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3D Mapping California's Household Water Conservation Alternatives

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Abstract

The human and ecosystem water needs in California, United States, are increasingly threatened by population and economic growths, climate change, and aging water infrastructures. Water cuts in the agricultural sector, which accounts for 80% of the state's human water consumption, are constrained by the state's prior-appropriation water rights system. As such, this Thesis seeks to provide a systematic and up-to-date assessment of the household water conservation potentials in California. The assessment considers the state-of-the-art water saving technologies and best practices, the related costs and energy consumption, and three urban environments representing the state's three distinct regions: Northern, Central, and Southern. The results indicate the potential household water savings are considerable, with minimal or negative economic costs and prosperity of energy savings. On average, households may reduce current water use by 20%, water-related energy by 24%, and water bill by 19%, resulting in a 5% reduction of the state's total water use and 10% of the energy demand of water supply. 50-70% of the water saving is outdoor use reduction, by reducing excessive irrigation or using non-potable water supplies from wastewater reclamation or rainwater catchment systems. The indoor water savings are largely attributable to high-efficiency faucets, showerheads, toilets & clothes washers. The results are the most promising in Southern California, with a 29% and 33% reduction in water use and water-related energy use, respectively, achieved at a net annual economic benefit of 210 euros.

Acknowledgements

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Chapter 1

Introduction

1.1 Background

Around the world, water quality and availability are emerging as two of the largest challenges that humanity is facing. As demand and availability are often inverted, roughly 2/3 of the world population are estimated to live under severe water scarcity for at least one month per year. [1] This far surpasses previous assessments which did not account for seasonal fluctuations in both consumption and availability. Global water issues expand further, impacting both the economy and environment, as drinking water and sanitation access are still limited in regions of the world, wastewater flow damages ecosystems and climate change occurs in addition to the continued population growth. The key complication in global water governance is the fact that there are simply too many organizations involved, leaving structure, leadership and the general process of improvement unclear. Furthermore, the financing of water projects is often too difficult bureaucratically and lacking in total funds allocated. [2]

In the USA the quality of drinking water is very good and 80% of its sources are surface waters such as rivers, lakes, reservoirs, and streams while the remaining 20% originate from groundwater aquifers. In charge of drinking water safety is the United States Environmental Protection Agency (EPA) which sets national legal limits for contaminants. The individual states may also impose their own standards, enabled by the Safe Drinking Water Act (SDWA), given that they meet or exceed those of the EPA. However, the systems in place for water distribution are largely outdated and, at the current rate of repair, would take 200 years to replace. [3] It is estimated that, across the country, there are 240,000 water main breaks annually causing an average loss of 15,000m^3 each. Additionally, the EPA estimates up to 75,000 annual sewer overflow events which are considered a leading source of water pollution. [4] These impair water quality, public health as well as wildlife. The most intense case occurs when stormwater combines irregularly with wastewater.

In terms of financing the American Water Works Association (AWWA) estimates a cost of roughly 1 trillion dollars for the water management systems to be maintained and expanded with the growing demand over the next 24 years. [3] The EPA believes an additional 271 billion dollars will be required for the wastewater infrastructure for the next 25 years. [4] Currently funding is largely provided by three sources: loans by the federal government through the Drinking Water State Revolving Fund (DWSRF), the EPA supporting projects with the states matching 20% to the EPA's investment and also the Water Infrastructure Finance & Innovation Act (WIFIA) funds which are designated for projects over 20 million dollars. [3]

The state of California is exceptionally interesting to look at as its domestic water use is one of the highest throughout the country [5] and water supply commonly travels large distances until its end use. While water efficiency is lacking, a lot of progress has already been made regarding energy efficiency. California was the first state to adopt statewide energy efficiency programs by passing climate change legislation (AB32, Global Warming Solutions Act of 2006) [6] and later Senate Bill 350, which was enacted in 2015, requiring half of the state's electricity to come from renewable resources by 2030. [7] Regarding available water sources California has recently felt the hardships of the 2012-2016 drought followed by record levels of precipitation in 2017. [8] Considering this drastic climate change which can occur, improvements in urban water conservation and efficiency are urgent. Savings are possible both inside and outside homes but also require the necessary funding and public education to be successful. [9] Currently, the local agencies in California raise 84% of the 30+ billion dollars spent annually on its water sector. [8] However, these spendings are focused on urban centers, leaving disadvantaged communities with inadequate water quality and without the necessary policies to change. According to the 2017 Infrastructure Report Card [3], over the next 20 years, California needs an additional 44.5 billion dollars invested in drinking water infrastructure and 26.2 billion dollars into wastewater infrastructure.

Considering all the above there is still a lot that needs to be done in the fields of water and embedded energy efficiency. For starters, data for updated estimates of the various end uses should be collected in order to better evaluate the benefits of water conservation & more energy-efficient water systems. Throughout this, water quality must be ensured and the human & environmental needs' assessment should improve. Possible trade-offs of new water & energy technologies must be recognized and the cooperation of water & energy operations should be explored further. Only then can the appropriate benchmarks be set. In addition to this, more extensive exploration of the Water-Energy-Food Nexus, which is largely unknown, and the accompanying interconnected policies is required. The amount of agencies involved tends to be too high and processes should be streamlined to allow for faster adjustments. Finally all systems must be designed to reduce vulnerability to drought & climate change, whilst adopting new policies & technologies to improve the assets' management.

1.2 Problem Statement

Continued population growth and worsening climate change increases the pressure on water & energy supplies. This means growing demand, increasing temperature, floods, droughts and rising sea levels which threaten coastal aquifers. The knowledge to mitigate the potential impacts is not shared at full potential yet and relevant data is still missing. Policies & regulations are ineffective as there are too many actors involved. Financing is generally difficult and too low with existing agreements vague & unprepared for the necessary changes. The sector most straightforward to improve is the domestic household. Unlike agriculture and energy production, it's not bound by as many complicating policies. In California this approach is definitely required as there is presently a massive overdraft of groundwater [10] and shortage of domestic water. Greenhouse gases & climate change are core issues for California as the state is subject to swift variations, affecting its social and economic well-being. Furthermore, it is interesting to ask why Silicon Valley, arguably the world's leading technology hub, has thus far not solved its local water problems through technological advancements.

1.2.1 Research Question

Which state-of-the-art water conservation alternatives are the most appropriate to implement for the Californian household considering their water conservation potential, embedded energy, and financial benefit?

1.2.2 Objective

This work intends to quantify the water cycle, its losses, and water saving potentials within a household. Renewed and improved diagrams, highlighting the potentials of water conservation and its embedded energy are created. Cost-effective analysis of the conservation alternatives is performed to ultimately advise on how to reduce strain on the existing systems and overall water usage. The majority of these are presented in the form of marginal cost curves (MCCs) for the 14 chosen alternatives. This is based on a technique premiered by McKinsey in February of 2007 with their first global greenhouse gas abatement curve. [11] This all is done to identify reasonable water conservation potentials at minimal or even negative energy and monetary costs.

1.2.3 Scope of Work

This Bachelor thesis is conducted internally at the University of Twente (UT) facilities of the Water Management Group under the direct supervision of dr. Ranran Wang. It is an empirical modeling assignment, focusing on quantifying the water, energy, and monetary flows associated with the household water conservation alternatives. These are chosen to best suit the particular environmental and socio-economical needs in the State of California, USA.

1.3 Report organization

The subsequent report is organized as follows. In Chapter 2 a literature study is conducted, exploring both the water usage and the individual conservation alternatives to reduce this on a household level. Chapter 3 clarifies how the literature study was executed and highlights the most important terminology. It also describes the analysis approach and introduces the accompanying calculations. Then Chapter 4 presents the results for both water and related energy conservation showing clearly the respective costs and potential. These are discussed. Finally, in Chapter 5, conclusions and recommendations are given.

