (2)	6019	5082
Scottsdale	247,975	72,063 (29%)	85,862	36,261 (42%)	162,114 (2.9)	35,802	102,886
Sun City	43,457	13,022 (30%)	2755	1209 (44%)	40,702 (15.8)	11,814	18,367
Sun City West	29,240	8765 (30%)	1891	811 (43%)	27,348 (15.5)	7954	7659
Surprise	117,620	34,865 (30%)	31,658	14,155 (45%)	85,962 (3.7)	20,711	27,547
Tempe	186,060	52,808 (28%)	137,220	63,567 (46%)	48,841 (1.4)	−10,759	61,258
Tolleson	7239	2142 (30%)	30,631	16,524 (54%)	23,393 (0.2)	−14,381	5047
Wickenburg	7387	2208 (30%)	8458	4484 (53%)	1071 (0.9)	−2276	2028
Total Flow	4,125,275	1,072,174	2,583,530	1,072,174	1,541,745	0	1,040,401

Table A5: Virtual Inflows and Outflows by Commodity

SCTG Commodity Code	Description	Metropolitan Area $V_{c,In}$ (Thousand m^3)	$V_{c,Out}$ (Thousand m^3)	E_c (Thousand m^3)	Per Capita Import Commodity Flow (m^3 per capita)	Export Commodity Flow (m^3 per capita)	Net Import Commodity Flow (m^3 per capita)
1	**Live animals/fish***	**256**	**1604**	**−1348**	**0.07029431**	**0.44**	**−0.37**
2	Cereal grains	516,881	76,348	440,533	142.02	20.98	121.04
3	Other ag prods.	1,461,388	547,476	913,912	401.54	150.43	251.11
4	Animal feed	724,881	397,863	327,018	199.17	109.32	89.85
5	Meat/seafood	41,283	11,608	29,675	11.34	3.19	8.15
6	**Milled grain prods.**	**1,053,797**	**1,282,106**	**−228,309**	**289.55**	**352.28**	**−62.73**
7	Other foodstuffs	17,774	845	16,929	4.88	0.23	4.65
8	Alcoholic beverages	5170	180	4990	1.42	0.05	1.37
9	Tobacco prods.	1037	34	1003	0.28	0.01	0.27
10	**Building stone**	**5589**	**21,094**	**−15,505**	**1.54**	**5.79**	**−4.25**
11	**Natural sands**	**1903**	**7162**	**−5259**	**0.52**	**1.97**	**−1.45**
12	Gravel	1055	40	1015	0.29	0.01	0.28
13	**Nonmetallic minerals**	**3645**	**7244**	**−3599**	**1**	**1.99**	**−0.99**
14	Metallic ores	4208	15	4193	1.16	0	1.16
15	**Coal**	**14**	**51**	**−37**	**0**	**0.01**	**−0.01**
16	**Crude petroleum**	0	0	0	0	0	**0**
17	Gasoline	8421	433	7988	2.31	0.12	2.19
18	Fuel oils	3846	230	3616	1.06	0.06	1
19	**Coal−n.e.c.**	**31,061**	**213,543**	**−182,482**	**8.53**	**58.68**	**−50.15**
20	Basic chemicals	4397	245	4152	1.21	0.07	1.14
21	Pharmaceuticals	15,271	1739	13,532	4.2	0.48	3.72
22	Fertilizers	1067	42	1025	0.29	0.01	0.28
23	Chemical prods.	5118	230	4888	1.41	0.06	1.35
24	Plastics/rubber	4804	241	4563	1.32	0.07	1.25
25	Logs	182	8	174	0.05	0	0.05
26	Wood prods.	6094	266	5828	1.67	0.07	1.6
27	Newsprint/paper	1654	80	1574	0.45	0.02	0.43
28	Paper articles	3389	214	3175	0.93	0.06	0.87
29	Printed prods.	2610	106	2504	0.72	0.03	0.69
30	Textiles/leather	8760	239	8521	2.41	0.07	2.34
31	Nonmetal min. prods.	9559	348	9211	2.63	0.1	2.53
32	Base metals	8429	333	8096	2.32	0.09	2.23
33	Articles-base metal	13,352	599	12,753	3.67	0.16	3.51
34	Machinery	54,307	2294	52,013	14.92	0.63	14.29
35	Electronics	21,756	2269	19,487	5.98	0.62	5.36
36	Motorized vehicles	17,841	633	17,208	4.9	0.17	4.73
37	Transport equip.	4493	320	4173	1.23	0.09	1.14
38	Precision instruments	4562	249	4313	1.25	0.07	1.18
39	Furniture	5664	198	5466	1.56	0.05	1.51
40	Misc. mfg. prods.	10,894	810	10,084	2.99	0.22	2.77
41	Waste/scrap	2333	83	2250	0.64	0.02	0.62
43	Mixed freight	27,107	1530	25,577	7.45	0.42	7.03
99	Unknown	9424	2581	6843	3	1	2
	Total	**4,125,276**	**2,585,782**	**1,539,494**	**26**	**17**	**10**

* Bolded items indicate next export.

