Water Scarcity, South Africa, Cape Town

Systems Modeling Team Project

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1 Introduction

The city of Cape Town in South Africa has recently experienced difficulties providing enough water for its residents. Ninety-seven per-cent of the water supply is provided by municipal supply. In 2017, water restrictions entailed a ban on all use of municipal drinking-quality water for outside and non-essential purposes. Rainwater harvesting and greywater reuse have proved to be effective tools for enhancing non-potable local supply in other parts of the world. According to 2010 Census Data, the 3.4 million population is distributed in about one million households. More than one third of the population has an income of less than $250 USD per month. Currently Cape Town has a residential stepwise tariff system that penalizes large consumers with higher rates. There are tariff level differences based on income distribution, but the rates increase dramatically after a certain threshold. Introducing household water supply (HWS) alternatives would also theoretically reduce municipal revenue, potentially creating additional stress for maintaining or expanding the city's water infrastructure.

A couple of common terms that are used in the literature to distinguish sources of wastewater for residential use are black and gray water. Black water is commonly associated with wastewater generation at toilets and the kitchen. Gray water is relatively less contaminated and typical sources include bathroom sinks and washer machines. When show to be cost-effective, residents could install systems designed to channel these sources for outdoor demand to improve the reliability of their water supply. About a third of total residential water consumption is for outdoor use in South Africa. This has become a target for conservation measures at the expense of economic activity in the form of urban ecosystem services. "For many of the intended end-uses water can be reused directly without treatment (Milne, 1979), but issues regarding environmental pollution and community health (Govender et al., 2011) are becoming increasingly important, especially for greywater reuse (Cardenet al., 2017)".

Globally there has been a growing interest in developing rain harvesting projects. "A rainwater harvesting system consists of a number of integrated components, including a catchment area, a storage vessel and a distribution system". Cape Town receives more than 30 in of accumulated rainfall every year on average. However, climate data analysis shows that the level of rainfall has been declining for the past ten years. In addition, the variability of this resource presents a challenge for shifting the timing of precipitation to meet water demand. The authorities have now imposed mandatory conservation measures to avoid going below critical levels on the city's hydroelectric dams. "Dobrowksy et al. (2014) noted that acceptance of rainwater as a source and training of consumers to maintain and use the tank system optimally was essential to ensure that social development projects involving rainwater use would be sustainable. Mukheibir et al. (2014) revealed a data gap in knowledge about rainwater tank functionality and the performance of existing rainwater tank systems, noting also that ongoing maintenance of the rainwater system is essential to ensure continued substitution of potable water supplied via the distribution system."

2 Literature Review

[6] The residential end-use model (REUM), initially presented by Jacobs and Haarhoff (2004a), was used in this study to assess the theoretical impact of supplementary HWS on potable water demand. HWS for domestic purposes in a serviced area could be deemed 'legal' in the general case. No registration of the particular use is required. Additional research is required to determine what fraction of users would be likely to apply HWS, or are doing so already.

Table 1 Summary of earlier research for groundwater, rainwater and graywater

TABLE 1
Overview of supplementary household water sources

Type of HWS	Previous research	Comment based on earlier research			
		Typical yield (Y) or Flow rate (Q) per household	Source water quality	Possible application	Advantages and disadvantages
Groundwater	Wright and Jacobs (2016)	Relatively high yield[1] $0.1\ L{\cdot}s^{-1} < Q < 1.0\ L{\cdot}s^{-1}$	Normally non-potable, but depends on aquifer	Outdoor use and toilet flushing; no storage needed	High yield possible, but not guaranteed; very high capital and high energy cost; possible environmental impact (e.g., lowering groundwater table)
Rainwater: not internally plumbed	Dobrowksy et al. (2014); Mukheibir et al. (2014); Fisher-Jeffes et al. (2017)	Varies notably[2] Low summer yield in winter rainfall regions with $Y \approx 0$ in peak summer time	Non-potable	Outdoor use, hand washing of clothes, house cleaning (e.g. floors)	Yield is a function of rainfall, storage and roof size; potential mismatch between seasonal rainfall and highest demand; high capital cost; possible environmental impact (e.g., reduced urban streamflow impacts natural ecosystems)
Rainwater: Internally plumbed tanks	Beal et al. (2012)	Varies notably[2] Queensland Australia. Y varies from 54–260 $L{\cdot}hh^{-1}{\cdot}d^{-1}$, with ave. 137 $L{\cdot}hh^{-1}{\cdot}d^{-1}$	Non-potable	As above plus toilet flushing and clothes washing	
Greywater[4]	Christova-Boal et al. (1996); Eriksson et al. (2003); WHO (2006)	Reported Y varies from 218–346 $L{\cdot}hh^{-1}{\cdot}d^{-1}$; or about ± 100 $L{\cdot}c^{-1}{\cdot}d^{-1}$ (Jacobs and Van Staden, 2008)	Non-potable, relatively poor quality (Maimon et al., 2010)	Outdoor irrigation (Carden et al., 2017); toilet flush (Ilemobade et al., 2012)	Relatively constant yield; yield reduces in line with indoor water savings; relatively high community health risk and environmental risks; high capital and energy cost if treated