Chapter 2

Literature Review

2.1 Water Use in California Household

2.1.1 Water

According to the 'Residential End Uses of Water, Version 2' executive report by the Water Research Foundation (WRF) [12] the average 2016 US household has decreased its annual water usage by 22% since 1999 to a countrywide average of 330m^3 (Figure 2.1). The total range of use is 160-660m^3, influenced by climate & weather patterns as well as local regulations. Indoor usage is averaging 520L per day overall and 415L for newer homes (i.e., 180 & 150 m^3/yr). The largest contributors to this are toilets, using 24% of daily indoor water, as well as faucets & showers each using 20%. Leaks make up 13% and dishwashers only 2%. Of the total indoor water use, 33% is used as hot water with the showers and faucets remaining very high users at 39.1% and 33.8% respectively. Outdoor usage for landscape-incorporating homes is at 50% of the total annual water use, with 13% of these homeowners excessively irrigating and comprising the majority of the usage. The conservation potential for indoor use is estimated to be 25%, with toilets & clothes washers generally furthest behind in fulfilling efficiency criteria, while that of outdoor use is only 16% and largely focused on educating excess users. [12]

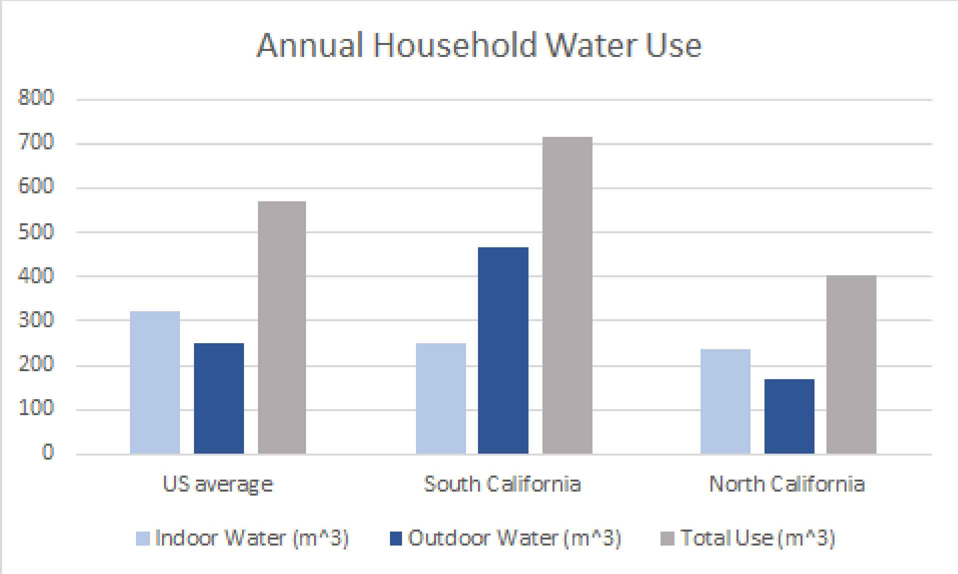

Figure 2.1: US & California residential households' water usage. [12] [13]

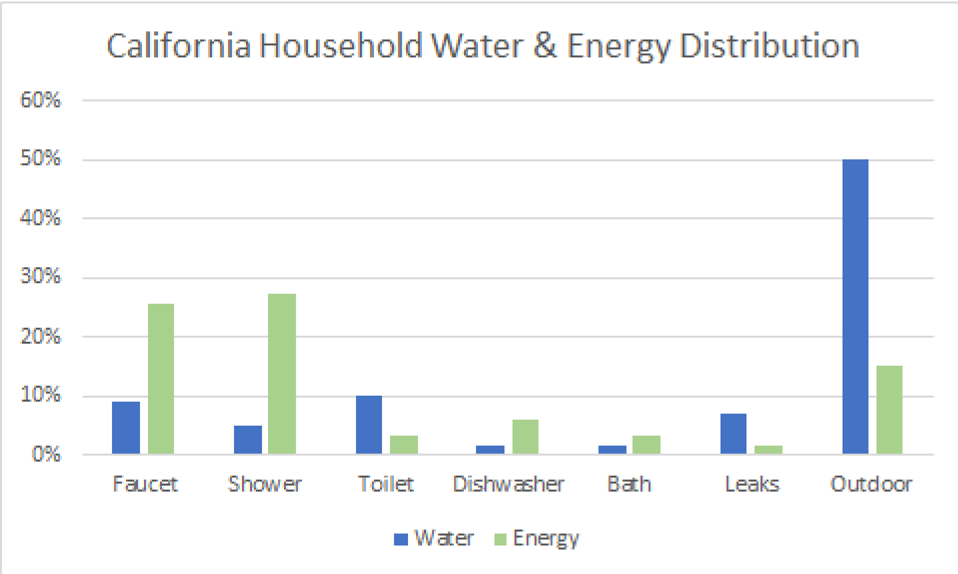

Figure 2.2: Embedded energy within household water usage. [7] [13]

Looking at California more specifically, researchers have found in 2011 [13] that the average annual indoor water use per household does not differ very much from north to south at 235m^3 and 250m^3 respectively. These values are 27% lower than the US average. Toilets use 20%, clothes washers 19%, showers 10% and dishwashers less than 5%. Leaks occur for 14% of the households for losses larger than 190L per day. Annual outdoor use, however, was found to be 270% higher in the south at 465m^3 compared to 170m^3 in the north. In total, it was found that 87% of the households irrigate, creating an overall indoor-outdoor water use ration of 47:53 which is still comparable to that of the whole US average. Unfortunately, the number of excessively irrigating homeowners in California is also large at 54% with 62% of the total excess being caused by only 15% of all homeowners. Furthermore, it was found that 18% of survey respondents owned pools of which 60% used pool covers. It is not specified whether these were in solid form, as solar panels or liquid blankets.

A 2012 survey from the California Air Resources Board (CARB) [14] gives some insights into the average households' use of the garden space. From the 2,999 people who completed the survey, of which 22.1% of the respondents were from Los Angeles, 66% owned a lawn and used gardening equipment. However, only 38% maintained their gardens themselves with 44% choosing to outsource this job. It was also found that 69% of the respondents lived in a house & 19.9% lived in an apartment. Overall the data showcased an increased use of the lawn since their last study.

2.1.2 Cost of Water

The cost of water facing the homeowner consists of a few components besides the amount used. Usually, there is a monthly meter base fee which is based on meter size as well as season and location within California. An electric charge may also be added depending mostly on the elevation of the property and implied pumping involved. A large number of the counties in California also use separate codes of regulation adjusting their own service charge, public fire protection charge as well as excess charges and sewer fees. In the south, the city of San Diego is chosen as an example, where the typical home has a 3/4-inch meter leading to a monthly base fee of 19.80EUR. The monthly average amount of water used is $59m^3$ and the price of water is $1.74EUR/m^3$. Therefore the average monthly residential water bill in San Diego is 122.46EUR, excluding a sewer fee of 78EUR. [15] In the northern part of California in Contra Costa County, right by San Francisco, the situation is very different. Service, fire protection & electricity charges add up to a monthly total of 18.58EUR which is already lower than the base fee in San Diego. Moreover, the usage in the north is lower at only $34m^3$ for a price of $1.19EUR/m^3$. Therefore, the monthly total is 59.04EUR and 51% lower than that in the south. [16]

2.1.3 Energy embedded in Water

Water-related energy is another big factor that must be considered to fully understand the impacts of conservation. Water systems in California are very energy intensive with the majority of it being related to residential end-use. According to a report by the Public Policy Institute of California (PPIC) [7] from 2016, using data from 2001 [17], water systems' energy makeup 10% of the states' greenhouse gas emission and use 20% of the state's electricity. This total energy use by the water sector is 175,950GWh with 42% of this being residential end use. An additional 4% & 2% of the total energy are required for the regional water systems conveyance, essentially the energy embedded in transport, and treatment respectively. Many different sources exist for the production of this energy, including hydropower, thermoelectric power and a rapidly growing amount of renewable energies. However, most important to note is that of this energy production 29% is water related and facing risks in cases of drought.

