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Urban water crises driven by elites' unsustainable consumption

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Over the past two decades, more than 80 metropolitan cities across the world have faced severe water shortages due to droughts and unsustainable water use. Future projections are even more alarming, since urban water crises are expected to escalate and most heavily affect those who are socially, economically and politically disadvantaged. Here we show how social inequalities across different groups or individuals play a major role in the production and manifestation of such crises. Specifically, due to stark socioeconomic inequalities, urban elites are able to overconsume water while excluding less-privileged populations from basic access. Through an interdisciplinary approach, we model the uneven domestic water use across urban spaces and estimate water consumption trends for different social groups. The highly unequal metropolitan area of Cape Town serves as a case in point to illustrate how unsustainable water use by the elite can exacerbate urban water crises at least as much as climate change or population growth.

The sustainable management of urban water supply constitutes one of the key challenges of our time[1]. During the first two decades of the twenty-first century alone, more than 80 large metropolitan areas have experienced extreme drought and water shortages[2]. Urban water crises are expected to become more frequent[3], with over one billion urban residents projected to experience water shortages in the near future[4,5]. In both the Northern and the Southern hemispheres, metropolitan areas experience extreme droughts and unsustainable levels of water consumption[6] (Fig. 1). In the face of fluctuating supplies, meeting the growing urban water demands and finding a sustainable balance among the city, its rural hinterland and environmental flow requirements is becoming increasingly challenging[4,7,8].

Scientific studies tend to explain increasing water demand as a consequence of the expansion of urbanized areas alongside population growth[4]. Climate change, in most cases, is considered the force that jeopardizes the availability of freshwater resources by altering the spatiotemporal characteristics of temperature and precipitation[2,9]. Physical and engineering sciences have made important progress in advancing methodologies to capture the intensity of anthropogenic pressure on hydrometeorological hazards and their resulting water crises[10]. However, these analyses fail to recognize how social power and heterogeneity in society shape both the way urban water crises unfold and who is vulnerable to them. The problem with depoliticized analyses is that they often lead to technocratic solutions that are likely to perpetuate the same logic and, in turn, reproduce the uneven and unsustainable water patterns that have contributed to the water crisis in the first place[10].

In this Article, we interpret urban water crises as social-environmental extremes[11] and retrace hydroclimatic and sociopolitical processes generating the increasing gap between water supply and demand, along with the resulting uneven levels of water insecurity. In particular, we draw on critical social sciences to explain urban water crises as generated by asymmetrical power relations that determine who controls water and how water is redistributed within a city[12–15]. This scholarship explains that conditions of water scarcity and limited access to water result from the prevailing politics and power dynamics that govern the city[16–18].

Building on this critical understanding of society, we develop a system-dynamic model that represents unequal human–water

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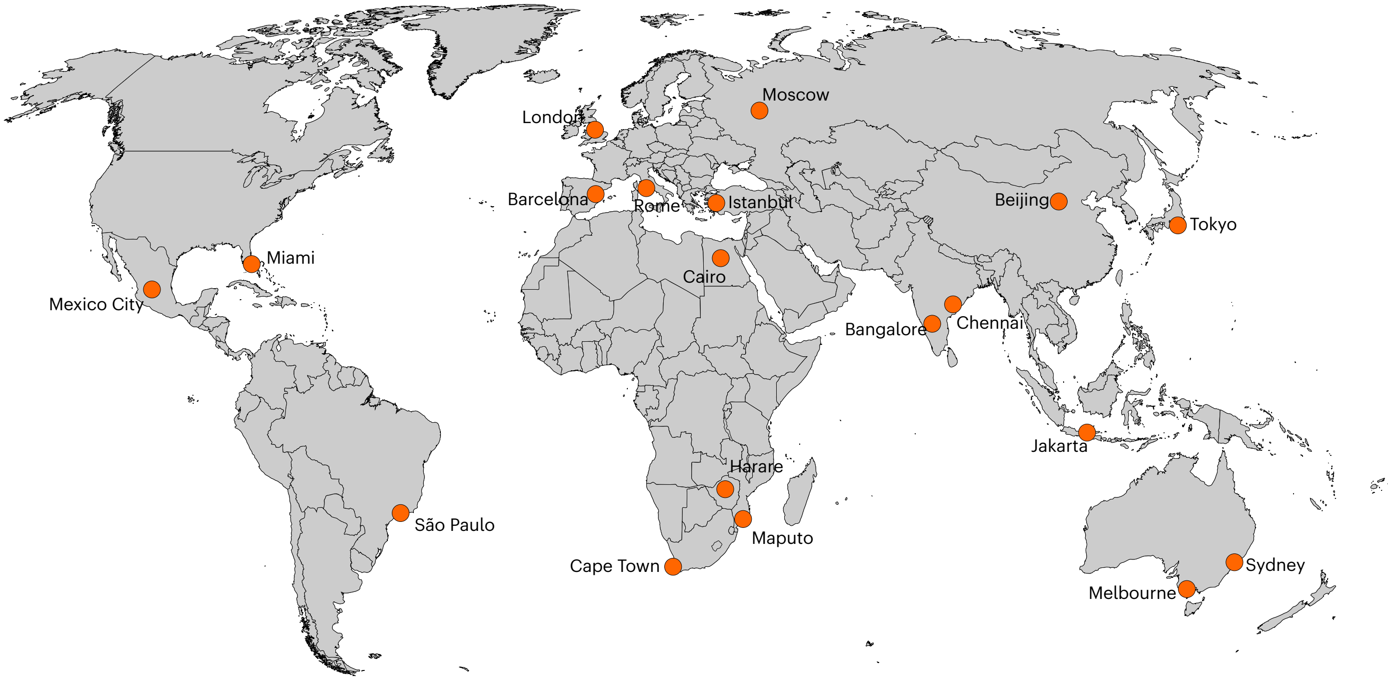

Fig. 1 | Global water crises. The locations of some of the direst urban water crises over the past two decades, as reported from several media outlets[70–89] (see also Supplementary Table 1 for additional details). Figure created with Matlab R2022b (ref. 90).

interplay within a city. We specifically analyse domestic water use of urban residents to capture how economic inequalities shape consumption trends and, in turn, urban water crises. Our model shifts the focus away from averages of urban water consumption and simulates consumption levels across different social groups. This approach allows an exploration of the role that the elite and higher-income classes play in the water balance of a city, while also assessing their ability to respond to drought-related water crises relative to other social groups. Specifically, to account for urban inequalities, the model is discretized into households that are further reaggregated into distinctive social groups. The social power of each such group is expressed through different parameters and coefficients that differentiate water access and consumption patterns across the city. This model employs the metropolitan area of Cape Town as a case in point for two main reasons. First, the city is marked by stark socioeconomic inequalities and a starkly segregated urban space. Second, between 2015 and 2017, Cape Town experienced a severe drought, which unfolded into an unprecedented water crisis, widely known as Day Zero. The model simulates the uneven water consumption across Cape Town's different social groups before, during and after the occurrence of the drought, thereby exploring and assessing the implications that consumption by elites have on the sustainability of the urban water system. Cape Town's urban form and features are not unique to this city but rather are common to many metropolitan areas across the world[19]. Thus, the model is flexible and can be adjusted to analyse urban water dynamics in other cities characterized by socioeconomic inequalities, uneven patterns of water consumption and varied access to private water sources and public water supply. Specifically, the model can reproduce water consumption patterns at the household level and simulate the aggregated impact of each social group on the urban water balance.

We first describe the model's estimates of different water consumption levels across an unequal urban space. The results highlight the disproportionate water uses of privileged social groups relative to the rest of the city. Next, we examine patterns of water inequalities during the occurrence of drought. These results show that each social group diversely experiences and responds to drought events. Last, we compare five scenarios to assess the influence that privileged water consumption has on urban water balance relative to other potential drivers. The results of this numerical analysis show that water crises such as the Day Zero drought in Cape Town are also a product of the unsustainable practices of the elite brought about by the uneven power dynamics of the city. Thus, rather than being reactive, future drought resilience strategies should be more proactive and be able to recognize the long-term socioenvironmental patterns that engender urban water crises. Hence, this model opens up possibilities for more just and sustainable approaches to managing and distributing water in cities.