[8] This reference provides a comprehensive assessment of risks, costs and benefits of using greywater and stormwater to enhance local supplies. In summary, it provides useful design principles based on previous experiences with this type of projects in the United States. Greywater has proved useful for arid residential applications. There are challenges associated with stormwater quality management because of spatial variability of the contaminants present in the water. Demand and cost parameters were cross validated with data from the systems described on this study. The following guidelines were used to define the scope for the model.

3 Model

We model the investments of different water systems of our hypothetical community using a Mixed Integer Linear Program (MILP) whose objective is to minimize the cost of supplying water to this community. There is limited research for using a MILP to model how to optimally provide water via decentralized infrastructure with the most notable example being from [1]. However, whereas they modeled one specific technology, a community scale waste recycling facility, our model chooses between five different technologies and calculates how much each technology contributes to the water demand.

The objective function, constraints, and symbols are given in Figure 1. The objective minimizes cost by considering the price of water at various tariff levels, the capital costs of each technology, the operating costs of each technology, and the energy costs of each technology. The demand of water must be satisfied by either an invested technology or water from the mains as seen in the first two constraints. A technology can only satisfy water demand if the model invests in it as seen in the constraints 3-5. The technologies that depend on rainwater can only provide as much water as the rain allows as seen in the constraints 6-9. The technologies that depend on greywater can only provide as much water as the households provide in the form of grey water as seen in constraints 10-12. The water from the mains increases in price at certain levels as seen in constraints 13-15. The storage size of the system is bound by the tank sizes of the technologies that are invested in and the amount of water in storage is determined in each time period as seen by constraints 16 and 17. And finally the energy usage is determined by the flow rates of each technology as seen in constraint 18.

We used GAMS, industrial mathematical software, to create the model and CPLEX, an industrial mathematical solver, to solve it.

Figure 1 Mathematical Formulation of the Model

$$\min\ f_{rho}y_{rho} + f_{hgw}y_{hgw} + f_{cgw}y_{cgw} + f_{rhi}y_{rhi} + f_{csw}y_{csw} + \sum_t [c_{rho}v_{rho,t} + c_{rhi}(x_{rhi,t} + v_{rhi,t}) + c_{csw}v_{csw,t} + c_{cgw}(x_{cgw,t} + v_{cgw,t}) + c_{hgw}v_{hgw,t}] + \sum_t (p_w w_t + p_{w1}w_{t1} + p_{w2}w_{t2} + p_{w3}w_{t3} + p_s s_t) + \sum_t c_{kwh}e_t$$

s.t.

$$\sum_i (x_{i,t} + v_{i,t}) + w_t + w_{t1} + w_{t2} + w_{t3} + s_{t-1} \geq D_{inside,t} + D_{outside,t} + s_{flow,t}$$

