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AVOIDING "DAY-ZERO": A TESTBED FOR EVALUATING INTEGRATED FOOD-ENERGY-WATER MANAGEMENT IN CAPE TOWN, SOUTH AFRICA

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ABSTRACT

Deep connections between water resources and food and energy production—the food-energy-water (FEW) nexus—complicate the challenge of sustainably managing an uncertain water supply. We present an agent-based model as a testbed for studying different approaches to managing the FEW nexus and apply the model to the 2017–2018 water crisis in Cape Town, South Africa. We treat the FEW nexus connecting municipal water use by urban residents, agricultural water use by vineyards, and hydroelectric generation from reservoirs. We compare two scenarios for responding to drought: business-as-usual (BAU), and holistic-adaptive management (HAM), where BAU takes no action until the monthly supply is insufficient to meet demand, whereas HAM takes action by raising water tariffs when the reservoir storage level drops below its pre-drought monthly average. Simulation results suggest that holistic-adaptive management can alleviate the impact of drought on agricultural production, hydropower generation, and the availability of water for residential consumption.

1 INTRODUCTION

Uncertainty about temporal variation in rainfall creates a challenge to the sustainable management of water resources. The effects of global climate change exacerbate the uncertainty that arises from ordinary year-to-year variations in weather. The challenges of managing water supplies under this uncertainty are complicated by the complex interdependencies between food, energy, and water (FEW) (Perrone and Hornberger 2014): food production requires water and energy, energy production requires water (both for hydroelectric generation and for cooling thermoelectric generators), and the water supply requires energy for treatment and delivery. Moreover, climate and weather affect both the supply of water and the demand for water and energy. Sustainable management of the FEW nexus in a changing climate requires robust management strategies that can assure adequate supplies of food, energy, and water under uncertain conditions.

The FEW nexus is affected both by the physical environment (e.g., weather and climate) and also by governance and management of FEW services. Some countries have made plans and policies at the national level for guiding the management of the FEW resources, but detailed planning at the local level needs to be developed as well (Mukheibir and Ziervogel 2007).

The deep connections among food, energy, and water mean that the capacity of one service may depend on the other two (Perrone and Hornberger 2014). For example, hydroelectric generation depends on the amount of water stored in a reservoir; agricultural production may require both a supply of irrigation water and energy to pump it; and the supply of safe drinking water requires energy for water treatment and is affected by agricultural runoff. The importance of systematic regional planning is widely recognized as critical to assuring effective performance of the FEW system (Biggs et al. 2015). Specifically, the trade-offs among food, energy, and water supply can be analyzed and the allocation of resources can be optimized through simulation modeling.

Simulation modeling is widely used for comparing different policy approaches to managing certain aspects in the complex FEW systems (i.e., irrigation for crops) and for optimizing the system's performance under uncertainty and climatic change (Hyun et al. 2019; Yang et al. 2018). Previous studies have applied agent-based modeling (ABM) techniques to water management in urban settings and interactions between water management policies and hydrology at the watershed scale and beyond (e.g., inter-basin water transfer) (Kanta and Zechman 2014; Murphy et al. 2015). Water-energy interrelationships, such as hydroelectric dam optimization, have been extensively studied by applying optimization algorithms in simulation models (Dai et al. 2018). Our study investigates holistic management of water resources and performance assessments for all three sectors of the FEW nexus.

We chose Cape Town as a test case for our modeling approach because the city faces extreme stress resulting from a variety of problems, such as changing rainfall patterns, multiple sectors competing for limited resources, and policy and governance conflicts that arise from this inter-sectoral competition (Muller 2017). In this paper, we restrict our analysis to improving the management of existing water supply sources across the food, energy, and water sectors in and around Cape Town and do not consider alternative water or energy sources, such as desalination or solar electricity generation. Our model framework will allow future research to investigate these possibilities.

In 2018, Cape Town almost encountered a "day-zero" crisis where more than four million of people would have lost access to the municipal water supply. The Cape Town region experienced a sustained decrease in precipitation that started in early 2016. This led to a series of water use restrictions and the imposition of high water tariffs in Cape Town. Water restrictions were structured with multiple levels of severity across different sectors. The most serious restrictions, level 6b, would have limited water consumption for the entire city to 450 million liters per day (MLD), corresponding to 50 liters per person for residential use, and would have completely curtailed agricultural water allocations (DWS. 2018c). The wine industry forms an important part of the regional economy of Cape Town and Western Cape Province. The water crisis severely harmed wine production and the health of the vines; some vineyards only received 20% of their demand for irrigation water even before the government completely shut down agricultural water allocation (Browdie 2018).

