UNIVERSITY OF CALIFORNIA,
IRVINE

Energy analysis of crop irrigation:
Role of water reclamation and water exportation

DISSERTATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in Engineering

with a Concentration in Environmental Engineering

by

Trung Derek Nguyen

Dissertation Committee:
Professor Diego Rosso, Chair
Professor Betty H. Olson
Professor David L. Feldman

2015

DEDICATION

This dissertation is dedicated to my family:

Xuan D. Nguyen
Hanh T. Tran
Tony Nguyen
Hoa K. Nguyen
Danny Nguyen
Dat D. Nguyen
Thuy Thu Bui
Suong T. Nguyen
Trinh V. Nguyen
Brian B. Nguyen
Jenny Tran
Paul D. Nguyen
Mimi Nguyen
Mindy Nguyen
Mikey Nguyen
Huy D. Nguyen
Tai D. Nguyen
Ngan Thu Nguyen
Hieu D. Nguyen
Kaylyn Nguyen

and my fiancée:

Tracy Tuyet Le

In recognition of their love and support

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Water Quality Engineer

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Project Engineer

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PEER-REVIEWED ARTICLES

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ABSTRACT OF THE DISSERTATION

Energy analysis of crop irrigation:
Role of water reclamation and water exportation

By

Trung Derek Nguyen

Doctor of Philosophy in Engineering

University of California, Irvine, 2015

Professor Diego Rosso, Chair

Freshwater availability is the major constraint to agriculture in arid and semi-arid regions. Worldwide, agricultural irrigation is the leading sector in the overall water consumption. As the largest agricultural region in the United States and the leading exporter of many commodities, California was chosen as a spatial domain to model the carbon footprint reduction and resource savings (water and energy) when applying reclaimed water to crop irrigation. An extensive compilation of the most recent publicly available datasets was used to calculate the energy intensity for each water supply source, associated carbon footprint reduction and monetary savings for employing reclaimed water versus traditional groundwater application. Furthermore, a quantification of water exported through agricultural trades was performed. Exported water is defined as the physical water content contained in crops plus the associated induced evapotranspiration due to their irrigation. Exported water differs from virtual water in that the former is the physical water exported outside of a geographical boundary and the latter is cumulative water footprint required to reach the final product. Therefore, the exported water is permanently lost and is no longer available for the natural hydrologic cycle from its origin.

Our calculations indicate that on an average basis for the time domain 1998-2010, the fractional water use for agriculture, and urbanized consumption in California was 0.81 and 0.19 respectively. Annually, crop irrigation consumed an average of 4.2 x 10^{10} m^3 of fresh water, of which 1%, 46.8% and 52.2% came from reclaimed water, groundwater, and surface water, respectively. Each of these three main water sources is associated with a range of energy intensity (in kWh m^{-3}), depending on the process and environmental characteristics of the end-use location. The analysis of multiple process and environmental configurations produced a detailed energy intensity database, with the associated carbon intensities (in $kg_{CO2,eq}$ kWh^{-1}). The overall exported water (i.e., contained in and evaporated/transpired from crops) in California's agricultural commodities was 2.88 x 10^{10} m^3 yr^{-1}, equivalent to 68.3% of the total water used in irrigation. The majority of the exported water was in the form of induced evapotranspiration, amounting to 67.7% of the irrigation water use, whereas approximately 2.32 x 10^8 m^3 yr^{-1} or 0.6% of the water used for irrigation leaves the agricultural spatial domain as content of the crops. Our results show that the physical water content contained in crops is minor relative to the associated evapotranspiration of the irrigated crops, confirming the hypothesis that for each unit of water exported, the loss of water via evapotranspiration induced by each crop far outweighs the crop water content.

CHAPTER 1. Introduction

1.1. Background

The fact that the annual water used in growing California agricultural products is far greater than the total urban water use is well known (Letey and Birkle, 2003). As pressures on water resources intensify globally, there is a growing interest in evaluating the complex ways in which human activities impact the world's water resources (Postel et al., 1996; Vorosmarty et al. 2007., Alcamo et al. 2007; Hoekstra and Chapagain 2008; Gleick and Palaniappan 2010; Fulton et al., 2012). Globally, the majority of water consumption is used in the production of agricultural products (Mekonnen and Hoekstra, 2011, Mubako et al., 2013). As a result, the agriculture industry is by far, the most dominant water-using sector. To assess the amount of water used throughout the production and distribution process to produce a final product, researchers have used the term 'water footprint', to describe this quantity (Hoekstra and Chapagain, 2007). Water footprint assessment had emerged as a tool for quantifying consumption of goods and services in one location and the cumulated water use associated with the production of those goods and services in other distant locations (Fulton et al., 2014).

Following the introduction of the water footprint concept, various studies were conducted to quantify global virtual water footprints and assessed virtual water flows between nations (Hoekstra and Hung, 2002, 2003), (Chapagain & Hoekstra, 2003), (Zimmer and Renault, 2003) and (Oki et al., 2003). Virtual water flows and water footprint assessments became important elements in evaluating local, national, and global water budgets as reported by Chen and Chen (2011a), Duarte et al., (2002), Guan and Hubacek (2007), Hubacek et al. (2009), Velazquez (2006), Yang et al. (2006), Yu et al. (2010), Zhao et al., (2009, 2010). Mekonnen and Hoekstra

(2011a) showed that the international virtual water trade in agricultural and industrial products were 2320 billion cubic meter (Gm^3) per year in the period 1996-2005, equivalent to 26% of the global water footprint of 9087 Gm^3. (Mekonnen and Hoekstra, 2011) noted that although practically, every country participates in the global virtual water trade, few governments explicitly consider assessing virtual water footprint and its impact in their management policies.

1.2. Research Motivation

The majority of the water footprint studies have examined international virtual water footprints between nations (Hoekstra and Hung, 2002; Hoekstra and Chapagain, 2008; Hanasaki et al., 2010, Konar et al., 2011; Mekonnen and Hoekstra, 2011, Dalin et al., 2012; Zhan-Ming and Chen., 2013). Few have also analyzed the virtual water footprints at a sub-national or state level such as regions within Australia (Lenzen, 2009), China (Guan and Hubacek, 2007; Zhao et al., 2010), India (Verma et al., 2009), and Spain (Dietzenbacher and Velazquez, 2007; Aldaya et al., 2009). Within the United States, two studies have been conducted. Fulton et al., (2012) reported that California imported more than twice virtual water as it exported and that more than 90% of its water footprint is associated with agricultural products. Mubako et al., (2013) quantified virtual water for California and Illinois, and reported that the two states were net virtual exporters in agricultural water trades.

Previous studies on virtual water footprints only aimed to quantify the cumulative water footprint required to produce a final product. No study has focused specifically on quantifying the physical water content contained in agricultural commodities and the associated evapotranspiration being exported. The total exported water in agricultural products is distinctively different than the virtual water footprint in that the former is physically exported outside of a geographical boundary, whereas the majority of the water used in quantifying virtual water footprint may remain within the local geographical boundary and be absorbed or reused in some ways. The exported water content in crops is permanently lost and is no longer available for natural hydrologic cycle. This research seeks to fill the gap of knowledge by quantifying the exported water contained in agricultural products and associated induced evapotranspiration. The research also seeks to analyze the energy advantage of applying reclaimed water in crop irrigation, by assessing the carbon footprint reduction and monetary savings for using reclaimed water in arid and semi-arid regions.

1.3. Research Hypothesis and Goal

The **central hypothesis** of this research is: **for each unit of water exported from an agricultural spatial domain, there is a greater loss of water via evapotranspiration as a result of irrigation than the water content of the crop itself**. Furthermore, since the production of crops induces major evapotranspiration from the agricultural spatial domain, a **corollary hypothesis** is: **the application of reclaimed water to crop irrigation produces a net savings of groundwater, energy, and carbon emissions.**

The *goal* of this research is to *further our understanding on the role of reclaimed water application in offsetting the natural groundwater resource, associated energy requirements and carbon footprint reduction in agricultural irrigation*. This study sheds light on monetary savings and environmental incentives to apply reclaimed water more extensively to crop irrigation. The work also reveals the magnitude of evapotranspiration as it relates to the water content in crops. Subsequent studies should extend the application of our methodology to crops in other regions of the world.

CHAPTER 2. Literature Review

2.1. Overview of California Water Infrastructure

Fresh water availability has always been the major constraint to growth and development in California. Although there are extensive resources in the state, most urban population reside in the water-scare coastal and southern region and most agricultural activities are in semi-arid lands. To accommodate the growth in population, California and the federal government, built a complex and expansive network of dams, aqueducts, and pumping facilities to harness California's water supplies and deliver them to its cities and agricultural areas (Hundley 2001; Nadeau 1997; Reisne 1993).

Today, California's water resources support over 38.3 million people (CDOF, 2014), a $2.2 trillion economy (IMF, 2014), and the largest agricultural sector in the country (CDFA, 2014). California's rivers, streams, lakes, and estuaries are also home to a vast array of aquatic species and habitats, and support substantial aquatic recreation. The state's water system has a total storage capacity of about 43 million acre-feet (MAF) and includes hundreds of miles of aqueducts to deliver supplies to places of need and hundreds of thousands of wells to tap the state's vast groundwater resources (DWR 2003). The system is comprised of federal, state and local projects and it's operated by federal, state, regional, and local organizations as shown in Figure 2-1.

Figure 2-1. California Water Infrastructure (MWD, 2012)

2.1.1. Central Valley Project

The Central Valley Project (CVP) was authorized in 1935 by the federal government to increase the Central Valley's resilience to drought and protect it from flooding. Shasta Dam was the first dam to be built as part of the CVP and was initiated in 1938. In 1979, the last dam, New Melones, was completed. The CVP system includes 18 other dams and reservoirs, 11 power plants, and 500 miles of conveyance and related facilities (USBR 2005). The CVP has facilities on the Trinity, Sacramento, American, Stanislaus, and San Joaquin Rivers, and it serves over 250 long-term water contractors in the Central Valley, Santa Clara Valley, and the San Francisco Bay Area (USBR 2005). The total annual contract exceeds 9 MAF (DWR/USBR 2002).

Historically, 90% of CVP deliveries serve agricultural users. In 2000, the CVP and other smaller federal projects delivered about 7.5 MAF to users. About 35% went to the Sacramento River region, 31% went to the Tulare Lake region, and 24% went to the San Joaquin region. Smaller shares went to the North Coast, San Francisco and Central Coast regions (Groves 2006). Agricultural users served by the CVP will likely experience additional price increases (Gleick et al 2005). CVP contractors are currently behind on repaying the project costs. Under the original contracts, which were negotiated and signed in the late 1940s, the project was to be paid off 50 years after its construction (USBR 1988). By 2002, however, irrigators had repaid only 11 percent of the project cost (EWG 2004). Based on an analysis of 120 CVP irrigation contracts and a review of full cost rates, which include cost of service and interest on unpaid capital costs since1982 (USBR 2000), water contractors will need to pay on average an additional 196 percent to be brought up to full cost rates. Combining the estimated price increases for CVP contractors with rising cost of service rates for the remainder of agricultural water users, Gleick et al 2005 projected that overall agricultural water price will increase by 68 percent statewide between 2000 and 2030.

2.1.2 State Water Project

The State Water Project (SWP) was the first stage of an ambitious strategy outlined in 1957 State Water Plan (DWR 1957) to improve the reliability and capacity of water delivery throughout California. The SWP captures large amounts of water behind 28 different dams in the Western Sierra Nevada. The Oroville Dam, the largest in the system with a capacity of 3.5 MAF, began construction in 1961 and was completed in 1967. The dams control the flow of water through the Sacramento River system, in order to maximize (subject to environmental and recreational considerations) the amount of fresh water that can be pumped out of the Bay-Delta into the California Aqueduct. The California Aqueduct then transports the supply south through the San Joaquin Valley to Southern California and the Central Coast. The transport of water is facilitated by 26 pumping and generating plants and about 660 miles of aqueducts. The last major component of the system – the Coastal Branch, which delivers supply to Santa Barbara and San Luis Obispo counties, was completed in 1997.

Prior to the commencement of construction of the SWP, contracts were signed between the DWR, the managers of SWP, and urban and agricultural water districts. Since the signing of the contracts in the 1960s, the capabilities of the system have not fully developed, and the SWP regularly does not meet all of its obligations. In 1998, existing long-term SWP water supply contracts totaled about 4.1 MAF (these obligations are frequently referred to as SWP Table A supplies), and these contracts are scheduled to increase to about 4.2 MAF by 2020 (DWR 2002). In the year 2000 (an average year hydrologically), however, the SWP delivered only 2.9 MAF of Table A water (DWR 2002). DWR's *State of Water Project Delivery Reliability Report* confirms that without additional facilities, the SWP will consistently be unable to meet its obligations to Table-A contractors.

The Department of Water Resources administers long-term water supply contracts to 29 local water agencies for water service from the State Water Project. These water supply contracts are central to the SWP construction and operation. In return for State financing, construction, operation, and maintenance of Project facilities, the agencies contractually agree to repay all associated SWP capital and operating costs. To provide a convenient reference, SWP Analysis Office has prepared consolidated contracts for several contracting agencies. These contracts contain the amendments integrated into the language of the original contract. Listed below, under the names of the contracting agencies, are the consolidated contracts and original contracts. DWR plans to add more consolidated long-term water supply contracts as they are completed. The 29 State Water Project contractors are shown in Table 2-1.

Table 2-1. California State Water Project Contractors (DWR, 2011)

No.	SWP Contractor Name
1	Alameda County Flood Control and Conservation District
2	Alameda County Water District
3	Antelope Valley – East Kern Water Agency
4	Butte County
5	Castaic Lake Water Agency
6	Coachella Valley Water District
7	Crestline – Lake Arrowhead Water Agency
8	Desert Water Agency
9	Dudley West Side Irrigation District
10	Empire West Side Irrigation District
11	Kern County Water Agency
12	Kings County
13	Littlerock Creek Irrigation District
14	Metropolitan Water District of Southern California
15	Mojave Water Agency
16	Napa County Flood Control and Water Conservation District
17	Oak Flat Water District
18	Palmdale Water District
19	Plumas County Flood Control and Conservation District
20	San Bernardino Valley Municipal Water District
21	San Gabriel Valley Municipal Water District
22	San Gorgonio Pass Water Agency
23	San Luis Obispo County Flood Control and Water Conservation District
24	Santa Barbara County Flood Control and Conservation District
25	Santa Clara Valley Water District
26	Solano County Water Agency
27	Tulare Lake Basin Water Storage District
28	Ventura County Watershed Protection District
29	City of Yuba

While the actual amount of entitlement for each State Water Project contractor might vary depending upon the population it serves, each agreement has a specified annual allotment amount and the duration of the contract. Contract agreement may be terminated by both parties. Table 2.2 below shows the contract agreement for the Metropolitan Water District of Southern California.

Table 2-2. Contract agreement for MWD (DWR, 2009)

Table A. Annual Entitlements		
Year No.	**Calendar Year**	**Total Annual**
1	1972	154,772
2	1973	354,600
3	1974	454,900
4	1975	555,200
5	1976	655,600
6	1977	755,900
7	1978	856,300
8	1979	956,600
9	1980	1,057,000
10	1981	1,157,300
11	1982	1,257,600
12	1983	1,358,000
13	1984	1,458,300
14	1985	1,558,700
15	1986	1,659,300
16	1987	1,759,800
17	1988	1,860,400
18	1989	1,961,000
19	1990	2,011,500
20	1991	2,011,500
21	1992	2,011,500
22	1993	2,011,500
23	1994	2,011,500
24	1995	2,011,500
25	1996	2,011,500
26	1997	2,011,500
27	1998	2,011,500
28	1999	2,011,500
30	2000	2,011,500
31	2001	2,011,500
32	2002	2,011,500
33	2003	2,011,500
34	2004	2,011,500
And each succeeding year thereafter, the amount is 1,911,500 effective Jan. 1,		1,911,500

2.1.3 Bay-Delta Region

The Bay-Delta ecosystem is a major hub of the state's water re-distribution system. In order for the large freshwater of the Sacramento River and its tributaries to be made available to users in the southern half of the state, they must flow from north through the Sacramento-San Joaquin Delta and then be pumped out of the Delta in South into the aqueducts of the State Water Project. An extensive system of levees (over 1700 km) has also developed over the years to protect agricultural and urban land holdings within the delta from water intrusion and flooding. Together, the pumping of freshwater from the south to the delta and the artificial support of the Delta's numerous islands has dramatically altered the natural hydrology and ecosystem function of the Bay-Delta system.

In response to dramatic declines in Delta ecosystem quality during the 1987-1992 drought, a Federal and State partnership was established in 1994. The purpose of the multi-billion dollar restoration and management effort, now managed by the California Bay-Delta Authority (established by the California Bay-Delta Act of 2003) is to restore ecosystems within the Delta, improve the quality and reliability of water supplies from the Delta, and stabilize the Delta's levee systems (CALFED 2006; Costa 2003). The challenge of this mandate is immense, particularly when considered along with potential climate change (Dettinger et al. 2004; Mount and Twiss 2005). The incongruent nature of the program's objectives has arguably hampered its effectiveness to date, yet the effort continues and will remain a significant consideration in future California water management and planning.

Prior to extensive human development, the San Francisco Bay-Delta was largely marsh, river channels, and islands, bounded in the west by the Golden Gate Strait and Pacific Ocean and in the East by the confluence of the Sacramento and San Joaquin Rivers which drain the Sierra

Nevada Mountains to the Pacific Ocean. The Bay-Delta in its natural state was an enormous estuary and supported extensive habitat for fish, birds, and other terrestrial animals.

Water flowing through the Delta is the main source of supply for two major California water delivery projects, the SWP and the Federal CVP. From these projects, a majority of Californian relies on water flowing through the Delta for all or part of their drinking water. In addition, approximately one third of the state's cropland uses water flowing through the Delta (DWR 2005). Figure 2-2 shows the Bay Delta water distribution during a typical hydrological year.

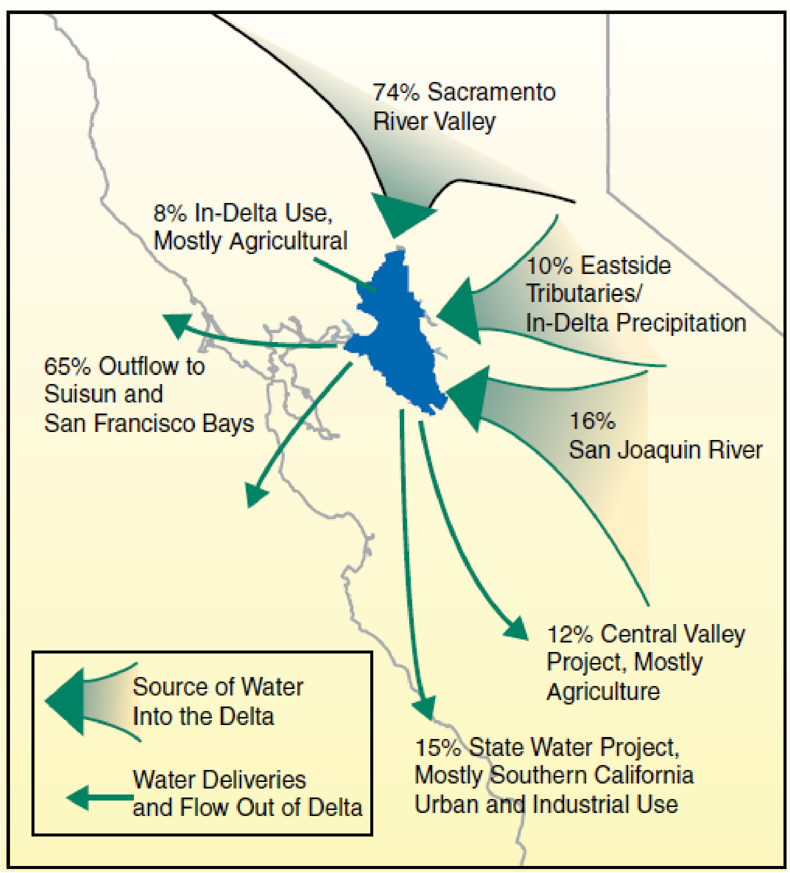

Figure 2-2. San Francisco Bay-Delta Water Distribution (DWR, 2005)

2.1.4. Colorado River Aqueduct

Several other major surface water projects serve California's cities and agricultural regions. The Colorado River supplies Southern California with more than 4 MAF a year of water via the Colorado River Aqueduct and the Coachella and All American Canals. The Colorado River Compact, signed six states bordering the Colorado River in 1922, established California's base water entitlement to be 4.4 MAF a year. In recent years, however, California has relied upon the unused allocation of upstream states, importing more than 0.8 MAF a year of additional supply some years (DWR 2005). Due to growing water use by other states, California was forced to reach an agreement to gradually eliminate its use of surplus water. The Colorado River Quantification Settlement Agreement resolves much of the uncertainty over Colorado River allocations, but an on-going drought in the Colorado River basin still threatens future Colorado River water availability to California.

The iconic Colorado River supplies water to millions of people in fast-growing cities in Colorado River's watershed, such as Las Vegas, Mexicali, Phoenix, and St. George, Utah. Tens of millions of people outside the watershed, from Denver to Albuquerque and from Salt Lake City to Los Angeles, San Diego and Tijuana, also receive water exported from the basin to meet at least some of their residential and commercial water needs. More than half of the people receiving water from the basin live in Southern California (Cohen, M. 2011). Figure 2-3 shows historical water supply and usage for the Colorado River Basin from 1914 to 2007.

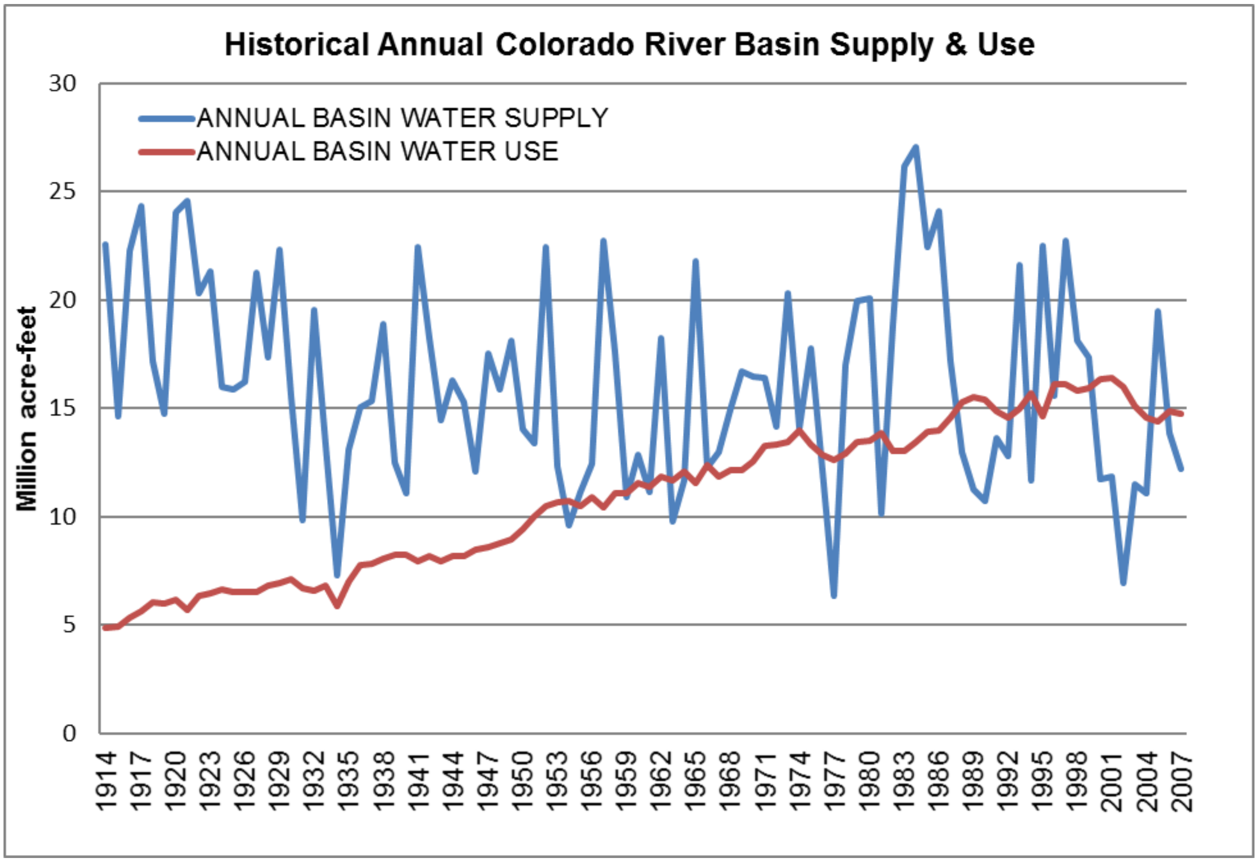

Figure 2-3. Historical Colorado River Supply and Demand (USBR, 2011)

2.6. Other surface water supply projects

Local cities in California have also taken initiative to develop water supplies. The cities of Los Angeles, San Francisco, and several in the East Bay region have all financed and constructed infrastructure to capture, store, and transport water from sources far away from the municipalities. Specifically, the Los Angeles Aqueduct transports water over 200 miles from the Owens Valley to the Los Angeles area; the O'Shaughnessy Dam captures and stores water in the Hetch Hetchy Valley for delivery to San Francisco and surrounding cities; and the Pardee

Reservoir and Mokelumne Aqueducts supply the East Bay Municipal Water District service area with supplies from the western slopes of the Sierra Nevada (Reisner 1993 and Hundley 2001).

2.1.5. Groundwater Development

Groundwater is a major source of water for California's agricultural industry and municipalities. During an average year a third of the state's water supply comes from groundwater. Some regions are entirely dependent on groundwater, and 40-50% of Californians use some amount of groundwater (DWR 2003). Much of the state's groundwater resources have been developed locally by individual landowners or municipalities. Such decentralized management has led to unsustainable groundwater use in California. Estimates by DWR in 1980 suggest that use of groundwater exceeds recharge by between 1 and 2 MAF per year (DWR 2003). Such overuse has led and will continue to lead to many serious problems including land subsidence, sea water intrusion, and degradation of groundwater quality.

Groundwater is currently managed through local water agencies, local groundwater management ordinances, and court adjudication. Importantly, state and regional planning agencies have little influence or control over the management of groundwater, making it difficult to implement integrated surface and groundwater management plans.

The total groundwater storage in California is estimated to be about 1.3 billion acre-feet and about 140 MAF of precipitation percolates into the state's aquifer annually (DWR 1994). These estimates however, do not characterize the potential water supply for the region – many other factors limit the development potential of an aquifer (DWR 2003). Most of the state's groundwater is located in the aquifers beneath the Central Valley, although Southern California also has considerable amount of groundwater.

Groundwater is a major contributor to the state's water supply and even more so in dry years. As shown in Figure 2-4, groundwater supplies on average 30 percent of California's overall demand and up to 40 percent in dry years (DWR 2003). In some areas where surface water supplies are not accessible or economically feasible, groundwater provides 100 percent of a community's public water (DWR 2003). During years where surface water deliveries are not available, groundwater may also provide up to100 percent of irrigation water for certain areas. About 43 percent of Californians obtain at least some of their drinking water from groundwater sources.