$$\sum_i (x_{i,t}) + w_t + w_{t1} + w_{t2} + w_{t3} \geq D_{inside,t}$$

$$\sum_t x_{i,t} \leq My_i$$

$$\sum_t v_{i,t} \leq My_i$$

$$y_i \leq h$$

$$x_{RWI,t} \leq rw_t * y_{RWI}/h$$

$$v_{RWO,t} \leq rw_t * y_{RWO}/h$$

$$v_{CSW,t} \leq swi * rw_t * y_{CSW}$$

$$x_{RWI,t} + v_{RWO,t} + v_{RWI,t} \leq rw_t$$

$$x_{CGW,t} \leq ugw * D_{inside,t} * y_{CGW}$$

$$v_{HGW,t} \leq ugw * D_{inside,t} * y_{HGW}/h$$

$$x_{CGW,t} + v_{HGW,t} + v_{CGW,t} \leq ugw * D_{inside,t}$$

$$w_t \leq mw$$

$$w_{t1} \leq mw1$$

$$w_{t2} \leq mw2$$

$$s_t \leq \sum_i u_i * y_i$$

$$s_{flow,t} = s_t$$

$$\sum_i eu_i * x_{i,t} + eu_i * v_{i,t} + v_{RWI,t} = e_t$$

Table 2 Model Parameters and Decision Variables

Symbol	DV or Parameter	Description
f_i	Parameter	Fixed Cost of Technology i
c_i	Parameter	Variable Cost of Technology i
p_w	Parameter	Price of main water at various tariff levels
p_s	Parameter	Cost of using water from storage
c_{kwh}	Parameter	Cost of a kWh
h	Parameter	Number of households
rw_t	Parameter	Total rainwater available for the community in month t
swi	Parameter	Multiplier for Rainwater available via the stormwater system
ugw	Parameter	Fraction of inside water available for greywater recycling
mw	Parameter	Upper bound for various water tariff price levels
u_i	Parameter	Upper bound of water storage for technology i
eu_i	Parameter	Energy usage (kL/ kwh) of technology i
M	Parameter	Extremely Large Number
D_{inside}	Parameter	Demand for Water to be Used Inside
$D_{outside}$	Parameter	Demand for Water to be Used Outside
x_i	Decision Variable	Amount of water produced that can be used inside by technology i
v_i	Decision Variable	Amount of water produced that can be only used outside by technology i
w_t	Decision Variable	Amount of water bought from the mains at various tariff levels
s_t	Decision Variable	Water storage level at time t
$s_{flow,t}$	Decision Variable	Amount of water going to the storage tank at time t
e_t	Decision Variable	Amount of energy used by all technologies at time t
y_i	Decision Variable	Decision to purchase technology i

3.1 Technology Types

[2] investigated decentralized water infrastructure and how it could provide water resiliency. [3] investigated rainwater harvesting systems in urban environments. [4] also provided a review of large-scale decentralized wastewater treatment systems; however, many of their solutions are too large scale for our analysis.

[5] listed various distributed water infrastructures based on four different water strategies; they predicted community based non-potable water sources and a non-potable supply from greywater would be useful for places with limited central infrastructure. Furthermore, [6] specifically investigates supplementary water sources for South African households and includes rainwater and greywater at a variety of scales. [1] looked specifically at a sequencing batch reactor with a reverse osmosis unit and [7] used a reverse osmosis unit as well to clean well water.

[8] explored how different stormwater and community scale water recycling technologies could reduce water costs and expand water resiliency

Therefore, we chose the five technologies based on previously researched technologies and real-world systems. Household rainwater harvesting for outdoor water use (RWO) as shown in [5] household rainwater harvesting for indoor/outdoor water use (RWI) as shown in [3] and [6], Household greywater recycling for outdoor water use (HGW) as shown in [5], community scale stormwater harvesting for outdoor use (CSW) as shown in [5] and [8], and community scale greywater recycling for indoor/outdoor use (CGW) as shown in [1] and [9].

3.2 Capital Costs

The capital costs of all the technologies are annuitized based on the payback period and the discount rate. One of the advantages of this paradigm is that the annual operating and maintenance costs can be included in the annuitized capital costs and are done in our model. Therefore, our model only has energy costs and capital costs.

We decided to model a 1000-gallon rain harvesting system because it struck a good balance between cost and size. The tank is the largest expense in a rain harvesting system and a 1000-gallon tank costs less than $1,000 [10]**.** The only difference between a rain harvesting system to be used for indoors vs. outdoors is the filtration system which according to [11] is about $1,000. [11] also has information on the rest of the costs for the rain harvesting system and we round up to $2,000 for the RWO system and add an additional $1,000 for a total cost of $3,000 for the RWI system.

We modeled our household greywater system on the Aqua2Use greywater system which is a popular and highly rated [12] greywater recycling system. It treats greywater and then ejects it outside. It only costs about $1,000 but can cost another $1,000 to install so we set the cost to $2,000.

We modeled the community greywater system based on the PVRO system [9] installed in Mexico. It is a 1000 L / day system that cost $10,000 including installation and labor. This system uses similar technology as the proposed system in [1]; however, this system was actually created and implemented. We wanted at least 2 kL / day, so we doubled the cost to $20,000.

Information on community stormwater systems at our scale are limited so we estimated the cost based on the information from [8] which gave a cost of **$X / kL.** We sized our stormwater to **Y kL** based on the estimated rainfall and that gave a capital cost of $75,000.

All capital costs are listed in **Table 3**.

3.3 Energy Usage and Costs

The energy intensity of rainwater harvesting has been studies extensively [13] and [14] and the range is generally between 0.55 and 1.0 kWh/kL. We gave the RWO unit an energy intensity of 0.55 kWh/ kL and the RWI double that energy intensity (1.1 kWh/kL) because of the extra energy needed to filter the water.

