Household Water Withdrawal Behaviour under Intermittent Water Supply

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Abstract

Piped networks are the predominant method of distributing water to households in urban areas. In many cities across the world, the piped network operates intermittently with water supplied for less than 24 hours per day. These Intermittent Water Supply (IWS) networks are estimated to affect over one billion people worldwide, predominantly in the Global South. Operating intermittently requires households to adapt their water withdrawal habits in order to manage their access to water, for example, storing water for the ‘dry pipe’ periods. The effects of IWS are not felt equally amongst the served community as intermittent operation causes unequal distribution of water across the network.

Efforts to better manage IWS networks and, if possible, transition to continuous ‘24/7’ water supply are hampered by the current lack of models that can simulate IWS behaviour accurately. A significant obstacle is the paucity of data regarding household withdrawal behaviour, a key driver of the water dynamics in a piped water network. This study aimed to investigate the influence of supply conditions and household characteristics on water withdrawal behaviour under IWS conditions

A comprehensive data collection programme in an operational IWS network enabled new insights that can unblock progress towards effective management of IWS systems. In partnership with The Beacon Project, the IWS network of Lahan, Nepal was monitored in greater detail than any previous study. A series of 56 household volumetric flow meters were installed coupled with a household survey and pressure sensors distributed across the network. Together they form a first-of-its-kind dataset revealing the dynamics of an IWS network.

The data revealed ‘pooling’ phenomena where water drains down the network and sits at the lowest elevations, leading to a portion of Lahan receiving continuous water supply. Households employed a range of adaptations that were influenced by both their wealth and local supply conditions. Highly variable withdrawal behaviours were observed; the specific withdrawal signature of a household was strongly associated with their volume of storage. Current simplifications utilised by modellers do not accurately reflect this highly heterogeneous and coupled behaviour.

The quantity of water that households withdraw was not found to correlate with their local supply hours suggesting a more complex relationship between household water demand and IWS conditions. Widespread use of other water sources complicates the notion of ‘consumer demand satisfaction’, leading to a proposed separation of piped water demand and total water demand. Analysis of the Lahan case study led to the development of a new framework that describes the relationships and processes that govern water access under IWS supply. The framework highlights the crucial intersection of supply conditions and household adaptations to determine inequitable access to water. This has wide-ranging implications for hydraulic models of IWS, long-term demand forecasting and network management approaches.

Contents

Key Terms

Water Withdrawal	The abstraction of water from the piped network
Water Withdrawal Behaviour	The manner in which water is abstracted, including both the quantities and temporal variation
Water Withdrawal Practices	The methods used by households to abstract and store water from the piped network
Consumer Withdrawal	Water withdrawal that refers to any type of piped water connection (including offices, and schools)
Household Withdrawal	Water withdrawal that specifically refers to households connected to the piped network
Water Usage	The use of water by consumers for any purpose (from any type of water source)
Piped Water Demand	The volume of water desired by the consumer from the piped network
Total Water Demand	The total volume of water desired by the consumer from any water source
Water Consumption	The volume of water withdrawn from the piped network over a given time frame
Consumer Demand	The piped water demand of a connection in a piped network (may represent a single household or grouped consumers)
Supply Conditions	The temporal variation in pressure within the piped network or a specific locality within the piped network

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1 Introduction

In 2015, all 191 United Nations (UN) member states adopted the Sustainable Development Goals (SDGs), one of which, SDG 6.1, aims to 'achieve universal and equitable access to safe and affordable drinking water for all' by 2030. Evidently, there is a united pursuit to provide water access for all; however, the pace of change is not matching the ambitions of this goal. In 2023, UNICEF & WHO (2023) reported that a six-fold increase in the current rate of progress is required in order to realise safely managed drinking water by 2030. Therefore, despite the global ambition, more work needs to be done to bring it to fruition.

The global indicator for SDG 6.1 is the 'population using safely managed drinking water services' (WHO & UNICEF, 2017). 'Safely managed' sits at the top of the service-level ladder and must satisfy the following three criteria:

- It should be accessible on premises;
- Water should be available when needed; and
- The water supplied should be free from contamination.

It has been demonstrated across the world that piped networks have the potential to meet this standard. This is achieved through continuous pressurisation of the piped network and active management of water quality, providing an often-unnoticed transfer of water from source to consumers. Piped networks are therefore the prevailing method of distributing water across urban areas playing a critical role in securing equitable health in their communities. However, in many cities across the world, they are operated intermittently; meaning water is supplied to consumers for less than 24 hours a day. Such networks are referred to as Intermittent Water Supply (IWS) networks and are estimated to serve one billion people worldwide (Bivins et al., 2017). Under intermittent conditions, the extent to which the piped network meets the criteria of 'safely managed' is dubious (Lee & Schwab, 2005). This will be discussed further in the literature review chapter.

Intermittency forces households to make adaptations such as storing water and using other sources (Kumpel et al., 2017). It creates several inequalities, both directly through unequal distribution of water across the network and indirectly by imposing the need for households to adapt to their water supply (Grasham et al., 2022). Intermittent operation of the network creates several pathways for water contamination (Kumpel & Nelson, 2016); the predominant mode being water entering the pipes during the non-supply times due to the lack of positive pressure (Taylor et al., 2018). Other issues relate to the scour of biofilms during the filling stage and increased water age due to households storing water (Vásquez, 2016).

Intermittent water supply is not a modern phenomenon; papers from the 19th century reveal associations between IWS and public health outbreaks in London (Blaxall, 1873). Carpenter (1875) connected outbreaks of fever in Croydon, UK to the practice of IWS. The author makes the link between sewage intrusion and the pipes being de-pressurised during the day during high demand. The paper concludes that continuous water supply (CWS) must be the goal for piped water supply. A more recent study that has used data from this period, found that London’s conversion from IWS to CWS explains approximately a fifth of the decline in waterborne diseases over this period (Troesken et al., 2021). In addition, a one percent increase in the local population with access to CWS caused up to a 0.4 percent decrease in deaths caused by waterborne diseases (Troesken et al., 2021).

At a superficial level, IWS appears to be ‘low-hanging fruit’ in the quest to achieve SDG 6.1; the infrastructure is there, what else is required? In reality, achieving a transition to CWS has proven to be a challenging task (Charalambous & Laspidou, 2017). In fact, the modern day existence, prevalence and perpetuation of IWS is a complicated multi-disciplinary problem, which goes far beyond purely technical challenges (Klassert, 2023). Transitioning to sustainable, CWS necessitates an array of actors and specific socio-political conditions to be achieved (Vathanan, 2024). Thus, the problem of IWS will require knowledge from a range of disciplines to see the progress of change that is required. That withstanding, this thesis views the challenge of IWS predominantly through the lens of the network managers. Although they are just one piece of the puzzle, they are a critical component in shaping water access in their localities (Vairavamoorthy et al., 2007). Furthermore, transitioning a network is redundant if the operators do not have the capacity to keep it running in the long-term.

Currently, their agency is being strangled by a lack of tools to help manage IWS networks (Sarisen et al., 2022). Hydraulic models are the predominant method of managing the complicated nature of piped networks (Speight et al., 2010). Traditionally, hydraulic models of IWS have relied on the same programmes that were designed for CWS conditions. This has resulted in critical features of the intermittent cycle, such as the filling and draining phases, not being effectively simulated (Sarisen et al., 2022). Furthermore, a key roadblock in developing accurate models is a lack of understanding of how consumers withdraw water under intermittent conditions (Abdelazeem & Meyer, 2024). A paucity of data from IWS networks has led to far-reaching assumptions having to be made.

In order to enable better management tools for IWS networks, this thesis aims to fill those gaps through a comprehensive study of an IWS network. Crucially, synchronised data from both the network and households that use the piped supply have been collected. In doing so, greater attention is brought to the human behavioural elements of household water usage under IWS. Untangling these relationships will enable essential tools for managing the water supply system in the short and long-term.

Analysis of a case study (Lahan, Nepal) will be conducted through close partnership with The Beacon Project (a collaboration between Anglian Water and WaterAid) as well as the National Water Utility of Nepal, NWSC. The coordinated work of the partner staff, and the close relationships maintained throughout the project, has been central to enabling the following research to be conducted.

2 Literature Review

This review aims to establish the current academic understanding of Intermittent Water Supply (IWS) systems in order to identify areas that require further research. Firstly, an overview of the problem will be synthesised, establishing why it warrants attention. Following this, the unique challenges of managing IWS networks will be explored, followed by a thorough examination of the difficulties it presents for the served communities. Assessment of current management methods will identify the most pressing barriers to progress. Attention is drawn to existing approaches of forecasting demand as well as modelling IWS systems. Identifying precisely how these methods fall short, will direct where additional research is required. The chapter will conclude with a summary, reflecting on the key findings of the literature review and highlighting the critical gaps in collective understanding.

2.1 Intermittent Water Supply: A Global Problem

IWS refers to the supply of water through piped networks that regularly operate for less than 24 hours per day. Estimates suggest IWS is operated in 41% of networks in lower and middle-income countries, affecting 1 billion people (Charalambous & Laspidou, 2017). It has significant impacts on public health with an estimated 4.5 million diarrhoeal disease cases per year and 1560 deaths resulting from it (Bivins et al., 2017).

Galaitsi et al. (2016) categorise types of intermittency into three categories: predictable, irregular, and unreliable. Predictable intermittency, the least burdensome, is when both the quantity and timing of the water supply are known. Irregular intermittency refers to situations where the quantity is predictable, but the timing is not. The most burdensome is unreliable intermittency, where neither the quantity nor the timing of the supply is known, placing the greatest burden on the consumer. In reality, IWS systems are unlikely to fit into these neat categories, exhibiting varying degrees of regularity and reliability at different times. However, the general concept is helpful in reflecting the wide range in conditions that sit under the banner of IWS.

Several attempts have been made to identify the root causes of intermittency (Ilaya-Ayza et al., 2016; Kaminsky & Kumpel, 2018). Totsuka et al. (2004) attempted to categorise IWS based on the underlying cause of the intermittency: absolute scarcity (a lack of water), technical scarcity (a lack of operational ability) and economic scarcity (a lack of finance). Galaitsi et al. (2016) aimed to investigate the causes of IWS through a literature review. They found that the factors of highest influence were anthropogenic and not a scarcity of water resource, denouncing the simplistic explanation of not having enough water. The factor of greatest influence identified by the authors was prioritising the broadest network distribution to connect the maximum number of residents. This results in a system that cannot meet demand, thus resulting in intermittency.

In South Africa, it was estimated the population experiencing IWS increased by 26% from 2000 – 2017 (Loubser et al., 2021). The authors of the study suggest the prevalence of IWS in South Africa is a combination of an over-emphasis on adding more connections to the network, neglecting maintenance and not ensuring adequate water resources. In Zambia, Simukonda et al. (2018a) concluded that the causes of intermittency were five-fold: (i) Governance: There is a lack of available resources to fund problem solving, (ii) Demographics: Much of the population lives in peri-urban areas without structured development, (iii) Hydraulic regime change: Building on aquifer re-charge areas is depleting the water resources, (iv) System management and operation: Poor database management means there is insufficient data, (v) Unplanned system extensions. The authors conclude that interdisciplinary approaches are required to explore solutions to IWS.

Mokssit et al. (2018) propose a generalised assessment of IWS systems using the following parameters: availability, affordability, quantity, quality, accessibility and equity. The framework is designed to give scores to the different terms to identify the appropriate interventions. These are reasonable parameters yet their breadth makes it difficult to point of any specific direction once the assessment has been carried out. They may give an overall impression of the service quality of an IWS system but offer little value beyond that.

The studies from across the world show the breadth and complexity of IWS systems. The causes span both technical and societal realms highlighting the need for interdisciplinary approaches to explore the issue and design relevant interventions. Managers of IWS networks have a difficult task given the array of factors that are contributing to the prevalence and persistence of IWS.

2.2 The Challenge of Managing IWS Networks

This section will review the issues associated with IWS from the perspective of the water network manager. The review highlights that intermittency presents challenges for the water utility beyond those experienced under continuous water supply conditions.

2.2.1 Unequal Distribution

Operating IWS is known to effect the equality of supply within the network (Sánchez-Navarro et al., 2021). During the filling phase, different households receive water at different times; a study by Weston et al. (2023) used a combination of lab experiments and field data to quantify the disparities caused by the network filling. They found that elevation plays a crucial role in the network response to filling; in higher elevation areas, trapped air in the pipes elongates the filling process. The authors of that work recommend strategically placed air-release valves to help counter this issue, potentially reducing inequalities.

Erickson et al. (2020) continuously monitored the pressures in an IWS network in Arraiján, Panama. They found significant variation in supply conditions between differently operated IWS networks and within networks: ‘For instance, 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.’

A study in Kathmandu used a household survey (n=369) to measure the inequality in distributed water producing a Gini coefficient of 0.67 (Guragai et al., 2017). The Gini coefficient is a statistical measure of inequality calculated as the deviation from a linear cumulative frequency (for example, inequality of income levels worldwide is estimated to have a Gini coefficient between 0.61-0.68 (UNDP, 2010)). The Hoover Index for the city was 0.51 indicating that 51% of the supply hours need to be redistributed in order to achieve equality of supply hours. The groups with the lowest received supply hours had a significantly higher desire for greater frequency of supply indicating this was a major barrier to demand satisfaction. It was also found that the regularity of supply was weighted as important as an increase in volume received. A wide range of supply hours were reported by residents connected to the piped network of Sulaimani Province, Iraqi Kurdistan (Nareeman et al., 2024). Fifty percent of residents reported CWS, while in the IWS group, reports ranged from having water once a week to several times a day. In the IWS group, only 13% of respondents said the quantity was not sufficient while 45% said it was sometimes sufficient. Scarcity was significantly higher during the summer season.

Ghorpade et al. (2021) observe unequal pressure in IWS systems in India, which is attributed to ‘pressure drops at various locations’. This is supported by (Andey & Kelkar, 2007) who found significant variation in the measured pressure across four IWS networks in India. Sánchez-Navarro et al. (2021) recorded the pressure at 347 points within an IWS network over 3 years. The results showed significant variation in the local pressure at different points in the network. Klingel (2012) argues that the variance in pressure distribution is exaggerated by high flow rates. High flow rates exist as consumers aim to receive as much water as possible during the supply period leading to greater head loss in the pipes meaning greater losses in pressure. The use of household pumps to draw out water from the piped network is widespread despite it being illegal in many areas (D. D. J. Meyer et al., 2021). The practice could lead to greater inequalities as water is diverted to those that can employ the pumps.

2.2.2 Water Quality

IWS impacts water quality via several pathways; Kumpel & Nelson (2016) review the various contamination pathways within IWS networks. These are grouped into: Intrusion and backflow, biofilms, loose deposits and microbial growth. The lack of a continuous positive pressure creates a pathway for contaminants to enter into the pipes. Although the contamination pathways are well established, data is scarce regarding measured negative pressures in IWS networks. Erickson et al. (2020) measured pressures across a year and found steady-state negative pressures were common in one location at the crest of a hill, the authors suggest this is due to siphoning over the hill. Transient pressures were also detected regularly in this study associated with the operation of a nearby pump.

Intermittency can cause wet-dry cycles within the pipes, this has been found to make biofilms more susceptible to detachment (Douterelo et al., 2013). Biofilms grown in stagnant water also exhibit higher microbial growth exacerbating the problems caused by intrusion (Manuel et al., 2007). At the end of the distribution system, the use of household storage is another water quality risk; residence time of treated water is positively correlated to microbial growth (Grayman et al., 2004). Coelho et al. (2003) found that the storage material had no effect on the bacteriology; however, the stagnation time was correlated with an increase in bacterial growth. Judah et al. (2024) found that stored household water had greater concentrations of coliforms than the source water. The authors tested methods of improving the water quality of the stored water concluding that regular cleaning using a solution of sodium hypochlorite was the most effective approach. The practicality of maintaining this behaviour was not studied however.

2.2.3 Leakage

Operating a piped network intermittently is thought to increase the rate of network deterioration causing higher leakage rates (Christodoulou & Agathokleous, 2012; Mckenzie, 2016). Mokssit et al. (2018) interviewed twelve operators of IWS networks across the world. They found a consensus that operating intermittently increased rates of leakage and maintenance costs. A network in Cyprus temporarily operated IWS for two years following a drought before returning to CWS. The system was monitored during this period and it was found that there was a 200% and 100% increase in mains and connection breaks respectively (Charalambous & Laspidou, 2017). The authors found initial reduction in water input after converting to IWS followed by increased input after the second year despite consumer consumption remaining steady, indicating an increase in leakage. Contrasting results were reported in an IWS network in Makkah, Saudi Arabia, where the majority (63%) of the leaks were attributed to property connections as opposed to the network mains (Al-Ghamdi, 2011).

Urban water demand management (UWDM) is a commonly applied approach to managing the water demands of piped networks (Sharma & Vairavamoorthy, 2009). Reducing leakage is one of the principal components of UDWM; a first step to achieving this requires an understanding of the current levels of water losses in the network. The IWA Water Audit is a method of calculating a water balance of a water distribution network with particular focus on revenue and non-revenue water. First published by (Alegre et al., 2000), the audit method was adopted by the AWWA and adapted several times for use in different contexts (Fanner et al., 2007; Georgia Association of Water Professionals, 2016; McKenzie & Seago, 2005; Radivojević et al., 2020). Mastaller & Klingel (2018) apply the IWA water balance to a DMA in in IWS network in which there is no consumer metering. The study installed household meters in a sample of the population to estimate the billed authorised usage of water. The results showed that 40% of the system input volume was lost to leakage (Real Losses). While a further 33% of the input volume was non-revenue water resulting from unbilled authorised consumption.

Conducting a water balance is a useful tool for network operators; however, it relies on sufficient, reliable data regarding the operation of the network (Charalambous & Laspidou, 2017). Such data is notoriously difficult to achieve in IWS contexts as will be outlined in the following sections.

2.2.4 Revenue Collection and Metering

The collection of revenue is critical to the sustainability of a water supply system (Simukonda et al., 2018b). In Kathmandu, it was found the willingness to pay across all income bands was almost six times higher than the current amounts spent on adaptations, which itself was almost twice as much as that spent on the monthly water bill (Pattanayak et al., 2005). Many systems where IWS is prevalent often have poor revenue collection performance due to both the tariff structure and quality of metering (Mastaller & Klingel, 2018). In Kathmandu, recommendations for a new tariff structure based on volumes consumed were highlighted to complement the infrastructure investment of the new Malamchi Supply Project (Ayadi et al., 2020).

Improved tariff structures must also be accompanied by the ability to measure usage volumes accurately; metering in IWS conditions is hampered by the expulsion of air as the system fills resulting in inaccurate readings. Walter et al. (2018) demonstrated this in lab experiments testing both single-jet and multi-jet meters. They found that up to 93% of the air volume expelled out of the pipe is registered by the meter. Ferrante et al. (2022) also conducted lab experiments to quantify over-registration of meters due to air expulsion. They estimated, under a worst-case scenario, that over-registration could amount to up to 90m3/year. This was assuming all the air from the nearby pipes were to be ejected through the meter. They also found five out of the six meters they were using for the test broke due to the axel failing because of spinning at rotations four times greater than their design speed. When air was being expelled, the meters rotated 14-17 times more quickly than when water was expelled. However, this is under laboratory conditions and it cannot be confirmed how this corresponds to field conditions where there are many pathways through which air could be expelled.

Meter under-registration is also a concern when flows are very low; Criminisi et al. (2009) aimed to quantify the under-registration of meters under lab conditions. They found errors were highly correlated with meter age. Meters in the 40-45 year category returned errors up to 83% under registration whilst meters in the 0-5 year category had an average error of 2.6%. The impact of household tanks with float valves was also tested. If tanks are almost full then the float valve will limit the flow meaning very low flow rates will occur. In these circumstances, significant meter under-registration occurs (Criminisi et al., 2009).

2.2.5 Monitoring IWS Networks

A major conclusion from Erickson et al.'s (2020) study in Arraiján, Panama was that intermittent supply could be made more reliable at a local level by using pressure and flow monitoring routinely and/or as a diagnostic tool. On a wider level, reducing water losses, providing adequate storage capacity and improving monitoring could make supply more continuous and reliable. However, showing utilities the value of monitoring systems was crucial to ensure they are sufficiently maintained. The author concluded that data is fundamental to making informed decisions and optimisation attempts. An unresolved issue however, is determining the appropriate balance of affordable but sufficient network data.

There have been attempts to implement customer notification texts to help make unpredictable IWS more predictable. Kumar et al. (2018) attempted this in Bangalore, India. The program returned little improvement in service, which was attributed to poor transfer of information, highlighting the complexity of disseminating information to the public.

Due to a lack of available measured network data, D. D. J. Meyer et al. (2023) utilised water utility data at a higher level, analysing supply schedules to assess the range in supply regimes in India. They uncovered high inequalities in supply hours and timings across the 3278 different supply schedules. The authors discuss the limitations of using this coarse data and the self-reported nature of it potentially adding bias. A major recommendation is for water utilities with IWS to systematically measure and document network performance.

Sioné et al. (2022) used a citizen-science approach to collect data regarding the operation of an IWS network in Kathmandu. They found that the approach was successful in generating reliable data that was accepted by the network operators. However, they noted that the willingness to participate varied amongst different communities, potentially resulting in a non-representative sample. In addition, the attrition rate of long-term contributions was highlighted as a possible issue with the method, although it was not a problem in this study due to its short-term nature.

2.3 Consumer Challenges and Household Adaptations

The lack of supply continuity shifts the responsibility of managing access to water from the network operator onto the household connected to the network. Consequently, IWS places burdens on the consumer that do not exist in continuous (Huberts et al., 2023). In the literature, there are several terms that are used to refer to these burdens, such as: coping costs, coping strategies, coping mechanisms, adaptation costs, adaptation strategies, etc. For simplicity, they will be referred to as household adaptations throughout this thesis.

2.3.1 Use of Other Water Sources

A common practice amongst households under IWS conditions is to use other sources of water to fulfil demand. The reuse of grey water is limited by the fact household plumbing often just consists of a yard tap, making collection and reuse unrealistic. Shrestha et al. (2020) argue that having access to multiple sources increases the resilience of households. They examined the change in use of other sources pre- and post- an earthquake in Nepal. A total of ten different sources were used: piped water, private groundwater, rainwater, neighbour’s piped water, neighbour’s well, public well, surface water (lake/pond), stone spout, jar water, and tanker water. Following the earthquake, the use of more than one source increased from 74 to 84%. The use of other sources may increase resilience in one sense but the water quality of the different sources is not assessed. Having to rely on unregulated sources for a large proportion of water-use activities has potential health consequences.

A study based on focus group discussion in Greater Accra, Ghana found that sachet water was the predominant alternative to the intermittent piped supply (Tutu & Stoler, 2016). They found prices increase by 100-150% when supply interruptions increase demand. The time burden of seeking other sources of water often led students to miss school and adults to be late for work.

Household surveys in Greater Amman, Jordan found that across all demographics, the average spent on bottled water was 3.5 times greater than that spent on water bills (Potter et al., 2010). A study in Kathmandu found users spent 3.4 times as much on vended water compared to mains supply (Raina et al., 2019). A different study estimated that the cost of tankered water was 27 times greater than piped water (Guragai et al., 2017). In Delhi, it was estimated that household’s spend on average 5.5 times more on adaptations than what they pay for the piped water supply (Zérah, 1998). Costs include installing and maintaining tube wells, acquiring storage tanks, treatment of water and estimates associated with time costs of managing their water supply and income losses from illness associated with the poor water quality.

Aljadhai & Abraham (2020) investigated the short-term decision making processes of households in a city in the Middle East. They found that 71% of households would source water from a tanker truck even if they had water currently in their storage tank and 56% would pay twice the price to receive tanker truck water within 24 hours rather than wait. Household characteristics, wealth and previous experiences all affected when they would seek tanker truck water in response to piped supply outages.

The use of different sources also influences the type of household water purification different consumers utilise. In Kathmandu, jar-water users preferred using boiling while groundwater users used reverse-osmosis / ultraviolet purification methods (Khanal et al., 2023). Both methods achieved moderate to high removal rates but recontamination was a common problem.

2.3.2 Household Storage

Often households acquire storage to enable water use during non-supply hours. A study in Kathmandu found that 66% of household have a basement tank while 75% have a rooftop tank (Guragai et al., 2017). Basement tanks were typically made of reinforced concrete with a mean volume of 6.7m3. This was larger than the volume reported by Yoden (2010) who conducted a survey of households in Kathmandu seven years prior and found the mean to be 4m3. The authors suggest the discrepancy is due to households building more storage due to the worsening intermittency of the piped network. The self-reported supply hours of the households in the study were very low with over half of respondents receiving less than 6 hours per week. Most households only received up to three supply periods week.

The rooftop tanks were typically made of plastic and had a mean volume of 1.2m3 (Guragai et al., 2017). A study in San Lorenzo, Guatemala found a mean volume for rooftop tanks to be 0.8m3 (Vásquez, 2016). However, only 5.5% of households owned rooftop tanks; 55% and 50% of consumers stored water in barrels and buckets respectively. The supply in San Lorenzo was significantly more continuous than Kathmandu with an average of 2-3 interruptions per week.

A study across 10 middle-income countries found that the emotional distress and stressful behaviours of households with intermittent supplies had a negative correlation with storage volume (Thomson et al., 2024). Thus suggesting that storage plays an important role in mitigating the effects of intermittency. The emotional distress and stressful behaviours of households was also reduced if the interruptions were more predictable (a reduction of 25 and 50% respectively). The Household Water Insecurity Experiences (HWISE) questionnaire was used to measure emotional distress and stressful behaviour. Responses were compared against the self-reported frequency of interruptions, and whether they had received prior notification of the interruption. The lack of comparison with measured data of the water supply schedule to back up the reports of interruption is a limitation of the study. However, the general correlations between both storage volume and predictability of the intermittency against household stress still hold.

2.3.3 Inequalities Related to Wealth

Having to make adaptations can disproportionately affect the poor. In Greater Amman, it was found low-income households had five times less storage than their more affluent counterparts (Potter et al., 2010). A study of 1500 households in Kathmandu found that on average costs associated with household adaptations were just under twice as much as the cost of the monthly water bill (Pattanayak et al., 2005). In South Africa, the wealth band of the consumer had a large effect on how they perceived the water supply with 85% of respondents in a low-income band rating the supply as bad compared to 25% in the high-income band (Pamla et al., 2021). The differences reflect that 72% of low-income households use tap water for drinking compared to 8% of high-income households.

Time is also a cost imposed by IWS on the consumer; individuals have to spend the time to ensure their own water needs are met (Rosenberga et al., 2008). This can involve queueing at public taps waiting for supply to be turned on, filling various storage receptacles when supply is on and planning daily activities around the water supply hours. The management of water also disproportionately burdens women who are often responsible for its collection (Potter et al., 2010). In Calabar, Nigeria 32% of households adapted to their inconsistent supply schedule by employing water conservation techniques such as changing routine or reusing water (Nchor & Ukam, 2024). Some households reported they may move location if adequate water services were not provided, this was significantly more prevalent in households with lower income level.

A meta-study by Achore et al. (2020) investigated the factors that influence the adaptations made by households to cope with water insecurity. Analysis across a broad range of literature found that the three most influential factors were the ability to pay, the distance to the alternative water source and the perceived reliability and quality of the water source. The study reports that the poor spend more of their time fetching water at the expense of income-generating or leisure activities; this is disproportionally felt by women and girls who tend to have primary responsibility for water-collection in households.

2.4 Transitioning to CWS

Due to the numerous challenges that IWS imposes on both the network managers and consumers, attempts have been made to transition systems to CWS. There are very few reported transitions and the optimal strategy to accomplish it sustainably is still unresolved. Ilaya-Ayza et al. (2018) suggest a gradual transition to CWS is the most feasible given the financial constraints on utilities operating IWS. The authors propose an optimisation method to select the areas for transition using a sector-by-sector approach. This approach pre-supposes a network, which is hydraulically separated and can be operated to increase supply in discrete zones. The authors applied the approach to a case study resulting in only two stages with 13 out of the 15 sectors being recommended for transition in the first stage.

El Achi & Rouse (2020) developed a hybrid hydraulic model incorporating both intermittent and continuous delivery modes. The model is used to simulate converting DMAs to CWS in a similar zone-by-zone approach. The model used WaterGEMS software and showed both operation types could coexist with some pressure reducing valves being the only requirement to achieve acceptable pressure. The authors concluded that transition necessitates DMAs that can be isolated and a reliable and coherent database is indispensable to create models that represent reality. The need for a sufficient system database is reflected by Klingel & Nestmann (2014) who propose a conceptual approach to transition. The authors note that most IWS systems do not have such a database and this is a key part of enabling the transition.

A transition to CWS was completed in a pilot district in Hubli-Dharwad, India (Burt et al., 2018). The study focussed on the benefits of transitioning for the served community. It was estimated that the average consumer time saved by the transition was 22.5 hours per month. Total expenditures decreased under CWS for all wealth quintiles when including the value of consumer time, which was the main source of economic gain. The health impacts of the transition were also studied, a comparison was made with a neighbouring district that remained under IWS operation (Ercumen et al., 2015). The investigation found children <5yrs from lower income households had a 37% reduction in prevalence of dysentery in the CWS system. There were also 42% fewer households with one or more reported cases of Typhoid. The results were indicative of lower mortality of children <2yrs following the transition. In higher income households, there were no significant associations between CWS and reduced diarrhoeal diseases in children. The study suggests the wealth of the household is a significant factor in the health implications imposed by IWS. Transitioning to CWS could have significant health benefits depending on the circumstances of the household, the evidence from this study showed poorer households may benefit significantly more from CWS.

A transition was also achieved in a district within Nagpur, India (Hastak et al., 2017). The study focussed more on the benefits to the water operator than the consumer. They report an improvement in water quality samples from 63% to 96% compliance following the transition. The transition was accompanied with a change in tariff structure, improved metering and increase in connections resulting in a reported revenue increase of 68%.

Evidence from the few systems that have made a successful (and documented) transition to CWS suggest that there are significant benefits for both consumers and operators. However, the widespread prevalence of Intermittent Water Supply (IWS) and the scarcity of documented transitions indicate that such a shift is a complex and challenging endeavour. The following sections evaluate key technical tools used in managing water supply networks, with a specific focus on consumer demand forecasting and hydraulic modelling. The primary motivation is that improving the management of IWS networks can lead to immediate improvements in water access while also serving as an enabler toward transitioning to CWS. This review examines the existing literature on these tools' applications in continuous supply conditions, which is well documented, and considers how they have been or could be adapted to intermittent supply scenarios.

2.5 Consumer Demand Forecasting

Consumer demand forecasting is the process of predicting the quantities of water consumers will desire over a specific period. Models enable future scenarios to be analysed allowing an assessment of future water demands.

2.5.1 Consumer Demand under CWS

Abu-Bakar et al. (2021) review the existing literature regarding household water demand management and consumption measurement across CWS systems. They produce Figure 2.1 that summarises the factors thought to influence household consumption. These are categorised into exogenous factors (predominantly climate and population variables affecting aggregate demand), behavioural factors (primarily variables relating to household attitudes and concerns about water conservation) and endogenous factors (primarily relating to household socio-economic variables as well as household characteristics such as being metered).

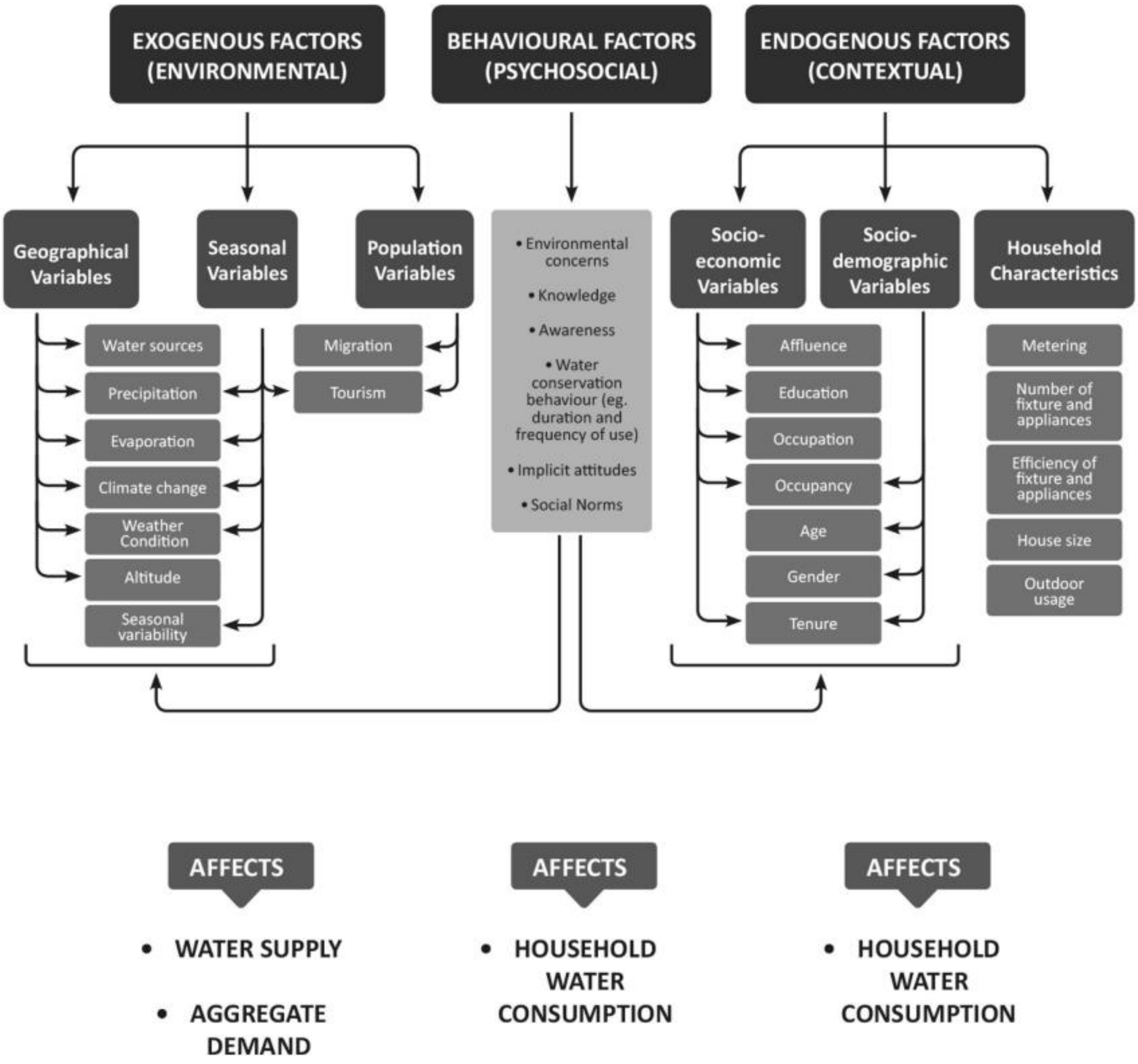


Figure 2.1: A Schematic Diagram of the Types of Household Water Demand Determinants. Source:(Abu-Bakar et al., 2021)

Within the exogenous category, the review found mixed evidence on the extent to which weather influences usage. A study of household usage in the UK reported negligible effects of temperature/rainfall on water consumption; a 10% increase in temperature equated to 0.3% increase in consumption (Manouseli et al., 2019). In contradiction, a study in Melbourne, Australia report a 34% decrease in total household consumption from summer to winter, predominantly attributed to reductions in watering gardens (Gato-Trinidad et al., 2011). The variation in impact of weather indicates that conclusions from one location cannot be applied to other places. This is likely because of differences in climates between locations as well as the differences in how water is typically used in the household.

Within the behavioural category, Russell & Knoeri (2020) found that attitudes, norms and habits played a key role in determining intentions to conserve water. The study found that households with the highest intention to conserve water were also those who reported the smallest water bills. The authors argue this demonstrates the pivotal role behaviours have on water consumption. However, as the authors note, using self-reported water bills as a proxy for water consumption is far weaker evidence than actual water usage quantities. Willis et al. (2011) explored the relationship between household water consumption and the household's level of understanding and concern for the environment and water conservation. They found that households with very high concern used significantly less water than households who were less concerned. It was also found that lower income households tended to be in the higher concern group, however, the difference was not statistically significant.

The endogenous category looks at variables that directly relate to consumption volumes. Abu-Bakar et al. (2021) report that studies from several locations have shown that variables such as property ownership, household income level and household characteristics (such as the presence of bathtubs and gardens) influence water consumption. The impact of wealth on water consumption has a complicated relationship; Beal et al. (2011) found that high-income level did not correlate with greater consumption whilst Fielding et al. (2012) and Kim et al. (2007) found that monthly income was associated with higher consumption.

A survey that measured water use data in Queensland, Australia found that those who had experienced drought conditions and water-restrictions tended to use less water than those who had not had those experiences (Fielding et al., 2012). Manouseli et al. (2019) evaluated the effectiveness of an efficiency programme involving households obtaining water efficiency measure such as aerated showerheads and rainwater harvesting tanks. The implementation led to an average reduction in water usage of 15% across the 450 households with greater changes observed in single resident and financially stretched households.

2.5.2 Consumer Demand under IWS

As discussed in section 2.2, intermittently operated piped networks exhibit distinct characteristics compared to continuously operated ones. Under intermittent water supply (IWS) conditions, withdrawal volumes depend not only on demand but also on network supply characteristics, making it challenging to predict changes in withdrawal volumes under new supply scenarios.

Burt et al. (2018) compared matched cohorts of households experiencing IWS and CWS in Hubli-Dharwad, India. They found that CWS households consumed significantly more piped water, with IWS households using only 34–79% of the CWS volume. The average CWS withdrawal was 22 m^3/month. Additionally, private tube well use was about 50% lower in the CWS group, and CWS households rarely used public standpipes or bore wells, partly due to their removal by the authorities to reduce non-revenue water (NRW). The significant differences in the availability and use of alternative water sources obscure the factors driving increased withdrawals under CWS. This increase may be due to higher demand under CWS conditions or a greater reliance on piped water to meet household needs. The widespread use of other sources introduces additional complexity in assessing piped water demand

A transition to CWS in Nagpur, India resulted in significantly different results (Hastak et al., 2017). The average billed volume of water per connection per day changed from 1910 to 1979 Litres, a change of < 1%. It was observed that the consumption of many connections reduced, the authors attribute this to a change in tariff structure alongside installing more accurate meters so more households were billed according to their consumption and were therefore incentivised to use less water.

A study of four towns in India that transitioned to CWS found that water consumption increased by between 11-42% (Andey & Kelkar, 2007). Each town started with a different average supply hours ranging from 3-16 hours per day; however, there was no clear relationship between the initial supply hours of the respective towns and the increases in consumption. Citizens were asked prior to the transition if the current supply hours were adequate, in Jaipur where supply lasts for 3 hours/day, 77% of respondents found the supply to be adequate, while in Panaji, where supply lasts 5 hours/day, 85% found the supply to be inadequate. The authors suggest this unexpected result was due to more households having adequate storage capacity in Jaipur than Panaji. This is perhaps corroborated by the average withdrawal volume per household being larger in Jaipur (174 LPCD) than Panaji (120 LPCD) (Andey & Kelkar, 2007).

Twelve households in Dhaka were studied using in-depth observations to assess their water habits (Sultana et al., 2022). The study used several days of observations to establish water habits and estimate associated volumes used for different activities. Interestingly the sample included some households that had 24 h access to water and some that did not, even though they were situated in the same neighbourhood. It was observed that the total volume used as well as the volume used for domestic hygiene purposes (e.g. washing dishes or bathrooms) was less in the group of households without 24 h access.

Households in Khulna, Bangladesh were estimated to use 594 Litres/day equating to 116 LPCD (Lewis et al., 2024). However, the study arrived at these values using estimates based on a questionnaire as opposed to measured values. In addition, the estimates relate to their total water usage not just from the piped supply. Similarly, a study in Kathmandu calculated average water usage by asking households how much they consumed from different water sources, as measured by the storage containers that were typically used (Ito et al., 2023). They found average total consumption was 91 LPCD ranging between 16 – 158 LPCD. Higher wealth and the use of multiple sources were associated with higher consumption, while larger household occupancy was associated with lower per capita consumption. A study in China, estimated water consumption from a detailed survey of water use activities alongside water diaries from a sample of the population (Fan et al., 2014). They surveyed four different networks with supply hours varying from 1-24 hours per day. They found that supply hours were correlated with consumption volume, with estimates ranging from 34 – 71 LPCD. Figure 2.2 summarises the breakdown in water-use activities of households across the different networks showing that areas with shorter supply hours tended to perform fewer water use activities. This suggests that supply restrictions may be associated with differences in the water use activities of households.

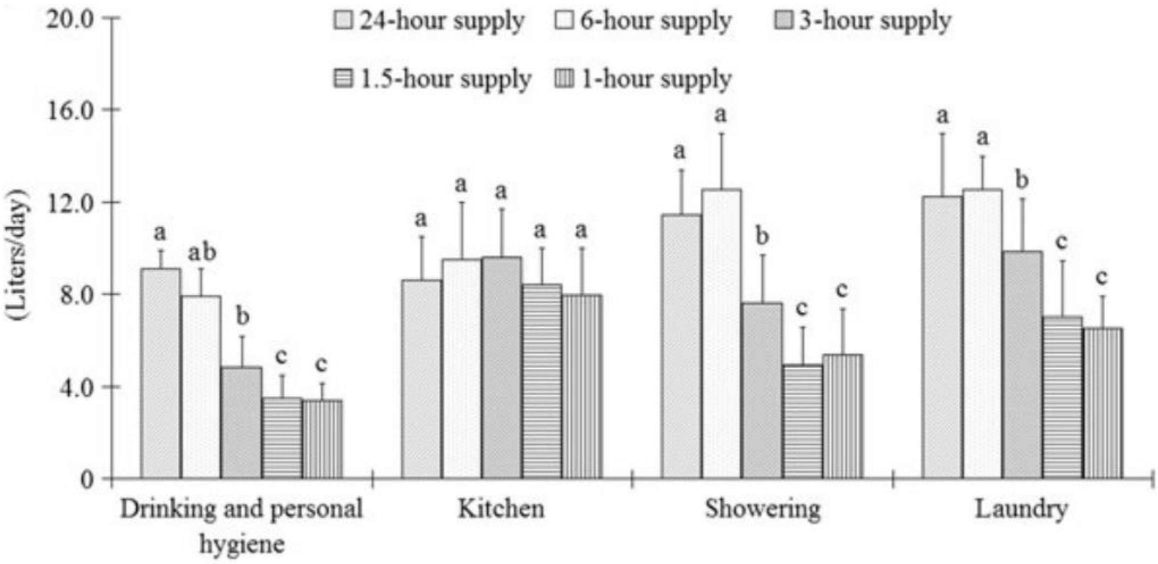


Figure 2.2: Water use patterns (litres per capita per day) under different water supply hours. Note: Mean scores with a different letter differ significantly (P<0.05), a>b>c. Source: (Fan et al., 2014)

2.5.3 The Concept of Consumer Demand Satisfaction (CDS)

The degree to which a household has their demands met under IWS has been termed consumer demand satisfaction (CDS) (Taylor et al., 2019). The author simplifies a hydraulic network into a single average consumer and a single average leak, evaluating how they change in response to changes in supply duration. The model is validated against reference hydraulic models. The approach is effective in identifying the important role demand satisfaction has in determining the distribution of water at the global scale of an IWS network. However, as the author acknowledges, it fails to reflect the inequality in an IWS system by using a single average consumer. The effect of network interventions on the range in consumers across the network cannot be examined and so strategies to improve or control inequalities in an IWS network are beyond its scope.

The framework highlights that in some networks there may be a greater volume of unmet demand (i.e. lower demand satisfaction) than in other networks, therefore requiring more water in order to transition to CWS. As such, the author argues that IWS systems can be categorised into satisfied and unsatisfied types and that this is a key criteria for determining the ‘ease’ at which they can transition. Satisfied IWS networks will only require small increases in input volume to achieve CWS since the additional volume will not be used by consumers. This conclusion is only valid given a significant implicit assumption; the author states that daily consumer demand is considered independent of duty cycle. In other words, the supply conditions of an IWS network do not affect the household’s demand for the piped water. In addition, the demand for piped water is also not influenced by wider variables such as their household adaptations or access to other sources of water. Given the myriad household behaviours identified in section 2.3, this seems like a questionable assumption. In the future work section, the author proposes that pressure should be treated as an endogenous factor; perhaps this should also extend to consumer demand.

This discussion points towards further research to assess the relationship between household adaptations and piped water demand. Which could provide significant insight into demand forecasting under IWS conditions.

2.6 Modelling Intermittent Water Supply

Hydraulic models are widely used to manage water distribution networks under CWS conditions (Speight et al., 2010). They aim to capture the physical processes occurring in the network, enabling the effect of interventions on the hydraulic conditions of the network to be assessed.

Hydraulic models of water distribution networks derived from pipe network analysis, a field that aims to estimate flows and pressures within piped networks. Methods such as the Hardy-Cross method were capable of resolving only the simplest of piped networks until the advent of computers (Ramalingam et al., 2002). Computing power enabled complex, iterative calculations to be feasibly calculated, enabling computation of flows and pressure across large, complex piped networks. EPANET, developed by US Environmental Protection Agency (EPA) is a free, open architecture modelling software that has been widely adopted for application and research purposes (Ormsbee, 2006). Many computer programs have been developed since; however, they follow variations of the same underlying hydraulic equations designed for piped networks that are continuously pressurised. Hydraulic models have proven a useful tool for water operators to design and manage piped water networks in areas where CWS is the norm (Speight et al., 2010). When attempting to model IWS networks, such models were the obvious starting point. The unique conditions of IWS networks, however, have presented multiple challenges to effectively applying such models to IWS systems.

2.6.1 Air in the Network

IWS involves a range of hydraulic conditions due to the filling, pressurised and draining stages. The inclusion of air in the network makes the network behaviour fundamentally different to CWS (Sashikumar et al., 2003). De Marchis et al. (2010) consider the effects of the filling process as the water supply is turned on in the network. They developed a 1-D filling process that operates perpendicular to the cross-section of the pipe. This was criticised by (Mohan & Abhijith, 2020) who argue it is only applicable to small diameter pipes (although the authors do not define what they regard to be ‘small’). In addition, the model is applied to a single case study site and therefore its ability to effectively model networks of different configurations has not been validated. Lieb et al. (2016) developed a 2-D filling process using the Preissman slot formation. The model overcomes some of the limitations of earlier models however; they do not consider the effects of water demand in the network, which is the prevailing driver of pressure deficiency (Mohan & Abhijith, 2020).

An alternative approach to the problem of modelling air in the network is to use EPA's Storm Water Management Model (EPA-SWMM), a hydraulic modelling package designed to model drainage systems. Since drainage systems operate with air in the pipes, the model is designed to be capable of switching from free surface to pressurised flows. (Cabrera-Bejar & Tzatchkov, 2009) First used SWMM for modelling the filling process of an IWS cycle, however, they did not have field data to validate the model output. Campisano et al. (2018) validated the output of a SWMM model simulating the filling phase with field data from a WDN in Italy. Comparisons of the model output with pressure gauge data showed good alignment, validating the use of SWMM to model the filling phase of the IWS cycle.

The inability of SWMM to model the dynamics of the air in pipes led to an updated version, AirSWMM, which was validated using experimental data (Ferreira et al., 2023, 2024). The model showed good ability to predict the presence and fate of air in a single pipe. The authors suggest the same approach can be extended to piped networks but this is yet to be proven. The model aims to simulate the movement of air in the network, how this interacts with the distribution of water across the network during the filling and draining phases are undetermined. Significant complexity is added by changes in elevation due to the local geography of real-world piped networks; the ability of AirSWMM to accurately simulate the fate of trapped air under this complexity is unproven.

Mohan & Abhijith (2020) aim to model the partial flow regime using a pressure dependent analysis model. However, their model was criticised by D. Meyer et al. (2021) for not conserving mass leading to unreasonable drain times (faster than a frictionless pipe would). Gullotta et al. (2021) use EPA SWMM to model the IWS cycle but lack detailed information on how the draining phase is modelled. The effect of including or ignoring the draining phase was not assessed limiting the possible evaluation of their approach. Abdelazeem & Meyer (2024) compared 30 different approaches to modelling IWS networks; they found that only three examples modelled the draining phase of the IWS cycle, none of which provided adequate detail to replicate. In addition, they found that modelling the filling phase was consequential; comparing models that simulated filling against those that did not, resulted in a 20% difference in the predicted demand satisfaction of the most disadvantaged consumers.

2.6.2 Optimising Equality and Equity

The unequal distribution of water associated with IWS has led to many studies aiming to optimise the equality and/or equity of supply across the network using hydraulic models (Sarisen et al., 2022). Several metrics have been proposed to assess inequity; Fontanazza et al. (2007) use the ratio of the volume supplied to a user against their demand, henceforth termed supply ratio (SR). However, the value used for the demand component is not provided. Chandapillai et al. (2012) used a similar approach, their overall metric for quantifying the inequity of the network is 1 – minimum(SR). The minimum supply ratio is defined by the node that has the lowest SR at the moment when the first node achieves 100% demand satisfaction i.e. their SR = 1.

Gottipati & Nanduri (2014) proposed the ‘Uniformity Coefficient’, UC = 1 – (ADEV/ASR). Where ADEV refers to the mean of the absolute deviation of each node’s supply ratio from the network average supply ratio (ASR). Ceita et al. (2023) observed that the metric proposed by Chandapillai et al. (2012) is only effective when modelling unrestricted flow to all nodes, while the UC metric returns negative values if more than half of nodes are not supplied making it unsuitable in highly unequal scenarios. The authors therefore proposed an alternative metric the volumetric coefficient (VC). The metric derives from the concept that every node has a share of the total input supply; the share percentage varies from node to node thus indicating the inequality in distribution. A significant advantage of the VC metric is its incorporation of nodal demand. Nodes that have a larger water demand will contribute more to the equity of the network as they are associated with a larger concentration of people.

Vairavamoorthy et al. (2007) use a different approach to optimising the equity of the system, focussing on the equality of pressure across the network. One of their design objectives is to minimise the diversity in pressure through optimal valve locations and valve settings. The aim being to minimise high-pressure points so that adequate pressure is distributed more widely across the network. Their proposals for the optimal design and operation of IWS networks address many of the unique conditions of IWS, however, their analysis and subsequent recommendations are undermined by a reliance on hydraulic models that cannot represent the full cycle of IWS as discussed in section 2.6.1. Hence, their methods of optimising pressure across the network are limited until new tools are available to re-assess their proposals.

Several attempts have been made to optimise the equity of IWS systems; Chandapillai et al. (2012) re-designed a network to maximise equity through changing pipe diameters. The strategy aimed to optimise cost but this was only based on the price of pipes and not the cost of construction within an existing water supply network. Ameyaw et al. (2013) use the location and capacity of storage tanks placed in the network to optimise equity and cost. Gullotta et al. (2021) argue the installation of storage would require heavy investment therefore optimising equity through network valves is a more viable approach. They developed an optimisation algorithm to place both closed and controllable valves in strategic locations to maximise equality of supply across the network. The tests applied to a network model showed improvement in global equity.

Ghorpade et al. (2021) propose the use of multi-outlet storage tanks to improve the equitable distribution of water. The tanks aim to separate flows into smaller regions to reduce the total range in inequity. The tanks are advertised as a simple and cheaper option to improve equity. Walter & Klingel (2021) propose a re-designed network to improve equity in a system where supply does not meet demand. The system is gravity driven and requires a complex network of decentralised storage areas and weirs to direct the flow to smaller units in the network. A significant limitation recognised by the authors is that there is “a crucial prerequisite limiting the application of the solution are sufficient elevation differences within the supply area, which enable gravitational water transport and pipe routing in accordance with the design criteria.” (Walter & Klingel, 2021).

The only study to date that has incorporated the filling and draining phases in equity analysis is Ceita et al. (2023). It has the potential to provide far superior simulation of the unequal distribution of water compared to the other methods; however, it currently relies on modelling different parts of the cycle in different software making it challenging to implement. Furthermore, their methods have only been applied to two reference networks with relatively simple configurations.

All of these metrics can be used to measure the equality of water distribution across a network; however, it is unclear what the authors are referring to when they use inequity as opposed to inequality. They all assume a constant demand value at the household without providing a justification. They do not take into account the circumstances of the household, for example, how the household storage capacity may influence their withdrawal characteristics and thus their ability to utilise the supply.

The literature review has highlighted that the terms inequality and inequity are often used interchangeably in the literature. A stricter use of the terms could enable more precision when discussing the aims of different optimisation schemes. Therefore, a goal of this thesis will be to characterise the differences between the terms in relation to IWS systems.

2.6.3 Alternative Approaches

Taylor et al. (2019) use a different approach, attempting to model an IWS network using the principle of parsimony. The author models the demand as an aggregated single customer and the leakage as a single leak. The model is successful in predicting the global characteristics of the network in comparison to more detailed hydraulic simulations. As the author discusses, it has disadvantages in that it is unable to represent the variation in the network and includes pressure as an exogenous parameter. The model can therefore only provide output that can assist broad management decisions/policy such as the likely volume of water required to increase supply hours given an estimated static demand of consumers.

2.7 Modelling Consumer Withdrawal

Speight et al. (2010) comment that “capturing how customers are using water across a distribution system is probably the most difficult part of modelling”. The withdrawal of water from the network plays a pivotal role in the network hydraulics making it a crucial component to reflect accurately.

2.7.1 IWS Approaches

In hydraulic models of IWS, how to simulate consumer withdrawal is an unresolved question (Abdelazeem & Meyer, 2024). The typical method under CWS conditions uses a demand dependent approach where the water withdrawn by the customer (or node) is simply defined by their demand. This is valid under continuous pressurisation as water withdrawal is possible whenever it is desired by the customer. Under IWS, it is not valid, since the demand of consumers is limited to the supply period. Because consumers cannot access water continuously, their actual ‘demand’ for water is concentrated to the supply period. Abdelazeem & Meyer (2024) categorise the alternative methods into three groups: volume-restricted, unrestricted and flow-restricted.

The first approach to modelling consumer demand in IWS networks was taken by Battermann & Macke (2001) who used a volume-restricted approach. They assumed a storage tank was connected to every node with flow ceasing once tanks are full. This approach was extended by the work of Taylor et al. (2019) who grouped households to an equivalent node with a tank sized to match their cumulative demand. The tanks fill passively according to the local supply conditions, if the tank fills within the supply period, the connected consumers are considered to have their demand satisfied. A similar approach was taken by Sivakumar et al. (2020), who also connect demand nodes to a tank but use a pressure-sustaining valve (PSV) to ensure the tank filling does not change the pressure head. This is more likely to imitate real scenarios as tanks are filled from the top. In addition, they use a different approach to define the pressure required to achieve a nodes desired flow rate (P_{req}). In Taylor et al. (2019) this parameter is established based on physical parameters while the approach taken by Sivakumar et al. (2020) is to estimate P_{req} based on the loss coefficient of an artificial pipe. D. Meyer et al. (2021) discuss these differences and conclude that the PSV is more appropriate but comes with a computational cost. With additional uncertainty around the positioning of the tank, there is negligible benefit. In addition, estimating P_{req} based on the physical arrangement of pipes is likely to be more practical for practicing engineers then the artificially derived estimates made by Sivakumar et al. (2020).

Gullotta et al. (2021) use a similar approach but use SWMM software instead of EPANET. They connect a tank to each node, which is equivalent to the number of houses the node represents. It is assumed all houses have a 1m^3 tank with a float valve stopping flow when they are full. An important addition the authors make is modelling consumer demand as an outflow from the tanks. The demands are represented by a typical diurnal demand pattern as derived from CWS systems. The model is used to decide the optimal locations of valves in the network to improve the equity of distribution. As with the EPANET based approaches, the demand of nodes is applied homogeneously across the network and entirely dependent on a 1m^3 tank.

An alternative assumption for representing consumer demand in hydraulic models is to assume all taps are open all the time, therefore the flow out of consumer nodes is directly dependent on the pressure. This is referred to as unrestricted demand. Batish (2003) and Mohapatra et al. (2014) employ this method by modelling demand nodes as reservoirs within EPANET software to imitate pressure-dependent demand. It has been criticised for overestimating withdrawal at some connections if the node receives sufficient pressure (Abdelazeem & Meyer, 2024). This leads to unrealistic withdrawal volumes and is therefore inappropriate for most circumstances.

The third assumption used to model consumer demand is that households withdraw water at a rate that exactly meets their demand by the end of the supply period. This method is referred to as flow-restricted demand and was employed by Jinesh Babu & Mohan (2012) by adding flow control valves between the demand node and an artificial reservoir. Gorev & Kodzhespirova (2013) built on this approach by adding resistance to the pipe connecting the reservoir and demand node. Abdy Sayyed et al. (2015) utilised an emitter instead of a reservoir to simulate the pressure dependent demand before EPANET 2.2 was published, which enables pressure dependent analysis to be conducted without the need for these additions (Rossman et al., 2020).

Abdelazeem & Meyer (2024) test different methods of modelling the supply period and consumer demands in EPANET and SWMM hydraulic models. They tested the effects of the different consumer withdrawal approaches discussed previously using three test networks with two supply period durations (4 and 12 hours). They assessed how the different approaches affected the demand satisfaction ratio of connections assuming a desired demand of 400L/day. The inequality of the network could then be compared by compiling the satisfaction ratios. The use of a constant and homogeneous value for desired volume is highly simplistic and will not represent an actual network that consists of variable household characteristics. However, it is an effective measure of the inequality in supply distribution across the network, which is the purpose of the study. A reflection of the inequity of water access of households would require a much greater appreciation for the variability of household circumstances. The authors conclude that the different approaches to modelling consumers is highly influential in the distribution of water and thus inequalities in demand satisfaction. The specific method of achieving each modelling approach has negligible impact, however. The study highlights the importance of modelling assumptions related to connection withdrawal and their impact on the model output. Determining which methods best represent behaviour in actual IWS networks is evidently a pressing issue and a major hurdle to overcome.

Underlying the consumer modelling approaches discussed in this section is the assumption that consumer demand for water in an IWS network can be represented by a storage tank volume (volume-restricted demand) or a continuously open tap (unrestricted and flow-restricted demand). There is no differentiation between households, for example; some may have storage tanks, some may not; some may use the piped water for all their needs while others only use it for drinking/cooking. The modelling approaches do not consider the range in adaptations identified in section 2.3 and their interaction with the withdrawal behaviour of the connection. There is clearly a need to interrogate these assumptions using data from actual IWS networks. This omission is addressed to some extent in Appendix A of Taylor et al. (2019), which discussed the concept of storage-restricted consumers. The author acknowledges that some consumers may not have sufficient storage to satisfy their supply-cycle demands, however, the absence of data from real IWS networks relating to consumer storage and water withdrawal, currently inhibits this theory being developed.

2.7.2 CWS Approaches

Under CWS conditions, withdrawal of water at network nodes is determined by the demand that is prescribed by the modeller. There are two fundamentally different methods of prescribing consumer demand: (a) Average demand patterns, and (b) Stochastic demand generation. The state of the art of both approaches are summarised in the following, including how higher resolution meter data has led to recent advancements.

2.7.2.1 Average Demand Patterns

To model how demand varies over time, for example in extended period simulations, a demand pattern is required. This is typically a diurnal pattern giving weights to each hour of the day according to when demand is greatest (Speight et al., 2010). A peak in the morning and evening period are typical, as exemplified by Figure 2.3.

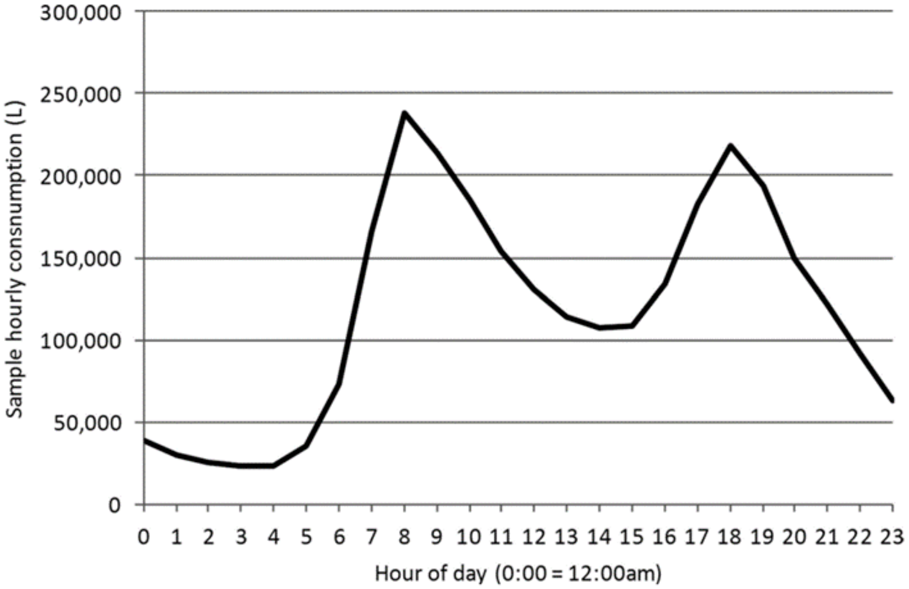


Figure 2.3: A diurnal pattern of average hourly consumption under continuous supply conditions across 2884 sampled households in Queensland, Australia [Source: Cole & Stewart (2013)]

The effect IWS has on the demand pattern of households was studied by Mastaller (2020). They compared an IWS in Tiruvannamalai, India with a CWS network in Stuttgart to determine if the times of day when households desired water was different. They found that the demand patterns were remarkably similar except for a slightly enlarged morning peak in the IWS network.

In the most basic model development, the same demand pattern is applied to all network consumer nodes. However, following the proliferation of smart meters, several attempts have been made to refine this simplification by creating different demand patterns that can be applied to different consumer types. High-resolution usage data provided by smart meters have been used to cluster and classify households into different types. Mounce et al. (2016) used data from 3428 smart meters recording usage at 15-minute intervals. The data was aggregated into representative daily demand patterns before applying k-means++ clustering. The clustering showed best separation when three clusters were specified, the resulting clusters were labelled post-analysis based on their property type. The clearest difference in make-up of the clusters was between residential and commercial customers. The authors then applied classification techniques to test whether property type could be predicted based on usage profile. The Ensemble of RUSBoosted decision trees produced the best accuracy of 84% and 92% for commercial and residential respectively. The clustering and classification analysis shows that aggregated daily usage profiles enable some identification of different user types.

2.7.2.2 Stochastic Demands

The demand patterns described in the previous section are developed by averaging daily usage across a period of time. On any given day, the water usage of a household will look very different with short pulses occurring randomly in a stochastic manner (S. G. Buchberger & Wells, 1996). Attempts to model the stochastic nature of water demand instances can be separated into two categories based on the scale at which the generation method applies (Creaco et al., 2017). The first method models the household as a single entity generating demand instances at the household level (S. G. Buchberger & Wu, 1995); the second method models demand at the end-use level meaning the household demand generation is a sum of all water-use activities (Blokker et al., 2010).

The first method originated from the work of S. G. Buchberger & Wu (1995) who proposed that household water demand might follow a non-homogeneous Poisson Rectangular Pulse (PRP) model. PRP models were developed from queuing theory and had been applied to predicting other stochastic processes such as rainfall events. The PRP model was tested against measured data by S. G. Buchberger & Wells (1996). Household water usage recordings on a 1-second time-scale were collected for four households and used to assess whether household water usage can be modelled as a PRP process. Usage instances were separated into random (e.g. use of a tap) and deterministic (e.g. washing machine cycle) as they were expected to exhibit distinct behaviour. The five parameters that define the PRP model are:

1.	$\bar{\lambda}$	Average expected number of pulse arrivals per unit time
2.	σ_1	Mean duration of pulses
3.	μ_1	Variance of pulse durations
4.	σ_2	Mean intensity of pulses
5.	μ_2	Variance of pulse intensities

A sixth parameter, $\frac{\lambda_m}{\bar{\lambda}}$, defines the relative number of pulse arrivals expected per hour of the day. This is essentially equivalent to the average demand pattern.

For the PRP model to be applicable, the measured pulse data must exhibit two characteristics; firstly, the pulses should be reasonably equivalent to a rectangular shape i.e. relatively constant intensity (i.e. the flowrate). The authors concluded that this was a reasonable approximation. The second characteristic is that the pulse arrivals should have a distribution such that the mean is equal to the variance (the definition of a Poisson distribution). The data revealed this is not the case with the deterministic consumption type having a variance that is less than the mean and the random consumption type having a variance that is significantly greater than the mean. The authors hypothesise this may be due to varying occupancy within households, for example having guests staying causing significantly greater pulse frequency, and conversely, occupants being away from the home causing zero pulse frequency. Although this does not appear to affect the mean greatly, it will cause the variance to be much larger.

S. Buchberger (2003) performed a larger study of 21 households measuring usage again at a 1-second granularity. They compared simulations of the PRP model to the measured data and concluded that the pulse intensities and durations both follow a lognormal distribution. The parameters defining these distributions (i.e. the mean and variance) are derived from the 'method of moments' (Hall, 2004) that directly uses the measured 1-sec data to select the appropriate parameters to represent the data. S. G. Buchberger & Li (2007) developed a program to implement the PRP model called PRPsym; this model addresses the fact arrival rates were not found to closely follow a Poisson distribution. The authors include an additional variation applied to mimic the fluctuating daily demands. This is modelled as either a Poisson or normally distributed variation.

Creaco et al. (2015) process the same household usage data to test whether the pulse intensities and durations are correlated. They found a non-negligible positive correlation, which is defined by the Pearson Coefficient. This is the 'correlation coefficient in the bivariate probability distributions' of the duration and intensity variables. Implementing the PRP model with correlated durations and intensities improved model fit. Creaco et al. (2016) develop a process of parametrising the pulse generation model using 1-minute and 15-minute household usage data. This enables calibration of the model in the absence of 1-sec usage data. By comparing the statistical features of the measured 'coarse' usage data and the synthetically generated pulses using the PRP approach, the appropriate parameters for defining the intensity and duration distributions can be determined. The definition of the Poisson distribution describing the arrival rate, lambda, is found for hourly or bihourly timeslots across the day representing the typical diurnal pattern of demand.

S. G. Buchberger & Wells (1996) classify uses into indoor and outdoor use. Outdoor use is defined as any pulse that either is greater than 30 minutes in duration or has a volume above 303 Litres. B. E. Meyer et al. (2021) test the accuracy of this approach using a high-resolution dataset of household consumptions. They compare the upper bound limit (UBL) method against various algorithms in their ability to classify water use events into either indoor or outdoor. The models input is simply the duration, volume and intensity of the pulses. The models all outperform the UBL method while the Random Forest algorithm produces the greatest accuracy. It significantly outperforms the others achieving an 87% specificity and 96% recall score on the test dataset.

The second method investigates end-use activities in the household to assemble the consumer's stochastic demands. Blokker et al. (2010) developed SIMDEUM, a model that use the same PRP approach to describe demand but disaggregates demands into each end-use such as showering, flushing the toilet etc. To apply such an approach, statistical data regarding the water-use appliances and activities within the household is required. A review comparing the accuracy of the two approaches against a dataset of 21 households found that there was little separating the approaches (Creaco et al., 2017). SIMDEUM has the added benefit of being able to perform long-term scenario analysis based on changes to the household circumstances.

2.7.3 Modelling Households as Open or Closed Boxes

Underlying the different approaches to modelling consumer withdrawal is the definition of a household. Raven et al. (2021) investigate the conceptualisation of households in literature, particularly in relation to sustainability transitions. They categorise two different approaches to defining households: closed box and open box entities. In closed box conceptualisations the internal dynamics of the household and their decision-making is not considered, instead they are a simple singular unit. This generally aligns with the methods used to model consumers in hydraulic models, The open box approach considers the household as a dynamic unit that is influenced by their social and technical context. Open box approaches attempt to unpack the household unit and understand the drivers for different behaviours enabling the reasons for changing behaviours to be realised. It results in a better understanding of the diversity of households and behaviours and could therefore result in more representative modelling of households, particularly under different future scenarios.

Klassert et al. (2015) employs an open-box type approach to household water demand under IWS. They utilise an agent-based approach to model how consumers select different water sources in Amman, Jordan. They model households as agents that make water source decisions based on their circumstances and availability of water from the piped network. How households make decisions under different levels of access to the piped network is not investigated in detail however, as the study did not have any measurements from the piped networks. To estimate the local availability of piped water, coarse data regarding the supply hours in different distribution zones are used. The model includes institutional decision making as the driver of water distribution as opposed to physical attributes of the piped network that would be relevant in a hydraulic model. The study is therefore limited in its ability to recommend how the piped network should be operated following the identified inequities.

Wunderlich et al., (2021) also consider the decision making process of households under IWS. They assess the different water source options available to a household in an IWS network, aiming to optimise their investments to maximise their overall access to water. Again, this considers the household as a decision-making entity; however, it does not couple this with the piped network meaning conclusions relating to the operation of the piped network is limited to scheduling supply on non-consecutive days.

2.8 Summary

The literature review uncovered the following key areas where more research is needed:

- The majority of literature relating to IWS uses desk-based modelling approaches (section 2.6.2), very few field studies providing data from actual IWS conditions have been conducted (Sarisen et al., 2022). This is particularly limiting given the wide spectrum of IWS systems. This paucity of data may be due to the significant financial and organisational challenges of conducting fieldwork. Moreover, with the exception of India and Italy, much of the research derives from institutions in the Global North while IWS is most prevalent in the Global South. Therefore, international partnerships are required, which add further complexity, making extensive fieldwork more challenging.
- More data from active IWS networks will benefit much of the current roadblocks in IWS research. Most notably, the current assumptions that have to be made in hydraulic models of IWS, particularly relating to modelling consumer demand (Abdelazeem & Meyer, 2024). Section 2.7.1 found that a lack of measured data is forcing modellers to make unjustified simplifications, which may therefore be producing unrepresentative results. The effect of different consumer modelling choices have been shown to have a significant effect on the modelling outcome, therefore improved methods, grounded in measured data, would be highly beneficial.
- There is currently conflicting evidence regarding the withdrawal volumes of households under IWS and the factors that drive them (see section 2.5.2). The literature review suggests that both supply conditions and household characteristics may contribute to withdrawal volumes. However, no study has collected simultaneous datasets of both the supply conditions and household characteristics, limiting our ability to examine these relationships in detail. Such a dataset may be able to unpick why different behaviours have been observed in different contexts. The effect of this is that demand-forecasting approaches are extremely limited causing significantly more uncertainty for network managers seeking to transition the network to CWS.
- Section 2.6.2 highlighted the inconsistent use of inequality and inequity in studies aiming to optimise water access under IWS conditions. The definitions of these terms are consequential in directing key performance indicators and thus the approaches taken to optimise the piped network. Greater clarification is required to establish the contributing factors to inequality and inequity under IWS conditions, therefore providing greater clarity to the purpose and effects of different management interventions.

3 Aims and Objectives

The aim of this thesis is to answer the question:

How do variable local supply conditions and household characteristics affect water withdrawal behaviour under intermittent water supply conditions?

The study will identify and quantify the range of withdrawal behaviours and their associated drivers across an IWS network. This will inform how consumer withdrawal could be more effectively simulated in models of IWS and bring new insight to demand-forecasting approaches. Additionally, findings from the case study will be used to evaluate inequity of water access in IWS systems and ultimately inform management practices.

Objectives:

1. Review the literature to understand the global reach of intermittent water supply and the common issues associated with it. Synthesise the current state-of-the-art regarding IWS research, highlighting key areas that require further investigation;
2. Assess the water withdrawal behaviour of households across an operational IWS network by measuring household characteristics, high-resolution piped water withdrawal and network pressures. In doing so, characterise the temporal and spatial variability in supply conditions and associated water withdrawal behaviour;
3. Develop a framework to conceptualise IWS systems based on the understanding gained from the case study analysis in combination with the literature review. Use findings from the case study and the framework to determine the implications for modelling the IWS cycle, modelling consumer withdrawal under IWS conditions and forecasting demand;
4. Evaluate how the case study and framework shapes our understanding of piped water access of households under IWS conditions and thus the resulting inequity within IWS systems. Evaluate the implications for managing IWS networks and planning a transition to CWS.

4 Methodology

This section summarises how the aim and objectives of the research were investigated. A case study approach was employed to understand the relationships between household characteristics, supply conditions and water withdrawal behaviour in an operational IWS network. Measuring these three areas concurrently, produced a novel dataset enabling new insights into the relationships between network and consumer. Various statistical tests were employed to assess the strength of associations between different groups within the dataset. This enabled insight into the key processes driving the system interactions, which could then be formulated into a new conceptual framework of the IWS system. Specific details of the case study site can be found in section 5.

4.1 Employing a Case Study Approach

The literature review highlighted that a lack of field data is preventing progress towards understanding and modelling IWS systems (Sarisen et al., 2022). Currently consumer withdrawal behaviour is a source of uncertainty, as generalised assumptions have to be made regarding their behaviour (Abdelazeem & Meyer, 2024). Measuring the actual behaviour of households under intermittent conditions represents the ideal method to investigate the subject. As a result, a case study has been employed in order to produce data that can reduce these uncertainties and expand our understanding of intermittent systems. To thoroughly investigate the complexities of IWS, the study collected data from both the network and households. These complimentary and synchronised datasets enable new understanding of the interactions governing the IWS system.

4.2 Data Collection

A methodology was developed in order to gain a thorough understanding of household withdrawal behaviour. This methodology centred on three core aspects:

1. Supply conditions: The spatial and temporal distribution of water across the network
2. Household characteristics: Their assets and current water consumption practices
3. Withdrawal characteristics: The variation in piped water withdrawal behaviour of households

In addition, an understanding of the network configuration and operation was achieved through long-term communication with the network operator and collection of existing data such as maps and surveys.

4.2.1 Supply conditions

In order to establish the temporal and spatial distribution of water, pressure loggers were installed across the network. The pressure loggers were placed near the input sources of the network and at the ends of the network to be able to interpolate the conditions in between. The higher the temporal resolution and spatial distribution of the pressure data, the more precise the estimates could be. However, a compromise had to be made between resolution and practical constraints such as cost and battery life.

For the purposes of this study (characterisation of the supply conditions), a measurement interval of 15 minutes was deemed an adequate compromise.

4.2.2 Household Characteristics

To collect household information, a survey was designed that aimed to determine three types of information:

1. The household attributes, perceptions and practices that may contribute to their water withdrawal characteristics
2. The current household piped water availability
3. The household's desire for more water

The survey questions were formulated following a literature review of previous studies in the field of IWS as well as through a preliminary site visit to the area undertaken three months prior to the fieldwork. A survey consisting of a mixture of open and closed questions was used. The choice of question style was tailored to each individual question and the desired detail of the response: the closed questions enable straightforward categorisation of answers and consistency across households, while open questions ensure detail proffered by the respondent is captured. Additional text boxes were also included to enable extra information to be recorded, for example, where the interviewee wanted to expand on an answer, or responses prompted follow-up questions.