Results

Water access and consumption across unequal urban spaces

The system-dynamic model uses Cape Town as a case in point to simulate different consumption patterns across an unequal urban space. In particular, on the basis of the Socio-Economic Index developed by the Western Cape Province (Case study), the urban population can be classified into five social groups: the elite, upper-middle income, lower-middle income, lower income and, ultimately, the informal areas[20]. According to the 2020 census, 1.4% of the city inhabitants belong to the elite and 12.3% to the upper-middle-income group. While 24.6% are classified as lower-middle-income group, about 40.5% of the population live in lower-income areas and 21% inhabit the shacks of the informal settlements scattered at the edges of the city[21]. Throughout the paper, the elite and upper-middle-income areas are clustered into the broader category of 'privileged groups'. These groups usually live in spacious houses with gardens and swimming pools and consume unsustainable levels of water, while informal dwellers do not have taps or toilets inside their premises[22]. On average, the model estimates that the elite and upper-middle-income households can reach a water consumption of respectively 2,161 litres per household (HH) per day and 988.78 l HH^{-1} d^{-1}, while lower-income and informal households are estimated to consume about 178 l HH^{-1} d^{-1} and 41 l HH^{-1} d^{-1} (Fig. 2a).

The stark differences in water consumption patterns resulting from this simulation are largely confirmed by literature from Cape Town and other cities, which suggests that income is a major factor influencing domestic water use[22–24]. Overall income level, type and size of house, and amenities are key to explaining the relatively higher level

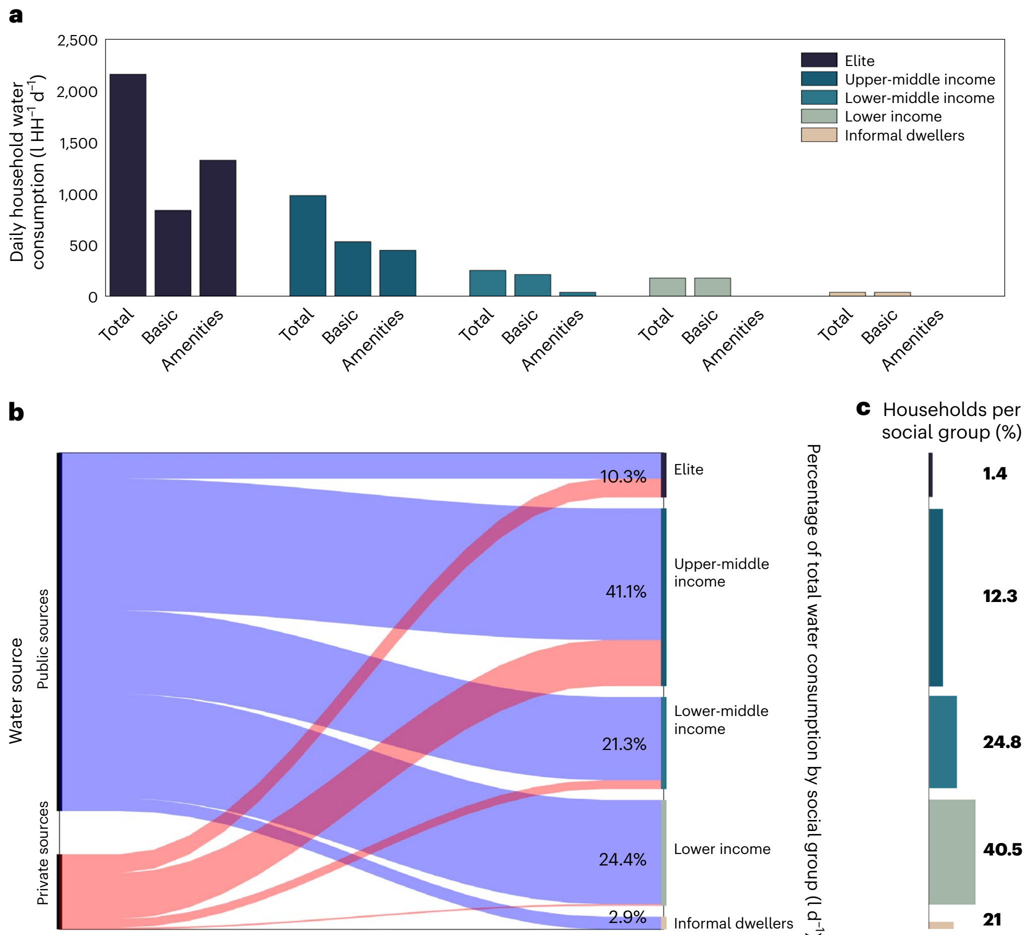

Fig. 2 | Modelled water consumption across Cape Town social groups. a, Daily household water consumption of each social group. Daily household consumption is disaggregated into the water that households use to satisfy basic water needs and the water used for amenities. **b**, Percentage of total water consumed daily by each social group. The figure distinguishes between public and private water sources. **c**, Percentage of households belonging to each social group.

of water consumption among elite and upper-middle classes. In addition, the results show that most of the water consumed by privileged social groups (elite and upper-middle income) is used for non-basic water needs (amenities) such as the irrigation of residential gardens, swimming pools and additional water fixtures, both indoor and outdoor. Conversely, most of the water consumed by other social groups (lower-middle income, lower income and informal dwellers) is used to satisfy basic water needs such as drinking water, hygiene practices and basic livelihood (Fig. 2a). What is most striking from these results is the total amount of water consumed by the elite and upper-middle-income groups. Despite representing only 1.4% and 12.3% of the total population, respectively, elite and upper-middle-income groups together use more than half (51%) of the water consumed by the entire city (Fig. 2b). Informal dwellers and lower-income households constitute together 61.5% of Cape Town's population but consume a mere 27.3% of the city's water. Privileged groups have access to private water sources in addition to the public water supply (Fig. 3b). Although we use the term 'private' to identify the additional sources used mostly by privileged social groups, these sources become private only after a process of enclosure and dispossession of common water resources (mostly groundwater) for the sole disposal and benefit of privileged users[25].

These excessive and uneven consumption patterns are rooted in the modern political–economic system, which fosters consumerism in the name of individual freedom, financial merits and economic growth[26,27]. While benefiting a privileged minority, this political–economic system is unsustainable because it reduces the availability of natural resources for the less-advantaged population and causes various forms of environmental degradation[27,28]. Overall, these results support the argument that domestic water consumption in unequal urban areas such as Cape Town is likely to become unsustainable as a result of excessive consumption among privileged social groups. Specifically, privileged water consumption is unsustainable because in the short term, it disproportionally uses the water available for the entire urban population. In the long term, privileged consumption constitutes an environmental threat to the status of local surface- and groundwater sources. By unsustainably using public water, well-to-do Capetonians directly affect the amount of water available in the city's reservoirs. Concurrently, when employing private boreholes, these privileged groups could eventually deplete the groundwater sources of the area.