The energy intensity of the household greywater system is given by the Aqua2Use system specs [15] and we chose the upper bound of 2 kWh/kL for the model.

The energy intensity of the community greywater system was estimated in both [1] and [9]and due to its larger scale it has a much lower energy intensity, so we used a value of about 0.1 kWh/kL based on the [9] data.

The energy intensity of a community stormwater system was difficult to estimate because there isn't any information of a system of this scale. However, we assumed that the only energy using component of a stormwater system would be the pump, so we found the energy requirements of a pump sized to move the vast amounts of water a stormwater system would hold and used that to give an estimate of the energy intensity. This pump uses has an energy intensity of about 0.5 kWh/kL [16] so that was our estimate for the energy intensity of the storm water system.

The cost of energy is given by the average cost of a kWh in South Africa which is $0.10 / kWh [17]**.**

All energy intensities for their respective technologies are listed in **Table 3.**

3.4 Harvesting Capabilities of Each Technology

We assume each household has 1000 sq ft. of roof space and that they can harvest 600 gallons per inch of rain [18]**.** Therefore, RWO and RWI can harvest up to 600 gallons per inch of rain. We assume that the CSW system can harvest up to 10 times as much rain as the household units because it has a much larger surface area to draw from.

We assume that about 75% of the water used inside is greywater and can be recycled. That gives the upper bound for both HGW and CGW with the latter being a single households greywater availability multiplied by the number of households.

3.5 Payback Period and Discount Rate

We assumed a payback period of 5 years and a discount rate of 5% for the base scenario. Therefore, using the initial costs of the equipment, the payback period, the discount rate, and an appropriate time value of money equation we can calculate the annuitized costs which are shown in **Table 3.**

Table 3 Technology Capital, Energy and Storage Parameters

Technology	Capital, O & M Costs	Annuitized Capital, O & M Costs	kWh per kL	Storage Upper Bound (gallons)
1000-gallon Rainwater Harvesting for Outdoor Use (RWO)	$ 2,000.00	$ 461.95	1.1	1000
1000-gallon Rainwater Harvesting for Indoor Use (RWI)	$ 3,000.00	$ 692.92	0.55	1000
Household Grey Water System (HGW)	$ 2,000.00	$ 461.95	2.0	25
Community Grey Water System (CGW)	$ 20,000.00	$ 4,619.50	0.1	25*h
Community Stormwater System (CSW)	$ 75,000.00	$ 17,323.11	0.5	10*1000*h

3.6 Changes in Costs to Tech

Our assumptions about the capital and energy costs inform the model's optimal decisions. Although, the energy costs could vary the relationship of energy costs between the technologies would probably remain the same even if the magnitude was different. Furthermore, even when adjusting the energy costs magnitude, they have little effect on the optimal decision, so we did not model scenarios with different energy costs.

However, changing the capital costs does make a dramatic difference in the optimal solution. So, we modeled cases where the community technologies were more expensive and other scenarios where the household technologies were cheaper.

3.7 Relevant Assumptions

We assumed we are making decisions from a community scale. Therefore, while we must invest in the entire community technology investment, we do not have to have every house have identical technologies. In other words, if we choose to invest in a household technology, say RWO, we do not have to invest in 100 RWO units we can instead choose to invest in 20 units.

If we were making decisions on a household scale, the results would be much more conservative since there would be no fractional decisions for household technology investments and you would have to invest in all 100 RWO units if you were to use the technology at all.

From a model standpoint it means that the decision to invest in CGW or CSW is a binary variable, but the decisions to invest in RWO, RWI, or HGW are continuous variables whose upper limit is the number of households.

Due to the simplistic time scale of the model, we assume that the technologies don't overflow. In other words, the storage capacity of all the technologies is large enough to store and then use all the water regardless of source. Therefore, the tanks for RWO, RWI, and CSW are assumed to big enough to handle all the rainfall and dispatch decisions made by the community.

3 Scenarios

Optimization models are deterministic and provide a mathematically optimal solution for a given set of parameters. However, the answer depends on the parameterization and they do not consider stochasticity. We counteract these limitations by performing a large set of scenarios that give us insights on how different conditions and costs would affect the optimal decision.

The list of scenarios tested, and their results are listed in Tables 4 and 5.