4.2.3 Withdrawal Characteristics

To understand withdrawal behaviour in detail, high-resolution household meter data was required. Since most of the analysis of the data was to be conducted in the UK, and a continuous dataset was sought, using smart technology to transfer the data online was highly preferable.

Water meters that record volumetric flow rate at a high resolution have become relatively ubiquitous over the past decade following advances in technology. This provides an opportunity to measure withdrawal at a resolution that has never been recorded before in an IWS network. To date, measurements at a weekly frequency (Mendoza García & Navarro Gómez, 2022) and an hourly frequency across three days are the best available data (Reyes et al., 2017) in studies of IWS networks. Measuring household water withdrawal on a one-minute interval would provide a novel dataset, revealing significantly more detail than any previous study.

4.3 Data Analysis Techniques

The three datasets were first analysed separately to establish a detailed understanding of the properties of the system. The pressure data was used to define the typical supply characteristics of the network. Interpolation between pressure loggers was used to estimate the spatial variation of pressure. Analysis of the temporal variation in pressure enabled estimations of the local daily supply hours at the locations of the surveyed households. Thus providing a characterisation of the local supply conditions of each sample location.

A variety of statistical tests were employed to assess for significant associations between different groups. The specific test used under each circumstance was determined by the nature of the data (e.g. continuous vs categorical data, parametric vs non-parametric distributions).

Firstly, the survey data was assessed to establish whether wealth influences household assets using pairwise correlation. The survey results were also mapped to establish spatial patterns in responses.

The household withdrawal data was assessed to establish the variation in withdrawal quantities of the sample as well as the seasonal variation over time. The probability of withdrawal across the day was calculated for each household to establish their daily withdrawal patterns. The characteristics of the withdrawal instances themselves were determined by calculating their duration and flow rate (and thus enabling calculation of volume).

Once individually analysed, relationships between the datasets were assessed to establish patterns of behaviour, specifically how network and household characteristics influence withdrawal characteristics. Pairwise correlation was used alongside a range of parametric and non-parametric tests to test relationships between categorical and continuous variables.

The IWS network was not hydraulically modelled, as the focus of this investigation was to address the assumptions made in models of IWS, not the challenge of modelling itself. The literature review highlighted the current difficulties in modelling IWS, therefore it was decided that a hydraulic model would bring significantly more uncertainty and provide little insight.

4.4 A Conceptual Framework to Understand IWS Systems

A framework was developed that aimed to describe the principles by which network and household characteristics combine to determine household water withdrawal under IWS. The framework consolidates the findings gained from the case study investigation at a high level, with the aspiration of developing a generalisable structure that can be used to assess IWS networks more broadly. As such, it combines understanding from the literature review with the results from the case study.

The framework was then used to evaluate the implications of the case study findings on the broader spectrum of IWS. Combining findings from the case study and the framework enabled new approaches to modelling IWS and forecasting demand to be explored. The implications for understanding inequity under IWS conditions followed naturally from this. Finally, the case study findings and the framework supported new insights into network management to be developed.

5 Case Study

This section introduces the case study site used in the research and summarises its general characteristics. To enable the data collection programme required in this study, the research project partnered with the Beacon Project to investigate the water supply network of Lahan, Nepal. Lahan is an IWS network in the Southeastern Terai region of Nepal, located in the Siraha District (Figure 5.1). Lahan is the focus of the Beacon Project, a long-term collaboration between Anglian Water (UK Water Company) and WaterAid (INGO), spanning 2017 – 2030.

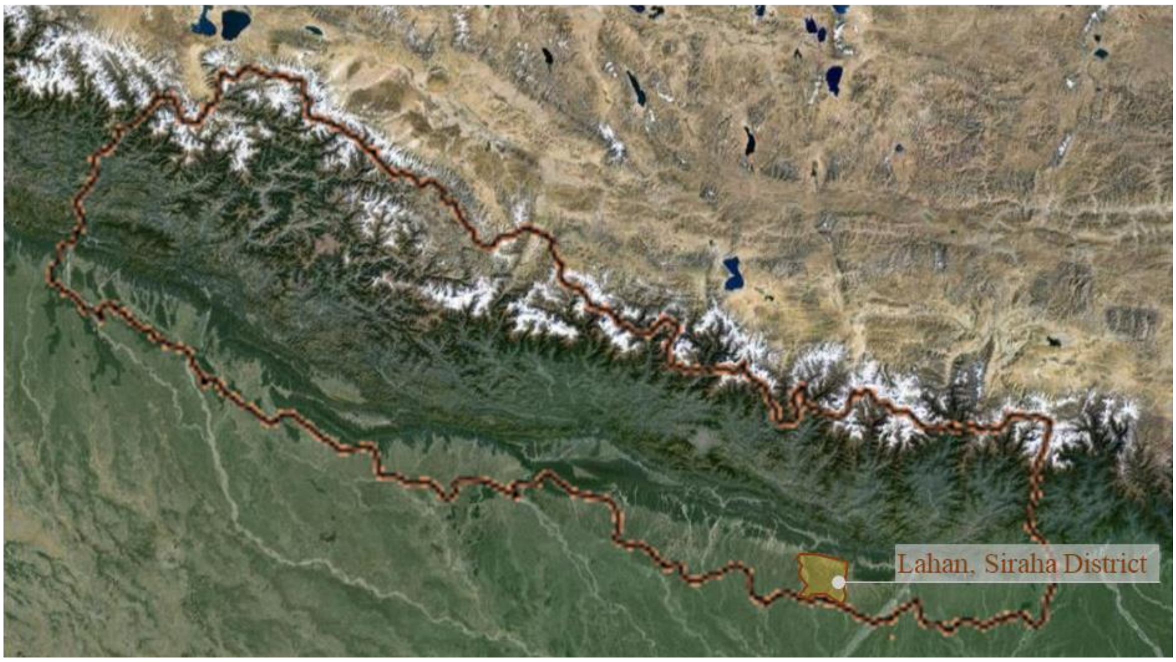


Figure 5.1: Location of Lahan (Siraha District), Nepal

5.1 The Beacon Project

The Beacon Project is an example of a Water Operator Partnership (WOP), a model created by the UN as a means of progressing towards SDG 6 (Pascual Sanz et al., 2013). The model aims to achieve knowledge transfer and capacity development across water utilities based on principles of solidarity between global water professionals (GWOPA, 2021).

The Beacon Project is designed such that WaterAid facilitate learning between Anglian Water and the state-owned water utility, Nepal Water Supply Corporation (NWSC). Unlike typical WOPs, The Beacon Project involves a much wider range of actors including WaterAid Nepal, DJKYC, Lahan Municipality, and the Ministry of Water Supply. Overall, the project aims to achieve progress towards SDG 6 in Lahan, thus spanning improvements in water supply, sanitation and hygiene. One of the major focusses of the project is to improve the existing water supply network, using the technical capabilities within Anglian Water to enable a transition to continuous water supply.

The water supply network in Lahan is run and operated by NWSC, the state-run water utility responsible for operating 21 water supply networks in major cities across Nepal, with the exception of Kathmandu (run by KUKL). The NWSC Lahan branch is composed of seven permanent and ten contracted staff. Up until July 2023, the Head of NWSC Lahan was also responsible for managing the larger water supply network in nearby Janakpur, a city of 174,000 people. The staff operating the network aim to provide as good a water supply as possible, minimising customer complaints and maximising revenue. Prior to the establishment of The Beacon Project, there were no tools to assist in the management of the network, instead the knowledge of staff was relied upon when making operational decisions and changes to the network.

5.2 Existing Data

The following is a summary of the existing data available from Lahan prior to any fieldwork conducted for the purposes of this study.

5.2.1 Census Data

A national survey was conducted in 2021 by the Government of Nepal (National Statistics Office Nepal, 2021). Lahan is considered a municipality meaning the census collected data at the ward level across Lahan. This provides useful statistics of the population and their general attributes, putting the water supply network into a wider context.

The key characteristics of Lahan are summarised in Table 5.1, including specific values for wards 1-10 (the wards within which the piped network is situated). Figure 5.2 compares the main water source for households in Lahan Municipality against only households in wards 1-10, highlighting the increased prevalence of a piped water connection in the central wards. Note that the census question asks which is the households' main water source, therefore a household could have a piped connection but still regard their tube well as their main source. A tube well refers to a shallow well installed by boring a steel tube into the ground, water can be extracted using either a hand-operated or electric pump.

Table 5.1: Summary of Key Attributes of Lahan Municipality and Wards 1 – 10 Specifically

Attribute	**Lahan Municipality (All wards: 1 – 24)**	**Urban Centre (Wards: 1 – 10)**
Climate	Temperature variation: 17 – 37ºC Monsoon season: June - August	
Population	102,031	38,572
Number of households	20,577	7,798
Average household size	4.96	4.95
Literacy rate	69.2%	76.1%
Access to a toilet (of any kind)	90.7%	92.9%
Material of outer wall of house:		

• Mud bonded bricks	9.5%	9.1%
• Cement bonded bricks	53.5%	73.1%
• Wood/planks	2.7%	1.1%
• Bamboo	33.8%	16.1%
Type of Roof:		
• Galvanised sheet metal	41.7%	28.9%
• Reinforced cement concrete	36.6%	58.3%
• Thatch/straw	8.1%	2.8%
• Tile	13.3%	9.4%

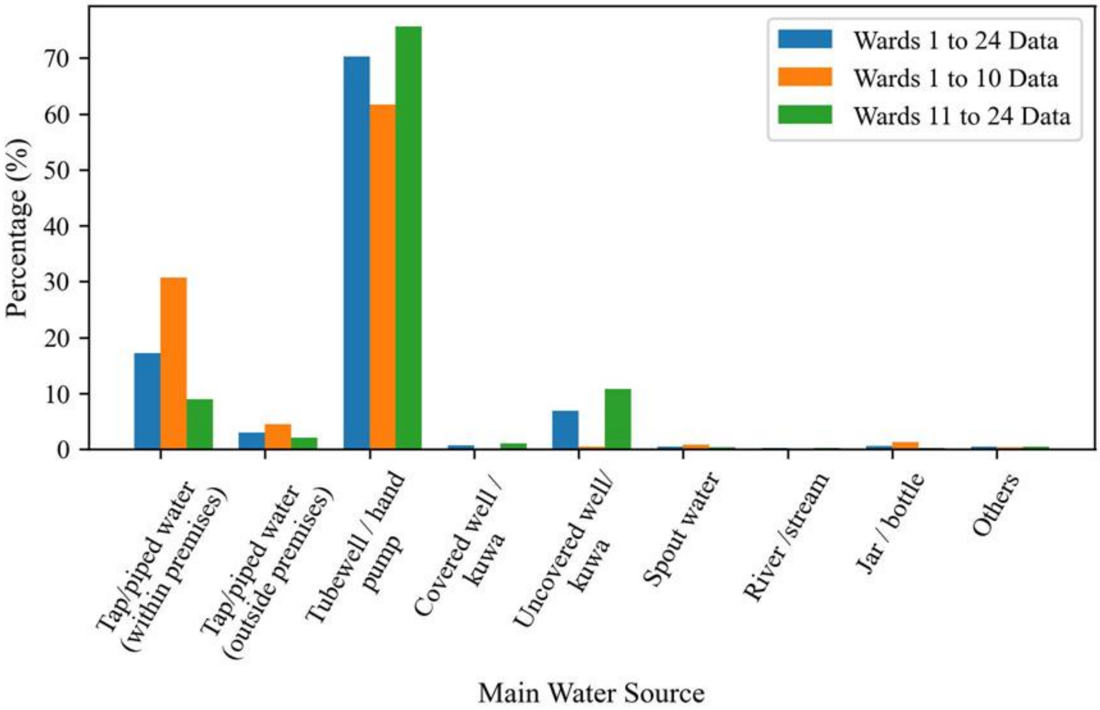


Figure 5.2: Comparison of the Main Water Source for Households in the Lahan Municipality vs Only Wards 1-10

5.2.2 NWSC Lahan Data

The key characteristics of the water supply network are summarised in Table 5.2. This data has been gathered from the project partners The Beacon Project and NWSC. As of September 2023, the network reached 49% of the urban population. The supply schedule is nominally 6 hours per day, split across two supply periods. This is a regular and reliable morning and evening pattern; however, it is subject to daily, as well as seasonal variations. Valves and pumps are operated manually by staff meaning day-to-day variations in operation is common. In addition, the multiple inputs into the network mean timings vary in different locations.

NWSC require households have a mechanical meter installed on the inlet to their property for billing purposes. Meters are read monthly by physical reading of the meter dial. This provides a coarse understanding of withdrawal volumes across Lahan, however, up to a third of meters are non-functional.

Table 5.2: Summary of the Key Attributes of the NWSC Piped Network in Lahan

Attributes of Piped Network	**Value**
Total elevation change	~15 metres
Total length of Pipelines	91 km
Number of Boreholes	4 – feeding directly
	6 – feeding OHTs
Overhead Storage Tanks (OHT)	2 – OHT1, OHT2
Treatment	1 – sedimentation tank
	Chlorination on all inputs to supply
Input supply schedule	Daily:
	5 – 8AM 5 – 8PM
Number of connections (99.9% located in wards 1-10)	2,881 (February 2020)
	3,813 (September 2023)
Approximate population served by the network	14,290 (February 2020)
	18,912 (September 2023)

5.2.3 Beacon Project Data

The project conducted a consumer survey of network connections to establish baseline information in February 2020 (WaterAid Nepal, 2020). The survey aimed to cover all connections in the network, recording their coordinates, elevation and some key statistics. Attributes such as meter condition, service pipe size and tap type were recorded. Households were also asked to estimate their local supply hours, the number of leaks they had observed and for their assessment of the water quality. A key finding of the survey was that 13 households reported to have 20+ hours of supply. All of these households were located in ward two at the southernmost end of the network, as highlighted in Figure 5.3. In addition to the house connection information, the network pipe configuration was also digitalised in a GIS. A map of the key assets in the piped water network, alongside the consumer connection locations and elevations, are shown in Figure 5.4. The elevation range is 15 metres, highlighting how flat the terrain is in Lahan. The number of connections in the Lahan network increased by 932 (32%) between the household surveys in 2020 and September 2023. The precise locations and elevations of these connections are not known.

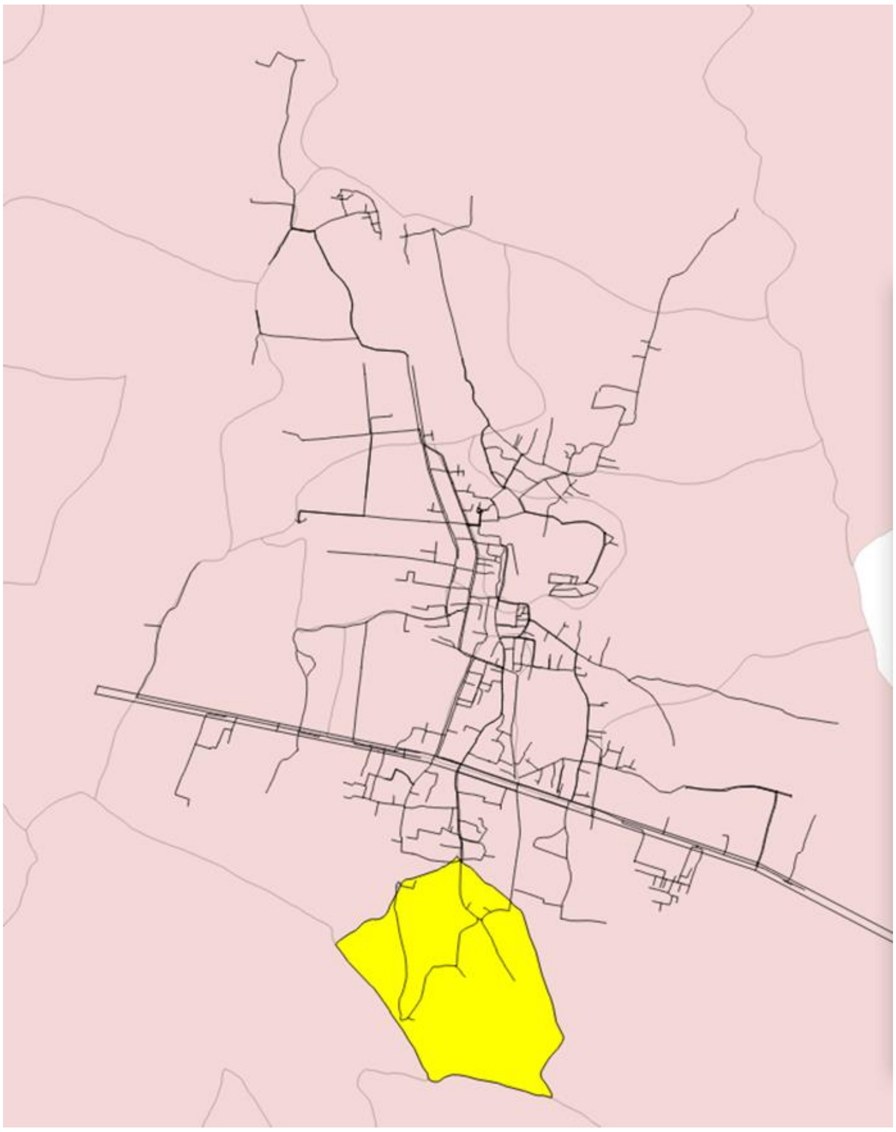


Figure 5.3: Network Map of Lahan with Ward Two Highlighted

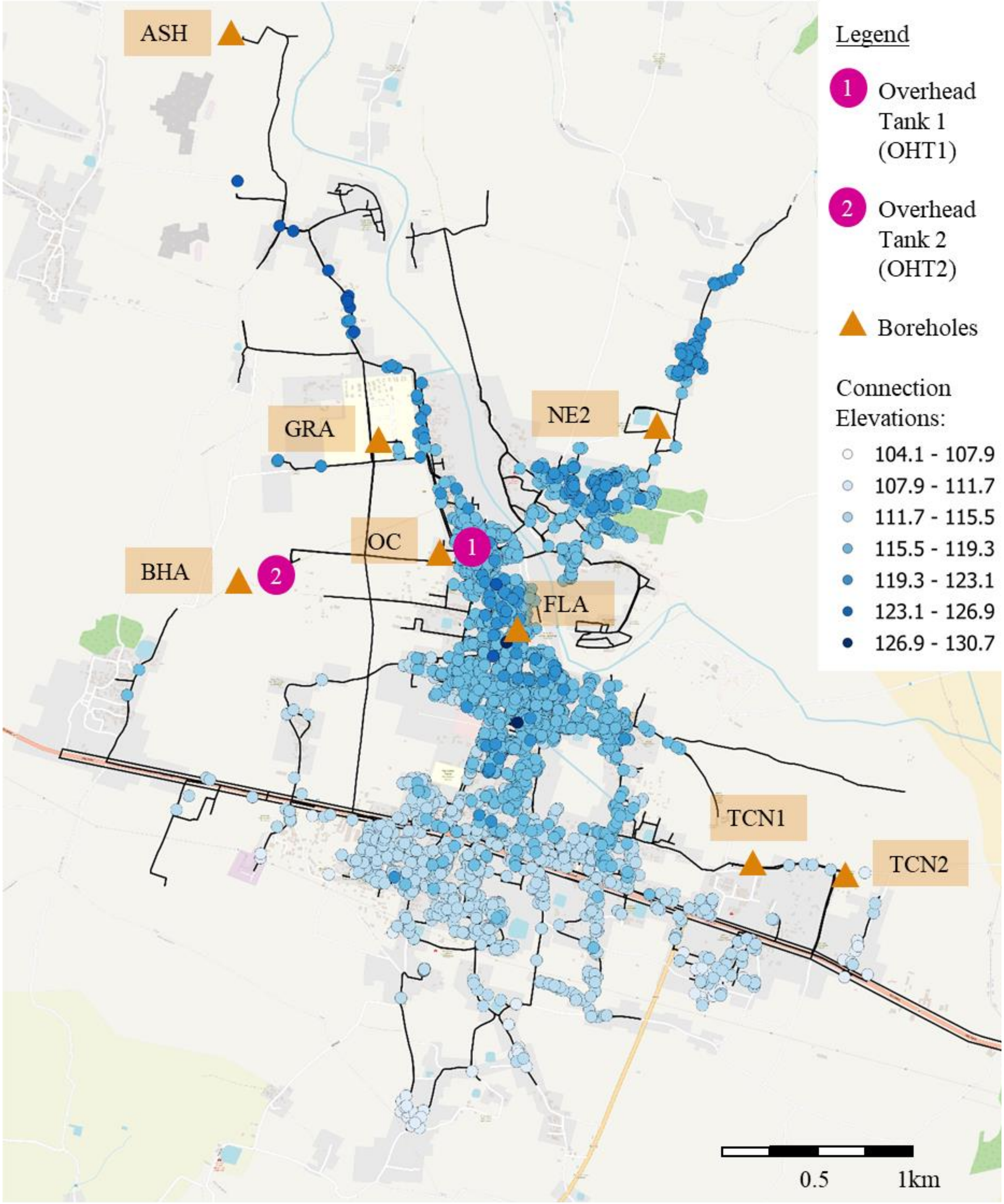


Figure 5.4: Consumer Connections overlaid on the Lahan Piped Network alongside Key Network Assets

6 Methods

This section summarises the methods used to collect, process and analyse the data collected in this study.

6.1 Introduction

As outlined in the methodology, the supply conditions were determined through installation of pressure loggers. The installation of the pressure loggers was carried out by the project partners with input from the author. The household characteristics were collected via a survey and the withdrawal characteristics through the installation of household meters. This was led by the author with assistance from enumerators and plumbers from the project partners during fieldwork carried out September – December 2022. The meters were installed on the same houses that were surveyed to enable comparison between datasets (a key objective of this research). Key milestones that occurred during the study period that dictated the collection of data can be found in Appendix A.

6.2 Pressure Data

Pressure loggers were installed in the network by the project partners, The Beacon Project. A total of 14 I2O loggers were installed directly onto tappings on the pipes between December 2023 – January 2024. The pressure loggers were installed across the network (Figure 6.1), recording pressure head at a 15-minute frequency, sending the data to an online portal via the 4G network. The initial schematic placement of the loggers can be seen in Figure 6.2. Two of the loggers (NTWRPM and SETKPM) are placed within the transmission zone of the network measuring pressures at inlets and outlets of storage infrastructure, while 11 are installed on the distribution pipes.

On 8th March 2024 the network valve arrangement was altered so water leaving OHT2 that used to feed into OHT1 now fed directly into the western region of the network. The updated schematic can be seen in Figure 6.3. Unfortunately, NTWRPM (the pressure logger adjacent to OHT2) stopped working on 7th February meaning the operation of the tower cannot be directly measured after this date.

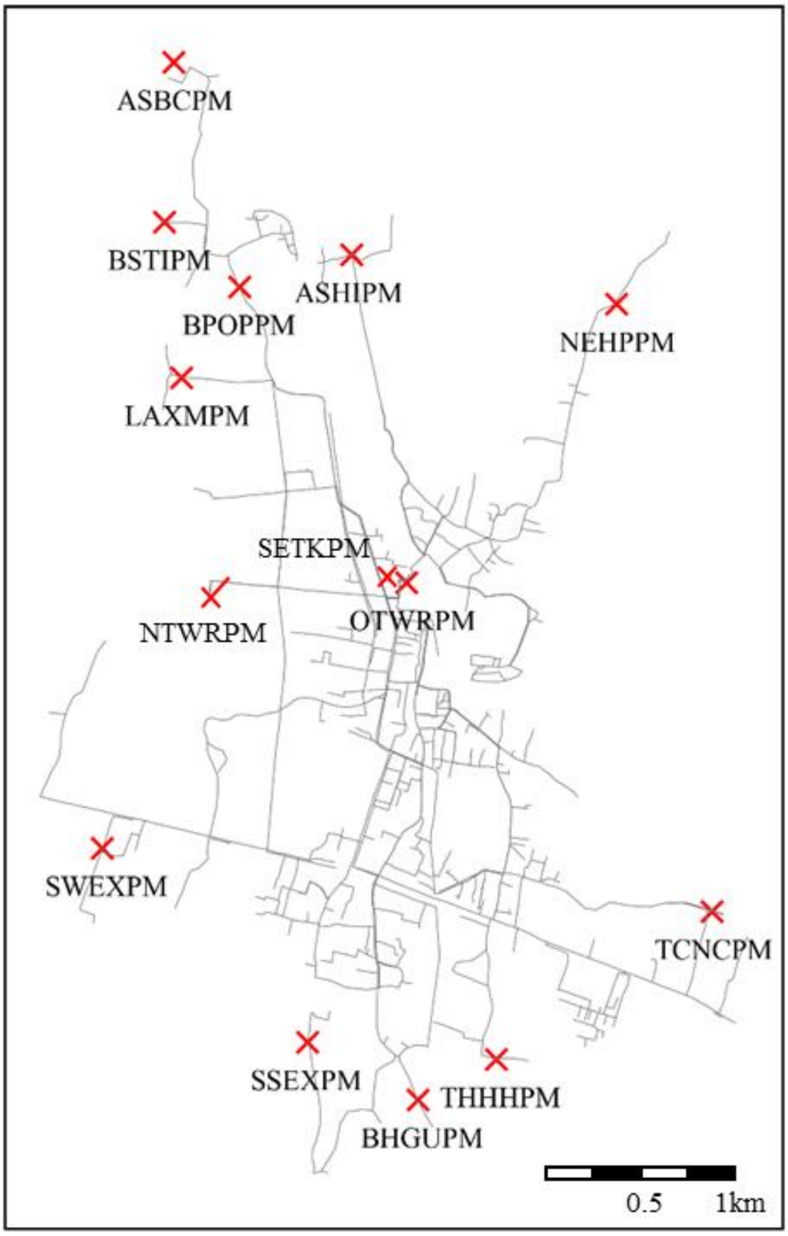


Figure 6.1: Installation Locations of I2O Pressure Loggers

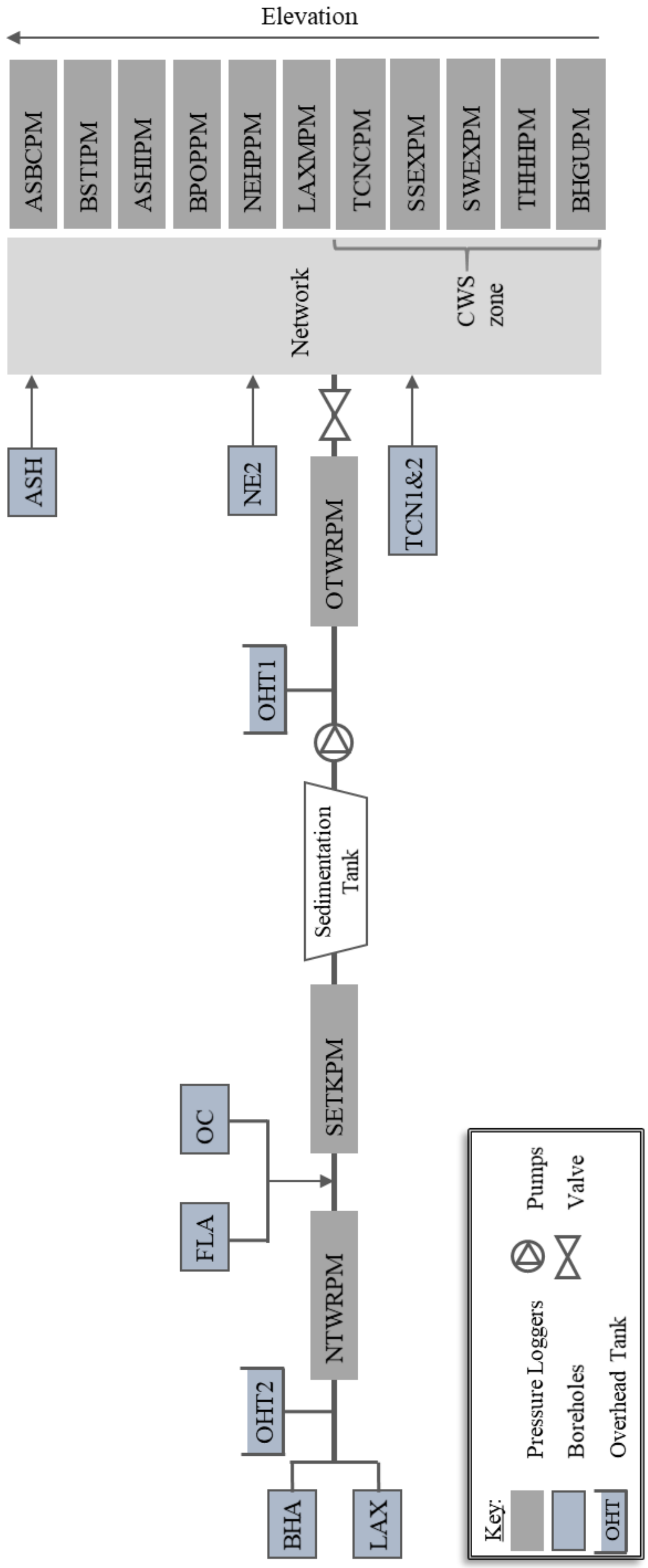


Figure 6.2: Schematic Arrangement of the Water Distribution Network Prior to 8th March 2024

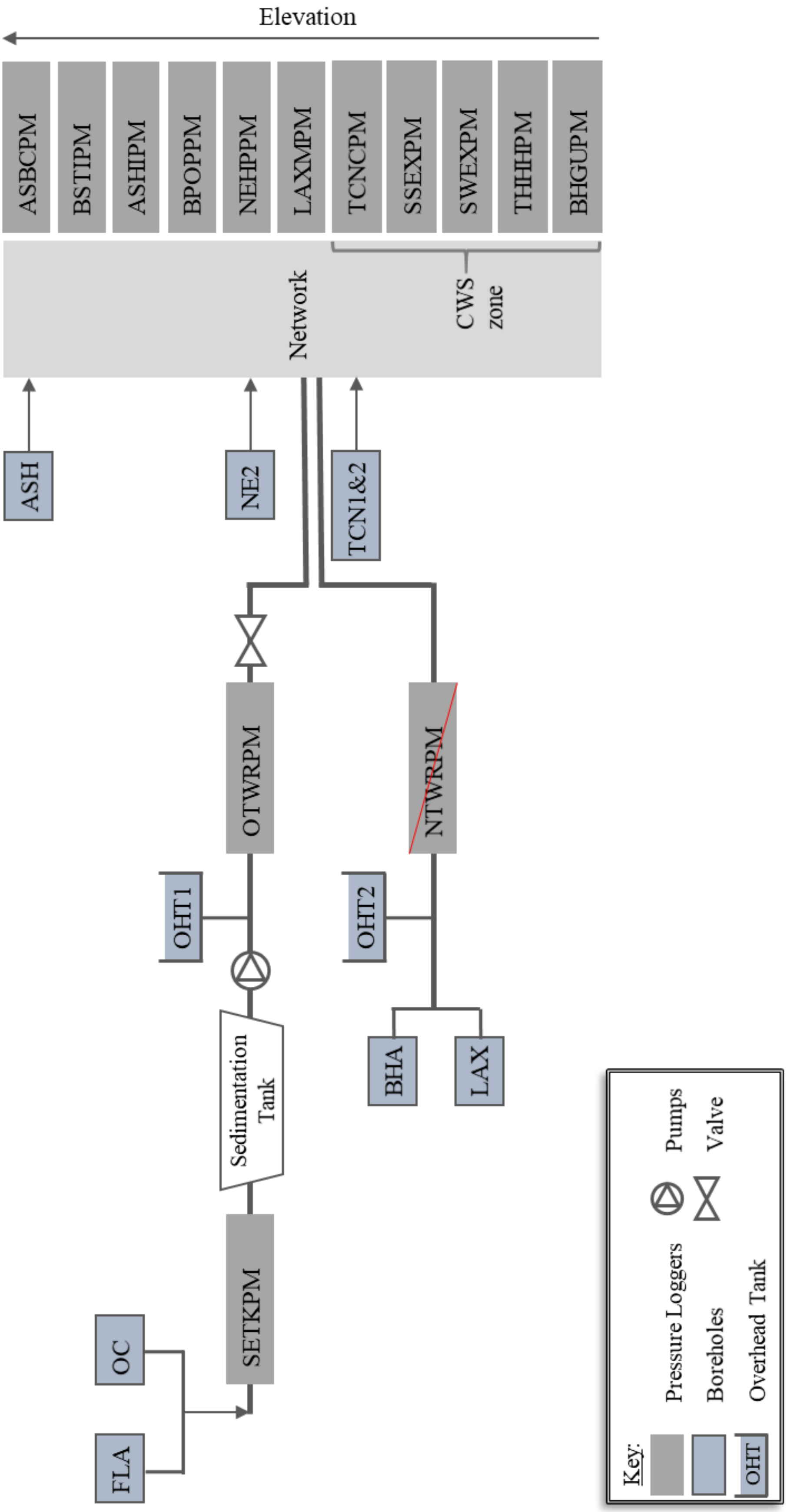


Figure 6.3: Schematic Arrangement of the Water Distribution Network After the 8th March 2024

6.2.1 Pressure Data Processing

OTWRPM is installed prior to the valve that is opened and closed signifying the start and end of supply from OHT1. Therefore, this pressure logger is only hydraulically connected to the network for the duration that the valve is open. The pressure trace from OTWRPM was manually processed to mark when these changes occurred. Figure 6.4 illustrates the marking procedure that records all the change points. The fall in pressure while the valve is closed indicates a leak and results in the water tank often being topped up prior to the supply period.

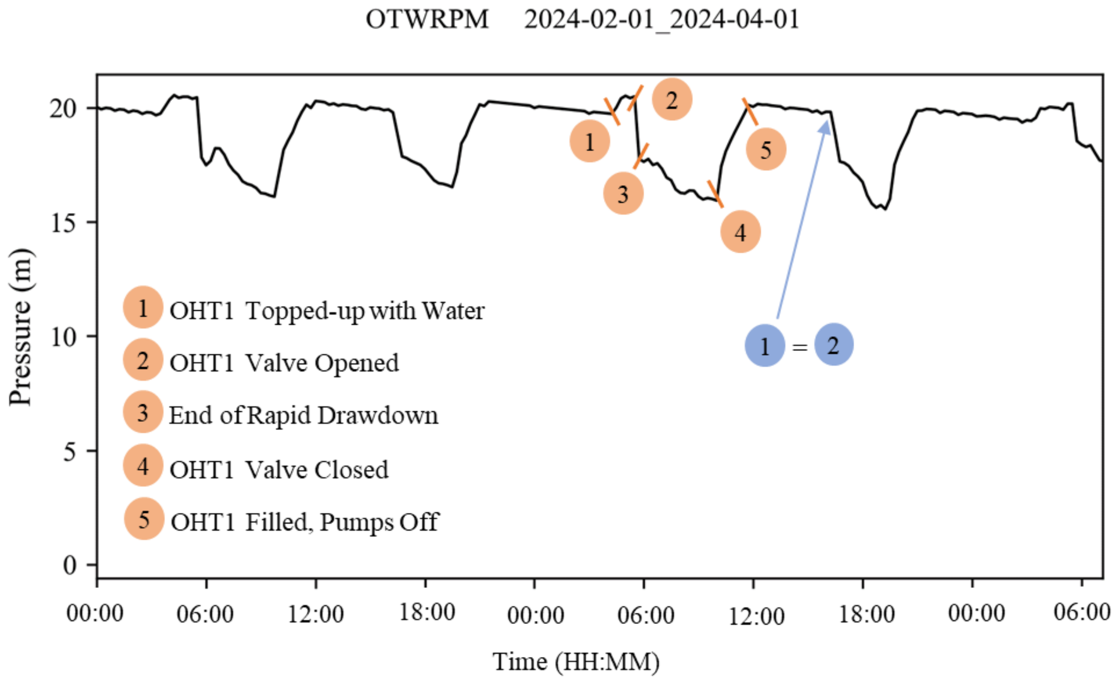


Figure 6.4: Example of the Marking Process to Define the Different Regimes Associated with the Operation of the OHT1 Valve

6.2.1.1 Logger Errors

Prior to using the pressure data, it was screened to determine if the data required offsetting. Offsetting may be necessary if the devices are not set to zero correctly creating a systematic error. To evaluate whether each device required offsetting, four steps were taken:

1. Examine time series of pressure data to assess whether they regularly flat line
2. Plot a histogram of values between -5 and 5m
3. Repeat (2) but only for measurements taken between 12 – 4AM (the time that zero values would be most expected)
4. Calculate the modal value

Figure 6.5 shows three examples of time series produced in step (1) alongside histograms created in step (3). Figure 6.5(a) is a logger that did not require offsetting, Figure 6.5(b) a logger that did require offsetting and Figure 6.5(c) a logger that could not be offset using this methodology. The equivalent histogram for every pressure logger can be found in Appendix A. Table 6.1 summarises the identified errors.

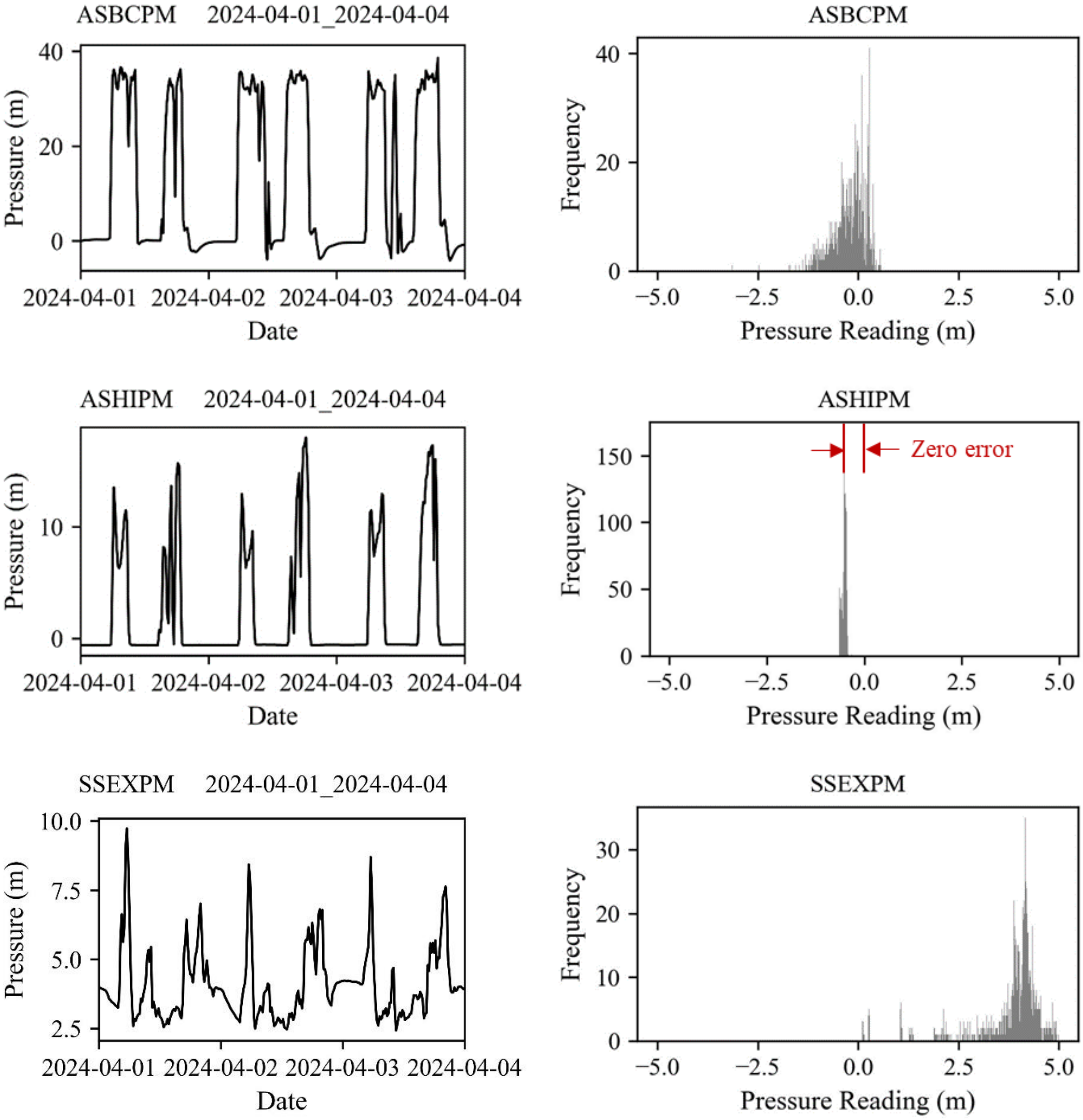


Figure 6.5: Timeseries and Histograms of Low Readings for Pressure Loggers (a) ASBCM, (b) ASHIPM, (c) SSEXPM

The steps were effective at determining offset requirements for loggers that regularly experience no pressure (e.g. Figure 6.5(a) and Figure 6.5(b)). However, eight of the loggers are in locations that are typically continually pressurised and therefore it could not be determined if they required offsetting (e.g. Figure 6.5(c)). As shown in Table 6.1, the errors range from 0.3 to 1.7m therefore all pressure values must be considered with an uncertainty of up to 2m.

The identified errors all required an uplift to the recorded values suggesting unidentified errors may similarly be causing an underestimation of pressures. This has the knock-on effect of underestimating local supply hours. The estimations of supply hours, particularly in the southern regions, are therefore likely to be lower bound estimates.

Table 6.1: Summary of the Systematic Errors Identified in the Pressure Loggers

Logger ID	Error Value (taken from mode of night time pressures)
ASBCPM	None
BPOPPM	- 0.32
BSTIPM	- 0.73
LAXMPM	- 1.07
OTWRPM	NA
SETKPM	NA
ASHIPM	- 0.62
BHGUPM	NA
SSEXPM	NA
TCNCPM	NA
THHHPM	NA
NTWRPM	NA
SWEXPM	NA
NEHPPM	- 1.7

6.3 Fieldwork Preparation

This section summarises the work to prepare for the fieldwork. The key tasks involved advertising the project to encourage households to respond positively when asked to participate, assessing the ethical implications of the study to mitigate potential for harm and selecting the locations that were desired within the sample.

6.3.1 Priming Households

The fieldwork involved contacting and recruiting households to take part in the study. This presented several challenges that needed to be addressed from the inception of the work. Firstly, our ability to recruit households was dependent on trust in who we were and our motivations, association with The Beacon Project ensured a large part of this effort was already in place. Beacon had been working in Lahan for five years prior to the fieldwork and had built a positive reputation with the community in that time. Additionally, having the support of NWSC ensured local accountability and a known point of contact if households had issues with the research.

To enhance our recognisability and raise awareness of the project, a brief leaflet was made. The leaflet aimed to outline the intentions of the research and what it asked of the participants. With the help of WaterAid staff, the leaflet was translated into Nepali and distributed by NWSC at the payment counter of the NWSC Lahan office as well as by meter readers who circulate across all households every month. This enabled some familiarity with the project prior to approaching households for their consent.

6.3.2 Ethics Approval

Appropriate methods and materials for recruiting households were established and refined through the University of Sheffield's Ethics Review Procedure. A consent form was developed to inform participants of what the research would involve and their rights as partakers in the research. The responsibilities of the research investigators were clearly defined as well as how the participant's data would be stored and used. An accompanying information sheet explained in detail what the project was doing and what participants' involvement would require. Both forms were translated to Nepali through an independent translation service and reviewed by colleagues in WaterAid Nepal.

A copy of the approved ethics application and consent form can be found in Appendix A.

6.3.3 Sampling Locations

To enable comparison across the datasets, the installation of the household smart meters would coincide with the locations of the household characteristics survey. The proposed locations aimed to achieve two key criteria:

1. A geographic spread across the water distribution network; ensuring households at all elevations were included, as well as at all ends of the network.
2. A range of household types based on construction type, size and household water assets; ensuring houses from all parts of the income spectrum were included.

Criteria (1) was chosen because elevation was expected to be a major driver in the distribution of water across the network. Relative elevation is a component in the local pressure head and therefore is thought to be a particularly influential parameter in the filling and draining phases of the water supply cycle (Erickson et al., 2020). In addition, data from the partner survey suggested that areas of the Lahan network at the lowest elevations experience continuous water supply (WaterAid Nepal, 2020). To capture this and the resulting differences in local supply hours across the network, the stratified sampling technique was employed.

Network elevation data that had been previously collected by The Beacon Project enabling stratification of households based on elevation. Figure 6.6 shows the network with connection points coloured according to elevation. This information was used to select target locations, ensuring that all elevation bands would be sampled. Approximately 32 samples were required to cover the desired spread in elevation and cover the ends of the network.

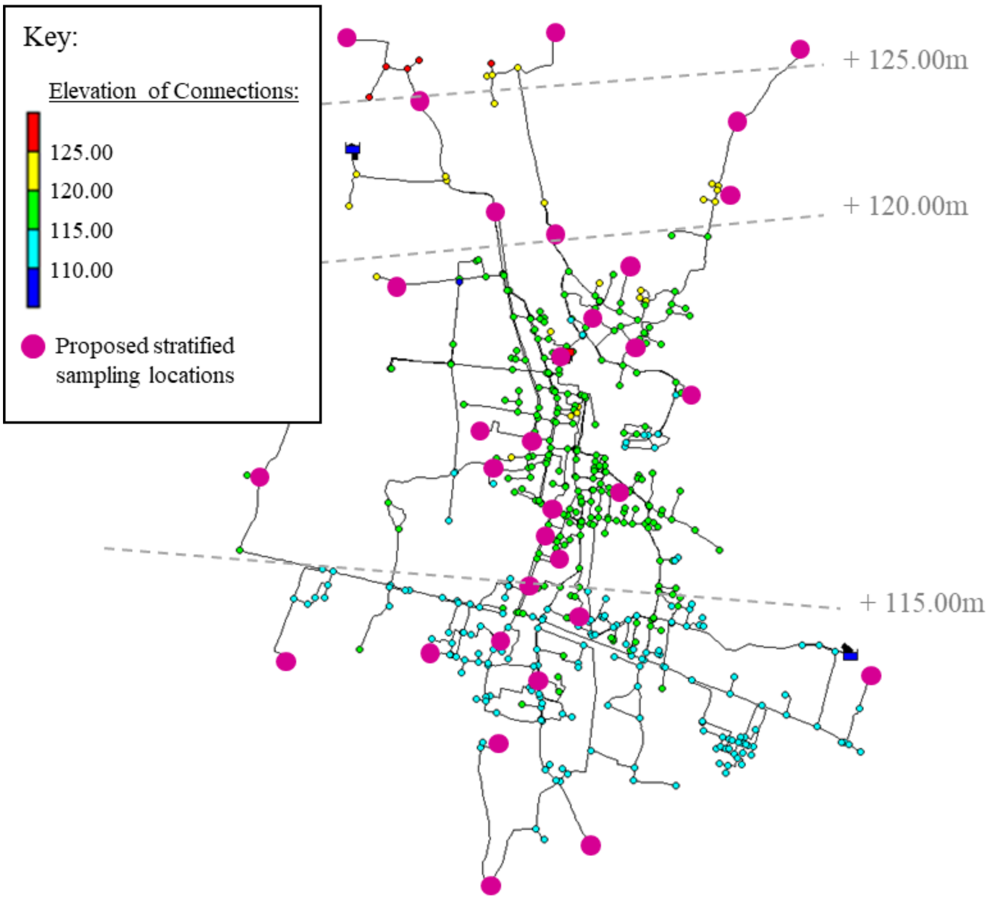


Figure 6.6: Lahan Piped Network with Connections Coloured According to Elevation and Sampling Locations Overlaid in Pink

To achieve criteria (2), detailed household level data on wealth and construction type would be required. This information was not available prior to the fieldwork commencing meaning households could not be preselected. Instead, the range in household types would need to be achieved 'on-the-go', by tracking the household types that had been sampled as we progressed through the fieldwork. This approach meant a certain level of flexibility would be required for the sampling locations.

The remaining 28 of the total 60 samples were allocated across the map based on the density of connections in those areas. As such, the sampling was partially population-proportioned but only within the confines of achieving the spread desired in criteria (1). As Figure 6.6 indicates, the central district has the greatest density of connections; therefore, most of the additional 28 samples were positioned there.

6.4 Survey of Household Characteristics

This section details how the household survey was designed, carried out and processed.

6.4.1 Designing the Household Survey

In order to collect data relating to the household characteristics, a survey was designed. The survey questions were selected based on the literature review and a preliminary site visit to Lahan conducted several months prior to the fieldwork. To minimise disruption to the participants, and increase the likelihood of obtaining willing participants, the survey was restricted to the minimum desired information. The survey was divided into three parts as follows.

6.4.1.1 Part 1: Mix of Questions Relating to Household Water Usage

The first part of the survey had several aims, the first of which was to record the number of people using the piped supply so that the water consumption in litres per capita per day could be calculated. The practice of households sharing connections was highlighted by Kumpel et al. (2017) in their study of the water network in Hubli-Dharwad, India. Therefore, information relating to the household size as well as the number of households sharing the connection was required.

The next aim was to record the household assets relating to their water access. As identified in section 2.3, households employ adaptations such as using storage containers and other sources of water. This was verified in the preliminary trip to Lahan; the prevalence of household tube wells in Lahan was particularly evident. The household storage volume was estimated using the volume and quantity of their storage containers (larger containers are typically labelled with their volume making this a reliable estimate). The households were also asked to estimate the contribution of the piped supply to meeting their water needs in comparison to other sources.

A significant objective of the research is to establish how households behave in relation to their piped water supply. Therefore, questions relating to the typical manner in which households use water were included in the survey. This would enable cross-examination with the measured withdrawal data to determine congruence.

The household’s perceptions of their current piped water supply were assessed in terms of both hours of supply per day and their perceived water quality. These questions were asked in WaterAid Nepal (2020), which showed a range of responses. It was thought that re-assessing these variables with the wider information gained in this study might provide useful insight into the spatial distribution. They also link to the following set of questions regarding desires for increased piped water.

The final aim of the household survey was to establish households’ consumer demand satisfaction (CDS) and their attitudes towards changes in the water supply. CDS is a challenging attribute to measure directly. Instead, two questions regarding the household’s desire for longer supply hours and for more water were selected. These aimed to establish their desire for increased piped water availability, which could be viewed as a proxy for their current demand satisfaction.

The survey questions were checked against the ‘Core questions on drinking water, sanitation and hygiene for household surveys’ (UNICEF & WHO, 2018). This survey includes all the relevant questions set out in the ‘core questions for drinking water’ section of this international standard.

The questions forming the first part of the survey are listed in Table 6.2.

Table 6.2: Survey Questions Part 1

Users of the Piped Supply			
How many people typically live in your household (including both adults and children)?			
Do you share your connection with any other households? If so, how many?			
Water Related Assets			
Is the household fully plumbed or just a yard tap?			
In litres, what is the total water storage volume of your household?*			
What other sources of water are used to supplement your piped water supply?			
➔ Approximately what percentage of your total water usage is provided by the piped water?			
Piped Water Practices			
During a supply period, is water mainly used directly for household activities or is it stored to be used later?			
Typically, do you have the tap open the entire duration of the supply period or do you close it?			
Typically, what happens when your storage tank is full?			
Perceptions of Current Water Availability			
How many hours of supply do you receive per day?			
What is the piped water quality like?			
Good	Dirty Water	Bad Smell	
Desires for Increase Piped Water Availability			
If the duration of the supply period increased, would you use more water?			
Yes, a lot	Yes, a little	No	Don’t know
What would you use the extra water for?			
Would you like the hours of supply to increase?			
Yes, a large increase	Yes, a small increase	No	Don’t know

* Household storage volume relates specifically to storage that is connected to the piped supply, it does not include storage that is connected to other sources of supply such as a tube well.

6.4.1.2 Part 2: International Wealth Index (IWI)

The second part of the survey aimed to establish the relative wealth of the households. Many studies have investigated the relationship between wealth and water usage (Beal et al., 2011; Fielding et al., 2012; Kim et al., 2007); a metric for measuring household wealth was therefore desired. The International Wealth Index (IWI) is a global standard aimed at estimating household wealth in a universally comparable way based on household assets (Smits & Steendijk, 2015). Other asset-based methods exist; a study by Mayfour & Hruschka (2022) found that all are highly correlated, but crucially IWI was best at accounting for variation when predicting key health measures. The questions that make up the IWI scale are listed in Table 6.3. The IWI scale runs from 0 – 100, where higher scores indicate greater wealth.

Table 6.3: Questions from the International Wealth Index (IWI) Scale (Smits & Steendijk, 2015)

Does the household own or have a:			
1. TV			
2. Refrigerator			
3. Phone			
4. Bike			
5. Car			
6. Cheap utensil (<$50)			
7. Expensive utensil (>$300)			
8. Electricity			
What is the quality of:			
1. Main source drinking water	Low	Middle	High
2. Toilet facility usually used	Low	Middle	High
3. Main floor material	Low	Middle	High
4. Number of rooms used for sleeping	Zero/One	Two	Three +

6.4.1.3 Part 3: Household Water Insecurity Experiences (HWISE)

To assess the current piped water availability of households from a water security perspective, the Household Water InSecurity Experiences (HWISE) (Young et al., 2019) survey was employed. The HWISE scale aims to measure water insecurity in a universal scale to aid comparison across locations and cultures. HWISE operates at the household scale and assesses a range of criteria that are relevant to the Lahan context making it a suitable metric for this study. The questions that make up the HWISE scale are listed in Table 6.4. The HWISE scale runs from 0 – 36, where higher scores indicate greater water insecurity.

Table 6.4: Questions from the Household Water Insecurity Experiences (HWISE) Scale (Young et al., 2019)

HWISE Evaluation
1. In the last 4 weeks, how frequently did you or anyone in your household worry you would not have enough water for all of your household needs?
2. In the last 4 weeks, how frequently has your main water source been interrupted or limited (e.g. water pressure, less water than expected, river dried up)?
3. In the last 4 weeks, how frequently have problems with water meant that clothes could not be washed?
4. In the last 4 weeks, how frequently have you or anyone in your household had to change schedules or plans due to problems with your water situation? (Activities that may have been interrupted include caring for others, doing household chores, agricultural work, income-generating activities, sleeping, etc.)
5. In the last 4 weeks, how frequently have you or anyone in your household had to change what was being eaten because there were problems with water (e.g., for washing foods, cooking, etc.)?
6. In the last 4 weeks, how frequently have you or anyone in your household had to go without washing hands after dirty activities (e.g., defecating or changing diapers, cleaning animal dung) because of problems with water?
7. In the last 4 weeks, how frequently have you or anyone in your household had to go without washing their body because of problems with water (e.g., not enough water, dirty, unsafe)?
8. In the last 4 weeks, how frequently has there not been as much water to drink as you would like for you or anyone in your household?
9. In the last 4 weeks, how frequently did you or anyone in your household feel angry about your water situation?
10. In the last 4 weeks, how frequently have you or anyone in your household gone to sleep thirsty because there wasn’t any water to drink?
11. In the last 4 weeks, how frequently has there been no useable or drinkable water whatsoever in your household?
12. In the last 4 weeks, how frequently have problems with water caused you or anyone in your household to feel ashamed/excluded/stigmatized?

6.4.2 Conducting the Survey

This section describes the process of collecting the household characteristics survey. This was performed concurrently with installing meters on the households that chose to participate in the survey. The fieldwork was conducted alongside research partners in Lahan, Nepal from September to December 2022. The fieldwork aimed to install household smart meters to measure water usage at a high temporal frequency, and to perform household surveys to capture household characteristics. A total of 60 surveys were conducted and 56 successful smart meter installations were completed. The meters were installed in batches across the fieldwork window; all meters had begun recording usage by 31st December 2022.

6.4.2.1 House visit Procedure

The process that was used to approach households and conduct the survey is summarised by Figure 6.7. The installation of the smart meters occurred separately to the household survey to minimise the idle time of the plumber. Performing the tasks separately was more efficient but it presented a critical challenge: The correct logger must be installed at the correct household to match the database. Otherwise, the received data may refer to the wrong location and household survey information, undermining the aims of the fieldwork. To ensure this was done correctly several steps were taken:

1. Each house was given a unique identification number, this was recorded on the house visit checklist (available in Appendix A), marked on the pipe where the meter was to be installed and marked on the information sheet given to the household owner;
2. The coordinates of the house were recorded on the checklist and a photo of the location taken to enable the plumber to easily locate it;
3. Each smart meter was individually packaged with the check list that contained the logger ID number and household location information;
4. Once the plumber had installed the meter, he was requested to photograph the installation and the logger with the serial number visible;
5. All installations were checked at a later date and photos of serial numbers taken again. These were crosschecked with the database information. The checks confirmed all meters had been installed correctly according to the criteria set out in 6.5.2.

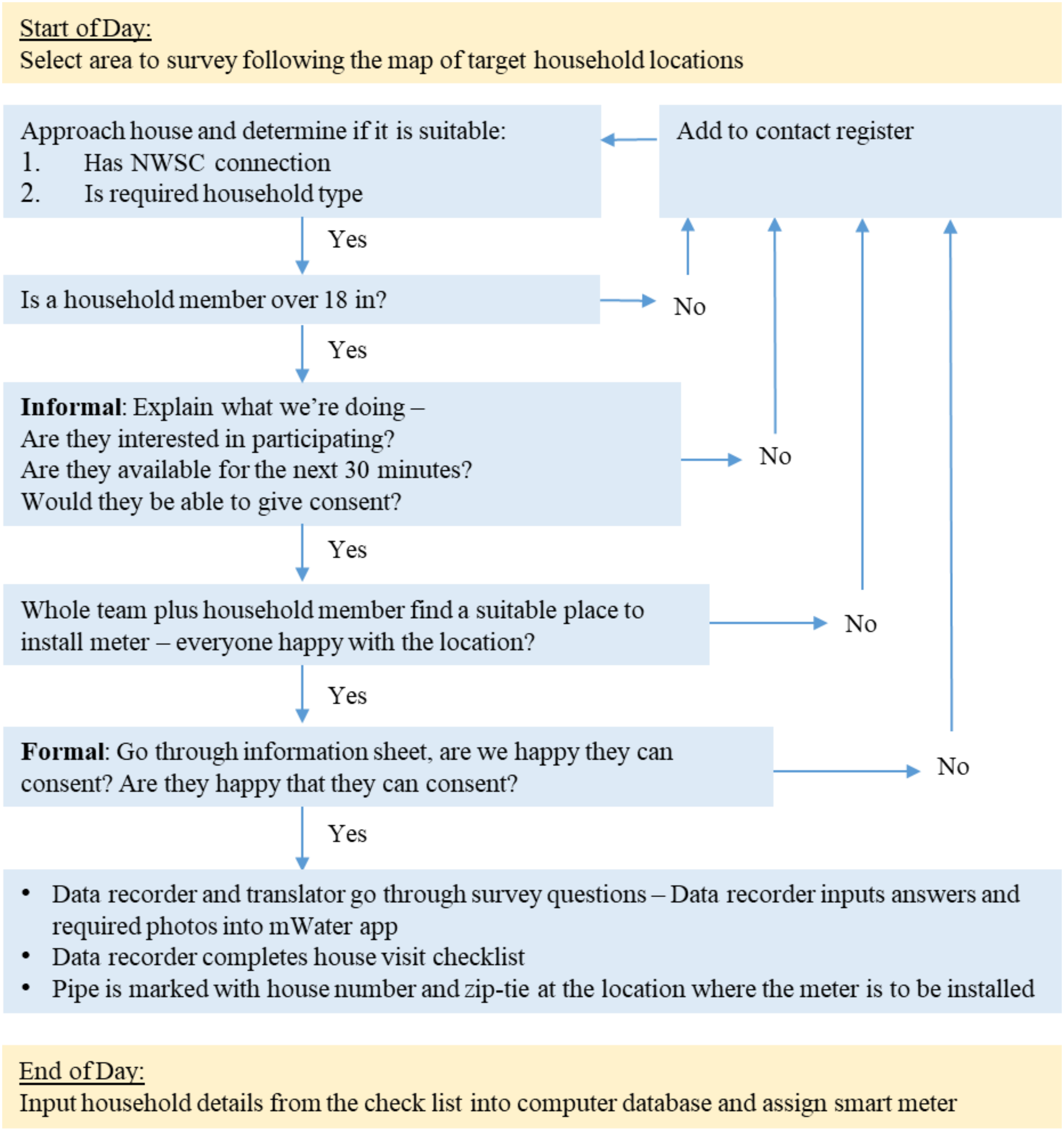


Figure 6.7: Flow Diagram of the Fieldwork Procedure

6.4.2.2 Administering the Survey Questions

The household survey was conducted with the aid of a local translator who spoke both the national language: Nepali, as well as the local dialect: Maithili. The survey questions were asked by the translator and the responses relayed back to the author in English. For simplicity, and to avoid the survey taking up too much of the participant’s time, the translator did not translate responses word-for-word. The responses therefore involved some interpretation and summarising by the translator. The possibility of information being lost in translation was noted prior to commencing the fieldwork. To mitigate this concern, the translator received a thorough briefing that emphasized the importance of accurately reflecting the participants' responses. The purpose of each question was explained to help enable suitable interpretation of participant responses to be made.

Occasionally some back-and-forth was required to obtain a satisfying answer; the comments box on the survey form was useful for noting down any additional relevant information that was thought necessary for future interpretations of the response. The responses were recorded by the author using the mWater app. The use of mWater as a tool for conducting surveys was recommended by the project partners, WaterAid, and it proved to be an effective method of recording responses. The data was stored on a secure, password-protected online portal allowing encrypted access and retrieval of data from any location.

6.4.2.3 Sampling Bias

To be eligible for the study, households were required to have a stretch of accessible pipe that allowed a meter to be attached. This requirement raised the concern that the selection of houses may be skewed to a particular type; however, observations from the field did not identify a pattern between the availability of appropriate pipework and household type. The desired range of household types was still achieved despite this requirement.

Another source of potential bias resulted from some households wanting the head of the household to be present to give permission. This was typically the male homeowner, who, in circumstances when they were away working, could not give permission resulting in the household not being added to the study. Consequently, the sample is biased towards households where the homeowner does not work away from the house. This bias could not be corrected but is considered insignificant.

As expected, some households declined participation in the study. This was often due to mistrust in our intentions and a general apprehension to having the smart meter installed. Whilst conducting the survey, there was no observed correlation with a particular societal group, however, this may be another bias that it has not been possible to correct.

The Lahan water distribution network includes approximately 20 community taps that were excluded from the study. The research ethics review highlighted that adding a meter to the tap could discourage their use, as users may believe the meters were being used for billing, and would therefore incur charges for using the water. To avoid any potential of disrupting normal usage patterns and causing greater water insecurity, they were not considered in the sample selection.

A target map (Figure 6.8) was used to guide where the fieldwork would be conducted. The map allowed progress to be tracked, ensuring the target number of households in each elevation band were sampled (criteria (1)). On-the-ground decisions were made to maintain the desired balance of household types (criteria (2)).

The actual sample locations are shown in Figure 6.8(a), a comparison with Figure 6.8(b) shows the sampled locations align closely with the target locations. The spread of elevations was achieved however every 'end' of the network (such as the far west) could not be sampled. This was due to the low density of connections in those locations and an inability to locate a willing participant.

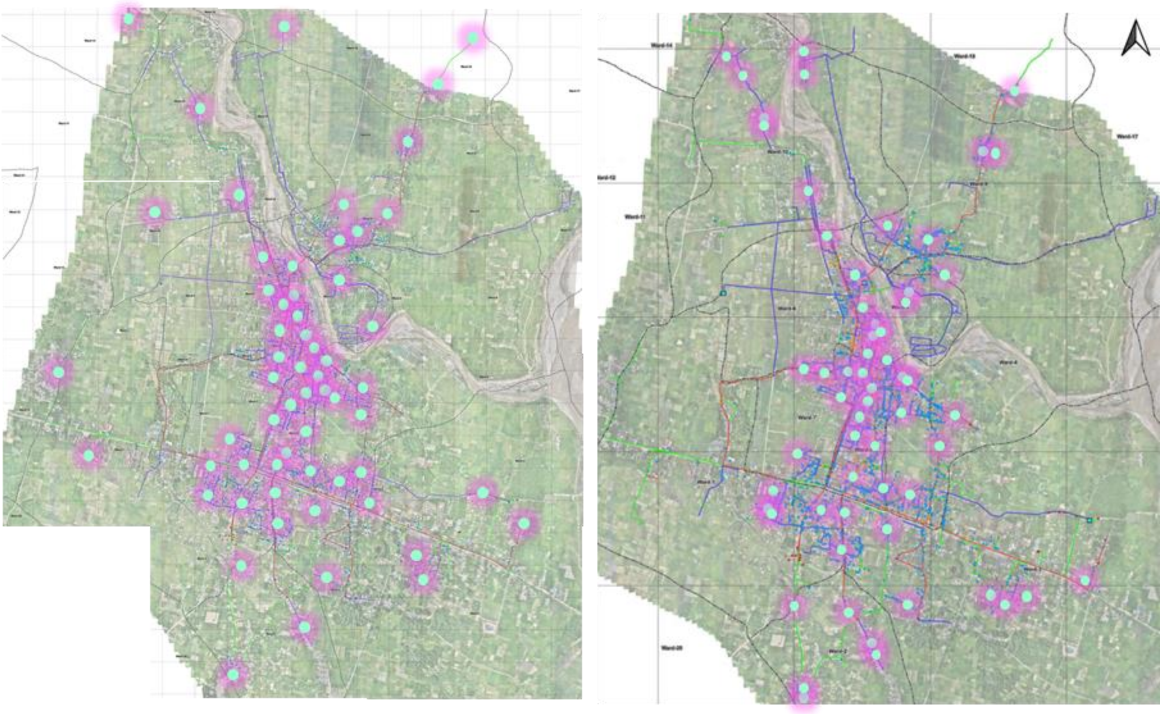


Figure 6.8: Maps of the (a) Target Sampling Locations and (b) Actual Sampling Locations

6.4.3 Question Adjustments

Following completion of the surveys, some responses were 'encoded' to improve the comparability of responses. The categories used in the 'What is the piped water quality like?' question of (a) Good, (b) Dirty Water (c) Bad Smell, were chosen so that they would correspond with the categories used in the preceding survey by the project partners (WaterAid Nepal, 2020). Alongside each response, detail could be added in a 'white box' format. At an early stage when conducting the survey, it was decided this box would be used to distinguish between 'generally good', 'generally bad' and 'sometimes good, sometimes bad' water quality. This information enabled the responses to be post-processed into these categories, which are more helpful for the study aims.

6.5 Measuring Household Water Withdrawal

6.5.1 Metering Equipment

To observe the temporal variation in household piped water withdrawal, volumetric flow meters that log usage at high temporal resolution were required. To understand usage patterns and seasonal effects the meters would be installed for a minimum of one year, this required the data to be collected and transferred to the UK for analysis beyond the length of the fieldwork. To avoid having to hire support to manually download the data (requiring regular access to private property), and the potential for data being mixed-up in transfer, internet enabled equipment was regarded as the best option. ‘Smart meters’ offer these capabilities and were therefore the chosen equipment.

The required measurement frequency of the smart meter was chosen as a compromise between battery longevity and a desire for the smallest possible interval. As discussed in the methodology, a 1-minute interval would be advantageous for the studies aims. A small measurement interval provides the greatest information on when and how water is being consumed from the connection, but the higher the frequency, the quicker the battery is drained. After reviewing existing technology, a frequency of one sample per minute was deemed feasible. This would provide substantial detail of usage behaviour whilst allowing the desired battery life.

To provide the required data for this study, the household meters had the following requirements:

1. Ability to record at one-minute frequency whilst maintaining battery life for 1+ years
2. Ability to transfer the data via the 4G telecommunications network. Assessment of the telecommunications networks in Lahan (via Lahan-based colleagues and a reconnaissance trip in June 2022) identified 4G as the strongest and most reliable medium
3. A reputable meter manufacturer to maximise reliability
4. Ability to be installed on ½ inch household pipes

The meters were to be installed within residential properties at a range of locations across the city. These uncontrolled environments presented several risks to the effectiveness and longevity of the recording devices. To maximise the likelihood of long-term, reliable measurements of household usage, the meters also had the following desirable properties:

1. IP68 waterproofing
2. ‘Closed-box’ design to minimise interest and potential of theft
3. Small and inconspicuous to enable ease of installation in homes and minimise inconvenience
4. Ability to be installed in both horizontal and vertical positions

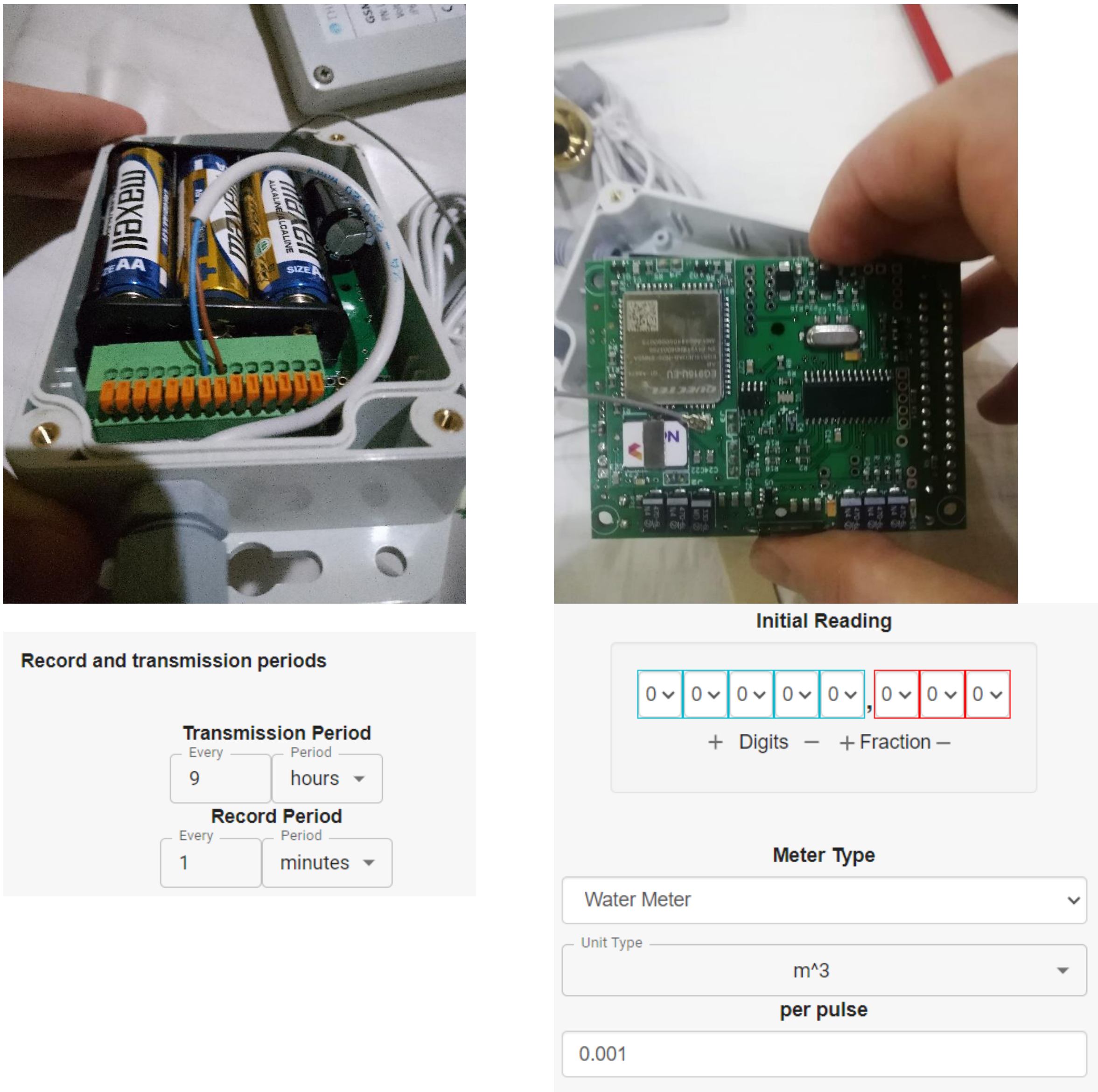
Several metering configurations were considered before the optimal equipment was chosen. This consisted of a BMeters Single jet GSD8-I meter fitted with a pulse emitter (Figure 6.9(a)) connected to a ThingsLog 4G Data Logger (Figure 6.9(b)). The data logger is fitted with a Nepalese NCell SIM card providing 4G capabilities. The flow of water through the meter pushes a turbine that is then connected to a rotating dial, whenever the dial passes one litre, the meter emits a pulse that is transmitted via a cable to the data logger. The data logger records the number of pulses received over a set period (minimum one minute) and stores the data before transferring it to a web server at another pre-determined transmission period. The data sent to the web server can be accessed via the manufacturer's online portal and/or via an API request. An additional benefit of the chosen devices was that they use AA batteries as opposed to more specialised Lithium based options. In the eventuality that batteries needed replacing, replacements could be easily obtained locally and replaced without difficulty.

The BMeters GSD8-I meter is approved by the Water Regulations Approval Scheme (WRAS) and the Measuring Instrument Directive (MID). It is therefore in accordance with all water safety regulations as well as having a robust accuracy testing. The model has a R100 rating when installed horizontally and R50 when installed vertically. The Minimum flow rate is 16 Litres/h, transitional flowrate is 25.6 Litres/h and the overload flow rate is 2000 Litres/h. Between the minimum and transitional flowrate, the accuracy is +- 5%, between the transitional and maximum flow rate, the accuracy is +- 2%.

Figure 6.9: Equipment Used for Household Smart Metering (a) BMeters GSD8-I (b) ThingsLog 4G Data Logger

6.5.1.1 Initial Setup

Setting up the equipment involved connecting the pulse cables from the meter into the appropriate channels of the data logger as shown in Figure 6.10. The loggers were configured using the specifications in Figure 6.10. The transmission period of nine hours was selected as it represents the maximum amount of data the loggers can store when set to a record period of 1 minute. This maximises the battery life by minimising the regularity of energy-consuming transmissions. The initial reading was set to match the dial reading of the connected meter. To be satisfied the device was working correctly, air was blown through the meter causing the counter to spin. The accurate recording of this could then be checked via the online portal.



