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Household drinking water consumption: a qualitative system approach

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ABSTRACT

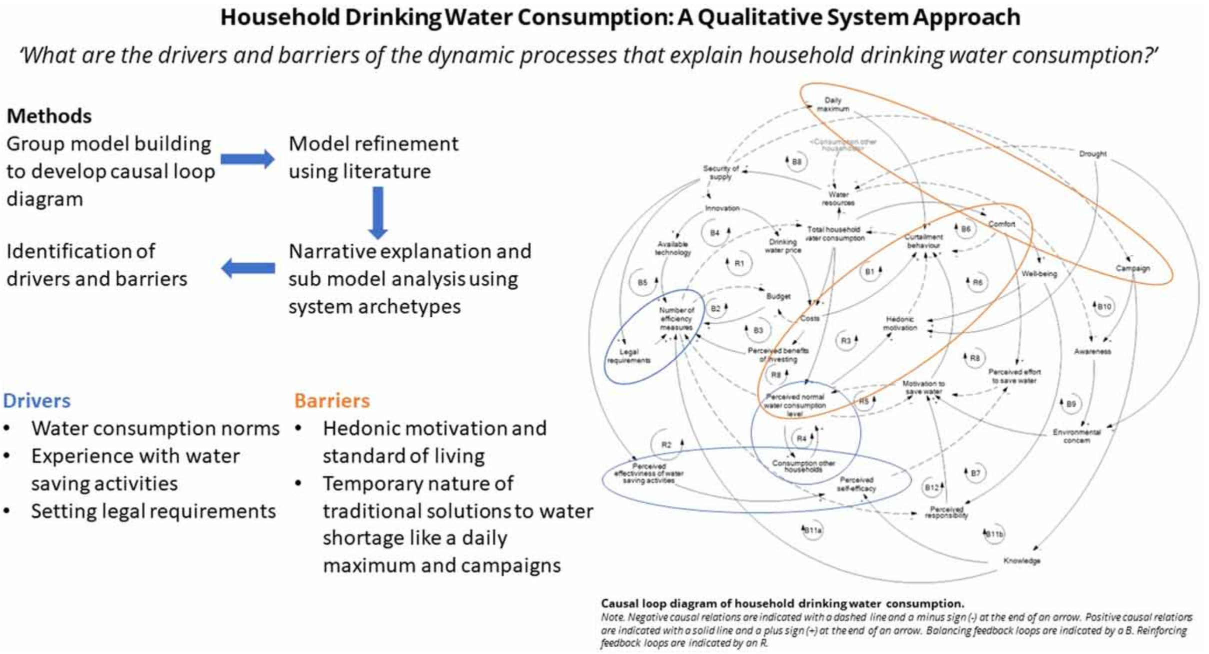
The Netherlands is known as a water-rich country with high-quality drinking water services. However, under the current conditions, it is expected that there will be insufficient drinking water supply by 2030. In this study, we developed a qualitative dynamic system to identify the drivers and barriers of the dynamic processes that explain household drinking water consumption. A causal loop diagram was constructed as a working theory on how household drinking water consumption could develop over time. System archetypes were used to explain the potential dynamic behavior of sub-models. Motivation to save water, hedonic motivation, security of supply and water price are the linking variables between the sub-models. Sub-model analysis reveals that hedonic motivation and drought response are the main barriers to reducing drinking water consumption. Social norms and water-saving experience are the drivers of reducing drinking water consumption by households. We discuss how smart meters and setting legal requirements can provide promising interventions with the potential to facilitate these drivers. We recommend future research to develop a simulation model to test the dynamic structure and to further investigate the impact of hedonic motivation as a barrier to saving drinking water.

Key words: Causal loop diagram, Drinking water, Feedback loops, Systems thinking, Water consumption

HIGHLIGHTS

- A qualitative system approach was used to develop a working theory of household drinking water consumption.
- The causal loop diagram consists of 13 balancing and eight reinforcing feedback loops.
- Hedonic motivation and drought responses are hypothesized as barriers to saving drinking water.
- Social norms and experience with water-saving practices are hypothesized as drivers of saving drinking water.

GRAPHICAL ABSTRACT



INTRODUCTION

The Netherlands is known as a water-rich country with high-quality drinking water services. However, under the current conditions, it is expected that there will be insufficient drinking water supply by 2030 (Van Leerdam *et al.* 2023), mainly because droughts are expected to become more prevalent in the future and the total population is projected to increase (Baggelaar *et al.* 2022; van der Brugge & de Winter 2024). More than two-thirds of the available drinking water is used by households (Geudens & Kramer 2022). Showering or bathing, washing and toilet flushing are the main uses of drinking water in Dutch households (Van Thiel 2017; Bakker *et al.* 2022). Drinking the water from the tap comprised only 1.6% of total daily drinking water consumption per person in 2021 (Bakker *et al.* 2022). Between 1995 and 2013, drinking water consumption steadily decreased from 137 to 118 liters per person per day (lpppd) (Van Thiel 2017; Geudens & Kramer 2022). However, drinking water consumption has increased to 128 lpppd in 2021 (Bakker *et al.* 2022). The Dutch government has set a goal to decrease the consumption to 100 lpppd by 2035, in order to remain within the limits of the drinking water supply (Ministry of Infrastructure & Water Management 2022). Yet, the prognoses are that lpppd will remain between 118 and 132 by 2035, with 127 being the most likely scenario (Baggelaar *et al.* 2022) (Figure 1).

There have been many theoretical studies on the determinants of household drinking water consumption. Most of these studies and reviews have used linear models as a theoretical framework for understanding this behavior (for an overview, see, among others, Lam 1999; Russell & Fielding 2010; Yuriev *et al.* 2020; Ehret *et al.* 2021; Shahangian *et al.* 2021; Ambaum *et al.* 2024). There are growing insights that drinking water consumption is subject to dynamic processes, and the many elements that influence drinking water consumption are best understood as a complex system (Masrahi *et al.* 2021; Perello-Moragues *et al.* 2021; Shahangian *et al.* 2023). While linear models do provide useful insights into which determinants influence drinking water consumption, they are not particularly well-suited when aiming to take complex dynamic interactions between determinants into account,

Fig. 1 | Average daily drinking water consumption per person, including projected developments. *Note*: Historic behavior and projections based on Baggelaar *et al*. (2022), desired consumption based on the Ministry of Infrastructure & Water Management (2022).

they often take only a small number of variables into account and consider these as independent determinants. Yet, the presence of rebound effects suggests a high interdependence, as seemingly unrelated processes affect each other (Beal *et al*. 2014; Truelove *et al*. 2014; Guzzo *et al*. 2024). Moreover, these determinants are often not static but dynamic and change over time. For example, feedback on water consumption is based on past consumption but influences future consumption (Karlin *et al*. 2015; Fréjus & Martini 2016; Otaki *et al*. 2017), creating a continuous loop of behavior. Linear models would consider a change in consumption at the end of the analysis, while a complex system perspective considers it part of a process where cause and effect continuously affect each other.

This paper provides a complex systems perspective on drinking water consumption of households. Such a perspective is aimed at identifying and understanding the interrelations of many elements that together produce dynamic system-level behavior (Meadows 2009). Complex systems thinking helps to better inform policies aiming at sustainable water management (Meadows 2009; Blair & Buytaert 2016). The main tool to map dynamic systems is the causal loop diagram (CLD) (Sterman 2000). In this paper, a CLD aids in developing a dynamic perspective on household drinking water consumption. The CLD should be considered a working theory on how the household drinking water consumption has developed over time (Sterman 2000). A CLD helps to identify barriers and drivers of the dynamic processes that result in drinking water consumption and, therefore, provides guidance in developing policies for decreasing it. To accomplish this goal, this paper answers the question 'What are the drivers and barriers of the dynamic processes that explain household drinking water consumption?'.