Table A6: The Fraction of Potable Deliveries Mobilized via Labor Within the PMA

Municipality	$V_{L,n \to m}$	$V_{L,m \to n}$	CF_L	$E_{L,PMA}$	U_m^{urban}	$\frac{V_{L,n \to m}}{U_{m,urban}}$	$\frac{V_{L,m \to n}}{U_{m,urban}}$
	Virtual Water of Labor Flows (Thousand m^3)				**Thousand m^3**		
Anthem	2114	3093	383	−979	3518	60%	77%
Apache Junction	2035	3960	382	−1925	16,014	10%	22%
Avondale	4940	7072	641	−2132	16,371	26%	39%
Buckeye	1581	3917	322	−2336	5274	24%	68%
Cave Creek	684	414	104	270	2128	27%	15%
Chandler	25,133	23,170	6440	1963	73,272	26%	23%
Gilbert	19,121	15,267	3886	3854	57,013	27%	20%
Glendale	20,324	19,340	4175	984	59,348	27%	26%
Goodyear	3938	6106	756	−2167	10,220	31%	52%
Litchfield Park	2	715	31	−713	14,271	0%	5%
Maricopa	630	3150	334	−2521	6566	4%	43%
Mesa	40,899	46,541	14,013	−5642	110,839	24%	29%
New River	1496	2022	306	−526	2554	47%	67%
Paradise Valley	5828	1850	308	3978	12,966	43%	12%
Peoria	13,263	11,458	2304	1805	33,769	32%	27%
Phoenix	133,834	116,343	69,309	17,490	376,218	17%	13%
Queen Creek	2037	6416	295	−4379	10,186	17%	60%
San Tan Valley	3440	5047	602	−1608	5082	56%	87%
Scottsdale	47,227	34,540	16,004	12,688	102,886	30%	18%
Sun City	2387	5470	523	−3083	18,367	10%	27%
Sun City West	746	3758	258	−3012	7659	6%	46%
Surprise	8945	14,731	1213	−5787	27,547	28%	49%
Tempe	21,483	25,009	6328	−3525	61,258	25%	30%
Tolleson	332	2738	57	−2406	5047	5%	53%
Wickenburg	619	910	571	−291	2028	2%	17%
Total	363,038	363,038	0	0	1,040,401	22%	22%

Table A7: The Adjusted GPCD of PMA Municipalities to Reflect the Flow of Virtual Water Associated With Labor Flow and Commodity Flow

Municipality	E (Ag and Urban)	E (No Ag)	U		V_{In}				V_{Out}			
	E_m	E_{urban}	U_{urban}	U_{farm}	$CF_{C,m}^{import}$	$\sum_{n,C} V_{C,n\to m}$	$\sum_{k,C} V_{C,k\to m}$	$V_{In,m}$	$CF_{C,m}^{export}$	$\sum_{n,C} V_{C,m\to n}$	$\sum_{k,C} V_{C,m\to k}$	$V_{Out,m}$
	Net Water Footprint	Net Urban Water Footprint	Potable Deliveries	Agricultural Withdrawals	Circular (%)	Intra-PMA (%)	US (%)	**Sum**	Circular (%)	Intra-PMA (%)	US (%)	**Sum**
					Virtual Water flow Adjusted GPCD							
Anthem	620	642	128	0	11	310	496	**839**	11	241	73	**325**
Apache Junction	895	660	341	256	9	271	541	**831**	9	322	190	**511**
Avondale	679	597	165	77	10	287	523	**823**	10	238	143	**391**
Buckeye	1564	−3272	87	4841	33	239	548	**823**	33	2294	1854	**4183**
Cave Creek	1046	604	309	457	15	324	471	**825**	15	324	191	**530**
Chandler	577	268	230	306	43	282	495	**819**	43	396	342	**781**
Gilbert	612	289	211	323	33	284	503	**820**	33	374	334	**742**
Glendale	743	646	186	98	24	286	510	**819**	24	201	135	**359**
Goodyear	787	250	125	550	15	280	525	**825**	15	415	274	**700**
Litchfield Park	3842	−2607	1921	6312	0	247	576	**823**	0	2978	2305	**5351**
Maricopa	810	−1172	137	1995	17	241	561	**831**	17	1,157	958	**2140**
Mesa	752	528	183	224	49	264	507	**819**	49	252	172	**474**
New River	494	476	161	0	19	321	482	**803**	19	315	154	**488**
Paradise Valley	1425	986	712	449	44	521	252	**822**	44	345	181	**548**
Peoria	734	671	165	68	17	293	509	**822**	17	180	121	**316**
Phoenix	741	669	188	72	96	217	507	**820**	96	115	128	**339**
Queen Creek	1443	−2353	314	3765	22	289	511	**816**	22	2036	1412	**3482**
San Tan Valley	463	464	58	0	10	274	535	**824**	10	225	177	**418**
Scottsdale	929	876	341	53	61	342	418	**820**	61	181	42	**284**
Sun City	1113	1117	340	6	9	281	528	**830**	9	115	−72	**53**
Sun City West	981	976	216	0	6	261	552	**813**	6	121	−73	**53**
Surprise	857	795	195	66	13	277	530	**822**	13	187	20	**223**
Tempe	824	485	269	339	41	300	479	**820**	41	362	201	**604**
Tolleson	1925	−2129	566	3964	11	272	532	**815**	11	2141	1314	**3511**
Wickenburg	1088	100	222	977	67	255	499	**821**	67	533	333	**943**

