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A MODEL OF INTERMITTENT WATER SUPPLY SIMULATING THE INEQUITABLE DISTRIBUTION OF WATER

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Abstract

Over one billion people worldwide with access to piped water experience Intermittent Water Supply (IWS), where consumers receive water for only a fraction of the day or week. A widely observed problem associated with IWS is the inequitable distribution of water across the network. This results in different consumers in the network receiving different volumes of water. Modelling the inequity within IWS systems remains an open research field. To date, simulations have often adapted hydraulic modelling software to understand the distribution of water with little attention to the consumer interaction with the network. This paper proposes a conceptual model based on a more holistic understanding of water distribution in IWS systems. Understanding the spatial and temporal variation in received volumes, as well as the variation in consumer access within the network, enables a more representative simulation of the inequitable quantity of water received by consumers.

Keywords
Intermittent water supply, Inequity, Modelling distribution systems.

1 BACKGROUND

Intermittent operation of piped water supply networks is prevalent throughout the world; estimates suggest IWS is operated in 41% of networks in lower and middle-income countries [1]. This is despite the fact there are few, if any, systems that have been intentionally designed to operate intermittently [2]. IWS can affect water quality; frequent de-pressurisation of the network during 'dry-tap' periods creates contamination pathways, causing a substantially higher risk of intrusion of environmental contaminants than in continuous water supply systems [3]. The induced wet-dry cycles and high flow rates influence biofilm detachment, whilst water stagnation and household storage of water increases retention time and bacteriological growth [2]. Moreover, dynamic hydraulic forces in IWS may accelerate infrastructure deterioration, leading to increased leakage rates [4]. Different studies have found that the impact of such mechanisms vary significantly between systems in different locations [5], [6]. Despite this, it is estimated IWS causes significant impacts to public health resulting in an estimated 4.5 million diarrhoeal disease cases and 1560 deaths per year [7].

1.1 Inequitable Distribution of Water

Attempts to quantify volumes of water received by different users in an IWS network have often shown widespread inequity. A study in Hubli-Dharwad, India, used household surveys to calculate the consumed volumes of water of different consumer groups. The authors found the water usage ranged from 21.0 to 97.1 Litres per capita per day (LPCD) [8]. In Kathmandu, Nepal, a household survey (n=369) measured the inequality in distributed water [9]. It found dependence on tankered water to supplement water demand varied from 8 - 51% between different household groups, indicating large differences in the adequacy of the piped supply. The variation in Kathmandu produced a Hoover Index for the city of 0.51 indicating that 51% of the supply hours need to be redistributed in order to achieve equality of supply hours.

This paper proposes grouping the factors influencing the inequitable quantity of water received by consumers into three broad categories:

(a) Supply characteristics

(b) Network hydraulics

(c) Consumer access (to the network connection and storage volume)

1.2 Supply Characteristics

Observations from systems across the globe have recorded the wide range of intermittency regimes. These have been categorised into unreliable, irregular and predictable supply [10]. Unreliable supply means water is supplied at random times with gaps between supply periods ranging from days to weeks. This induces the greatest hardship for consumers and can lead to drastic action such as local protests [6]. Irregular supply means a reliable total volume supplied but with unknown delivery timings, while predictable supply means a consistent supply schedule with a guaranteed volume received each week. With enough storage, predictable supply can enable households to mitigate the majority of the effects of intermittency [10]. In Kathmandu, consumers placed equal expectations on improvement in regularity of supply as they did for the total volume supplied, highlighting the value placed on predictability of supply [9]. In summary, the mode of operation of an IWS network has a profound impact on the adequacy of the supplied water.

1.3 Network Hydraulics

Erickson et al. [6] found large variation in received supply between differently operated IWS networks and within networks in Panama: “walking 50 yards up a hill in Zone 1 could take you from a house where supply rarely went out to a house where supply went out most afternoons” [6]. Spatial variation in hydraulic conditions resulted in service quality being unequal between neighbours as well as between neighbourhoods.

An unequal distribution of pressure across IWS networks has also been widely observed, for example, Ghorpade et al [11] observe inequitable pressure in IWS systems in India. This is supported by Andey & Kelkar [12] who found significant variation in the measured pressure across four IWS networks also in India. Sánchez-Navarro et al [13] recorded the pressure at 347 points within an IWS network in Chihuahua, Mexico, over 3 years. The results showed significant variation in the local pressure at different points in the network. Chandapillai et al. [14] conclude that the pressure dependency in IWS networks make them innately inequitable.

1.4 Consumer Access

Having sufficient storage availability can mitigate the impact of intermittency and ensure an adequate volume of water for the household. In Jaipur, 77% of respondents found a three-hour supply period to be adequate, where 76% of respondents in Panaji said that their five-hour supply period was inadequate [12]. The authors suggest this discrepancy is a result of greater household storage volume in Jaipur compared to Panaji.