Table 4 Demand and Rainfall Scenarios for Technology Selection

	Modification	Rw	Dw	RWI	RWO	CSW	CGW	HGW
0'	Base Case (house decsions)	1	1	0	0	0	1	0
0	Base Case (community decsions)	1	1	0	0	0	1	0
1	Increased Rainwater	1.8	1	0	0.2	0	1	0
1'	Bigger Increase in Rainwater	2.3	1	0.04	0.15	0	1	0
3	Increased Demand	1	1.4	0	0	1	1	0
4	Decreased Demand	1	0.2	0	0	0	0	0
5	Increased Rainwater and Demand	1.9	1.4	0	0.27	0	1	0
5	Increased Rainwater and Demand	2.4	1.4	0.05682	0.21	0	1	0
7	Decreased RW and Increased Demand	0	1.4	0	0	0	1	0
8	Change in discount rate to 86%	1	1	0	0	0	0	0
9	Change in number of households to 140 houses	1	1	0	0	1	1	0
10	Change in payback period (PBP) to 10 years	1	1	0	0	1	1	0
11	10 yr PBP and Increased Rainwater	1.4	1	0.07	0.26	0	1	0
12	10 yr PBP and Increased Demand	1	27.3	0	0.02	1	1	0
13	10 yr PBP and 20x Costs of CSW and CGW	1	1	0	0.37	0	0	0
14	10 yr PBP and 20x Costs of CSW and CGW Increased Rain	1.4	1	0.28	0.26	0	0	0
15	10 yr PBP, 20x Costs of CSW and CGW, Increased Demand	1	1.6	0	0	0	0	0.72
16	Double Discount Rate (10%) and Increased Demand	1	1.6	0	0	1	1	0
17	10 yr PBP, 10x Costs of CSW and CGW, Increased Demand	1	1.5	0	0.86	0	1	0
18	5 yr PBP and 20x Costs of CSW and CGW	1	2.3	0	0	0	0	0.36
19	Base Case with 1/2 Cost Household Tech	1	1	0	0.37	0	1	0

Table 5 Water, Capital and Energy Cost for each Scenario

	Modification	Rw	Dw	Cost	% Tech Water	kWh
0'	Base Case (house decsions)	1	1	$23,763	48.60%	1620
0	Base Case (community decsions)	1	1	$23,763	48.60%	1620
1	Increased Rainwater	1.8	1	$23,313	78.20%	2701
1'	Bigger Increase in Rainwater	2.3	1	$20,693	86.00%	3276
3	Increased Demand	1	1.4	$30,594	83.80%	2595
4	Decreased Demand	1	0.2	$7,392	0.00%	0
5	Increased Rainwater and Demand	1.9	1.4	$30,027	83.80%	3522
5	Increased Rainwater and Demand	2.4	1.4	$27,121	83.80%	3522
7	Decreased RW and Increased Demand	0	1.4	$31,420	86.00%	4586
8	Change in discount rate to 86%	1	1	$36,963	0.00%	0
9	Change in number of households to 140 houses	1	1	$30,594	83.80%	2595
10	Change in payback period (PBP) to 10 years	1	1	$18,482	83.80%	1854
11	10 yr PBP and Increased Rainwater	1.4	1	$18,258	86.00%	3276
12	10 yr PBP and Increased Demand	1	27.3	$295,951	78.20%	49643
13	10 yr PBP and 20x Costs of CSW and CGW	1	1	$36,612	29.50%	1082
14	10 yr PBP and 20x Costs of CSW and CGW Increased Rain	1.4	1	$33,078	60.90%	3379
15	10 yr PBP, 20x Costs of CSW and CGW, Increased Demand	1	1.6	$57,817	35.10%	7488
16	Double Discount Rate (10%) and Increased Demand	1	1.6	$34,947	83.80%	2966
17	10 yr PBP, 10x Costs of CSW and CGW, Increased Demand	1	1.5	$54,089	29.50%	1623
18	5 yr PBP and 20x Costs of CSW and CGW	1	2.3	$89,556	17.70%	5436
19	Base Case with 1/2 Cost Household Tech	1	1	$22,278	78.20%	2702

4 Base Cases

The base case uses a payback period of 5 years, a discount rate of 5%, and the capital and energy costs that were specified in the above sections.

The rainfall demand of the base scenario is given by the average monthly rainfall of Cape Town which is given by [19].

The water demand is based off the average water demand of Cape Town 185 L/day where 35% or 1.95 kL/ month is used outside and the remaining 3.6 kL/ month is used inside [20].

4.1 Changes in Rainfall

Some scenarios change the rainfall while leaving all the other parameters constant. Decreasing rainfall can be thought of as either observing a drier year or having less roof space to collect rainwater. Increasing rainfall can be thought of as the opposite either more roof space to collect rainwater or having more rainwater than average. These scenarios are modeled as a multiplier against the base case.