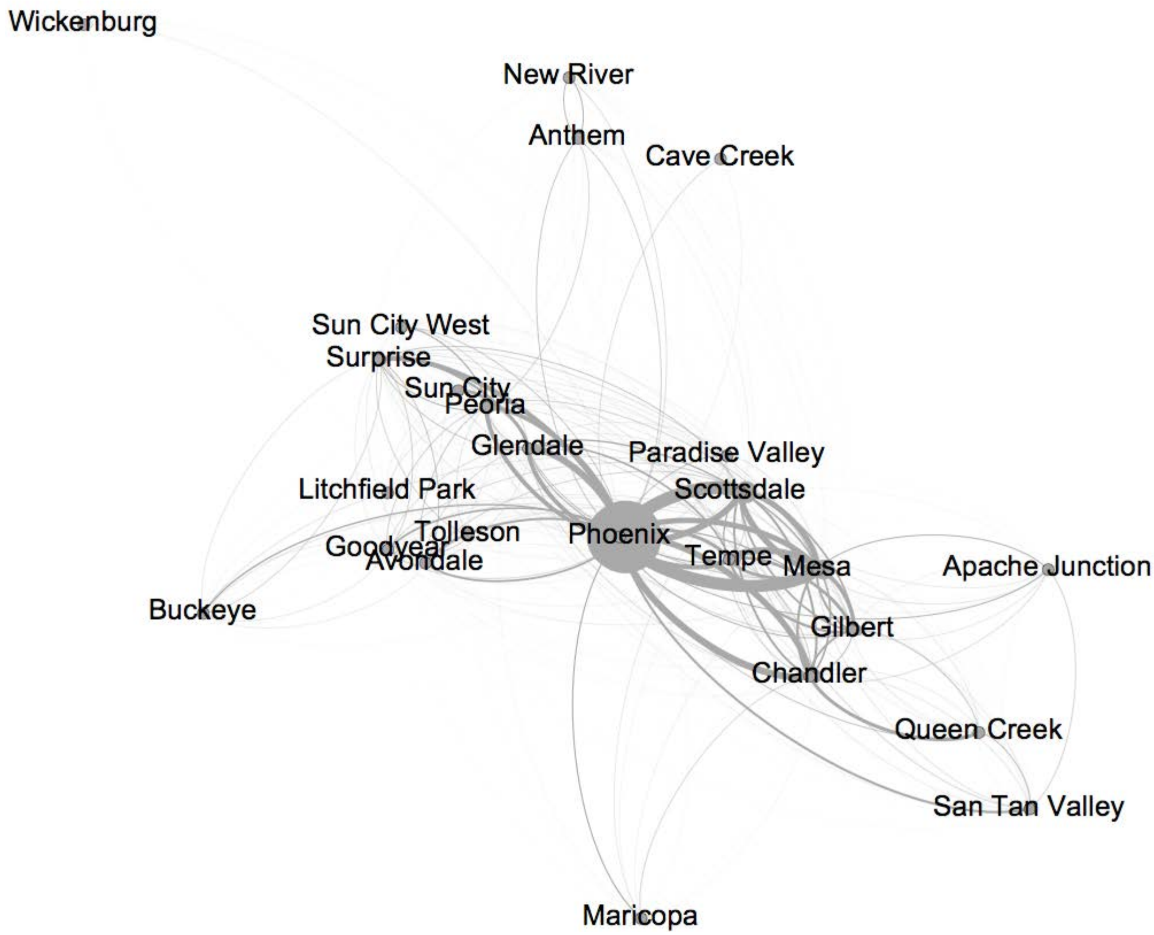


Figure A1: A weighted digraph of the virtual water flows associated with labor commuting between PMA municipalities ($\boldsymbol{V_{L,m \rightarrow n}}$). This is a graphical representation of the data in Table S2 PMA municipalities are geolocated within the weighted, directed network.

