Water Supply

Water Supply Vol 22 No 5, 4781 doi: 10.2166/ws.2022.188

Equity – performance trade-off in water rationing regimes with domestic storage

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ABSTRACT

Water rationing contributes to inequalities in the water supply. Household storage tanks complicate the performance and the hydraulic modelling of these systems. Rationing is often not based on insights into system performance and fails to achieve equity and the operators struggle to explain the rationing tactics to the stakeholders. Understanding the behaviour of water networks rationed regularly is essential to resolve the supply inequalities. We present a contextual analytical framework for understanding and managing water rationing based on the duration of supply (cycle time), rationing fraction (duration of non-supply) and domestic storage to analyse the equity and performance in the water network. The framework was tested using a model of a distribution network in Kakkapalliya, Sri Lanka, under different rationing schemes. The results show that large household tanks create inequities, which can be reduced through a trade-off by increasing the cycle-time of the rationing with a minor reduction in performance. Very small or non-existent domestic storage also negatively impacts the performance and equity of stressed water networks. Resolution of supply inequalities can be achieved through the trade-off between equity and performance is possible through the operation of the water network and by the regulation of domestic storage in water rationing regimes.

Key words: hydraulic modelling, intermittent water supply, water rationing, water scarcity, water security

HIGHLIGHTS

- Combine the complexity of domestic water storages with intermittent water supply to identify the impacts on supply performance and equity.
- Larger domestic storages create inequity at shorter rationing cycle times.
- Longer cycle times can mitigate inequity at a small cost on supply performance.
- In stressed networks, small (~daily demand volume) domestic storage can improve performance and equity as opposed to no storage.

1. INTRODUCTION

Increasing population, changes in per capita demand, pollution of water resources (Ma *et al.* 2020), and variability of rainfall due to climate change exert enormous pressure on the water supply networks of the world (Tzanakakis *et al.* 2020). Urban water supply systems can experience water shortages due to drought caused by climate variability and change, rapid urbanization, population growth, diminishing water resources, also short-term failures such as earthquakes, pipe bursts, chemical contamination of rivers and other water sources, etc. Water networks are often designed for 24×7 days water supply as the goal. However, in practice, many are forced to resort to intermittent supplies due to the mismatch between the demands and the available water supply, particularly during water-scarce situations (Vairavamoorthy *et al.* 2008).

Water rationing, a reactive measure of water scarcity management (Kimengsi & Amawa 2015), is a common tactic of demand management during severe droughts (Lund & Reed 1995). Rationing can be considered as a good management strategy as better rationing practices can resolve problems due to water shortage (Liu *et al.* 2018). Often water rationing practices are implemented without a plan, schedule, time frame, or advanced warning to the customers (Kimengsi & Amawa 2015). Further, many water utilities are not inherently interested in water rationing because it reduces the revenue of water utilities,

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and deliberation of the need to ration water supply is often considered as a 'failure', leading sometimes to negative socio-political repercussions (Remali *et al.* 2016). Usually, the focus is on the transition from rationing (intermittent water supply) to a continuous supply (Nyahora *et al.* 2020). Few studies have discussed water rationing up to date (Lund & Reed 1995; Kimengsi & Amawa 2015).

Rationing the supply varies from a few hours of each day to once per week in cities such as Algiers and Amman (Jordan), and Delhi (India) (Darmame & Potter 2011). Although water rationing is applied as a solution to provide access to water to all consumers in a system, sometimes it leads to the formation of inequality between wealthy and low-income consumers. For example, frequent rationing leads consumers to adapt by introducing and increasing the size of domestic water storage. High-income consumers are in a better position to implement such measures compared to the poor. Low-income families are affected profoundly by water rationing (Darmame & Potter 2011). However, when implemented properly, the rationing approach can create positive outcomes, although there can be some drawbacks based on the way of implementation of the water rationing plans by different water services (Kimengsi & Amawa 2015). Poor planning or no planning, inadequate consumer awareness, non-reliable timetables, and schedules keep people in precarious conditions (Anand 2017). Pressure control is the main technical measure used to address the inequalities in a water distribution system (Freni *et al.* 2014). For example, Freni *et al.* (2014) found that introducing pressure reduction valves in the distribution network leads to reducing the inequalities formed due to pressure fluctuations in different pressure zones.

Consumers strive to circumvent the impact of intermitted water supply by installing individual domestic tanks to regulate the daily water requirements. Generally, most tanks are oversized, and this impacts the distribution system hydraulics (Wunderrlich *et al.* 2021). When water is available in the network often the first domestic tanks of upstream customers are filled. Consumers attempt to collect as much water as possible while water is available in the network and the performance of the water network is directly impacted by the short-term (demand pattern change, ad-hoc water collection at household level) and long-term (creating increasingly voluminous household storage) consumer behaviour. Therefore managing intermittent water supply under rationing is a highly complex and critical issue for water managers to ensure equitable water distribution among consumers (Wang *et al.* 2012).

Typical water network analysis assumes that the domestic water usage pattern behaves according to typical demand patterns used during the design phase of water distribution networks (Blokker *et al.* 2010; David *et al.* 2020). However, the presence of domestic storage tanks disconnects that demand pattern of the consumer from the hydraulics of the network. As a result, the performance of the hydraulic model can vary significantly from the reality if the model does not consider these storage provisions. This phenomenon can become much critical in intermittent water supply situations as, in addition to the hydraulic parameters like network pressure, the water availability itself can be influenced by the size and distribution of domestic storage. Hence analyzing the performance of intermittent water supply systems along with the presence of domestic water storage tanks needs to be considered to model the real behaviour of a network (Ingeduld *et al.* 2006).

Empirical research is lacking on the role of domestic storage in water distribution during rationing and other intermittent water supply scenarios. Hence in this study, the impact of domestic water storage tanks on equity and performance of water supply under rationing scenarios was investigated to propose scientifically sound practices to ensure equitable water supply for all consumers irrespective of their location in the network. The original research described in this study included three components: (1) analysis of water availability during drought to understand the water shortage situation; (2) a social survey to establish the nature and size of domestic storage and the experience and responses of consumers during water rationing; and, (3) the model-based study, which focused on the impact of domestic storage tanks on network performance. For brevity and focus, we limit the scope of this article to components 2 and 3.

2. METHODS

The research methods applied in this study are fourfold (Figure S1 in.Supplementary Materials).

1. Establishment of criteria for quantifying the water supply performance and equity
2. Selection of hydraulic analysis tools
3. Collection of the necessary data with a household survey
4. Hydraulic model setup and analysis

2.1. Equity, performance, and rationing schemes

There is no universally accepted measuring mechanism to quantify the inequality of water supply (Wang *et al.* 2012). Ilyas-Ayza *et al.* (2018) and Nyahora *et al.* (2020) have used the sum of the normalized deviations of nodal available demand fraction, termed *Uniformity Coefficient*, to quantify it. Cullis & Koppen (2007) measured the inequality of water use in the Olifants River water management area applying the Gini index (Figure S2). The Gini index is traditionally used to measure the inequality of income and land distribution in a particular society or country. The Gini index is used to calculate possible water rationing fractions, to understand the scale of impact to the network (Wang *et al.* 2012).

$$G = \frac{A}{(A+B)} = 1 - \int_0^1 \frac{f(x)dx}{0.5} \tag{1}$$

where, G is the Gini index, $f(x)$, the function for the Lorenz curve, which represents the cumulative amount of water distribution for all consumers below population fraction x, with consumers ordered from least water received to the most. A and B are areas under the Lorenz curve and area under a diagonal line, respectively.

