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California’s Water Footprint: recent trends and framework for a sustainable transition

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California’s Water Footprint:

recent trends and framework for a sustainable transition

By

Julian Fulton

A dissertation submitted in partial satisfaction of the

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Doctor of Philosophy

in

Energy and Resources

in the

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of the

University of California, Berkeley

Committee in charge:

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Spring 2015

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This dissertation presents three studies on California’s water footprint, which is defined as the amount of water required to produce everyday goods and services demanded by California consumers on a yearly basis. Such a consumption-based indicator of water use is novel, and I introduce water footprint science as an *expanded reading* of water that adds value to conventional approaches to understanding society’s relationship with water resources. California, as a water-limited state, presents a useful case study for examining how demands on water resources have shifted within and outside of the region through its water footprint. The Introduction section discusses the history of water use in California from a conventional perspective as well as what water footprint assessment, as an evolving science, might offer in terms of an expanded reading of water for sustainability decision making.

The first study (Chapter 2) shows that scaling water footprint assessment to the state level both illuminates California’s unique arrangement with respect to internal and external water resources and provides a basis for policy consideration at a relevant decision-making level. The second study (Chapter 3) focuses on the water footprint of California’s energy system in order to show how environmental policymaking, particularly climate mitigation policies in the energy sector, can result in maladaptation with respect to water systems and that water footprint assessment provides a useful tool for avoiding redistribution of water impacts. The third study (Chapter 4) presents a time-series of California’s overall water footprint, indicating an externalization of water footprint demands in recent decades and a decreasing of dependence on internal water resources for instate consumption of everyday goods.

The Conclusion section reflects on what water footprint assessment has thus far provided in terms of an expanded reading of water for California, and how that information might support sustainability decision making in various facets of governance. I identify shortcomings of the method and ways in which improvements can be made in the future, particularly through interdisciplinary research. Water footprint information offers important insights into California’s recent development as well as tools for developing future sustainable transitions.

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Preface

This spring of 2015 marked one of the driest rainy seasons on record for California. It was the fourth consecutive spring with below-average precipitation and Governor Jerry Brown has declared a Continued State of Emergency due to drought conditions. On April 1st the Governor announced mandatory drought restrictions in cities for the first time in the state's history, adding that "in almost every way conceivable, Californians have to get used to a very different world, and we're going to have to live just a little bit differently."[1] While California has seen deep droughts before, the Governor was alluding to the onset of climate change. Indeed, the current drought has recently been causally attributed to anthropogenic greenhouse gas emissions.[2]

Reactions to the drought, and the Governor's actions, have been varied and vocal from the public and the press alike. Many residents, told to reduce outdoor watering and take shorter showers, have pointed fingers at agricultural users, and the almond and beef industries have come under particular scrutiny for their large water use. The New York Times ran an article provocatively titled "California Drought Tests History of Endless Growth,"[3] questioning the state's ability to negotiate the limits of nature. California's water management and delivery agencies have scrambled to cope with conditions and to impose measures fairly among water users. Larger shifts are also taking place in California water management, with the passage of significant groundwater legislation and a $7.5 billion infrastructure bond in the fall of 2014.

California is coming to terms with the drought and its place in a changing climate. However, as this dissertation shows, the state has in many ways already been insulating itself from the effects of drought for decades. At least for the foreseeable future, there will be no violent conflict, no starvation, no dustbowl-style migration, as seen in droughts of previous generations. The agricultural sector will take a hit, and there will be hardship in support industries and farming communities, but the overall economy will register a minor shock. Food prices may rise, but supermarkets will still be stocked. Many Californians may notice the drought very little.

Still, California's relative insulation from drought comes with new challenges. Much of the insulation stems from California's ability to import goods produced elsewhere, thereby relying on hydrologic conditions and ways in which water is used in those places. California also supplies agricultural goods to other parts of the country and the world, connecting its hydrologic conditions to the dependence of others. These redistributions can be understood as creating new forms of climate risk or resilience, thus pointing to looming questions that have been sharpened by the current drought: Should California continue to be such a large food supplier to the nation and world? Should California be more self-sufficient in its own food and water systems? If not, to what extent should California engage in water governance elsewhere? This dissertation only begins to engage with these questions; they will be answered in coming decades.

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[1] http://www.pbs.org/newshour/bb/gov-jerry-brown-california-change-whats-comfortable-address-drought/

[2] Diffenbaugh, NS, DL Swain, and D Touma. 2015. "Anthropogenic Warming Has Increased Drought Risk in California." *Proceedings of the National Academy of Sciences* 112 (13).

[3] http://www.nytimes.com/2015/04/05/us/california-drought-tests-history-of-endless-growth.html

Acknowledgements
This document represents the culmination of a six-year journey into academia, along which I have benefited from many supporters and companions. I am endlessly grateful to all those who have helped me along the way and with whom I have enjoyed friendship, laughter, anguish, and intellectual exchange.

My dissertation committee has provided incredible mentorship through rounds of funding applications, prospectus drafts, manuscript revisions, and seemingly endless versions of research questions. Dick Norgaard provided unwavering support from the moment I stepped into ERG, often with a prod to broaden my thinking, but always through grounded conversation that inevitably came back to people, rivers, and real-world experiences. Isha Ray keenly forced my hand at many junctures, causing me to rethink my claims on water and moreover teaching me that the craft of research is as important as the findings themselves. John Dracup sparked my early interest in California water and has been a tireless advocate and guide since I started graduate school in 2006. Peter Gleick has been a tremendous force on my academic and professional development, and provided a nurturing off-campus venue in which to carry out my research. I also benefited from considerate time and suggestions from other campus faculty, including Dan Kammen, Dara O'Rourke, David Roland-Holst, Nancy Peluso, and Jeff Romm.

I am grateful to my colleagues in ERG and the supportive environment cultivated by current and former ERGies. The ERG Water Group has been a particularly collegial platform for students exchanging ideas and constructively critiquing each other's work. ERG staff have provided unparalleled administrative support and in ensuring my financial security over the past six years through ERG block grants and GSI positions. This work has also benefited from financial awards from UC Berkeley's Graduate Division, Institute of European Studies, and Institute of International Studies, as well as the Association of California Water Agencies.

This work would not have been possible without support from off campus. Heather Cooley at the Pacific Institute has been my closest collaborator and mentor throughout this research. I owe her and the Water Program a great deal of gratitude for backing this work and assisting our collaborations with others. Most directly, we worked with Fraser Shilling and Susana Cardenas at UC Davis, Abdul Khan and Rich Juricich at the Department of Water Resources, and Vance Fong and Don Hodge at EPA Region 9. These individuals and many others whom we worked with through stakeholder meetings provided invaluable feedback.

Friends and family have provided me a treasured support network throughout graduate school. Giorgos Kallis has been an incredible mentor in both my intellectual development and in the life of academia. My classmate and friend, Jalel Sager, has been a steady wingman in finding that healthy distance from our work. My parents, Liz and Gordon, have been infinitely understanding of my life choices and supportive beyond words, while my brother Orion and family have always been there for me. Finally, my partner Ingrid has provided not only hundreds of hours of patient feedback and editing, but that essential ingredient for a successful graduate career, love.

Chapter 1: Introduction

Background

In late 2014, the United States Geologic Survey (USGS) released *Estimated Use of Water in the United States in 2010* (Maupin et al. 2014), a benchmark national water report issued every five years. According to the USGS, which measures not only precipitation and streamflow within the U.S. but also the amount of water used by our society, total water withdrawals in the U.S. had fallen below 500 cubic kilometers (km^3) per year, a level not seen since before 1970 (Figure 1). The report confirmed a downward trend in measured water use since 1980, when withdrawals reached a maximum of about 600 km^3 per year.

Considering persistent population increase and near-exponential economic growth in the U.S., this trend plausibly supports a story that the U.S. is on a path towards more efficient, productive, even *sustainable* use of water. Reactions in the media were unanimously positive, citing "good news for the environment, great news in times of drought and a major victory for conservation (Muskal 2014)." Water scientist Peter Gleick considered the news from USGS as evidence of the "the slowly unfolding story of *peak water* in the United States and elsewhere" (Gleick 2014, emphasis my own).

Indeed, in support of Gleick and Palaniappan's (2010) *peak water* framework, decreasing water use accounts have been noted in many industrialized countries across agricultural, industrial and domestic sectors (Rock 2000; Duarte, Pinilla, and Serrano 2013). With growing populations and economies, these figures appear even more stunning on per-capita and per-dollar-of-productivity bases and have led to a body of work using environmental Kuznets theory, which I review later in the literature review section of this introduction.

Here though, while these figures are likely based on careful measurement and sound interpretation, I argue and situate this dissertation within the argument that, ultimately, they are emblematic of conventional *readings* of water that are insufficient to guide our present social systems toward a sustainable relationship with water. By *readings* of water, I mean the ways in which water bodies and water processes become legible (Scott 1998) to a management context and for which management criteria and goals become applied.

I consider the USGS' reading of water conventional because it is takes a production-based perspective of water use within bounded political units. As seen in Figure 1, water is measured as withdrawal for productive economic activities in the agricultural, thermoelectric, or public supply sectors within the U.S. (withdrawals for individual states and counties are also reported). Water resource management goals, in turn, may be oriented around improving productivity (with respect to water) within a given economic sector or political unit. Many such management goals have been successfully implemented in the U.S. through a range of policies and technologies, and doubtless contributed to the overall downturn in nationwide withdrawals.

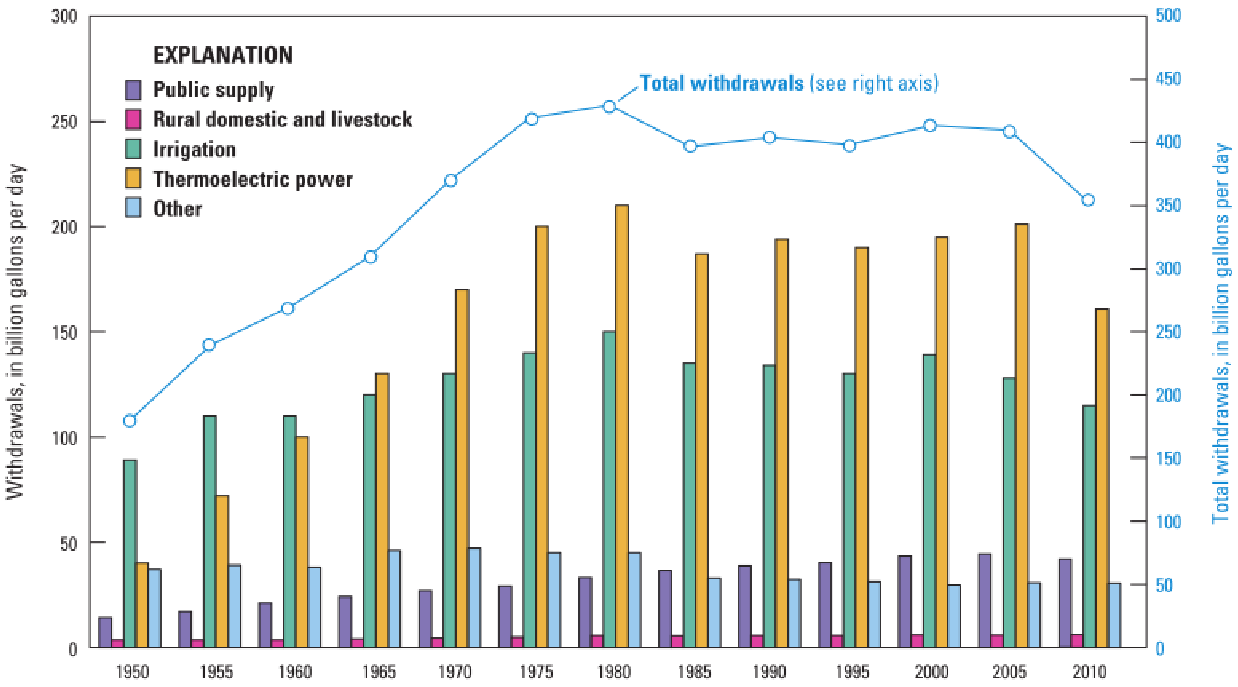

Figure 1: Trends in total U.S. water withdrawals by water-use category, 1950–2010 (Maupin et al. 2014)

Water resources management is concerned with much more than the study of quantitative water withdrawals. Questions of the impacts of withdrawing water from different sources, of changing watershed dynamics, of impacting habitat, or of degrading water quality are all crucial to water resource managers. Also crucial are the economic and institutional questions about managing and allocating water resources equitably among stakeholders according to market and institutional rules and logics. Still, these questions tend to be addressed with a conventional reading of water, that is, a production-based perspective bounded by political units. This conventional approach makes sense given that, historically, much of the power to govern water resources has resided with domestic agencies tasked with enabling or regulating production processes.

But looming questions remain if water resources management is to come to terms with global-scale phenomena, particularly economic globalization, human development, and climate change. Economic globalization refers to the interconnections of domestic economies through exchanges of money and goods. Human development refers to accessing basic needs and improving quality of life for humanity at large. Climate change refers to shifting regimes in precipitation and other climatic variables. How do these global-scale phenomena relate to water resource management at local- to regional-scales?

Throughout this dissertation I engage an alternative reading of water, namely water footprint assessment, which brings a consumption-based perspective to water-use accounting and is particularly attentive to the interconnections between local and global scales, and between economies, people, and their environments. A consumption-based perspective reads water use as ultimately driven by demand for products and production processes, and can thus be thought of as the inverse of a production-based perspective. As such, I use water footprint assessment not to replace a conventional reading of water, but rather to complement it. I hope this expanded reading will contribute to more adaptive and ultimately more fit management strategies that meet the particularly complex challenges presented by globalization, human development, and climate change.

My primary concern in mobilizing an expanded reading of water is a persisting *global water crisis*, a term which can be broadly summed as a failure of development to provide safe and sustainable use of water for social reproduction in all of its biological, economic, and spiritual dimensions. This global water crisis can be observed by its many faces: by nearly 1 billion humans who lack access to improved drinking water sources; by over 2 billion humans who lack access to proper sanitation; by nearly 1 million water-related deaths per year[1]; by a lack of, and overburdening of, water infrastructure in cities; by contamination of waterways and destruction of aquatic habitats; by the overexploitation of surface water flows and aquifers (Gleeson et al. 2012; Srinivasan et al. 2012; UN Water 2014).

This shocking culmination of water crisis at the global scale ultimately breaks down to myriad water problems manifested at the local to regional scale. But while conventional readings of water view these as local to regional problems with local to regional solutions, a consumption-based perspective maintains that there are still important global dimensions to understanding the drivers of these problems. Thus, seemingly distant water problems have important connections to human activities around the globe. I also see this as indicative that solutions must address both environmental and social drivers of water problems at multiple scales.

Developing a research methodology to accompany an expanded reading of water and to account for the complexities of global water challenges from a consumption perspective is challenging. Water footprint assessment aims to provide such a methodology. The next section of this introduction traces the intellectual origins of water footprint assessment through literatures on water and growth from both a production- and consumption-based perspective. I then discuss why studying California is a good case for this research.

Literature Review: water footprint antecedents

Production-based perspectives

The relationships between demands on water resources and economic and population growth are a key motivation of this dissertation. Questions of growth and aridity have motivated countless

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[1] This number refers to diarrhea deaths attributable to inadequate water, sanitation, and hygiene, as estimated by the World Health Organization (UN Water 2014). Many experts consider a broader definition of "water-related" deaths, which would be well in excess of 1 million people per year.

works, particularly contextualized understandings of the history of California and the American west (Reisner 1986; Worster 1992; Hundley 2001). Generalized understandings of water and growth have primarily taken a top-down econometric approach with the goal of testing the environmental Kuznets curve (EKC) hypothesis. Simon Kuznets' original work in the 1950s on the relationship between income inequality and economic growth was reinvigorated by environmental and natural resource economists in the 1990s. Simply put, the EKC hypothesis states that, as per-capita income increases, so does environmental damage up to a turning point, after which damages gradually decrease due to technology improvements and political commitment to a cleaner environment. Evidence of this inverted-U-shaped curve was initially shown for a number of pollutants and has since garnered intense debate in the academic literature as to its application to other environmental and resource issues (Rothman and Bruyn 1998).

Water use entered rather late into the EKC literature, beginning with Rock (1998), who found support for the EKC in international cross-sectional data as well as panel data for water use in U.S. states. Subsequent studies produced similar findings using different water use data sources and different statistical methods (Cole 2004; Barbier 2004; Duarte, Pinilla, and Serrano 2014), as well as specifically for the agricultural (Goklany 2002; Bhattarai 2004) and industrial (Hemati 2011; Jia et al. 2006) sectors. While the breadth of these studies implies a rather robust statistical support for the EKC hypothesis in water use, all of them stop short of identifying any historically specific mechanisms or consequences of their findings. For example, in a follow-up study, Rock (2000) did a regression on the determinants of water use among 68 countries for one year, ending with the brief conclusion that the inverted-U curve is primarily shaped by limited national water endowments, domestic environmental policy, and economic restructuring.

Rock's conclusion summons two fundamental critiques of the EKC hypothesis, which also provide convenient departure points for this research project. The first critique, which was also raised in response to the original Kuznets theory, is that the curve itself shows a cross section, or snapshot of countries whereas the hypothesis posits a dynamic progression for individual countries. This denies historically specific processes within and between countries that may be important determinants of environmental degradation. Second, to the extent that countries do become "greener" as they become wealthier, EKC models have been criticized for not accounting for the effects of international trade and the possibility that trade allows impacts, along with production, to be outsourced to other countries and escape national accounts of environmental degradation (Katz 2008). In line with this second critique, I turn next to consumption-based approaches to understanding the relationship between water and growth.

Consumption-based perspectives

Consumption-based approaches to understanding social uses of water account for the water required to produce goods and services throughout their production chain. These uses of water are said to be embedded or embodied in products as they travel from producers to consumers. Because this volume accounts for the amount used and not the water physically contained in products, it has been termed “virtual water.” Virtual water use, from the consumption-based perspective, is attributed to the point of final consumption.

The virtual water concept can be traced to the early 1990s when British geographer Tony Allan began studying water-constrained development in the Middle East and North Africa (MENA) region. Allan is credited with having coined the term “virtual water” as one explanation for the apparent absence of resource conflict among MENA countries (Allan 1996a). As these countries seemed to be reaching the limits of developing their domestic water supplies, the import of virtual water, mostly in the form of food grains, was found to be an important mechanism for coping with water scarcity in the face of rising demand (Figure 2).

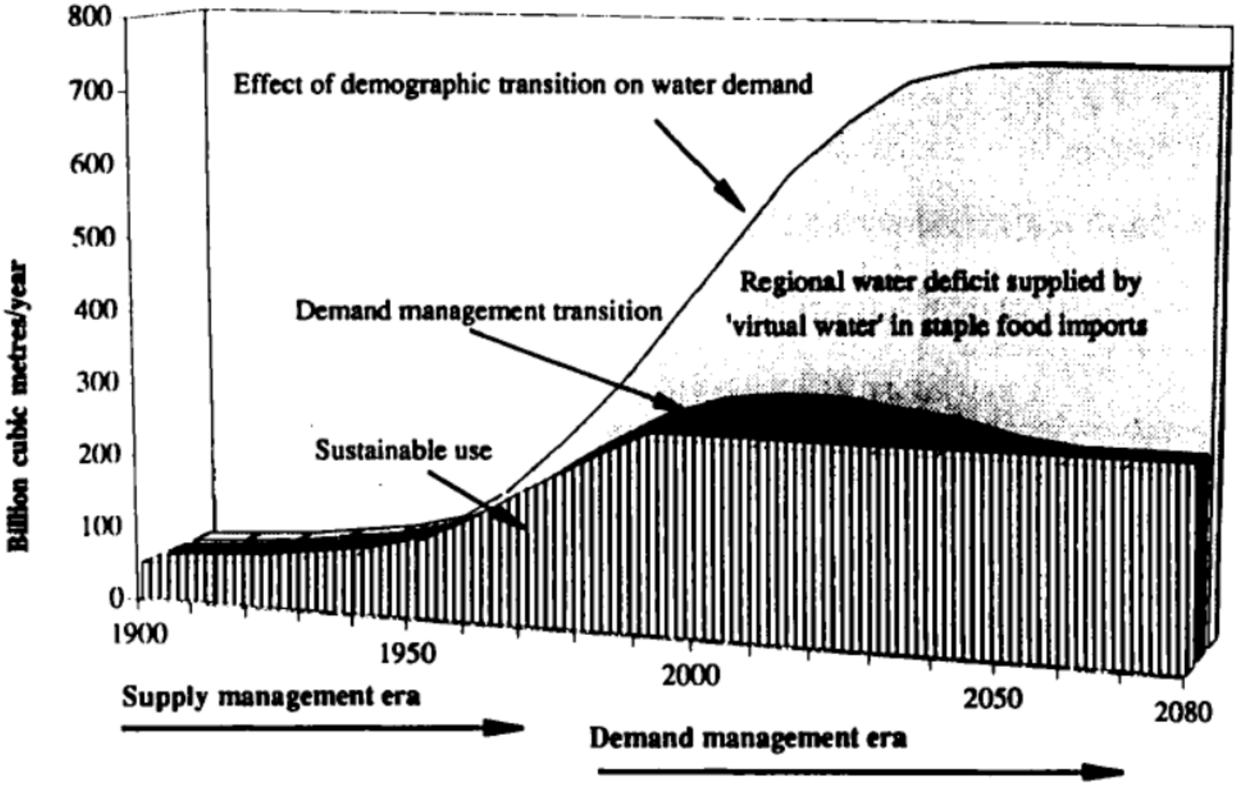

Figure 2: Estimates of water use and availability in the MENA region (Source: (Allan 1996a)

Allan continued to promote what he called the “economically invisible, politically silent” policy option of virtual water throughout the late 1990s (Allan 2002; Allan 1998; Allan 1997; Allan 1996b). By the early 2000s, several other authors began studying different aspects and applications of the “virtual water strategy” as the concept became known. Earle (2001) applied the concept to the agricultural product trade regimes of four Southern African countries, and provided some initial statistical evidence that domestically available renewable water sources (often referred to in the literature as the water “endowment” of a country) was a good explanation for why countries engage in virtual water trade. Yang and Zehnder (2001) found the strategy applicable at the sub-national level, arguing for integrating virtual water into planning decisions around regional scarcity within China. They also applied the water endowment thesis (analogous to comparative advantage) to six southern Mediterranean countries (Yang and Zehnder 2002) and later to all the countries of Africa and Asia. These studies showed that over the previous two decades, with rising populations putting strain on domestic resources, countries with financial resources to do so began importing more and more virtual water in the form of food grains (Figure 3) (Yang et al. 2003).

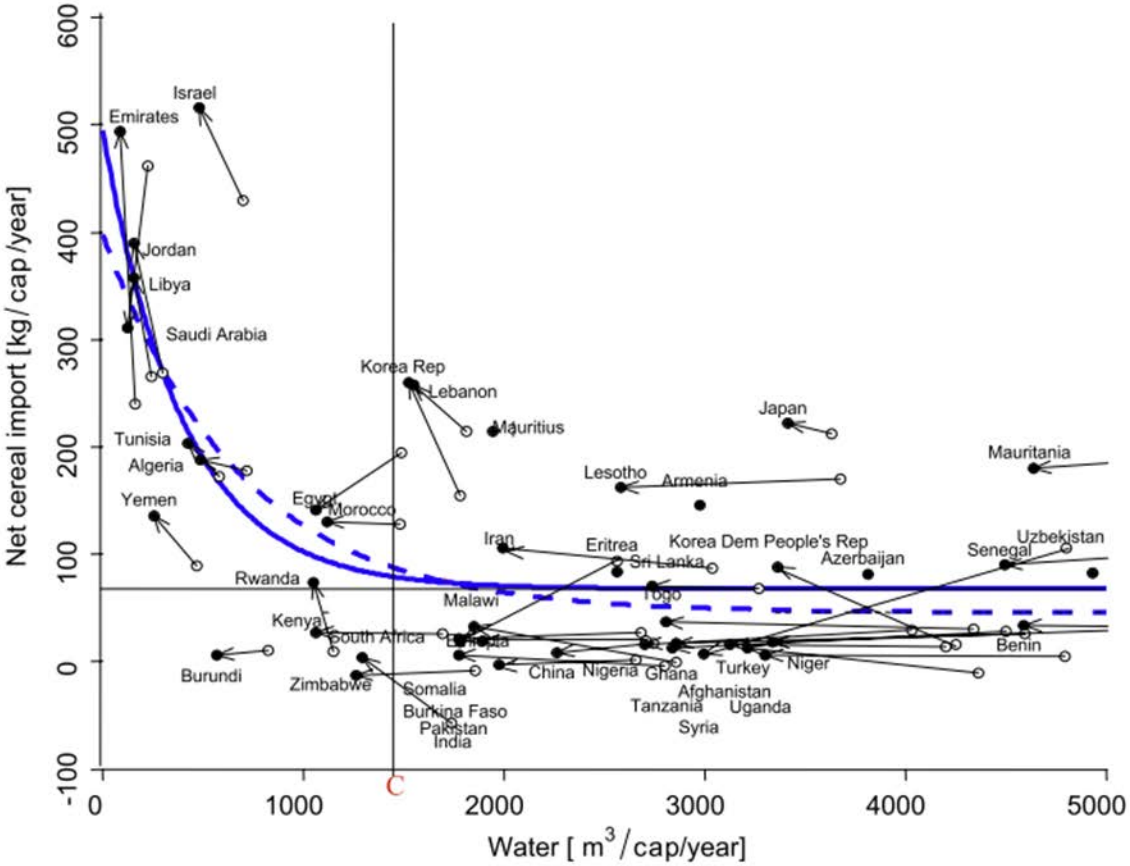

Figure 3: Patterns of change in per-capita net cereal import versus per-capita available water resources. Dashed curve and open circles are the fits of the model with the water variable only for the investigation period 1980–1984, and solid curve and solid circles with country names are the fits for the investigation period 1996–2000. Arrows in the diagram indicate movements of the positions of the countries from the first to the last period. Source: (Yang and Zehnder 2007)

Wichelns (2011a; 2011b; 2010; 2004; 2001) has argued consistently from the economic standpoint against the primacy of virtual water in explaining a region's or country's trade flows. In his 2001 article he discussed the virtual water trade regime of Egypt, showing that other factors such as land and labour, as well as the influence of agricultural policies on famers' valuation of water, were more important determinants of water use and trade. This also helped to explain the observations from later studies, which showed that in some cases, virtual water actually flows from areas of low water endowment to areas of high water endowment, seemingly the antithesis of the virtual water strategy (Fraiture et al. 2004; Verma et al. 2009). In later papers, Wichelns has continued to acknowledge the value of the virtual water concept from a descriptive mode of analysis, but that when it comes to identifying meaningful correlation for purposes of policy prescription, hydrologic indicators such as water endowment are insufficient, and that comparative advantage theory must be understood in the context of a greater set of criteria.

Although these initial studies laid the groundwork of the virtual water concept as both a strategy and an explanatory factor in trade flows, they were limited in both their contextual geographic applications and their rough quantification of virtual water. The scope of inquiry on virtual water increased significantly after the first attempt to calculate virtual water flows between all countries of the world, carried out in 2002 at the Institute for Water Education in the Netherlands. The report (Hoekstra and Hung 2002) was limited to agricultural crops (omitting animal-based or industrial products), but it provided the basic calculation methods that have been repeatedly used in virtual water studies up to the present.

Hoekstra and Hung (2005; 2002) averaged global virtual water flows in the form of crops over the period of 1995–1999 and found that total flows amounted to about 695 cubic kilometres per year (Gm^3/y), or about 13% of total global water use. The report also provides virtual water balances for all nations, world regions, and continents, and compares them with scarcity metrics. Figure 4 shows “water dependency,” defined as the extent to which a country relies on imported virtual water, versus water scarcity, defined as the relative degree to which a country’s water resources are already being used. Contrary to the relationship found earlier between virtual water import and resource endowments (Yang et al. 2003), this global study found a more scattered relationship, indicating that other factors besides water scarcity or endowment drive virtual water trade, and that such trade relationships must be analysed on a more case-by-case basis.

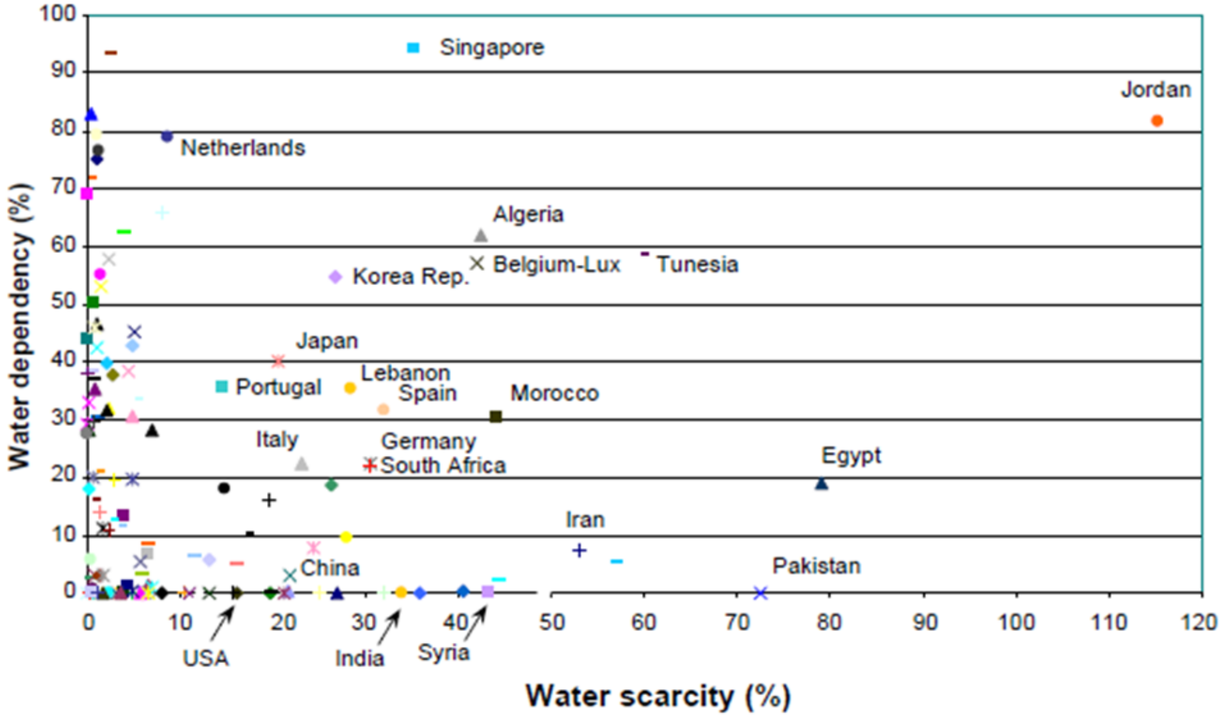

Figure 4: Water dependency versus water scarcity for all countries of the world (1995–1999). Water scarcity is defined as ratio of total water use to water availability; water dependency is calculated as the ratio of the net virtual water import into a country to the total national water appropriation. Source: ***(Hoekstra and Hung 2005)***

These topics, and many others, were taken up in 2002 at the International Expert Meeting on Virtual Water Trade. The proceedings (Hoekstra 2003) provide evidence for a range of perspectives on the application of virtual water, but also some analytical convergence that helped define the field going forward. While regional assessments were still clearly important contributions to the virtual water literature, it was acknowledged that virtual water trade was clearly a global phenomenon and should be studied as such.

Mekonnen and Hoekstra (2010) calculated upstream water requirements (virtual water flows) of traded goods for nearly every country in the world between 1996 and 2005. Average net virtual water import per year is shown in Figure 5 along with major bilateral flows. The country patterns are similar to the results from other material flow studies, however climatic and bio-geographical conditions add another perspective. Most countries of Europe, the Middle East, and North Africa are net virtual water importers. Japan, South Korea, and Mexico are also notable importers. The largest virtual water exporters are found in North and South America, as well as South and Southeast Asia, and Australia.

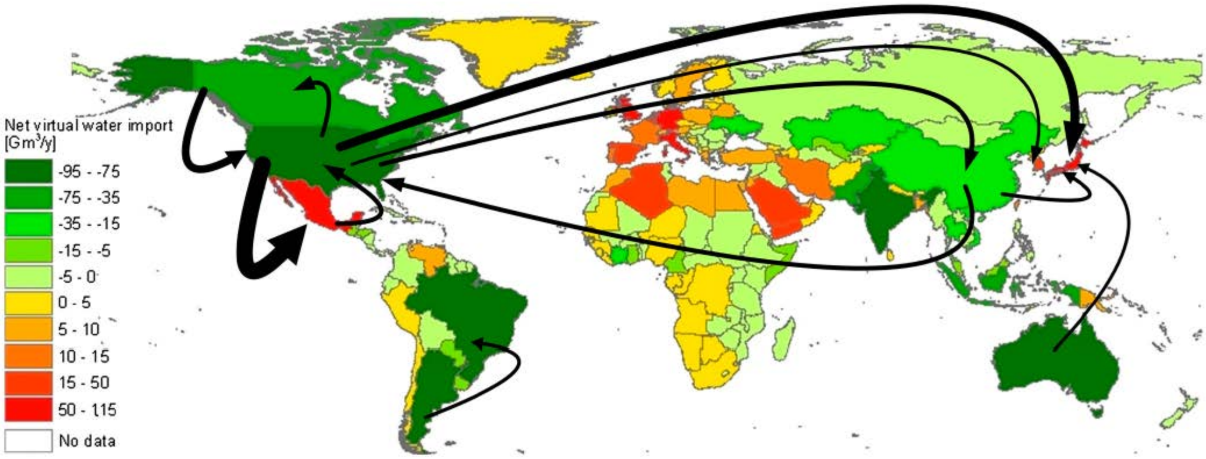

Figure 5: Virtual water balance per country and direction of gross virtual water flows related to trade in agricultural and industrial products over the period 1996–2005. Only the largest gross flows (>15 Gm^3/y) are shown. Source: (Mekonnen and Hoekstra 2010)**.**

Subsequent work on global virtual water trade has assessed the structure and logic of the virtual water trade system. D'Odorico et al. (D'Odorico, Laio, and Ridolfi 2010) develop a simple model of the virtual water trade network in order to test the long-term resilience to shocks such as drought, concluding that globalization has provided short term benefits via virtual water but resulted in less resilience due to the locked in interdependencies that make dynamic virtual water transfer difficult. Konar et al. (Konar et al. 2011); Suweis et al., (Suweis et al. 2011) develop a more formal predictive model, using complex network theory to show that the virtual water trade network operates as a hierarchy with water endowed countries forming trade clusters that will be increasingly difficult for water-scarce countries to penetrate under climate change scenarios. Similar conclusions were found by Yang et al. (Yang et al. 2012) using ecological network analysis. Dalin et al. (Dalin et al. 2012) build on the modelling of Konar et al. (Konar et al. 2011) to trace the evolution of the virtual water trade network since 1986 (Figure 6) in order to identify contributing political-economic factors like trade agreements in the changing formation of the network.

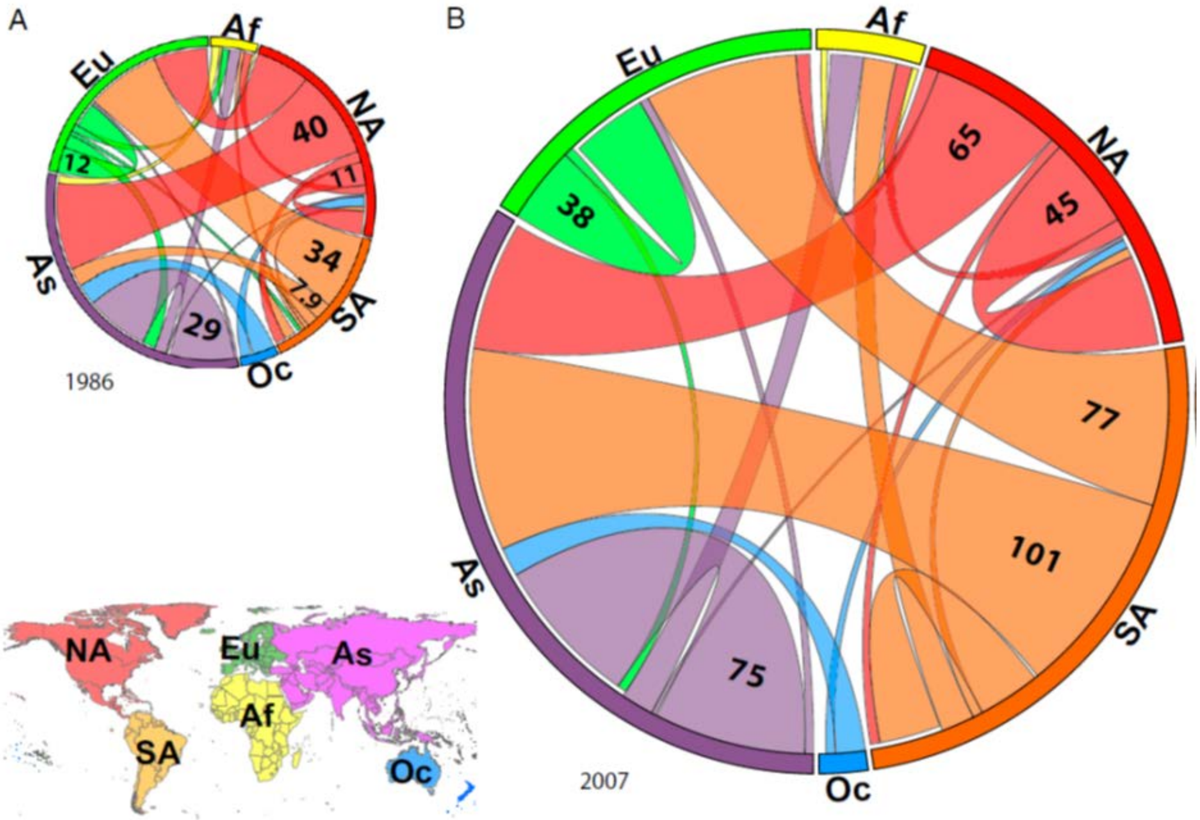

Figure 6: Virtual water flows between the six world regions, 1986 and 2007. Numbers indicate the volume of VWT in km^3, and the links' colours correspond to the exporting regions (colour scheme given in bottom left). The circles are scaled according to the total volume of VWT. Note the large difference between total VWT in 1986 (A; 259 km^3) and 2007 (B; 567 km^3) Source: ***(Dalin et al. 2012)***

Considering these ongoing developments, the study of virtual water has matured substantially over the last 20 years. It has been shown to be a strong, if only partial, explanatory factor in how water-stressed countries and regions have coped with rising demand from population expansion and development. This strategy may have limited application from a policy perspective and is far from being a realistic criterion for optimizing trade systems. Nevertheless the literature generally indicates that virtual water trade flows provide an important descriptor for the interaction between the hydrosphere and the global economy.