4.2 Changes in Demand

Some scenarios change the demand while leaving all the other parameters constant. Decreasing demand can be thought of as using better water conservation techniques such as low flow toilets. Increasing demand can be thought the average household using more water. These scenarios are modeled as a multiplier against the base case.

4.3 Changes in Demand and Rainfall

There is no reason to believe changes in demand and rainfall would happen in isolation. Therefore, we also modeled changes in both simultaneously to observe their effects. Again, these scenarios are modeled as a pair of multipliers against the base case.

4.4 Changes in Payback Period and Discount Rate

Discount rates and payback periods can vary wildly due to a variety of different circumstances. We changed both values to see the effects if any on the optimal decisions.

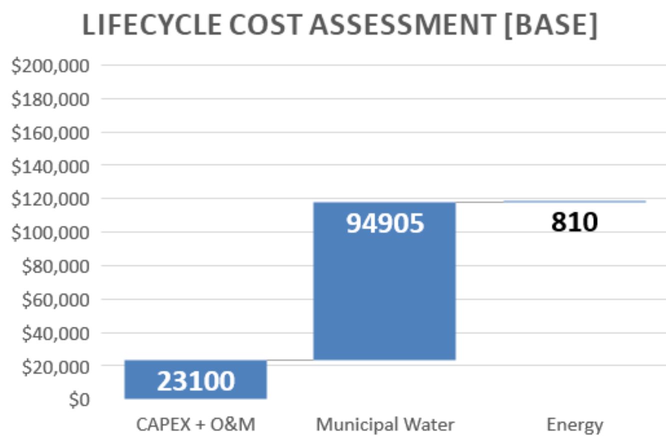
4.5 Changes in Cost Paradigms

Our estimates for the different technologies are not perfect and could be substantially different in real life. Based on our results, we explored cases where the community technologies were significantly more expensive and cases where the household technologies were significantly cheaper.

5 Results

The model output shows which technologies are selected by individual households and the community based on total cost minimization. Savings were calculated using a 5-year payback period and a 5% discount rate. For the original 100 household community, the model selected community graywater first among the five HSW alternatives. The total lifecycle costs were broken down into three categories. The first portion combined capital expenditures (CAPEX) and operations and maintenance (O&M) into a single annuitized cost for each technology and capacity. The second and largest cost is the variable water cost that still must be paid to the municipal water supply entity. The third cost category that was considered is energy cost. Power requirement calculations for each of the technology alternatives were performed and the results showed that varying energy parameters within a reasonable range will not change the optimal technology selection because it is only a small fraction of total cost.

Figure 2 *Project Costs Using Optimal Technology Selection (CGW) and a 5-year payback period*



Compared to municipal rates, the optimal solution has the potential to save the community up to $12,000 per year by cutting municipal water demand in half. Unlocking these savings would cost less than R3,500 per year per resident. Residents of low-income neighborhoods can benefit from economies of scale to further reduce the costs of these systems. The parameters for the base case were normalized, scaling individual household demand and community rainfall under different scenarios.

5.1 Sensitivity Analysis

The technology selection at the household and community level can be influenced by variations in demand and rainfall parameters. The combination of technologies that are selected under different scenarios are presented on Table 2. The following conventions were used to compare the results with the base case.

The first two rows on this table show the technology selection for the base demand (Dw) and rainfall (Rw) parameters: 185 L/day, and 760 mm, respectively. This is represented by the number 1 corresponding to the community Gray Water (CGW) cell. A zero indicates no investment into that technology because the costs offset the benefits. The two parameters were varied until a change in the combination of selected technologies was observed. Some changes resulted in the decision to invest in new technologies indicated by the green color. Conversely, changes leading to the pull-back of investment from a previously selected technology is indicated by the orange color.