In Hubli-Dharwad, a survey of the population was used to define their access to the piped network [8]. The study found a range of consumer access that they classified by (i) connection access (i.e. whether the connection was shared with neighbours) and (ii) storage volume (i.e. whether they had an overhead storage container or not). The volumes received varied accordingly, with a difference of 76.1 LPCD between the lowest and highest access groups. In Greater Amman, Jordan, household surveys revealed a stark contrast in the available household storage volume with average volumes of 3.12 and 16.24m^3 for low and high-income households, respectively [15]. This appeared to correlate with the average consumption values of the two groups of 32.68 and 70.24 m^3 per quarter.

1.5 Modelling IWS

Modelling the distribution of water in IWS systems is an ongoing challenge. The majority of literature aiming to simulate IWS has thus far focussed on using hydraulic modelling software [16], [17], such as EPANET, which are designed for continuously operated systems, i.e., water is distributed according to demand. Various attempts have been made to adapt existing hydraulic models to better represent intermittent systems. Batish [18] modelled demand nodes as reservoirs in EPANET to imitate pressure dependent demand. The effect of consumer storage has been modelled by replacing the reservoirs with tanks, which fill during supply hours resulting in volume dependent demand [19]. These models are more realistic as they are able to represent how the storage volume available to a consumer limits the quantity of water they can receive during a supply period.

De Marchis et al [16] consider the effects of the filling process when water supply is turned on in the network. The unique hydraulic conditions during the filling and emptying stages of IWS networks may be significant in determining the received quantities of water, however, there is insufficient data to validate their model. These models are limited to only analysing the network hydraulics of the system and partial effects of consumer storage volume. The wider structure of the system such as the supply characteristics and other consumer access issues are not captured. Additionally existing models have a fundamental problem: they are difficult to implement in IWS settings due to the requirement for detailed network data that is often highly uncertain.

In response to this problem, an alternative approach has taken the principle of parsimony to model an IWS network in order to maximise learning with minimal input requirements [20]. The author simplifies a hydraulic network into a single consumer and a single leak. The model reveals the relationship between the bulk values of consumer usage and leakage against changes in supply duration. Taylor et al. [20] propose a new parameter termed consumer demand satisfaction (CDS), which is the degree to which consumers are satisfied with the volume of water they receive. Crucially, CDS defines the point at which consumers will turn off their taps, re-directing water to other areas in the network. In this way, the model begins to explore the interplay between consumers and the network; however, the variability in the distribution of water within the network cannot be reflected.

The models to date cannot incorporate all the factors highlighted. The modelling techniques revolve around the network with much less attention given to how consumers use and store the delivered water. The temporal effects of these factors require particular attention. The first step to develop more representative models is to interrogate all the factors influencing the quantity of water received by a consumer over a period of time.

2 METHODS: AN ANALYSIS OF THE QUANTITY OF WATER RECEIVED BY A CONSUMER IN AN IWS SYSTEM

This investigation is split into three sections following the three categories defined previously. Firstly, the influence of supply characteristics is considered. Secondly, the network hydraulics are assessed through analysis of a single supply period. Finally, the impacts of consumer access are discussed. Figure 1 summarises the key determining factors and their grouping.

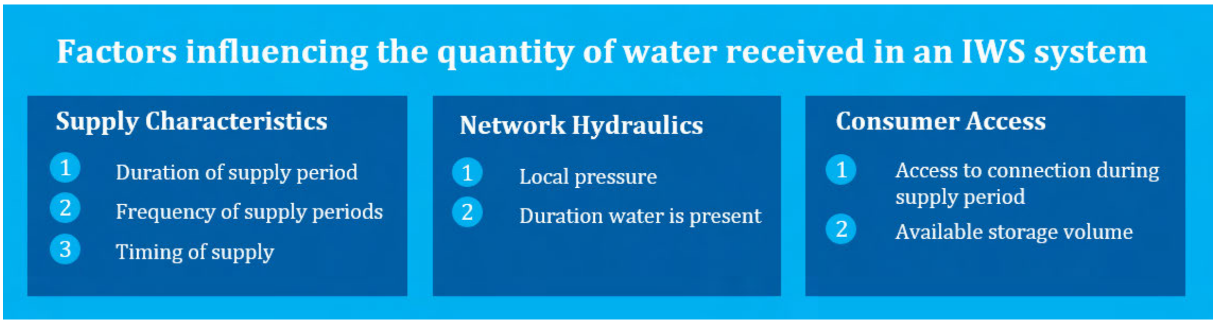

Figure 1. Categorisation of the factors influencing the volume of water received by consumers in IWS systems

2.1 Supply Characteristics

The supply characteristics govern all aspects of the quantity of water received by a consumer in an IWS system. A longer supply period allows water to reach further in the network for longer, thus, supplying water to more consumers. More frequent supply periods reduce the duration of the non-supply period reducing the reliance on storage volume.