Cape Town's rigorous and strict water use restrictions avoided a day-zero crisis but produced severe hardship and economic losses. June 2018 brought increased rainfall and reservoir storage levels returned to over 50% of their total capacity. A post-crisis assessment by Ziervogel (2018) summarized a number of problems that contributed to the near day-zero crisis. These included a lack of collaboration and joint management of the water resources across government agencies—both laterally (across regions) and vertically (between national, provincial, and municipal levels of government)—and the lack of understanding of the local water system. Muller (2017) also suggested that the water overuse in the agricultural sector in the 2015–16 planting season contributed to the vulnerability of the water supply to diminished rainfall over the next two years.

For this study, we designed a model that represented different stakeholders from the municipal, water, energy (hydropower), and food sectors to serve as a test bed for simulating and comparing FEW system outcomes under various policy scenarios. We tested two policy scenarios:

1. Business-as-usual (BAU baseline): No joint-management or minimal communication between the departments of Energy, Water, and Food (agriculture). The tariffs of water and threshold levels of reservoir storage for restrictions used in this policy scenario are taken from the city of Cape Town;
2. Holistic adaptive management (HAM): Allocate water resources across FEW sectors to satisfy the municipal demand, similarly for hydropower generation, and agricultural production. This policy scenario incorporates a market-driven adaption strategy in which water prices are adjusted in response to changes in the stored water supply.

The BAU policy scenario served as a baseline and the model parameters were calibrated to match the historical system performance (reservoir storage levels, water use). The HAM policy scenario represented an alternative holistic management strategy to optimize performance of the water, energy, and food sectors.

2 STUDY AREA

Our model represents the city of Cape Town and its adjacent wine regions including Swartland, Stellenbosch, Breede Valley, Langeberg, Drakenstein, and Witzenberg (Figure 1). The city of Cape Town, with more than 4 million people, consumes more than half of the water from the Western Cape water supply system. The wine regions have over 90,000 hectares of irrigated land for wine grapes (WCDA. 2019) and consume the vast majority of the remaining water. The other urban areas in Western Cape Province consume less than 7% of the water (DWS. 2018c).

This region relies mainly on surface water from the six largest reservoirs in Western Cape Province, which have a total storage capacity of 900 billion liters (DWS. 2018c). We obtained historical records for rainfall and temperature at weather stations across the region (Figure 1) (SAWS. 2019). We used historical records of monthly reservoir storage and water consumption for urban and agricultural sectors (Figure 2) from the Big Six Monitor developed by the University of Cape Town using data provided by the city of Cape Town (CSAG. 2019).

Agricultural irrigation starts with the planting season in early October, and peaks in January and February. Agricultural water demand drops to nearly zero during the winter rainy season, which begins at the end of April.

3 MODEL DESIGN

Previous research largely emphasized using simulation models to optimize water consumption by a single sector, but in arid regions where multiple sectors compete for the limited resources, tradeoffs among different sectors require a holistic approach to water allocation. In this model, we account for competition for water resources between municipal, agricultural, and energy (hydropower) sectors within the FEW nexus. We incorporate stakeholders representing all three sectors: residents of Cape Town; farmers; and the manager of the Steenbras hydro-electrical station, which needs to maintain a sufficient storage level in the reservoir to generate power. The water allocation among these sectors is overseen by a water manager agent.

This section briefly describes the model design. A complete ODD description of the model, along with the NetLogo code for the model, is available at the model repository (Ding et al. 2019).

We used the model to simulate the ten-year period 2009–2018, with monthly temporal resolution. The inputs to the model include initial reservoir storage, monthly water inflow, monthly water demand by sectors, water price, and the price elasticity of demand (CSAG. 2019; Sahin et al. 2016; DWS. 2018c). The initial reservoir storage, monthly inflow, and the baseline monthly demand were taken from historical data. The baseline BAU policy scenario used historical values for the price of water and the HAM policy scenario used adaptive water pricing as described below.