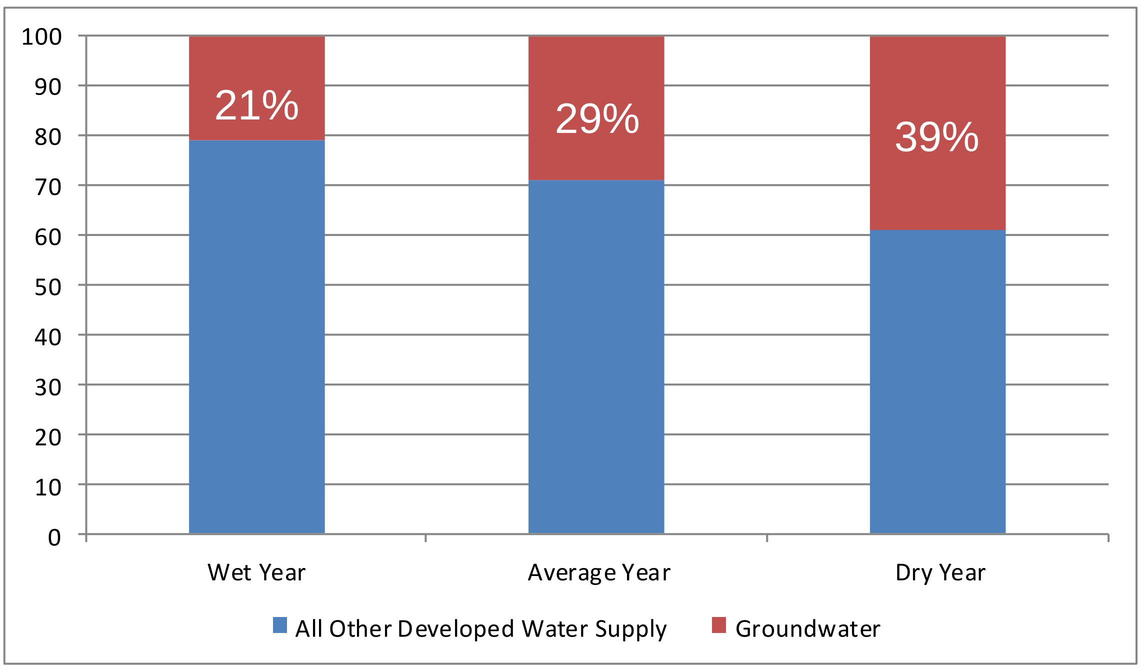

Figure 2-4. Typical Groundwater Supply in California (DWR, 2003)

2.1.6. Urban water reuse

Local municipalities and regional water agencies are increasingly turning to alternative sources of water supply. Treated urban wastewater is becoming an important source of water for agriculture, industry, landscaping, and some non-potable uses in commercial and institutional buildings. In many regions it is discharged into rivers and streams and thus used by downstream users. In some regions it is also blended with conventional sources and is injected or allowed to percolate into groundwater basins. The Southern California Comprehensive Water Reclamation and Reuse Study (USBR 2002), for example, provides a comprehensive assessment of existing reuse and reuse potential in Southern California.

2.2. History and Timeline of Major California Water Projects

The following is a review of key moments in history that changed water policy, from passage of water rights legislation to the voter approval of the State Water Project (SWP). Although there are other significant events, however, they are not deemed as relevant and significant to this research and hence are not included. As shown in Figure 2-5, the first Colorado River delivery was made to the farmlands of the Imperial Valley was in 1901 and the major compact agreement was signed in 1922, designating specific allocation to the upper and lower Colorado basins for all seven states (Wyoming, Colorado, Utah, Nevada, New Mexico, Arizona and California). The Central Valley Project and State Water Project were authorized for construction in 1933 and 1951 respectively. In 1973, the first State Water Project delivery was made to Southern California and the Federal Safe Drinking Water Act was passed in 1974 setting the first ever standard for drinking water throughout the country. In 1998-2003, the Colorado Quantification Settlement Agreement was reached between California and other Colorado River Basin states and the Federal Government. As a result of this agreement, California received its allocation of 4.4 MAF which still serves as the state’s allotted water share even until today.

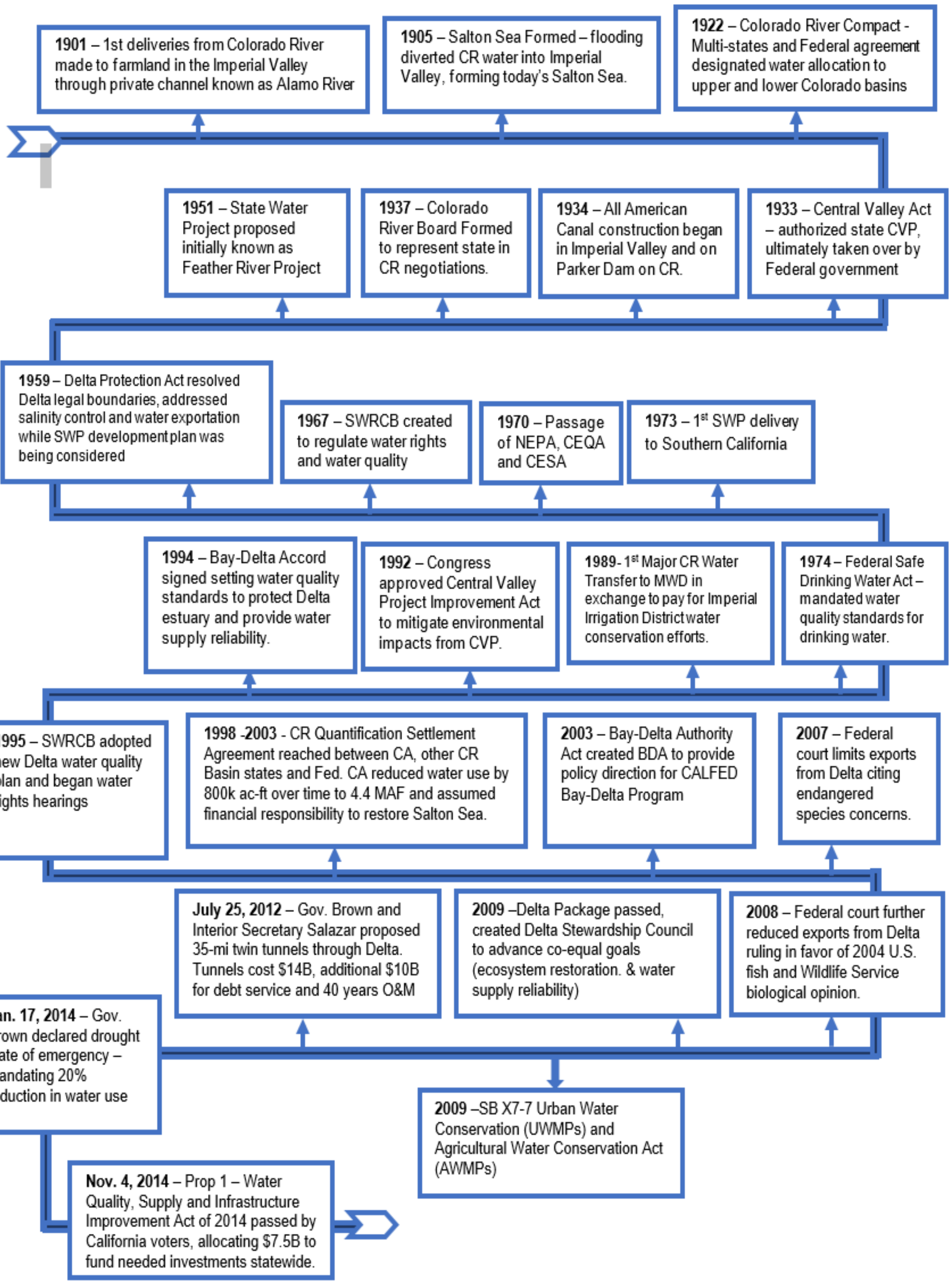

Figure 2-5. Historical timeline of major California water projects (DWR, 2011)

2.3. State Agencies Involved with Water Management

Many state agencies are involved with California water management as shown in Table 2-3. While overlapping responsibilities might occur in terms of broad objectives, generally, there is not duplication of functions. Most agencies focus on a specific subset of water management, for example, the State Water Resources Control Board (SWRCB) and the Department of Water Resources (DWR) are the two leading water management agencies. They have mandated water supply objectives, however, their roles differ greatly. DWR focus on water delivery, water supply planning, and infrastructure development, while SWRCB is more of a regulatory body, managing water rights and water quality permitting (both of which have effects on water supply). These roles are complementary and often require the two agencies to work in concert to address water management at the state level.

Table 2-3. State Agencies Involved in Water Management (SWRCB, 2003)

State Agency	**Responsibilities**		
	Water Supply	**Water Quality**	**Flood Control**
Department of Water Resources	X		X
State Water Resources Control Board	X	X	
California Public Utilities Commission	X	X	
Colorado River Board	X		
Department of Pesticide regulation		X	
Department of Toxic Substances Control		X	
Office of Environmental Health Hazard Assessment		X	

The management of California water systems consists of three main components: water supply, water quality, and flood control. Most agencies involved in one or more of these components also have responsibilities for scientific activities and monitoring and administering financial assistance for local water infrastructure. For example, several financial assistance programs attempt to jointly address water quality and water supply needs at the local levels, thereby providing more comprehensive local water supply reliability. Other state agencies not listed may be involved with water management as part of their greater mission (for example, the Department of Conservation manages a state watershed program).

2.3.1. Non-State Agencies Involved with Water Management

At the federal level, most agencies have distinct roles, for example, the United States Environmental Protection Agency focuses on water quality, while the United States Bureau of Reclamation focuses on water supply. However, these roles can overlap and potentially duplicate state efforts, for example, both state and federal entities estimate the state's water supply resources, although the state has a more comprehensive role through the efforts of DWR.

At the local and tribal levels, most entities play multiple roles including both water supply and water quality ones. Local entities can be both regulated and regulatory entities, receiving permits from state agencies for water quality while in return regulating their constituents to meet those permitting requirements as shown on Table 2-4. In some respects, these roles may duplicate those of state and federal efforts. For example, federal, state and local water agencies may each be independently investigating the development of new water supply sources to potentially serve the same region of the state.

Table 2-4. Non-State Agencies Involved in Water Management (SWRCB, 2003)

Non-State Agency	Responsibilities		
	Water Supply	Water Quality	Flood Control
Federal Agencies			
Bureau of Reclamation	X		X
Army Corps of Engineers	X		X
Environmental Protection Agency		X	
Geological Survey	X	X	
Other Entities			
Tribal Governments	X	X	X
Cities and Counties	X	X	X
Special Districts[1]	X	X	X
Private Water Companies	X		

[1]The 1,200 plus water districts in California perform a wide range of activities, both water and non-water related. Many districts provide more than one of the three designated water services (water delivery, sanitation, or flood control). Lighting, recreation and park, and street maintenance services are the most common non-water activities performed by the state's water districts.

2.3.2. Challenges of Water Regions Definitions

Water regions defined by DWR and SWRCB are similar but not identical. SWRCB works in conjunction with nine semiautonomous regional boards (each having policy-setting responsibilities) while the DWR divides the state into ten hydrological regions governed from Sacramento headquarters. Although, some activities of DWR and SWRCB require coordination among regions and between the two state agencies, their differences in regional definitions can pose a challenge for implementing programs, planning or accounting for California water resources. Figure 2-6 shows the difference in regional boundaries between DWR and SWRCB.

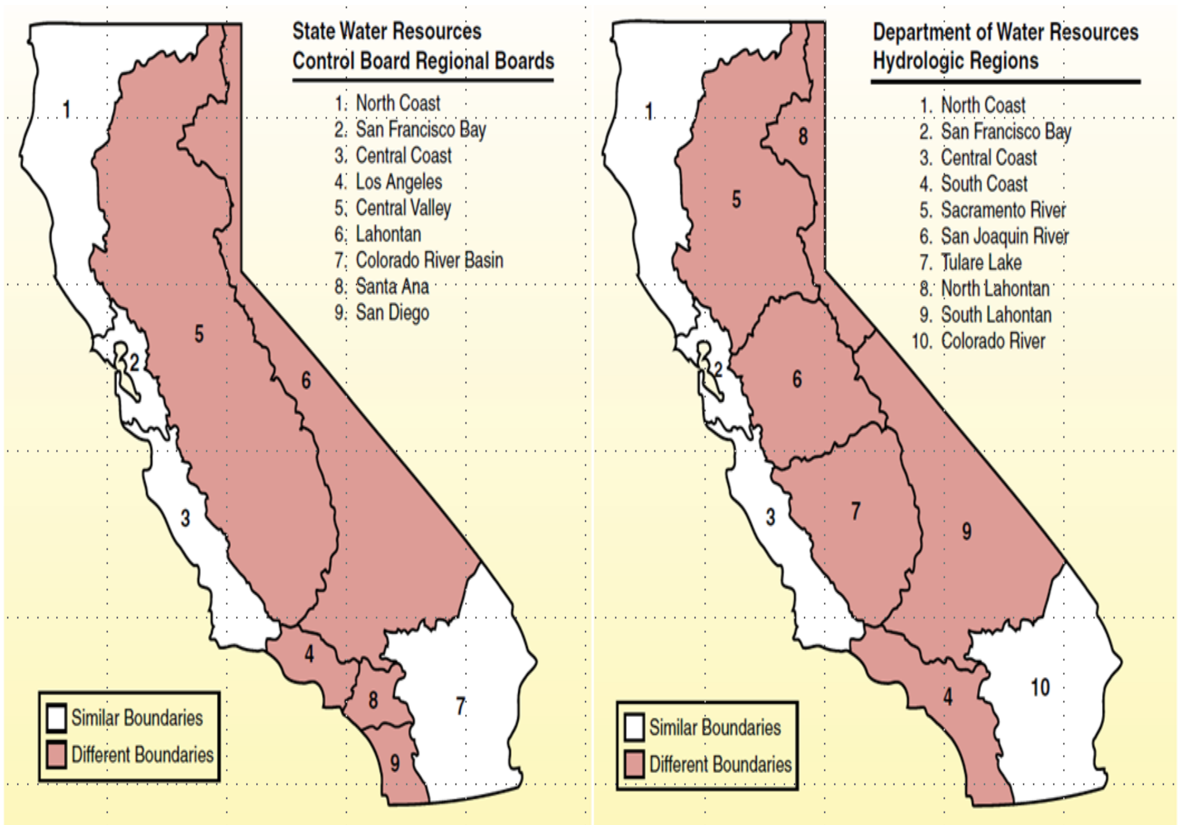

Figure 2-6. SWRCB and DWR Regional Boundaries (DWR, 2009)

2.3.3. California Top Water Rights Holders

Water right is legal permission to use a specified amount of water for a beneficial purpose such as drinking, fishing, irrigation, farming or industry. SWRCB regulates water rights for those taking water from lakes, rivers, streams, and creeks. It does not regulate the rights to use underground water supplies (groundwater), which are primarily regulated by a patchwork of local laws. Figure 2-7 shows the top water rights holders in California as indicated by the SWRCB.

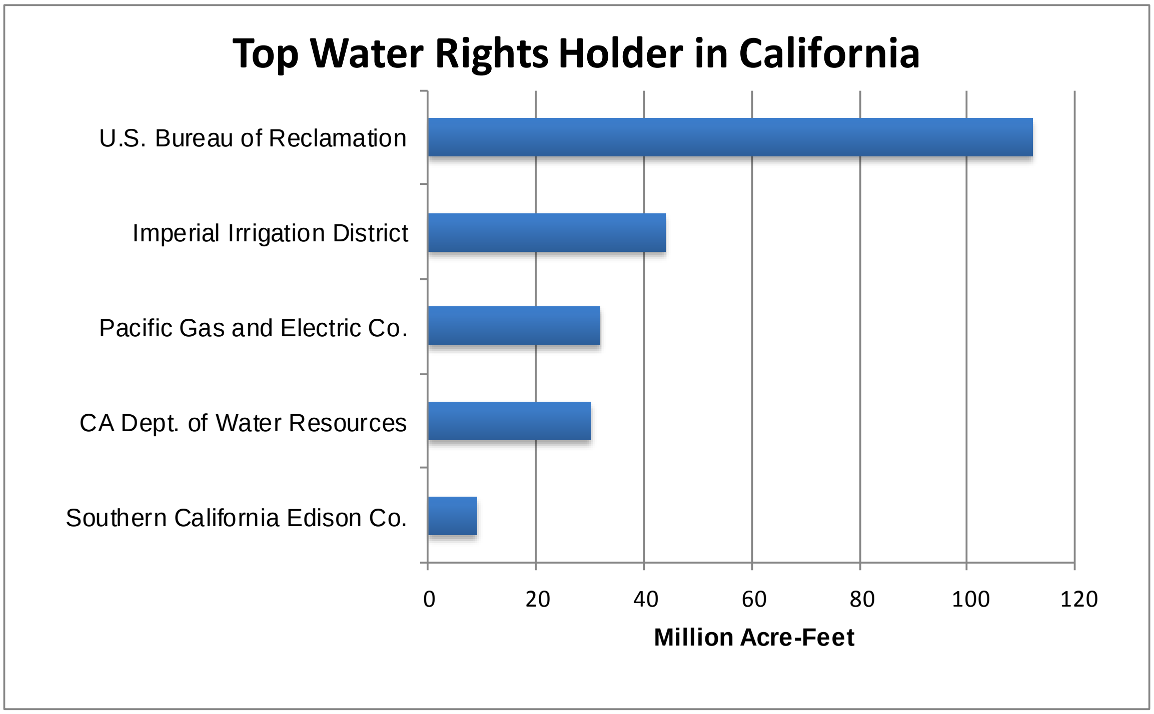

Figure 2-7. Top Water Rights Holders in CA (adapted from DWR, 2009)

The Federal government holds the most (in volume) water rights in the state with over 112 MAF of water rights mainly for delivery through the federal Central Valley Project. Second to this area are the water rights held by Imperial Irrigation District (44 MAF) serving mainly farms in the Colorado River region. Water rights exceed actual total water volume availability on almost all river systems of the state. This is partly because water may be reused as it runs off farms or may be returned to the river after use for a non-consumptive purpose such as energy production. In some cases, water rights are oversubscribed and exceed actual water availability (SWRCB).

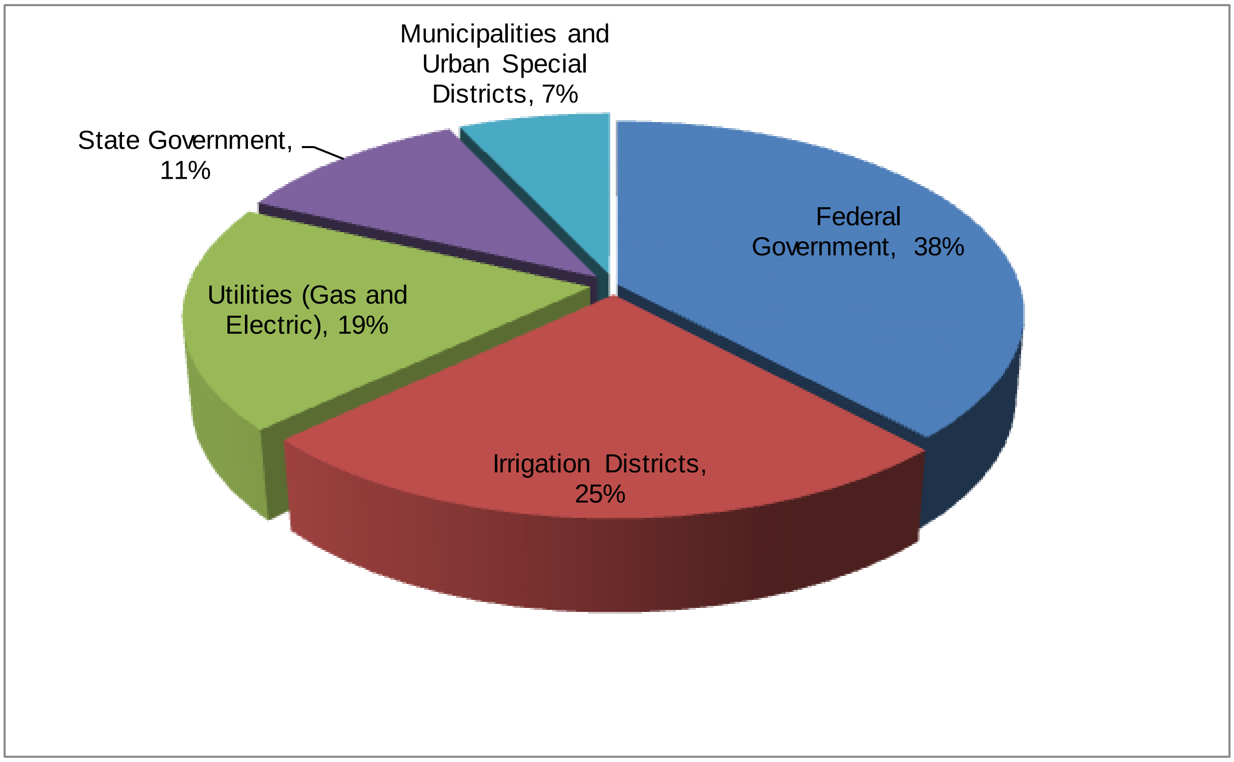

Figure 2-8. Percentage of Water Rights Holder (data from DWR, 2009)

Of the top 25 water rights holders (generally over one MAF), the federal government holds much of the water rights, while irrigation districts and utilities make up much of the rest of the water rights holders as shown in Figure 2-8. State and urban local agencies hold less than 20 percent of the water available.

2.4. Current Water Use and Supply

As described above, California's water supplies originate from many sources including local surface water projects, groundwater, inter-regional surface water deliveries such as State Water Project, Colorado River imports, treated wastewater, and natural stream flow. In 2005, DWR estimated that California used about 40.2 million acre-feet of water. Of this amount, roughly 78% (31.2 million acre-feet) was used by the agricultural sector, while the remaining 22% (9 million acre-feet) was used by urban users.

Table 2-5 shows historical estimates of urban water use published by DWR for the years 1972 to 2005. Urban water appears to have grown along with the state's population (Figure 2-9). Water declined during the drought in the 1990's, but appears to have rebounded. Per capita urban water use does not appear to have changed significantly over time (Figure 2-10). From 2000 to 2005, per capita water use averaged 229 gallons per capita per day. The data appear to show that statewide average per capita urban water use has changed little over time over the period from 1972 to 2005 (Christian-Smith et al 2012).

Table 2-5. Historical urban water use in California (CDOF, 2011)

Year	Urban Water Use (maf/year)	Population (millions)	Per Capita Water Use (gal/person/day)
1972	5.04	20.6	219
1975	5.07	21.8	208
1980	5.76	23.8	216
1985	6.59	26.1	225
1989	7.36	29.1	226
1990	7.24	30.0	215
1991	6.45	30.6	188
1992	5.79	31.3	165
1993	6.88	31.7	194
1994	7.57	32.1	211
1995	7.27	32.1	203
1998	7.84	32.7	214
2000	8.86	34.0	233
2001	8.62	34.5	233
2002	9.00	34.9	232
2003	9.00	35.4	227
2004	10.08	35.8	237
2005	9.05	36.0	224

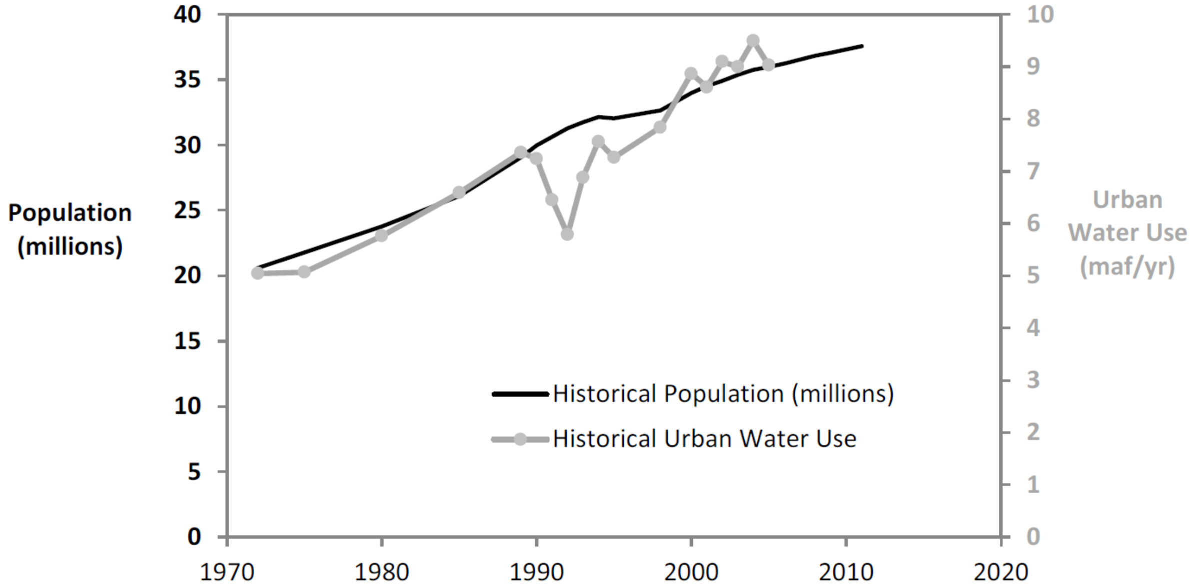

Figure 2-9. Historical population and urban water use in California (Christian-Smith et al., 2012)

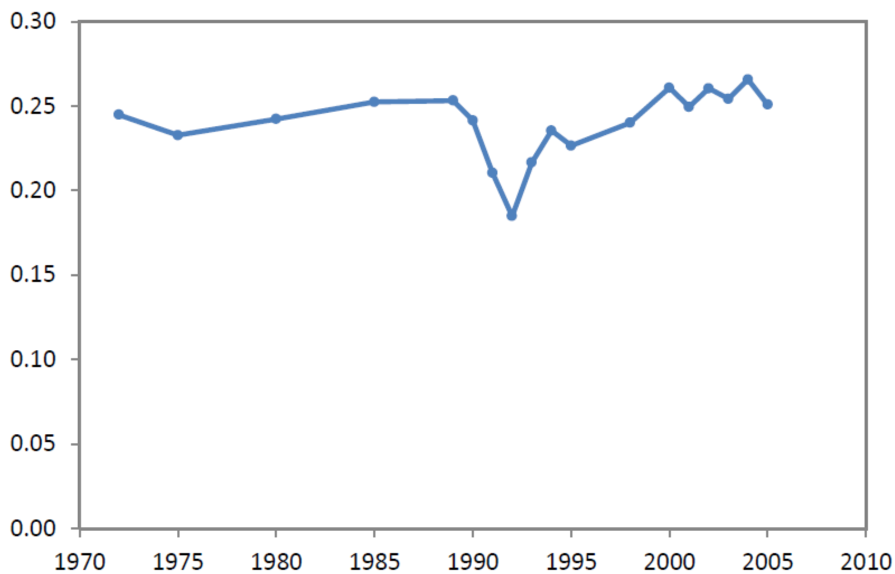

Figure 2-10. Urban water use factor acre-feet per person per year (Christian-Smith et al., 2012)

Compare to the year 2000, a typical water year, total water supply of 43.1 MAF was used to supply agricultural and urban sectors. Figure 2-11 shows the proportions of water use by each sector and the corresponding non-stream supply for California for this year. Almost 80% of non-environmental water supply is used by the agricultural sector, and more than half of the urban use is by households. One third of all supply originated from local sources and another third is from groundwater and reuse. The remaining third came from the big water management projects – the State Water Project, the Central Valley Project and the Colorado River.

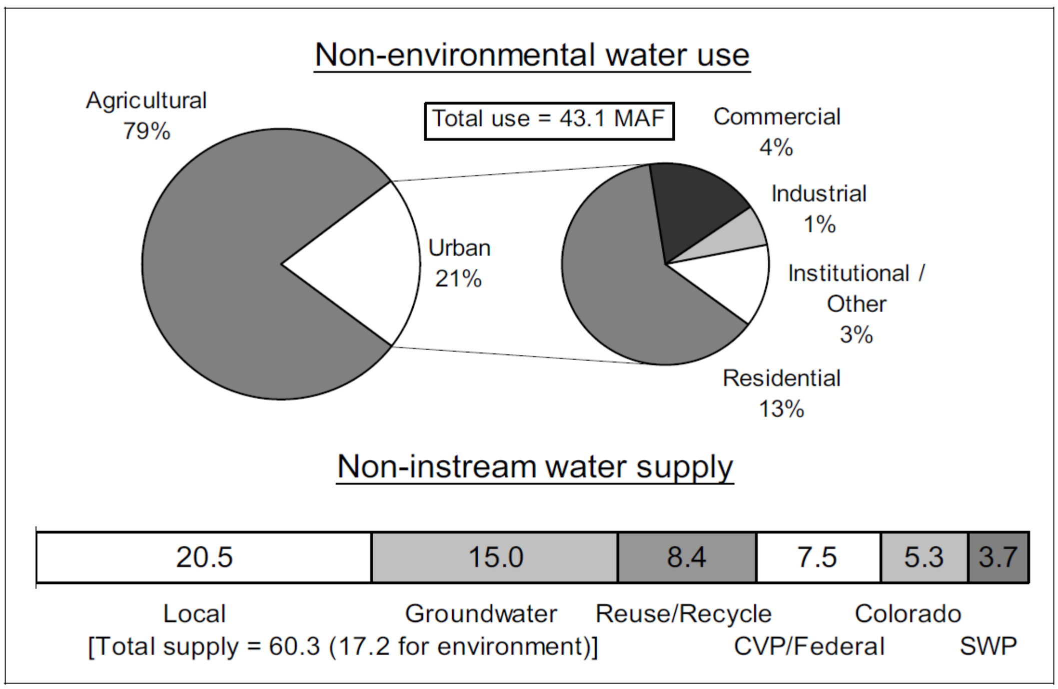

Figure 2-11. California Water Supply (DWR, 2003, Groves 2006)

Figure 2-12 shows a graphic (created by DWR) that illustrates the significant movement of water across the state. The figure shows that about a quarter of the water that flows into the Bay-Delta region from the Sacramento and San Joaquin Rivers and other tributaries (over 11 MAF in 2000) is diverted from the Bay-Delta region for distribution throughout the southern portion of the state. Much of the supply exported from the Bay-Delta (about 2.5 MAF in 2000) is delivered to agricultural regions in the southern Central Valley, supplementing their surface water (7.5 MAF in 2000) and groundwater supplies (1.9 MAF in 2000). The remaining Bay-Delta exports (1.5 MAF in 2000) are delivered via the California Aqueduct to urban regions along the Central Coast and to Southern California. Southern California also imports substantial water supply from the Colorado river (about 1.3 MAF in 2000) to supplement its local resources.