For the average household, energy distributes across water tasks as follows: shower 33%, faucet 30.9%, clothes washer 21.4%, dishwasher 7.1%, bath 4.7% and leaks 2.4%. From all this, the most intensive energy usage occurs during heating, covering 90% of the household's water-related energy end use and 25% of its total energy. Considering these values, it is obvious that improving water-use efficiency will ultimately reduce energy use and also applies the other way around. The report also found that, due to the long transport and a large amount of pumping involved, southern California's water is more energy intensive than that of the north (see Table 3.1). Therefore expensive, large-scale, wastewater reclamation could decrease the water's total energy footprint in the south.

Cost of the Energy

The average residential household in California uses 573kWh of electricity per month which is 36% less than the national average. With an average rate of 0.13EUR per kWh, this ends up costing the residential households 72EUR per month. This is still almost 18% below the national average of 87EUR. [18]

2.2 Conservation Alternatives

2.2.1 Domestic Water Appliances

Domestic water appliances are the common technologies on household level to target reductions in water usage. They can further be separated into lower and upper-class appliances, referring to their respective price ranges. Within the lower class are modern faucets, shower heads, and water meters. As these are rather cheap, their contribution can be maximized when the smartest versions of these technologies are chosen. Their cost effectiveness is relatively high and can be seen as a strong first step in the direction of water conservation. [19] Shower heads for instance generally reduce the flow rate to 6.2L per minute at an investment of only 20-50EUR. Similarly, low flow faucets reduce the flow rate to below 9L per minute. [13] For the case of the water meter it may be enough to improve its location within the house and simply check the level before and after a 1-2 hour period of absolutely no water usage. If done regularly this will keep leaks to a minimum. There are also solutions for this which already incorporate monitoring of the simplest water statistics directly with your smartphone. Within the upper class are more premium appliances such as dishwashers, washing machines, and toilets. These start around prices of 100EUR but can easily reach 500EUR if the top models are chosen. Their contribution is very reliable and larger than that of the lower class with water savings of 40%-70% attainable. [20] The related energy is also decreased by roughly 50%. [21] Low-flow toilets have however been proven far less cost-effective than lower class appliances, such as shower heads, but their overall saving potential is high enough to make up for it in the long term. [19] To further increase these technologies' profitability their outflows (grey water) could be reused on-site for another water requiring application such as the lawn.

2.2.2 Intelligent Irrigation

The single largest contributor to residential water use in California, according to both the WRF [12] and Aquacraft [13], at 50% of the total residential water use is outdoor irrigation. This is partially due to the fact that too often extravagant plants are grown rather than placing native ones. The chosen plants should ideally be drought resistant and require the least water to ensure a low-water garden design. Additionally, watering activities are inefficient as they are usually scheduled rather than on-demand deep soak for the water to truly reach the roots and be most beneficial. Placing mulch around trees further reduces losses due to evaporation. When comparing simple drip irrigation, which has a low flow rate, to overhead irrigation one finds a massive difference in in their water use due to the drastically higher flow rate of overhead irrigation. [13] Hoekstra 2017 [22] has explored different irrigation methods in-depth for agricultural purposes and developed marginal cost curves for the reduction of crop water. A similar approach to find the best cost effectiveness may be applied to the household garden, only to find that improving the irrigation method does not necessarily lead to large water conservation. Much more important is the mental approach to the task and, particularly in California, the branding associated with it during drought periods. The bigger improvement would be using recycled water for the lawn either from a water re-use or rainwater catchment system. The problem with rainwater catchment is a low precipitation level and high precipitation fluctuation in California. The average statewide precipitation is 54cm with annual variations up to +/-38cm. [8]

2.2.3 Recirculation

Water reuse systems are another technology with the potential to reduce potable water use while also providing a reliable, local grey water supply. In order to turn this into drinking water, purification, which is not yet efficient enough for households, is required. In the past the general public has expressed its strong concerns as ”toilet to tap” and only been set to rest with Orange County’s exemplary purification plant. This has been in operation since 2008 and cost the state 481 million dollars. [23]

Current research by the State Water Resources Control Board (SWRCB) for the State of California has further highlights the feasibility and recent improvements as well as some remaining short-term research to guarantee public health. [24] The grey water however is useful enough already on the household level and may even reduce the severity of drought periods and other issues related to the water supply.

The systems creating this grey water supply can be separated into two groups: interior and outdoor, named by the water's destination after it has been used. Purely interior reuse is already common in some countries such as Japan were the water from washing one's hands in the sink is then used to flush the toilet. This is even done for cheap toilets, however then the sink is mounted right on top the toilet box. This technology can similarly be applied to all other drains, including that of the shower as well the washing machine, to for example feed an outdoor irrigation system. According to the US EPA water recycling can, amongst others, also be used for public parks, golf course irrigation and as coolant for power plants. It can therefore "satisfy most water demands, as long as it is adequately treated to ensure water quality appropriate for the use". [25] The amount of wastewater being reused in California was only 13% in 2012 leaving roughly 5 cubic kilometers unused and an estimated potential to save 1.85 cubic kilometers of potable water. [26] This technology can therefore provide not only environmental benefits by reducing wastewater flows and diverting these from reaching streams and rivers, but also, directly visible for the homeowner, economic savings. The investment required to achieve this is only a few new pipes and a grey water reservoir which may be as cheap as 100EUR depending on the household. Hot water recirculation is another branch of this technology, with efficient and simple to setup products being as cheap as 200EUR like the Watts 500800 or the tank-less option of the Laing 6050E7000 for roughly 400EUR. These products often claim to save thousands of liters annually resulting in a 10% reduction of a homeowners water bill. [27]

2.2.4 Pool Covers

Depending on the location, swimming pools could be commonplace in California, with which come both great water and heat losses through evaporation. Optimized circulation systems are an expensive option to improve this but only have a minimal effect compared to more conventional methods. These include turning off any water features (e.g. water fountains), reducing the water temperature and adding windbreaks; all in an effort to reduce evaporation. The cleanest improvement would obviously be to prohibit outdoor pools, but that is not very likely. There is however another effective technology grouping related to covering the pool and trapping the heat. Primarily it consists of both floating and suspended covers, where suspended covers are inferior in the suppression of evaporation compared to floating solutions. [28] Unfortunately, the installation of these is difficult at times due to peculiar pool shapes as well as size issues and is considered too costly for this research. An alternative, which has gained public appeal, are liquid blankets which are products that can be added to any pool in liquid or solid-dissolving form. It then disperses evenly around the pool automatically as a protective layer which is completely invisible and biodegradable. Most manufacturers deliver products that protect a 100m^3 pool one month long for a price around 10EUR. [29] Different products claim divergent percentages of water evaporation conservation ranging from 30% to 60%. Considering that, if not refilled, the average Californian pool of 70m^3 volume, which loses 1.2-5cm weekly off the top due to evaporation, would empty completely over one year period, suggesting decent water saving potential of up to 42m^3 annually. [30]

2.2.5 Home Gardening

The next water conservation alternative researched comes in the form of an investment into home-gardening with an aquaponics setup. This is a closed water system with the capability to grow basic vegetables, such as lettuce and tomatoes, as well as edible fish while reducing the area required compared to common gardening. The benefit lies in the reduction of the water embedded in the food cycle of the house. Although this is arguably just an emerging technology, research has grown largely since 2010 and looks promising for both urban and rural application. [31] The potential for aquaponics is further highlighted by its superiority even over hydroponic setups. [32] Achievable savings, if aquaponics is suited for enough households in California, should be quite overwhelming at almost 50% for embedded water in food, particularly when set up properly and connected to rainwater collection. [33] However, for most home-owners who do not already grow food in their garden, this technology would have both initial and maintenance costs which were previously covered by the agriculture industry. With the simplest kind of setup, being a basic raft system which only claims a volume of 0.15m^3, initial costs may be around 100EUR with monthly replenishing of required materials for 10EUR. [34] Shifting the issue over to the large-scale agricultural producers, it was already proven in 2009 that recirculating aquaculture systems are twice as water efficient as conventional farming techniques whilst also producing large amounts of fish. [35] Therefore this might prove as an adequate implementation of this technology into the mainstream.