The evolution in the study of virtual water also inspired the water footprint concept. The water footprint of a country, as conceived by Hoekstra and Chapagain (2006), is defined as the total amount of water that is used to produce the goods and services consumed within that country. Countries with high levels of consumption or that consume very water intensive products have relatively large per-capita water footprints. For countries that depend heavily on virtual water imports to meet their consumption, the national water footprint will depend more on external water sources. As such, water footprints are conceived as a measure of global water resource appropriation by consumers in a given country or region. The water footprint method has also evolved considerably in recent years and it still faces several limitations, as discussed in greater detail in Chapter 5. Nevertheless, chapters 2, 3, and 4 use aspects of water footprint methods in order to ask specific questions with regards to California's relationship with water.

The case: California water

California provides a useful case for understanding the role of virtual water in the state's development and evolving water footprint. This section provides a brief history of state water development in relation to population and economic growth in order to motivate the overarching question of California's evolving relationship with water in the next three chapters.

Water has been a fundamental concern for people living in California throughout its history. From California's first inhabitants, through its earliest settlers, and to its expanding population since statehood, social uses of water have changed dramatically, but its importance to social development of Californians has not (Hundley 2001). Water was termed the "lifeblood of California" by the first State Water Engineer, Edward Hyatt (1928), and indeed the state's water engineering works provide a useful lens for observing the historical evolution of California's relationship with water. The twentieth century marked a dramatic dam-building era for California such that, by the century's end, nearly the average full natural flow of the state's rivers could theoretically be stored in reservoirs (Figure 7). Accompanying this water storage capacity was the development of a vast network of hydraulic infrastructure allowing water to be moved across the entire state, from east to west and north to south. This manipulation of water not only led to the spatial expansion of California's agricultural and urban areas, it permitted California's development to overcome the temporal variability of its Mediterranean climate by allowing for water withdrawals for agricultural and urban uses throughout the year.

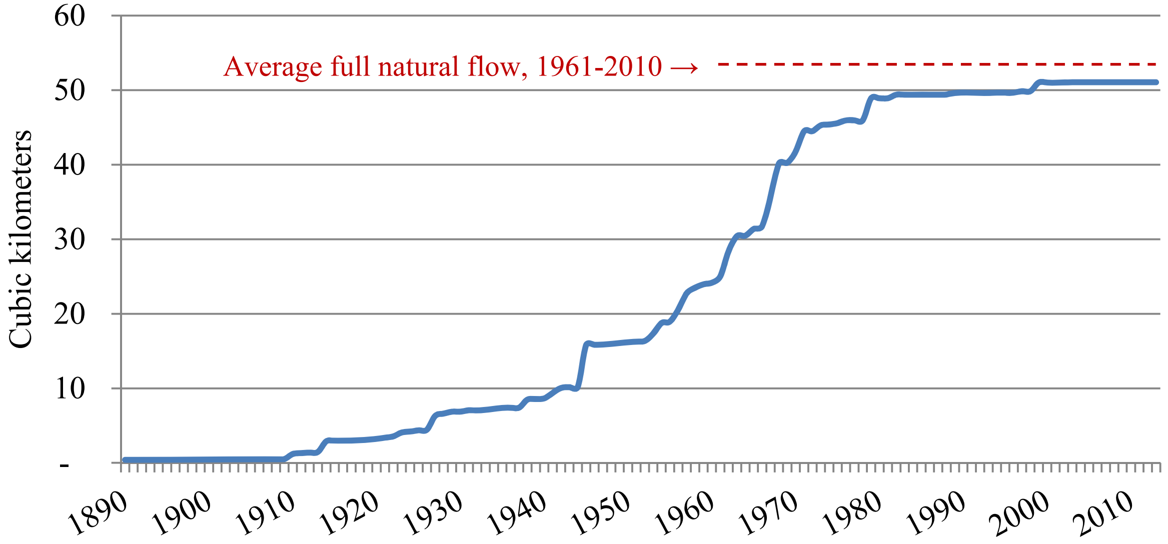

Figure 7: Cumulative storage capacity in California's developed reservoirs, 1890-2010 (Source: CDWR 2012; 2015).

The ability to use water wherever and whenever it was demanded had profound effects on the development of the state. Considering the latter half the twentieth century, Figure 8 depicts California's total water withdrawals in relation to its population and economy. The year 1980 marks an important turning point in the relationship between these three variables. Indeed, this "decoupling" of water withdrawals from population and economic growth tracks closely with the national level statistics described in the background section of this introduction.

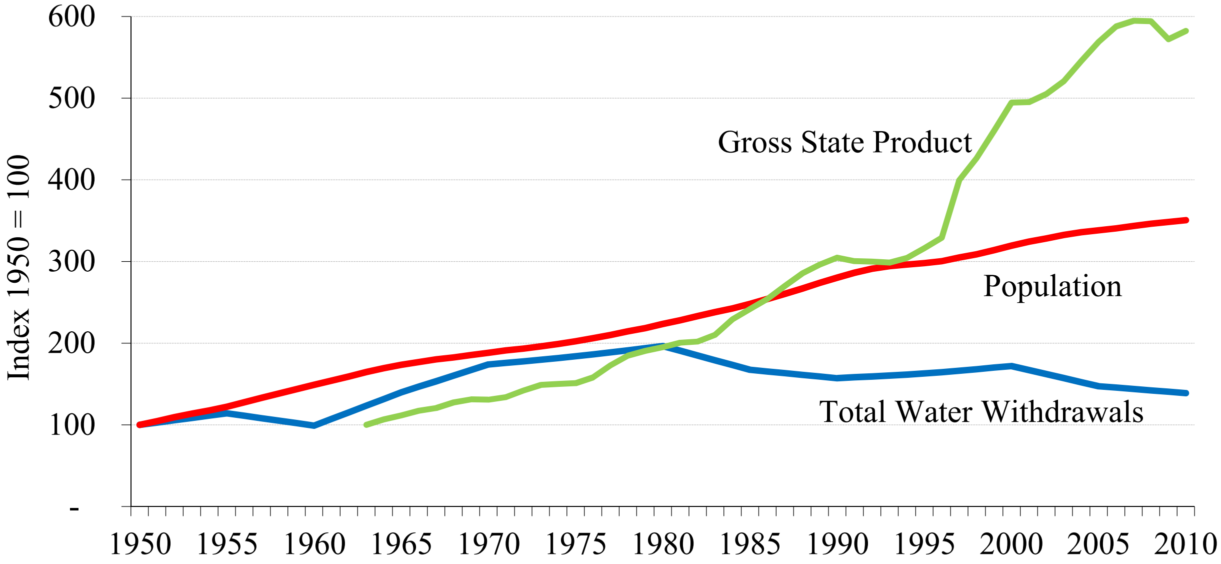

Figure 8: California total water withdrawals, population, and gross state product, 1950–2010. Sources: (CDF 2011; Maupin et al. 2014)

Using the production-based perspective, this reading of California's relationship (as the U.S.) conforms neatly with the EKC theory, where rates of water use per capita and per dollar of GDP fall over time. Drivers of these changes are doubtless attributable to improvements in water use technology across California's water use categories, as well as policies that limit water withdrawals. These limits have not necessarily been imposed due to absolute water scarcity but rather in order to protect environmental flows or other socially valued criteria such as recreation or existence value, what has been termed *peak ecological water* (Gleick and Palaniappan 2010). Still, California has seen instances of more absolute peak water: *peak renewable water*, as is the case with diverting the entire flow of the San Joaquin River; and *peak nonrenewable* water, as is the case with overdrafted aquifers that cannot be recharged due to subsidence.

From a consumption-based perspective, we must also consider the role of traded virtual water in continuing to support population and economic growth when internal water supplies are limited. Since 1980, the point of observed decoupling, the total value of international trade through California ports has quadrupled in real terms (Figure 9). This trade has been heavily weighted towards imports such that by 2010, the value of imports were double that of exports. This observation thus sets up a fundamental question that this dissertation seeks to address: how has virtual water trade changed California's social relationship with water in recent decades? The following three chapters each focus on individual aspects of this question, but overall tell a story that I see as contiguous with California's historical relationship with water, as has been presented in this section.

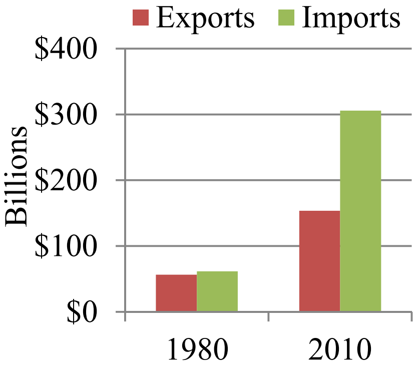

Figure 9: Inflation-adjusted value of international trade through California ports, 1980 and 2010. Source: (CDF 2011)

Chapter summaries

Chapter 2 presents my co-authored article, "Water Footprint Outcomes and Policy Relevance Change with Scale Considered: Evidence from California." This work shows the value of scaling water footprint assessment to policy-relevant jurisdictional units. We find that state-level water footprint outcomes are at odds with previously conducted national-level assessments. Results show that California has a nearly equivalent per-capita water footprint volume as the rest of the U.S., and related to the same types of consumer products, however there are key differences in terms of the location and type of water resources that make up those water footprints. These differences highlight the policy relevance for decision makers in California to consider how water-related risks and impacts in locations outside the state can inform food security and sustainability policies.

Chapter 3 presents my co-authored article, "The Water Footprint of California's Energy System, 1990–2012." This work identifies how environmental policymaking, particularly climate mitigation policies in the energy sector, can result in maladaptation with respect to water systems. We analyze twenty three years of production, trade, and consumption data on energy products, including electricity, liquid fuels, and natural gas. These products have been supplied through a mixture of energy sources and technologies that has been heavily guided by state-level energy policies. We find that the water footprint of energy products consumed in California grew substantially and that this growth occurred completely outside the state's jurisdiction. We identify this growth as being primarily driven by specific energy policies that increased demand for bioethanol, which has mostly been produced through rainfed agriculture in the U.S. Midwest and in other countries. Although we do not characterize the relative impacts of this outsourcing, we argue that water footprint method can provide a useful tool for assessing and avoiding redistribution of those impacts.

Chapter 4, "California's water footprint 1992–2012: considerations for policy and further research," presents a water footprint time series for a fuller range of products consumed in California, including agricultural, industrial, and energy products. As such, it tells a story that is contiguous with California's historical relationship with water, showing that the state's population and economic growth have been enabled by accessing external water sources through virtual water trade. I discuss ways in which state-level policymakers can begin to acknowledge California's changing relationship with water.

Chapter 5 presents conclusions of this work and reflects on the value of water footprint as an expanded reading of water. I discuss its potential contribution to water governance, as well as its methodological limitations in doing so. I also identify opportunities for further research and suggest ways to deepen the interdisciplinary understanding of virtual water, which I see as a promising contribution to water resources sustainability going forward.

References

Allan, JA. 1997. *"Virtual Water": A Long Term Solution for Water Short Middle Eastern Economies?* SOAS Water Issues Study Group, Occasional Papers. London: University of London.

Allan, JA. 1996a. "Water Use and Development in Arid Regions : Environment , Economic Development and Water Resource Politics and Policy." *Water Use and Development* 5 (2).

———. 1996b. "Policy Responses to the Closure of Water Resources: Regional and Global Issues." *Water Policy Allocation and Management in Practice*.

———. 1998. "Virtual Water: A Strategic Resource; Global Solutions to Regional Deficits." *Ground Water* 36 (4): 545–46. doi:10.1111/j.1745-6584.1998.tb02825.x.

———. 2002. "Water Resources in Semi-Arid Regions: Real Deficits and Economically Invisible and Politically Silent Soulutions." In *Hydropolitics in the Developing World: A Southern African Perspective.*, edited by T. Turton and R. Henwood. University of Pretoria. South Africa.

Barbier, EB. 2004. "Water and Economic Growth." *Economic Record* 80 (248): 1–16. doi:10.1111/j.1475-4932.2004.00121.x.

Bhattarai, M. 2004. *Irrigation Kuznets Curve Governance and Dynamics of Irrigation Development. Ageconsearch.umn.edu*. Sri Lanka: International Water Management Institute.

CDF, California Department of Finance. 2011. "California Statistical Abstract." http://www.dof.ca.gov/HTML/FS_DATA/STAT-ABS/Statistical_Abstract.php.

CDWR, California Department of Water Resources. 2015. "California Data Exchange Center: Full Natural Flow Data." Accessed April 21. http://cdec.water.ca.gov/cgi-progs/stages/FLOWOUT.201409.

———. 2012. *Dams Within the Jurisdiction of the State of California. Department of Safety of Dams*.

Cole, MA. 2004. "Economic Growth and Water Use." *Applied Economics Letters* 11 (1): 1–4. doi:10.1080/1350485042000187435.

D'Odorico, P, F Laio, and L Ridolfi. 2010. "Does Globalization of Water Reduce Societal Resilience to Drought?" *Geophysical Research Letters* 37 (13): 1–5. doi:10.1029/2010GL043167.

Dalin, C, M Konar, N Hanasaki, A Rinaldo, and I Rodriguez-Iturbe. 2012. "Evolution of the Global Virtual Water Trade Network." *Proceedings of the National Academy of Sciences* 109 (16): 5989–94. doi:10.1073/pnas.1203176109.

Duarte, R, V Pinilla, and A Serrano. 2013. "Is There an Environmental Kuznets Curve for Water Use? A Panel Smooth Transition Regression Approach." *Economic Modelling* 31. Elsevier B.V.: 518–27. doi:10.1016/j.econmod.2012.12.010.

———. 2014. "Looking Backward to Look Forward: Water Use and Economic Growth from a Long-Term Perspective." *Applied Economics* 46 (2): 212–24. doi:10.1080/00036846.2013.844329.

Earle, A. 2001. *Theh Role of Virtual Water in Food Security in Southern Africa*. 33.

Fraiture, C, X Cai, U Amarasinghe, M Rosegrant, and D Molden. 2004. *Does International Cereal Trade Save Water? The Impact of Virtual Water Trade on Global Water Use*. Colombo, Sri Lanka: International Water Management Institute (IWMI), Comprehensive Assessment Secretariat.

Gleeson, T, Y Wada, MFP Bierkens, and LPH van Beek. 2012. "Water Balance of Global Aquifers Revealed by Groundwater Footprint." *Nature* 488 (7410): 197–200. doi:10.1038/nature11295.

Gleick, PH. 2014. "Peak Water: United States Water Use Drops to Lowest Level in 40 Years." *Huffington Post*, November 5.

Gleick, PH, and M Palaniappan. 2010. "Peak Water Limits to Freshwater Withdrawal and Use." *Proceedings of the National Academy of Sciences* 2010 (25): 11155–62. doi:10.1073/pnas.1004812107.

Goklany, IM. 2002. "Comparing 20 Th Century Trends in U. S. and Global Agricultural Water and Land Use." *Water International* 27 (3): 321–29.

Hemati, A. 2011. "New Vision on the Relationship between Income and Water Withdrawal in Industry Sector." *Natural Resources* 02 (03): 191–96. doi:10.4236/nr.2011.23025.

Hoekstra, AY, and AK Chapagain. 2006. "Water Footprints of Nations: Water Use by People as a Function of Their Consumption Pattern." *Water Resources Management* 21 (1): 35–48. doi:10.1007/s11269-006-9039-x.

Hoekstra, AY. 2003. *Virtual Water Trade: Proceedings of the International Expert Meeting on Virtual Water Trade.* No. 12. Value of Water Research Report Series. Delft, the Netherlands: UNESCO-IHE.

Hoekstra, AY, and PQ Hung. 2002. *Virtual Water Trade: A Quantification of Virtual Water Flows Between Nations in Relation to International Crop Trade.* No. 11. Value of Water Research Report Series. Delft, the Netherlands: UNESCO-IHE.

Hoekstra, AY, and PQ Hung. 2005. "Globalisation of Water Resources: International Virtual Water Flows in Relation to Crop Trade." *Global Environmental Change* 15 (1): 45–56. doi:10.1016/j.gloenvcha.2004.06.004.

Hundley, N. 2001. *The Great Thirst : Californians and Water -a History*. Berkeley: University of California Press.

Hyatt, E. 1928. *Water Is the Life Blood of California: The Division of Engineering and Irrigation of the State Department of Public Works, What It Does and How It Operates*. Sacramento, CA: California Division of Engineering and Irrigation.

Jia, S, H Yang, S Zhang, L Wang, and J Xia. 2006. "Industrial Water Use Kuznets Curve: Evidence from Industrialized Countries and Implications for Developing Countries." *Journal of Water Resources Planning and Management* 132 (3): 183. doi:10.1061/(ASCE)0733-9496(2006)132:3(183).

Katz, DL. 2008. "Water, Economic Growth, and Conflict: Three Studies." *PhD Dissertation*. University of Michigan.

Konar, M, C Dalin, S Suweis, N Hanasaki, A Rinaldo, and I Rodriguez-Iturbe. 2011. "Water for Food: The Global Virtual Water Trade Network." *Water Resources Research* 47 (5): 1–17. doi:10.1029/2010WR010307.

Maupin, MA, JF Kenny, SS Hutson, JK Lovelace, NL Barber, and KS Linsey. 2014. *Estimated Use of Water in the United States in 2010: U.S. Geological Survey Circular 1405*.

Mekonnen, MM, and AY Hoekstra. 2010. *National Water Footprint Accounts: The Green, Blue and Grey Water Footprint of Production and Consumption, Volume 1: Main Report.* No. 50. Value of Water Research Report Series. Delft, the Netherlands: UNESCO-IHE.

Muskal, M. 2014. "Water Conservation Efforts Pay off: U.S. Usage Lowest in Decades." *Los Angeles Times*, November 11.

Reisner, Marc. 1986. *Cadillac Desert : The American West and Its Disappearing Water*. New York N.Y. U.S.A.: Viking.

Rock, MT. 2000. “The Dewatering of Economic Growth What Accounts for the Declining Water-Use Intensity of Income?” *Journal of Industrial Ecology* 4 (1). Wiley Online Library: 57–73. doi:10.1162/108819800569294.

Rock, MT. 1998. “Freshwater Use, Freshwater Scarcity, and Socioeconomic Development.” *The Journal of Environment & Development* 7 (3): 278–301. doi:10.1177/107049659800700304.

Rothman, DS, and SM De Bruyn. 1998. “Probing into the Environmental Kuznets Curve Hypothesis.” *Ecological Economics* 25: 143–45.

Scott, J. 1998. *Seeing like a State: How Certain Schemes to Improve the Human Condition Have Failed*. New Haven: Yale University Press.

Srinivasan, V, EF Lambin, SM Gorelick, BH Thompson, and S Rozelle. 2012. “The Nature and Causes of the Global Water Crisis: Syndromes from a Meta-Analysis of Coupled Human-Water Studies.” *Water Resources Research* 48 (10): 1–16. doi:10.1029/2011WR011087.

Suweis, S, M Konar, C Dalin, N Hanasaki, A Rinaldo, and I Rodriguez-Iturbe. 2011. “Structure and Controls of the Global Virtual Water Trade Network.” *Geophysical Research Letters* 38 (10). American Geophysical Union: L10403. doi:10.1029/2011GL046837.

UN Water. 2014. *UN-Water Global Analysis and Assessment of Sanitation and Drinking-Water (GLAAS) 2014 Report: Investing in Water and Sanitation: Increasing Access, Reducing Inequalities*. Geneva Switzerland: World Health Organization.

Verma, S, D Kampman, P van der Zaag, and AY Hoekstra. 2009. “Going against the Flow: A Critical Analysis of Inter-State Virtual Water Trade in the Context of India’s National River Linking Program.” *Physics And Chemistry of the Earth Parts* 34 (4-5): 261–69.

Wichelns, D. 2001. “The Role of ‘virtual Water’ in Efforts to Achieve Food Security and Other National Goals, with an Example from Egypt.” *Agricultural Water Management* 49 (2): 131–51. doi:10.1016/S0378-3774(00)00134-7.

———. 2004. “The Policy Relevance of Virtual Water Can Be Enhanced by Considering Comparative Advantages.” *Agricultural Water Management* 66 (1): 49–63. doi:10.1016/j.agwat.2003.09.006.

———. 2010. “Virtual Water: A Helpful Perspective, but Not a Sufficient Policy Criterion.” *Water Resources Management* 24 (10): 2203–19. doi:10.1007/s11269-009-9547-6.

———. 2011a. “Virtual Water and Water Footprints. Compelling Notions, But Notably Flawed.” *GAIA - Ecological Perspectives for Science and Society* 20 (3): 171–75.

———. 2011b. “Assessing Water Footprints Will Not Be Helpful in Improving Water Management or Ensuring Food Security.” *International Journal of Water Resources Development* 27 (3): 607–19. doi:10.1080/07900627.2011.597833.

Worster, D. 1992. *Rivers of Empire: Water, Aridity, and the Growth of the American West*. Oxford University Press.

Yang, H, P Reichert, K Abbaspour, and A Zehnder. 2003. “A Water Resources Threshold and Its Implications for Food Security.” *Environmental Science & Technology* 37 (14): 3048–54.

Yang, H, and A Zehnder. 2001. “China’s Regional Water Scarcity and Implications for Grain Supply and Trade.” *Environment and Planning A* 33 (1): 79–95. doi:10.1068/a3352.

———. 2002. “Water Scarcity and Food Import: A Case Study for Southern Mediterranean Countries.” *World Development* 30 (8): 1413–30. doi:10.1016/S0305-750X(02)00047-5.

———. 2007. “‘Virtual Water’: An Unfolding Concept in Integrated Water Resources Management.” *Water Resources Research* 43 (12): 1–10. doi:10.1029/2007WR006048.

Yang, Z, X Mao, X Zhao, and B Chen. 2012. “An Ecological Network Analysis on Global Virtual Water Trade.” *Environmental Science & Technology*, January. American Chemical Society, 120103173709002. doi:10.1021/es203657t.

Chapter 2: Water Footprint Outcomes and Policy Relevance Change with Scale Considered: Evidence from California

Included in this dissertation with the permission of co-authors Heather Cooley and Peter H. Gleick.

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Abstract: Methods and datasets necessary for evaluating water footprints (WFs) have advanced in recent years, yet integration of WF information into policy has lagged. One reason for this, we propose, is that most studies have focused on national units of analysis, overlooking scales that may be more relevant to existing water management institutions. We illustrate this by building on a recent WF assessment of California, the third largest and most populous state in the United States. While California contains diverse hydrologic regions, it also has an overarching set of water institutions that address statewide water management, including ensuring sustainable supply and demand for the state's population and economy. The WF sheds new light on sustainable use and, in California, is being considered with a suite of sustainability indicators for long-term state water planning. Key to this integration has been grounding the method in local data and highlighting the unique characteristics of California's WF, presented here. Compared to the U.S., California's WF was found to be roughly equivalent in per-capita volume (6 m^3d^{-1}) and constituent products, however two policy-relevant differences stand out: (1) California's WF is far more externalized than the U.S.'s, and (2) California depends more on "blue water" (surface and groundwater) than on "green water" (rainwater and soil moisture). These aspects of California's WF suggest a set of vulnerabilities and policy options that do not emerge in national-level assessments. Such findings demonstrate that WF assessments may find more policy relevance when scaled to analytical units where water-related decision making occurs.

Keywords: water footprint; virtual water; analytical scale; California

Introduction

As pressures on water resources intensify globally, there is growing interest in evaluating the complex ways in which human activities affect the world's water resources (Postel, Daily, and Ehrlich 1996; Vorosmarty et al. 2000; Alcamo, Flörke, and Märker 2007; Hoekstra and Chapagain 2008; Gleick and Palaniappan 2010). "Water footprint" assessments have emerged as a tool for identifying the links between consumption of everyday goods and services in one location and water use associated with their production in other, sometimes distant, locations.

The water footprint (WF) of a product (good or service) has been defined as the quantity of fresh water consumptively used both directly and indirectly throughout its production chain (Hoekstra et al. 2011). Consumptive use refers to the portion of withdrawn water that is made unavailable for reuse in the same basin, such as through conversion to steam, loss to evapotranspiration, seepage to a saline sink, or contamination (Gleick 2003). A WF is typically divided into three components: green water, which is precipitation and in-situ soil moisture; blue water, which is surface or ground water; and grey water, which is the volume of freshwater needed to assimilate pollutants from a production process back into water bodies at levels that meet governing standards.

Because a WF is based on the set of goods and services consumed, it can be calculated at different levels of consumer activity, i.e., for individuals, households, regions, states, nations, or even all of humanity. The WF of an individual or a group of individuals is the aggregate WF of products used by that individual or group of individuals over a given period of time. It includes the total amount of water required in the location where water use occurs. A WF, then, provides an estimate of how much water, from where, and what kind of water a society demands through its consumption patterns.

The WF concept has developed substantially in scientific literature over the last decade and resulted in numerous publications and extensive datasets, many of which have emerged through the work of the Water Footprint Network. The WF's conceptual validity with respect to hydrologic sciences and its value in water resource management have also been discussed at length in this and other journals (Yang and Zehnder 2007; Aldaya, Martínez-Santos, and Llamas 2009; Wichelns 2010; Gawel and Bernsen 2013; Ridoutt and Huang 2012; Kumar and Singh 2005; Pfister and Hellweg 2009). Noting the novelty and limitations of the method, our priority here is to highlight the importance of analytical scale when using the WF tool to draw conclusions about a particular place, its connection to global water resources, and the relevant policy options for addressing sustainability concerns.

The vast majority of WF scholarship has chosen as its unit of analysis the nation state, and with consideration of interactions between nation states (Mekonnen and Hoekstra 2011; Konar et al. 2011; Dalin et al. 2012). This is likely due to the fact that most production and trade statistics — essential to the calculation of the WF — are gathered and reported at the national level. However for the United States, as with many countries, a national-level WF is functionally an average of smaller and potentially diverse constituents. Therefore it is important to understand how the WF of a smaller unit might differ from that of a larger unit, since (a) the phenomenon of interest, that is the connections between consumption patterns and global water resource concerns, may differ, and (b) the decision making and ability to enact relevant policy may also differ.

To address these concerns, we report here the results of our recent assessment of California’s WF (Fulton, Cooley, and Gleick 2012) and compare those results with previous WF studies that refer to the U.S. as a whole. California was chosen for several reasons. As the state with the largest population and GDP in the nation (about one-eighth on both counts), California represents a substantial share of U.S. economic activity, both in terms of consumption and production. Among U.S. states, however, it is unique climatically and hydrologically, with minimal precipitation during the summer and fall and very little runoff flowing to other states or nations. Thus, California makes a good comparative case because while its size suggests it to be representative of the whole, its unique physical characteristics create a counterpoint to examine why its WF may be different.

Related research in this field that delves into the subnational scale has looked at regions within Australia (Lenzen 2009), China (Guan and Hubacek 2007; Zhao et al. 2010), India (Verma et al. 2009), and Spain (Aldaya, Martínez-Santos, and Llamas 2009; Dietzenbacher and Velázquez 2007). The goal of these studies, by and large, has been to understand the interactions between subnational and national units in terms of the WF of traded products, or “virtual water” flows. This is typically done using environmentally extended economic input-output methods, which are useful in capturing inter-industry demands within and between geographically defined production matrices. Similar work was carried out for California a half century ago (McGauhey et al. 1960) but subnational studies of this nature in the U.S. have since been absent in the literature. The novelty of our work differs from these previous studies in our focus on the WF of consumption within our selected subnational unit, rather than its interactions with other units. In the following two sections, we present the methods used and results from our assessment of California’s WF, concluding with a comparison with results at the national level. In the discussion section, we address the implications of our findings in the context of ongoing water management and policy initiatives in California.

Methods and Data

The basic approach in calculating a WF is to combine consumptive use factors (volume of water per unit of economic production) of blue, green, and grey water for individual products with statistics on production, trade, and consumption of those products. Direct uses of water, such as residential consumption, are also considered. The method has been advanced by the Water Footprint Network (WFN) and our analysis used methods described in their Water Footprint Assessment Manual (Hoekstra et al. 2011). We used as much locally relevant information as possible for California, and in a manner that closely replicates methods used by WFN for national assessments. Furthermore, we limited the scope of our assessment to crop, animal, and industrial products, as well as direct uses of water, in order to make our study comparable to the national study. Some of the economic sectors that were excluded in our study and from the national-level study, for example energy, would likely add noticeably to overall WF values (see King and Webber, 2008; Scown et al., 2011).

The total WF of products consumed in California in 2007 (the last year for which comprehensive production and consumption data are available) has an internal component and an external component (Figure 10, top row). The internal WF is calculated as the WF of products produced within California minus the WF of products produced in California and exported out of the state. The external WF is calculated as the WF of products that are imported and consumed within California.

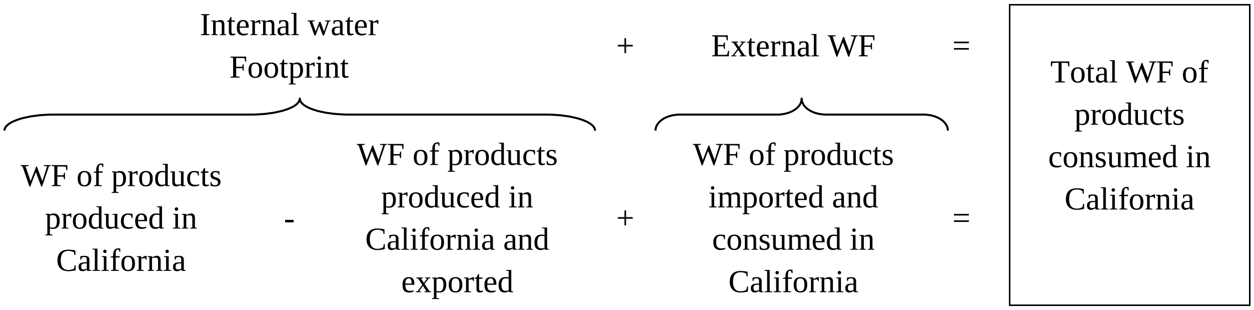

Figure 10: California's water footprint accounting framework, modified from Hoekstra et al. (2011).

The following sections describe the data and calculations that were used for each component of California's WF. First, we describe how the WF of products produced in California was calculated using methods described in Hoekstra et al. (2011) and locally relevant data. Second, we describe available data for the WF of products produced outside of California. Finally, we discuss how trade data were applied to provide a geographical picture of California's internal and external WFs.

The Water Footprint of Products Produced in California

For our analysis, we used California-specific data to get an accurate estimate of the WF of crop, animal, and industrial products that are produced inside of California.

Crop Products

The California Department of Water Resources (CDWR) regularly models annual evapotranspiration rates of applied water (ETAW) and of precipitation (EP) for 20 crop categories (see Appendix 1 in Fulton et al., 2012). These data are reported on a per-acre basis in CDWR's Land and Water Use Survey (LWUS), which we compiled for the years 1998–2005. As 2007 data were not yet available, we used average ETAW and EP factors from this time period to represent blue and green water consumptive use factors, respectively, for the 20 crop categories.

For land area in agricultural production in California, the CDWR LWUS also reports irrigated crop area (ICA) for each crop category. However, as CDWR does not survey non-irrigated crop area, i.e., purely rainfed agriculture, we used County Agricultural Commissioner's (CAC) Data provided by the U.S. Department of Agriculture (USDA), which reports "harvested acres" for 281 distinct commodities on an annual basis. We related each CAC commodity to one of CDWR's 20 crop categories according to Appendix 1 (Fulton, Cooley, and Gleick 2012) in order to check the difference between harvested acreage (according to CAC) and irrigated crop area (according to CDWR) for the years 1998–2005. In most cases, the difference was less than 10%, indicating that purely rainfed, non-irrigated agriculture is uncommon in California. However, substantial acreage of pasture and grains was not irrigated, so blue water consumptive use factors were only applied to the proportional acreage of those crops that were irrigated.

For the remainder of crops, blue and green water consumptive use factors were multiplied by the actual harvested acreage (2007) of the 281 CAC commodities. The total volumes of green and blue water for these 281 commodities were divided by commodity production statistics (also contained in the CAC dataset), resulting in a dataset of green water and blue water consumptive use in units of water volume-per-weight of produced product. The crops in the USDA dataset were then coded to a list of commodities that we generated (see Appendix 2 in Fulton et al., 2012) that could be related to traded products. Because many products are traded in a condition that is different from the "farm-weight" (as reported by CAC), standard conversions were applied using factors from Mekonnen and Hoekstra (2010a) and USDA (1992). Grey water factors for crop production in California were not calculated using local data, but rather derived using state-level data from Mekonnen and Hoekstra (2010a) so as to match the methods and scope of pollutants covered in the national study.

Animal Products

Producing animal products, like meat and dairy, consumes a large volume of water, primarily due to growing the forage and fodder crops used to feed the animal. Other water uses such as for washing and hydrating animals and for the processing of animal products are typically only around 1% of animal product WFs (Mekonnen and Hoekstra 2010b) and are therefore not included in this analysis. The WFs of feed and forage crops, calculated as described above, were allocated to animal products based on international biomass-to-product conversion rates published in Mekonnen and Hoekstra (2010b). Data on the production of animal products were obtained from the 2007 USDA Census of Agriculture. According to these sources, an estimated 57.3 million (metric) tons of biomass were needed for animal production in California in 2007. Data on animal feed in California is limited, so the supply of biomass to the animal products industries was assumed to be composed of crops specified by CAC as feed or silage, as well as alfalfa, hay, and pasture. California pasturelands were assumed to generate 336 tons of biomass per square kilometer, which is consistent with findings from George et al. (2001). The biomass demand from California's animal product industries exceeds the supply from instate sources, thus imported feed crops also make a large contribution to the production of animal products. California exports some animal feed and forage crops, chiefly alfalfa, so those exports were treated as separate commodities and excluded as an input to animal products within California. Careful attention was paid to avoid double counting the WFs of animal feed and animal products.

Industrial Products and Direct Use

The WF associated with industrial production within California was calculated using the best available local data. The most recent dataset for industrial water use in California comes from CDWR's 1995 survey of commercial, industrial, and institutional water use. The dataset was not published but was analyzed by Gleick et al. (2003). In the report, water withdrawal factors were developed for 20 manufacturing sectors on a per-employee basis. Subsequent work translated these factors into gallons-per-dollar of revenue for each sector (Cox 2011). These factors represent total blue water use, i.e., consumptive and non-consumptive uses. Using California-level data from USGS, we estimated that consumptive blue water use represented 28% of water withdrawals in the industrial sector (Solley, Pierce, and Perlman 1998).

These industrial blue water factors were then applied to inflation-adjusted revenues in all manufacturing sectors as reported in the U.S. Census Bureau's Economic Census of 2007. It is important to note that this approach assumes that the water use factor has not changed and therefore does not account for efficiency improvements within industrial sectors that may have occurred since 1995. While this assumption likely overestimates the blue water footprint of industrial products, data are not currently available to develop more accurate estimates. Grey WF factors for industrial products were not available at the state level, so national level statistics (assumptions are described in Section 2.2) from Mekonnen and Hoekstra (2011) were used.

Direct consumption in the residential, commercial and institutional sectors were derived from supporting Technical Guide from the California Water Plan Update 2009 (CDWR 2009). These data show that the average consumption rate for all urban uses from 1998–2005 was 31% of withdrawal, and this percentage was applied to withdrawal volumes in the residential, commercial, and institutional sectors to determine their average blue WF volumes.

Water Footprint of Products Produced Outside of California

Many products that are consumed in California are produced in other U.S. states and other countries. For agricultural products, we used WF factors developed by WFN. Using country-level data from the United Nations Food and Agriculture Organization (FAO), Mekonnen and Hoekstra (2010a) calculated blue, green, and grey WF factors for over 300 crops and crop-derived products in 225 countries. Factors have also been calculated for over 100 animal products in 202 countries (Mekonnen and Hoekstra 2010b). These factors are based on the weight of the product, i.e., cubic meters of water-per-ton of product. All products are reported using codes from the Harmonized System (HS), which corresponds to trade data, as described below.

Industrial consumptive use factors are not differentiated by product in any global dataset. Mekonnen and Hoekstra (2011) calculated average blue and grey water factors per-dollar (value added) of industrial production for 230 countries based on FAO-reported industrial withdrawal and an assumption that blue water consumptive use is 5% of withdrawal (note that this assumption is much smaller than for California since FAO industrial withdrawal statistics often include thermoelectric uses (Kohli and Frenken 2011)). Green water is assumed to not factor into industrial production. Industrial grey water factors are calculated using United Nations Statistics Division data showing country-level average percentage of wastewater that is treated. That percentage is multiplied by the amount of industrial water withdrawn but not consumed (95% of withdrawal) (Mekonnen and Hoekstra 2011).

Trade

Trade data are needed to calculate California's internal and external WFs. The U.S. Census Bureau collects state-level trade data with domestic and international trade partners. Domestic trade is reported in the Commodity Flow Survey (CFS), conducted every five years in coordination with the Bureau of Transportation Statistics (BTS). We used CFS data from 2007, the most recent year available, to calculate domestic shipments to and from California. State of origin, destination, shipment weights, and values are organized by both the North American Industrial Classification System (NAICS) and the Standard Classification of Transported Goods (SCTG) at the two digit level. For industrial goods, the NAICS data provides the same level of resolution as the WF factors mentioned above, allowing us to map domestic virtual water flows on a per-dollar basis. For agricultural goods, however, the SCTG trade data are disaggregated into 9 categories, so blue, green, and grey water coefficients were generated as a weighted average over several agricultural industries (for example all fruits and vegetables are combined into one category) in order to estimate the virtual water flows inside the U.S. This is a major data limitation in our study, and we note that it adds uncertainty in domestic virtual water flows.

International trade data are organized according to the Harmonized System (HS) of classification and are available at a much finer resolution of products than domestic data. State-level HS data are tracked annually by the U.S. Census Bureau and reported in its "USA Trade *Online*" system. Exports from California to global trading partners are available for 2007 on a value and weight basis. We included 285 exported products, which were aggregated into 75 product categories (Appendix 3 in Fulton et al., 2012). Data on imports to California are available for 2008, which we assumed are comparable to 2007 levels, and are reported on a "state of final destination" basis, meaning that goods destined to other states that go through California ports are not counted. We included 389 imported products, with the additional products not included in Appendix 3 (ibid) being categorized as “other” and listed in Appendix 4 (ibid).

Data from USA Trade *Online* only reports weight values for commerce traded by sea and air, thus missing the weight of overland agricultural trade with Canada and Mexico. For these agricultural trade flows, we transformed the values of overland shipments to weights using value-to-weight ratios from BTS’ North American Transborder Freight Database, as well as aggregations of 10-digit value-to-weight ratios derived from USA Trade *Online*. For industrial trade flows, monetary values were sufficient to be applied to industrial WF factors from trading partner countries.

Uncertainty

In using state-level data sources, uncertainty was introduced at several stages of our analysis. The WFs of crop, animal, and industrial products produced in California were subject to both statistical and modeling uncertainties. Land use and production data from the LWUS, the CAC, the 1995 CDWR survey, as well as the Economic Census are subject to survey and sampling errors. None of these datasets reported a quantified estimate of error, however the Economic Census discusses sources of sampling and non-sampling error in USDC-CB (2007). Assumptions embedded in LWUS modeling — on crop coefficients, reference evapotranspiration, effective precipitation, etc. — are provided by Hillaire and Cornwall (2004). Modeled estimates aggregated to the state level generally corresponded with statewide estimates of consumptive water use; however, spatial and inter-annual variations due to climate or production technologies were not captured in our approach. In many cases, averaging allowed for data to converge around 2007; however, results should not be taken as a function of particular regional climatic or economic conditions in 2007.