This novel perspective on human–water dynamics (Xu *et al*. 2018) could provide theoretical guidance on why interventions to reduce household drinking water consumption are often short-lived or have a modest effect

(Abrahamse *et al.* 2005; Ehret *et al.* 2021). A CLD helps to identify potential drivers of a system or reveal dynamics that lead to policy resistance (Ghaffarzadegan *et al.* 2010; de Gooyert *et al.* 2016), for example, by showing how those seemingly unrelated processes are, in actuality, connected. The CLD approach to explain a complex system allows (1) a broad system boundary so it could reveal many interdependencies in determinants, (2) have a high a degree of endogeneity which shows how a system drives its own behavior and find the sources of policy resistance and (3) allows to integrate the findings of many frameworks and theories (de Gooyert *et al.* 2024).

Systems thinking helps to identify root causes and could aid decision-makers in developing long-term solutions by analyzing CLDs (Mirchi *et al.* 2012). Hence, aside from its theoretical contribution, this paper could help policymakers develop long-term strategies for decreasing household drinking water consumption. In decision-making, people often rely on heuristics such as to wait and see the effects of their behavior. Yet, due to its complex dynamics, the potential effects can often be misjudged and interventions tend to be reactive rather than proactive (Moxnes 2023). Experiments have shown that comprehension of core feedback structures and basic system knowledge improves decision rules and performance (Gary & Wood 2017). For example, complex systems thinking helped Kotir *et al.* (2017) identify policy options for sustainable water resource management in the Volta River Basin. Also, in other dynamic environments, this perspective has helped the Dutch government to develop a response to the COVID-19 pandemic (Veldhuis *et al.* 2023) or in the energy sector, where Gürsan *et al.* (2024) identified drivers and barriers for the transition toward a climate-neutral city in the Netherlands.

In this study, we first explain the methods we used to answer the research question. In the results, we present the CLD, which visualizes and explains the dynamic processes causing household drinking water consumption. The discussion follows with an answer to the research question and the limitations of this study. The last section comprises the conclusion. Here, we discuss the implications of this study.

METHODS

This section explains the steps that were taken to develop the system and identify the drivers and barriers of household drinking water consumption dynamics. First, we elaborate on the CLD. Second, to develop the initial structure of the CLD, group model building (GMB) was used. GMB is a participatory method to engage stakeholders and experts in the development of a dynamic system. In GMB, the theoretical ideas of the experts are elicited and combined in a shared model that integrates the knowledge of the group (Vennix 1996). In this study, the input of eight practice and theory-oriented experts was used to lay the foundation of the system. Third, the model was refined using additional literature. A literature review was used to complement the GMB (Ambaum *et al.* 2024). Non-scientific reports analyzing the Dutch drinking water sector helped to build confidence in the causal links and system structure that was drawn in the GMB sessions. Fourth, the model was checked for its quality. Fifth, we explain how the model was analyzed using a narrative explanation and comparison with system archetypes to, ultimately, provide a qualitative dynamic system structure of household drinking water consumption.

Causal loop diagram

CLDs are the main tool to visualize feedback processes and draw dynamic hypotheses for the behavior of complex systems. Visualizing feedback processes can reveal how seemingly unrelated variables still affect each other through a web of interconnections (Vennix 1996; Sterman 2000). CLD's main purpose is to aid in making mental models tangible so they can be shared, discussed and improved (Black 2013; Turner & Goodman 2023). A CLD consists of various variables of a system that are connected through causal links. These connections can be negative (−) for a causal effect in the opposite direction, or positive (+) to indicate a change of the subsequent variable in the same direction (Uleman *et al*. 2024). By connecting different causal relations, feedback loops could be identified. These feedbacks are either balancing the system's behavior or reinforcing it. Balancing feedbacks have a self-limiting effect and drive a system back to their original state. Reinforcing feedbacks have a self-strengthening effect and push a system out of their original state (Sterman 2000; Uleman *et al*. 2021).

CLDs are qualitative tools and cannot be used to forecast or predict behavior. Instead, CLDs provide dynamic hypotheses that can be tested through complex simulation methods like system dynamics (Richardson 1986; Lane 2008; Crielaard *et al*. 2024). Still, they offer a useful way to describe a system, teaching system thinking requiring limited previous knowledge of complex systems (Richardson 1986; Turner & Goodman 2023) and help conceptually understand the structure of a complex system (Vugteveen *et al*. 2015). CLDs allow for broader system boundaries and higher endogeneity than simulation models (de Gooyert *et al*. 2024). This flexibility supports a deeper understanding of the system's complexity and interconnections.

Model-building process

In the summer of 2022, two GMB sessions for two different groups were organized. The purpose of those meetings was to develop a CLD of drinking water consumption and its feedback loops. The two groups each consisted of four people with practical and academic expertise on drinking water consumption. The practice-oriented experts were selected based on their knowledge of the Dutch drinking water sector, efficiency and curtailment behaviors and drinking water consumers. The practice-oriented experts were working for drinking water companies, the Dutch provincial authorities or had a business in drinking water saving technologies. The academic experts were selected based on their theoretical expertise in determinants of water-saving behaviors or pro-environmental behavior in general. The academic experts had their roots in behavioral, social and policy sciences in relation to the environment. The groups were mixed, so practice and academic expertise were balanced within and between the two groups.

Because the sessions were held online via Microsoft Teams, the groups were kept relatively small to ensure easier dialogue and active engagement. During the sessions, there was a facilitator and technological support. For the two sessions, GMB scripts were used to structure the meetings (Anderson & Richardson 1997). Those scripts were adjusted for the online environment as according to Wilkerson *et al*. (2020). For the first session, the aim was to build a preliminary CLD. With the aid of Mural (LUMA Institute n.d.), the session started with generating graphs over time in combination with 'Hopes and Fears' (Anderson *et al*. 2022) to get a sense of the perception of the problem by each of the participants. The other scripts used in the first session were 'Variable Elicitation' and 'Creating Causal Loop Diagram from Variable List' (Anderson *et al*. 2022). With these scripts, participants wrote down as many problem-related variables as they could. These were all listed, and subsequently, the participants proposed to add a particular variable to the CLD. Each variable that had consensus on its cause or effect was added to the model. GMB processes could be sensitive to group dynamics such as groupthink (Vennix 1996). The small group and strong online etiquette helped create a safe environment for discussions. The online environment also allowed for individual exercises, so there was room for participants to diverge and reflect on their own perspective on the model, before the facilitator aimed to converge these perspectives and reach consensus on the model's causal relations.

The modeling was done in Vensim (Ventana Systems n.d.). Because of the use of Microsoft Teams, participants were able to see the modeling process live through screen sharing. A preliminary model was used to start the process. This model consisted of three variables: the drinking water consumption was the sum of the number of water-efficient measures and the frequency and time of water-intensive activities. We recognized that these water behaviors might have different causes and effects (Russell & Fielding 2010; Ambaum *et al*. 2024); therefore, we proposed the preliminary model to the participants, which they thought was a good classification of water-saving practices.