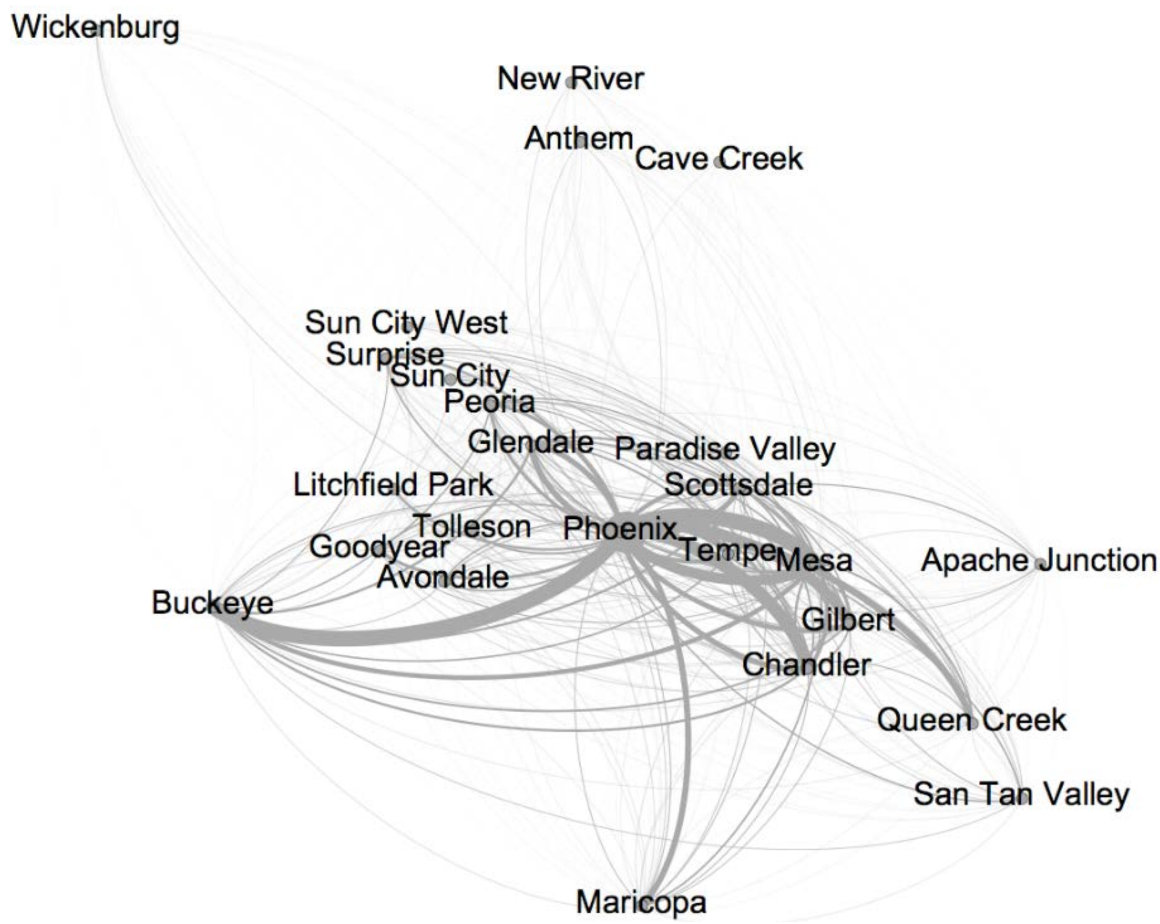


Figure A2: A weighted digraph of the virtual water flows associated with commodity flows between PMA municipalities ($\boldsymbol{V_{C,m \to n}}$). The network diagram is a disaggregation of the data in Table S4. PMA municipalities are geolocated within the weighted, directed network.

APPENDIX B

SUPPLEMENTARY INFORMATION FOR THE VULNERABILITY AND FUNCTIONAL DIVERSITY OF A CITY'S WATER FOOTPRINT: THE CASE OF FLAGSTAFF, ARIZONA

Introduction

This Supplemental Information provides detailed supporting information to the main text. There is one section of supplemental text that contains detailed description of the hydro-economic traits (A^r) in the *RHED* Index and the supporting references, and how the rationale supported the development of the A^r indicators. The supplemental figures detail the regression analyses performed to determine the system properties that explain virtual water flows. The supplemental tables contain information on the locations that are the top contributors to Flagstaff's virtual water inflow and outflow networks. The final supplemental tables contains the results of the log-likelihood tests comparing the fit heavy-tailed distributions on the volume of virtual water inflows by trading partners for Flagstaff's virtual water trade network.

Text S1. Description of the hydro-economic traits (A^r) in the *RHED* Index

Drought Correlation Indicator (DI)

The DI was measured by averaging the monthly Palmer Drought Index (NCDC, 2015) for each county over the history of the NCDC database (dating back to 1895) and correlating county-level drought to the drought intensity in Flagstaff (Coconino County). Since the NCDC database is limited to the continental United States, the DI of Alaska and Hawaii were assumed to be uncorrelated ($R^2 = 0$) rather than directly or indirectly correlated ($R^2 = 1$ or $R^2 = -1$).

Physical Distance Indicator (PDI)

The *PDI* is the distance between Flagstaff and the geometric center of each county in the virtual water trade network. Calculated distances were normalized between 0 and 1 by dividing each distance by the maximum distance between Flagstaff and a trading partner.

Infrastructure Connectivity Indicator (ICI)

Connectivity was measured as the number of transportation modes in the FAF[3] database connecting an origin and destination zone and the associated counties.

Urban Classification Indicator (UCI)

Counties were assigned a score from 1 (highly rural) to 6 (highly urban using the National Center for Health Statistics' (NCHS) Urban-Rural Classification Scheme for Cities. The score is based on population and the role a county has within a metropolitan/micropolitan area (Ingram & Franco, 2014).

Hydro-Economic Specialization Indicator (HESI)

A *HESI* score was assigned to each county based upon its hydro-economic role as defined by its dominant virtual water exporting sector. Counties that export virtual water predominantly in agricultural goods were given a score of 1; in livestock products a score of 2; in mining products a score of 3; and in industrial goods a score of 4.

Shared River Basin and Water Governance Regime Indicator

The shared river basin indicator (*SRBI*) was defined as the Colorado River planning area. Counties within this area were assigned a score of 0, all other counties were assigned a score of 1. The shared water governance indicator (*SWGI*) were created for each county. The *SWGI* was derived similarly to the *SRBI* for the State of Arizona boundaries.

References

Ingram, D. D., & Franco, S. J. (2014). *2013 NCHS urban–rural classification scheme for counties*. Vital Health Stat.