Unequal drought experiences and responses

The model simulates how a city unequally experiences droughts and resulting water crises. In agreement with most literature about urban droughts and their social impacts[15,29], the model's results indicate that water management strategies to cope with droughts can seriously affect the water security of poor households by reducing their access to water. Specifically, the model reproduces the various droughts that occurred between 2008 and 2019 across the metropolitan area of Cape Town. Besides the 2011 drought, the most significant event occurred between

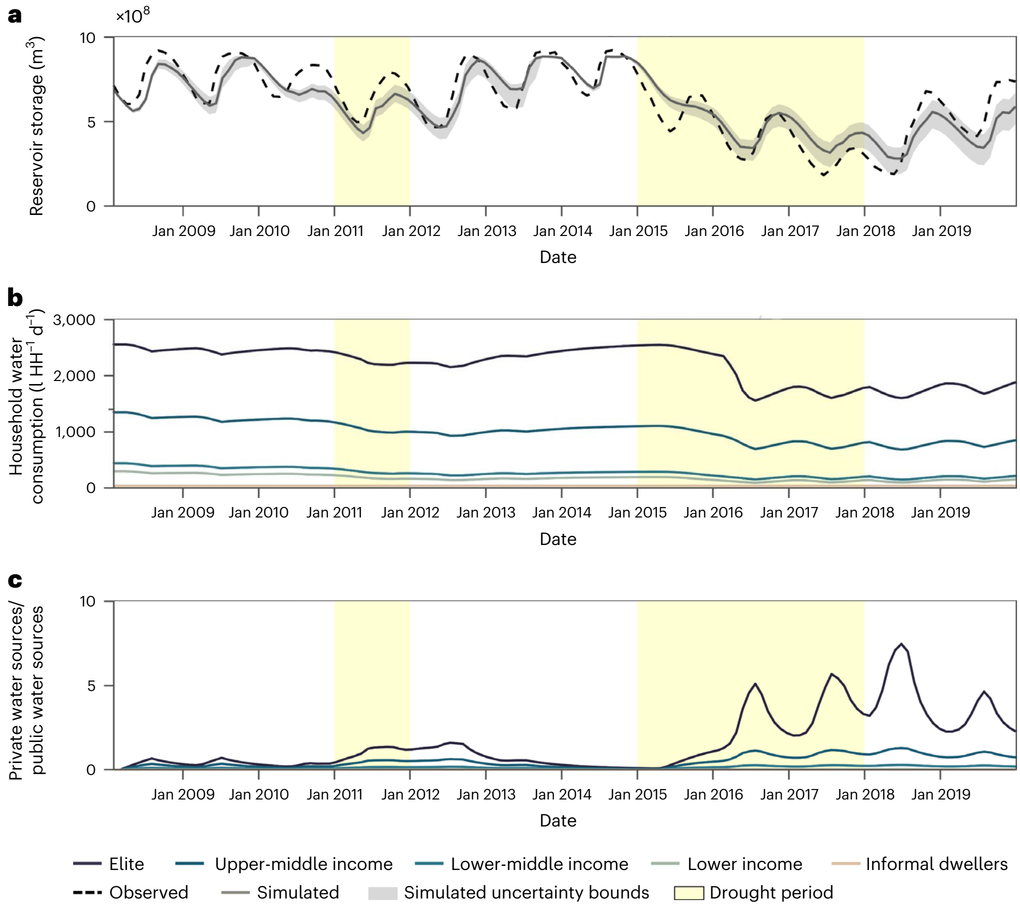

Fig. 3 | Differentiated water consumption trends across Cape Town social groups. a, Observed and simulated storage level of the municipal reservoirs from February 2008 until December 2019. The figure displays the occurrence of drought periods in 2011 and between 2015 and 2017. The uncertainty bounds and simulated value are representative of the 5th percentile, 95th percentile and median, respectively, of the 10^5 simulated reservoir storage obtained by perturbing the model parameters by 30% of their assigned value. **b**, Simulated household water consumption for each social group, including public and private water sources. During droughts, due to municipal water restrictions, every social group reduces its level of water consumption per capita. **c**, Ratio between simulated private and public water consumption for each group. Restrictions on public water use trigger a significant increase in consumption of private water sources (groundwater) among the elite and upper-middle-income groups.

2015 and 2017 and engendered one of the most extreme urban water crises ever recorded. Towards the end of that meteorological drought, the dams of the Cape Town Water Supply System had reached the alarming level of 12.3% of usable water. In response, the municipality imposed severe water restrictions and other measures to avoid 'Day Zero', the day in which the entire city would have run out of water. The restrictions included water rationing to 350 l HH^{-1} d^{-1} (or 50 l person^{-1} d^{-1}), increased water tariffs, fines for overconsumption or illicit water uses, withdrawal of the free water allocation for households classified as non-indigent and other measures to enforce the compliance of such restrictions[22,30]. The increasing block tariff, designed to charge incrementally higher rates to heavier consumers and cross-subsidize light users, was only partially successful in meeting the needs of the poorest population. Indeed, low-income users could not afford the revised tariff. Very often, these residents live in overcrowded units where more than eight people share the same tap and end up being charged unaffordable water bills and fines[22,23]. The model accounts for these water restrictions and reproduces the drought responses of different social groups. Accordingly, the water consumption trends simulated by the model (Fig. 3b,c) indicate that low-income residents are significantly more vulnerable to the demand-management measures enforced by the city than are more-affluent inhabitants, who can afford tariff increases and can access and develop alternative water sources.

In particular, the water consumption trends in Fig. 3b show that throughout the drought period of January 2015 to July 2017, the lower-income group had to reduce their already limited daily consumption from 197 l HH^{-1} d^{-1} to 101 l HH^{-1} d^{-1}, a reduction of 51%. These results indicate that drought-related restrictions can leave lower-income households without enough water to meet their basic water demands for bathing, laundry, cooking and sustaining their livelihoods. Conversely, the consumption trends of the elite and upper-middle-income groups show that these households have sufficient water for their basic needs even during drought restrictions. Privileged groups experienced the highest reduction of water use during drought but also a quick recovery from drought-related shocks. From, respectively, 2,542 l HH^{-1} d^{-1} and 1,103 l HH^{-1} d^{-1}, the per capita water use of the elite and upper-middle-income groups fell to 1,604 l HH^{-1} d^{-1} and 699 l HH^{-1} d^{-1} (Fig. 3b). Yet although such households recorded the highest reductions of water use relative to lower-income households, their reductions were due largely to the suspension of non-basic water uses such as garden watering, car washing and filling swimming pools.

Privileged groups are shown to access higher amounts of water and are thus more resilient to drought relative to the lower-income groups (Fig. 3c). The higher amount of water available for the elite and upper-middle-income households in the immediate aftermath of the drought is explained largely by the ability of these privileged groups to access alternative water sources. In the short term, additional sources encompassed mostly bottled and spring water. In the longer term, elites' strategies to cope with reduced public water availability extended to the development of private water sources, such as rainwater harvesting systems or boreholes located on the premises of their households. Figure 3c shows that restrictions on public water use triggers a significant increase in consumption of water from private boreholes for only the social groups that can afford the access and use of such sources. By contrast, low-income areas do not have the resources to cope with tariff increases or to access private water wells. For each simulated drought, Fig. 3c shows that after drought periods, private water use by the elite and upper-middle classes increases, respectively, up to 7.5% and 1.3% relative to public water use. At the same time, informal dwellers and lower-income groups (with, respectively, 0.04% and 0% maximum ratios) do not have access to these private sources.

Ultimately, as depicted by the simulated water consumption trends (Fig. 3b, c), the elite and upper-middle-income groups tend to enhance their level of water security after a drought while low-income groups become more water insecure. Such trends also reveal differentiated levels of resilience to future droughts across different social groups. Privileged households are not affected by tariff increases and continue to rely on the private water sources developed in response to the recent drought. On the contrary, low-income groups become less resilient as they cannot easily afford the tariff increases that have become permanent after the drought, and they have limited or no access to private water sources. This uneven picture is rooted in the water inequalities observed before the drought and, in turn, the socioeconomic features that characterize Cape Town's urban fabric. From here it follows that the manner in which each social group experiences and responds to drought is also rooted in the distinctive political–economic regimes that shape urban form and conditions of access to water and other resources[22,28,29].