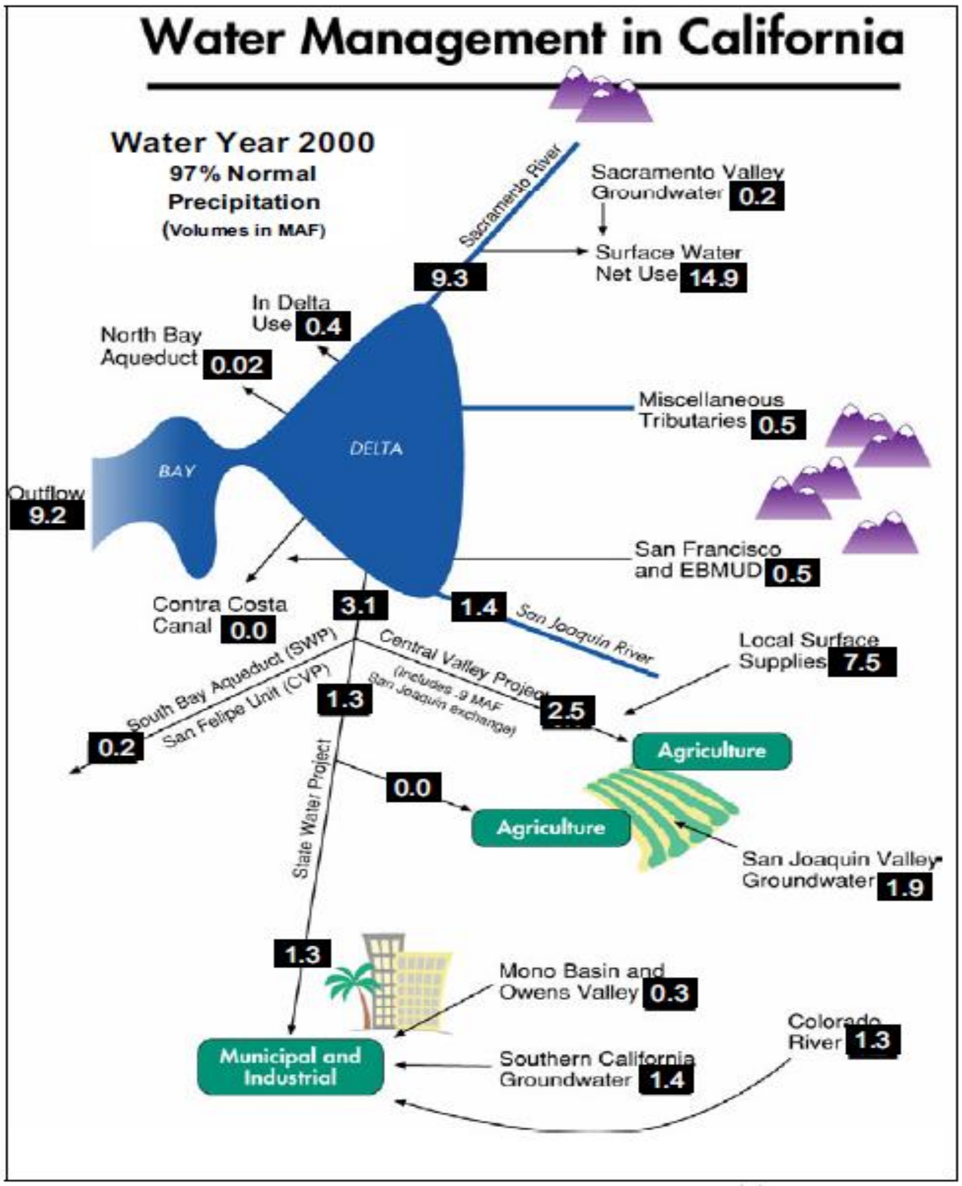

Figure 2-12. State-wide water management (DWR, 2003)

2.5. Water-Energy Relationship

Water and energy are inseparable. The two resources are inextricably entwined. Energy is needed to pump, treat, transport, heat, cool and recycle water. Likewise, the force of falling water turns the turbines that generate hydroelectric electricity, and most thermal power plants are dependent on water for cooling (CEC 2005). In California, concurrent demands for energy and water usage have continued to rise. As a result, the need to plan and implement efficient technologies and using alternative sources are critical to the success of California's future.

Water usage for energy generation in California varies greatly, depending on the primary energy source, conversion technologies, and cooling technologies used. Figure 2-13 illustrate the state's typical water use cycle.

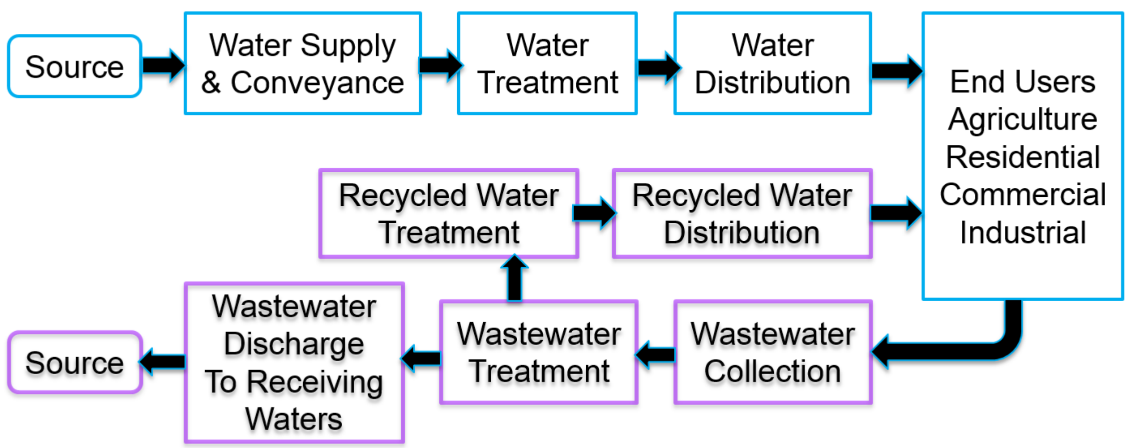

Figure 2-13. Typical Water Use Cycle (Wilkinson, 2000)

Water is first extracted from a source. It is then transported to water treatment facilities and distributed to end users. What happens during end use depends on whether water is for agricultural or urban use. Wastewater from urban uses is collected, treated and discharged back to the environment, where it might become a source for someone else. Energy is required in all stages of the water use cycle. It is difficult to measure the amount of water-related energy that is actually consumed. Figure 2-14 indicate the total water-related energy consumption used in California at approximately 19% of all electricity and 32% of all natural gas generated in the state in the year 2005 (CEC 2005).

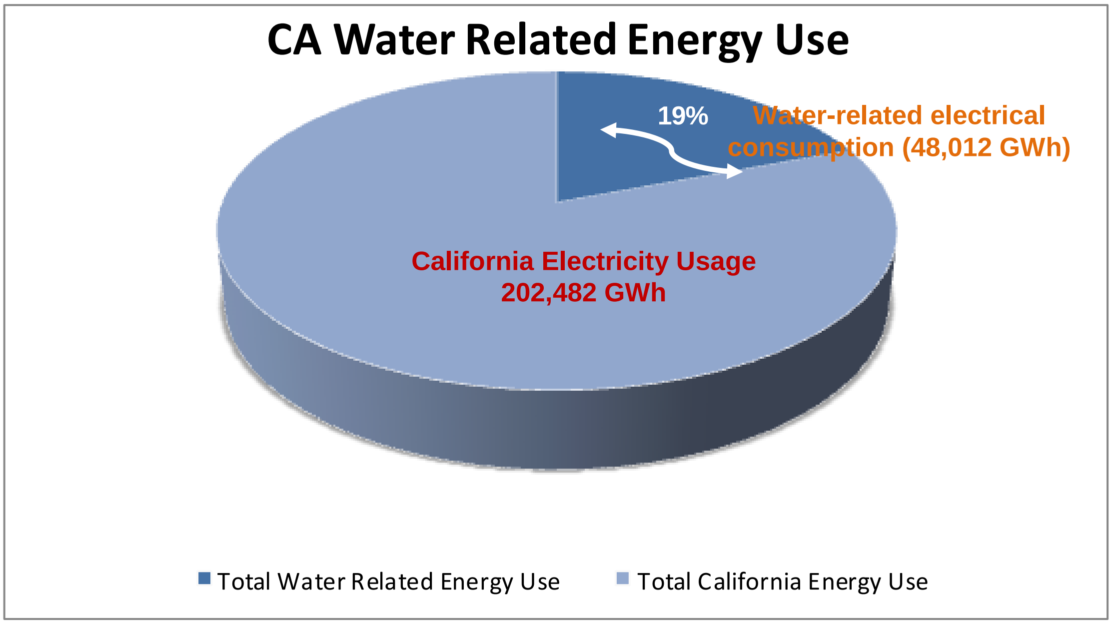

Figure 2-14. Water Related Energy Use (CEC, 2005)

A closer analysis of the 19% electrical consumption related to water-energy indicates that 50% of this energy is utilized in transporting the water and using it at home as shown in Figure 2-15.

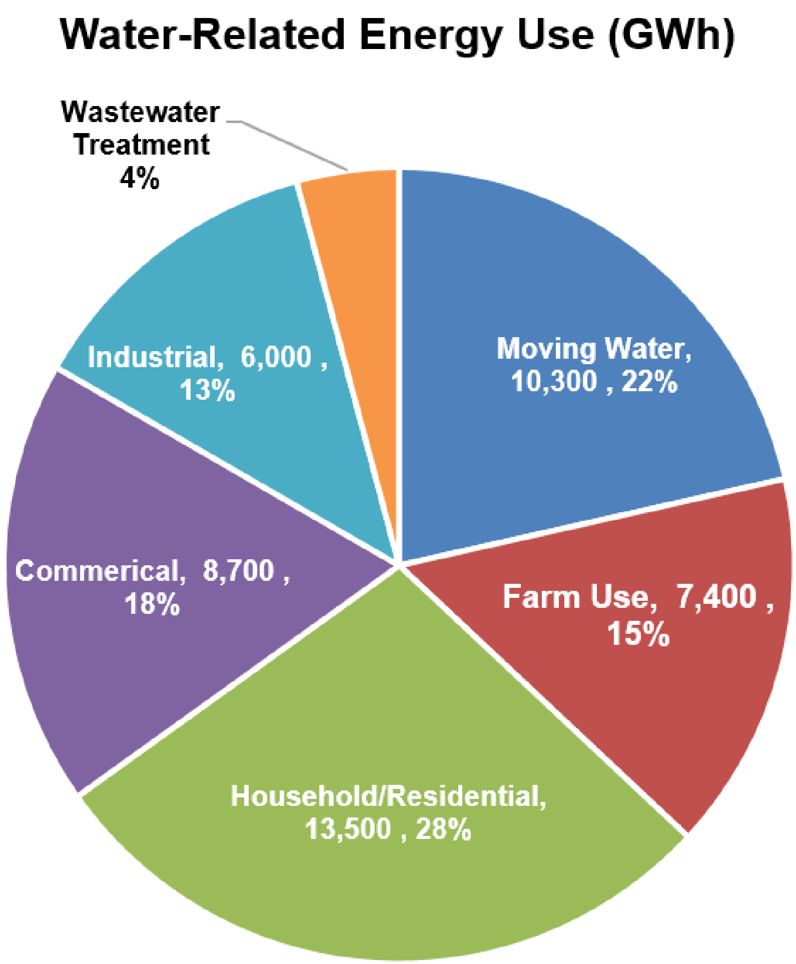

Figure 2-15. Household water use (CEC, 2005)

Due to significant variations in energy used to convey water supplies form one place to another, the average energy intensity of water use cycle in Southern California is much greater than in Northern California. This is due to the fact that Southern California imports about 50% of its water from the Colorado River and from the State Water Project (SWP). Each of these supply sources is more energy intensive than any single source of water supply used in Northern California (CEC 2005). Table 2-6 illustrates the combined energy intensity of the water use cycle for urban communities in Northern and Southern California.

Table 2-6. Electricity Use in Typical Urban Water Systems (adapted from CEC, 2005)

Category	Northern California	Southern California
	(kWh/m^3)	(kWh/m^3)
Water Supply and Conveyance	5.68.E+05	3.37.E+07
Water Treatment	3.79.E+05	3.79.E+05
Water Distribution	4.54.E+06	4.54.E+06
Wastewater Treatment	9.46.E+06	9.46.E+06
Total	1.50.E+07	4.81.E+07

2.6. Climate Change Effects

By and large, California's reservoirs and water delivery systems were designed and operated based on historical hydrology. However, with climate change, this mode of traditional operation may no longer be valid (DWR 2009). When it comes to climate impacts in the next 20-50 years, "utility planners will have to grapple with many of them prospectively rather than as phenomena that are already observable" (Cromwell et al. 2007). According to DWR, temperatures across California has risen one degree Fahrenheit on average. This increase in temperature has decreased the spring snowpack in the Sierra Nevada Mountains by about 10 percent which is equivalent to a reduction of 1.5 million acre-feet of water. Seasonal snowpack in the Sierra Nevada has always been the largest surface water storage for the state. Sea level along the California's coast has also risen by about 7 inches (DWR 2009). Climatology experts advise that the warming of air temperatures may cause our normal precipitation to shift from snow to rain. This would lead to serious reduction in the amount of snowpack, an important natural reservoir for storing water in the winter and supply California with water in the spring snowmelt. Figure 2-16 provides an estimate of the average reduction in snowmelt water content based on rising temperatures.

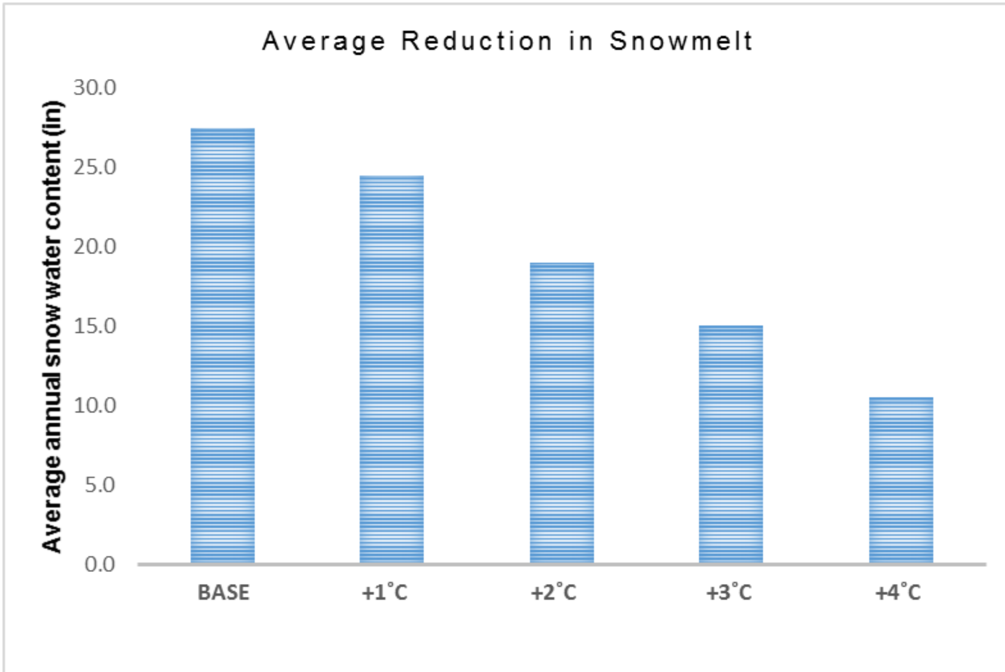

Figure 2-16. Average Annual Snowmelt, Lake Oroville, California (NOAA, 2005)

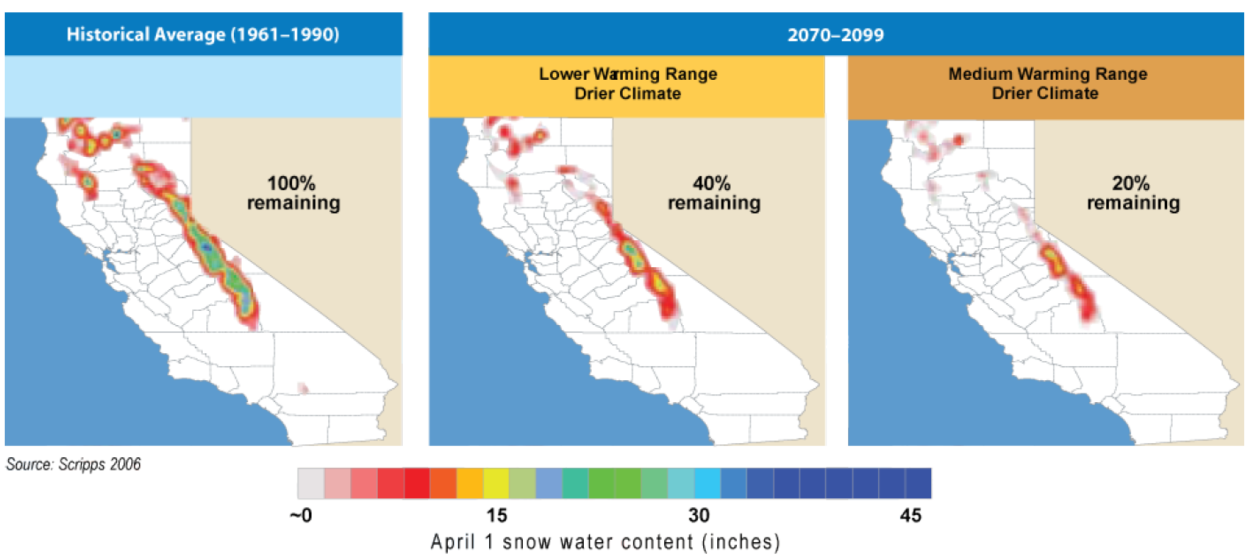

Figure 17. Decreasing California Snowpack (Scripps, 2006)

California water planners further suggest that more changes are expected to come as we head towards the year 2050 and beyond. Some of those changes may include another rise in mean temperature by 1.5 degrees Fahrenheit which may decrease the Sierra Nevada snowpack further to 25 percent, a near storage volume of about 3.8 million acre-feet. Figure 2-17 provides an estimate of the snowmelt reduction based on projected future temperatures. Figure 2-18 shows the increased in flood events as recorded by DWR from 1910 to 2000.

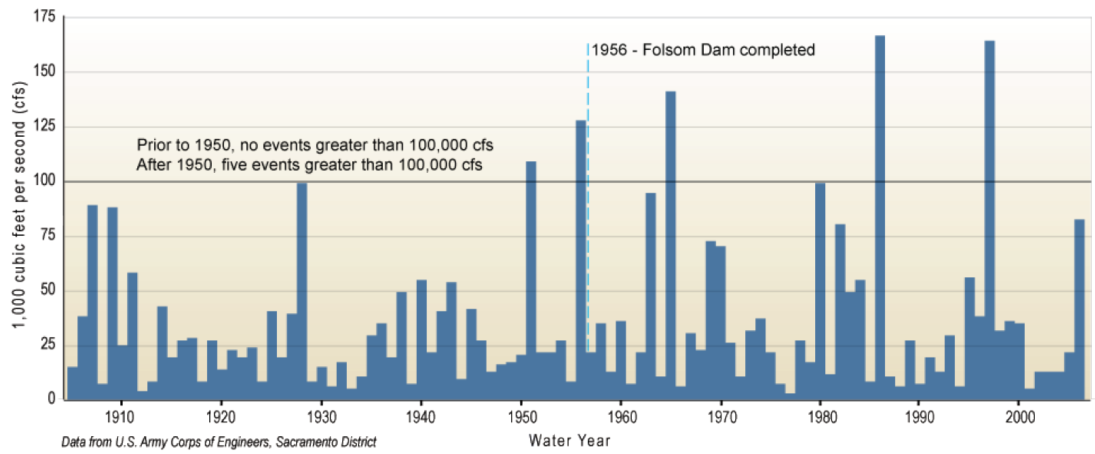

Figure 2-18. Historical Annual Runoff - American River (USACE, 2010)

Climate change is already having a profound effect on California's water systems as evidenced by the changes in snowpack storage, river flows, and sea levels. Scientific studies show these changes will increase stress on the water systems in the future. Because some levels of the climate change is inevitable, California water systems must be adaptable to change (DWR 2009). The impacts of these changes will gradually increase during this century and beyond. California needs to plan for water system modifications that adapt to the impacts of climate change. Figure 2-19 shows a possible global sea level rise of 4 to 6 inches by mid-century. Higher sea levels will increase the salinity in the Delta, disrupting the freshwater supply and quality that many Californians traditionally rely on.

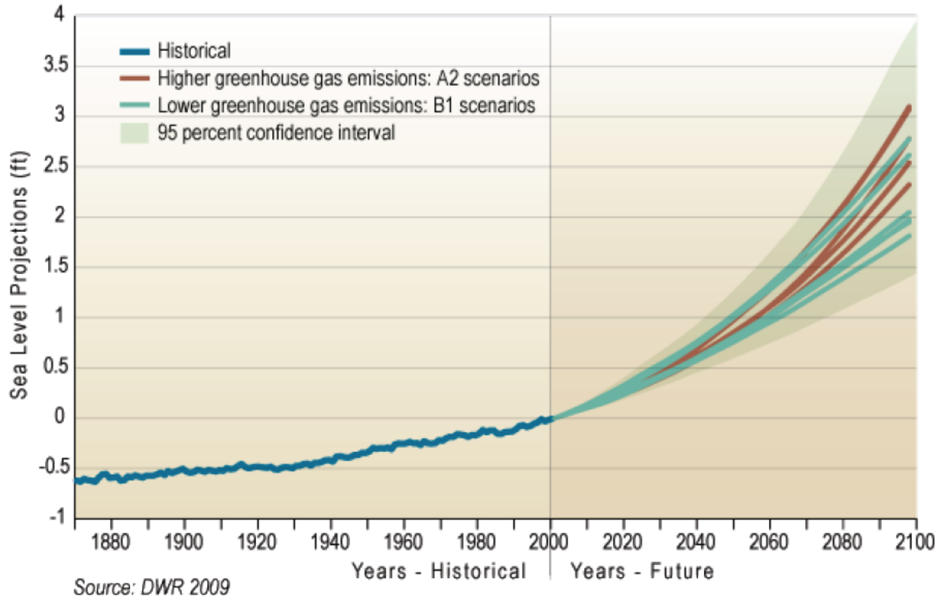

Figure 2-19. Historical and Projected Sea Level at Golden Gate (DWR, 2009)

2.7. Water Conservation

While California's urban water use has grown steadily with population, some areas of the state have succeeded in lowering per capita water use. For example, in 2011, urban water use in Los Angeles was 123 gpcd, among the lowest in the state (LA DWP, 2012). A Study by DeOreo et al. 2011 found that more than half (53%) of California water use for single-family residences was for outdoor uses. DWR 2011 also reported that residences account for about two-thirds of urban water use. In 2005, residential use accounted for an estimated 66% of total urban water use in California. Water planners believe that this number can be curtailed with improvements in water-use efficiency and conservation by means of rebates and incentives. Studies have shown that people consume less water at higher prices (Campbell et al, 2004; Olmstead and Stavins, 2007). Water agencies and utilities are also encouraged to implement conservation and efficiency programs, termed best management practices, outlined in the of California Urban Water Conservation Council's Memorandum of Understanding (CUWCC 2011). Statewide regulations mandating conserving practices have also been put in place, most notably were in 2004, a law requiring water suppliers to install water meters on all customer connections by 2025 (AB 2572); the imposition of water budgets and water-efficient landscaping on most new large landscapes (Model Landscape Ordinance AB 1881, 2010); and the requirement that water suppliers and local governments improve the coordination between land and water use planning through preparation of Urban Water Management Plans and Urban Water Shortage Contingency Analyses (SB 221 and SB 610, 2001).

In 2001, Orang et al. (2005) conducted an irrigation method survey throughout California. That analysis shows that for all crops combined, the use of gravity/flood irrigation and sprinklers has declined, while micro/drip and sub-irrigation use has increased (Figure 2-18). Using historical data on irrigation methods by crop type (grouped as field, vegetable, orchard, and vineyard crops) between 1972 and 2001. Gleick et al 2005 used a linear trend to calculated and project the irrigation method for 2030. The result of their estimate is shown in Figure 2-20.

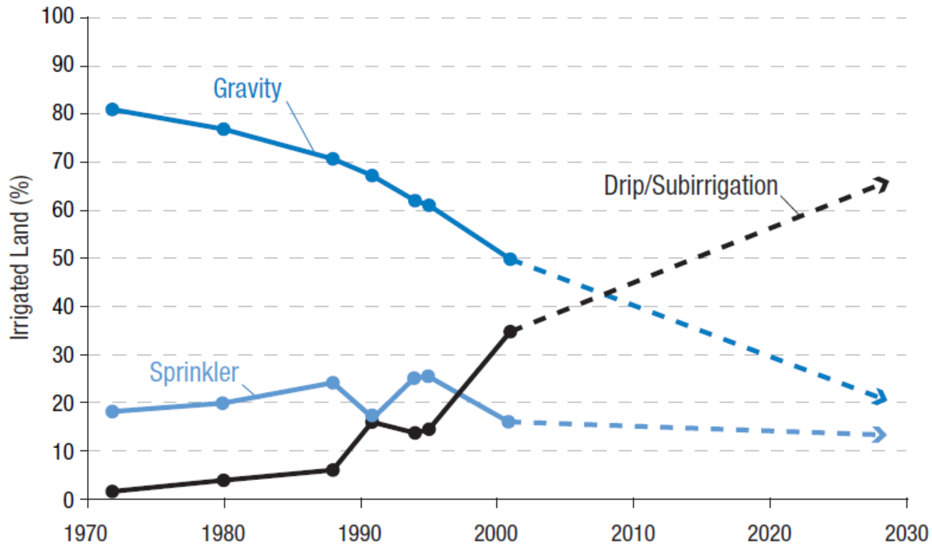

Figure 2-20. Historical Irrigation Methods (Gleick et al, 2005)

2.8. Summary of Literature Review

Water footprint assessment has become as a useful quantitative tool for assessing water consumption of goods and services. Following the introduction of the virtual water footprint concept, various studies were conducted to quantify global virtual water flows between nations as have been carried out by Hoekstra and Hung (2002, 2003), Chapagain & Hoekstra (2003), Zimmer and Renault (2003) and Oki et al (2003). Virtual water flows and water footprint assessments became important elements in evaluating global and national water budgets as noted by Chen and Chen (2011a), Duarte et al., (2002), Guan and Hubacek (2007), Hubacek et al. (2009), Velazquez (2006), Yang et al. (2006), Yu et al. (2010), Zhao et al., (2009, 2010).

The majority of water footprint studies thus far have been limited to quantifying the overall virtual water requirement as a cumulative measure to reach a final crop product. No study to date has focused specifically on quantifying the physical water content contained in agricultural products being exported and relating it to the water exportation induced through evapotranspiration. The total exported water in agricultural products will physically leave a geographical boundary, whether in the crops or in a form of evapotranspiration or combination of both, whereas a significant portion of the virtual water footprint may still remain within the same spatial domain. Hence, from a hydrological perspective the exported water content causes a spatial imbalance in the water supply cycle, irreversibly for the portion contained in the crops. It is therefore warranted that research be conducted to quantify the exported water content to better assess water use efficiency and practices in agricultural irrigation. It is also warranted to analyze the associated energy intensity and carbon footprint assessment of water supply sources used in irrigation to assess and determine effective uses of California's water and energy resources. Table 2-7 and 2-8 illustrate existing water footprint studies currently available in the literature.