The WFs of products produced outside of California, but that contribute to California’s WF through virtual water import, are subject to many of the same sources of uncertainty (Mekonnen and Hoekstra 2011). Quantification of WF uncertainty has been attempted in very few studies and locations. Zhuo et al. (2014) performed a sensitivity analysis of WFs for four crops in the Yellow River Basin, finding that climatic variables alone could account for a ±20% variation in total WF. Sun et al (2013) found similar results through a time-series analysis of maize WF values in Beijing.

Uncertainty in trade data is also an important factor that can compound overall uncertainty in California’s WF. As mentioned above, the lower resolution of domestic trade data compared to international trade data is one such source of uncertainty. The Census Bureau does not report error estimates for international trade data. It does estimate sampling errors for domestic trade data, reported as coefficients of variation. In the case of California’s domestic imports and exports, coefficients of variation ranged from 6 to 48 percent.

In light of differing availability of uncertainty estimates in the data, we have not attempted to quantify overall uncertainty in our analysis, and the exactness of results should be used with caution. Nevertheless, findings can be seen as *indicative* of California's WF configuration and, to the extent that they can be compared with the U.S. as a whole, can offer insights for state-level policy consideration in light of ongoing water resource management challenges. Adaptive management of water resources calls for acknowledging the inevitability of uncertainty in water systems and incorporating ranges of uncertainty into decision making (Pahl-Wostl 2006; Keur et al. 2008; Pahl-Wostl et al. 2010). Water footprint analysis presents the additional layer of global trade and attendant uncertainties associated with economic statistics, and any subsequent policy decisions must consider (and be presented with) the relevant uncertainties.

Results

The Water Footprint of California

We estimated that California's statewide WF in 2007 associated with the consumption of agricultural and industrial goods, as well as residential, commercial, and institutional water consumptive use was 55 km^3 (cubic kilometers) of green water, 24 km^3 of blue water, and 51 km^3 of grey water (Figure 11).

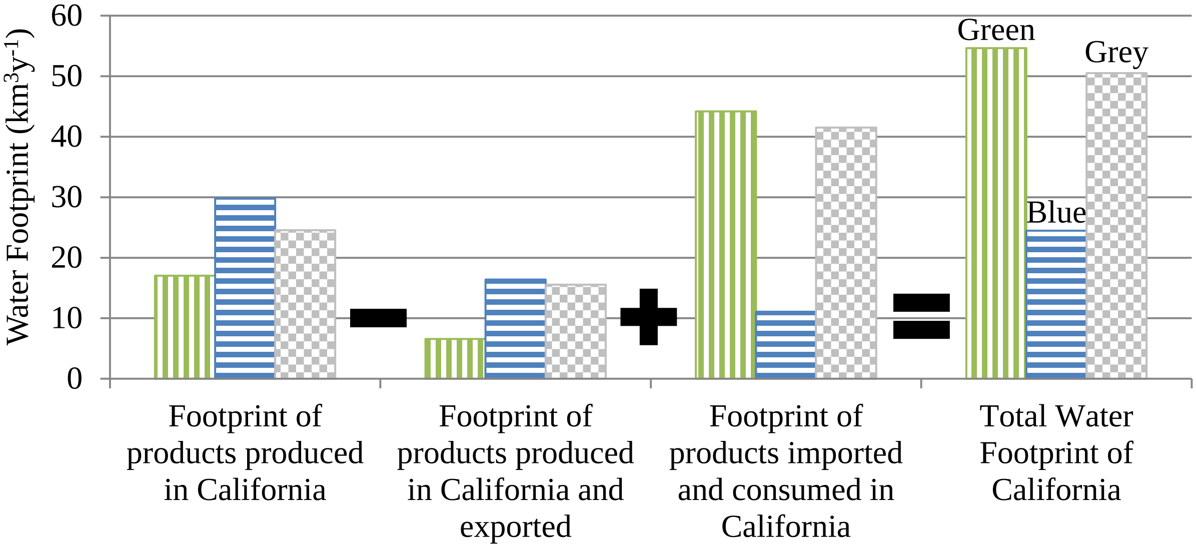

Figure 11: California's green, blue, and grey water footprints in 2007 (cubic kilometers per year)

We do not add these three values together in a combined WF as has been done in other WF studies. This is primarily because grey water is an indicator of water quality rather than a measure of consumptive water use. Even though the contamination of surface waters is by definition a consumptive use (Gleick 2003), contaminated water can and does often still serve multiple uses like navigation or cooling. Thus, in order to eliminate double counting of upstream grey water footprints by downstream blue water uses in this report, we present grey WF separately. We feel that the grey WF is a useful quantitative indicator for water quality issues, but that methodologically it should be reported separately from the green and blue water footprints. For these reasons only blue and green WFs will be compared with the national case in the next sections.

California-U.S. Water Footprint Comparison

In this section, we compare the WF of California with that of the U.S. on a per-capita basis. The WF of the U.S. is taken from a global assessment of national level water footprints (Mekonnen and Hoekstra 2011). California's combined green and blue WF is about 5.7 $m^3cap^{-1}d^{-1}$ (cubic meters per capita per day), which is just slightly lower than the average American's, at just over 6.0 $m^3cap^{-1}d^{-1}$. Figure 12 shows a comparison of California's WF (left column) with that of the U.S. (right column) along three dimensions.

First, in both cases the WF is related to similar classes of products (top row). Food makes up over 90% of the WF, followed by industrial products and direct consumptive use. Meat and dairy products make up about half of the food WF in both cases. These findings are not surprising since there is little reason to expect Californian's consumption patterns to be any different from the rest of the country. Rather, the approximate equivalent of product-level WFs may offer some validation for our chosen methods and data sources at the state level.

The second comparison shows the geographic distribution of California and U.S. WFs (middle row). About 30% of California's WF is associated with goods that are produced and consumed in California, referred to as California's *internal* WF. The *external* component is 70%: 50% from other places in the U.S. and 20% related to imports from other countries. In marked contrast, the WF of the U.S. is 80% internal.

The third comparison depicts the relative contribution of blue and green water to each WF (bottom row). California's WF is more heavily weighted in blue water, which is related to the abstraction of surface and groundwater used to produce the goods and services consumed in California. This is compared to the far larger percentage of green water, or precipitation and soil moisture, used to produce the goods consumed by the average American.

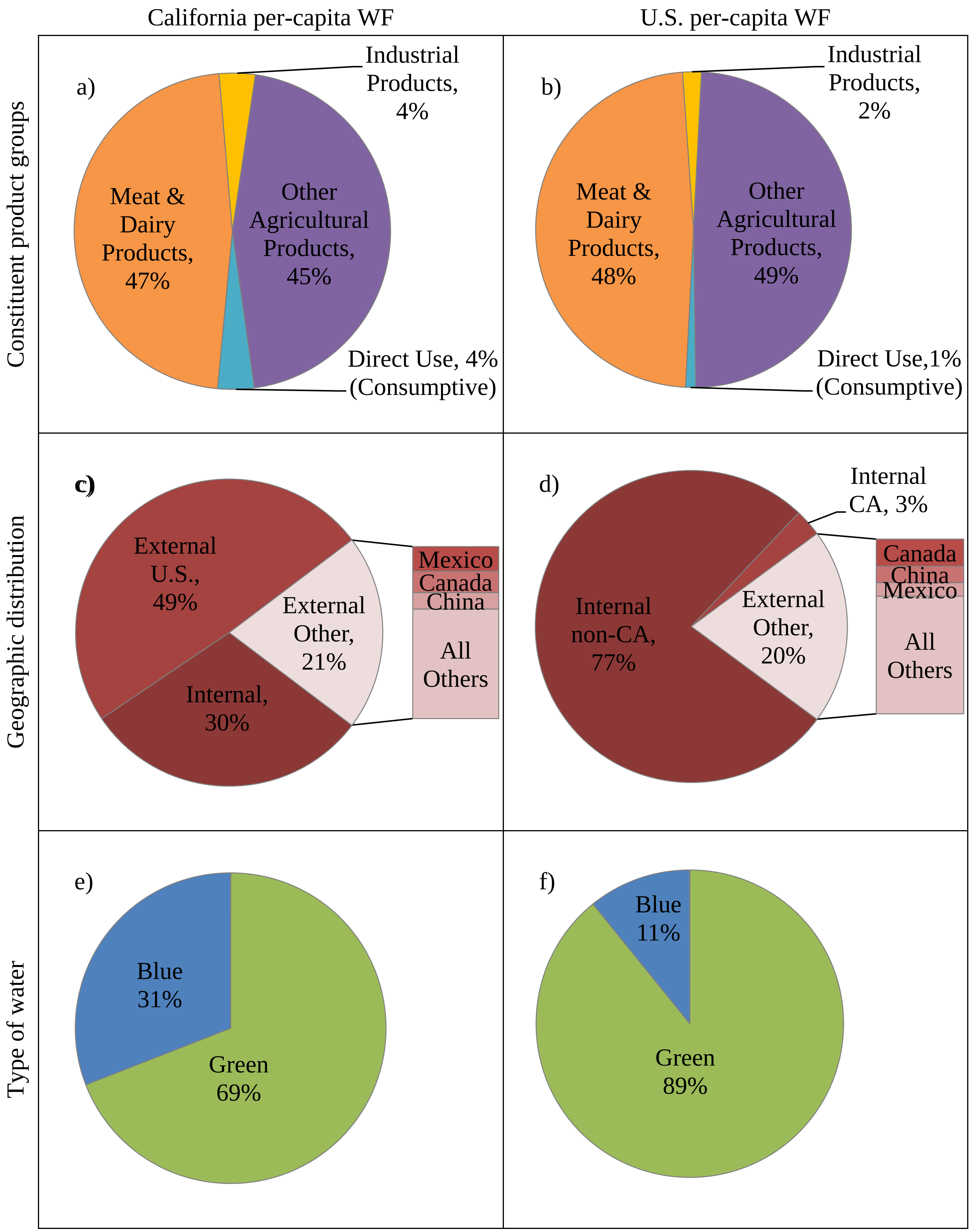

Figure 12: **California's per-capita WF (left column) and that of the U.S. (right column), which in volume are 5.7 and 6.0 $m^3 cap^{-1} d^{-1}$, respectively, compared along three dimensions: constituent product groups (top row), geographic distribution (middle row), and type of water (bottom row).**

Discussion

Globalization has forged increasing interconnectedness among people, economies, and resources, including water resources that have traditionally been thought of as a local or regional issue. In light of these connections, better understanding is needed of the ways in which observed water resource challenges have important global dimensions. The WF is a tool and indicator for understanding the connections between consumption of everyday products and global water use. The WF indicator also offers new insights into water policy options and governance strategies (Hoekstra 2010). The results of the California WF assessment permit a deeper discussion of the implications of water strategies at multiple scales.

The comparison between the California and U.S. water footprints illustrates the similarities and differences that result from the scale of a WF assessment. With WF magnitude and constituent products being nearly identical, the WF of a national and a subnational unit can differ substantially in the source and type of water entailed. In our case, California's WF, compared to that of the U.S., is far more dependent on water from outside of its political boundaries, and more dependent on blue water, suggesting a different context and set of vulnerabilities for policy consideration.

These results raise a number of sustainability questions for potential policy consideration. For example, should California's per-capita WF be reduced and what are the possible mechanisms to do so? After all, the WF of the average American or Californian is roughly 50% larger than their counterparts in other highly-industrialized nations, and about 80% higher than the global average (Hoekstra and Mekonnen 2012a). Were the entire world's population to have American-level WFs, the demand on global water resources would more than double (ibid). To address this type of question, our findings indicate that an assessment at the national scale provides adequate information, since the WF of a Californian is quantitatively, and with respect to constituent products, the same as the WF of an American. Options for reducing the per-capita WF might urge changes in consumer behavior in favor of less water-intensive products like chicken instead of beef, or a reduction in overall meat consumption. While such a strategy may not sit comfortably within the domain of public policy, it could be seen as akin to a local water utility incentivizing its customers to reduce per-capita water use during a shortage or in order to allow for alternative uses like environmental flows or further development.

Other more complex sustainability questions might pertain to *how* or *what kind of* water resources are mobilized to fulfill a society's consumption habits, and the relative scarcity in locations where water is being used. These concerns have important policy relevance in addressing issues like climate change, where changing patterns of water availability pose risk to food and other provisioning systems. Here, WF findings are relevant not to consumer behavior but to the domains of policymakers or water managers that actually govern resource provision through a range of political and economic mechanisms.

When it comes to using WF findings to formulate policy, especially with respect to climate change planning, national and subnational decision makers face different considerations. In our case, there are significant differences between the national and state-level options. Since the national WF is largely internal (i.e., not dependent on water from outside the U.S.) and green (i.e., largely dependent on rainfed agriculture as opposed to irrigated agriculture), national policies should be oriented around domestic water issues and technologies that increase green water productivity. Conversely, California's water-related vulnerabilities are 70% external, and to a far greater extent (30%) related to blue water resources (note from Figure 11 that this 30% is not simply the same 30% that is internal, rather almost half of California's blue WF is external). Policymakers in California must therefore consider how important its dependence on external sources of water might be and whether there are strategies that can affect the management of water outside of their direct jurisdiction. Similarly, blue water resources entail different management strategies from green water and this must be considered when developing comprehensive tools for addressing the implications of water footprints.

These differences also raise the question about the effectiveness and practicality of climate-related adaptation strategies: a WF that is highly dependent on precipitation patterns and green water may be more vulnerable to climate change than one with the flexibility and reliability offered by some forms of irrigated management. We can see this in the context of recent efforts to expand supplemental irrigation in Alabama and Georgia on lands that previously were entirely dependent on precipitation and green water sources (AWAWG 2012). Climate change-relevant WF policies may thus differ significantly based on national versus subnational assessments. Our findings thus highlight the importance of explicit scale choice in conducting WF assessments that are used to inform policy responses. Scaling our analysis to the state level allowed a more accurate understanding of water resource dependencies, vulnerabilities, and impacts.

Other scales may provide important insights as well: for example a more appropriate unit of analysis might be a river basin, which forms a more hydrologically-unified basis for decision making than a traditional political unit. Indeed, the issue of appropriate governance scale is not new to the field of water management, as evidenced by debates around implementing Integrated Water Resources Management (Conca 2006). While it has been possible to use WF methods to estimate the WF of products *produced* within a river basin (e.g. Zeng et al., 2012), there remains a disconnect with the availability of trade statistics required to calculate the WF of products *consumed* within such a geographic region. Additional data collection and statistical interpolation techniques may help in scaling WF analyses in ways that are useful to river basin management.

Further iterating the WF methodology will also help its relevance in water resources management at various scales. Of particular concern is relating water footprint quantities to more qualitative indices of water scarcity, quality, and impacts to environments and livelihoods (Hoekstra and Mekonnen 2012b). The method could also improve its sensitivity to efficiency and productivity to reflect technological improvements, as well as its ability to integrate other factors in a sustainable production calculus like land, labor, and energy. Nevertheless, water resource managers are beginning to acknowledge the global dimension to their work, made ever more relevant through economic globalization and climate change. In California, CDWR has taken the step of integrating the WF into a framework of sustainability indicators being developed for long-term state water resource planning. While it remains to be seen how WF information might eventually be used to formulate policy, awareness of the vulnerabilities associated with dependence on external water resources such as the Colorado River is not new to California. Reduced flows, mismanagement, and allocation disputes in the Colorado River Basin have long been a source of vulnerability for Southern California's water supply. But while the magnitude of this dependence has been below 10% of the state's overall direct water supply, the external dependence of its WF is 70%. This presents new challenges that state decision makers may choose to take up in coming years. Other policy arenas in California may offer precedent for taking action on indirect resource use, as evidenced by California's Global Warming Solutions Act of 2006, which requires carbon emissions associated with imported energy to be counted toward the state's greenhouse gas inventory.

The WF tool is useful in describing the interconnectedness of people, economies, and resources, and suggests a global dimension that water managers must acknowledge in order to tackle today's water challenges. However, because most WF studies to date have relied on national and international data to illustrate this phenomenon, policy "solutions" have tended to conform to these analytical scales. WF findings have therefore gained little traction with existing governance institutions where most water management expertise and decision making still resides. Findings presented here suggest that the WF tool can be informative at the local to regional level of decision making when analytical units are relevant to jurisdictional units.

Acknowledgements

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References

Alcamo J, Flörke M, Märker M (2007) Future long-term changes in global water resources driven by socio-economic and climatic changes. Hydrol Sci J 52:247–275.

Aldaya MM, Martínez-Santos P, Llamas MR (2009) Incorporating the Water Footprint and Virtual Water into Policy: Reflections from the Mancha Occidental Region, Spain. Water Resour Manag 24:941–958.

AWAWG (2012) Water Management Issues in Alabama: A Report to the Honorable Robert Bentley, Governor of Alabama. Alabama Water Agencies Working Group

CDWR (2009) California Water Plan Update 2009. Caliornia Department of Water Resources, Sacramento CA.

Conca K (2006) Governing water : contentious transnational politics and global institution building. MIT Press, Cambridge Mass.

Cox RW (2011) Open IO: Developing a Transparent, Fully Accessible Economic Input-Output Life Cycle Assessment Database. Sustainability Consortium, Fayetteville, AK

Dalin C, Konar M, Hanasaki N, et al. (2012) Evolution of the Global Virtual Water Trade Network. Proc Natl Acad Sci 109:5989–5994.

Dietzenbacher E, Velázquez E (2007) Analysing Andalusian Virtual Water Trade in an Input–Output Framework. Reg Stud 41:185–196.

Fulton J, Cooley H, Gleick PH (2012) California's Water Footprint. Pacific Institute for Studies in Development, Environment, and Security, Oakland CA

Gawel E, Bernsen K (2013) What is wrong with virtual water trading? On the limitations of the virtual water concept. Environ Plan C Gov Policy 31:168–181.

George M, Bartolome J, McDougald N, et al. (2001) Annual Range Forage Production: Rangeland Management Series Publication 8018. University of California, Davis CA

Gleick P, Haasz D, Henges-Jeck C, et al. (2003) Waste not, want not: the potential for urban water conservation in California. Pacific Institute for Studies in Development, Environment, and Security, Oakland, CA

Gleick PH (2003) Water use. Annu Rev Environ Resour 28:275–314.

Gleick PH, Palaniappan M (2010) Peak water limits to freshwater withdrawal and use. Proc Natl Acad Sci 2010:11155–62. doi: 10.1073/pnas.1004812107

Guan D, Hubacek K (2007) Assessment of regional trade and virtual water flows in China. Ecol Econ 61:159–170. doi: 10.1016/j.ecolecon.2006.02.022

Hillaire T, Cornwall J (2004) Ag Water Use and ETAW Model version 2.20. California Department of Water Resources: Sacramento, CA

Hoekstra A (2010) The Global Dimension of Water Governance: Why the River Basin Approach Is No Longer Sufficient and Why Cooperative Action at Global Level Is Needed. Water 3:21–46.

Hoekstra A, Chapagain A (2008) Globalization of Water: Sharing the Planet's Freshwater Resources. 232.

Hoekstra A, Chapagain A, Aldaya M, Mekonnen M (2011) The Water Footprint Assessment Manual: Setting the Global Standard. Earthscan, London.

Hoekstra A, Mekonnen M (2012a) The water footprint of humanity. Proc Natl Acad Sci U S A 109:3232–7

Hoekstra A, Mekonnen M (2012b) Reply to Ridoutt and Huang: From water footprint assessment to policy. Proc Natl Acad Sci 109:E1425–E1425

Keur P, Henriksen HJ, Refsgaard JC, et al. (2008) Identification of Major Sources of Uncertainty in Current IWRM Practice. Illustrated for the Rhine Basin. Water Resour Manag 22:1677–1708

King C, Webber M (2008) Water intensity of transportation. Environ. Sci. Technol. 42:21

Kohli A, Frenken K (2011) Cooling water for energy generation and its impact on national-level water statistics. Fod and Agriculture Organization, Rome

Konar M, Dalin C, Suweis S, et al. (2011) Water for food: The global virtual water trade network. Water Resour Res 47:1–17

Kumar MD, Singh OP (2005) Virtual Water in Global Food and Water Policy Making: Is There a Need for Rethinking? Water Resour Manag 19:759–789

Lenzen M (2009) Understanding virtual water flows: A multiregion input-output case study of Victoria. Water Resour Res 45:W09416

McGauhey P, Erlich H, Lofting E, et al. (1960) Economic evaluation of water. Sanitary Engineering Research Laboratory, University of California Berkeley

Mekonnen M, Hoekstra A (2011) National water footprint accounts: the green, blue and grey water footprint of production and consumption, Value of Water Research Report Series No. 50. UNESCO-IHE, Delft, the Netherlands

Mekonnen M, Hoekstra A (2010a) The green, blue and grey water footprint of crops and derived crop products, Value of Water Research Report Series No. 47. UNESCO-IHE, Delft, the Netherlands

Mekonnen M, Hoekstra A (2010b) The green, blue and grey water footprint of farm animals and animal products, Value of Water Research Report Series No. 48. UNESCO-IHE, Delft, the Netherlands

Pahl-Wostl C (2006) Transitions towards adaptive management of water facing climate and global change. Water Resour Manag 21:49–62.

Pahl-Wostl C, Jeffrey P, Isendahl N, Brugnach M (2010) Maturing the New Water Management Paradigm: Progressing from Aspiration to Practice. Water Resour Manag 25:837–856.

Pfister S, Hellweg S (2009) The water "' shoesize '" vs . footprint of bioenergy. Proc Natl Acad Sci 106:93–94.

Postel SL, Daily GC, Ehrlich PR (1996) Human Appropriation of Renewable Fresh Water. Science (80-) 271:785–788.

Ridoutt BG, Huang J (2012) Environmental relevance--the key to understanding water footprints. Proc Natl Acad Sci U S A 109:E1424; author reply E1425.

Scown CD, Horvath A, McKone TE (2011) Water footprint of U.S. transportation fuels. Environ Sci Technol 45:2541–53.

Solley WB, Pierce RR, Perlman HA (1998) Estimated use of water in the United States in 1995: U.S. Geological Survey Circular 1200. U.S. Dept. of the Interior U.S. Geological Survey, Reston, VA

Sun SK, Wu PT, Wang YB, Zhao XN (2013) Temporal Variability of Water Footprint for Maize Production: The Case of Beijing from 1978 to 2008. Water Resour Manag 27:2447–2463.

USDA (1992) Weights, Measures, and Conversion Factors for Agricultural Commodities and Their Products. United States Department of Agriculture - Economic Research Service, Rockville, MD

USDC-CB (2007) 2007 Economic Census Methodology. United States Department of Commerce - Census Bureau, Washington, DC

Verma S, Kampman D, van der Zaag P, Hoekstra A (2009) Going against the flow: A critical analysis of inter-state virtual water trade in the context of India's National River Linking Program. Phys Chem Earth 34:261 – 269.

Vorosmarty C, Green P, Salisbury J, Lammers R (2000) Global Water Resources: Vulnerability from Climate Change and Population Growth. Science (80-) 289:284–288

Wichelns D (2010) Virtual Water: A Helpful Perspective, but not a Sufficient Policy Criterion. Water Resour Manag 24:2203 – 2219

Yang H, Zehnder A (2007) "Virtual water": An unfolding concept in integrated water resources management. Water Resour Res 43:1–10

Zeng Z, Liu J, Koeneman PH, et al. (2012) Assessing water footprint at river basin level: a case study for the Heihe River Basin in northwest China. Hydrol Earth Syst Sci 16:2771–2781

Zhao X, Yang H, Yang Z, et al. (2010) Applying the input-output method to account for water footprint and virtual water trade in the Haihe River basin in China. Environ Sci Technol 44:9150–6

Zhuo L, Mekonnen MM, Hoekstra a. Y (2014) Sensitivity and uncertainty in crop water footprint accounting: a case study for the Yellow River Basin. Hydrol Earth Syst Sci Discuss 11:135–167

Chapter 3: The Water Footprint of California's Energy System, 1990-2012

Included in this dissertation with the permission of co-author Heather Cooley.

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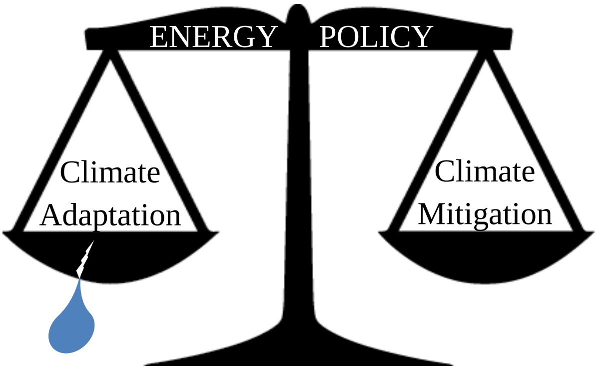


Abstract: California’s energy and water systems are interconnected and have evolved in recent decades in response to changing conditions and policy goals. For this analysis, we use a water footprint methodology to examine water requirements of energy products consumed in California between 1990 and 2012. We combine energy production, trade, and consumption data with estimates of the blue and green water footprints of energy products. We find that while California’s total annual energy consumption increased by just 2.6% during the analysis period, the amount of water required to produce that energy grew by 260%. Nearly all of the increase in California’s energy-related water footprint was associated with water use in locations outside of California, where energy products that the state consumes were, and continue to be, produced. We discuss these trends and the implications for California’s future energy system as it relates to climate change and expected water management challenges inside and outside the state. Our analysis shows that while California’s energy policies have supported climate mitigation efforts, they have increased vulnerability to climate impacts, especially greater hydrologic uncertainty. More integrated analysis and planning are needed to ensure that climate adaptation and mitigation strategies do not work at cross purposes.

Introduction

Water and energy systems are interdependent across spatial and temporal scales, and the term "energy-water nexus" has been used to draw attention to these connections (Schnoor 2011; DOE 2006; Klein 2005; King, Holman, and Webber 2008). Water and sewerage systems, for example, use large amounts of energy for pumping, storage, treatment, and usage of water, accounting for about 13% of national electricity usage in the United States (Sanders and Webber 2012). Energy systems, in turn, use and pollute large volumes of water for hydropower generation, extraction and processing of fuels, energy transformation, and end uses (Maupin et al. 2014). While these processes can have more immediate, regional impacts (Sovacool and Sovacool 2009; Averyt et al. 2013; Mauter et al. 2014), they can also have longer term global impacts, as greenhouse gas emissions from energy systems drive shifts in the global hydrologic cycle (Schewe et al. 2014; Schaeffer et al. 2012; Hayhoe et al. 2004).

Given these interdependencies as well as constraints on both water and energy supplies, energy and water policies that do not balance demands and impacts across resource categories risk shifting adverse impacts geographically and temporally rather than alleviating them. Here we focus on water impacts of energy systems. Energy policies are increasingly driven by the need to curtail anthropogenic greenhouse gas emissions in light of well-documented atmospheric limits and expected climate impacts. Despite growing recognition of the "global water crisis" (Srinivasan et al. 2012; UNDP 2006) and the potential for climate change to exacerbate these concerns (Gleick 2010; Vörösmarty et al. 2010; Oki and Kanae 2006), policy- and decision-makers have often failed to consider the implications of energy policies on water resources. Thus, a motivating question that this paper seeks to address is whether and how energy policies intended to mitigate climate change can simultaneously allow energy systems to adapt to climate impacts, especially hydrologic uncertainty. Specifically, we examine the case of California's energy system from 1990-2012 to understand how energy policies have affected demands on water resources and provide insight into the impacts of climate mitigation policies.

California's energy system has faced real and perceived constraints based on the availability of water resources. Most directly, seasonal precipitation and snowpack in the Sierra Nevada mountain range determines the state's hydropower generation, which provides an average of about 15% of in-state electricity generation. During drought years, hydropower generation is curtailed, forcing the state's grid operator to generate electricity from other in-state resources or import more electricity from other states to meet demand. This trend was apparent most recently in 2012 and 2013, as well as in 2014, the worst drought year on record (EIA 2014). Similarly, some groups have called for a ban on further development of California's shale oil resources using hydraulic fracturing and other well stimulation techniques due to the drought and other water supply constraints (Onishi 2014).

Over the past several decades, California has emerged as a leader in energy efficiency, renewable energy generation, and greenhouse gas (GHG) management. 1990, as the benchmark for the state’s GHG inventory, represents a logical starting year for our analysis. By 2012, California’s total energy use was only 2.6% higher than in 1990 (EIA 2014a) and the state’s GHG inventory for energy was below 1990 levels (CARB 2014; CARB 2007). Meanwhile, the state’s population increased by 27%, and gross domestic product grew by 68% (Figure 13) (CDF 2011). These energy achievements were primarily made through aggressive greenhouse gas management policies, including a low carbon fuel standard, a renewables portfolio standard for electric utilities, and, most recently, a cap and trade program (McCollum et al. 2012). Energy efficiency programs, demographic changes, prices, and consumer preferences have also played a role in shaping California’s energy landscape (Sudarshan 2013). Each of these changes has resulted in shifts in the amount and type of fuel use as well as in production technologies and locations.

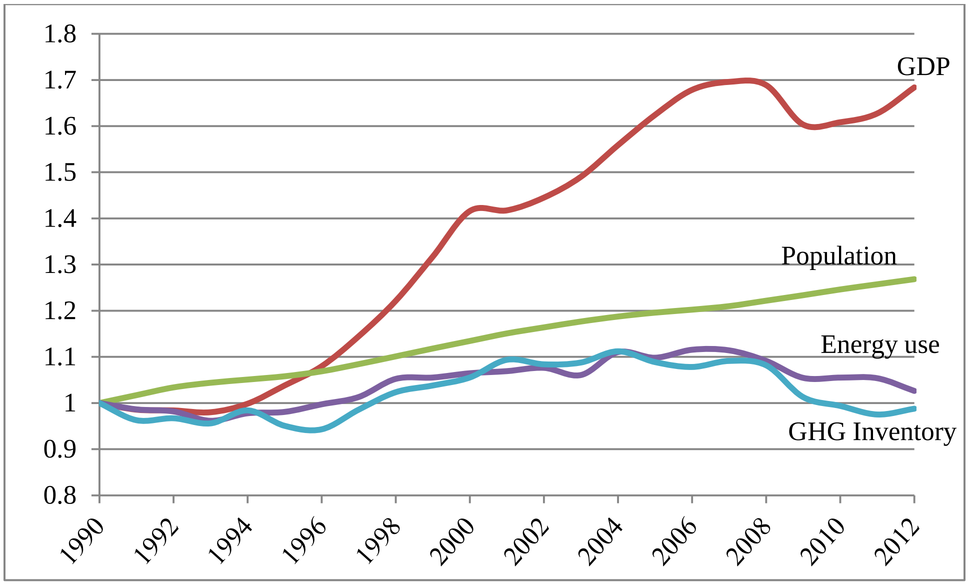


Figure 13: Changes in California GDP, Population, Energy Use, and Energy Greenhouse Gas Inventory from 1990 to 2012 (CARB 2014; CARB 2007; EIA 2014a; CDF 2011).

Energy and other policies can be aided by analytical tools to describe and provide decision-making frameworks on complex interactions between social systems and energy, water, and other environmental systems (Galli et al. 2012; McGlade et al. 2012; Pfister, Koehler, and Hellweg 2009; Boulay, Hoekstra, and Vionnet 2013). In this article, we use a water footprint approach to highlight three features of California’s energy-related water footprint (EWF), including (1) the *intensity*, or volume of water consumptively used for the state’s energy system; (2) the *type* of water consumed, i.e., blue or green water; and (3), the *location* where the water consumption occurred, i.e., inside or outside of California. Each of these pertains to specific water resource impacts and risks in locations where the energy activities occur. While we do not quantitatively characterize these impacts or the associated risks to California’s energy system, we identify how future energy planning might do these analyses.

Interest in the energy-water nexus has increased in recent years, although studies on water uses of energy systems date back at least three decades. Harte and El-Gasseir (1978) assessed regional hydrologic constraints on U.S. electric power generation. Gleick (1994) provided one of the most-cited in-depth studies on water intensity (on a gallons per unit energy basis) of various energy sources, including hydropower, for the entire fuel cycle. Review studies of the water intensity of various fuel sources have also been published (Fthenakis and Kim 2010; Mielke, Anadon, and Narayanamurti 2010; Macknick et al. 2011). While these early efforts focused primarily on electricity sourcing and generation, later research expanded into the areas of transportation fuels, including unconventional fuels and biofuels. King & Webber (2008) analyzed the water intensity across the full fuel cycle for a set of transportation fuels on a gallons-per-mile basis and calculated water demand scenarios based on national energy projections (King, Webber, and Duncan 2010). Fingerman et al (2010) identified regional water considerations in bioethanol production, while Scown et al (2011) included several additional fuel sources, including electricity, to compare stress-weighted upstream water impacts in the U.S.

More recent research has taken a systems approach to assessing how water demands for energy are distributed within and among regions, and with consideration for supply chain impacts. Input-output (I-O) approaches figure prominently in the broader water footprint literature (Dietzenbacher and Velázquez 2007; Lenzen 2009; Blackhurst, Hendrickson, and Vidal 2010; Zhao et al. 2010; Daniels, Lenzen, and Kenway 2011; Cazcarro, Duarte, and Sanchez 2013; Zhang and Anadon 2014), though there have been fewer applications to water-energy nexus studies in particular. Scown et al (2011) based their study on a U.S. economy-wide I-O framework. Zhang and Anadon (2013) used China’s linked, province-level I-O tables to trace interregional and intersectoral demands on water resources, and related those demands to human, ecosystem and resource impacts at the watershed scale using a life cycle impact assessment method.

Our analysis differs from previous energy-water nexus studies in three ways. First, by focusing on California, we are able to identify the water implications of a specific set of energy policies. Second, we examine these implications using panel data, allowing trends to provide insights that may be missed in a snapshot analysis. Third, we bring together previous studies that have looked at the water footprint of discrete segments of energy systems, to present a comprehensive understanding of the water footprint of California’s total energy system. We expect these attributes of our study to be informative for current and future energy-water decision making and energy policy discussions.

Materials and Methods

We define California’s energy system as the full range of energy products consumed within the state’s borders, including electricity and direct use of fuels for the household, industrial, commercial and transportation sectors. Energy products make use of multiple energy carriers — natural gas, coal, nuclear fuel, hydropower, geothermal, biomass, wind, and solar — through a range of extraction, processing, refining, and electricity generation activities. While all of these activities take place to varying extents within the state's borders, California also depends on imports of energy products (in one form or another) from neighbors and distant trading partners. Furthermore, energy products within the state are somewhat fungible between different end uses, e.g. natural gas or electric-powered vehicles. The above-mentioned factors make evaluating California's energy system, and the effects of policy on it, complex.

California's energy system underwent significant changes between 1990 and 2012, making it an important time period to study, but also complicating data collection efforts. To account for these complex and dynamic energy patterns, we utilized the framework of the California Energy Balance (CALEB) database, maintained by Lawrence Berkeley National Laboratories (de la Rue du Can, Hasanbeigi, and Sathaye 2013). CALEB contains highly disaggregated data on annual energy supply, transformation, and end-use consumption for 30 distinct energy products, from 1990 to 2008. Figure 14 shows a sample Sankey diagram produced by CALEB for 2008, represented in million British thermal units of energy (BTUs). We used data in physical units (barrels of oil, million cubic feet of natural gas, etc.) from CALEB to quantify energy product flows over time. Following methods in de la Rue du Can (2013), we updated physical unit statistics for years 2009–2012. To identify the origin and type of imported energy products, we used data from the California Energy Commission on electricity (CEC 2013) and natural gas (EIA 2013a), and from the Energy Information Administration on oil, and ethanol (EIA 2013b). More information on these energy flows can be found in the Supporting Information (Appendix A).

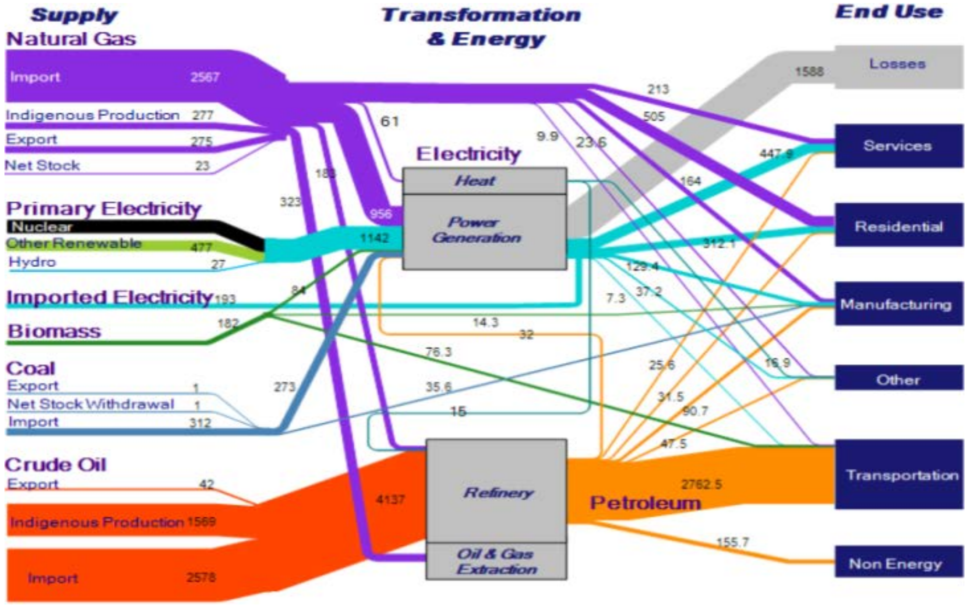


Figure 14: 2008 California energy flows in million BTUs, as shown in De la Rue du Can et al (2013).

Nearly every stage in the production of energy products consumes water, whether through evaporation, contamination, or other ways in which water is unavailable for reuse in the same river basin (Gleick, Christian-smith, and Cooley 2011). We characterize the EWF of an energy product by its “blue” and “green” components: the blue water footprint (blue EWF) of an energy product refers to the consumption of surface or ground water, such as evaporation of water for power plant cooling; the green water footprint (green EWF) refers to the consumption of precipitation and in-situ soil moisture, such as through transpiration from the production of bioenergy feedstocks (Gerbens-Leenes, Hoekstra, and van der Meer 2009). The related “grey” water footprint, i.e., the volume of water to assimilate pollutants into water bodies at levels that meet governing standards, is not addressed explicitly in this analysis due to lack of data, although we describe water quality in the discussion section.

Blue EWF factors for energy extraction, processing, and electricity generation were derived from several sources and are shown in Table 1. Meldrum et al (2013) recently completed a review and harmonization of life cycle water use factors on various electricity fuel cycle and generation technologies. We used reported median consumptive use factors for natural gas, coal, nuclear, solar, wind, and geothermal power. We used a related study from the National Renewable Energy Laboratory for consumptive use factors for biomass and hydropower (Macknick et al. 2011). All these factors were further weighted for the composition of California’s electricity consumption when different types of fuel cycle, generation, and cooling technologies could be identified by location and year. Table 2 shows blue and green EWF factors used for extraction, processing and refining of liquid fuels. Consumptive water use factors for oil products were taken from Wu et al. (2011). For bioethanol production, we used country-level weighted average factors from Mekonnen and Hoekstra (2010), including refining and on-farm green and blue water requirements of bioethanol feedstocks. Further details on calculation steps for EWF factors can be found in the Supporting Information (Appendix A).