2.2.6 Indirect Alternatives

Local sustainable energy production is another way to reduce water losses, these are associated with the cooling of power stations, by an average of 8%, according to the EPA. This is roughly 7.5 Liters per kWh. [36] Other possible technologies include smart monitoring, which allows leaks to be repaired faster and optimizes water flows. This issue has however already been addressed with the far cheaper method of regularly controlling the water meter. Common drinking water vs. bottled water research was also looked into but only had negligible benefits for the case of California. Tap water is well regulated by the SWRCB Division of Drinking Water (DDW) and simply needs better advertising to further increase its use.

Chapter 3

Methodology

3.1 Data Sourcing

This research focused on the most recent undertakings, findings, and values reported in the recent years, specifically for the case of end use in a typical California household. Water & energy pricing data were taken from government sources & utility providers of the specific location. However, some research from the early 2000s was also included given its relevant for the alternatives' potentials, proven reliable, and has not necessarily advanced since then.

The main tools to conduct this were the University of Twente's research sources, namely Google Scholar, Scopus & Web of Science. The approach was searching for key words such as 'California Water End Use' or 'State of California Water Regulations'. Most of the research was contributed by non-profit, state agency & academic researchers such as works by the WRF, the PPIC, the SWRCB for the State of California, Water Resources Research as well as from the journals of Environmental Management & Energy Efficiency. Additional tools were Water Research, Environmental Research letters and California Energy Commission. Data from the Pacific Institute and Water in the West was also used. Furthermore, the US EPA was cited largely for regulations and technicalities while industry reports and surveys served as data for the conversation alternatives. Regarding Aquaponics research was focused on the journals of Water 2016 & 2017 as well as Aquaculture Engineering.

3.2 System Technicalities

To begin we define our primary system as one block representing the overall house with an inflow (i.e., water withdrawal) and outflow (i.e., return flow/sewage). The inflow represents the gross water use of the house and the outflow is the gross water use minus all losses (i.e., the consumptive water use). In an ideal case, with no losses, one could setup a water flow balance across this system which reads $Inflow$ - $Outflow = 0$. This is sadly not very realistic and will more commonly equal the net flow which is equal to the losses of the house. Adding the other necessary flows: precipitation, evaporation, and leakage, to the household water cycle is shown in the basic diagram in Figure 3.1. This corresponds to end use within the larger water system diagram in Appendix A.1.

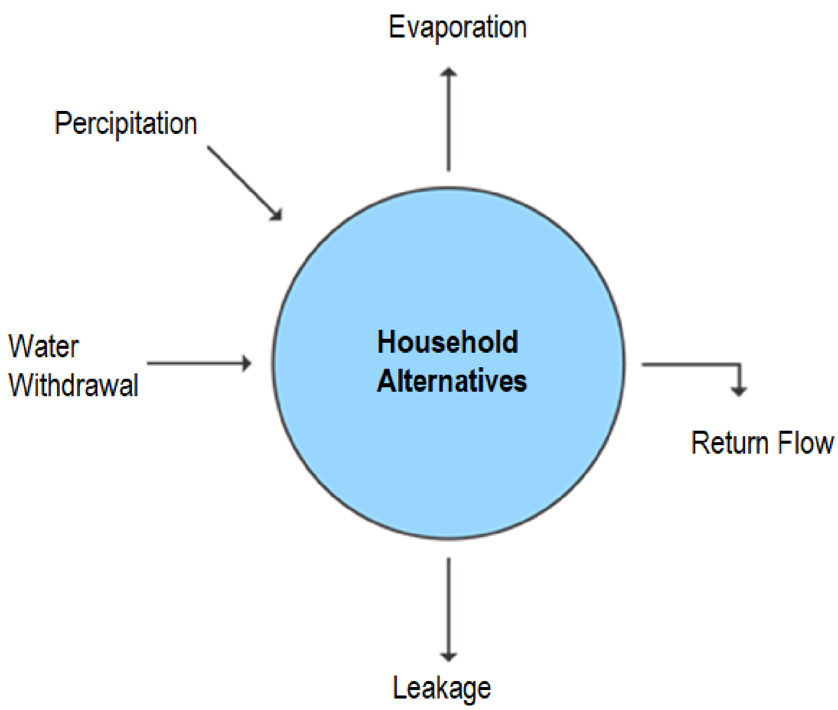

Figure 3.1: General Household Water Flows

Given that all the data sources in this paper originate from the USA, conversions were done from gallons to m^3 and dollar to EUR. This, and all other calculations, were carried out in Microsoft Excel with occasional usage of Matlab to create plots.

3.3 Design Inputs

This segment intends to highlight the possible ranges of applicability per conservation alternative to the household level gross water use. It is important for the calculation of the results and further discussion based on these. Table 3.1 shows the major design ranges of water end use. The data is presented in three parts: minimum, average and maximum amount using the final row to also give an overall average. The costs here only account for the amount of water used & its embedded energy and do not include metering fees, fire protection fees or any other charges. Additional parameter tables are available in Appendix A.2.

Table 3.1: Annual water & embedded energy end use per household. [6] [15] [16] [37] [38]

Location	Water use (m^3/yr)	Embedded Energy (kWh/yr)	Costs (EUR/yr)
San Diego	500-639-830	5954-7610-9880	1703-2177-2828
Fresno	85-116-215	518-708-1312	135-184-342
San Fransisco	315-364-520	1331-1539-2198	547-633-900
CA average	373	3286	998

3.4 Calculation Procedure

First, the necessary water & energy data of the typical California residential household are compiled for each location. This includes the amounts, associated costs as well as indoor-outdoor water use split and embedded energy factors. Then the alternatives are chosen and reasonable costs of each investment are found. Through research, the possible saving and contribution percentages are used to determine a design factor to calculate the relevant water & embedded energy reductions. The cost effectiveness of both water & embedded energy is calculated. Based on these a preliminary decision can be made to chose the optimal combination of alternatives for a location (i.e., front). To justify this, the financial benefit of the alternatives is calculated. Using this one can create MCCs of the alternatives and come up with more viable fronts for the three chosen locations. Finally, front analysis is mainly based on summation of the relevant elements of the chosen conservation alternative set. Again the cost effectiveness and financial benefit are calculated.

3.5 Equations

The units of these calculations are always per household and per year. Water is measured in m^3, energy in kWh and costs in EUR. The most significant input, water use, is take from Table 3.1.