Another important parameter of a distribution system is water availability, which can describe the performance of a water supply system. In this study, the water availability was represented by the available demand fraction (ADF, Ozger & Mays 2004). ADF refers to the cumulative water supplied to all the consumers and the total demand of all consumers in the system during water rationing:

$$ADF = \frac{Total\ water\ supplied}{Total\ demand} = \int_0^T Q_s\ dt \Big/ \int_0^T Q_d\ dt \tag{2}$$

where, Q_s and Q_d are supply and demand of water at a time (t). T is the total time duration considered.

In this study, the term ‘rationing fraction’ is used to indicate the time fraction over which water is not supplied to the network. The time difference between the beginning of one water stoppage to the beginning of the subsequent is called ‘cycle time’. For example, if the water is stopped for 12 h period every 2nd day, then the rationing fraction and cycle time are 25% and 48 h respectively.

2.2. Hydraulic modelling tools

EPANET, a model that is widely used for the analysis of water supply networks, was used in this study (Rossman 1994). There is an open-source library of modelling tools called WNTR (Klise *et al.* 2017) for hydraulic analysis of water supply networks, implemented in Python programming language. Among others, it provides EPANET as a modelling engine. While EPANET desktop provides a simple to learn graphical user interface, for complex and repetitive analyses, it can end up being inconvenient due to the sheer amount of manual work involved. The current analysis was implemented as a set of Python scripts based on the WNTR library.

Depending on the application context, sometimes analysts have to resort to much more advanced (typically non-fixed demand, and transient) modelling tools. For example, EPANET cannot simulate intermittent supplies as they require pressure-dependant demand formulation; therefore, it is typically not used for the analysis of intermittent water supplies. These hydraulic models can represent the demand as an increasing function of pressure under low-pressure (stressed) situations. Such pressure-dependent demand (PDD) models were developed by Pathirana (2010) (EPANET-Emitter software) and Klise *et al.* (2017) (the WNTR hydraulic engine), among others. Version 2.2 EPANET also provides a PDD engine (USEPA 2020). When pipe-filling/emptying are of significance (in the current study, the impact of these is relatively smaller compared to the impact of tanks) a model that can handle non-steady flows (Campisano *et al.* 2018) should be employed. Further, when sudden opening and closing of the valves, open/close of pumps etc., and their water-hammer-like impacts are being considered, a model with capabilities to handle surge analysis (Xing & Sela 2020) is needed.

Typically a case study that involves water scarcity should be analysed with a PDD model (e.g. Pathirana 2010; Klise *et al.* 2017; USEPA 2020). However, when the consumer demands are modelled with domestic water storage in between the demands and the network, typical fixed-demand models such as EPANET can model intermittent supplies effectively. This is because of the nature of the EPANET's treatment of storage. Whenever the storage runs empty, the model automatically disconnects the downstream (demand-side) of the tank. Therefore, whenever the tanks are empty, the demands by default are set to zero. This provides the essential level of realism to intermittent supplies with models simulated on EPANET and similar fixed-demand software (Trifunović & Abu Madi 1999). However, this is not the case with demands connected to the network without storage in between – they will show spurious demands even when the network cannot supply water and result in (spurious) negative pressures.

The above theoretical argument was further validated during the trials. At least one scenario of each of the trials was run using the PDD scheme of EPANET 2.2 and compared with DD results to ensure that using DD approach in the context of this study does not cause any significant departure from (more accurate) PDD. Figure S3 shows such a comparison. Further, in this study, the standard tank filling and emptying schemes used in EPANET engine were used. The tank filling and emptying behaviour during water scarce situations can be complicated and may depend on factors such as the behaviour of float valves.

2.3. Social survey

A social survey was carried out for collecting information about characteristics of household storage tanks and consumer experience during water rationing in the water supply scheme. Major parameters such as household storage capacity, number of tanks and elevation of them, and diameter of the supply pipe were collected. A survey was carried out through the KoBoToolbox web application (https://www.kobotoolbox.org/), installed on a smart mobile phone. KoBoToolbox is a set of tools, widely used for field data collection in challenging environments in the world, and it is a free and open-source mobile application. Data-collecting through KoBo-toolbox is very secure and convenient (Florence *et al.* 2016). The use of KoBoToolbox enables fast summarising and analysis of data. This web-based data collection application is time-saving and enables the quick generation of GPS-based maps as well.

2.4. Model setup and analysis

The modelling and analysis of the impact of rationing under significant storage at the household level were assessed in two stages: (1) a simplified, idealized network was created to understand the impact at a conceptual level (Figure 2(a)), and then (2) a reduced complexity model of the water supply scheme was created and analysed to ascertain the rationing practices.

Simulation of a large number of tanks in EPANET (and similar) can be numerically challenging and time-consuming. Internal rules should be applied to tank filling and emptying and iterative solving is often needed. Therefore, one of the challenges of the modelling work in this study was the issues of modelling taking a long time to run and sometimes non-convergence. Therefore, first, the many tanks that are present in a node were represented by a single tank (with the volume equal to the sum of the volumes) connected to the network by a single connection (represented by a single pipe that is hydraulically equivalent to all the household connections). Further, to understand the network behaviour and outcomes, initially, a simple water network (idealized model) was set up, which presents the simplification of a real network. The outcome of the model, which is the amount of water received by each unit (i.e., demand node), is based on the tank elevation, capacity, location in the network, and total water supply, thus variation in equity and ADF can be estimated. As manual calculations for equity and ADF are not feasible for a complex network a python script was developed to automate these calculations for both idealized and simplified real-world simulations.

3. CASE STUDY AND APPLICATION IN KAKKAPALLIYA, SRI LANKA

3.1. Case study

Puttalam District in North-Western province, located in the dry zone in Sri Lanka (Figure 1) is been a highly vulnerable region experiencing severe drought as a result of climate change (Abeysekera 2018). Puttalam district received deficient rainfall in the 2016–2017 period, which was well below the average (Figure 1). Kakkapalliya Water Supply Scheme (KWSS) was built by the National Water Supply and Drainage Board (NWS&DB) in 2007. It provides drinking water for nearly 35,000 people through 7,140 domestic water connections in addition to 1,300 commercial water connections (NWS&DB 2017). A treatment plant with a capacity of 5,000 m^3/day, located in Nelumpokuna, provides water to the network. Water storage of the reservoir declined drastically as a result of the drought in 2016–2017. The water source, Kadupiti-Oya, is in the intermediate zone (Figure 1), which receives 1,000–1,500 mm annual rainfall.

The water operator, NWS&DB allows the customers to have small domestic storage to manage water supply during frequent intermittency of water supply. However, it is suspected that most of the consumers have large storage at the