Table 2-7. Summary of Water Footprint Studies

Water Footprint Studies	Author(s)
GLOBAL / INTERNATIONAL LEVEL	
Global water footprint and International virtual water flows between nations	Hoekstra and Hung, 2002; Zimmer and Renault, 2003; Hoekstra and Chapagain, 2008; Hanasaki et al., 2010; Konar et al., 2011; Mekonnen and Hoekstra, 2011; Dalin et al., 2012; Zhan-Ming and Chen., 2013
NATIONAL LEVEL	
Australia	Lenzen, 2009
China	Guan and Hubacek, 2007; Zhao et al., 2010
India	Verma et al., 2009
Spain	Dietzenbacher and Velazquez, 2007; Aldaya et al., 2009
SUB-NATIONAL / REGIONAL LEVEL	
California Water Footprint	Fulton et al., 2012
California and Illinois Virtual Water Trades	Mubako et al., 2013

Table 2-8. Summary of Literature Review

Research Topic	Availability	Author(s)
Virtual water trade between nations	Yes	Hoekstra and Hung (2002, 2003)
Virtual water flows between nations in livestock and product trades	Yes	Chapagain & Hoekstra (2003)
Globalization of water resources	Yes	Hoekstra and Hung (2005)
Global virtual water in food production	Yes	Zimmer and Renault (2003)
Global water trade and world water resources	Yes	Oki et al (2003
Modeling of greenhouse gas emissions and natural resources of world economy	Yes	Chen and Chen (2011a
Virtual water use in Spain	Yes	Duarte et al., (2002
Quantification of exported water in California agricultural products	No	
Assessment of virtual water flows in China	Yes	Guan and Hubacek (2007
Environmental implications of ecological and water footprints of China	Yes	Hubacek et al. (2009)
Analyzing water relationships in Andalusia		Velazquez (2006)
Energy analysis of applying reclaimed water for crop irrigation in arid and semi-arid regions	No	
Assessing regional and global water footprints for UK	Yes	Yu et al. (2010)
National water footprint of China	Yes	Zhao et al., (2009, 2010).
Energy intensity analysis for West Basin Municipal Water District	Yes	Wilkinson, R. (2007)
Energy footprint of brackish groundwater in inland areas of Arabian Peninsula	Yes	Sobhani et al., (2012)
Analysis of Energy Intensity of Inland Empire Utility Agency	Yes	Wilkinson, R (2000)
Virtual water transfers of California and Illinois	Yes	Mubako et al., (2013)
California Virtual Water Footprint	Yes	Fulton et al., (2012)

CHAPTER 3. Quantification of water exported through agriculture: case of California

3.1. Abstract

Agricultural irrigation plays a significant role in the overall water consumption of the world's water resources. As the largest agricultural region in the U.S. and the leading exporter of many agricultural products, we used California as a case study to assess the overall exported water associated with agricultural water trades. We used the term 'exported water' to differentiate from that of the virtual water footprint in that the former is the physical water content exported outside of a geographical boundary. Therefore, the exported water is permanently lost and is no longer available for local hydrologic cycle from its origin. The total exported water is defined as the physical water content contained in crops plus the induced evapotranspiration as a result of irrigation. A data set was compiled for 50 of the top exported commodities using most recent and available data from the years 2000-2012. Our results show that on average, the overall exported water in California's agricultural products was 2.88 x 10^{10} m^3 yr^{-1}, equivalent to 68.3% of the total water used in agricultural irrigation. The majority of the exported water is in the form of induced evapotranspiration, totaling 67.7% of the total water used in irrigation annually. The physical water content contained in the crops was found to be approximately 2.32 x 10^8 m^3 yr^{-1} representing only 0.6% of the total water used in irrigation and is less than 1% of the associated induced evapotranspiration. Our results show that the physical water content contained in crops was insignificant relative to the associated evapotranspiration of the irrigated crops. The results confirm that irrigation contributes to the increase in surface

evapotranspiration and that a significant amount of exported water is lost to the atmosphere via evapotranspiration. Figure 3-1 provides a graphical summary of the findings.

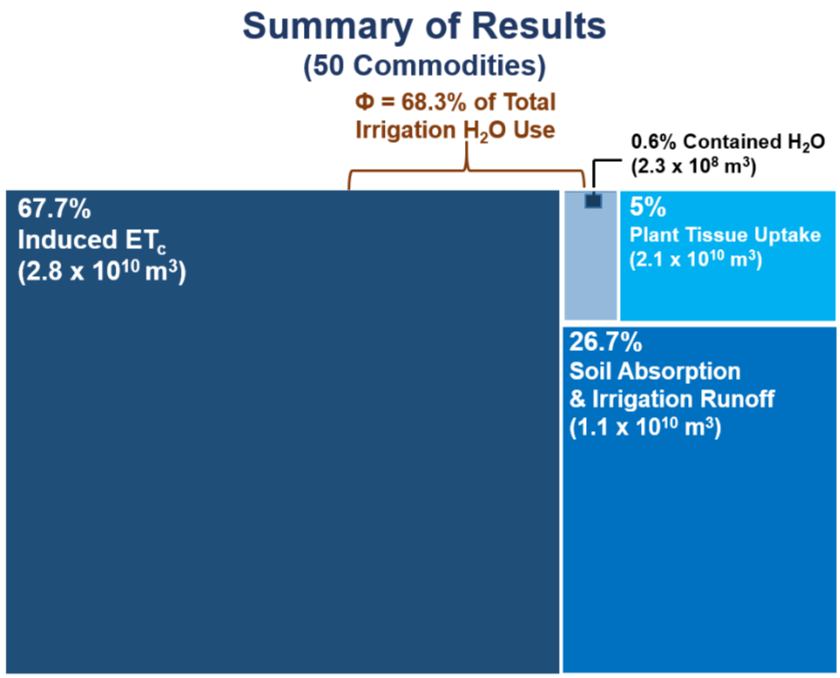

Figure 3-1. Summary of calculated ETc and contained water content

3.2. Introduction

The fact that the annual water used in growing California agricultural products is far greater than the total urban water use is well publicized (Letey and Birkle, 2003). On average, the Californian agricultural industry consumes 80.6% of the state's water resources, while urban water use consumed 19.4% from the years 1998-2010 (Nguyen et. al., 2015). California exports agricultural products to more than 156 countries with earnings totaled $18.18 billion USD (CDFA 2013, 2014) as shown in Figures 3-2 and 3-3. Today, California's water resources support over 38.3 million people, see Figure 3-4 (CDOF, 2014), a 2.2 USD yr-1 trillion economy, (IMF, 2014) as shown in Figure 3-5 and the agricultural region with largest cash receipt in the United States (CDFA, 2014) as shown in Figure 3-6. In a typical year, the Californian agricultural industry irrigates 3.3 x 10^6 ha of land using approximately 4.2 x 10^{10} m^3 of freshwater (Nguyen et al., 2015).

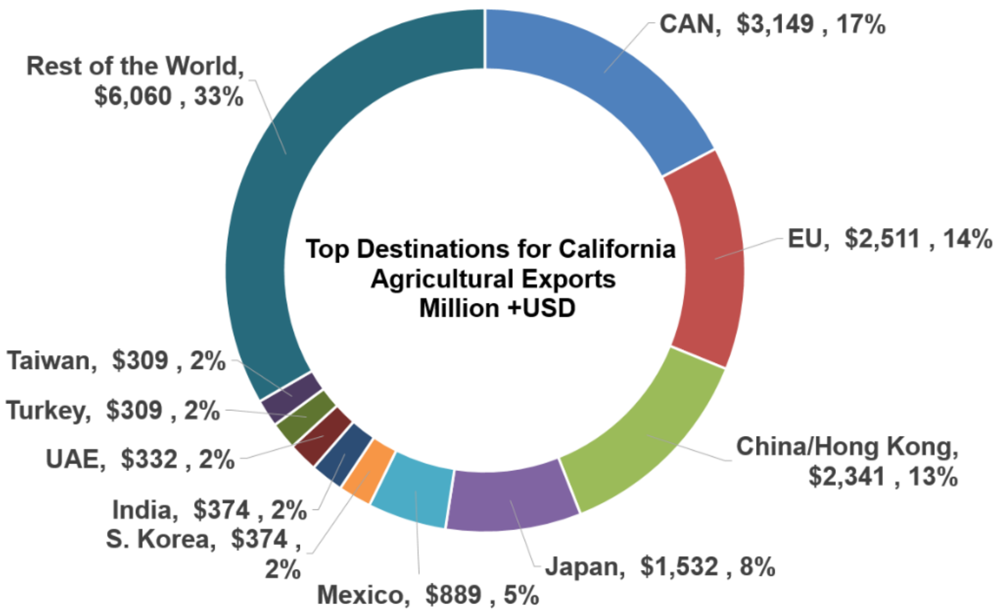

Figure 3-2. Top Destinations for California Agricultural Exports (CDFA 2014)

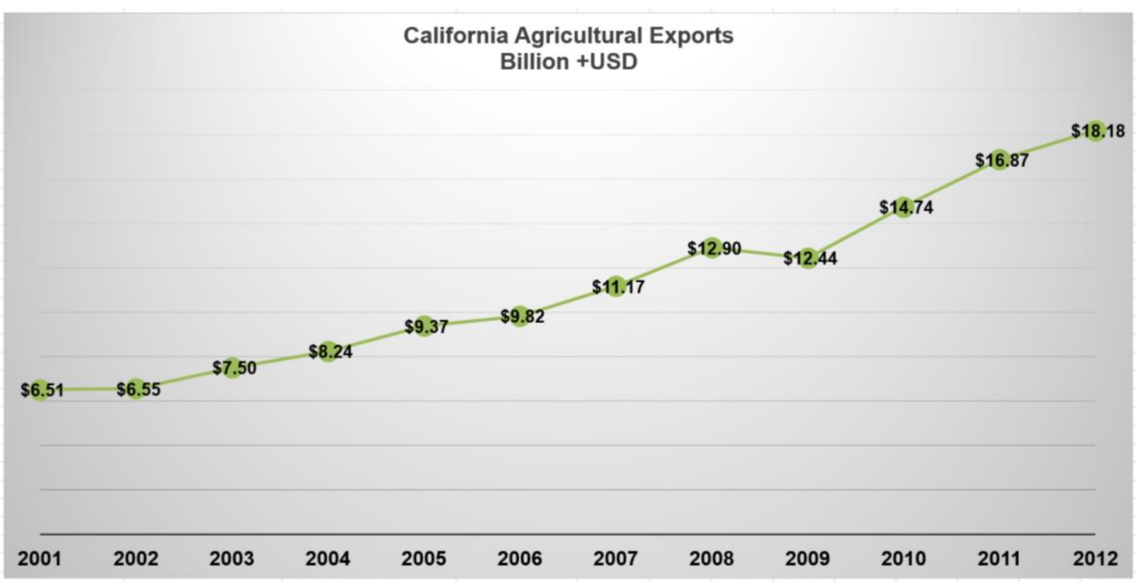

Figure 3-3. Historical Export Revenues (Adapted from CDFA, 2013)

As pressures on water resources intensify globally, there is a growing interest in evaluating the complex ways in which human activities impact the world's water resources (Postel et al., 1996; Vorosmarty et al. 2007., Alcamo et al. 2007; Hoekstra and Chapagain 2008; Gleick and Palaniappan 2010; Fulton et al., 2012). Globally, the majority of water consumption is used in the production of agricultural products (Mekonnen and Hoekstra, 2011, Mubako et al., 2013). As a result, the agriculture industry is by far, the most dominant water-using sector. To assess the amount of water used throughout the production and distribution process to produce a final product, researchers have used the term 'water footprint', to describe this quantity (Hoekstra and Chapagain, 2007). Water footprint assessments have emerged as a tool for quantifying consumption of everyday goods and services in one location and the cumulated water use associated with the production of those goods and services in other distant locations (Fulton et al., 2014).

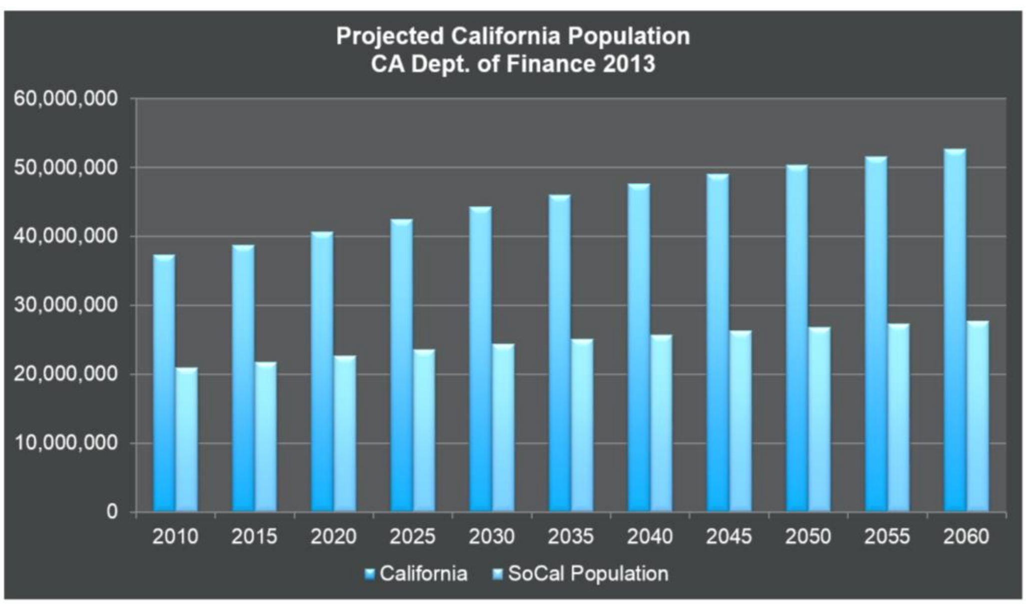

Figure 3-4. California project population (adapted from CDOF, 2013)

Originated from an ecological standpoint (Odum, 1971, 1983), the concept of 'virtual water' was first introduced by Allan (1993, 1994) to describe the transfer of water resulting from exports of water-intensive commodities from comparatively water-abundant regions to water-scare regions. Allan (1998, 1999, 2003) argued that international agricultural food trades were equivalent to exporting water in its virtual form and observed the trend in national governments becoming more dependent on other countries for their water security. Hoekstra and Hung (2002, 2003) then introduced the concept of 'water footprint,' as a quantitative measure to assess virtual water content consumed by an individual or individuals of a nation for goods and services.

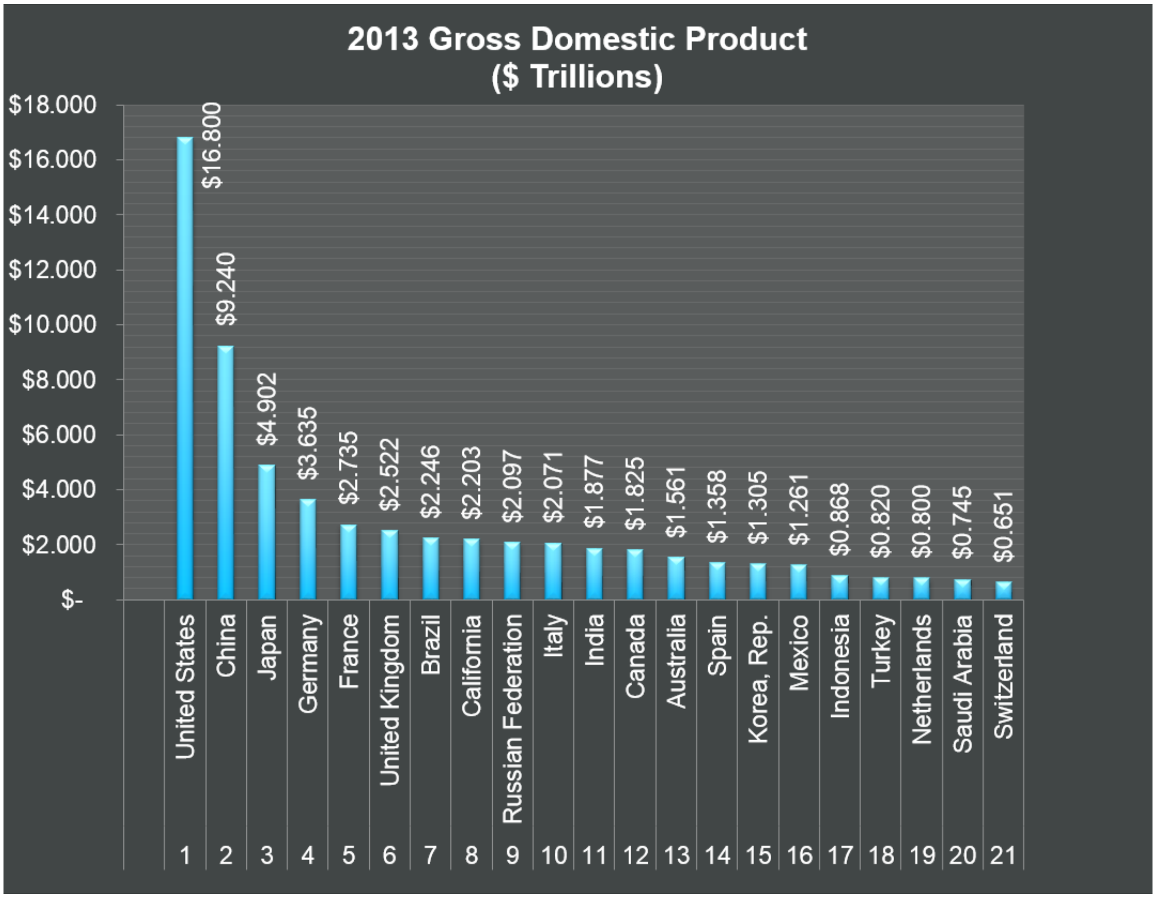

Figure 3-5. World Economic Outlook (adapted from IMF, 2014)

Following the introduction of the water footprint concept, various studies were conducted to quantify global virtual water footprints and assessed virtual water flows between nations (Hoekstra and Hung, 2002, 2003), (Chapagain & Hoekstra, 2003), (Zimmer and Renault, 2003) and (Oki et al., 2003). Virtual water flows and water footprint assessments became important elements in evaluating local, national, and global water budgets as reported by Chen and Chen (2011a), Duarte et al., (2002), Guan and Hubacek (2007), Hubacek et al. (2009), Velazquez (2006), Yang et al. (2006), Yu et al. (2010), Zhao et al., (2009, 2010). In addition to assessing virtual water footprints in food products, virtual water footprints in non-food products were also examined. Hoekstra and Chapagain (2007), assessed water footprints of different countries using calculated data from Chapagain and Hoekstra (2003) and Hoekstra and Hung (2002, 2005).

Subsequently, Mekonnen and Hoekstra (2011) improved upon data presented by Hoekstra and Chapagain (2007) and provided a more complete and detailed global virtual footprint assessment. By categorizing global water resources into green, blue, and gray water, Mekonnen and Hoekstra (2011a) showed that the international virtual water trade in agricultural and industrial products were 2320 billion cubic meter (Gm3) per year in the period 1996-2005, equivalent to 26% of the global water footprint of 9087 Gm3. (Mekonnen and Hoekstra, 2011) noted that although practically, every country participates in the global virtual water trade, few governments explicitly consider assessing virtual water footprint and its impact in their management policies.

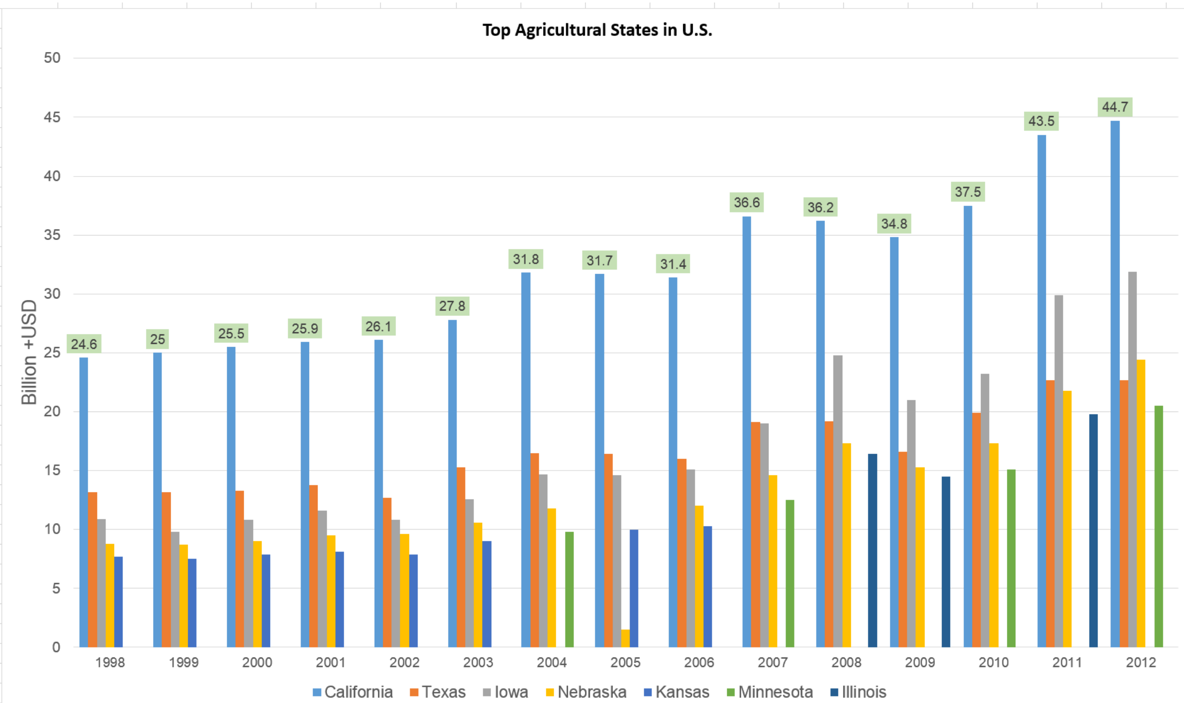

Figure 3-6. California Historical Cash Receipts (adapted from CDFA, 2014)

The majority of water footprint studies have examined international virtual water footprints between nations (Hoekstra and Hung, 2002; Hoekstra and Chapagain, 2008; Hanasaki et al., 2010, Konar et al., 2011; Mekonnen and Hoekstra, 2011, Dalin et al., 2012; Zhan-Ming and Chen., 2013). Few have also analysed the virtual water footprints at a sub-national or state level such as regions within Australia (Lenzen, 2009), China (Guan and Hubacek, 2007; Zhao et al., 2010), India (Verma et al., 2009), and Spain (Dietzenbacher and Velazquez, 2007; Aldaya et al., 2009). Within the United States, two studies have also been conducted. Fulton et al., (2012) reported that California imported more than twice virtual water as it exported and that more than 90% of its water footprint is associated with agricultural products. Mubako et al., (2013) quantified virtual water for California and Illinois, and reported that the two states were net virtual exporters in agricultural water trades.

Previous studies on virtual water footprints at global, national and sub-national levels including the ones conducted by Fulton et al., (2012) and Mubako et al., (2013) only aimed to quantify the cumulative water footprint required to produce a final product. None however, has focused specifically on quantifying the physical water content contained in agricultural products being exported. The total exported water in agricultural products is distinctively different than the overall virtual water footprint in that the former is physically exported outside of a geographical boundary, whereas parts of the water used in quantifying virtual water footprint may still remain within the local geographical boundary and may be absorbed or reused in some ways. Thus, from a hydrological perspective, the exported water content in crops is permanently lost and is no longer available for local regeneration from where it originated. We make a distinction to differentiate this quantity of exported water content in agricultural products because previous virtual water studies only focused on quantifying the cumulative virtual water flows or the total water footprint. In addition to the physical water content contained in agricultural products, irrigation associated with agricultural activities has also been shown to have a direct contribution on local and regional climate by increasing surface evapotranspiration

(Sorooshian et al., 2011, 2012; Kueppers and Snyder 2012; Wei et al., 2013 and Lo and Famiglietti 2013).

Our research hypothesis is that for each unit of crop exported, there is a greater loss of water induced through evapotranspiration than the physical water content contained in the crops. The aim of this research is to test our hypothesis by using California as a case study to assess the overall exported water associated with agriculture by (i) quantifying the contained water content in the exported crops and (ii) quantifying the direct induced evapotranspiration associated with those exported crops. Due to availability of public data and the extensive number of crops produced in California, we focus our research on the top 50 crops which make up the majority of water consumption and gross receipt for California by examining the latest available data from the years 2000-2012.

3.3. Methods

3.3.1. Model structure

Using data provided by the United States Department of Agriculture (USDA), California Department of Food and Agriculture (CDFA), and the Irrigation Training and Research Center from California Polytechnic State University San Luis Obispo (ITRC), a data set was compiled including each of the 50 crops analyzed, associated production acreages, total mass of production and percentage of exports. To quantify for the actual water contained in the crops and the induced evapotranspiration, we developed the following equations.

$$\sum H_2O_{exported} = \sum (H_20_{contained} + H_20_{InducedET_c}) \quad (1)$$

where $H_2O_{contained}$ is the actual physical water content contained in each of the crop being analyzed. To find the physical water content in each of the crop, we calculate the water content using the following equation.

$$H_2O_{contained} = (\%_{MoistureContent} \cdot mass_{crop}) \quad (2)$$

where percent (%) $_{\text{MoistureContent}}$ is obtained from USDA Nutrient Database Laboratory (see appendix).

H_2O $_{\text{Induced ETc}}$ is the induced evapotranspiration as a result of a specific crop calculated using the ET factor for each commodity provided by ITRC times the total planting area of the crop.

$$H_2O_{InducedETc} = ETc \cdot Area_{crop} \quad (3)$$

Additionally, using the results of the data we compiled, three dimensionless ratios were also computed. Contained Water Index, Induced Evapotranspiration Index and Exported Water Index.

Contained Water Index (χ) is calculated as follows.

$$\chi = \frac{massH_2O_{Contained}}{mass_{CropExported}} \quad (4)$$

Induced Evapotranspiration Index (ω) is calculated as follows.

$$\omega = \frac{mass_{H_2O,InducedET}}{mass_{CropExported}} \quad (5)$$

Exported Water Index (**Ω**), is therefore, calculated as follows.

$$\Omega = \chi + \omega \quad (6)$$

A diagrammatic structure of the model we have developed **is** illustrated in Figure 3-7.

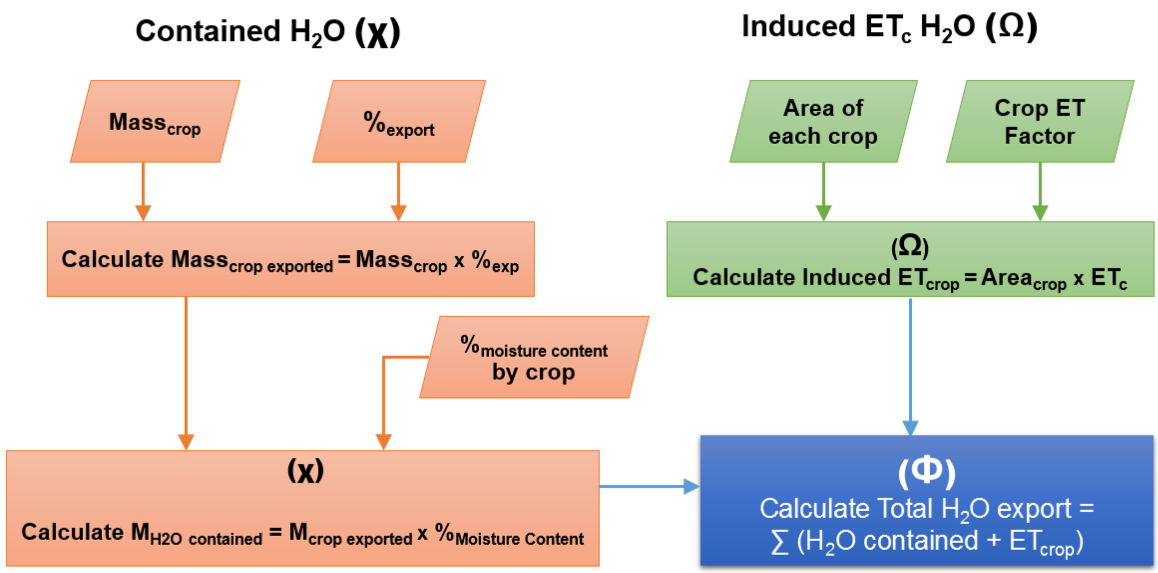

Figure 3-7. Exported water model developed using data from USDA, CDFA, and ITRC

3.3.2. Spatial domain

California was selected as the region to test this model. The state has a total area of 4.2 x 10^5 km^2 which includes 58 counties, all of which has agricultural activities totaling 44.7 billion +USD in cash receipt and export revenues of 18.2 billion +USD (USDA, 2013). California consistently ranks at the largest agricultural state in the U.S. for many decades. The region is home to 305 known agricultural products and is the sole producer of 99 percent or more of many commodities exclusively grown for international exports (USDA 2013). California agricultural industry is the largest water user with estimate of 4.2 x 10^{10} m^3 yr^{-1} of freshwater use for agricultural activities (Nguyen et al., 2015).