Table 1: Factors used to calculate California’s blue EWF for electricity.

Fuel	Location	Fuel Cycle (l water/MWh)	Generation (l water/MWh)	Source
Coal	All	96	1,895	(Meldrum et al. 2013)
Natural Gas	All	24*	737	“ ”
Nuclear	All	212	1,817	“ ”
Conventional Hydropower	All	17,000†	-	(Macknick et al. 2011)
Geothermal	All	-	2,265	(Meldrum et al. 2013)
Biomass	All	-	2,090	(Macknick et al. 2011)
Solar PV	All	-	329	(Meldrum et al. 2013)
Solar Thermal	All	-	3,975	“ ”
Wind	All	-	4	“ ”
Unspecified Imported Electricity	All	1,291	1,399	“ ”

Note: EWF factors are weighted by extraction, processing, and electricity generation technologies pertaining to California's energy system. See Supporting Information for further details.

[*] The equivalent factor for direct use of natural gas is 0.13 l water/m^3 gas.

[†] This quantity refers to evaporative losses from reservoirs, which often serve other uses such as storage for flood control, urban and agricultural water supply, and recreation. However, as no methodology exists to accurately allocate consumption among the various uses, we used existing assumptions in the literature that all evaporative losses are attributable to electricity production (Macknick et al. 2011).

Table 2: Factors used to calculate California's blue and green EWF for liquid fuels.

Fuel	Location	Extraction/Farming (l water/l fuel)		Refining (l water/l fuel)	Source
		Green Water	Blue Water		
Crude Oil	Alaska & California	n/a	5.4	1.5	(May Wu and Chiu 2011)
Crude Oil	Foreign Countries	n/a	3.0	1.5	" "
Ethanol	California	n/a	n/a	3	" "
Ethanol	USA (Corn)	1,220	148	3	(Mekonnen and Hoekstra 2010)
Ethanol	Brazil (Sugar)	1,224	54	3	" "
Ethanol	Canada (Corn)	1,149	13	3	" "
Ethanol	China (Corn)	1,848	172	3	" "
Ethanol	Costa Rica (Sugar)	1,404	245	3	" "
Ethanol	El Salvador (Sugar)	1,476	54	3	" "
Ethanol	Guatemala (Sugar)	1,283	127	3	" "
Ethanol	Jamaica (Sugar)	2,085	271	3	" "
Ethanol	Nicaragua (Sugar)	1,459	161	3	" "
Ethanol	Trinidad & Tobago (Sugar)	2,223	78	3	" "
Ethanol	Other (Sugar)	1,400	575	3	" "

Blue and green EWF factors (e.g. liters of water per liter of ethanol) were multiplied by physical units of energy consumed in California (e.g., liters of ethanol) for each year between 1990 and 2012. This method assumed that blue and green EWF factors did not change over the 23-year time frame. In reality, we expect that many of these factors likely have decreased due to efficiency improvements, weather, etc. Many of these factors were derived with data from around the middle of our time series (2000) but we lack data with which to model changes before and after these points. Thus, results are indicative of how California's EWF has changed with respect to changes in its energy system. Further research into how consumptive water use factors have changed in the energy sector could further enrich this approach and subsequent findings.

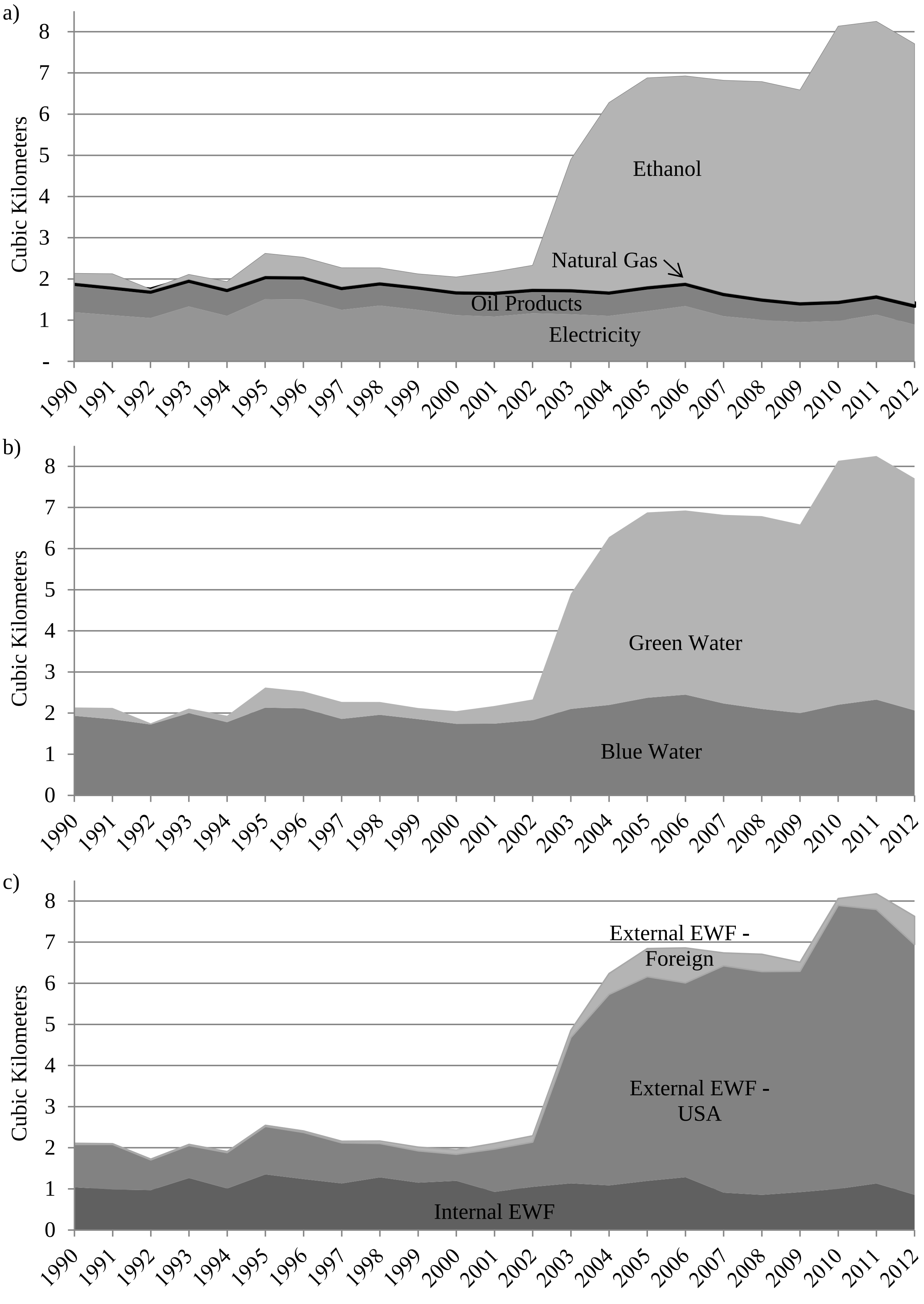
Results

The amount of water required to support California's total energy system has changed significantly over the time period examined (Figure 15a). In 1990, the state's total EWF was about 2.1 cubic kilometers (km^3) while in 2012, it was 7.7 km^3, representing more than a three-fold increase. Much of the increase is attributable to water consumed for ethanol production, which increased from 0.2 km^3 in 1990 to 6.3 km^3 in 2012. Indeed, California's EWF is highly sensitive to the role of ethanol (given our methods and assumptions) and we discuss this role at greater length below, after examining the EWF of other energy sources.

The EWF of California's natural gas consumption for the residential, commercial, industrial, and electric power sectors increased from 0.005 km^3 in 1990 to 0.013 km^3 in 2012, representing a 150% increase over this period. The consumption of natural gas, however, increased by only 24% during this period. This disparity resulted from the growing application of hydraulic fracturing techniques around the U.S. to extract unconventional natural gas resources, which doubled the technology-weighted water intensity of California's natural gas consumption between 1990 and 2012, from 0.1 to 0.2 liters per cubic meters. Despite this growth, natural gas remained a relatively small component of the state's total EWF. However, regional variation in the water intensity and impacts in shale gas exploitation exist (Mauter et al. 2014), making natural gas an important energy product to monitor and manage in California's future energy-water portfolio.

The EWF of oil products consumed in California declined from 0.7 km^3 in 1990 to less than 0.5 km^3 in 2012, representing a 30% decrease. During this period, however, the quantity of oil products consumed in California declined by only 2%. Thus, the drop in oil's EWF was due primarily to shifting from more water-intensive oil production in California to less water-intensive production locations. In 1990, California produced around half of its domestic demand; however, by 2010 that number had dropped to 37% (CEC 2014).

The EWF of California's electricity consumption also decreased, from 1.2 km^3 in 1990 to 0.9 km^3 in 2012, though it reached a peak of 1.5 km^3 in 1995. The relatively high degree of variability compared to other energy products is due to the complexity of California's portfolio of generation sources and the wide range in water requirements for those different generation technologies. While total electricity consumption increased over this time period, most of this electricity was produced by relatively less water-intensive generation technologies, such as gas turbine or combined-cycle natural gas power plants, wind turbines, and solar photovoltaics. Hydroelectric generation, an extremely water-intensive form of electricity generation due to high evaporative losses from reservoirs, also decreased as a share of California's total electricity portfolio.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External EWF - USA
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Figure 15: California's energy-water footprint between 1990 and 2012, broken down by energy type (a), by green and blue water (b), and by internal and external locations (c).

Between 1990 and 2012, there have been dramatic changes in the "type" of water consumed, i.e., green vs. blue water (Figure 15b). In 1990, only 10% of California's EWF was green water and the remaining 90% was blue water, of which 63% was attributed to the electricity sector and 35% to oil products. Since 2003, however, green water has dominated California's EWF, and in 2012, blue water made up only 27% of the state's EWF. Plant-based ethanol accounts for all of this green water and 33% of the blue water, while electricity, oil products, and natural gas make up the remainder of the blue EWF.

The location of blue and green water use is relevant to local water resource concerns, as discussed earlier. Figure 15c shows California's EWF by internal and external sources, including in the U.S. and in foreign countries. In 1990, 1.0 km^3, or about half, of California's total EWF was internal to the state, i.e. using California's water resources (for comparison, this represented about 3% of total in-state consumptive use for all purposes) (Solley, Pierce, and Perlman 1993). By 2012, the volume of California's internal EWF was slightly smaller (0.9 km^3), but it made up just 11% of the state's total EWF. This means that all of the increase in California's EWF occurred outside of the state's borders. Indeed, much of this growth occurred in ethanol-growing regions of the US Midwest, but also substantially in other countries where ethanol and oil extraction have increased.

Discussion

An examination of the water footprint of California's energy system sheds light on how much, what type, and where water is consumed to produce the state's energy products. Understanding these linkages is of growing importance as the impacts of climate change on water and energy resources intensifies and as efforts to adapt to and mitigate these impacts are implemented. Our assessment highlights the need for more careful, integrated consideration of the implications of the water-energy nexus for water resource and energy system planning.

Our study shows that California's EWF has substantially increased over recent decades without utilizing more of the state's water resources, but rather relying more heavily on external sources of water. The increase in the EWF has been primarily associated with green water, i.e., precipitation that is used directly by biofuel crops in the field. While green water utilization may have added benefits in that it does not require pumping or associated infrastructure, it also links California's energy future directly to future precipitation and soil management regimes in biofuel-growing regions. To the extent that California's increased ethanol demand has relied on blue water, its energy system has also become linked to surface and groundwater management issues in those regions, such as the over-pumping of the Ogallala aquifer (Dominguez-Faus et al. 2013). The Midwest drought of 2011-2012 highlights one risk of these linkages, as this drought constrained the ethanol supply and resulted in higher ethanol prices in California markets (EIA

2012; Langholtz et al. 2014). Moreover, foreign sources of ethanol, which have constituted up to 12% of California's supply, may face similar climate-related challenges (Haberl et al. 2011; de Lucena et al. 2009).

Although we did not present the grey water footprint of ethanol, factors provided from Mekonnen & Hoekstra (2010) indicate that California's grey EWF associated with ethanol consumption ranged from one to two cubic kilometers per year (see Supporting Information in Appendix A). This grey water is associated with heavy use of fertilizers and pesticides, which then pollute local and regional waterways. As most of California's grey EWF related to biomass production within the Mississippi River Basin, California's energy system requires an additional 0.2% to 0.4% of the average annual discharge of the Mississippi River to bring pollutants to acceptable levels. As California's ban on MTBE was brought about by water quality concerns in the state's urban groundwater basins, we note that the substitution with ethanol may have shifted water quality burdens outside the state rather than mitigate them altogether. This initial finding could be refined with further analysis of the pollutant persistence and relative impacts of these burdens. Nevertheless, these burdens may yet pose supply risks to California's energy system, as producing regions grapple with tradeoffs between high agricultural yields and low water quality from runoff (Dominguez-Faus et al. 2009). Water quality concerns exist with other bioenergy sources as well as with the extraction and processing of other fuels and electricity generation.

Many of these observed trends in California's EWF can be linked to effects of the state's energy policies. The increased reliance on bioethanol was initially driven by the need for an alternative gasoline oxygenate following an executive order banning of MTBE in 2003 (Davis 2002). More recent energy policies have encouraged additional ethanol blending in gasoline to meet state greenhouse gas targets. California's Low Carbon Fuel Standard (LCFS) of 2007, pursuant to its landmark Global Warming Solutions Act of 2006, has reinforced demand for bioethanol as a means to reduce the greenhouse gas intensity of transportation fuels. Although early LCFS policy assessments raised the issue of water demands and impacts from increased biofuel production (Farrell and Sperling 2007), any subsequent efforts to track or address those impacts through policy have been lacking (CARB 2011).

Expected trends in California's biofuel demand pose deeper consideration for integrated research and policy. Since 2009, bioethanol has been blended into California reformulated gasoline to 10% by volume, and an emerging market for E85 (85% ethanol fuel) is likely to increase the state's demand for bioethanol. These developments have been further abetted by a broader policy environment including the federal Renewable Fuel Standard (RFS), which since 2007 has mandated an increasing share of biofuels in U.S. transportation energy (EPA 2007). A recent study assessed the regional water impacts of various potential RFS-technology-policy scenarios, highlighting the need for attention to local effects and integrated approaches to federal policy (Jordaan et al. 2013). Still, California holds a unique position in the national biofuels landscape, as the state with the largest demand yet little economically viable production capacity (EIA 2013c). State-level energy policies have played, and will continue to play, a strong role in determining California’s biofuel demand. Our research suggests that expected trends would substantially increase and further externalize the state’s EWF in the future and that a closer examination of associated tradeoffs and climate risks is needed.

Shifts in other energy products have also driven the externalization of California’s EWF. In-state crude oil extraction has declined since the mid-1980s, the demand having been made up by Alaskan oil initially, then imports from foreign sources. In this case, the blue water footprint of most sources of foreign oil is lower than that of California or Alaska, so California’s blue EWF declined by 31% as a result of this shift (despite near constant overall supply). While this effect was unlikely intentional, it is not surprising that current efforts to “re-shore” energy production face increasing opposition on grounds of impacts to local water resources (Jordaan et al. 2013). Still, if California’s consumption of oil products does not wane, water impacts may continue to accrue inside and outside the state’s borders.

Electricity is another sector where consideration of water resources inside and outside of California is important (Sattler et al. 2012; Sathaye et al. 2013). Imported electricity has long been an important source of the state’s energy portfolio (30% of electricity on average), providing a flexible supply when hydropower potential is low or other factors restrict in-state generation. Yet, when California’s grid operator outsources electricity, the state’s EWF goes up. This is because out-of-state thermoelectric sources, especially older coal plans, tend to be more water intensive than newer in-state plants and coastal generators that use saline water for cooling (Ruddell and Adams 2014). Because this outsourced electricity also tends to be more greenhouse gas intensive, we see greenhouse gas-driven energy policies having a synergistic effect with reducing California’s EWF. The opposite was found in China, where electricity production in the arid north uses dry cooling, and is therefore less water- intensive, however energy efficiency goes down in such systems, resulting in higher greenhouse gas-per-kilowatt hour produced (Zhang et al. 2014). Further synergistic effects can be found with energy conservation policies, which are not exclusively associated with climate change concerns (Bartos and Chester 2014).

We conclude from our research that as California’s energy policies have sought to mitigate climate change, water systems and resources, considered extremely vulnerable to the effects of climate change, have received little attention. When energy policies have considered impacts to water, such as the MTBE ban, policy outcomes may have simply shifted burdens rather than alleviate them. Given the exigencies of both climate change *and* the global water crisis, the interconnectedness of energy and water systems deserves closer attention in both academic and policy arenas. Climate and water goals are not mutually exclusive in energy policy; rather, to the extent that existing energy sources are fungible, climate and water goals can be achieved simultaneously. Additionally, many renewable sources of energy already have few water impacts (Meldrum et al. 2013). Policy makers should seek to ask questions about unforeseen or unintended consequences of proposed energy policies and pathways. Analytical tools, such as the water footprint used here, provide a starting place and a framework to answer such questions; however, much more is needed.

Further research should focus more precisely on characterizing the relative impacts and risks of water footprint assessments such as California's EWF (Wu, Chiu, and Demissie 2012). Weighting green, blue, and grey water footprint values by their relevant water stress, opportunity costs, and water quality impacts can inform better decision making by energy supply chain managers and energy policy designers. Interconnected water and energy systems need not be a source of risk for California or other entities; rather, integrated analysis and deeper understanding of these essentially linked resources can increase productivity at the energy-water nexus and simultaneously support climate change mitigation and adaptation strategies.

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Supporting Information Available

Supporting information includes statistics on California's energy product flows for each year from 1990 to 2012, calculation steps and data sources for Table 1, as well as grey water footprint estimates for ethanol consumption in California. This information is available in Appendix A of this dissertation as well as free of charge via the Internet at http://pubs.acs.org/.

References

Averyt, K, J Macknick, J Rogers, N Madden, J Fisher, J Meldrum, and R Newmark. 2013. "Water Use for Electricity in the United States: An Analysis of Reported and Calculated Water Use Information for 2008." *Environmental Research Letters* 8 (1): 015001. doi:10.1088/1748-9326/8/1/015001.

Bartos, MD, and MV Chester. 2014. "The Conservation Nexus: Valuing Interdependent Water and Energy Savings in Arizona." *Environmental Science & Technology* 48 (4): 2139–49. doi:10.1021/es4033343.

Blackhurst, M, C Hendrickson, and J Sels I Vidal. 2010. "Direct and Indirect Water Withdrawals for U.S. Industrial Sectors." *Environmental Science & Technology* 44 (6): 2126–30. doi:10.1021/es903147k.

Boulay, AM, AY Hoekstra, and S Vionnet. 2013. "Complementarities of Water-Focused Life Cycle Assessment and Water Footprint Assessment." *Environmental Science & Technology*, 11926–27.

CARB, California Air Resources Board. 2007. *Staff Report: California 1990 Greenhouse Gas Emissions Level and 2020 Emissions Limit*. Sacramento, CA.

———. 2011. *Staff Report: Initial Statement of Reasons for Proposed Rulemaking: Proposed Amendments to the Low Carbon Fuel Standard*. Sacramento, CA.

———. 2014. *2014 Edition California Greenhouse Gas Emission Inventory.* Sacramento, CA.

Cazcarro, I, R Duarte, and J Sanchez. 2013. “Multiregional Input − Output Model for the Evaluation of Spanish Water Flows.” *Environ. Sci. Technol* 47: 12275–83.

CDF, California Department of Finance. 2011. “California Statistical Abstract.” http://www.dof.ca.gov/HTML/FS_DATA/STAT-ABS/Statistical_Abstract.php.

CEC, California Energy Commission. 2013. “Total Electricity System Power.” http://energyalmanac.ca.gov/electricity/total_system_power.html.

———. 2014. "Energy Almanac: Oil Supply to California Refineries." http://energyalmanac.ca.gov/ petroleum/statistics/crude_oil_receipts.html.

Daniels, PL, M Lenzen, and SJ Kenway. 2011. “The Ins and Outs of Water Use - A Review of Multi-Regional Input-Output Analysis and Water Footprints for Regional Sustainability Analysis and Policy.” *Economic Systems Research* 23 (4): 353–70.

Davis, Grey. 2002. "Governor of the State of California Executive Order D-52-02.” http://www.arb.ca.gov/fuels/gasoline/oxy/eo5202.pdf

De la Rue du Can, S, A Hasanbeigi, and J Sathaye. 2013. *California Energy Balance Update and Decomposition Analysis for the Industry and Building Sectors: Final Project Report*. Lawrence Berkeley National Laboratory and California Energy Commission: Sacramento, CA.

De Lucena, AFP, AS Szklo, R Schaeffer, RR de Souza, BSMC Borba, IVL da Costa, AOP Júnior, and SHF da Cunha. 2009. “The Vulnerability of Renewable Energy to Climate Change in Brazil.” *Energy Policy* 37 (3): 879–89. doi:10.1016/j.enpol.2008.10.029.

Dietzenbacher, E, and E Velázquez. 2007. “Analysing Andalusian Virtual Water Trade in an Input–Output Framework.” *Regional Studies* 41 (2): 185–96. doi:10.1080/00343400600929077.

DOE, U.S. Department of Energy. 2006. *Energy Demands on Water Resources: Report to Congress on the Interdependency of Energy and Water*. Washington, DC.

Dominguez-Faus, R, SE Powers, JG Burken, and PJ Alvarez. 2009. “The Water Footprint of Biofuels: A Drink or Drive Issue?” *Environmental Science & Technology* 43: 3005–10.

Dominguez-Faus, R, C Folberth, J Liu, AM. Jaffe, and PJJ Alvarez. 2013. “Climate Change Would Increase the Water Intensity of Irrigated Corn Ethanol.” *Environmental Science and Technology* 47: 6030–37. doi:10.1021/es400435n.

EIA, Energy Information Administration. 2012. “Drought Has Significant Effect on Corn Crop Condition , Projected Ethanol Production.” *Today in Energy*, August 30.

———. 2013a. “California International and Interstate Movements of Natural Gas by State.” http://www.eia.gov/dnav/ng/ng_move_ist_a2dcu_sca_a.htm.

———. 2013b. “Petroleum and Other Liquids: Company Level Imports.” http://www.eia.gov/petroleum/imports/companylevel/.

———. 2013c. “State Energy Data System: Table F4: Fuel Ethanol Consumption Estimates, 2013.” http://www.eia.gov/state/seds/sep_fuel/html/pdf/fuel_use_en.pdf.

———. 2014a. “State Energy Data System.” http://www.eia.gov/state/seds/seds-data-complete.cfm?sid=CA.

———. 2014b. “Current Drought Reduces Hydro Generation Forecast for California.” *Today in Energy*, February 6.

EPA, Environmental Protection Agency. 2007. “Renewable Fuel Standard.” http://www.epa.gov/otaq/fuels/renewablefuels/index.htm.

Farrell, AE, and D Sperling. 2007. "A Low-Carbon Fuel Standard for California." http://www.arb.ca.gov/fuels/lcfs/lcfs_uc_p1.pdf

Fingerman, KR, MS Torn, MH O’Hare, and DM Kammen. 2010. “Accounting for the Water Impacts of Ethanol Production.” *Environmental Research Letters* 5 (1): 014020. doi:10.1088/1748-9326/5/1/014020.

Fthenakis, V, and HC Kim. 2010. “Life-Cycle Uses of Water in U.S. Electricity Generation.” *Renewable and Sustainable Energy Reviews* 14 (7): 2039–48. doi:10.1016/j.rser.2010.03.008.

Galli, A, T Wiedmann, E Ercin, D Knoblauch, B Ewing, and S Giljum. 2012. “Integrating Ecological, Carbon and Water Footprint into a ‘Footprint Family’ of Indicators: Definition and Role in Tracking Human Pressure on the Planet.” *Ecological Indicators* 16 (May). Elsevier Ltd: 100–112. doi:10.1016/j.ecolind.2011.06.017.

Gerbens-Leenes, W, AY Hoekstra, and TH van der Meer. 2009. “The Water Footprint of Bioenergy.” *Proceedings of the National Academy of Sciences of the United States of America* 106 (25): 10219–23. doi:10.1073/pnas.0812619106.

Gleick, PH. 1994. “Water and Energy.” *Annual Review of Energy and the Environment* 19 (1): 267–99. doi:10.1146/annurev.energy.19.1.267.

———. 2010. “Climate Change, Exponential Curves, Water Resources, and Unprecedented Threats to Humanity.” *Climatic Change* 100 (1): 125–29. doi:10.1007/s10584-010-9831-8.

Gleick, PH, J Christian-smith, and H Cooley. 2011. “Water-Use Efficiency and Productivity : Rethinking the Basin Approach.” *Water International* 36 (7).

Haberl, H, K-H Erb, F Krausmann, A Bondeau, C Lauk, C Müller, C Plutzar, and JK Steinberger. 2011. “Global Bioenergy Potentials from Agricultural Land in 2050: Sensitivity to Climate Change, Diets and Yields.” *Biomass & Bioenergy* 35 (12): 4753–69. doi:10.1016/j.biombioe.2011.04.035.

Harte, J, and M El-Gasseir. 1978. “Energy and Water.” *Science*, 199 (4329): 623–34.

Hayhoe, K, Daniel C, CB Field, PC Frumhoff, EP Maurer, NL Miller, SC Moser, et al. 2004. “Emissions Pathways, Climate Change, and Impacts on California” *Proceedings of the National Academy of Sciences,* 101 (34).

Jordaan, SM, LD Anadon, E Mielke, and DP Schrag. 2013. “Regional Water Implications of Reducing Oil Imports with Liquid Transportation Fuel Alternatives in the United States.” *Environmental Science & Technology* 47 (21): 11976–84. doi:10.1021/es404130v.

King, CW, AS Holman, and ME Webber. 2008. “Thirst for Energy.” *Nature Geoscience* 1 (May): 283–86. doi:10.1038/ngeo195.

King, CW, ME Webber, and IJ Duncan. 2010. “The Water Needs for LDV Transportation in the United States.” *Energy Policy* 38 (2). Elsevier: 1157–67. doi:10.1016/j.enpol.2009.11.004.

King, CW, and ME Webber. 2008. “Water Intensity of Transportation.” *Environmental Science & Technology* 42 (21): 7866–72.

Klein, Gary. 2005. *California’s Water – Energy Relationship: Final Staff Report*. California Energy Commission: Sacramento, CA.

Langholtz, M, E Webb, BL Preston, A Turhollow, N Breuer, L Eaton, AW King, S Sokhansanj, SS Nair, and M Downing. 2014. “Climate Risk Management for the U.S. Cellulosic Biofuels Supply Chain.” *Climate Risk Management* 3. Elsevier B.V.: 96–115. doi:10.1016/j.crm.2014.05.001.

Lenzen, M. 2009. “Understanding Virtual Water Flows: A Multiregion Input-Output Case Study of Victoria.” *Water Resources Research* 45 (9): W09416. doi:10.1029/2008WR007649.

Macknick, J, R Newmark, G Heath, and KC Hallett. 2011. *A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies*. National Renewable Energy Laboratory. Golden, CO.

Maupin, MA, JF Kenny, SS Hutson, JK Lovelace, NL Barber, and KS Linsey. 2014. *Estimated Use of Water in the United States in 2010: U.S. Geological Survey Circular 1405*.

Mauter, MS, PJJ Alvarez, A Burton, DC Cafaro, W Chen, KB Gregory, G Jiang, et al. 2014. “Regional Variation in Water-Related Impacts of Shale Gas Development and Implications for Emerging International Plays.” *Environmental Science & Technology* 48 (15): 8298–8306. doi:10.1021/es405432k.

McCollum, D, C Yang, S Yeh, and J Ogden. 2012. “Deep Greenhouse Gas Reduction Scenarios for California – Strategic Implications from the CA-TIMES Energy-Economic Systems Model.” *Energy Strategy Reviews* 1 (1). Elsevier: 19–32. doi:10.1016/j.esr.2011.12.003.

McGlade, J, B Werner, M Young, M Matlock, D Jefferies, G Sonnemann, M Aldaya, et al. 2012. *Measuring water use in a green economy, A Report of the Working Group on Water Efficiency to the International Resource Panel.* United Nations Environment Program.

Mekonnen, MM, and AY Hoekstra. 2010. *The Green, Blue and Grey Water Footprint of Crops and Derived Crop Products - Volume 2: Appendices*. UNESCO-IHE: Delft, the Netherlands.

Meldrum, J, S Nettles-Anderson, G Heath, and J Macknick. 2013. “Life Cycle Water Use for Electricity Generation: A Review and Harmonization of Literature Estimates.” *Environmental Research Letters* 8 (1): 015031. doi:10.1088/1748-9326/8/1/015031.

Mielke, E, LD Anadon, and V Narayanamurti. 2010. "Water Consumption of Energy Resource Extraction, Processing, and Conversion: a Review of the Literature for Estimates of Water Intensity of Energy- Resource Extraction, Processing to Fuels, and Conversion to Electricity." *Energy Technology Innovation Policy Discussion Paper No. 2010- 15, Belfer Center for Science and International Affairs, Harvard Kennedy School*; Harvard University.

Oki, T, and S Kanae. 2006. “Global Hydrological Cycles and World Water Resources.” *Science* 313: 1068–72. doi:10.1126/science.1128845.

Onishi, N. 2014. “California’s Thirst Shapes Debate Over Fracking.” *New York Times*, May 14.

Pfister, S, A Koehler, and S Hellweg. 2009. “Assessing the Environmental Impacts of Freshwater Consumption in LCA.” *Environ. Sci. Technol.* 43 (11): 4098–4104. doi:10.1021/es802423e.

Ruddell, BL, and EA Adams. 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: 1–16. doi:10.1002/2013WR014531.Received.

Sanders, KT, and ME Webber. 2012. “Evaluating the Energy Consumed for Water Use in the United States.” *Environmental Research Letters* 7 (3): 034034. doi:10.1088/1748-9326/7/3/034034.

Sathaye, JA., LL Dale, PH Larsen, GA Fitts, K Koy, SM Lewis, and AFP de Lucena. 2013. “Estimating Impacts of Warming Temperatures on California’s Electricity System.” *Global Environmental Change* 23 (2): 499–511. doi:10.1016/j.gloenvcha.2012.12.005.

Sattler, S, J Macknick, D Yates, F Flores-Lopez, a Lopez, and J Rogers. 2012. “Linking Electricity and Water Models to Assess Electricity Choices at Water-Relevant Scales.” *Environmental Research Letters* 7 (4): 045804. doi:10.1088/1748-9326/7/4/045804.

Schaeffer, R, AS Szklo, AFP de Lucena, BSMC Borba, LPP Nogueira, FP Fleming, A Troccoli, M Harrison, and MS Boulahya. 2012. “Energy Sector Vulnerability to Climate Change: A Review.” *Energy* 38 (1). Elsevier Ltd: 1–12. doi:10.1016/j.energy.2011.11.056.

Schewe, J, J Heinke, D Gerten, I Haddeland, NW Arnell, DB Clark, R Dankers, et al. 2014. “Multimodel Assessment of Water Scarcity under Climate Change.” *Proceedings of the National Academy of Sciences of the United States of America* 111 (9): 3245–50. doi:10.1073/pnas.1222460110.

Schnoor, JL. 2011. “Water-Energy Nexus.” *Environmental Science & Technology* 45 (12). American Chemical Society: 5065. doi:10.1021/es2016632.

Scown, CD, A Horvath, and TE McKone. 2011. “Water Footprint of U.S. Transportation Fuels.” *Environmental Science & Technology* 45 (7): 2541–53. doi:10.1021/es102633h.

Solley, WB, RR Pierce, and HA Perlman. 1993. *Estimated Use of Water in the United States in 1990: U.S. Geological Survey Circular 1081. U.S. Geological Survey*.

Sovacool, BK, and KE Sovacool. 2009. “Identifying Future Electricity–water Tradeoffs in the United States.” *Energy Policy* 37 (7): 2763–73. doi:10.1016/j.enpol.2009.03.012.

Srinivasan, V, EF Lambin, SM Gorelick, BH Thompson, and S Rozelle. 2012. “The Nature and Causes of the Global Water Crisis: Syndromes from a Meta-Analysis of Coupled Human-Water Studies.” *Water Resources Research* 48 (10): 1–16. doi:10.1029/2011WR011087.

Sudarshan, A. 2013. “Deconstructing the Rosenfeld Curve: Making Sense of California’s Low Electricity Intensity.” *Energy Economics* 39 (September). Elsevier B.V.: 197–207. doi:10.1016/j.eneco.2013.05.002.

UNDP, United Nations Development Program. 2006. *Human Development Report 2006: Beyond Scarcity: Power, Poverty and the Global Water Crisis*. New York.

Vörösmarty, CJ, PB McIntyre, MO Gessner, D Dudgeon, A Prusevich, P Green, S Glidden, et al. 2010. “Global Threats to Human Water Security and River Biodiversity.” *Nature* 467 (7315): 555–61. doi:10.1038/nature09440.

Wu, M, Y Chiu, and Y Demissie. 2012. “Quantifying the Regional Water Footprint of Biofuel Production by Incorporating Hydrologic Modeling.” *Water Resources Research* 48 (10): W10518. doi:10.1029/2011WR011809.

Wu, M, and Y Chiu. 2011. *Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline - 2011 Update*. Argonne National Laboratory: Agronne, IL.

Zhang, C, and LD Anadon. 2013. “Life Cycle Water Use of Energy Production and Its Environmental Impacts in China.” *Environmental Science & Technology* 47 (24): 14459–67. doi:10.1021/es402556x.

———. 2014. “A Multi-Regional Input–output Analysis of Domestic Virtual Water Trade and Provincial Water Footprint in China.” *Ecological Economics* 100 (April). Elsevier B.V.: 159–72. doi:10.1016/j.ecolecon.2014.02.006.

Zhang, C, LD Anadon, H Mo, Z Zhao, and Z Liu. 2014. “Water−Carbon Trade-off in China’s Coal Power Industry.” *Environ. Sci. Technol* 48: 11082–89.

Zhao, X, H Yang, Z Yang, B Chen, and Y Qin. 2010. “Applying the Input-Output Method to Account for Water Footprint and Virtual Water Trade in the Haihe River Basin in China.” *Environmental Science & Technology* 44 (23): 9150–56. doi:10.1021/es100886r.

Chapter 4: California’s water footprint 1992–2012: considerations for policy and further research

Abstract: Benefits and burdens of water and other natural resource uses are increasingly affected by patterns of globalized trade and consumption. We use a water footprint approach to examine how California’s reliance on internal and external water resources has evolved between 1992 and 2012. Four findings emerge: first, California’s water footprint (WF) has grown at a rate faster than population growth, indicating increasing per-capita WFs; second, California’s WF relates primarily to food products, although energy products are also important; third, all of California’s WF growth has relied on external water resources, while internal water resources have increasingly served consumption outside the state; fourth, California’s external WF relates predominately to “green water,” or non-managed water sources. In light of climate change and an ongoing global water crisis, California policymaking must grapple with these realities in order to serve as a model for sustainable water management. We discuss potential policy levers and propose a research agenda to support decision making for WF management in California and elsewhere.

Introduction

Water problems have both environmental and social drivers at local to regional scales (Liu and Yang 2012), and with increasing recognition of pressures at the global scale from climate change and globalization (Alcamo, Flörke, and Märker 2007). For example, falling groundwater levels from agricultural extraction might be linked at the local scale with aquifer geology as well as irrigation practices of farmers; at the regional scale with river basin hydrology as well as national energy developments; and at the global scale with changing precipitation regimes as well as international market trends for agricultural products. Such observations have led to calls for studying and managing water with consideration for a global *hydro-commons,* rather than solely as a local-to-regional resource (Hoekstra and Chapagain 2008).

Policies to address these global dimensions to water problems must then seek to understand how both environmental and social drivers operate not only within various scales but across them. Setting aside environmental drivers for the time being, we deal in this article primarily with social drivers, specifically the demand for and consumption of everyday products like food, clothing, energy and industrial products. We use a *water footprint* approach to study how, in effect, this demand distributes water use impacts across geographic scales as products move from producers to consumers — in our case consumers in California. Such a demand-side or consumption approach acknowledges the role of the consumer, in marked contrast from a more conventional production perspective that looks at water use and impacts within production sectors. Still, consumer decisions take place within economic structures, signaling a broader set of social drivers related to the growth and restructuring of society. Thus from our standpoint, we view seemingly distant water problems as partially driven by more proximate activities, some of which we believe are tractable in a sustainability policy context, as supported later in this article using examples of existing governance mechanisms.

In addition to these social drivers, the environmental drivers of water problems — for example droughts — come back into play when considering policies to address the sustainability of water footprints. Motivations for such policies may range from acknowledging global limits in a changing climate (Orlowsky et al. 2014), to a practical desire to manage risks such as droughts in food and energy systems (Fulton and Cooley 2015), to equity concerns that seek to redress the impacts of consumption (Seekell, D'Odorico, and Pace 2011). In any case, there is a need to examine how manageable social and economic systems grow, restructure, and both affect and adapt to environmental conditions. A time series of water footprints is thus helpful to identify trends and ways in which policymaking might approach developing a more sustainable relationship with the global hydro-commons.

In this article we define California's water footprint as an estimate of the amount of freshwater consumptively used to produce the goods demanded by consumers within its borders. On a per-capita basis, California's WF was previously found to be similar in quantity to that of the United States as a whole, but to have particular features regarding location (internal/external) and type (green/blue) of water used (Fulton, Cooley, and Gleick 2014). Whereas this earlier analysis showed the policy relevance of California's water footprint by comparing analytical scales, here we present a temporal comparison of California's water footprint between 1992 and 2012. A time series is useful to identify trends that a snapshot analysis cannot, thereby providing additional information for policy consideration and goal setting. We discuss these trends as grounds for such policy consideration and suggest further lines of research to support such an effort.

We build on inter-scalar and inter-temporal water studies in two main bodies of literature: water footprint and coupled human-water systems. Water footprint studies have mostly used nation states as the unit of analysis, with trade flows between nations conceived of as *virtual water* transfers (Konar et al. 2011; Hoekstra and Mekonnen 2012). Some authors have looked at inter-temporal changes in virtual water trade between nations (D'Odorico et al. 2012; Dalin et al. 2012; Duarte, Pinilla, and Serrano 2014). Others have studied aspects of water footprints and virtual water at the state/provincial scale (Mubako and Lant 2013; Zhang and Anadon 2014) and river basin scales (Vanham and Bidoglio 2014; Zhao et al. 2010), however research into temporal dynamics at this scale have not been adequately covered. Our study contributes to this gap in the water footprint literature.

Research into the coupled nature of human-water systems has also wrestled with scalar issues (Moss and Newig 2010), both in terms of synthesizing common traits across globally dispersed case studies (Hubbard and Hornberger 2006; Srinivasan et al. 2012) as well as recognizing and incorporating global drivers into their analysis (Alcamo et al. 2008; Ruddell and Adams 2014). While this literature seeks to find commonality, there is also an explicit recognition of the need to ground findings in real cases with real governance options (Srinivasan et al. 2012; Sivapalan, Savenije, and Blöschl 2012). Thus an important contribution of our work is in identifying both the global dimensions of California's WF and possible touch-points within an existing sustainability policy framework.