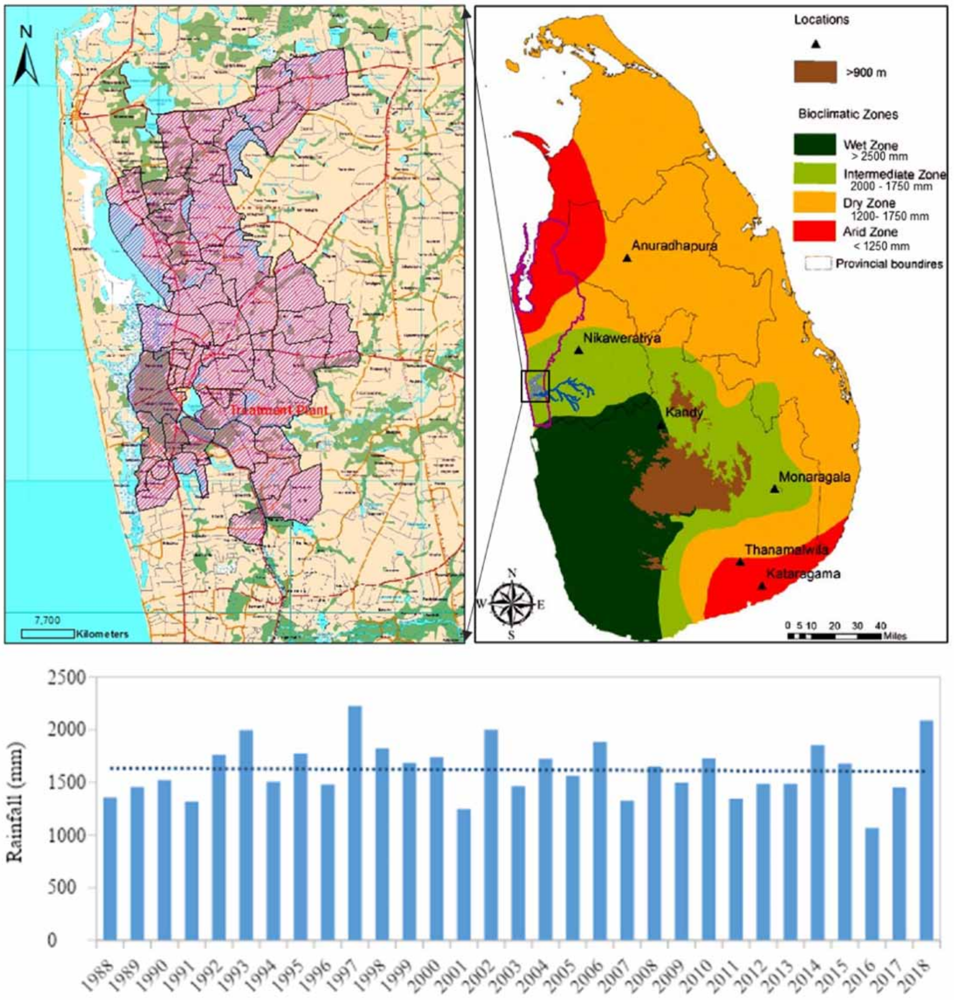

Figure 1 | The Kakkapalliya water supply network (top left) belongs to the intermediate climate zone of Sri Lanka (top right) and receives about 1,600 mm of annual rainfall (bottom). This climatic zone classification is based on the Sri Lankan context. According to 31 years (1988–2018) of rainfall data, the 2016–2017 period received significantly less rainfall compared to the average (bottom).

household level, which is not recommended or allowed. Due to the drought of 2016–2017, water rationing was initiated in May 2017 by cutting off the supply a few hours per day in the KWSS, and it was extended to a few days per week. Zonal officers of the KWSS intended to practise water rationing measures to minimize the impact on consumers. They applied various water rationing time fractions (the fraction of time the water is made available) based on reservoir storage. Purely based on operational experience, they had realized that extending cycle time, especially to multiple days (with and without water) could provide water for consumers in the tail-end compared to a cycle that supplies water on alternate days. However, consumers launched protest campaigns and public representatives requested clarifications on the water rationing strategies of NWSDB (Samantha 2017). It was hard to explain to the consumers or public representatives the advantages of an extended period of water rationing (cycle time) because there was no evidence, in terms of data or models regarding the practice, as there were no systematic studies on water rationing and the impact of domestic storage tanks in the water supply scheme. The managers of NWS&DB were unable to justify the method they used. This issue received the attention of mass media and mass media highlighted this as a failure of the management of NWS&DB (Samantha 2017).

Conventional water rationing practices used by NWS&DB are based on experience, not on systematic data gathering and scientific analysis. Therefore, these practices are challenging to be replicated in other similar cases (drought scenarios or different causes of water scarcity) because there is no scientific basis for the rationing strategies. Up to date, there is no study done for assessing the impact on consumers caused by water rationing practices in Sri Lanka. Further, there are few studies on this topic in the context of case studies with significant household storage.

The social survey was carried out for collecting information about characteristics of household storage tanks and consumer experience during water rationing in the KWSS. Major parameters such as household storage capacity, number of tanks and elevation of them, and diameter of the supply pipe were collected through the survey and some questions were used to collect other relevant information (Table S1). The completed questionnaires for 250 households were stored in KoBoToolbox, which formed the basis of the situation analysis.

Results show that 83% of connections are domestic, and only 16 and 1% are commercial and industrial, respectively. Among the consumers who responded to the questionnaire, most (52%) have a storage capacity of 1 m^3 followed by 0.5 m^3 (24%) (Table S2). A very few households (6%) have 5 m^3 or more. The average capacity of household tanks is 1,200 L. Some consumers (2%) had a size of 0.1 m^3 as well. The average tank capacity of rural, suburban, and urban consumers is 0.5, 1.0, and 1.6 m^3, respectively. Locations of tanks were identified in four elevation categories: ground (12%) and first floor (61%) (at 3 m height) and (2) second (19%), and third floor (8%) (at 6 m height). The rearrangement into two main elevation levels was done to simplify the model-based analysis. Approximately 73% of tanks are considered to be 3 m in height, and 27% 6 m or above. Based on the survey results, major model parameters values are summarised in Table 1, which were used in the model study.

Furthermore, consumers presented distinct suggestions, complaints, and opinions regarding water rationing based on their experience. Those were ranked based on the most frequent answers and the eight responses were selected for the analysis (Table S3). There were a few interesting proposals such as to distribute water day after day, preferred by 40% of the consumers. Some consumers (25%) argued for the higher storages capacities of urban consumers. These findings show the necessity for in-depth knowledge regarding water rationings as people need clarification on the strategies used by the water operator (e.g., NWS&DB in this case study).

3.2. Model setup and analysis

3.2.1. Rationing fractions and cycle times

The water quantity supplied by the KWSS is from the daily recording at the water treatment plant (WTP). The water operator (staff of NWS&DB) determines the rationing fraction based on empirical experience, considering parameters such as reservoir capacity, forecasted drinking water demand, forecasted irrigation demand, expected rainfall, etc. The most common rationing fraction they use is 50%. There are many ways to supply the constant amount by changing the cycle time. As an example, within 96 h of the total period, an equal amount of water can be supplied using three different patterns (Figure S4).

3.2.2. Idealized model

An idealized simple EPANET model was set up to represent a simple linear (4,000 m long) water supply scheme over flat terrain, with a production capacity of 4.2 L/s assuming 600 consumers are attached to the water supply system. Per-capita consumption was taken as 120 L/day referring to design parameters of Sri Lanka (NWS&DB 1989). Hence, the daily household water requirement was estimated as 600 L by assuming five members in a family (household). This model includes six demand nodes with 100 households (500 consumers) at each node. Social survey results show that each of the consumers has a domestic tank. These tanks were represented as a node. About 73% of the tanks were assumed on the first-floor level (3 m), while 27% of tanks were on the second-floor level (6 m) and the average volume of a domestic tank was 1.2 m^3. The internal diameter of the house connection was taken as 12 mm. These data were lumped (e.g. total volume of 3 m and 6 m level tanks connected by a hydraulically equivalent pipe representing 500 households with 12 mm connections).

Table 1 | Summary of major parameters found through household tank survey

Description of the parameter	Value
Tanks elevations (m)	3 m and 6 m from ground level
Percentage of the first floor and second floor	73%, 27%
Distance between junction and tanks	10 m
Distance between tank and usage node	1.5 m
The average area of a domestic tank	0.8 m^2
The diameter of the supply line	12 mm

Tank height was assumed to be 1 m. Then, to calculate the volume of the tank, the diameter of the common domestic tank was calculated based on the number of consumers and the average diameter of individual domestic tanks.

$$D = \sqrt{(nd^2)} \tag{3}$$

where D is the diameter of the representative tank, n is the number of consumers, and d is the average diameter of individual tanks. These characteristics and other model parameters are shown in Table 2. Model setup with added household tanks is shown in Figure 2(a).