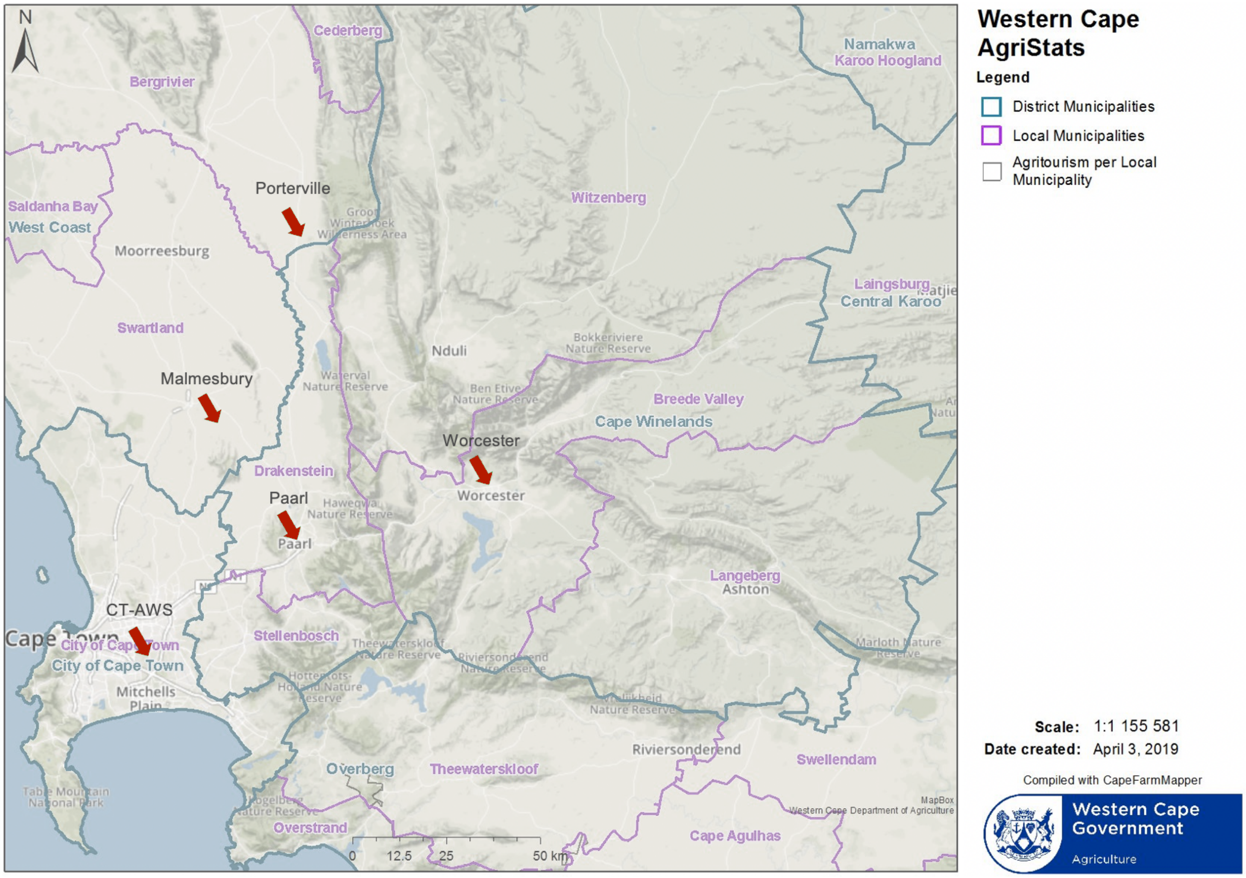

Figure 1: The municipalities map of Western Cape Province adjacent to the city of Cape Town. The locations of the Porterville, Malmesbury, CT-AWS, Paarl, and Worcester weather stations are indicated by arrows.

Each month, the water manager receives the requested demand from each stakeholder and determines the allocation to each sector based on the total reservoir storage level and the rules for the chosen policy scenario. The reservoir storage is then updated based on the allocation and the monthly inflow (Algorithm 1). The sub-models and the rules for the two policy scenarios are described in Sections 3.1–3.5 and Algorithms 2–3.