Impact of elites' unsustainable consumption on urban water balance

The simulation of the different water consumption trends shown in Fig. 3 reveals that the unsustainable water consumption by the elite and the upper-middle-income groups constitutes a threat for the long-term sustainability of an urban water system. Moreover, the increasing use of private boreholes by these privileged groups represents an environmental threat for the local aquifers. Specifically, the availability of private boreholes within the premises of elite or upper-middle-income households risks triggering what ecological economists[31] and sociohydrologists[7] define as the supply–demand cycle. The supply–demand cycle attributes an unforeseen increase in water demand to the expansion or construction of additional water infrastructure. In this case, the development of private boreholes by the most privileged groups could produce a supply–demand cycle, which, in the longer term, might deplete the local aquifers and thus limit the future availability of water for basic needs. These results are relevant for any city that allows privileged groups to consume at comparable levels to those observed among Cape Town's elites. The risks are even greater considering that drought projections suggest that meteorological and hydrological droughts will most likely increase across South Africa and in many other regions of the world[32–34].

Finally, to test the extent to which water consumption by the elite and upper-middle-income groups contributes to urban unsustainable water patterns, the model simulates a number of scenarios. Each scenario examines the implications of different drivers on the long-term patterns of urban water consumption. Specifically, the model compares the (1) baseline with scenarios of (2) urban population growth by 2% per year[35]; (3) climate change with an increase in temperature of 2 °C[36] and a 10% decrease in run-off[37]; (4) increase in unsustainable water consumption by the privileged groups; and (5) more equal and sustainable use of water by every social group. Although these drivers occur simultaneously, we simulate them separately to perform a scenario-based analysis of the relative impacts that each driver might have on the city's water balance. Figure 4 shows that the most unsustainable scenario is the one that foresees an increase of inequality and, in turn, unsustainable levels of water consumption among the elite and upper-middle-income groups. Here an increase of unsustainable water consumption by the most privileged social groups has the potential to be more detrimental than the effect of population growth (on water consumption) or climate change (on the availability of surface water sources). Concurrently, the results of the population growth scenario do not significantly deviate from the baseline conditions. Instead, the climate change scenario interestingly shows that as a result of extreme drought conditions and related water restrictions, the elite and upper-middle-income groups considerably increase their access and usage of private boreholes, thereby substantially depleting the groundwater resources available within the area. Last, the scenario that considers a more equal distribution of water across the different social groups along with more sustainable levels of consumption leads to reductions in total water use and pressure on the urban water balance. In this scenario, private boreholes are not exploited and the local aquifer remains relatively preserved. Thus, with respect to Cape Town, we conclude that if every social group had used a similar amount of water and limited the amount of water used for amenities, the city could have averted some of the worst effects of Day Zero.

Discussion

Projections of future water demand and drought show an alarming risk of water crisis for many, if not most, cities across the world[38]. The management of urban water systems thus represents one of the most compelling and serious challenges society must address. Current policies aimed at tackling drought and urban water crises focus mostly on building resilient cities through additional as well as more-efficient water infrastructure and technologies, alongside progressive water pricing[9,39]. Yet such techno-managerial solutions are insufficient to address future water crises because they overlook some of the root causes. First, as we have shown here, resilience strategies relying solely on increased water supply are counterproductive as they expand the water footprint of cities while perpetuating unequal levels of consumption. Second, as shown by our results (Fig. 3), even when aimed at cross-subsidizing low-income households, increasing tariffs have proved ineffective in terms of both fairness and environmental sustainability. Thus, future drought resilience strategies should shift away from reactive approaches based on the notion that droughts are episodic. Instead, more proactive adaptation strategies are needed to recognize and address the long-term socioenvironmental patterns that engender urban water crises.

Our results show that urban water crises can be triggered by the unsustainable consumption patterns of privileged social groups. Critical social sciences explain that these patterns are generated by distinctive political–economic systems that seek capital accumulation and perpetual growth to the exclusive benefit of a privileged minority[15,18]. In other words, there is nothing natural about urban elites overconsuming and overexploiting water resources and the water marginalization of other social groups. Instead, water inequalities and their unsustainable consequences are products of history, politics and power[16].

To conclude, theories on degrowth suggest that the only way to counteract the unsustainable and unjust patterns of elites is by reimagining a society in which elitist overconsumption at the expense of other citizens or the environment is not tolerated[40]. Our analysis confirms that the only way to preserve available water resources is by altering privileged lifestyles, limiting water use for amenities and redistributing income and water resources more equally. The difficulty with such actions is that they stand in stark contrast with the prevailing political–economic system built on overexploitation of natural resources alongside the exclusion, segregation and marginalization

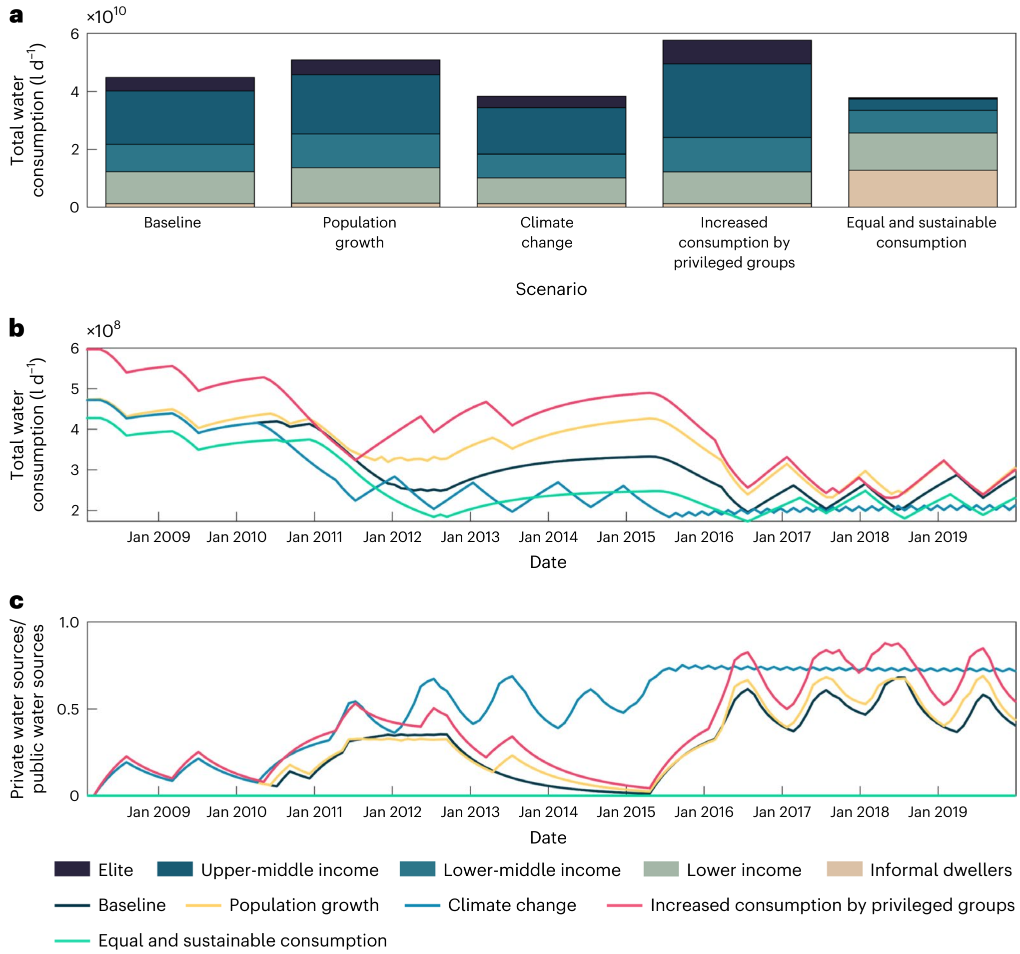

Fig. 4 | Scenario analysis. a, Total amount of water consumed every day by each social group in the following scenarios: (1) baseline—with existing inequalities; (2) population growth; (3) climate change; (4) increased water consumption by privileged groups (elite and upper-middle income); (5) equal and sustainable water consumptions. **b**, Comparison of the total amount of water used by the city over time in each possible scenario. **c**, Ratio between the total amount of private and public water sources in each scenario.

of underprivileged classes[41]. We suggest reorienting current water management and drought adaptation policies towards new political–economic paradigms that prevent overconsumption and inequalities. As Cohen[29] points out, “the era of cheap and plentiful drinking water has passed”: it is time to agree about how society should share life’s most essential natural resource.