3.2.3. Performance of water rationing options

This idealized model was tested by incorporating one water rationing option to test the model behaviour. With the water rationing fraction of 50%, various options are available for water supply to the customers such as 12, 24, 48, 72, 144, 288, and 576 h. (It should be noted that very large cycle times such as 288 and 576 hours were included only for theoretical interest, with the caveat that implementing such long periods without water is not practically useful.) When the idealized model runs at 12 h cycle time, Node2_tank_0 (nearest to the main supply source and lowest elevated household tank), shows little impact due to water rationing, because the tanks are never emptied throughout the rationing period (Figure 2(b)). On the other hand, the farthest customers with high elevated tanks (at Node7_tank_1 in Figure 2(a)) don't receive adequate water supply during the rationing period. Their tanks become emptied after 48 hours, to be never refilled.

This analysis was repeated for different cycle times. Figure 2(c) shows the results for 48 h, which is quite similar in pattern to the 24 h case. The nearest consumers to the main supply source are not impacted by water rationing, as their household tanks never become empty and the furthest customers never receive water after about 65 h since the start of the rationing.

Further to understand the system behaviour under different rationing fractions and cycle time, we applied the same procedure for 25 and 75% rationing fractions. Results show that an increase in rationing fraction affects the nearest consumer as pressure drops gradually to zero (Figure S5). Under 75% rationing fraction, water shortage at the tail end consumer also starts at an earlier time (~50 h). It is observed that the tail end user is more highly affected than the nearest consumer with any rationing fractions.

3.2.4. KWSS model

The KWSS consists of a 300 km pipe network and two elevated tanks to supply water for 8,140 consumer service connections. The entire pipe network consists of polyvinyl chloride and ductile iron pipes of diameters 50 mm, 90 mm 110 mm, 160 mm, 225 mm, and 280 mm. Similar to the idealized network, the network model was developed with EPANET first considering all the pipe diameters. Then model complexity was then reduced using the 'Skelebrator' tool kit of the WATERGEMS (www.bentley.com). First, smaller diameters, 50 and 90 mm, were removed ('branch trimming') lumping the demands into network nodes. Secondly, each set of parallel pipes was replaced with a single hydraulically equivalent connection. Serial connected, similar diameter, short pipes were joined together to form a longer pipe. The water distribution network could be divided into two zones that are largely independent of each other (Figure S6). A 1,000 m^3 distribution tank is located at the treatment plant, and another (450 m^3) is located in the place called Karukkuwa grounds. Zone 1, fed from distribution tank 1, provides water for around 4,600 consumers. Zone-2, supplies water for 3,740 consumers, from tank 2. Each zone has

Table 2 | Model parameters

Parameter	Value
Household capacity (m^3)	1.2
Tank elevations (m)	3 and 6
Percentage of the first floor	73
Percentage of the second floor	27
House connection diameter (mm)	12

Same values were used in both idealized and KWSS models.

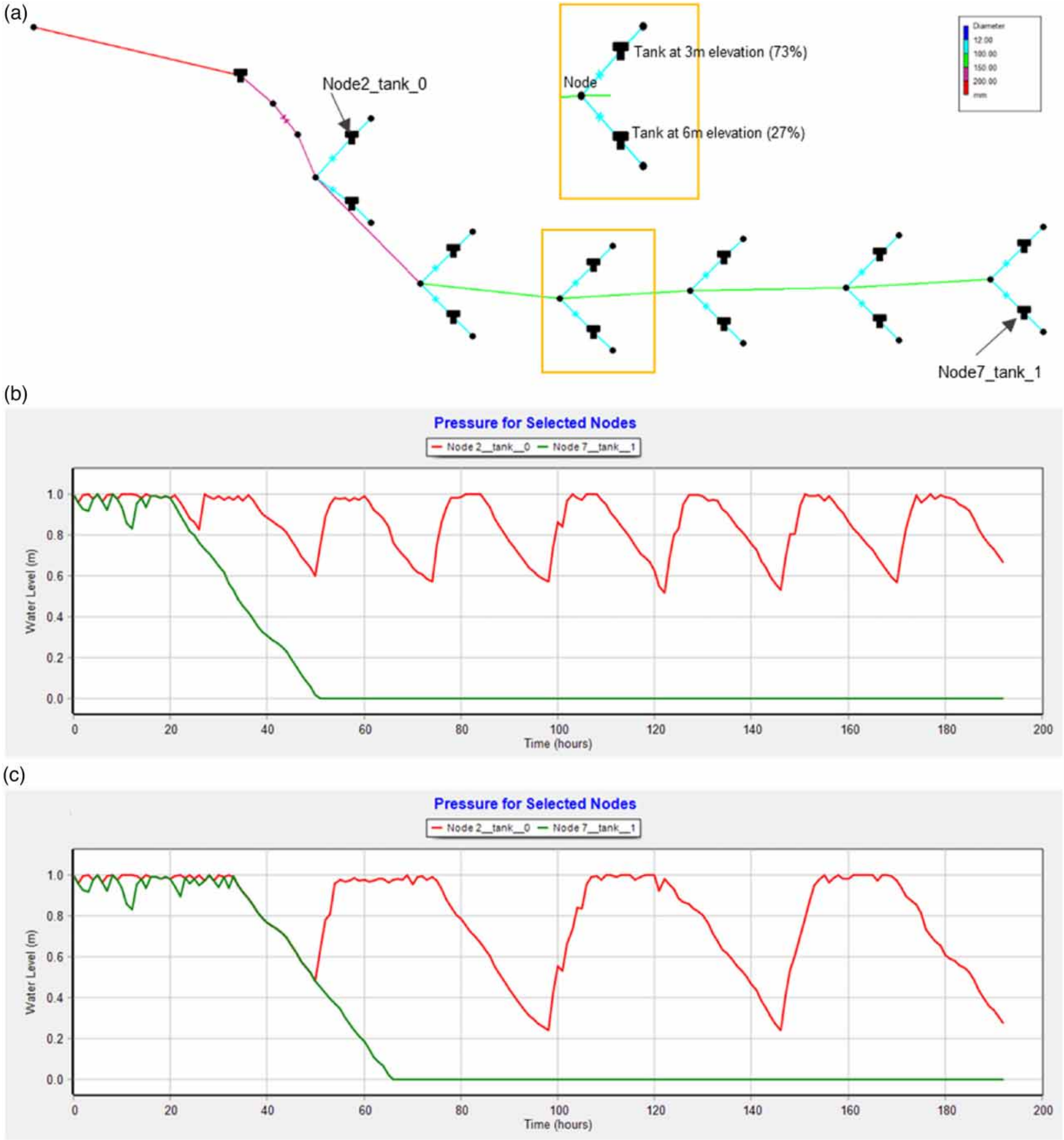

Figure 2 | The idealized network (a) and tank level variation at nodes at two extremities (node_2 at the head end and node_7 at the tail end) for (b) 24 h cycle time and (c) 48 h cycle time under 50% rationing fraction. The idealized network has six demand nodes spaced at 500 m intervals. Two tanks with different elevations (3 m and 6 m) are attached at each demand node representing the sum of the household storage at that node.

distinct network characteristics (Figure S6), which may lead to obtaining different performance levels of the actual network. Most rural consumers are attached to zone 2, as some isolated villages are covered under this water supply. Zone 1 supplies largely urban consumers.

3.2.5. Analysis

EPANET model simulations were carried out at 1 h hydraulic time steps for 24 days (576 h). The hourly simulated demands at each node were collected and summed up to find the daily realized demand. Both models (two zones) were simulated for several cycle times such as 12 h, 24 h, 48 h, 72 h, 144 h, 288 h, and 576 h with adopting the 50% water rationing fraction and considering the average tank size of 1.2 m^3. Then both zones were analyzed to find the variation of Gini index and ADF.