NCDC. (2015). Historical Palmer Drought Indices. Retrieved from http://www.ncdc.noaa.gov/temp-and-precip/drought/historical-palmers/

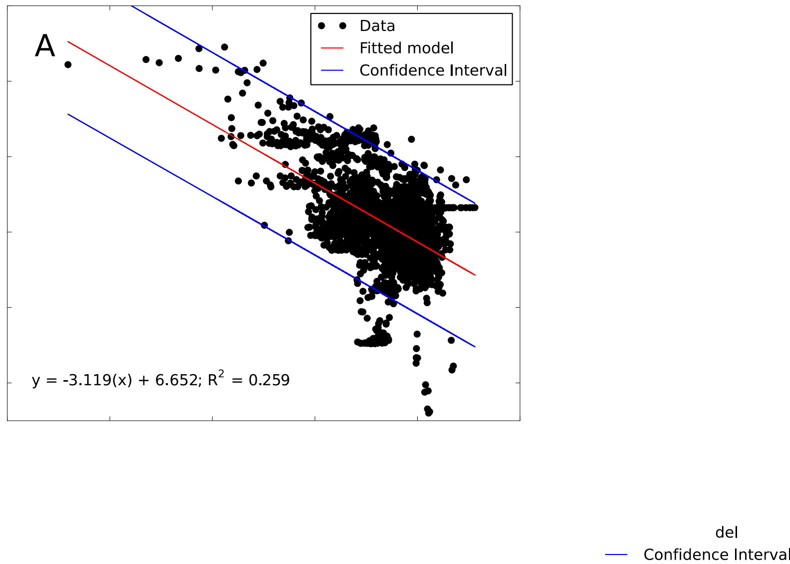
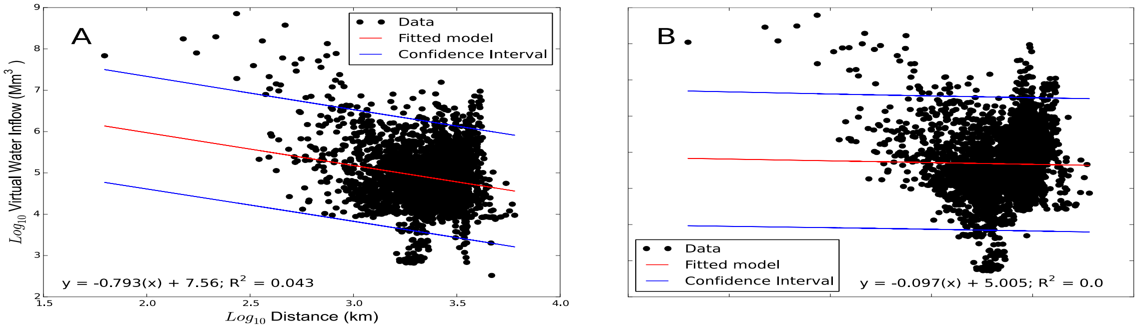


Figure A3: (A) The relationship between virtual water export volume and the population of trading partners. (B) The relationship between virtual water import volume and trading partner size. (C) The relationship between virtual water export volumes and the distance between Flagstaff and a trading partner. (D) The relationship between virtual water import volumes and the distance between Flagstaff and a trading partner.



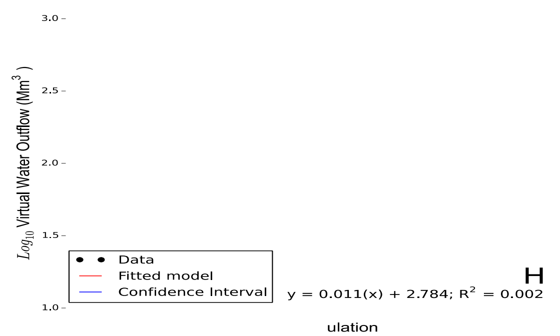


Figure A4: (A&B) The amount of value transferred between Flagstaff and its trading partners decreases with distance, but this relationship is not statistically significant. Similarly, there is no relationship between the value of commodity outflows and distance. (C&D) The value intensity of a gallon of water increases significantly as the trading partner distance increases. However, there is no relationship between the value of commodity outflows and distance. (E&F) The amount of value transferred between a trading partner and Flagstaff increases significantly with trading partner size for both commodity and virtual water inflows and outflows. (G&E) There is no relationship between the value intensity of a gallon of water and trading partner size for commodity and virtual water inflows and outflow.

Table A8: Virtual Water Inflows (V_{In}) by Geographic Location and Commodity Class

Rank	FAF Zone	Mm^3	Rank	Commodity	Mm^3
1	Remainder of Arizona	28.37	1	Milled grain products	16.28
2	Phoenix AZ MSA	15.33	2	Other agricultural products	12.63
3	Nebraska	2.99	3	Animal feed	10.72
4	New Mexico	2.6	4	Cereal grains	3.66
5	Remainder of California	1.15	5	Coal-n.e.c.	2.47
6	Los Angeles CA CSA	1.09	6	Coal	2.44
7	Tucson AZ MSA	0.91	7	Meat/seafood	1.24
8	Remainder of Utah	0.86	8	Miscellaneous manufacturing products	0.79
9	Idaho	0.48	9	Metallic ores	0.79
10	Denver CO CSA	0.41	10	Machinery	0.61
-	Remainder of USA	2.36	-	Remainder of USA	4.92
	Total	56.55		Total	56.55