Methods

An interdisciplinary approach to modelling urban water flows

To quantify the unequal urban water interplay and its long-term impacts on urban water systems, this system-dynamics model brings together concepts from physical and engineering sciences and critical social sciences. While physical and engineering sciences have advanced understanding on the way in which human activities play a role in exacerbating urban droughts and water crises[10,42–44], critical social sciences further the analysis by moving beyond interpretation of society as homogeneous or water and drought management as apolitical. By combining critical social studies with physical and engineering sciences, the model quantifies the role of different social groups in altering urban water balances. The contribution of both disciplines is crucial in the development of our new system-dynamic model. On the one hand, critical social sciences enable more complex understandings of urban water dynamics by examining the prevailing power structures that constitute and reshape cities[16,45]. Specifically, critical theories elucidate the role that elites play in reshaping the water demand and supply of a city relative to other social groups[15,16,46]. On the other hand, engineering and physical studies provide the tools to quantify human–water interplays and retrace their long-term implications within cities[43,44].

This paper employs a state-of-the-art methodology developed by engineering and physical scientists over the past decades to quantify human influences on water systems alongside retracing the interplay of water and society[47,48]. We used system-dynamic modelling as it is particularly suitable for reproducing the behaviour of complex human–water systems and their responses to certain interventions over time[49,50]. By integrating critical social sciences into a system-dynamic model, this paper examines the inequalities of human–water interplays within a city. Relative to previous accounts of water inequalities across urban spaces, this interdisciplinary model simulates and quantifies the long-term trends of these unequal water consumption patterns along with their impacts on the city’s water balance.

To account for urban inequalities, the model is discretized into households, which are further reaggregated into distinctive social groups, each of which expresses different levels of power and distinctive patterns of water consumption. Our hypothesis is that the power relations between different social groups influence different levels of consumption and, in turn, shape water availability and future water shortages in cities. The model simulates diverse water consumption patterns employing specific coefficients and parameters that express distinctive characteristics of the social groups and ultimately households. To determine the urban water balance, the model considers both the public and private water sources that supply the households. Each household, depending on its socioeconomic features, can access or not private water sources in addition to public water. In this model, private water sources are boreholes drilled within the household's premises. While not directly depleting the public water supply, the use of private boreholes has a long-term effect on the availability of groundwater sources within the study area. Besides their socioeconomic status, households also change their consumption patterns in response to droughts and municipal water restrictions. Thus, depending on the amount of water available in the city's reservoir, the municipal water policies change and enforce different levels of water restriction. Restrictions may include water tariff increases and, in turn, limit the ability of some households to afford water. Moreover, municipal water restrictions also influence the awareness of the household[51]. In this model, awareness represents a crucial variable as it directly influences the amount of water consumed within each household. As a result, for a certain period, the household would limit its use of public water and, if possible, access private sources.

Supplementary Fig. 1 illustrates the model structure and the causal links that relate all the variables. At an urban scale, the main variables are the reservoir storage, municipal water polices, public water demand, private water demand and private water sources. Together, these variables determine the water balance of the city. The remaining variables characterize the human–water interplay within one household and determine the total amount and type of water consumed by the household. The model structure (Supplementary Fig. 1) shows how the water consumption of every household is aggregated into five different social groups, which differently affect the urban water balance either by reducing the water available in the municipal reservoir or by reducing the availability of private water sources. To account for emerging dynamics during drought events, the model retraces domestic water consumption over time for each social group using a monthly time step[52]. While this model has been built on Cape Town's socioeconomic and hydrological features, its structure constitutes a useful representation of urban water dynamics adaptable to other cities characterized by socioeconomic inequalities and where households have access to both public and private water sources.

Case study

The model is applied and tested on the Cape Town urban area as it recently faced a severe drought, which unfolded into an unprecedented water crisis. Thus, the city represents a case in point of the threat that water crises pose to urban environments. Specifically, Cape Town is an example of a Mediterranean climate, and the catchments that supply water to the metropolitan area have mean annual precipitation that varies between 334 and 694 mm. The city is an ideal case study because it is characterized by stark socioeconomic inequalities and spatial segregation[53], making it relevant to analyses of the impacts of uneven and unjust water consumption patterns. These distinctive features originate from the colonial era and are further exacerbated by apartheid and post-apartheid regimes. Since the seventeenth century, colonial policies have excluded the native population from the city's land, resources and political spaces to serve the interests of white European settlers. Over time, and especially throughout the apartheid regime, the development of urban infrastructure and the exploitation of natural resources enabled the expansion of a rich urban centre with a relatively high level of public services enjoyed exclusively by the white elite[54]. After the end of apartheid (1994), the city underwent substantial reforms marked by a strong neoliberal ideology, which further exacerbated basic services inequalities in the city. Despite some attempts to redress social inequalities, these reforms did not succeed in completely overhauling apartheid policies and ended up perpetuating deeply rooted injustices. These political–economic conditions enabled unsustainable water consumption by elites through the establishment of world-class services in privileged urban areas and the creation of unsafe spaces with substandard services on the outskirts of the city[53–55].

According to the 2020 census, Cape Town includes over one million households, of which 1.4% belong to the elite, 12.3% to upper-middle income, 24,8% to lower-middle income, 40.5% to lower income and, ultimately, 21% to informal areas[21]. The classification into five distinctive social groups is based on an index developed by the Western Cape Government for the City of Cape Town and other municipalities in the Western Cape[20]. The Socio-Economic Index provides a qualitative assessment of Cape Town's urban areas on the basis of their income levels, education, type of housing and access to basic services. In turn, each such group is also characterized by a different level of water access and different consumption patterns. These specific socioeconomic features that characterize Cape Town's social groups are used only to define the model structure and, for the simulation, characterize the input data such as parameters and coefficients.

Most of the model's values are based on a fieldwork undertaken in Cape Town between May 2019 and March 2020 (Supplementary Tables 2–4). Primary qualitative data were collected through 65 interviews and 5 focus groups with households and governmental and non-governmental organizations. The interviews with non-governmental organizations and water-sector organizations focused mostly on the technical specification, operation and maintenance of Cape Town Water Supply System along with the governmental response to droughts and water shortages. The semi-structured interviews and focus groups with households focused on the household water consumption patterns and their experience of the drought, including changes in everyday water practices and coping strategies. The interview participants were selected across diverse socioeconomic groups and urban areas to capture different experiences of the drought. Qualitative primary data were triangulated with media outlets and reports and further combined with data collected through a documentary analysis. Quantitative data, including time series of rainfall, temperature, monthly inflow, reservoir storage, population and daily water consumption, have been retrieved, respectively, from the city of Cape Town data portal, the Hydrological Service of the South African Department of Water and Sanitation and the South African Weather Service[56–58].

Since this model aims to simulate the interplay between human and water systems rather than the complexity of specific social or hydrological processes, it unavoidably makes a number of simplifying assumptions. First, the model focuses on socioeconomic inequalities, which are often easier to quantify. Thus, it does not explicitly capture the city's racial polarization. Indeed, the legacy of apartheid remains vivid in Cape Town, where economic inequalities and geographical segregation are deeply entangled with racial categorization[54]. The model thus simplifies critical intersectional dimensions of water insecurity that still differentiate conditions of water access and insecurity. Second, run-off generation does not account for the hydrological processes of percolation, infiltration and groundwater changes. This assumption does not produce any instability in the model as private water sources do not directly affect reservoir storage values (Supplementary Fig. 1). Third, the model could not be validated against observed values of water consumption by the different social groups due to the lack of data. Last, the model focuses on intra-urban inequalities and consumption dynamics. As such, it does not simulate the increasing competitions and conflicts between the cities and their surrounding areas[4]. Yet it does offer an analytical framework that can be further extended for future studies integrating domestic and rural consumptions with the goal of broadening the scope of the analysis beyond the city.