4. RESULTS

4.1. Equity and reliability

While supplying water at 50% rationing fraction for cycle time such as 12 h, 24 h, 48 h, and 72 h, approximately 30% of the consumers receive no water at all (Figure 3(a)). The number of consumers having zero supply reduces gradually when the water supply cycle time increases. For example, under 576 h cycle time, the Lorenz curve reaches towards the continuous line, which represents maximum equity.

Further to understand the variation of equity vs cycle time under extreme rationing fraction, we developed the Lorenz curve for 75% rationing fraction (Figure S7). It proves that Lorenz curves at low cycle times deviate from the maximum equity line. In contrast, under 25% rationing fraction, this deviation is minimum (Figure S8). Since this case study site has practically applied the 50% rationing fraction, therefore our analysis focused on the same.

The longest cycle time (576 h) results in the best equity (lowest Gini-Index) in the network. In comparison, the least equity (high Gini index) can be seen in 12 h water rationing scenario (Figure 3(b)). Equity in water distribution for shorter cycle times such as 12 h, 24 h, and 48 h are almost the same, and thereafter equity decreases rapidly while increasing the cycle time.

However, the overall ADF of the network generally declines with increasing cycle time. ADF somewhat increases until the cycle time of 48 h and, then the value of ADF reduces with the increases of the cycle time (Figure 3(c)). However, the reduction of ADF (from 48 h to 576 h cycle time) is only about 5% from the initial value, while the drop of the Gini index is 75% (varies from 0.51 to 0.12 of Gini index). Therefore, the cycle time does not have a significant influence on ADF.

4.2. Sensitivity analysis for characteristics of household tanks

We hypothesized that the domestic storage capacity makes a significant influence on the performance of a water distribution system during water rationing because domestic tanks react as a regulatory device between the consumer and the pipe network. The impacts of the size of domestic storage on the performance of the system were further studied by incorporating different sizes of storage capacities and elevation of the tanks during the water rationing period.

4.2.1. Impacts of household tank size

With the typical average household size in the area being 5, the daily water consumption is estimated as 0.6 m^3(5×120 L). The daily water consumption of 120 L/per person is based on the Design Manual of NWS&DB (NWS&DB 1989). Therefore a tank size of 0.6 m^3 is an important size, which is the volume that is required to store the average daily demand. The storage sizes of 0.2, 0.463, 0.6, 0.8, 1.0, 1.2, 1.6, and 3.0 m^3 were analyzed.

When the cycle time changes, the Gini index for each tank capacity shows distinct changes (Figure 4(a)). However, the overall tendency of all curves shows that the Gini index reduces nearly to zero as the cycle time increases. If the storage capacity is low (0.2 m^3), the Gini index starts to drop at the first cycle time (12 h) and is stable after cycle time of 72 h, because the elevation of the tanks becomes the leading parameter for both small or no- tanks. However, the leading parameter for larger volume is cycle time. On the other hand, if the household storage is high (1.6 m^3), the Gini index remains constant until the cycle time of 192 h, and after that, it falls. The system without any household tanks shows an almost constant Gini index (~0.32). When the household storage tanks are very small, practically no tanks, the Gini index does not change; however, it keeps above zero. This scenario was further studied in the section on the impact of tank elevation.

In general, for different tank sizes, the ADF does not change significantly with the increase of cycle time, however, except for the lowest tank size (0.2 m^3), in which case ADF reduces from 0.56 to 0.45 (Figure 4(b)). The ADF for tank size more than 0.2 m^3 remains at the value of 0.5. When there are no domestic tanks, the ADF does not reach that value of 0.5.

4.2.2. Impacts of tank elevation

According to the above results, the Gini index and the ADF have less variability under no domestic tank conditions than other tank sizes. Tank elevation was considered as a sensitivity parameter to understand this situation. In this analysis, two elevation scenarios were considered: (1) households are at different elevations (3 m/6 m from the ground level), and (2) all the houses are at the same elevation. The result was compared with the scenarios for the tank of sufficient volume to store the daily demand of an average household (0.6 m^3) (Figure 5).

During the water rationing, the Gini index is higher when households are at different elevations than they are at the same elevation (Figure 5). This implies that in a water-scarce network, inequitable water distribution is unavoidable when the households are at different elevations. However, under both elevations, the variability of the Gini index is small with the

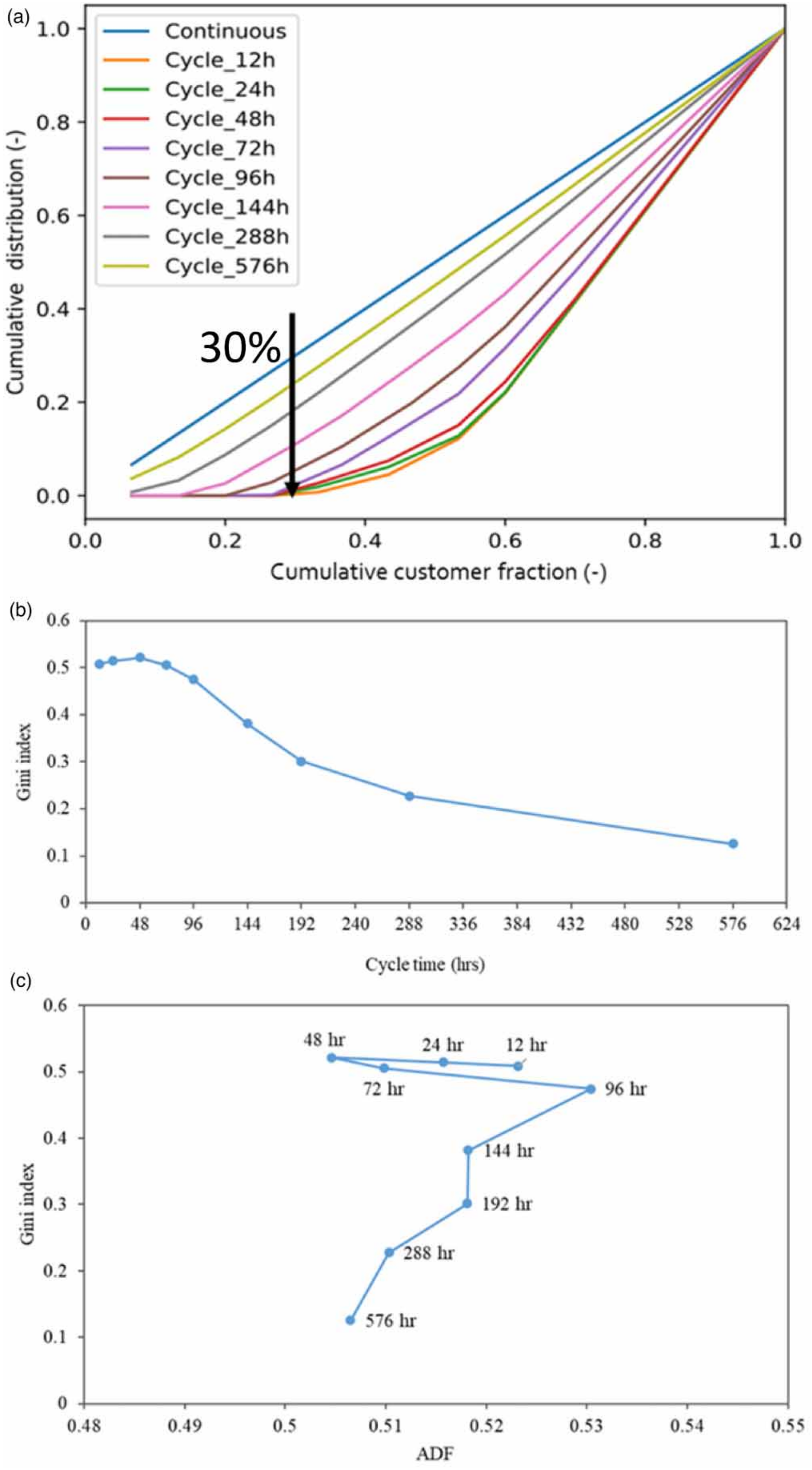

Figure 3 | (a) Lorenz curves for different cycle times under 50% rationing fraction, (The verticle arrow denotes 30%) (b) Changes in the Gini index with cycle time, and (c) variation of Gini index and ADF for different cycle times. Data labels indicate cycle times.