California provides an excellent case to study an evolving water footprint with respect to social and environmental drivers. Conventional indicators of overall water use in California have remained stable for nearly three decades, despite population and economic growth. Over this time period California's economy has also significantly opened up to global trade, the water resource implications of which we investigate using a water footprint approach. As this opening continues through today, we see grounds for policy consideration in a state often recognized for its forward thinking and early movement on environmental issues.

Methodology

The water footprint (WF) of a product is an estimate of consumptive freshwater use throughout its production chain (Hoekstra et al. 2011). Consumptive use refers to the portion of withdrawn water that is made unavailable for further use within the same basin, such as through evaporation, transpiration, loss to a saline sink, or contamination (Gleick 2003). WF methods differentiate between green and blue water, where green water is precipitation used in situ and blue water is applied surface and groundwater. Grey water, as a measure of contamination, is not included in this assessment.

For California's WF, we consider a basket of goods including agricultural, industrial, and energy products consumed in the state, as well as direct consumptive use of non-industrial municipal water. The basic operation for a calculation of California's WF is to multiply the per-unit WF (factor) of products by the number of units consumed in California. Because comprehensive consumption data for these goods and their origins is not available to permit a bottom-up WF approach, we calculate consumption from the top-down as a function of production minus exports plus imports. Both domestic and international trading partners are considered, however we could not differentiate individual states or countries due to the coarseness of our trade data. We assumed that traded goods were produced in the state or country of export rather than imported and then re-exported. Thus, California's WF for a given year can be described as

$$WF_{total} = \sum(P_i \times WF_i) - \sum_i(X_i \times WF_i) + \sum_i \sum_j(I_{i,j} \times WF_{i,j}) \text{ (in m}^3\text{)},$$

where *WF* is the sum of green and blue WF factors in m^3 per unit of a particular good *i* produced in a particular location *j*, and *P*, *X*, and *I* represent yearly statistics for Californian production, export and import, respectively.

Production and trade statistics were gathered from a variety of sources at the local, state and federal levels. These statistics were multiplied by green and blue WF factors for individual products or product groups, which were also derived from multiple sources in as bottom-up fashion as was practical. Figure 16 depicts our accounting framework, where purple boxes are data sources, red boxes are intermediate WF calculation steps, and orange boxes are final WF calculations relevant to our study results. A comprehensive description of these data sources and how they were processed can be found in the Supplementary Information (Appendix B).

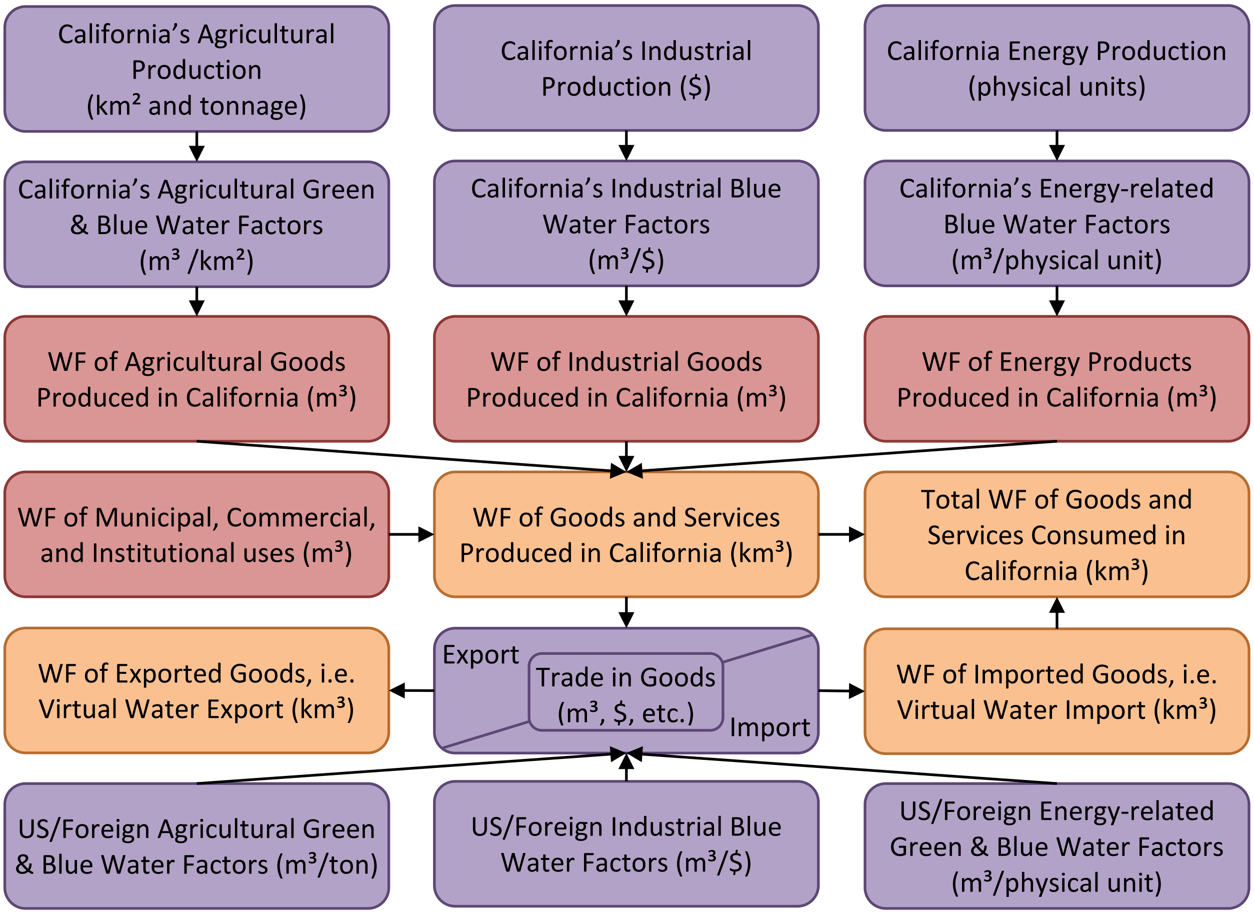

Figure 106: Data and accounting framework for calculating California's WF. Purple boxes are data sources, red boxes are intermediate WF calculation steps, and orange boxes are final WF calculations. Arrows represent process steps. See Supplementary Information (Appendix B) for more details.

We calculated the total WF of goods and services consumed in California, including imports and exports, at 5-year intervals between 1992 and 2012. While our study methodology affords insight both along this longitudinal dimension as well as from its wide latitude of product types, we note at least three shortfalls. First, we do not fully capture full lifecycle water uses for many products consumed in California, which may have important impacts elsewhere. For example, the WF of industrial products imported from another U.S. state is counted using the U.S. WF factor (m^3/\$), whereas some of the value added for those products may occur in other countries with much higher WF factors. Second, because other time-series WF studies have not been conducted outside of California, WF factors for externally produced products were held constant over the

23-year time period, thus not capturing productivity gains that may have been achieved in those locations. These two shortfalls provide sources of uncertainty for our overall study, which leads us to the third shortfall. Third, our data sources, particularly trade data, did not offer the opportunity to quantitatively assess uncertainty in these historic projections. While there are significant sources of uncertainty in our methodology, we take them into account in drawing conclusions on our results in the discussion section.

Results and Discussion

We first present the overall trend in California's consumption-based WF (CAWF) in relation to population and economic growth for the state. As shown in Figure 17, CAWF has grown from 66 km^3 in 1992 to 106 km^3 in 2010, representing a 3.4% average yearly growth rate. This growth rate is over three times the average growth rate of population during this time period (1.1%), however it is slightly less than average economic growth rate (3.7%). Indeed, CAWF appears to be more tightly correlated with economic growth than with population. Grounds for comparing CAWF to California's gross domestic product (GDP) are that personal consumption consistently makes up largest percentage (about 66%) of the state's GDP (BEA 2014). On a per-dollar of GDP basis, CAWF in 2010 (57 l/$) was roughly the same as in 1992 (55 l/$). There was variation in this rate, however our results indicate only a relative decoupling of California's economic growth and WF trend.

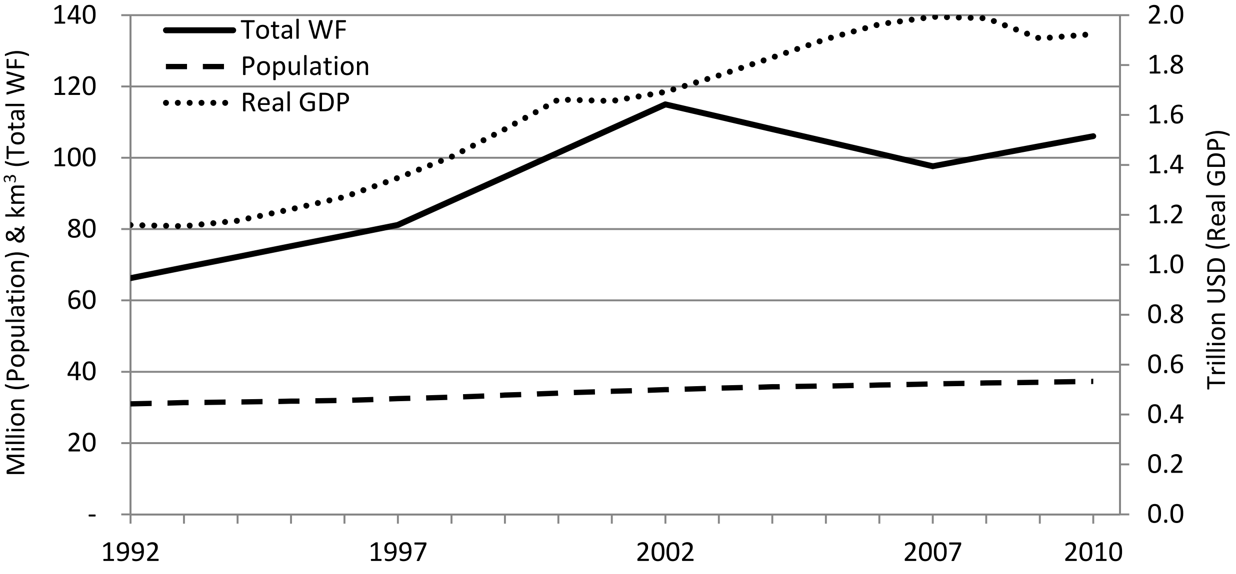

Figure 17: Trends in California's water footprint, population, and gross domestic product.

Because the WF is an indicator of consumption, it is also useful to consider per-capita WF rates. The WF of the average Californian has grown from 5.9 kiloliters per capita daily (kLPCD) in 1992 to about 7.8 kLPCD in 2010. This 33% increase suggests that Californians are consuming more water-intensive products and/or more products than in the past. In general these findings suggest that population growth, as well as with economic growth, can increase demand for water resources unless efficiency gains are made across the supply chain of products that the population and related economic activities consume. In the following sections we parse CAWF trend in three ways: by product types, by location, and by type of water. We also present trends in the WF of exports, or virtual water exports, which do not pertain to CAWF.

WF products

Here we break down CAWF into energy, industrial, and food products, as well as direct consumption of water through residential, commercial, and institutional uses (Figure 18). These are all essential products for sustaining California's population, and there is little fungibility between them. Nevertheless, CAWF is an aggregate of consumer choices and decisions among myriad products, each with differing WF values. The WF of different diets, for example, has received particular attention in recent WF studies (Jalava et al. 2014; Vanham, Mekonnen, and Hoekstra 2013). Our study design did not allow such resolution of product types, but rather indicates WF trends of product groups for possible further examination.

As seen in 18, food products represent a dominant but decreasing share of CAWF. In 1992, food products were 94% or CAWF whereas in 2010 there were 89%. Food products include primary agricultural products such as grains, legumes, fruits, and vegetables, as well as derived products like processed foods, dairy, and meat. Animal-based products have especially high product water footprints, primarily associated with the amount of biomass needed to raise them. Nationally, consumption of meat and dairy products has increased by 20% and 8%, respectively, between 1992 and 2012 (USDA 2015). An earlier study showed that in 2007 about half of California's agricultural WF related to meat and dairy products (Fulton, Cooley, and Gleick 2014). However, in this study it was not possible to definitively parse animal and vegetable-based food products, primarily due to the complex market for grains in California involving energy products. For example, the large WF for food products in 2002 (the bump in the middle of the CAWF trend) is attributable to the import of over 25 million metric tons of cereal grains that year (87% was from Iowa). Cereal grain imports in 1997 and 2007 were below 10 million metric tons. It is unclear from our data which end-use products these grains were used in, however there is evidence around 2002 of grain stockpiling in anticipation of California's transition to ethanol blending in gasoline (USDA 2001).

An important result of this ethanol blending is that energy products represented the fastest-growing share of CAWF, from 3% in 1992 to 7% by 2010. Of the 8.1 km^3 WF for energy products in 2010, ethanol makes up 82% (6.7 km^3), followed by electricity (12%) oil products (6%), and direct use of natural gas (<1%) (Fulton and Cooley 2015). Industrial products make up the smallest share of CAWF, at less than 1%. Some industrial products derived from timber and fiber — for example paper and cotton — were not included this analysis and would likely increase the industrial product portion of CAWF (see Chapagain *et al* 2006, Oel and Hoekstra 2011). Direct consumptive water use for residential, commercial, and institutional uses makes up a small and decreasing portion of CAWF — about 3%. This is because direct water consumption in absolute terms did increase over this time period, and at a rate comparable to population growth — 1.1% per year. While there was variation in this rate over time, these trends nevertheless indicate that direct water consumption is more tightly coupled with California's population than the WF of their consumption of products, which has grown at a much faster rate.

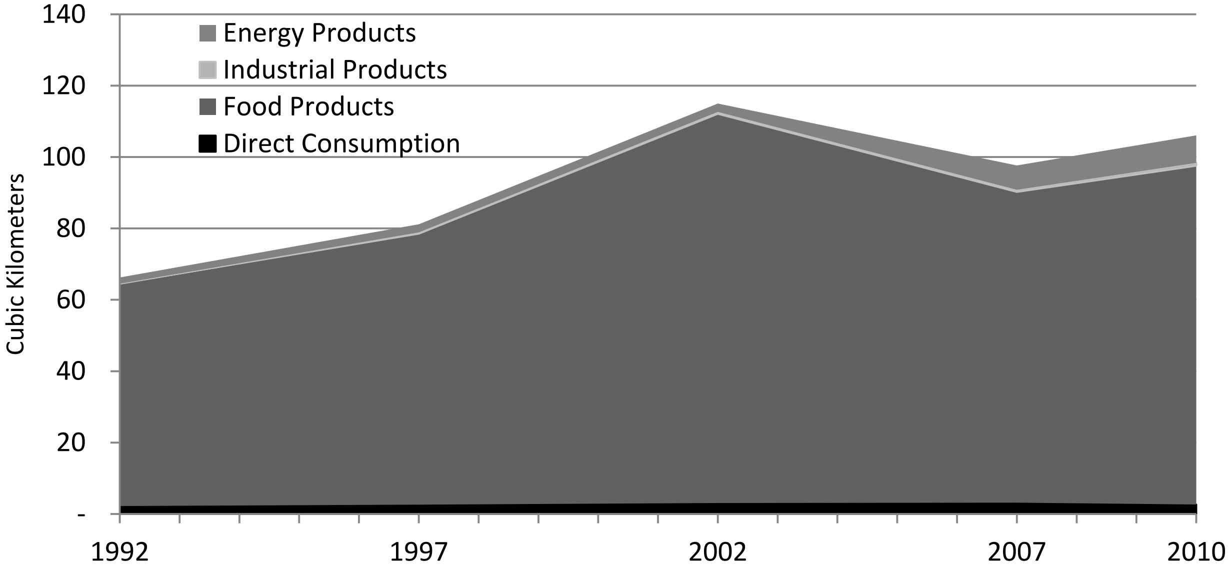

Figure 18: Trend in California's water footprint, by product types, 1992–2010.

WF locations

We next present CAWF in terms of its internal and external components, indicating the location where water use occurred to sustain California's consumption. The internal component refers to the WF of goods and services produced and consumed in California (i.e., with exports removed), while the external component refers to the WF of goods imported from U.S. and international trading partners. While use and management of internal water resources is a familiar concept, identifying the role of external water resources in sustaining California's population and economy provides additional information that may be valuable for policy formulation.

As Figure 19 indicates, all of the growth of CAWF has been external to the state, such that between 1992 and 2010, CAWF switched from being internally dominant to externally dominant. The external proportion of California's WF grew from 40% in 1992 to 80% in 2010. In turn, California's internal WF decreased proportionally, but it also decreased in absolute terms from 40 km^3 to 23 km^3, indicating a decreasing dependence on internal water resources to fulfill instate consumption.

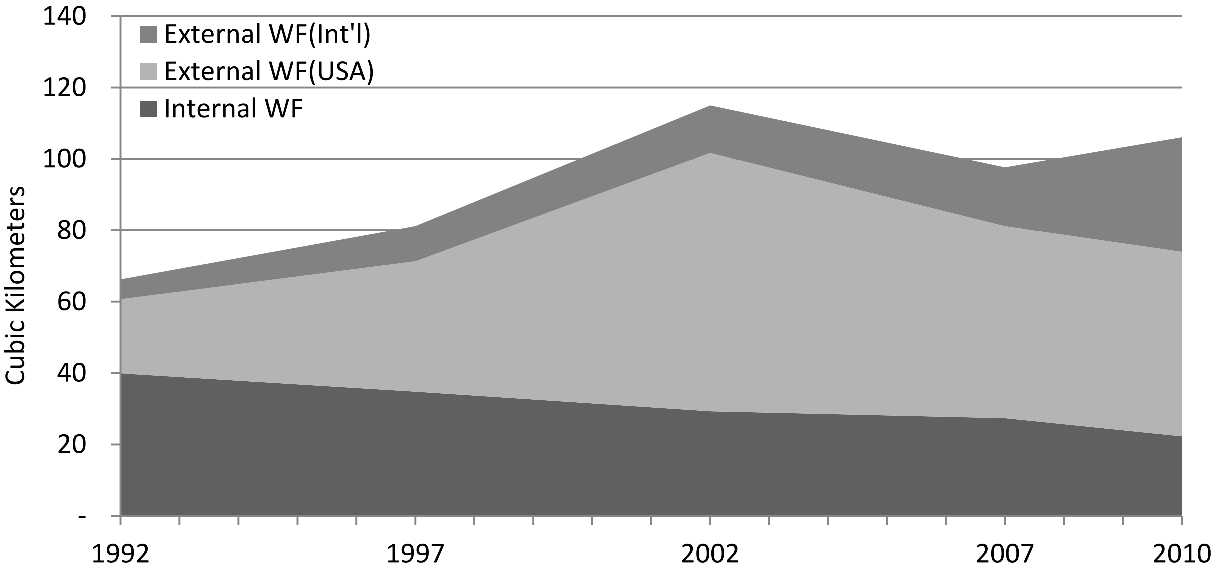

Figure 19: Trend in California's water footprint, by internal and external components, 1992–2010.

Within the external component of CAWF, the proportion relating to international water use increased from 21% in 1992 to 38% in 2010. This increase was especially notable between 2007 and 2010, when imported products increased significantly across all product types except cereal grains, prepared meat, and tobacco. The domestic portion has still dominated the external CAWF over this time period, however it continued to decrease between 2007 and 2010, due to reduced cereal grain imports following the spike in 2002 (see above). Taken together, these results indicate a general externalization of CAWF, that is, consumption in California is becoming more dependent on water use outside its borders, and with a notable rise in the international component of that WF.

WF colors

Next, we consider the types of water use entailed in CAWF, whether blue water or green water. Blue and green water have very different water management implications in the locations where water is used. Green water pertains to patterns and cycles of precipitation, which operate largely outside the domain of water resource management, except perhaps in how efficiently precipitation is stored and used in surface soils. Blue water, on the other hand, sits squarely in the domain of water resources management, where surface and ground waters are stored, transported, and applied to various end uses. Thus we can differentiate between the opportunity cost of green water, relating to alternative land covers for a given location utilizing precipitation and soil moisture differently, and the opportunity cost of blue water, relating to alternative end uses of water in that location versus elsewhere.

As seen in Figure 20, CAWF has become increasingly dependent on green water, from 47% in 1992 to 70% in 2010. Meanwhile, the blue water component of CAWF has remained relatively level, even declining slightly in absolute terms from 35 to 32 km^3. Combined with information from 19, we find that California's internal portion of its blue WF has declined even more, from 26 to 16 km^3. The green, internal portion also declined (from 14 to 7 km^3), indicating that the observed growth of California's green WF in Figure 20 is entirely external to the state. This growth can be attributed primarily to the increased importation of rainfed grains produced in the U.S. Midwest as well as live animals that depend on rainfed agriculture, both domestically and internationally.

The growing contribution of green water to CAWF raises concerns about the risk of relying on precipitation and the potential impacts of climate change. For example, recent droughts in the U.S. Midwest have affected grain supplies in California and provided evidence of California's susceptibility to changes (including climate changes) in regions outside of its borders (EIA 2012). Incidentally, increased dependence on blue water could also expose California to potential impacts of climate change since, ultimately, sources of blue water such as surface water reservoirs and groundwater aquifers, and rivers, canals, and streams are also directly dependent on the overall precipitation and temperature in an area. Nevertheless, management of blue water offers some flexibility to cope with year-to-year variations in precipitation.

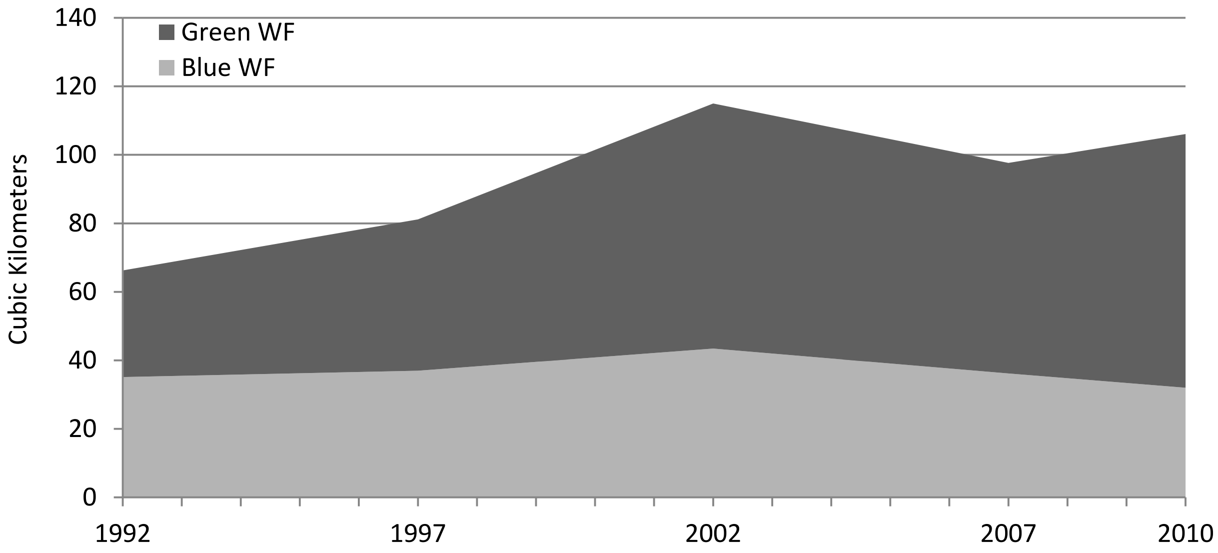

Figure 20: Trend in California's water footprint, by blue and green water components, 1992–2010.

Virtual Water Exports

Last, we present California's virtual water (VW) exports, which are not captured in CAWF since they pertain to consumption outside the state. Nevertheless, VW exports do relate in important ways to CAWF, for example, in deciding on incentives for products derived from California's water to fulfill instate consumption versus to be sold to external markets. For California, we did not differentiate between U.S. and international destinations, and VW exports pertain almost entirely to agricultural products, so we only differentiate here between green and blue components of California's VW exports. As shown in Figure 21, California's total VW exports have more than doubled between 1992 and 2010 from 15 to 32 km^3, respectively. Blue water accounts for about 70% of total VW exports consistently throughout this time span, indicating the extent to which exported crops are irrigated with the state's surface and groundwater. Rice and almonds, both relatively water-intensive products, consistently rank highest in international exports, by weight (AIC 2012). Given that California's rainy season and growing season do not generally overlap by much, it is not surprising that the state's VW export is composed mostly of managed blue water. Still, taken together with green VW exports, these results show that over recent decades an increasing share of California's total water resources have been used to produce goods that are exported and consumed outside the state's borders.

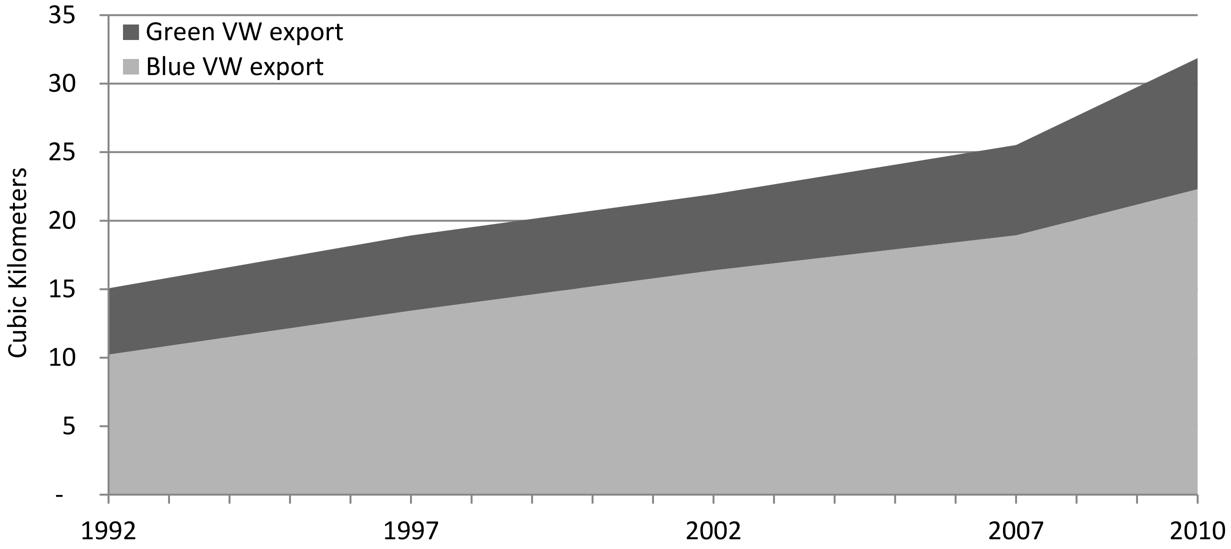

Figure 21: Trend in California's virtual water export, by blue and green water components, 1992–2010. Note that the vertical scale is 1/4th of previous figures.

Conclusions

We posit that a water footprint approach is helpful in identifying how seemingly local actions relate to the global hydro-commons, which is threatened by both social and environmental drivers. For California, we show through its water footprint trends that consumption of everyday products in the state accounts for an increasing share of water use outside its borders, while decreasing its reliance on internal water resources. California's sustenance, in effect, is already deeply integrated with global water resource use and management. This finding leads us to identify concerns that we see as relevant to California water management. We discuss policy considerations and suggest research that we hope will lead to innovative ways for California to deliberately address this situation.

Recent work suggests that, globally, current consumption patterns cannot be sustained given projected climate change effects on scarcity (Orlowsky et al. 2014). The growth of California's external WF, therefore, raises serious concerns about our ability to manage water resource impacts and risks associated with our demand for goods and services.

Given both these concerns and our findings, we see grounds for developing water footprint-related policymaking in California. While coordinated management of internal water resources is a familiar and core function of government in California and elsewhere, the concept of managing external water resources sits awkwardly at the heart of this proposition. Nevertheless, we do find precedent for accounting for indirect environmental impacts in California's Global Warming Solutions Act of 2006, which requires carbon emissions associated with imported electricity to be counted toward the state's greenhouse gas inventory. Here, we explore three levers of potential water footprint-related policymaking.

First, trade agreements with bilateral and regional partners are an important force in shaping where and how production takes place. We find precedent for embedding water resource concerns within such agreements, for example, in California's recently established trade agreement with China. This agreement included some environmental and labor provisions, however more coordinated water management goals and baseline standards could also be established. California water managers and practitioners could join trade missions to advise policymakers on overall WF efficiencies that could be made through trade agreements. Such efficiencies relate not just to imports from China but to exports from California (or the U.S.).

Second, California policymakers can engage with corporations whose supply chains involve water-intensive production overseas. Many companies have already moved forward on corporate water stewardship with the help of nongovernmental actors (Schulte and Morrison 2011). These efforts have yielded results in corporate practice, but there is a role for public agency support as well. Furthermore, we see the need to expand these efforts from highly branded market actors like beverage and clothing companies to more primary-commodity actors in agriculture and mining. For example, many large California-based agricultural producers have contract-based operations in Mexico and overseas where water problems exist and could be managed through better corporate practice (for example see Zlolniski 2011).

Third, California water managers could provide knowledge, technology, and financial support to governance efforts in other locations to reduce water impacts across agricultural, industrial, and other sectors. This could include not just contributing to a common knowledge base — for example through conferences— but collaborating directly and substantively with water managers in other locations, from grain-growing regions of the U.S. Midwest to coffee production in Brazil. To the extent that knowledge, technology and financial support already exist (primarily at the international level), it is based in the *moral* notion of development aid. Acknowledging the water footprint, that is, the indirect, yet real connections between consumption and global water problems, provides a *material* basis for such efforts. Additionally, more direct partnerships between water managers in producing and consuming regions helps fill a middle ground between large-scale development projects and grassroots people-to-people initiatives.

These suggestions, if taken up by policymakers, would ultimately need to be situated in the larger policy landscape of environmental management in California. For water specifically, the turn in recent years towards regional self-sufficiency, as a stated goal of the Governor's Water Action Plan, seems to pose a challenge to the scale of our suggested interventions. Nevertheless, frameworks to support thinking across scales in water management are developing (Savenije, Hoekstra, and van der Zaag 2014). Beyond water, the state's climate goals in particular have been found at times to work at cross purpose with water efficiency goals, by pushing greenhouse gas mitigation with little consideration for impacts to water systems (Fulton, Cooley, and Gleick 2014). Other resource management goals — from land management to forest management — as well as social goals, may pose additional coordination challenges. Thinking in terms of systems integration (Liu et al. 2015), and adaptive management (Pahl-Wostl 2006) will be key, where complexity and changing information can be incorporated in a social learning process. California has a relatively long history of attempted adaptive water governance (Kallis, Kiparsky, and Norgaard 2009), and new sustainability efforts continue to incorporate adaptive management principles (Shilling et al. 2014).

Although this article is indicative of the importance of water footprint assessment for California, a much deeper understanding is needed to begin supporting sustainability planning for the state. We identify three areas of needed research.

First, although we parse CAWF trend in three ways (by product types, location, and type of water), our results are volumetric and therefore provide limited meaning in terms of their relative value or where interventions might be targeted. The benefit or burden of consumptively using one cubic meter of water may differ wildly from location to location. Weighting water footprint values by water stress indices or other metrics of relative value is one way this has been approached in a limited number of studies (see Ridoutt and Pfister 2010). These top-down studies should also be enriched (or interrogated) through grounded research that combines both environmental and social sciences. Research in the vein of political ecology is particularly well suited to identify how social relations become reworked under changing resource uses, particularly around and along global commodity chains (Walsh 2008). Better characterization of water quality impacts, the so-called "grey" water footprint, is also needed and has been largely overlooked in top-down approaches to water footprint assessment.

Second, better coordination with novel sustainability research efforts in other resource management domains is needed. In the energy field, consumption-based accounting and sophisticated modeling of embedded energy flows through the economy have advanced. However, water remains on the sideline of such efforts. Novel ways of approaching water management have excelled at the local to regional levels, for example California's Integrated Regional Water Management program has been instrumental in collective decision making across multiple management domains. However, acknowledging the interlinkages of local and global forces within regional water management has been slow.

Lastly, water footprint policy development for California must happen collaboratively with the public. Consumers provide the driving force behind the phenomenon that water footprint assessment ultimately seeks to reveal. Educating consumers about the water impacts of their decisions is an important first step, but their consumption behavior inevitably takes place within an economic structure defined by limited possibilities. These possibilities are of course somewhat limited by physical constraints (e.g. food cannot be produced without water), but they are also limited by politics to which they play the part of citizen. Thus participation from the public, as consumers *and* citizens, is necessary to fundamentally alter the structure of possibilities and reflect individual aspirations to live more sustainably with water.

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References

AIC, UC Agricultural Issues Center. 2012. “2012 California Export Data: Table 6.” *Table 6*. http://aic.ucdavis.edu/pub/exports.html.

Alcamo, JM, M Flörke, and M Märker. 2007. “Future Long-Term Changes in Global Water Resources Driven by Socio-Economic and Climatic Changes.” *Hydrological Sciences Journal* 52 (2). IAHS Press: 247–75.

Alcamo, JM, CJ Vörösmarty, RJ Naiman, DP Lettenmaier, and C Pahl-Wostl. 2008. “A Grand Challenge for Freshwater Research: Understanding the Global Water System.” *Environmental Research Letters* 3: 010202. doi:10.1088/1748-9326/3/1/010202.

BEA, US Department of Commerce - Bureau of Economic Analysis. 2014. “Personal Consumption Expenditures by State, 1997-2012 (Prototype Estimates).” http://www.bea.gov/newsreleases/regional/pce/pce_newsrelease.htm.

Chapagain, AK, AY Hoekstra, HHG Savenije, and R Gautam. 2006. “The Water Footprint of Cotton Consumption: An Assessment of the Impact of Worldwide Consumption of Cotton Products on the Water Resources in the Cotton Producing Countries.” *Ecological Economics* 60 (1). Elsevier: 186–203. doi:10.1016/j.eco.

D’Odorico, P, J Carr, F Laio, and L Ridolfi. 2012. “Spatial Organization and Drivers of the Virtual Water Trade: A Community-Structure Analysis.” *Environmental Research Letters* 7: 034007. doi:10.1088/1748-9326/7/3/034007.

Dalin, C, M Konar, N Hanasaki, A Rinaldo, and I Rodriguez-Iturbe. 2012. “Evolution of the Global Virtual Water Trade Network.” *Proceedings of the National Academy of Sciences* 109 (16): 5989–94. doi:10.1073/pnas.1203176109.

Duarte, R, V Pinilla, and A Serrano. 2014. “The Effect of Globalisation on Water Consumption: A Case Study of the Spanish Virtual Water Trade, 1849-1935.” *Ecological Economics* 100. Elsevier B.V.: 96–105. doi:10.1016/j.ecolecon.2014.01.020.

EIA, Energy Information Administration. 2012. “Drought Has Significant Effect on Corn Crop Condition , Projected Ethanol Production.” *Today in Energy*, August 30.

Fulton, J, and H Cooley. 2015. “The Water Footprint of California’s Energy System, 1990–2012.” *Environmental Science & Technology*, 150304134544008. doi:10.1021/es505034x.

Fulton, J, H Cooley, and PH Gleick. 2014. “Water Footprint Outcomes and Policy Relevance Change with Scale Considered: Evidence from California.” *Water Resources Management* 28 (11): 3637–49. doi:10.1007/s11269-014-0692-1.

Gleick, PH. 2003. “Water Use.” *Annual Review of Environment and Resources* 28 (1): 275–314.

Hoekstra, AY, and MM Mekonnen. 2012. “The Water Footprint of Humanity.” *Proceedings of the National Academy of Sciences of the United States of America* 109 (9): 3232–37. doi:10.1073/pnas.1109936109.

Hoekstra, AY, and AK Chapagain. 2008. *Globalization of Water: Sharing the Planet’s Freshwater Resources*. Malden, MA: Wiley-Blackwell.

Hubbard, S, and G Hornberger. 2006. “Introduction to Special Section on Hydrologic Synthesis.” *Water Resources Research* 42 (December 2005): 2–5. doi:10.1029/2005WR004815.

Jalava, M, M Kummu, M Porkka, S Siebert, and O Varis. 2014. “Diet Change—a Solution to Reduce Water Use?” *Environmental Research Letters* 9 (7). IOP Publishing: 074016. doi:10.1088/1748-9326/9/7/074016.

Kallis, G, M Kiparsky, and R Norgaard. 2009. “Collaborative Governance and Adaptive Management: Lessons from California’s CALFED Water Program.” *Environmental Science & Policy* 12 (6): 631–43. doi:10.1016/j.envsci.2009.07.002.

Konar, M., C. Dalin, S. Suweis, N. Hanasaki, A. Rinaldo, and I. Rodriguez-Iturbe. 2011. “Water for Food: The Global Virtual Water Trade Network.” *Water Resources Research* 47 (5): 1–17. doi:10.1029/2010WR010307.

Liu, J., and W. Yang. 2012. “Water Sustainability for China and Beyond.” *Science* 337: 649–50. doi:10.1126/science.1219471.

Liu, J, H Mooney, V Hull, SJ Davis, J Gaskell, T Hertel, J Lubchenco, et al. 2015. “Systems Integration for Global Sustainability.” *Science* 347 (6225). doi:10.1126/science.1258832.

Moss, T, and J Newig. 2010. “Multilevel Water Governance and Problems of Scale: Setting the Stage for a Broader Debate.” *Environmental Management* 46 (July): 1–6. doi:10.1007/s00267-010-9531-1.

Mubako, ST, and CL Lant. 2013. “Agricultural Virtual Water Trade and Water Footprint of U.S. States.” *Annals of the Association of American Geographers* 103 (March 2015): 385–96. doi:10.1080/00045608.2013.756267.

Oel, PR, and AY Hoekstra. 2011. “Towards Quantification of the Water Footprint of Paper: A First Estimate of Its Consumptive Component.” *Water Resources Management* 26 (3): 733–49. doi:10.1007/s11269-011-9942-7.

Orlowsky, B, AY Hoekstra, L Gudmundsson, and SI Seneviratne. 2014. “Today's Virtual Water Consumption and Trade under Future Water Scarcity.” *Environmental Research Letters* 9 (7). IOP Publishing: 074007. doi:10.1088/1748-9326/9/7/074007.

Pahl-Wostl, C. 2006. “Transitions towards Adaptive Management of Water Facing Climate and Global Change.” *Water Resources Management* 21 (1): 49–62. doi:10.1007/s11269-006-9040-4.

Ridoutt, BG, and S Pfister. 2010. “A Revised Approach to Water Footprinting to Make Transparent the Impacts of Consumption and Production on Global Freshwater Scarcity.” *Global Environmental Change* 20 (1): 113–20. doi:10.1016/j.gloenvcha.2009.08.003.

Ruddell, BL, and EA Adams. 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: 1–16. doi:10.1002/2013WR014531.Received.

Savenije, HHG, AY Hoekstra, and P van der Zaag. 2014. “Evolving Water Science in the Anthropocene.” *Hydrology and Earth System Sciences* 18 (1): 319–32. doi:10.5194/hess-18-319-2014.

Schulte, P, and J Morrison. 2011. “Global Water Trends, Business Risk, and the Future of Stewardship Response.” Pacific Institute.

Seekell, DA, P D’Odorico, and ML Pace. 2011. “Virtual Water Transfers Unlikely to Redress Inequality in Global Water Use.” *Environmental Research Letters* 6 (2): 024017. doi:10.1088/1748-9326/6/2/024017.