Participants received a workbook with a summary of the sessions and questions to start with for the next sessions to clarify some variables. For example, participants were asked to reflect on variables that were proposed but had not reached consensus. The second session started with these reflections and a review of the model of the first session. Then, we continued to add variables from the list until a saturation point was achieved: the model could tell the story of the graphs over time. After the second session, participants received another workbook with the summary of the process and the final model, along with the opportunity to make some final suggestions. The models that were created by the two groups are found in the Supplementary material (Dutch only). The sessions were recorded to aid model refinement and the analyses.

Model refinement

After the four sessions, the two models were combined into one CLD. The causal links and feedback loops of the two CLDs were combined using an iterative coding process. The CLDs were assessed on similarities and differences. Causal links and feedback loops that were mentioned in only one of the groups were checked in the literature for their importance and impact on household drinking water consumption. To increase confidence in the model, each causal link has to be substantiated by high-quality literature evidence (Crielaard *et al.* 2024). All causal links and feedback loops that were drawn in the GMB sessions could be validated by literature or were logical arguments. For example, the causal relation between drinking water price and household costs is not explicitly tested for in the literature, but can be regarded as a logical argument. The studies must be either published by a peer-reviewed journal or reports from Dutch research institutes for the water sector, the Dutch government or the Dutch national association for drinking water companies: Vewin. To refine the model, we used various literature reviews of household drinking water consumption (Russell & Fielding 2010; Ehret *et al.* 2021; Ambaum *et al.* 2024) to clean chains of causal links that were drawn during the GMB sessions. For example, both groups mentioned costs as a factor, but did not include the factor of budget, while previous studies have identified this as a significant causal link. An overview of the individual causal links and the corresponding literature can be found in the Supplementary material.

Model quality

Turner & Goodman (2023) defined guidelines for reporting on qualitative non-simulated system dynamics models. Some of these are guidelines on how to report a CLD, like having clear names, polarity and feedback loop indications, as well as being visually consistent and readable. Other criteria require more reflection. We highlight the three most important criteria. First, the model should have a clear purpose. In this case, the modeling purpose is to identify drivers and barriers of the dynamic processes that explain household drinking water consumption. Second, there should be a link to the reference model. A reference model is the behavior that the system should be able to replicate or visualize (Vennix 1996; Sterman 2000). During the GMB session, the participants were asked to draw a reference mode of behavior that will be linked to the model in the analysis to provide a sense of time and development. For this analysis, we used historical data on water consumption to link with the CLD (Figure 1). Third, the model should have the appropriate boundaries. A system perspective assumes that everything is connected; hence, a model can become easily too large. Therefore, the CLD should have clear boundaries to keep the structure as minimalistic as possible. In this case, the focus was on the drinking water use of a single household.

Model analysis

The model analysis consists of three steps. First, the feedback loops and narrative that the model presents are compared with the development of drinking water consumption (Figure 1). Second, to explain the model in more detail, five sub-models were distinguished. These sub-models consist of feedback loops that provide an explanation for a specific part of the narrative of the model. Presenting a reduced number of variables and feedback loops with each sub-model decreases the overall complexity that must be considered at once, thereby enhancing the clarity and communicability of the results. For these five sub-models, the feedback loops are discussed using a narrative explanation. This is done by showing the consequences when one of the variables increases or decreases for the subsequent variables. Mind that these sub-models are still connected to each other. Third, the sub-models are compared with system archetypes. These archetypes are previously defined and validated feedback structures that produce common patterns of behavior (Senge 1990; Meadows 2009). Senge (1990) identified 10 different system archetypes and the behavior they produce typically over time. To match the archetype with the sub-model, the structure of feedback loops and the described system behavior was compared. This provides additional insight into the dynamics that influence drinking water consumption of households and should aid in understanding how structure drives behavior (Moallemi *et al*. 2022). The typical behavior for these archetypes is also documented with graphs over time (Moallemi *et al*. 2022). The Supplementary material contains a graph over time for each of the sub-models with their potential dynamic behavior based on these system archetypes.

RESULTS

In this section, we present the CLD. First, the CLD is discussed in general. Next, five sub-models are presented and their dynamics are discussed in more detail.

Drinking water consumption

A decrease in water consumption can be achieved via two routes: efficiency behavior and curtailment behavior (Lam 1999; Russell & Fielding 2010). Efficiency behavior is a one-time investment in water-saving equipment (Karlin *et al*. 2012). Curtailment behavior refers to repeated behaviors that do not require an investment and can be seen as 'everyday actions to save water' (Shahangian *et al*. 2021), for example, taking shorter showers. This considers both the frequency and duration of a water-consuming activity. These behaviors have different causes and effects, yet are very much interconnected through feedback loops.

The CLD has 13 balancing feedback loops and eight reinforcing feedback loops (Figure 2). Together, they form the dynamic system containing the mechanisms responsible for the development of household drinking water consumption. In this CLD, we distinguish five sub-models: the comfort sub-model, water consumption norms, maintaining motivation, drinking water costs and responses to drinking water shortage. These sub-models resemble different archetypical structures that are known to produce more specific system behavior. In the paragraphs below, we explain the dynamics of each sub-model. Keep in mind that these interconnected sub-models work together to form the drinking water consumption system. For example, the costs are indirectly influenced by responses to shortage and the norms about water consumption.

Aside from the central variables, efficiency measures and curtailment behavior, there are four other variables that can be considered linking pins between sub-models. First, motivation to save water is connected to the sub-models of maintaining motivation, water consumption norms and the traditional solutions. The motivation also directly influences curtailment behavior, which, in turn, is connected to the remaining sub-models. Hence, this can be considered a key variable in the system. Second, the connection between water resources and security of supply is an important dynamic. This macro-level dynamic is caused by the water consumption of the household of interest and other households, hence directly affected by the norms. Moreover, it sets in motion various interventions and determines whether motivation to save water is maintained. Third, hedonic motivation is a variable that is influenced by both the comfort sub-model, the norms and by the only exogenous factor in the model: drought. Hedonic motivation is a household's pursuit to improve their mood or pleasure (Lindenberg & Steg