A system-dynamic model for unequal cities

The model simulates the unequal interplay between water availability (from public and private water sources) and water consumption (from basic needs and amenities) of different income groups. Each social group can reshape its drought response depending on its socioeconomic conditions along with the restriction levels imposed by the municipality and the ultimate water costs. In turn, every household can respond to drought restrictions by either reducing their use of public water or by increasing their use of private water sources (for example, constructing boreholes for groundwater abstraction). The model reproduces the household's decision-making process, its water consumption patterns and behavioural response to drought restrictions via the establishment of causal links between physical and socioeconomic variables (Supplementary Fig. 1). For example, lower levels of reservoir storage lead to higher water restrictions by the municipality, and in turn to higher levels of drought awareness across the different social groups, which will be compelled to reduce their public water consumption. This reduction of public water use leads to a higher consumption of private water sources depending on the socioeconomic conditions of each income group.

The model assumes that the main public water supply consists of a system of surface water reservoirs, as is the case for the metropolitan area of Cape Town. Indeed, Cape Town relies on the Western Cape Water Supply System, consisting of six main reservoirs, as its main source of water[59]. The model uses external observed data as monthly input of the public water sources. Change in time of the reservoir storage V (in m^3) is calculated as:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = Q_t^{\mathrm{I}} - W_t - Q_t^{\mathrm{A}} - Q_t^{\mathrm{S}} - Q_t^{\mathrm{E}} - \mathrm{ET} \tag{1}$$

where Q^{I} is the observed monthly reservoir inflow, W (m^3 month^{-1}) represents water withdrawals for water supply, Q^{A} (m^3 month^{-1}) is the observed water consumption for agricultural purposes, Q^{S} (m^3 month^{-1}) is the spillway release, Q^{E} (m^3 month^{-1}) is the environmental flow and ET [m^3 month^{-1}] is evapotranspiration. To define and assess the amount of water outflowing from the reservoir, the model employs Draper and Lund's[60] standard operational rules, which calculate the total withdrawal from the reservoir, as:

$$W_t = \begin{cases} \frac{V_t + Q_t^{\mathrm{I}}\Delta t - Q_t^{\mathrm{E}}\Delta t}{K_{\mathrm{P}}\Delta t} \text{ if } V_t + Q_t^{\mathrm{I}}\Delta t - Q_t^{\mathrm{E}}\Delta t < K_{\mathrm{P}} \sum\limits_{S=1}^{5} \mathrm{Pu}_t^S \mathrm{HH}^S \\ \sum\limits_{S=1}^{5} \mathrm{Pu}_t^S \mathrm{HH}^S \text{ Otherwise} \end{cases} \tag{2}$$

where V (in m^3) is the reservoir storage, Pu (m^3 month^{-1} HH^{-1}) is the total public water demand required by all the income groups in Cape Town, HH is the number of households, S is the five different social groups and K_{p} is the hedging release slope.

Once the maximum storage capacity of the reservoir V_{MAX} (in m^3) is reached, the spillway releases an amount of water equal to:

$$Q_t^S = \begin{cases} V_t + Q_t^{\mathrm{I}}\Delta t - Q_t^{\mathrm{E}}\Delta t - V_{\mathrm{MAX}} \textit{ if } V_t + Q_t^{\mathrm{I}}\Delta t - Q_t^{\mathrm{E}}\Delta t \geq \sum\limits_{S=1}^{5} \mathrm{Pu}_t^S \mathrm{HH}^S + V_{\mathrm{MAX}} \\ 0 \text{ else} \end{cases} \tag{3}$$

The environmental flow released by the reservoir, required to sustain downstream natural ecosystems, is calculated considering a presumptive standard of 20% the monthly reservoir inflow, according to ref. 61.

Finally, the losses from evapotranspiration are calculated using the method proposed by ref. 62:

$$\mathrm{ET}_t = 0.00409 \times 6.11 \times \exp\left(\frac{17.3T_t}{237.3 + T_t}\right) \tag{4}$$

Where T (°C) is the average monthly temperature.

The volume of water consumed by each household is divided into water used for basic needs and water used for water-dependent amenities. In this model, basic water is supplied by public water sources (from the reservoirs system), and its amount depends mostly on income, societal awareness about water shortage and water tariff of each social group. In particular, the change in per capita water use for basic needs B (m^3 HH^{-1} month^{-1}) is estimated as:

$$\frac{\mathrm{d}B^S}{\mathrm{d}t} = \begin{cases} -B_t^S\left[A_t^S\alpha_{\mathrm{D}}\left(1 - \frac{B_{\min}^S}{B_t^S}\right)\right] \text{ if } \frac{A_t^S}{\mathrm{d}t} > 0 \\ +B_t^S\left[A_t^S\alpha_{\mathrm{D}}\left(1 - \frac{B_t^S}{B_{\mathrm{MAX}}^S}\right)\right] \text{ if } \frac{A_t^S}{\mathrm{d}t} < 0 \end{cases} \tag{5}$$

where $B_{\min}$ and B_{MAX} are model parameters representing the minimum and maximum per capita water use for basic needs (Supplementary Table 4), A is the drought awareness and α_{D} is a parameter representing the decay rate of changes in consumption for basic needs. In this study, drought awareness is considered as a function of municipal water restriction, household income and total cost of water. In particular, we assumed that an abrupt change of awareness occurs after the adoption of water restrictions by the municipality due to a water shortage (first component of equation (6)). In addition, we assume that the sense of awareness decays over time[63] when no restrictions are in place (second component of equation (6)):

$$\frac{A_t^S}{\mathrm{d}t} = \frac{R_t}{R_{\mathrm{MAX}}}\left(1 - A_t^S\right) - \mu_{\mathrm{D}}\frac{C_t^S - I^S}{I^S}A_t^S \tag{6}$$

where μ_{D} (1 month^{-1}) represents the decay rate of drought awareness over time and I is the mean income (rand month^{-1}). Here we used existing sociohydrological studies[51] to define the decay rate of awareness and assumed that the value will decay in the same way for the five social classes. To test the impact of this assumption on the model's results, we run additional simulations that consider different values for each social group. The results of this sensitivity analysis confirm the validity of our choice and the robustness of the model (Supplementary Fig. 2). R is the restriction levels identified by the local water authorities during drought periods, R_{MAX} is the maximum restriction level that can be implemented and T (rand month^{-1} m^{-3}) is the water tariff. Municipal restrictions entail a price increase of the water tariff and an increase in the awareness of the different social groups.

Different restriction levels are triggered when the reservoir level reaches certain thresholds (Supplementary Table 5). Such restrictions have an influence on both water tariff and in the drought awareness of the different social groups, resulting in different allocation of water to the metropolitan area.

The water cost C (rand month^{-1}) is calculated as the product of the water tariff T (rand month^{-1} m^{-3}) (Supplementary Table 6) and the total water use (the sum of water demand from basic water needs and amenities M (m^3 HH^{-1} month^{-1}); see the following). Water tariff varies by the monthly volume consumed per household and is assessed on the basis of the public water use Pu of each social group and the ongoing restriction level (Supplementary Tables 5 and 6).

Once the water fee is known, the total water cost C (rand month^{-1}) is calculated as:

$$C_t^S = T_t^S\left(B_t^S + M_t^S\right) \tag{7}$$

where M (m^3 HH^{-1} month^{-1}) is the water demand from water-dependent amenities, highly dependent on the social group. As mentioned, high-income social groups will consume more water for amenities relative to lower-income groups as these privileged groups often use water for filling swimming pools, washing cars and gardening[22]. In particular, the initial value of water amenities is assessed as:

$$M_{t=1}^S = \varepsilon_{\mathrm{W}}\delta^S + \varepsilon_{\mathrm{G}}^S B_{t=1}^S + \varepsilon_{\mathrm{C}}^S \chi^S \eta^S \tag{8}$$

where ε_W is the average water demand for a swimming pool per month, δ is the percentage of households with a swimming pool in a given social group, ε_G is the percentage of water use for gardening, ε_C is the average water demand for car cleaning per month, χ is the average number of cars in the household of a given social group and η is the number of car cleanings per month. The variation of water amenities over time is calculated as:

$$\frac{\mathrm{d}M^S}{\mathrm{d}t} = \begin{cases} M_t^S A_t^S \alpha_M \frac{I^S}{I_{MAX}} & if\, R < 2 \\ 0 & if\, R = 2 \\ -M_t^S A_t^S \frac{I^S}{I_{MAX}} \left(1 - \frac{M_{min}}{M_t^S}\right) & if\, R > 2 \end{cases} \quad (9)$$

where α_M is a parameter representing the increasing rate of changes in water amenities, M_{min} is the minimum value of amenities, I is the mean income of a given social group and I_{MAX} is the maximum income among the groups.