3.4. Results and Discussion

The results show that from 2000 to 2012, of the 50 commodities we have analyzed in this study, the annual average crop production was 1.57 x 10^9 metric tons in California, of which an estimated 17% was exported internationally for a total of 2.63 x 10^8 metric tons. The contained water content associated with the exported crops was calculated at 2.32 x 10^8 m^3 yr^{-1} representing 0.6% of the total annual water used in irrigation for California. In contrast with the water uptake by plant tissues, typically reported at 5% of irrigation water use (McElrone et al., 2013), the contained water content represents 11% of the total water absorbed by plant tissues calculated at 2.1 x 10^9 m^3 yr^{-1}. The induced evapotranspiration water associated with irrigation for the exported crop was calculated at 2.85 x 10^{10} m^3 yr^{-1} equivalent to 67.7 % of the total annual water used in crop irrigation. The total exported water (contained water content in crops plus induced evapotranspiration water) associated with the exported commodities altogether was calculated at 2.88 x 10^{10} m^3 yr^{-1} which represents 68.3% of the total water used in irrigation annually. Our results show that the actual water contained in the crop is significantly less relative to the associated exported water in the form of induced evapotranspiration. The results indicate that the actual physical water contained in crops only represent 0.81% of the total induced evapotranspiration water resulted from irrigating and growing of the exported crops. When comparing the results of the calculated induced evapotranspiration to the Field Capacity Model recently reported by Sorooshian et al., (2014), our results represented 97% of the model prediction. This finding suggests that irrigation of agricultural products play a significant role in consuming the total water used in crop production. The results also confirm that agricultural irrigation does have a direct impact in contributing to the increase in surface evapotranspiration as previously reported by Wei et al., (2013), and Lo and Famiglietti, (2013).

When computing for the overall total exported water for each crop (contained water content plus associated induced evapotranspiration water), we find that hay, grapes, almonds, rice, cotton, wheat, walnuts, tomatoes, oranges, lettuce, pistachios, plums, peaches and nectarines, broccoli and avocados were the leading 15 crops consuming most of the water used in irrigation. A detailed list of annual exported water consumed by each of the 50 crops is shown in Figure 3-8.

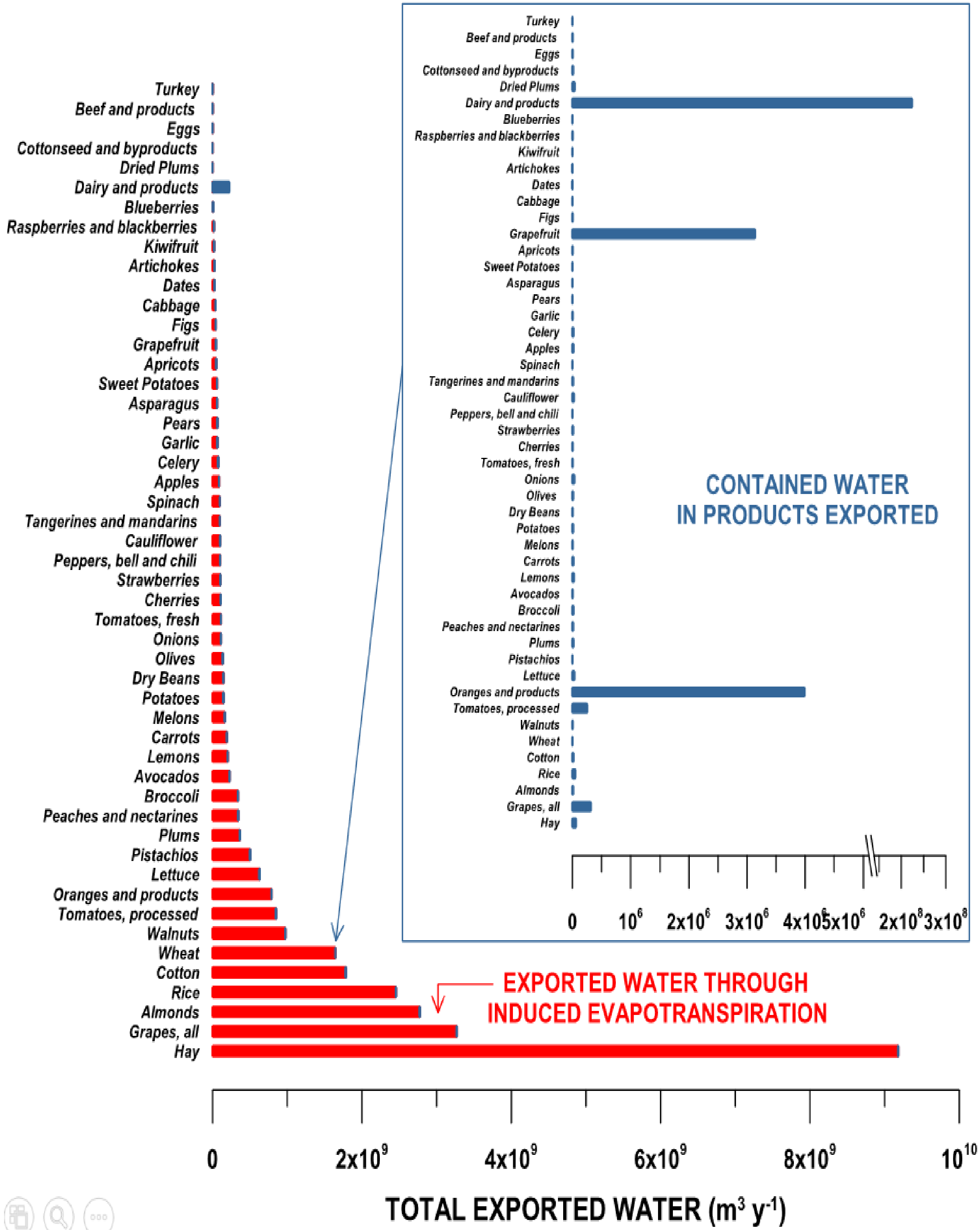

Figure 3-8. Total exported water calculated based on mass of contained water content in crops plus associated induced evapotranspiration

When computing for the dimensionless ratios (contained water index, induced ETc index and exported water index), we find that cotton, almonds, pistachios, walnuts, plums, rice, olives, cherries, beans, and figs were the top 10 with the highest overall exported water indexes. This result suggests that compared to other crops grown in equivalent planting area and exported percentages, the top ten crops with the highest exported water indexes would consume the majority of the water. However, when taking into account of the actual export percentages and planning areas, the total exported water for each of crop from the average 13 years (2000-2012), the results are shown in Figure 3-8. As an index reference, we report the three dimensionless ratios below in Table 3-1 to indicate the actual amounts of water contained in each crop and their respective water equivalents as a result of direct evapotranspiration and overall resultant exported water content. These indexes may be used to compute future exported water and associated induced evapotranspiration contribution as the outcome of agricultural irrigation.

Table 3-1. Calculated CWI, Induced ETc and EWI

Agricultural Commodity	**Contained Water Index (CWI), (χ)** Kg H_2O / Kg Crop	**Induced ETc Index (ω)** Kg of Induced ETc / Kg of crop	**Exported Water Index EWI, (Ω)** Total kg H2O / kg of exported crop
Cotton	0.06	4076.4	4076.5
Almonds	0.04	2108.0	2108.0
Pistachios	0.04	1016.1	1016.1
Walnuts	0.04	656.1	656.1
Plums	0.87	276.8	277.6
Rice	0.10	234.5	234.6
Olives	0.84	208.0	208.8
Cherries	0.82	169.1	169.9
Dry Beans	0.72	138.2	138.9
Figs	0.79	90.1	90.9
Raspberries and blackberries	0.88	89.2	90.1
Blueberries	0.84	76.2	77.0
Kiwifruit	0.83	67.7	68.6
Dates	0.21	58.2	58.4
Apples	0.86	48.7	49.6
Grapes, all	0.84	41.5	42.4
Wheat	0.12	33.7	33.9
Avocados	0.72	32.3	33.0
Apricots	0.86	32.0	32.9
Asparagus	0.93	26.0	27.0
Cauliflower	0.92	25.7	26.6
Hay	0.93	10.1	11.0
Broccoli	0.89	8.8	9.7
Garlic	0.59	5.9	6.5
Lemons	0.89	5.3	6.2
Peaches and nectarines	0.89	3.8	4.7
Onions	0.89	3.7	4.6
Tomatoes, fresh	0.95	2.8	3.8
Carrots	0.88	2.8	3.7
Potatoes	0.79	2.9	3.7
Pears	0.84	2.7	3.6
Tomatoes, processed	0.88	2.6	3.5
Artichokes	0.85	2.3	3.2
Spinach	0.91	2.2	3.1
Oranges and products	0.86	1.9	2.7
Sweet Potatoes	0.77	1.8	2.6
Celery	0.95	1.4	2.4
Lettuce	0.95	1.3	2.3
Strawberries	0.91	1.3	2.3
Melons	0.90	1.2	2.1
Cabbage	0.92	0.6	1.6
Grapefruit	0.90	0.6	1.5
Peppers, bell and chili	0.88	--	1.3
Tangerines and mandarins	0.85	0.1	0.9
Dairy and products	0.89	--	0.9
Eggs	0.76	0.0	0.8
Beef and products	0.72	--	0.7
Turkey	0.69	--	0.7
Dried Plums	0.31	0.0	0.3

3.5. Conclusions

The study found that from 2000 to 2012, California exports approximately 2.63×10^8 metric tons of crops and commodities, resulting in approximately 2.32×10^8 m^3 of water contained in the crops, equivalent to 0.6% of the total irrigation water use. The associated induced evapotranspiration from the exported crops (ETc) was calculated at 2.85×10^{10} m^3 yr^{-1} equivalent to a total of 67.7% of the overall irrigation usage. The calculated ETc is approximately 123 times greater than the physical water contained in the crops, confirming our hypothesis that for each unit of water exported, there is a greater loss of water through evapotranspiration as a result of irrigation. As a comparison, Nguyen et al., (2015) estimated that the average annual urban water consumption in California was 1.01×10^{10} m^3, thus the average induced evapotranspiration as a result of agricultural irrigation is 2.8 times greater than the total annual water consumed by municipalities. Of the 50 crops analyzed, alfalfa hay, grapes, almonds, rice, cotton, wheat, walnuts, tomatoes, oranges, lettuce, pistachios, plums, peaches and nectarines, broccoli and avocados were the 15 leading crops consuming most of the exported water. When comparing the results of our calculations to the Field Capacity Model from Sorooshian et al., (2014) the calculated ETc represented 97% of the model prediction, reaffirming that ETc plays an important role in contributing to the majority of the water consumed in irrigation and that agricultural irrigation adds to the increase in surface evapotranspiration. The overall exported water for all 50 crops was calculated at 2.88×10^{10} m^3 yr^{-1}, representing approximately 68% of the total water used in irrigation. When compared to the estimate associated with California agricultural production reported by Fulton et al., 2012, our total exported water was approximately 26% higher than the estimated 2.28×10^{10} m^3 previously reported. The difference could be that Fulton et al., 2012 used California data from 1998-2005, whereas, the data analyzed in this study was from 2000-2012. Export production reported in recent years has increased approximately by 26.5% since 2005. Taking this difference into account, our results are consistent with the outcome of the virtual water footprint previously reported.

Quantitative research in the field of exported water and virtual water footprint is still very much underdeveloped despite the many virtual water studies conducted over the years. Data presented in this research should be considered as estimates. The work presented here shows the importance of including induced evapotranspiration and contained water content as exported water in trade analysis when drafting water policies. Enhanced procedures to account for exported water and references should be developed and disseminated. These results highlight the need to consider water use efficiency in agricultural irrigation to prevent further loss of evapotranspiration.

The findings suggest that California's water resources are being exported outside its borders in magnitudes greater than that of the water consumed in state by the people of California. Thus, the state might be vulnerable to water-supply constraints if the trend continues indefinitely into the future. It further suggests that California has the potential of exacerbating the local environment by exporting more water than it can naturally regenerate through its hydrologic cycle. The figures and methodology developed in this study are intended to be useful to managers, policy makers, planners, researchers, educators and to all those who are concerned with California water use. With better water management practices and sound public policies and increased investment in water infrastructure and efficiency, farmers and other water users can get more use out of each unit of water. Continuing the practice of business as usual in the current water use scenario will likely lead to a long-term devastating effect that will only produce environmentally-damaging consequences for California and the global agricultural market in which California is a major player.

CHAPTER 4. Energy analysis of reclaimed water application for crop irrigation in arid and semi-arid regions

4.1. Abstract

Freshwater availability is the major constraint to agriculture in arid and semi-arid regions. The energy advantage of applying reclaimed water versus groundwater for crop irrigation was analysed, using Southern California as spatial domain for model testing. An extensive compilation of the most recent publicly available datasets was used to calculate the energy intensity for each water supply source, the associated carbon footprint reduction and the monetary savings associated with using reclaimed water over groundwater. Our results indicate that for 1998-2010 in California the fractional water use for agriculture is 0.81 and for urban use is 0.19. During this same period, an average of 4.2 x 10^{10} m^3 of water were used for crop irrigation, of which 1%, 46.8% and 52.2% came from reclaimed water, groundwater, and surface water, respectively. Each of these three main water sources is associated with a range of energy intensity (in kWh m^3), depending on the process and environmental characteristics of the end-use location. Our analysis of multiple process and environmental configurations produced a detailed energy intensity database, with the associated carbon footprint. These databases are used to quantify the energy and carbon footprint difference between applying the current groundwater source and reclaimed water for irrigation. Figure 4-1 provides a summary of the energy intensity of water supply sources calculated from our study.

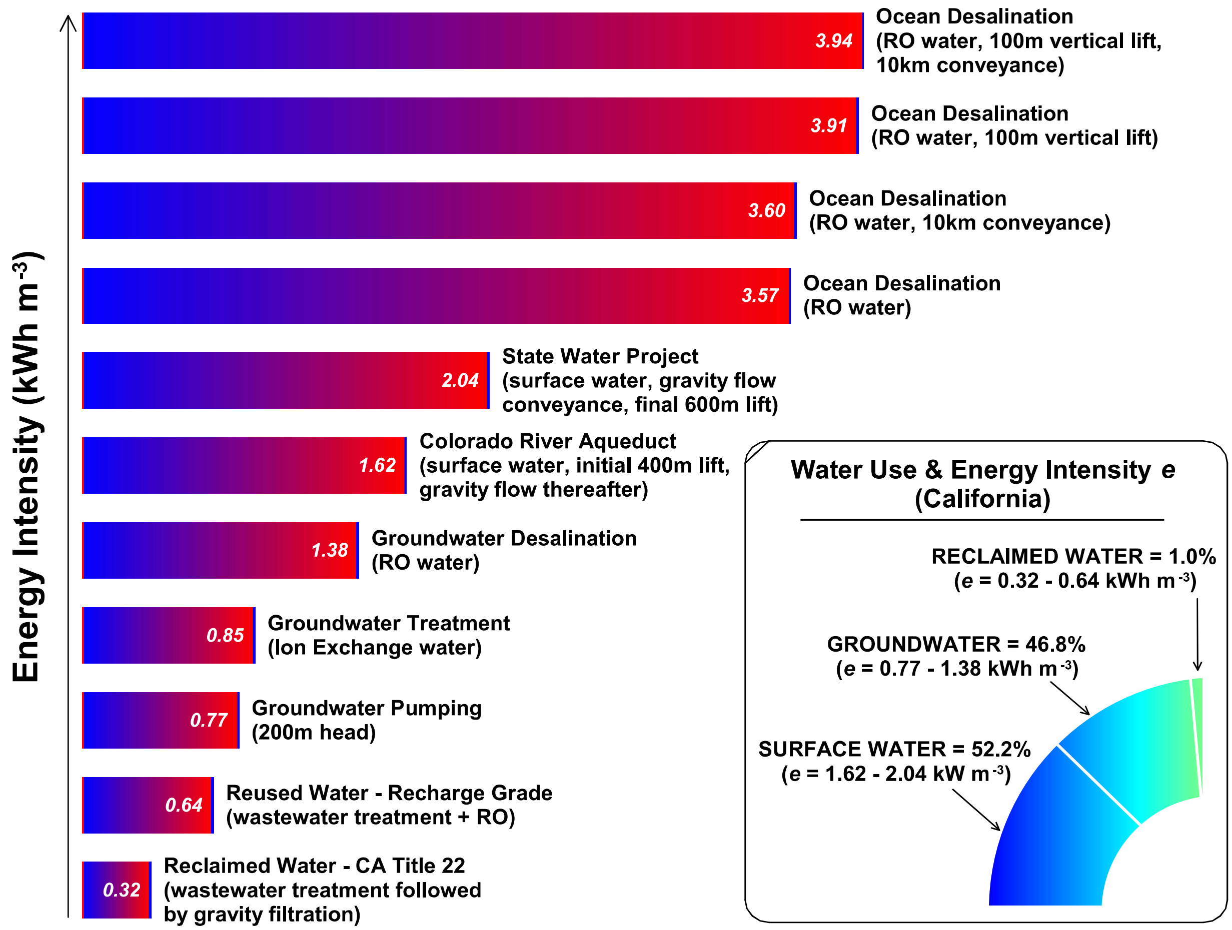

Figure 4-1. Summary of Energy Intensity for Water Supply Sources

4.2 Introduction

California's unique geography and climate have allowed the state to become one of the most productive agricultural regions in the world. Situated across an arid and semi-arid region, California's agricultural industry benefits from its naturally warm and dry summers, and mild winters, with average yearly temperature ranging between 13°C and 21°C (NOAA, 2015). The local government reported a record $43.5 billion in cash receipt in 2011 for overall agricultural production, making it the largest agricultural producer in the United States (CDFA, 2012).

The history of California's agricultural industry and the limit of its growth are connected to the current water shortage created by a prolonged drought (DWR, 2013). Although there exist extensive water resources within the state boundaries, like in most mediterranean climatic regions the majority of population resides along the water-scarce coastal region, which in California corresponds to the southern region. Today, California's water resources support over 38 million people (CDOF, 2013) as shown in Figure 4-2, a 2.2 USD yr^{-1} trillion economy (World Bank, 2013) and the agricultural region with largest cash receipt in the United States (CDFA, 2012). In a typical year, the Californian agricultural land (approximately 2.5 x 10^3 ha) is irrigated using approximately 4.2 x 10^{10} m^3 of groundwater (DWR, 2013). To accommodate the growth in population, the State of California and the US Federal Government built a complex hydraulic infrastructural network (dams, aqueducts, canals, reservoirs, and pumping facilities) to harness the inland water supply and deliver it to the cities and agricultural areas (Reisne, 1993; Nadeau, 1997; Hundley, 2001).

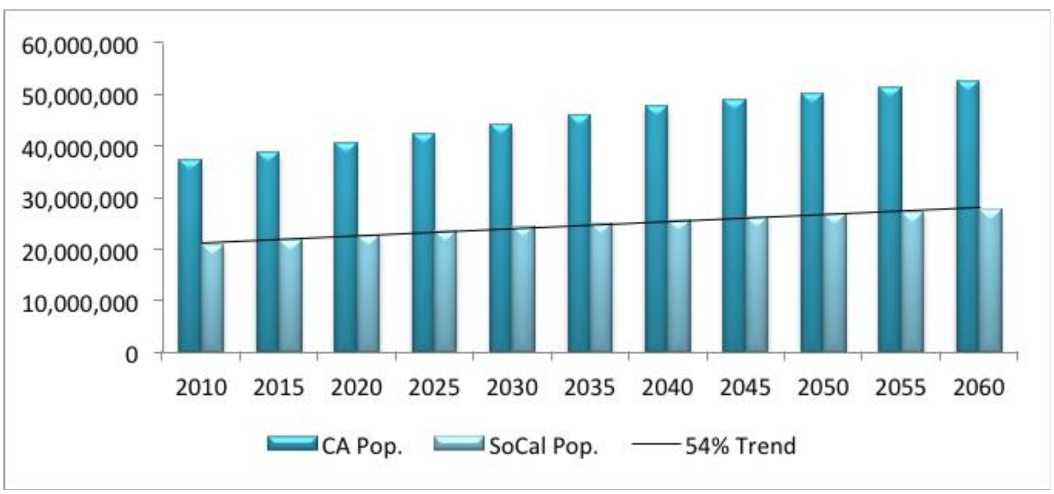

Figure 4-2. The population of Southern California is estimated assuming that in the coming future the current percent (54%) of Californians living in the Southern region

Reduced water supply and growing population are exacerbating the effects of multi-year droughts in many regions, threatening the already stressed and fragile water systems. Previous studies (Alcamo et al., 2003; Smakhtin et al., 2004; Oki and Kanae, 2006; Famiglietti, 2014) have shown that California's water supply is severely under stress. This is the case where the water to meet demand from urban areas, industry, ecosystems, agriculture and other sectors is nearing its limit under current management practices (Sabo et al., 2010). In the coming decades, the agricultural throughput is projected to match the population expansion both within California and in North America (Rosegrant et al, 2002). For these reasons, the cost of providing water continues to rise as municipalities seek to create and expand capital-intensive infrastructure to secure a reliable water supply (Miller, 2006). In many parts of California, the growing demand for water is outstripping the available supply, thus it is imperative to take proactive steps in conserving and augmenting the limited water supply resources (Chen et al, 2013). Increasing attention has been directed in recent years to the use of reclaimed urban wastewater (Pereira et al., 2011). In fact, with advances in technology, reclaimed water is expected to meet the stringent potable quality requirements at a competitive cost providing a more sustainable resource for the industry in a drought-resilient fashion (Levine and Asano, 2004; Kiziloglu et al., 2008; Molinos-Senante et al., 2011). The potential uses for reclaimed water in urban landscaping and agricultural irrigation provide an effective way to relieve the water resource demand in arid and semi-arid regions (Gunston, 2008). Many studies have also confirmed the benefits (cost savings, resource conservation, reliability, etc.) of using reclaimed water for crop irrigation (Yadav et al., 2002; Parsons et al., 2010; Rebora et al., 2010).

The goal of this research is to analyse the energy advantage of applying reclaimed water for crop irrigation, and to quantify the associated carbon footprint reduction of using reclaimed water versus traditional groundwater pumping in arid and semi-arid areas. Using California as a case study, the water, energy, and carbon-equivalent flows were quantified. In addition, the monetary advantage of substituting traditional water supply sources with reclaimed water, where possible, was assessed.

4.3 Methods

4.3.1. Model structure

Using data previously reported by Wilkinson (2000, 2007), USBR (2002), CEC (2005) and DWR (2013), a data set was compiled, including each of the $i=\{1,..,s\}$ sources, $Q(i)$ ($m^3\ y^{-1}$) in the water supply portfolio Q ($m^3\ y^{-1}$), the energy intensity of each water supply source $e(i)$ ($kWh\ m^{-3}$), and the carbon emission intensity $k(j)$ ($kg_{CO2eq}\ kWh^{-1}$) for each of the power generation sources $j=\{1,..,p\}$in the area of study. Using the conceptual model illustrated in Figure 1, for each point in space (x,y) the water supply portfolio Q is.

$$Q = \sum_{i=1}^{s} Q(i) \quad \forall\ (x,y) \quad i=\{1,..,s\} \tag{1}$$

For each source s, the energy footprint of the source $E(s)$ ($kWh\ y^{-1}$) is calculated as.

$$E(i) = Q(i) \cdot e(i) \quad \forall\ (x,y) \quad i=\{1,..,s\} \tag{2}$$

Thus, the overall energy footprint EFP ($kWh\ y^{-1}$) for each point is.

$$EFP = \sum_{i=1}^{s} E(i) = \sum_{i=1}^{s} \left[Q(i) \cdot e(i) \right] \quad \forall\ (x,y) \quad i=\{1,..,s\} \tag{3}$$

The area studied may be supplied by power utilities from a diverse power generation portfolio relying on p sources (such as hydroelectric, nuclear, thermoelectric, eolic, photovoltatic, etc.) associated with different carbon emission intensities $k(j)$ ($kg_{CO2eq}\ kWh^{-1}$). For each point (x,y) where the water source i is supplied, the carbon-equivalent emission has to be calculated from the weighted-average carbon emission intensity $<k>$ (kg_{CO2eq} kWh^{-1}).

$$<k> = \frac{\sum_{j=1}^{p}\left[k(j)\cdot W(j)\right]}{\sum_{j=1}^{p}\left[W(j)\right]} \quad \forall (x,y) \quad j=\{1,..,p\} \tag{4}$$

where $W(j)$ (kWh) is the energy produced for each of the $j=\{1,..,p\}$ power sources employed to supply power to the point (x,y).

Hence, the carbon emission intensity of each water source $c(i)$ (kg_{CO2eq} m^{-3}) is.

$$c(i) = e(i)\cdot <k> \quad \forall (x,y) \quad i=\{1,..,s\} \tag{5}$$

Therefore, the carbon footprint for each water source $C(i)$ (kg_{CO2eq} y^{-1}) can be calculated as.

$$C(i) = c(i)\cdot Q(i) = e(i)\cdot <k> \cdot Q(i) \quad \forall (x,y) \quad i=\{1,..,s\} \tag{6}$$

The overall carbon footprint CFP (kg_{CO2eq} y^{-1}) is then.

$$CFP = \sum_{i=1}^{s} C(i) = \sum_{i=1}^{s}\left[e(i)\cdot <k> \cdot Q(i)\right] \quad \forall (x,y) \quad i=\{1,..,s\} \tag{7}$$

4.3.2. Spatial domain

Southern California was selected to test this model. This 10^5 km^2 area includes six counties (Ventura, Los Angeles, San Bernardino, Orange, Riverside and San Diego), collectively amounting to more than 54% of California's population at the time of this study (CDOF, 2000, 2013). Figure 4-3 illustrates the special domain and the rational procedure to for our model calculations.

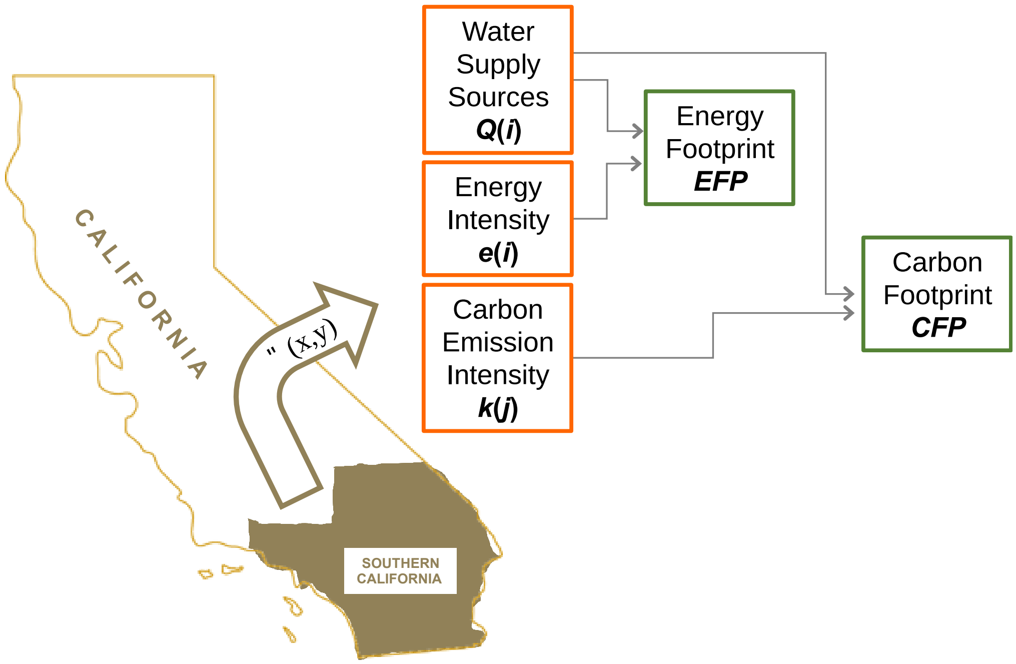

Figure 4-3. Illustration of the rational procedure to calculate energy- and carbon- footprint for the *i*={1,..,*s*}water supply sources in each point (x,y), using their associated energy footprint *e*(*i*), and the carbon-equivalent emission of the power generation k(*j*) for each *j*={1,..,*p*} power source used to supply the point (x,y).

4.3.3. Water reclamation processes

For this study, the authors assumed that a typical Southern California water use cycle follows the process diagram identified in Figure 4-4. The use of reverse osmosis (RO) as the technology to reclaim wastewater for aquifer recharge is currently used in many areas of this region.