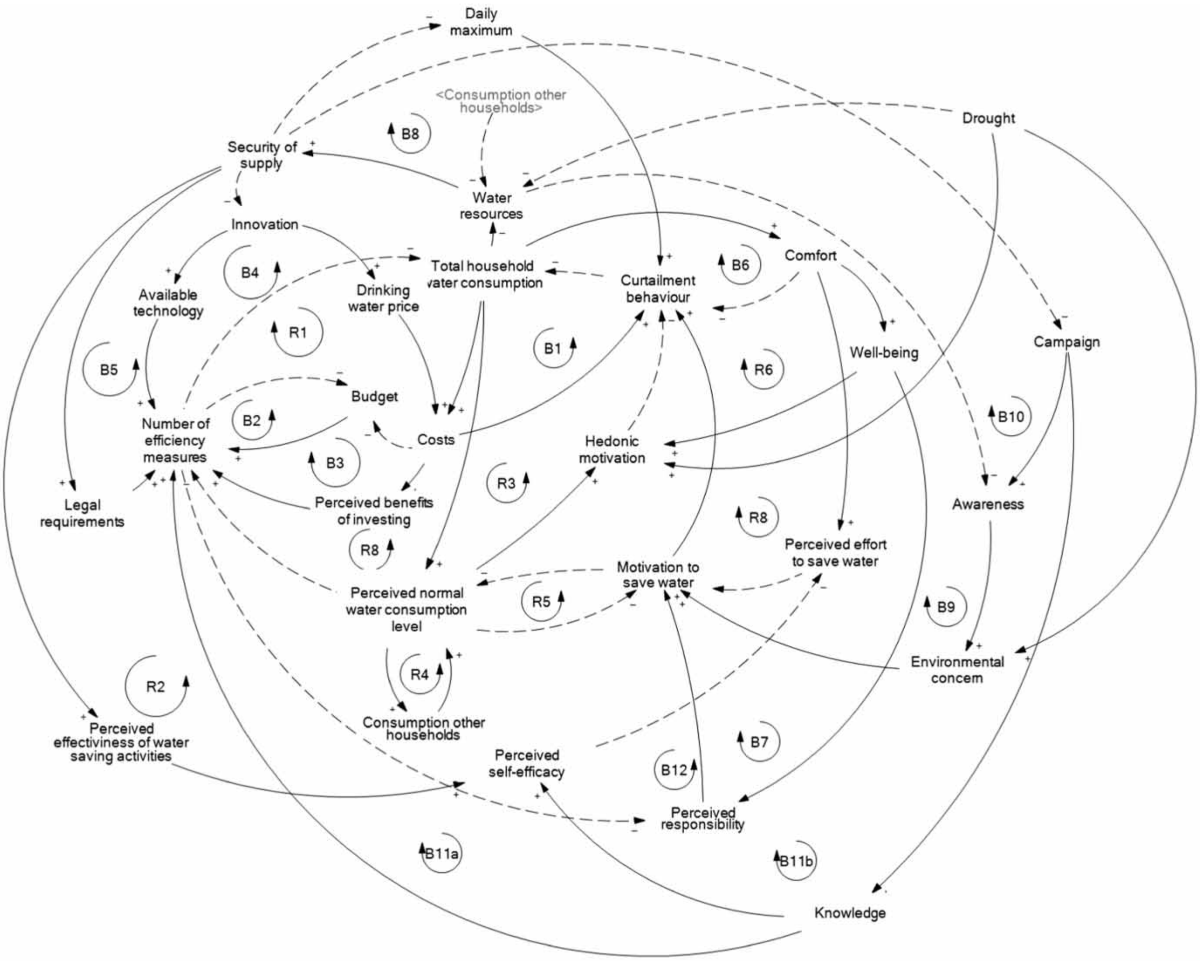


Fig. 2 | Dynamic system of household drinking water consumption. *Note*: Negative causal relations are indicated with a dashed line and a minus sign (−) at the end of an arrow. Positive causal relations are indicated with a solid line and a plus sign (+) at the end of an arrow. Balancing feedback loops are indicated by a B. Reinforcing feedback loops are indicated by an R.

2007). The fourth linking variable is the drinking water price. It connects the price sub-model with the developments in the macro environment of the household. While quantitative models are better equipped to evaluate the impact of these variables, their position in the system already indicates that they can have a substantial impact on the system's behavior.

Daily water consumption driven by hedonic motivation

This sub-model (Figure 3) explains that household drinking water consumption has goal-seeking dynamic (Sterman 2000). Curtailment behavior is driven by hedonic motivation and the current level of comfort a household has. Hedonic motivation is the desire of households to 'feel better right now' (Lindenberg & Steg 2007). The level of comfort a household has indicates the extent to which they feel good right now. If a household does not feel as comfortable right now, it decreases its curtailment behavior, for example, taking a shower. Balancing loop

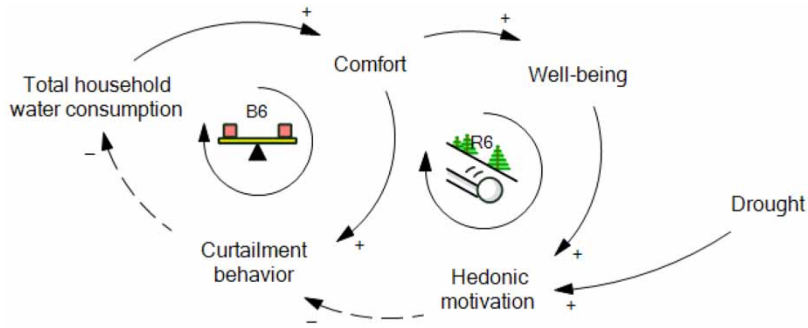


Fig. 3 | Comfort sub-model. *Note*: Negative causal relations are indicated with a dashed line and a minus sign (−) at the end of an arrow. Positive causal relations are indicated with a solid line and a plus sign (+) at the end of an arrow. Balancing feedback loops are indicated by a B and a scale. Reinforcing loops are indicated by an R and a snowball.

B6 shows a household's routine. Household comfort reaches a certain threshold as a result of drinking water consumption (Fujimi *et al.* 2016; Dean *et al.* 2021; Sanguinetti *et al.* 2022). The household reduces its consumption until the comfort level is too low for their desired comfort and they start consuming drinking water again (Karlin *et al.* 2012; Harding & Hsiaw 2014; Fujimi *et al.* 2016; Köhler 2017; Tilov *et al.* 2020; Sanguinetti *et al.* 2022). This is a daily dynamic, as households every day can adjust their water consumption habits. However, from day to day, these dynamics remain at a relatively stable level, as explained by the balancing feedback loop. Yet, as households become accustomed to a particular level of well-being, they will increase their hedonic motivation in the long term (Köhler 2017; Seebauer 2018; Tilov *et al.* 2020). In addition, droughts can temporarily increase the hedonic motivation as well (Beal *et al.* 2014; Ebbs *et al.* 2018; Cominola *et al.* 2023), for example, to prevent the lawn from turning brown (Dean *et al.* 2021) or to take a refreshing shower.

This dynamic resembles the archetype fixes that fail (Meadows 2009). This dynamic structure explains how a short-term fix can have counterintuitive side effects on the long term. In this case, the household routine (B6) shows the short-term solution for not ever increasing the total household water consumption. Yet, in the long term, the comfort levels create the expectations of living standards (R6) which they aim to maintain or even increase. It provides a possible explanation of why the frequency and duration of showering have steadily increased over the last few decades. Accustomed levels of comfort can lead to resistance to decreasing consumption levels (van Raaij & Verhallen 1983; Tilov *et al.* 2020).

