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Water shortages worsened by reservoir effects

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The expansion of reservoirs to cope with droughts and water shortages is hotly debated in many places around the world. We argue that there are two counterintuitive dynamics that should be considered in this debate: *supply-demand cycles* and *reservoir effects*. Supply-demand cycles describe instances where increasing water supply enables higher water demand, which can quickly offset the initial benefits of reservoirs. Reservoir effects refer to cases where over-reliance on reservoirs increases vulnerability, and therefore increases the potential damage caused by droughts. Here we illustrate these counterintuitive dynamics with global and local examples, and discuss policy and research implications.

Throughout history, societies have been severely affected by drought. The collapse of various ancient civilizations, such as the Maya, has been attributed to prolonged periods of drought[1]. Individuals, communities, and societies have reacted and adapted to drought primarily by exploiting groundwater, building dams and expanding infrastructure for surface water storage and transfer, which aim to stabilize water availability. Consequently, the hydrological regime has become highly artificial in many regions of the world[2,3], and low flow conditions are influenced by both climatic and anthropogenic factors[4-6], including reservoir management[7,8].

Drought occurrences can trigger temporary reductions of water availability, often leading to water shortages when water demand cannot be satisfied by the available water. Societal responses to water shortages can result in a series of cascading effects. The blue loop of Figure 1 shows one traditional response: the expansion of reservoir storage. More specifically, economic damage from water shortages triggers public pressure for action, which can then result in the expansion of reservoirs to increase water availability (blue arrows in Fig. 1). This response tends to decrease the frequency, severity, and duration of water shortage (Fig. 1, negative feedback between supply and shortage).

Dams and reservoirs can supply a reliable source of water[9,10], and are key for a variety of human activities and needs[11]. Over the past 100 years, the number, and total storage capacity, of large dams and reservoirs has rapidly increased[12-14]. More than half of the world's reservoirs are designed and managed to supply water for domestic, industrial and agricultural purposes[12]. These reservoirs store water during periods of excess, to bridge periods of water deficit or increased demand. Other dams and reservoirs provide different services, such as flood control and hydropower generation[12].

There are ongoing discussions in many areas around the world about potential new reservoirs to increase water availability. The impact of hydro-climatic and socio-economic trends is part of these debates[15,16]. In water management and planning[16], hydro-climatic trends derived from climate projections are utilized to better understand future water availability in the coming decades[17] (e.g. decreasing streamflow). Socio-economic trends from various scenarios (e.g. population growth) inform projections of future water demand[16]. The grey arrows in Figure 1 indicate the potential role of these two external drivers of change: hydro-climatic and socio-economic trends.

Reservoirs have enabled economic growth and poverty alleviation in many regions around the world[18]. Notably, the benefits accrued depend not only on the construction of reservoirs, but also on the development of institutional or human capacities to manage such water infrastructure[19], and effectively use the available water for agricultural, industrial or civil purposes.

When considering the benefits of additional reservoir capacity, it is important to consider perspectives from multiple stages of economic growth[20]. Most high-income countries have reaped the benefits of reservoir construction by developing the majority of their feasible storage capacity, while many low- and middle-income countries have further potential for reservoir development[19]. The United States, and other high-income countries, have transitioned from an era of reservoir expansion to an era of environmental protection and soft-path approaches[21]. Yet, in low- and middle income countries, many new reservoirs are still being planned or built, such as the Grand Ethiopian Renaissance Dam[22,23].

Despite clear benefits, dams remain controversial. The operation and construction of reservoirs require significant capital investments that do not always pay off[24]. Aside from financial risks, dams are often socially and politically contested due to their potentially negative impacts on environment and society[11,16,21,25]. As a result, proposals for new reservoirs often encounter resistance from the local population, facing displacement or ecological degradation in their communities.

Moreover, we know that the benefits of reservoirs are not equally distributed between upstream and downstream regions. They may likewise be counteracted by increases in evaporation, sedimentation, and unfavourable temporal and spatial redistribution of water resources[4,5]. As a result, while reservoirs can alleviate hydrological drought in certain areas, they can enhance it in others [26,27].

A prominent negative example is the drying of numerous lakes and wetlands around the world due to continuously increasing water depletion using irrigation systems, which are supplied by water from reservoirs. For example, Lake Urmia, in northwest Iran, was once the second largest saltwater lake on Earth. Over the past 40 years, its area has decreased by around 80%, with most of the change occurring from 2009[28]. Since 2000, 20 dams started operation in the lake's basin[29], diverting the lake's freshwater inflow for irrigation and farming purposes, leading to noticeable environmental degradation[30].