Shilling, F, A Khan, R Juricich, V Fong, and D Hodge. 2014. “The California Water Sustainability Indicators Framework.” In *California Water Plan Update 2013*, 1–90. Sacramento, CA: California Department of Water Resources.

Sivapalan, M, HHG Savenije, and G Blöschl. 2012. “Socio-Hydrology: A New Science of People and Water.” *Hydrological Processes* 26 (November 2011): 1270–76. doi:10.1002/hyp.8426.

Srinivasan, V, EF Lambin, SM Gorelick, BH Thompson, and S Rozelle. 2012. “The Nature and Causes of the Global Water Crisis: Syndromes from a Meta-Analysis of Coupled Human-Water Studies.” *Water Resources Research* 48 (10): 1–16. doi:10.1029/2011WR011087.

USDA, United States Department of Agriculture: Agricultural Marketing Service. 2015. “Economic Research Service - Food Availability (Per Capita) Data System.” Accessed May 1. http://www.ers.usda.gov/data-products/food-availability-(per-capita)-data-system/.aspx#26705.

———. 2001. “Grain Transportation Report.” *GRAIN TRANSPORTATION REPORT*, October 30.

Vanham, D, and G Bidoglio. 2014. “The Water Footprint of Agricultural Products in European River Basins.” *Environmental Research Letters* 9. IOP Publishing: 064007. doi:10.1088/1748-9326/9/6/064007.

Vanham, D, MM Mekonnen, and AY Hoekstra. 2013. “The Water Footprint of the EU for Different Diets.” *Ecological Indicators* 32 (September). Elsevier Ltd: 1–8. doi:10.1016/j.ecolind.2013.02.020.

Walsh, C. 2008. “Building the Borderlands a Transnational History of Irrigated Cotton along the Mexico-Texas Border.” College Station : Texas A & M University Press,.

Zhang, C, and LD Anadon. 2014. “A Multi-Regional Input–output Analysis of Domestic Virtual Water Trade and Provincial Water Footprint in China.” *Ecological Economics* 100 (April). Elsevier B.V.: 159–72. doi:10.1016/j.ecolecon.2014.02.006.

Zhao, X, H Yang, Z Yang, B Chen, and Y Qin. 2010. “Applying the Input-Output Method to Account for Water Footprint and Virtual Water Trade in the Haihe River Basin in China.” *Environmental Science & Technology* 44 (23): 9150–56. doi:10.1021/es100886r.

Zlolniski, C. 2011. “Water Flowing North of the Border: Export Agriculture and Water Politics in a Rural Community in Baja California.” *Cultural Anthropology* 26 (4): 565–88. doi:10.1111/j.1548-1360.2011.01112.x.

Chapter 5: Conclusion

The preceding three chapters tell a story about California's evolving relationship with water using the water footprint concept as an alternative reading of water that expands on conventional readings. Chapter 2 showed that scaling water footprint assessment to the state level both illuminates California's unique arrangement with respect to internal and external water resources and provides a basis for policy consideration at a relevant decision-making level. Chapter 3 focused on the water footprint of California's energy system in order to show how environmental policymaking, particularly climate mitigation policies in the energy sector, can result in maladaptation with respect to water systems and that water footprint assessment provides a useful tool for avoiding redistribution of water impacts. Chapter 4 presented a time-series of California's overall water footprint, indicating an externalization of water footprint demands in recent decades and a decreasing of dependence on internal water resources for instate consumption of everyday goods.

In this concluding chapter I wish to critically reflect on water footprint assessment as an alternative reading of water and its usefulness for improving global water sustainability going forward. With "water sustainability," I am concerned not only with the stability and thresholds of water systems but in the equity dimensions to how social systems organize and interact via water systems. Important questions remain. I first reflect on what water footprint information adds to a conventional reading of water, and where synergies and challenges lie. Second, I consider the water management context, asking how water footprint information could be worked into sustainability policy and governance approaches in general. Finally, I consider how the method could be improved through further research to guide water management towards realizing a more sustainable relationship between society and water.

Water footprints: what's new?

Returning to the conventional readings of water discussed in Chapter 1, as exemplified by USGS water withdrawal statistics, this section asks what is new and different about water footprint assessment as an expanded reading of water, and how it helps us answer questions about water sustainability.

Methodologically, water footprint assessment is in many ways similar to conventional understandings of how water is used in human activities. For example, calculating the water footprint of agricultural products is based on textbook understandings of plant physiology and crop water demands, which are firmly rooted in agricultural sciences going back centuries. Other concepts are borrowed from related disciplines, for example differentiating green and blue water is a construct from hydrology (Falkenmark and Rockström 2006), while the assimilation approach to calculating grey water footprints derives from environmental toxicology. I return below to epistemological questions of what these methods tell us about water sustainability.

While these methodological similarities offer synergistic opportunities for research, there are important differences in the ways that water use figures are put together to form understanding about social uses of water. First and foremost, water footprint assessment views society's demand for water as ultimately driven by demand for products. Second, while conventional readings of water take a *sectoral* view on water demand, water footprint assessment takes an *integrated* approach based on the view that demand for products often places water use demands on multiple sectors. Third, water footprint assessment acknowledges that, because of global trade, this demand for water *via* demand for products occurs not just across sectors but across countries and regions. These unique[2] aspects may be summed as a consumption-based reading of water use.

As this new reading attributes water use to consumer products, it necessarily raises questions about changing attribution of responsibility. If consumer demand is ultimately the driver of production, then should consumers ultimately bear the responsibility for water use in production? Here the water footprint concept quickly enters the realm of water governance, which is another dimension to which our expanded reading of water poses new and unique challenges. Water governance is conventionally approached within jurisdictional boundaries of countries, states, or regions, and with increasing jurisdiction placed at the "natural" scale of river basins (Conca 2006). Water footprint assessment, by its nature, cuts across these scales and is thus seemingly at odds with existing geometries of water governance.

Water footprint governance

Conventional approaches to governing society's uses of water are based on the jurisdictional responsibility of governing bodies. For example, water withdrawals in California are governed by the California Water Code and overseen by the State Water Resources Control Board. Specific water use projects must be permitted by state agencies, such as the California Environmental Protection Agency, and may be directly managed as well by state agencies, for example the California Department of Water Resources. The overall water governance landscape in California extends beyond and within the state, to federal, county, city, and district levels. Hydrologic Region units and Integrated Regional Water Management units also form a basis for collective decision making on water in California.

Sustainability as a management goal has been defined variously within these governing bodies, but typically refers to balancing social uses of water with ecological uses, and avoiding degradation of these uses over time. However it is defined, sustainability rarely considers impacts to water resource systems outside the jurisdiction of relevant governing bodies. Information provided by water footprint assessment, with its inter-sectoral and interregional dimensions, may therefore have limited relevance to conventional water governance activities.

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[2] This uniqueness pertains only to thinking about water use. There is a long history in economic sciences to approaching the issue of inter-industry demands using input-output analysis.

What, then, might water footprint governance look like and how might it relate to conventional water governance? How can sustainability be thought of in this context?

I first wish to reiterate my view of water footprint assessment, and the possibility of water footprint governance, not as a challenge to conventional water governance but as a complement to it. Conventional water governance has made headway towards sustainability goals in recent decades around improving efficiency and decreasing impacts to water systems. This is not to say that conventional water governance doesn't still face challenges, nor can conventional water governance be said to even be *conventional* in facing these challenges; innovations occur constantly in the field of water resources management. This is to say that water footprint assessment provides an expanded reading of social uses of water, and that water footprint governance is vital to any definition of sustainability that considers the global scale.

Governance of socio-ecological systems (Ostrom 2009) includes not just the role of government but the role of informal rules and norms of actors in regulating interactions with common-pool resources. Water can be viewed as a common-pool resource with both a local dimension, as made clear by the scale at which water is accessed and experienced, as well as a global dimension, as evidenced by the scale at which water is shared virtually and through water footprints (Gupta, Pahl-Wostl, and Zondervan 2013). Thus, any analytical framework for water footprint governance would necessarily include actors along the supply chain of products where water use occurs. For the case of California, this could include consumers in California, vendors that market and sell products to consumers, corporations that produce those products, nongovernmental organizations, water agencies and regulators in producing locations, as well as actual water users in those locations, whether farmers, manufacturers, etc.

Evidence of water footprint governance across these actors has already emerged in several forms. First, the arena of corporate water stewardship has expanded in recent years through efforts such as the CEO Water Mandate, which promotes disclosure and management of water impacts in corporations' global supply chains (Schulte et al. 2014). Second, nongovernmental actors have played an important role in verification and certification of water stewardship practices globally (Hoekstra 2014). Third, a market for "water restoration credits" has been established for businesses to purchase certificates that intend to offset their water footprints by arranging water rights transfers in depleted river basins (Sattler and Matzdorf 2013). Finally, a wide range of recent marketing campaigns have sought to tilt consumer decision making toward more water-benign products (Vos and Boelens 2014).

As water footprint governance has emerged among these various actors in global supply chains, the role of government has so far remained sidelined. Various national or international water footprint governance schemes — taxes, pricing protocols, or withdrawal quotas, for example — have been proposed, though so far received little traction (Hoekstra 2010). Nevertheless, the findings of this dissertation indicate that governments may yet play a role in water footprint governance. California's population and economy depend increasingly on external water resources, an observation that will be difficult for the state to ignore. On what grounds, then, can policy makers in California approach managing the state's water footprint if 1) much of the associated water use occurs outside its jurisdictional borders, 2) governing water footprints means regulating (free) trade, and 3) governing water footprints means influencing consumer choices? In response to these concerns I highlight three observations from existing policies.

First, regarding managing resource burdens outside state jurisdiction, I highlight the mechanisms of California's Renewable Portfolio Standard (RPS). Under the RPS, greenhouse gas emissions associated with imported electricity must be accounted for on the state's greenhouse gas inventory. This law was created pursuant to California's climate change mitigation goals and implemented through its landmark Global Warming Solutions Act of 2006. If policies can target out-of-state emissions associated with California's energy consumption based on concern for global climate change, it stands to reason that out-of-state water use impacts associated with California's consumption of energy and other products can also be addressed through policy. Global water challenges are no less a concern than global climate challenges — in fact many of these challenges are the same — so addressing the impacts of climate change through water footprint governance complements those mitigation efforts.

Second, regarding implications for free trade, environmental and social concerns often figure in bilateral and multilateral trade agreements and economic integration policies at the federal level. For example, the U.S. Environmental Protection Agency's (EPA) Office of Water participates in the U.S. Department of State's Trade and Environment Policy Advisory Committee. EPA also recently collaborated with the Chinese Ministry of Environmental Protection to form a U.S.-China Clean Water Action Plan. For a decade China has been the number one source of U.S. imports (by dollar value), many of which are water intensive goods such as food, fuels, metals, electronics, and apparel. With this economic integration, initiatives such as the above-mentioned are increasingly recognizing the need to understand and act on the interlinking environmental impacts as well. China is also California's largest trading partner, and the recently inaugurated California-China Office of Trade and Investment can use federal environment-trade initiatives as a template for governing water resources across those trade flows.

Third, regarding government influencing consumer choices, I suggest two examples. First is the U.S. Department of Agriculture's nutritional guideline, or "food pyramid," which recommends daily food consumption ratios to maintain a healthy diet. Different diets can have drastically different water footprints for consumers and collectively as a society. A recent study suggested that the overall water footprint of the European Union could be reduced by 23% if only Europeans ate according to their recommended nutritional guidelines (Vanham, Mekonnen, and Hoekstra 2013). Establishing what constitutes a "healthy diet" can also be complemented by what constitutes a "sustainable diet" (Alvarez 2015). The second example specifically regards California government intervention in the water sector in response to the current statewide drought. Through executive order of mandatory rationing, the governor has demonstrated a willingness not only to force reductions on water consumption, punishable by fines, but a willingness to impose those reductions *differentially*, such that larger water users face higher reductions (Boxall, Stevens, and Morin 2015). It stands to reason from this example that if government can intervene in citizens' consumption habits in response to a statewide drought, it could also intervene, albeit in more limited way, in response to issues of global water scarcity tied to citizens' water footprints.

Though government has thus far remained on the sideline of water footprint governance, these observations can provide a basis for political entities such as California playing a more active role. California's Department of Water Resources has already shown interest in using water footprint assessment as a sustainability indicator (Fulton et al. 2013). I expect water footprint assessment to be developed more formally in coming years as a tool both at the state level and at the regional level within the state water planning apparatus. Still, for the method to gain further policy relevance, its uncertainties and limitations must be acknowledged and addressed through further research.

Limitations and future research

In this section I discuss the state of water footprint science and how it can be improved. In particular, I reflect on my concerns posed in Chapter 1 on global water challenges related to globalization, human development, and environmental change. I have applied water footprint assessment methods using the case of California to study these concerns from a consumption-based perspective; what I have referred to as an expanded reading of water. But does this reading of water, given this method, show what I wish it to show? Here, the simple answer is no. How, then, can water footprint assessment better serve an expanded reading of water and a goal of developing a more sustainable social relationship with water? I raise three points related to physical science aspects and three points related to interdisciplinary aspects of water footprint assessment.

First, as mentioned in Chapters 2, 3, and 4, water footprint assessment is severely limited by its volumetric approach to characterizing the impacts of product consumption. Water use impacts must be characterized by more than gallons or cubic meters. Differentiating water footprints by blue and green water is a first step toward understanding the relative impacts of water uses to water systems where production occurs. Blue water could be further disaggregated by its source, whether groundwater or surface water from free-flowing rivers or irrigation projects. These volumetric accounts can be further contextualized with spatially explicit indicators on the relative scarcity of water in producing regions, such as the Water Stress Index (Ridoutt and Pfister 2010). Other indicators attempt to characterize the social aspects of water use, including access to water resources or human development indices (Ohlsson 2000). These top-down approaches can be further contextualized using bottom-up methods, as described below.

Second, while my three studies focused on blue and green water footprints, the so-called "grey water footprint" pertaining to water quality impacts is arguably just as important to understanding how water systems are impacted by global production systems. Like blue and green consumptive water uses, water contamination also represents a consumptive use of water when discharge-receiving water sources can no longer be used for social or ecological purposes. Methods to characterize grey water footprints have been proposed (Franke, Boyacioglu, and Hoekstra 2013), but they lack resolution due to data limitations at the global scale. Additionally, globally consistent data sets on water pollution focus only on major contaminants such as nitrogen and phosphorous, missing a growing range of pollutants such as toxins and endocrine disruptors that impair social and ecological uses of water systems.

The third issue related to the physical science aspects of water footprint assessment is uncertainty particularly around important variables such as changes in water use efficiency over time, and production and trade statistics. Because the method draws on such diverse data sources, from plant physiology databases to production and trade statistics, tracking how uncertainty propagates through the method and affects final results is difficult. Additionally, many data providers do not offer any sense of uncertainty within their datasets, forcing users to hazard guesses as to how reliable the statistics are. Nevertheless, policy makers should be presented with ranges of uncertainty in order to make informed decisions. Policy makers also may also require projections in how water footprints may interact with climate change and other global variables. Water footprint science has the potential to contribute to integrated modeling and projection (e.g. Purkey et al. 2006), though uncertainty characterization stands as a major barrier to this integration.

Although my work on California's water footprint is beset by all three of these methodological limitations, it has yielded defensible findings and usable insights when compared over geographic scales (Chapter 2) and temporally (Chapters 3 and 4). These findings indicate that California's relationship with global water is unique among U.S. states, and that this relationship has changed in recent decades. These aspects raise concerns for long-term sustainability in California's relationship with water, thus compelling further refinement of this research. Still, even if the three limitations discussed on physical science grounds were to be remedied, water footprint methodology would fall short of my desired usefulness as a sustainability science. The sustainability questions I wish to ask — particularly questions related to equity — using water footprint methodology as an expanded reading of water require a more interdisciplinary approach. I suggest three points for further interdisciplinary research using water footprint methods.

First, with regards to characterizing the relative value of water in producing locations, water's value can be heavily contested and can be understood through a number of disciplinary lenses. Considering social scientists' interpretations of water's value, an economist will likely have a very different answer from an anthropologist. Either interpretation can be worked into a virtual water framework and inform physical science-based interpretations of scarcity and water quality. Such an interdisciplinary approach is laborious and is thus better taken on for, perhaps, individual commodity chain studies rather than for entire economies. Already, the virtual water concept has been used by other disciplines, including economics (Duarte, Pinilla, and Serrano 2014) and anthropology (Zlolniski 2011). Water footprint science, in turn, must be open to other disciplinary perspectives and epistemologies.

Second, by integrating social sciences into understanding water's social value in different regions of the world, the water footprint concept becomes less about water itself and more about social relationships with water as its medium. As such, questions of equity and power come to the fore, providing a crucially understudied dimension to global water sustainability. Here, water footprint science can contribute to the emerging field of *hydrosocial* research (Linton and Budds 2014), which addresses the hydrologic cycle as a social construct that has tended to obscure scientists' understanding of human dimensions to water processes. As such, this nascent body of research proposes the "hydrosocial cycle" and seeks to identify how power and social relations become expressed through and embodied by distributions of water. The conception of virtual water as being an embodied water resource, can thus contribute to hydrosocial research by expanded its conceptual basis to include issues of power and equity.

Finally, interdisciplinary approaches can provide a crucial reflexivity for water footprint science in shaping debates around concepts like *sustainability*. In the introduction to this dissertation, I began by critiquing a conventional reading of water use, as presented by USGS water withdrawal figures. Such readings, I cautioned, can lead to assessments of what becomes defined as sustainable or unsustainable. Unsustainable water use might be conveniently defined as demand exceeding supply while the reverse might serve a definition of sustainable use. Though few thoughtful scientists would defend such a narrow definition of sustainability, the possibility of mediating such complex processes in reductionist terms remains an epistemological tendency in physical sciences. I have proposed water footprint science as an expanded reading of water, however these potential epistemological pitfalls remain. Earlier in this section I identified several ways in which water footprint research can be improved, however other scientific traditions can help researchers further refine methods and working definitions of sustainability. Water footprint researchers must continually and critically assess the role of their science in collective learning processes about sustainability, and how that science becomes enrolled in sustainability policy.

References

Alvarez, C. 2015. "Will the U.S. Miss the Boat of Sustainable Dietary Guidelines?" *Huffington Post*. http://www.huffingtonpost.com/cristina-alvarez/will-the-us-miss-the-boat_b_7062342.html.

Boxall, B, M Stevens, and M Morin. 2015. "State Water Board Issues Revised Drought Regulations for Californians." *Los Angeles Times*.

Conca, K. 2006. *Governing Water : Contentious Transnational Politics and Global Institution Building*. Cambridge Mass.: MIT Press.

Duarte, R, V Pinilla, and A Serrano. 2014. "Looking Backward to Look Forward: Water Use and Economic Growth from a Long-Term Perspective." *Applied Economics* 46 (2): 212–24. doi:10.1080/00036846.2013.844329.

Falkenmark, M, and J Rockström. 2006. "The New Blue and Green Water Paradigm : Breaking New Ground for Water Resources Planning and Management." *Journal of Water Resources Planning and Management* 132 (June): 129–32.

Franke, NA, H Boyacioglu, and AY Hoekstra. 2013. *Grey Water Footprint Accounting: Tier 1 Supporting Guidelines, Value of Water Research Report Series No. 65*. Delft, the Netherlands.

Fulton, J, H Cooley, S Cardenas, and F Shilling. 2013. "Trends and Variation in California's Water Footprint" in *California Water Plan Update 2013.* California Department of Water Resources. Sacramento: CA.

Gupta, J, C Pahl-Wostl, and R Zondervan. 2013. "'Glocal' Water Governance: A Multi-Level Challenge in the Anthropocene." *Current Opinion in Environmental Sustainability* 5 (6). Elsevier B.V.: 573–80. doi:10.1016/j.cosust.2013.09.003.

Hoekstra, AY. 2014. "Water Scarcity Challenges to Business." *Nature Climate Change* 4 (May): 318–20. doi:10.1038/nclimate2214.

Hoekstra, AY. 2010. "The Global Dimension of Water Governance: Why the River Basin Approach Is No Longer Sufficient and Why Cooperative Action at Global Level Is Needed." *Water* 3 (December): 21–46. doi:10.3390/w3010021.

Linton, J, and J Budds. 2014. "The Hydrosocial Cycle: Defining and Mobilizing a Relational-Dialectical Approach to Water." *Geoforum* 57: 170–80. doi:10.1016/j.geoforum.2013.10.008.

Ohlsson, L. 2000. "Water Conflicts and Social Resource Scarcity." *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere* 25 (3): 213–20. doi:10.1016/S1464-1909(00)00006-X.

Ostrom, E. 2009. "A General Framework for Analyzing Sustainability of Social-Ecological Systems." *Science (New York, N.Y.)* 325 (5939): 419–22. doi:10.1126/science.1172133.

Purkey, DR., A Huber-Lee, DN Yates, M Hanemann, and S Herrod-Julius. 2006. "Integrating a Climate Change Assessment Tool into Stakeholder-Driven Water Management Decision-Making Processes in California." *Water Resources Management* 21 (1): 315–29. doi:10.1007/s11269-006-9055-x.

Ridoutt, BG, and S Pfister. 2010. “A Revised Approach to Water Footprinting to Make Transparent the Impacts of Consumption and Production on Global Freshwater Scarcity.” *Global Environmental Change* 20 (1): 113–20. doi:10.1016/j.gloenvcha.2009.08.003.

Sattler, C, and B Matzdorf. 2013. “PES in a Nutshell: From Definitions and Origins to PES in Practice-Approaches, Design Process and Innovative Aspects.” *Ecosystem Services* 6. Elsevier: 2–11. doi:10.1016/j.ecoser.2013.09.009.

Schulte, P, J Morrison, S Orr, and G Power. 2014. *Shared Water Challenges and Interestes: The Case for Private Sector Engagement in Water Policy and Management*. Oakland, CA: Pacific Institute.

Vanham, D, MM Mekonnen, and AY Hoekstra. 2013. “The Water Footprint of the EU for Different Diets.” *Ecological Indicators* 32 (September). Elsevier Ltd: 1–8. doi:10.1016/j.ecolind.2013.02.020.

Vos, J, and R Boelens. 2014. “Sustainability Standards and the Water Question.” *Development and Change* 45 (2): 205–30. doi:10.1111/dech.12083.

Zlolniski, C. 2011. “Water Flowing North of the Border: Export Agriculture and Water Politics in a Rural Community in Baja California.” *Cultural Anthropology* 26 (4): 565–88.

Appendices

Appendix A: Supporting Information for Chapter 3

Energy Flows for 1990 – 2012

Year	Energy Type	Stage	Flow	Unit	Quantity	Notes	Source(s)
1990	Ethanol	Feedstock	In-state	KBBL	0		1,2
1990	Ethanol	Feedstock	Net Import	KBBL	1,048	a	1,3
1990	Ethanol	Refined	In-state	KBBL	85		1,3
1990	Ethanol	Refined	Net Import	KBBL	963	b	1,3,4
1990	Oil Products	Extraction	In-state	KBBL	336,083		1,5
1990	Oil Products	Extraction	Net Import	KBBL	360,327		1,5
1990	Oil Products	Refined	In-state	KBBL	696,410		1
1990	Oil Products	Refined	Net Import	KBBL	-29,566		1,6
1990	Natural Gas	Extraction	In-state	MMCF	362,748		1,7
1990	Natural Gas	Extraction	Net Import	MMCF	1,620,118		1,7
1990	Electricity - Coal	Generation	In-state	MWh	3,692,000		1,8
1990	Electricity - Petroleum	Generation	In-state	MWh	4,449,000		1,8
1990	Electricity - Natural Gas	Generation	In-state	MWh	76,082,000		1,8
1990	Electricity - Nuclear	Generation	In-state	MWh	36,586,000		1,8
1990	Electricity - Hydropower	Generation	In-state	MWh	26,092,000		1,8
1990	Electricity - Geothermal	Generation	In-state	MWh	16,038,000		1,8
1990	Electricity - Biomass	Generation	In-state	MWh	6,644,000		1,8
1990	Electricity - Solar Thermal	Generation	In-state	MWh	681,000		1,8,9
1990	Electricity - Solar PV	Generation	In-state	MWh	0		1,8,9
1990	Electricity - Wind	Generation	In-state	MWh	2,418,000		1,8
1990	Electricity - Other	Generation	In-state	MWh	4,000		1,8
1990	Electricity - Coal	Generation	Net Import	MWh	34,049,344	c	1,8,10
1990	Electricity - Natural Gas	Generation	Net Import	MWh	10,877,032	c	1,8,10
1990	Electricity - Nuclear	Generation	Net Import	MWh	7,793,390	c	1,8,10
1990	Electricity - Hydropower	Generation	Net Import	MWh	26,949,235	c	1,8,10
1990	Electricity - Geothermal	Generation	Net Import	MWh	0	c	1,8,10
1990	Electricity - Biomass	Generation	Net Import	MWh	0	c	1,8,10
1990	Electricity - Solar Thermal	Generation	Net Import	MWh	0	c	1,8,9
1990	Electricity - Solar PV	Generation	Net Import	MWh	0	c	1,8,9
1990	Electricity - Wind	Generation	Net Import	MWh	0	c	1,8,10
1990	Electricity - Other	Generation	Net Import	MWh	0	c	1,8,10
1991	Ethanol	Feedstock	In-state	KBBL	0		1,2
1991	Ethanol	Feedstock	Net Import	KBBL	1,324	a	1,3
1991	Ethanol	Refined	In-state	KBBL	100		1,3
1991	Ethanol	Refined	Net Import	KBBL	1,224	b	1,3,4
1991	Oil Products	Extraction	In-state	KBBL	336,620		1,5
1991	Oil Products	Extraction	Net Import	KBBL	346,838		1,5
1991	Oil Products	Refined	In-state	KBBL	683,458		1

1991	Oil Products	Refined	Net Import	KBBL	-30,442		1,6
1991	Natural Gas	Extraction	In-state	MMCF	378,384		1,7
1991	Natural Gas	Extraction	Net Import	MMCF	1,623,684		1,7
1991	Electricity - Coal	Generation	In-state	MWh	3,050,000		1,8
1991	Electricity - Petroleum	Generation	In-state	MWh	523,000		1,8
1991	Electricity - Natural Gas	Generation	In-state	MWh	75,828,000		1,8
1991	Electricity - Nuclear	Generation	In-state	MWh	37,167,000		1,8
1991	Electricity - Hydropower	Generation	In-state	MWh	23,244,000		1,8
1991	Electricity - Geothermal	Generation	In-state	MWh	15,566,000		1,8
1991	Electricity - Biomass	Generation	In-state	MWh	7,312,000		1,8
1991	Electricity - Solar Thermal	Generation	In-state	MWh	719,000		1,8,9
1991	Electricity - Solar PV	Generation	In-state	MWh	0		1,8,9
1991	Electricity - Wind	Generation	In-state	MWh	2,669,000		1,8
1991	Electricity - Other	Generation	In-state	MWh	0		1,8
1991	Electricity - Coal	Generation	Net Import	MWh	32,594,525	c	1,8,10
1991	Electricity - Natural Gas	Generation	Net Import	MWh	10,412,291	c	1,8,10
1991	Electricity - Nuclear	Generation	Net Import	MWh	7,460,403	c	1,8,10
1991	Electricity - Hydropower	Generation	Net Import	MWh	25,797,781	c	1,8,10
1991	Electricity - Geothermal	Generation	Net Import	MWh	0	c	1,8,10
1991	Electricity - Biomass	Generation	Net Import	MWh	0	c	1,8,10
1991	Electricity - Solar Thermal	Generation	Net Import	MWh	0	c	1,8,9
1991	Electricity - Solar PV	Generation	Net Import	MWh	0	c	1,8,9
1991	Electricity - Wind	Generation	Net Import	MWh	0	c	1,8,10
1991	Electricity - Other	Generation	Net Import	MWh	0	c	1,8,10
1992	Ethanol	Feedstock	In-state	KBBL	0		1,2
1992	Ethanol	Feedstock	Net Import	KBBL	53	a	1,3
1992	Ethanol	Refined	In-state	KBBL	105		1,3
1992	Ethanol	Refined	Net Import	KBBL	-52	b	1,3,4
1992	Oil Products	Extraction	In-state	KBBL	331,638		1,5
1992	Oil Products	Extraction	Net Import	KBBL	332,708		1,5
1992	Oil Products	Refined	In-state	KBBL	664,346		1
1992	Oil Products	Refined	Net Import	KBBL	-31,236		1,6
1992	Natural Gas	Extraction	In-state	MMCF	365,632		1,7
1992	Natural Gas	Extraction	Net Import	MMCF	1,610,708		1,7
1992	Electricity - Coal	Generation	In-state	MWh	3,629,000		1,8
1992	Electricity - Petroleum	Generation	In-state	MWh	107,000		1,8
1992	Electricity - Natural Gas	Generation	In-state	MWh	87,032,000		1,8
1992	Electricity - Nuclear	Generation	In-state	MWh	38,622,000		1,8
1992	Electricity - Hydropower	Generation	In-state	MWh	22,373,000		1,8
1992	Electricity - Geothermal	Generation	In-state	MWh	16,491,000		1,8
1992	Electricity - Biomass	Generation	In-state	MWh	7,362,000		1,8
1992	Electricity - Solar Thermal	Generation	In-state	MWh	700,000		1,8,9
1992	Electricity - Solar PV	Generation	In-state	MWh	0		1,8,9
1992	Electricity - Wind	Generation	In-state	MWh	2,707,000		1,8

1992	Electricity - Other	Generation	In-state	MWh	2,000		1,8
1992	Electricity - Coal	Generation	Net Import	MWh	28,425,383	c	1,8,10
1992	Electricity - Natural Gas	Generation	Net Import	MWh	9,080,463	c	1,8,10
1992	Electricity - Nuclear	Generation	Net Import	MWh	6,506,149	c	1,8,10
1992	Electricity - Hydropower	Generation	Net Import	MWh	22,498,006	c	1,8,10
1992	Electricity - Geothermal	Generation	Net Import	MWh	0	c	1,8,10
1992	Electricity - Biomass	Generation	Net Import	MWh	0	c	1,8,10
1992	Electricity - Solar Thermal	Generation	Net Import	MWh	0	c	1,8,9
1992	Electricity - Solar PV	Generation	Net Import	MWh	0	c	1,8,9
1992	Electricity - Wind	Generation	Net Import	MWh	0	c	1,8,10
1992	Electricity - Other	Generation	Net Import	MWh	0	c	1,8,10
1993	Ethanol	Feedstock	In-state	KBBL	0		1,2
1993	Ethanol	Feedstock	Net Import	KBBL	464	a	1,3
1993	Ethanol	Refined	In-state	KBBL	111		1,3
1993	Ethanol	Refined	Net Import	KBBL	353	b	1,3,4
1993	Oil Products	Extraction	In-state	KBBL	342,762		1,5
1993	Oil Products	Extraction	Net Import	KBBL	328,924		1,5
1993	Oil Products	Refined	In-state	KBBL	671,686		1
1993	Oil Products	Refined	Net Import	KBBL	-32,999		1,6
1993	Natural Gas	Extraction	In-state	MMCF	315,851		1,7
1993	Natural Gas	Extraction	Net Import	MMCF	1,654,135		1,7
1993	Electricity - Coal	Generation	In-state	MWh	2,548,686		1,8
1993	Electricity - Petroleum	Generation	In-state	MWh	2,084,718		1,8
1993	Electricity - Natural Gas	Generation	In-state	MWh	70,714,733		1,8
1993	Electricity - Nuclear	Generation	In-state	MWh	36,579,088		1,8
1993	Electricity - Hydropower	Generation	In-state	MWh	41,594,963		1,8
1993	Electricity - Geothermal	Generation	In-state	MWh	15,769,935		1,8
1993	Electricity - Biomass	Generation	In-state	MWh	5,759,704		1,8
1993	Electricity - Solar Thermal	Generation	In-state	MWh	856,703		1,8,9
1993	Electricity - Solar PV	Generation	In-state	MWh	0		1,8,9
1993	Electricity - Wind	Generation	In-state	MWh	2,867,446		1,8
1993	Electricity - Other	Generation	In-state	MWh	0		1,8
1993	Electricity - Coal	Generation	Net Import	MWh	27,032,317	c	1,8,10
1993	Electricity - Natural Gas	Generation	Net Import	MWh	8,635,449	c	1,8,10
1993	Electricity - Nuclear	Generation	Net Import	MWh	6,187,296	c	1,8,10
1993	Electricity - Hydropower	Generation	Net Import	MWh	21,395,427	c	1,8,10
1993	Electricity - Geothermal	Generation	Net Import	MWh	0	c	1,8,10
1993	Electricity - Biomass	Generation	Net Import	MWh	0	c	1,8,10
1993	Electricity - Solar Thermal	Generation	Net Import	MWh	0	c	1,8,9
1993	Electricity - Solar PV	Generation	Net Import	MWh	0	c	1,8,9
1993	Electricity - Wind	Generation	Net Import	MWh	0	c	1,8,10
1993	Electricity - Other	Generation	Net Import	MWh	0	c	1,8,10
1994	Ethanol	Feedstock	In-state	KBBL	0		1,2
1994	Ethanol	Feedstock	Net Import	KBBL	687	a	1,3

1994	Ethanol	Refined	In-state	KBBL	123		1,3
1994	Ethanol	Refined	Net Import	KBBL	564	b	1,3,4
1994	Oil Products	Extraction	In-state	KBBL	319,193		1,5
1994	Oil Products	Extraction	Net Import	KBBL	346,209		1,5
1994	Oil Products	Refined	In-state	KBBL	665,402		1
1994	Oil Products	Refined	Net Import	KBBL	-32,608		1,6
1994	Natural Gas	Extraction	In-state	MMCF	300,236		1,7
1994	Natural Gas	Extraction	Net Import	MMCF	1,853,279		1,7
1994	Electricity - Coal	Generation	In-state	MWh	2,654,696		1,8
1994	Electricity - Petroleum	Generation	In-state	MWh	1,954,415		1,8
1994	Electricity - Natural Gas	Generation	In-state	MWh	95,024,511		1,8
1994	Electricity - Nuclear	Generation	In-state	MWh	38,828,236		1,8
1994	Electricity - Hydropower	Generation	In-state	MWh	25,626,000		1,8
1994	Electricity - Geothermal	Generation	In-state	MWh	15,572,761		1,8
1994	Electricity - Biomass	Generation	In-state	MWh	7,173,491		1,8
1994	Electricity - Solar Thermal	Generation	In-state	MWh	798,026		1,8,9
1994	Electricity - Solar PV	Generation	In-state	MWh	0		1,8,9
1994	Electricity - Wind	Generation	In-state	MWh	3,293,383		1,8
1994	Electricity - Other	Generation	In-state	MWh	0		1,8
1994	Electricity - Coal	Generation	Net Import	MWh	28,119,377	c	1,8,10
1994	Electricity - Natural Gas	Generation	Net Import	MWh	8,982,709	c	1,8,10
1994	Electricity - Nuclear	Generation	Net Import	MWh	6,436,108	c	1,8,10
1994	Electricity - Hydropower	Generation	Net Import	MWh	22,255,809	c	1,8,10
1994	Electricity - Geothermal	Generation	Net Import	MWh	0	c	1,8,10
1994	Electricity - Biomass	Generation	Net Import	MWh	0	c	1,8,10
1994	Electricity - Solar Thermal	Generation	Net Import	MWh	0	c	1,8,9
1994	Electricity - Solar PV	Generation	Net Import	MWh	0	c	1,8,9
1994	Electricity - Wind	Generation	Net Import	MWh	0	c	1,8,10
1994	Electricity - Other	Generation	Net Import	MWh	0	c	1,8,10
1995	Ethanol	Feedstock	In-state	KBBL	0		1,2
1995	Ethanol	Feedstock	Net Import	KBBL	2,404	a	1,3
1995	Ethanol	Refined	In-state	KBBL	119		1,3
1995	Ethanol	Refined	Net Import	KBBL	2,285	b	1,3,4
1995	Oil Products	Extraction	In-state	KBBL	320,824		1,5
1995	Oil Products	Extraction	Net Import	KBBL	321,384		1,5
1995	Oil Products	Refined	In-state	KBBL	642,218		1
1995	Oil Products	Refined	Net Import	KBBL	-72,110		1,6
1995	Natural Gas	Extraction	In-state	MMCF	280,147		1,7
1995	Natural Gas	Extraction	Net Import	MMCF	1,705,718		1,7
1995	Electricity - Coal	Generation	In-state	MWh	1,136,264		1,8
1995	Electricity - Petroleum	Generation	In-state	MWh	488,590		1,8
1995	Electricity - Natural Gas	Generation	In-state	MWh	78,378,329		1,8
1995	Electricity - Nuclear	Generation	In-state	MWh	36,185,917		1,8
1995	Electricity - Hydropower	Generation	In-state	MWh	51,665,014		1,8

1995	Electricity - Geothermal	Generation	In-state	MWh	14,266,754		1,8
1995	Electricity - Biomass	Generation	In-state	MWh	5,969,035		1,8
1995	Electricity - Solar Thermal	Generation	In-state	MWh	792,601		1,8,9
1995	Electricity - Solar PV	Generation	In-state	MWh	0		1,8,9
1995	Electricity - Wind	Generation	In-state	MWh	3,181,628		1,8
1995	Electricity - Other	Generation	In-state	MWh	0		1,8
1995	Electricity - Coal	Generation	Net Import	MWh	27,481,966	c	1,8,10
1995	Electricity - Natural Gas	Generation	Net Import	MWh	8,779,089	c	1,8,10
1995	Electricity - Nuclear	Generation	Net Import	MWh	6,290,214	c	1,8,10
1995	Electricity - Hydropower	Generation	Net Import	MWh	21,751,314	c	1,8,10
1995	Electricity - Geothermal	Generation	Net Import	MWh	0	c	1,8,10
1995	Electricity - Biomass	Generation	Net Import	MWh	0	c	1,8,10
1995	Electricity - Solar Thermal	Generation	Net Import	MWh	0	c	1,8,9
1995	Electricity - Solar PV	Generation	In-state	MWh	0		1,8,9
1995	Electricity - Wind	Generation	Net Import	MWh	0	c	1,8,10
1995	Electricity - Other	Generation	Net Import	MWh	0	c	1,8,10
1996	Ethanol	Feedstock	In-state	KBBL	0		1,2
1996	Ethanol	Feedstock	Net Import	KBBL	2,079	a	1,3
1996	Ethanol	Refined	In-state	KBBL	49		1,3
1996	Ethanol	Refined	Net Import	KBBL	2,030	b	1,3,4
1996	Oil Products	Extraction	In-state	KBBL	322,238		1,5
1996	Oil Products	Extraction	Net Import	KBBL	345,120		1,5
1996	Oil Products	Refined	In-state	KBBL	644,488		1
1996	Oil Products	Refined	Net Import	KBBL	-61,387		1,6
1996	Natural Gas	Extraction	In-state	MMCF	277,955		1,7
1996	Natural Gas	Extraction	Net Import	MMCF	1,673,576		1,7
1996	Electricity - Coal	Generation	In-state	MWh	2,870,189		1,8
1996	Electricity - Petroleum	Generation	In-state	MWh	692,938		1,8
1996	Electricity - Natural Gas	Generation	In-state	MWh	66,710,762		1,8
1996	Electricity - Nuclear	Generation	In-state	MWh	39,752,939		1,8
1996	Electricity - Hydropower	Generation	In-state	MWh	47,883,472		1,8
1996	Electricity - Geothermal	Generation	In-state	MWh	13,539,345		1,8
1996	Electricity - Biomass	Generation	In-state	MWh	5,556,894		1,8
1996	Electricity - Solar Thermal	Generation	In-state	MWh	832,442		1,8,9
1996	Electricity - Solar PV	Generation	In-state	MWh	0		1,8,9
1996	Electricity - Wind	Generation	In-state	MWh	3,154,077		1,8
1996	Electricity - Other	Generation	In-state	MWh	342,960		1,8
1996	Electricity - Coal	Generation	Net Import	MWh	30,893,696	c	1,8,10
1996	Electricity - Natural Gas	Generation	Net Import	MWh	9,868,963	c	1,8,10
1996	Electricity - Nuclear	Generation	Net Import	MWh	7,071,109	c	1,8,10
1996	Electricity - Hydropower	Generation	Net Import	MWh	24,451,616	c	1,8,10
1996	Electricity - Geothermal	Generation	Net Import	MWh	0	c	1,8,10
1996	Electricity - Biomass	Generation	Net Import	MWh	0	c	1,8,10
1996	Electricity - Solar Thermal	Generation	Net Import	MWh	0	c	1,8,9