Water consumption norms are pushed in one direction

The perceived normal level of water consumption is what a household considers an appropriate level of water consumption. Figure 4 shows that this variable is part of four reinforcing feedback loops. If people perceive low water consumption as normal, they are more likely to invest in efficiency measures (R8) or decrease their hedonic motivation (R3) to match their household water consumption to their water consumption norm (Cialdini & Jacobson 2021). In turn, their previous consumption influences what they perceive as normal (Geelen *et al.* 2012; Seebauer 2018). This is also consistent with the value–identity–personal norm model: the idea that pro-environmental behavior depends on one's identity, which is partly created by past behavior (van Valkengoed *et al.* 2022). Water consumption is also shaped by social norms, as indicated by R4. The consumption of other households influences what a particular household perceives as an appropriate level of water consumption (Bernedo *et al.* 2014; Otaki *et al.* 2017; Cialdini & Jacobson 2021). They themselves influence other households too, creating a feedback loop in which they confirm each other's norm. Reinforcing feedback loop R5 is a

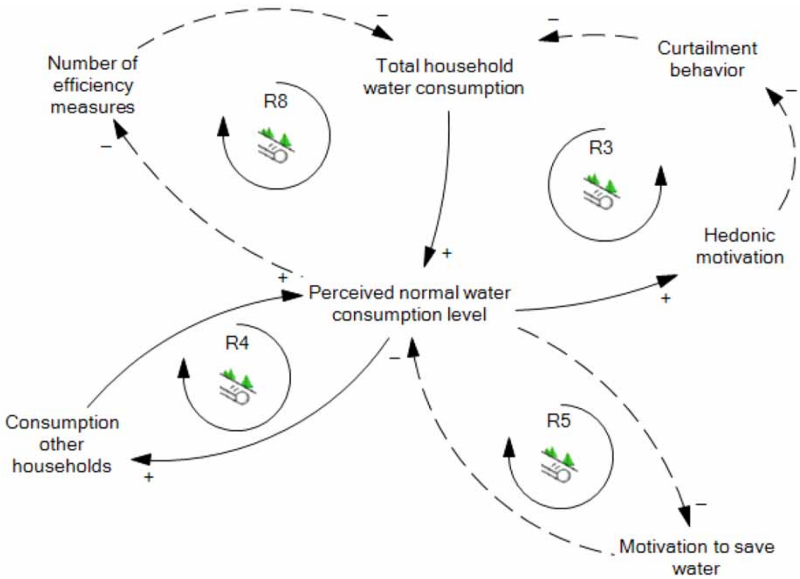


Fig. 4 | Water consumption norm sub-model. *Note*: Negative causal relations are indicated with a dashed line and a minus sign (−) at the end of an arrow. Positive causal relations are indicated with a solid line and a plus sign (+) at the end of an arrow. Reinforcing feedback loops are indicated by an R and a snowball.

representation of the personal norm, a person's internal standards to engage in target behavior (Schultz *et al.* 2014). If a household is motivated to save water, it will adjust its norm on drinking water (Lam 1999), and if it has lowered its norm of drinking water, it will become more motivated to save water and achieve that norm (Cialdini & Jacobson 2021). Also, the other way around, if the household considers high drinking water consumption normal, it is less likely to be motivated to save drinking water.

These four reinforcing feedback loops indicate that if the perceived normal water consumption level of a household decreases or increases, their norm will keep developing in that direction. This resembles the escalation archetype (Meadows 2009). This common system structure is an explanation for exponential growth or decay (Mirchi *et al.* 2012; Moallemi *et al.* 2022). It explains why it is difficult to stop a trend in household water consumption. These feedback loops are connected to many other feedback loops. Therefore, an increased perceived normal water consumption level can be considered an important barrier to decreasing household water consumption. If the norm can be decreased, it can also be one of the main drivers of further consumption reduction.

Maintaining motivation to save water is a balancing act

The sub-model for motivation to save water (Figure 5) consists of three balancing and two reinforcing feedback loops. The reinforcing feedback loops are concerned with the dynamics between motivation and perceived effort to save water (Dreijerink *et al.* 2022), as indicated by R7 and R2. Households experiencing high levels of comfort perceive it as much effort to reduce their consumption as it threatens their lifestyle (Köhler 2017). Hence, perceived effort can be a barrier to motivation to save drinking water. If the household consumption is already low, they perceive saving water as more achievable (Harding & Hsiaw 2014). R2 explains that saving water provides motivation to continue or save even more drinking water (Abrahamse & Steg 2013; Barth *et al.* 2021). If one is aware that there is sufficient water available and there is no threat to the security of supply, it helps to

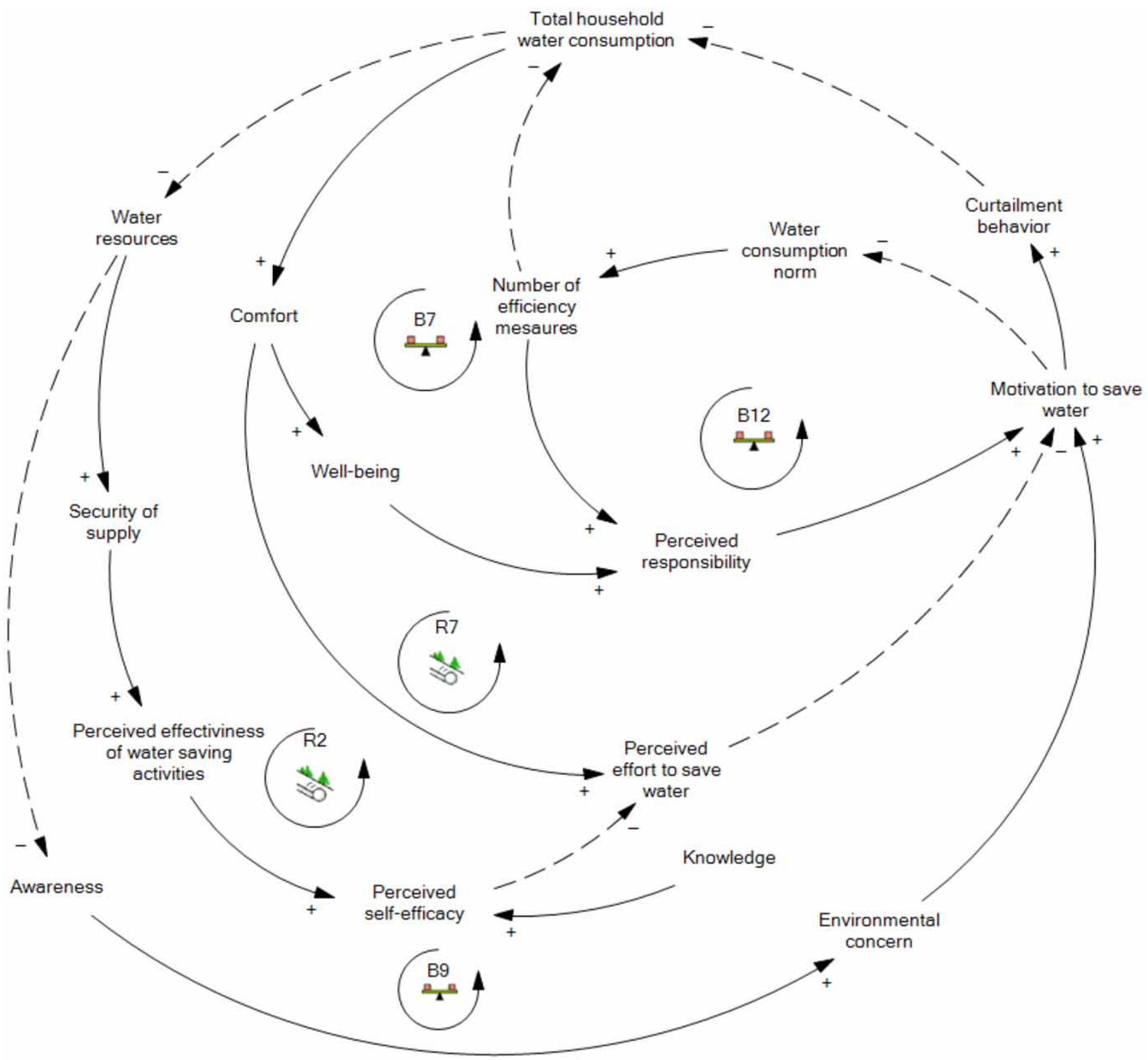


Fig. 5 | Maintaining motivation sub-model. *Note*: Negative causal relations are indicated with a dashed line and a minus sign (−) at the end of an arrow. Positive causal relations are indicated with a solid line and a plus sign (+) at the end of an arrow. Balancing feedback loops are indicated by a B and a scale. Reinforcing feedback loops are indicated by an R and a snowball.

strengthen the perception that one can make a difference. This idea of self-efficacy is a known motivator to behave pro-environmentally (Dreijerink *et al.* 2022). Hence, once a household starts saving water, they are likely to maintain motivation to save water and reduce household water consumption following these dynamics.