The total water use TW (m^3 $month^{-1}$ HH^{-1}) consumed by each social group is the sum of basic (B) and amenities (M) water uses. Total water use can be supplied either by public water sources (reservoirs) or by private sources (groundwater). We first calculated the private water demand Pr (m^3 $month^{-1}$ HH^{-1}), and we assessed the public water demand Pu (m^3 $month^{-1}$ HH^{-1}) as the difference between total water use and private water. We assumed that each social group can increase its private water on the basis of drought awareness, convenience and distance to the private water source. Specifically, we calculate Pr and Pu as follows:

$$\mathrm{Pr}_{t+1}^S = (1 - d^S)\, A_{t+1}^S c^S \mathrm{TW}_{t+1}^S \quad (10)$$

$$\mathrm{Pu}_{t+1}^S = \mathrm{TW}_{t+1}^S - \mathrm{Pr}_{t+1}^S \quad (11)$$

where d is the normalized average distance of the social group to the private water sources, assumed 0 for high-income groups and 1 for lower-income groups, TW (m^3 $month^{-1}$ HH^{-1}) is the total water use, while c is the model parameter representing the convenience of private water use (Supplementary Table 6). In this model, we assumed that informal dwellers do not have access to private water sources as described in ref. 22. Model parameters and model initial conditions are based on values retrieved from the interviews and focus groups with households and governmental and non-governmental organizations undertaken in Cape Town between May 2019 and March 2020. These values were further triangulated with an in-depth literature review on water consumption in Cape Town[21,22,64]. Observed values of reservoir storage, monthly reservoir inflow and average monthly temperature are retrieved from South African Weather and Hydrological Data Services[56,57].

Scenarios description

To understand the manner and extent to which the unsustainable water consumption of privileged groups influences the water balance of a city, this work simulates and compares the occurrence of five different scenarios of water consumption. The aim of those scenarios is to consider the differential effect of the unsustainable water consumption of privileged groups relative to other drivers of water depletion. The first two scenarios focus, respectively, on population growth and climate changes because these drivers are considered as the major forces that threaten the availability of freshwater resources by altering the spatiotemporal characteristics of temperature and precipitation along with increasing the level of water consumption[2,9]. The population growth scenario does not use different population growth rates across social groups as this detailed information is not available or is too uncertain. It should be noted, however, that if the model had incorporated these differentiated trends, the relative impact of population growth on the urban water balance would probably have been even smaller as projections suggest that informal settlements will grow more than the rest of the population[38]. In this scenario-based analysis, the population growth and climate change scenarios are compared with three other scenarios characterized by different levels of social inequalities and, in turn, diverse amounts of unsustainable water consumption by privileged social groups. These are, respectively, a baseline scenario with existing inequalities, a scenario with more-extreme inequalities with increased water consumption by privileged groups and a scenario that foresees a more-egalitarian society with sustainable and equal consumption of water across the city. Supplementary Table 7 summarizes the values and coefficients attributed to each scenario.

Model evaluation

To assess the model's ability to quantify observed hydrological and socioeconomic variables, we carried out a model evaluation by means of structural and behaviour validity tests[65,66]. The structural test aims to assess whether the designed model structure can effectively represent the problem under investigation, whether it has a logical structure and whether the links between the model's variables have been properly conceptualized. In our study, we used three different types of structural test, as proposed by ref. 67. First, we performed a structure examination test to check whether the model structure is consistent with the descriptive knowledge of the real system under study. In addition, the empirical research carried out in Cape Town served to define the model structure, the relationships between social groups and urban water systems, the socioeconomic characteristics and decision-making process of each such group and their influence on the urban water balance. Governmental documents and official reports served instead to examine the robustness of the model and, in particular, its causal links and polarities (the positive or negative signs in Supplementary Fig. 1), its equations and general assumptions. These reports provided specific information regarding municipal water policies, drought-related restriction, households' consumption patterns and awareness[68,69]. Second, we performed a dimensional consistency test. This test verifies the dimensionality of each mathematical equation by checking the measurement units on both sides of a given equation. Third, we ran the extreme condition test on the model using extreme values for each parameter to assess whether the model exhibits a logical behaviour and whether it remains numerically stable (Supplementary Fig. 3). We multiplied the model parameter values by three and found a higher water consumption leading to lower reservoir values and higher dependency on additional water sources as water fees increased. Eventually, this test did not detect any numerical instability under extreme parameter values. It is worth noting that we did not multiply the parameters linked to the initial values of water amenities (equation (8))—that is, number of households HH and mean income I—as this would have led to unrealistic values of water consumption, consequent drastic reduction of the reservoir volume and constant dependency on public water sources. Ultimately, the model did not show any numerical instability also in the case of unlimited use of private water sources. In the behaviour validity test (Supplementary Fig. 4), we evaluated the model results with observations of the real system. First, we compared observed and simulated values of the reservoir volumes and obtained a Nash–Sutcliffe efficiency of 0.84 (with 1.00 representing a perfect model). Second, we compared the observed values of annual average water consumption (Ml d^{-1}) with the model simulation between 2011 and 2019. This test returned a satisfying root mean square error of 133 Ml d^{-1}.

Ethical approval

The research protocol for this study was approved by the Municipality of Cape Town (PSRR-0259). The research team followed established guidelines and protocols for ethical research, including those provided by the Italian Research Ethics and Bioethics Committee (protocol 0043071/2019), the Swedish Ethical Review Authority (Dnr 2019-03242) and the European Union under Horizon 2020 (FAIR Data Management and EU General Data Protection Regulation).

We obtained oral informed consent from all participants, which included clear and detailed information about the context and purpose of the interview, the expected duration of participation, the funders and lead researchers of the project, data protection, confidentiality, privacy and the storage duration of personal data. We also made it clear to participants that they were not obligated to answer any questions and that they could withdraw from the interview at any time.

Our team took great care to ensure that the ethical principles of the research were followed throughout the study and that the rights and well-being of participants were protected at all times.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Qualitative data that support the findings on Cape Town, South Africa, are available on request from the corresponding author. The data are not publicly available because they contain information that could compromise research participant privacy/consent. Quantitative data for monthly inflow, reservoir storage, environmental flow, losses and evapotranspiration of Cape Town Water Supply System were obtained from the Hydrological Data Service of the South African Governmental Department of Water and Sanitation (https://www.dws.gov.za/Hydrology). Quantitative data for precipitation and temperature in Cape Town were obtained from the South African Weather Service of the South African Governmental Department of Forestry, Fishery and the Environment (https://www.weathersa.co.za/). Quantitative data characterizing Cape Town's urban demography are obtained from and freely available at the following link: https://www.cogta.gov.za/ddm/wp-content/ uploads/2020/11/City-of-CT-September-2020.pdf. Quantitative data characterizing the water consumption of different social groups in Cape Town are freely available and retrieved from the Cape Town Open Data Portal (https://web1.capetown.gov.za/web1/OpenDataPortal/) as well as from the public report 'City of Cape Town Residential Water Consumption Trend Analysis' written by N. Viljoen and available at https://www.greencape.co.za/assets/Sector-files/water/Water-conservation-and-demand- management-WCDM/Viljoen-City-of-Cape- Town-residential-water-consumption-trend-analysis-2014-15-2016.pdf. Source data are provided with this paper.