3.1 Urban Sub-Model

For simplicity, we aggregated the urban demand for Cape Town (residential, commercial, and other) into a single representative agent, `CPers`. The `CPers` represents a population of 3.9 million people at the beginning of 2009 with an annual growth rate of 0.8%. In the city of Cape Town, the unrestricted per-capita urban water demand is calculated based on the monthly average of urban water usage from 2009–2015 (CSAG. 2019). In all policy scenarios, the monthly municipal water allocation is calculated by the water manager in response to the urban demand using Equation (1):

$$\text{Allocation}_{\text{urban},i} = \text{Population}_i \times \text{Demand}_{\text{urban}} \times (1 - \text{Reduction}) \tag{1}$$

where Population_i is the population at time-step i.

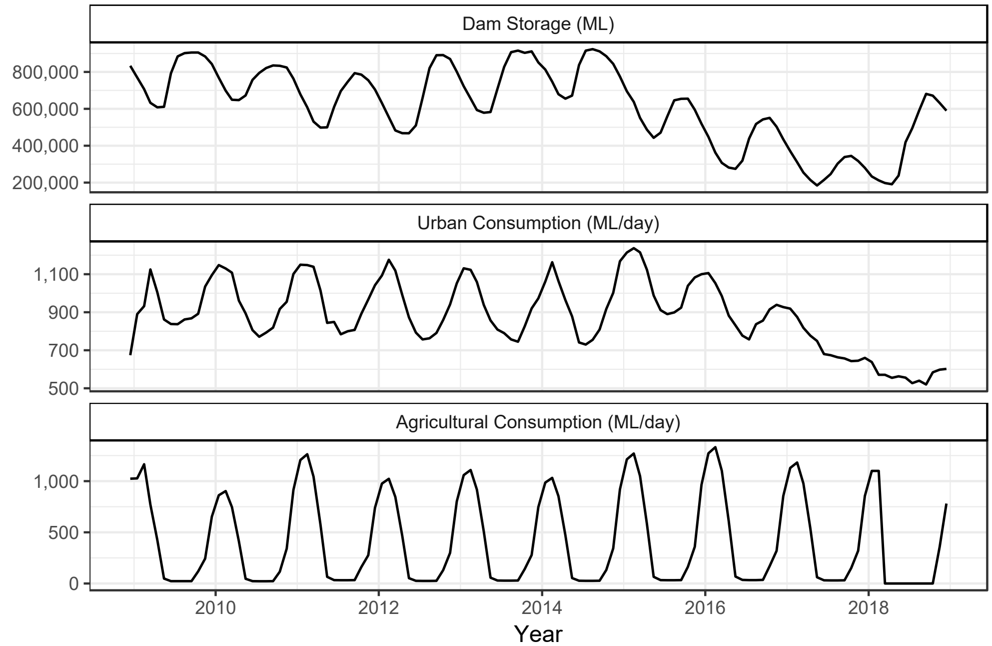

Figure 2: Historical monthly reservoir storage in millions of liters (ML), and agricultural and urban water consumption in millions of liters per day (ML/day).

3.2 Agricultural Sub-Model

In the agricultural sub-model, the irrigation demand is calculated using the soil moisture deficit (SMD), where SMD is calculated by a simple water balance approach. We used the Palmer Drought Index (PDI) tool developed by Jacobi et al. (2013), which uses the Thornthwaite method to calculate the monthly potential evapotranspiration (PET) and applies water balance to calculate the resulting soil moisture content (SMC). This tool is used in agricultural research to assess drought and soil moisture (Gunda et al. 2016; Nawagamuwa et al. 2018). We obtained the available water-holding capacity (AWC) for the soil in each of the agricultural regions from Schulze and Horan (2007) and obtained the monthly rainfall and average temperature for each agricultural region from the closest weather station (SAWS. 2019). We used the PDI tool to calculate the monthly SMD for each agricultural region from these data.

For this study, we focused on the irrigation of vineyards. On average, wine vineyards represent 43% of total irrigation in the Western Cape Province (WCG. 2015). The non-wine crops are mainly located outside our region of interest, so our model allocates 57% of average monthly irrigation demand to non-wine crops