These processes are balanced by three feedback loops. Feedback loop B9 shows how environmental awareness influences the motivation to save drinking water. The central dynamic here is that if water resources are up to standards, there is little awareness of potential water shortage (Russell & Fielding 2010; Sun *et al.* 2019), and hence, households become less motivated to save water (van Valkengoed *et al.* 2022) (B9). In addition, households that experience high levels of well-being often feel more responsible for contributing to a more sustainable environment (Truelove *et al.* 2014) (B7). Therefore, they are more motivated to save drinking water. Yet, if they do save drinking water and experience less comfort, they might perceive a reduction in well-being and hence feel less responsible. If there is a lack of responsibility, households are less inclined to be motivated to save drinking water (van Valkengoed *et al.* 2022). Lastly, feedback loop B12 explains the rebound effect (Truelove *et al.* 2014; Seebauer 2018). If within a household few efficiency measures are implemented, they feel more responsible for the overconsumption of water in society. Or if the household has already invested in many efficiency measures and thus saved drinking water, they will be more inclined to refrain from further drinking water saving measures. It must be mentioned, however, that households differ and that their sensitivity to these motivators might also differ (Brouwer *et al.* 2019a; Ambaum *et al.* 2024).

The dynamic structure of the motivation sub-model can be viewed as an elaborated version of eroding goals (Senge 1990) (also known as drift to low performance (Meadows 2009) and eroding ambitions (Moallemi *et al.* 2022)). This archetype explains why growth in a particular direction cannot be continued forever. For example, if the motivation to save water is increased initially, after a while it will decrease due to the effect of awareness (R2). The balancing feedback loops could put a stop to that development due to reduced perceived responsibility (B7; B12) or due to a lack of perceived environmental urgency (B9). These dynamics could, for instance, be the reason why several experimental studies did not find maintained effects of their intervention (i.e. Fielding *et al.* 2013; Brouwer 2022) or why it is difficult to maintain behavior in response to droughts.

Even though price inelastic, costs do play a role

Drinking water consumption is often considered to be price inelastic (Ghavidelfar *et al.* 2015; Grafton *et al.* 2023). Yet, costs dynamics can still be used to explain drinking water consumption (Figure 6). Balancing feedback B1 shows that people will still adjust their behavior according to the costs of water. While the causal effect might be weakened due to the price inelasticity (Ebbs *et al.* 2018), the increased costs would reduce the consumption to some extent (Biesiot & Noorman 1999; Nguyen *et al.* 2016). If the costs are low, households are less inclined to perform curtailment behavior. Reduced costs can also further reduce drinking water consumption. Reinforcing

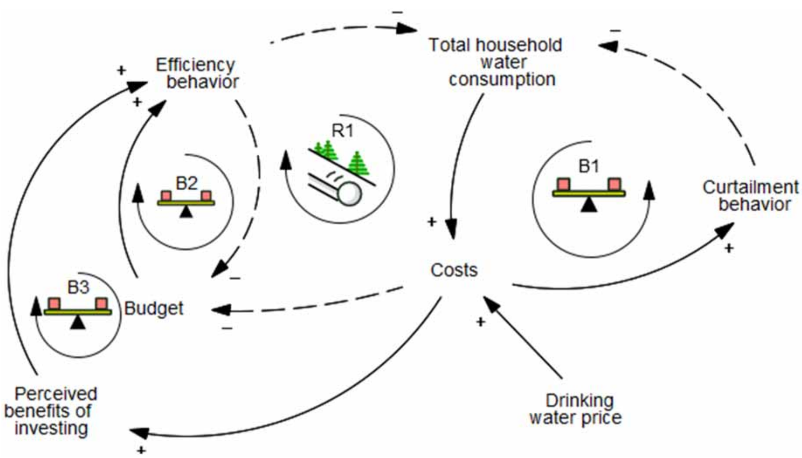


Fig. 6 | Price dynamics sub-model. Note. Negative causal relations are indicated with a dashed line and a minus sign (−) at the end of an arrow. Positive causal relations are indicated with a solid line and a plus sign (+) at the end of an arrow. Balancing feedback loops are indicated by a B and a scale. Reinforcing feedback loops are indicated by an R and a snowball.

loop R1 explains that if a household takes an efficiency measure, over time their costs decrease and subsequently their budget increases due to the reduced overall water consumption they have (Cochran & Cotton 1985; Biesiot & Noorman 1999; Adua *et al*. 2019; Adha *et al*. 2021). If all else is equal, this household would have a greater budget to make a new investment, reducing their water consumption costs, which allows them to make new investments. This is balanced by two feedback loops. B2 indicates that an investment in efficiency measures immediately reduces the budget. This limits the number of investments a household can make. B3 explains the mechanism by which a household makes a rational decision about the investment. If the costs of drinking water are high, then investing in cost-reducing measures results in financial benefits over time, hence the household is more likely to make the investment (Shahangian *et al*. 2022). This ultimately reduces the costs, making a new investment less attractive. Hence, this balances the number of efficiency measures.

The costs dynamics in household water consumption resemble the archetype of downplayed problems (Senge 1990; Moallemi *et al*. 2022). This archetype is characterized by conflicting goals and their effects. For example, there could be the goal of increasing efficiency measures and increasing curtailment behavior, which are both affected by costs, both with different polarities. Hence, a decrease in costs can both stimulate efficiency behavior but decrease curtailment behavior. Depending on the relative effects of both types of behavior, the state of the other can be masked for some time. Potentially due to technologies becoming more efficient over the years, there is less incentive to increase curtailment behavior, especially since the technological improvements could compensate for the decrease in curtailment behavior. Moreover, budget limits the reinforcing effects of investing in efficiency measures.

Traditional responses to water shortage are temporal in nature

The last sub-model (Figure 7) applies to the interventions that are more traditional responses to insecurity of supply: campaigns, daily maximum, legal requirements and innovations. If water resources go below a certain level due to too much consumption by households or droughts, the security of supply decreases. The technological solution (B4) is that drinking water companies or other businesses respond by investing in innovation, which could result in new technologies that households can use to become more water efficient (Adua *et al*. 2019). Increasing efficiency measures can also be enforced (B5) by authorities, for instance, through making the use of grey water mandatory for new construction projects (Van Leerdam *et al*. 2023). Other common responses to a decreased security of supply are by educating on technology (B11b), water-saving practices (B11a) and raising awareness for the environment (B10). This can be done via various sorts of campaigns or other types of information provision (Sun *et al*. 2019; Brouwer *et al*. 2020a). These campaigns increase the knowledge of households on how to save water and what the effects of their (over)consumption are (Thompson & Stoutemyer 1991; Brouwer *et al*. 2020a) and how to make their homes more water efficient (Harding & Hsiaw 2014; Ebbs *et al*. 2018; Ehret *et al*. 2021). This increased knowledge helps to increase self-efficacy (van Valkengoed *et al*. 2022), which in turn decreases the perceived effort of reducing drinking water consumption (Dreijerink *et al*. 2022). If security of supply is immediately threatened, a daily maximum allowed consumption is another instrument the authorities have (van Leerdam 2019). A daily maximum could be implemented to restrict and reduce high-frequency behavior (van Leerdam 2019; Koop *et al*. 2023). The effect of this legal instrument depends on the compliance of households (Howlett *et al*. 2009). Like all the aforementioned interventions, the daily maximum is a temporal measure. If the measures have an effect, their intensity could be alleviated once the security of supply is restored. Feedback loops B4 and B5 could have after effects due to path dependencies and delays. Yet, for the other dynamics, their effects could be balanced out quickly after the security of supply has been restored.