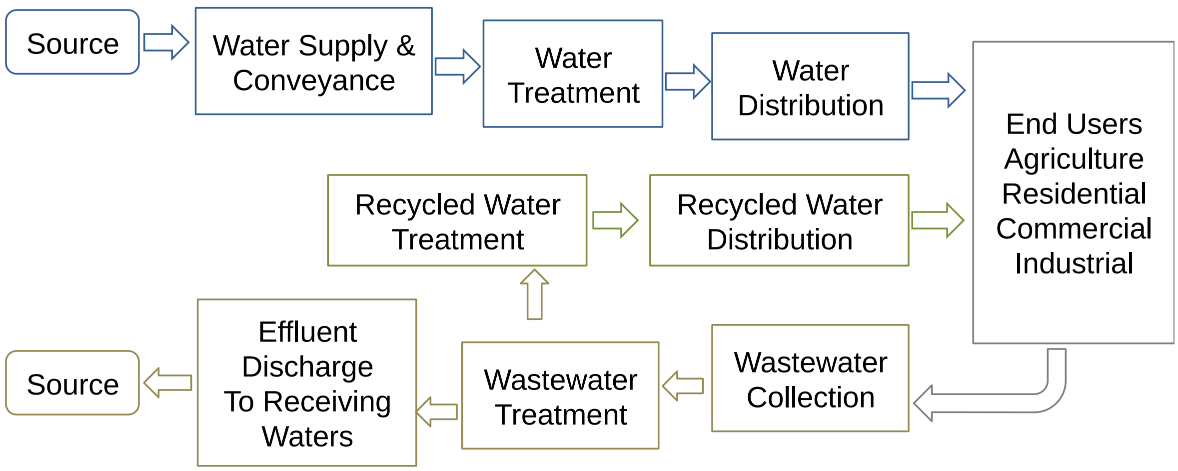

Figure 4-4. Schematic of the water use cycle of an urban system interacting with nearby agricultural areas (after Wilkinson, 2007).

A typical advanced water and wastewater treatment facility utilizes the RO process diagram similar to Figure 4-5. The following equation (USBR, 2002) was used to determine the size of the RO treatment system.

$$Q_F = \frac{(TDS_S - TDS_D)}{1 - R - L + (R + L) \times TDS_S} Q_D \qquad (8)$$

where Q_F = feed flow (m^3 d^{-1})

Q_D = demand (i.e., target) flow (m^3 d^{-1})

TDS_D = demand (i.e., target) TDS (mg l^{-1})

TDS_S = source TDS (mg l^{-1})

R = membrane salt rejection (%)

L = volumetric loss (%)

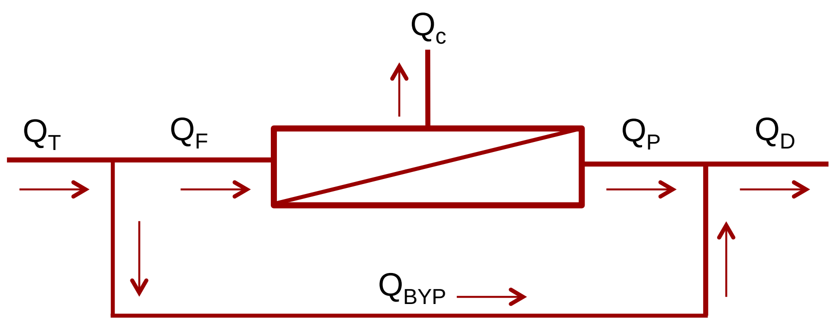

Figure 4-5. Reverse Osmosis Process Diagram (USBR, 2002). Key: Q_T = total flow; Q_F = Feed flow into RO treatment system; Q_C = Concentrate flow; Q_P = Permeate flow; Q_D = Demand flow; Q_{BYP} = Bypass flow.

The membrane salt rejection is the fraction of ions rejected by the membrane, which typically exceeds 90% for the brackish water RO membranes employed in water reuse (MWH, 2013). For this study, the authors followed the assumptions from USBR (2002) for volumetric loss of 20%, i.e. Q_P/Q_F=0.8.

Based on the information presented in figures 1-3, the authors calculated the energy intensities for water supply sources across Southern California using the energy intensity $e(i)$ for each of the water supply sources $i=\{1,..,s\}$.

4.3.4 Water conveyance and lift

Using the method previously reported by Sobhani et al. (2012), the energy intensity for conveyance and lift were calculated as.

$$e_C(i) = x \times z \quad (9)$$

$$e_L(i) = w \times h \quad (10)$$

where ξ = energy requirement per unit conveyance ($1.86\ 10^{-3}$ kWh km^{-1})

z = conveyance distance (km)

ω = energy requirement per unit lift ($3.43\ 10^{-3}$ kWh m^{-1})

h = conveyance distance (m)

4.3.5 Carbon footprint

To calculate for the carbon footprint associated with the water usage in each point (x,y), the authors used a value for the carbon emission intensity $k = 0.5$ kg_{CO2eq} kWh^{-1} as average representation of the Southern California basin. Since each point (x,y) within this spatial domain may have a different $k(x,y)$, plausibly ranging between 0.3 and 0.7 kg_{CO2eq} kWh^{-1}, a sensitivity analysis was performed to show the effect of k variations on the overall carbon footprint CFP. Figure 4-6 provides the results of our sensitivity analysis.

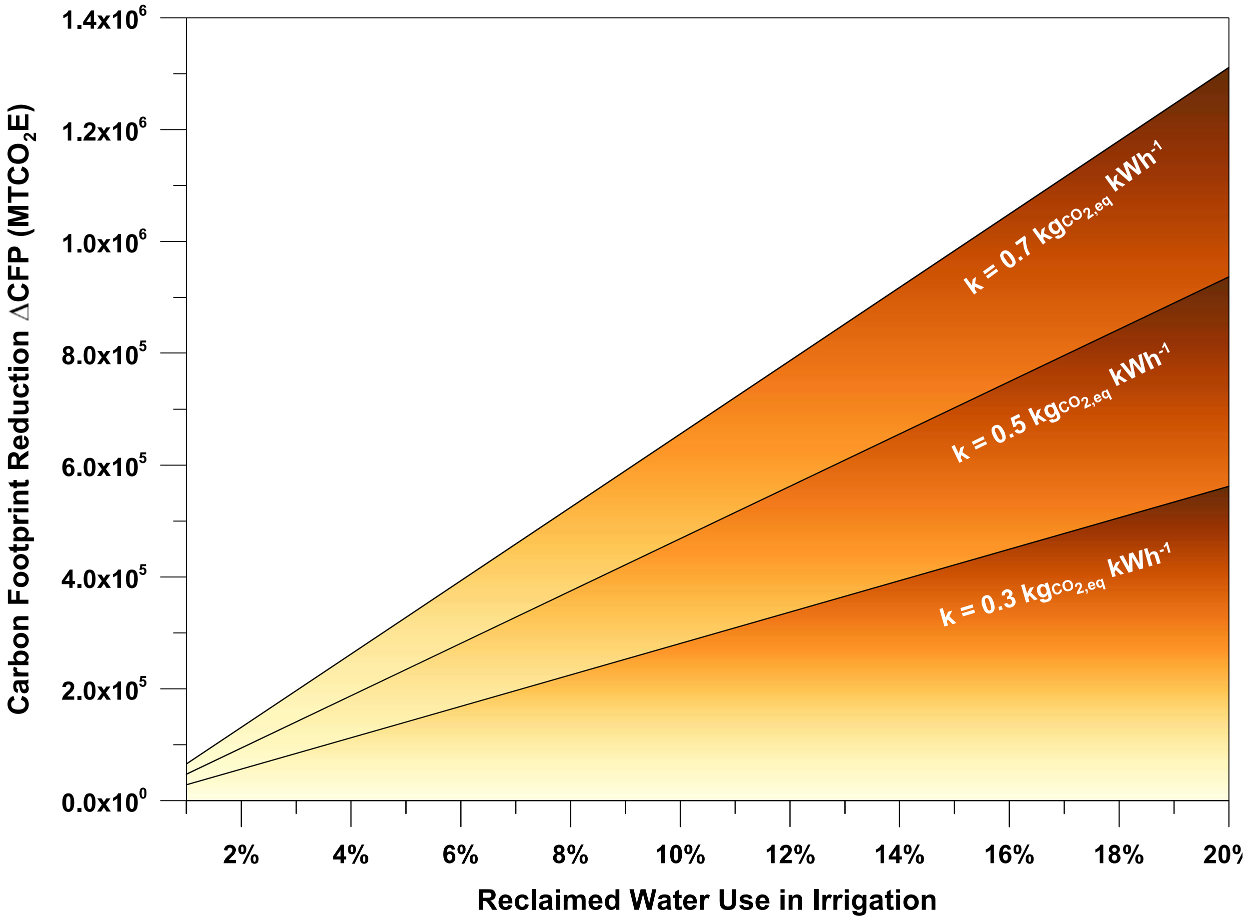

Figure 4-6. Sensitivity analysis: effect of carbon-emission intensity *k* on the annual carbon footprint reduction □CFP associated with replacing groundwater with reclaimed water in irrigation.

4.3.6 Costs and savings

For monetary savings, an agglomerate electric rate of 0.135 USD kWh^{-1} was assumed. Due to the equilibrium nature of this model, the electrical rate incorporates without discrimination the service and peak power demand charges, the averaged electrical tiered rates, and all applicable taxes. The electric rate used in our calculation is consistent with the utility rate currently being applied to large treatment facilities (>$5x10^4$ m^3 d^{-1}) by Southern California Edison, the largest electrical utility provider in the state of California (CEC, 2015).

4.4 Results and Discussion

The results show that from 1998 to 2010, the annual average water used in crop irrigation was 4.2 x 10^{10} m^3, 46.8% of which came from groundwater, 52.2% from surface water, while only 1% came from reclaimed urban wastewater. During the same period, the authors found that the average annual urban water use was approximately 19.4% of the total 5.21 x 10^{10} m^3 used for the entire state, while 80.6% was used for crop irrigation. The time domain of the available data is set by the release schedule of public records. Within much smaller spatial domains, it is conceivable that direct measurements can be carried out with any desired frequency, however the modelling effort at the regional scale must rely on public programs for data collection and compilation in published repositories.

Urban water reclamation can be used for landscape and crop irrigation without the need for membrane filtration or reverse osmosis treatment, both of which are required to address public health concerns (i.e., pathogen abatement). In areas where groundwater recharge was practiced to replenish aquifers for potable end use (i.e., Los Angeles, Orange, and Riverside Counties), reverse osmosis and membrane filtration were used. In these instances, the calculated energy intensity for water reclamation to meet the potable water standard was 0.640 kWh m^{-3}.

Our results show that there are savings in both groundwater supply and energy resources when applying reclaimed water for crop irrigation. The use of gravity filtration to reclaim water is the most economical method to meet regulatory compliance for landscape and irrigation end uses (Table 4-1).

Table 4-1. Water supply sources and associated energy intensities calculated from datasets for Southern California.

Water Supply Source, *i*	**Energy Intensity, *e*(*i*) [kWh m^{-3}]**
Reclaimed Water (Title 22 Gravity Filtration)	0.32
Reuse Water – Recharge Grade	0.64
Groundwater Pumping	0.77
Groundwater (Ion Exchange Water)	0.85
Groundwater Desalination (RO Water)	1.38
Colorado River Aqueduct	1.62
State Water Project	2.04
Ocean Desalination (RO)	3.57

In fact, where microfiltration membranes or reverse osmosis have energy intensities of 0.52 kWh m^{-3} and 0.64 kWh m^{-3}, respectively, gravity filtration (assumed here to be carried out with dual media filters) has an energy intensity of 0.32 kWh m^{-3}. Since reverse osmosis is not required for the production of reclaimed water suitable for irrigation, the energy intensity value for gravity filtration was selected as comparison term with the current groundwater scenario. The authors found that for Southern California the average energy requirement for groundwater pumping was 0.770 kWh m^{-3} while reclaimed water production with gravity filtration was 0.324 kWh m^{-3}. Hence, the energy advantage of applying reclaimed urban wastewater for crop irrigation over groundwater pumping within this spatial domain would be 0.446 kWh m^{-3}.

The calculated energy savings for applying reclaimed water in lieu of traditional groundwater results in 57.9% reduction of energy usage. Annually, this amounts to approximately 187 GWh y^{-1} of energy savings for California, resulting in a reduction of 4.68 x 10^7 $MTCO_2E$ (metric tonne of CO_2 equivalent) of carbon emission. If reclaimed water use were increased from 1% to 5%, 10%, 15%, or 20%, the respective total energy savings, monetary savings and carbon footprint reduction would increase linearly, as tabulated in Table 4-2.

Table 4-2. Energy savings (kWh y^{-1}), monetary savings (USD^{+} y^{-1}) and carbon footprint reduction ($MTCO_2E$ y^{-1}) per year as a function of reclaimed water use. [1]Calculated using energy savings of 0.446 kWh m^{-3} (difference between groundwater energy intensity of 0.77 kWh m^{-3} and reclaimed water energy intensity of 0.324 kWh m^{-3}; [2]Calculated using electrical rate of 0.135 USD^{+} per kWh; [3]Calculated using conversion factor, k = 0.5 $kg_{CO2,eq}$ kWh^{-1}; [+]2015 Dollars.

Average Annual Agricultural Water Use in California ($4.2 \times 10^{10} m^3$)	Percentage of Applied Reclaimed Water Use				
	1%	5%	10%	15%	20%
Reclaimed Water Use (10^6 m^3)	420	2099	4199	6298	8398
[1]Total Energy Savings (GWh y^{-1})	187	935	1,870	2,805	3,740
[2]Monetary Savings (USD^{+} y^{-1})	\$25.2M	\$126.4M	\$252.5M	\$379.4M	\$506.3M
[3]Carbon Footprint Reduction ($MTCO_2E$ y^{-1})	4.68×10^7	2.34×10^8	4.68×10^8	7.01×10^8	9.35×10^8

The calculated energy intensities for other supply sources such as imported water from Northern to Southern California and from the Colorado River Aqueduct system, ocean desalination, and impaired groundwater recovery were also calculated (Figure 4). Reclaimed water (obtained through gravity filtration) required the least amount of energy, whereas ocean desalination had an energy intensity approximately 11 times higher. When compared to traditional groundwater pumping, the energy intensity associated with water reclamation was discounted by 58%, highlighting the importance of reclaimed water as a potential competitive source.

When considering the energy requirements for water distribution along a 10 km of horizontal conveyance and 100 m of vertical lift (the average elevation for urban areas in Southern California), the energy contributions for conveyance and lift were 0.026 kWh m^{-3} and 0.34 kWh m^{-3}, respectively. Therefore, to account for the full energy requirements from point of treatment to point of use, the energy intensities for horizontal and vertical conveyance must be added to the calculated data presented in Table 4-3.

Table 4-3. Summary of Energy Intensity for the water sources considered in this research

Water Supply Sources	**Energy Intensity of Water Production (kWh m^{-3})**	**Energy Intensity of Conveyance (kWh m^{-3} km_{conv})**	**Energy Intensity of Lift (kWh m^{-3} m_{lift})**	**Total Energy Intensity (kWh m^{-3})**
Ocean Desalination (RO water, 100m vertical lift, 10km conveyance)	3.57	0.026	0.34	3.94
Ocean Desalination (RO water, 100m vertical lift)	3.57		0.34	3.91
Ocean Desalination (RO water, 10km conveyance)	3.57	0.026		3.60
Ocean Desalination (RO water)	3.57			3.57
State Water Project (surface water, gravity flow conveyance, final 600m lift)			2.04	2.04
Colorado River Aqueduct (surface water, initial 400m lift, gravity flow thereafter)			1.62	1.62
Groundwater Desalination (RO water)	1.38			1.38
Groundwater Treatment (Ion Exchange water)	0.85			0.85
Groundwater Pumping (200m head)			0.77	0.77
Reused Water - Recharge Grade (wastewater treatment + RO)	0.64			0.64
Reclaimed Water - CA Title 22 (wastewater treatment followed by gravity filtration)	0.32			0.32

The authors recognize that there may exist infrastructural and administrative limitations among water agencies and agricultural users within a region as to the extent in which reclaimed water can be produced, conveyed, applied, and accepted. Also, locations without proper infrastructure or with cultural incompatibility with reclaimed water may be unable to consider water reclamation as an option for their water supply portfolio. However, it is important to frame the transition to reclaimed water within the context of energy savings and monetary benefits. At the present moment, California would be unable to substitute all its groundwater use for reclaimed water, due to limits in existing infrastructure for both production and conveyance. Furthermore, the majority of population within this spatial domain is located in the Southern coastal region, hence investments in infrastructure would be necessary to deliver reclaimed water from urban areas to places where agricultural activity is abundant, such as in the Central Valley, Coachella Valley, and the Imperial Valley farming areas. However, when the water source for water reclamation is brackish agricultural runoff (Lee and Jones-Lee, 2007) or brackish groundwater (Sobhani et al, 2012) from areas near or corresponding to the agricultural production, the energy requirements for conveyance and lift may be substantially abated.

It is important to recognize the long-term benefits of matching water quality with the actual end use application. Reclaimed water should be used for crops irrigation while pristine groundwater should remain reserved for potable consumption. Given that water demand for urban, agricultural, and environmental needs is projected to rise (DWR, 2013), resource allocation efficiency and demand management must be taken into consideration during the policymaking. Thus, decision makers should consider the energy intensity of water (i.e., including the contributions from conveyance and lift) as quantitative metrics to support the other factors in the evaluation of projects. Moreover, by requiring end users to apply the least energy-intensive source of supply, whenever feasible, the regulatory framework would not only promote monetary savings but also accomplish the goal of placing the appropriate value to all water sources, a task impossible to achieve when differential pricing, incentives and subsidies, and lack of regulation are applied to some but not all water sources.

4.4.1 Comparison with other energy uses

When examining the average energy requirements for agricultural harvest and crop processing in California, the California Energy Commission reported 3.7 x 10^3 GWh y^{-1} (CEC, 2008). However, future research should revisit this value to discriminate between crops and final product. In contrast, the energy consumed to provide an estimated 1.9 x 10^{10} m^3 of groundwater pumping for crop irrigation was calculated here at 1.5 x 10^4 GWh yr^{-1}, making the energy requirement for groundwater irrigation the largest energy contributor in the food production chain, at approximately 4.1 times higher than the energy required to harvest and process all crops. Further examination of other energy uses in California indicated that the energy consumed in agriculture, predominantly in food production (planting, tilling, watering, harvesting, processing, waste/refuse processing), was approximately 7% of the total energy produced in California, 2% higher than the energy used in transportation, communication, and utilities combined, and 6% higher than the annual electricity required for all street lightings in California (CEC, 2009).

In 2012, the California agricultural industry reported an export value of 18.18 billion USD, a record 42.7% cash receipt for all crops produced in the state (CDFA, 2013). As the country's sole exporter of many agricultural commodities, supplying >99% of almonds, artichokes, dates, figs, raisins, kiwi, olives, peaches, pistachios, plums, pomegranates, rice, and walnuts, California's agricultural export is expected to continue to rise (CDFA, 2013). One area of knowledge gaps is the quantification of the water embedded in agricultural exports. Further research in this area is needed to determine how the agricultural exports from one region affect the overall water portfolio for that region and the region receiving its water-bearing produce.

4.4.2 Climate change effects

Following a global trend, California has undergone a warming trend in recent decades with more rain than snow in total precipitation volume (DWR, 2013). Increasing temperatures are melting snowpack earlier in the year and pushing the snowline at higher elevations, resulting in less snowpack storage. The current trend is projected to become more frequent and persistent for the region. As a result, surface water supply is projected to erode with time, while the rainfall will experience increased variability, possibly leading to more frequent and extensive flooding (Fissekis, 2008). Rising sea levels will also increase the susceptibility to coastal and estuarine flooding and salt water intrusion into coastal groundwater aquifers (Hanak and Moreno, 2008). In California that sea level is estimated to rise between 150 and 610 mm by 2050 (DWR, 2013). As the reliability of surface water is reduced due to the effects of climate change, if water reclamation is not implemented with higher market penetration, the demand on groundwater pumping is expected to increase, resulting in higher energy usage for crop irrigation. Our calculations show that for every percent increase in groundwater pumping over 2015 values, the state would consume an additional 323 GWh y^{-1} of energy generating a net increase of 8×10^4 $MTCO_2E$ y^{-1}. This additional energy usage will amount to approximately 43.7 million USD for every percent increase in groundwater pumping applied to crop irrigation, calculated in 2015 dollars. Further research is warranted to determine the effect of climate change on carbon footprint associated with the energy requirements for irrigation water, particularly for crops grown exclusively for export and how this carbon emission compares with other societal compartments of the energy portfolio.

4.4.3 Effects of varying power generation portfolios

A sensitivity analysis was performed to show the effect of variable *k* on the overall carbon footprint associated with the energy savings of applying reclaimed water in lieu of traditional groundwater pumping (Figure 4-2). For this analysis, the *k* values ranging between 0.3 and 0.7 kg_{CO2eq} kWh^{-1} were used to account for the different *k*(x,y) within a spatial domain analysed in our study. Furthermore, this sensitivity analysis addresses the global drive to mandate increasing shares of renewables in power generation portfolios (Energy Efficiency - Invisible Fuel, 2015). For example, in 2011 California Senate Bill No. 2 requires electric service providers to increase procurement from eligible renewable energy resources from 20% to 33% by 2020 (CPUC, 2015).

4.4.4 Extension to other regions

In 1994, in its General Assembly meeting to combat desertification in countries experiencing serious droughts, the United Nations defined arid and semi-arid regions as areas having the ratio of annual precipitation to potential evapotranspiration within the range of 0.05 to 0.65 (UNCCD, 1994). According to this definition, regions in California and other Mediterranean countries such as Chile, Spain, France, Italy, South Africa and portions of

Australia are classified as arid and semi-arid regions. Other regions of the world such as Central Asia, South Asia, East and Southern Africa, Central Africa and West Africa also meet this definition. The information presented in our research is intended to serve as a baseline for reference in areas sharing similar climate conditions as defined by the UNCCD.

4.5. Summary and conclusions

The study found that currently the use of reclaimed water application in California for the agricultural industry is very low, an average 1% for the period 1998 - 2010. For every percent increase in reclaimed water use in agriculture, the resulting energy saving is 187 GWh yr^{-1}, which at the current energy cost equates to more than 25 million USD. Aside from the energy saving and economic benefit, the application of reclaimed water for crop irrigation also produces a direct safeguard of 4.2×10^8 m^3 in groundwater supply and a reduction in carbon footprint of 4.68×10^7 MTCO2E y^{-1}.

If reclaimed water use increased from the current 1%, the energy savings, carbon footprint reduction, and economic benefits were calculated for both the current power generation portfolio and for the projected increase of renewable energy. Even in the scenario of a substantial reduction of CO_2-equivalent emissions by meeting and exceeding targets for renewable energy, the increase in reclaimed water use would still provide a net carbon footprint reduction. Figure 4-7 shows the results of our model calculations.

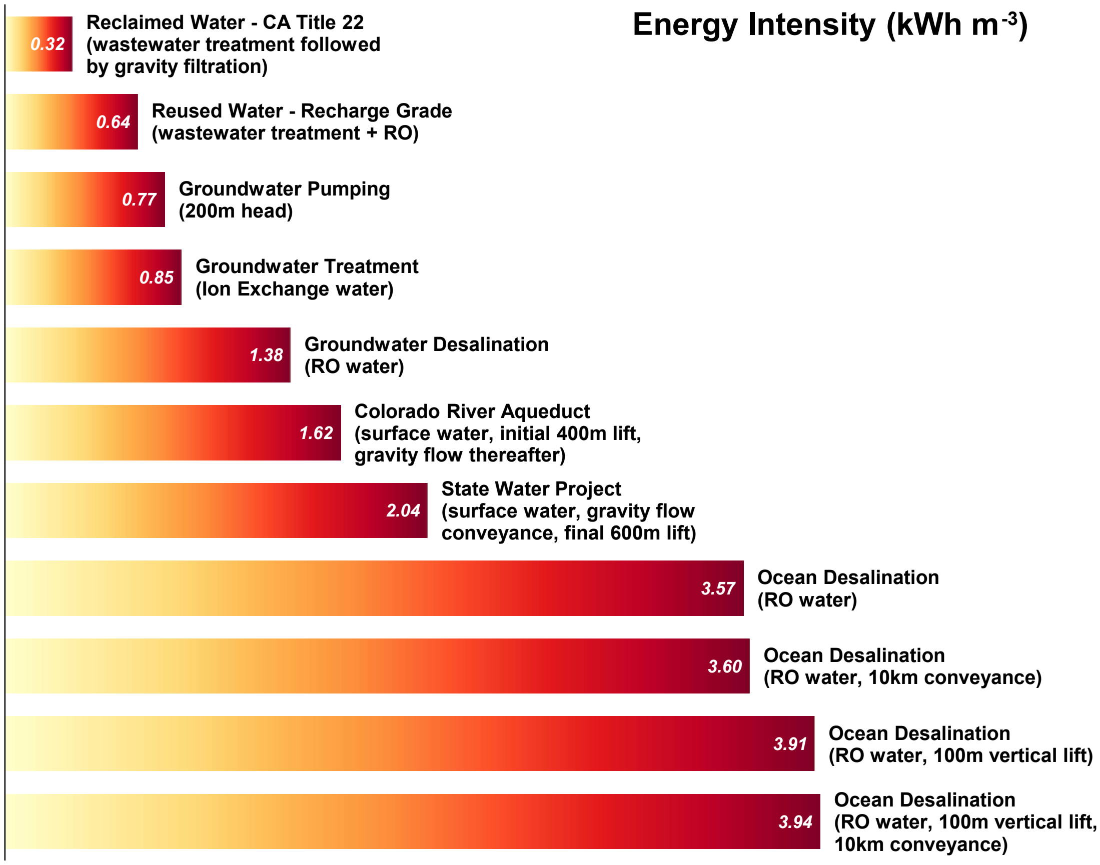

Figure 4-7 Water Supply Energy Intensities (inverted vertical scale).

This research is intended to serve as a baseline reference and used as a planning tool to help water resources planners. Specific location, availability of reclaimed water supply, conveyance infrastructure and methods of treatment will influence the calculated results and associated costs presented. Nonetheless, the results of this study furthers our current understanding on the role of reclaimed water on curbing groundwater withdrawal in an arid and semi-arid region like that of Southern California, by providing the context of its existing usage, estimated energy consumption, carbon footprint reduction, and potential monetary savings that can be realized. The trends observed in this study may be applicable to other regions of the world where water scarcity, energy costs, and climatic conditions require the use of reclaimed water as a sustainable water source.

CHAPTER 5. Conclusions

5.1. Exported water content

The central hypothesis of this research was tested and yielded a positive result: we found true the statement that for each unit of water exported from an agricultural spatial domain there is greater loss of water from evapotranspiration than from the water contained in the exported crops. The calculated contained water content was in the 50 crops exported was 2.32×10^{8} m^3, equivalent to 0.6% of the total irrigation water use. The associated induced evapotranspiration from the exported crops (ETc) was 2.85×10^{10} m^3 yr^{-1} equivalent to a total of 67.7% of the overall irrigation usage. Of the 50 crops analyzed, alfalfa hay, grapes, almonds, rice, cotton, wheat, walnuts, tomatoes, oranges, lettuce, pistachios, plums, peaches and nectarines, broccoli and avocados were the 15 leading crops consuming most of the exported water. The calculated ETc is approximately 123 times greater than the physical water contained in the crops, confirming our hypothesis that for each unit of water exported, there is a greater loss of water through evapotranspiration as a result of irrigation. As a comparison, the annual urban water consumption in California is approximately 1.01×10^{10} m^3, thus the induced evapotranspiration as a result of agricultural irrigation is 2.8 times greater than the total annual water consumed by municipalities. When comparing the results of our calculations to those from the Field Capacity Model that produce evapotranspiration estimates from atmospheric measurements, our results are in agreement with less than 3% error.

5.2. Energy Intensity

The research hypothesis tested true: in fact, the application of reclaimed water not only preserves groundwater resources but also decreases the energy footprint and carbon emissions associated with crop irrigation. The results show that there are savings in both groundwater supply and energy resources when applying reclaimed water for crop irrigation. For California, the average energy requirement for groundwater pumping was 0.770 kWh m^{-3} while reclaimed water production with gravity filtration was 0.324 kWh m^{-3}. Hence, the energy advantage of applying reclaimed urban wastewater for crop irrigation over groundwater pumping within this spatial domain would be 0.446 kWh m^{-3}. The calculated energy savings for applying reclaimed water in lieu of groundwater resulted in 57.9% reduction of energy usage. Annually, this amounts to approximately 187 GWh y^{-1} of energy savings for California, creating in a reduction of 4.68 x 10^7 $MTCO_2E$ (metric tonne of CO_2 equivalent) of carbon emission. If reclaimed water use were increased from 1% to 5%, 10%, 15%, or 20%, the respective total energy savings, monetary savings and carbon footprint reduction would increase linearly. Based on the calculations, reclaimed water (obtained through gravity filtration) required the least amount of energy, whereas ocean desalination had an energy intensity approximately 11 times higher. When compared to traditional groundwater pumping, the energy intensity associated with water reclamation was discounted by 58%, highlighting the importance of reclaimed water as a potential competitive source.