Algorithm 1 Main model sequence

Setup: initialize parameters and load input data
loop
  Water manager obtains urban demand // *Urban sub-model*
  Water manager obtains agricultural demand // *Agricultural sub-model*
  Water manager obtains current reservoir levels // *Hydroelectricity sub-model*
  Water manager allocates water according to scenario
  Update reservoir storage
  Calculate hydropower generation // *Hydroelectricity sub-model*
  tick $\leftarrow$ tick $+ 1$ // *Advance to next month*
end loop

and does not apply any water-rationing or price adjustments to it. The irrigation demand by wine vineyards is calculated by the water manager in response to the agricultural demand using Equation (2):

$$\mathrm{Demand}_{\mathrm{wine},m} = \mathrm{SMD}_m \times \mathrm{Area} \times \mathrm{Kc}_m \times \mathrm{Ef}_{\mathrm{wine}} \tag{2}$$

where SMD_m is the soil moisture deficit in month m, Area is the irrigation area of each wine region, Kc_m is the Crop Coefficient of wine grapes for month m, and $\mathrm{Ef}_{\mathrm{wine}}$ is the irrigation efficiency of the vineyard (WSU. 2016). We calibrate the model parameters under the BAU policy scenario to match the historical performance of the system (Figure 2). The calibrated model parameters were used in the HAM policy scenario as well.

3.3 Hydropower Sub-Model

In the Big Six dam system, the Steenbras Upper Dam is the only pumped-storage hydropower dam. To maintain the maximum generation capacity, the reservoir needs to be maintained at its full level (DWS. 2018c). The Steenbras Upper and Lower Dams coordinate their operations: the lower dam pumps the water to the upper dam during off-peak hours, and the upper dam releases water during the peak hours for electricity demand, providing up to 180 megawatts (MW) of electricity to the grid. The storage capacities of the Steenbras Upper and Lower dams are similar, and the combined storage accounts for 10% of the total capacity of the Big Six system. The water supply system in Western Province cannot release water when the reservoir storage level is below 10% of the total capacity. Thus, we assume that if the total reservoir storage level is above 20% of the total reservoir storage capacity, the Steenbras Upper Dam can remain at full storage, thus achieving its maximum generation capacity. When the total reservoir storage level is lower than 15% of the total storage capacity, water in the Steenbras Upper Dam reservoir will be released for municipal water use, and no hydropower can be generated. In between 15% and 20% of the total reservoir storage, we assume hydropower generation capacity decreases linearly.

3.4 Business-as-Usual Policy Scenario

Under the BAU policy (Algorithm 2), the model adopts the restrictions imposed by the city of Cape Town from 2015–2018 (DWS. 2018c). There are various levels of restrictions imposed on the study region, with major water use reductions occurring at levels 2, 3, and 6b, which are triggered when combined reservoir storage reaches 50%, 45%, and 20%, respectively, of the maximum storage capacity (DWS. 2018c). At these levels, mandatory reductions of 20%, 30%, and 100% are imposed on agricultural allocations. At levels 2 and 3, municipal allocations are reduced by 20% and 30%, respectively, and additional tariffs are imposed. At level 6b, municipal use is also curtailed to no more than 450 ML/day. Under the BAU policy, the model observes these trigger levels and applies the corresponding allocation reductions to reproduce the historical patterns of water allocation.

3.5 Holistic Adaptive Management Policy Scenario

The BAU policy responds passively to drought: no demand-management is implemented until reservoir storage levels reach trigger points. This policy may avoid system failure during short-lived droughts, but under extended droughts this policy may wait too long before taking action and may thus risk system failure. The recent Cape Town water crisis illustrates such a system failure: it resulted from a combination of factors, including a drought characterized both by historically low rainfall levels and long duration, and by overuse of water during the early stages of this drought (Ziervogel 2018; Muller 2017).

The HAM policy (Algorithm 3) considers the interplay between the agricultural, energy, and urban demand for water and attempts to optimize system performance by holistically managing the demand and allocation for each sector. The HAM policy takes a simple adaptive approach to imposing water use restrictions: Each month, the water manager compares the current reservoir storage level with the seasonally adjusted average pre-drought (2009–2015) storage level corresponding to the current month. If

Algorithm 2 Allocations for Business-As-Usual (BAU) scenario

```
if V > 0.5V_max then
    Allocate full water demand to each sector        // No restriction
else if V > 0.45V_max then
    Allocate 80% of demand to each sector        // Level 2 restriction
else if V > 0.2V_max then
    Allocate 70% of demand to each sector        // Level 3 restriction
else
        // Level 6b restriction
    Allocate 450 MLD to urban supply
    Allocate 0 MLD to agriculture
end if
```