Besides stressed lakes, another important negative impact is the so-called closure of river basins[31,32] where no (or limited) usable water reaches the basin's outlet. Prominent examples are the Colorado, Indus, and Murray-Darling rivers. The main drivers behind basin closure are human activities aiming at augmenting, conserving, and reallocating the available water by investing in water infrastructure, such as reservoirs.

Long-term dynamics

While the negative impacts of reservoirs have been widely studied and are currently considered in water management and planning, we posit that there are long-term dynamics that should be considered when expanding reservoirs or designing water infrastructure: the *supply-demand cycle*[33] and the *reservoir effect*. The supply-demand cycle describes instances where increasing water supply enables higher water demand, quickly offsetting the initial benefits of reservoirs. The reservoir effect refers to cases where over-reliance on water infrastructure increases vulnerability, and therefore increases the potential damage from water shortages.

We argue that we currently lack datasets and analytical tools to quantify these two phenomena. As the two long-term dynamics can occur within the planning horizon of reservoirs (20-30 years), these missing tools challenge the evaluation of strategies to reduce the negative impacts of drought and water shortage. In the next paragraphs, we describe these long-term dynamics based on our hypothesis depicted in Figure 2, and discuss various examples. We then propose a research call to unravel and quantify the feedback mechanisms between social, technical and hydrological processes, which can produce these two phenomena in different contexts.

Supply-demand cycles

The *supply-demand cycle* refers to instances where increasing water supply enables agricultural, industrial or urban expansion resulting in increasing competition for water resources[33,34], thereby leading to a water demand higher than expected when considering socio-economic trends alone (Fig. 2, orange positive feedback loop). Consequently, the supply-demand cycle can quickly offset the initial benefits of reservoirs as an additional source of water supply.

The supply-demand cycle can be explained as a rebound effect, or Jevon's paradox[35], which is well-known in economics: as availability increases, consumption tends to increase. This rebound effect has been considered in water resources management and planning[36,37], but mainly with reference to irrigation efficiency. The orange loop of Figure 2 shows that, in the context of reservoirs and water shortage, the rebound effect can potentially produce self-reinforcing (positive) feedbacks and lock-in conditions. The occurrence of a new water shortage may be addressed by further expansion of reservoir storage to, again, increase water supply[29]. Hence, the supply-demand cycle can trigger the unintended effect of an accelerating spiral towards unsustainable exploitation of water resources and environmental degradation.

We see the supply-demand cycle at the global scale when comparing annual water demand to storage capacity of large water supply reservoirs[13]. Figure 3 shows that water storage capacity has grown faster than water demand in the 1960's (300% vs. 15%, respectively) and 1970's (130% vs. 25%). In more recent decades, however, demand has grown faster than storage capacity (e.g. 20% vs. 2%, respectively, in the 1990's), thereby offsetting the initial benefits of many reservoirs. As a result, drought occurrences can trigger more severe water shortages or, if groundwater extraction is used to cope with drought, lead to significant aquifer depletion[38,39].

The supply-demand cycle also exists at the local level. Here we show the water histories of three cities: Athens (Greece), Las Vegas (United States), and Melbourne (Australia). We focus on urban environments because the two long-term dynamics discussed here are more visible in cities. Furthermore, long time series of water demand are difficult to obtain for rural environments. Lastly, there is global concern about increasing urban water demand, which is expected to increase by 80% in 2050[40].

The history of Athens has been intertwined with severe water shortages[41]. Over the past 150 years, the city has undergone a profound transformation: Kallis[33] describes Athens in 1830, just after Greece's liberation, when thousands of Athenians returned home to find "nothing but piles of scattered ruins" and "people around water fountains waiting to fill their buckets, others pulling water from wells". The situation looks different in 2004: "four million people, no fountains or wells, but four large reservoirs and a complex system of canals supplying water to the city"[33]. The implementation of water infrastructure, from the Marathon dam to the Evinos dam (Fig. 4a), has continuously increased water supply. This process has not only met water needs, but has also enabled a growing population that, along with changing norms and habits[33], has led to higher water demand and pressure on the available resources.