3.5.1 General

$$\text{Embedded energy} = \text{Water use} \times \text{Embedded energy ratio}$$
$$\text{Costs} = (\text{Water use} \times \text{Water price}) + (\text{Embedded energy} \times \text{Energy price})$$

3.5.2 For Each Conservation Alternative

Lifecycle costs $=$ Initial investment $+$ (Annual costs $\times$ Lifespan)
Water reduction $=$ Design factor $\times$ Water use
Embedded energy reduction $=$ Water reduction $\times$ Embedded energy ratio
Cost effectiveness (Water reduction) $=$ Water reduction$/$Lifecyle costs
Cost effectiveness (Embedded energy reduction) $=$ Embedded energy reduction$/$Lifecycle costs
Cost Savings $=$ (Water reduction $\times$ Water price) $+$ (Embedded energy reduction $\times$ Energy price)
Financial benefit $=$ Lifecycle costs $-$ Cost Savings

3.5.3 For Fronts

Front costs $= \sum$ (Costs of front's alternatives)
Front water reduction $= \sum$ (Water reduction of front's alternatives)
Front embedded energy reduction $= \sum$ (Embedded energy reduction of front's alternatives)
Cost effectiveness (Water reduction) $=$ Front water reduction$/$Front costs
Cost effectiveness (Embedded energy reduction $=$ Front embedded energy reduction$/$Front costs
Front financial benefit $= \sum$ (Financial benefit of front's alternatives)

Chapter 4

Results and discussion

4.1 Alternative Results

4.1.1 Overview

Table 4.1: Cost of the conservation alternatives investigated in this research

Alternative	Lifespan (yrs)	Initial Costs (EUR)	Maintenance Costs (EUR/yr)
Faucet	15	25.00	2.50
Shower	20	35.00	2.50
Metering	25	15.00	1.00
Toilet	30	130.00	18.00
Clothes washer	25	200.00	15.00
Leak repair	1	0.00	150.00
Dishwasher	20	180.00	15.00
Aquaponics	20	150.00	80.00
Energy production	40	1000.00	30.00
Drip irrigation	25	200.00	15.00
Rainwater catchment	20	200.00	30.00
Grey water reuse	20	150.00	30.00
Hot water recirc.	20	200.00	25.00
Liquid blankets	1	8.30	91.30

The data presented in Table 4.1 is that of the chosen minimum requirements, based on the research, to efficiently use a conservation alternative. This is assuming no damage occurs due to misuse by the homeowner. Most of the lifespans are very similar at 20 years. Hopefully by that time, more efficient replacement models are available.

Judging the annual total costs presented in Table 4.2 they are reasonably low, encouraging any household to invest in at least a few of these alternatives given their large possible water & energy reductions. Some of the highest water reductions can be achieved through the simplest tasks such as more attentive water metering, leak repair, and upgrading faucets.

Table 4.2: Costs and savings associated with each conservation alternative. Calculated using factors in Appendix A.2.

Alternative	Costs (EUR/yr)	Water (m^3/yr)			Embedded Energy (kWh/yr)		
		South	Central	North	South	Central	North
Faucet	4.17	16.1	5.8	14.9	191.8	35.7	63.0
Shower	4.25	8.9	3.2	8.3	106.5	19.8	35.0
Metering	1.60	**71.6**	13.0	**40.8**	**852.4**	79.3	**172.4**
Toilet	22.33	17.9	6.5	16.6	213.1	39.7	70.1
Clothes washer	23.00	17.0	6.2	15.8	202.4	37.7	66.6
Leak repair	150.00	**80.5**	14.6	**45.9**	**958.9**	89.2	**194.0**
Dishwasher	24.00	3.6	1.3	3.3	42.6	7.9	14.0
Aquaponics	87.50	26.8	1.6	8.9	319.6	9.9	37.7
Energy production	55.00	2.3	0.1	0.8	27.4	0.8	3.2
Drip irrigation	23.00	15.5	0.9	5.1	184.1	5.7	21.7
Rainwater catchment	40.00	**49.7**	3.0	16.5	**591.8**	18.4	69.8
Grey water reuse	37.50	**68.2**	4.1	22.7	**812.1**	25.2	95.8
Hot water recirc.	35.00	2.6	0.9	2.4	30.4	5.7	10.0
Liquid blankets	99.60	9.7	0.6	3.2	115.1	3.6	13.6
Total	607.00	390.3	62.0	205.3	4648.3	378.6	867.1

Mapping all alternatives onto a plot of annual water savings against annual total costs as done in Figure 4.1 visualizes their benefits. The ideal location is the upper left quadrant. Unfortunately, there are only a few that fit into this category which are water metering and on-site grey water reuse. Other efficient alternatives include domestic water appliances, improved irrigation technology, and rainwater catchment. Home-gardening is on the edge of looking promising while liquid blankets are misrepresented given the small number of pool owners. Local sustainable energy production is the least contributing as water savings don't occur at the household level but within the energy production sector. Common leak repair is the annually most expensive method but can be applied to all households, assuming they all experience at least 1 leakage per year.

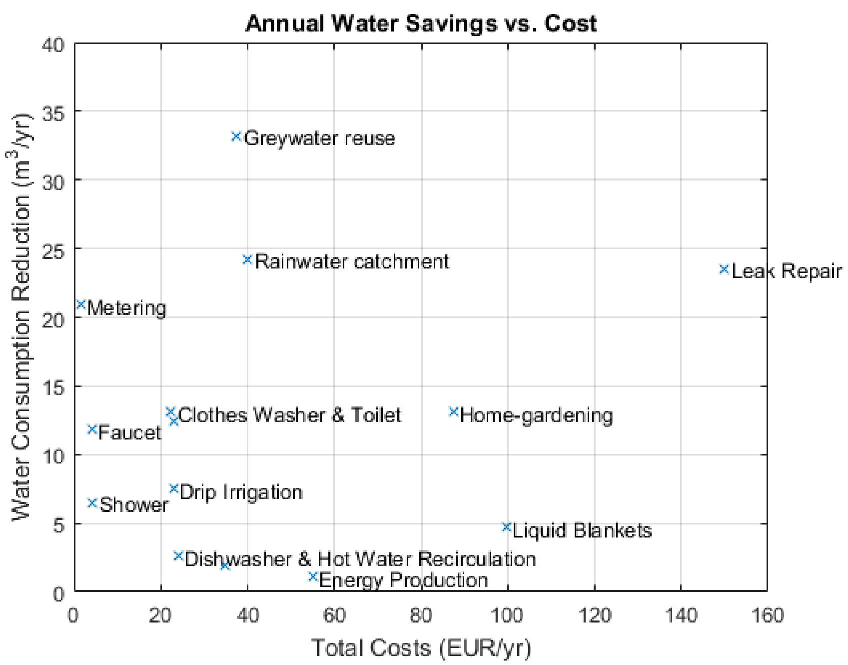

Figure 4.1: Plot of alternatives' water savings vs. total costs

Table 4.3 gives all reduced water & energy cost effectivenesses for the different locations. Cost effectiveness is consistently the highest in the south, followed by the north & lowest in the center. Using Figure 4.1 in addition to this, we now have enough information to setup a preliminarily optimal combination of conservation alternatives. This combination will be called the **standard** front and consist of the essential water conservation improvements. These are chosen to include all modern household conservation appliances except the dishwasher as its cost effectiveness is too low.

Grey water reuse is also included in this front. The two most common to improve conservation, leak repair & attentive metering, will not be included in any fronts as these are too general and apply as advice to any household. In order to improve the applicability of the alternatives, Section 4.2 will evaluate, in addition to the standard front, three location-based fronts with greater precision.

Table 4.3: Location-based water & embedded energy cost effectiveness.