*n.e.c. - not elsewhere classified

Table A9: Virtual Water Outflows (V_{Out}) by Geographic Location and Commodity Class

Rank	FAF Zone	Mm^3	Rank	Commodity	Mm^3
1	Remainder of Arizona	2.8	1	Electronics	0.85
2	Phoenix AZ MSA	1.11	2	Machinery	0.84
3	Los Angeles CA CSA	0.49	3	Motorized vehicles	0.81
4	Detroit MI CSA	0.43	4	Base metals	0.38
5	Tucson AZ MSA	0.28	5	Building stone	0.36
6	Remainder of Michigan	0.18	6	Mixed freight	0.29
7	Las Vegas NV CSA	0.13	7	Precision instruments	0.22
8	Dallas-Fort Worth TX CSA	0.12	8	Nonmetallic minerals	0.19
9	Mexico	0.12	9	Textiles/leather	0.19
10	Remainder of California	0.1	10	Natural sands	0.18
-	Remainder of USA	1.39	-	Remainder of USA	2.84
	Total	7.15		Total	7.15

Table A10: Results of Log-Likelihood Tests of the Distribution of Virtual Water Flows

Power Law (PL) Distribution

Virtual Water Flow	Distribution Fit Parameters			Distribution Comparisons					
				PL to LN		PL to SE		PL to ETPL	
	α	x_{min}	*D*	R	P	R	P	R	p
V_{In}	1.46	$1.4\text{x}10^{-4}$	0.056	**3.04**	**<0.01**	**2.31**	**<0.01**	**3.94**	**<0.01**
V_{Out}	1.72	$7.8\text{x}10^{-4}$	0.025	0.68	0.5	-0.08	0.94	1.75	0.11

Lognormal (LN) Distribution

Virtual Water Flow	Distribution Fit Parameters				Distribution Comparisons					
					LN to PL		LN to SE		LN to ETPL	
	μ	σ	x_{min}	D	R	p	R	p	R	p
V_{In}	-17.56	5.23	$1.4\text{x}10^{-4}$	0.064	**-3.04**	**<0.01**	0.19	0.85	-0.07	0.94
V_{Out}	-26.4	5.52	$7.8\text{x}10^{-4}$	0.02	-0.68	0.5	-0.67	0.5	1.16	0.24

Stretched Exponential (SE) Distribution

Virtual Water Flow	Distribution Fit Parameters				Distribution Comparisons					
					SE to PL		SE to LN		SE to ETPL	
	Λ	β	x_{min}	D	R	p	R	p	R	p
V_{In}	$4.26\text{x}10^{-5}$	0.09	$1.4\text{x}10^{-4}$	0.074	**-2.31**	**<0.01**	-0.19	0.85	-0.13	0.89
V_{Out}	$3.69\text{x}10^{-9}$	0.09	$7.8\text{x}10^{-4}$	0.029	0.08	0.94	0.67	0.5	0.92	0.36

Exponentially Truncated Power Law (ETPL) Distribution

Virtual Water Flow	Distribution Fit Parameters				Distribution Comparisons					
					ETPL to PL		ETPL to LN		ETPL to SE	
	α	λ	x_{min}	D	R	p	R	p	R	p
V_{In}	-1.43	$2.0\text{x}10^{-4}$	$1.4\text{x}10^{-4}$	0.054	**-3.94**	**<0.01**	0.07	0.94	0.13	0.89
V_{Out}	-1.69	$6.0\text{x}10^{-4}$	$7.8\text{x}10^{-4}$	0.02	-1.75	0.11	-1.16	0.24	-0.92	0.36

APPENDIX C

CURRICULUM VITA

Richard Rushforth is a PhD Candidate in Civil, Environmental, and Sustainable Engineering at Arizona State University. His research focuses on how complex adaptive hydro-economic networks formed economic trade and how to foster economic resilience to water resource shocks, such as drought. He has written journal articles and book chapters on various topics, including resource footprinting and developing collaborative sustainability projects. As a project manager at the Global Sustainability Solutions Service, he has managed and developed projects on measuring and managing greenhouse gas emissions; served as a Subject Matter Expert to the World Bank; managed GIS projects-to-reduce water usage at industrial greenhouses; and provided technical guidance on a water science primer for institutional investors. Previously, he has served as a technical advisor to low-income neighborhoods in Phoenix, Arizona, on a controversial groundwater remediation site and represented their interested in public fora and in the media; developed environmental remediation business models centered around renewable energy development; and helped developed a novel bioremediation technique for abandoned copper and lead mines. Mr. Rushforth has expertise in water resources management; greenhouse gas inventorying; and hydro-economic analysis.