Lake Mead Reservoir was constructed in 1936 to provide water for California, Arizona and Nevada. At the time, Las Vegas had sufficient groundwater to meet demands. Later on, the Las Vegas Valley Water District built the Southern Nevada Water System to withdraw and distribute water from Lake Mead with the Colorado River pipeline and the In-take no. 1 (Fig. 4b). Following a logic similar to the one depicted in Figure 1, the original intention of this infrastructure was to cope with increasing demand in Las Vegas caused by socio-economic trends, i.e. a growing population that was projected to expand up to 400 thousand people by the end of the century[44]. However, Las Vegas' population grew much faster than expected and by the year 2000 was four times bigger (~1.5 million). Our hypothesis (Fig. 2) is that this mismatch between projected and actual growth of water demand was partly related to the fact that increased water supply enabled urban growth, beyond growth expectations. This rapid growth continued into the early 2000's with Las Vegas being the fastest growing city in the US, in the fastest growing state since World War II[45]. In the 2000's, drought conditions threatened one of the in-take structures, which would have gone out of service if Lake Mead water levels had dropped further. As a result, in 2005 the Southern Nevada Water Authority board authorized the construction of a third and lower in-take structure, which was completed in 2015 (In-take no. 3, Fig. 4b).

Australia has experienced several droughts during the past 80 years, including three major events lasting more than five years[46]. In response to these multi-year droughts, Melbourne increased its storage capacity to prevent water shortages (Fig. 4c). The Thomson reservoir was added in 1984 with the intention to drought-proof Melbourne, increasing storage capacity by around 250%. However, the additional storage led to more competition for water, as well as population and industrial growth, and subsequently significant increases in water demand were seen[47]. In 1984, the total water use was around three times higher than that in the 1940's (Fig. 4c). Accordingly, the supply-demand cycle in Melbourne is an illustrative example of how increased reservoir capacity can lead to increasing water consumption.

Reservoir effects

A second type of long-term dynamic associated with the expansion of water supply is termed here as the reservoir effect, following White's levee effect[7,48]. This phenomenon is related to instances when the construction of reservoirs reduces the incentive for adaptive actions on other levels (e.g. individuals, community), thus increasing the negative impacts of water shortages during severe droughts. In Figure 2 (red loop), we hypothesize that extended periods of abundant water supply, supported by reservoirs, generate an increasing dependence on water infrastructure, which in turn increases vulnerability and economic damage when water shortages eventually occur (Fig. 2, red loop).

In Melbourne, for example, the addition of reservoirs prevented water shortages only during minor drought conditions[47]. The anthropogenic increase in human water use in Melbourne not only doubled the severity of the Millennium Drought (2001-2009) in terms of streamflows[46], but also made the region more vulnerable to extreme and prolonged drought conditions because of increased reliance on reservoirs. The Millennium Drought demonstrated that, as a result of increased dependence on water resources, Melbourne's economy, agriculture and environment were severely affected[47].

In Athens, the Mornos reservoir overflowed in 1985. This event created pride and political enthusiasm among the population, as Athens had -for the first time since becoming capital of the Greek state- more water available than needed[40]. As a result, in 1987, a new law declared water a "natural gift" and an "undeniable right" for every citizen[40]. The Mornos reservoir was considered sufficient for meeting water demands of areas not yet connected to the network. Two years later, however, when a severe drought occurred, the system was pushed to its operating limits and government responses were slow[41]. While inflows decreased in 1989 and 1990, withdrawals remained initially unchanged, and conservation measures were undertaken only when water availability became very critical[41].

As for the introductory example of the Maya civilisation, additional storage of water initially brought many benefits and allowed agricultural growth under normal and minor drought conditions. Yet, the increased dependence on water resources made the population more vulnerable to extreme drought conditions, and plausibly contributed to the collapse of the Maya civilisation[49].

The reservoir effect can also be explained as a safe development paradox[50]: increased levels of safety can paradoxically lead to increasing damage. While this paradox has been widely documented in flood risk[7,48,51], it remains largely unexplored in regard to drought and water shortage. This is a major research gap because the safe development paradox is potentially more dangerous in the context of drought. More specifically, the increase of potential flood damage caused by higher reliance on levees[7,48,51], or other structural protection measures, can be balanced by the corresponding reduction of the frequency of flooding[51]. Instead, the potential enhancement of drought damage due to increased reliance on reservoirs might not be counterweighed by a reduced frequency of shortages, if the supply-demand cycle quickly offsets the initial benefits of increased water supply.

Interdisciplinary research call

The two long-term dynamics described here, supply-demand cycle and reservoir effect, are caused by feedback mechanisms between human and natural systems, and by the interplay of technology and policy to manage hydrological variability. Although not explicitly put in these terms before, both phenomena have been discussed in different contexts[33,49,52,53]. Identifying the interactions between infrastructure and policy choices and emergent hydrological and social dynamics can inform more sustainable approaches.