Record and transmission periods

Transmission Period
Every: 9
Period: hours

Record Period
Every: 1
Period: minutes

Initial Reading

0 0 0 0 0 , 0 0 0

Meter Type
Water Meter

Unit Type: m^3

per pulse
0.001

Figure 6.10: Household Smart Meter Setup and Configuration

6.5.2 Meter Installations

The household smart meters were installed on the inlet pipe to the household, typically placed after the existing manual meter used by NWSC for billing purposes, as shown in Figure 6.11. This ensures they record the total volume of water used by the household before any household plumbing divides the flow. The meter specifications state that they can be installed with no requirement for straight pipes either side, since the supplied connections were sufficient to ensure consistent flow entering into the turbine mechanism. In addition, they can be installed both horizontally and vertically. The plumber was given the following instructions to ensure consistent installation, minimise hazards / inconvenience of the meters and maximise the longevity of the installation:

1. Once the meter is attached, the data logger should be fastened at an appropriate location, the adjoining cable shall be wound up and fastened to the pipe neatly;
2. Take three photos of the logger serial number, meter serial number and overall installation;
3. Once installed, flush out the new plumbing before the water is used by the household.

Figure 6.11: Example Household Smart Meter Installations

The project partners, The Beacon Project, have an office in Lahan that is connected to the piped water network. This was selected as a site for a smart meter as it provided a useful test location and was desired by the project partners. A local school was also monitored with a smart meter (as requested by the project partners). A smart meter was also installed in a different office location after confusion about how the building was being used. This resulted in three locations being monitored that were non-residential dwellings (one school and two offices).

Following completion of the survey and acceptance of having a smart meter installed, two households later retracted their consent due to changes to their plumbing arrangements making it not practicable. Two smart meters had a fault causing them to not record any flow despite usage being observed. The faults could not be resolved following inspections and were therefore decommissioned. As a result, of the 60 available smart meters, 56 were successfully installed and recording usage from 31st December 2022. Of these, 53 were connected to residential dwellings.

6.5.3 Potential for Meter Errors

There is the potential for errors in the meter data resulting from issues such as fouling and meter drift. This is the phenomenon by which meters lose accuracy overtime, typically under-recording flows. A study by Hofman et al. (2002) found that volumetric meters such as the type used in this study are least prone to meter drift and predicted a lifetime of 10-12 years, which is far beyond this study duration. However, the water supply in Lahan is likely to have higher turbidity and therefore fouling rates may be higher. Despite this, during a period of less than two years it is unlikely significant errors would have developed in the meters.

There is also the potential that the meters are recording air going through and thus not giving a representative measure of water withdrawal. As discussed in section 2.2.4, this could cause over registration of withdrawal volumes. Air passing through the meters will tend to occur at the beginning of a supply period as air is released from the pipes. The air will only escape via consumer taps if they are left open at the beginning of the supply period. The survey asks this question, which will allow an assessment of how common this practice is in Lahan. In addition, customers are incentivised to limit air going through their meter as it adds to their bills and so they are likely to employ strategies to reduce it.

The potential for air being recorded by the meters was tested by analysing the withdrawal data. In laboratory experiments Ferrante et al. (2022) found that single-jet meters installed on ½ inch pipes (the same criteria as this study) tended to spin 14 times more quickly when air passed through as opposed to water. Therefore, two metrics were used to try to identify unusually high flowrates. The volume of water that was recorded by each meter above a certain flowrate threshold was calculated. The fraction that this represented of the total water volume recorded by the meter was subsequently calculated. Two thresholds were tested: (1) flowrates exceeding five times the 90th percentile flowrate of the meter, and

(2) any flowrates exceeding 25 L/minute. The full results can be found in Appendix A. In summary, of the 56 meters, five showed a volume under threshold 1 that was greater than 1% of their total recorded volume. The two highest percentages were 8% and 5.2%. Graphs of the flowrate data associated with these two meters can also be found in Appendix A. Under the second threshold, nine meters recorded a volume that was greater than 1% of their total recorded volume. The second threshold is perhaps too conservative as it is far lower than the maximum flowrates recorded by Ferrante et al. (2022) of 738 L/minute.

6.5.4 Withdrawal Data Processing

This section summarises the initial processing of the data obtained from the household smart meters. First, the amount of data lost due to faulty equipment or communication issues is quantified. Followed by a description of the steps taken to calibrate and clean the meter data.

6.5.4.1 Data Loss across Recording Period

Three meters stopped recording data between January and October 2023 either because they stopped working or were uninstalled by the household. In November, approximately one third of the meters stopped transmitting data followed by a similar proportion in February. This was determined to be a result of the Nepal Telecommunication Authority launching a campaign to disconnect SIM cards that have not been explicitly registered to a mobile device. Unfortunately, this inadvertently affected the smart devices. By April 2024, most devices had been brought back online resulting in a total of 37 functioning devices.

Data was occasionally lost in transmission between the logger recordings and abstraction from the manufacturer’s data servers. All devices experienced some loss in data with an average of 1.07% (range: 0.58 – 2.04%) across the January – October 2023 period.

6.5.4.2 Calibration of the Meter Data

An installation check was conducted to ensure the devices had been installed in the correct configuration and check the mechanical dial reading matched the online readings sent via the smart meter. The checks confirmed the meters had been installed in the correct location, i.e. measuring the total volume into the house before any pipes branched off. The dial reading checks revealed some devices had discrepancies with the online readings. A second round of checks was conducted for all meters in May followed by a third round for the seven meters that showed a discrepancy that was more than 5%. Calibration factors were calculated for the erroneous meters as summarised in Table 6.5. Calculation of the calibration parameters can be found in Appendix A (note some meters were checked on more than three occasions).

Table 6.5: Calibration Parameters Applied to Selected Household Smart Meters

Logger ID	**Calibration Equation**
3	$Y = 0.6279x - 44.26$
12	$Y = 1.1493x + 9.88$
15	$Y = 1.1524x - 1.86$
23	$Y = 0.7034x - 2.17$
57	$Y = x + 110.6$
58	$Y = 1.2651x + 1.73$
59	$Y = 1.0578x - 0.16$

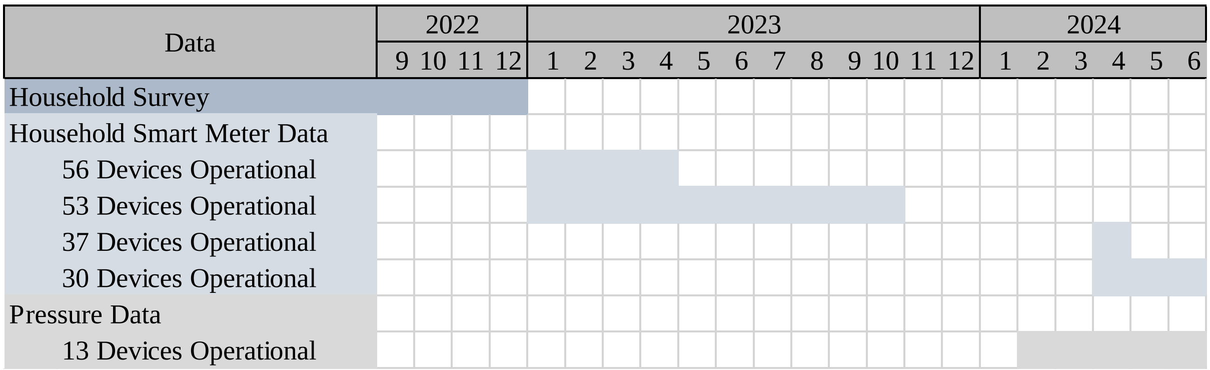
6.5.4.3 Cleaning the Withdrawal Data

As mentioned in section 6.5.4.1, there were occasional gaps in the transmission of data. The flowrate value directly following such a gap would include the total accumulated flow since the previous data recording. This often resulted in extremely high flowrates that are not representative of the flow during that 1-minute timestep. Consequently, a data cleaning procedure was employed that removed this extreme flowrate from the data set. When calculating daily averages and behaviours, days that had any missing data were removed to ensure that only full days of data were included. This ensures the removal of the erroneous data points did not affect the calculated averages.

6.6 Summary of Data Capture

Table 6.6 summarises the data collected in Lahan across the study period. The dataset used in the results and analysis sections are specified throughout and can be crosschecked against this table.

Table 6.6: Summary of the Duration of Data Capture across the Study Period



Data	2022				2023												2024					
	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6
Household Survey	▨	▨	▨	▨																		
Household Smart Meter Data																						
56 Devices Operational					▨	▨	▨	▨														
53 Devices Operational					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨								
37 Devices Operational																				▨		
30 Devices Operational																				▨	▨	▨
Pressure Data																						
13 Devices Operational																		▨	▨	▨	▨	▨

6.7 Pressure Data Analysis

The following section describes the methods used to analyse the data obtained from the pressure loggers. Since most of the supply inputs into the network were recorded by an adjacent pressure logger, data was used to characterise the network input supply. An interpolation procedure was then used to estimate pressure across the network, specifically the locations of the sample households. The estimated pressures were then used to approximate the local supply hours across the network.

6.7.1 Characterising Input Supply

Figure 6.12 shows each daily pressure trace of a logger adjacent to an input supply borehole across April 2024. The day-to-day variation in input supply is evident. Defining the 'typical' input supply hours from this source therefore requires a method of defining daily supply hours. As shown in Figure 6.12, a minimum pressure threshold needs to be chosen to define when the supply is considered 'on'. A sensitivity analysis was conducted to assess how thresholds defined from 1-5m affect the resulting calculation of supply hours. For each pressure threshold the median supply hours over the course of the month was calculated. Figure 6.13 summarises the results from this sensitivity analysis. The sensitivity analysis led to a 4m pressure threshold being chosen. This was because it was above the 'noisy' behaviour at the low-pressure thresholds and the resulting estimations of supply hours levelled off at this threshold for all the input sources. Equivalent figures for each of the other network inputs are presented in results section 7.1.1.

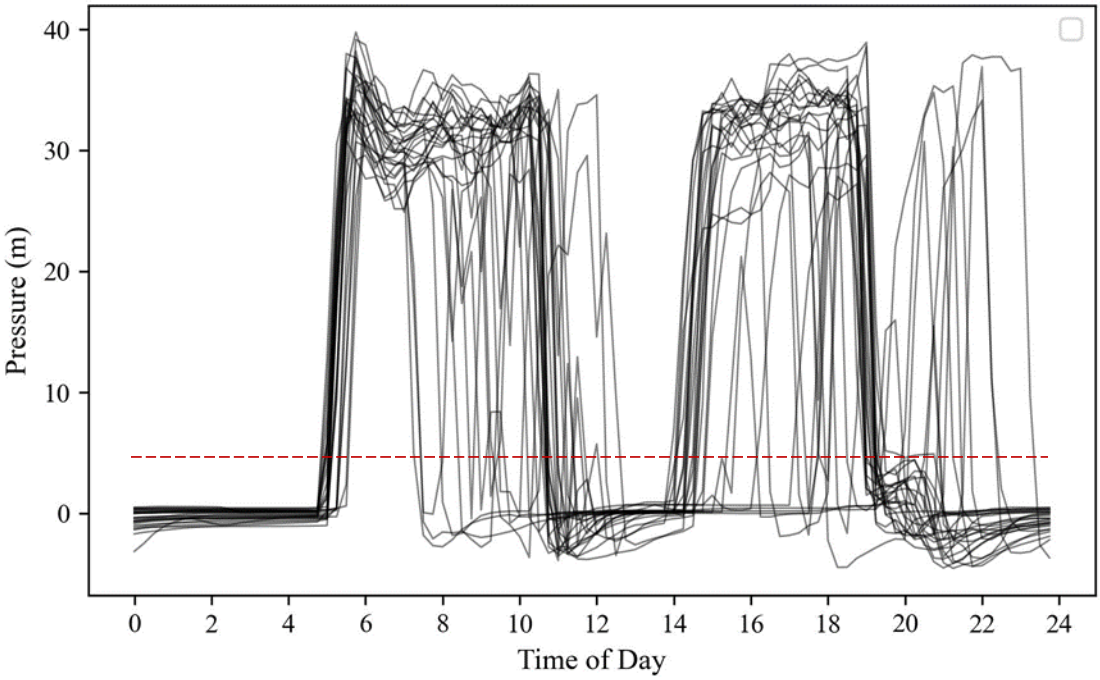


Figure 6.12: A pressure Trace from each day in April 2024 of a Pressure Logger Adjacent to ASH Input supply Borehole. The Red Line Represents a 4m Minimum Pressure Threshold for Defining Supply Hours

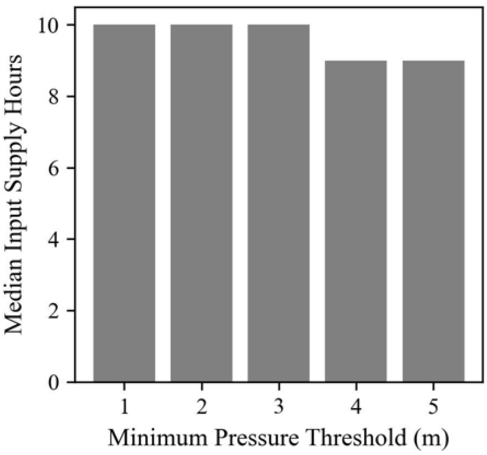


Figure 6.13: The Estimated Input Supply Hours of the Borehole Associated with Figure 6.12 given Different Minimum Pressure Thresholds

6.7.2 Network Interpolation

In order to estimate the local pressure at each surveyed household, a method of interpolation was required using the known pressure values recorded at the pressure logger locations. Typically, pressure data would be used to calibrate a hydraulic model of a water supply network, but as section 2.6.1 of the literature review highlighted, there is not an established method of hydraulically modelling the full IWS cycle (including filling and draining stages). An alternative approach was to employ a numerical method of interpolation. Although this approach does not have a physical basis as with hydraulic models, it introduces fewer uncertainties in the outcome.

The density of pressure loggers deployed in Lahan means the reliability of interpolated results was deemed relatively high during the supply periods and non-supply periods. The estimates are less reliable during the draining phase. As the network drains, there will be a free surface that moves down the network according to elevation. Therefore, the interpolation procedure would ideally interpolate between this free surface and the pressure recordings of the loggers in the undrained areas (i.e. at the lowest elevation). Above the free surface, the pressure would be atmospheric as the pipes are empty. The interpolation method used does not reflect this physical process of draining, instead interpolating between pressure loggers, hence generating some uncertainty in the local pressure estimations.

The two loggers, NTWRPM and SETKPM, which are connected to transmission pipes, were naturally not included in the interpolation process as it aims to estimate pressures in the distribution network. Pressure records from OTWRPM were only included during the periods when the valve at the base of OHT1 was open and it was therefore hydraulically connected to the network (as described by Figure 6.4). At other times, it was not included in the interpolation procedure.

Estimating local pressures across a network using nodes with known values is essentially a spatial interpolation problem. To solve this, two deterministic methods were applied and compared in order to establish the optimal approach. Firstly, Inverse Distance Weighting (IDW), and secondly, using a

Residual Basis Function (RBF) to interpolate between known nodal values. IDW determines the value at unknown points by averaging the values of the nearby known points based on a weighting that is inverse to the distance away from the known values. RBF assigns a distribution (typically Gaussian, which is used in this instance) to each known value with the point being at the centre of the distribution. This allows unknown values to be estimated based on their distance from the nearby known points and the shape of the distributions associated with them. Values are interpolated by a weighted sum of the nearby points.

To represent the nature of the piped network, the distance between points was calculated along the piped network as opposed to using Euclidean distance. The importance of this was exemplified in the Northern region where the river separates the network; Figure 6.1 shows pressure loggers ASBCPM and ASHIPM have a short Euclidean distance while their separation via the piped network is much further. Figure 6.14 compares the output via the IDW and RBF approaches. Crucially, the IDW method requires the definition of the distance decay parameter ‘p’, this defines the rate at which the value at the known node reduces as the distance increases. The definition of such a term has a significant impact on the outcome and requires careful adjustment (Lu & Wong, 2008). The RBF approach is based on distributions associated with each known value, meaning locations in between where the interpolation is calculated are affected by all adjacent nodes by default. This property is highly favourable for the purposes of this analysis.

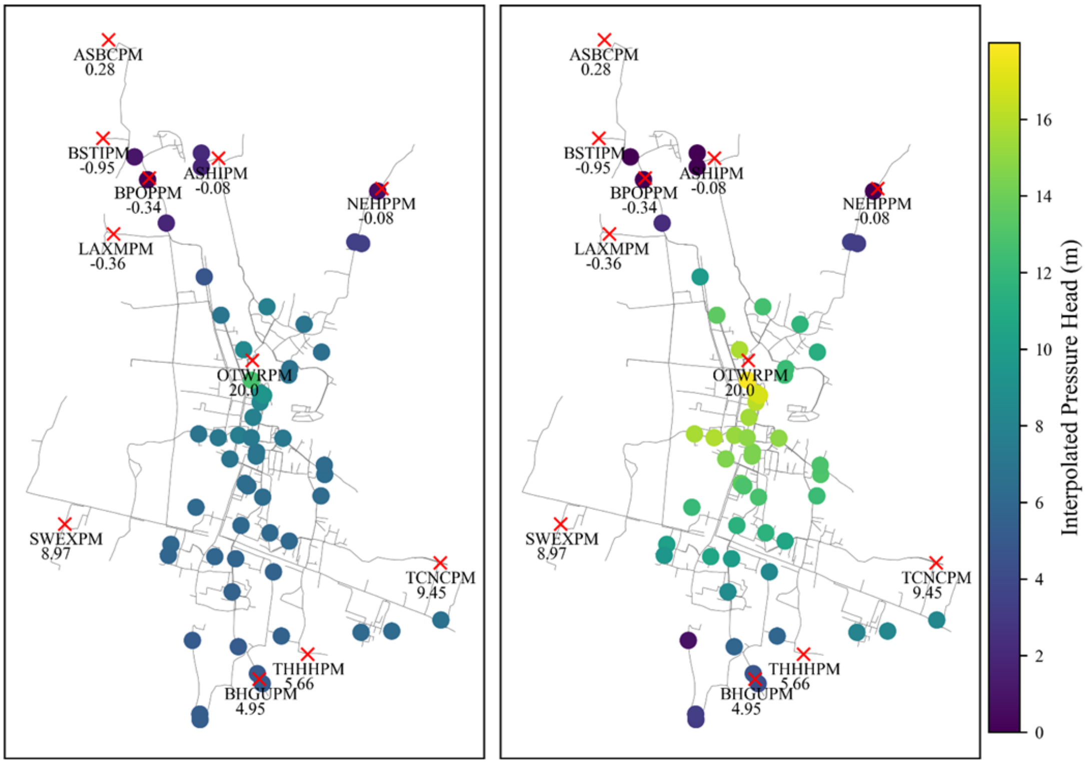


Figure 6.14: Interpolated Pressure at Household Locations Using (left) IDW Method and (right) RBF Method for a Single Timestep. Note ‘X’ marks denote pressure logger locations and measured pressure values (in metres)

The relative success of both methods at producing reasonable interpolations was assessed firstly by plotting a weeklong pressure trace of all the household locations. This assessment showed both approaches produced results within the expected bounds, but further comparison was limited. Next, the pressure values were plotted on a map to visualise the variation between points. Comparison of the mapped output gave much greater indication of how the methods were operating. Figure 6.14 shows the RBF method produces estimations that are much more closely aligned with expectations. The IDW function is inappropriate as the estimated pressures are too heavily weighted to their nearest pressure point and not an interpolation between known values. This does not reflect the nature of pressure distribution across a piped network where all points are hydraulically connected. The output produced by the RBF method was therefore deemed more successful and was selected for this analysis.

6.7.2.1 Limitations of Local Pressure Estimations

The large area without a pressure logger in the middle of Lahan means interpolations from the south to the north are over relatively long distances. This is reduced significantly when OHT1 valve is opened during the supply period (and therefore incorporated into the interpolation calculations). However, during the draining phase (when the valve has been closed) it is hydraulically disconnected and not used in calculations. The precision of the estimations is therefore reduced.

6.7.3 Estimating Local Supply Hours

An estimation of local pressure enables the calculation of the corresponding local supply hours simply by summing the amount of time that the pressure is above a minimum value. Selecting this minimum value however introduces another layer of uncertainty; what is the minimum pressure that is required for withdrawal to be possible at the household? This value is dependent on the household plumbing arrangement, specifically the elevation at which the tap or storage container is located. Consequently, a range of ‘minimum pressure thresholds’ are tested and their effect on the estimated local supply hours are presented in section 7.1.1. The local supply hours are calculated from the interpolated pressure values across April 2024. Each day the estimated number of hours is calculated and an overall average determined for the month of April.

In addition, the minimum pressure at which withdrawal from the household occurred was also investigated. First, the estimated pressures that correspond to times that withdrawal is occurring were selected, this subset of the data was then analysed to calculate the minimum, 1st percentile, and 5th percentile pressures (at which withdrawal is occurring).

6.8 Withdrawal Data Analysis

The withdrawal data from the household smart meters was used to establish key withdrawal habits of the households. This section outlines the methods used to determine household daily withdrawal patterns as well as household withdrawal instance characteristics.

6.8.1 Daily Withdrawal Patterns

A household's typical withdrawal pattern was determined by first splitting the 24 hours in a day into 15-minute timeslots. Within each timeslot the probability that the household withdraws water was calculated i.e. the number of days the household withdraws some water divided by the total number of days. The data was aggregated to 15-minute intervals as this analysis was aiming to establish the typical times of the day that water is withdrawn for different households. Using 1-minute timeslots was too granular to give the general trend in behaviour that was sought. Figure 6.15 shows an example output from this analysis for a single household. A value of one would indicate that the household uses water during that 15-minute timeslot every day. For every occasion that withdrawal occurs during the timeslot, the flowrate was also recorded allowing the shading of the bars according to the mean flowrate.

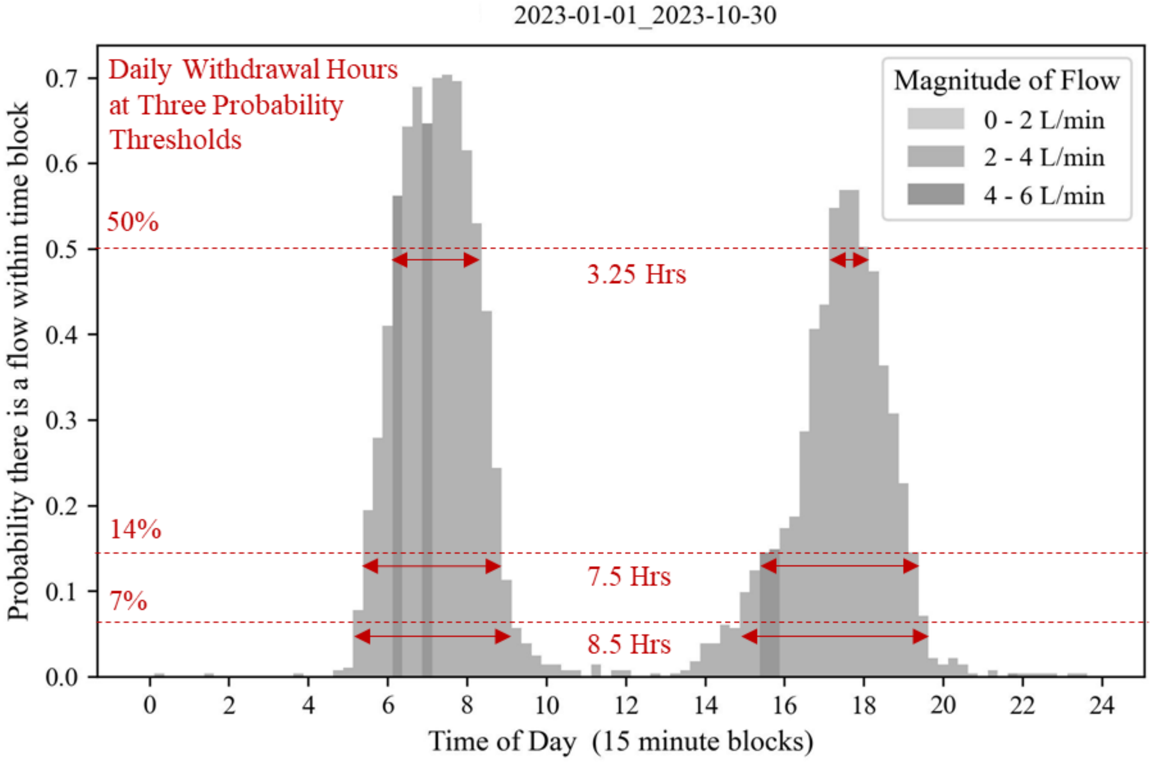


Figure 6.15: Example of the Daily Withdrawal Pattern of a Household and Estimation of the Daily 'Withdrawal Hours' of a Household Calculated at three different Probability Thresholds

Overlaid on Figure 6.15 are lines associated with the calculation of daily 'withdrawal hours'. The calculation of the withdrawal hours is essentially an attempt to quantify the daily withdrawal pattern of households. Three thresholds of probability were chosen providing three metrics for each household. The withdrawal hours can be defined as the number of hours per day that households typically withdraw water within. A probability of withdrawing water of more than 7%, 14% and 50% were investigated as they indicate a regularity of water withdrawal of at least once-a-fortnight, once-a-week and every-other-day respectively. The example household in Figure 6.15 has daily withdrawal hours of 8.5, 7.5 and 3.25 hours per day respectively for the three thresholds.

6.8.2 Withdrawal Instance Analysis

The withdrawal characteristics of a household were further characterised by investigating the withdrawal instances. Figure 6.16 shows the meter data from a single household across a single day, a withdrawal instance is defined as each occasion of continuous water withdrawal (for example turning the tap on to wash your hands, turning the tap on to fill your storage tank etc.). Analysing the unique series of withdrawal instances enables a characterisation of the typical household withdrawal habits. Multiplying the duration of the withdrawals by the average flowrate gives the volume of withdrawal. In addition, the duration since the previous withdrawal was also calculated for each withdrawal instance.

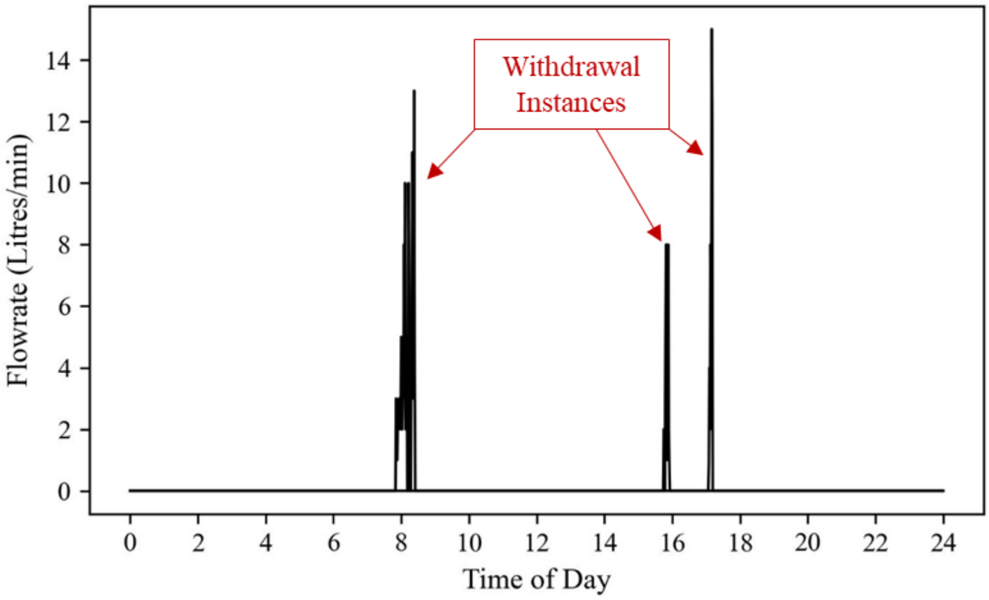


Figure 6.16: Example Meter Data across a Single Day for a Single Household Highlighting the Withdrawal Instances

6.8.3 Analysing Seasonal Effects

To assess seasonal effects associated with the withdrawal of water, climate data was also required. This was obtained from OpenWeatherMap using an API to abstract hourly records of average (feels like) temperature (°C) and precipitation (mm). The weather data is provided by ‘different sources such as global and local weather models, satellites, radars, and a vast network of weather stations’ (OpenWeatherMap, 2024). The hourly weather data was aggregated to daily average temperatures and daily total precipitation for analysis of seasonal trends.

6.9 Investigating the Effects of Weighting the Survey and Withdrawal Data

The aim of the sampling approach was not primarily to achieve a representative sample of Lahan. As discussed in section 6.3.3, priority was given to achieving criteria (1) Stratification based on elevation, and (2) A range of household types. This was to maximise the chances of sampling the range in conditions and behaviours across the water supply network. As a result, the sample is skewed. There is a greater density of households in the centre of Lahan, which will be underrepresented by this approach. This section aims to investigate the effects of this sampling bias.

The samples were weighted according to the density of connections across the network. It is important to note that this study is focussed solely on households that are connected to the piped network, which is a defined subsection of the total population of Lahan. Henceforth ‘population’ refers to all households in Lahan that are connected to the piped network, not the population of Lahan.

The density of connections in Lahan was established using WaterAid Nepal (2020). Figure 6.17 shows the area of the Lahan network divided into a 500m x 500m grid, within which the number of NWSC connections and the number of household samples were counted.

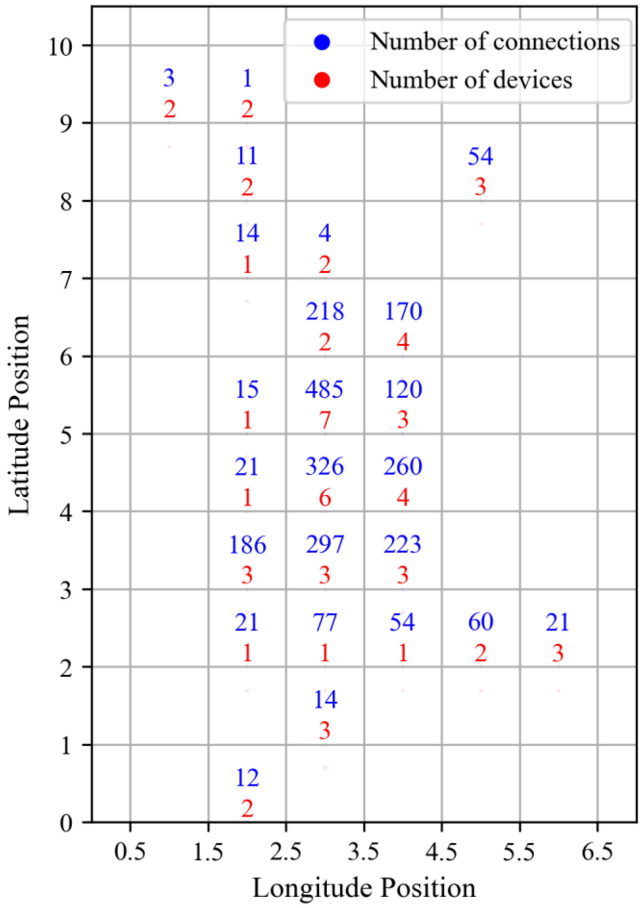


Figure 6.17: Density of Connection Population vs Sampled Households

Figure 6.18 overlays the sample size within each grid against the number of connections. The vertical axis have been scaled according to the relative sizes of the two groups enabling comparison of the difference between sample size and connection population across the grid squares. The areas with the greatest discrepancy are in the far northern and southern regions which is overrepresented by the sample.

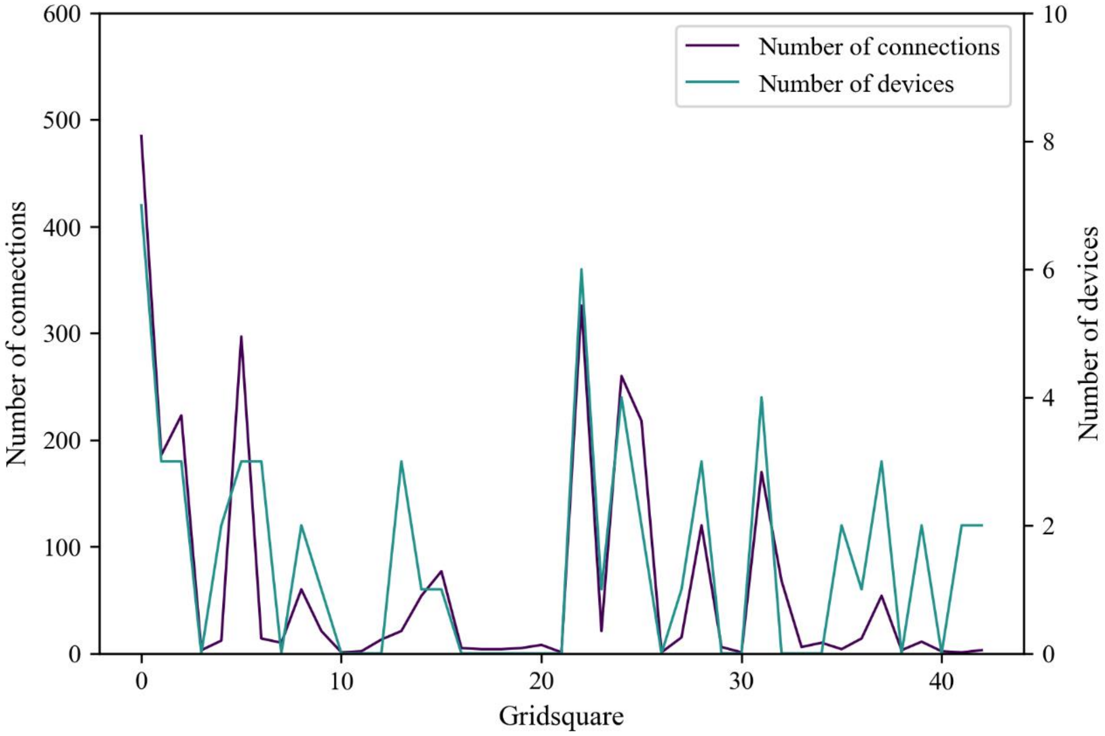


Figure 6.18: Number of Connections per Grid Square vs Number of Samples

Figure 6.19 shows histograms of the household elevations both without (a) and with (b) the weighting. The overrepresentation of the highest and lowest elevations is evident, which corresponds with the north and south of Lahan respectively. This is reflected in Figure 6.20(a), which shows the cumulative distribution of the sample and population according to their elevations. The overrepresentation of the lowest and highest elevations is again visible.

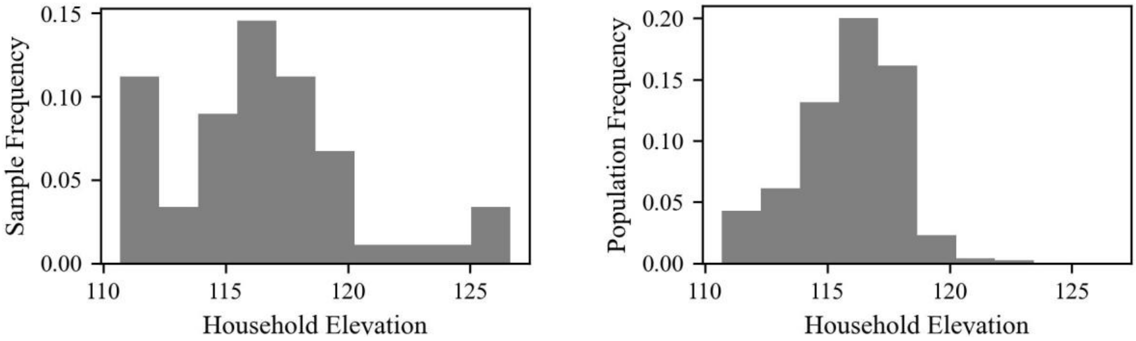


Figure 6.19: Frequency of Households at Different Elevation Bands of the (a) Sample Group and, (b) Population Group

Table 6.7 shows the effect of weighting the sample on categorical data from the survey. The most significant difference is in the percentage of the population that report having 24 hours of supply, which is unsurprising given that this group is situated in the overrepresented southern region.

Table 6.7: Effect of Weighting the Sample on Survey Categorical Variables

Percentage of households reporting…	**Survey Sample**	**Weighted Population**
24 hours of supply	16%	6.5%
A yard tap (not fully plumbed)	50%	42%
Storage volume < 500 Litres	52%	45%
Owning a tube well	70%	67%
Being North of the highway	73%	74%
Perception of water quality:	Generally bad: 38% Sometimes good, sometimes bad: 21% Generally good: 41%	45% 14% 41%
Mainly using water directly or stored during a supply period	Stored: 47% Directly: 53%	58% 42%
Having the tap open the entire duration of the supply period	Open entire duration: 14% Closed: 86%	19% 81%
Use more water if the supply duration increased	No: 41% Yes, a little: 20% Yes, a lot: 39%	35% 24% 42%
Wanting the hours of supply to increase	No: 29% Yes, a small increase: 29% Yes, a large increase: 43%	25% 26% 49%

The continuous data collected from the survey was plotted in cumulative frequency charts alongside the equivalent population dataset as shown in Figure 6.20. The Kolmogorov-Smirnov (KS) test was applied to the two distributions to assess whether they are statistically unique, the results are summarised in Table 6.8. For all variables, the KS test resulted in the null hypothesis not being rejected, thus the two samples are likely drawn from the same distribution. This indicates the sample data is not significantly different to the population data at the 95% confidence interval. The p-value for household elevation was by far the lowest of all the variables at 0.085. An additional analysis was applied to the household elevation; the one-sample Wilcoxon Signed Rank test (since the distribution of the sample data is non-parametric). The result of which gave a p-value of 0.546 meaning the null hypothesis could not be rejected at the 95% confidence level, indicating the sample and population come from the same distribution. This corroborates the result from the KS test.

The number of sampled households is not a representative sample size of the piped water connections in Lahan. A sample size of 347 would have been required, which was not practically feasible for this study (calculated using Cochran's Formula). Therefore, all statistics based off the sample have the caveat that they are not representative of the population as a whole. Hence, the data analysis conducted in this study is not representative of the piped water population in Lahan with or without weighting the data. Combined with the fact that the sample is not significantly skewed compared to the population, the decision was made to not use the weighted sample when applying statistical methods to the results. It is argued that presenting the raw results reduces the chances of misinterpretation of the data. Furthermore, the purpose of this study is not to present the characteristics of Lahan; the purpose is to investigate relationships between supply conditions, household characteristics and household withdrawal behaviours. Since generalities are being sought, it is equally valid to be using this sample and therefore it does not compromise the research aims.

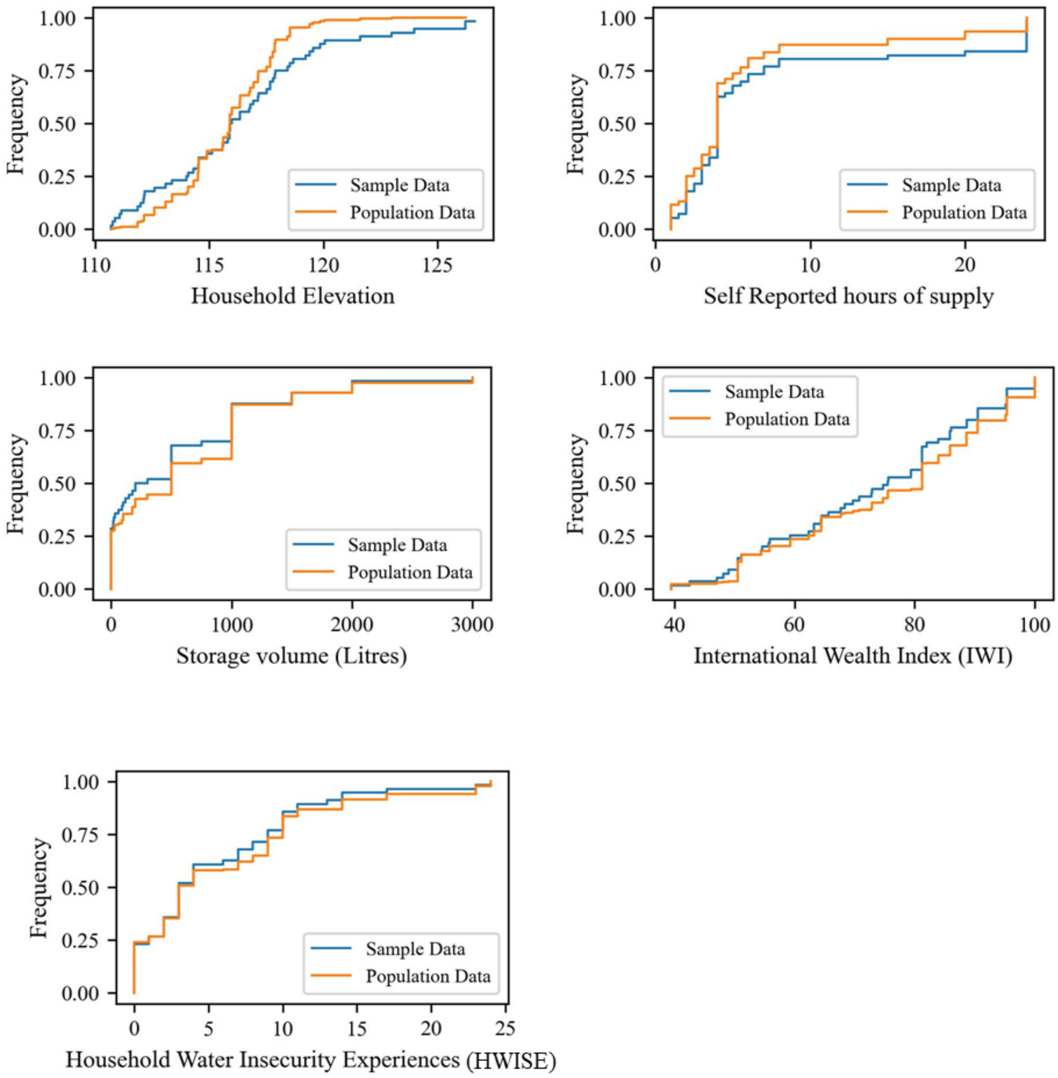


Figure 6.20: Effect of Weighting the Sample on the Cumulative Distribution of Survey Continuous Variables. Sample data shown in Blue, Weighted sample in Orange

Table 6.8: The KS Statistic Applied to the Cumulative Distributions of Sample and Population Survey Data

Variable	**KS Statistic**	**P-value**	**Likely from same distribution? (P-value > 0.05)**
Household Elevation	0.17	0.085	Yes
Volume used per day	0.088	0.76	Yes
Self Reported hours of supply	0.095	0.67	Yes
Storage volume (Litres)	0.091	0.71	Yes
International Wealth Index (IWI)	0.095	0.68	Yes
Household Water Insecurity Experiences (HWISE)	0.065	0.96	Yes

The effect of weighting the data on the water withdrawal recorded by the household meters is reflected in Figure 6.21. Alongside Table 6.9, it shows the stratification of the sample has not resulted in a statistically significant difference in the sample and population distributions.

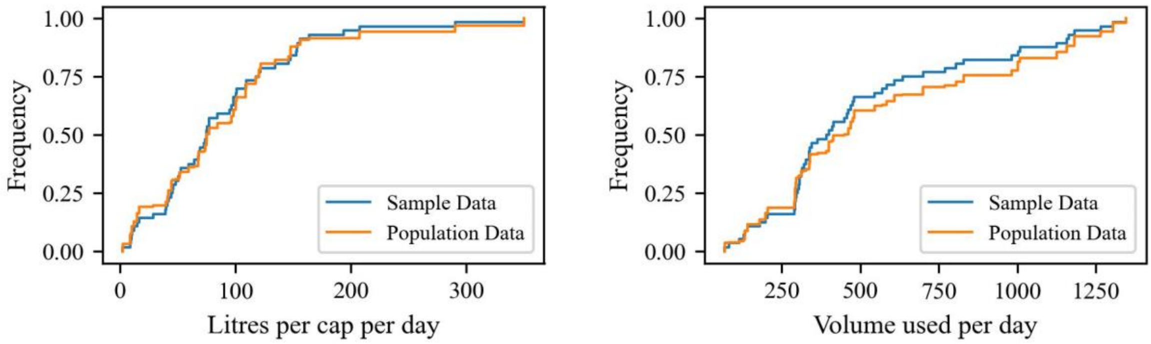


Figure 6.21: Effect of Weighting the Sample on the Cumulative Distribution of Measured Household Water Withdrawals. Sample data shown in Blue, Weighted sample in Orange

Table 6.9: The KS Statistic Applied to the Cumulative Distributions of Sample and Population Water Withdrawal Data

Variable	**KS Statistic**	**P-value**	**Likely from same distribution?**
Litres per cap per day	0.056	0.99	Yes
Volume used per day	0.088	0.76	Yes

6.10 Statistical Analysis

Statistical tests were used to determine the significance of relationships between variables. Different approaches were employed depending on whether the variables were continuous or categorical in nature.

6.10.1 Comparing a Continuous Variable between Different Categorical Groups

For continuous data, there are several different statistical tests, each being the preferred method given different conditions of the data. The process of selecting the appropriate test is summarised by Figure 6.22. This is derived from well-established statistical theory as summarised by Parab & Bhalerao (2010).

For each test, the null hypothesis was tested; this states that there is no significant difference between the two groups. A confidence interval of 95% (i.e. p-value <0.05) was selected as the threshold of significance.

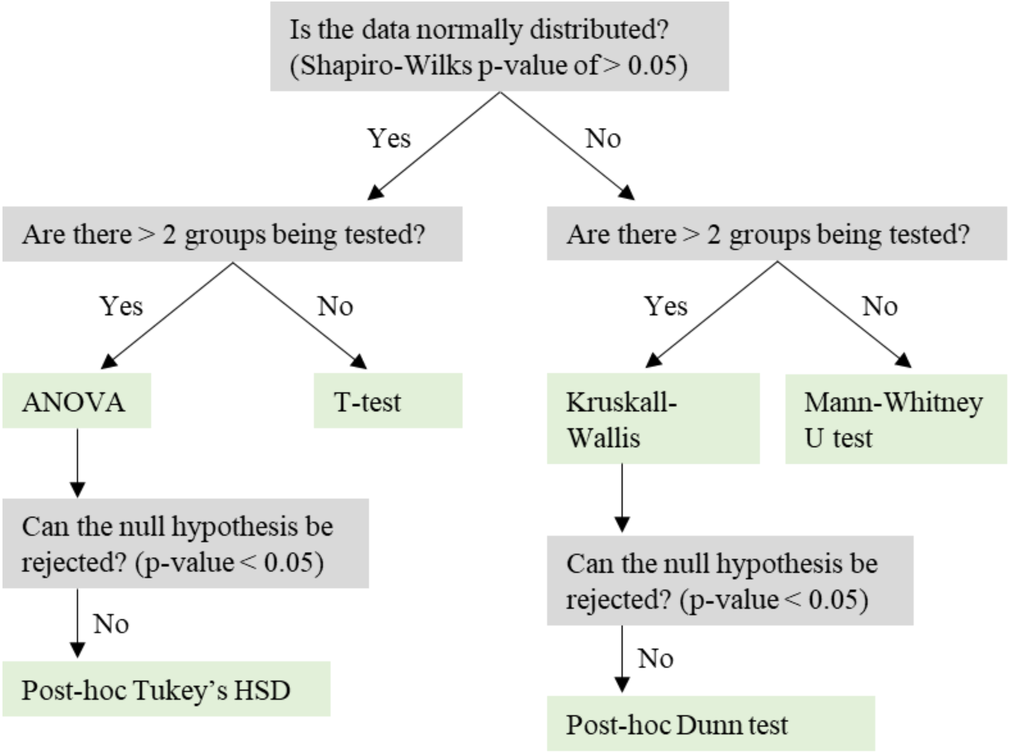


Figure 6.22: Flow Chart Describing the Process of Selecting the Appropriate Statistical Test to Compare Variables

Table 6.10 summarises the key attributes of each test. To determine whether the data is normally distributed, the Shapiro-Wilks test was employed prior to selecting the appropriate significance test. A Shapiro-Wilk p-value of > 0.05 indicates there is insufficient evidence to reject the null hypothesis, hence the data is normally distributed and one of the parametric tests is employed.

Table 6.10: Description of the Different Statistical Tests used for Continuous Data

Test	**Description**
Unpaired, 2-sample t-test	Tests whether the mean of two groups are significantly different
Analysis of Variance (ANOVA)	Tests whether the mean of two or more groups are significantly different by comparing variance between groups
Wilcoxon / Mann-Whitney U test	Tests whether the sum of the ranks of two groups are significantly different by ranking all of the values and summing the ranks for each group
Kruskall-Wallis	Tests whether the sum of the ranks of two or more groups are significantly different by ranking all of the values and summing the ranks for each group

If the null hypothesis cannot be rejected after applying the Kruskall-Wallis test, a post-hoc Dunn test was applied to ascertain which combination of the variables showed a significant difference (p-value < 0.05). Similarly, if the null hypothesis could not be rejected after applying the ANOVA test, a post-hoc Tukey's HSD test was applied for the same purpose.

6.10.2 Comparing Two Sets of Categorical Variables

For categorical variables, the process of testing for significant differences was different. First the data was divided into groups using a contingency table, this places each sample according to which category it is in within both categorical variables. The contingency table enables statistical tests to be employed to test for significance between the groups. There are two standard tests for assessing contingency tables; Pearson's Chi-squared test and the Fischer test. The Fisher test was employed if any cell in the contingency table of the data had a value of < 1 or 20% of cells have expected values of < 5.

6.10.3 Comparing Two Continuous Variables

When comparing the correlation between two continuous variables, the data was plotted and simple linear regression was applied resulting in an R^2 value. If the points lie close to the regression line, the R^2 value is greater indicating there is a strong linear correlation between the variables.

7 Results

The following section details the results collected from the case study site. The results are organised according to the three categories of data that were collected, firstly the supply conditions are presented using the data from the pressure loggers, secondly the household characteristics from the household survey and finally the water withdrawal behaviour using the household smart meter data.

7.1 Supply conditions (Pressure Data)

This section starts with a characterisation of the network inputs using the pressure traces of the loggers placed adjacent to them. Following this is an investigation into the occurrence of negative pressures in the network. The effect of the changes to the network configuration described in section 6.2 is then assessed. The pressure data is then used to establish the supply characteristics across the network by analysing the variation in pressure both spatially and temporally. Finally, estimations are made of the local supply hours across the network, in particular at the surveyed household locations. Unless otherwise stated, the pressure data is taken across the month of April 2024.

7.1.1 Characterising Input Supply

As shown in section 6.2, prior to 8th March 2024, there are four direct inputs into the network: OHT1 plus three borehole locations: ASBCPM, NEHPPM and TCNCPM. The estimated supply hours from OHT1 is calculated using the manual change point method described in section 6.2. The other three locations all have a pressure logger adjacent to the input. After the change in valve settings, OHT2 becomes a fifth input into the network, however, the pressure logger adjacent to the tower lost functionality so the pressure cannot be measured across April 2024. The daily pressure traces at each of the four input locations are shown in this section, illustrating the general trend of operation as well as significant amounts of deviation.

Figure 7.1 shows logger NEHPPM associated with the Northeast borehole. It has zero pressure between the hours of midnight to 5AM every day, the pressure changes rapidly at around 5:30AM consistently each day, presumably due to the borehole pump being turned on. During the morning supply period, the pressure rises rapidly to between 10-20m head then drops over the course of 1-2 hours before returning to the original pressure. This is likely due to the network filling and then pressure rising once the pipes are filled. The time when the pump is turned off is less consistent, ranging between 8 – 12AM. The afternoon supply period shows significantly less consistency. The supply is turned on at approximately 3PM but this is highly variable. In contrast to the morning supply period, the pressures do not show the same double hump characteristics. The phases of network charging and the network being pressurised are less discernible. The time when the borehole is turned off varies between 6PM and midnight. There are no negative pressures recorded in this location, however, there is evidence of supply periods being 'missed' as the pressure trace remains zero on at least one occasion.

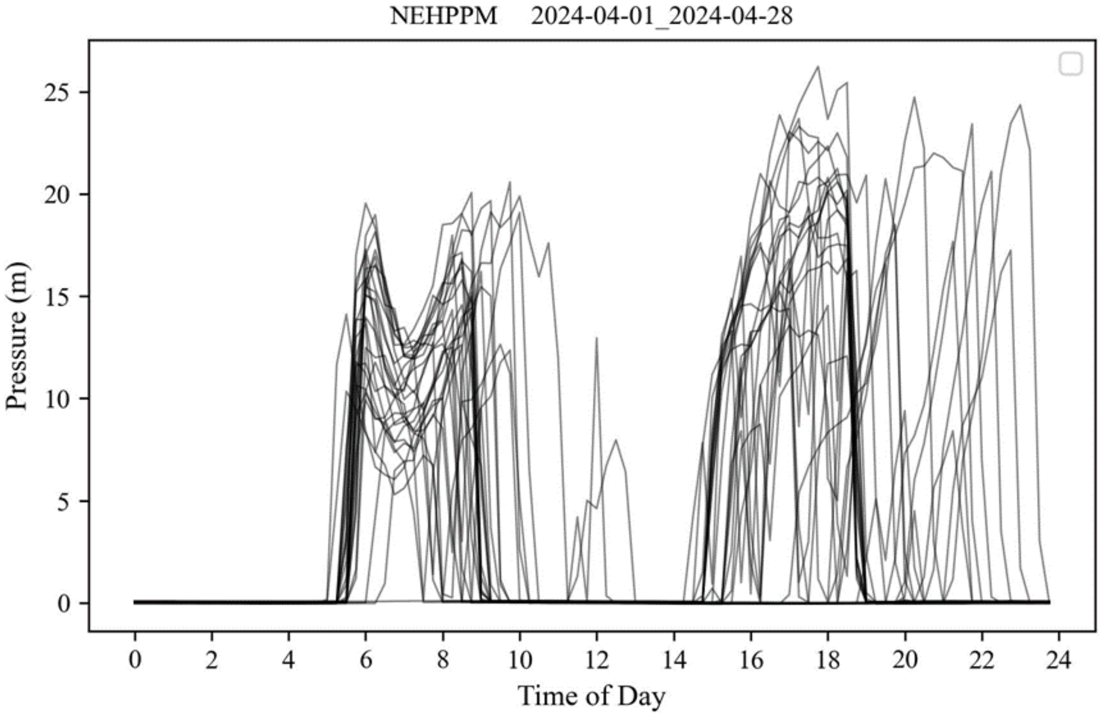


Figure 7.1: Daily Pressure at Northeast Borehole across April 2024

Figure 7.2 shows logger ASBCPM associated with the Northwest borehole. It has either zero pressure from midnight to 5AM or negative pressures up to -2m head. The borehole is turned on relatively consistently at 5AM increasing the pressure to approximately 35m head. Similarly to NEHPPM, the pressure drops by about 5m head over the course of 1-2 hours presumably due to the network filling. In addition, the end of the supply period is inconsistent ranging between 8-12AM; the most frequent end time is 11AM, approximately 1.5 hours later then NEHPPM. Directly following the end of the supply period are negative pressures on a consistent basis. The afternoon supply period typically begins between 2-3PM and ends at 7PM with a relatively steady pressure of 30-35m head. Frequently, there are pressures between 8PM to midnight as was the case with NEHPPM. There were no ‘missed’ morning supply periods with the borehole being on every day between the hours of 5-7AM. It is unclear whether there are any missed supply periods in the afternoon due to the inconsistency of timings.

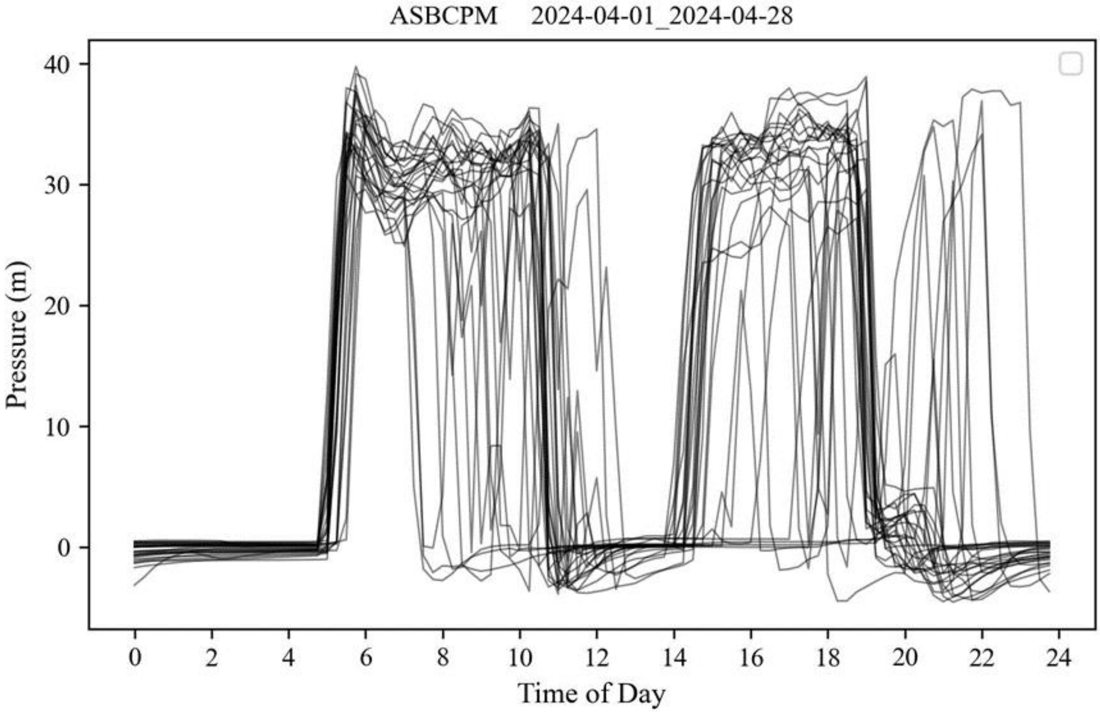


Figure 7.2: Daily Pressure at Northwest Borehole across April 2024

Figure 7.3 shows logger TCNCPM associated with the Southeast borehole. The pressure trace shows more variability then the first two. Typically, pressures are above zero from midnight to 5AM, usually between 0-2m. On two occasions, the pressure was noticeably higher at around 10m head, which may be an indication that a borehole pump was left on. The borehole is turned on earlier than the previous two with pressures increasing at approximately 4AM. The pressure increases to 15-20m head before dropping by approximately 5m on most occasions; however, there are several occasions when the pressure only rises to 10-15m head. This dual mode may be explained by the fact TCNCPM is placed at the common outlet of two boreholes, TCN1 and TCN2. The pressure traces suggest on some occasions both boreholes are operated and other occasions only one.

In a similar manner to NEHPPM and ASBCPM, the pressures drop by about 5m after the initial spike before increasing again, suggesting the network is filling. The supply is usually off between 11AM and 1PM with the pressures reducing from 2 to 0m head. The afternoon supply period is very inconsistent with pressures being highly variable between 1 – 5PM; the pressures tend to drop down to below 5m at 8PM before slowly reducing to 0-2m head. The slow reduction of pressure at the end of the supply period is different to NEHPPM and ASBCPM, which immediately drop to zero or negative pressures. This indicates the network drains more gradually in this area over the course of 2-4 hours, suggesting supply hours in this region may be longer.

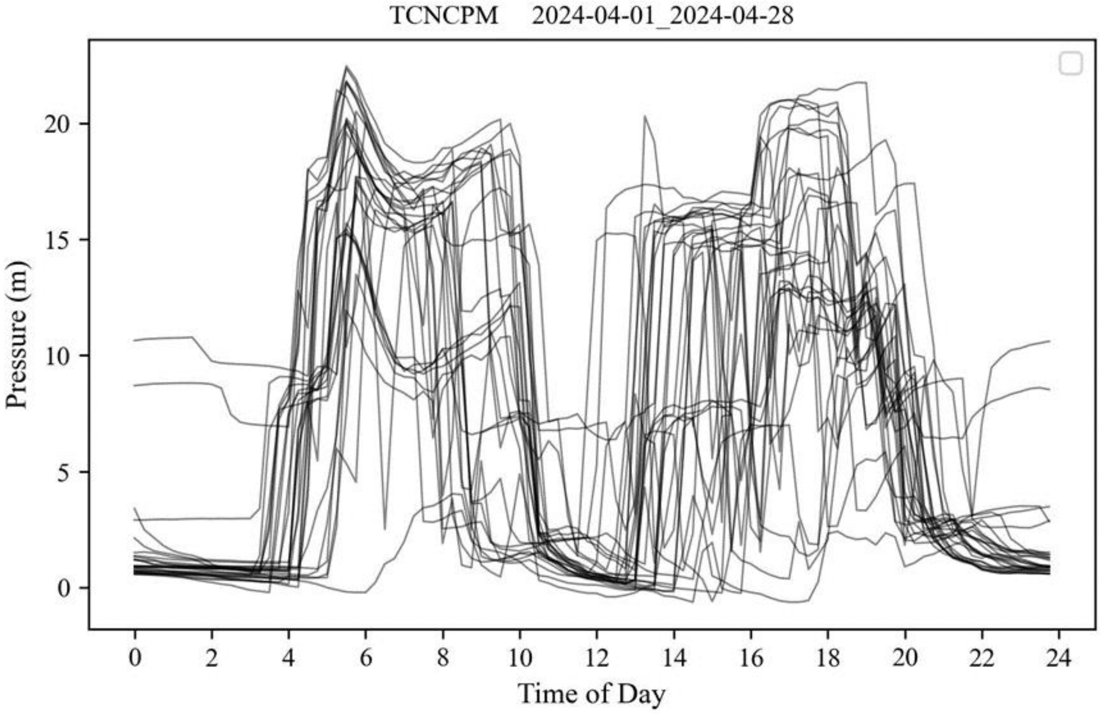


Figure 7.3: Daily Pressure at Southeast Borehole across April 2024

Figure 7.4 shows the OTWRPM pressure trace, which relates to the overhead tower, OHT1. It is very different to the previous three inputs as it is not a borehole source. The pressure logger is placed at the base of the overhead tower before the valve that is operated to control the supply periods, therefore the pressure is equivalent to a measure of the water level in the tank. Before reading the pressure trace, it is important to note that the y-axis starts at 14m not 0m like the other pressure traces, this has the effect of exaggerating the differences in pressure.

The tank is not consistently filled to the same level as the pressures vary between 18-21m during the midnight to 5AM period. A consistent slow reduction of the pressure indicates the tank is losing water presumably due to water passing through the valve at the base of the tower. Occasionally, the tank is topped up with water as indicated by the small increases in pressure directly preceding the morning supply period, however this occurs infrequently. The level of the tank drops by approximately 3-5m over the course of about 4 hours. The pressures increase again as the tank is filled following the morning supply period. The level it returns to is inconsistent and the lack of horizontal lines between midday and 4PM suggests some water may be being supplied to the network. The afternoon supply period begins between 4 – 6PM lasting to approximately 8PM.

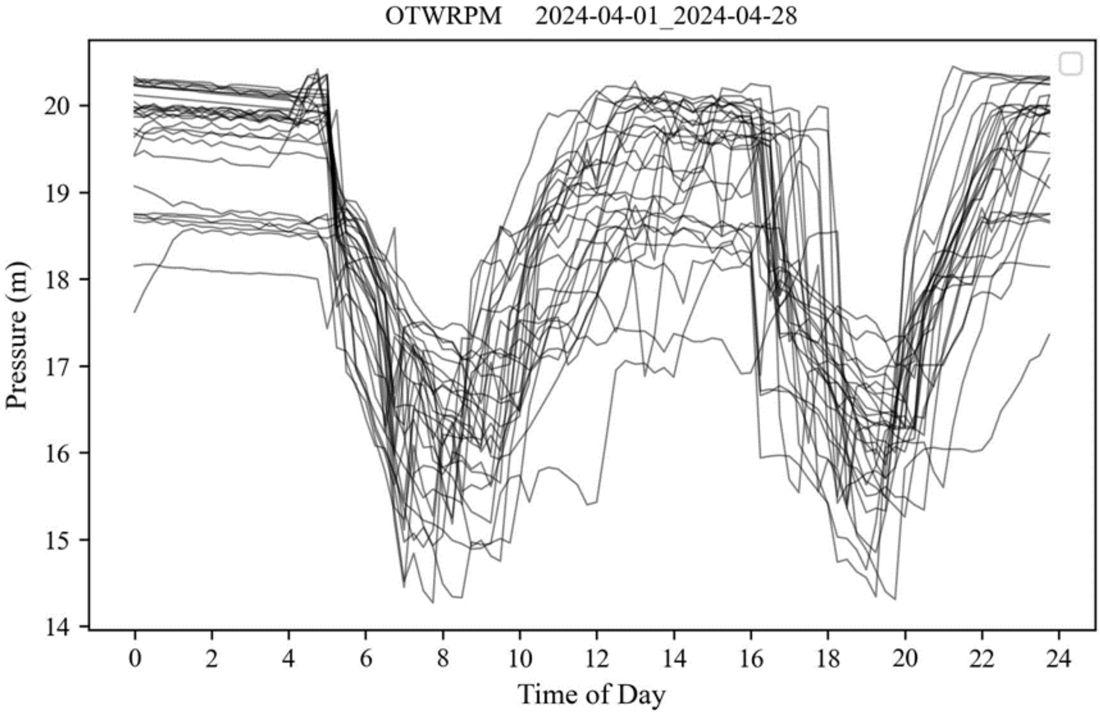
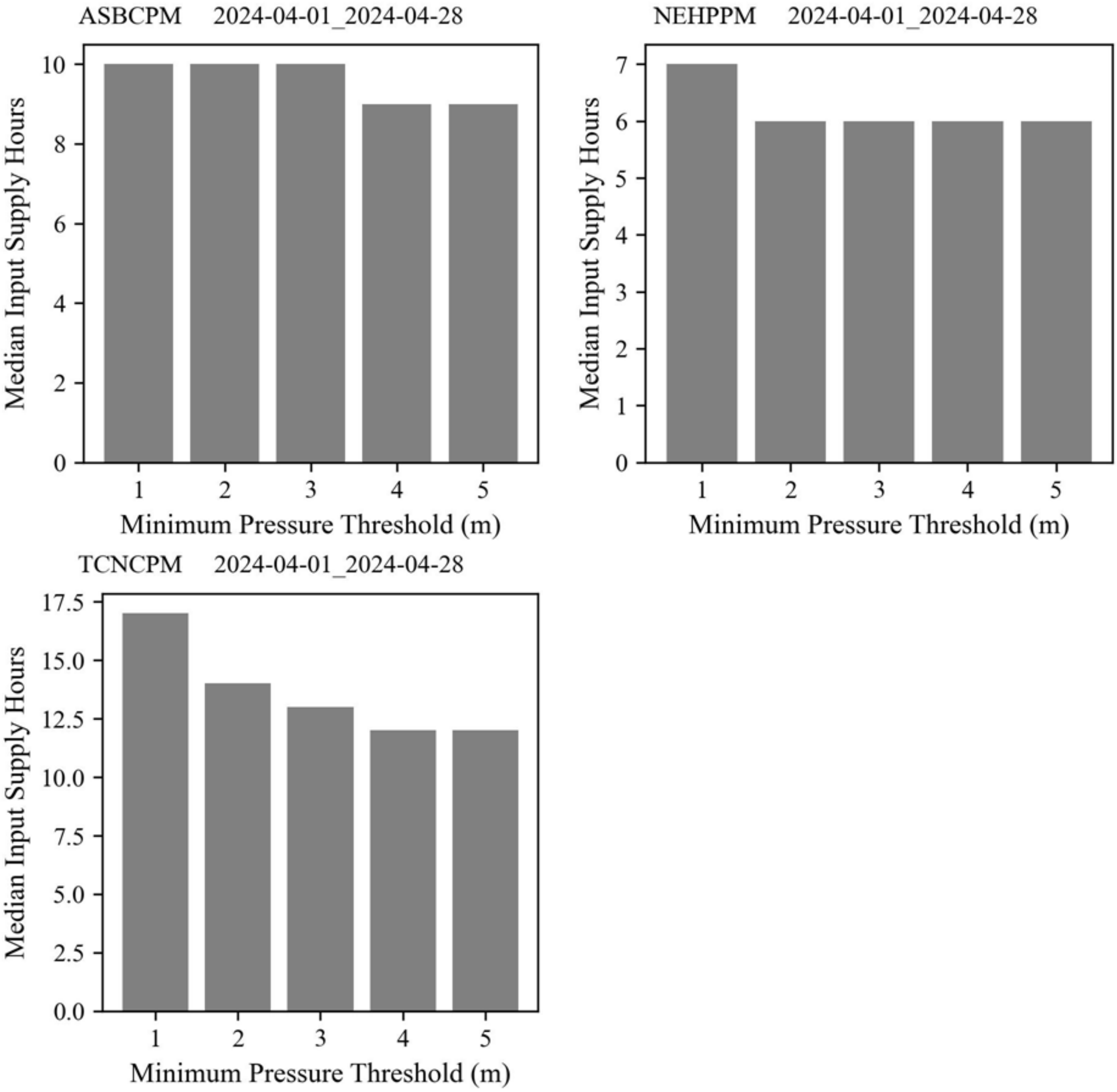


Figure 7.4: Daily Pressure at Overhead Tower 1 (OHT1) across April 2024

For each day, the resulting supply hours have been estimated from the pressure traces. As described in section 6.7.1, several minimum pressures at which to define the supply hours were assessed leading to a threshold of 4m being chosen. The resulting calculation of median supply hours according to each definition is shown in Figure 7.5. TCNCPM shows significant variation depending on the minimum pressure with supply hour estimates ranging from 12-16 hours. The supply hour estimates of the other two boreholes only vary by 1 hour under the different pressure thresholds.


ASBCPM 2024-04-01_2024-04-28

NEHPPM 2024-04-01_2024-04-28

TCNCPM 2024-04-01_2024-04-28

Figure 7.5: Effect of the Definition of the Minimum Pressure on the Estimation of Daily Borehole Input Supply Hours

Figure 7.6 shows the estimated supply hours from each input source based on a > 50% probability of having at least 4m of pressure. The resulting daily supply hours are summarised in Table 7.1. NEHPPM has the shortest supply hours at 6 hours per day while TCNCPM has double the supply hours at 12 hours per day. Moreover, TCNCPM never drops to a 0% probability indicating there is no single hour in the day that there was no supply across the one-month period. The OTWRPM result shows that the supply period deriving from OHT1 starts later in the afternoon then the other sources at approximately 4.30PM. OTWRPM is also the only trace to show 100% probability of some supply at both the morning and evening supply periods. The regularity of supply from NEHPPM in the afternoon supply period is particularly low at around 60%.

The supply hours from OHT1 are driven by fundamentally different processes to the satellite borehole inputs. While the satellite boreholes are controlled by the operation of pumps, OHT1 is an overhead tank that is therefore a gravity fed system. As a result, the flowrate into the network from the tank is dependent on the outflows from the network (a combination of consumer withdrawal and leakage). The 'supply hours' resulting from OHT1 are therefore coupled with the rate of withdrawal in the network. If demand was extremely low, the amount of time it would take to drain the tank would be longer and thus the supply hours would be longer unless the operators chose to close the valve prematurely.

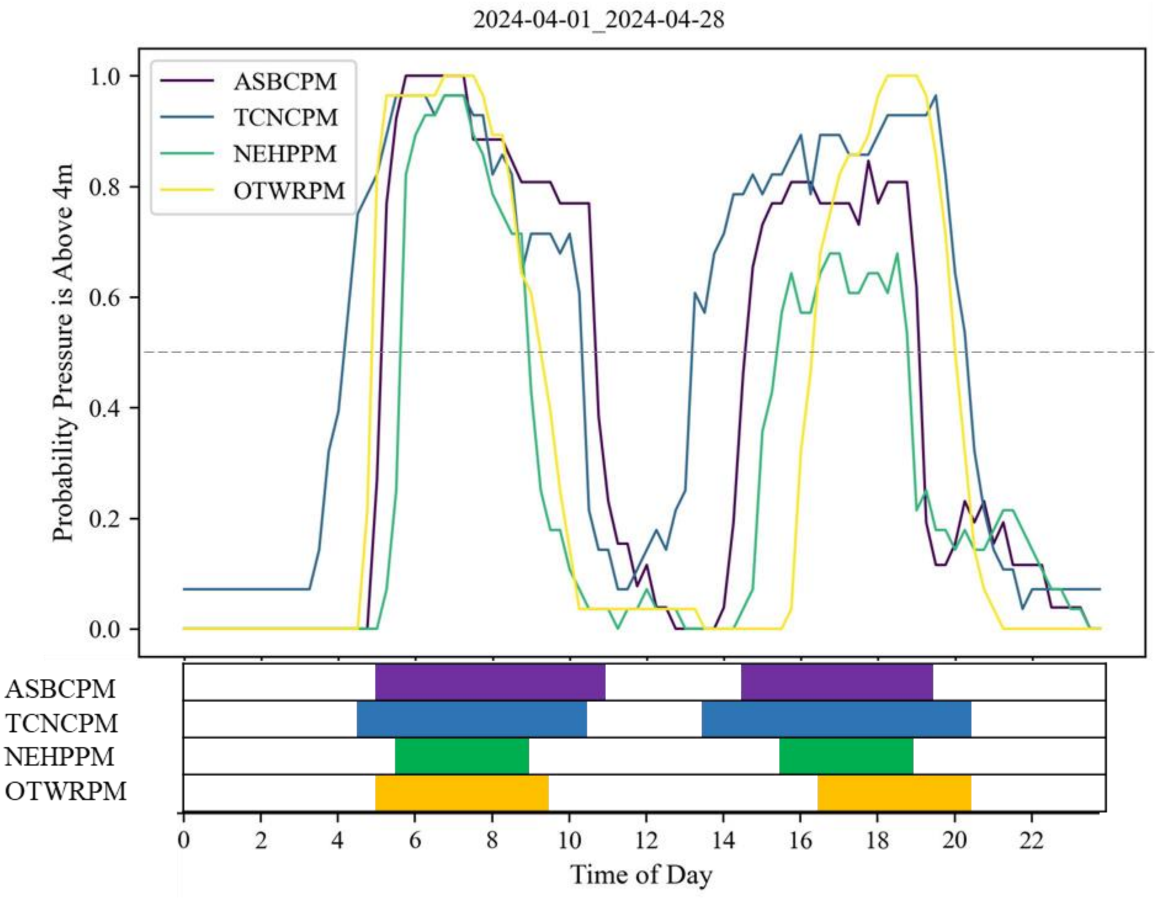


Figure 7.6: Probability Pressures are Above 4m at Input Sources for each Time step Across April 2024 alongside the Resulting Supply Durations using a 50% Probability

Table 7.1: Estimated Supply Hours

Input Source	**Estimated Daily Supply Hours**
ASBCPM	9
TCNCPM	12
NEHPPM	6
OTWRPM	7.5

7.1.2 Negative Pressures

Significant negative pressures are observed in the far northwest adjacent to the ASH borehole as was seen in Figure 7.2. A pressure trace of three consecutive days is shown in Figure 7.7. The downward spike and return to zero pressure in Figure 7.7(a) shows that there has been negative pressure in the ASBCPM region. The exponential return to zero indicates something is intruding into the pipe to equalise the negative pressure. A short distance downstream of ASH at a lower elevation, the BSTIPM pressure logger shows much smaller negative pressures occurring (Figure 7.7(b)), thus indicating the negative pressures have been equalised in the preceding stretch of pipeline. There are several possible intrusion pathways that could have caused the equalisation. Water/air entering via a leak in the pipe, air entering via open consumer taps or air entering via an air-valve.