EMPLOYMENT HISTORY

Project Manager, Global Sustainability Solutions Service, Arizona State University, Tempe, AZ, USA, 3/2013 – Present

Responsible for managing technical projects and developing sustainability projects around water resources, air emissions, and environmental quality. This includes:

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- Subject Matter Expert to the World Bank for the development of the City Climate Planner Certification training course on GHG emissions inventorying and the corresponding certification exam.
- Lead Technical Project Manager on a field study of studying the application of compost to Phoenix-area parks to estimate the potential for water savings and climate change adaptations.
- Lead Project Manager on the Phoenix metropolitan area regional Greenhouse Gas (GHG) emissions inventory effort, a collaboration between Phoenix-area municipalities, civil society organizations, and ASU.
- Conducted municipal operations GHG emissions inventory for the city of Avondale, Arizona.
- Established strong partnership with environmental officials in the city of Phoenix by designing and conducting a municipal operations GHG emissions inventory in 2012.
- Lead project to reduce energy and water consumption, and optimize CO_2 and waste reuse using GIS analysis.
- Developed algorithm to geolocate rural Albanian schools from satellite image data within climate zones.
- Won ASU President's Award for Sustainability for building a zero-waste program analysis tool for the Salt River Project.

- Developed water science tutorial tailored to institutional investors for a Chinese NGO.
- Provided analysis for ASU University Sustainability Practices to secure $492,000 to upgrade HVAC units at the Downtown Phoenix Campus.

Co-Founder, TerraVoyant, LLC, Tucson, AZ, USA 9/2009 – 3/2013

Served as Superfund Technical Advisor to Lindon Park Neighborhood Association through a US EPA Technical Assistance Grant. Responsibilities included:

- Protected the interests of a low-income neighborhood in Phoenix by providing technical services on behalf of the neighborhood association and advocating for their position in public forums.
- Prevented a Fortune 500 company from running a waste pipe through an elementary school's grounds, persuading both the school board and the EPA that the potential health risks were sufficient to reroute a treated effluent pipeline.
- Ensured remediation of air quality problems in 20% of the neighborhood's homes by providing evidence that on-site testing procedures failed to detect dangerous levels of carcinogens.

Developed environmental remediation business model that integrate remediation strategies coupled with renewable energy development to offset remediation costs.

Research Assistant, University of Arizona, Tucson, AZ, USA, 8/2007 – 8/2010

Responsible for designing and developing an environmental monitoring system to assess the efficacy of a novel soil remediation technology. This included:

- Designed and built novel environmental sampling devices to analyze the efficacy of a new environmentally benign in situ technology to remediate acid mine tailings.
- Created a policy document that characterized the use of water by the high-tech manufacturing sector in Arizona.

OTHER PROFESSIONAL EXPERIENCE

- Member-at-large, University of Arizona Students Advancing Green Enterprise (SAGE) Funding Board. August 2009 – August 2010.
- Sustainability Coordinator, Cats in the Community Day, University of Arizona. Designed green remodeling of the Wildcat School and organized 300 volunteer works to implement the school remodeling. March 6, 2010.
- Commissioner, the Tucson-Pima County Metropolitan Energy Commission. Served February 2008 – August 2010.
- Special Awards Judge, Water Sustainability Program Award, Southern Arizona Regional Science and Engineering Fair. Tucson Convention Center, Tucson, Arizona. 2009 and 2010.
- Sustainability Coordinator – Cats in the Community Day, University of Arizona.

- Board Member-at-Large – University of Arizona Student Services Fee Advisory Board. Oversight and allocation of $3 million (USD) for use in scholarship, retention, and diversity program creation.

PUBLICATIONS & PRESENTATIONS

Peer Reviewed Publications

Rushforth, R. R., & Ruddell, B. L. (2016), The vulnerability and resilience of a city's water footprint: The case of Flagstaff, Arizona, USA, Water Resour. Res., 52, 2698–2714, doi:10.1002/ 2015WR018006.

Rushforth, R. R., & Ruddell, B. L. (2015). The hydro-economic interdependency of cities: Virtual water connections of the Phoenix, Arizona, metropolitan area. *Sustainability, 7*(7), 8522–8547.

Paterson, W.; **Rushforth, R**.; Ruddell, B.L.; Konar, M.; Ahams, I.C.; Gironás, J.; Mijic, A.; Mejia, A. (2015). Water footprint of cities: A review and suggestions for future research. *Sustainability, 7*(3), 8461-8490.

Ruddell, B. L., Adams, E. A., **Rushforth, R.**, & Tidwell, V. C. (2014). Embedded resource accounting for coupled natural-human systems: An application to water resource impacts of the western US electrical energy trade. *Water Resources Research*, *50*(10), 7957–7972.

Rushforth, R. R., Adams, E. A., & Ruddell, B. L. (2013). Generalizing ecological, water and carbon footprint methods and their worldview assumptions using Embedded Resource Accounting. *Water Resources and Industry,* 1, 77–90.

Rushforth, R., & Phillips, C. F. (2010). Gathering under a green umbrella: Collaborative rainwater harvesting at the University of Arizona. *International Journal of Social Ecology and Sustainable Development, 1*(3), 23–33.

Book Chapters

Rushforth, R., & Phillips, C. F. (2012). Gathering under a green umbrella: Collaborative rainwater harvesting. *Sustainable Policy Applications for Social Ecology and Development,* Hershey, PA: IGI-Global, 139-149.

Publications in Review

Foley, R., Wiek, A., Kay, B., **Rushforth, R.** Ideal and Reality of Multi-Stakeholder Collaboration on Sustainability Problems - A Case Study on a Large-scale Industrial Contamination in Phoenix, Arizona. In review at *Sustainability Science.*

Publications in Preparation

Rushforth, R., and Ruddell, B. The three Colorado Rivers: The hydrologic, legal, and economic allocations of the water in a shared river basin

Ruddell, B., and **Rushforth, R.** The US blue water footprint and vulnerability to drought.