Code availability

The code used to develop the model is available at the following Zenodo repository: https://doi.org/10.5281/zenodo.7664403.

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Author contributions

E.S. conceived the study; E.S. and M.M. developed the methodological framework; E.S. collected and analysed the data; M.M. developed the model and interpreted the model results in collaboration with E.S.; M.M. performed the model validation in collaboration with G.d.B.; E.S. wrote, reviewed and edited the manuscript in collaboration with M.M., M.R., H.C. and G.d.B.; M.R., H.C. and G.d.B. gave technical support and conceptual advice.

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Competing interests

The authors declare no conflicting interests.

Additional information

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Software and code

Policy information about availability of computer code

Data collection	No computer code was used for data collection.
Data analysis	The system dynamic model was implemented by means of code and mathematical algorithm developed using the computer programming language Matlab r2022b (license from Vrije Universiteit Amsterdam). Custom code is deposited in the following public Zenodo repository: 10.5281/zenodo.7664403

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Qualitative data that support the findings on Cape Town, South Africa, are available on request from the corresponding author [ES]. The data are not publicly available due to them containing information that could compromise research participant privacy/consent. Quantitative data for monthly inflow, reservoir storage, environmental flow, losses and evapotranspiration of Cape Town Water Supply System were obtained from the Hydrological Data Service of the South African Governmental Department of Water and Sanitation (https://www.dws.gov.za/Hydrology). Quantitative data for precipitation and temperature in Cape Town were obtained from the South African Weather Service of the South African Governmental Department of Forestry, Fishery and the Environment (https://www.weathersa.co.za/). Quantitative data characterizing Cape Town's urban demography are obtained from and freely available at the following link: https://www.cogta.gov.za/ddm/wp-content/uploads/2020/11/City-of-CT-September-2020.pdf. Quantitative data characterizing the water consumption of different social groups in Cape Town are freely available and retrieved from the Cape Town Open Data Portal at the following link: https://web1.capetown.gov.za/web1/OpenDataPortal/ as well as from the public report "City of Cape Town Residential Water Consumption Trend Analysis" written by Viljoen, Nina and available at: https://www.greencape.co.za/assets/Sector-files/water/Water-conservation-and-demand-management-WCDM/Viljoen-City-of-Cape-Town-residential-water-consumption-trend-analysis-2014-15-2016.pdf.

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	Qualitative data used in this research was collected through semi-structured and unstructured interviews administered respectively to stakeholder of different sex (both female and men). However no sex- or gender- analysis was performed from these data because the study focused exclusively on the economic status of the stakeholder at household level.
Population characteristics	The research samples included adult urban dwellers (men and female) residing in different neighborhoods of Cape Town as well as stakeholders representative of the water and environmental sector, including government officials, water utility managers, small-scale water providers, consultants, charities and NGOs. The covariate-relevant population characteristics accounted for in this study included mostly economic status and location within Cape Town.
Recruitment	Households were selected using convenience sampling with the criterion of at least two blocks distance between each household and based on location (e.g. a neighborhood that were particularly affected by the drought). Stakeholders in the water and health sector, including government officials, water utility managers, small-scale water providers, consultants, charities and NGOs were selected based on the role they played in managing the drought event. Although selection criteria were put in place to avoid potential biases, this study still acknowledges the potential biases that might have been present when interpreting the study's findings. One of the main biases in this study can be classified as a self-selection bias, as the households that agreed to participate may differ from those who declined or were unavailable. Additionally, participants may provide socially desirable or expected answers, rather than their true beliefs or experiences, leading to social desirability biases.
Ethics oversight	The research protocol for this study was approved by the Municipality of Cape Town (PSRR-0259). The research team followed established guidelines and protocols for ethical research, including those provided by the Italian Research Ethics and Bioethics Committee (protocol 0043071/2019), the Swedish Ethical Review Authority (Dnr 2019-03242), and the European Union under Horizon 2020 (FAIR Data Management and EU General Data Protection Regulation). We obtained oral informed consent from all participants, which included clear and detailed information about the context and purpose of the interview, the expected duration of participation, the funders and lead researchers of the project, data protection, confidentiality, privacy, and the storage duration of personal data. We also made it clear to participants that they were not obligated to answer any questions and that they could withdraw from the interview at any time. Our team took great care to ensure that the ethical principles of the research were followed throughout the study, and that the rights and well-being of participants were protected at all times.

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Behavioural & social sciences study design

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Study description	The project adopted a mixed method employing both qualitative and quantitative data. The mix of qualitative and quantitative research methods, included semi-structured interviews, unstructured interviews, observations, focus groups discussions. Different data analysis techniques were used (discourse analysis, life histories, summative analysis, historical and comparative analysis).
Research sample	The research sample is qualitative therefore it is not statistically relevant, meaning that the sample was not intended to be representative of any specific population or group, but rather to provide in-depth and context-specific analyses of social behaviors, cultural beliefs, institutional changes, and perceptions of different stakeholders. The research sample for the study included

households (male and female household members) belonging to a different economic status and living in different location within Cape Town. The study also included representative of national and provincial government, municipal officials, local public health and water sector organisations, and other stakeholders involved in managing the drought. The study does not focuses on age as a demographic characteristic relevant for this research but no minors were invited to participate in the project.
The rationale for the chosen study sample was to capture diverse water consumption patterns and differential responses to the drought event by engaging with a range of stakeholders who have different experiences, perspectives, and roles in managing the drought. By including a range of stakeholders, the study provides a comprehensive and nuanced understanding of how the drought affected various groups and how different stakeholders responded to the water scarcity.

Sampling strategy	Snowball sampling was used to ensure a variegated sample of stakeholders. We undertook about sixty-five interviews in Cape Town, including key public and private stakeholders in the water and environmental sector, consultants and non-governmental organization, allowing for a robust understanding of the water consumption patterns and differential responses to the drought events across Cape Town urban area. Saturation was achieved by including the complete range of stakeholders that were involved in managing the drought event. Households were selected using convenience sampling with the criterion of at least two blocks distance between each household and based on location (e.g. a neighborhood that were particularly affected by the drought). Where needed, permission from any relevant authority was asked (e.g. chiefs, local municipal authorities) to ensure they are duly informed. Household responses across intra-urban spaces revealed a number of consistent patterns, associated with income, coping strategies, technical specification of the network. We thus became confident that this category was saturated.
Data collection	Semi-structured and unstructured interview were undertaken by the corresponding author [ES]. As part of the informed consent procedure, the researcher asked permission for audio recording the interview, which was granted in the large majority of the interviews. Interviewees were informed that such practice would not affect the confidentiality and anonymity (if requested), and that data collected both through audio recordings and through text would be safely stored in virtual storage facilities provided by the university. As most qualitative research, this study focuses on exploring participants' experiences, perceptions, and opinions in-depth. Unlike in quantitative research, where blinding can reduce the risk of bias and improve the reliability of the results, this qualitative study aims to interpret and understand the data, rather than to be objective. Whilst not being amongst its primary concerns this study set out to minimise biases by the use of reflexivity, or else a process of self-reflection and critical analysis of the researcher's own biases, values, and assumptions that may influence the research process and the interpretation of the data. Reflexivity in this study involved acknowledging and examining the researcher's positionality, background, and subjectivity, and considering how they may impact the research process and the findings. Moreover, throughout the research process, the researcher also worked to enhance the rigor and transparency of qualitative research by using a systematic approach to data collection and analysis, and by involving multiple researchers and stakeholders in the process. This enabled this study to ground its finding in the data and not being overly influenced by the researcher's personal biases or preconceptions.
Timing	In Cape Town, qualitative data were collected between May 2019 and March 2020. Quantitative data were collected from May 2019 to September 2022.
Data exclusions	No data were excluded.
Non-participation	No participant declined to participate.
Randomization	Participants were not allocated into experimental groups.

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