Alternative	Water CE (m^3/EUR)				Energy CE (kWh/EUR)			
	South	Central	North	Average	South	Central	North	Average
Faucet	3.86	1.40	3.58	**2.82**	46.03	8.57	15.13	22.40
Shower	2.10	0.76	1.95	**1.54**	25.07	4.67	8.24	12.20
Metering	44.73	8.12	25.52	13.06	**532.73**	49.58	107.78	103.70
Toilet	0.80	0.29	0.74	**0.58**	9.54	1.78	3.14	4.64
Clothes washer	0.74	0.27	0.69	0.54	8.80	1.64	2.89	4.28
Leak repair	0.54	0.10	0.31	0.16	6.39	0.59	1.29	1.24
Dishwasher	0.15	0.05	0.14	0.11	1.78	0.33	0.58	0.86
Aquaponics	0.31	0.02	0.10	0.15	3.65	0.11	0.43	1.19
Energy production	0.04	0.00	0.01	0.02	0.50	0.02	0.06	0.16
Drip irrigation	0.67	0.04	0.22	0.33	8.00	0.25	0.94	2.60
Rainwater catchment	1.24	0.08	0.41	**0.60**	14.79	0.46	1.75	4.80
Grey water reuse	1.82	0.11	0.61	**0.88**	21.66	0.67	2.56	7.03
Hot water recirc.	0.07	0.03	0.07	0.05	0.87	0.16	0.29	0.42
Liquid blankets	0.10	0.01	0.03	0.05	1.16	0.04	0.14	0.37

4.1.2 Financial Benefit and Marginal Cost Curve (MCC)

In order to create MCCs the financial benefit of the alternatives is required in addition to the water savings presented earlier. These are shown in Table 4.4. For the average location, 6 of the alternatives are financially beneficial while for the central location only 3 are. The standout of these is the toilet which is financially viable in all locations except the central. In the south, the alternatives are most beneficial with many of them earning their initial investment back within 1-3 years. The north also looks promising although grey water reuse is surprisingly not financially viable.

Table 4.4: Annual financial benefit.

Alternative	Financial Benefit (EUR/year)			
	South	Central	North	Average
Faucet	-48.02	-4.69	-20.97	-24.56
Shower	-30.71	-1.70	-11.54	-14.65
Metering	-199.69	-15.46	-58.95	**-91.37**
Toilet	-20.73	**15.07**	-1.05	-2.23
Clothes washer	-43.42	11.70	-7.00	-12.91
Leak repair	-76.45	130.80	81.89	**45.41**
Dishwasher	10.61	21.72	17.87	16.73
Aquaponics	31.37	85.91	77.63	64.97
Energy production	50.41	54.87	54.22	53.17
Drip irrigation	-8.36	22.11	17.63	10.46
Rainwater catchment	-48.26	37.49	26.76	5.33
Grey water reuse	**-83.61**	34.05	**19.33**	-10.08
Hot water recirc.	25.01	33.30	30.49	29.60
Liquid blankets	74.73	98.60	94.89	89.51

Looking at the location averaged MCC in the top left corner of Figure 4.2 we can distinguish the alternatives which induce additional costs if implemented. In this case, they are energy production (1) (i.e., reducing water consumed by energy production), hot water recirculation (2), liquid blankets (4) and aquaponics (10) in addition to the previously excluded dishwasher (3). Drip irrigation (6), leak repair

(12) and rainwater catchment (13) are almost beneficial. Furthermore, we find that the beneficial alternatives, i.e., (9), (14), (8), (7), (5), and (11), have very similar marginal costs, largely in the range of -0.50 to -2.00EUR/yr/m^3. Combined they have an average marginal cost of -1.70EUR/yr/m^3 with a potential to reduce water use by 97.8m^3/yr. This is 26% of the average household's annual water usage.

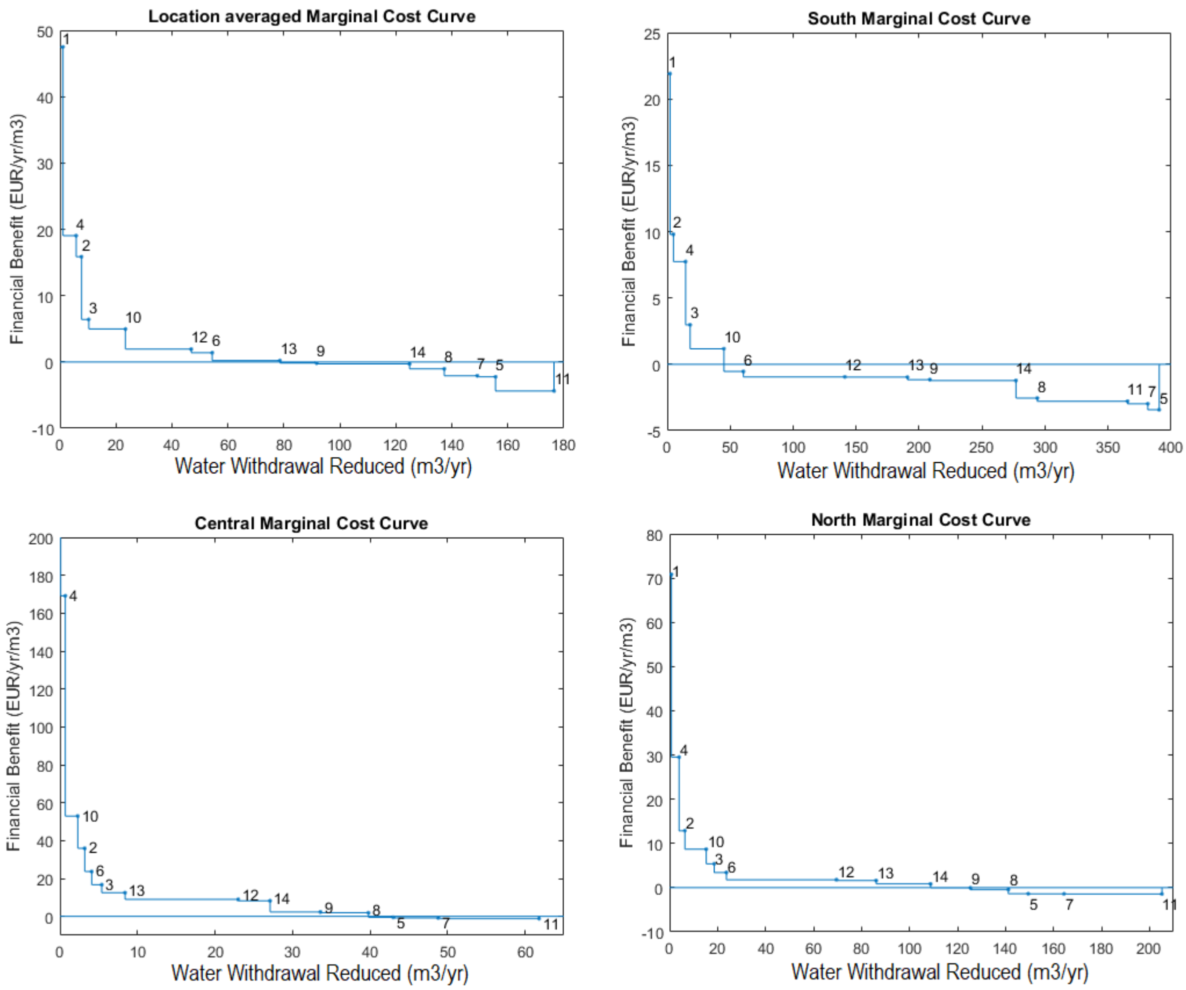

Figure 4.2: MCCs of the conservation alternatives for the locations: average, south, central, and north, presented on varying axes ranges.
Legend: (1) energy production; (2) hot water recirculation; (3) dishwasher; (4) liquid blankets; (5) shower; (6) drip Irrigation; (7) faucet; (8) clothes washer; (9) toilet; (10) aquaponics; (11) metering; (12) leak repair; (13) rainwater catchment; (14) grey water reuse.