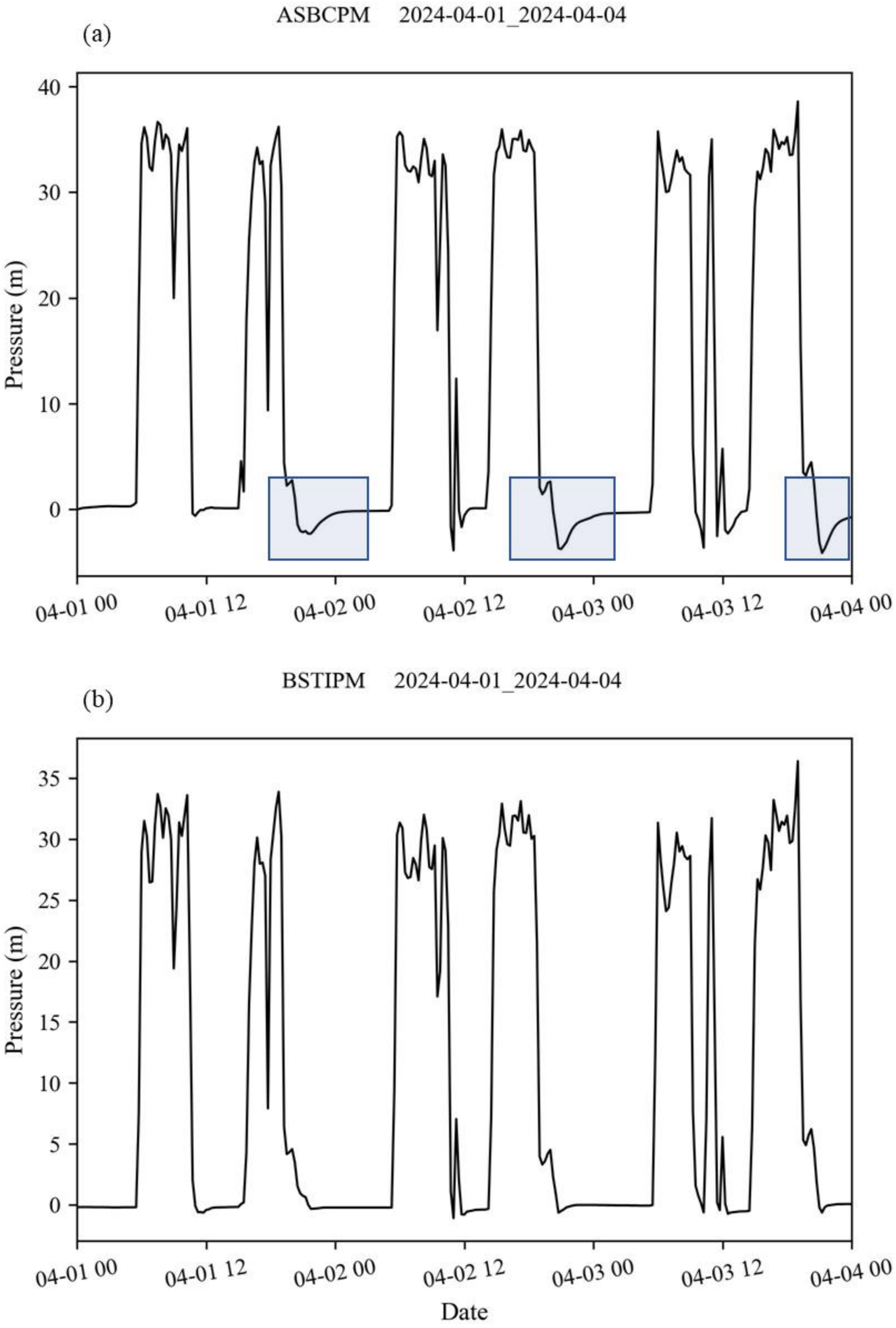


Figure 7.7: (a) Pressure Timeseries Indicating Significant Negative Pressures at ASBCPM, (b) Pressure Timeseries Indicating Negative Pressures Largely Equalised at BSTIPM

Figure 7.8(a) shows the pressure traces at ASBCPM over the course of three months. The occurrence of negative pressures directly after the morning supply period are regular and of similar magnitude. After the afternoon supply period, the negative pressures occur more strongly two hours after the supply period and remain negative for a longer period of time. Figure 7.8(b) shows a histogram of the lowest pressures recorded at ASBCPM, this reinforces the regularity of negative pressures between 0 and -1m and shows that pressures drop to around -4m head.

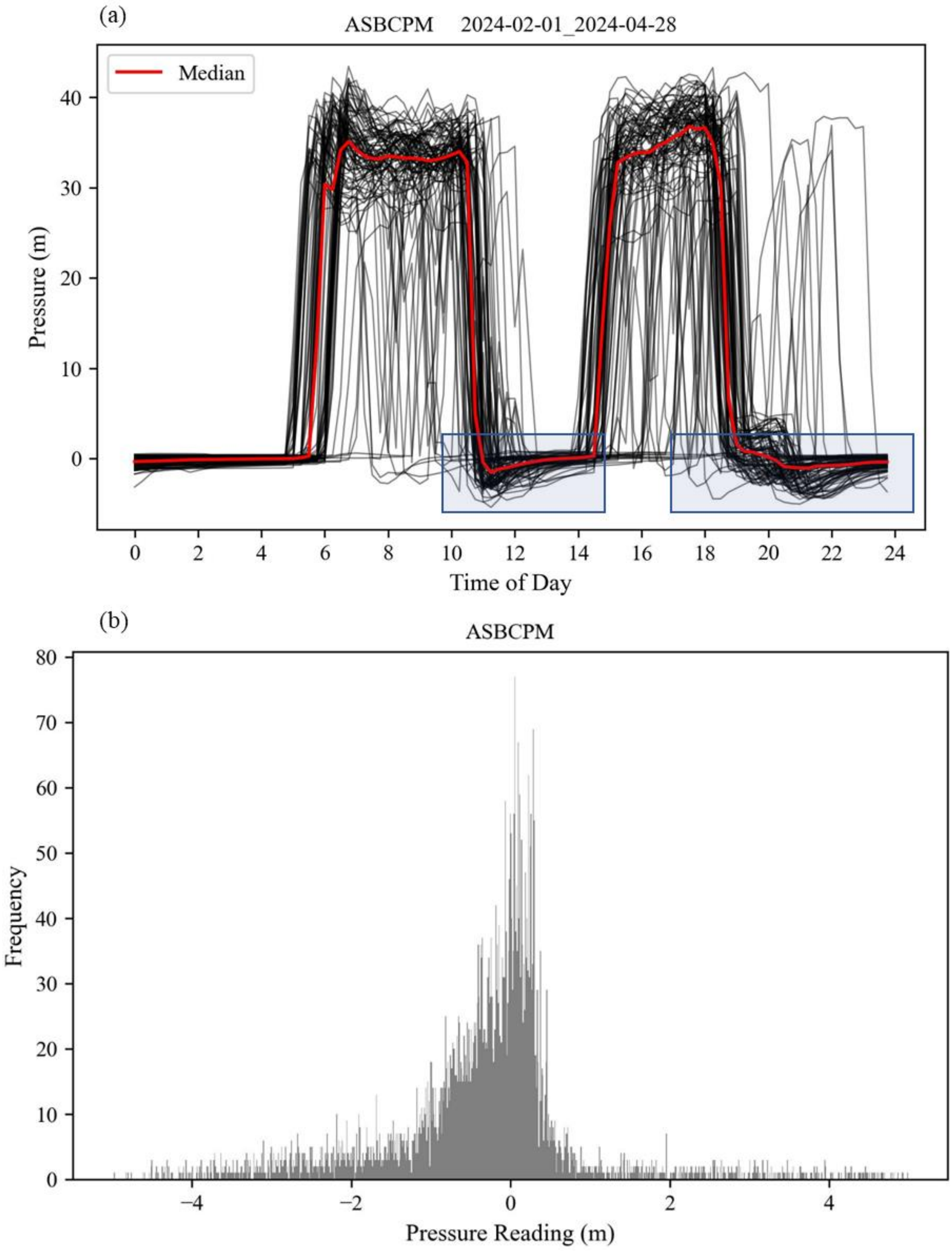


Figure 7.8: Pressure Recorded at ASBCPM 01-02-2024 to 28-04-2024 (a) Daily Timeseries Overlain, (b) Histogram of Pressures Between -5 to 5 m

7.1.3 Effect of OHT2 Redirection

Water from overhead tower 2 (OHT2) was redirected straight into supply from the 8th March (see Figure 6.3). The effect of the change was investigated by visualising the long-term trends of the pressure loggers both before and after this date. Logger SWEXPM is the closest to the input of OHT2, Figure 7.9 shows a noticeable increase in the pressure in that location following the change. In contrast, the long-term trend of the other loggers did not show a clear and consistent change in behaviour resulting from the new operation (plots are available in Appendix B).

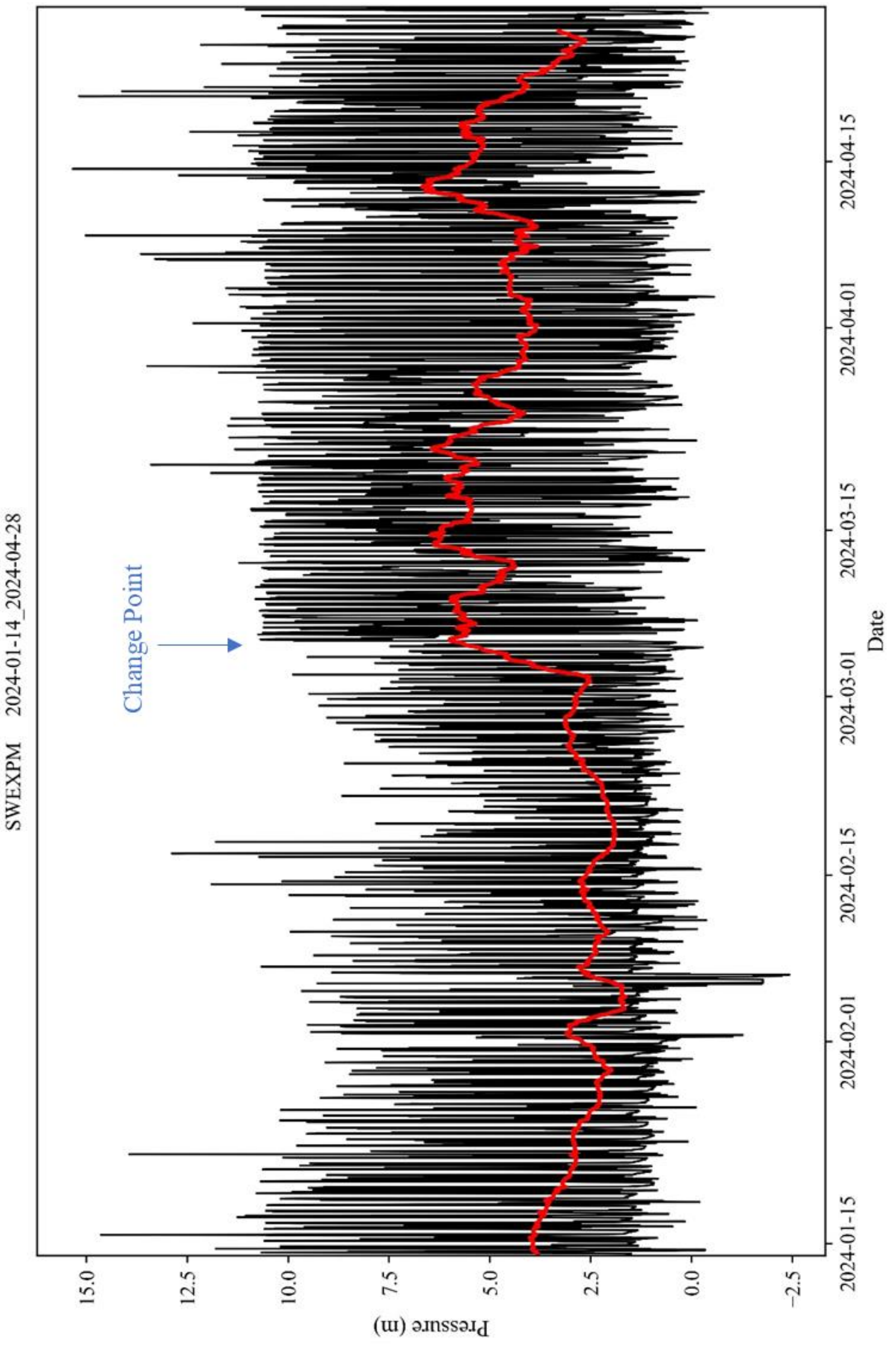


Figure 7.9: Change in Pressure Recorded in the South-West Region Following the Change in Valve Setting (the Red Line Represents the 3-day Rolling Average)

7.1.4 Temporal and Spatial Variation of Pressure

Figure 7.10 shows three days' worth of pressure data from all loggers that tap into the distribution network. The loggers are in order from high to low elevation. As described in section 6.2.1, data from logger OTWRPM is only included during the open-valve times of the day. The pressures reflect the regular morning and evening supply periods; this is most pronounced in the higher elevation loggers where the start and end of the supply period is clearly defined. The loggers at the lower elevations show increases in pressure during the 'supply periods' but they do not drop back down to zero. Instead, the draining of the network can be seen by the steady decrease in pressure between supply periods, in some instances the pressures never reach zero before the following supply period indicating there is 24/7 pressurisation in some locations (albeit at pressures typically below 4m head).

Figure 7.11 shows the magnitude of the pressures during the supply periods also varies significantly. The group of loggers that are far from the input sources rarely reach pressures above 10m head while the pressures are typically above 10m near the inputs during the supply periods. ASHIPM shows the most limited network pressures, this logger is in the North of Lahan but a considerable distance from the nearest input source, NEHPPM. For most of the day, it has zero pressure apart from during the supply periods where it rises to 5 - 15m. This location appears to be heavily reliant on the NEHPPM borehole as the pressure traces are mirrored. The supply from the next nearest input, OTWRPM, does not appear to significantly influence the local pressure at ASHIPM.

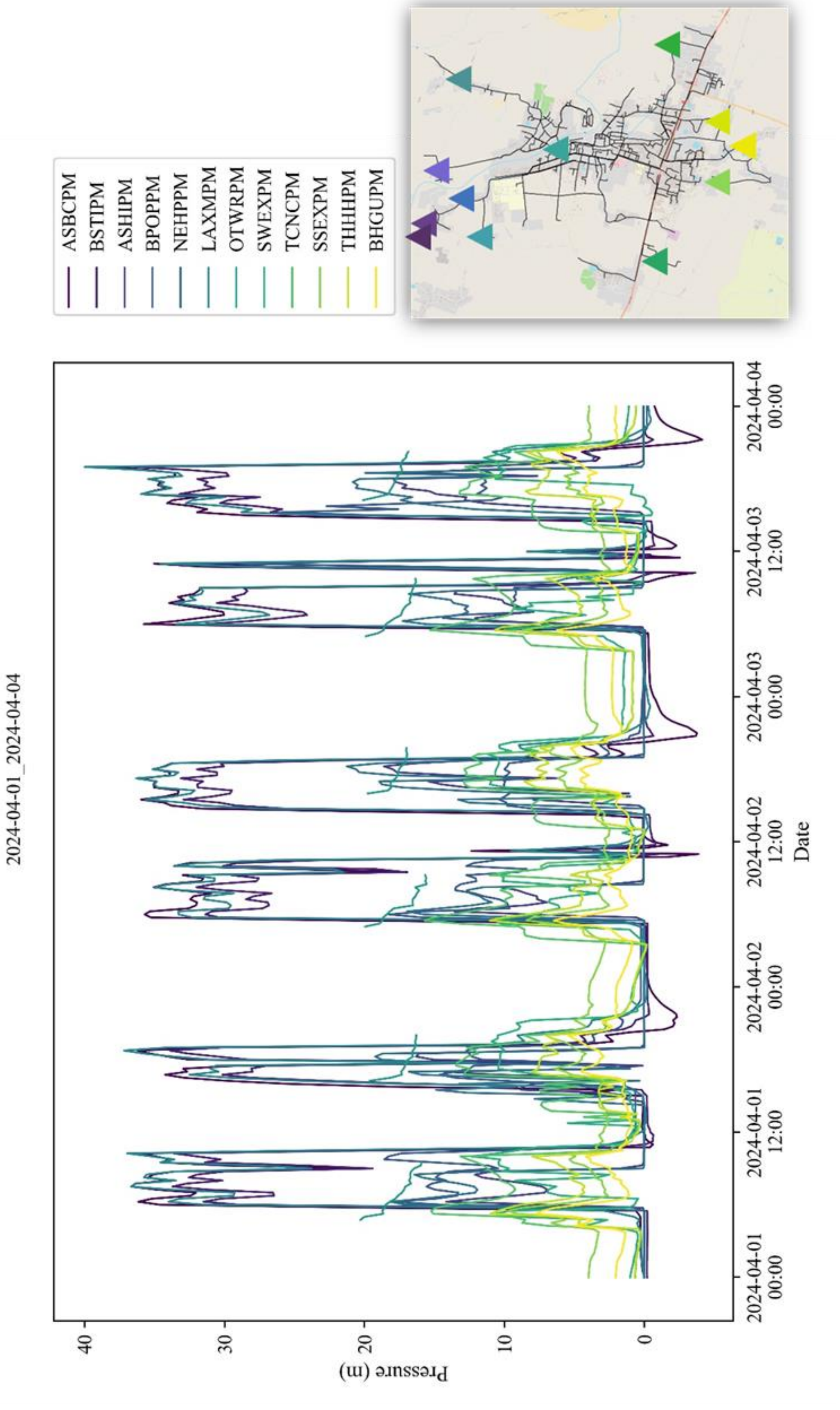


Figure 7.10: Variation of Pressure Across Three Days for all Pressure Loggers in Distribution Network

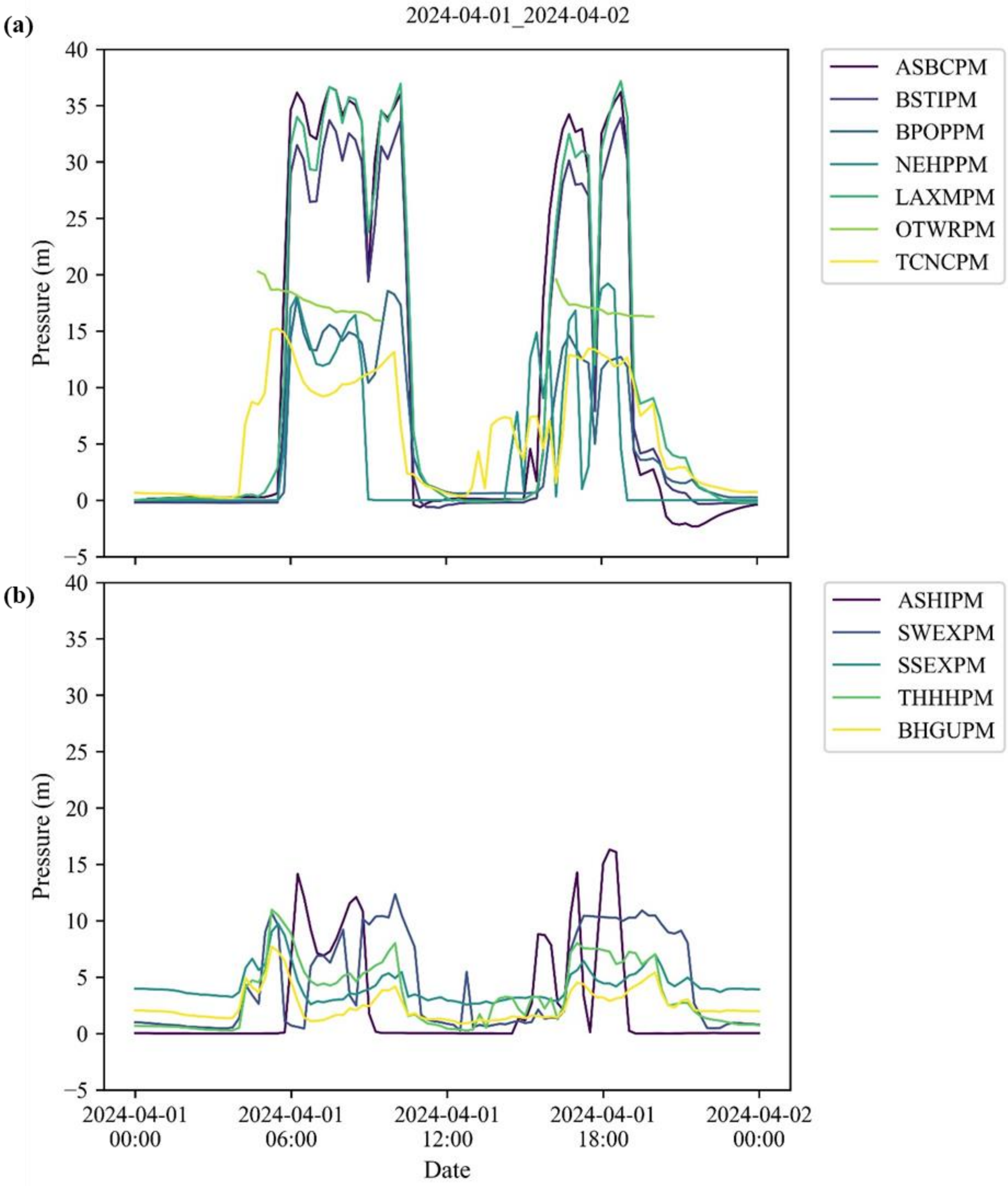


Figure 7.11: A Single Days Pressure Timeseries for (a) Loggers near Input Sources, and (b) Loggers at Extremities

Figure 7.12 highlights two loggers in closer detail, illustrating the difference in pressure conditions at a high-elevation location near an input source (LAXMPM) and a low-elevation location far from an input source (BHGUPM). Both locations tend to feel the effect of the morning supply period between 5-6AM as the pressures rise significantly. For LAXMPM this is a rise from 0m to 30-35m head while at BHGUPM there is a rise from 2m to 6-8m head. During the supply periods, the pressure at LAXMPM is maintained between 30 – 35m while at BHGUPM it is between 2 – 8m. Between supply periods, the pressure tends to drop to zero at LAXMPM but, on occasion, sits at 0 – 5m in the middle of the day. At BHGUPM, pressure never drops to zero but hovers around 2m during non-supply period hours. The supply conditions are significantly more predictable at LAXMPM but vary greatly between supply and non-supply times. At BHGUPM there is much less of a difference between the supply and non-supply times with low positive pressure maintained throughout the day.

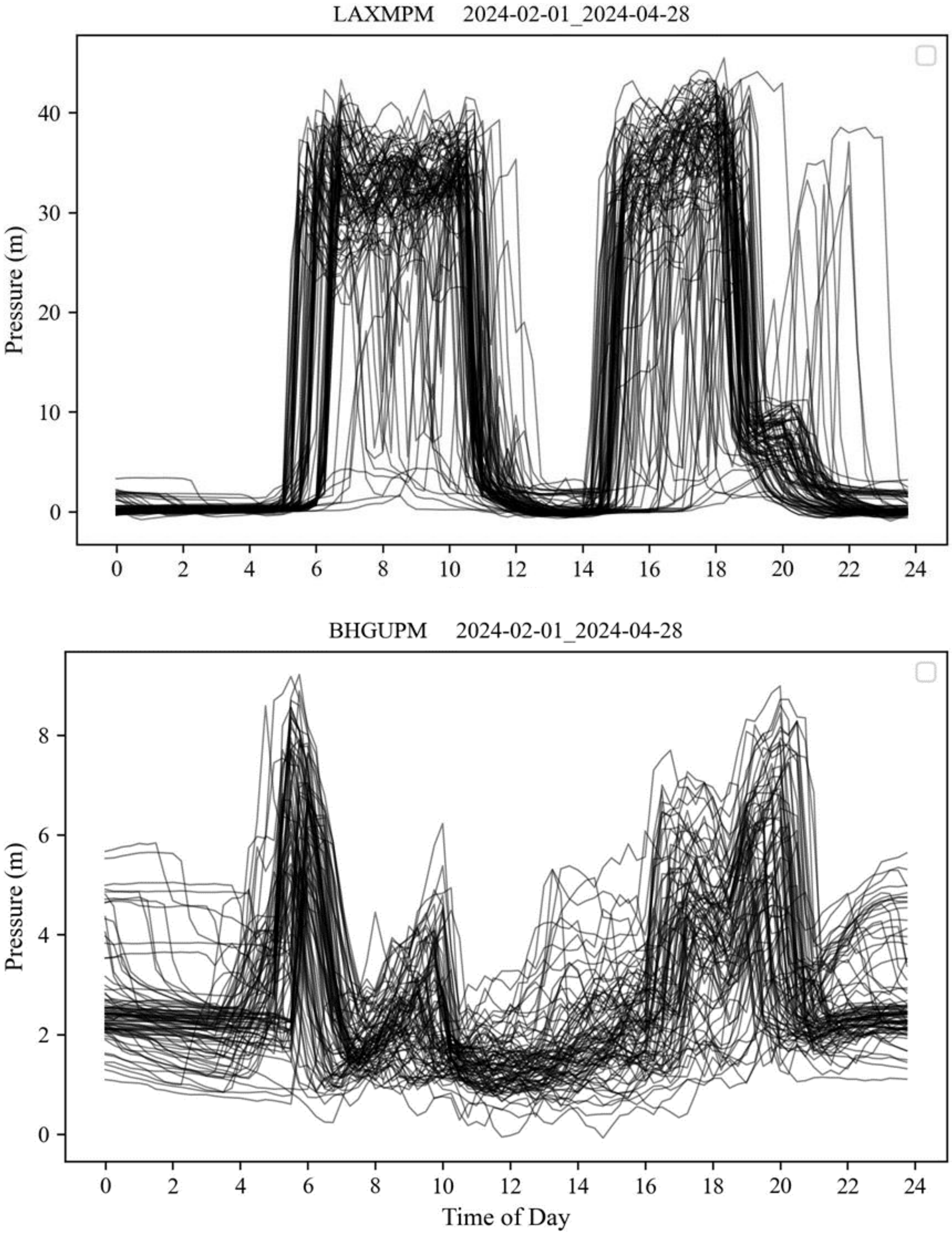


Figure 7.12: Daily Pressure Traces February to April 2024 for (a) Northern Pressure Logger, (b) Southern Pressure Logger. Note: The y-axis are scaled differently

Figure 7.13 shows the pressures estimated at the household level via the interpolation procedure enabling the spatial variation in pressure head across the network to be seen in detail. Note that the colour bar has a different scale for each plot to help visualise the differences within the network. During the non-supply times, pressure is greater in the low elevation areas while during the supply period pressure is much greater at the locations nearer the input sources (which tend to be in the northern region).

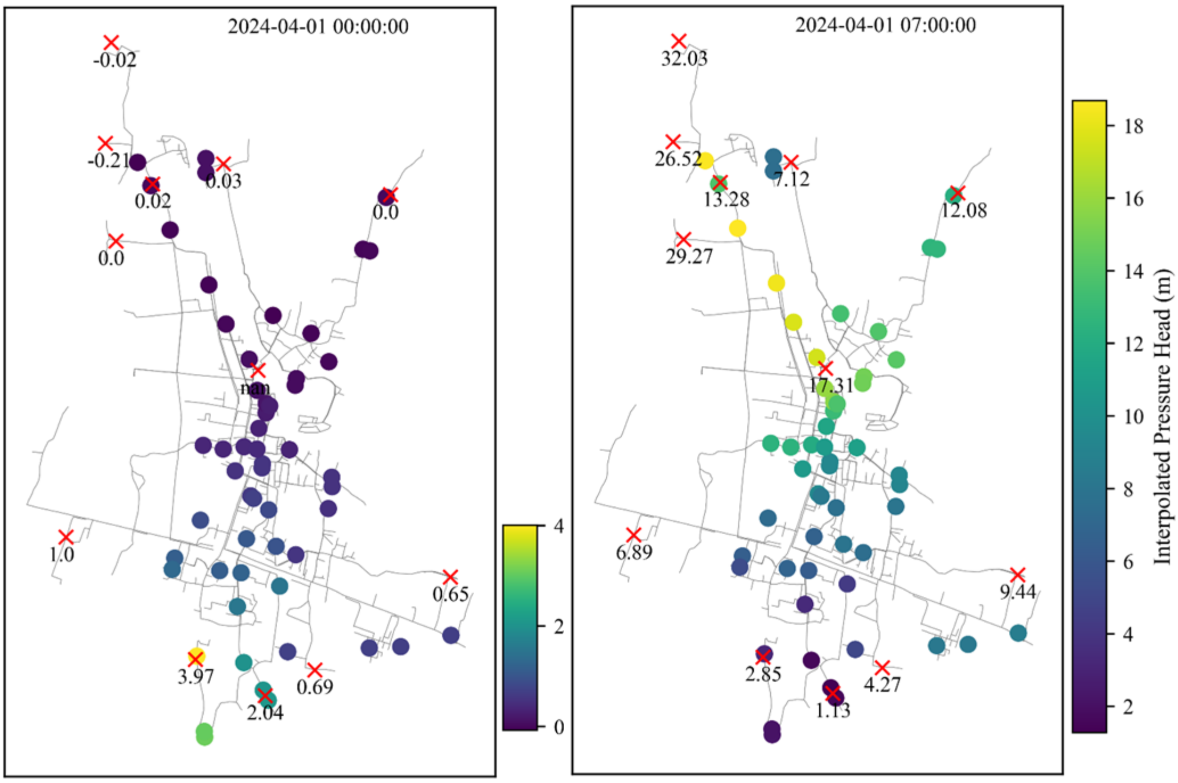
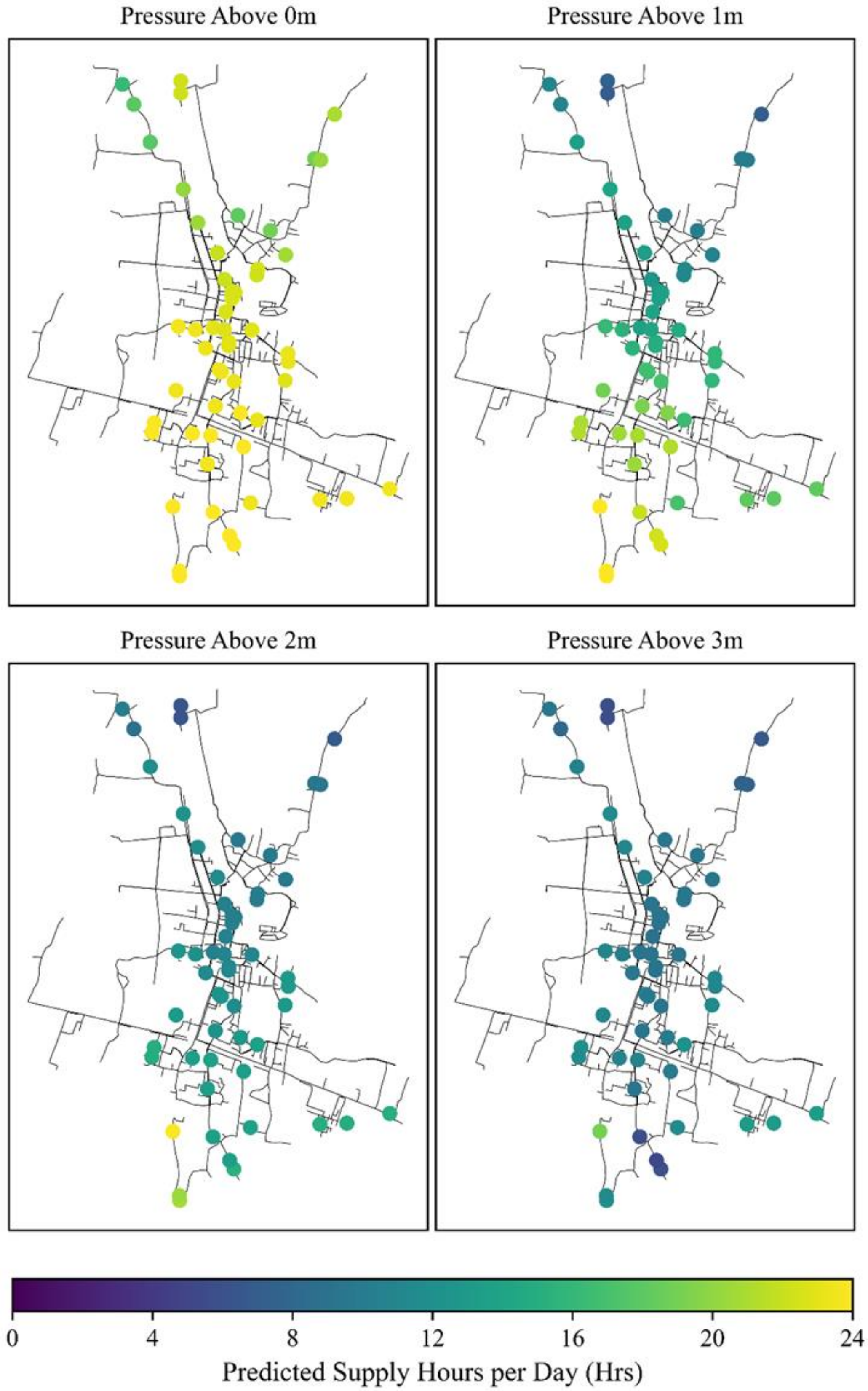


Figure 7.13: Estimated Household Pressure Head at (Left) Non-supply Time, and (Right) Supply Time. 'X' marks denote pressure logger locations and pressure values (in metres)

7.1.5 Estimating Household Supply Hours

Having estimated the local pressure at household locations, the corresponding local supply hours are calculated by summing the amount of time pressure is above a certain 'minimum pressure'. Figure 7.14 shows the effect of different thresholds of 'minimum pressure' on the estimated local supply hours. In this figure, the colour bar is kept consistent across the plots to enable direct comparison. The estimated local supply hours are calculated as a daily average from pressure data taken over the month of April. This threshold plays a significant role in determining local supply hours, particularly in the southern region. Arguably, the southeast area has the 'best' supply conditions with above average supply hours under all thresholds.



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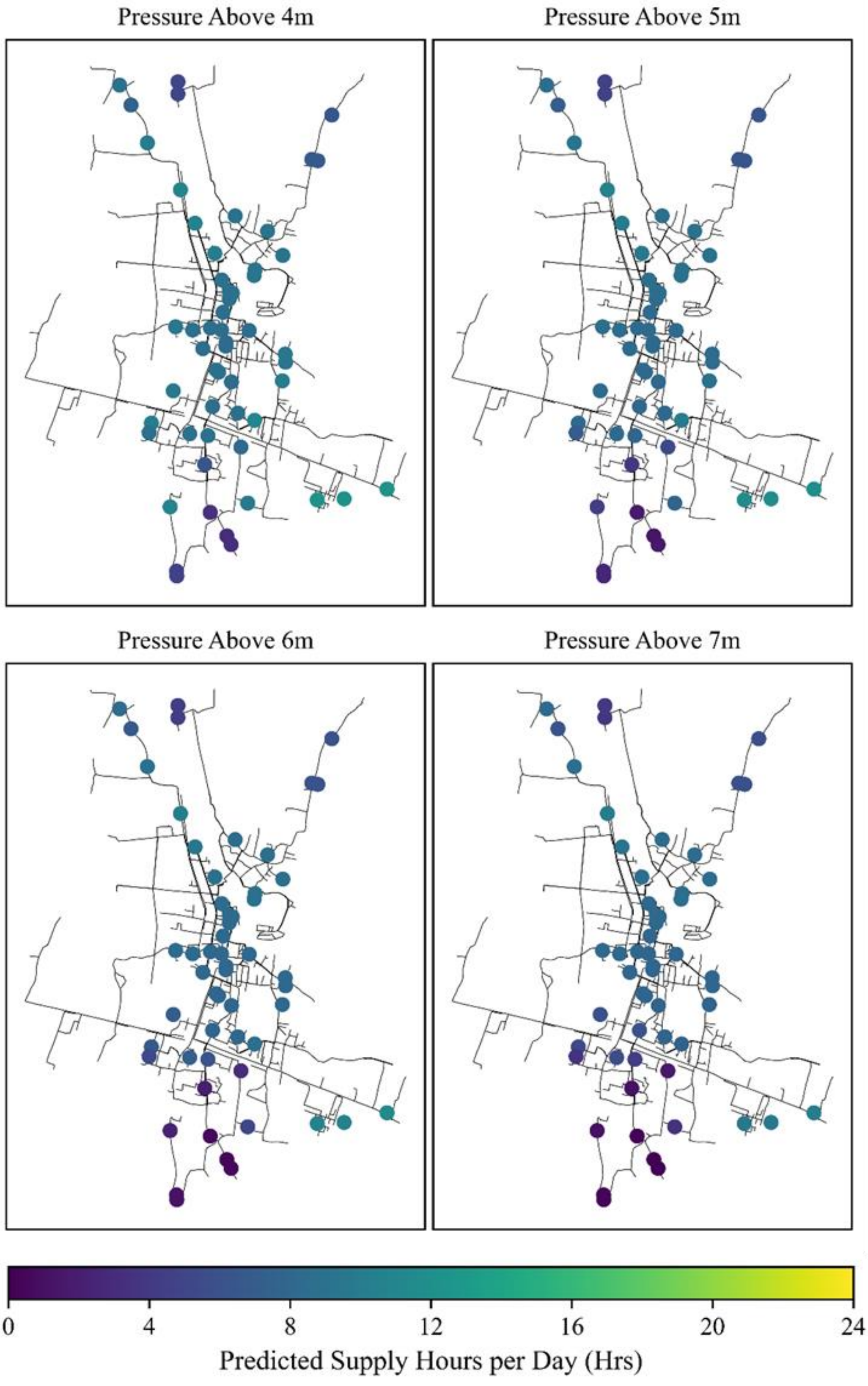


Figure 7.14: Estimated Local Supply Hours Based on Different 'Minimum Pressure' Definitions

In Figure 7.15, the effect of different definitions of minimum pressure on the estimated supply hours of three households is presented. The three households have been selected to illustrate the range in conditions in the network and therefore come from high, medium and low elevations. As summarised in Table 7.2, household 2 is nearest an input source (OHT1) while households 1 and 3 are both significantly further away from an input. The definition of the minimum pressure threshold has the greatest effect on house 3; the estimated supply hours drop from 24 to 0 hours as the threshold increases from 1 to 8m head. House 1 shows a very consistent reduction in estimated supply hours while there is negligible difference for house 2 between thresholds of 4 to 8m.

Table 7.2: Basic Characteristics of the Three Example Households

Characteristic	**House 1**	**House 2**	**House 3**
Elevation	126.6	116.8	110.8
Distance from nearest input source (metres)	2340	990	3500
Storage volume (Litres)	150	2000	25

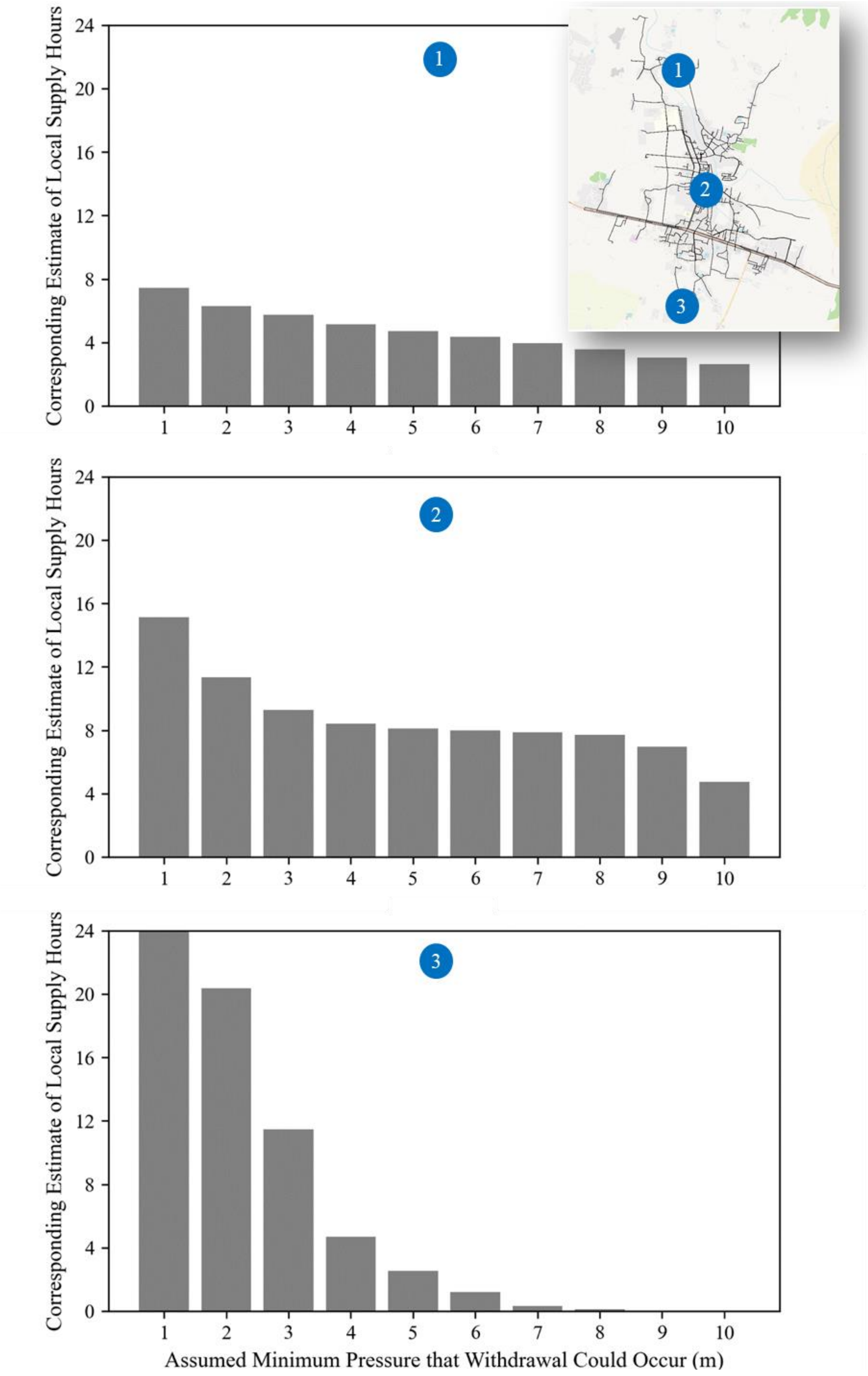


Figure 7.15: The Variation in Estimated Local Supply Hours of Three Households According to the Definition of the Minimum Pressure that Withdrawal can Occur

Figure 7.16 shows the resulting range in supply hours estimated at the locations where household meters were installed. The thresholds of 1m, 4m and 7m have been chosen as they approximately represent a tap at the ground floor, first floor and second floor respectively. The mean supply hours are 15.7 [range: 7–24], 8.6 [range: 3.4-12.4] and 6.2 [range: 0.22-10.3] hours respectively. The range is much larger under the 1m pressure threshold with three houses having 24 hours of supply. Five households receive less than 1 hour per day under the 7m threshold.

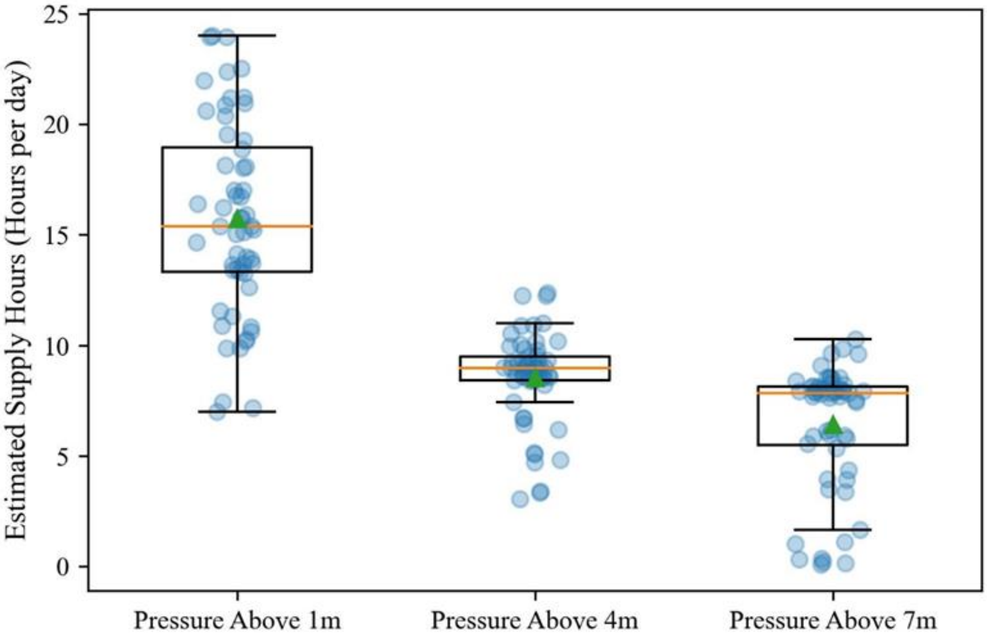


Figure 7.16: The range in Estimated Supply Hours of the Metered Connections According to Different Minimum Pressure Thresholds

Figure 7.17 and Figure 7.18 show the relationship between estimated household supply hours vs. elevation and distance from an input source respectively. Note the scale of the y-axis of the plots is different at the different pressure thresholds. Under the 1m threshold, elevation has a strong correlation with supply hours, the lower the elevation the longer the supply hours. This indicates that the water drains down the network after the supply has ended and pools in the lowest elevations.

Under the 4m and 7m thresholds, there is no clear relationship between elevation and supply hours. In both plots there appears to be two groups forming at the lowest elevations. This reflects the results shown in Figure 7.14, where there is a group of three households in the south east that are both at low elevation and near an input source and therefore maintain long hours of supply at high pressures. This corresponds with the group at the top right of these two plots. In the bottom right of the 4m and 7m plots are a larger group of households that have much lower supply hours at the higher-pressure thresholds.

Figure 7.18 shows a clear relationship between the distance to the nearest source and the estimated supply hours under the 7m threshold. At a pressure threshold of 4m, there is no clear relationship whilst at 1m there is an inverse relationship. The inverse relationship is likely to be a by-product of the fact the lowest elevations also tend to be further from the input sources (since the input sources are in the centre, northeast, northwest and eastern areas).

The combination of Figure 7.17 and Figure 7.18 indicates there are two key processes that drive the duration and magnitude of pressure across the Lahan network. Elevation drives the draining and pooling of water, which is reflected in the duration of low-pressure supply hours. The distance to the nearest inlet reflects the head losses and therefore the duration that medium to high pressures are experienced across the network. The combination of these two phenomena explain why the south east area has the ‘best’ supply conditions in the network; the area has both a close proximity to an inlet source (TCN) and relatively low elevation. While the central northern area (represented by example house 1) arguably has the worst supply conditions due to its combination of high elevation and long distance to an inlet source.

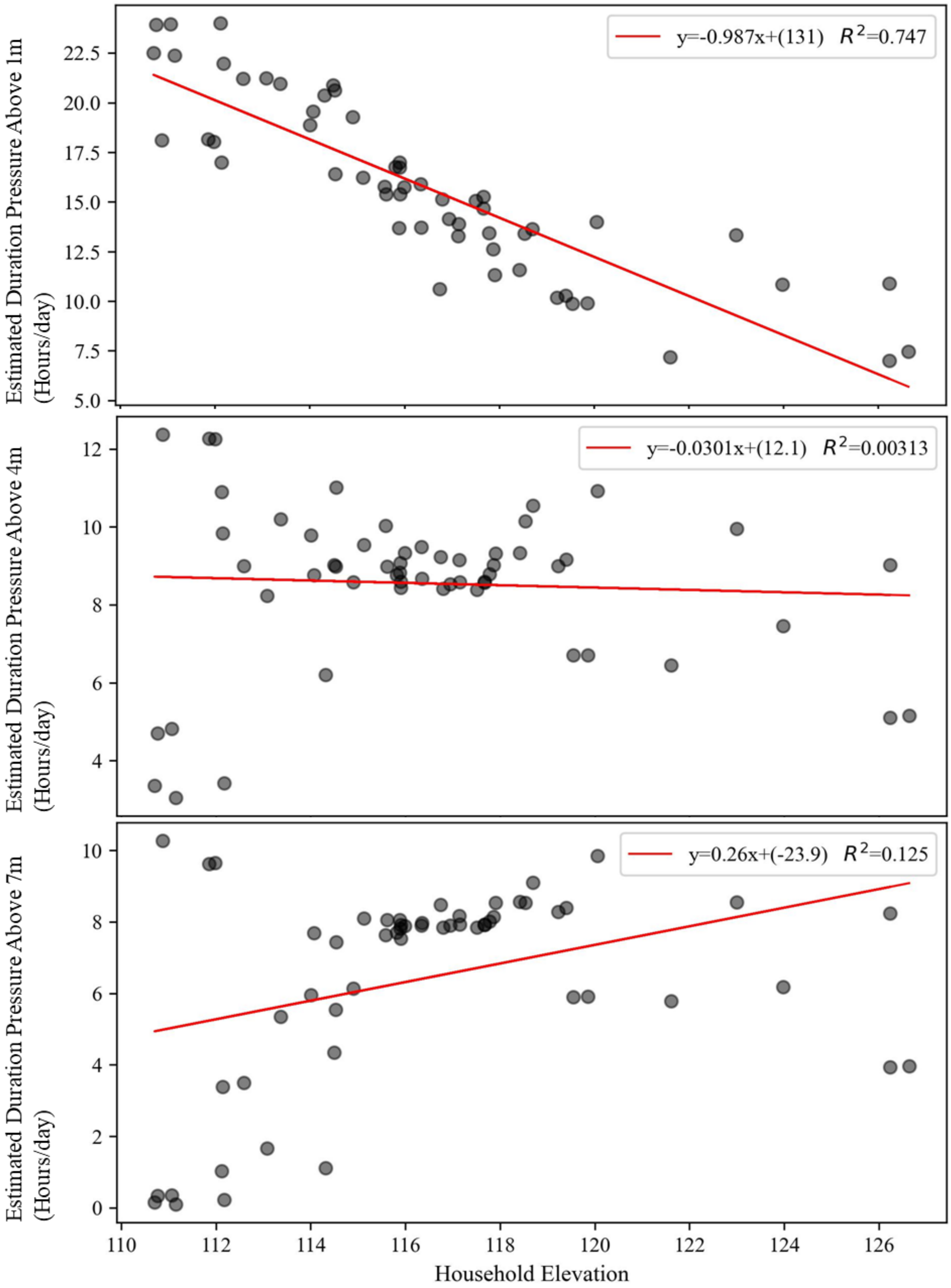


Figure 7.17: The Effect of Elevation on the Mean Duration that the Local Estimated Pressure is Above 1m, 4m and 7m Head.

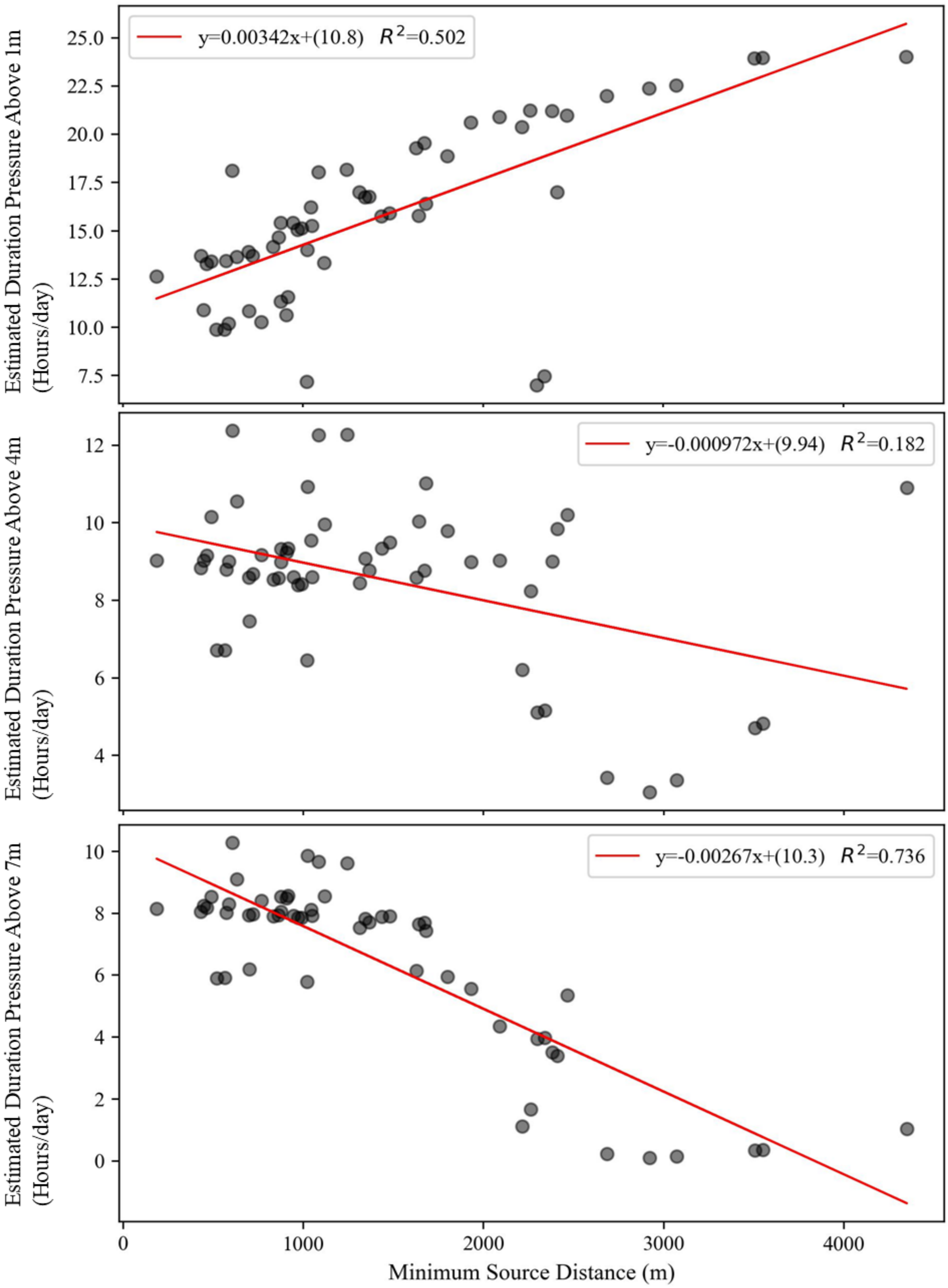


Figure 7.18: The Effect of Distance to the Nearest Network Input on the Mean Duration that the Local Estimated Pressure is Above 1m, 4m and 7m Head.

7.2 Household Characteristics (Survey Data)

The following section reports the key findings from the household survey data. As discussed in the methods section, unless otherwise reported, the results derive from the unweighted sample. The variation in household characteristics across Lahan will be reported as well as any relationships between household characteristics. Firstly, the self-reported hours of supply are presented as they corroborate with the findings from the previous section, highlighting the role of elevation.

7.2.1 Self-Reported Hours of Supply

Households reported a wide range of supply hours across Lahan ranging from 1 to 24 hours per day. Figure 7.19 shows the reported supply hours of the sample data, highlighting the group of nine households that reported 24/7 water. It should be noted that 50% of these households added the caveat that it is 'low pressure except for mornings and evening sessions'. Figure 7.20 plots the reported supply hours against the elevation of the households, there is a clear relationship between the household elevation and their reported supply hours. Specifically, a cluster of the CWS households emerges at the lowest elevations. Households with elevations higher than 114m show little correlation between the reported supply hours and elevation. Figure 7.21 shows the geographical grouping of the CWS households in the southern reaches of the network that corresponds to the lowest elevations.

Figure 7.19: Survey Respondents Estimated Hours of Supply per Day

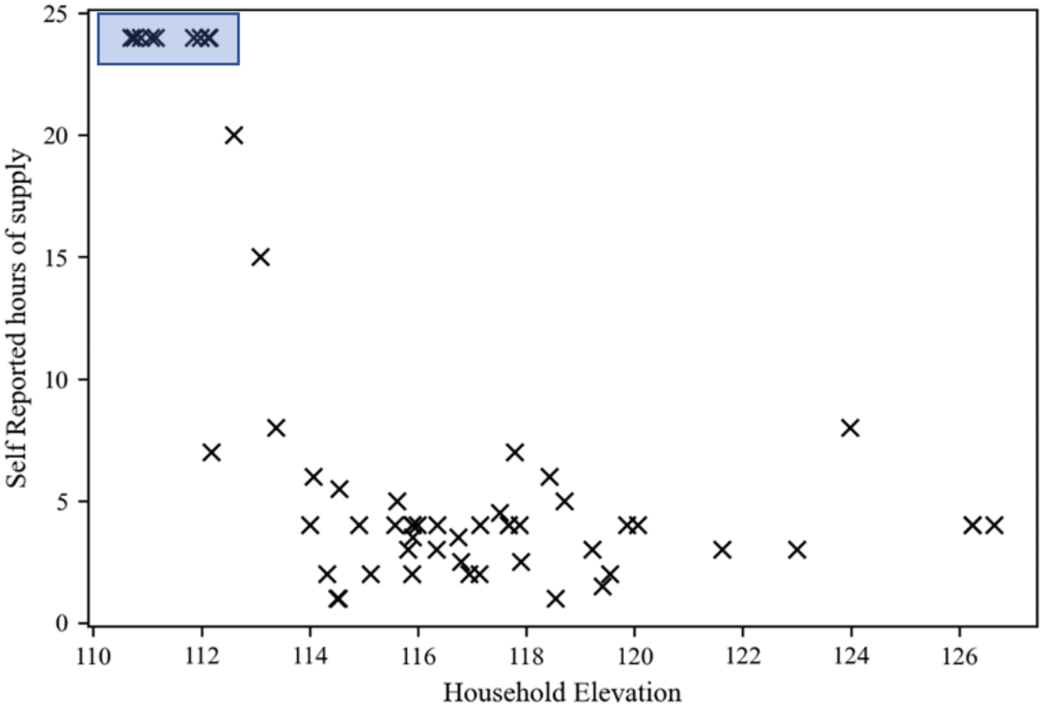


Figure 7.20: Self-Reported Hours of Supply against the Household Elevation (Households Reporting CWS are Highlighted in blue)

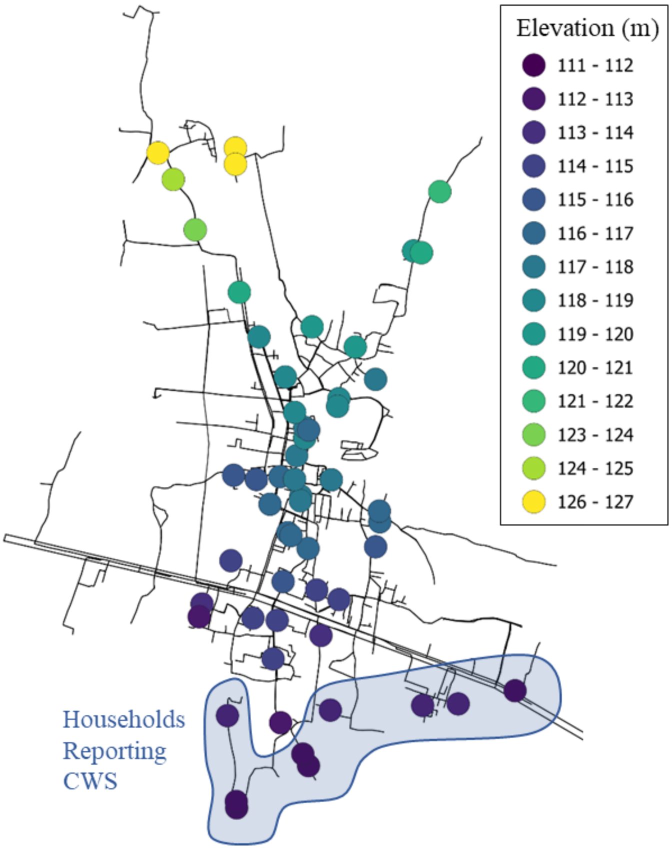


Figure 7.21: Map of Surveyed Households Coloured according to Elevation (Households Reporting CWS are Highlighted in blue)

7.2.2 Variation in Household Assets

Figure 7.22 shows the variation in household assets across the sample.

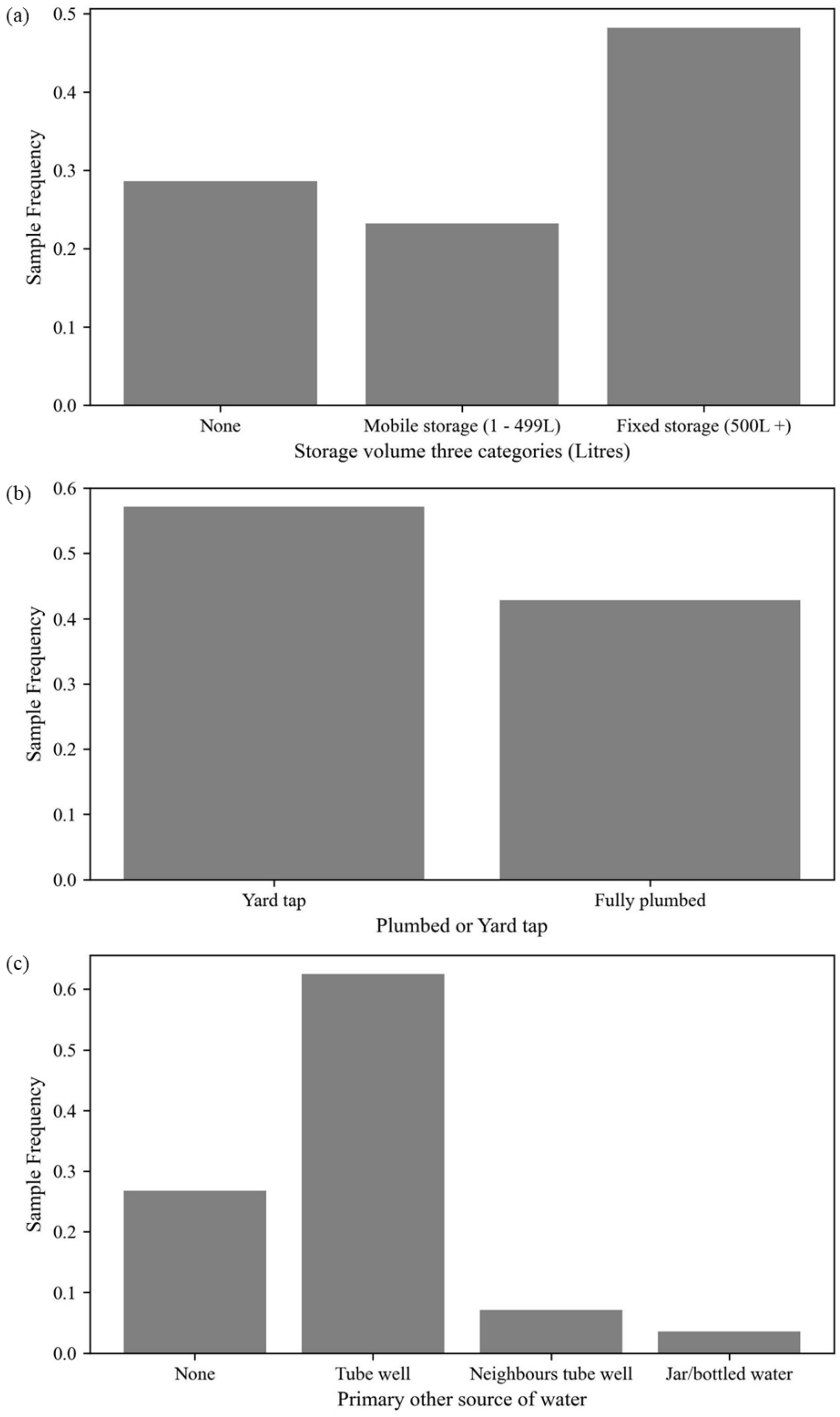


Figure 7.22: Proportion of Households in the Survey Sample with Different Household Assets

The storage volumes of households were grouped into the following three categories:

a. No storage [N = 16]
b. Mobile Storage (1 – 499 Litres) [N = 13]
c. Fixed Storage (500 + Litres) [N = 24]

The categories have a physical basis such that the 'mobile' storage involves smaller vessels that can be moved such as buckets, jerry cans, barrels and large cooking bowls. The 'fixed' storage involves more formalised containers designed specifically for the purpose of storing water. In Lahan, these were usually plastic tanks. These are typically built into a specific location and are often a part of the plumbing of a household. Figure 7.23 Shows examples of both types of storage category sold in local shops and installed in homes.

Figure 7.22(a) shows just over a quarter of households in the sample do not have any storage. Households also reported having storage connected to their alternative sources, exemplified by the following three quotes from households:

'We have a 1000 litre tank but it is connected to the tube well'

'We have a barrel connected to the piped water and 1000 litre tank connected to the tube well'

'We have a 1000 litre storage tank but the pressure can't reach it so we're not currently using it'.

There was a relatively even split between Yard Tap and Fully Plumbed installations in the sample as shown in Figure 7.22(b). Figure 7.24 shows typical examples of each arrangement.

Figure 7.23: Examples of Different Types of Storage Container Sold in Shops and Installed in Homes in Lahan for (a) Small 'Mobile' Type Storage Containers and (b) Large 'Fixed' Type Storage Containers

Figure 7.24: Typical Examples of a Yard Tap Arrangement vs a Fully Plumbed Installation

Figure 7.22(c) highlights the prevalence of a private tube well with over half of households owning one. In addition, some households reported their tube well as their main source of water with the piped supply only used for particular household activities. The following notes from the survey exemplify the variation in household access and use of other sources:

‘We have a hand pump but we have not been using it for a month because we have sufficient water.’

‘The neighbours have a hand pump; we use it if water is scarce and for watering cattle. If we’re desperate, we wash clothes in the river.’

‘We only use piped water, even for feeding the cow. We use a filter from the market for our own consumption.’

‘The hand pump is the main source because the piped connection has only been installed for two years so all the plumbing is connected to the hand pump and we’re used to drinking the hand pump water.’

‘We have a hand pump but it is not used.’

‘We have a hand pump but it is not working.’

‘We have a tube well, and use bottled water for guests.’

Figure 7.25 illustrates this with examples of a functioning tube well (operated via a hand pump), a water bottle delivery truck and two examples a broken tube well in households in Lahan.

Figure 7.25: Examples of (a) Other Sources of Water Used by Households in Lahan and (b) Non-functioning Tube Wells

Figure 7.26 shows the variation in how households view their piped water and the extent to which it is used to satisfy their water needs. The majority of households claim to utilise other sources in addition to the piped water supply, while 40% use the piped water for 100% of their needs. This is a higher proportion then the number reporting to not have any other sources of water (Figure 7.22(c)); hence, some households must have access to another source but only use their piped supply. The results of Figure 7.26 must be viewed with the strong caveat that responses are self-reported and highly sensitive to individual’s estimates.

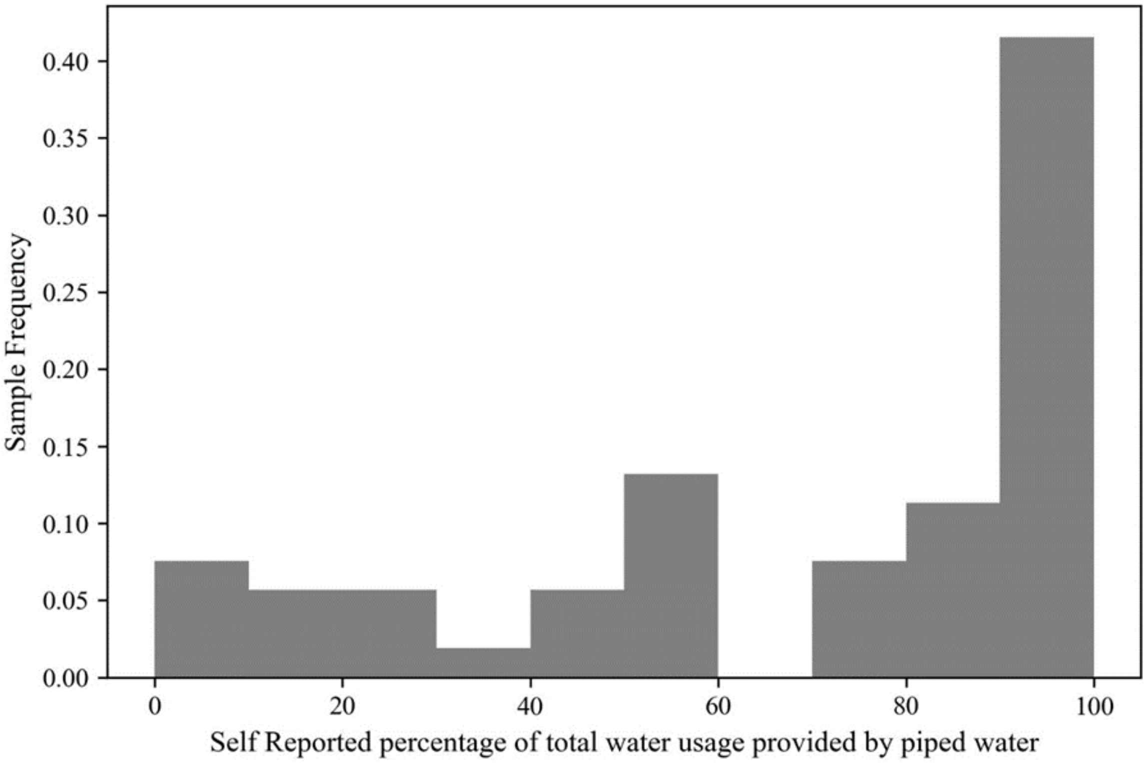


Figure 7.26: The Self-Reported Percentage of Total Water Usage that is Provided by the Piped Supply

7.2.3 Spatial Variation

Most parameters do not exhibit a spatial trend across Lahan. Figure 7.27 shows wealth tends to be slightly higher in the central regions of Lahan. This is reflected in Figure 7.28 with households tending to be plumbed in the central region. The clearest spatial trend is the division of the CWS group from the IWS households. As previously illustrated, this is a reflection of the elevation in Lahan. There does not appear to be any spatial correlation with perceptions of piped water quality. There is, however, a cluster of households in the central region close to OHT1, which only relies on the piped water for their water needs. This cluster of households also do not have other sources of water and they tend to be fully plumbed (Figure 7.28).