However, this is challenging as the feedback mechanisms generating these long-term dynamics remain poorly quantified. It is still unclear how relevant these phenomena are across different contexts, i.e. how diverse combinations of hydrological, technical, and social factors play a role in accelerating or mitigating the underlying feedback mechanisms. For instance, using the local examples above, research questions that we are still unable to address are: To what extent was the increasing demand in Athens after the construction of the Mornos Dam planned? To what extent has expanding water infrastructure in Las Vegas enabled its fast urban growth? What would have been the impact of the Millennium Drought on Melbourne had the Thompson Reservoir not been built?

This lack of knowledge prevents an explicit account of internal feedbacks and long-term dynamics in reservoir management and planning. As a result, policies and measures based on current methods might have unintended effects: the supply-demand cycle can produce an acceleration towards peak water limits[54], while excessive reliance on water infrastructure (reservoir effect) can lead to damaging water shortages.

Thus, we call upon water managers, social scientists, policy makers, economists, ecologists and hydrologists to collaborate and develop datasets and analytical tools capturing the long-term dynamics produced by the interactions of physical, social and technical processes. To this end, we can draw upon new methods and concepts recently developed for the study of human-nature interactions in various interdisciplinary fields, e.g. social-ecological systems, sociohydrology and sustainability science[55-60].

More specifically, formulating and testing alternative hypotheses, such as the ones depicted in Figure 1 and 2, can guide the process of collecting useful data to explore the relative weight of internal and external factors in driving long-term dynamics. These hypotheses about feedback mechanisms and long-term dynamics can be used to build new models able to: i) quantify the way in which social, technical and hydrological factors interact and influence each other; and ii) capture the emergence of supply-demand cycles and reservoirs effects.

Locations that have faced consecutive water shortages and significant changes in water policies and infrastructure can be suitable study areas for exploring the causal mechanisms behind the supply-demand cycle and the reservoir effect. To unravel the chicken-and-egg dilemma about the causality of changes in water supply and demand, we also need to monitor behavioural changes during water shortages in both users (e.g. households, farmers) and decision makers (e.g. water authorities), and how such responses are in turn influenced by the reliance on water infrastructure. This requires a more systematic monitoring of vulnerability changes across decades, such as longitudinal studies, and motivates new data collections and aggregation efforts.

The hypothesis-driven research proposed here can help reveal what can, or cannot, be generalized, and develop new tools to project the long-term effects of reservoirs, and other types of water infrastructure, on the spatiotemporal (re)distribution of both water supply and demand.

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Author contributions

G.D.B. conceived the study and wrote the manuscript. N.W. developed the global analysis of reservoir storage analysis and water demand. A.A., L.K., S.R., T.I.E.V., M.G., P.R.v.O., K.B. and A.F.V.L. contributed data or insights, discussed the argument, and edited the manuscript.

Competing interests

The authors declare no competing financial interests.

Figures

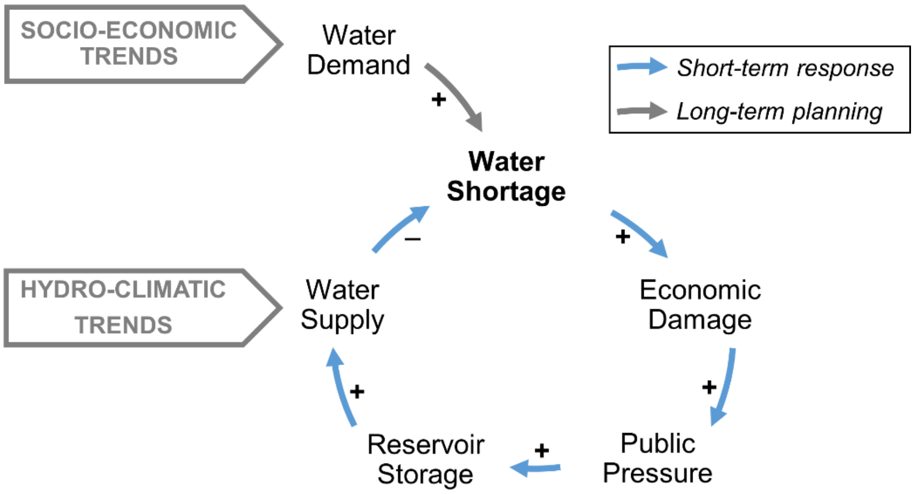

Figure 1 | Water supply to cope with water shortage. The causal loop diagram shows the positive (+) and negative (-) feedbacks between physical, technical and social processes. This diagram is based on traditional approaches in water management and long-term planning that emphasise the role of external drivers of change (big grey arrows): socio-economic trends influencing water demand, and hydro-climatic trends influencing water supply.