The archetype that this sub-model resembles is the band-aid solutions or shifting the burden (Meadows 2009; Moallemi *et al*. 2022). In this dynamic structure, short-term driven solutions lead to only moderate progress that

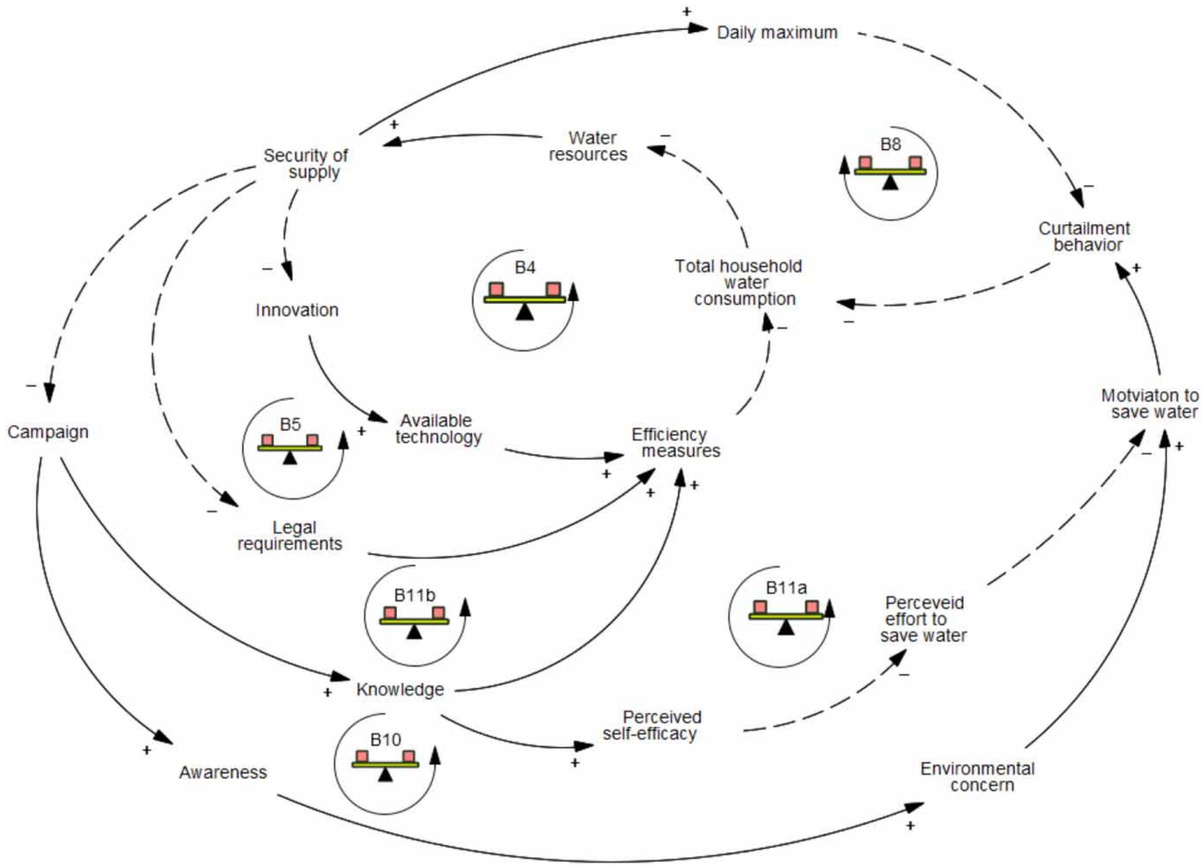


Fig. 7 | Response to the shortage sub-model. *Note*: Negative causal relations are indicated with a dashed line and a minus sign (−) at the end of an arrow. Positive causal relations are indicated with a solid line and a plus sign (+) at the end of an arrow. Balancing feedback loops are indicated by a B and a scale. Reinforcing feedback loops are indicated by an R and a snowball.

might dissuade policymakers from implementing more transformative interventions (Moallemi *et al.* 2022). The interventions in this model are all endogenous processes and part of balancing feedback loops. Hence, if they are effective, their effects are ultimately diminished because of their own processes. Therefore, sustainable drinking water consumption might not be able to rely solely on these interventions.

DISCUSSION

Considering the historic development of average drinking water consumption per capita (Figure 1), it is likely that the last 30 years balancing loops have been the dominant feedback loops in this system. Even though the dominance of the specific feedback loops cannot be assessed in this qualitative analysis, the many balancing feedback loops indicate a tendency toward its original state. Average daily drinking water consumption per person has steadily decreased from 1995 until 2016, yet it has always remained above the desired 100 L per person. This indicates that balancing loops have prevented reinforcing effects from causing a significant decrease in drinking water consumption. Plausible explanations are the technological innovations during that time span, which became more accessible for households. For example, water-reducing showerheads might have compensated for the increase in shower activity in the same time period (Van Thiel 2017). Reinforcing feedback loops could provide an explanation for more recent trends. The increase in water consumption from 2016 and 2021 indicates exponential growth caused by reinforcing feedback loops in the undesired direction. A plausible explanation is that the drought of 2018 caused hedonic motivation to increase, which increased the water consumption norm through reinforcing loop R3 which might have initiated a trend toward increasing water consumption.

Barriers and drivers of sustainable drinking water consumption

The CLD reveals several mechanisms that can be considered drivers or barriers for sustainable drinking water consumption. Sustainable consumption happens when households can satisfy their hedonic motivation, but do not jeopardize the security of supply. Therefore, hedonic motivation is the first of two barriers to achieving sustainable drinking water consumption. As pointed out in the previous section, hedonic motivation is a key variable in the system. Yet, hedonic motivation in the Netherlands is high due to a high standard of living. People are biased to value their own interests, like maintaining comfort, over collective interests (van Vugt *et al.* 2014), hence an increase in curtailment behavior becomes unlikely. For example, the frequency of showering has increased between 2016 and 2021 (Van Thiel 2017; Bakker *et al.* 2022) despite suggestions from drinking water companies to decrease the number of showers to relieve pressure from drinking water resources (Vitens 2019). In addition, a survey in the Netherlands found that more than half of the people were not willing to sacrifice comfort to reduce drinking water consumption (Brouwer *et al.* 2019b). Motivations like these accentuate that decreased curtailment behavior is likely to increase the amount of drinking water consumption that is perceived as normal behavior.