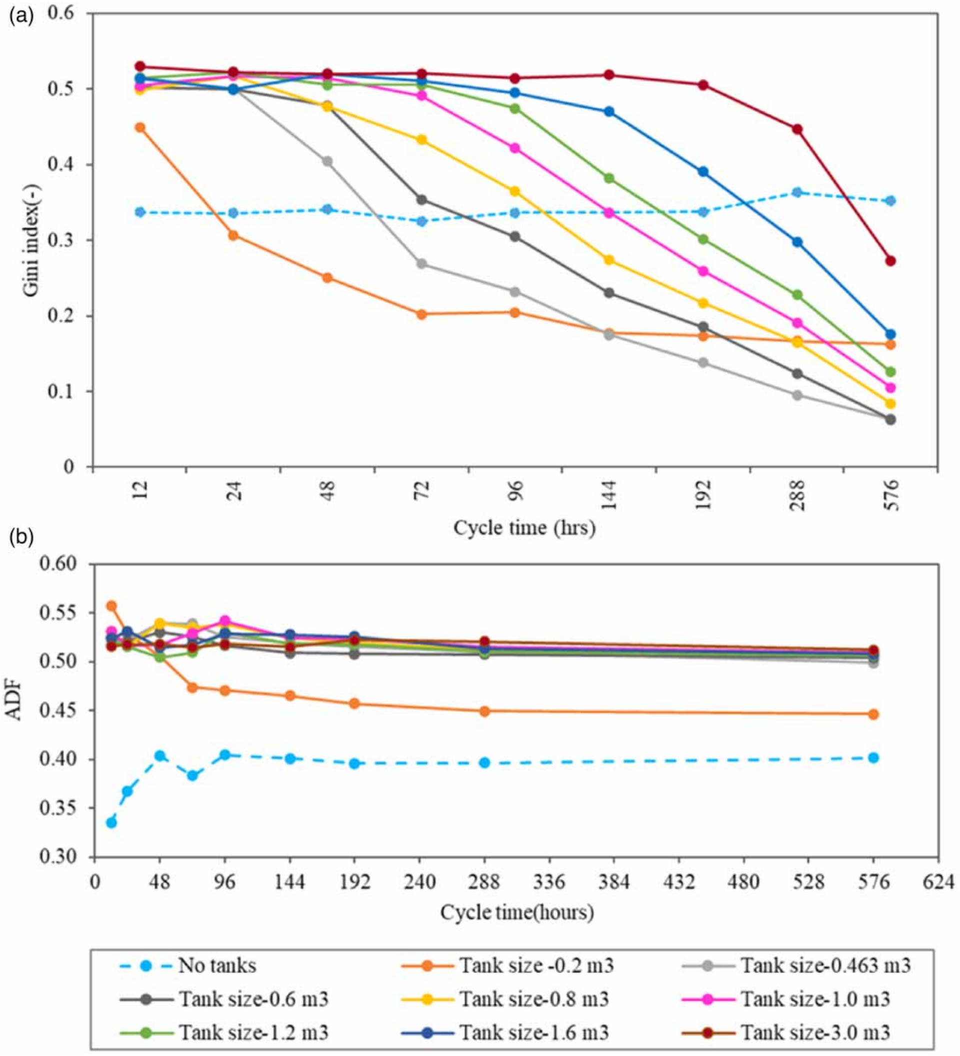

Figure 4 | Variation of Gini index (a) and ADF (b) with cycle time for the different domestic storage tanks.

increasing cycle time. But when households have tanks, the Gini index starts at a high value, then reduces with increasing cycle time (Figure 5).

In this analysis, we have 'lumped' the four elevations into two for brevity. The results clearly show that the lower the tank level is, the more privileged the customer to receive water during scares situations (e.g. rationing).

4.2.3. Tank size and performance during continuous water supply

The continuous water supply scenario represents a straight line of the Lorenz curve (Figure 3(a)). A set of simulations under continuous supply was done to understand the behaviour of the Gini index and the ADF with different tank sizes (Figure 6). When there are no tanks, the ADF and Gini index are 0.68 and 0.36, respectively. When each household has a tank size of 0.6 m^3 or larger, ADF becomes 1 and G=0, indicating best performance with no inequity.

4.3. KWSS

The two zones of the network were simulated for several rationing fractions such as 12 h, 24 h, 48 h, 72 h, 144 h, and 288 h with adopting the 50% water rationing fraction and considering the average tank size of 1.2 m^3.

There is a difference in Lorenz curves between Zone-1 and Zone-2 (Figure 7(a) and 7(b)). Even under continuous supply, Zone-2 has consumers who do not receive significant amounts of water (Figure 7(b)). The model shows that approximately 15% of the consumers in Zone-2 do not receive any water during the simulation period. The Gini index reduces with

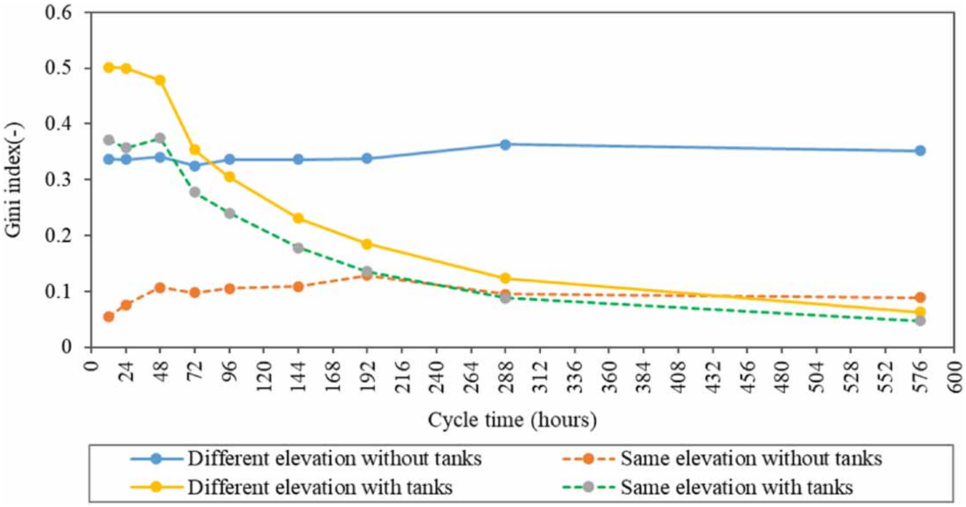

Figure 5 | Impact of elevations of tanks on the Gini index (no storage and storage volume equivalent to the daily demand of an average household 0.6 m^3).

increasing the cycle time of water rationing as the idealized model does (Figure 7(c)). If the rationing scenario is 12 hours or 24 hours, 35% of consumers do not have a water supply. This percentage also reduces with the increase of the cycle time of water rationing. While increasing the cycle time up to 72 h, there is no considerable reduction of the Gini index in all three models (viz., Zone-1, Zone-2, and idealized models). It implies that there are no changes in the equitable water distribution for shorter water rationing fractions such as 12 h, 24 h, and 48 h. Further, the ADF (Figure 7(d)) is not significantly affected by changing cycle time. This outcome is significant in making decisions on water rationings.