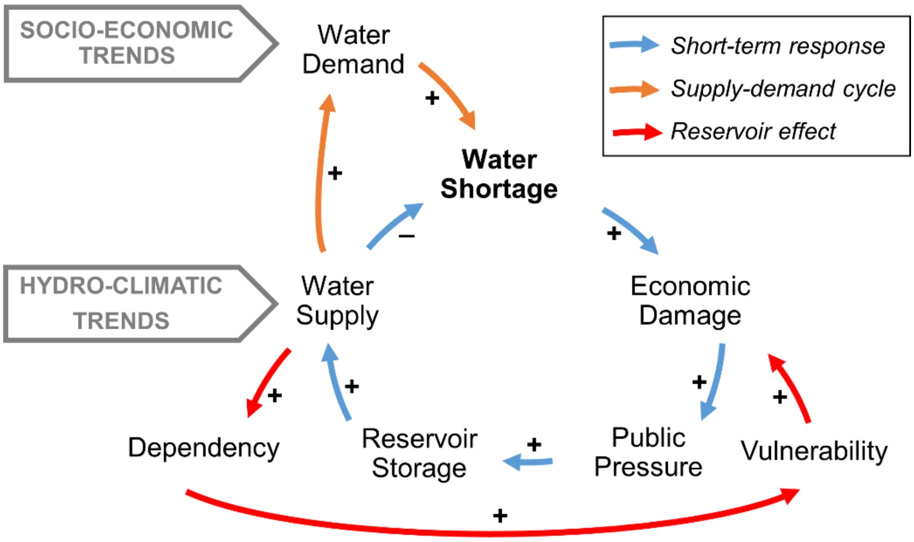

Figure 2│ Water supply can worsen water shortage. The causal loop diagram shows the positive (+) and negative (-) feedbacks between physical, technical and social processes. Our hypothesis emphasises the role of internal feedback mechanisms, and the potential emergence of long-term dynamics: *supply-demand cycle* (orange loop) and *reservoirs effect* (red loop).

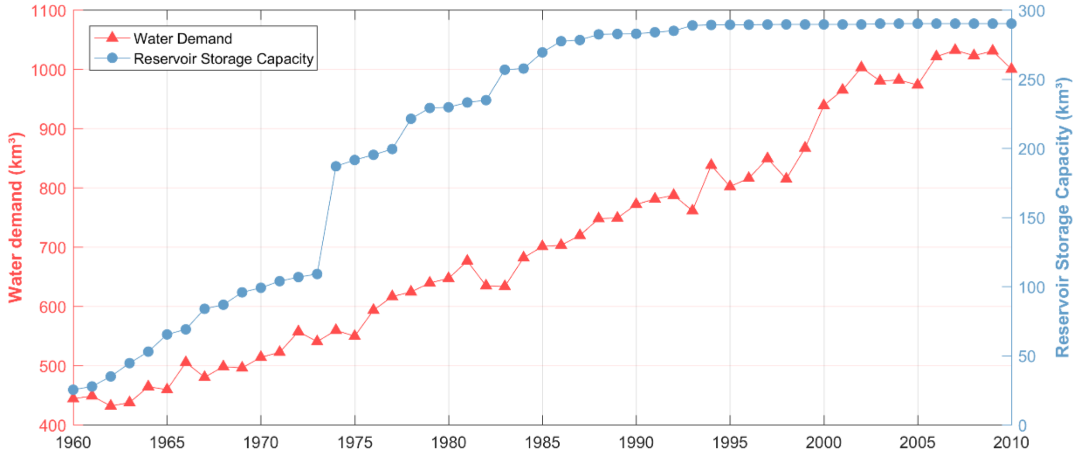

Figure 3│ Global reservoir storage capacity versus water demand. Data over the past five decades from World Bank statistics and GRanD database[12]. Storage capacity refers only to reservoirs that have water supply or irrigation as one of their main purposes in the GRanD database. Annual water demand[61] refers to areas downstream of these reservoirs as derived from the HydroSHEDS[62] draining network. We assume that the reservoir dependency is limited to 200km downstream of reservoirs.