the current reservoir storage level is greater than 90% of the average, the water manager will not impose any restrictions and each stakeholder is allocated their full demand. When the current reservoir storage level is lower than the 90% threshold a mandatory restriction is imposed, reducing allocation to each sector by the ratio $(V_{\text{avg}} - V_{\text{current}})/V_{\text{avg}}$. In addition, the water price is raised in order to reduce demand. The relationship between price and demand is described by the demand-elasticity ε_D (Equation 3) (Sahin et al. 2016):

$$\varepsilon_D = \frac{\%\Delta\text{Demand}}{\%\Delta\text{Price}}. \tag{3}$$

Algorithm 3 Allocations for Holistic Adaptive Management (HAM) scenario

```
if V > 0.9V_max then
    Allocate full water demand to each sector        // No restriction
else
    Calculate desired change in urban consumption: %ΔD        // Urban sub-model
    Assign urban tariff based on price-elasticity of demand (E_d)        // Urban sub-model
    Calcuate reduced allocation to agriculture: A = D × (V_avg − V)/V_avg        // Agricultural sub-model
    Allocate water
end if
```

4 RESULT

4.1 Calibration

For each policy scenario, we ran the model ten times each for several different values of key parameters. For the BAU policy scenario, we varied the irrigation efficiency from 0.6 to 0.7 in steps of 0.01 and for the HAM policy scenario we varied the price elasticity of demand from -0.1 to -0.8 in steps of 0.1. Under the baseline BAU scenario, the monthly reservoir storage levels most closely approximated the historical values for an irrigation efficiency of 0.7 (Figure 2 vs. Figure 3b). The crop coefficient Kc varies from month to month. We started with the values of Kc reported in WSU. (2016), and adjusted those values to match the monthly agricultural water consumption to the historical pattern (Figure 2 vs. Figure 4a). The calibrated values for Kc were used for both policy scenarios, and the HAM scenario used 0.7 for the irrigation efficiency.

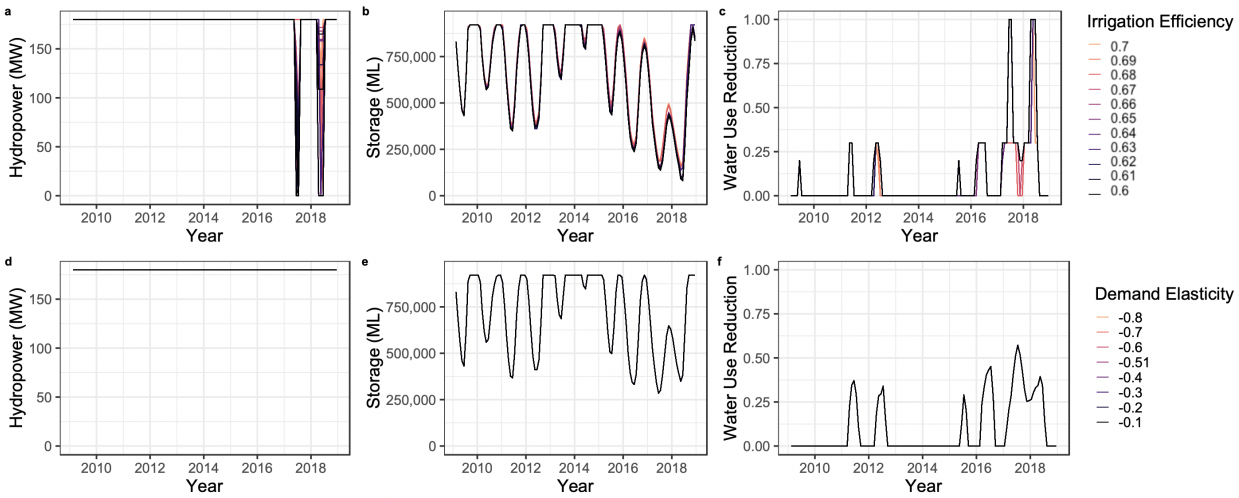

Figure 3: Model simulation results of (a,d) average hydropower generation capacity, (b,e) reservoir storage, and (c,f) water use reduction from 2009 to 2018. (a–c) corresponds to the baseline (BAU) scenario and (d–f) correspond to the holistic adaptive scenario. The BAU scenario (a–c) is fairly insensitive to variation in irrigation efficiency. The holistic adaptive scenario (d–f) shows no sensitivity to demand elasticity because the policy sets prices relative to elasticity.