Supply Timing: When the supply is on, households use the water to fill storage and complete domestic tasks. The timing of supply impacts how usable water is during these supply hours. Inconvenient timings, such as a supply period during the night, make it far less convenient to use water during supply, therefore limiting a consumer's access to water. The impact of supply timing is mitigated by having sufficient storage, since household tasks do not need to be concentrated around the delivery of water. Consequently, the timing of supply compounds the disadvantage of inadequate storage and disproportionately reduces access to water for those with limited storage.

2.2 Network Hydraulics

This analysis aims to identify the principles governing the distribution of water in an IWS network, focusing on the factors that affect the quantity of water received in different locations. The volume of water which leaves the network through a leak or consumer connection, is a function of time t, pressure H and orifice area A as per equation (1):

$$V_L = C_d . t . A . (2gH)^{\alpha} \tag{1}$$

$C_d = Factor\ to\ account\ for\ orifice\ shape$
$g = Gravitational\ acceleration$
$\alpha = Factor\ to\ account\ for\ the\ flow\ rate's\ pressure\ dependency$

The volume of water that leaves a given orifice will therefore depend on the duration that water is present and the local water pressure. An IWS cycle consists of several stages that impact the magnitude of these two parameters across the network.

Filling: When the water is turned on, it fills the network from the inlet sources. The velocity at which water travels through the network will be dependent on the following factors: inlet pressure, relative elevation, frictional losses from the pipes, water demand and the ease at which air is released from the pipes. Therefore, the time it takes to arrive at a particular location in the network, will depend on these factors in combination with the distance from the inlet.

Water Delivery: Once the network has filled, the Bernoulli equation shows that the pressure at any point in the network is a function of the relative elevation and the frictional losses. It follows that locations in the network which are closest to the inlet location and at a low elevation will have the highest local pressures.

Emptying: When the input supply is turned off, the network will drain out of the orifices (leaks and consumer taps). The network will drain under gravity meaning it will empty from the higher elevations down to the lower elevations. As in the case of the filling stage, this results in different durations of water being present in different locations.

These stages of the supply period result in differential local pressures and supply durations across the network. The orifice equation shows that this will result in different total volumes of water leaving orifices in different locations. As a result, leakage volumes and the volume of water received by different consumers will vary across the network.

2.3 Consumer Access

Consumer Access during the supply period: The delivery of water from the inlet sources to consumer connections is only part of what determines how much water individual consumers receive. During supply, if a connection serves more than one household, the received supply time is divided by the number of groups sharing the connection. An additional consideration is the rate at which water can realistically be used by a household. Once storage vessels are filled, households must use water as effectively as possible for household tasks. There is a limitation on what is physically possible which may be less than the flow rate of water out of the tap (depending on the local pressure).

Storage Volume: The storage volume and the length of time between supply periods dictate the access to water during the non-supply period. For instance, we can compare two systems that both supply seven hours of water per week. In the first system, a household receives water for seven hours once a week; while in the second system, a household receives water for one hour seven times a week. The individual household storage volume will drastically alter the quantity of usable water received over the course of the week in the two scenarios. Without a very large storage tank, the household water supply in the first scenario will be severely restricted while in the second scenario a small storage volume will not have such an effect.

3 RESULTS: A CONCEPTUAL MODEL OF IWS SYSTEMS

The analysis of how water is distributed from source to point-of-use results in the conceptual model shown in Figure 2. It follows the flow of water through the system and therefore how different consumers will receive different volumes of water. The model operates over a fixed period of time, be that a week or month, to establish the operation of the system and the volumes of water received by consumers.

The output of the model is the received volumes and associated consumer demand satisfaction of the different consumer groups. Utilising demand satisfaction ensures water is re-distributed to other groups simulating taps being turned off. The range in consumer demand satisfaction in turn describes the inequity in the system. The number of network 'zones' and 'access groups' required to represent the system is dictated by the local context.