The second barrier is the temporary nature of traditional solutions to water shortage. The policies that are enacted to alleviate pressure on the drinking water supply are reactive and temporary, as indicated by the balancing feedback loops. Policies like a daily maximum or campaigns quickly change the system behavior, yet have a short-lasting impact. These policy options are the main tools drinking water companies and government bodies have to influence consumption (van Leerdam 2019). The recently adopted National Plan for Reducing Drinking Water still emphasizes campaigns as the main strategy to influence drinking water consumption of households (Ministry of Infrastructure & Water Management 2024), but their effectiveness is often only temporary (Brouwer *et al.* 2020b; Koop *et al.* 2023). These band-aid solutions shift the attention away from long-term solutions. As drinking water security has been vulnerable since 2018, the issue has been on the political agenda continuously. As a consequence, there has been increased attention for long-term solutions like adjusting construction laws to oblige the adoption of water-efficient technologies (Ministry of Infrastructure & Water Management 2021; Van Leerdam *et al.* 2023). Efficiency measures are less dependent on the volatility of human behavior and can therefore contribute to a more sustainable reduction of household drinking water consumption.

One of the main drivers with the biggest potential to decrease drinking water consumption is to decrease the water consumption norm. Decreasing the norm can initiate various reinforcing loops to keep the water consumption at a sustainable level. It has both an influence on efficiency behavior and curtailment behavior, and can keep the motivation to save drinking water at a high level. Currently, the descriptive norm is still above the injunctive norm (visualized in Figure 1). The CLD does not detail how the perception of normal drinking water consumption changes, but it does show which dynamics influence the norm. Getting experience with and knowledge of saving drinking water are connected to decreasing the norm through feedback loops R2 and B11b and should therefore be considered the second driver. Experiencing the effect of your efforts and increasing your knowledge helps to increase the perceived self-efficacy, which can stimulate you to save water. Third, setting legal requirements for installing efficiency measures is a driver for saving drinking water, as efficiency measures have a lasting effect on drinking water consumption.

A notable difference between the drivers and barriers is that the barriers are short-term processes, while the drivers are long-term processes. The band-aid solutions are barriers because of their short-term nature and the comfort-desire initiates high-frequency habitual behavior. Yet, establishing norms or noticing the effect of your water-saving efforts takes time. Smart meters are a promising intervention that have the potential to facilitate these drivers and reduce the duration of the connected feedback loops (Otaki *et al.* 2020; Cominola *et al.* 2021; Koop *et al.* 2021; Ambaum *et al.* 2024). They can provide a goal, show consumption levels and visualizations of the impact of their consumption (Asensio & Delmas 2016; Otaki *et al.* 2020; Vivek *et al.* 2021), which could decrease the time it takes to perceive the effectiveness of drinking water saving activities. These technologies also could use social comparison and other social-norm-based mechanisms to influence behavior (Bernedo *et al.* 2014; Otaki *et al.* 2017). This would increase the ability and speed of households to influence each other's consumption level. Combined with the other water-reducing influences, smart meters could help maintain low water consumption levels (Cominola *et al.* 2021; Koop *et al.* 2021; Ambaum *et al.* 2024). Future research could help identify how smart meters could be used most effectively (Otaki *et al.* 2024).

Limitations

This study falls into the grounded theory approach of systematic studies (de Gooyert 2018). Hence, it provides a working theory that provides explanation and guidance for policy development, but it remains a theory (Sterman 2000). To determine which interventions are most effective, this CLD should be transformed into a simulation model (Richardson 1986; Crielaard *et al.* 2024). This is the first shortcoming of this study and of CLDs in general. A CLD is ideal to develop a hypothesis that captures system dynamics, but cannot test these hypotheses themselves. Crielaard *et al.* (2024) can be used as a guiding document on how to build a simulation model from a CLD.

A second shortcoming is that this CLD is a generic model for an average household based on the Dutch drinking water context. This has three implications. First, the base levels of particular variables like knowledge, budget or well-being could differ, providing a different outcome if simulated. These household characteristics are important for their initial drinking water consumption (Ambaum *et al.* 2024). Second, different types of households could differ with respect to the strength of particular causal relations. For example, Perello-Moragues *et al.* (2021) describe how some households are more receptive to curtailment behavior and some more to efficiency measures. Brouwer *et al.* (2019a) segment drinking water consumers based on their interests and concerns. They state that this is important in order to influence drinking water consumers. Moreover, households with different demographic characteristics might also be more or less sensitive to particular dynamics. For example, studies have shown that households with children are less susceptible to energy-saving interventions as they are less flexible in changing their lifestyle (Fréjus & Martini 2016; Wang *et al.* 2020). It could also be the case for drinking water consumption that households with children perceive increased levels of effort to change their consumption. Third, this model is based on the Dutch drinking water context and research conducted in countries with a similar sociocultural context. Because this model is generic, it is expected that the dynamics also largely apply to households from other contexts. However, some dynamics might be different. For example, a CLD by Kotir *et al.* (2017) for water management in West Africa considers access to education as an important dynamic, while in the sociocultural context of this study, this access is taken for granted.

Another, related, shortcoming of this study is that some dynamics still have black box mechanisms. For example, it is known and tested that motivation to save water and water consumption norms influence each other (Lam 1999); however, one could still wonder how this happens. While such exploration could be added to the CLD, it would not contribute to the overall implications and conclusions. It is important to keep a model as simple as possible and within the system boundaries (Turner & Goodman 2023). From a system perspective, everything could be connected to each other, yet modeling everything defines the purpose of the study, nor would it be insightful. It might be possible that some dynamics are not included in this model, for example, because these dynamics were not mentioned by the experts, but are, in actuality, important. Future research could expand the model or focus on a part of the model and make a more specific model. Future research could also focus on building a simulation model based on this CLD. This would allow for testing the hypotheses. Future studies could choose whether to specify this model for a region, household type or keep the model generic.

CONCLUSION

The CLD and the identified barriers and drivers of household drinking water consumption have both theoretical and practical implications. First, the CLD provides hypotheses for the development of household drinking water consumption. The sub-models and the archetypical system behavior provide a starting point. For example, the hypothesis that increasing hedonic motivation results in oscillating curtailment behavior or that traditional responses to water shortages fail to secure water supply in the long term. For the system, one could study to what extent the identified barriers and drivers are driving the system's dynamics.

Second, this paper answers the call from socio-hydrologists to social scientists to 'become more involved in the field to investigate human-water dynamics from their own perspectives' (Xu *et al*. 2018, p. 82). Studies in socio-hydrology are mainly focused on explaining water management strategies (Phan *et al*. 2021) and not on the behavior of an individual household in relation to water systems. Water demand is often reduced to the product of the pricing of water and population size. The CLD in this paper could aid socio-hydrological research by capturing human agency in drinking water consumption (Yu *et al*. 2022).

Third, and more practically, this study provides a basis for policy design to influence household drinking water consumption. A feedback perspective helps to identify what processes could cause policy resistance (de Gooyert *et al*. 2016). Policy resistance occurs when policies fail to deliver the desired outcome (Sterman 2000; Ghaffarzadegan *et al*. 2010). Sustainability transitions often suffer from policy resistance due to dynamic processes that push back the policies (de Gooyert *et al*. 2016). The CLD in this paper shows where such policy resistance could occur. Hedonic motivation and drought response are identified as the main barriers to reducing drinking water consumption. A pathway forward is to decrease perceived normal levels of drinking water consumption. Changing norms is a slow process, but policymakers could rely on the system's interdependencies and reinforcing feedback loops. For example, setting legal requirements for water-saving equipment or stimulating smart meter technology to decrease the time between perceived effect and water-saving activity could have a flywheel effect. A small change in a part of the system could change the direction of the entire system.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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