4.2 Demand-Reduction and Allocation

Under the BAU policy, when the water supply is insufficient to meet demand, agricultural and municipal allocations are cut and tariffs on municipal use are raised. Under the HAM policy, prices are gradually raised for both municipal and agricultural users as reservoir levels fall. By all criteria, the holistic adaptive management policy outperformed the baseline. The HAM policy did not result in any curtailment of hydroelectric capacity and it imposed less mandatory reduction of water use. Under the BAU policy, agricultural allocation was reduced to zero several times in 2017–2018 (water-use reduction rose to 100%), whereas under HAM, allocations are cut by less than 60% for both agricultural and municipal users (c and f of Figure 3). July 2017 is the only month in which the municipal water allocation under HAM is less than the lowest allocation at level 6b of the BAU scenario (450 ML/day) (b and e of Figure 4). Patterns of monthly agricultural water allocations are similar for the two policy scenarios (a and d of Figure 4). In general, we see less extreme reduction and less total water allocation in the HAM policy scenario (Figures 3 and 4). Furthermore, the reservoir storage levels under the HAM policy are constantly higher (in a safer zone) than under BAU (Figure 3).

4.3 Hydropower Generation

Under the holistic adaptive managemement policy, the hydropower dam never fell below its maximum generating capacity, whereas under the BAU policy hydropower generation had to shut down several times in 2017–2018. Thus, the HAM policy produces significantly better performance in the energy sector because the monthly reservoir levels were maintained constantly above the threshold of 20% of total storage capacity.

4.4 Water Price

In the BAU policy, the water tariff set by the city of Cape Town increases for stricter levels of restrictions (DWS. 2018a; DWS. 2018b; DWS. 2018c). The baseline water price is 5.2 R/kL (1.4 USD/kGal) without any restriction. When scarcity reaches level 3 the city of Cape Town imposes high and progressive water tariffs, which rise as household consumption reaches different brackets. The baseline water price for level 3

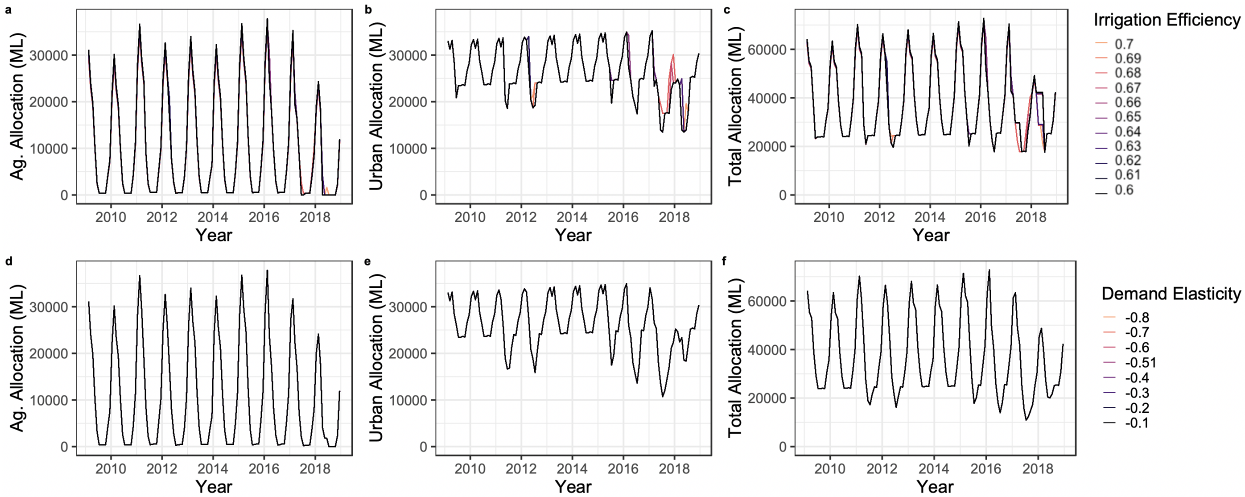

Figure 4: Model simulation results of (a,d) agriculture, (b,e) municipal, and (c,f) total monthly water allocations from 2009 to 2018. (a–c) corresponds to the baseline (BAU) scenario and (d–f) correspond to the holistic adaptive scenario. As with Figure 3, the BAU scenario (a–c) is fairly insensitive to variations in irrigation efficiency and the holistic adaptive scenario (d–f) shows no sensitivity to demand elasticity.