5.3. Research Limitations

The results of this study further our current understanding on the role of reclaimed water on curbing groundwater withdrawal in arid and semi-arid regions. The findings in this research are also intended to serve as a quantitative tool to support decision makers. The trends observed in this study may be applicable to other regions of the world where water scarcity, energy costs, and climatic conditions require the use of reclaimed water as a sustainable water source. Quantitative research in the field of exported water is still very much underdeveloped despite the many virtual water studies conducted over the years. The data presented in this research can serve as estimate but further research should address the uncertainty. Enhanced procedures to account for exported water and references should be developed and disseminated. These results highlight the need to consider water use efficiency in agricultural irrigation. Our findings suggest that California’s water resources are being exported outside its borders in magnitudes greater than that of the water consumed by the municipalities within the state. Thus, the state might be vulnerable to water-supply constraints if the trend continues indefinitely into the future. With better water management practices and sound public policies and increased investment in water infrastructure and efficiency, farmers and other water users can increase the yield of each water unit consumed. The current scenario appears to promote a positive feedback mechanism of resource draining resulting in environmental consequences for California’s water resources.

CHAPTER 6. Future Steps

6.1. Observed trend in agricultural irrigation

California agriculture under growing pressure of water is beginning to explore innovative uses of reclaimed water. Some growers already use reclaimed wastewater in different ways, depending on the level of treatment the water receives. Most common is the use of secondary-treated wastewater on fodder and fiber crops. Increasingly, however, growers are irrigating fruits and vegetables with tertiary-treated wastewater producing high-quality crops and high yields. Wong et al., (1999) reported that the Cities of Visalia and Santa Rosa have developed projects to irrigate more than 6,000 acres of farmland including a walnut orchard with secondary-treated wastewater. Though the projects were primarily designed to reduce wastewater discharge, both cities have gained from the water-supply benefits of applying reclaimed water.

The mix of California crops and planting patters has been changing. These changes are the result of decisions made by large numbers of individuals, rather than the intentional actions by state policymakers. California farmers are planting more and more high-valued fruit and vegetable crops, which have lower water requirements than the field and grain crops they are replacing. They can also be irrigated with more accurate and efficient precision irrigation technologies. As a result, California is slowly increasing the water productivity of its agricultural sector, increasing the revenue or yield of crops per unit water consumed. Over time, these changes have the potential to dramatically change the face of California agriculture, making it even more productive and efficient than it is today, while saving vast quantities of water.

In the past two decades, California farmers have made considerable progress converting appropriate cropland and crops to water-efficient drip irrigation. Much of this effort has focused on orchard, vineyard, and berry crops. Recent innovative efforts now suggest that row crops not previously irrigated with drip systems can be successfully and economically converted. This case provides the example of two farmers converting bell peppers row crops to drip irrigation with great success. Subsurface drip irrigation substantially increased pepper yields, decreased water consumption, and provides greatly improved profits.

6.2. Extension to all crops

Due to limited availability of public data, our research could only examine 50 of the top exporting commodities in California. According to the California Department of Food and Agriculture, there are 305 known crops produced in the region. Additional research should be extended to assess the exported water of the remaining 255 crops and to evaluate the overall effects of evapotranspiration for all crops commercially produced in California. Since many regions of California are classified as arid and semi-arid areas sharing similar climate conditions to those of other Mediterranean countries, such as Chile, Spain, France, Italy, South Africa and portions of Australia according to UNCCD. The information presented in our research model can be used as a baseline for reference for calculating exported water of other crops grown in similar climate conditions.

6.3. Energy exportation from crops (beyond irrigation)

Previous study by Nguyen et al., 2015 reported that groundwater pumping consumes approximately 1.5×10^4 GWh yr^{-1}, making the energy requirement for groundwater irrigation the largest contributor in the food production process. As shown from the results of our calculations, the majority of exported water was in the form of evapotranspiration induced by crop irrigation. Thus, it warrants that further research be conducted to examine the energy being exported as a result of induced evapotranspiration beyond the energy requires to irrigate. This research will shed light on the overall energy consumption in the entire food production process including energy expended within a spatial domain and the exported quantity induced via evapotranspiration.

6.4. Future research studies

One area of research which has not been conducted is the effects of positive feedback mechanism of the overall exported energy of crops as a result of induced evapotranspiration. Future research should be extended to cover all remaining crops commercially produced in California. The outcomes of this model can be extended to quantify the overall exported energy from irrigation that is lost by induced evapotranspiration to that of the energy consumptions from other sectors of the California economy. The results of this future study will help close the loop on the life-cycle energy consumption analysis for California agriculture industry.

CHAPTER 7. References

Alcamo, J., Doll, P., Henrichs, T., Kaspar, F., Lehner, B., Rosch, T., Siebert, S., 2003. Global estimates of water withdrawals and availability under current and future "business-as-usual" conditions. Hydrological Sciences Journal 48, 339-348.

Alcamo J, Florke M, Marker M, 2007. Future long-term changes in global water resrouces 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

Allan, J.A., 1993. Fortunately there are substitutes for water otherwise our hydro-political futures would be impossible. In. Priorities for Water Resources Allocation and Management. ODA, London, United Kingdom.

Allan, J.A., 1994. Overall perspectives on countries and regions. In. Rogers, P., Lydon, P. (Eds.), Water in the Arab World. Perspectives and Prognoses. Harvard University Press, Cambridge, MA.

Allan, J., 1998. Virtual Water. A Strategic Resource; Global Solutions to Regional Deficits. Groundwater, 36 (4), pp. 545-546

Allan, J.A., 2003. Virtual water – the water, food and trade nexus. Useful concept or misleading metaphor? Water International 28, 106-113.

CALFED. (2002). "Evaluating and Comparing Proposed Water Management Actions - DRAFT." CALFED Bay-Delta Program.

California Department of Finance, 2000. Land and water areas of California County. http.//www.dof.ca.gov/html/fs_data/stat-abs/documents/A1.pdf (Accessed 21 January 2015)

California Department of Finance. 2013. Total Population Projections for California and Counties. July 1, 2015 to 2060 in 5-year Increments. Sacramento. California. http.//www.dof.ca.gov/research/demographic/reports/projections/P-1/documents/Projections_Press_Release_2010-2060.pdf (Accessed 10 August 2014)

California Department of Finance, Demographic Research Unit. 2014. Web. http.//www.dof.ca.gov/research/demographic/reports/estimates/e-1/view.php (Accessed 8 February 2015)

California Department of Water Resources. 2013. California Plan Update. Web. http.//www.waterplan.water.ca.gov/cwpu2013/ (Accessed 10 August 2014)

California Department of Food and Agriculture. 2012. Agricultural Statistics Review. Web. http.//www.cdfa.ca.gov/Statistics/ (Accessed 8 August 2014)

California Department of Food and Agriculture. 2013. Agricultural Statistics Review. Web. http.//www.cdfa.ca.gov/Statistics/ (Accessed 7 February 2015)

California Department of Food and Agriculture. 2014. Agricultural Statistics Review. Web. http.//www.cdfa.ca.gov/Statistics/ (Accessed 10 February 2015)

California Energy Commission, 2005. Integrated Energy Policy Report, November 2005, CEC-100-2005-007-CMF

California Energy Commission, 2008. California's Food Processing Industry Energy Efficiency Initiative, March 2008, CEC 400-2008-006-REV

California Energy Commission, 2009. Integrated Energy Policy Report, January 2010, CEC–100–2009–003-CMF

California Energy Commission. Energy Almanac. Overview of California (2009). Retrieved October 4, 2011, from http.//energyalmanac.ca.gov/overview/energy_sources.html

California Energy Commission, 2015. California Electric Sector Overview. http.//energyalmanac.ca.gov/electricity/overview.html (Accessed 18 January 2015)

California Public Utility Commission. 2015. Renewable Portfolio Standard. RPS Program Overview. Web. http.//www.cpuc.ca.gov/PUC/energy/Renewables/overview.htm (Accessed 22 January 2015)

California Urban Water Conservation Council (CUWCC). 1991. "CUWCC Memorandum of Understanding (MOU). "Sacramento, CA. http.//www.cuwcc.org/mou-main-page.aspx

Campbell, H.E, Johnson, R.M, and Larson, E. H. 2004. "Prices, Devices, People, or Rules. The Relative Effectiveness of Policy Instruments in Water Conservation." Review of Policy Research.

Chapagain, A.K., Hoekstra, A.Y., 2003. Virtual water flows between nations in relation to tradein livestock and livestock products. Value of Water Research Report Series No. 13 UNESCO-IHE, Delft, the Netherlands. http.//www.waterfootprint.org/Reports/Report13.pdf.

Chen, G.Q., Wu, B., 2010. Status and development of water reuse in Tianjin. Water Technology, 4(2). 61-64.

Chen, G.Q., Chen, Z.M., 2011a. Greenhouse gas emissions and natural resources use by the world economy. Ecological input-output modeling. Ecol. Model. 222, 2362-2376.

Cohen, M. 2011. Municipal Deliveries of Colorado River Basin. Pacific Institute for Studies in Development, Environment, and Security, Oakland. California.

Cooley, H., Christian-Smith, J., Gleick, P.E., Cohen, M. J., and Heberger, M. 2010. California's Next Million Acre-Feet. Saving Water, Energy, and Money. Pacific Institute. http.//www.pacinst.org/reports/next_million_acre_feet/

Cromwell, J. E, Smith, J. B., and Raucher, R. S. 2007. Implications of Climate Change for Urban Water Utilities. Washington, DC. Association of Metropolitan Water Agencies. http.//www.amwa.net/gallerties/climate-change/AMWA_Climate_Change_Paper_12.13.07.pdf

Dalin C, Konar M, Hanasaki N, et al. 2012. Evolution of the global virtual water trade network. Pro Natl Aca Sci 109.5989-5994

DeOreo, W. B., Maye, P. W., Martien, L, Hayden, M., Funk, A., Kramer-Duffield, M., Davis, R. et al. 2011. California Single-Family Water Use Efficiency Study. Sacramento, CA. California Department of Water Resources/U.S. Bureau of Reclamation CalFed Bay-Delta Program. http.//aquacraft.com/sites/default/files/pub/DeOreo-%282011%29-California-Single-Family-Water-use-Efficiency-Study.pdf

Dennen, A., D. Larson, C. Lee, J. Lee, and S. Tellinghuisen. 2007. California's Energy-Water Nexus. Water Use in Electricity Generation. Bren School of Environmental Management and Science. University of California, Santa Barbara.

Department of Finance (DOF). 2011. Interim Projections for California and Counties. July 1, 2015 to 2050. Sacramento, California.

Department of Water Resources (DWR). 1957. The California Water Plan. Bulletin 3. Sacramento, California

Department of Water Resources (DWR). 1964. The California Water Plan. Status Report. Bulletin 160-64. Sacramento, California.

Department of Water Resources (DWR). 1966. The California Water Plan Update. Bulletin 160-66. Sacramento, California.

Department of Water Resources (DWR). 1970. The California Water Plan Update. Bulletin 160-70. Sacramento, California.

Department of Water Resources (DWR). 1974. The California Water Plan Update. Bulletin 160-74. Sacramento, California.

Department of Water Resources (DWR). 1983. The California Water Plan Update. Bulletin 160-83. Sacramento, California.

Department of Water Resources (DWR). 1987. The California Water Plan Update. Bulletin 160-87. Sacramento, California.

Department of Water Resources (DWR). 1993. The California Water Plan Update. Bulletin 160-93. Sacramento, California.

Department of Water Resources (DWR). 1998. The California Water Plan Update. Bulletin 160-98. Sacramento, California.

Department of Water Resources (DWR). 2003. California Water Plan Update. Bulletin 160-03. Sacramento, CA. California Department of Water Resources. http.//www.waterplan.water.ca.gov/previous/cwpu2003/index.cfm

Department of Water Resources (DWR). 2005. The California Water Plan Update. Public Review Draft (May 2005). Bulletin 160-05. Sacramento, California

Department of Water Resources (DWR). 2005. California Water Plan Update. Bulletin 160-05. Sacramento, CA. California Department of Water Resources. http.//www.waterplan.water.ca.gov/previous/cwpu2005/index.cfm

Department of Water Resources (DWR). 2009. California Water Plan Update. Bulletin 160-09. Sacramento, CA. Department of Water Resources. http.//www.waterplan.ca.gov/cwpu2009/index.cfm

Department of Water Resources (DWR). 2011. Statewide Water Balance (1998-2005). Sacramento, CA. Department of Water Resources.

Dietzenbacher E, Velázquez E (2007) Analysing Andalusian Virtual Water Trade in an Input–Output Framework. Reg Stud 41.185–196.

Duarte, R., Sanchez-Choliz, J., Bielsa, J., 2002. Water use in the Spanish economy. an input-output approach. Ecol. Econ. 43, 71-85.

Environmental Working Group (EWG). 2004. Water Subsidies. Large Agribusiness Operations – Not Small Family Farmers – Are Reaping a Windfall From Taxpayers – Subsidized Cheap Water. http.//www.ewg.org/reports/watersubsidies/

Famiglietti, J.S., 2014. The global groundwater crisis. Nature Climate Change 4, 945-948 doi.10.1038/nclimate2425. Published online 29 October 2014.

Fissekis, A., 2008. Climate Change Effects on the Sacramento Basin's Flood Control Projects. Department of Civil and Environmental Engineering, University of California – Davis, 150 pp.

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

Fulton J, Cooley H, Gleick, PH (2014) Water Footprint Outcomes and Policy Relevance Change with Scale Considered. Evidence from California. Springer Science and Business Media Dordrecht.

Gleick, P. H. 1995. California Water 2020. A Sustainable Vision. Oakland, CA. Pacific Institute. http.//www.pacinst.org/reports/California_water_2020/index.htm

Gleick, P. H., Cooley, H., and Groves, D. 2005. California Water 2030. An Efficient Future. Oakland, CA. Pacific Institute.

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.

Gunston, H., 2008. Wastewater use in irrigated agriculture. Confronting the livelihood and Environmental realities. In. Scott, C.A., Faruqui, N.I., Raschid-Sally, L. (Eds.), Experimental Agriculture. CABI Publishing, p. 93.

Hanak, E. 2005. Water for Growth. California's New Frontier. Public Policy Institute of California. San Francisco, California.

Hanak, Ellen and Georgina Moreno, 2008. California Coastal Management with a Changing Climate, Public Policy Institute of California, San Franciso, California.

Hanasaki, N.T., Inuzuka, S., Kanae, Oki, T., 2010. An estimation of global virtual water flow and sources of water withdrawal for major crops and livestock products using a global hydrological model. Journal of Hydrology 384, 232-244.

Hoekstra, A.Y., Chapagain, A.K., 2007. Water footprints of nations. water use by people as a function of their consumption pattern. Water Resour. Manage. 21. 35-48.

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

Hoekstra, A.Y., Hung, P.Q., 2002. Virtual water trade. a quantification of virtual water flows between nations in relation to international crop trade. Value of Water Research Report Series No. 11. UNESCO-IHE. Delft, The Netherlands.

Hoekstra, A.Y., Hung, P.Q., 2005. Globalization of water resources. international virtual water flows in relation to crop trade. Global Environ. Change 15, 45-56.

Hubacek, K., Guan, D., Barrett, J., Wiedmann, T., 2009. Environmental Implications of urbanization and lifestyle change in China. ecological and water footprints. J. Clean, Prod. 17, 1241-1248.

Hundley, N. 2001. The Great Thirst. Californians and Water. a History, University of California Press, Los Angeles, California.

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007. the physical science basis. working group 1 contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge. Cambridge University Press. http.//www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html

International Monetary Fund, World Economic Outlook Database. 2015. Web. http.//www.imf.org/external/pubs/ft/weo/2014/01/weodata/index.aspx (Accessed 11 February 2015)

Johnson, H. 2008. "Population Projections for California Climate Change Scenarios." In California Plan Update 2009. Vol. Vol 4 Reference Guide. http.//www.waterplan.water.ca.gov/docs/cwpu2009/0310final/v4c02a13_cwp2009.pdf

Kenny, J. F., Barber, N.L., Huton, S.S., Lindsey, K. S., Lovelace, J.K., and Maupin, M.A., 2009. Estimated Use of Water in the United States in 2005. Circular 1344. Reston, VA. U.S. Geological Survey. http.//pubs.usgs.gov/cir/1344/

Kiziloglu, F.M., Turan, M., Sahin, U., Kuslu, Y., Dursun, A., 2008. Effects of untreated and treated wastewater irrigation on some chemical properties of cauliflower (Brassica olerecea L, var. botrytis) and red cabbage (Brassica olerecea L. var. rubra) grown on calcareous soil in Turkey. Agric. Water Manage. 95, 716-724.

Klein, G., Krebs, M., Hall, V., O'Brien, T., and Blevins, B.B. 2005. California's Water-Energy Relationship. Final Staff Report. Sacramento, CA. California Energy Commission. http.//www.energy.ca.gov/2005publications/CEC_700-2005-011/CEC-700-2005-011-SF.pdf

Konar M, Dalin C, Suweis S, et al. (2011) Water for food. The global virtual water trade network. Water Resour Res 47.1–17

Kueppers, L., and M. Snyder (2012), Influence of irrigated agriculture on diurnal surface energy and water fluxes, surface climate, and atmospheric circulation in California, Clim. Dyn., doi.10.1007/s00382-011-1123-0.

Lee, G.F, Jones-Lee, A. 2007. Agriculture and the Environment - 2007 Conference, Central Coast Agricultural Water Quality Coalition, Monterey, CA, November (2007)

Legislative Analyst's Office. (2009). Water Rights: Issues and Perspectives. Senate Natural Resources and Water Committee.

Letey, J. and D. Birkle. The Amount of Water We Eat. University of California Water Resources Center. Winter 2003, Volume 4, Issue 1

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

Levine, A.D., Asano, T., 2004. Recovering sustainable water from wastewater. Environmental Science and Technology 38, 201A-208A.

Lo, M., and J. Famiglietti (2013), Impact in California's Central Valley strengthens the southwestern U.S. water cycle, Geophys. Res. Lett., 40, 301–306, doi.10.1002/grl.50108.

Los Angeles Department of Water and Power (LADWP). 2012. "LADWP Reminds Customers to Conserve Water. Reduced Snowpack & Increased Water Use Call for Increased

Conservation.” Los Angeles Department of Water and Power. http.//www.ladwpnews.com/go/doc/1475/1426279/

Mekonnen, M.M., Hoekstra, A.Y., 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

Metropolitan Water District of Southern California. 2012. Map of California Water Systems. Nobriga, Keith. Email Communication. July 2012. http.//www.mwdh2o.com

McElrone, A. J., Choat, B., Gambetta, G. A. & Brodersen, C. R. (2013) Water Uptake and Transport in Vascular Plants. Nature Education Knowledge 4(5).6

Miller, G.W., 2006. Integrated concepts in water reuse. Managing global water needs. Desalination 187, 65-75.

Molinos-Senate, M., Hernandez-Sancho, F., Sala-Garrido, R., 2011. Cost-benefit analysis of water-reuse projects for environmental purposes. A case study for Spanish wastewater treatment plants. J. Environ. Manage. 92, 3091-3097.

Mubako, S., Lahiri, S., Lant, C., 2013. Input-output analysis of virtual water transfers. Case study of California and Illiois. Ecological Economics 93 (2013) 230-238.

MWH, Inc. (2013) Water treatment principles and design (3nd ed.), John Wiley & Sons - ISBN 978-0-470-40539-0

Nadeau, R., 1997. The Water Seekers. Crest Publishers, Santa Barbara. California.

National Oceanic and Atmospheric Administration. (2005). "Water Supply Outlook - February 2005." California Nevada River Forecast Center, Sacramento, CA.

National Oceanic and Atmospheric Administration. 2015. National Climatic Data Center. Climate at a Glance. Los Angeles annual average temperature 1940-2014. Web. http.//www.ncdc.noaa.gov/cag/time-series.us (Accessed 21 January 2015).

Nguyen, D., Tseng, L., Sobhani, R., Rosso, D., 2015. Resource and energy conservation through reclaimed water application for irrigation in arid and semi-arid regions. In review. Resource, Conservation and Recycling. In Review.

Odum, H.T., 1971. Environment, Power, and Society. Wiley-Interscience, New York, NY.

Odum, H.T., 1983, Systems Ecology. John Wiley and Sons, Inc., New York, NY.

Oki, T., Kanae, S., 2004. Virtual water trade and world water resources. Water Sci. Technol. 49, 203-209.

Olmstead, S., M, and Stavins, R. N. 2007. “Managing Water Demand. Price Vs. Non-Price Conservation Programs.” A Pioneer Institute White Paper, No. 39, July.

Orang, M.N., R.L. Snyder, and J.S. Matyac. 2005. “Survey of irrigation methods in California 2001.” In California Department of Water Resources (DWR). The California Water Plan Update. Bulletin 160-05. Sacramento, California.

Parsons, L.R., Panchal, N.S., Pandey, I.B., Pandey, A.N., 2010. Reclaimed water as an alternative water source for crop irrigation. Hortscience 45, 1626-1629.

Pereira, B.F.F., He, Z.L., Silva, M.S., Herpin, U., Nogueira, S.F., Montes. C.R., Melfi, A.J., 2011. Reclaimed wastewater. impact on soil-plant system under tropical conditions. Journal of Hazardous materials 192, 54-61.

Postel SL, Daily GC, Ehrlich PR (1996) Human Appropriation of Renewable Fresh Water. Science (80-) 271.785–788.

Prairie, J., United States Bureau of Reclamation. Email Communication Oct 7, 2011.

Rebora, C., Lelio, H., Gomez, L., 2010. Use of urban wastewater in grape (Brassica napus L.) production destinated to biofuel. Rev. Fac. Cien. Agrarias 42, 207-212.

Rosegrant, Mark., Cai, X., Cline, S., 2002. World water and food to 2025. Dealing with scarcity. 2002

Reisner, M. 1993. Cadillac Desert. The American West and its Disapearing Water. Penguin Books, New Yor, New York.

Sabo, J.L., Sinha, T., Bowling, L.C., Schoups, G.H.W., Wallender, W.W., Campana, M.E., Cherkauer, K., et al., 2010. Reclaiming freshwater sustainability in the Cadilac Desert. Proceedings of the National Academy of Sciences of the United States of America 107, 21263-21270.

Scripps Institute of Oceanography. (2006). Our Changing Climate: Assessing the risks to California. A Summary Report from the California Climate Change Center.

Smakhtin, V., Revenga, C., Doll, P., 2004. A Pilot global assessment of environmental water requirements and scarcity. Water International 29, 307-351.

Sobhani, R., Abahusayn, M., Gabelich, C., Rosso, D. 2012. Energy footprint analysis of brachkish groundwater with zero liquid discharge in inland areas of the Arabian Peninsula. Desalination, Volume 291, 2 April 2012, Page 106-116.

Sorooshian, S., J. Li, K. Hsu, and X. Gao (2011), How significant is the impact of irrigation on the local hydroclimate in California's Central Valley? Comparison of model results with ground and remote-sensing data, J. Geophys. Res., 116, D06102, doi.10.1029/2010JD01775.

Sorooshian,S.,J.Li,K.Hsu,andX.Gao(2012),InfluenceofirrigationschemesusedinRCMsonETestimation.Resultsandcomparativestudies from California’s Central Valley agricultural regions, J. Geophys. Res., 117, D06107, doi.10.1029/2011JD016978.

Sorooshian,S.,A.AghaKouchak,andJ.Li (2014), Influence of irrigation on land hydrological processes over California, J.Geophys.Res.Atmos.,119,doi.10.1002/ 2014JD022232.

SWRCB. (2003). "2002 California 305(b) report on water quality." State Water Resources Control Board, Sacramento, CA

The Economist. Energy Efficiency – Invisible Fuel. 2015. 414(8921), Special Report – Energy and Technology.

University of California Berkeley. Web 2015. Museum of Palaeontology. http.//www.ucmp.berkeley.edu/exhibits/biomes/deserts.php (Accessed 12 January 2015)

United Nations General Assembly. Convention to Combat Desertification in Countries Experiencing Serious Droughts and/or Desertification, Particularly in Africa. 12 September 1994.

United States Army Corps of Engineers. (2010). American River Watershed. Hydrology Technical Documentation. Post-Authorization and Interim General Reevaluation Report.

United States Bureau of Reclamation (USBR). 1998. Irrigation and Annual Ratebook. Central Valley Project. Sacramento, California.

United States Bureau of Reclamation (USBR). 2000. Irrigation and Annual Ratebook. Central Valley Project. Sacramento, California.

United States Bureau of Reclamation. 2002. Southern California Comprehensive Water Reclamation and Reuse Study Phase II.

United States Energy Information Administration. California Energy Fact Sheet (2011). Retrieved October 5, 2011, from http.//www.eia.gov/state/state-energy-profiles.cfm?sid=CA

Velazquez, E., 2006. An input-output model of water consumption. Analyzing inter-sectoral water relationships in Andalusia. Ecol. Econ. 56, 226-240.

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

Wei, J., P. A. Dirmeyer, D. Wisser, M. G. Bosilovich, and D. M. Mocko (2013), where does the irrigation water go? An estimate of the contribution of irrigation to precipitation using MERRA, J. Hydrometeorol., 14, 275–289

Wilkinson, Robert C., 2000. Methodology for Analysis of the Energy Intensity of California's Water Systems.

Wilkinson, Robert C., 2007. Analysis of the Energy Intensity of Water Supplies for West Basin Municipal Water District.

World Bank. Web. 2013. The World Bank Data GDP Ranking. http.//data.worldbank.org/data-catalog/GDP-ranking-table (Accessed 12 August 2014)

Wong, A., Owens-Viani, L., Steding, A., Gleick, P., Haasz, D., Wilkinson, R., Fidell, M., Gomez, S. (1999). Sustainable Use of Water: California Success Stories.

Yadav, R.,K, Goyal, B., Sharma, R.K., Dubey, S.K., Minhas, P.S., 2002. Post-irrigation impact of domestic sewage effluent on composition of soils, crops and ground water. a case study. Environ. Int. 28, 481-486.

Yu, Y., Hubacek, K., Feng, K., Guan, D., 2010. Assessing regional and global water footprints for the UK. Ecol. Econ. 69, 1140-1147.

Zhan-Ming, C., Chen, G.Q., 2013. Virtual water accounting for the globalized world economy. National water footprint and international virtual water trade. Ecological Indicators 28, 142-149.

Zhao, X., Chen, B., Yang, Z.F., 2009. National water footprint in an input-output framework – a case study of China 2002. Ecol. Model. 220, 245-253.

Zhao, X., Yang, H., Yang, Z.F., Chen, B., Qin, Y., 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, 9150-9156.

Zimmer, D., Renault, D., 2003. Virtual water in food production and global trade. Virtual Water Trade. Proceedings of International Expert Meeting on Virtual Water Trade. Value of Water Research Report Series No. 12. UNESCO-IHE, Delft, the Netherlands.