1996	Electricity - Solar PV	Generation	Net Import	MWh	0	c	1,8,9
1996	Electricity - Wind	Generation	Net Import	MWh	0	c	1,8,10
1996	Electricity - Other	Generation	Net Import	MWh	0	c	1,8,10
1997	Ethanol	Feedstock	In-state	KBBL	0		1,2
1997	Ethanol	Feedstock	Net Import	KBBL	2,047	a	1,3
1997	Ethanol	Refined	In-state	KBBL	87		1,3
1997	Ethanol	Refined	Net Import	KBBL	1,960	b	1,3,4
1997	Oil Products	Extraction	In-state	KBBL	322,198		1,5
1997	Oil Products	Extraction	Net Import	KBBL	322,552		1,5
1997	Oil Products	Refined	In-state	KBBL	644,750		1
1997	Oil Products	Refined	Net Import	KBBL	-56,004		1,6
1997	Natural Gas	Extraction	In-state	MMCF	279,782		1,7
1997	Natural Gas	Extraction	Net Import	MMCF	1,640,703		1,7
1997	Electricity - Coal	Generation	In-state	MWh	2,276,487		1,8
1997	Electricity - Petroleum	Generation	In-state	MWh	142,725		1,8
1997	Electricity - Natural Gas	Generation	In-state	MWh	74,340,548		1,8
1997	Electricity - Nuclear	Generation	In-state	MWh	37,266,727		1,8
1997	Electricity - Hydropower	Generation	In-state	MWh	41,399,524		1,8
1997	Electricity - Geothermal	Generation	In-state	MWh	11,950,311		1,8
1997	Electricity - Biomass	Generation	In-state	MWh	5,700,998		1,8
1997	Electricity - Solar Thermal	Generation	In-state	MWh	810,216		1,8,9
1997	Electricity - Solar PV	Generation	In-state	MWh	0		1,8,9
1997	Electricity - Wind	Generation	In-state	MWh	2,738,748		1,8
1997	Electricity - Other	Generation	In-state	MWh	895,869		1,8
1997	Electricity - Coal	Generation	Net Import	MWh	22,531,960	c	1,8,10
1997	Electricity - Natural Gas	Generation	Net Import	MWh	7,197,814	c	1,8,10
1997	Electricity - Nuclear	Generation	Net Import	MWh	5,157,231	c	1,8,10
1997	Electricity - Hydropower	Generation	Net Import	MWh	17,833,503	c	1,8,10
1997	Electricity - Geothermal	Generation	Net Import	MWh	0	c	1,8,10
1997	Electricity - Biomass	Generation	Net Import	MWh	0	c	1,8,10
1997	Electricity - Solar Thermal	Generation	Net Import	MWh	0	c	1,8,9
1997	Electricity - Solar PV	Generation	Net Import	MWh	0	c	1,8,9
1997	Electricity - Wind	Generation	Net Import	MWh	0	c	1,8,10
1997	Electricity - Other	Generation	Net Import	MWh	0	c	1,8,10
1998	Ethanol	Feedstock	In-state	KBBL	0		1,2
1998	Ethanol	Feedstock	Net Import	KBBL	1,507	a	1,3
1998	Ethanol	Refined	In-state	KBBL	103		1,3
1998	Ethanol	Refined	Net Import	KBBL	1,404	b	1,3,4
1998	Oil Products	Extraction	In-state	KBBL	317,817		1,5
1998	Oil Products	Extraction	Net Import	KBBL	326,636		1,5
1998	Oil Products	Refined	In-state	KBBL	644,453		1
1998	Oil Products	Refined	Net Import	KBBL	-42,314		1,6
1998	Natural Gas	Extraction	In-state	MMCF	311,193		1,7
1998	Natural Gas	Extraction	Net Import	MMCF	1,829,537		1,7

1998	Electricity - Coal	Generation	In-state	MWh	2,701,047		1,8
1998	Electricity - Petroleum	Generation	In-state	MWh	122,525		1,8
1998	Electricity - Natural Gas	Generation	In-state	MWh	82,052,360		1,8
1998	Electricity - Nuclear	Generation	In-state	MWh	41,715,083		1,8
1998	Electricity - Hydropower	Generation	In-state	MWh	48,756,692		1,8
1998	Electricity - Geothermal	Generation	In-state	MWh	12,554,343		1,8
1998	Electricity - Biomass	Generation	In-state	MWh	5,265,840		1,8
1998	Electricity - Solar Thermal	Generation	In-state	MWh	839,058		1,8,9
1998	Electricity - Solar PV	Generation	In-state	MWh	0		1,8,9
1998	Electricity - Wind	Generation	In-state	MWh	2,775,920		1,8
1998	Electricity - Other	Generation	In-state	MWh	230,409		1,8
1998	Electricity - Coal	Generation	Net Import	MWh	20,327,897	c	1,8,10
1998	Electricity - Natural Gas	Generation	Net Import	MWh	6,493,728	c	1,8,10
1998	Electricity - Nuclear	Generation	Net Import	MWh	4,652,754	c	1,8,10
1998	Electricity - Hydropower	Generation	Net Import	MWh	16,089,040	c	1,8,10
1998	Electricity - Geothermal	Generation	Net Import	MWh	0	c	1,8,10
1998	Electricity - Biomass	Generation	Net Import	MWh	0	c	1,8,10
1998	Electricity - Solar Thermal	Generation	Net Import	MWh	0	c	1,8,9
1998	Electricity - Solar PV	Generation	Net Import	MWh	0	c	1,8,9
1998	Electricity - Wind	Generation	Net Import	MWh	0	c	1,8,10
1998	Electricity - Other	Generation	Net Import	MWh	0	c	1,8,10
1999	Ethanol	Feedstock	In-state	KBBL	0		1,2
1999	Ethanol	Feedstock	Net Import	KBBL	1,300	a	1,3
1999	Ethanol	Refined	In-state	KBBL	95		1,3
1999	Ethanol	Refined	Net Import	KBBL	1,205	b	1,3,4
1999	Oil Products	Extraction	In-state	KBBL	306,856		1,5
1999	Oil Products	Extraction	Net Import	KBBL	329,342		1,5
1999	Oil Products	Refined	In-state	KBBL	636,198		1
1999	Oil Products	Refined	Net Import	KBBL	-1,129		1,6
1999	Natural Gas	Extraction	In-state	MMCF	361,232		1,7
1999	Natural Gas	Extraction	Net Import	MMCF	1,877,750		1,7
1999	Electricity - Coal	Generation	In-state	MWh	3,601,930		1,8
1999	Electricity - Petroleum	Generation	In-state	MWh	54,576		1,8
1999	Electricity - Natural Gas	Generation	In-state	MWh	84,702,714		1,8
1999	Electricity - Nuclear	Generation	In-state	MWh	40,419,250		1,8
1999	Electricity - Hydropower	Generation	In-state	MWh	41,627,230		1,8
1999	Electricity - Geothermal	Generation	In-state	MWh	13,251,127		1,8
1999	Electricity - Biomass	Generation	In-state	MWh	5,663,114		1,8
1999	Electricity - Solar Thermal	Generation	In-state	MWh	837,579		1,8,9
1999	Electricity - Solar PV	Generation	In-state	MWh	0		1,8,9
1999	Electricity - Wind	Generation	In-state	MWh	3,432,910		1,8
1999	Electricity - Other	Generation	In-state	MWh	0		1,8
1999	Electricity - Coal	Generation	Net Import	MWh	21,149,793	c	1,8,10
1999	Electricity - Natural Gas	Generation	Net Import	MWh	6,756,282	c	1,8,10

1999	Electricity - Nuclear	Generation	Net Import	MWh	4,840,874	c	1,8,10
1999	Electricity - Hydropower	Generation	Net Import	MWh	16,739,552	c	1,8,10
1999	Electricity - Geothermal	Generation	Net Import	MWh	0	c	1,8,10
1999	Electricity - Biomass	Generation	Net Import	MWh	0	c	1,8,10
1999	Electricity - Solar Thermal	Generation	Net Import	MWh	0	c	1,8,9
1999	Electricity - Solar PV	Generation	Net Import	MWh	0	c	1,8,9
1999	Electricity - Wind	Generation	Net Import	MWh	0	c	1,8,10
1999	Electricity - Other	Generation	Net Import	MWh	0	c	1,8,10
2000	Ethanol	Feedstock	In-state	KBBL	0		1,2
2000	Ethanol	Feedstock	Net Import	KBBL	1,474	a	1,3
2000	Ethanol	Refined	In-state	KBBL	115		1,3
2000	Ethanol	Refined	Net Import	KBBL	1,359	b	1,3,4
2000	Oil Products	Extraction	In-state	KBBL	326,371		1,5
2000	Oil Products	Extraction	Net Import	KBBL	332,338		1,5
2000	Oil Products	Refined	In-state	KBBL	658,709		1
2000	Oil Products	Refined	Net Import	KBBL	10,261		1,6
2000	Natural Gas	Extraction	In-state	MMCF	361,963		1,7
2000	Natural Gas	Extraction	Net Import	MMCF	1,993,535		1,7
2000	Electricity - Coal	Generation	In-state	MWh	3,183,381		1,8
2000	Electricity - Petroleum	Generation	In-state	MWh	449,362		1,8
2000	Electricity - Natural Gas	Generation	In-state	MWh	106,877,677		1,8
2000	Electricity - Nuclear	Generation	In-state	MWh	43,533,040		1,8
2000	Electricity - Hydropower	Generation	In-state	MWh	42,052,513		1,8
2000	Electricity - Geothermal	Generation	In-state	MWh	13,455,810		1,8
2000	Electricity - Biomass	Generation	In-state	MWh	6,086,033		1,8
2000	Electricity - Solar Thermal	Generation	In-state	MWh	860,008		1,8,9
2000	Electricity - Solar PV	Generation	In-state	MWh	0		1,8,9
2000	Electricity - Wind	Generation	In-state	MWh	3,604,221		1,8
2000	Electricity - Other	Generation	In-state	MWh	0		1,8
2000	Electricity - Coal	Generation	Net Import	MWh	11,442,907	c	1,8,10
2000	Electricity - Natural Gas	Generation	Net Import	MWh	3,655,426	c	1,8,10
2000	Electricity - Nuclear	Generation	Net Import	MWh	2,619,112	c	1,8,10
2000	Electricity - Hydropower	Generation	Net Import	MWh	9,056,785	c	1,8,10
2000	Electricity - Geothermal	Generation	Net Import	MWh	0	c	1,8,10
2000	Electricity - Biomass	Generation	Net Import	MWh	0	c	1,8,10
2000	Electricity - Solar Thermal	Generation	Net Import	MWh	0	c	1,8,9
2000	Electricity - Solar PV	Generation	Net Import	MWh	0	c	1,8,9
2000	Electricity - Wind	Generation	Net Import	MWh	0	c	1,8,10
2000	Electricity - Other	Generation	Net Import	MWh	0	c	1,8,10
2001	Ethanol	Feedstock	In-state	KBBL	0		1,2
2001	Ethanol	Feedstock	Net Import	KBBL	2,013	a	1,3
2001	Ethanol	Refined	In-state	KBBL	126		1,3
2001	Ethanol	Refined	Net Import	KBBL	1,887	b	1,3,4
2001	Oil Products	Extraction	In-state	KBBL	323,583		1,5

2001	Oil Products	Extraction	Net Import	KBBL	331,672		1,5
2001	Oil Products	Refined	In-state	KBBL	655,255		1
2001	Oil Products	Refined	Net Import	KBBL	56,665		1,6
2001	Natural Gas	Extraction	In-state	MMCF	371,825		1,7
2001	Natural Gas	Extraction	Net Import	MMCF	2,086,308		1,7
2001	Electricity - Coal	Generation	In-state	MWh	4,040,777		1,8
2001	Electricity - Petroleum	Generation	In-state	MWh	379,154		1,8
2001	Electricity - Natural Gas	Generation	In-state	MWh	116,369,054		1,8
2001	Electricity - Nuclear	Generation	In-state	MWh	33,293,819		1,8
2001	Electricity - Hydropower	Generation	In-state	MWh	24,987,848		1,8
2001	Electricity - Geothermal	Generation	In-state	MWh	13,524,811		1,8
2001	Electricity - Biomass	Generation	In-state	MWh	5,761,322		1,8
2001	Electricity - Solar Thermal	Generation	In-state	MWh	833,708		1,8,9
2001	Electricity - Solar PV	Generation	In-state	MWh	2,576		1,8,9
2001	Electricity - Wind	Generation	In-state	MWh	3,242,300		1,8
2001	Electricity - Other	Generation	In-state	MWh	37,825		1,8
2001	Electricity - Coal	Generation	Net Import	MWh	27,748,396	c	1,8,10
2001	Electricity - Natural Gas	Generation	Net Import	MWh	8,864,200	c	1,8,10
2001	Electricity - Nuclear	Generation	Net Import	MWh	6,351,196	c	1,8,10
2001	Electricity - Hydropower	Generation	Net Import	MWh	21,962,187	c	1,8,10
2001	Electricity - Geothermal	Generation	Net Import	MWh	0	c	1,8,10
2001	Electricity - Biomass	Generation	Net Import	MWh	0	c	1,8,10
2001	Electricity - Solar Thermal	Generation	Net Import	MWh	0	c	1,8,9
2001	Electricity - Solar PV	Generation	Net Import	MWh	0	c	1,8,9
2001	Electricity - Wind	Generation	Net Import	MWh	0	c	1,8,10
2001	Electricity - Other	Generation	Net Import	MWh	0	c	1,8,10
2002	Ethanol	Feedstock	In-state	KBBL	0		1,2
2002	Ethanol	Feedstock	Net Import	KBBL	2,292	a	1,3
2002	Ethanol	Refined	In-state	KBBL	172		1,3
2002	Ethanol	Refined	Net Import	KBBL	2,120	b	1,3,4
2002	Oil Products	Extraction	In-state	KBBL	317,321		1,5
2002	Oil Products	Extraction	Net Import	KBBL	343,679		1,5
2002	Oil Products	Refined	In-state	KBBL	661,000		1
2002	Oil Products	Refined	Net Import	KBBL	27,343		1,6
2002	Natural Gas	Extraction	In-state	MMCF	352,466		1,7
2002	Natural Gas	Extraction	Net Import	MMCF	1,703,891		1,7
2002	Electricity - Coal	Generation	In-state	MWh	4,275,442		1,8
2002	Electricity - Petroleum	Generation	In-state	MWh	87,190		1,8
2002	Electricity - Natural Gas	Generation	In-state	MWh	92,752,050		1,8
2002	Electricity - Nuclear	Generation	In-state	MWh	34,353,329		1,8
2002	Electricity - Hydropower	Generation	In-state	MWh	31,359,370		1,8
2002	Electricity - Geothermal	Generation	In-state	MWh	13,395,647		1,8
2002	Electricity - Biomass	Generation	In-state	MWh	6,195,631		1,8
2002	Electricity - Solar Thermal	Generation	In-state	MWh	848,325		1,8,9

2002	Electricity - Solar PV	Generation	In-state	MWh	2,462		1,8,9
2002	Electricity - Wind	Generation	In-state	MWh	3,546,106		1,8
2002	Electricity - Other	Generation	In-state	MWh	35,080		1,8
2002	Electricity - Coal	Generation	Net Import	MWh	26,865,000		1,8,10
2002	Electricity - Natural Gas	Generation	Net Import	MWh	8,582,000		1,8,10
2002	Electricity - Nuclear	Generation	Net Import	MWh	6,149,000		1,8,10
2002	Electricity - Hydropower	Generation	Net Import	MWh	21,263,000		1,8,10
2002	Electricity - Geothermal	Generation	Net Import	MWh	0		1,8,10
2002	Electricity - Biomass	Generation	Net Import	MWh	0		1,8,10
2002	Electricity - Solar Thermal	Generation	Net Import	MWh	0		1,8,9
2002	Electricity - Solar PV	Generation	Net Import	MWh	0		1,8,9
2002	Electricity - Wind	Generation	Net Import	MWh	0		1,8,10
2002	Electricity - Other	Generation	Net Import	MWh	0		1,8,10
2003	Ethanol	Feedstock	In-state	KBBL	0		1,2
2003	Ethanol	Feedstock	Net Import	KBBL	14,026	a	1,3
2003	Ethanol	Refined	In-state	KBBL	202		1,3
2003	Ethanol	Refined	Net Import	KBBL	13,824	b	1,3,4
2003	Oil Products	Extraction	In-state	KBBL	289,416		1,5
2003	Oil Products	Extraction	Net Import	KBBL	392,641		1,5
2003	Oil Products	Refined	In-state	KBBL	682,057		1
2003	Oil Products	Refined	Net Import	KBBL	15,486		1,6
2003	Natural Gas	Extraction	In-state	MMCF	333,108		1,7
2003	Natural Gas	Extraction	Net Import	MMCF	1,758,679		1,7
2003	Electricity - Coal	Generation	In-state	MWh	4,269,104		1,8
2003	Electricity - Petroleum	Generation	In-state	MWh	102,928		1,8
2003	Electricity - Natural Gas	Generation	In-state	MWh	94,715,112		1,8
2003	Electricity - Nuclear	Generation	In-state	MWh	35,593,790		1,8
2003	Electricity - Hydropower	Generation	In-state	MWh	36,341,074		1,8
2003	Electricity - Geothermal	Generation	In-state	MWh	13,328,799		1,8
2003	Electricity - Biomass	Generation	In-state	MWh	6,092,067		1,8
2003	Electricity - Solar Thermal	Generation	In-state	MWh	756,571		1,8,9
2003	Electricity - Solar PV	Generation	In-state	MWh	1,949		1,8,9
2003	Electricity - Wind	Generation	In-state	MWh	3,315,596		1,8
2003	Electricity - Other	Generation	In-state	MWh	108,460		1,8
2003	Electricity - Coal	Generation	Net Import	MWh	31,794,000		1,8,10
2003	Electricity - Natural Gas	Generation	Net Import	MWh	9,649,000		1,8,10
2003	Electricity - Nuclear	Generation	Net Import	MWh	6,331,000		1,8,10
2003	Electricity - Hydropower	Generation	Net Import	MWh	14,037,000		1,8,10
2003	Electricity - Geothermal	Generation	Net Import	MWh	0		1,8,10
2003	Electricity - Biomass	Generation	Net Import	MWh	0		1,8,10
2003	Electricity - Solar Thermal	Generation	Net Import	MWh	0		1,8,9
2003	Electricity - Solar PV	Generation	Net Import	MWh	0		1,8,9
2003	Electricity - Wind	Generation	Net Import	MWh	0		1,8,10
2003	Electricity - Other	Generation	Net Import	MWh	0		1,8,10

2004	Ethanol	Feedstock	In-state	KBBL	0		1,2
2004	Ethanol	Feedstock	Net Import	KBBL	19,193	a	1,3
2004	Ethanol	Refined	In-state	KBBL	185		1,3
2004	Ethanol	Refined	Net Import	KBBL	19,008	b	1,3,4
2004	Oil Products	Extraction	In-state	KBBL	274,396		1,5
2004	Oil Products	Extraction	Net Import	KBBL	380,451		1,5
2004	Oil Products	Refined	In-state	KBBL	654,847		1
2004	Oil Products	Refined	Net Import	KBBL	36,949		1,6
2004	Natural Gas	Extraction	In-state	MMCF	318,863		1,7
2004	Natural Gas	Extraction	Net Import	MMCF	1,908,431		1,7
2004	Electricity - Coal	Generation	In-state	MWh	4,085,791		1,8
2004	Electricity - Petroleum	Generation	In-state	MWh	126,924		1,8
2004	Electricity - Natural Gas	Generation	In-state	MWh	105,358,130		1,8
2004	Electricity - Nuclear	Generation	In-state	MWh	30,241,360		1,8
2004	Electricity - Hydropower	Generation	In-state	MWh	34,489,953		1,8
2004	Electricity - Geothermal	Generation	In-state	MWh	13,493,669		1,8
2004	Electricity - Biomass	Generation	In-state	MWh	6,080,025		1,8
2004	Electricity - Solar Thermal	Generation	In-state	MWh	739,123		1,8,9
2004	Electricity - Solar PV	Generation	In-state	MWh	1,956		1,8,9
2004	Electricity - Wind	Generation	In-state	MWh	4,257,823		1,8
2004	Electricity - Other	Generation	In-state	MWh	47,689		1,8
2004	Electricity - Coal	Generation	Net Import	MWh	33,062,000		1,8,10
2004	Electricity - Natural Gas	Generation	Net Import	MWh	13,187,000		1,8,10
2004	Electricity - Nuclear	Generation	Net Import	MWh	6,729,000		1,8,10
2004	Electricity - Hydropower	Generation	Net Import	MWh	13,300,000		1,8,10
2004	Electricity - Geothermal	Generation	Net Import	MWh	0		1,8,10
2004	Electricity - Biomass	Generation	Net Import	MWh	0		1,8,10
2004	Electricity - Solar Thermal	Generation	Net Import	MWh	0		1,8,9
2004	Electricity - Solar PV	Generation	Net Import	MWh	0		1,8,9
2004	Electricity - Wind	Generation	Net Import	MWh	0		1,8,10
2004	Electricity - Other	Generation	Net Import	MWh	0		1,8,10
2005	Ethanol	Feedstock	In-state	KBBL	0		1,2
2005	Ethanol	Feedstock	Net Import	KBBL	20,463	a	1,3
2005	Ethanol	Refined	In-state	KBBL	363		1,3
2005	Ethanol	Refined	Net Import	KBBL	20,100	b	1,3,4
2005	Oil Products	Extraction	In-state	KBBL	266,052		1,5
2005	Oil Products	Extraction	Net Import	KBBL	408,224		1,5
2005	Oil Products	Refined	In-state	KBBL	674,276		1
2005	Oil Products	Refined	Net Import	KBBL	37,514		1,6
2005	Natural Gas	Extraction	In-state	MMCF	314,480		1,7
2005	Natural Gas	Extraction	Net Import	MMCF	1,789,360		1,7
2005	Electricity - Coal	Generation	In-state	MWh	4,283,120		1,8
2005	Electricity - Petroleum	Generation	In-state	MWh	148,147		1,8
2005	Electricity - Natural Gas	Generation	In-state	MWh	97,110,187		1,8

2005	Electricity - Nuclear	Generation	In-state	MWh	36,155,312		1,8
2005	Electricity - Hydropower	Generation	In-state	MWh	40,262,536		1,8
2005	Electricity - Geothermal	Generation	In-state	MWh	13,292,204		1,8
2005	Electricity - Biomass	Generation	In-state	MWh	6,076,084		1,8
2005	Electricity - Solar Thermal	Generation	In-state	MWh	658,333		1,8,9
2005	Electricity - Solar PV	Generation	In-state	MWh	1,989		1,8,9
2005	Electricity - Wind	Generation	In-state	MWh	4,084,054		1,8
2005	Electricity - Other	Generation	In-state	MWh	24,369		1,8
2005	Electricity - Coal	Generation	Net Import	MWh	29,722,000		1,8,10
2005	Electricity - Natural Gas	Generation	Net Import	MWh	12,598,000		1,8,10
2005	Electricity - Nuclear	Generation	Net Import	MWh	5,552,000		1,8,10
2005	Electricity - Hydropower	Generation	Net Import	MWh	14,584,000		1,8,10
2005	Electricity - Geothermal	Generation	Net Import	MWh	0		1,8,10
2005	Electricity - Biomass	Generation	Net Import	MWh	0		1,8,10
2005	Electricity - Solar Thermal	Generation	Net Import	MWh	0		1,8,9
2005	Electricity - Solar PV	Generation	Net Import	MWh	0		1,8,9
2005	Electricity - Wind	Generation	Net Import	MWh	0		1,8,10
2005	Electricity - Other	Generation	Net Import	MWh	0		1,8,10
2006	Ethanol	Feedstock	In-state	KBBL	0		1,2
2006	Ethanol	Feedstock	Net Import	KBBL	19,028	a	1,3
2006	Ethanol	Refined	In-state	KBBL	936		1,3
2006	Ethanol	Refined	Net Import	KBBL	18,092	b	1,3,4
2006	Oil Products	Extraction	In-state	KBBL	254,498		1,5
2006	Oil Products	Extraction	Net Import	KBBL	400,990		1,5
2006	Oil Products	Refined	In-state	KBBL	655,488		1
2006	Oil Products	Refined	Net Import	KBBL	36,331		1,6
2006	Natural Gas	Extraction	In-state	MMCF	309,732		1,7
2006	Natural Gas	Extraction	Net Import	MMCF	1,859,853		1,7
2006	Electricity - Coal	Generation	In-state	MWh	4,190,000		1,8
2006	Electricity - Petroleum	Generation	In-state	MWh	133,682		1,8
2006	Electricity - Natural Gas	Generation	In-state	MWh	109,315,722		1,8
2006	Electricity - Nuclear	Generation	In-state	MWh	32,035,823		1,8
2006	Electricity - Hydropower	Generation	In-state	MWh	48,558,574		1,8
2006	Electricity - Geothermal	Generation	In-state	MWh	13,093,137		1,8
2006	Electricity - Biomass	Generation	In-state	MWh	5,861,057		1,8
2006	Electricity - Solar Thermal	Generation	In-state	MWh	613,591		1,8,9
2006	Electricity - Solar PV	Generation	In-state	MWh	2,297		1,8,9
2006	Electricity - Wind	Generation	In-state	MWh	4,901,531		1,8
2006	Electricity - Other	Generation	In-state	MWh	34,355		1,8
2006	Electricity - Coal	Generation	Net Import	MWh	28,662,000		1,8,10
2006	Electricity - Natural Gas	Generation	Net Import	MWh	15,258,000		1,8,10
2006	Electricity - Nuclear	Generation	Net Import	MWh	6,191,000		1,8,10
2006	Electricity - Hydropower	Generation	Net Import	MWh	13,399,000		1,8,10
2006	Electricity - Geothermal	Generation	Net Import	MWh	260,000		1,8,10

2006	Electricity - Biomass	Generation	Net Import	MWh	550,000		1,8,10
2006	Electricity - Solar Thermal	Generation	Net Import	MWh	0		1,8,9
2006	Electricity - Solar PV	Generation	Net Import	MWh	0		1,8,9
2006	Electricity - Wind	Generation	Net Import	MWh	443,000		1,8,10
2006	Electricity - Other	Generation	Net Import	MWh	0		1,8,10
2007	Ethanol	Feedstock	In-state	KBBL	0		1,2
2007	Ethanol	Feedstock	Net Import	KBBL	20,963	a	1,3
2007	Ethanol	Refined	In-state	KBBL	2,128		1,3
2007	Ethanol	Refined	Net Import	KBBL	18,835	b	1,3,4
2007	Oil Products	Extraction	In-state	KBBL	251,445		1,5
2007	Oil Products	Extraction	Net Import	KBBL	387,744		1,5
2007	Oil Products	Refined	In-state	KBBL	639,189		1
2007	Oil Products	Refined	Net Import	KBBL	75,841		1,6
2007	Natural Gas	Extraction	In-state	MMCF	301,331		1,7
2007	Natural Gas	Extraction	Net Import	MMCF	2,035,538		1,7
2007	Electricity - Coal	Generation	In-state	MWh	4,216,683		1,8
2007	Electricity - Petroleum	Generation	In-state	MWh	103,308		1,8
2007	Electricity - Natural Gas	Generation	In-state	MWh	120,459,281		1,8
2007	Electricity - Nuclear	Generation	In-state	MWh	35,698,095		1,8
2007	Electricity - Hydropower	Generation	In-state	MWh	27,104,694		1,8
2007	Electricity - Geothermal	Generation	In-state	MWh	13,028,734		1,8
2007	Electricity - Biomass	Generation	In-state	MWh	5,742,581		1,8
2007	Electricity - Solar Thermal	Generation	In-state	MWh	665,750		1,8,9
2007	Electricity - Solar PV	Generation	In-state	MWh	2,208		1,8,9
2007	Electricity - Wind	Generation	In-state	MWh	5,569,733		1,8
2007	Electricity - Other	Generation	In-state	MWh	14,951		1,8
2007	Electricity - Coal	Generation	Net Import	MWh	45,821,000		1,8,10
2007	Electricity - Natural Gas	Generation	Net Import	MWh	18,200,000		1,8,10
2007	Electricity - Nuclear	Generation	Net Import	MWh	9,164,000		1,8,10
2007	Electricity - Hydropower	Generation	Net Import	MWh	16,667,000		1,8,10
2007	Electricity - Geothermal	Generation	Net Import	MWh	440,000		1,8,10
2007	Electricity - Biomass	Generation	Net Import	MWh	838,000		1,8,10
2007	Electricity - Solar Thermal	Generation	Net Import	MWh	0		1,8,9
2007	Electricity - Solar PV	Generation	Net Import	MWh	7,000		1,8,9
2007	Electricity - Wind	Generation	Net Import	MWh	1,079,000		1,8,10
2007	Electricity - Other	Generation	Net Import	MWh	0		1,8,10
2008	Ethanol	Feedstock	In-state	KBBL	0		1,2
2008	Ethanol	Feedstock	Net Import	KBBL	20,730	a	1,3
2008	Ethanol	Refined	In-state	KBBL	2,270		1,3
2008	Ethanol	Refined	Net Import	KBBL	18,460	b	1,3,4
2008	Oil Products	Extraction	In-state	KBBL	249,993		1,5
2008	Oil Products	Extraction	Net Import	KBBL	405,765		1,5
2008	Oil Products	Refined	In-state	KBBL	655,758		1
2008	Oil Products	Refined	Net Import	KBBL	-17,071		1,6

2008	Natural Gas	Extraction	In-state	MMCF	288,182		1,7
2008	Natural Gas	Extraction	Net Import	MMCF	2,011,797		1,7
2008	Electricity - Coal	Generation	In-state	MWh	3,977,170		1,8
2008	Electricity - Petroleum	Generation	In-state	MWh	91,680		1,8
2008	Electricity - Natural Gas	Generation	In-state	MWh	123,036,421		1,8
2008	Electricity - Nuclear	Generation	In-state	MWh	32,482,351		1,8
2008	Electricity - Hydropower	Generation	In-state	MWh	24,459,593		1,8
2008	Electricity - Geothermal	Generation	In-state	MWh	12,906,641		1,8
2008	Electricity - Biomass	Generation	In-state	MWh	5,926,831		1,8
2008	Electricity - Solar Thermal	Generation	In-state	MWh	730,152		1,8,9
2008	Electricity - Solar PV	Generation	In-state	MWh	3,103		1,8,9
2008	Electricity - Wind	Generation	In-state	MWh	5,723,998		1,8
2008	Electricity - Other	Generation	In-state	MWh	38,616		1,8
2008	Electricity - Coal	Generation	Net Import	MWh	51,852,000		1,8,10
2008	Electricity - Natural Gas	Generation	Net Import	MWh	17,999,000		1,8,10
2008	Electricity - Nuclear	Generation	Net Import	MWh	11,786,000		1,8,10
2008	Electricity - Hydropower	Generation	Net Import	MWh	13,380,000		1,8,10
2008	Electricity - Geothermal	Generation	Net Import	MWh	755,000		1,8,10
2008	Electricity - Biomass	Generation	Net Import	MWh	657,000		1,8,10
2008	Electricity - Solar Thermal	Generation	Net Import	MWh	0		1,8,9
2008	Electricity - Solar PV	Generation	Net Import	MWh	22,000		1,8,9
2008	Electricity - Wind	Generation	Net Import	MWh	1,607,000		1,8,10
2008	Electricity - Other	Generation	Net Import	MWh	0		1,8,10
2009	Ethanol	Feedstock	In-state	KBBL	0		1,2
2009	Ethanol	Feedstock	Net Import	KBBL	22,175	a	1,3
2009	Ethanol	Refined	In-state	KBBL	1,178		1,3
2009	Ethanol	Refined	Net Import	KBBL	20,997	b	1,3,4
2009	Oil Products	Extraction	In-state	KBBL	239,070		1,5
2009	Oil Products	Extraction	Net Import	KBBL	366,031		1,5
2009	Oil Products	Refined	In-state	KBBL	605,101	d	1
2009	Oil Products	Refined	Net Import	KBBL	-17,429		1,6
2009	Natural Gas	Extraction	In-state	MMCF	266,267		1,7
2009	Natural Gas	Extraction	Net Import	MMCF	1,957,740		1,7
2009	Electricity - Coal	Generation	In-state	MWh	3,734,604		1,8
2009	Electricity - Petroleum	Generation	In-state	MWh	66,801		1,8
2009	Electricity - Natural Gas	Generation	In-state	MWh	117,276,727		1,8
2009	Electricity - Nuclear	Generation	In-state	MWh	31,509,268		1,8
2009	Electricity - Hydropower	Generation	In-state	MWh	29,220,423		1,8
2009	Electricity - Geothermal	Generation	In-state	MWh	12,907,233		1,8
2009	Electricity - Biomass	Generation	In-state	MWh	6,095,937		1,8
2009	Electricity - Solar Thermal	Generation	In-state	MWh	840,520		1,8,9
2009	Electricity - Solar PV	Generation	In-state	MWh	10,763		1,8,9
2009	Electricity - Wind	Generation	In-state	MWh	6,248,588		1,8
2009	Electricity - Other	Generation	In-state	MWh	20,044		1,8

2009	Electricity - Coal	Generation	Net Import	MWh	20,312,000		1,8,10
2009	Electricity - Natural Gas	Generation	Net Import	MWh	8,637,000		1,8,10
2009	Electricity - Nuclear	Generation	Net Import	MWh	7,570,000		1,8,10
2009	Electricity - Hydropower	Generation	Net Import	MWh	3,151,000		1,8,10
2009	Electricity - Geothermal	Generation	Net Import	MWh	738,000		1,8,10
2009	Electricity - Biomass	Generation	Net Import	MWh	885,000		1,8,10
2009	Electricity - Solar Thermal	Generation	Net Import	MWh	0		1,8,9
2009	Electricity - Solar PV	Generation	Net Import	MWh	0		1,8,9
2009	Electricity - Wind	Generation	Net Import	MWh	3,127,000		1,8,10
2009	Electricity - Other	Generation	Net Import	MWh	46,712,000		1,8,10
2010	Ethanol	Feedstock	In-state	KBBL	0		1,2
2010	Ethanol	Feedstock	Net Import	KBBL	28,899	a	1,3
2010	Ethanol	Refined	In-state	KBBL	1,685		1,3
2010	Ethanol	Refined	Net Import	KBBL	27,214	b	1,3,4
2010	Oil Products	Extraction	In-state	KBBL	231,420		1,5
2010	Oil Products	Extraction	Net Import	KBBL	375,798		1,5
2010	Oil Products	Refined	In-state	KBBL	607,218	d	1
2010	Oil Products	Refined	Net Import	KBBL	-17,034		1,6
2010	Natural Gas	Extraction	In-state	MMCF	268,094		1,7
2010	Natural Gas	Extraction	Net Import	MMCF	1,906,240		1,7
2010	Electricity - Coal	Generation	In-state	MWh	3,405,820		1,8
2010	Electricity - Petroleum	Generation	In-state	MWh	51,665		1,8
2010	Electricity - Natural Gas	Generation	In-state	MWh	109,915,901		1,8
2010	Electricity - Nuclear	Generation	In-state	MWh	32,214,395		1,8
2010	Electricity - Hydropower	Generation	In-state	MWh	34,327,355		1,8
2010	Electricity - Geothermal	Generation	In-state	MWh	12,739,680		1,8
2010	Electricity - Biomass	Generation	In-state	MWh	5,960,141		1,8
2010	Electricity - Solar Thermal	Generation	In-state	MWh	878,835		1,8,9
2010	Electricity - Solar PV	Generation	In-state	MWh	33,479		1,8,9
2010	Electricity - Wind	Generation	In-state	MWh	6,171,676		1,8
2010	Electricity - Other	Generation	In-state	MWh	11,789		1,8
2010	Electricity - Coal	Generation	Net Import	MWh	19,019,000		1,8,10
2010	Electricity - Natural Gas	Generation	Net Import	MWh	11,955,000		1,8,10
2010	Electricity - Nuclear	Generation	Net Import	MWh	8,211,000		1,8,10
2010	Electricity - Hydropower	Generation	Net Import	MWh	1,887,000		1,8,10
2010	Electricity - Geothermal	Generation	Net Import	MWh	673,000		1,8,10
2010	Electricity - Biomass	Generation	Net Import	MWh	1,149,000		1,8,10
2010	Electricity - Solar Thermal	Generation	Net Import	MWh	0		1,8,9
2010	Electricity - Solar PV	Generation	Net Import	MWh	51,000		1,8,9
2010	Electricity - Wind	Generation	Net Import	MWh	7,364,000		1,8,10
2010	Electricity - Other	Generation	Net Import	MWh	34,859,000		1,8,10
2011	Ethanol	Feedstock	In-state	KBBL	0		1,2
2011	Ethanol	Feedstock	Net Import	KBBL	25,181	a	1,3
2011	Ethanol	Refined	In-state	KBBL	4,321		1,3

2011	Ethanol	Refined	Net Import	KBBL	20,860	b	1,3,4
2011	Oil Products	Extraction	In-state	KBBL	229,555		1,5
2011	Oil Products	Extraction	Net Import	KBBL	371,154		1,5
2011	Oil Products	Refined	In-state	KBBL	600,709	d	1
2011	Oil Products	Refined	Net Import	KBBL	-24,433		1,6
2011	Natural Gas	Extraction	In-state	MMCF	254,945		1,7
2011	Natural Gas	Extraction	Net Import	MMCF	2,032,982		1,7
2011	Electricity - Coal	Generation	In-state	MWh	3,120,236		1,8
2011	Electricity - Petroleum	Generation	In-state	MWh	36,230		1,8
2011	Electricity - Natural Gas	Generation	In-state	MWh	91,276,227		1,8
2011	Electricity - Nuclear	Generation	In-state	MWh	36,666,434		1,8
2011	Electricity - Hydropower	Generation	In-state	MWh	42,731,417		1,8
2011	Electricity - Geothermal	Generation	In-state	MWh	12,684,690		1,8
2011	Electricity - Biomass	Generation	In-state	MWh	5,986,321		1,8
2011	Electricity - Solar Thermal	Generation	In-state	MWh	888,843		1,8,9
2011	Electricity - Solar PV	Generation	In-state	MWh	208,396		1,8,9
2011	Electricity - Wind	Generation	In-state	MWh	7,598,382		1,8
2011	Electricity - Other	Generation	In-state	MWh	13,083		1,8
2011	Electricity - Coal	Generation	Net Import	MWh	20,850,000		1,8,10
2011	Electricity - Natural Gas	Generation	Net Import	MWh	12,344,000		1,8,10
2011	Electricity - Nuclear	Generation	Net Import	MWh	8,031,000		1,8,10
2011	Electricity - Hydropower	Generation	Net Import	MWh	1,510,000		1,8,10
2011	Electricity - Geothermal	Generation	Net Import	MWh	574,000		1,8,10
2011	Electricity - Biomass	Generation	Net Import	MWh	419,000		1,8,10
2011	Electricity - Solar Thermal	Generation	Net Import	MWh	0		1,8,9
2011	Electricity - Solar PV	Generation	Net Import	MWh	137,000		1,8,9
2011	Electricity - Wind	Generation	Net Import	MWh	6,977,000		1,8,10
2011	Electricity - Other	Generation	Net Import	MWh	41,825,000		1,8,10
2012	Ethanol	Feedstock	In-state	KBBL	0		1,2
2012	Ethanol	Feedstock	Net Import	KBBL	22,358	a	1,3
2012	Ethanol	Refined	In-state	KBBL	4,216		1,3
2012	Ethanol	Refined	Net Import	KBBL	18,142	b	1,3,4
2012	Oil Products	Extraction	In-state	KBBL	228,173		1,5
2012	Oil Products	Extraction	Net Import	KBBL	390,825		1,5
2012	Oil Products	Refined	In-state	KBBL	618,999	d	1
2012	Oil Products	Refined	Net Import	KBBL	-33,119		1,6
2012	Natural Gas	Extraction	In-state	MMCF	232,664		1,7
2012	Natural Gas	Extraction	Net Import	MMCF	2,225,103		1,7
2012	Electricity - Coal	Generation	In-state	MWh	1,579,898		1,8
2012	Electricity - Petroleum	Generation	In-state	MWh	89,985		1,8
2012	Electricity - Natural Gas	Generation	In-state	MWh	121,761,384		1,8
2012	Electricity - Nuclear	Generation	In-state	MWh	18,491,016		1,8
2012	Electricity - Hydropower	Generation	In-state	MWh	27,459,245		1,8
2012	Electricity - Geothermal	Generation	In-state	MWh	12,733,172		1,8

2012	Electricity - Biomass	Generation	In-state	MWh	6,120,576	1,8
2012	Electricity - Solar Thermal	Generation	In-state	MWh	866,941	1,8,9
2012	Electricity - Solar PV	Generation	In-state	MWh	967,378	1,8,9
2012	Electricity - Wind	Generation	In-state	MWh	9,242,199	1,8
2012	Electricity - Other	Generation	In-state	MWh	14,334	1,8
2012	Electricity - Coal	Generation	Net Import	MWh	21,106,000	1,8,10
2012	Electricity - Natural Gas	Generation	Net Import	MWh	9,279,000	1,8,10
2012	Electricity - Nuclear	Generation	Net Import	MWh	8,763,000	1,8,10
2012	Electricity - Hydropower	Generation	Net Import	MWh	1,914,000	1,8,10
2012	Electricity - Geothermal	Generation	Net Import	MWh	497,000	1,8,10
2012	Electricity - Biomass	Generation	Net Import	MWh	1,048,000	1,8,10
2012	Electricity - Solar Thermal	Generation	Net Import	MWh	0	1,8,9
2012	Electricity - Solar PV	Generation	Net Import	MWh	775,000	1,8,9
2012	Electricity - Wind	Generation	Net Import	MWh	9,983,000	1,8,10
2012	Electricity - Other	Generation	Net Import	MWh	49,500,000	1,8,10

Notes:

a. This value accounts for the feedstock for all ethanol consumed in California (refined inside or outside of the state).

b. Calculated as total ethanol consumption minus instate ethanol production (refining). Foreign sources are differentiated by Ref. 4.

c. The portfolio of imported electricity for years 1990-2001 was broken down by percentage according to 2002 values from Ref. 10.

d. Oil product production for 2009-2012 was calculated as 120% of crude oil supply (Ref. 5), which was the average over the previous 10 years.