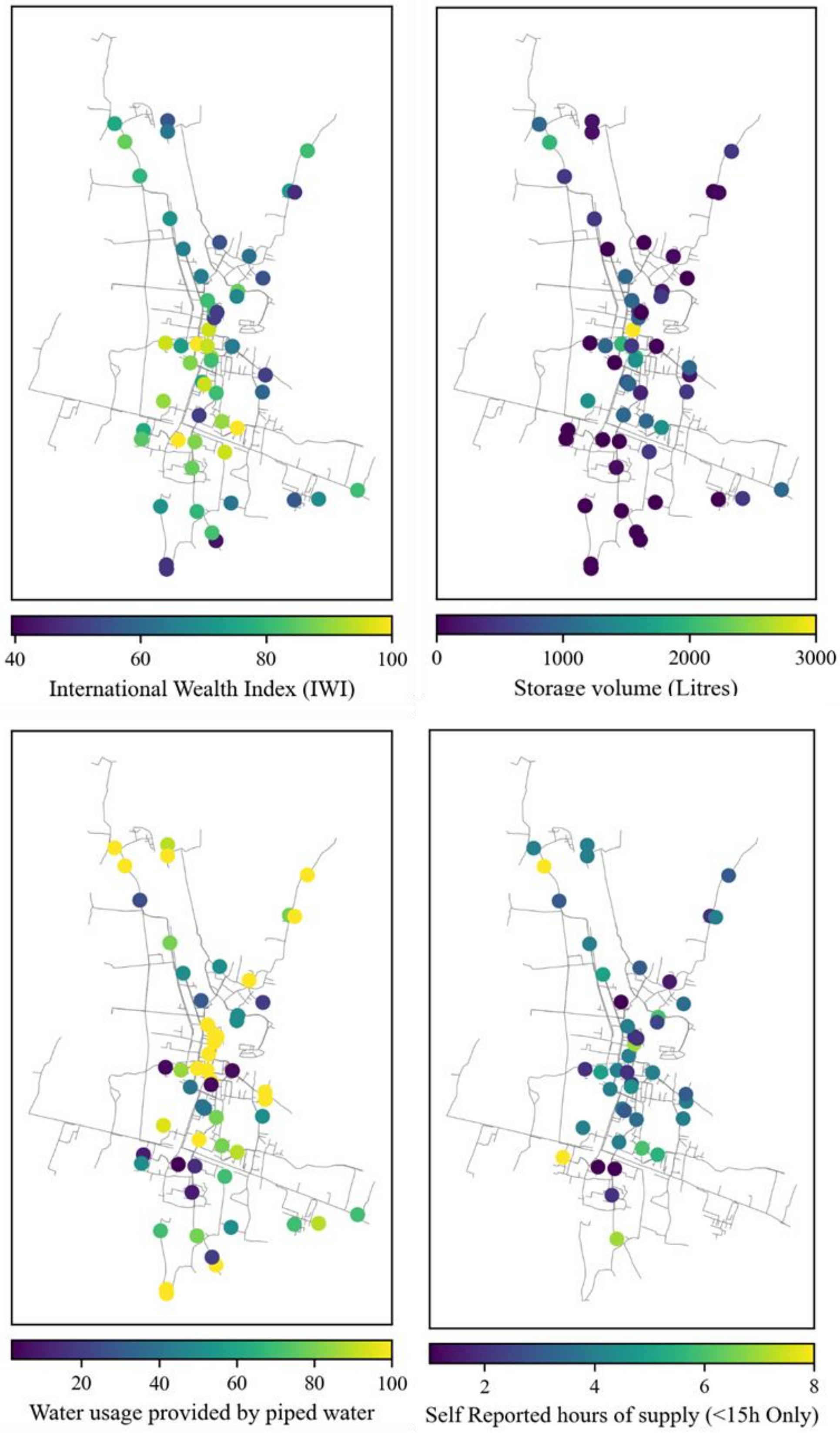


Figure 7.27: Spatial Variation of Household Continuous Variables

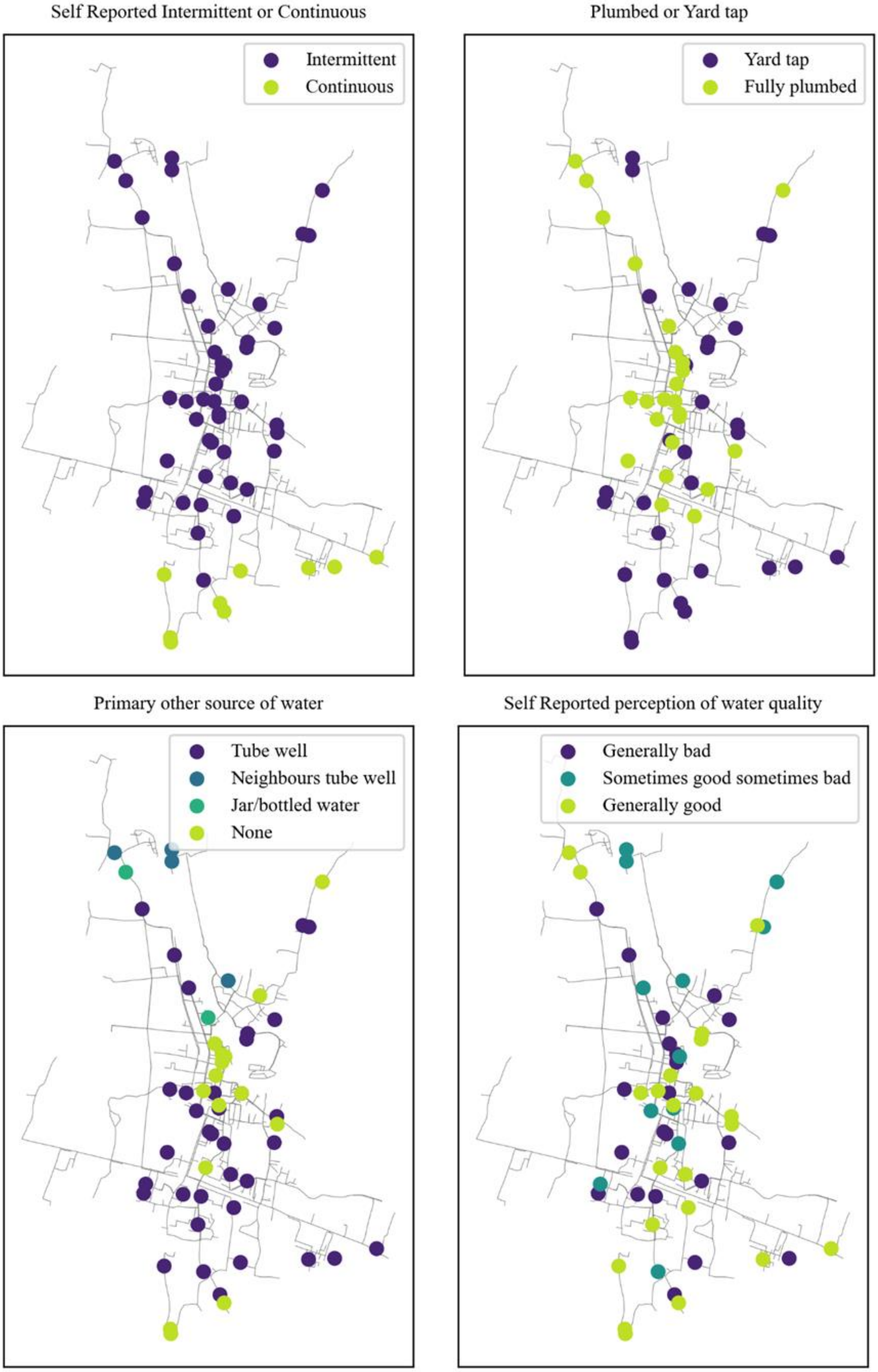


Figure 7.28: Spatial Variation of Household Categorical Variables

7.2.4 Commonalities between Household Characteristics

Comparisons of common assets were made to identify typical household arrangements. Table 7.3 shows households that are fully plumbed are much more likely to have fixed storage while households with a yard tap tend to have either mobile storage or none at all. The Fischer test returned a p-value of < 0.05 indicating a statistically significant association between the variables. Table 7.4 compares storage volume against whether the household has a tube well. Pearson's Chi-squared test was applied; there was not a statistically significant association between the two variables (p=0.19), therefore the null hypothesis cannot be rejected. Table 7.5 compares the households' perception of the piped water quality and whether they have a tube well. The Fischer test was applied; there was not a statistically significant association between the two variables (p=0.317), therefore the null hypothesis could not be rejected.

Table 7.3: Contingency Table Comparing Storage Volume and whether the Household has a Yard tap or is Fully Plumbed

		Yard tap or Fully Plumbed?		
		Yard tap	Fully Plumbed	Total
What is your storage volume?	None	13	3	16
	Mobile (1-499 L)	13	0	13
	Fixed (500+ L)	5	19	24
	Total	31	22	53

Table 7.4: Contingency Table Comparing Storage Volume and Ownership of a Tube Well

		Household has a personal tube well?		
		Yes	No	Total
What is your storage volume?	None	13	2	15
	Mobile (1-499 L)	6	5	11
	Fixed (500+ L)	15	7	22
	Total	34	14	48

Table 7.5: Contingency Table Comparing Perception of Piped Water Quality and Ownership of a Tube Well

		Household has a personal tube well?		
		Yes	No	Total
Self-Reported perception of water quality	Generally good	11	8	19
	Sometimes good, sometimes bad	7	2	9
	Generally bad	16	4	20
	Total	34	14	48

Figure 7.29 shows the relationship between household storage volume and their water usage practices. A Kruskal-Wallis test and post-hoc Dunn test was applied, resulting in statistical significance between the 'Directly' group and all other groups. The other groups showed no statistically significant difference between them (p>0.05).

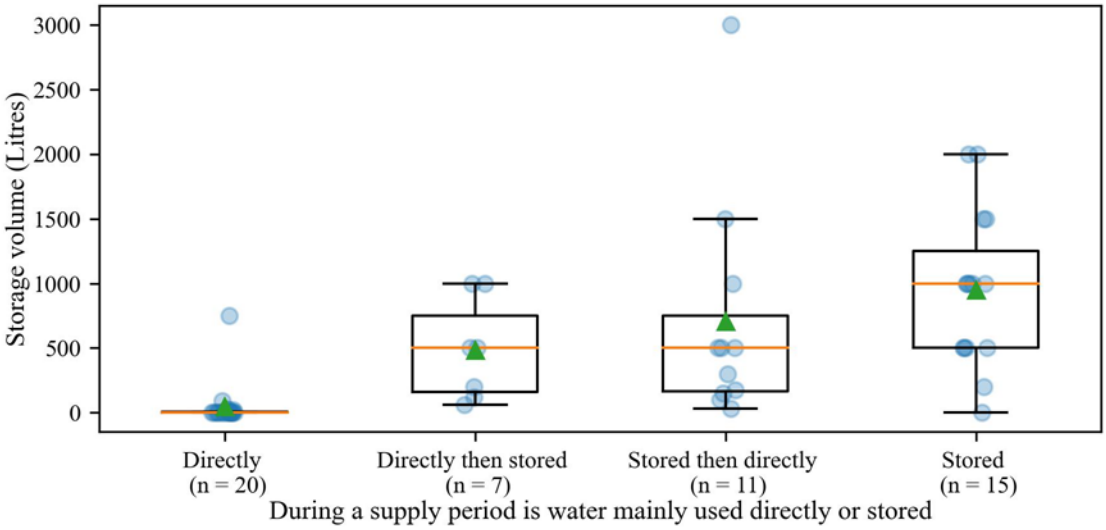


Figure 7.29: The relationship between household storage volume and their tendency to use water directly or store it during a supply period

7.2.5 Influence of Wealth on Household Assets

The influence of wealth on the adaptations of households was assessed using the International Wealth Index metric, where a higher IWI score indicates greater wealth. Table 7.6 lists the statistical tests assessing the null hypothesis that wealth does not affect different household variables. The results show that a higher IWI score is associated with a greater tendency to be fully plumbed as opposed to having a yard tap. A higher IWI is also associated with a greater likelihood that a household has a tube well as well as a greater likelihood of having a fixed (500+ Litres) rather than mobile (<500 Litres) storage. The box plots illustrating these relationships can be found in Appendix B.

Table 7.6: Statistical Tests for Significance between Household Categorical Variables and IWI Score

Variable	**Test**	**Statistic (p-value)**	**Null hypothesis (p-value > 0.05)**	**Outcome**
Plumbed or yard tap	Unpaired, 2-tailed t-test	-4.07 (0.000164)	**Rejected**	Higher IWI = more likely to be plumbed
Primary other source of water (Tube well vs None)	Unpaired, 2-tailed t-test	2.40 (0.0206)	**Rejected**	Higher IWI = more likely to have tube well
Storage volume three categories (Litres) [All Households]	1-way ANOVA	6.26 (0.0038)	**Rejected***	Higher IWI = more likely to have 'Fixed' vs 'Mobile' storage

Storage volume three categories (Litres) [IWS Only]	1-way ANOVA	4.83 (0.013)	**Rejected****	Higher IWI = more likely to have ‘Fixed’ vs ‘Mobile’ storage

* A post-hoc Tukey’s HSD test results in a p-value of 0.003 between the ‘Mobile’ and ‘Fixed’ storage groups. All other combinations gave a p-value > 0.05.

** A post-hoc Tukey’s HSD test results in a p-value of 0.009 between the ‘Mobile’ and ‘Fixed’ storage groups. All other combinations gave a p-value > 0.05.

7.3 Water Withdrawal (Smart Meter Data)

The water withdrawal behaviour of households is reported in this section using the household smart meter data.

7.3.1 Withdrawal Quantity (Litres per Capita per Day)

This section reports the water withdrawal quantities of connections measured in litres per capita per day (LPCD). Analysis referring to household withdrawal uses only data from household connections; analysis referring to consumer withdrawal uses data from all connections (i.e. including 1x school and 2x offices).

The practice of sharing a connection between households does not appear to be common in Lahan; only two sampled households reported sharing the connection with neighbours. For these two cases, the total number of people who use the connection from all households was used when calculating the volume withdrawn in litres per capita per day.

The mean withdrawal quantity in Lahan across January to October 2023 is 88.1 LPCD as shown in Figure 7.30 (b). Figure 7.30 (a) shows no clear spatial variation of withdrawal quantity. Figure 7.30 (c) shows a histogram of the withdrawal quantities; a K-S test was applied resulting in a lognormal distribution best describing the distribution of withdrawal quantities (D-value of 0.0742 and a p-value of 0.91 indicating the null hypothesis was strong and the distributions are well matched).

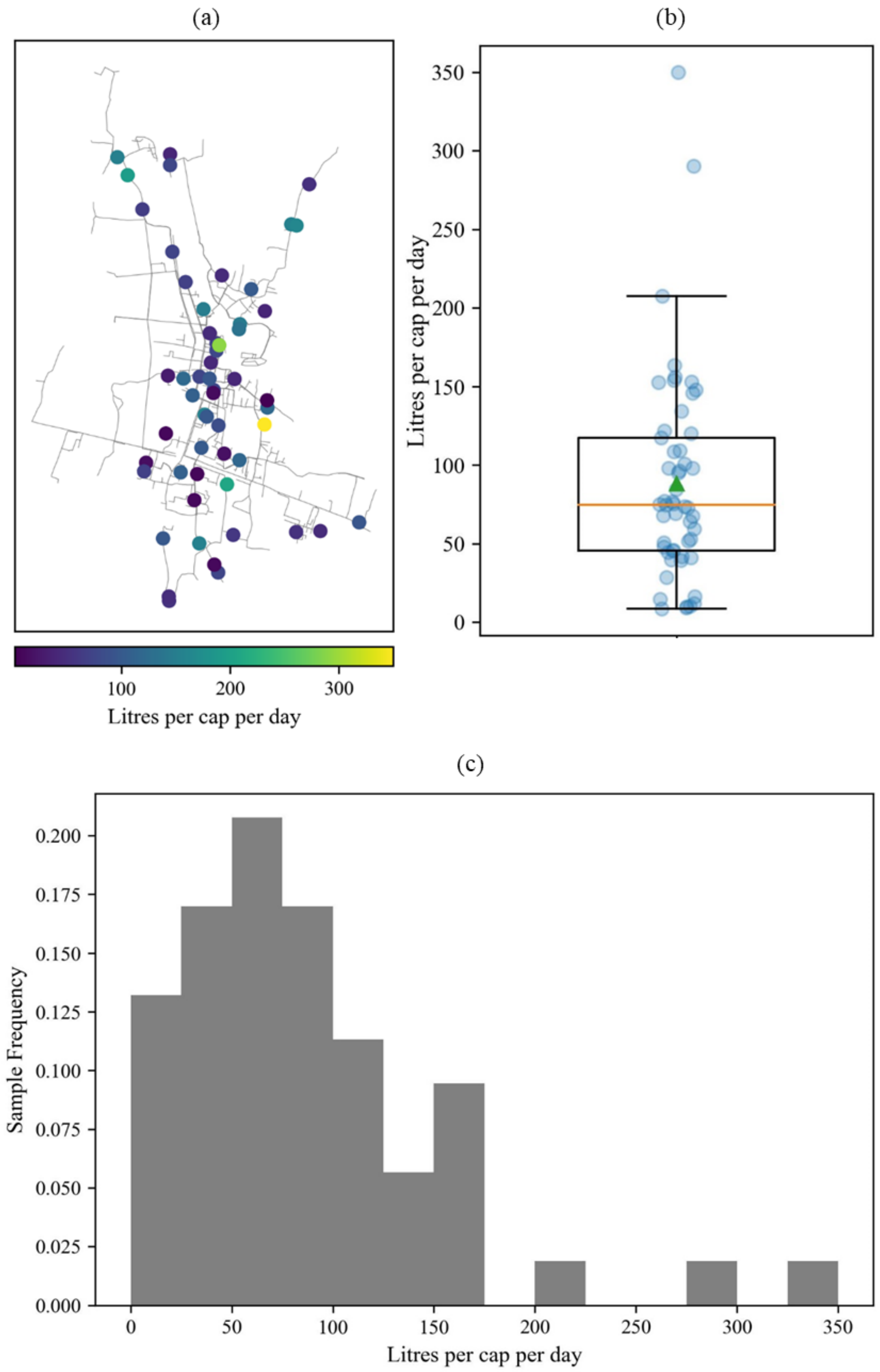


Figure 7.30: Mean Daily Water Withdrawal Volume per Person for all Sampled Households Plotted as (a) A Map, (b) Boxplot, (c) Histogram

7.3.2 Seasonal Variation

The three devices that stopped working during the 10-month period have been removed from this analysis. Across all devices during the 10-month period, a total of 80 days' worth of data has been removed due to partial missing transmissions; this represents 0.5% of the data.

Figure 7.31 shows an increase in withdrawal volume up to a peak around July, following this, withdrawal volume reduces again. Figure 7.33 indicates that the mean withdrawal volume is correlated with both temperature and rainfall. As the temperature increases between January to July, the average withdrawal also increases. When the monsoon rainfall arrives in July and August, we see a drop in the average withdrawal volume whilst the temperatures remain high. Consequently, both temperature and rainfall appear to influence withdrawal volume.

An increase in household demand could result in greater inequalities in withdrawal as households in the more favourable positions may consume more water meaning less is left for other households. This was assessed in Figure 7.32 that looks at the difference between the 5th and 95th percentile withdrawal volumes across the measured households. The spread increases between January to July indicating inequalities may have increased over this period. Whether this change is due to the low withdrawal households not receiving enough water to satisfy their demand is less clear however. It may be because households that rely predominantly on other sources of water do not have a significant change in withdrawal volume over this period, whilst households that do rely on the piped water show much larger increases in demand.

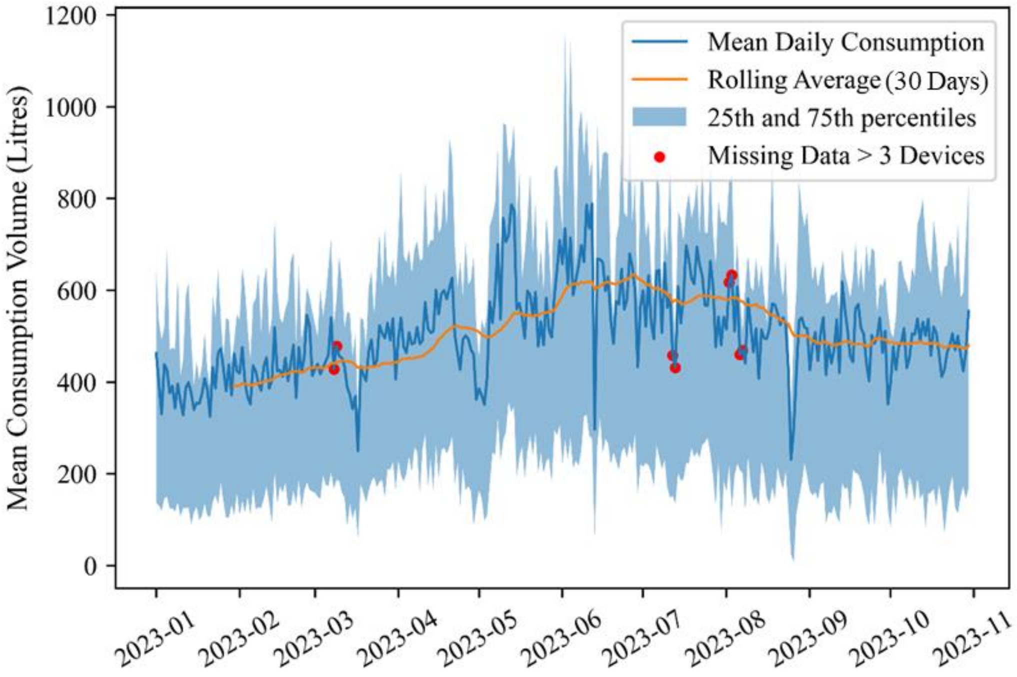


Figure 7.31: Change in Mean Consumer Withdrawal Volume from January to October 2023

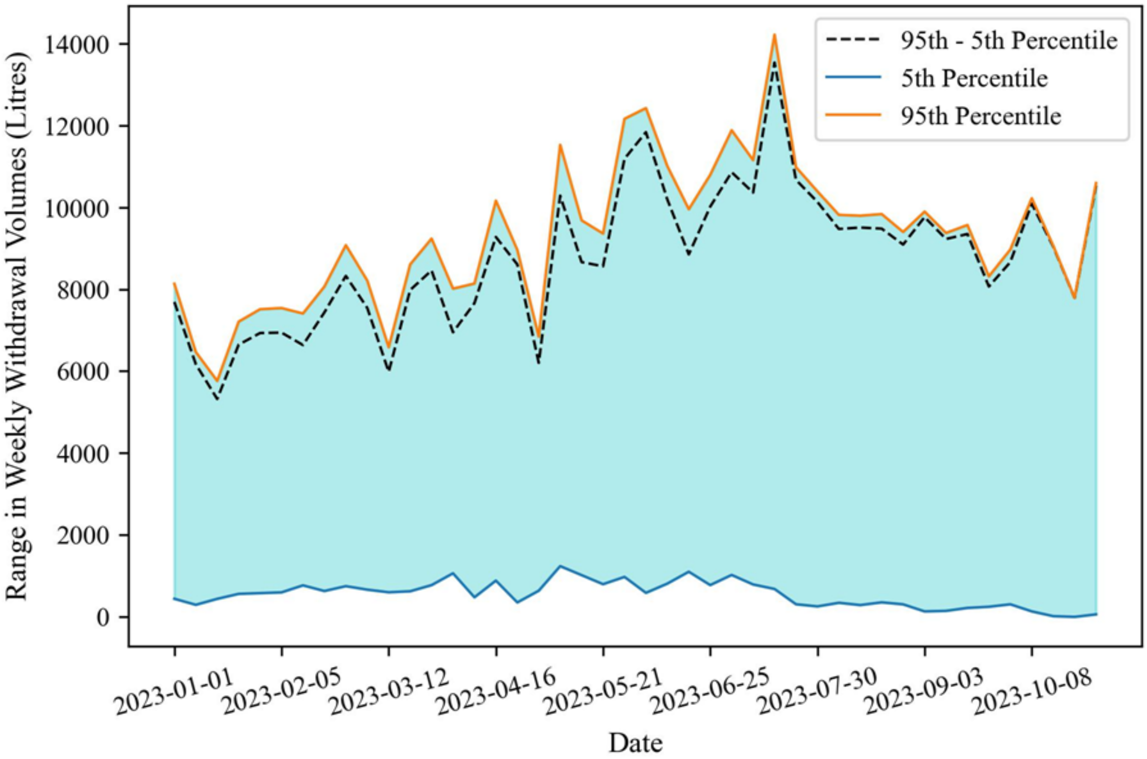


Figure 7.32: The change in the Spread of Withdrawal Volumes across the Measured Households between January to October 2023

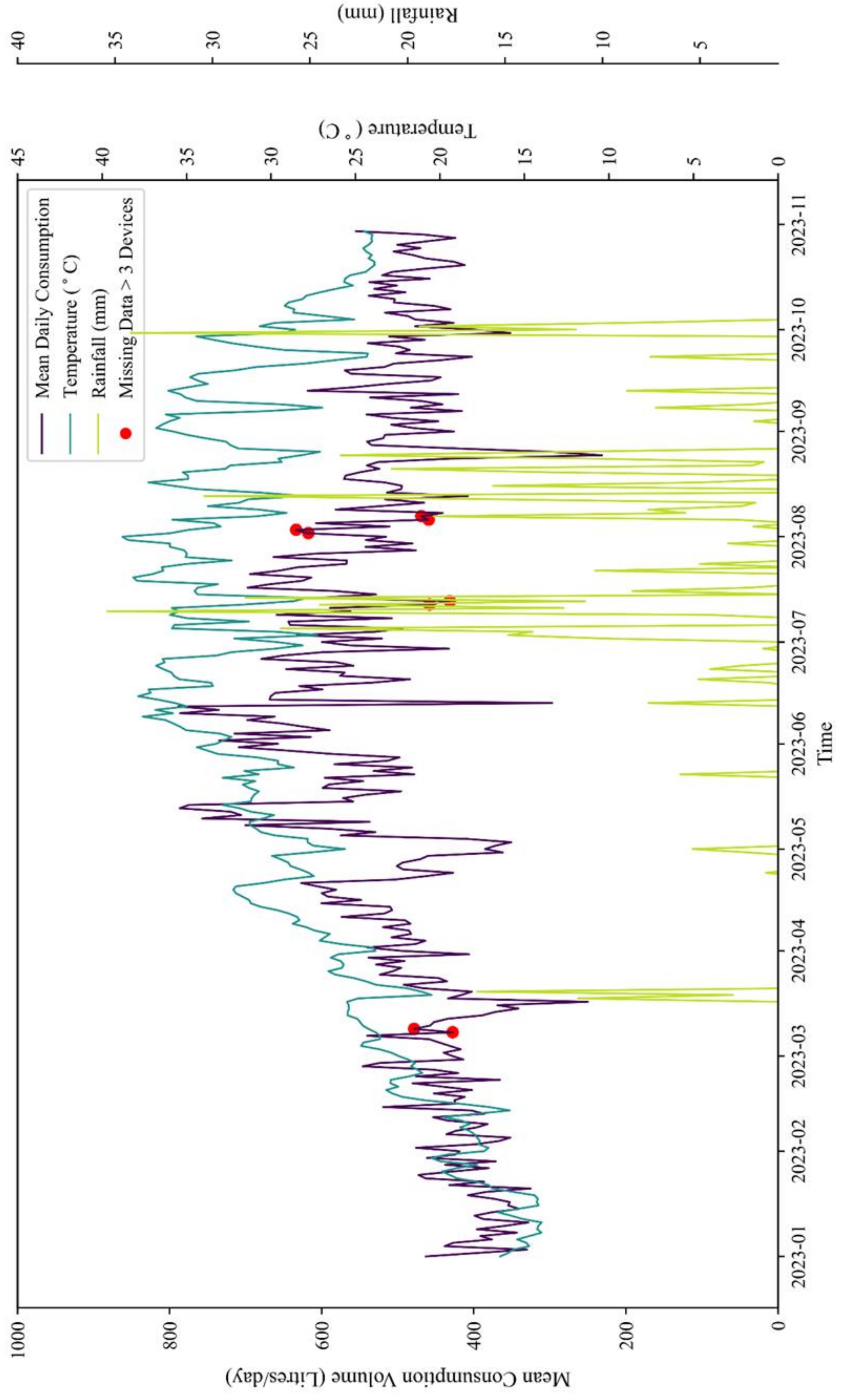


Figure 7.33: Change in Mean Consumer Withdrawal Volume Alongside Weather Data from January to October 2023

7.3.3 Monthly Variation

The month-on-month changes in household withdrawal volume are assessed in this section. Figure 7.34 shows the cumulative consumption volume of households across January to October 2023. The consumption is normalised to enable comparison between consumers. The black, dotted line indicates a consistent month-on-month withdrawal volume; the extent to which a consumer deviates from this line indicates the degree of variation between their monthly withdrawal volumes. A slight sinusoidal pattern is observed as the majority of consumers are below the average (dotted) line prior to June, and the majority are above the average line around September; this indicates higher consumption rates in the summer period corroborating with Figure 7.31. Some household consumption varies significantly month-on-month as illustrated by the distance from the straight, dotted diagonal line. Bimodal distribution can be seen in some households where the rate of consumption changes significantly at a specific point in time. This suggests a sudden change in behaviour or circumstances.

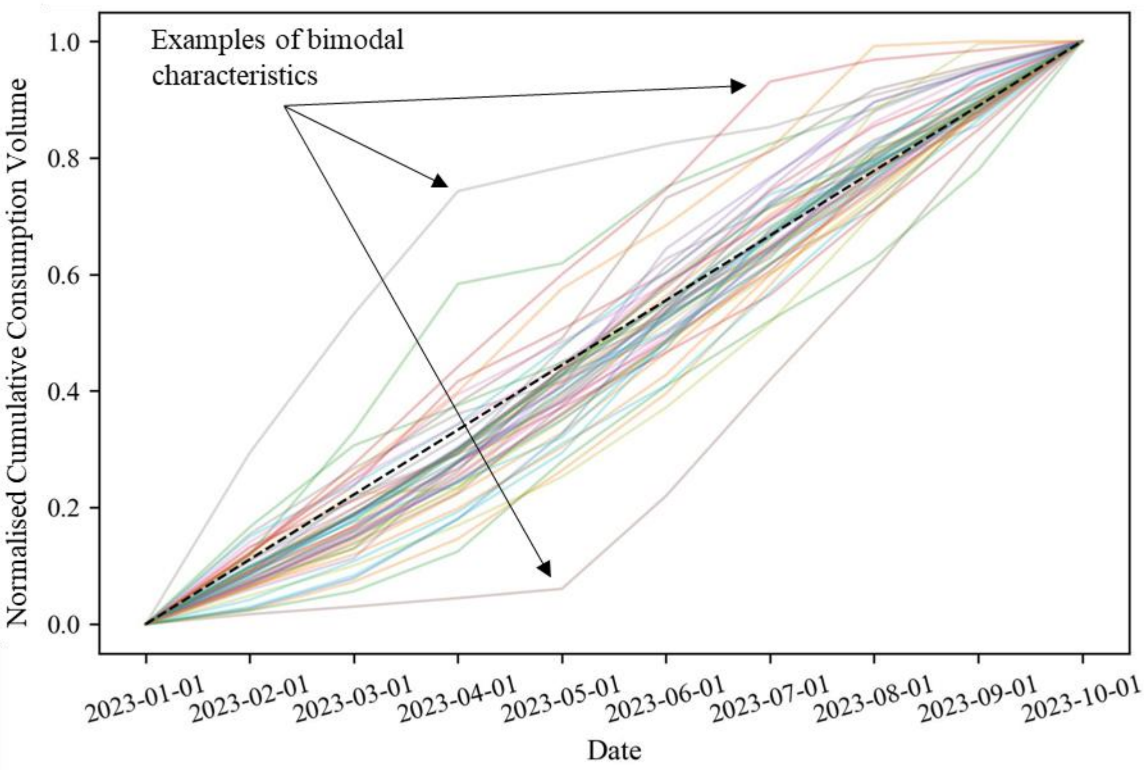


Figure 7.34: The Normalised Cumulative Withdrawal Volume of Connections. The Black Dotted Line Represents a Perfectly Consistent Withdrawal across the Time period

Figure 7.35 shows the difference in withdrawal volume of connections between equivalent months in 2023 and 2024. This is to remove the seasonal effects identified previously. Generally, the connections show highly variable withdrawal volumes. Some houses (such as the 3rd across) show a consistent pattern of withdrawing approximately 100% less water volume in 2024 compared to 2023, which corroborates with the bimodal distribution identified in Figure 7.34. A table of the data can be found in Appendix B.

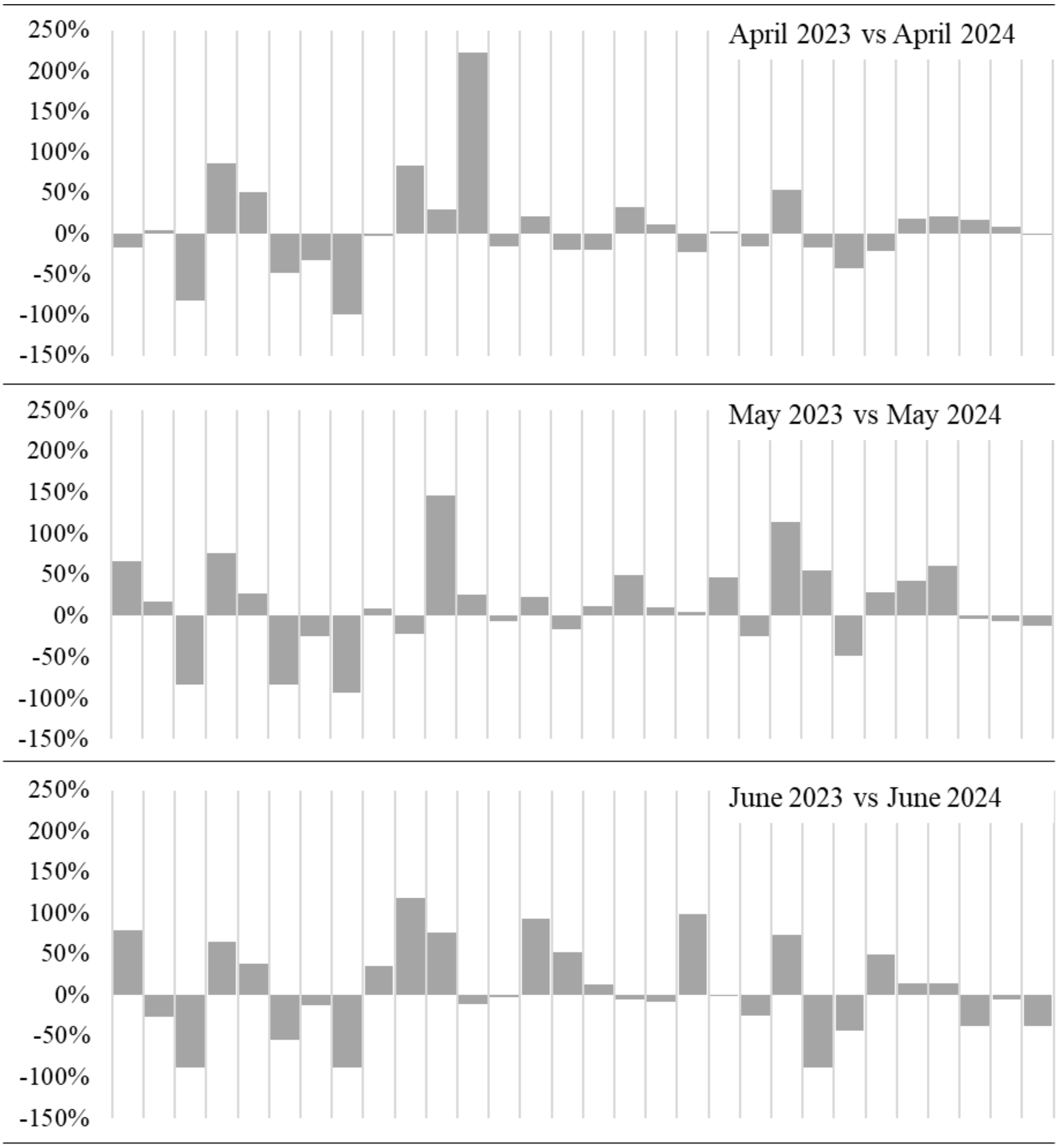


Figure 7.35: Percentage Difference in Monthly Withdrawal Volumes between Equivalent Months in 2023 and 2024 for Households with Available Data (N=30). Note households are in the same order so comparison between months is possible.

7.3.3.1 Differences between April 2023 and April 2024

As described in the Methods chapter, there are two sets of data relating to the household withdrawals; the Jan-Oct 2023 data and April 2024 data. To determine the similarity of the withdrawal volumes between these two time-periods, data from April 2023 was compared with April 2024. The Mann-Whitney U test was applied to test for statistical difference between the two distributions in Figure 7.36 resulting in a p-value of 0.897, hence there is insufficient evidence the distributions are different. However, Table 12.3 shows the individual changes of each household in the dataset, indicating large differences for many households. This may be the result of changes in household circumstances such as number of occupants but this is unlikely to be the case for all households that have shown a large difference. This suggests the differences may derive from changing household habits.

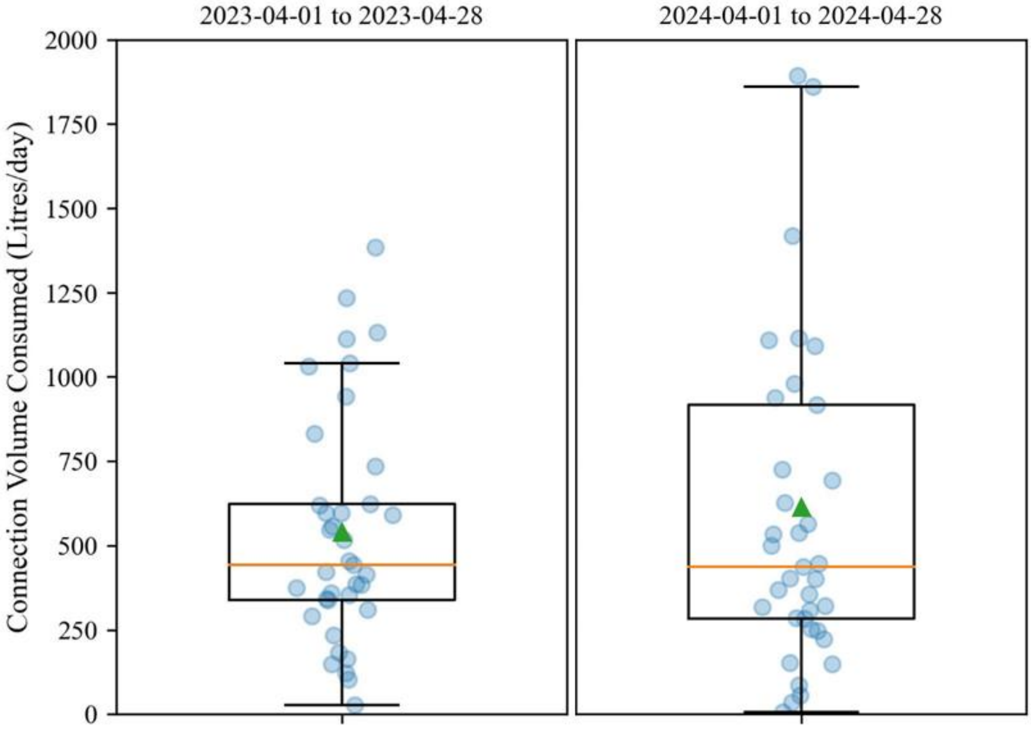


Figure 7.36: Comparison of Water Withdrawal Volumes of Households between April 2023 and April 2024

7.3.4 Daily Withdrawal Patterns

The daily withdrawal patterns of households were calculated and plotted as per the procedure described in section 6.8.1. Figure 7.37 shows three examples of household's patterns at different locations in the network. Household one typically withdraws water between 6 – 9AM and 5 – 7PM although there is never a greater than 70% likelihood of withdrawal. They never withdraw water between 10PM and 4AM and the withdrawal flowrates are all below 6 L/min. Household two has much larger flowrates up to 10 L/min in the 6 – 7AM period, which is also when there is a 100% likelihood of withdrawal, indicating highly consistent withdrawal during those hours. There is some withdrawal throughout the day, which may be indicative of a leak. Household three consistently withdraws water throughout the day with a greater than 40% probability of withdrawal from 6AM to 7PM.

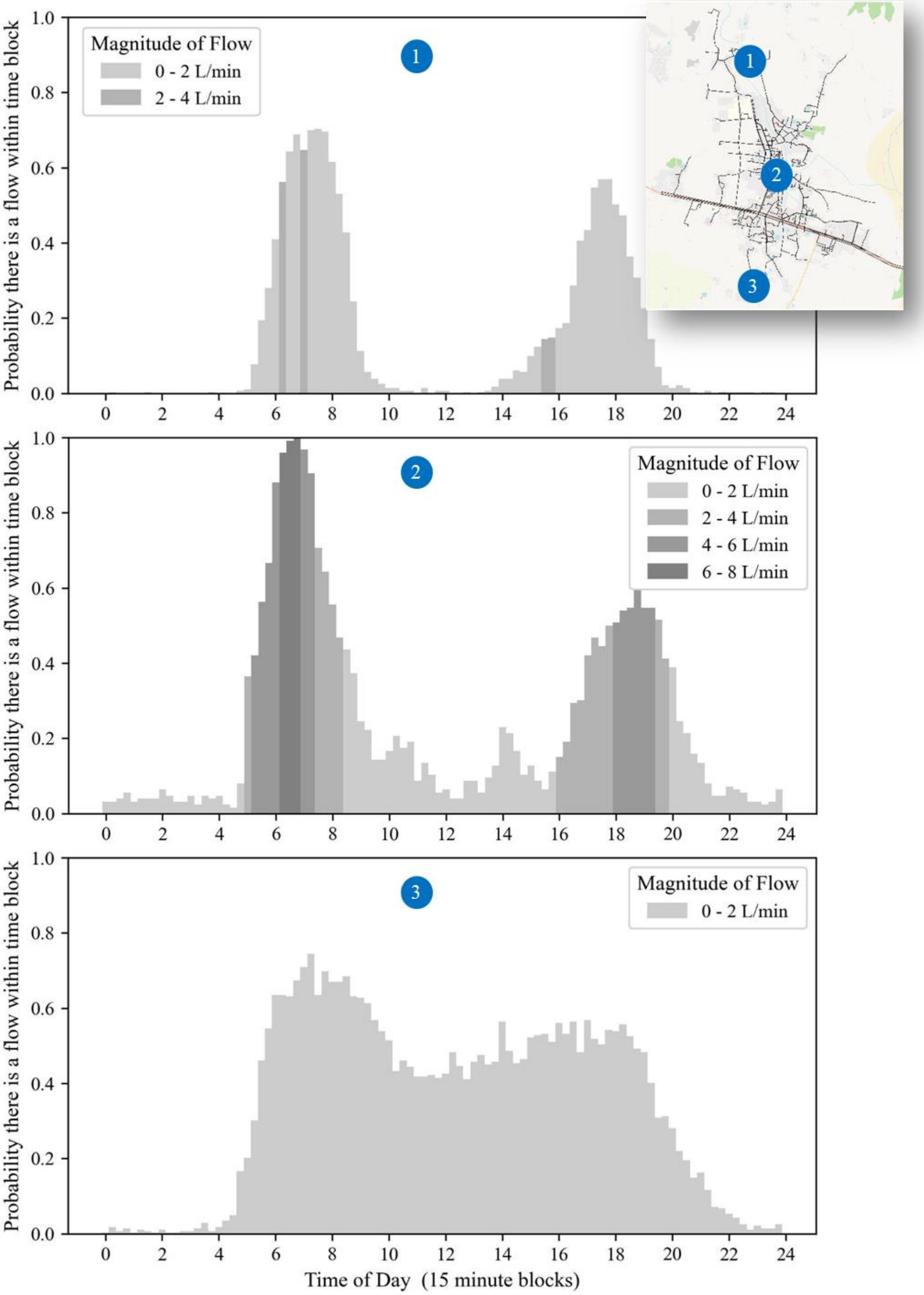


Figure 7.37: Example Daily Withdrawal Patterns of three Households at Different Elevations in Lahan. Shading Reflects the Magnitude of Flow During Withdrawal Instances (Note: Same Households as in 7.1.5)

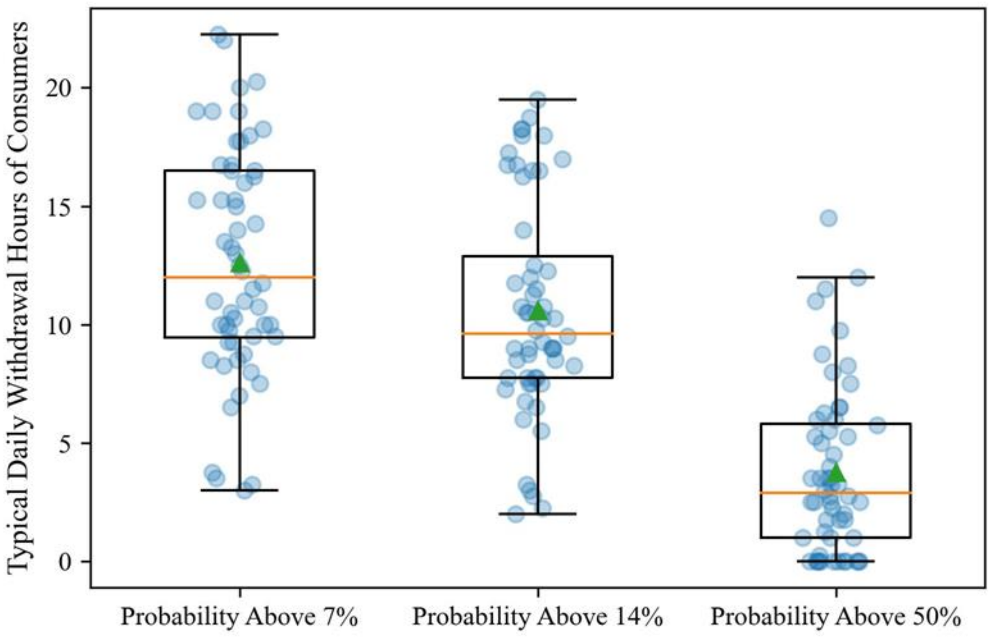


Figure 7.38: The 'Withdrawal Hours' of all the Sampled Consumers for three Definitions of Regularity

The resulting estimates of daily withdrawal hours for all the sampled households is shown in Figure 7.38. The mean values are 12.6 [range: 3-22.3], 10.6 [range: 2-19.5] and 3.8 [range: 0-14.5] for the respective probability thresholds. 21% of households had withdrawal hours of zero for the 50% threshold, meaning they do not withdraw water on an every-other-day basis across any 15-minute timeslot of the day. This indicates a lack of consistency of withdrawal behaviour or infrequent withdrawal of the piped water.

7.3.5 Withdrawal Instance Analysis

The following results assess the withdrawal characteristics using the methods described in section 6.8.2. Figure 7.39 shows histogram and cumulative frequency plots of the withdrawal instance characteristics across all meters between January to October 2023. Each bar of the histograms represents 1 minute and 1 litre respectively. The plots have also been cut to a maximum value of 100 on the x-axis for ease of visualisation. It is crucial to note that there are instances with durations and volumes far exceeding 100 minutes or litres, these will be examined in future chapters. Figure 7.39 shows just over 50% of withdrawals are for less than 1 minute and 40% of withdrawals are of up to 1 litre volume. In terms of frequency, the vast majority of withdrawals are therefore short durations with small volumes withdrawn.

The withdrawal instances have been grouped according to their associated volume. Figure 7.40 shows the contribution of each group to the total water withdrawal volume of each house in Lahan. This shows a very different aspect than the frequency plots. Even though the larger withdrawals are much less common, they are much more significant in terms of their contribution to the total withdrawal of the households. Any withdrawal instance volume exceeding 250 litres is untypical of indoor household activities and is therefore likely to be associated with storage tank filling. The 250 – 750 Litre group accounts for 23% of the withdrawal volumes indicating the significant role tank-filling type behaviour plays in the withdrawal characteristics of the households.

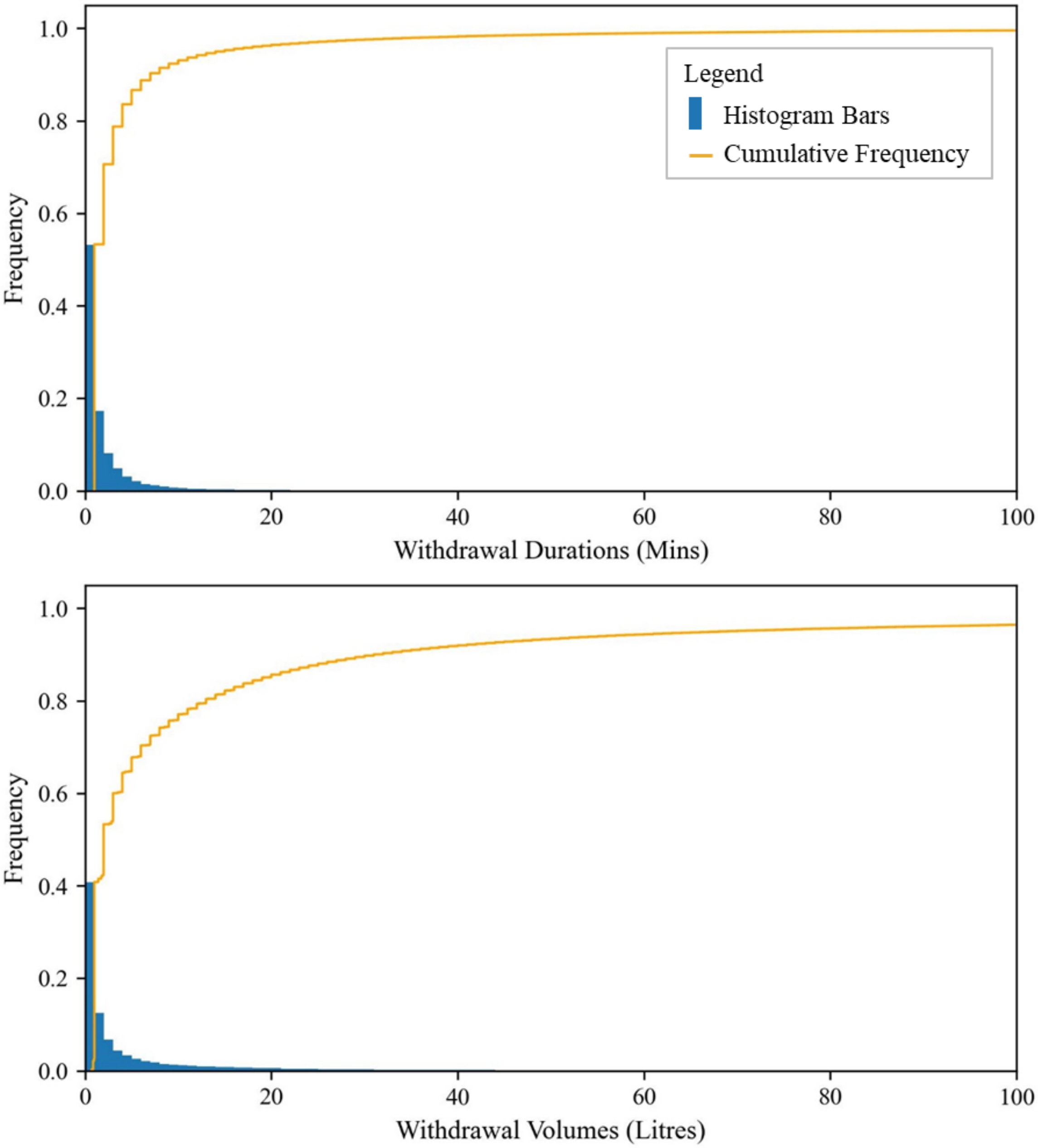


Figure 7.39: Histogram and Cumulative Frequency Plots of the Withdrawal Instance Durations, Volumes and Flowrates across all Meters between January to October 2023

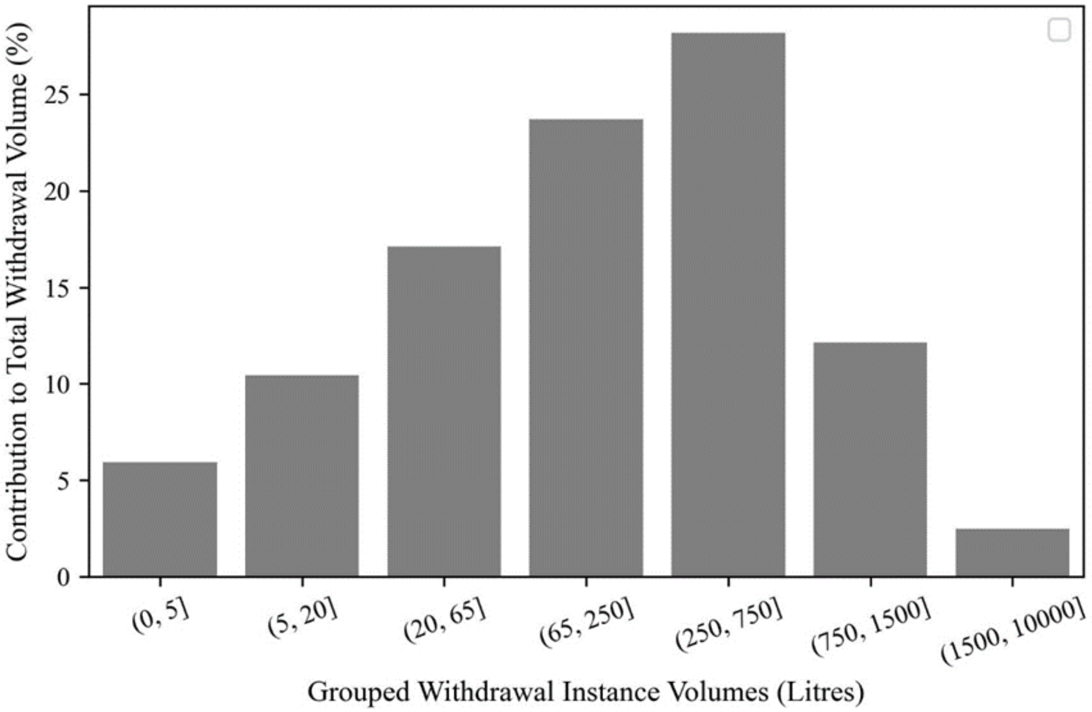


Figure 7.40: The Contribution that Grouped Withdrawal Instances make towards the Total Withdrawal Volume of all Households

The variability between households is demonstrated by Figure 7.41. Household three withdraws the majority of their water via 5 – 65 litre withdrawals while household two utilises withdrawals of 250 – 1500 litres. Household one is in between the two extremes, withdrawing the majority of their water in 20 – 250 litre withdrawals.

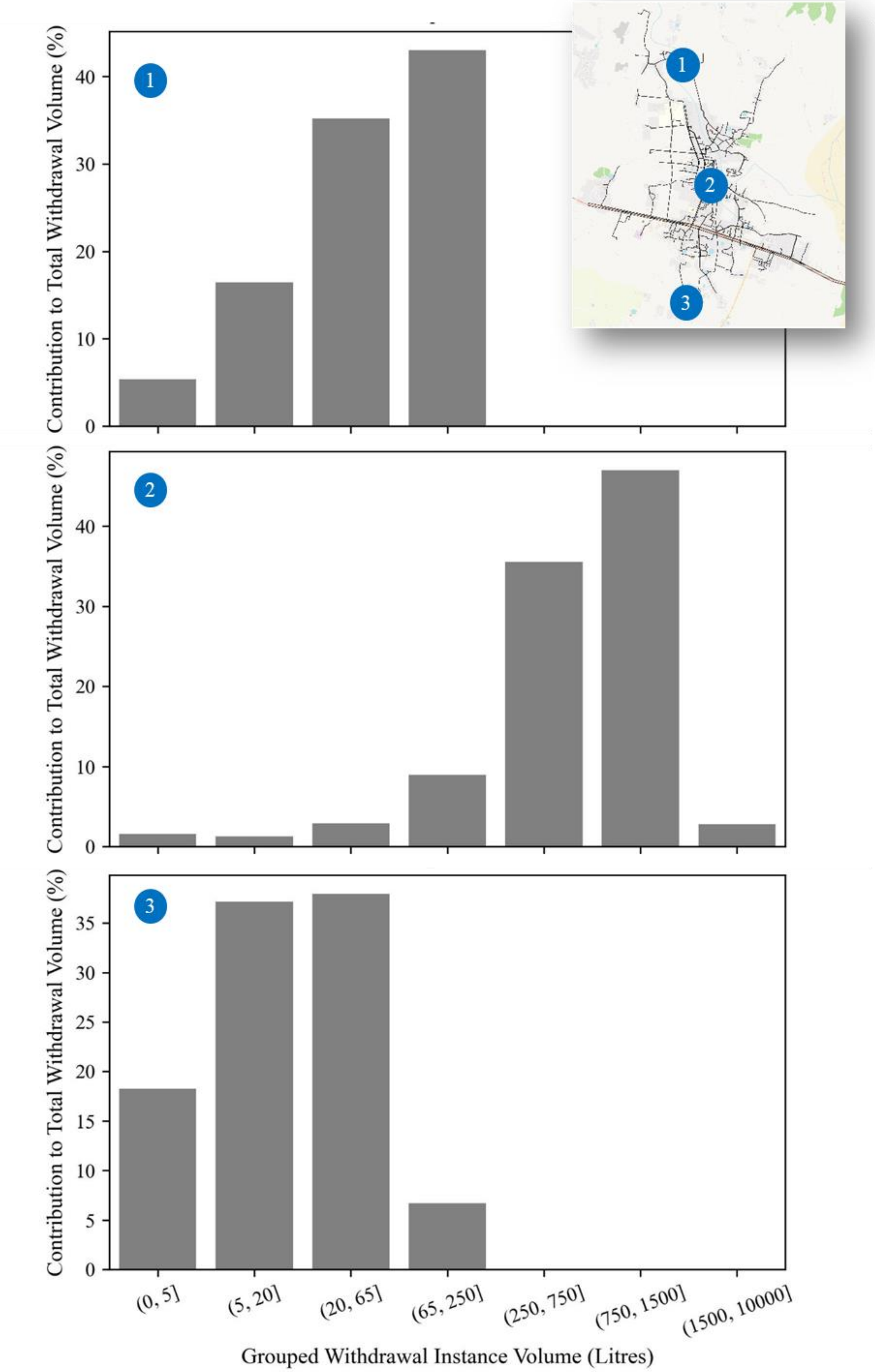


Figure 7.41: Example Withdrawal Instance Volume Characteristics of three Households at Different Elevations in Lahan (Note: Same Households as in 7.1.5)

7.3.5.1 The Effect of the Duration before the Withdrawal

The amount of time that precedes each withdrawal instance was also calculated. This is compared with the volume associated with the withdrawal instance as shown in Figure 7.42. Clustering can be observed in the durations before withdrawal instances. This is to be expected, as they are associated with the typical length between input supply periods, as illustrated by the grouping in Figure 7.42. Greater detail can be observed in Figure 7.43; the majority of withdrawals are small and have a short duration before. The frequency of the 1 litre volume, 1 minute frequency withdrawals was far greater than all other withdrawals, as a result the z-axis shows the Log of the frequency values to enable the differences between the clusters to be visualised. The Characteristics of the withdrawal volumes for each group is shown in Figure 7.44, illustrating the tendency for withdrawals to be larger in volume the longer the duration preceding them. The frequency of withdrawals within each group differs greatly; the proportion of withdrawals within each group is 94.4%, 5.5% and 0.4% respectively.

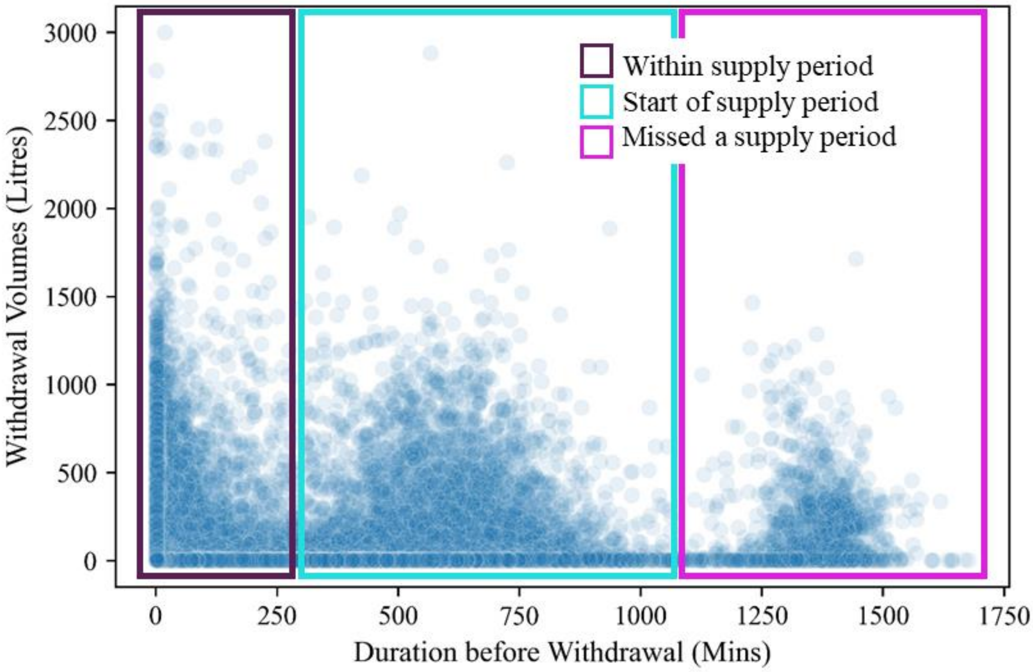


Figure 7.42: Grouping of Withdrawal Instances According to Duration before Withdrawal

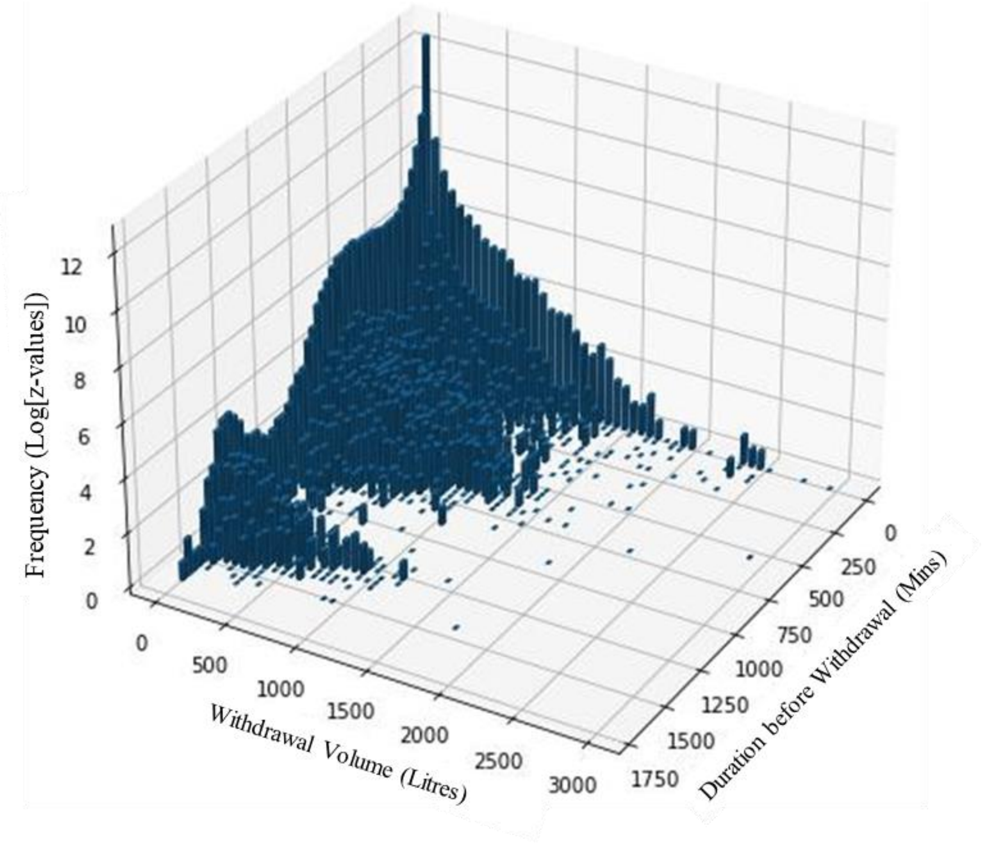


Figure 7.43: 3D Plot of the Withdrawal Volume against the Duration before Withdrawal with the z-axis Showing the Natural Logarithm of the Frequency

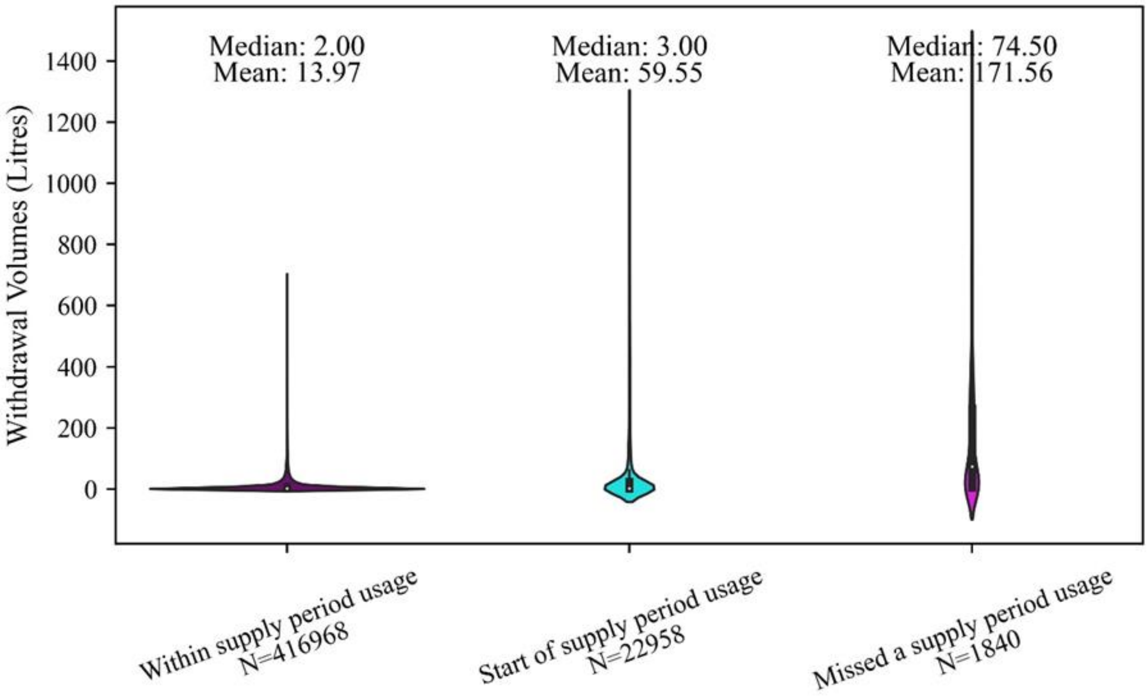


Figure 7.44: Violin Plot of Withdrawal Volumes for Instances Grouped by the Duration before the Withdrawal. This includes data from all Meters between January to October 2023. Note: Outliers Removed

8 Analysis Part 1: Comparing Supply conditions, Household Characteristics and Water Withdrawal

This section aims to investigate the relationships between the three datasets reported in section 7.

8.1 Comparison between IWS and CWS Households

The first area of analysis compares the differences between the intermittent and continuous supply groups. The process of estimation of local supply hours showed that there is not an absolute boundary between intermittent and continuous supply. This section will be defining the groups based solely on the survey response of households i.e. the CWS group being those that reported supply hours of 24 hours per day.

Statistical tests were employed to test the null hypothesis that there is no difference between the IWS and CWS groups at the 95% confidence interval across several continuous variables. Table 8.1 presents the results; there is a statistically significant difference in HWISE and IWI score between the IWS and CWS groups, meaning the CWS group are less water insecure and are less wealthy at the 95% confidence interval. There is also a statistically significant difference in the storage volume of the IWS and CWS groups, with the CWS households tending to have less storage. The withdrawal quantity is less for the CWS group but the difference is not statistically significant. The corresponding boxplots can be seen in Figure 8.1.

Statistical tests were also employed to test the null hypothesis that there is no difference between the IWS and CWS groups at the 95% confidence interval across several categorical variables. Table 8.2 presents the results; the only statistically significant relationship is CWS households being less likely to be fully plumed.

Table 8.1: Statistical Tests Comparing Continuous Variables against the IWS and CWS groups

Variable	**Test**	**Statistic (p-value)**	**Null hypothesis (p-value > 0.05)**	**Outcome**
HWISE	Mann-Whitney U test	309 (0.00823)	**Rejected**	CWS correlates with a lower HWISE score
IWI	Unpaired, 2-tailed t-test	2.32 (0.0242)	**Rejected**	CWS correlates with a lower IWI score
Litres per cap per day	Mann-Whitney U test	253 (0.197)	Not rejected	No statistical significance
Storage volume	Mann-Whitney U test	301.5 (0.0423)	**Rejected**	CWS correlates with less storage volume

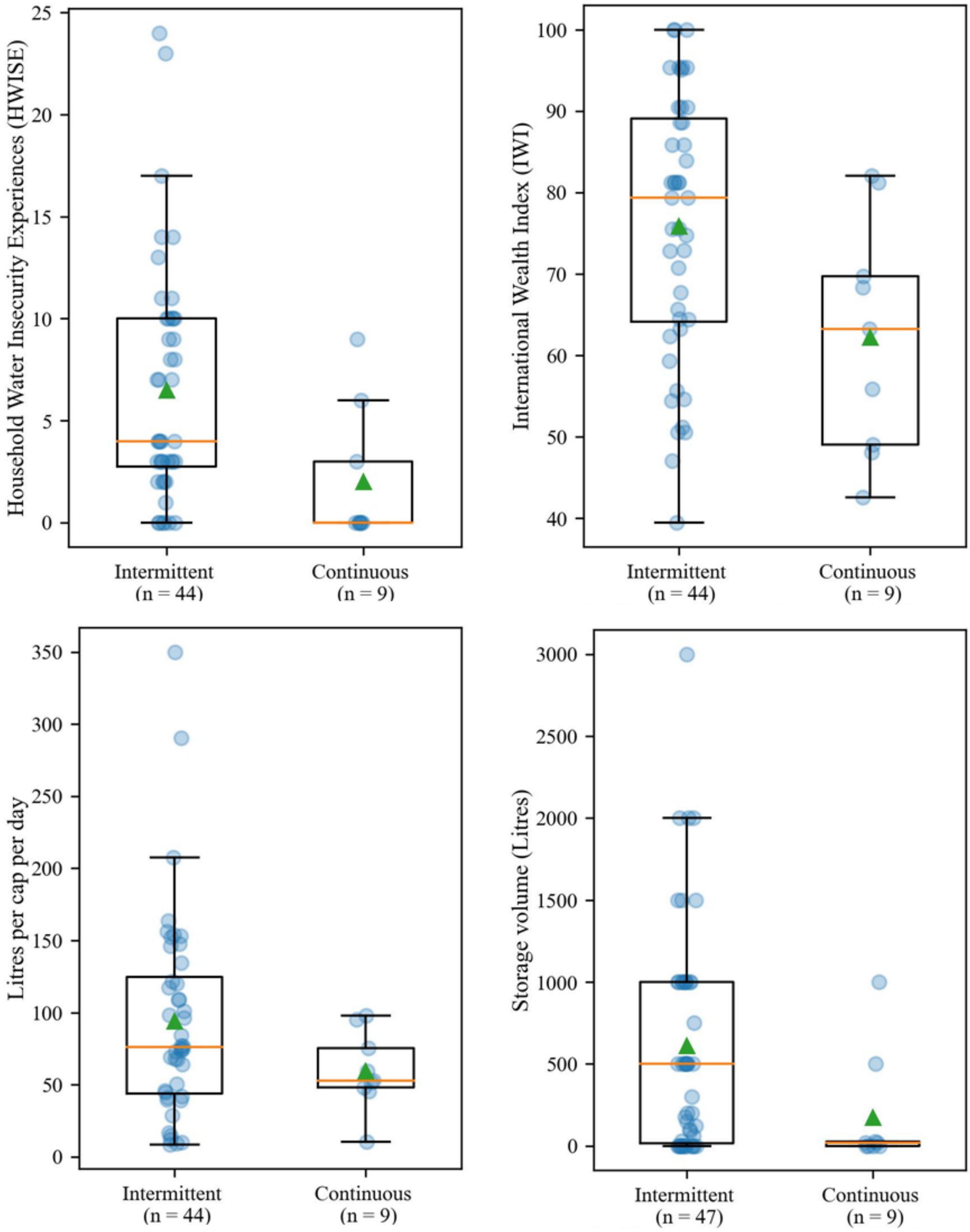


Figure 8.1: Boxplots Comparing Continuous Variables against the IWS and CWS groups

Table 8.2: Statistical Tests Comparing Categorical Variables against the IWS and CWS groups

Variable	**Test**	**P-value**	**Null hypothesis (p-value > 0.05)**	**Outcome**
Storage volume three categories (Litres)	Fisher	0.291	Not rejected	No statistical significance at 95% level
Primary other source of water	Fisher	1.0	Not rejected	No statistical significance at 95% level
Self Reported perception of water quality	Fisher	0.0769	Not rejected	No statistical significance at 95% level
Plumbed or Yard tap	Fisher	0.00690	**Rejected**	Having CWS is associated with having a yard tap as opposed to being fully plumbed

The actual supply conditions experienced by the self-reported CWS and IWS groups are illustrated in Figure 8.2. This shows that at low pressures, CWS households receive significantly longer supply hours; however, at higher pressure the range of supply hours across the CWS group is very large indicating quite different local supply conditions. This is likely to be associated with their proximity to an input source, as identified in Figure 7.18. The withdrawal patterns of the IWS and CWS groups are compared in Figure 8.3 showing a clear difference; the CWS households use water throughout the day while the IWS group is limited to the input supply period.

A comparison of the withdrawal characteristics in Figure 8.4 illustrates that 60% of the withdrawal volume of CWS households derives from smaller withdrawals of 5 – 65 litres while the IWS group derives 55% of their water from the 65 – 750 litre withdrawal range.