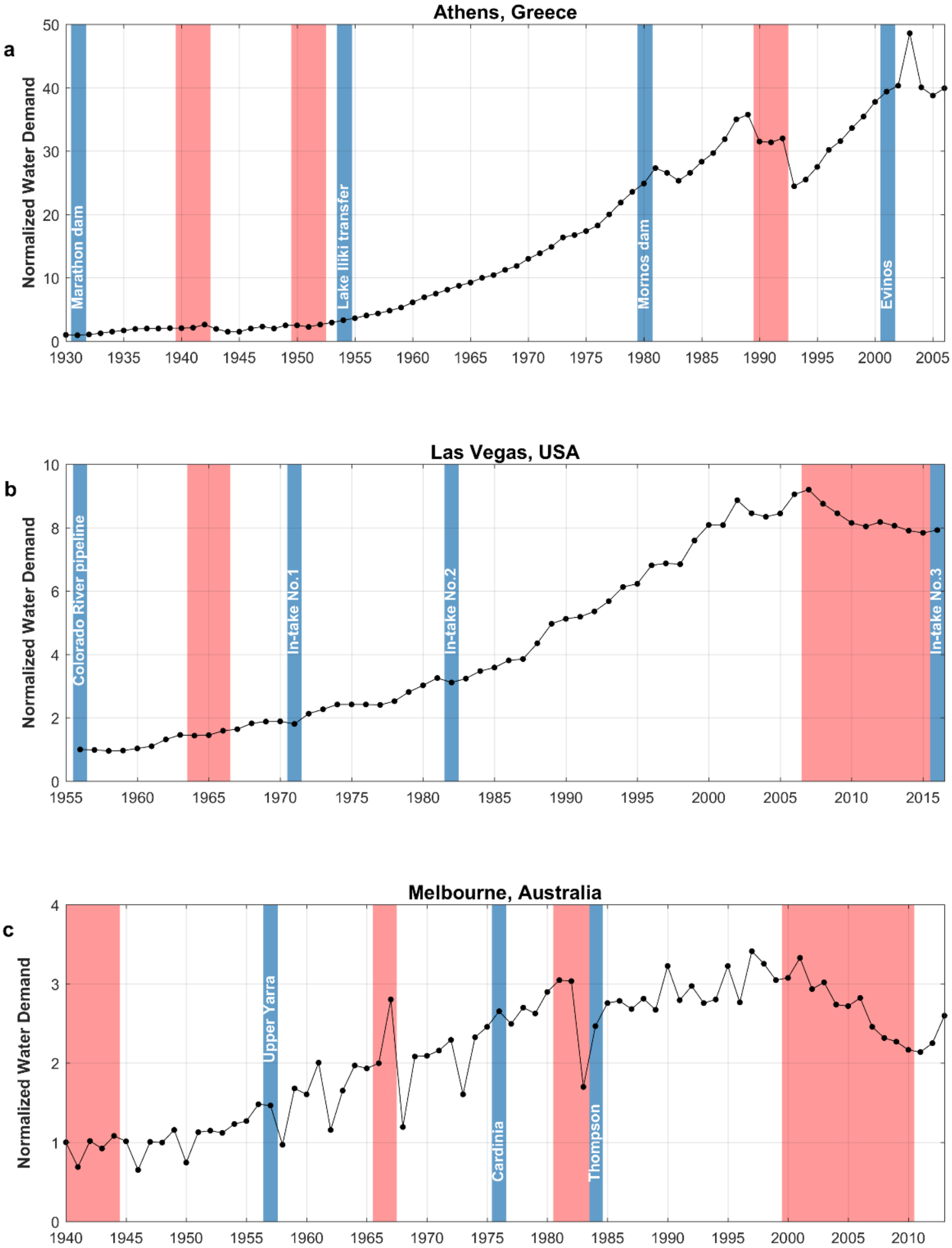

Figure 4│ Local examples of the supply-demand cycles over multiple decades: (a) Athens, (b) Las Vegas and (c) Melbourne. Time series of annual water demand normalized by its initial value (black line) and timing of the main measures that significantly increased water supply (blue). Drought periods (red) were derived from literature for Athens[33] and Melbourne[63], and from the periods in which the annual water levels in the Lake Mead were lower than 1100 feet and potentially affecting water supply to Las Vegas. Data sources: EYDAP, South Nevada Water Authority (SNWA), US Department of the Interior, and Melbourne Water.