Other energy sources consumed in California that might have been included in our analysis:

1. Wood and waste consumed outside the electric power sector, such as for residential heating or industrial and commercial uses, accounted for 75 trillion BTUs in 2012 (3). This was roughly equivalent to electric power sector biomass inputs, or one percent of total statewide energy consumption. However, like biomass used for electricity production, biomass for direct energy consumption comes from residues and byproducts from agriculture, timber, paper, and forest management activities (16). Further, because these sources were consumed directly or no information was available on their conversion to electricity, water consumption at the electricity generation stage was not considered.

2. Petroleum-fueled electricity generation in 1990 (and prior) made up about two percent of California's total electricity production, however it quickly decreased and has remained at less than one-tenth of one percent since 2002 (8). For this reason, as well as a lack of information on petroleum power plant water use, petroleum electricity water consumption was not considered.

Calculation steps for Table 1

Table 1: Factors used to calculate California's blue EWF for electricity.

Fuel	Location	Fuel Cycle (l water/MWh)	Generation (l water/MWh)
Coal	All	96	1,895
Natural Gas	All	24*	737
Nuclear	All	212	1,817
Conventional Hydropower	All	17,000	-
Geothermal	All	-	2,265
Biomass	All	-	2,090
Solar PV	All	-	329
Solar Thermal	All	-	3,975
Wind	All	-	4
Unspecified Imported Electricity	All	1,291	1,399

Note: EWF factors are weighted by extraction, processing, and electricity generation technologies. See Supporting Information for further details.

*The equivalent factor for direct use of natural gas is 0.13 l water/m^3 gas.

<u>Coal fuel cycle water consumption</u>

Surface mining: 22 gal/MWh$_e$ (11).
Underground mining: 56 gal/MWh$_e$ (11).
Western coal mining in 2009 was 90% surface mining, 10% underground mining (12).
(0.9 × 22 gal/MWh$_e$ + 0.1 × 56 gal/MWh$_e$) × 3.785 l/gal = **96 l water/MWh$_e$**

<u>Coal electricity generation water consumption</u>

Power plant construction: 1 gal/MWh$_e$ (11).

a. Recirculating cooling tower with subcritical boiler: 530 gal/MWh$_e$ (11).
b. Recirculating cooling tower with supercricital boiler: 500 gal/MWh$_e$ (11).
c. Once-through cooling with subcritical boiler: 140 gal/MWh$_e$ (11).
d. Once-through cooling with supercrictical boiler: 100 gal/MWh$_e$ (11).
e. Pond cooling with subcritical boiler: 740 gal/MWh$_e$ (11).
f. Pond cooling with supercritical boiler: 42 gal/MWh$_e$ (11).
g. Dry cooling with subcritical or supercritical boiler: 1 gal/MWh$_e$ (11).

In 2009, coal electricity generation within the Western Electricity Coordinating Council (WECC) was 63% type "a" (above), 23% "b," 2% "c," 1% "d," 6% "e," 2% "f," 1% "g," and the remainder pertained to saltwater cooling (13).
(1 gal/MWh$_e$ + 0.63 × 530 gal/MWh$_e$ + 0.23 × 500 gal/MWh$_e$ + 0.02 × 140 gal/MWh$_e$ + 0.01 × 100 gal/MWh$_e$ + 0.06 × 740 gal/MWh$_e$ + 0.02 × 42 gal/MWh$_e$ + 0.01 × 1 gal/MWh$_e$) × 3.785 l/gal = **1,895 l/MWh$_e$**

<u>Natural gas fuel cycle water consumption</u>

Conventional extraction: 4.2 gal/MWh$_e$ (11).
Tight gas extraction, including hydraulic fracturing: 5.2 gal/MWh$_e$ (11).
Shale gas extraction, including hydraulic fracturing: 16 gal/MWh$_e$ (11).

National natural gas extraction type changed on an annual basis as follows (14):

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
% Conventional	89	88	87	86	86	85	85	84	83	82	81	80	78	77	74	70	68	64	61	56	52	43	39
% Tight gas	10	11	12	13	13	14	15	15	16	16	17	18	19	20	23	26	27	28	29	28	26	22	20
% Shale Gas	1	1	1	1	1	1	1	1	1	1	2	2	2	3	3	4	6	8	10	17	23	35	40

Weighted consumption factors were calculated for each year, however Table 1 only shows 2009.
(0.56 × 4.2 gal/MWh$_e$ + 0.28 × 5.2 gal/MWh$_e$ + 0.17 × 16 gal/MWh$_e$) × 3.785 l/gal = **24 l/MWh$_e$**

*Natural gas direct use water consumption
Power plant thermal efficiency used in Ref. 11: 51% (0.51 MWh$_e$/MWh$_{th}$)
Heat content of natural gas used in Ref. 11: 1031 Btu/square-foot
24 l/MWh$_e$ × 0.51 MWh$_e$/MWh$_{th}$ × 2.93×10^{-7} MWh/Btu × 1031 Btu/ft^2 × 35.3 ft^2/m^3 = **0.13 l/m^3**

Natural gas electricity generation water consumption
Power plant construction: 1 gal/MWh$_e$ (11).

a. Recirculating cooling tower with combined cycle: 210 gal/MWh$_e$ (11).
b. Recirculating cooling tower with steam cycle only: 730 gal/MWh$_e$ (11).
c. Once-through cooling with combined cycle: 100 gal/MWh$_e$ (11).
d. Once-through cooling with steam cycle only: 290 gal/MWh$_e$ (11).
e. Pond cooling with combined cycle: 240 gal/MWh$_e$ (11).
f. Pond cooling with steam cycle only: 270 gal/MWh$_e$ (11).
g. Dry cooling with combined cycle: 4 gal/MWh$_e$ (11).

In 2009, natural gas electricity generation in the WECC was 79% “a” (above), 2% “b,” 1% “c,” 0% “d,” 4% “e,” 1% “f,” 5% “g,” and the remainder pertained to saltwater cooling (13).
(1 gal/MWh$_e$ + 0.79 × 210 gal/MWh$_e$ + 0.02 × 730 gal/MWh$_e$ + 0.01 × 100 gal/MWh$_e$ + 0.00 × 290 gal/MWh$_e$ + 0.04 × 240 gal/MWh$_e$ + 0.01 × 270 gal/MWh$_e$ + 0.05 × 4 gal/MWh$_e$) × 3.785 l/gal = **737 l/MWh$_e$**

Nuclear fuel cycle water consumption
Extraction and centrifugal enrichment: 56 gal/MWh$_e$ (11).
56 gal/MWh$_e$ × 3.785 l/gal = **212 l/MWh$_e$**

Nuclear electricity generation water consumption
Power plant construction: 0.25 gal/MWh$_e$ (11).
Recirculating cooling tower: 720 gal/MWh$_e$ (11).
In 2009, one-third of nuclear electricity generation in the WECC used recirculating cooling towers, and the remainder pertained to saltwater cooling (13).
(0.25 gal/MWh$_e$ + 0.666 × 720 gal/MWh$_e$) × 3.785 l/gal = **1,817 l/MWh$_e$**

Hydroelectric fuel cycle water consumption
Evaporative losses from storage reservoir: 4,491 gal/MWh$_e$ (15).
4,491 gal/MWh$_e$ × 3.785 l/gal = **17,000 l/MWh$_e$**
Note: hydroelectricity generation does not consume water during regular operations. Lifecycle water consumption factors for dam, power house, and other infrastructure were not available.

Geothermal electricity generation water consumption

Note: produced geothermal fluids are generally not counted as consumptive uses in geothermal energy production, except in cases where local blue water resources are used to stimulate wells.

Power plant construction: 2 gal/MWh_e (11).

a. Recirculating cooling tower with dry steam generator: 1,796 gal/MWh_e (15).
b. Recirculating cooling tower with flash steam generator: 11 gal/MWh_e (11).
c. Dry cooling with binary system generator: 290 gal/MWh_e (11).

In 2009, geothermal electricity generation in the WECC was 29% “a” (above), 45% “b,” and 26% “c” (13).

(2 gal/MWh_e + 0.29 × 1,796 gal/MWh_e + 0.45 × 11 gal/MWh_e + 0.26 × 290 gal/MWh_e) × 3.785 l/gal = **2,265 l/MWh_e**

Biomass electricity generation water consumption

Note: biomass fuel cycle water use was not included since biomass power plants generally use residues and byproducts from agriculture, timber, paper, and forest management activities.

Power plant construction: N/A

a. Recirculating cooling tower with steam generator: 553 gal/MWh_e (15).
b. Recirculating cooling tower with biogas generator: 235 gal/MWh_e (15).

In 2009, biomass electricity generation in the WECC was 99.6% “a,” and 0.04% “b” (13).

(0.996 × 553 gal/MWh_e + 0.004 × 235 gal/MWh_e) × 3.785 l/gal = **2,090 l/MWh_e**

Solar photovoltaic (PV) electricity generation water consumption

Power plant construction: 81 gal/MWh_e (11).

Flat panel cleaning and other plant uses: 6 gal/MWh_e (11).

(81 gal/MWh_e + 6 gal/MWh_e) × 3.785 l/gal = **329 l/MWh_e**

Solar thermal electricity generation water consumption

Power plant construction: 160 gal/MWh_e (11).

Recirculating cooling tower with parabolic trough collectors: 890 gal/MWh_e (11).

(160 gal/MWh_e + 890 gal/MWh_e) × 3.785 l/gal = **3,975 l/MWh_e**

Wind electricity generation water consumption

Power plant construction: 1 gal/MWh_e (11).

1 gal/MWh_e × 3.785 l/gal = **4 l/MWh_e**

Unspecified imported electricity fuel cycle water consumption

In 2009, imported electricity was 46% coal, 19% natural gas, 17% nuclear, 7% hydro, 2% biomass, 2% geothermal, and 7% wind (10).

0.46 × 96 l water/MWh_e + 0.19 × 24 l/MWh_e + 0.17 × 212 l/MWh_e + 0.07 × 17,000 l/MWh_e = **1,291 l/MWh_e**

Unspecified imported electricity generation water consumption

In 2009, imported electricity was 46% coal, 19% natural gas, 17% nuclear, 7% hydro, 2% geothermal, 2% biomass, and 7% wind (10).

0.46 × 1,895 l/MWh_e + 0.19 × 737 l/MWh_e + 0.17 × 1,817 l/MWh_e + 0.02 × 2,265 l/MWh_e + 0.02 × 2,090 l/MWh_e + 0.07 × 4 l/MWh_e = **1,399 l/MWh_e**

California's grey water footprint related to ethanol consumption

Grey EWF factors used in calculation (liter grey water/liter ethanol) (15).

USA (Corn)	412
Brazil (Sugar)	101
Canada (Corn)	349
China (Corn)	689
Costa Rica (Sugar)	60
El Salvador (Sugar)	180
Guatemala (Sugar)	36
Jamaica (Sugar)	15
Nicaragua (Sugar)	41
Singapore (Sugar)	453
Trinidad & Tobago (Sugar)	20
Other (sugar)	453

Grey EWF factors were multiplied by ethanol product flows from section I, above, resulting in Figure SI-1.

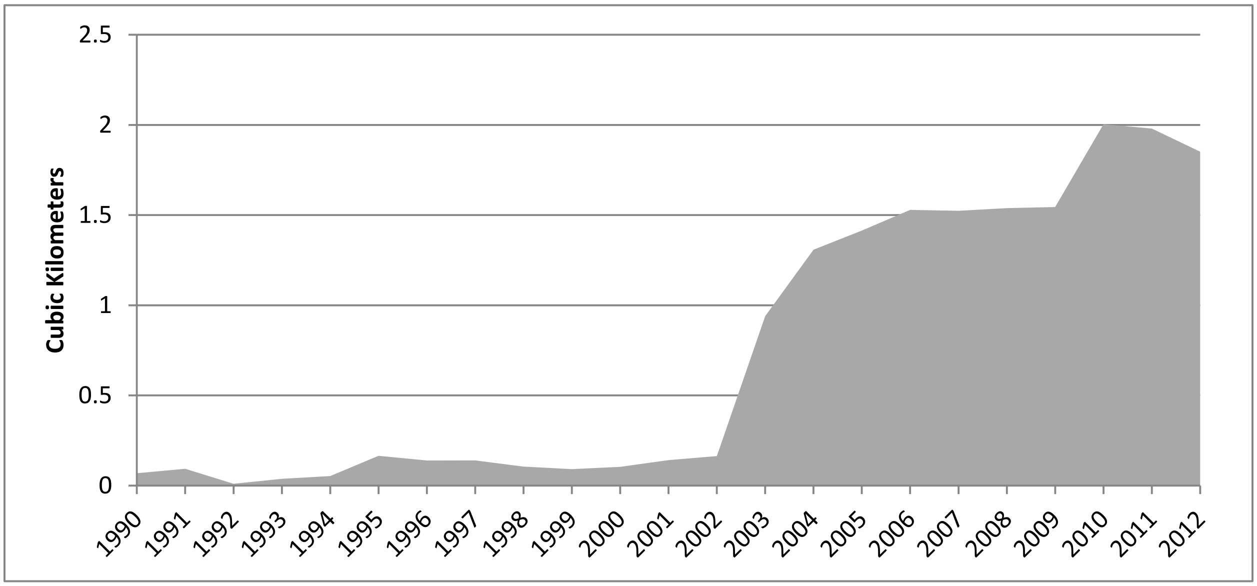

Figure SI-1: California's grey EWF related to the consumption of ethanol products, 1990-2012.

The main article states that one to two km^3 is approximately 0.2% to 0.4% of the average annual discharge of the Mississippi River. This statement is based on an historical average annual discharge of 520 km^3 at Vicksburg, MS (18).

References

(1) De la Rue du Can, S.; Hasanbeigi, A.; Sathaye, J. *California Energy Balance Update and Decomposition Analysis for the Industry and Building Sectors: Final Project Report*; Lawrence Berkeley National Laboratory and California Energy Commission: Sacramento, CA, 2013.

(2) Schlyer, L. Calgren Renewable Fuels, Pixley, CA. Personal Communication, 2009.

(3) U.S. Energy Information Administration. *State Energy Data System.* http://www.eia.gov/state/seds/seds-data-complete.cfm?sid=CA

(4) U.S. Energy Information Administration. *Petroleum and Other Liquids: Company Level Imports* http://www.eia.gov/petroleum/imports/companylevel/

(5) California Energy Commission. *Energy Almanac: Oil Supply Sources to California Refineries*. http://energyalmanac.ca.gov/petroleum/statistics/crude_oil_receipts.html

(6) U.S. Army Corps of Engineers. *Navigation Data Center: State to State and Region to Region Commodity Tonnages.* http://www.navigationdatacenter.us/data/datapdom.htm

(7) California Gas and Electric Utilities. *California Gas Report.* 1998 – 2014 available online: http://www.pge.com/pipeline/library/regulatory/cgr_index.shtml

(8) California Energy Commission. *Energy Almanac: California Electrical Energy Generation* http://energyalmanac.ca.gov/electricity/electricity_generation.html

(9) California Energy Commission. *Energy Almanac: Quarterly Fuel & Energy Report, Power Plant Owner Reporting Database.* http://energyalmanac.ca.gov/electricity/web_qfer/

(10) California Energy Commission. *Energy Almanac: Total Electricity System Power.* http://energyalmanac.ca.gov/electricity/total_system_power.html

(11) Meldrum, J.; Nettles-Anderson, S.; Heath, G.; Macknick, J. Life cycle water use for electricity generation: a review and harmonization of literature estimates. *Environ. Res. Lett.* **2013**, *8:1*.

(12) U.S. Energy Information Administration. *Historic Coal Production Data.* http://www.eia.gov/coal/data.cfm

(13) U.S. Energy Information Administration. *Power Plant Operations Report (Form 923) Database.* http://www.eia.gov/electricity/data/eia923/

(14) U.S. Energy Information Administration. *Annual Energy Outlook 2014: Market Trends: Natural Gas.* http://www.eia.gov/forecasts/aeo/mt_naturalgas.cfm

(15) Macknick, J.; Newmark, R.; Heath, G.; Hallett, K. C. *A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies.* **2011**. National Renewable Energy Laboratory: Golden, CO.

(16) Mekonnen, M.M; Hoekstra, A.Y. *The green, blue and grey water footprint of crops and derived crop products.* UNESCO-IHE: Delft, the Netherlands, **2010**.

(17) Friedman, G. Lost Coast Forest Products, Santa Rosa, CA. Personal communication, 2014.

(18) Meade, R.H. *Contaminants in the Mississippi River, 1987-92*; US Geologic Survey: Reston, VA, 1995.

Appendix B: Supporting Information for Chapter 4

Methods and Data Sources for Calculating Water Footprint Factors

Figure 4 depicts the modeling framework used to calculate the elements in Figure 3. Each element of California's overall water footprint from Figure 3 is shown in a purple box, while the components used to calculate those elements are in blue boxes. Each line connecting the boxes depicts a process step in collecting and combining various data sources. The following sections discuss these data sources and how they were used.

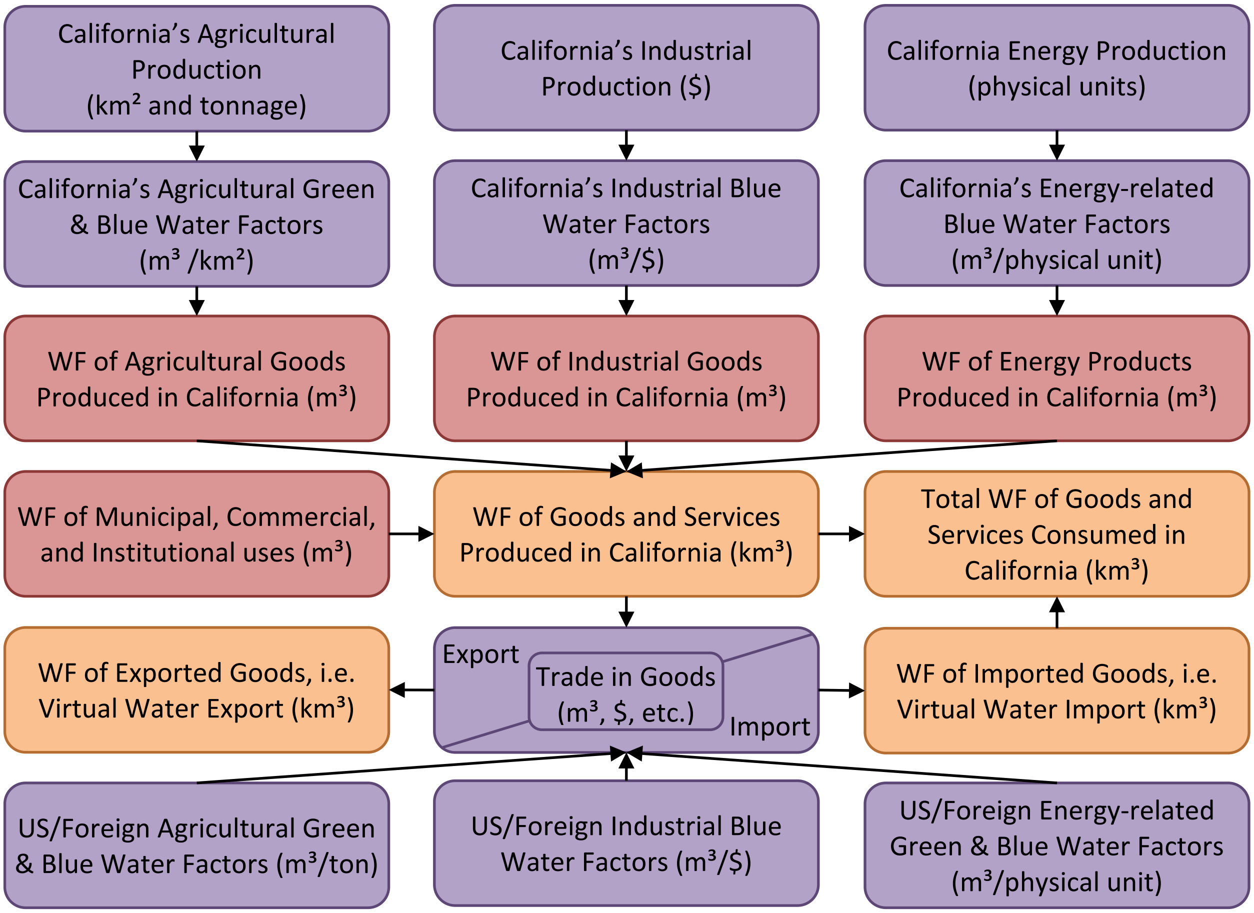

Figure 11: Modeling framework of water footprint calculation

Agricultural Products

For this analysis, we used California-specific data to estimate the water footprint of goods and services produced in California.[3] Consumptive water use factors for non-energy products were derived from several California Department of Water Resources (DWR) data sources. Consumptive use factors for agricultural products were derived from the California Simulation Evaporation of Applied Water (Cal-SIMETAW) model (Orang et al. 2013), which reconstructs

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[3] Note that we used different data sets from Fulton et al. (2012) in order to look in more detail at annual changes over longer time periods.

seasonal crop evapotranspiration (ETc) estimates (in units of acre-feet per acre) for 20 crop categories from 1992–2009 using recorded weather and cropping pattern data. ETc values were further divided between evapotranspiration of applied water (ETaw) and effective precipitation (EP).[4] ETaw values were used as blue water factors to calculate the blue water footprint of agricultural products. Green water factors were calculated as EP plus residual soil moisture (in other words, ETc minus ETaw). These factors were available at the combined Detailed Analysis Unit-County level (DAU-Co), which could then be aggregated to an individual county, hydrologic region, and the state as a whole.

Agricultural production statistics were taken from California County Agricultural Commissioner's statistics, which provided county-level harvested acreage and production tonnage for 281 agricultural commodities from 1992–2010. Harvested acreage of each commodity was multiplied by blue and green water factors for the appropriate DWR crop category to get the total quantity of water required to produce a given crop.[5] Water use for a given crop was then divided by production tonnage for that crop to derive blue and green water footprint factors in units of acre-feet-per-ton of product. These product-level water footprint factors were then combined with trade statistics, as described below.

It is important to note that California has non-irrigated agriculture. Specifically, most pasture and some grains are entirely rainfed. The California County Agricultural Commissioner's reports include data on both rainfed and irrigated agriculture. The land use dataset used in Cal-SIMETAW, however, only provides data on irrigated agriculture. To determine the amount of land devoted to rainfed crops, we subtracted Cal-SIMETAW irrigated land area statistics for crop categories from total land area provided in the California County Agricultural Commissioner's reports. For rainfed agriculture, we only apply green water factors available from the Cal-SIMETAW dataset.

Producing animal products, like meat and dairy, consumes a large amount of water, primarily to grow the forage and fodder required to feed the animals. Data on the production of animal products were obtained from the 2007 USDA Census of Agriculture. Using international biomass-to-product conversion rates published in (Mekonnen and Hoekstra 2010a), we estimated the amount of feed required to produce these animal products. According to these sources, an estimated 63.2 million tons of biomass were needed for animal production in California in 2007. The biomass estimates were multiplied by the water footprints of feed and forage crops, calculated as described above, to estimate the amount of water required to produce animal products. The water footprint of animal products, calculated on a gallons-per-ton basis, for 2007. When trade data were applied, as discussed below, the water footprint factor was developed for 2007 and applied to all other years analyzed. Other water uses, e.g., for washing and hydrating animals and for the processing of animal products, are typically only around 1% of animal

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[4] Cal-SIMETAW yearly values are for a "water year," which is Oct. 1 – Sept. 30. We assumed that water used for production in, for example, water year 2007 (Oct. 1, 2006 – Sept. 30, 2007), all pertains to products harvested in calendar year 2007. 2010 water use values were calculated as the average of 2005-2009.

[5] See Appendix 1 in Fulton et al. (2012) for the commodity categories used in this analysis.

product water footprints (Mekonnen and Hoekstra 2010a) and were not included in this analysis. The biomass demand from California's animal product industries exceeds the supply from in-state sources, thus imported feed crops make a major contribution to the production of animal products in California.[6]

Industrial Products

The water footprint associated with industrial products produced in California, as well as direct residential, commercial, and institutional uses, was derived using Water Portfolios from past California Water Plan Updates.[7] In some cases, only water withdrawals were reported. For these, we assume that 31% of water withdrawn was consumed.[8] For industrial products produced outside of California, we used national average water footprint factors on a gallons-per-dollar basis as developed by Mekonnen & Hoekstra (2011). We then combined these factors with trade data to estimate virtual water flows associated with industrial products into and out of California.

Energy Products

California's energy system is complex. The extraction, processing, refining, and generation of energy products take place within the state's borders, but there are also significant exchanges at all of these production stages with neighbors and distant trading partners. To account for these energy flows, the California Energy Commission's Public Interest Energy Research program has sponsored ongoing work at Lawrence Berkeley National Laboratory to create and maintain the California Energy Balance (CALEB) database. CALEB manages highly disaggregated data on energy supply, transformation, and end-use consumption for about 30 different energy commodities, from 1990 to 2008 (de la Rue du Can et al, 2010). Figure 5 shows an example flow chart produced by CALEB for 2008, represented in trillion British thermal units of energy (BTUs). We used CALEB data on the physical units of energy (barrels of oil, million cubic feet of natural gas, etc.). To identify the origin of imported supplies we used additional information from the California Energy Commission on electricity (CEC 2013) and from the Energy Information Administration on natural gas (EIA, 2013a) and oil (EIA, 2013b).

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[6] California exports some animal feed and forage crops, namely alfalfa, and those exports were excluded as an input to animal products within California.

[7] These data have been collected by DWR staff from older versions of Bulletin 160 (1972-1985), Annual Reports prepared by District Staff (1989-1995) and the Water Portfolio from California Water Plan Update 2013 (1998-2010).

[8] This estimate was based on the average for all urban uses from 1998-2005 as provided by the Technical Guide from the California Water Plan Update 2009.

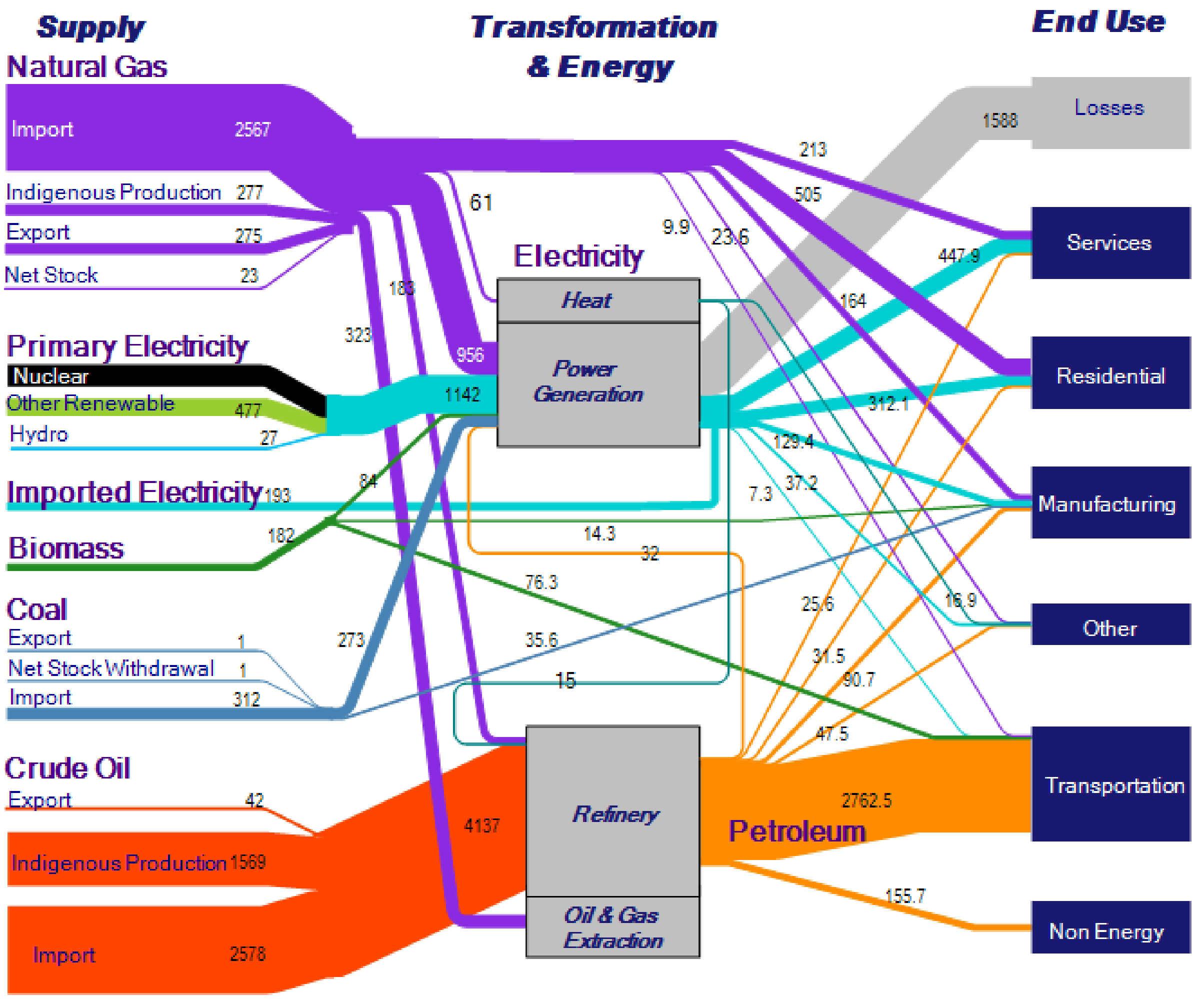

Figure 12: 2008 California Energy Flow Chart (in trillion British thermal units of energy)

Source: de la Rue du Can et al. 2010

Consumptive water use factors for energy were derived from several sources. The National Renewable Energy Laboratory (NREL) recently completed a review and harmonization of life cycle factors given by numerous publications on various electricity feedstock and generation technologies (Meldrum et al. 2013). We used NREL’s median factors for natural gas, coal, biomass, and nuclear supplies at the extraction, upgrading, and generation stages, as well as hydropower. For extraction, processing and refining of oil products we used factors from Wu et al. (2009). For bioethanol production in the US we used weighted average factors from Mekonnen and Hoekstra (2010), including refining and on-farm green and blue water requirements of bioethanol feedstocks. Grey water footprints of energy products were not calculated as part of this analysis.

Trade Data

As seen in Figure 2, California exports and imports many goods and services. The water footprint associated with traded goods and services is called a “virtual water flow.” To calculate these virtual water flows we combined water footprint factors, as described in the previous section, with trade statistics from the US Department of Transportation’s Freight Analysis Framework (FAF^3) for 1997, 2002, 2007, and 2010 (Southworth et al. 2011). FAF^3 combines Census Bureau and other data into a consistent modeling framework over time, and organizes data according to the 2-digit level of the Standard Classification of Traded Goods (SCTG) for both domestic and international trading partners. FAF^3 data were not available for 1992. We therefore used US Department of Transportation’s Commodity Flow Survey (CFS) for 1992 (USDC-BC 1993), which is also organized by SCTG. Because the CFS only includes domestic trade flows, we assumed that the proportion (by weight) of international to domestic trade flows in 1992 were the same as in 1997.

To calculate the water footprint of products produced in California and exported outside the state, i.e., “embedded water exports,” trade data were multiplied by blue and green water footprint factors. For agricultural products, green and blue water footprint factors (gallon per ton) were aggregated to the 2-digit SCTG level for each trade year and multiplied by export weights. For industrial products, export values (dollars of sales) for each trade year were multiplied by the average national industrial blue water footprint factor as provided by Mekonnen and Hoekstra (2011).

To calculate embedded water imports, trade data were multiplied by blue and green water footprint factors. For agricultural products, blue and green water footprint factors from Mekonnen and Hoekstra (2010a, 2010b) were used by taking a weighted average among US states as well as international trading partners and then aggregated to SCTG categories. For industrial products, we also used average US and global blue water footprint factors from Mekonnen and Hoekstra (2011) and multiplied them by the value of imported industrial products from US and international trading partners. As these datasets are averaged for 1996–2005, they were assumed to be the same for each trade year.

For the analysis of water footprint trends in California, the availability of trade data limited our analysis to 5-year increments from 1992 to 2007, as well as 2010. For each trade year, California’s Water Footprint was calculated using the accounting framework shown in Figure 3.

References

CEC, California Energy Commission. 2013. “Total Electricity System Power.” http://energyalmanac.ca.gov/electricity/total_system_power.html.

De la Rue du Can, S, A Hasanbeigi, and J Sathaye. 2013. *California Energy Balance Update and Decomposition Analysis for the Industry and Building Sectors: Final Project Report*.

Lawrence Berkeley National Laboratory and California Energy Commission: Sacramento, CA.

EIA, Energy Information Administration. 2013a. “California International and Interstate Movements of Natural Gas by State.” http://www.eia.gov/dnav/ng/ng_move_ist_a2dcu_sca_a.htm.

———. 2013b. “Petroleum and Other Liquids: Company Level Imports.” http://www.eia.gov/petroleum/imports/companylevel/.

Mekonnen, MM, and AY Hoekstra. 2010a. *The Green, Blue and Grey Water Footprint of Farm Animals and Animal Products, Value of Water Research Report Series No. 48 (Volume 1: Main Report)*. UNESCO-IHE, Delft, the Netherlands.

———. 2010b. *The Green, Blue and Grey Water Footprint of Crops and Derived Crop Products - Volume 2 : Appendices*. Vol. 2.

———. 2010c. *The Green, Blue and Grey Water Footprint of Crops and Derived Crop Products, Value of Water Research Report Series No. 47 (Volume 1: Main Report).*

———. 2011. *National water footprint accounts: the green, blue and grey water footprint of production and consumption, Value of Water Research Report Series No. 50 (Volume 2: Appendices).*

Meldrum, J, S Nettles-Anderson, G Heath, and J Macknick. 2013. “Life Cycle Water Use for Electricity Generation: A Review and Harmonization of Literature Estimates.” *Environmental Research Letters* 8 (1): 015031. doi:10.1088/1748-9326/8/1/015031.

Orang, MN, RL Snyder, G Shu, QJ Hart, S Sarreshteh, M Falk, D Beaudette, S Hayes, and S Eching. 2013. “California Simulation of Evapotranspiration of Applied Water and Agricultural Energy Use in California.” *Journal of Integrative Agriculture* 12 (8). Central Iron and Steel Research Institute: 1371–88. doi:10.1016/S2095-3119(13)60742-X.

Southworth, F, BE Peterson, H-L Hwang, S-M Chin, and D Davidson. 2011. *The Freight Analysis Framework Version 3 (FAF3)*. Washington DC.

USDC-BC, US Department of Commerce Bureau of Census. 1993. *1992 Census of Transportation , Communications , and Utilities*. Washington DC.

Wu, M, M Mintz, M Wang, and S Arora. 2009. *Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline.* Argonne National Laboratory: Argonne, IL.