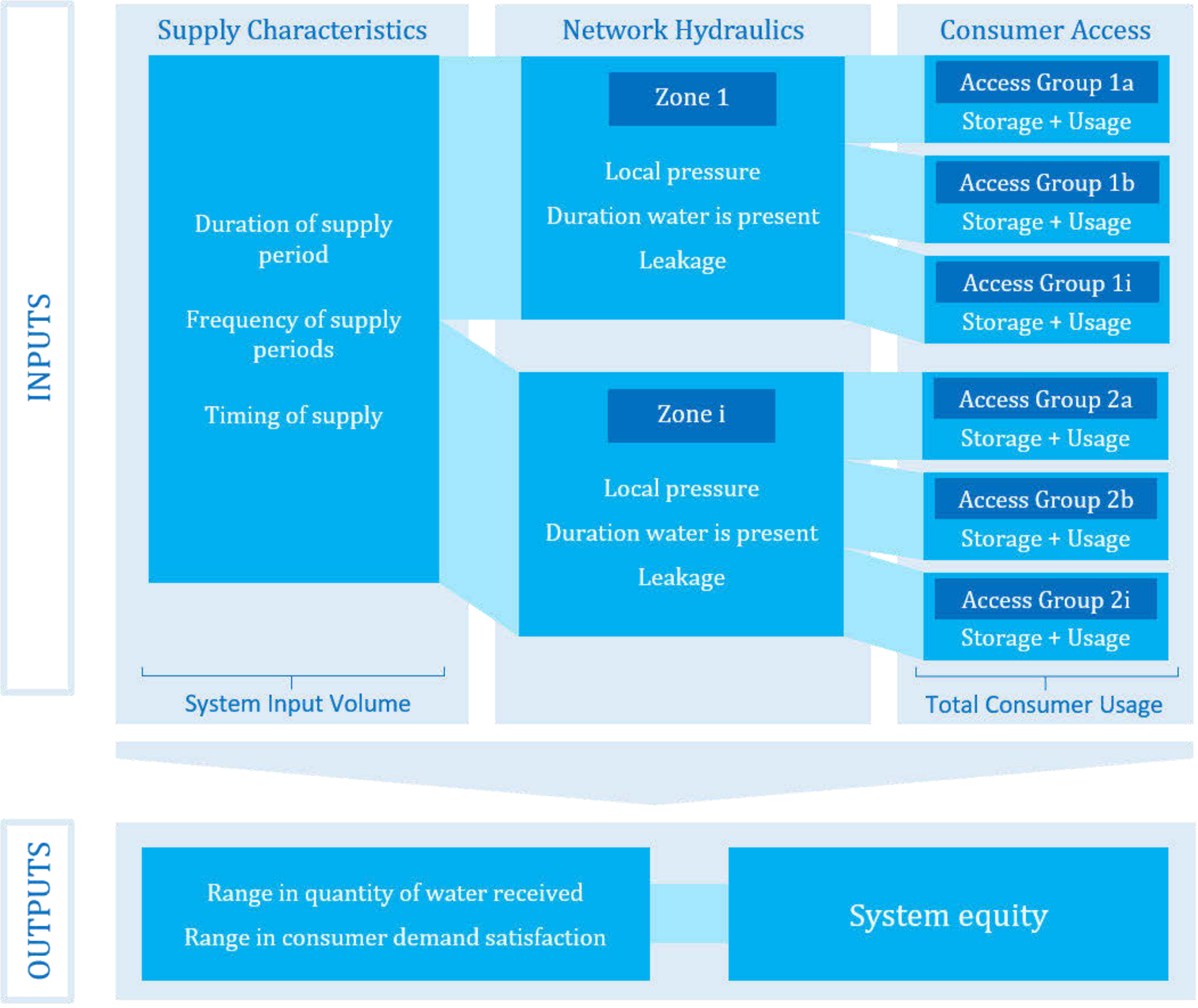

Figure 2. A conceptual model of the distribution of water through IWS systems

4 DISCUSSION

The model illustrated by Figure 2 enables an understanding of how an IWS system results in different quantities of water received by consumers. The hydraulic behaviour of IWS networks results in different pressures and duration that water is present for different zones in the network. The inequitable quantity of water received across the network is compounded by differences in access to the connection. Consumers sharing a connection must divide the volume supplied between themselves. Access to water during the non-supply period is constrained by the storage volume. Both of these categories are governed by the supply characteristics, which determine the volume received at a particular location during the supply period as well as over the course of a week or month.

Ultimately, the key output of the model is the range of consumer demand satisfaction in the system. Once the model represents a system, different scenarios can be run against the model to assess their impact on demand satisfaction. For example, increasing supply hours, changing supply frequency or ensuring one connection per household. The model will show that changes to the system do not result in uniform impact across all consumer groups. The unique characteristics of each group dictate the manner in which they will be affected.

5 CONCLUSIONS

To understand IWS systems it is important to consider the supply characteristics, network hydraulics and consumer access to their network connection. This allows a full consideration and representation of the inequity in the system. Currently models fail to appreciate the wider system beyond the network boundaries and therefore fail to represent the inequity of the system. By analysing both the hydraulics of a supply period and the wider factors of consumer access and input characteristics, a more representative model can be achieved.

This paper proposes an alternative approach to modelling IWS systems based on representing the distribution of water from source to point-of-use. The conceptual model presented in this paper builds the foundation for more detailed and applicable models. These will allow the inequity of an IWS system to be better represented and will also enable predictive capabilities of a wider range of system interventions.

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