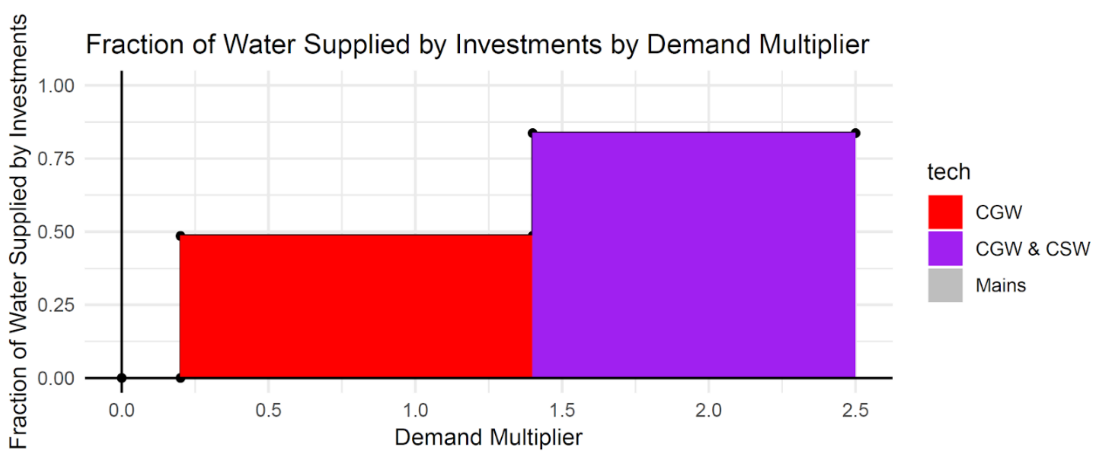
The performance implications of each scenario were summarized on Table 3. Positive impacts (decrease in cost and increase in water savings) are represented with blue whereas negative impacts are shown in red. Scenario four shows the required conservation (80%) to avoid investment. An 86% discount rate would also discourage investment into any of these technologies.

Figure 3 Scenario Analysis Color Coding

Legend	
Base Case	
Parameter Change	
Favorable Decrease or Increase	
Unfavorable Increase or Decrease	
New Investment	
Deviation from Original or Expected Investment	

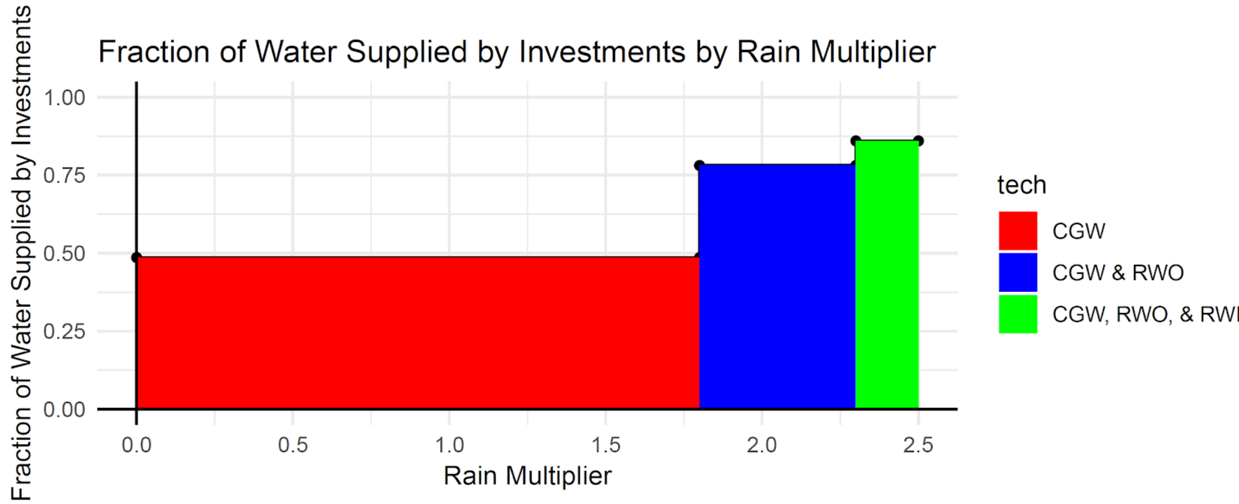
The following chart shows the demand range for selecting Community Greywater to invest. A 40% increase is required in order to justify investment in Community Stormwater (CSW).