Using the southern MCC in the top right corner of Figure 4.2 we find that only energy production (1), hot water recirculation (2) and liquid blankets (4) don't apply efficiently. The dishwasher (3) and aquaponics (10) are almost beneficial for this location with the remaining 9 alternatives all contributing nicely. This yields a high average marginal cost of -1.85EUR/yr/m^3 with an even higher potential to reduce the water use by 345.5m^3/yr. If applied this may reduce the southern Californian household's annual water usage by up to 54%.

The marginal cost curve for the central location in the bottom left corner of Figure 4.2 looks much less promising as only showers (5), faucets (7) and metering (11) are financially beneficial. This is because utility fees are lower. These three have an average marginal cost of -0.84EUR/yr/m^3 with a low total reduction in water use of only 22.1m^3. However, this would still be a reasonable decrease in household water usage of 19% for the given location. A lot of the other alternatives have marginal costs in the range of 1.00-40.00EUR/yr/m^3 with considerable water saving potentials leaving the household with several options to add for a later improvement stage.

The beneficial alternatives for the north location, shown in the bottom right corner of Figure 4.2, resemble those of the average location. The only alternative which is no longer beneficial is rainwater catchment (13) although its marginal cost is fairly low at 1.62EUR/yr/m^3. For those which are financially beneficial, the average marginal cost is -0.95EUR/yr/m^3 resulting in a total reduction in water use of 96.4m^3. This can reduce northern Californian household's annual water usage by up to 26.44%. A lot of the other alternatives, if applied to the north, have marginal costs in the range of 1.00-20.00EUR/yr/m^3 which is half of what they are for the central location giving the northern households more flexibility for future improvements.

4.2 Results of the Fronts

The combinations of different alternatives chosen, in addition to the standard front, introduced at the end of Section 4.1.1, are the south front for San Diego, central front for Fresno and north front for Contra Costa County. Within the south front are all alternatives of the standard front plus home-gardening, rainwater catchment and the modern dishwasher. In the central front, where an underprivileged location is used, are all alternatives of the standard front except the toilet. The north front includes the standard front alternatives plus rainwater catchment and the modern dishwasher. All values presented in the following Tables 4.5, 4.6 & 4.7 are calculated using the given location's specific parameters and are therefore only accurate for the given location.

Table 4.5: Front annual costs & savings.

Front	Total Costs (EUR/yr)	Water (m^3/yr)	Embedded Energy (kWh/yr)
Standard	91.25	76.9	610.9
South	242.75	187.4	2480.0
Central	68.92	19.4	136.2
North	155.25	145.1	414.4

The standard front, setting the benchmark for California, costs the household only 92 Euro annually and is able to save a considerable amount of water. All chosen alternatives within this front have a minimum water cost effectiveness of 0.54m^3/EUR leading to a high combined effectiveness of 0.84m^3/EUR. In the south, where water use is greater, higher annual investments are possible which reduce usage with similar effectiveness as the standard front. The largest contribution to reduction here is the combination of grey water reuse and rainwater catchment. This is profitable, because outdoor water use exceeds indoor use for the location. Additionally, embedded energy reduction is found to be most prominent in the south. For the central location in Fresno, which has less available funding per household, the annual costs were reduced compared to the standard front by removing the modern toilet. However, the potential water savings are even lower in comparison leading to a water cost effectiveness of only 0.28m^3/EUR. The north front saves up to 145.1m^3 of water annually while being most water cost effective at 0.93m^3/EUR. Unfortunately, it falls short in cost-effectiveness of reducing embedded energy.

Table 4.6: Cost effectiveness of the Fronts.

Front	Water CE (m^3/EUR)	Energy CE (kWh/EUR)
Standard	0.84	6.69
South	0.77	10.22
Central	0.28	1.98
North	0.93	2.67

Looking at Table 4.7 we find that the standard and south front are both financially beneficial while reducing water use by 23% and 29% respectively. The standard front has a low reduction of embedded energy due to not containing many alternatives which reduce highly energy-intense hot water use. The south front saves such a large percentage of embedded energy largely due to the greater amount of energy required to import parts of their water supply. Although the central front is not financially beneficial it does still reduce a considerable amount of water use at 16%. Finally, the north front saves the most water at 40% while remaining affordable. It's not financially beneficial but 23EUR per year to reduce the strain on existing water systems and contribute to sustainability is a price many in the San Francisco area would presumably pay.

Table 4.7: Annual financial benefit & overall reductions.

Front	Financial Benefit (EUR/year)	Water (%)	Embedded Energy (%)
Standard	-64.42	20.62	18.59
South	-209.48	29.33	32.59
Central	39.36	16.72	19.22
North	23.40	39.81	26.91

4.3 Discussion

To fully understand the possible water use reduction results presented in the previous Sections 4.1 & 4.2 one must view the front results as the reasonably implementable alternatives. Their reduction is conservatively lower than that of all beneficial alternatives but their adaption & applicability for the given locations is higher. Also critical to mention is the importance of regional heterogeneity in this assessment and corresponding policy recommendations.

This in mind we find residential California household water use savings in the range of 17-40% with an average of 27% which is very close to the estimated potential from literature [12] as well as the expected maximum reduction due to drought periods [8]. From this average a large amount is due to outdoor use reduction, which makes up 50-70%, targeting excessive irrigation or replacing it with a grey water source from reuse or rainwater catchment systems. Based on this we find a total water reuse, across all households in California, of roughly 0.44km^3 which is 32% of the residential reuse potential from literature [26]. This is enormous considering that grey water reuse costs the household at most 8.25EUR/yr over its lifespan. Contributing to high indoor water efficiency the most are faucets, showerheads, toilets & clothes washers although their energy efficiencies are what really matter. Regarding embedded energy in water use, we find a reduction in the range of 19-33% with an average of 24%. This is mostly due to hot water use reductions by faucets & shower heads and increased energy efficiency of the other alternatives.

Since economic feasibility is important to homeowners, we find that these savings would allow the Californian household to reduce its monthly water bill by 19% on average and up to 25% in the south. This is lower than the water use reduction percentage as water bills also include fixed fees. However, this is assuming savings to be fully focused on the household level rather than include contributions that may occur in the state's water sector.

Looking at the California water sector as a whole these household reductions would imply a state water use reduction in the range of 3-8% with an average of 5%. This is a lot lower than the household savings as residential water use only makes up about 20% of the state's water use. On the other hand, embedded energy in the water sector decreases by 8-14% with an average of 10%. This is due to the fact that residential water use is more energy intensive than other water uses such as irrigation for agriculture [7].

Considering the Excel model for the calculations of the results, there are a few issues and improvements which should be noted. Primarily local divergence of the chosen alternative base stats was not considered and alternatives were assumed scalable when in reality they are not. A few alternatives, such as aquaponics, liquid blankets, and local energy production, were simply not as widespread applicable as others and therefore their impact may be misrepresented. For future calculations, their contribution should be even more location specific and separate from the general calculation procedure. Also, some of the fronts require further tuning due to the fact that certain alternatives target reductions of the same flows.

Additionally, calculations are for reduced water use and do not distinguish consumption directly from this, with a few additions to the file this should definitely be possible. Embedded energy calculations also weren't ideal as alternative contributions weren't fully incorporated and only done through distinctions of cold, hot and grey water. Furthermore, it is important to clarify that the data presented in Sections 4.1 & 4.2 is merely one of many possible sets of results given the varying factors involved. Currently, every alternative has $4! \times 3!^{10}$ conceivable outcomes. Far more result sets are possible as the Excel model may be extended to include more specific parameters for a multitude of locations. It may also be improved by calibration, as water end use monitoring increases, with empirical data.