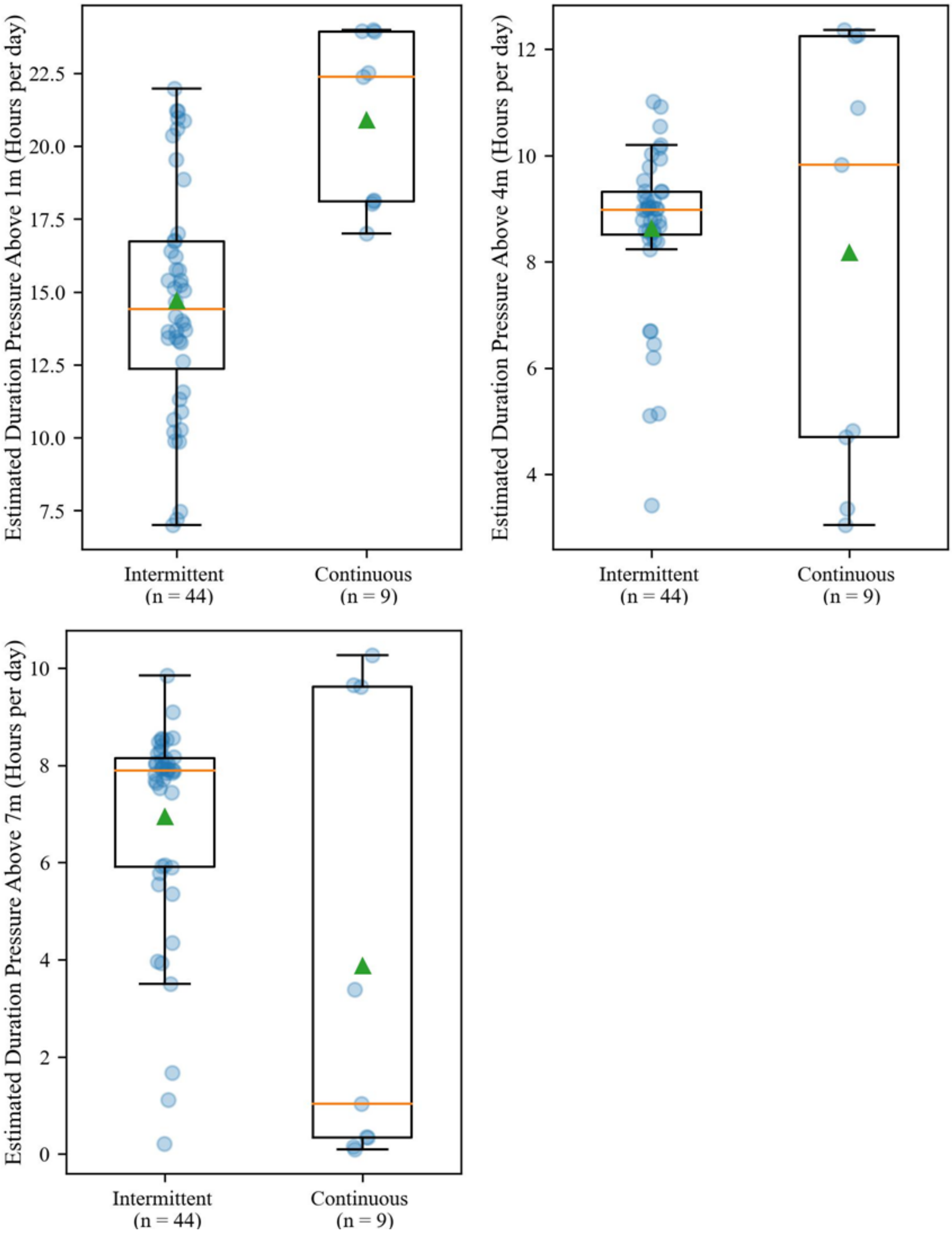


Figure 8.2: Estimated Supply Hours of the Self-reported CWS and IWS Households

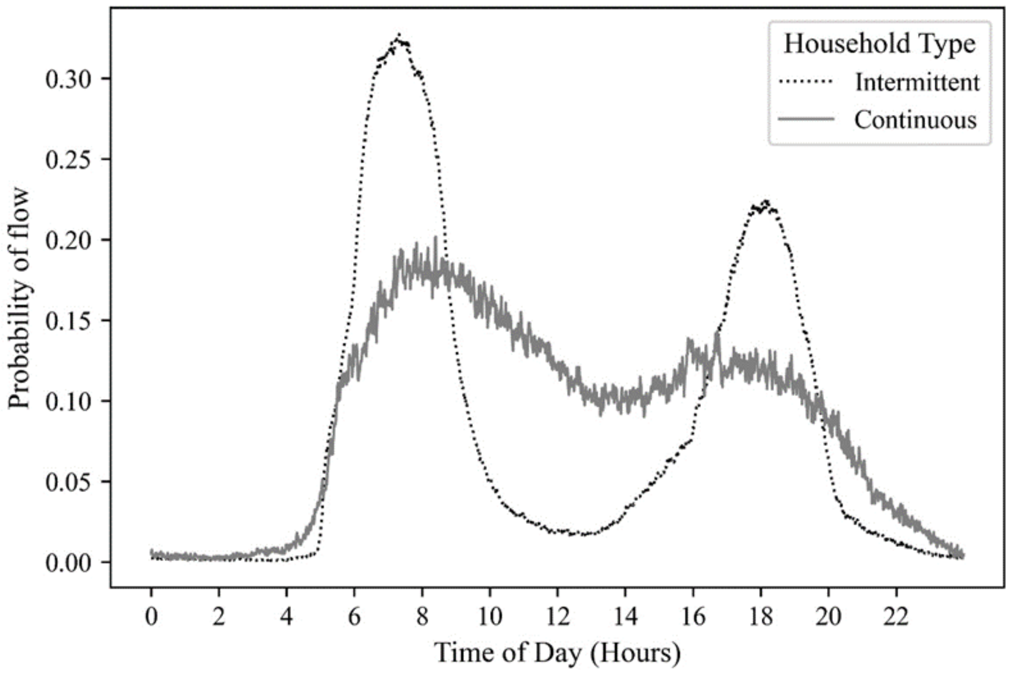


Figure 8.3: Average Daily Withdrawal Patterns of IWS and CWS Households

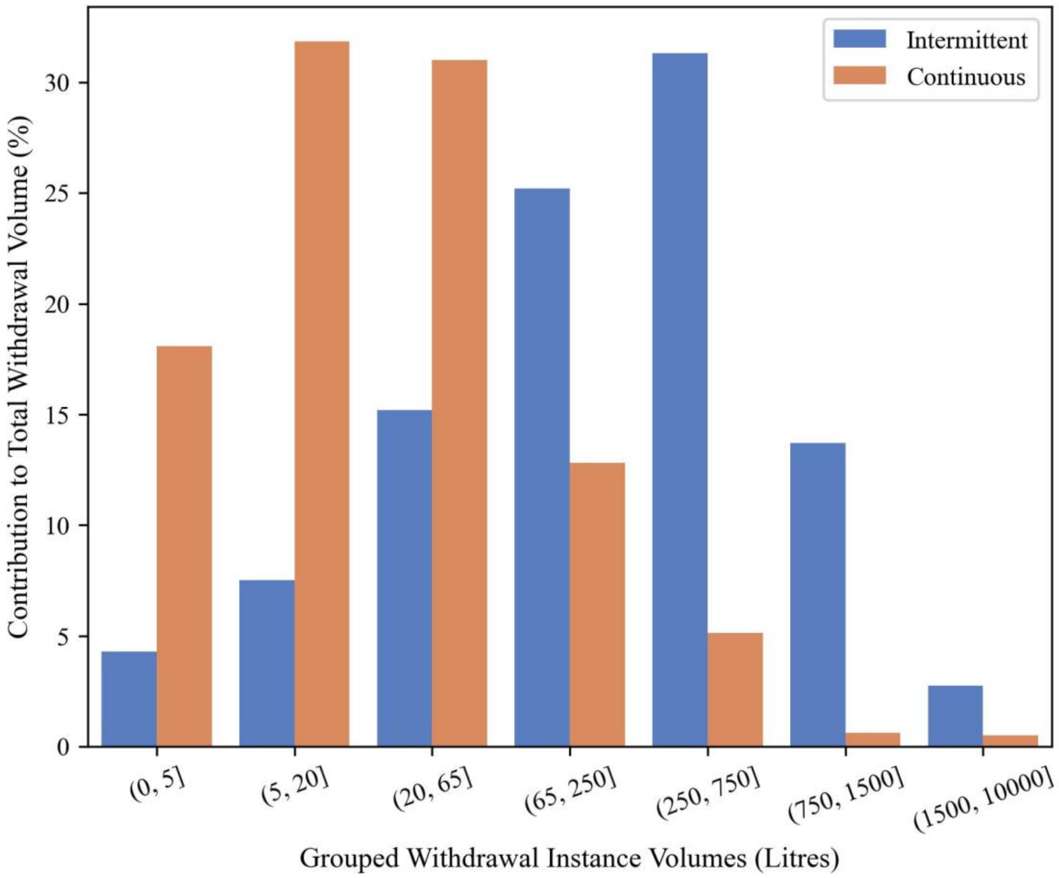


Figure 8.4: The Contribution Grouped Withdrawal Instances make towards the Total Withdrawal Volume of IWS and CWS Households

8.2 Do Supply conditions Influence Adaptations?

The aim of this section is to establish whether different local supply conditions influence the adaptations employed by households. This section uses data from April 2024 to describe supply conditions and compares against household characteristics recorded in the Sept-Dec 2022 survey.

A comparison between the duration of local supply hours and different household assets are reported in Table 8.3. The null hypothesis being tested states that the local supply conditions do not affect the household variable (e.g., having a yard tap or being fully plumbed). Having longer hours per day of medium or high pressure was found to be associated with a higher likelihood that the household has a fixed (large) storage container vs a mobile (small) storage container. Having longer hours per day of medium pressure is also associated with a higher likelihood that the household has a tube well. The box plots corresponding to these tests can be found in Appendix B.

Table 8.3: Statistical Tests Comparing Supply conditions with Adaptations. Supply conditions are defined as the duration of supply hours at a 1m, 4m and 7m minimum pressure thresholds.

Variable	Test	Statistic (p-value)	Null hypothesis (p-value > 0.05)	Outcome
Plumbed or yard tap – 1m Pressure	Unpaired, 2-tailed t-test	1.22 (0.227)	Not rejected	No statistical significance at 95% level
Plumbed or yard tap – 4m Pressure	Mann-Whitney	301 (0.47)	Not rejected	No statistical significance at 95% level
Plumbed or yard tap – 7m Pressure	Mann-Whitney	260 (0.146)	Not rejected	No statistical significance at 95% level
Storage volume three categories (Litres) – 1m Pressure	1-way ANOVA	1.47 (0.239)	Not rejected	No statistical significance at 95% level
Storage volume three categories (Litres) – 4m Pressure	Kruskal-Wallis	9.12 (0.0104)	**Rejected***	Longer hours of medium pressure = More likely to have fixed storage
Storage volume three categories (Litres) – 7m Pressure	Kruskal-Wallis	6.92 (0.0314)	**Rejected****	Longer hours of high pressure = More likely to have fixed storage
Owning a Tube well – 1m Pressure	Mann-Whitney	303 (0.143)	Not rejected	No statistical significance at 95% level
Owning a Tube well – 4m Pressure	Mann-Whitney	331 (0.0369)	**Rejected**	Longer hours of medium pressure = More likely to have a tube well
Owning a Tube well – 7m Pressure	Mann-Whitney	233 (0.919)	Not rejected	No statistical significance at 95% level

* Post-hoc Dunn test results in a p-value of 0.00455 between the 'Fixed Storage' and 'Mobile Storage' groups. 'Mobile Storage' vs 'None' had a p-value of 0.0115.

** Post-hoc Dunn test results in a p-value of 0.0154 between the 'Fixed Storage' and 'Mobile Storage' groups. 'Fixed Storage' vs 'None' had a p-value of 0.0629.

8.3 Which Factors Influence Households' Water Withdrawal Quantity?

This section investigates which factors influence the volume of water withdrawal of consumers in Lahan. Factors relating to both household adaptations and supply conditions will be assessed.

Table 8.4 reports the statistical tests investigating the null hypothesis that household variables do not influence the withdrawal volume of households (measured in litres per person per day). The results reveal that no single household characteristic showed a statistically significant effect on water withdrawal volume. This is further illustrated in Figure 8.5. Continuous variables were also compared with withdrawal volume as shown in Figure 8.6; showing household occupancy has the greatest association with withdrawal volume. The linear trend line drawn on Figure 8.6 may be unrepresentative of the best-fit line, which appears to be an exponential decrease.

The variables in Table 8.4 were also tested against the total withdrawal volume of the household measured in Litres per Day. There was also no statistically significant correlation found in these tests, the results of which can be found in Appendix B.

The effect of the local supply conditions on withdrawal volume was also assessed. Figure 8.7 shows that water withdrawal volume of households (measured in litres per person per day) shows no statistically significant association with their estimated local supply hours at any supply pressure threshold. Figure 8.7 uses withdrawal volumes taken from April 2024 to correspond with the measured supply conditions.

Table 8.4: Statistical Tests between Categorical Household Variables and Water Withdrawal Volume per Person

Variable	**Test**	**Statistic (p-value)**	**Null hypothesis (p-value > 0.05)**	**Outcome**
Plumbed or yard tap	Mann-Whitney	337 (0.950)	Not rejected	No statistical significance at 95% level
Primary other source of water (Tube well vs None)	Mann-Whitney	243 (0.919)	Not rejected	No statistical significance at 95% level
Storage volume three categories (Litres)	Kruskal-Wallis	0.768 0.681)	Not rejected	No statistical significance at 95% level
Self reported perception of water quality	Kruskal-Wallis	0.656 (0.720)	Not rejected	No statistical significance at 95% level

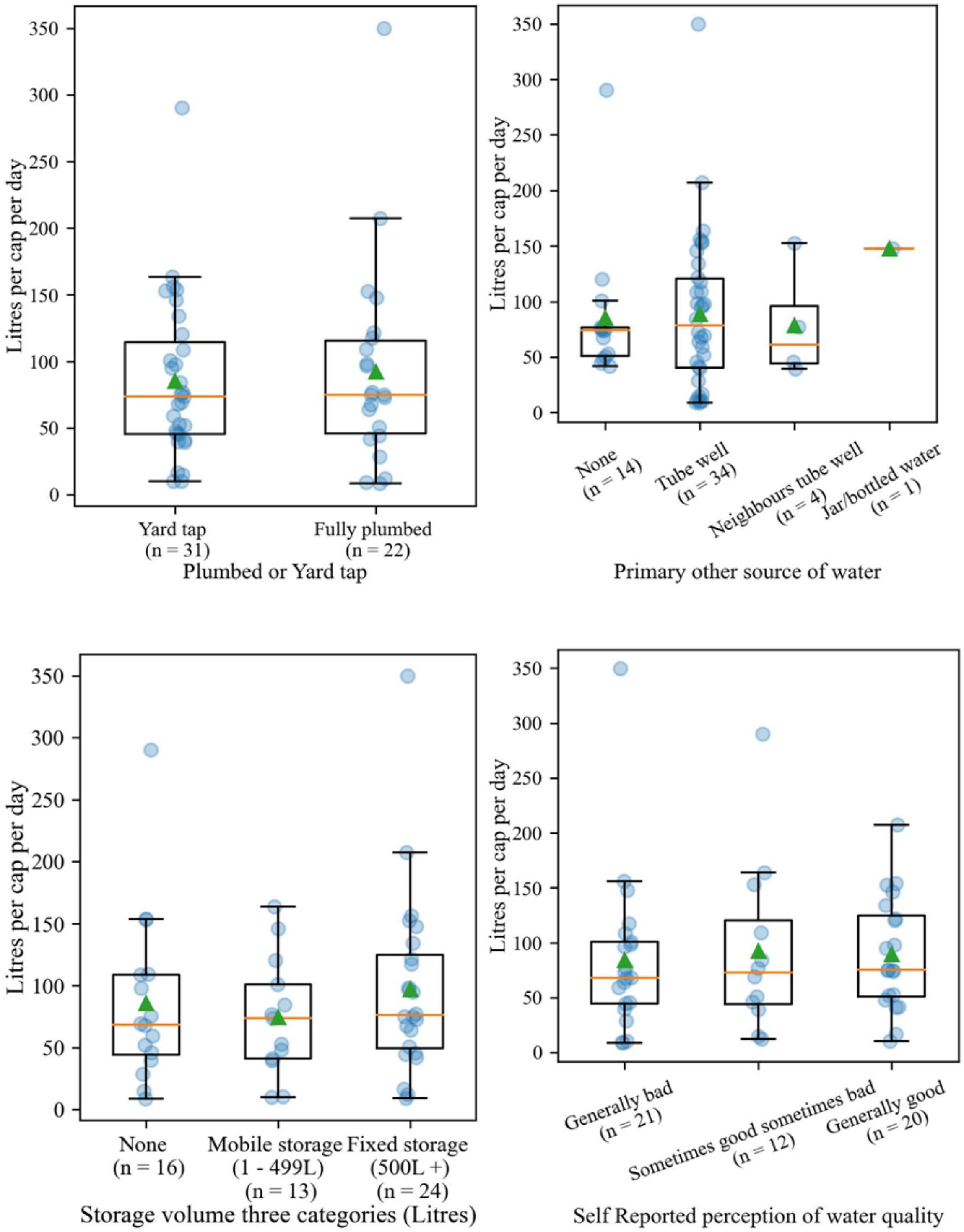


Figure 8.5: The Effect of Categorical Household Characteristics on Water Withdrawal Volume

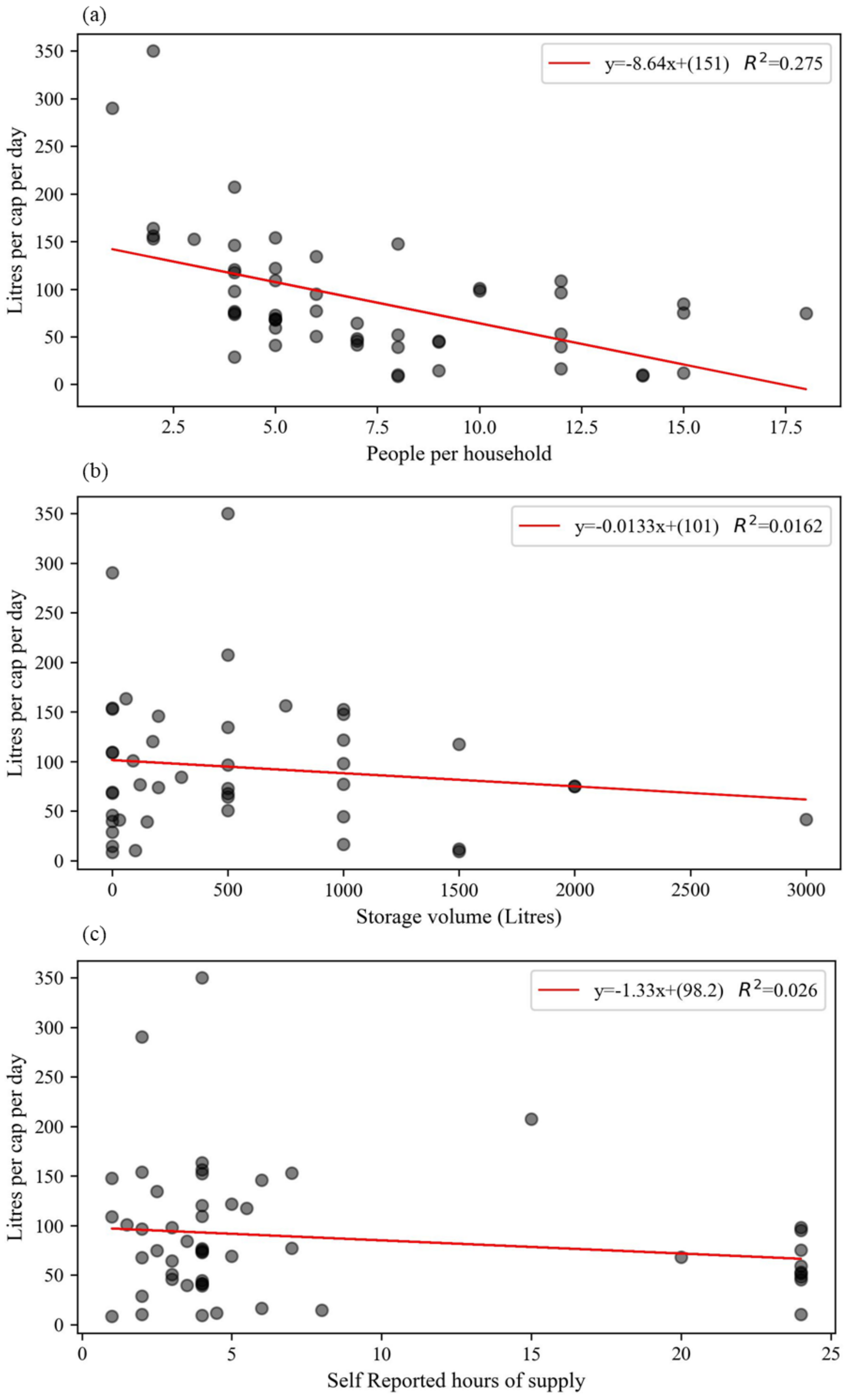


Figure 8.6: The Effect of (a) Household Occupancy, (b) Storage Volume, and (c) Self-reported Hours of Supply on Water Withdrawal Volume (LPCD)

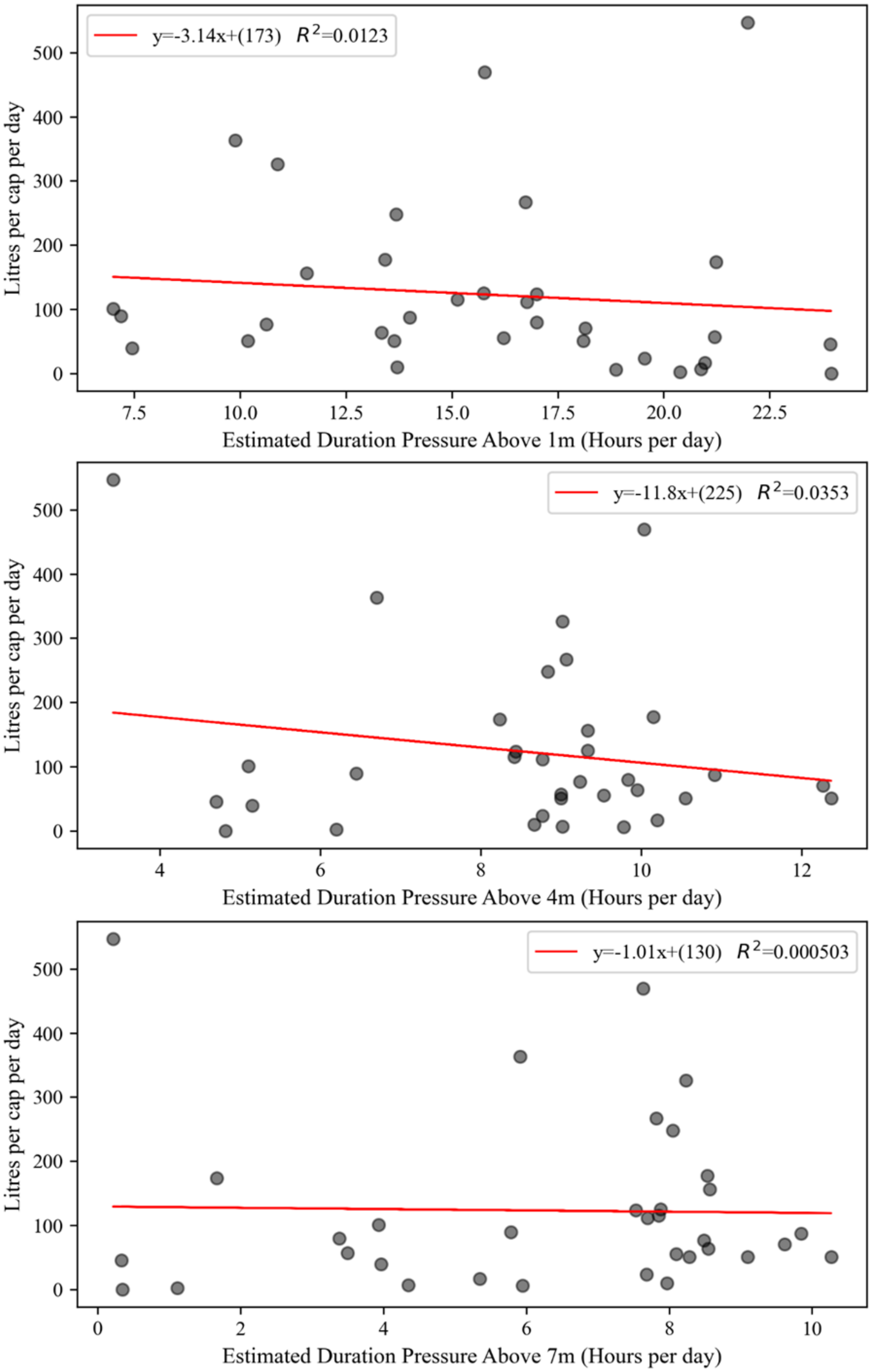


Figure 8.7: The Effect of Estimated Supply Hours on Water Withdrawal Volume (Using Data from April 2024 only)

8.4 Which Factors Influence HWISE Score?

This section presents the HWISE scores resulting from the household survey and assesses if any factors correlate with their score. Only data relating to household connections is included, as this is the scope of the HWISE metric. The maximum HWISE score is 36, households with a HWISE score of ≥ 12 are deemed to be water insecure (Young et al., 2019).

The mean HWISE score in Lahan is 5.5 (SD 5.7), 10.7% of the sampled households are deemed water insecure. After performing the weighting procedure described in section 6.9, this equates to 13.2% of the population.

Figure 8.8 shows there is no clear spatial pattern to household HWISE score. Table 8.5 summarises the statistical tests assessing the null hypothesis that various categorical variables do not correlate with HWISE score. In each test, the null hypothesis was not rejected, as there was no observed statistical significance at the 95% confidence interval. The corresponding boxplots can be found in Appendix B.

Figure 8.9 shows there is a negligible correlation between a households' IWI score and their HWISE score in this sample. Similarly, Figure 8.10 shows the supply conditions have a negligible correlation with HWISE score. This analysis uses data from April 2024 to compare the supply conditions with the HWISE score calculated in 2022.

Table 8.5: Statistical Tests for Significance between Categorical Variables and HWISE Score

Variable	**Test**	**Statistic (p-value)**	**Null hypothesis (p-value > 0.05)**	**Outcome**
Plumbed or yard tap	Mann-Whitney	361 (0.729)	Not rejected	No statistical significance at 95% level
Primary other source of water (Tube well vs None)	Mann-Whitney	221 (0.705)	Not rejected	No statistical significance at 95% level
Storage volume four categories (Litres)	Kruskal-Wallis	4.42 (0.110)	Not rejected	No statistical significance at 95% level

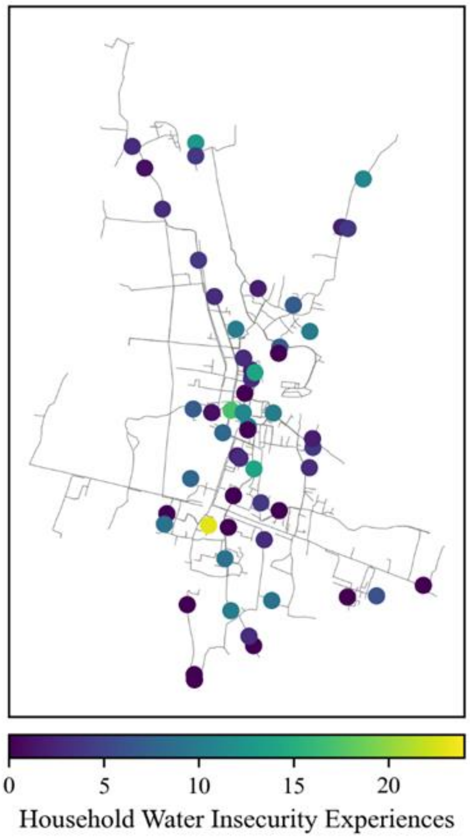


Figure 8.8: Spatial Variation of Household Water Insecurity Experiences Scores

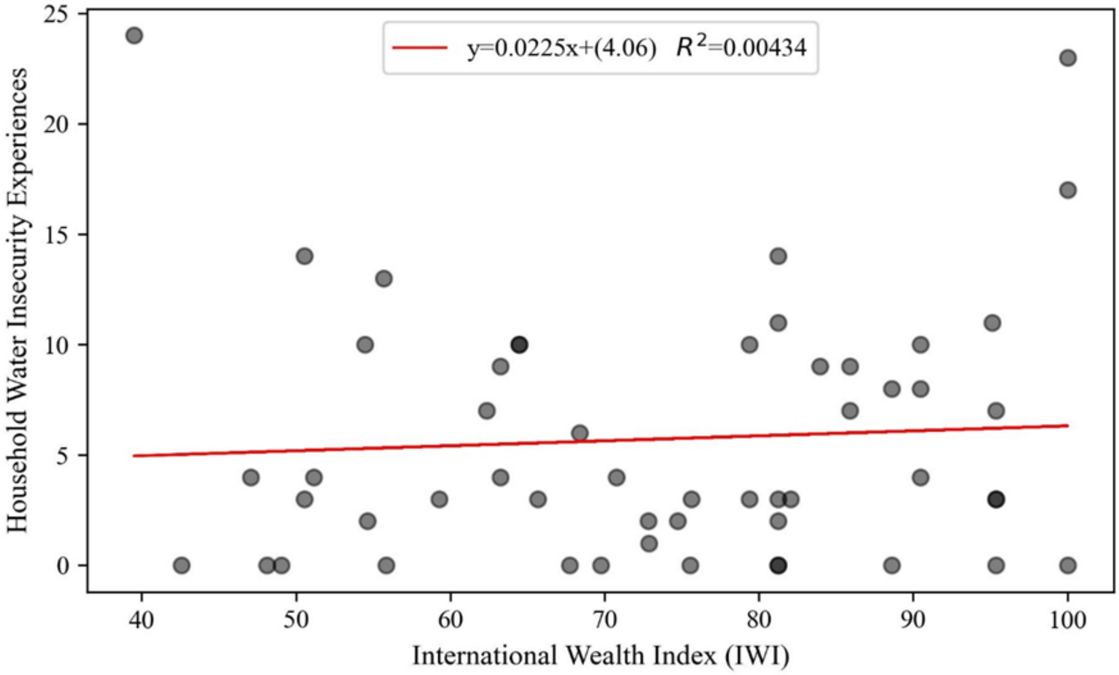


Figure 8.9: Effect of IWI Score on HWISE Score

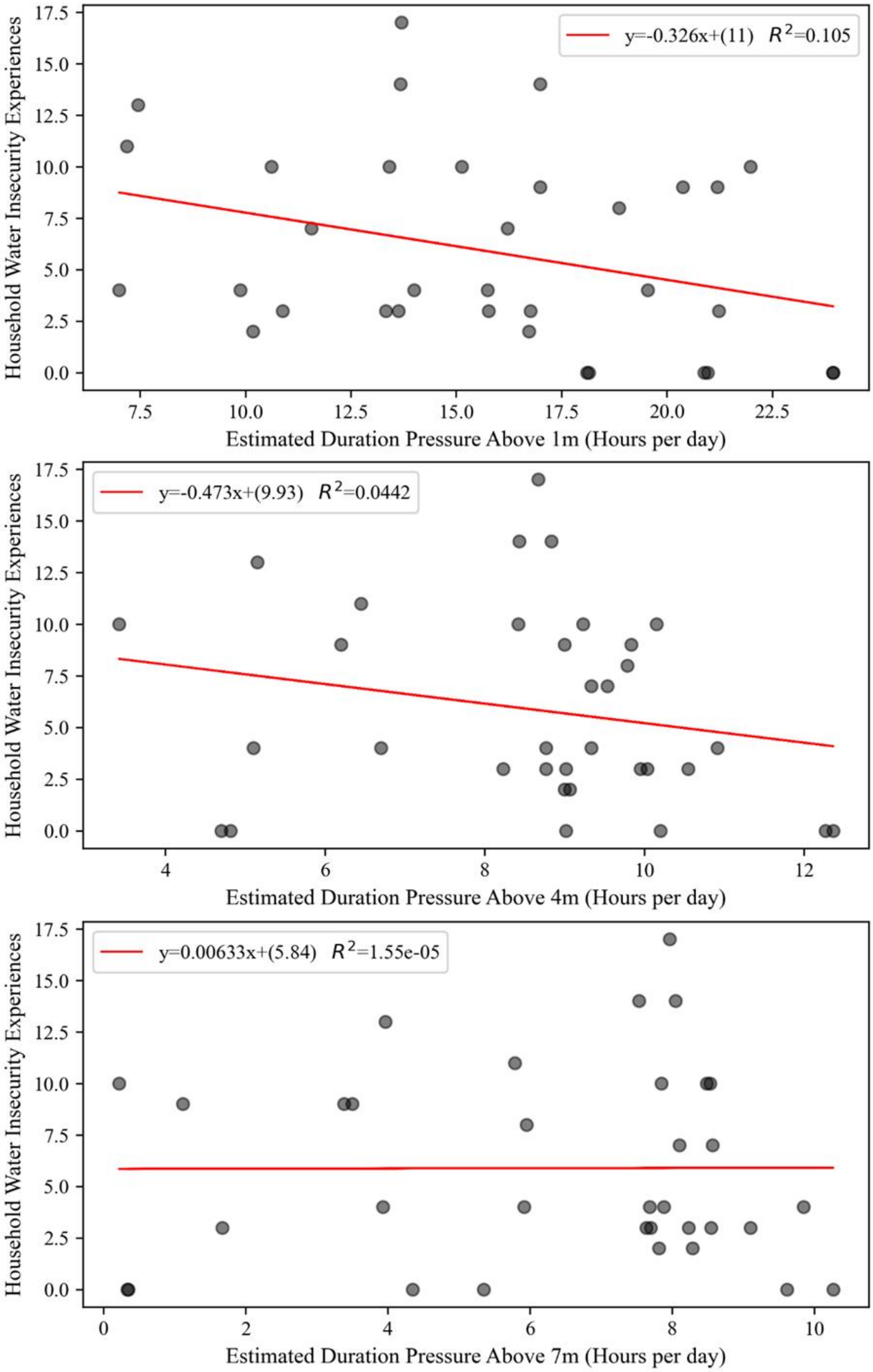


Figure 8.10: Effect of Estimated Supply Hours on HWISE Score

8.5 Which Factors Influence the Desire for More Water?

This section examines household desires relating to the following two survey questions:

a) If the duration of the supply period increased, would you use more water?
   Yes, a lot   Yes, a little   No   Don’t know

b) Would you like the hours of supply to increase?
   Yes, a large increase   Yes, a small increase   No   Don’t know

Since the questions relate to increases in supply hours, the CWS group were excluded, as the questions do not make sense for them. Out of the nine self-reported CWS households, one did respond saying they would use ‘a little’ more water if the supply duration increased (all others said ‘No’ to both questions). The household reported that the pressure was ‘low between supply periods’ and that ‘if the pressure increased so it was high all day we would stop using the hand pump’.

The two variables regarding consumer desires are compared in Table 8.6, the Fisher test was applied to the full 3x3 table of values resulting in a p-value of 0.00217. Therefore, a greater desire for longer hours of supply is associated with a belief that more water would be used if the supply duration increased. However, of the households that indicated they would like an increase in supply hours, 17% indicated they would not use more water. This suggests that some households want longer supply hours for the convenience, as opposed to simply desiring greater volume.

Table 8.6: Contingency Table of Consumer Desires for More Water

		Would you like the hours of supply to increase?			
		Yes a small increase	Yes a large increase	No	Total
If the supply duration increased, would you use more water?	Yes a little	5	5	0	10
	Yes a lot	8	14	0	22
	No	3	5	7	15
	Total	16	24	7	47

The spatial variation was assessed through the maps shown in Figure 8.11, which includes the CWS group. There is little evidence of a spatial trend apart from the obvious lack of desire for longer supply hours for the CWS households.

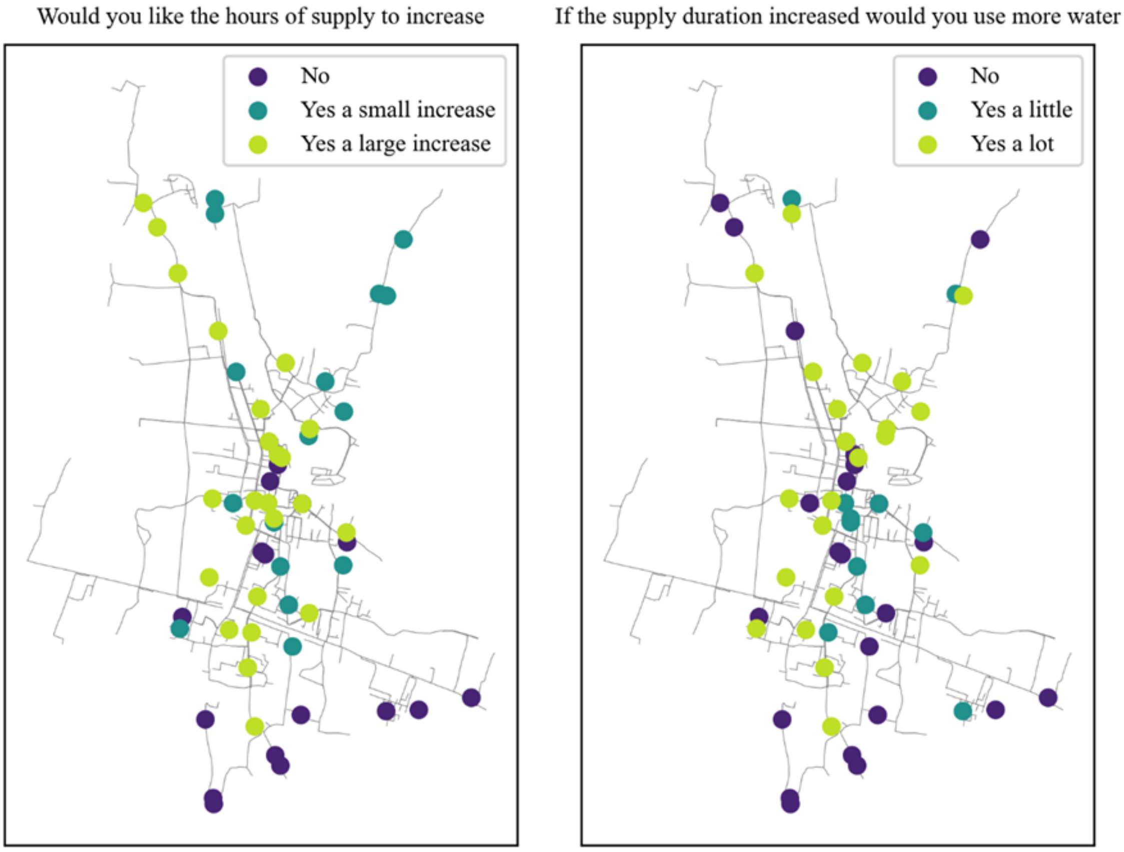


Figure 8.11: Spatial Variation of Consumer Desires including CWS Households

8.5.1 Investigating the Desire for Longer Supply Hours

Contingency tables were also produced comparing household categorical variables against the desire for longer supply hours, Table 8.7 summarises the statistical tests applied to them. For all variables, the null hypothesis that the categorical variable does not influence the desire for longer supply periods could not be rejected at the 95% confidence interval. However, the differences associated with having a yard tap or being plumbed were clearly the strongest and would be statistically significant at a 90% confidence interval. Of the households that are fully plumbed, 66% desired a large increase in supply hours as opposed to 35% of households that only have a yard tap.

Table 8.7: Statistical Tests between Categorical Variables and the Desire for Longer Supply Hours

Variable	Test	P-value	Null hypothesis (p-value > 0.05)	Outcome
Plumbed or Yard tap	Fisher	0.0769	Not rejected	No statistical significance
Storage volume three categories (Litres)	Fisher	0.639	Not rejected	No statistical significance
Primary other source of water	Fisher	0.307	Not rejected	No statistical significance
Self Reported perception of water quality	Fisher	0.394	Not rejected	No statistical significance

Continuous variables were also compared against the desire for longer supply hours, Table 8.8 summarises the resulting statistical analysis. The null hypothesis stated that the continuous variables do not correlate with a desire for longer supply hours. The results show no significant associations at the 95% confidence interval, although the self-reported supply hours have the strongest relationship, and would be statistically significant at a 90% confidence interval. The associated boxplots can be found in Appendix B.

Table 8.8: Statistical Tests between Continuous Variables and the Desire for Longer Supply Hours

Variable	**Test**	**Statistic (p-value)**	**Null hypothesis (p-value > 0.05)**	**Outcome**
IWI	Kruskal-Wallis	4.31 (0.116)	Not rejected	No statistical significance at 95% level
HWISE	Kruskal-Wallis	4.11 (0.128)	Not rejected	No statistical significance at 95% level
Self Reported hours of supply	Kruskal-Wallis	5.06 (0.0798)	Not rejected	No statistical significance at 95% level
Self Reported percentage of total water usage provided by piped water	Kruskal-Wallis	0.213 (0.899)	Not rejected	No statistical significance at 95% level
Litres per cap per day	Kruskal-Wallis	0.378 (0.828)	Not rejected	No statistical significance at 95% level
Estimated Duration Pressure Above 1m (Hours per day)	1-way ANOVA	1.78 (0.184)	Not rejected	No statistical significance at 95% level
Estimated Duration Pressure Above 4m (Hours per day)	Kruskal-Wallis	2.65 (0.265)	Not rejected	No statistical significance at 95% level
Estimated Duration Pressure Above 7m (Hours per day)	Kruskal-Wallis	2.18 (0.336)	Not rejected	No statistical significance at 95% level

8.5.2 Investigating the Expectancy that More Water Would be Used

Contingency tables were produced comparing household categorical variables against the expectancy that more water would be used, Table 8.9 summarises the statistical tests assessing the null hypothesis that the categorical variables have no correlation with the expectancy that more water would be used. The results show no significant associations at the 95% confidence interval. The strongest relationship, (significant at a 90% confidence interval) was that households with larger storage volumes tended to anticipate using more water if the supply duration increased than household with smaller storage volumes.

Overall, 32% of households indicated they would not use more water if the supply hours increased. Of households with a yard tap, 17% indicated they would not use more water as opposed to 46% of households that are fully plumbed. In addition, 32% of households with a fixed storage indicated they would use a lot more water as opposed to 75% of households with no storage. It is also noteworthy that of the households with fixed storage, 84% wanted either a small or a large increase to supply hours, yet only 52% expected to use more water if the supply hours increased.

Table 8.9: Statistical Tests between Categorical Variables and the Expectation that more Water will be used if the Supply Hours Increase

Variable	**Test**	**P-value**	**Null hypothesis (p-value > 0.05)**	**Outcome**
Plumbed or Yard tap	Fisher	0.124	Not rejected	No statistical significance at 95% level
Storage volume three categories (Litres)	Fisher	0.0803	Not rejected	No statistical significance at 95% level
Primary other source of water	Fisher	0.741	Not rejected	No statistical significance at 95% level
Self Reported perception of water quality	Fisher	0.334	Not rejected	No statistical significance at 95% level

Continuous variables were compared against the expectancy that more water would be used, Table 8.10 summarises the resulting statistical analysis. The results show a statistical significance at the 95% level between having a higher HWISE score and a greater expectation more water will be used if the supply duration increased. In addition, a statistical difference was found between having fewer hours of medium (4m) pressure and a greater expectation ‘a little’ more water will be used if the supply duration increased. Both of these results are difficult to interpret and are suspected to be a result of having a small sample size. The accompanying boxplots can be found in Appendix B.

Table 8.10: Statistical Tests between Continuous Variables and the Expectation that more Water will be used if the Supply Hours Increase

Variable	Test	Statistic (p-value)	Null hypothesis (p-value > 0.05)	Outcome
IWI	1-way ANOVA	0.190 (0.828)	Not rejected	No statistical significance at 95% level
HWISE	Kruskal-Wallis	6.56 (0.0376)	**Rejected***	Higher water insecurity = more likely to anticipate using ‘a lot’ more water if supply increased
Self Reported percentage of total water usage provided by piped water	Kruskal-Wallis	1.53 (0.465)	Not rejected	No statistical significance at 95% level
Self Reported hours of supply	Kruskal-Wallis	3.87 (0.144)	Not rejected	No statistical significance at 95% level
Estimated Duration Pressure Above 1m (Hours per day)	1-way ANOVA	0.137 (0.872)	Not rejected	No statistical significance at 95% level
Estimated Duration Pressure Above 4m (Hours per day)	Kruskal-Wallis	6.86 (0.0323)	**Rejected****	Fewer hours of medium pressure = more likely to anticipate using ‘a little’ more water if supply increased
Estimated Duration Pressure Above 7m (Hours per day)	Kruskal-Wallis	3.10 (0.212)	Not rejected	No statistical significance at 95% level
LPCD	Kruskal-Wallis	2.34 (0.310)	Not rejected	No statistical significance at 95% level

* A post-hoc Dunn test results in a p-value of 0.0166 between the ‘No’ and ‘Yes a lot’ groups. All other combinations showed a p-value > 0.05.

** A post-hoc Dunn test results in a p-value of 0.0231 between the ‘No’ and ‘Yes a little’ groups, and a p-value of 0.0135 between the ‘Yes a little’ and ‘Yes a lot’ groups. The other combinations showed a p-value > 0.05.

9 Analysis Part 2: The Influence of Supply conditions and Household Characteristics on Water Withdrawal Behaviour

This section takes a closer look at the withdrawal behaviour of households as measured by the household meters. It aims to assess the range in water withdrawal behaviours observed in Lahan and how they relate to the other two key datasets captured in the study: the supply conditions and household characteristics. The section will bring together these datasets to gain a detailed understanding of what is happening in the IWS system. To enable direct comparison with the local supply conditions, data from April 2024 is being used as this is the period when the two datasets overlap. Network parameters refers to the estimated local supply hours and pressure, while household parameters refers to data gathered from the October 2022 survey.

9.1 Overlaying Pressure and Withdrawal Data April 2024

The simultaneous measurements of pressure and withdrawals allows a deeper understanding of how household behaviour relates to local supply conditions. Figure 9.1 shows three examples of overlaying the estimated local pressure on the measured household withdrawals for the last week of April 2024. The plots illustrate both the differences in conditions and withdrawal behaviour between different households and locations.

Household one experiences pressures up to 20m head but for short, distinct periods, the majority of the time they have no pressure. The water supply periods are less reliable than for the other two households; there is a significantly smaller than usual supply period on the morning of 27th and the afternoon of 28th April. The withdrawal of water only occurs during the supply periods and is not always at the start of the supply period. During the last four afternoon supply periods, no withdrawal occurs apart from a very small withdrawal on the 28th.

Household two experiences reliable supply periods throughout the week with pressures reaching 10-12m during supply periods. There is evidence of the network draining after supply periods with pressures reducing down from approximately 2m to 0-1m head. Withdrawal typically occurs towards the start of the supply period but not always; during the afternoons of the 22nd, 23rd and 24th there are noticeable delays. This suggests an automatic float valve is not in operation as was likely the case in household one. Withdrawals tend to be of a long-duration indicating tank-filling type behaviour.

Household three shows very different behaviour to households one and two, both in terms of the supply conditions and withdrawal behaviour. The pressure trace shows there is relatively constant pressure in this location and thus CWS. In contrast to Figure 7.10 and Figure 7.11, pressures decrease from approximately 4m to 2m head during the supply periods with the highest pressures occurring overnight. Water withdrawals occur throughout the day; they are frequent but for short durations with flowrates rarely greater than 4 L/min.

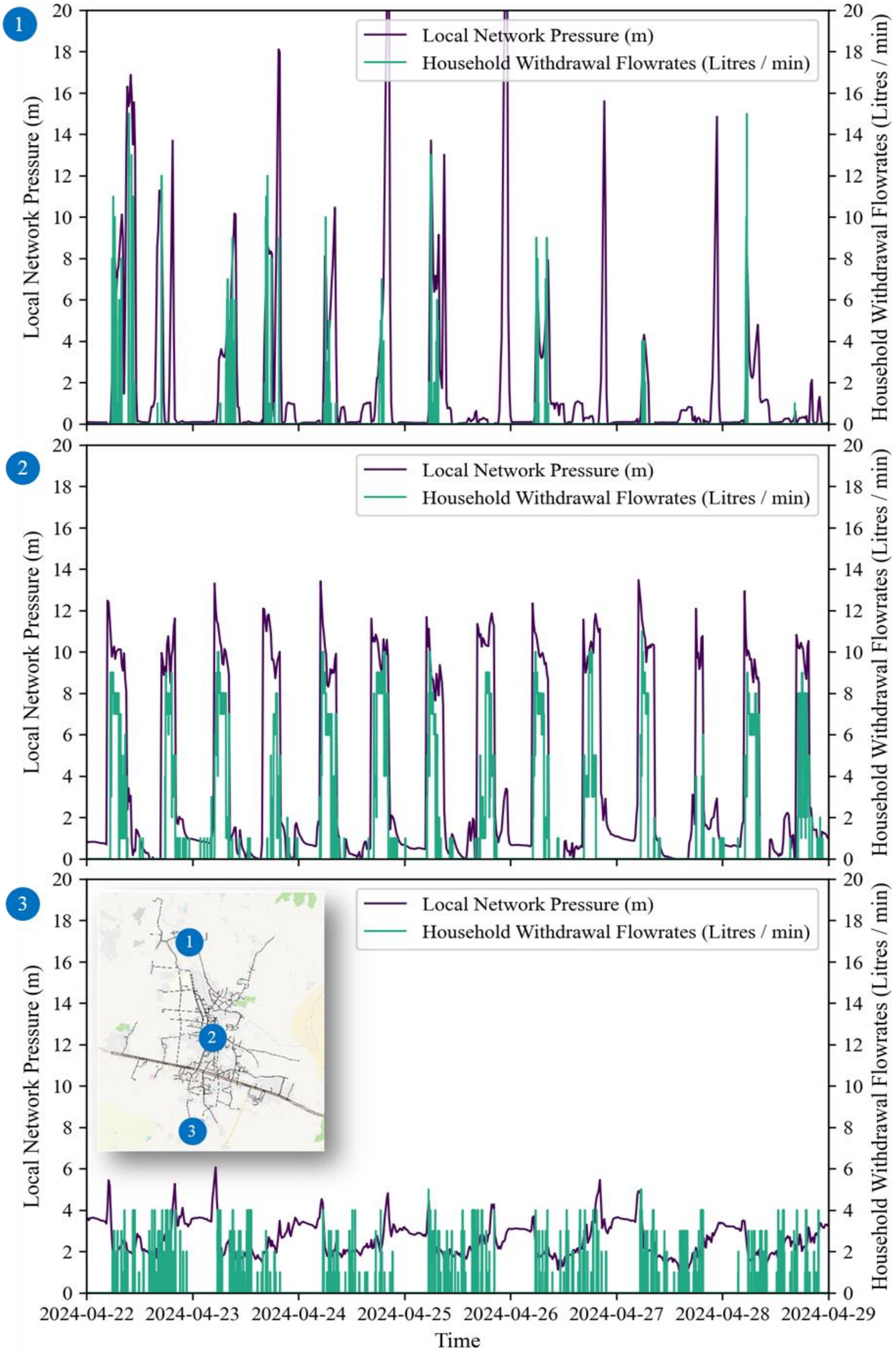


Figure 9.1: Example Overlaying of Pressure and Withdrawal Data of three Households at Different Elevations in Lahan (Note: Same Households as in section 7.1.5)

9.2 Estimated Pressures during Water Withdrawal

This section investigates the estimated local pressures whilst withdrawal is occurring at the metered households. Whenever withdrawal was occurring (i.e. non-zero) the pressure was logged giving a distribution of pressures during withdrawal for all households. Figure 9.2 shows three examples of the resulting histograms. Household one shows most of their withdrawal occurring between 5 – 10m but with a large spread, reaching a maximum of 26m head. Households two and three both show much less spread in the pressures during withdrawal. For household two, the vast majority of withdrawals are between 9 – 12m head, while for household three it is between 1 – 3m head. Household two also shows some withdrawal at low pressures.

Figure 9.3 shows the pressures associated with each household for specific points in their distribution. Firstly, the minimum pressures which is simply the lowest pressure that was logged at the same time as a withdrawal. Figure 9.3 shows that for some of the households this pressure is negative. The lowest recorded pressure during withdrawal is -1.8m, whilst the mean is -0.2m. The estimated pressures shown in Figure 9.3 contain significant uncertainty due to the imprecise method of estimating local pressures described in section 6.7.2.1. This may explain why the majority of households show negative pressures in the first boxplot. The alternative explanation is the widespread use of suction pumps to draw water out of the network. However, whilst conducting the survey the use of pumps was not observed to be common.

At the 1st percentile, the lowest pressure is -0.7m while the mean is positive at 0.8m. At the 5th percentile, no negative pressures are recorded with the lowest pressure being 0.1m and the mean 2.6m. The mean increases significantly at the median percentile with a value of 9.3m, there is a more modest increase up to 13.8m at the 95th percentile. The spread of the data increases significantly at the higher percentiles.

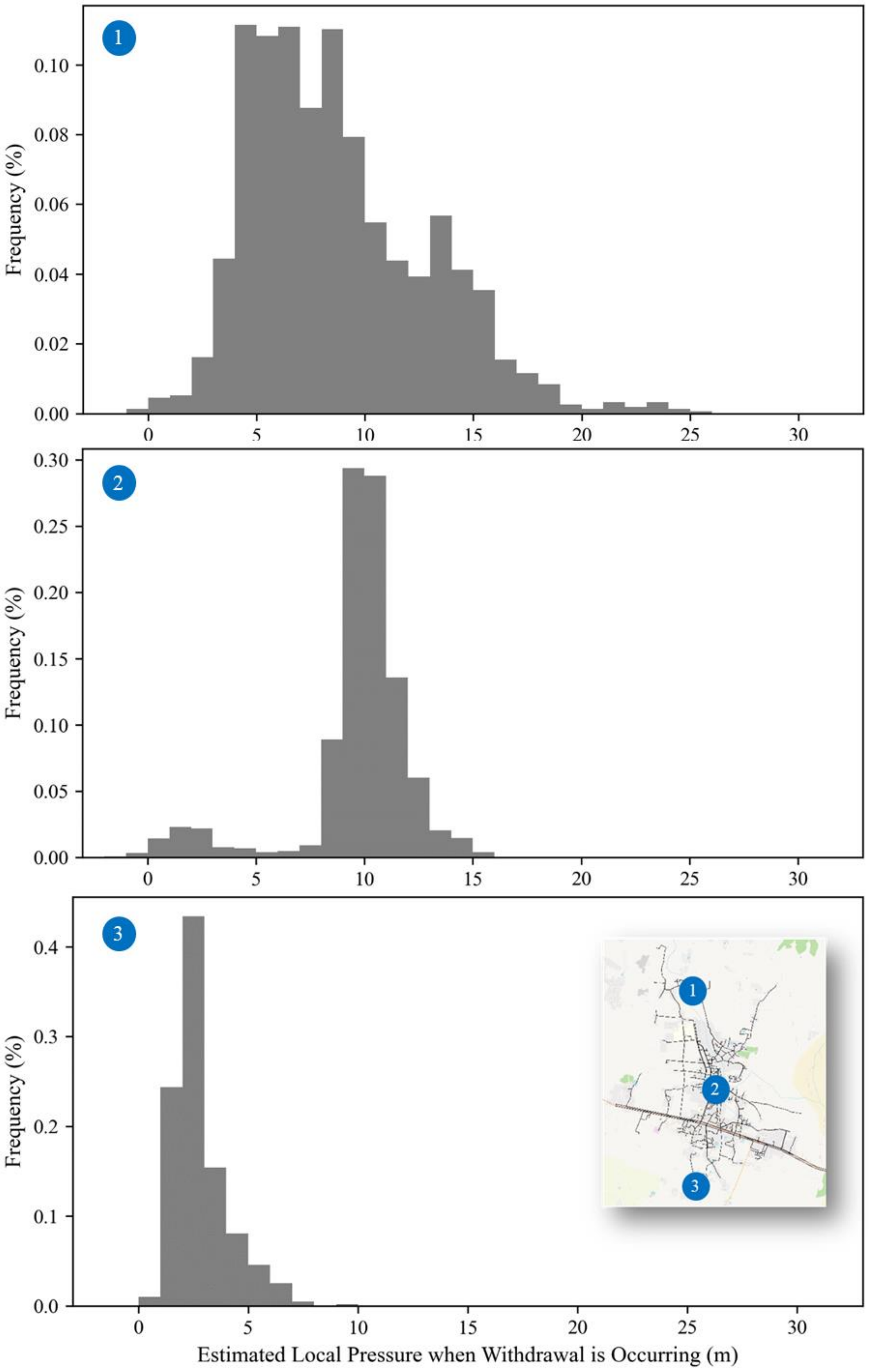


Figure 9.2: Histograms of the Pressures during Withdrawal for the Three Example Households

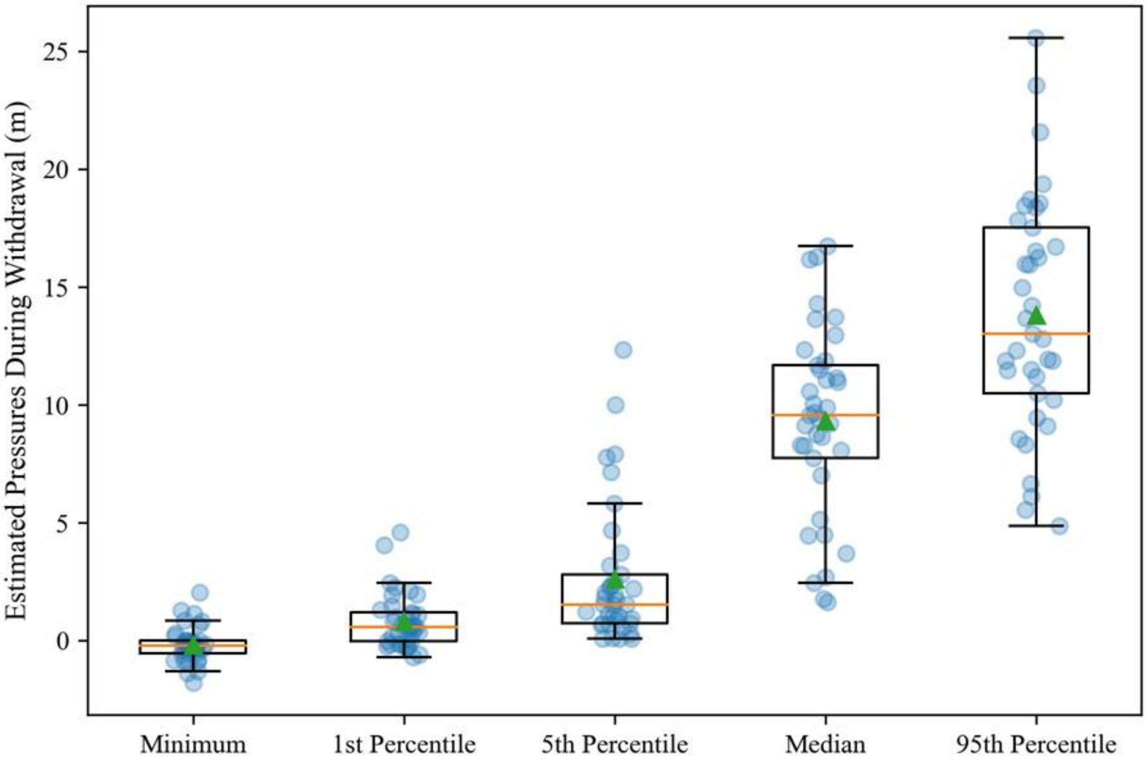


Figure 9.3: The Estimated Pressures during Withdrawal for all Measured Households across April 2024

9.3 Daily Withdrawal Patterns

The influence of household adaptations and supply conditions on the daily withdrawal patterns of households is examined in this section. Figure 9.4 shows that the shape of the withdrawal patterns are relatively consistent between the different storage volume categories, however, there is a discernible difference in flowrates. The larger storage households typically withdraw water at higher flowrates across the two supply periods. There are two interpretations of this. Firstly, that there is a correlation between households with large storage volume and high local pressure. Thus, they have the ability to withdraw water at higher flowrates. The second interpretation derives from the manner in which the meters record withdrawal. The household meters record withdrawal on a one-minute interval. Hence, a recorded flowrate of 5 litres/min could derive from either a withdrawal of water at a rate of 5 litres/min for the whole minute or withdrawal at 10 litres/minute for 30 seconds. As a result, longer duration withdrawals will be recorded as having higher flowrates than several small withdrawals. The tendency for households with larger storage volumes to withdraw water at longer durations therefore complicates the results.

Figure 9.5(a) shows no pattern between the estimated local supply hours and the withdrawal hours of households, however, when using data from the longer timeframe shown in Figure 9.5(b) there appears to be a correlation. The lack of clear correlations suggests the daily withdrawal patterns of households are affected by both the supply conditions and household adaptations.

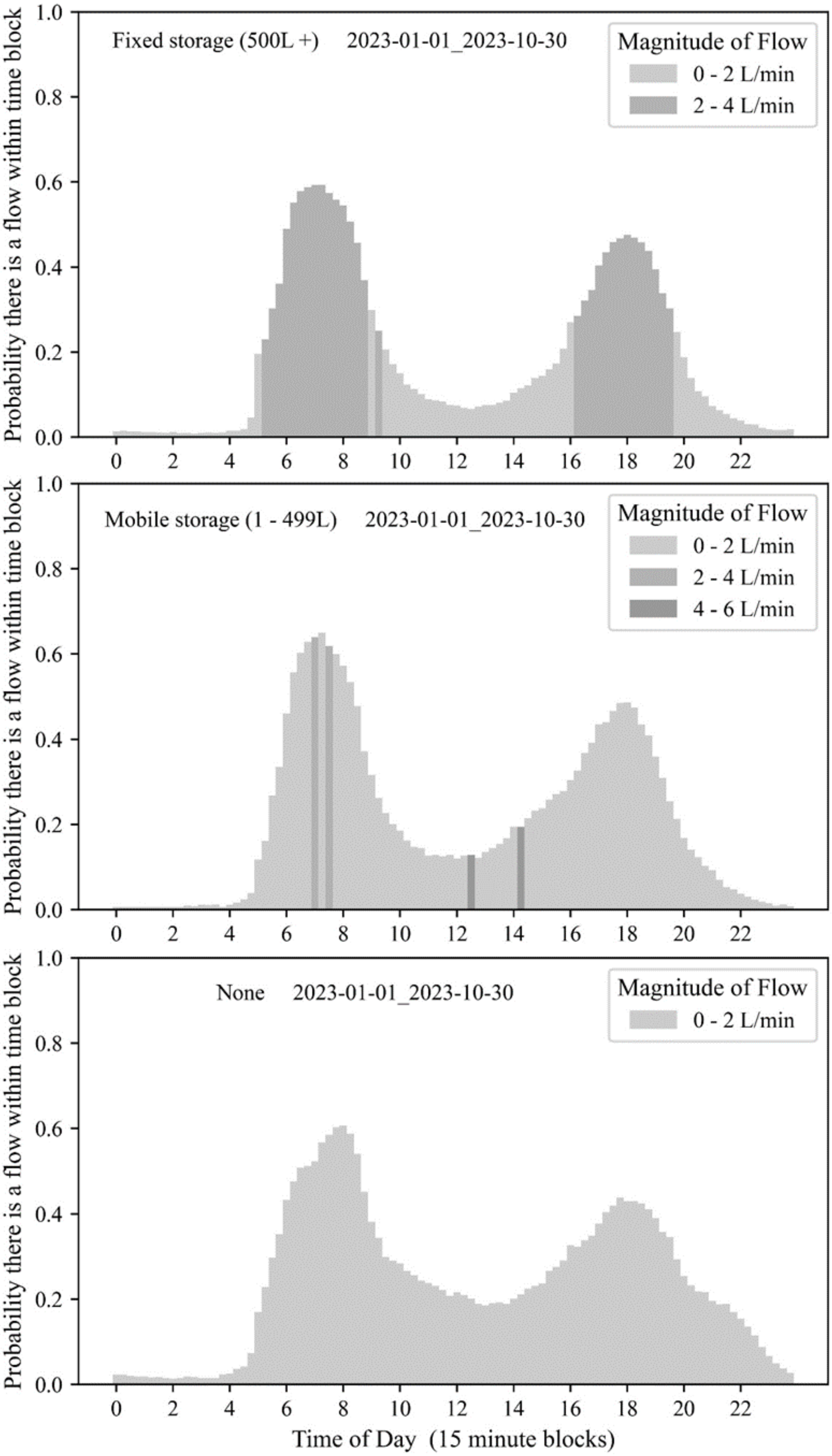
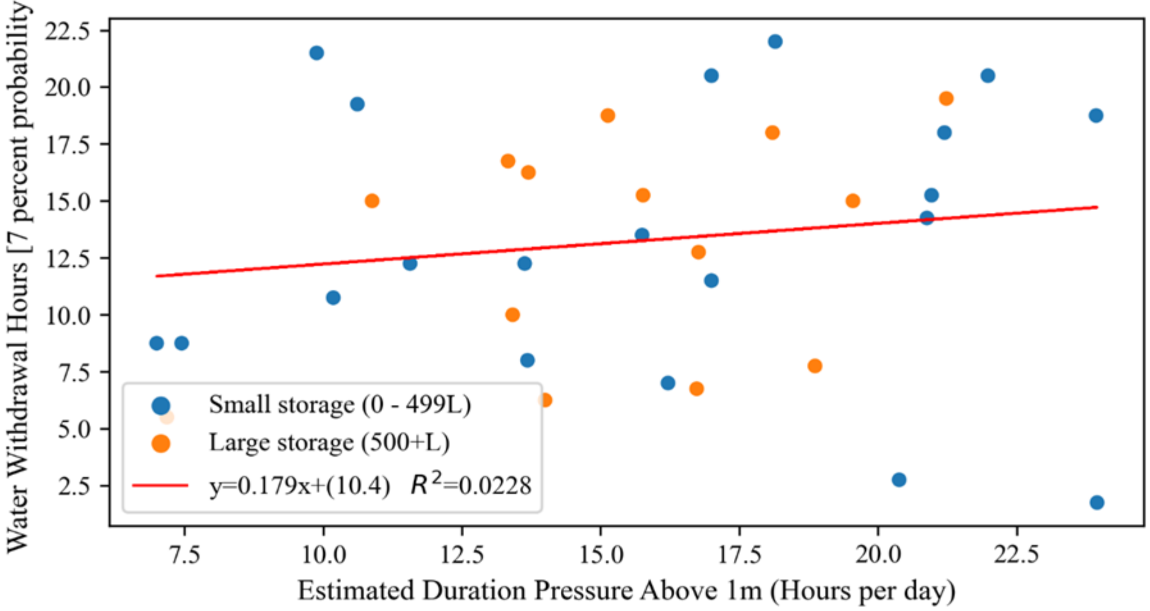


Figure 9.4: Effect of Storage Volume on the Daily Withdrawal Pattern of Households. The Shading Reflects the Magnitude of Flow During Withdrawal Instances

(a) Sample of 34 Households – Data: April 2024



(b) Sample of 53 Households – Data: January to October 2023

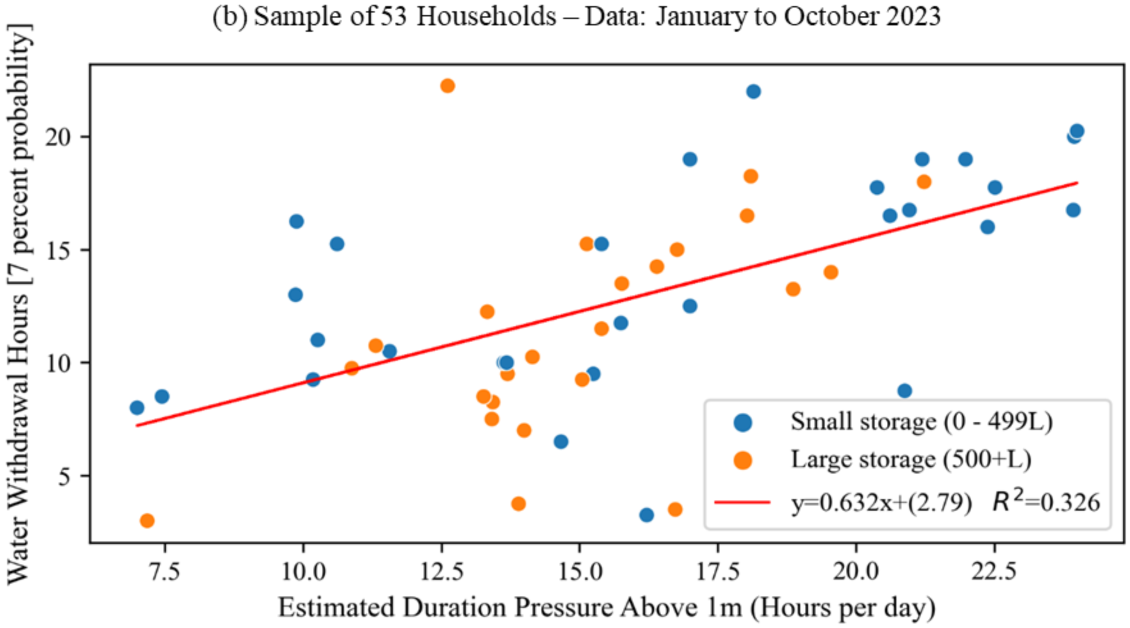


Figure 9.5: Effect of Estimated Local Low-Pressure Supply Hours on Household Withdrawal Hours

9.4 Withdrawal Instance Characteristics

Daily withdrawal patterns reveal the temporal variation in withdrawal; however, this section aims to reveal the characteristics of the withdrawals themselves. Analysis of the withdrawal instances enables a closer examination of the effects of household characteristics on withdrawal behaviour.

This section uses data from the January – October 2023 window as it is comparing withdrawal behaviour to household characteristics.

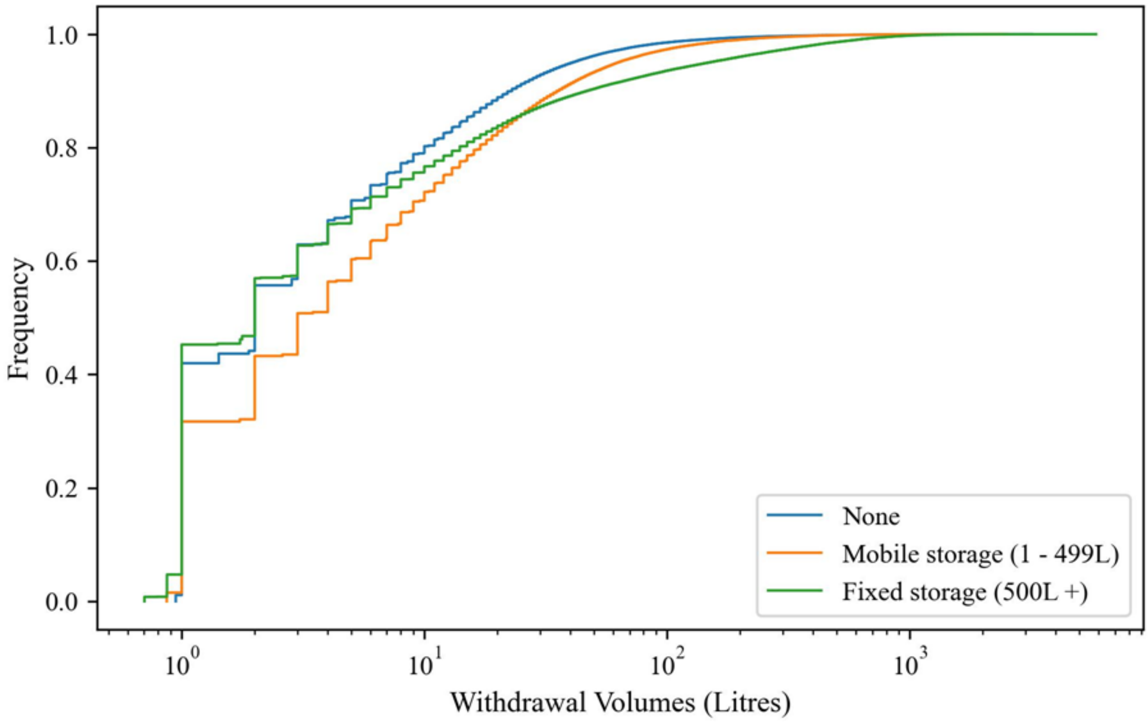


Figure 9.6: Effect of Household Storage Volume on the Frequency of Withdrawal Instances (Note the log-scale on the x-axis)

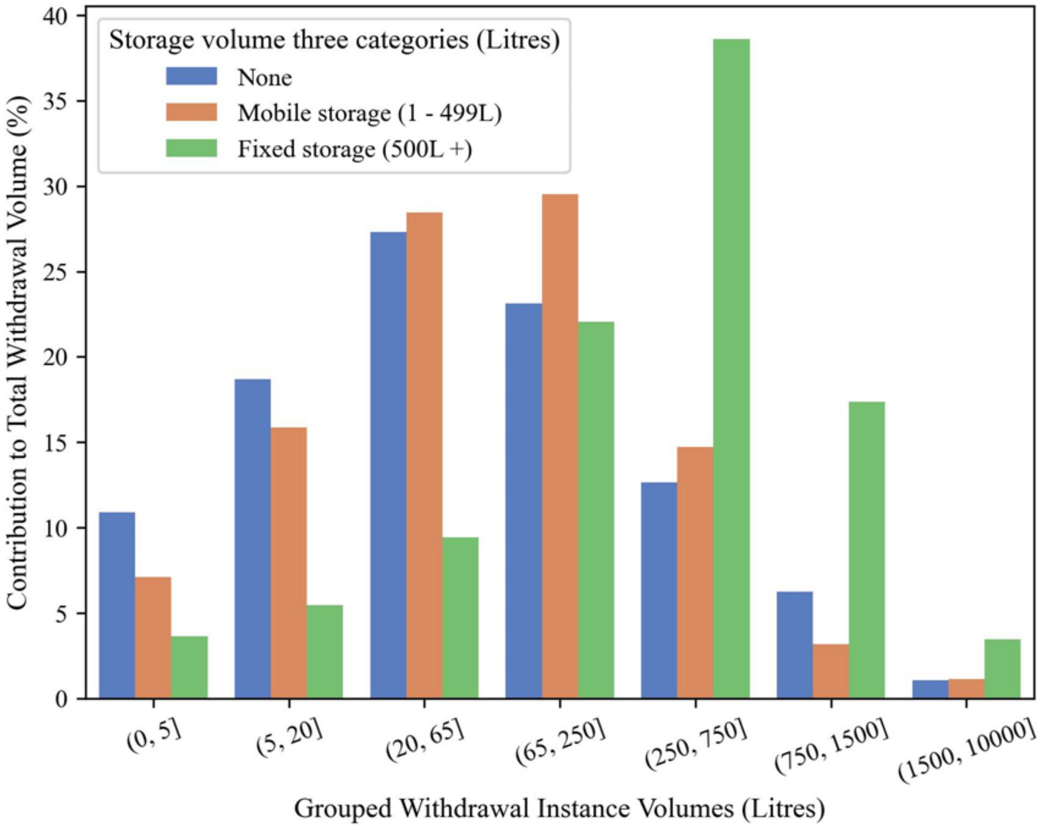


Figure 9.7: Effect of Household Storage Volume on the Types of Withdrawal Instances Households Exhibit

Figure 9.6 and Figure 9.7 show the effects of household storage volume on both the withdrawal instance frequency and magnitude. The households with no storage withdraw small volumes most frequently. Households with the largest storage volume, exhibit a lot of very small volume withdrawals as well as large withdrawals. The households with mobile storage withdraw relatively frequently within the 10 – 60 litre range compared to the other household types. In Figure 9.7 there is a clearer pattern with the larger the storage volume, the greater the large-withdrawals contribute to the total withdrawn volume. The no-storage and mobile-storage groups exhibit similar behaviour but this is significantly different to the fixed-storage group.

Table 9.1 assess the null hypothesis that household characteristics do not influence the withdrawal durations. The results show that storage volume does influence the mean withdrawal durations of households; having a fixed storage tank is associated with longer duration withdrawals than both no-storage households and mobile-storage households. Similarly, being fully plumbed is correlated with longer withdrawal durations. The self-reported practices of storing water vs using directly during supply periods was also tested. Households that reported storing water do tend to have longer average withdrawal durations than those who report using directly. Figure 9.8 shows the box plots associated with these relationships. Figure 9.9 shows negligible correlations between the distance from the input source and the flowrate of the withdrawals. The distribution of different storage volumes also does not show clear clustering; the only discernible pattern is at the furthest distances from a source where there are no households with a large storage tank.

Table 9.1: Statistical Tests Comparing the Relationship between Household Characteristics and the Duration of Withdrawals

Variable	**Test**	**Statistic (p-value)**	**Null hypothesis (p-value > 0.05)**	**Outcome**
During a supply period is water mainly used directly or stored	Kruskal-Wallis	14.6 (0.0022)	**Rejected***	Household reports of withdrawal practices correlate with withdrawal durations
Storage volume three categories (Litres)	Kruskal-Wallis	19.4 (6.07×10^{-5})	**Rejected****	Larger storage volume is correlated with longer withdrawal durations
Plumbed or yard tap	Mann-Whitney	151 (0.000118)	**Rejected**	Having a yard tap vs fully plumbed correlates with shorter withdrawal durations

* A post-hoc Dunn test returned a p-value of 0.000514 between the ‘Directly’ and ‘Stored’ groups and a p-value of 0.0199 between the ‘Directly then stored’ and ‘Stored’ groups.