APPENDIX

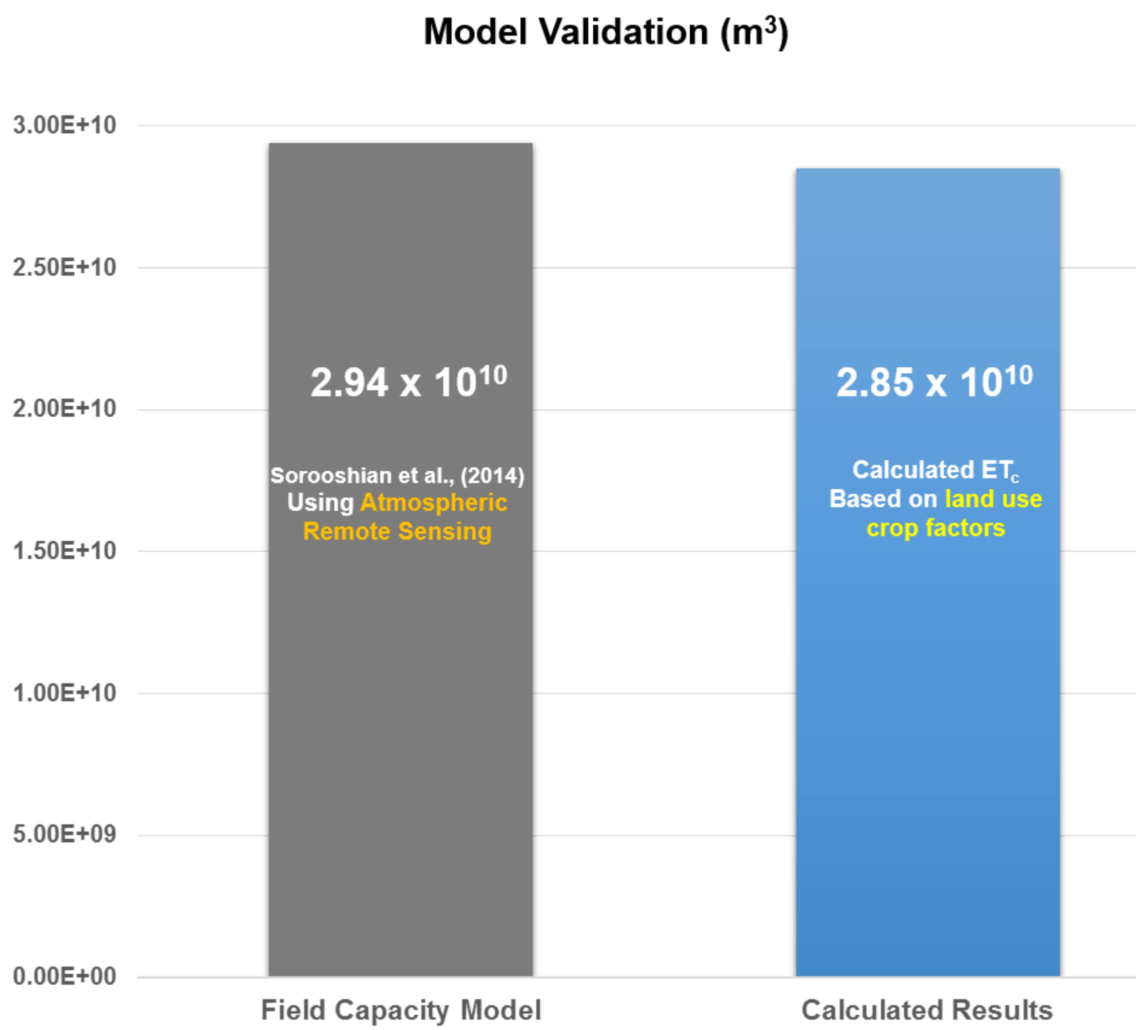

Figure A1 – Calculated Evapotranspiration Model Validation

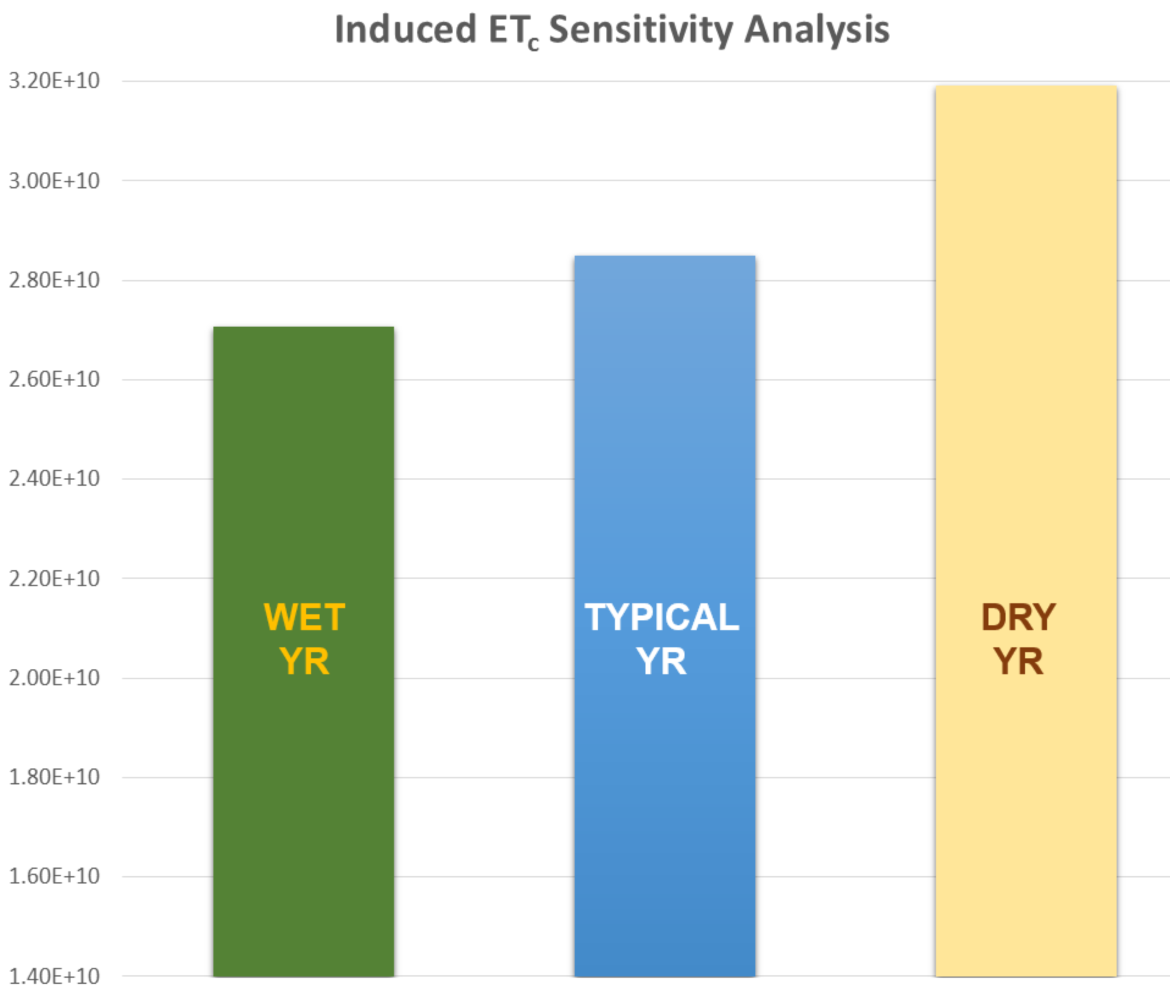

Figure A2 – Induced ET_c sensitivity analysis for wet and dry years

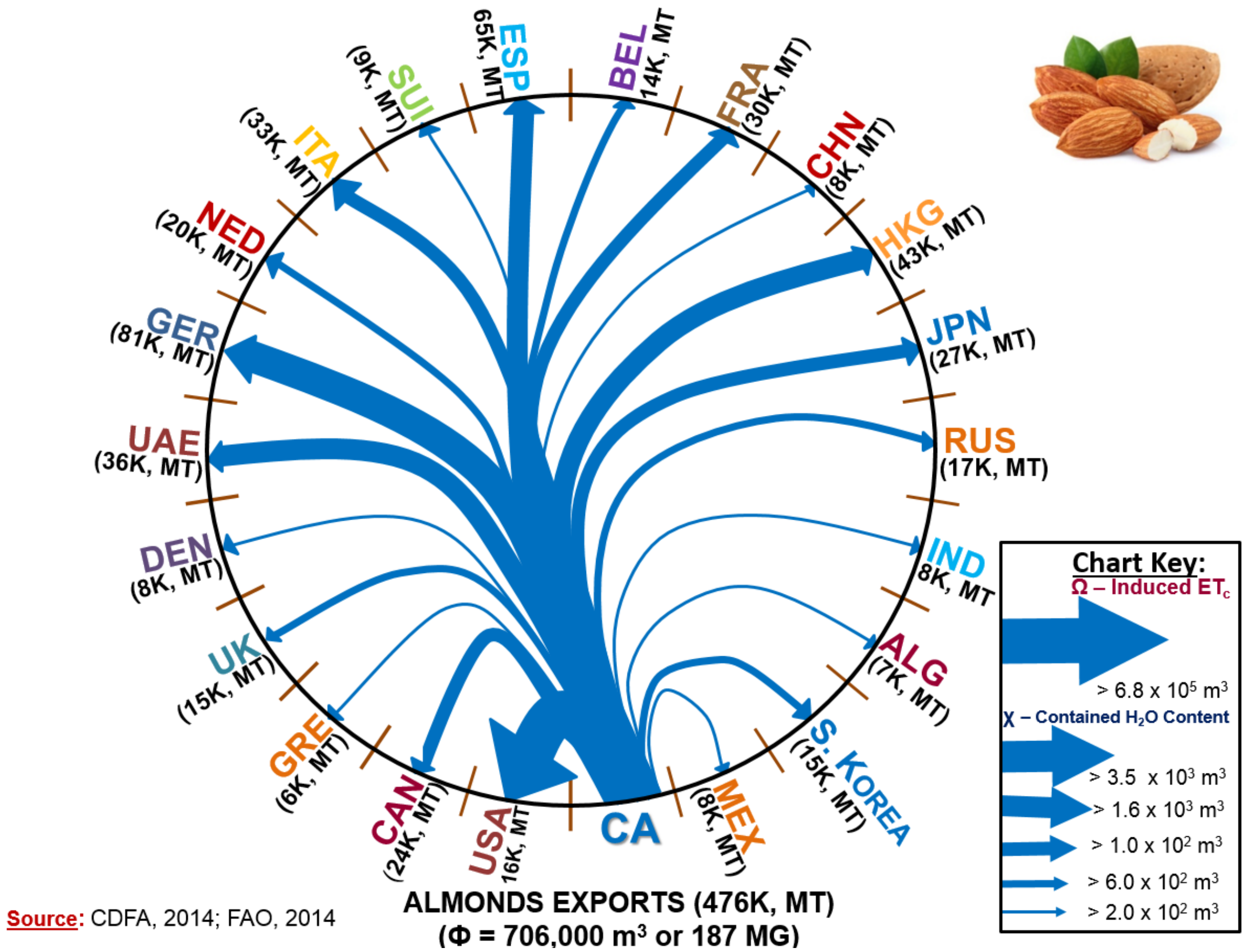

Figure A3 – California Almonds Exports

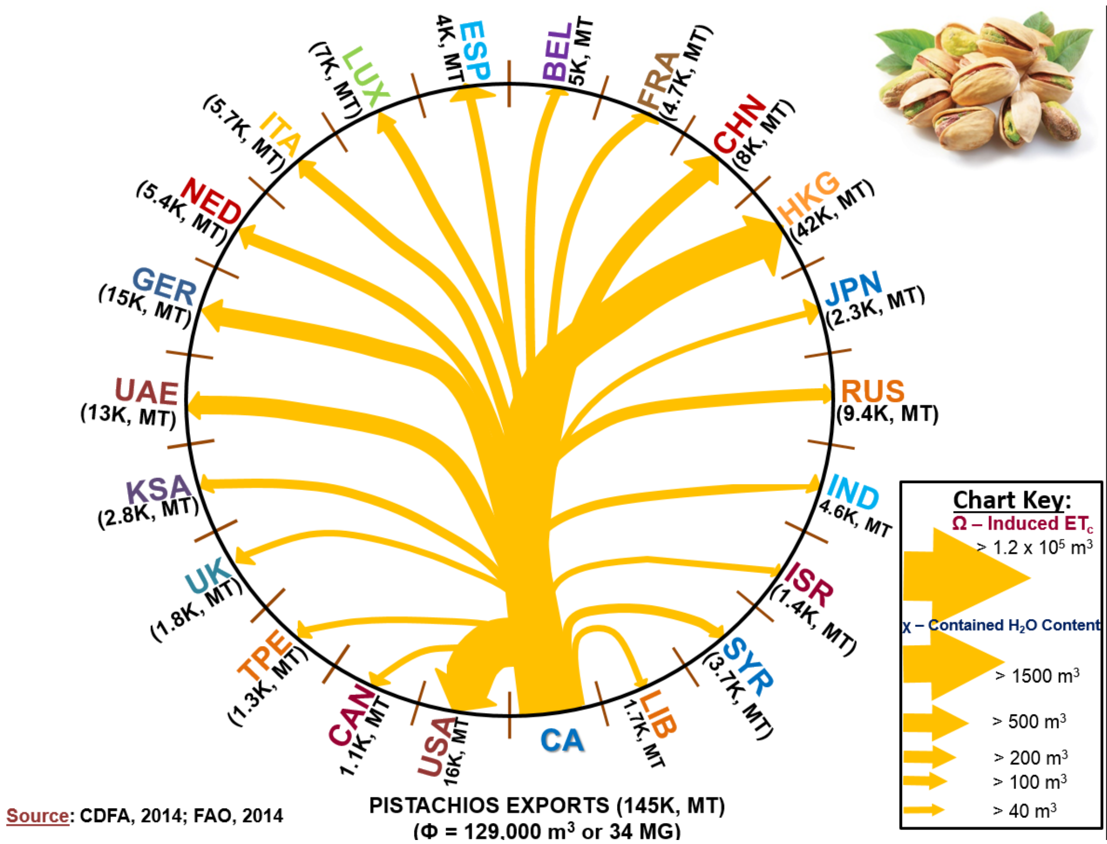

Figure A4 – California Pistachios Exports

CURRENT REGULATIONS

NOTE: This publication is meant to be an aid to the staff of the CDPH—formerly the Department of Health Services (DHS)—Drinking Water Program and cannot be relied upon by the regulated community as the State of California's representation of the law. The published codes are the only official representation of the law. Refer to the published codes—in this case, Title 17 and 22 CCR—whenever specific citations are required.

California Department of Public Health

Regulations Related to Recycled Water
June 18, 2014 (Revisions effective on 6/18/14)

Sections amended, adopted, repealed, or not included in the previous version are highlighted in yellow. If the text in a section, subsection, or paragraph is highlighted, it is new. If only the section/paragraph number is highlighted, it was amended or repealed. Nonsubstantive revisions may not be shown.

1

Last updated June 18, 2014—from Titles 22 and 17 California Code of Regulations
California Department of Public Health's Recycled Water Regulations

Figure A5 – California Regulations Related to Recycled Water

REGULATORY DEFINITIONS

- **§13050. Reclaimed water = Recycled Water**
  "Recycled water is treated wastewater suitable for direct beneficial use and therefore, is considered a valuable resource."
- **§60301.200 Direct beneficial use** = use of recycled water without intervening discharge to waters of the State.
- **§60301.330 Food crops** = crops for human consumption
- **§60304 disinfected tertiary water** for surface irrigation is permitted:
  - Food crops including **ALL edible root crops**, where recycled water comes into **contact with edible portion of the crop**
  - **Disinfected secondary** permitted for: Crops where edible portion is produced above ground and not contacted by recycled water
- **§60310** No disinfected tertiary within 100 ft. of domestic water supply well and no spray irrigation within 100 ft. of residence or public exposure
- **§60304** at least **undisinfected secondary**:
  - **Orchards** no contact with edible portion
  - **Vineyards** no contact with edible portion
  - **Non-food bearing trees** (Christmas tree farms)
  - **Fodder and fiber crops and pasture** for animals producing milk
  - **Ornamental nursery** stock and sod farms (**no irrigation 14 days before harvesting, retail sale or access by public**)

Disinfected Tertiary Water:

1. Max filter hydraulic loading rate and effluent turbidity requirements:
   - Effluent turbidity < 2NTU
   - Influent turbidity < 5 NTU (15 mins)
   - Influent turbidity never > 10 NTU
2. Chlorine CT value of 450 mg-min/L
   - Min. modal contact time of 90 mins
3. Requires 5-log virus reduction
   - 1-log credit for filtration
   - 4-log reduction through disinfection
4. 7-day median total coliform limit of 2.2 MPN/100 mL

Source: Title 22 and 17 of CA Code of Regs

Figure A6 – California Regulations on Disinfected Tertiary Water

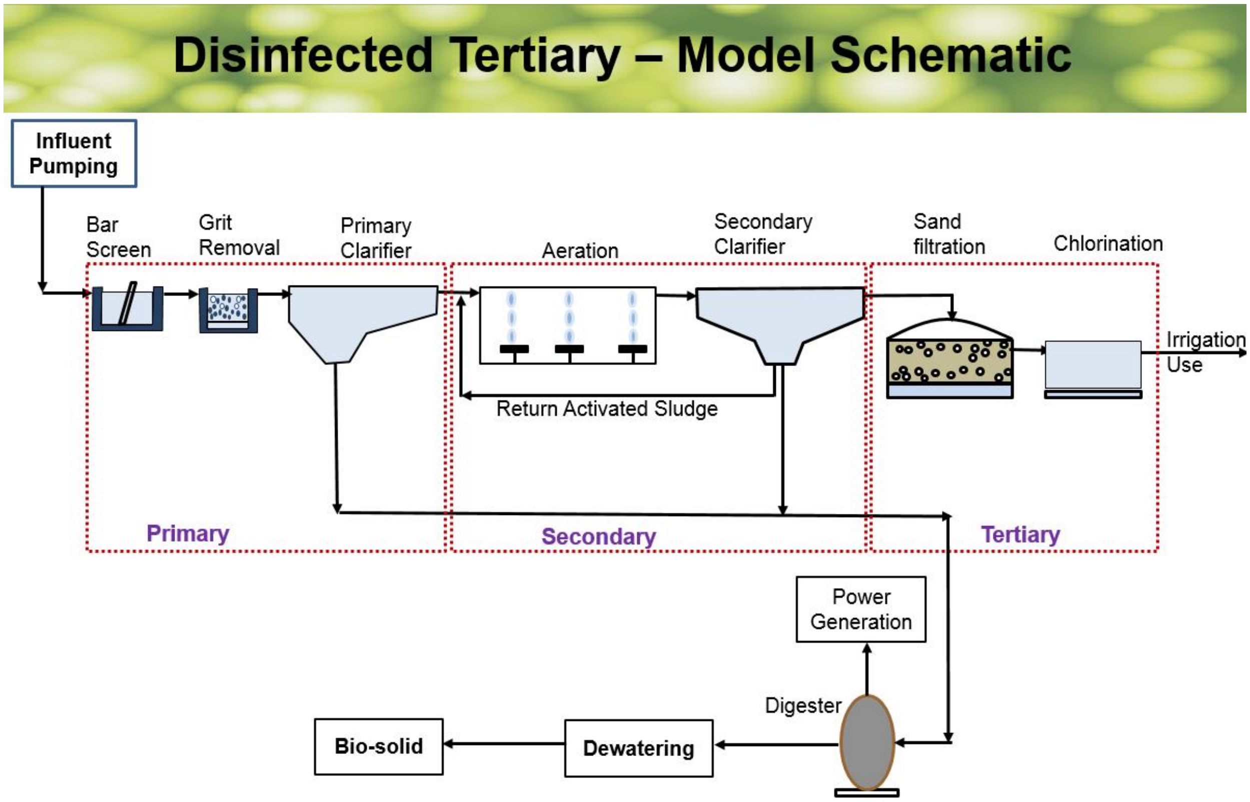

Figure A7 – Model Schematic of Disinfected Tertiary Water

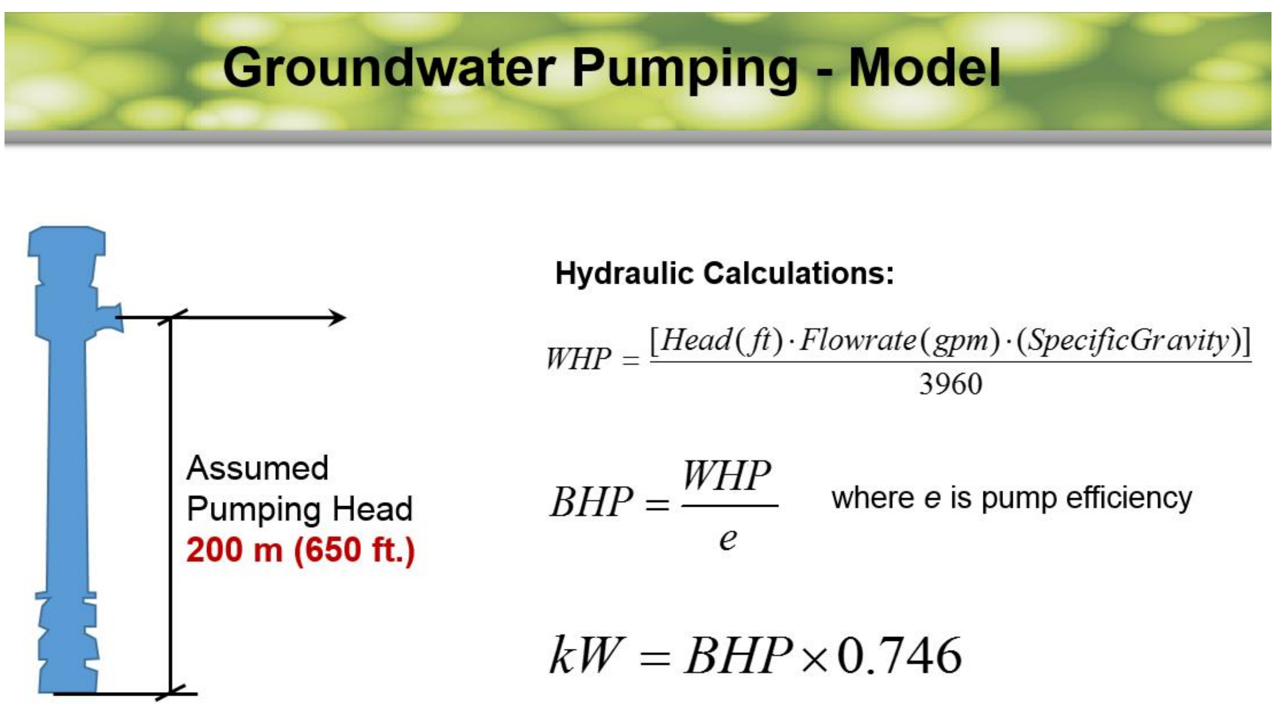

Figure A8 – Model Schematic of Disinfected Tertiary Water

Model Structure

Equation 1: $Q = \sum_{i-1}^{s} Q(i)$ ∀(x,y)   i = {1,..,s}

Equation 2: $E(i) = Q(i) \cdot e(i)$ ∀(x,y)   i = {1,..,s}

Equation 3: $eFP = \sum_{i=1}^{s} E(i) = \sum_{i=1}^{s} [Q(i) \cdot e(i)]$ ∀(x,y)   i = {1,..,s}

Equation 4: $<k> = \frac{\sum_{j=1}^{p} [k(j) \cdot W(j)]}{\sum_{j=1}^{p} [W(j)]}$ ∀(x,y)   j = {1,..,p}

Equation 5: $c(i) = e(i) \cdot <k>$ ∀(x,y) i= {1,..,s}

Equation 6: $C(i) = c(i) \cdot Q(i) = e(i) \cdot <k> \cdot Q(i)$ ∀(x,y) i= {1,..,s}

Equation 7: $CFP = \sum_{i=1}^{s} C(i) = \sum_{i=1}^{s} [e(i) \cdot <k> \cdot Q(i)]$ ∀(x,y) i= {1,..,s}

Figure A9 – Mathematical equations for energy analysis model structure

Results of H_2O Supply Intensities

H_2O Supply Source	Energy Intensities
Ocean Desalination	3.57 – 3.94 kWh m^{-3}
Surface Water	1.62 – 2.04 kWh m^{-3}
Groundwater	0.77 – 1.38 kWh m^{-3}
Reclaimed Water	0.32 – 0.64 kWh m^{-3}

Figure A10 – Range of water supply energy intensities

Model Validation

H_2O Supply Source	MWDOC 2011	Wilkinson, 2007	Cohen et al., 2004	MODEL RESULTS
Ocean Desalination	3.09	3.00 – 3.16	3.4 - 4.5	3.57 – 3.94 kWh m^{-3}
Surface Water	2.63	1.62 – 2.59	1.6 - 2.6	1.62 – 2.04 kWh m^{-3}
Groundwater	--	1.07	0.72	0.77 – 1.38 kWh m^{-3}
Reclaimed Water	--	0.32	0.1 – 1.0	0.32 – 0.64 kWh m^{-3}

Figure A11 –Validation for calculated water supply energy intensities

Avg. Annual Agriculture Water Use in CA (4.2×10^{10} m^3)	Percentage of Applied Reclaimed Water (RW) Use				
	1%	5%	10%	15%	20%
RW Use (10^6 m^3)	420	2,099	4,199	6,298	8,398
[1]Total Energy Savings (GWh y^{-1})	187	935	1,870	2,805	3,740
[2]Monetary Savings (USD yr^{-1})	$25.2M	$126.4M	$252.5M	$379.4M	$506.3M
[3]CFP Reduction (MT_{CO2eq} yr^{-1})	4.68×10^7	2.34×10^8	4.68×10^8	7.01×10^8	9.35×10^8

[1]Calculated using 0.446 kWh m^{-3} (ΔGW energy intensity of 0.77 kWh m^{-3} and RW energy intensity of 0.324 kWh m^{-3})
[2]Calculated using electrical rate of 0.135 USD per kWh in 2015 Dollars
[3]Calculated using carbon emission intensity, k = 0.5 kgCO2,eq kWh^{-1}.

Figure A12 – Market penetration of energy, carbon footprint and monetary savings

CHALLENGES	OPPORTUNITIES
Limited RW Supply Availability	• Start with areas where dense pop. are close to farming communities. • e.g.,Coachella and Imperial Valley in SoCal • As benefits of RW are monetized, others will follow.
Infrastructure Limitations	▪ Results show immediate monetary savings if RW is supplied vs. GW pumping. ▪ State and Federal grant monies available to help with infrastructure needs (e.g., Prop 1 Funding)
Crop sensitivity to salt	▪ Not all crops are compatible, many are tolerant, such as cotton, wheat, asparagus, olives, figs, hay, etc.
How to get over Politics	• Recent Sustainable GW Management Act changed the rule. 20 years to achieve sustainability, compliance by 2020 • Another opportunity to push for RW use

Figure A13 – Challenges and Opportunities for recycled water use in California Agriculture

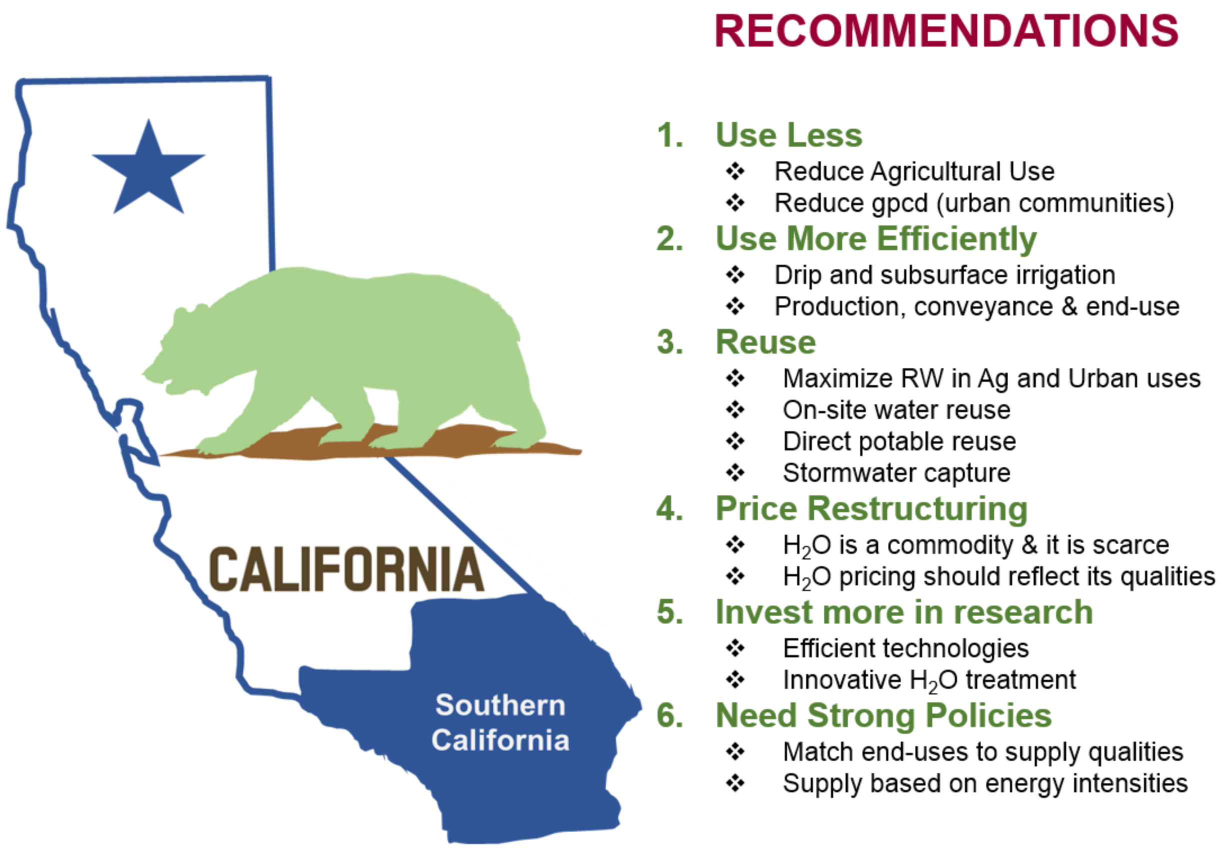

Figure A14 – Summary of Study Recommendations