Rushforth R., Epshtein, O., Seager, T. P., O'Neill, D., Buch, R. Arriving at resilient forest ecosystems via resilient supply chains: Can sustainable forest products economies thrive in the face of changing environmental management paradigms.

Grants

Lessons learned: Extending the student/staff/faculty collaborative work model to the K-12 environment. USGS 104B grant program, awarded $11,474.40. (December 2007)

Fellowships

Water Sustainability Program Student Fellow: Awarded $16,450. (April 2009 – May 2010)

Biosphere 2 Science and Society Fellow: Awarded $3,000. (April 2008 – April 2009)

Conference Presentations

Rushforth, R., & Ruddell, B. L. (2015, July). *Assessing the water stress of city-level trade: Operationalizing the water footprint concept.* Oral Presentation. The International Society for Industrial Ecology Conference: Taking Stock of Industrial Ecology, University of Surrey, Guildford United Kingdom.

Rushforth, R., & Ruddell, B .L. (2015, June). *Creating a virtual water complement to the Colorado River Compact: How is the Colorado River shared among the seven basin states?* Oral Presentation. 2015 UCOWR/NIWR/CUAHSI Annual Conference, Henderson, NV.

Rushforth, R. (2015). *Creating policies around how cities outsource water: Disaggregating virtual water trade to the watershed level to increase municipal resilience.* Oral Presentation. XVth World Water Congress. Edinburgh, United Kingdom.

Rushforth, R. (2015, June). *Intra-metropolitan water dependencies: A case study of water footprints and virtual water flows in the Phoenix metropolitan area.* Oral Presentation. 2015 International Symposium on Sustainable Systems and Technology. Detroit, MI.

Rushforth, R., & Ruddell, B. L. (2014, December). *Virtual water transfer within a large metropolitan area: A case study of Phoenix, Arizona.* Poster. 2014 AGU Fall Meeting. San Francisco, CA.

Rushforth, R., Foley, R. W., Wiek, A., & Kay, B. (2014, May). *Nanotechnology versus the dragon: CVOC-contaminated groundwater and the socially contested M52 Superfund Site.* Ninth International Conference on Remediation of Chlorinated and Recalcitrant Compounds. Monterey, CA.

Rushforth R., Epshtein, O., Seager, T. P., O'Neill, D., & Buch, R. (2014, May) *Arriving at resilient forest ecosystems via resilient supply chains: Can sustainable forest products economies thrive in the face of changing environmental management paradigms?* 2014 International Symposium on Sustainable Systems and Technology. Oakland, CA.

Rushforth R., O'Neill, D., & Buch, R. (2014, May). *Building a dynamic multi-city, regional GHG emissions inventory for the Phoenix metropolitan area.* 2014 International Symposium on Sustainable Systems and Technology. Oakland, CA.

Rushforth, R., & Ruddell, B. L. (2013, December). *Trade in and valuation of virtual water impacts in a city: A case study of Flagstaff, Arizona*. 2013 AGU Fall Meeting. San Francisco CA.

Rushforth, R., Kalinowski, T., & Foley, R. (2012, December). *Rethinking participatory technology assessment: Integrating diverse perspectives from the community, engineering, and sustainability.* Dupont Summit 2012: Pressing Issues amid the Political Maelstrom. Washington, DC.

Rushforth, R., Davis, L., Perino, L., McCormick, G., Davison, L., & Riley, J. (2008, July). *Promoting campus sustainability through interdisciplinary cooperation: The greening of the University of Arizona Visitor Center.* Soil and Water Conservation Society 2008 International Annual Conference.

Chaired Conference Sessions

Management of water resources: Urban water management at the *XVth World Water Congress.* Edinburgh, United Kingdom.

TEACHING

Teaching Associate, School of Sustainability, Arizona State University. Spring 2015.
School of Sustainability 598: Special Topics: Institutional Sustainability Assessment

Teaching Associate, School of Sustainability, Arizona State University. Fall 2014.
School of Sustainability 494: Special Topics: Greenhouse Gas Emissions Inventory
School of Sustainability 598: Special Topics: Greenhouse Gas Emissions Inventory

Teaching Assistant, School of Sustainability, Arizona State University. Spring 2013.
School of Sustainability 326: Systems Ecology

Teaching Assistant, School of Sustainability, Arizona State University. Fall 2012.
School of Sustainability 326: Systems Ecology

EDUCATION

Ph.D. Candidate, Civil, Environmental, and Sustainable Engineering Arizona State University, Tempe, AZ. Defending June 2016

M.B.A., W.P. Carey School of Business, Arizona State University, Tempe, AZ, May 2015.

M.Sc., Water Science, Policy, and Management, University Of Oxford, St. Cross College, School of Geography and the Environment, Oxford, UK, 2011

M.S., Soil, Water, and Environmental Science, University Of Arizona, Tucson, AZ, August 2010

B.S., Environmental Science, Cum Laude (Minor in Chemistry), University Of Arizona, Tucson, AZ, May 2007

LANGUAGES

Spanish – Basic Conversational Skills