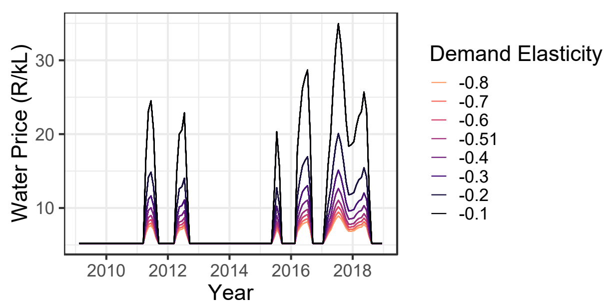

Figure 5: Monthly water price in the holistic adaptive management policy scenario under a range of values for demand elasticity.

and level 5 are 15.7 and 24.4 R/kL, respectively, for consumption below 6 kL; for household consumption in the next water usage bracket between 6 and 10.5 kL, the marginal price rises significantly to 22 and 39 R/kL, respectively (DWS. 2018a). In the HAM policy, tariffs are set based on the water price elasticity of demand (ε_D) and the necessary curtailment of consumption. Under that policy the water tariff is ≤ 35 R/kL even for extremely low values of demand elasticity (Figure 5). When the demand elasticity is within the range of values reported in the literature ($[-0.3, -0.8]$) (Sahin et al. 2016), the water price is between 5.2 and 15 R/kL.

5 DISCUSSION

This model functions as a testbed that can simulate a relatively complex system under different scenarios and compare the outcomes to evaluate different policies or strategies. Where detailed parameters characterizing human behavior or system performance are uncertain the testbed also allows users to test the sensitivity of the system performance to various parameters and to test the robustness of different policies under a range of parameter values. From the results of the model, in general, the holistic adaptive management policy achieved better hydropower generation, conserved more water and avoided zero-water allocation for the agricultural sector. Its water price is lower than what the city of Cape Town is currently imposing with level 3 restriction.

Although the HAM policy curtails water allocations more frequently than BAU under less severe drought conditions, the level of water allocation reduction is not devastating to the urban and agricultural users. For farmers, the less punitive reductions, compared to BAU, can ensure sufficient water to prevent the wines from fallowing even under severe drought conditions. Hydropower generation remains more secure under the HAM policy, across a wide range of parameters.

It is promising to see that a simple adaptive strategy can produce much better FEW system outcome, but further work is needed. The current model uses an agent-based structure, but aggregates each sector into a single representative agent. Future work will explore interactions among multiple heterogeneous agents in each sector, including consideration of economic inequality among Cape Town residents. We also plan to apply the model to studying adaptation to future climatic change, using projections for precipitation trends under different climate scenarios. Precision irrigation and regulated deficit irrigation can improve the economic performance of the vineyards and produce better wines (WSU. 2016). In the future the municipal and agricultural stakeholders can also be disaggregated to include more diversity and individual behavior in the model. The current model focuses solely on the management of existing water resources, but the model can be modified and expanded in future studies to consider alternative water sources, such as desalination, and the management of food and energy resources and services as well.

An important aspect of future work will be the consideration of economic inequality and equitable access to water. South Africa has one of the highest national rates of economic inequality in the world and Cape Town in particular suffers from severe economic inequality, with a Gini coefficient for income of 0.6 and a poverty rate of 19% (Karuri-Sabina 2016; Sieff 2018). Moreover, income inequality correlates strongly with race: on average, white South Africans enjoy considerably greater income and wealth than their black compatriots (Sieff 2018). Both demand-elasticity and the ability to pay for minimum necessary access to water both vary significantly with household income. South African law guarantees each household 6 kL of water per month free of charge (Muller 2008), but if the response to severe drought conditions is to impose a tariff even on this base level of water consumption, the economic inequality among Cape Town residents will result in unequal access to water. Under current (BAU) policy, level 3 restrictions in Cape Town impose a minimum price of 15.7 R/kL, or 4.2 USD/kGal (DWS. 2018a), which is higher than the average price in the United States ($3.4 per 1,000 gallons) (DOE. 2017) despite the much higher average household income in the U.S. The response to the 2017–2018 water crisis created a situation in which affluent residents of Cape Town found it "pretty cheap" to fill swimming pools at the same time that poor and lower-middle-class residents struggled to obtain enough water for basic hygiene (Sieff 2018). Thus, future policy analyses will need to address issues of equitable access to water under conditions of scarcity.

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