** A post-hoc Dunn test returned a p-value of 0.000043 between the ‘None’ and ‘Fixed Storage’ groups and a p-value of 0.003078 between the ‘Mobile Storage’ and ‘Fixed Storage’ groups.

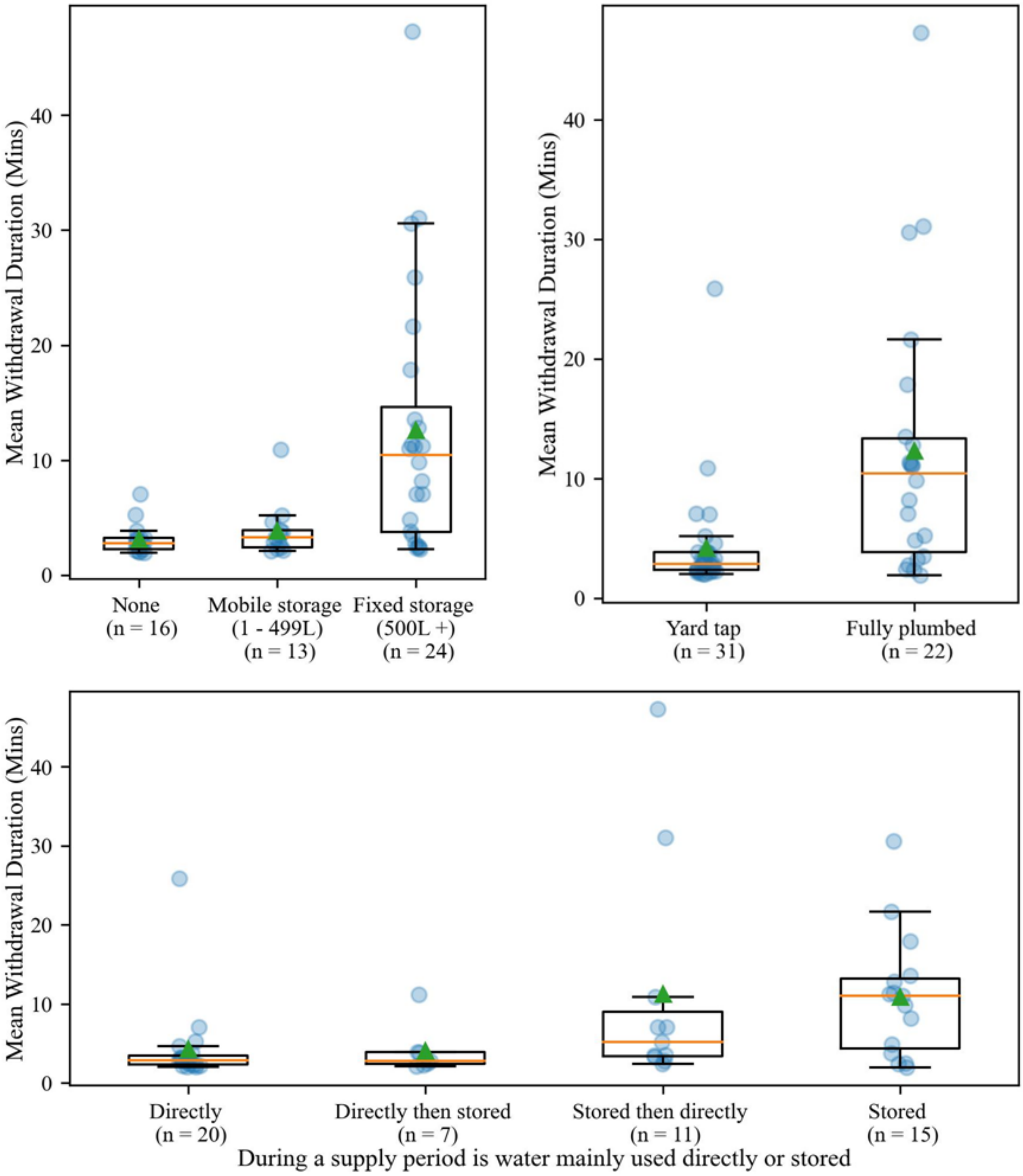


Figure 9.8: Effect of Categorical Household Characteristics on the Duration of Withdrawal Instances

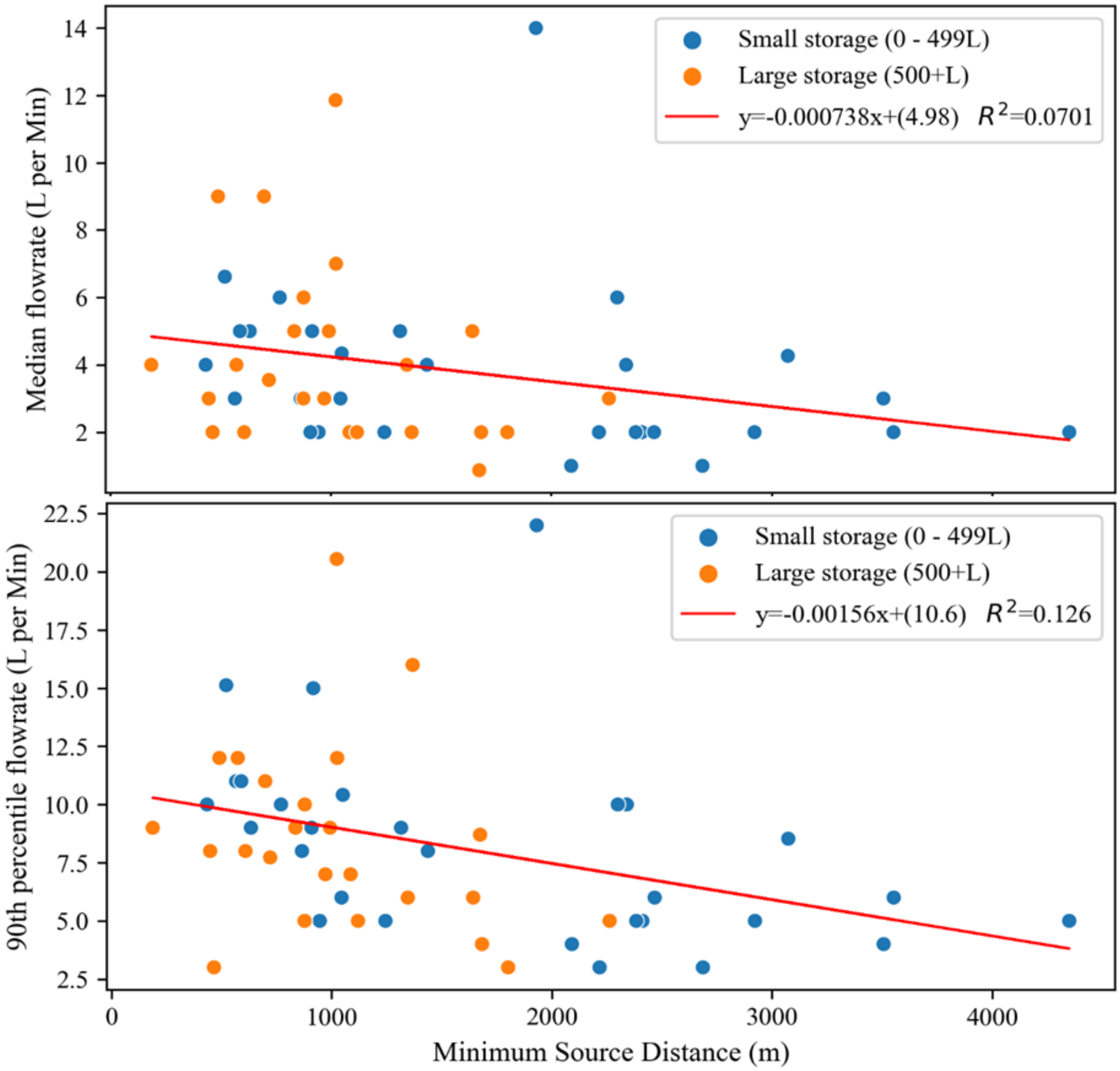


Figure 9.9: Effect of the Distance to the Nearest Network Input Source on the Withdrawal Instance Flowrates

9.5 The Utilisation of the Supply Period

The utilisation of the supply period is assessed in this section. The utilisation refers to the ratio between the duration that withdrawal is occurring and the estimated duration of supply at the connection. The estimated duration of supply is defined as the number of hours above a minimum pressure threshold. Minimum pressure thresholds of 1m, 4, and 7m have all been tested in this section.

Figure 9.10 shows that no households utilise the full supply period, with the greatest estimates at approximately 65%. Naturally, the utilisations increase under the different minimum pressure thresholds, as these are associated with shorter estimates of the supply period.

There is some uncertainty associated with the calculation of utilisations. The interpolation technique used to estimate local pressures would overestimate the duration of the supply periods for the households in the middle to lower elevations, particularly at the 1m pressure threshold. This area could be considered a ‘tidal zone’; the ‘tidal zone’ refers to the households in the middle elevation bands that receive neither CWS nor have clearly distinct supply periods such as those at high elevation. The network fills and empties in a similar manner to the tide with some areas receiving short, distinct supply time while others remain below low-tide receiving CWS. The area in the middle is the tidal zone where supply hours can be quite changeable due to the network draining at different rates. The utilisations are likely to be somewhat underestimated in this area. This error will effect estimates at the 7m threshold much less, as pressures in the southern regions are rarely above this level, so the interpolation error will not occur. Figure 9.11 shows the utilisation estimates are relatively consistent across the three pressure thresholds; this suggests the error is relatively small.

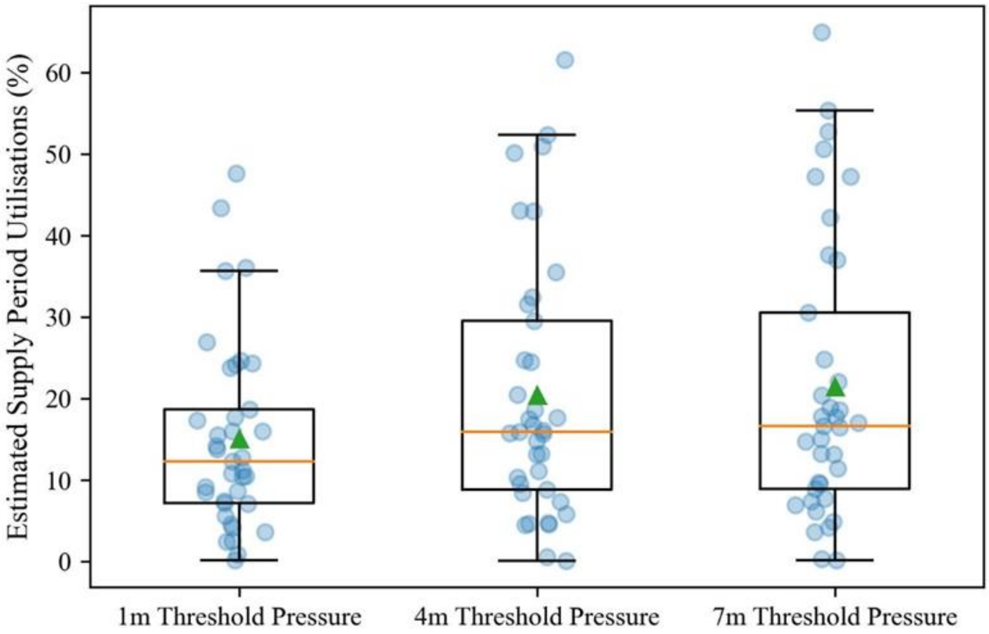


Figure 9.10: Effect of the Minimum Pressure Threshold on the Estimates of Supply Period Utilisation

Table 9.2 investigates the null hypothesis that household characteristics do not influence the utilisation of the supply. The results show that the supply utilisation does not have a significant association with either household storage volume or whether the household has a yard tap or plumbing. Although the association with storage volume is close to being statistically significant under the 7m pressure threshold. Figure 9.11 shows the corresponding box plots.

Table 9.2: Statistical Tests Comparing Household Characteristics and the Utilisation of the Supply Period

Variable	**Test**	**Statistic (p-value)**	**Null hypothesis (p-value > 0.05)**	**Outcome**
Plumbed or yard tap (1m pressure)	Mann-Whitney	151 (0.178)	Not rejected	No statistical significance at 95% level
Plumbed or yard tap (4m pressure)	Mann-Whitney	116 (0.134)	Not rejected	No statistical significance at 95% level
Plumbed or yard tap (7m pressure)	Mann-Whitney	113 (0.111)	Not rejected	No statistical significance at 95% level
Storage volume three categories (Litres) (1m pressure)	Kruskal-Wallis	1.95 (0.378)	Not rejected	No statistical significance at 95% level
Storage volume three categories (Litres) (4m pressure)	Kruskal-Wallis	4.56 (0.102)	Not rejected	No statistical significance at 95% level
Storage volume three categories (Litres) (7m pressure)	Kruskal-Wallis	5.44 (0.0659)	Not rejected	No statistical significance at 95% level

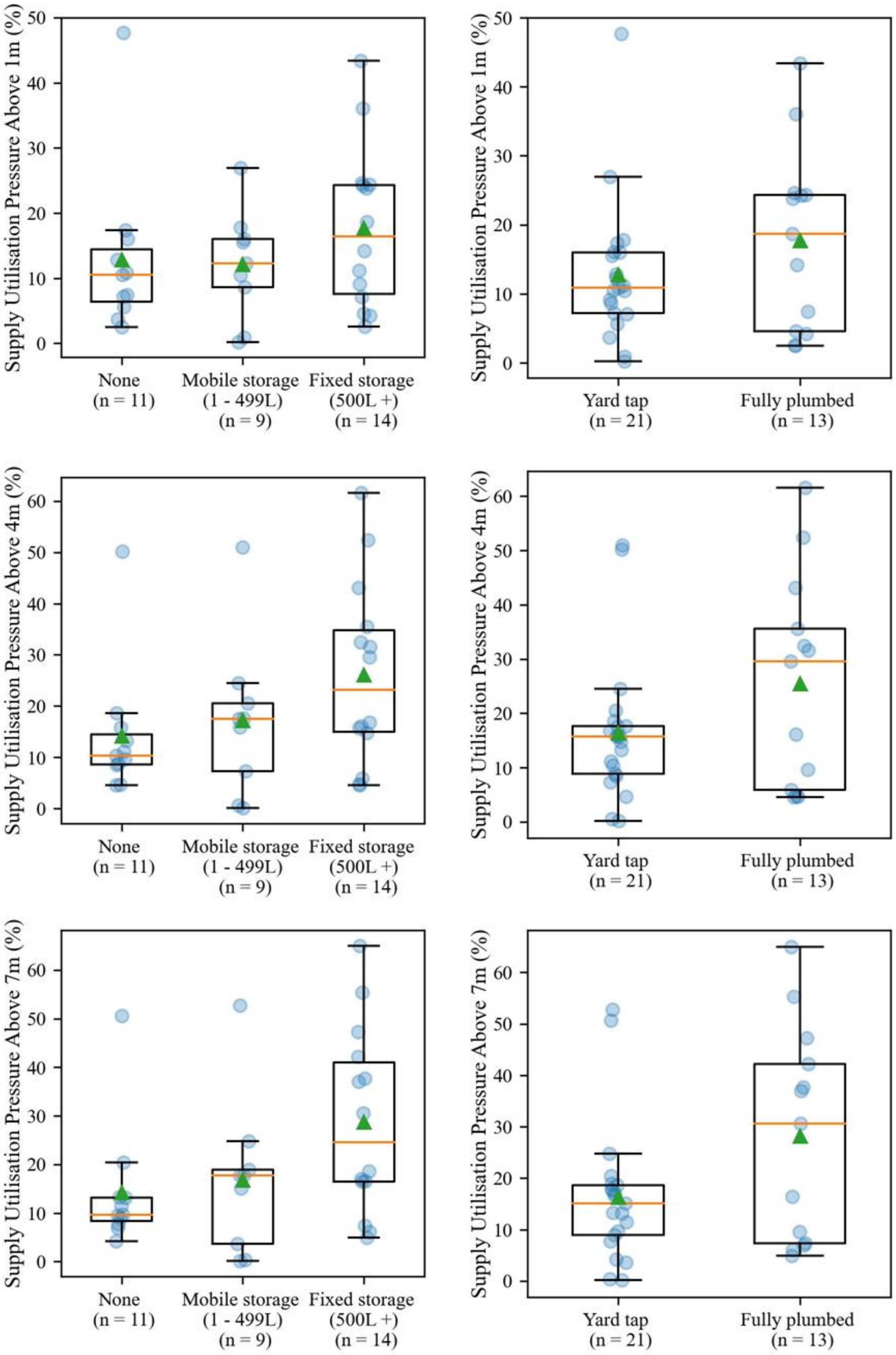


Figure 9.11: Effect of Categorical Household Characteristics on Estimates of Supply Period Utilisations

9.6 The 'Felt' Supply Hours of Households

The 'felt' supply hours of a household is defined as the duration of sufficient pressure to enable water withdrawal at the household inlet from the piped network. This is therefore affected by the household plumbing arrangements, specifically, the elevation of the household inlet.

Table 9.3 summarises the effects of different inlet heights on the estimated supply hours of the three example households used throughout the results sections. Household three, in the low elevation area, has the greatest range in estimated supply hours depending on the inlet height. This is because it experience long hours of low-pressure supply but rarely pressures above 7m. Household 1 also has a significant range but this is primarily because of its distance away from an inlet source meaning the pressures are limited. Household two arguably has the 'best' supply conditions with significantly longer supply hours at the 7m pressure band compared to the other two.

Table 9.3: The Hypothetical Supply Hours of the Three Example Households Depending on the Elevation of their Inlet

	Estimated Supply Hours Based on Household Inlet Elevation		
House Number	**Ground Level (1m)**	**1st Floor (4m)**	**2nd Floor (7m)**
1	7	5	4
2	15	8	8
3	24	4	0.5

10 Discussion

The discussion aims to reflect on the results and analysis sections to evaluate the conclusions that can be drawn from this study. The findings from this study will be compared against the current academic literature synthesised in section 2.

First, the different ways in which inequalities exist across the case study network will be explored. The variability in pressure and household characteristics contribute to several inequalities relating to supply conditions, withdrawal behaviours and water demands.

The findings from the case study analysis are then brought together in a new conceptual framework of IWS systems. The implications for modelling IWS are developed, in particular new methods of simulating consumer demands. Following this are two sections evaluating the implications for demand forecasting methods and understanding inequity under IWS conditions, with particular attention on evaluating current approaches in the literature.

The discussion ends with an evaluation of the implications of this study on planning a transition to CWS followed by a summary of the lessons learned from conducting the data collection and the limitations of the study.

10.1 Investigating Inequalities under IWS Conditions

The key results from the case study will be discussed through the lens of inequality.

10.1.1 Characterising the Unequal Supply of Water under IWS

The supply of piped water to a household can be characterised by the duration that water can be withdrawn from the connection combined with the flowrate of the water that leaves the connection. Section 7.1.1 showed that in Lahan, the input supply characteristics vary depending on the specific source. Figure 7.6 highlighted that the duration of input supply hours varies across the different borehole inputs and the overhead tower. The variable supply conditions are then further altered by two parameters: elevation and distance from the nearest input.

Sections 7.1.5 and 7.2.1 showed how elevation drives pooling behaviour, which determines the duration of ‘low-pressure’ supply hours (Figure 7.17). Water flows downhill, therefore it will drain down the network. The rate at which it drains depends on the outflows from the network, which can be categorised into consumer withdrawal and leakage. The relative length of time that water is present at the different elevations depends on this outflow. As the network drains, the area that the pooled water covers will reduce and thus the outflows (consumer demand and leakage) will reduce, hence the rate of drainage decreases. At the lowest elevations, if the outflows are small enough, the water will pool for long periods of time and potentially until the next supply period resulting in CWS, as recorded in Lahan.

It was also shown that the distance from the nearest water source is more influential in determining the ‘medium/high-pressure’ supply hours shown in Figure 7.18. This is unsurprising and follows well-established hydraulic principles observed in CWS networks i.e. pressure reduction is a function of the head losses and demand for water along the piped network. Therefore, the combination of the inlet pressure of the source, and distance from it, determines the local supply-period pressures during the pressurised phase of the supply cycle. In contrast to this expected behaviour, the low-pressure (1m head) supply hours were inversely correlated with the distance from the source; this surprising result can be explained by the co-correlation of elevation and distance from the nearest source. Due to a quirk in the Lahan network, the low elevation areas also happen to be some of the furthest from the network sources. Therefore, there was an inverse correlation, which is in fact further evidence that elevation is the dominant variable at the 1m threshold. These two factors (elevation and distance to nearest source) govern the local supply conditions at any location in the piped network determining both the duration and magnitude of water supply.

10.1.1.1 The Role of Household Adaptations

These network driven processes determine the temporal variation in pressure at the connection to the distribution pipe. However, the ‘felt’ conditions by the household is further moderated by their specific plumbing arrangements. The elevation of the household inlet alters the ‘felt’ pressure of water and therefore the duration that water will flow out of the tap. Section 9.6 lists the hypothetical differences in felt supply hours at three example households depending if the household has a ground level, 1st floor or 2nd floor inlet. The difference is stark and highlights the contribution of household characteristics to the unequal supply of water. The household inlet elevation is essentially comparable to the commonly used term H_{min} that defines the minimum pressure of withdrawal in hydraulic models applying Pressure Dependent Analysis (Abdelazeem & Meyer, 2024).

The installation of pumps can then enhance access by either drawing water directly from the network or pumping water from a ground tank up to a roof tank (effectively altering the inlet elevation). The effects of household pumps were not measured in this study but D. D. J. Meyer et al. (2021) suggest they are widespread and influential. Figure 10.1 shows a pump repair garage and a shop selling pumps in Lahan, suggesting the use of pumps may also be common in Lahan.

Figure 10.1: Photos of a Pump Repair Garage and Shop Selling Pumps in Lahan (Dec 2023)

The unequal supply of water under IWS conditions is therefore a function of the variability of local supply conditions (determined by elevation, distance to nearest input source and properties of nearest input source) moderated by the variability in the connection properties (elevation of the inlet and use of pumps). The important role that household adaptations make in defining the household supply of water suggests inequity is a more appropriate term than inequality, even when discussing the supply of water under IWS conditions. This is exemplified by the fact two adjacent households in an IWS network may still receive unequal supply of water.

10.1.2 Households Adapting to their Local Supply Conditions

Section 8.2 investigated whether the local supply conditions are correlated with the adaptations employed by households. Table 7.3 showed that there is a relationship between having a large storage tank and being fully plumbed (as opposed to having a yard tap). This could be because an overhead roof tank is indispensable when aiming to maintain continuous water pressure to household plumbing under intermittent conditions. Table 8.3 showed that having longer hours of medium or high pressure was correlated with a large, fixed storage tank as opposed to small, mobile storage. This suggests that household's ability to employ adaptations (such as large rooftop storage and a plumbed house) is constrained by the local high-pressure supply hours. Therefore, it follows that households utilise different adaptations according to their local supply conditions.

In section 7.2.3 it was observed that there is a cluster of households around the overhead tower that are fully plumbed, do not use another source of water and rely on the piped water for 100% of their needs. The overhead tower (OHT1) is the longest established and most reliable water source in Lahan. The satellite borehole sources have been installed at various points across history that is more recent. The clustering of households in this location that show high levels of reliance on the piped water network further indicates that households have adapted to their local 'good' supply conditions.

This conclusion is supported by section 8.1, which compared the IWS and CWS households in Lahan. Table 8.1 showed that CWS households tend to have less storage volume than the IWS group. The inference being that households do not feel the need to acquire storage if their supply hours are sufficient. The CWS supply households have the longest supply duration but the lowest pressures. The hours of medium or high-pressure supply is very limited meaning it would be unlikely an overhead roof tank could be adequately filled. Therefore, it is unsurprising that CWS households were also more likely to have a yard tap as opposed to being fully plumbed, providing further evidence that households adapt to their local supply conditions. Some nuance is required with these conclusions since Table 8.1 the CWS group is less wealthy. Moreover, Table 7.6 shows that lower wealth is associated with having a yard tap and correlated with lower storage volume. Hence, there is evidence that both wealth and supply conditions influence the implementation of different household adaptations.

10.1.3 Variation in HWISE Scores

Generally, HWISE scores were low with a mean of 5.5 and only 10.7% of the sample being deemed water insecure. A meta-study by Stoler et al. (2021) conducted the HWISE survey across 13 sites resulting in a mean score of 9.32. Interestingly, they found a difference in scores between conducting the survey in the rainy or dry seasons. The survey in this study was conducted across September to December, only a few months after the rainy season. Therefore, it is important to recognise this may have skewed the results of this study, which may have returned a higher score if it was conducted in the spring/summer time.

The results presented in section 8.4 found that no parameter correlated with HWISE score. Due to the wording of the HWISE questions (Table 6.4), they tend to assess the regularity of interruptions to water supply as opposed to the general level of water stress of the household. This may explain why the scores did not show any particular correlation.

10.1.4 Lack of Observed Relationships between Withdrawal Volume and Network/Household Variables

The per capita withdrawal volumes of households in Lahan were highly variable (Figure 7.30). Section 8.3 specifically investigated which factors correlate with the volume of withdrawal of households. Table 8.4 showed no correlations between household variables and their withdrawal volume measured in litres per capita per day (LPCD). Comparisons were also made against the total withdrawal volume of the households and this also returned no statistically significant relationships. The factor that showed the strongest relationship was the occupancy of the household; the higher the occupancy, the lower the withdrawal volume in LPCD. This follows observations from other studies on water demand; Jacobs (2004) found the relationship between occupancy and per capita consumption to be:

Per capita water use = SPC × $d^{-0.439}$ (SPC = single-person household, d = household occupancy)

Figure 10.2 shows this relationship fits relatively well when compared with the Lahan data.

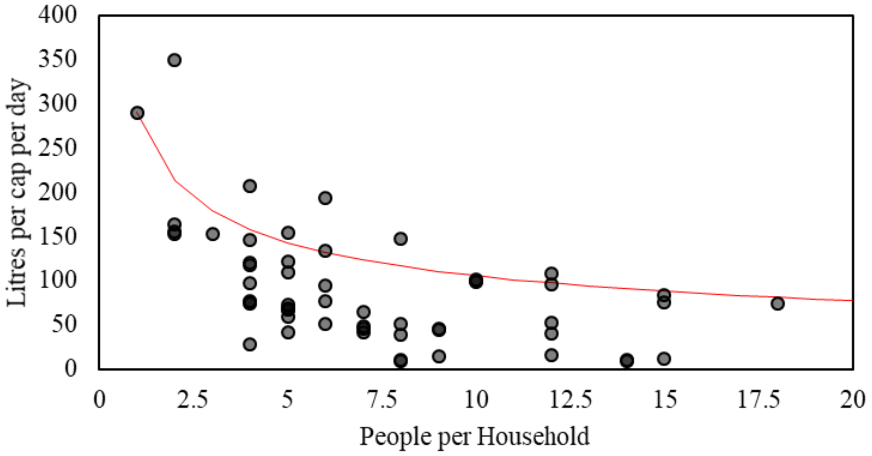


Figure 10.2: Relationship between Household Occupancy and Withdrawal Volume in the Lahan Sample compared to Relationship Proposed by Jacobs (2004) [Red Line]

The lack of correlation with any single parameter suggests that the withdrawal volume of households is complex. Figure 8.7 showed that withdrawal volume is not simply driven by supply hours in Lahan suggesting that forecasting water demand under IWS conditions is not a simple task. This will be evaluated further in section 10.4.

10.1.5 Variability in Monthly Demand

Figure 7.33 showed a seasonal pattern to water withdrawal in Lahan with higher piped water withdrawal in the hotter, drier summer months. Under IWS, any global increases in withdrawal volume implies that there must have been an increase in input or a reduction in leakage (since a reduction in leakage means more input volume is directed towards connections). Anecdotally, it was reported that the network operators increase the input supply during the hot, dry months in anticipation of increased demand. This therefore explains why the increase in withdrawal was possible in Lahan.

The increase in withdrawal volume implies an increase in demand over this period. Otherwise, the increased input would have simply been lost to leakage. However, the reason behind the increased demand is less clear; there are two options:

1. Households' fundamental piped water demand has indeed risen due to the hotter, drier climate

Or;

2. The increase in input volume means previously unmet piped water demand is now being met (i.e. there may not be an actual increase in total water demand)

The data presented here cannot reveal which of these options has occurred or whether it is a mixture of the two. The increased withdrawal of households may indicate a fulfilling of previously unmet demand or an actual increase in total demand due to the changing weather.

Table 12.3 showed significant variation in withdrawal between equivalent months in 2023 and 2024 that cannot be explained by seasonal effects. Some variability would be expected as changes to occupancy may have occurred within this timeframe. However, the number of households showing highly variable demands suggests that this cannot be the sole explanation. Bimodal patterns were identified in Figure 7.34, indicating a specific change in withdrawal behaviour. This indicates inconsistent demands and suggests that future withdrawal volumes cannot be predicted by current withdrawal time series. The variability in withdrawal volumes points towards wider influences that are not typically considered in demand forecasts under CWS conditions. One significant factor that may be behind the variability is the widespread use of other sources of water.

10.1.6 Use of Other Sources Complicates Forecasts

The household survey revealed the common practice of using other sources alongside piped water to fulfil water demands of households. Section 7.2.2 showed household estimations of the contribution that the piped water makes to their total water usage. Although the accuracy of this is highly questionable as it is self-reported, the range in responses indicates that the use of other sources is widespread.

The use of other sources complicates the situation and suggests the need to separate total water demand from piped water demand. An example of this complexity is illustrated in Figure 10.3, which highlights one of the households that showed a bimodal pattern in Figure 7.34. It was noted in the survey that this house had a 1000 Litre storage tank but it was currently connected to their tube well. At the time of the survey, they stated they only use the piped water for ‘2%’ of their water needs. They also reported that they were planning on connecting the piped water connection to their overhead tank and plumbing in the next few months. Figure 10.3 suggests that they followed through with this plan and consequently use significantly more piped water.

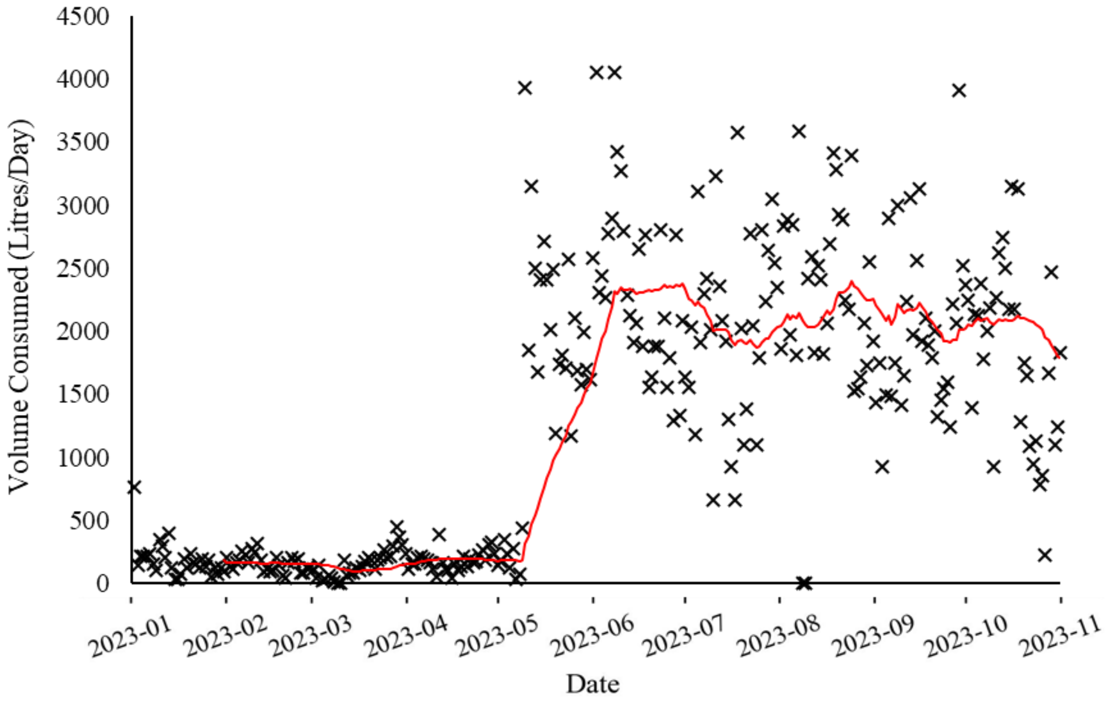


Figure 10.3: Daily Volume Consumed from a Single Household Indicating a Sharp Change in Withdrawal Volume in May 2025. Red line is a 30-day rolling average

Figure 7.25 corroborates the plausibility of this as defunct tube wells were observed. This example illustrates the separation between total water demand and piped water demand and how this can lead to sudden and dramatic changes in demand for the piped water.

Another example from the case study site relates to more widespread changes in behaviour observed between May and June 2023. As can be seen in Figure 7.33, the monsoon arrived in Lahan in July, approximately one month later than it typically begins. This led to the shallow aquifer in Lahan being unseasonably low and reports of household tube wells drying up. NWSC reported a sharp increase in the number of households requesting a piped connection be installed in their home. At the network scale, this creates a sudden and unplanned increase in demand for water.

Although this was a one-off incident, it has the potential to be a significantly more common and widespread issue. Figure 5.2 shows that a significant proportion of the population in Lahan is not currently connected to the piped network within both the central zone and wider wards. There is clearly significant potential for increases to the demand for piped water if these populations connect to the network. Furthermore, over 60% of households rely on shallow tube wells, if climatic changes were to cause these to dry up more widely, then the situation could change dramatically. Even without these changes, there was a 32% increase in the number of connected households between 2020 and 2023 (Table 5.2).

Both examples lead to sudden changes in the demand for piped water at both the network and household scale. These are driven by factors that are not typically considered in CWS contexts (see Figure 2.1).

10.2 Developing a Framework of the IWS System

Analysis of the network and household behaviour in Lahan has led to a new conceptualisation of how IWS systems operate. This section aims to describe what the conceptual framework is and justify its arrangement, given the findings from the case study of Lahan. The process by which the framework could be implemented into a functioning model is then presented by proposing and evaluating an ‘agent-hydraulic’ model of IWS.

The framework connects the delivery of water to the connection, and the demand for water at the connection, to the water withdrawal from the connection. This water withdrawal then results in the output of the framework: the extent to which the household has water ‘available when needed’. The framework aims to illustrate the inequity of water access under IWS conditions and highlights the coupled nature of household adaptations and supply conditions.

10.2.1 Conceptualising IWS Systems: The Hourglass Framework

The hourglass framework, Figure 10.4, brings together the dual influences of the supply conditions and household behaviour on water withdrawal at the connection. It also looks beyond this to how that water is used (either directly or stored) and thus the implications for water availability at the household.

The framework proposes that two spheres of influence affect the withdrawal of water in an IWS network: the delivery of water to the connection and the demand for water at the connection. The delivery of water to the connection is ultimately controlled by the water network operators and the assets they have at their disposal e.g. overhead towers and boreholes. The operation of these assets determines the input supply characteristics that define the global water availability. The hydraulic mechanisms of the piped network then determine the local supply conditions, which define the local water availability. Section 7.1.5 showed that the local supply conditions can vary significantly across an IWS network, an attribute that is shared with other IWS case studies (Erickson et al., 2020).

On the other side of the network connection is the second sphere of influence, the demand for water at the connection. This is initially a function of the total water demand of the household, a value that is dependent on many factors as summarised by section 2.5.1. The piped water demand is a subset of the total water demand and depends on the wider availability of water. How the piped water demand translates into the withdrawal of water from the piped network is moderated by the household adaptations/characteristics. For example, the storage volume limits the duration of withdrawals (Figure 9.8), the height of the inlet determines the 'felt' supply conditions (section Table 9.3) and the use of suction pumps augments the withdrawal flowrate (D. D. J. Meyer et al., 2021).

The two spheres meet at the piped network connection. Water is withdrawn for either direct-use or storage purposes; the specific mixture of withdrawal types associated with a connection depends on both spheres. The extent to which water is 'available when needed' is thus defined by their ability to get water from the tap or a storage container across a supply cycle.

In Figure 10.4, the two dark-blue spheres that encompass the two sides of the hourglass framework reflect a 'zooming-out' of the IWS system. The aim is to recognise the boundaries and wider forces that restrict or exacerbate all of the elements within them.

The complexity of the system derives from the interdependence of the boxes in the hourglass framework. The following sections will discuss these interdependencies in more detail as well as providing justification for the elements and structure of the framework.

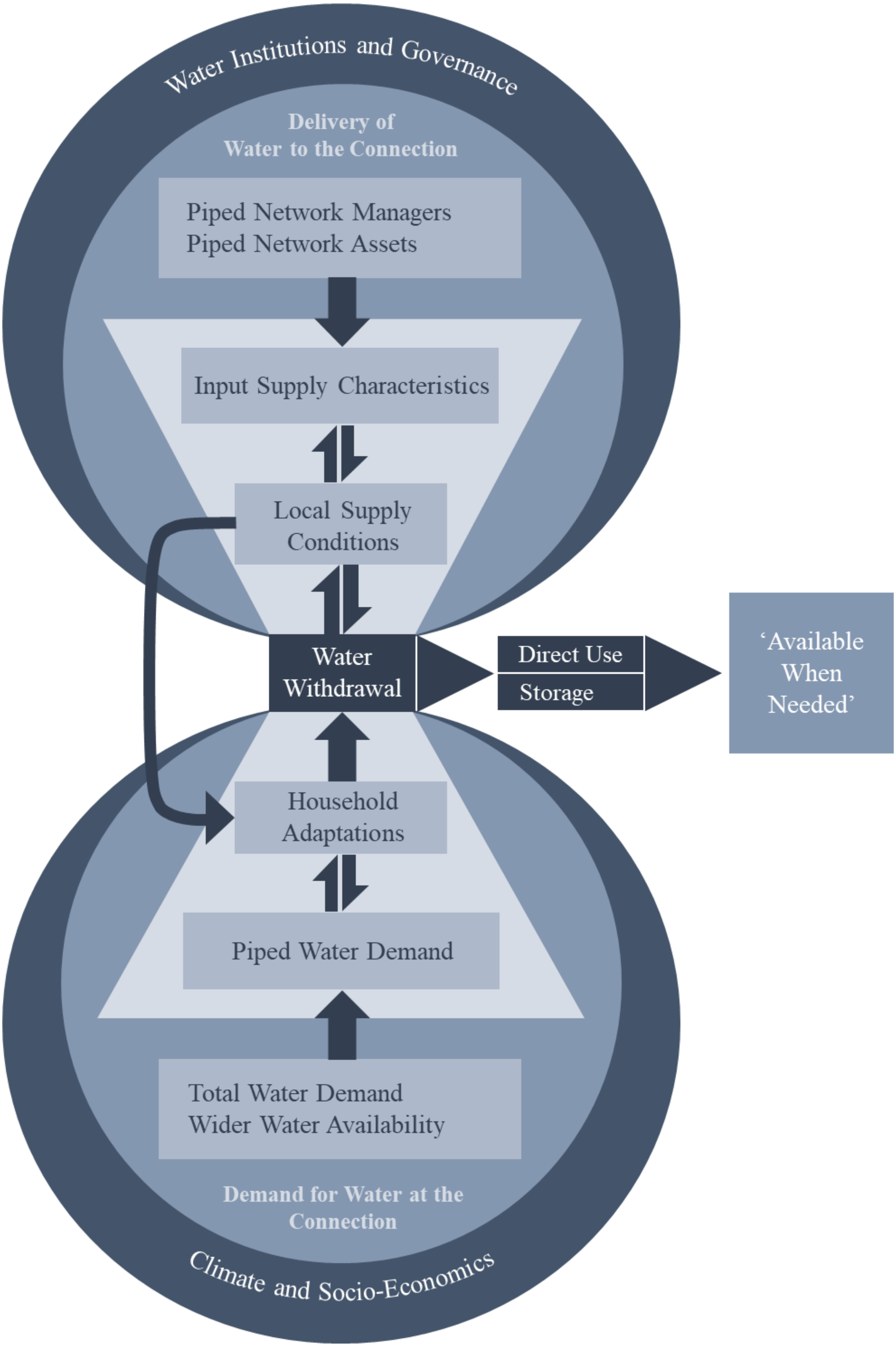


Figure 10.4: A Conceptualisation of the IWS System: The Hourglass Framework

10.2.1.1 Delivery of Water to the Connection

The supply characteristics and local supply conditions are ultimately controlled by the piped network assets and network operators. They operate the levers that determine the delivery of water to each connection in the network. Section 7.1.1 shows that the type of network input, and the operation of it, directs the input supply characteristics into the network. Figure 7.6 highlights the variation in input supply characteristics across the Lahan network. The input supply is further augmented by the piped network leading to variable local supply conditions at the connection. Figure 7.17 and Figure 7.18 show that local elevation and distance to the nearest input have significant effects on the spatio-temporal variation of local pressures.

There are reverse arrows between the input supply characteristics and local supply conditions as well as the water withdrawal and local supply conditions. This is because water withdrawal directs much of the hydraulic behaviour across a piped network (Speight et al., 2010). Abdelazeem & Meyer (2024) demonstrated that different withdrawal types influence the unequal distribution of water and hence the local supply conditions. How this then influences the input supply characteristics depends on the particular arrangement of the piped network. In Lahan, the overhead tower is operated by turning the valve off when the level gets to a certain minimum height. The time it takes for this to occur is directly dependent on the rate of water withdrawal in the network. Therefore the ‘supply hours’ are somewhat controlled by demand.

10.2.1.2 Demand for Water at the Connection

The demand for water at the connection is initially a function of the total water demand of the household, which can be estimated using similar methods to those employed in CWS systems. Factors that affect this have been researched widely within literature as summarised by Figure 2.1.

A key separation with IWS systems is the use of other sources to fulfil household demand. This was observed in the case study as shown in Figure 7.25 and Figure 7.26; in Lahan households commonly use tube wells either to supplement supply or as the primary water supply option. The use of other sources is also reported in the literature across many locations (Burt et al., 2018; Guragai et al., 2017; Potter et al., 2010). Klassert et al. (2015) evaluate how the availability and preference for other sources determine household choices, this will then determine their piped water demand.

A second distinction is that the piped connection is sometimes used by several households (Kumpel et al., 2017) meaning the piped water demand is the sum of the demand of all users. In the survey conducted in Lahan, two households reported sharing their connection with another household.

The piped water demand at the connection is translated into water withdrawal from the network via the medium of household adaptations (e.g. storage, suction pumps, plumbing arrangement). The withdrawal characteristics that are experienced by the piped network at the point of connection are augmented by the use of storage containers. Section 9.4 showed that connections joined to large storage volumes were strongly associated with withdrawals of large durations/volumes indicating tank-filling behaviour. Section 9.6 showed the height of the household inlet also affects withdrawal characteristics as the elevation alters the ‘felt’ pressure head.

In the hourglass framework, there is a reverse arrow between the piped water demand and the household adaptations. This signifies the intuitive hypothesis that a household’s adaptations may influence their piped water demand. Table 8.4 showed that there is no evidence overall that household adaptations influence water withdrawal volumes in Lahan. However, it also does not prove the opposite. Section 10.1.6 reflected on the fact that a household’s withdrawal volume appeared to change dramatically alongside a change in the plumbing arrangements of the house. This indicates there may be a relationship in this direction but further research is required to confirm or deny this.

10.2.1.3 Water Withdrawal and the ‘Available When Needed’ Metric

The delivery of water to the connection and demand for water at the connection combine to determine the water withdrawal characteristics. In Lahan, water withdrawal is a mixture of frequent small withdrawals and less frequent large withdrawals as illustrated by Figure 7.39 and Figure 7.40. These have been characterised as ‘direct-use’ and ‘tank-filling’ withdrawal types respectively. Direct-use is when water is withdrawn to fulfil a need at that point in time, while tank-filling is to build a reserve of water which can be used when the need arises. At any point in time, the fulfilment of a person’s desire for water will therefore be dependent on whether they can directly use water from the connection or whether there is water available in the storage container. If neither of these options are available, then the individual will have to alter their behaviour. They will have to alter their behaviour in one of three ways:

a) Not perform the water-use activity they wanted to (e.g. not wash hands, not cook food, not clean clothes);
b) Use an alternative source of water to fulfil their need. This is likely to be an unregulated source (e.g. borehole water) or unimproved source (e.g. river water) which could have associated health risks;
c) Delay doing the water-use activity until water is next available (e.g. save clothes to be washed later). This will result in greater accumulated water demand at the next supply period.

All three options incur a type of water stress on the individual. As a result, the framework proposes a new application of the SDG 6.1 metric to evaluate an IWS system’s performance: the extent to which piped water is ‘available when needed’. The availability of water when needed is not a new metric; as discussed in section 1, it is one of the three criteria used to define ‘safely managed’ water under SDG 6.1. This is simply proposing a new application of it within the realm of IWS systems. The aim of incorporating it into the framework is to underscore that it is the most holistic measure of the inequity of water access deriving from IWS.

The role of storage is central to determining the extent to which water is available when needed, as it augments the temporal availability of water. Taking the Lahan network as an example, the households in the low-elevation, CWS area have water available when needed, as it is constantly available from the connection. Households in other locations may also have piped water available when needed if they have sufficient storage (and sufficient supply hours/pressure to fill that storage) to provide for their water demands until the next supply period.

Overall, the framework illustrates how the two spheres combine to determine the variable fulfilment of water 'available when needed' within IWS systems, taking into account that both the piped supply and household adaptations contribute to the household's access to water.

10.2.1.4 The Coupled Nature of Withdrawal

An added layer of complexity of the system derives from the interdependence of the governing parameters. Section 10.1.2 discussed how households adapt to their local supply conditions; this then influences how they withdraw water, which feeds back into the network, determining local pressures and the unequal distribution of water. It is crucial to simulate this coupling when investigating long-term changes to the piped water network. This is reflected in the hourglass framework: the arrow connecting local supply conditions to household adaptations extends out of the hourglass shape as it operates over the long term while the central hourglass section operates over a supply cycle. Figure 10.5 summarises this feedback mechanism; it is essentially a zooming in on the central section of the hourglass framework.

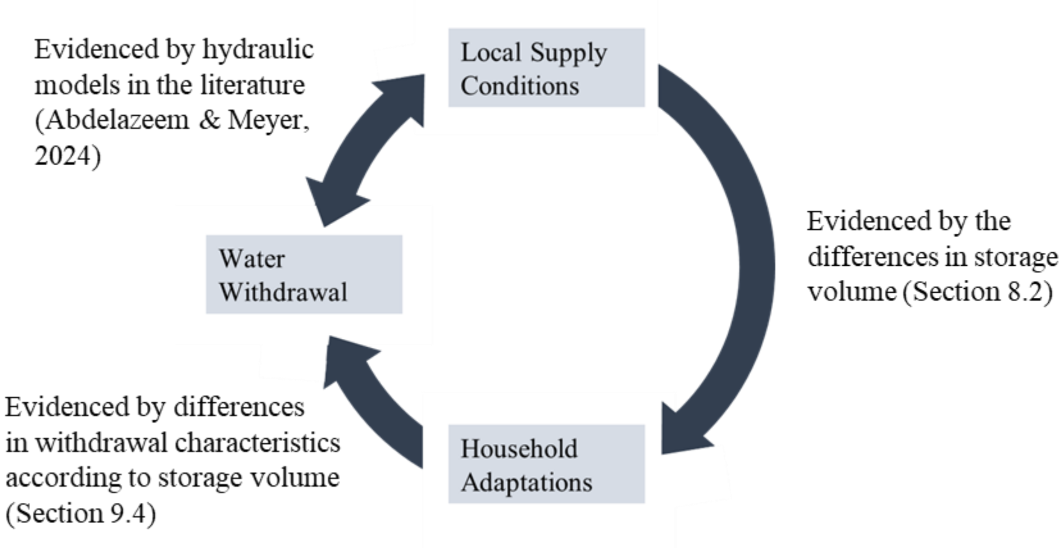


Figure 10.5: The Coupled Nature of Local Supply conditions, Household Adaptations and Water Withdrawal

10.2.1.5 Wider Influences on the System

The framework is purposefully centred on the piped water network as it aims to enable better management of the piped supply to maximise water access of the served community. However, the piped network is situated within a wider context, which is recognised by the inclusion of the largest spheres that encompass the processes within the framework. On the top side of the framework sits the ‘Water Governance and Institutions’, this represents the bodies that regulate the ability of the network operators to perform their duties. On the bottom side of the framework sits ‘Climate and Socio-Economics’, which influence water demand and the circumstances of the households (e.g. their ability to employ adaptations). The addition of these elements is admittedly crude, however, it points towards the necessity for collaboration with social science to develop a fuller picture of IWS systems and the need for joint approaches to ensuring their long-term improvement.

These wider spheres have derived partly from the literature review, but also from evidence and discussions from the Lahan case study. Section 7.2.5 showed the influence of wealth on household adaptations in Lahan, while section 7.3.2 indicated that the climate influences water demand. Anecdotal evidence also supports the influence of water governance on the top side of the model. Negotiations at the federal level of government in Nepal has halted NWSC as an organisation from being able to hire more staff since 2010. This has led to an even more stretched human resourcing problem (NWSC, 2023). As of June 2022, the Lahan branch had seven permanent staff and ten contracted staff and the branch manager was also responsible for managing a second branch in the nearby city of Janakpur, limiting all the workings of the network managers. It has been estimated that NWSC as a whole has 50% of the staff they require. When the head of the NWSC Lahan branch was asked by the author what their biggest struggle was in relation to running the water supply network, their response was ‘not having enough staff’.

The conceptual framework enables factors that may have previously been unconnected to the piped network to be assessed. Section 10.1.6 recounted how the monsoon arrived later in Lahan than is typical, and that this coincided with NWSC reports of an increase in the number of households requesting the installation of a piped connection. The possible ramification of this can be qualitatively evaluated by the framework. The following summarises how this situation could cause knock-on effects considering the relationships within the system:

Household tube wells dry-up

- Preference for piped water over other sources
  - Increased piped water demand
    - Connection of piped supply to household storage volume
      - Greater withdrawal
        - Reduced local pressure
          - Reduced supply hours in other locations

10.2.2 Modification of the Framework to Different IWS Regimes

The relative contribution of each side of the hourglass framework, and the categories within them, will depend on the specific circumstances of the IWS system. Since this study has only investigated one IWS network, there is limited understanding that can be brought to quantifying the relative influence of each category under different IWS regimes. In the absence of data, it is hypothesised that the top side of the framework will dominate the system dynamics under more water scarce situations while the bottom side dominates when the intermittency is more frequent and regular as summarised by Figure 10.6. Consequently, it is anticipated that in systems towards the lower end of the spectrum, households will increase their withdrawal volumes more directly in line with increases to the network supply. At the higher ends of the spectrum, the situation is more complex and potentially harder to predict. This is a hypothesis that needs to be tested when applying the framework to other IWS systems. The degree to which the framework is appropriate and flexible enough to describe other IWS networks is yet to be verified, this is a key area for further research proposed by this thesis.

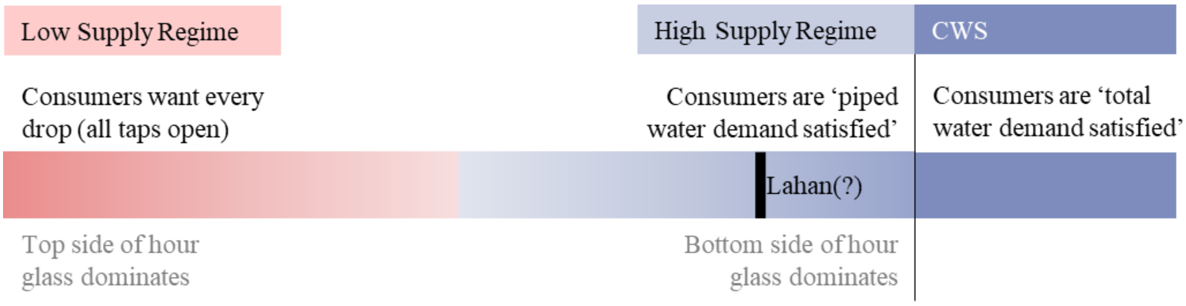


Figure 10.6: The Spectrum of IWS Regimes and Proposed Relationship to the Conceptual Framework

10.2.3 Modification of the Framework to Different Timescales

The time scale at which the network is being assessed also determines which elements of the hourglass framework are relevant. To estimate long-term changes the coupled nature of supply conditions and household characteristics is pertinent, as over time households are likely to adapt to new supply conditions. However, for short-term analysis of the network, this coupling is irrelevant. To understand current inequity in water access, the coupling between withdrawal behaviours and local supply conditions is still required. Figure 10.7 summarises how the framework can be adapted according to the timescale over which it is being applied.

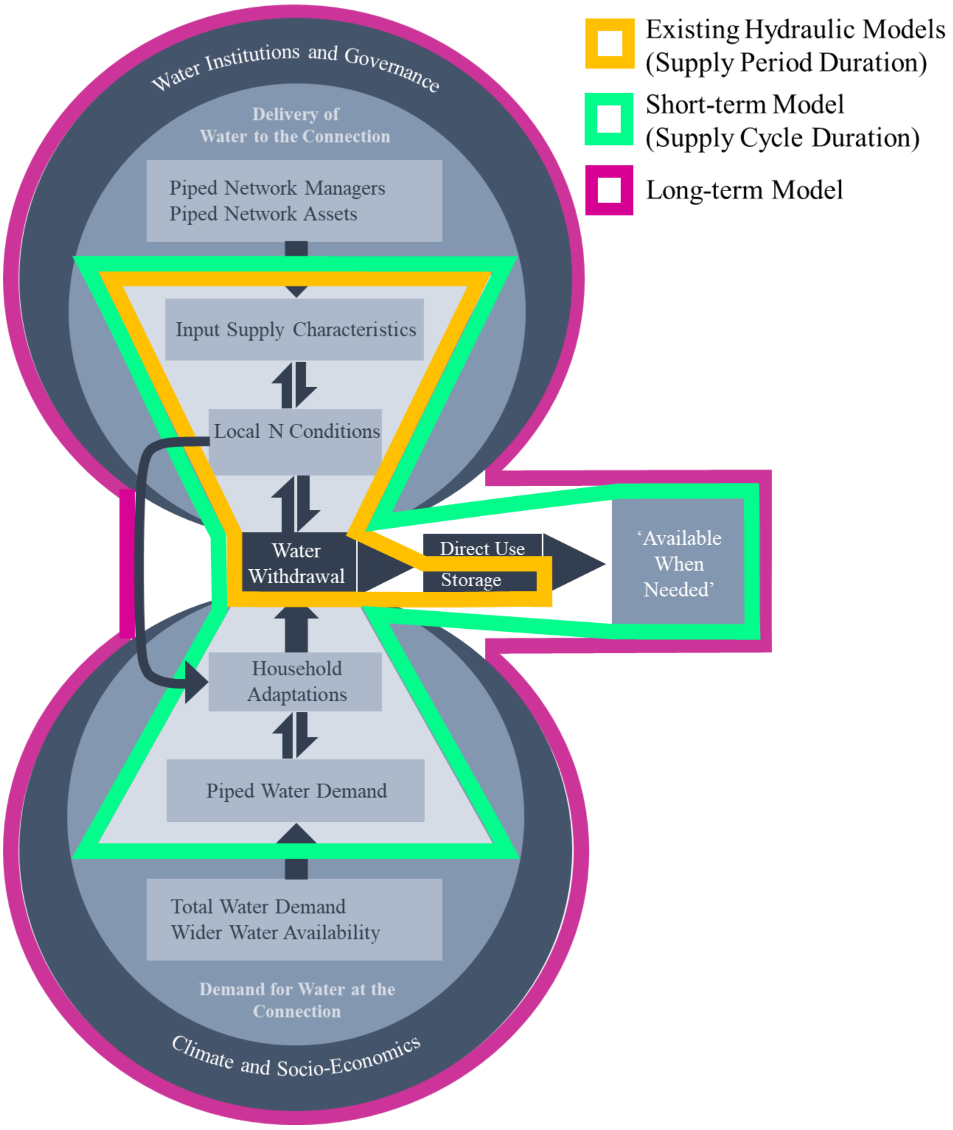


Figure 10.7: Application of the Hourglass Framework to Different Time Scales

10.3 Modelling IWS Networks

This section contrasts the framework presented in the previous section with the current approaches taken to model IWS networks as described in section 2.7.1 of the literature review. Attention will be drawn to the current assumptions made when modelling water withdrawal behaviour and how this compares with the findings of the case study and hourglass framework. Consequently, new methods of modelling IWS systems will be proposed as well as an evaluation of their relevance to different modelling applications.

10.3.1 Variability in Withdrawal Behaviour According to both the Local Supply conditions and Household Adaptations

In sections 7.3.4 and 7.3.5 it was observed that households withdraw water in different manners both in terms of the temporal pattern of withdrawal and the withdrawal instance characteristics. Figure 9.1 and Figure 9.2 illustrate the significant differences in supply conditions under which households in Lahan withdraw water, and how these differences influence their water withdrawal characteristics. In section 9.3 the ‘withdrawal hours’ of households aligned somewhat with the estimated local supply hours indicating households tend to withdraw water as and when it is available. Figure 9.4 suggests that households with larger storage volumes tend to withdraw water at higher flowrates. This finding should be viewed alongside Table 8.3, which showed that households with greater supply hours at medium/high pressures tend to have larger storage tanks. Therefore, the higher withdrawal flowrates could simply result from higher local pressures or from the use of large storage tanks. Section 9.4 showed that households with larger storage containers take the majority of their water from tank-filling type instances.

These results are relatively intuitive; however, the heterogeneity of behaviour is important. In Lahan, it was observed that the supply conditions (section 7.1.5) and the household adaptations (section 7.2.2) vary greatly across the network. Due to this variation, households behave differently both according to their location in the network and household type. The three example households highlighted throughout the results exemplify the variability in local conditions and associated withdrawal behaviours in the network. This has various implications and challenges current practices of modelling connections in IWS networks.

The first implication is that the full IWS cycle must be captured to fully reflect the variation in local supply conditions. The pooling phenomenon has a significant impact on withdrawal behaviour and must be simulated in hydraulic models if the inequality of supply is to be captured. The review of current modelling techniques by Abdelazeem & Meyer (2024), found only two examples of the draining phase being modelled and neither were replicable. Capturing the draining phase in hydraulic models is a hurdle that must be overcome as a priority. The results from the case study show that models that ignore the draining phase may drastically misrepresent the system.

Secondly, household withdrawal behaviour is not homogenous and therefore they should not be modelled as such. Current standard practice does not consider any variation between connections with no appreciation for their different characteristics (Abdelazeem & Meyer, 2024). Analysis of the case study has shown that these differences are highly relevant to the manner in which households withdraw water and therefore the hydraulics of the network. The hourglass framework incorporates this complexity highlighting the need for greater consideration of households.

The survey did not ask directly if households utilised a float valve to control their withdrawal of water. However, section 7.2.2 showed that 55% of households in Lahan did not have a formal storage tank (500+ litres), meaning they could not employ a float valve. In addition, 86% of the sample reported that they do not have the tap open the entire duration of the supply period further suggesting a float valve was not in use. Using a float valve would mean that household withdrawal would start exactly when the local supply period began, unfortunately, this cannot be tested with the available data due to the imprecision of the pressure interpolation method discussed in section 6.7.2.1. Despite this, it is reasonable to infer that the withdrawal behaviour of the vast majority of households in Lahan is stochastic not deterministic. It would certainly be inaccurate to model all households in Lahan as tanks that fill according to the local supply conditions. The current methods of modelling withdrawal behaviour in hydraulic models as described in section 2.7 (be it unrestricted, volume-restricted or flow-restricted) are therefore not representative of the case study. The influence of household choices is significant and largely determines when withdrawal occurs. Only for a minority of households that have a large storage tank and automatic control valve, would the volume-restricted approach be appropriate. As summarised previously, the nature of these stochastic demands is influenced by the temporal availability of water and the utilisation of large storage tanks.

10.3.2 Stochastic Demand Parametrisation

As discussed in section 2.7.2.2, the use of stochastic demands to represent household water consumption has become established within hydraulic models of CWS. The Poisson Rectangular Pulse model is the principal method for defining the stochastic demands of a connection. The nature of the stochastic demands is defined by six parameters. Figure 10.8 illustrates how the six parameters within the Poisson Rectangular Pulse model could relate to the categories within the framework.

The arrival rate pattern, $\frac{\lambda_m}{\bar{\lambda}}$, refers to the relative likelihood of withdrawal at a given timeslot across the day; this is comparable to the temporal variations shown in section 7.3.4. The results from Lahan show it is largely dependent on the local supply conditions that define the local supply hours. The pulse intensities σ_2 and μ_2 refers to the magnitude of the pulses that depend on the local network pressure.

The average arrival rate, $\bar{\lambda}$, is the overall frequency of withdrawals. Section 9.4 showed this is heavily influenced by the volume of household storage, the larger the volume the less frequent the withdrawals, as each withdrawal tends to be of a larger volume. The pulse durations, σ_1 and μ_1, are again largely driven by storage volume as shown in section 9.4; the larger the storage volume the longer the duration and thus the greater the withdrawn volume.

The arrival rate pattern and pulse intensities generally relate to variables within the piped network while the average arrival rate and pulse durations relate to the household demands and adaptations.

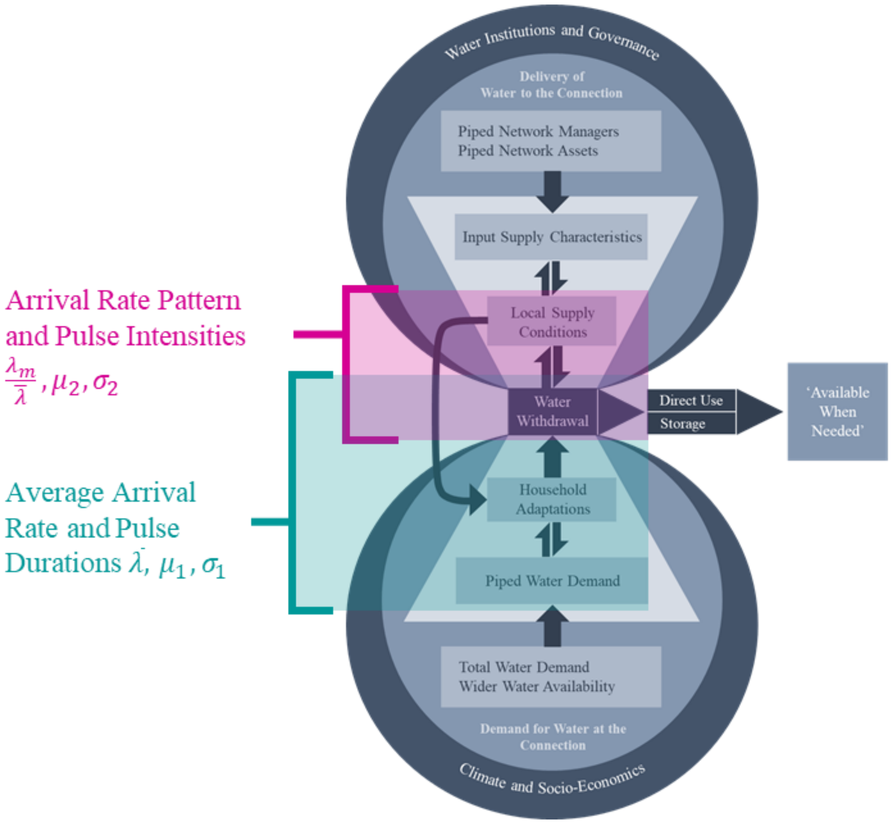


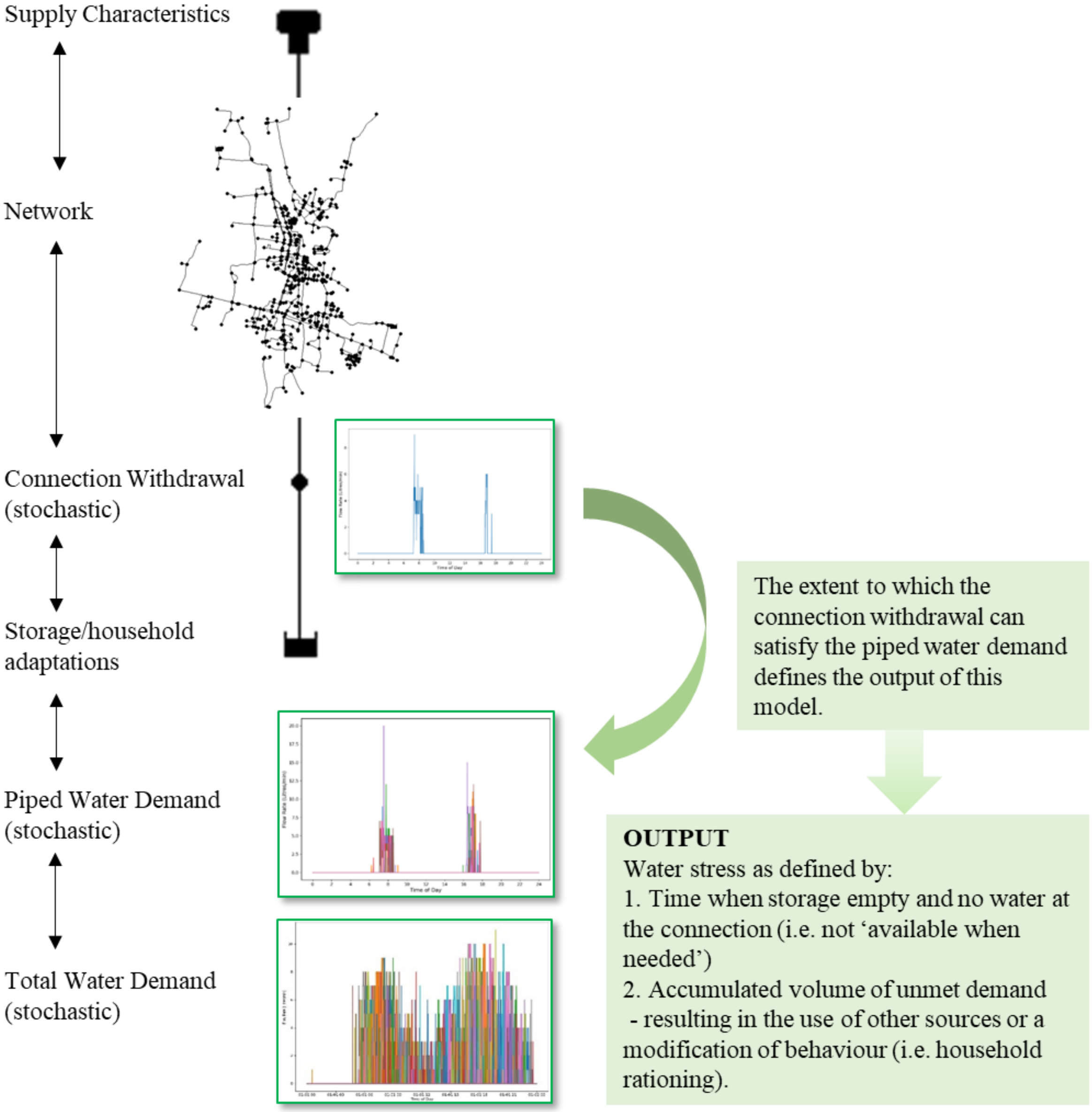
Figure 10.8: Relating the Variables that Define the Stochastic Demand Generation with the Categories from the Hourglass Framework

B. E. Meyer et al. (2021) developed a method implemented in CWS contexts that splits demands into indoor and outdoor use categories when parametrising stochastic demands. This could be adjusted in an IWS context into direct-use and tank-filling categories enabling separate parameterisation of the different withdrawal types. Households that do not have large storage tanks would only require the direct-use stochastic demand generation while households with storage would have two sets of stochastic demands that combine in the same way as the indoor-outdoor method.

The use of stochastic demands crucially enables both the frequency and characteristics of withdrawals to be defined. Section 9.3 and 9.4 showed that both of these vary significantly across the households in the Lahan IWS network, moreover the variation is correlated with both supply conditions and household adaptations. Stochastic demands therefore could enable a complete simulation of the water withdrawal behaviour observed in the case study and the variation between households.

10.3.3 The ‘Agent-Hydraulic’ Model of IWS

This section aims to discuss one application of the hourglass framework into a practical model that could provide useful output for network management. This model is referred to as the ‘agent-hydraulic’ model, as it combines hydraulic elements to determine the distribution of water across the network and agent-based elements to define the water withdrawal characteristics of connections. Such a model cannot currently be developed with the tools that exist, but is rather a destination that should be aimed for. As can be seen along the left-hand side of Figure 10.9, the model follows the structure set out by the hourglass framework.



The extent to which the connection withdrawal can satisfy the piped water demand defines the output of this model.

OUTPUT
Water stress as defined by:
1. Time when storage empty and no water at the connection (i.e. not ‘available when needed’)
2. Accumulated volume of unmet demand - resulting in the use of other sources or a modification of behaviour (i.e. household rationing).

Figure 10.9: A Schematic Showing how the Agent-Hydraulic Model of IWS Would Operate

10.3.3.1 Delivery of Water to the Connection

A hydraulic model such as EPANET or SWMM forms the engine for determining the flows and pressures in the piped network. As with all hydraulic models, this is controlled by the network inputs and connection withdrawals. Leakage is highly consequential in IWS networks and must be incorporated using existing procedures calibrated by a water balance of the system (section 2.2.3). As discussed in section 2.6.1 of the literature review, a fundamental limitation of current hydraulic models applied to IWS conditions is the challenge of modelling the filling and draining phases. The study of Lahan underscored the criticality of modelling the draining phase to replicate the variation in local supply conditions. This is a technical challenge that is currently a focus of several research studies. Before this is achieved, the agent-hydraulic model of IWS cannot be realised.

10.3.3.2 Demand for Water at the Connection

The focus of this research project has been the demand for water at the connection and therefore this part of the agent-hydraulic model of IWS will be discussed in more detail.

The conceptual framework posits that there are three levels to the water demand at a connection. The ‘total’ water demand, piped water demand and connection withdrawal. The proposal behind the agent-hydraulic model is that each level should have an associated demand characteristic that interacts with the other levels. In addition, the best method for defining the demand characteristics at each level is a stochastic demand time series.

The stochastic demands within the ‘total water demand’ level are defined by the water needs of the household. This could be determined by the SIMDEUM end-use approach discussed in section 2.7.2.2 of the literature review. These demands are somewhat hypothetical; they aim to replicate the household desire for water if water is abundantly available as is the case in fully plumbed CWS households. This is the ultimate access to water, the ultimate achievement of SDG 6.1, and the ultimate circumstances for the prevention of water related stress/ill-health.

The piped water demand is the ‘middle-man’ between the total water demand of the household and the water withdrawal at the connection. It will have a complex two-way relationship with both the total water demand and connection withdrawal. The profile of the households’ total demand is tapered by the use of other sources. The use of other sources is either an active decision that reduces the piped water demand out of preference or a reaction to not achieving sufficient water from the connection withdrawal to satisfy the piped demand.

Different demand profiles will be applied across the network according to the distribution in household characteristics. The piped demand is translated into a connection withdrawal via the household adaptations, such as storage. As such, a survey of the household characteristics of the consumers is necessary to parametrise the model. In some cases, where the household has a large storage tank and automatic valve, stochastic demands would not be necessary to model the connection withdrawal as the deterministic approach of volume-restricted demand holds. This is essentially a simplification that can be applied for a portion of the connections according to the survey results.

10.3.3.3 Feedback Loops

The consumer side of the agent-hydraulic model has both a forward and backwards direction. In the forward direction, the total demand tapers to the piped demand that is then shaped into the connection withdrawal. If the supply conditions are such that the connection withdrawal always meets the piped water demand, then there is no feedback mechanism and therefore it only needs to operate in one direction (the simplest scenario). However, in the event that connection withdrawal cannot occur (i.e. there is no availability of water in the network) an unmet demand is created. The volume of unmet demand can be ‘satisfied’ in three ways:

1. Increased withdrawal in the next supply period (an inflated demand that is met);
2. Other sources are used to supply the demand; Or
3. A modification of behaviour (i.e. household water rationing).

These operate both in the short and long term. In the short term, the household may adjust their behaviour to compensate, for example, saving a water-use activity for the next supply period or filling their storage tank more so that they have greater reserves. The coupling of behaviours in the system requires the model to be run iteratively for a length of time until an equilibrium is found between local supply conditions and the adaptive household withdrawal behaviours.

In the longer term, feedback loops operate at a network level. Households may employ different adaptations such as installing more storage volume or consistently relying on other sources to fulfil demands thus re-defining the difference between the total water demand and piped water demand. Widespread changes in household behaviour will result in changes to the supply conditions as the distribution of water is altered by the connection withdrawals. This then feeds back into the local supply conditions and may alter household adaptations further. Similarly, changes to the supply conditions deriving from operator interventions are likely to influence household behaviours. These behaviours then influence the withdrawal characteristics and thus the supply conditions.

10.3.3.4 Required Data to Calibrate the Agent-hydraulic Model

The complexities identified in the previous section imply the need for a range of datasets to be able to calibrate a hydraulic model of an IWS system. These datasets go beyond the traditional measurements made in the calibration of hydraulic models of CWS.

Firstly, careful placement of pressure sensors must be designed to ensure the variation in supply conditions is recorded throughout the network. In particular, identifying the lowest elevations in the network to establish the boundaries of any pooling locations. It would also be recommended to record pressure at all inputs to the network due to their variation and the affects this has on pressures across the network.

Unlike under CWS conditions, the results from Lahan indicate that information relating to the household characteristics are also pertinent. As a minimum, an understanding of the distribution of storage volume, typical inlet elevations and prevalence of automatic valves should be surveyed. This enables a distribution to be applied to the network connections and potentially any spatial relationships to be identified.

To capture the consumer behaviour and constant interaction with the piped supply conditions, an agent-based mechanism could be incorporated into the hydraulic modelling framework. An agent-based model enables consumer decision-making to be simulated, which is a key requirement that this study has identified. Households (or agents) can change their withdrawal behaviour according to their network and household characteristics enabling the full complexity of the system to be replicated. This opens the door to modelling long-term changes and the effects of exogenous factors such as the availability of other sources.