Chapter 5

Conclusions and recommendations

5.1 Conclusions

Overall we find that, there remains a compelling argument for even more improvement in household water saving in California. Given the drought phase which has finally ended, there is now great opportunity to make efficiency advances to fulfill the current & future needs of the state concerning the water sector. Furthermore, we find that, by sharing new knowledge, it is definitely possible to set new saving targets based on quantitative assessment. In order to be reliable, this must evaluate the efficiency potentials with the appropriate data, specific to different & more locations.

From the results we may conclude that the most appropriate alternatives for the Californian household are modern showerheads, faucets, toilets, and clothes washers. These, combined with location-dependent additions, should reduce household water use by 20% conservatively, or 5% of the total water use in the state. This water saving is to be achieved at minimal/negative monetary cost and co-benefits of energy saving. In the south, investments should be made into at least one or two outdoor water reducing alternatives, while in the north & center of the state one at most is enough. Additionally, the common alternatives of smarter water metering & leak repair have been proven very effective, being able to reduce up to 10% of household water use. Besides the sizable water savings which are possible, we also find that this does not require a lot of investment, a few hundred Euro per household would be enough to make significant changes. In total, a clear guideline for household water improvements is found which is to be progressively updated to follow the latest standards and codes.

This research did not show any alternative to be surprisingly beneficial, but rather set the non-beneficial alternatives in proper perspective to those which are. Some of these non-beneficially evaluated alternatives, such as aquaponics, energy production, and liquid blankets, are found to be misrepresented by the calculation procedure, given that they may not be integrated as naturally. However, this does not necessarily make them unviable in general, but rather their implementation for the chosen locations pessimal.

5.2 Recommendations

This research highlighted the regional heterogeneity through analysis of three distinct locations, representing a typical household in north, central, southern California. Future research should consider the additional variation at the sub-city scale and for more locations. Essential to building onto this research would be validation of the proposed changes followed by expanded data collection. This should generally be better in quality, transparency, and location specificness whilst also introducing additional parameters for individual alternatives. Moreover, research should aim to find further applicable alternatives and properly include water in food through investigation of the water-energy-food nexus.

Personally, I would continue this research by creating more visualizations of the data already processed. This would be in the form of MCCs for the minimum and maximum water savings, of the conservation alternatives, with a double y-axis to also include embedded energy. For the future, I hope someone will determine whether blockchain technology is valuable for the management of interconnected water systems.

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Appendix A

Extended Methodology

A.1 Water System Diagram

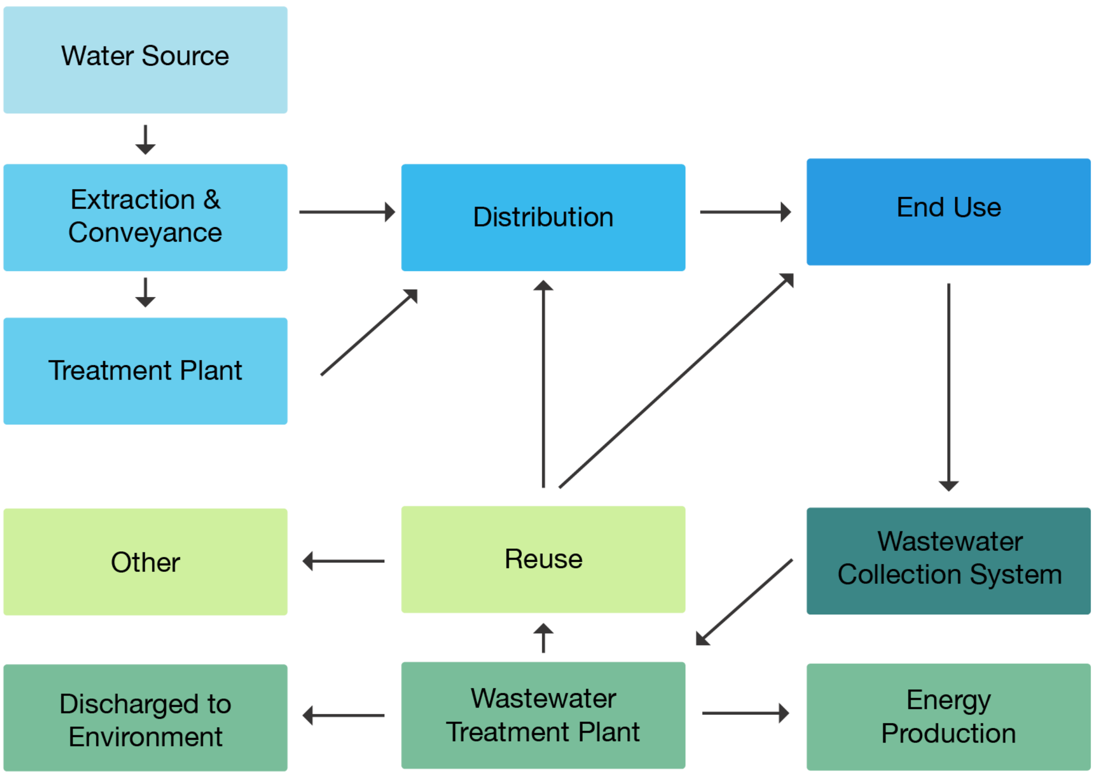

Figure A.1: General Water Infrastructure surrounding End Use

A.2 Design Parameters

Table A.1: Location Parameters. [15] [16] [17] [18] [37]

Location	Water Price	Electricity Price	Indoor Use	Embedded Energy Factor
	EUR/m^3	EUR/kWh	%	kWh/m^3
South	1.74	0.14	40	11.91
Central	0.80	0.13	80	6.11
North	1.19	0.13	65	4.22
Average	1.24	0.13	50	7.94

Table A.2: Household water factors - required to be multiplied by location's water price & embedded energy factor respectively. Excluding treatment of gray water due to on-site use. These estimates are based on findings by the WRF [12].

Water Type	Water Price Factor	Energy Factor
Cold potable	1	0.4
Hot potable	1	1.4
Gray water	0.7	0.35

Table A.3: Basic alternative factor ranges - required to be multiplied by location's water use. Water target is the % of the household water a given alternative impacts.

Alternative	Water Target (%)	Reduction (%)
Faucet	14-18-20	25-35-45
Shower	8-10-14	25-35-50
Metering	10-14-16	0-80-100
Toilet	15-20-22	25-35-40
Clothes washer	16-19-22	25-35-40
Leak repair	0-14-24	0-90-100
Dishwasher	2-4-5	25-35-40
Aquaponics	0-20-30	0-35-50
Energy production	5-7-9	0-8-10
Drip irrigation	15-20-35	0-20-30
Rainwater catchment	15-21-35	0-60-80
Grey water reuse	20-27-35	30-65-80
Hot water recirc.	5-10-15	5-10-20
Liquid blankets	0-6-20	10-40-50

Table A.4: Alternative water type factors - used to distinguish water savings.

Alternative	Cold potable (%)	Hot potable (%)	Gray (%)
Faucet	50	50	0
Shower	10	90	0
Metering	55	30	15
Toilet	1	0	0
Clothes washer	10	90	0
Leak repair	55	30	15
Dishwasher	20	80	0
Aquaponics	50	0	50
Energy production	35	0	65
Drip irrigation	40	0	60
Rainwater catchment	0	0	1
Grey water reuse	0	0	1
Hot water recirc.	10	90	0
Liquid blankets	90	10	0