5. DISCUSSION

Water rationing is a common water scarcity management practice around the world. Although studies related to water rationing are limited, there are various practices based on experiences gained through experience (Lund & Reed 1995; Kimengsi & Amawa 2015). An important consequence of water rationing is the resulting inequity in water distribution among consumers based on the location on the network, elevation, and variations in household-level storage.

This study focused on the performance of the water distribution network to ascertain the equity in distribution. Different water rationing fractions were analysed to understand the variation of equity among consumers. Under a rationing fraction of 50% and household tank size of 1.2 m^3, the analyses showed that improving the equity of the water supply (by about 75%) by increasing the cycle time (from 12 h to 576 h), will reduce the total water availability of the network only a small amount (ADF reduction of about 5%).

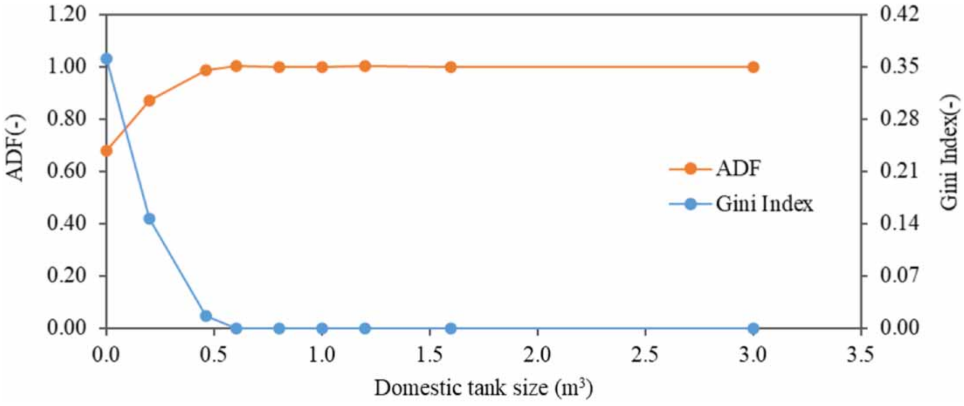

Figure 6 | Variation of Gini index and ADF against household capacity during continuous water supply.

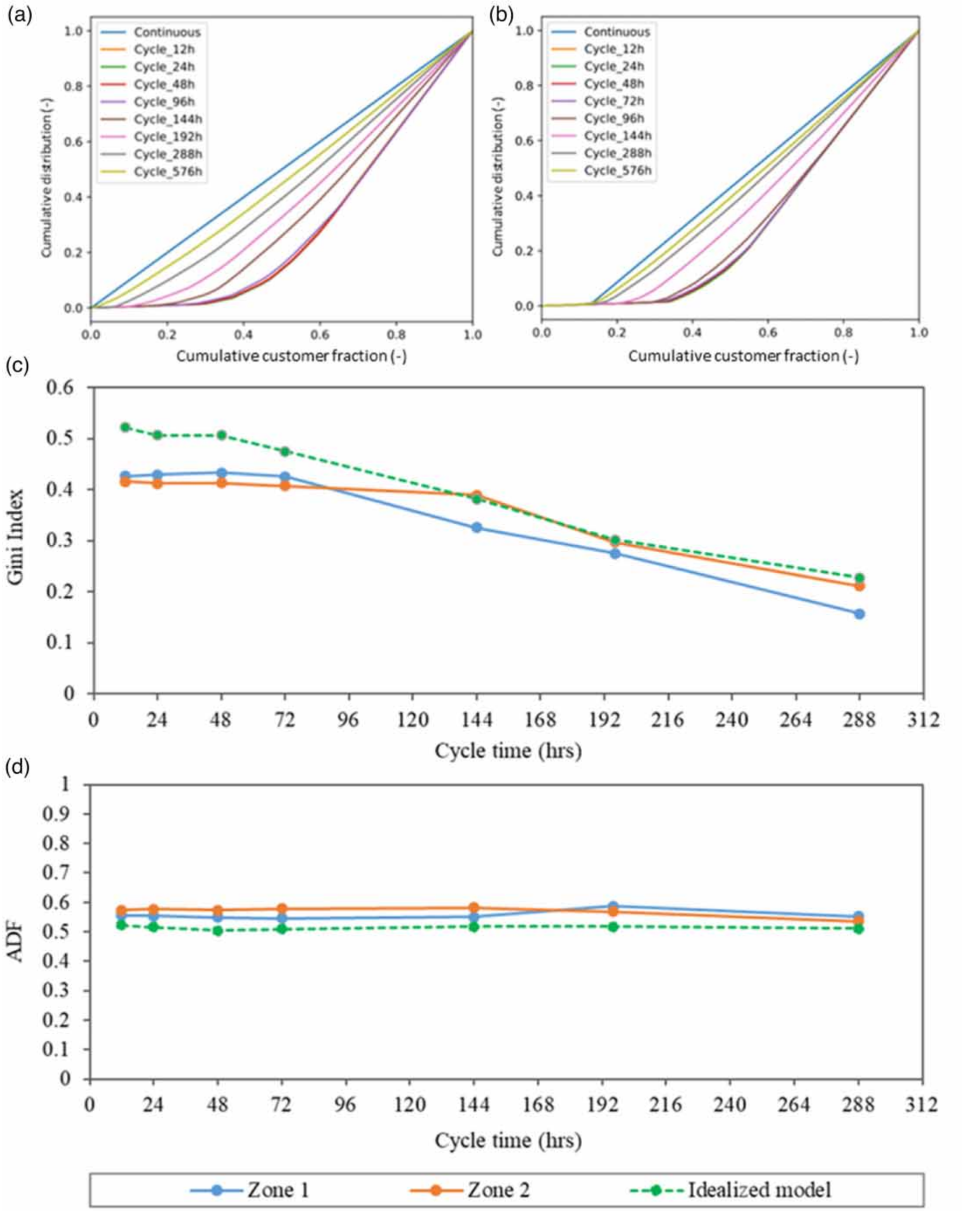

Figure 7 | Lorenz curves for different cycle times for Kakkapalliya network Zone 1(a), Zone 2 (b). Gini index (c) and ADF (d) variation with cycle time. (Idealized case is also shown).

The Kakkapalliya network model was separated into two zones based on the existing conditions. Among all the rationing fractions considered, the highest equity level was indicated to be with the 576 h cycle time, but this cycle time is practically not feasible to implement because too many days (~24 days) without water supply is not acceptable. Nevertheless, the equity increases with increasing cycle time for all three hydraulic models following the same tendency. As an example, the every-other-day water supply creates situations of zero water supplied to about 30% of consumers in both zones of the Kakkapalliya scheme. Hence, it can be concluded that the every-other-day water supply is not a good water rationing scenario for this scheme. The cycle time has to be longer to ensure better equity of supply. Therefore, the most significant outcome of the study is that the equity in water distribution can be increased during water rationing by extending the cycle-time in the intermittent water supply. These results contradict the global practice of water rationing (Fan *et al.* 2014). This is due to the impact of consumer storage tanks.

When the water supply is intermittent, such tanks behave as regulatory devices. When the supply rate is constant because of the normalization of the demand as the tank is acting as a buffer between the fluctuating household usage and the network.

Usually, a tank with a capacity of 1.2 m^3 can be filled within 2–3 h through a 15 mm diameter supply pipe that functions less than 1 bar pressure head difference. On the other hand, household water requirements follow a typical demand pattern, which is not directly transmitted to the system, as the household tanks disconnect the link between the actual demand node and the water supply system. Household tanks closer to the main supply point are not emptied if the rationing cycles are less than 48 hrs. In contrast, consumers at tail-ends and higher elevations may be completely cut-off from the supply.