Figure 4 Demand Scaling and Technology Selection



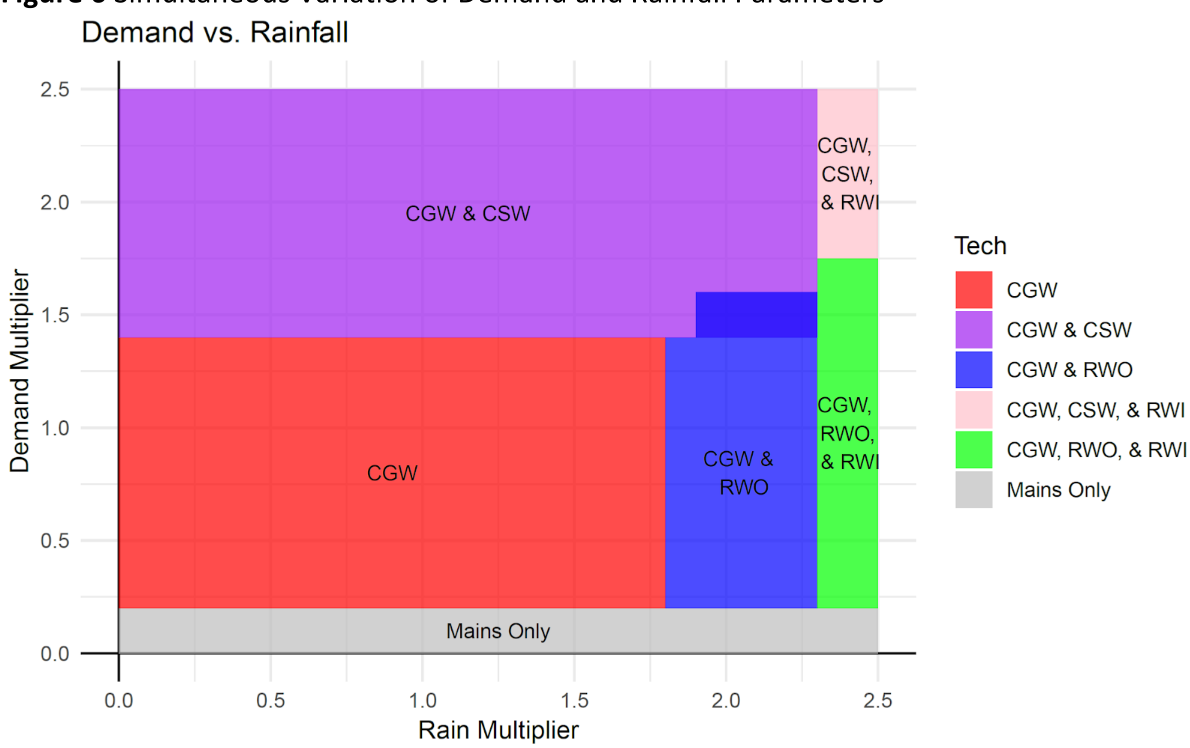
Since that the model assumes that demand is fixed and independent of rainfall, Community Greywater is still selected for scenarios that include zero rainfall. As expected, more rain would incentivize investment in rain harvesting systems, increasing the fraction of water supplied by these investments.

Figure 5 Rain Scaling and Technology Selection



Simultaneous variation of both parameters demand (y-axis) and rainfall (x-axis)results in the following tree chart. The regions indicated by the colors pink indicated a new combination of technology is selected which includes: Community graywater, Community Stormwater, and Rainwater Indoors.

Figure 6 Simultaneous Variation of Demand and Rainfall Parameters



6 Discussion

It is optimal to invest in distributed water technologies even in the base case. You can save water and money by investing in these technologies even before you hit the higher tariffs. It is also optimal to invest even in scenarios where demand is significantly lower. If there is no rain it is still optimal to invest. Increased demand and increased rain make the decision to invest more lucrative. Various combinations of demand and rainfall change the optimal investment decisions, but in almost all cases it is optimal to invest.

One significant result that is not represented on the figures is that when the demand increases by more than 60 per-cent, the most cost-effective option (namely CGW) is replaced by Household Greywater (HGW).

For a given scenario, if it is optimal to invest in more technologies than the optimal case the community energy usage and cost will increase, but it will be cheaper than getting water from the mains.

Compared to the base case, changing the rainwater parameter in either direction can only have a neutral or positive effect. In the case of decreasing water, the base case remains optimal with no change in cost; however, if you increase the amount of rainwater able to be harvested the overall costs decrease even as the energy costs increases.

Decreasing the demand lowers the overall cost and the energy cost, but increasing the demand increases the overall cost and the energy cost. This intuitively makes sense because if you need more water it will cost more. It's not until demand increases along with increasing rainwater availability is this effect tempered.

6.1 Future Directions

Our model is a simplification of the water system in both space and time. While the space simplification probably wouldn't affect too much, the time simplification ignores numerous nuances. For instance, a relatively rainy day could overwhelm the capacity of the technologies. Furthermore, by ignoring the time scale, the model doesn't consider the demand changes that happen day by day which could drastically affect the operation of the systems. Increasing the granularity of the time scale would allow us to see subtle effects that are not captured by the model.

Another limitation of the model are the relatively rigid technology options. In our model we don't allow the decision maker to choose the storage capacity of any of their technologies. While this is somewhat combated by making the choice to invest in household technologies discrete for community scale technologies the option is fixed. While this might not be as significant an assumption as the time scale it could have effects.

This model isolates the energy usage of each water technology, so incorporating distributed energy generation into this model to supply the energy for the water technologies and the household's energy demand is a logical next step. The distributed energy technologies could be modeled in an almost identical way as the water technologies but for energy instead of water. However, to incorporate energy generation technologies the time scale will have to be modified.

7 Sources

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