The presence and size of household tanks significantly influence both the equity and performance of the water systems during water rationing. The Gini index does not change with cycle time if there are no household tanks as the only impact on equity then would be the (constant) elevation of the houses. When the consumers have larger sizes of storage tanks, the cycle time has to be further increased to achieve equity in supply. If the average tank size is 3 m^3, the Gini index remains above 0.5 until the cycle time of 192 h (Figure 4). If the average capacity is about 0.6 m^3, the Gini index of 0.4 can be achieved already by the cycle time of 72 h. If rationing becomes a frequent occurrence, consumers may resort to increasing the tank sizes in response to the longer periods without water supply (increased cycle times). During the social survey, some consumers highlighted the use of higher tank capacities as a response to the intermittent water supply. Findings of the model-based investigation confirm that regulations and policies limiting larger household tanks are essential in water rationing conditions. The outcome of the research can be the basis for introducing regulation on household tank capacities.

The elevation of household tanks also influences the performance of the network and the equity of distribution. Elevation of households impacts the performance of the network (Ingeduld *et al.* 2006; Fan *et al.* 2014; Habi & Harrouz 2015). Elevation of the house is a geographical parameter that cannot be changed, but not the elevation of the household's tanks. Existing design norms in NWS&DB require at least a 6 m (0.6 bar) head at the consumer. This allows for consumers to locate their tanks up to about 6 m in height. If there is a continuous water supply, the impact of tank elevation is less. However, in intermittent systems, equity decreases with increasing variability in tank elevations. Discussions with consumers revealed that faced with chronic low pressure and intermittency, consumers resort to building tanks at lower elevations, even underground, with secondary pumping to supply to a higher-level tank.

The analyses also show that having small domestic storage (0.6 m^3) improves the equity and performance compared to no household tanks. This is because the domestic storages act as a buffer to even out the daily variation of water demand. Accordingly, the maximum level of equity and the maximum percentage of water availability (ADF) can be achieved when the household's tank capacity is about 0.6 m^3, which is almost equal to the average household's daily water demand. Therefore, for already stressed systems (much higher demand than it was designed for), having small domestic storage tanks improves performance and equity. However, increased sizes of storage would lead to inequity.

In the case of stressed water networks, even in the case of continuous supply, the equity and performance suffer when domestic tanks are not present. Consumers in the tail ends do not receive enough water as the system is unable to supply for the peak demand, where the domestic storage tank can regulate the peak demand and ensure that the water availability in the system is maximum, i.e., the highest possible ADF. This finding is useful for water utilities that operate continuous water supply, but under higher demands than designed for. Hence, for such networks, it is beneficial to have the household level storage volume of about the total daily water demand to achieve the best level of water equity in continuous supply systems as well.

Typical intermittent water supply analysis required PDD models (Pathirana 2010). However, as each household connection had a storage tank, the analysis was possible with a fixed-demand EPANET hydraulic engine. This is simply because when the tanks run empty, EPANET will disconnect the demand from the network automatically. However, if we had to model a mix of demands – including demand points directly connected to the network without any storage, then the analysis would have required a PDD formulation. Another important consideration for intermittent supplies is the impact of gradual filling of pipes (de Marchis *et al.* 2010) on equity. This requires a modelling system that can handle non-steady flow conditions. For example, Campisano *et al.* (2018) used the EPA-SWMM model to simulate these conditions. However, in the current context, the lengths of intermittency (hours and days, instead of smaller intervals) and the smaller size of the network, make the network filling times often negligible compared to the impact of tanks.

These findings are essential in the design phase as well as during the retrofitting of a water supply system. Generally, design engineers do not consider water rationing fractions while designing water systems, although almost all water distribution networks in Sri Lanka and many other developing countries have to undergo rationing situations sometimes (in some cases frequently) during their operational life (Pathirana *et al.* 2018). Conventional rationing practices are developed based on the prevailing water availability, production, operation, and maintenance conditions. The findings of this model-based study emphasize that it is essential to consider contingency scenarios like water rationing in the design phase of a water supply project, which can lead to informed decision-making to maintain equity in supply.

There is a range of water quality issues that need to be carefully analysed and addressed before optimising the rationing schemes as well as making concrete suggestions on household storage. Some of the pertinent water quality challenges are likely reduction in residual chlorine below critical levels due to larger cycle times and the resulting longer storage of water at the household level, infiltration into network exacerbated by the use of suction pumps that are common in rationed supply networks, etc. Further, the operators need to consider the trade-off between the ADF and Gini index using the operational parameters such as cycle time, rationing time, and size of domestic storage. This can be analysed using multi-objective optimisation techniques that are frequently used in network and water quality optimisation (e.g. Radhakrishnan *et al.* 2012). As rationing fraction and cycle time will have an impact on inequality, performance, and water quality it is possible to obtain a range of context-specific combinations of ADF, Gini index, and water quality parameters such as residual chlorine or desired values can use multiple objective optimisation techniques. Also finding an optimal solution requires detailed analysis and discussion with stakeholders on what is feasible and acceptable in a given community. This involves assessing many alternative measures to ensure water supply to the underserved people ensuring water for basic domestic water use for the poor and the population at the tail end. Therefore, a contextual analytical framework guided by social conditions and hydraulic modelling is necessary for understanding, managing, and communicating effective water rationing practices.

The way this study has been implemented has some key limitations, simplifications and assumptions, which should be taken into account when the results are interpreted. First, this analysis was done using DD analysis though simulations were verified using PDD as well. Issues such as tank float valve operation, network filling, and emptying can be neglected for the time scales (hours and days) considered in this analysis; some inaccuracies may be introduced in some cases. More advanced tank filling/emptying models than the standard algorithms of EPANET might be needed to precisely model those processes, though again, for the scales we are dealing with in this study, these may be neglected. For theoretical interest, we have analysed relatively long cycle times (e.g. 288 and 576 h) as well, though practically implementing such long cycle times is not advised as it would severely inconvenience customers and overall performance of the network will be dramatically reduced. Further, our modelling did not include the surge impact of closing and opening the network and its components (e.g. float valves). These need to be quantified if their impact on the network longevity and performance is to be estimated. In both the idealized model and the real-world case, we 'lumped' tanks at different elevations (ranging from 0 m – underground, to >6 m–3rd floor and higher) in to two classes, namely at 3 m and 6 m. These two classes clearly showed the impact of tank elevation on equity. However, it should be noted that most extreme equity differences would occur in the elevations between 0 m (underground) and >6 m elevated tanks.

6. CONCLUSIONS

Ascertaining the implications of water rationing on the equity and performance of an urban water supply with household water storage tanks is essential for taking actions to ensure equitable water services. The hydraulic model-based contextual analytical framework has proven to be useful in understanding water rationing based on the duration of supply (cycle time), rationing fraction (duration of non-supply), and domestic storage to analyse the equity and performance in the water network. Increasing the cycle time of water rationing in water supply networks with household tanks can improve equity at an expense of a small reduction in overall water availability. Also, the size of the household tanks influences equity and water availability. Larger storages lead to inequity in water distribution (even if all the consumers have the same tank capacity), necessitating long cycle-time-based rationing fractions to increase the level of equity. On the other hand, minimal or non-existent household storage can negatively impact water availability in a stressed network. Hence, better (water quantity) results, both in terms of equity and overall performance, can be achieved when the average household's storage capacity is around the daily demand of the household. Resolution of supply inequalities can be achieved through the trade-off between equity and performance is possible through the operation of the water network and by the regulation of domestic storage in water rationing regimes.

ACKNOWLEDGEMENTS

AR was supported by the OKP Netherlands Fellowship Programme (NFP). We would like to acknowledge the Kakkapalliya Water Supply Scheme, District, and Regional offices (North-western) of National Water Supply and Drainage Board, Sri Lanka for providing necessary data, information, and support given for the social survey.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories at https://github.com/asselapathirana/Equity-in-rationed-water-supply.

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First received 2 January 2022; accepted in revised form 22 April 2022. Available online 3 May 2022