10.3.3.5 The Potential for Integration with ISWMM

ISWMM is a very recently developed adaptation to the SWMM hydraulic model that aims to overcome the current limitations discussed in section 2.6.1 and section 0 (Abdelazeem & Meyer, 2024). Although there is no published article on ISWMM to date, it has come to the author’s attention at the IWA World Water Congress 2024. One of the key advantages of ISWMM is its potential to model all phases of the IWS cycle. There is clear congruence between the setup of ISWMM and the ‘agent-hydraulic’ model proposed here, presenting an exciting avenue for a new chapter of hydraulic modelling within IWS. The findings from this study help to develop appropriate consumer demand profiles reducing the uncertainty regarding modelling the consumer, a complimentary addition to the hydraulic mechanisms of ISWMM. The ‘agent-hydraulic’ model takes one-step further than ISWMM, integrating consumer decision making into the model using an agent-based attachment, allowing long-term modelling to be conducted. Integration of the two methods presents an exciting opportunity for future research.

10.3.4 Matching Model Complexity to Desired Output

The complexity discussed in 10.3.3 is relevant for the aim of accurately and precisely modelling connection withdrawal behaviour in models of IWS. For some uses of hydraulic models, this level of detail is unnecessary. As with all modelling applications, the precision at which the system needs to be modelled depends on the desired output.

The predominant output of the agent-hydraulic model is to assess the inequity in water access of households connected to the piped network, which requires the detail described in section 10.3.3. For other modelling applications, the detail described here may be redundant. For example, when selecting pipe sizes, more approximate methods such as average daily patterns could be sufficient since nodes are often aggregated and the specific interactions at the household level are not required. The application of the deterministic, volume-dependent demand approach may present a helpful worst-case scenario as it assumes all connections are open, resulting in maximum velocities and minimal pressures in the network.

The model could be simplified under different IWS contexts. In some locations, the use of large storage tanks and automatic float valves may be ubiquitous, in which case the simplification of deterministic, volume-restricted demands would be reasonable, as discussed in section 10.3.2. In other IWS regimes, the infrequency of supply periods may mean that taps are left open all the time (i.e. at the low end of the IWS spectrum in section 0). This makes the unrestricted assumption appropriate (see section 2.7.1), significantly simplifying the consumer modelling approach. It is posited, however, that the vast majority of IWS systems will have a mixture of different behaviours within the served community. Therefore, a range of consumer modelling techniques will need to be applied. Analysis of the behaviours in this case study, has demonstrated that the inclusion of stochastic demands are a necessary addition to the current available modelling methods. In essence, all other methods are simplifications that could be incorporated into the agent-hydraulic approach described here.

10.4 Long-term Demand Forecasting under IWS Conditions

The variability in monthly household withdrawal volumes and the implications for demand forecasting will be discussed in this section. The additional complexity resulting from the use of other sources will be explored, alongside the use of Consumer Demand Satisfaction (CDS) as a predictor of future demand. Finally, how this influences a transition to CWS and the generalisability to other IWS contexts will be reflected upon.

10.4.1 Lack of Clear Patterns Associated with the Desire for Longer Supply Hours

Section 8.5 investigated the factors associated with both a desire for longer supply hours and the expectation that more water would be used if the supply hours increased. These questions were in part an attempt to ascertain the Consumer Demand Satisfaction (CDS) of the surveyed households (Taylor et al., 2019). Table 8.6 shows that 85% of the IWS households desired an increase in the supply hours, while 68% of the IWS groups expected to use more water if the supply duration increased.

The two factors that had the largest influence on the desire for longer supply hours were the self-reported current hours of supply and whether the household had a yard tap or were fully plumbed. Both factors were not statistically significant at the 95% confidence interval but would be under a 90% confidence interval. The weak correlation with the self-reported hours of supply suggests there may be a relationship between supply hours and the sense that access to water is constrained. In contrast, the estimated supply hours at all pressure thresholds showed a much weaker relationship with a desire for longer supply hours. This suggests that actual supply hours are a weaker predictor of demand satisfaction than self-reported supply hours. Households that have a yard tap were less inclined to desire longer supply hours than the fully plumbed households. This was an unexpected result, perhaps suggesting that households with plumbing believe they could utilise the extra supply hours more than households with a yard tap. Households with a yard tap are therefore more satisfied with the current supply hours. Another unexpected result was that current per capita water withdrawal volume was not associated with a desire for longer supply hours. This suggests that current water withdrawal volume is not a good predictor of consumer demand satisfaction.

Households that desired longer hours of supply tended to also expect to use more water if the supply hours increased (section 8.5). However, 17% of households indicated they didn’t expect to use more water, suggesting that they desired the increase in supply hours for convenience as opposed to needing the additional volume of water. The variables that correlated with an expectation of using more water were a higher HWISE score and lower estimated supply hours above a 4m pressure threshold (Table 8.10). The correlation observed here suggests that higher water insecurity may be due to receiving insufficient water from the piped network. However, Section 10.1.2 discussed the fact that no household or network factors correlated with HWISE, casting doubt on this conclusion.

Table 8.10 showed a statistically significant relationship between having fewer hours of medium pressure (4m head) supply and a greater likelihood the household anticipates using ‘a little’ more water if the supply hours increased. Interestingly there was no correlation at the 1m threshold. This suggests current supply hours of a certain pressure are inhibiting households having sufficient quantities of water. There was also a weak correlation (p=0.08) between the size of household storage volume and a greater anticipation of using more water if supply hours increase. Therefore, it could be inferred that some households have insufficient hours of supply at the required pressure to fill their storage tank. In conjunction with the lack of correlations between these variables and the desire for longer supply hours, the implication is that some households with storage tanks desire increases in the pressure rather than simply hours of supply.

In summary, consumer demand satisfaction cannot be easily predicted in Lahan, as there were few correlations with household or network factors. There are indications that the level of demand satisfaction is influenced by household perceptions of their water supply and there was some evidence that the ability to utilise extra supply hours may influence the expectation that more water would be used if supply hours increased. It could be inferred that some households desire greater supply pressures as opposed to simply supply hours and there may be a correlation between the expectation of using more water and the household HWISE score, contradicting findings in section 10.1.2.

10.4.2 Evaluating the use of Consumer Demand Satisfaction to Forecast Demand

Figure 9.10 reports that no household has a supply period utilisation score of 100%, thus indicating they are not using all the available water. This could be interpreted as showing all connections have 100% consumer demand satisfaction (CDS). However, the survey results summarised in the previous section show that many households would like longer supply hours and believe they would use more water under those circumstances. Thus contradicting the assessment that all households are demand satisfied.

This begs the question of how demand ought to be defined and hence what constitutes demand satisfaction.

The first proposal of this thesis is that CDS should be split into Piped Water Demand Satisfaction (PWDS) and Total Water Demand Satisfaction (TWDS). Section 10.1.6 highlighted that different households rely on the piped water to different extents because of their varying access and use of other water sources. A household with a high PWDS may actually be withdrawing very little water from the piped network as their primary source is a private shallow tube well. Their demand for piped water may change very rapidly if their other source is no longer available. This was exemplified by the step change in demand of one household in Lahan as discussed in section 10.1.6. The demand satisfaction framework proposed by Taylor et al. (2019) fails to reflect the use of other sources. The proposed separation of Piped Water Demand (PWD) and Total Water Demand (TWD) may help improve attempts to forecast the water resource requirements to transition a network to CWS, incorporating the context of the specific network into the estimation process.

The second point is that the framework proposed by Taylor et al. (2019) assumes that piped water demands are static and independent of their local conditions. Section 8.2 showed that households employ different adaptations according to their local supply conditions. It could be inferred, therefore, that as the supply conditions change (e.g. longer supply periods) household adaptations may also change, resulting in different withdrawal practices. The exact way in which this will change the demand of the household requires more research. However, this study has highlighted the variability in demands and potential flaws in assuming household demands will remain static as supply conditions change.

10.4.3 Implications for Demand Forecasting

In section 8.2, households showed signs of adaptation to their current supply conditions. This suggests the system operates in a form of equilibrium between the supply conditions and household behaviours. When a large change to the supply conditions occurs, a new equilibrium will be found following a state of flux between the network and household behaviour. The length of time taken for this new equilibrium to happen cannot be estimated using the data gathered in this case study as it requires long-term measurements pre- and post- significant changes in the system.

Future changes to the system or interventions made by network operators will likely induce new equilibriums. Households may adapt to their new supply conditions and thus withdraw water differently. For example, relying less on storage if the supply hours increase, resulting in more frequent small withdrawals. Households will adapt to the new equilibrium over a period of time, it is this changing state of equilibrium that needs to be assessed and planned for.

The influence of human behaviour in the system means that planners must look beyond simple relationships between supply conditions and demand; including a wider assessment of the water landscape of the city is recommended. Understanding the current practices of households and what drives these behaviours will be crucial to making predictions of how they may change under future scenarios. There is a need for further research to understand the drivers of these behaviours.

Ultimately, the case study of Lahan suggests it is very challenging to forecast demand under IWS. It will likely be influenced by exogenous variables such as the relative desirability and access to other sources of water as well as a complex interaction between supply conditions and human behaviour. It is proposed therefore that more research is required in these areas to be able to formulate methods of forecasting demand under different IWS circumstances.

10.5 Inequity of Piped Water Access under IWS

The section reflects on how the study expands our understanding of inequity and its relationship to both supply conditions and household adaptations. It will highlight the need for greater distinction between the terms ‘inequity’ and ‘inequality’ within the literature. The failure to do so may lead to unintended consequences and potentially damaging network management decisions (such as intervening to make supply more equal which could cause a drastic reduction in piped water access for some households).

In a general sense, the distinction between inequality and inequity centres on how the consumer is viewed. When assessing inequalities, all consumers are considered the same, leading to a one-dimensional distribution of resources. When considering equity, the imbalanced circumstances of the consumers are considered, adding layers of inequality. In an IWS context, this means examining the circumstances of the households supplied by the piped water connection and their ability to satisfy their demand for water. Access to adequate storage and the means to fill their storage therefore become pertinent. In this section, piped water access refers to the availability of water deriving from the piped network, as described by the ‘available when needed’ metric in the hourglass framework.

The three example households presented throughout the results section will be used to explore the concept of inequity of piped water access under IWS. Section 7.1.5 summarises their local supply conditions. Household 3 has CWS but only at the 1m pressure band with their supply dramatically tailing off at higher-pressure thresholds. Household 2 has significantly longer medium and high-pressure supply hours whereas Household 1 has relatively short supply hours at low, medium and high-pressure thresholds.

Their supply hours are reflected in their withdrawal patterns as shown in section 7.3.4. Household 3 is able to regularly withdraw water throughout the day but Households 1 and 2 only withdraw during the supply periods. The withdrawal characteristics also vary significantly across all three households (section 7.3.5). Households 1 and 2 both receive IWS, however, Household 1 only has 150 Litres of mobile storage while Household 2 has 2000 litres of fixed storage. This is reflected in their withdrawal behaviours; Household 2 withdraws most of their water via large withdrawals (over 250 litres) while Household 1 tends to withdraw water via medium sized withdrawals (20-250 litres). Therefore, Household 1’s water-use activities are more likely to be constrained to the supply periods. Consequently, they are likely to have significantly reduced access to water, compared to Household 2.

In some ways, Household 3 has the best access to water due to the continuous water supply in that region. However, the water supply is of low pressure meaning flowrates are low and it could not feed a rooftop tank without the house having to install their own pumps. They are therefore more vulnerable to changes in supply hours as their storage options are limited. Household 2, on the other hand, consistently has eight hours of supply at a pressure that can fill a roof top storage tank. It could be argued that Household 2 has the better and more resilient access to water due to the regular and reliable supply periods that enable effective household adaptations such as a rooftop tank. This is perhaps reflected in Figure 7.27, which shows a clustering of households in the vicinity of Household 2 that all rely entirely on the piped water supply.

Section 7.2.5 showed that the storage volume a household acquires is associated with their wealth. This suggests that the ability to acquire and install large storage tanks is hindered by the affordability of the asset. The census results in Table 5.1 suggest other wealth related factors may also be relevant. In wards 1-10, 26.9% of households have walls that are not built from cement-bonded bricks and 41.7% of households do not have reinforced concrete roofs. Both of these construction types make it impracticable to install large rooftop storage tanks that could weigh several tonnes. The space requirement within the household compound to fit a large tank could also be a limiting factor.

Analysis of the three example households paints a far more complicated picture of inequitable water supply than is considered in many current studies.

10.5.1 The Crucial Difference between Inequality and Inequity of IWS Systems

A common aim in engineering studies of IWS is to optimise the equity of water supply across the network (section 2.6.2). This could help reduce the water stress of IWS households. However, the metrics used to define the water supply of households are crucial and fundamentally affect the outcome of the optimisation scheme. Many studies use the metric of consumer demand satisfaction or satisfaction ratio, which is measured as the volume of water that can be collected by a tank placed at the connection divided by the household demand (section 2.6.2). This means the equity score of the network is entirely defined by the equality of water distribution across the network. The previous section shows that this is significantly removed from a measure of the water access of households. The dual influence of supply conditions and household adaptations means the difference between inequality and inequity is consequential. This thesis argues that inequity must incorporate the effects of both unequal supply conditions and unequal household adaptations. An aim of minimising inequity is therefore very different to minimising inequality. Studies aiming to investigate and/or optimise inequity of piped water access must look beyond just the unequal supply of water across the network to gain a more complete view of genuine consumer demand satisfaction.

At its most extreme, the aim of optimising the equality of supply hours could cause significant increases in water stress of households. The findings discussed in section 10.1.2 suggest households make adaptations according to their local supply conditions; this leaves them vulnerable to changes. For example, the CWS group have significantly lower storage volume than the IWS group (Table 8.1). Optimising the equality of supply hours in Lahan could cause a drastic reduction in supply hours to some areas such as the CWS zone. Due to their lack of adaptations, this would reduce their access to piped water significantly. Similarly, interventions to optimise the equality of pressures across the network could lead to significant localised reductions in pressure. This could have the result of removing a households' access to piped water, due to insufficient pressure to reach their roof top tank. Interventions aimed at improving equity must therefore consider the range of households in the network and avoid focussing solely on improving metrics that only account for the average consumer.

The vulnerability of households to changes in the network or wider conditions has thus far lacked attention from the scientific literature. Vulnerability ought to be considered more carefully when promoting interventions in IWS systems. The CWS households in Lahan are vulnerable to network changes, the households with roof top tanks are vulnerable to input pressure changes and the households in the northern region are vulnerable to their local input source failing. The key benefit of the hourglass framework is to bring these issues to the fore. By highlighting the intersection of the unequal supply conditions and unequal household conditions, new avenues of achieving water access equity across an IWS network are opened up (for example, improving access to storage tanks). Viewing the IWS system through the lens of the hourglass framework, highlights the unintended consequences that have been discussed here, enabling a more holistic approach to optimising access to water under IWS.

10.6 Implications for Planning a Transition to Continuous Water Supply

The findings from this case study have several implications for planning a transition to CWS. Transitioning a network is usually the ultimate goal for IWS networks, as continuous operation negates the water quality issues relating to intrusion and achieves equity in water access amongst those connected to the piped network. The optimal steps to achieve a transition are not well established however (section 2.4). This section first discusses the differences between the IWS and CWS groups within the Lahan network and then summarises practical implications of the results in relation to a transition.

10.6.1 Differences between the IWS and CWS Groups

Figure 7.14 highlighted that the boundary between IWS and CWS is somewhat blurry, in this study the self-reported supply hours were therefore used in the analysis. The differences observed between the IWS and CWS groups in section 8.1 suggest that households will eventually change their household adaptations to new supply conditions. Therefore, in the event of a transition to CWS, one could expect that household behaviour will alter. As discussed in section 10.3.1, this will have knock-on effects for the withdrawal types of households and therefore the hydraulics of the network and distribution of water. The transition from IWS to CWS is just one example of the concept of changing equilibriums discussed in section 10.4.3.

10.6.2 Reduced Concern of Rapid Increases in Demand

The evidence from the case study suggests a rapid increase in demand from household withdrawals is unlikely to occur if the supply period increased to 24 hours a day. Currently the CWS group do not on average use more water than the IWS group. In addition, the water withdrawal volume was not correlated with local supply hours. As discussed previously, the withdrawal volume of households in Lahan is influenced by many overlapping variables with no clear relationship emerging. The extent to which this generalises to other IWS regimes cannot be assessed. As discussed in section 10.2.1.4, withdrawal characteristics in IWS regimes with fewer/shorter supply periods than Lahan, are likely to be more strongly influenced by the supply conditions. The tendency for withdrawal volume to be more elastic to changes in supply hours is therefore likely to be greater under those circumstances.

The hourglass framework aims to reflect the complexity of the system showing that many factors influence the withdrawal volume of households and that they derive from both the supply conditions and household characteristics. When planning a transition to CWS it is therefore recommended to have some level of understanding of both of these spheres to help evaluate the likelihood of increases in demand across the spectrum of consumers in the network.

10.6.3 Network Zoning

A common aim of piped network managers is to segment the network into zones (Charalambous & Laspidou, 2017). This enables better identification of leakage hotspots, as more precise water balances can be achieved. In addition, it is often considered easier to transition the network to continuous operation one zone at a time (Ilaya-Ayza et al., 2018). The findings from Lahan highlight the need for caution when planning network zoning. Any hydraulic separation of the network could have drastic consequences on the local supply hours of some areas due to the pooling phenomenon. In Lahan, water drains down to the lowest elevations, however, if valves were installed to separate a southern zone, then the pooling location would be moved to where the valve is. The water in the pipes of the southern zone would still pool at the lowest elevations, however, the volume from the rest of the network would not. This would likely reduce the local ‘low-pressure’ supply hours of many households.

The effects of the reduction in local supply hours of the CWS region would be amplified by their lack of adaptations to IWS. In Lahan, 89% of the sampled CWS households did not have a large storage tank; therefore, their water access is highly dependent on the local supply conditions. A reduction in supply hours would not be mitigated by storing water as is practiced in other parts of the network.

10.7 Lessons Learned from the Data Collection Programme

Implementing the data collection described in this thesis led to several practical findings that have not been documented previously, to the best of the authors knowledge. Recommendations for how the data collection would be done if it were to be repeated are also presented.

10.7.1 Telecommunication Network

There are several means of transferring data via ‘smart’ technologies that rely on different network infrastructure. For this study, the 4G network was selected based on discussions with local partners and assessment during a preliminary trip to Lahan. The use of 4G connectivity with local SIM cards proved to be a good choice with relatively consistent transfer of data (see section 6.5.4.1). The signal strength throughout the location was adequate allowing the widespread deployment of sensors. The rise of smart phone usage demands improvements to 4G networks, and this is therefore likely to be a good option in a number of localities. It would certainly be recommended by virtue of this fieldwork, but the conditions of the specific site must always be assessed in advance.

An unforeseen issue with using the 4G network with local SIM cards occurred in November 2023 and led to the reduction in available household meter data from this point onwards. The issue related to the National Telecommunications Authority of Nepal introducing a crackdown on ‘grey’ smart phones i.e. devices that did not have official registration with the authority. Unfortunately, this affected the household meter devices used in this study causing many to lose connectivity before being reconnected several months later. A thorough check of the local regulations is therefore advised.

10.7.2 Equipment Procurement

In this study, the household meters and pressure loggers were acquired in the UK and shipped to the case study site. Consideration was given to acquiring the equipment in country or through local supply chains, however, this proved to be difficult due to the specialised nature of the equipment and detailed specification. Acquiring them from more established vendors improved the chances of good quality equipment but did incur large costs at customs that could not be avoided. The added burden of shipping them was deemed worthwhile due to the benefits of quality assurance. In other locations, if the means of acquiring equipment locally are established and trusted, then this may be a better option, but it will depend on the local circumstances and partner experience.

10.7.3 Pressure Logger Locations

As described in section 10.3.3.4, the placement of pressure loggers needs to be well thought through in order to capture the wide variation of conditions within the network. Installing pressure loggers stratified according to elevation is recommended. This enables the pooling locations to be identified and would improve the interpolation technique employed to estimate pressures across the network. For the purposes of this study, the measurement interval of 15 minutes was adequate. Conducting a survey prior to the installation of loggers could also be highly beneficial as this may identify areas that warrant pressure measurement such as the pooling locations.

10.7.4 Surveys are a Reasonable Surrogate for Measured Network Data

The survey reveals a lot about the withdrawal practices of households and is a good surrogate for understanding how the network is functioning in the absence of measurement devices such as pressure loggers and household meters. Table 9.1 showed correlation between household responses and withdrawal practices. Self –reported supply hours did not show perfect alignment but was a reasonable approximation and crucially identified the CWS area. It is important when interpreting information such as the self-reported supply hours that the household characteristics are taken into account. The response will be equivalent to the ‘felt’ supply hours that section 9.6 showed will be highly influenced by the elevation of their inlet.

10.7.5 Improved Survey Design

Prior to conducting the fieldwork, colleagues in the social science departments at the University of Sheffield were contacted to discuss their experiences of conducting surveys in an international context. The practical advice received was very helpful for planning the survey approach outlined in section 0 and ensuring the ethics of involving human participants had been considered thoroughly. However, there was a missed opportunity to have greater input regarding the wording and design of the survey. When analysing the survey data, it became apparent that some questions lacked the rigour required to gain strong conclusions from respondent’s answers. This partly led to some questions being used more heavily in the data analysis than others.

When designing the survey, priority was given to keeping the survey as short as possible to limit the time burden on participants and increase the likelihood of households consenting. However, this limited the findings that could be drawn from the data. For example, when asking ‘how much of your water demand is provided by the piped supply?’ further questioning on the exact uses of the different sources would have added credibility to responses. The following are a list of questions that would have improved understanding of household behaviours beyond what was gleaned from this study. It is strongly recommended to include these questions (as a minimum), alongside input from experts in survey design, in any future research with similar aims to this study.

- *Detailed plumbing arrangements:*
    - *Where is the piped water entry point? E.g., yard tap, ground tank, rooftop tank, straight into household plumbing…*
    - *What storage containers do you use for your different water sources?*
    - *Are other water sources connected to the household plumbing?*
- *What is the elevation of the storage tank or household water entry point in relation to the connection tapping location?*
- *Do you have a float valve and is it functioning?*

- *For what activities are each water source typically used for?*
- *What are your preferences regarding the different available sources and why? Price, quality, reliability etc.*
- *Do you run out of water, if so, when?*
- *Do you have sufficient storage volume? If not, how much would you like? Why don't you purchase larger storage volume?*

10.8 Limitations of the Study

This section aims to evaluate the limitations of the data and results to ground the findings in context.

10.8.1 Using a Single Case Study

Given the spectrum of IWS systems and their highly varying properties (D. D. J. Meyer et al., 2023), the ideal dataset to investigate household water withdrawal behaviour under IWS conditions would involve multiple case study sites. The practicalities of conducting such a widespread field investigation were, unfortunately, beyond the scope of this study. Given the paucity of data on IWS networks, extensive field data from a single site still constitutes a significant contribution to progressing understanding of IWS, and achieved the studies aims.

A wide range of supply schedules come under the banner of Intermittent Water Supply, meaning generalisability between systems is limited. The supply regime in Lahan of two regular and reliable supply periods per day is towards the upper end of this spectrum and could be classed as 'good' IWS. Households receive a relatively high level of access to piped water compared to other systems. This obviously affects the supply conditions but also the household adaptations, both of which will be different in other IWS contexts. It is hoped that this study has identified some general principles of IWS that are reflected more widely in other IWS systems, but care must be taken in assessing the extent to which generalisation can be made.

10.8.2 Sample Size

The household sample size is not large enough to be representative of Lahan (approximately 1.4% of connections were sampled). Therefore, the findings cannot be used to characterise the Lahan network as a whole, rather they indicate the range of behaviours across the network. For the purposes of this study, this is not a significant problem as the aim was not to characterise the entire network but to understand in more detail the breadth of behaviours and, in particular, how they relate to both the piped supply conditions and household characteristics. Moreover, the sample size of this study far surpasses anything before it in relation to IWS networks.

10.8.3 Meter Errors

There was the potential for the meters to be providing erroneous data. This was largely mitigated through a series of manual checks and calibrations conducted in 2023 as described in section 6.5.4.2. Additionally, the concern that the meters would record air going through them resulting in distorted the water withdrawal measurements has been significantly alleviated. Section 6.5.3 showed that this does not seem to be a substantial problem. Furthermore, the results regarding the utilisation of the supply periods suggests consumers do not tend to leave their taps open the majority of the time minimising the risk of air escaping via customer taps. In addition, the survey asked whether households leave their tap open all the time and only 14% of respondents said they did, although this is difficult to verify.

10.8.4 Time Difference between Collection of Datasets

As explained in section 6.6, the survey was conducted between September to December 2022 while the pressure data was only available from April 2024, resulting in a maximum time difference of 1yr 7months. In this time, the household circumstances could have changed making the survey records no longer representative of the household. This generates some uncertainty in the results when comparing the ‘supply conditions’ and ‘household adaptations’ that could not be mitigated. However, it is unlikely that a significant proportion of the households changed circumstances drastically within this period. Moreover, the comparisons have been used to establish general trends and so some uncertainty can be accommodated.

10.8.5 Interpolation Approach Failing to Replicate Pooling Phenomena

As described in section 6.7.2, the interpolation approach uses a radial basis function to estimate pressure across the network between pressure sensors. The approach fails to capture the physical process of the network draining, in particular the movement of the free surface. This error feeds into the estimation of local supply hours that will particularly affect the lower elevations that are in the ‘tidal zone’. On the border between intermittent and continuous supply hours, the approximation of pressure will have greater uncertainty and thus the estimated supply hours must be taken with greater caution.

The imprecise interpolation technique means that comparisons between the synchronous local pressure estimations and the withdrawal data of households are somewhat limited. Estimating when the local supply period of a household has started with great precision is not possible. Therefore, calculations of the time difference between the local supply period beginning and household withdrawal occurring cannot be made with great certainty. As a result, this analysis was excluded from the thesis. As described in section 2.7.1 of the literature review, most methods of modelling consumers in hydraulic models assume that households withdraw as soon as water is supplied to the household. Therefore, this analysis would have been helpful to confirm/deny this behaviour in the case study. The available data still manages to largely address this question however. This behaviour would only occur if all households had an automatic valve attached to their tank. The survey showed just under one-half of households have a large storage tank where this would be implementable. Furthermore, it was informally observed that the use of float valves (or equivalent) was not widespread even within these households. Hence, the application of this simplification to all consumer nodes is not supported by the case study.

10.8.6 One-Minute Aggregation of Withdrawal Measurements

The household meters used in this study record withdrawal on a one-minute interval, this means the connection water withdrawal is essentially aggregated to one-minute. This limits our ability to know the exact manner in which withdrawal occurs. The effects of this are three-fold:

1. Withdrawing water at a rate of 5 litres/min for one whole minute will be recorded the same as withdrawal at 10 litres/minute for 30 seconds.
2. Any withdrawal that is less than one litre and does not cause the meter dial to pass the zero mark will not be recorded.
3. Non-continuous withdrawal where some water is taken in consecutive minutes cannot be distinguished from continuous withdrawal.

These errors relating to measurement precision will cause underestimations of flow rates, overestimations of continuous withdrawals and underestimations of very small withdrawals respectively. This does not however significantly alter the understanding of water withdrawal discussed in this thesis and has minimal effect on the key findings that follow.

11 Conclusions

To date, no other study has measured an IWS network as comprehensively as this study. The aim of this thesis was to investigate how supply conditions and household characteristics influence water withdrawal; the methods employed have produced a unique dataset enabling these relationships to be examined for the first time. The findings from the case study site, coupled with the development of a conceptual framework, have brought new perspectives to the field of IWS research.

Analysis of the case study has revealed the dual influence of supply conditions and household characteristics on withdrawal practices, and how this results in highly heterogeneous behaviour. Comparison with existing approaches has exposed that new methods of modelling consumers in hydraulic models of IWS are required. The findings put a spotlight on understanding household characteristics to inform such models. A wide range of valuable insights into the functioning of IWS networks can be obtained simply from household surveys. The finding that household decisions (such as acquiring storage volume) are coupled with supply conditions is a novel insight that must be incorporated into long-term scenario analysis.

The ‘hourglass’ framework provides a new lens for examining IWS systems and a helpful illustration of the complex relationships within it. The framework highlights the crucial intersection of supply conditions and household adaptations to determine inequitable access to water under IWS conditions. The framework proposes the use of the ‘available when needed’ metric to define water access under IWS, a significant departure from current approaches that tend to rely on some form of ‘supply ratio’. The study has revealed the vulnerabilities of different groups that have not been considered before; crucially, these must be taken into account when planning network interventions.

The research has demonstrated that the widespread use of other water sources complicates the popular notion of ‘consumer demand satisfaction’. The highly variable withdrawal volumes changes our understanding of consumer demand under IWS. This lead to a proposed separation of piped water demand and total water demand in the context of long-term demand forecasting. The study has brought new significance to understanding the availability and relative desirability of other water sources in order to estimate the required water to transition to CWS.

The findings from the case study, and development of the hourglass framework, challenge current approaches to improving ‘equity’ under IWS conditions. The thesis calls for greater distinction between the definitions of inequality and inequity in studies of IWS. Much of the current literature uses modelling methods that do not have sufficient evidence to justify their assumptions (e.g. deterministic demands). The work presented in this thesis highlights the potential dangers of this, and underlines the need for more field data to improve our understanding of the complex issue of IWS.

11.1 Summary of Key Findings

The following is a summary of the key findings from this study and how they relate to the initial objectives.

1. Household water access under IWS is determined by both the network and household characteristics. Many current studies investigating the equity of water distribution under IWS fail to capture the influence of household characteristics and therefore just measure the equality of water delivery across the network. This optimisation of equality is a different aim to optimising equity, which needs to be made explicit. Optimising equity could result in significantly different outcomes and recommendations for network management interventions. [Obj. 4]
2. Household withdrawal volume is not governed by any single parameter; both supply conditions and household characteristics influence withdrawal volume. It was also highly variable suggesting historical withdrawal volumes are not a sufficient predictor of future withdrawal volume. [Obj. 2]
3. The withdrawal behaviour of households was highly variable; households exhibited a mixture of frequent small withdrawals that were categorised as direct-use withdrawals and less frequent (but more impactful) tank-filling type withdrawals. The tendency for one withdrawal type to dominate the other was highly influenced by household storage volume. [Obj. 2]
4. In this case study, water withdrawal was not deterministic in nature, therefore, modelling withdrawal in hydraulic models of IWS networks as a passive emission of water (be it unrestricted, volume-restricted or flow-restricted methods) does not accurately represent the behaviour observed in the case study. [Obj. 2, Obj. 3]
5. Household choices play an active role in defining withdrawal characteristics. Utilising stochastic demands could enable the influence of both local supply conditions and household behaviour to be incorporated in the definition of withdrawal characteristics. [Obj. 3]
6. The adaptations employed by households are influenced by their local supply conditions. These strategies, particularly storage, affect the manner in which households withdraw water from the piped network (i.e. direct-use vs tank-filling). This in turn affects the distribution of water across the network and hence their local supply conditions. This creates a coupling between the network and households. [Obj. 2, Obj. 3]
7. A conceptual framework enabled the complex relationships identified in the case study to be ordered into a logical structure. The structure brings a new perspective to IWS systems, framing the complex relationships identified in the case study, and their relationship to the water access of households under IWS conditions. [Obj. 3]

8. The supply conditions ‘felt’ at the household are influenced by a combination of the supply conditions (source characteristics, proximity to source and relative elevation) and their household characteristics (inlet elevation and plumbing arrangements). Estimating a household’s access to piped water under IWS should consider both. [Obj. 2]
9. Elevation has a significant effect on the distribution of water across an IWS network, particularly in locations where ‘pooling’ occurs meaning some households have significantly longer supply hours than the average (although the pressures are low). [Obj. 2]
10. The draining phase of an IWS cycle must be included in models of IWS if the aim is to represent the unequal distribution of water across the network. [Obj. 3]
11. Wealth is influential in the adaptations that households employed in the case study. Socio-economic factors can therefore influence both water withdrawal behaviour and access to piped water under IWS conditions. [Obj. 4]
12. Exogenous variables such as the availability and desirability of other sources means piped water demand is different to total water demand. This adds complexity to the notion of demand satisfaction and estimations of future demand. [Obj. 3]
13. The SDG metric of ‘available when needed’ can characterise a household’s water access in the context of IWS better than the commonly used ‘satisfaction ratio’. This is because it can encompass the effects of both network and household conditions. [Obj. 3, Obj. 4]
14. Households employ adaptations according to their local supply conditions. Therefore, they could be vulnerable to interventions that change the local hydraulics, for example, schemes that segment the network. [Obj. 4]

11.2 Implications for Network Operators

The findings from this research offer valuable insights for operators of IWS networks. The subsequent section summarises key areas that merit the attention of network operators.

- Negative pressures were observed highlighting the potential for local contamination of the piped water
    - Strategic installation of air-release valves could enable a method of equalising the negative pressures through a controlled orifice, minimising the risk of contamination
    - Alternatively, CWS ensures these types of negative pressures would not occur
- Localised pooling phenomena requires careful management
    - Zoning the network may alter where water drains to and therefore dramatically change local supply hours which households aren’t adapted to, therefore it is important to measure where/when pooling happens

- Changes to household characteristics and the wider water landscape can affect supply conditions and vice versa
    - Demand forecasting should consider that piped water demands can drastically change
- Transitioning to continuous water supply may not lead to significant changes in piped water demand
    - Prioritise regularity and reliability of supply in the first instance as it allows households to adapt to the supply conditions (e.g. obtain appropriate storage)
- To create a representative hydraulic model of an IWS network, it is recommended to conduct a survey of the population to establish (as a minimum) distributions regarding: storage size (connected to piped supply), elevation of inlet, prevalence of float-valves

11.3 Implications for Planners/Policy-makers

The insights derived from this research also carry significant implications for planners and policymakers of IWS systems. The following section highlights key findings that relate to a more strategic perspective of system management:

- IWS does not achieve universal and equitable access to water (SDG 6.1), although it may do for some households in the network. CWS is the only truly equitable method of water delivery (for those connected to the piped network)
- Equity under IWS requires a measure of the unequal distribution of water across the network and the unequal ability of households to employ adaptations
- Aiming for equal supply hours is not the same as equitable water access
    - Some households have far lower capacity to cope with changes in supply hours
    - When making interventions, the vulnerability of households ought to be considered
- Alongside helping marginalised households get a piped water connection, helping them acquire sufficient storage may also be key to ensuring they have water ‘available when needed’
- Asking households about their current supply conditions could give a reasonable understanding of the piped network functionality in the absence of pressure and flow data
- To enable demand forecasts of an IWS network, it is recommended to conduct a survey of the population to establish distributions regarding: availability and use of other sources, water-use activities the piped supply fulfils, relative preference for different sources, plumbing configuration

11.4 Future Research

The need for further research has been noted throughout the discussion, however, a summary is provided here. This work has highlighted three key strands for future research:

(i) The need for further case studies across the spectrum of IWS systems;

(ii) Development of the proposed modelling techniques for consumer withdrawal under IWS;

(iii) Greater collaboration with social-science disciplines to understand the human behavioural elements of IWS systems.

11.4.1 More Case Studies of IWS

The complimentary datasets collected in this study have enabled new insights into the field of IWS research; however, more case studies are required. Studies using a similar approach in other IWS locations would allow the spectrum of IWS to be understood in greater detail. Understanding the similarities and differences in withdrawal behaviours under different supply regimes would enable the new modelling approaches proposed in this study to be evaluated.

In addition, recording an IWS network undergoing significant changes could bring new insights. It would help build on the concept of changing equilibriums that have been presented in this research. Understanding the rate of change of household behaviours in response to supply changes would inform long-term forecasts, aiding efforts to plan a transition to CWS.

Analysis of other cases studies would also help answer the question of the extent to which network pressure loggers and household surveys are sufficient to build an accurate model of IWS. Evaluating whether the range of withdrawal behaviours can be adequately predicted by survey and pressure data alone, would remove the need for costly and time-consuming installation of household meters.

11.4.2 Development of IWS Modelling Techniques

A key observation of this study was that withdrawal behaviour is stochastic and highly heterogeneous. Adapting the PRP method to an IWS context could enable these behaviours to be replicated. It is posited that the dual influence of household choices and supply conditions will cause withdrawal arrival times to differ significantly to the distributions used under CWS conditions. Significant adaptation of the PRP method may therefore be required to bring this to fruition.

Recent developments relating to the hydraulic simulation of the full IWS cycle make the ‘holy grail’ of IWS research (a calibrated, validated model of IWS) more attainable. Integrating the consumer withdrawal approaches described here with an effective hydraulic solver presents a promising avenue for future research.

Integration of agent-based models with a hydraulic model offers a possible route to implementing the complex feedback loops identified in this study. Developing the ideas proposed in this thesis into a functioning ‘agent-hydraulic’ model requires further work, particularly understanding the drivers of human behaviour that will define the decision making processes of the ‘agents’. Such research could unblock key restrictions to our ability to predict and plan long-term changes to IWS networks. This could help ‘grease the wheels’ of transitioning networks to CWS and ultimately achieve SDG 6.1.

11.4.3 Greater Insight into Human Behaviour

As previously highlighted, greater insight into the human behavioural elements of IWS would benefit the field of IWS and inform practical management approaches. This study has brought unprecedented attention to the value of understanding consumers in IWS systems and how household behaviours play a pivotal role in the system. However, there is significant potential to build on this, particularly through greater collaboration with disciplines in the social-sciences. Surveys that go into greater depth to understand the human behavioural elements of IWS will compliment engineering efforts to better manage the piped network.

Figure 11.1 summarises some of the key relationships in the hourglass framework that have not been examined in this study and require more data from other IWS sites.

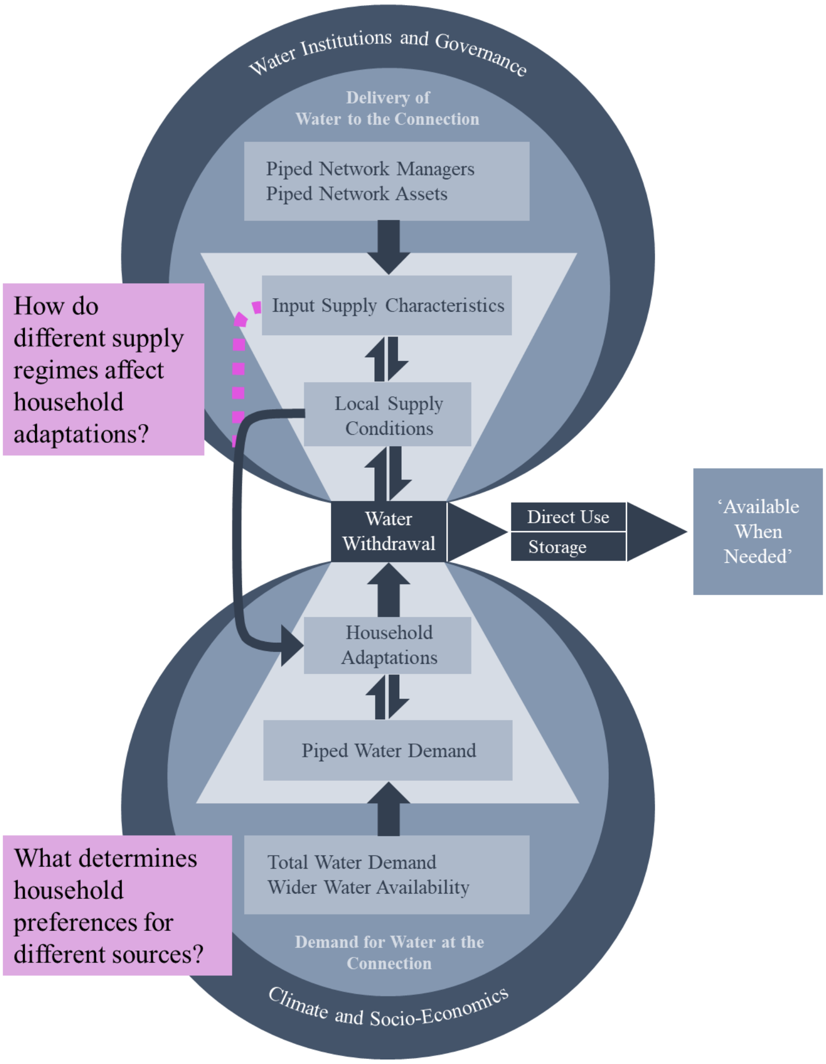


Figure 11.1: The Hourglass Model with Areas that Require Further Attention Highlighted

11.5 Outlook

Much of the literature related to IWS, particularly from engineering-focussed studies, overlooks the fact households (or nodes) are intelligent, active beings that must gain access to water and therefore have adapted to their current situation. This must be taken into account when considering interventions to the piped network. The drive of many studies has been to optimise ‘equity’ without having a grasp of what equity means in this context. They typically involve maximising equality of supply across the network and do so using heavily simplified (and inaccurate) modelling methods, ignoring the complexity of consumer withdrawal behaviour as well as key components of the water delivery cycle (the filling and draining phases). This thesis sheds more light on these assumptions, paving the way for more appropriate modelling of IWS systems. The hourglass framework brings a new perspective to the problem of IWS, shifting the viewpoint from the unequal supply of water, to the inequitable access to water of the served households. The hope is that improved models, that incorporate the complexity of the system, will inform better management strategies and ultimately improve access to water for all.

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Appendix A – Supplementary Procedural Information

i. Timeline of Events across the Study Period

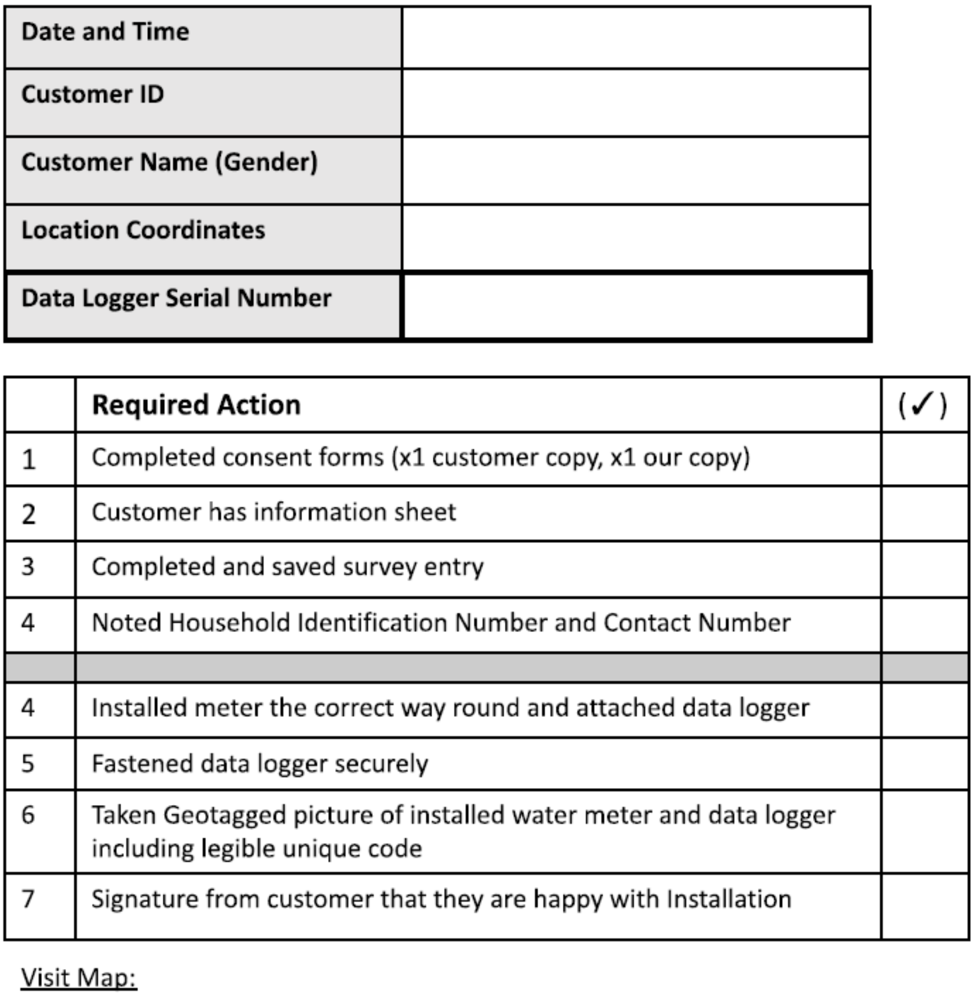
The table below summarises the timeline of events that occurred relating to the piped network and data collection across the study period 2022 – 2024.

Table 12.1: A summary of the key events related to the study of the piped network

Date	**Event**
6th – 17th June 2022	Reconnaissance trip to Lahan, Nepal
13th September – 17th December 2022	Fieldwork conducted in Lahan, Nepal
1st January 2023	All smart household meters installed by this date
June – July 2023	Five air valves installed in Northern locations
11th November 2023	Smart household meters started to lose connectivity due to issues with SIM card registration
30th November 2023 – 30th January 2024	Pressure logger installations
31st January 2024	All smart pressure loggers installed by this date
8th March 2024	Network valve adjusted so water from OHT2 is now feeding directly into distribution instead of feeding OHT1
April 2023 – April 2024	777 new household connections added across the network

ii. House Visit Checklist

The form below is a copy of the house visit checklist used when conducting the survey to ensure all necessary information was captured and crosschecks could be made with the master database.



Date and Time	
Customer ID	
Customer Name (Gender)	
Location Coordinates	
Data Logger Serial Number	

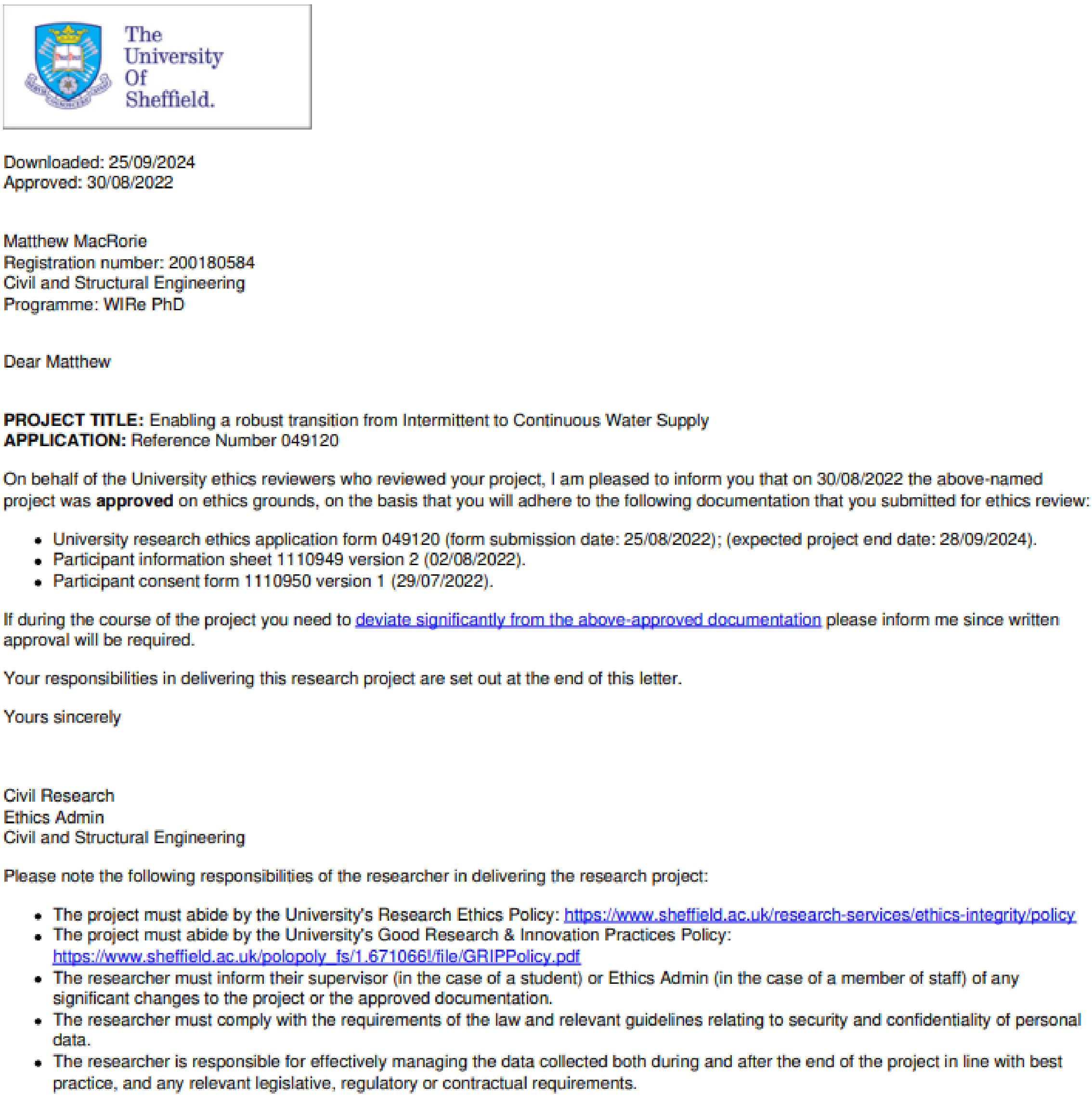
	Required Action	**(✓)**
1	Completed consent forms (x1 customer copy, x1 our copy)	
2	Customer has information sheet	
3	Completed and saved survey entry	
4	Noted Household Identification Number and Contact Number	
4	Installed meter the correct way round and attached data logger	
5	Fastened data logger securely	
6	Taken Geotagged picture of installed water meter and data logger including legible unique code	
7	Signature from customer that they are happy with Installation	

Visit Map:

Figure 12.1: Copy of the house visit checklist

iii. Ethics Review Approval Letter

The following is a copy of the ethics review approval letter granting permission to proceed with the fieldwork (September – December 2022) given that the ethical considerations have been addressed.



The
University
Of
Sheffield.

Downloaded: 25/09/2024
Approved: 30/08/2022

Matthew MacRorie
Registration number: 200180584
Civil and Structural Engineering
Programme: WIRe PhD

Dear Matthew

PROJECT TITLE: Enabling a robust transition from Intermittent to Continuous Water Supply
APPLICATION: Reference Number 049120

On behalf of the University ethics reviewers who reviewed your project, I am pleased to inform you that on 30/08/2022 the above-named project was **approved** on ethics grounds, on the basis that you will adhere to the following documentation that you submitted for ethics review:

- University research ethics application form 049120 (form submission date: 25/08/2022); (expected project end date: 28/09/2024).
- Participant information sheet 1110949 version 2 (02/08/2022).
- Participant consent form 1110950 version 1 (29/07/2022).

If during the course of the project you need to deviate significantly from the above-approved documentation please inform me since written approval will be required.

Your responsibilities in delivering this research project are set out at the end of this letter.

Yours sincerely

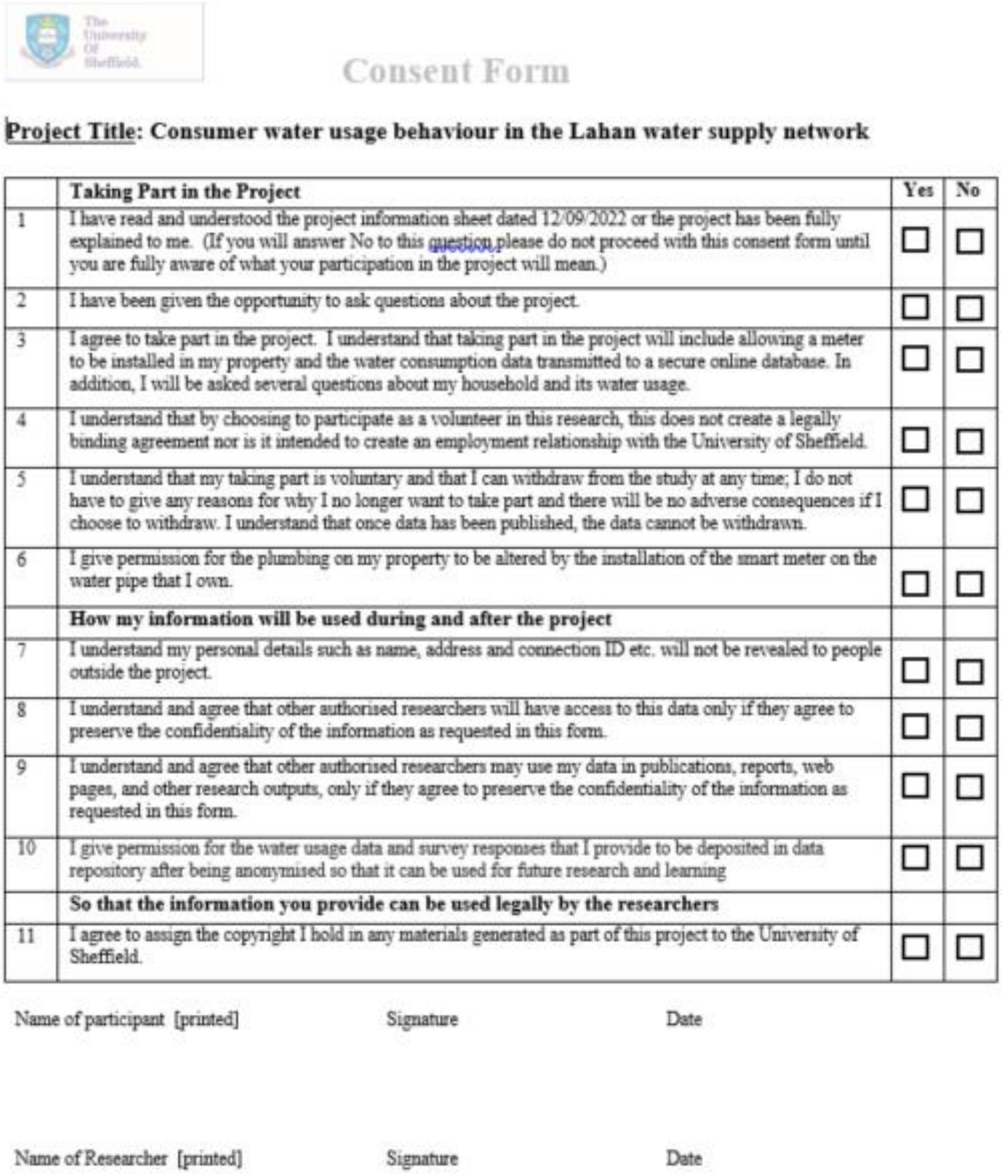
Civil Research
Ethics Admin
Civil and Structural Engineering

Please note the following responsibilities of the researcher in delivering the research project:

- The project must abide by the University's Research Ethics Policy: https://www.sheffield.ac.uk/research-services/ethics-integrity/policy
- The project must abide by the University's Good Research & Innovation Practices Policy: https://www.sheffield.ac.uk/polopoly_fs/1.671066!/file/GRIPPolicy.pdf
- The researcher must inform their supervisor (in the case of a student) or Ethics Admin (in the case of a member of staff) of any significant changes to the project or the approved documentation.
- The researcher must comply with the requirements of the law and relevant guidelines relating to security and confidentiality of personal data.
- The researcher is responsible for effectively managing the data collected both during and after the end of the project in line with best practice, and any relevant legislative, regulatory or contractual requirements.

Figure 12.2: Copy of the Ethics Review approval letter

iv. The Household Consent Form participants had to sign before proceeding



The University Of Sheffield.

Consent Form

Project Title: Consumer water usage behaviour in the Lahan water supply network

	Taking Part in the Project	**Yes**	**No**
1	I have read and understood the project information sheet dated 12/09/2022 or the project has been fully explained to me. (If you will answer No to this question please do not proceed with this consent form until you are fully aware of what your participation in the project will mean.)	☐	☐
2	I have been given the opportunity to ask questions about the project.	☐	☐
3	I agree to take part in the project. I understand that taking part in the project will include allowing a meter to be installed in my property and the water consumption data transmitted to a secure online database. In addition, I will be asked several questions about my household and its water usage.	☐	☐
4	I understand that by choosing to participate as a volunteer in this research, this does not create a legally binding agreement nor is it intended to create an employment relationship with the University of Sheffield.	☐	☐
5	I understand that my taking part is voluntary and that I can withdraw from the study at any time; I do not have to give any reasons for why I no longer want to take part and there will be no adverse consequences if I choose to withdraw. I understand that once data has been published, the data cannot be withdrawn.	☐	☐
6	I give permission for the plumbing on my property to be altered by the installation of the smart meter on the water pipe that I own.	☐	☐
	How my information will be used during and after the project		
7	I understand my personal details such as name, address and connection ID etc. will not be revealed to people outside the project.	☐	☐
8	I understand and agree that other authorised researchers will have access to this data only if they agree to preserve the confidentiality of the information as requested in this form.	☐	☐
9	I understand and agree that other authorised researchers may use my data in publications, reports, web pages, and other research outputs, only if they agree to preserve the confidentiality of the information as requested in this form.	☐	☐
10	I give permission for the water usage data and survey responses that I provide to be deposited in data repository after being anonymised so that it can be used for future research and learning	☐	☐
	So that the information you provide can be used legally by the researchers		
11	I agree to assign the copyright I hold in any materials generated as part of this project to the University of Sheffield.	☐	☐

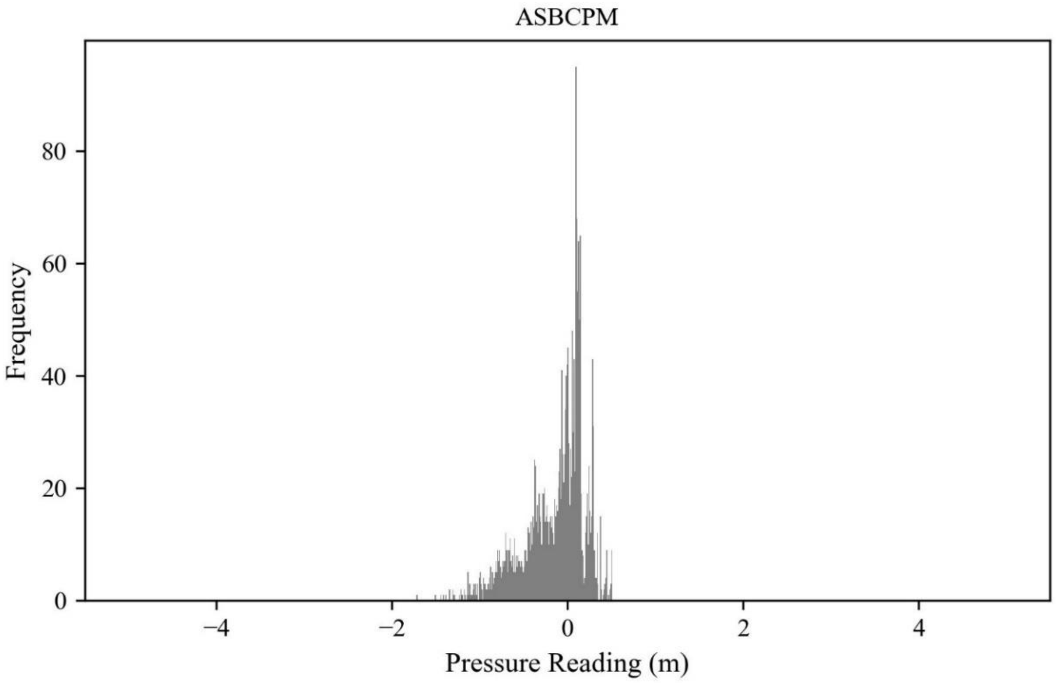
Name of participant [printed] Signature Date

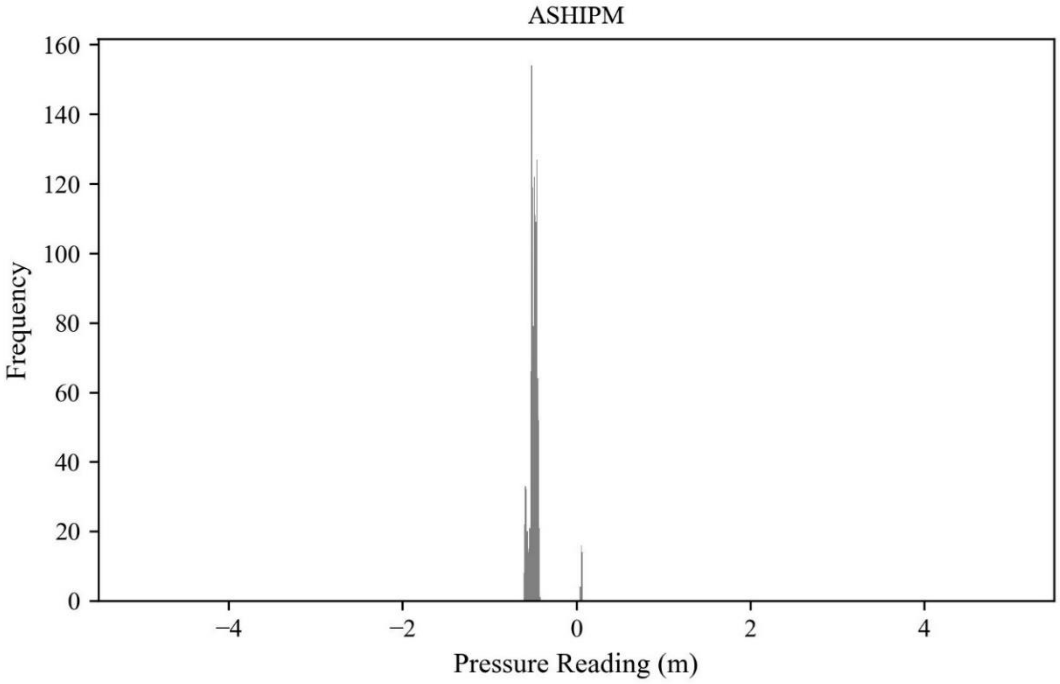
Name of Researcher [printed] Signature Date

Figure 12.3: Copy of the participant consent form

v. Pressure Logger Offsetting Procedure

The figures below are histograms of readings between -5 and 5m head for all pressure loggers used in this study. They are used to help assess whether the logger requires offsetting due to a consistent zeroing error.





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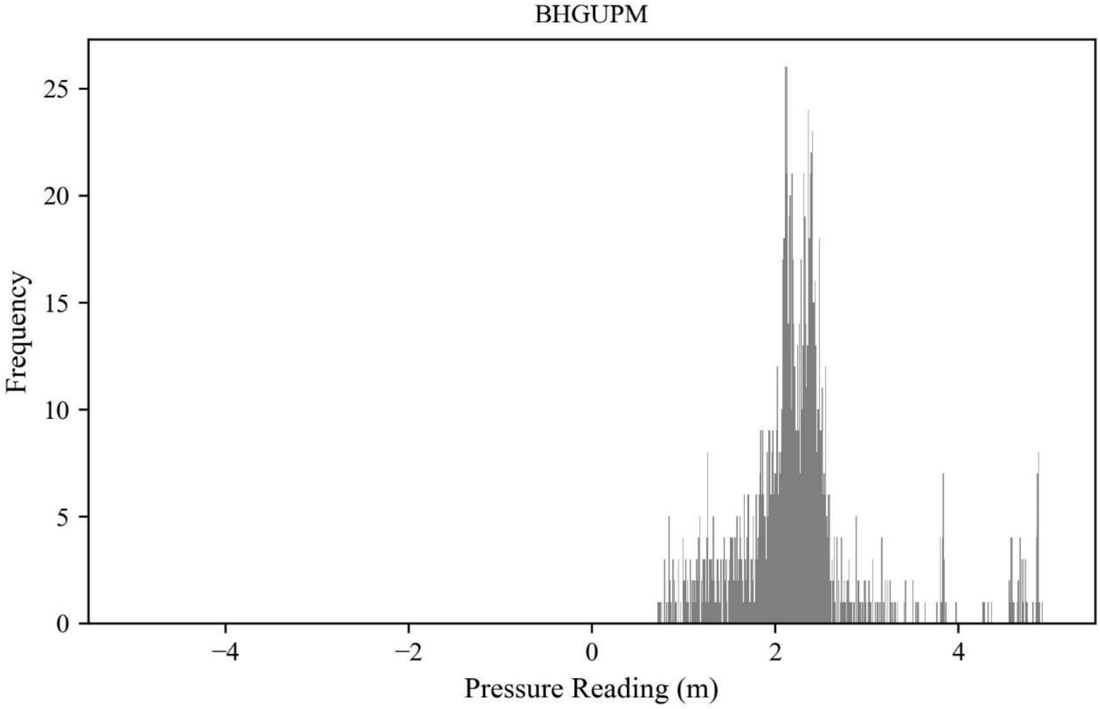

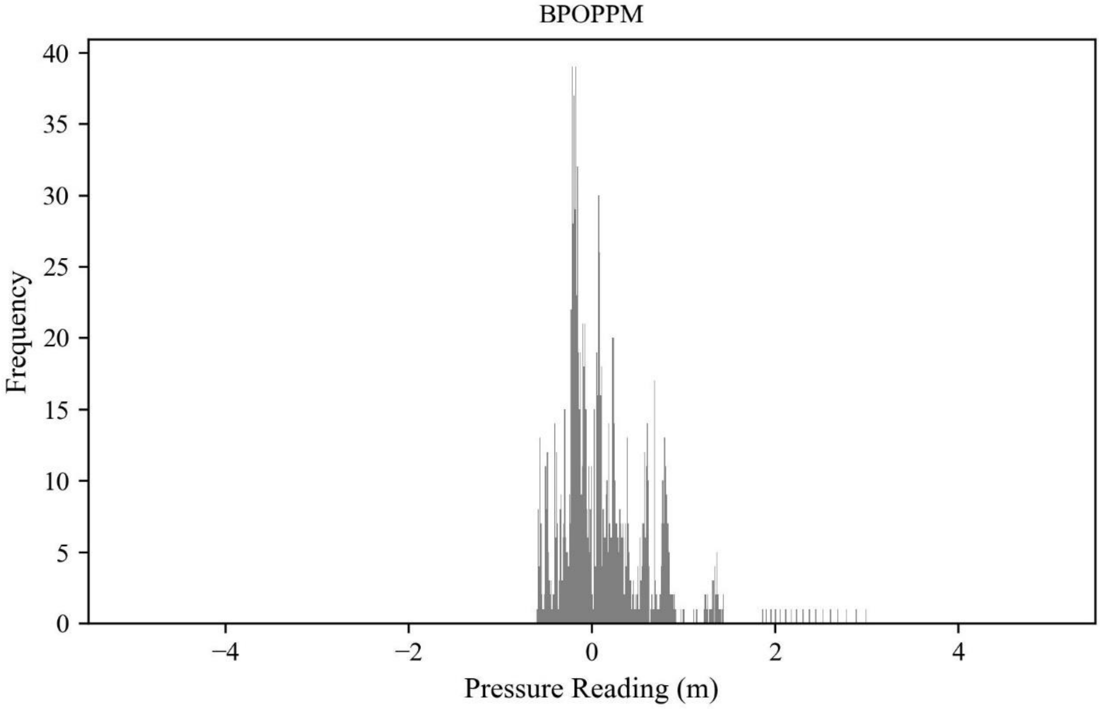

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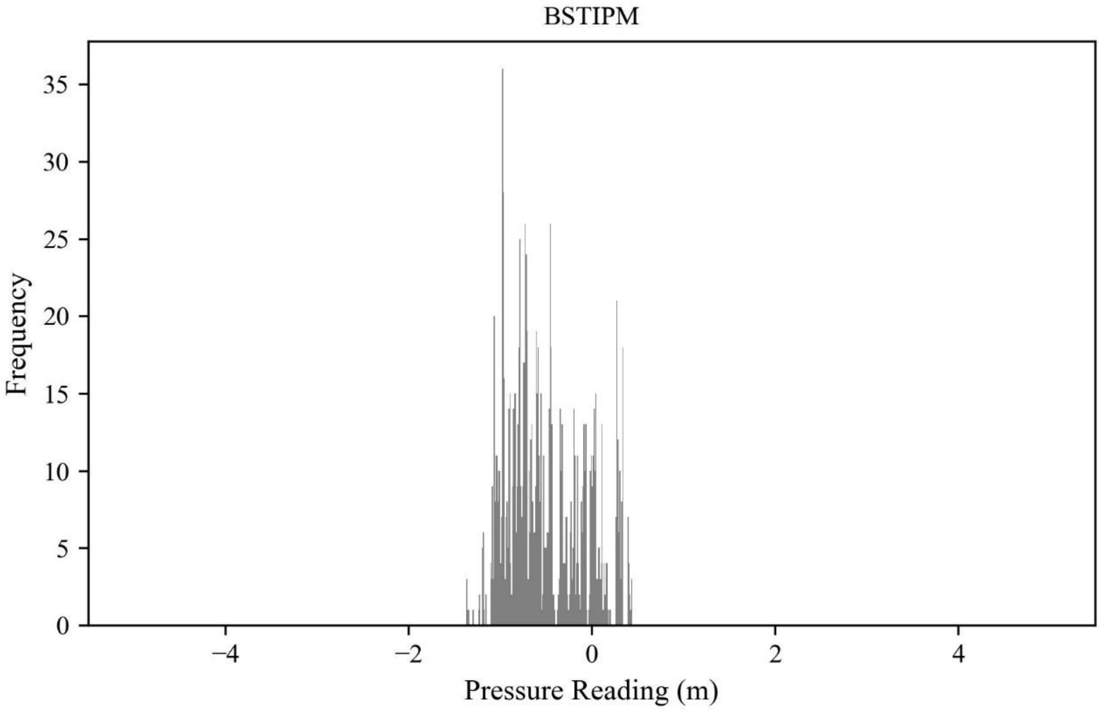

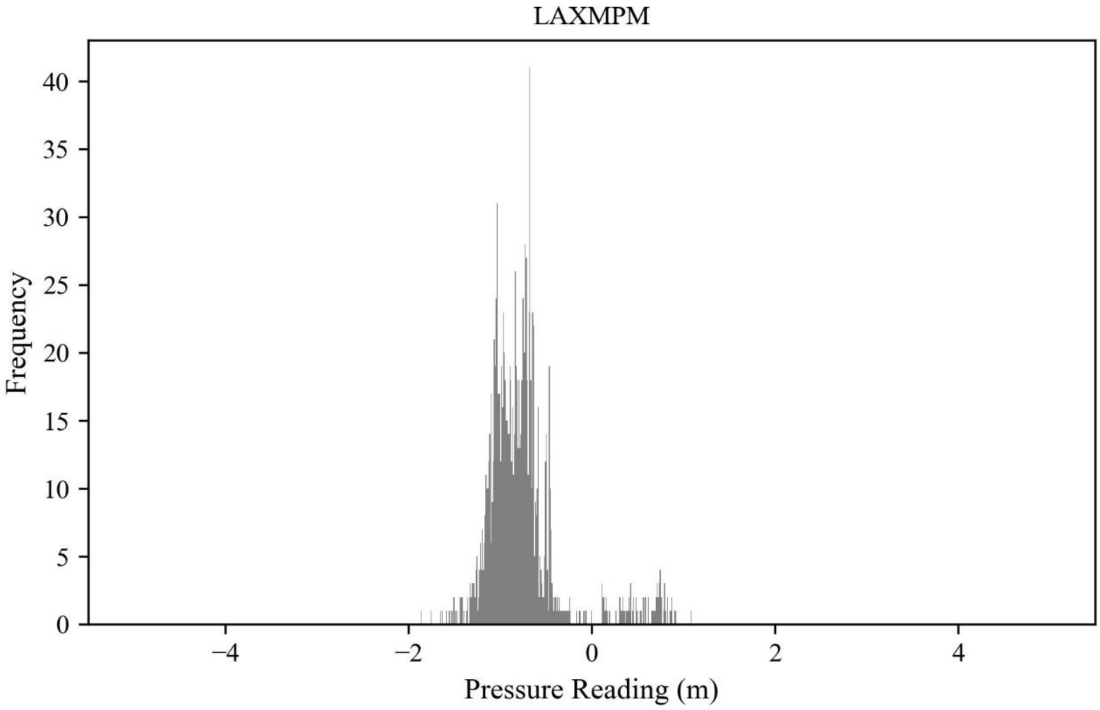

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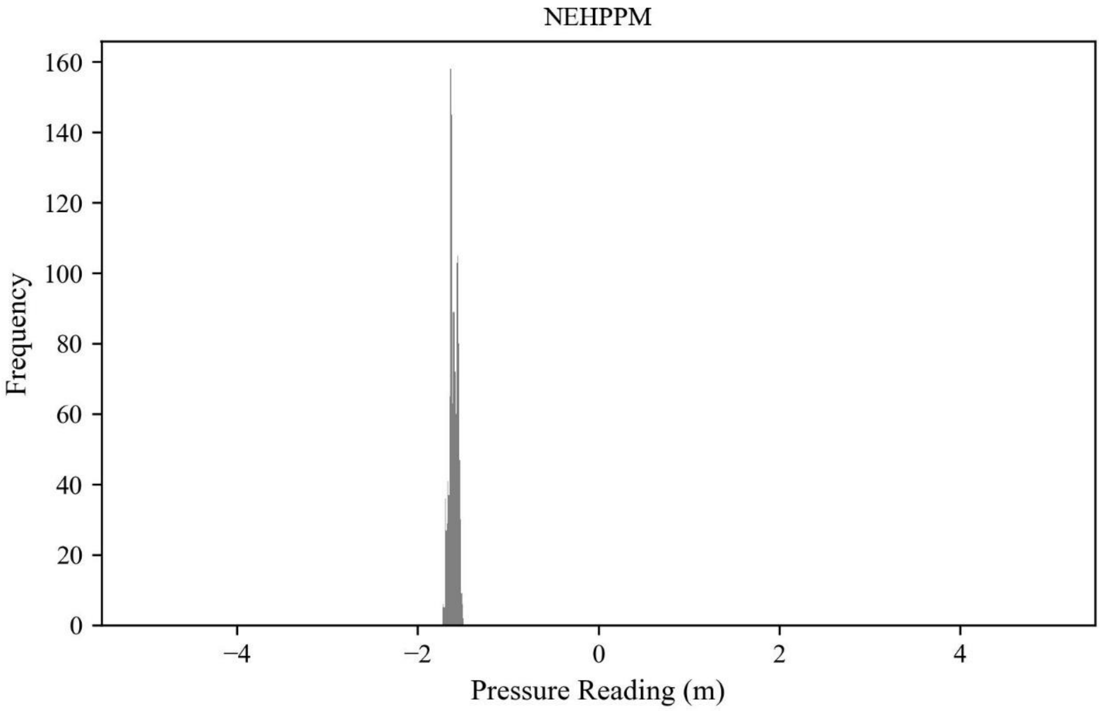

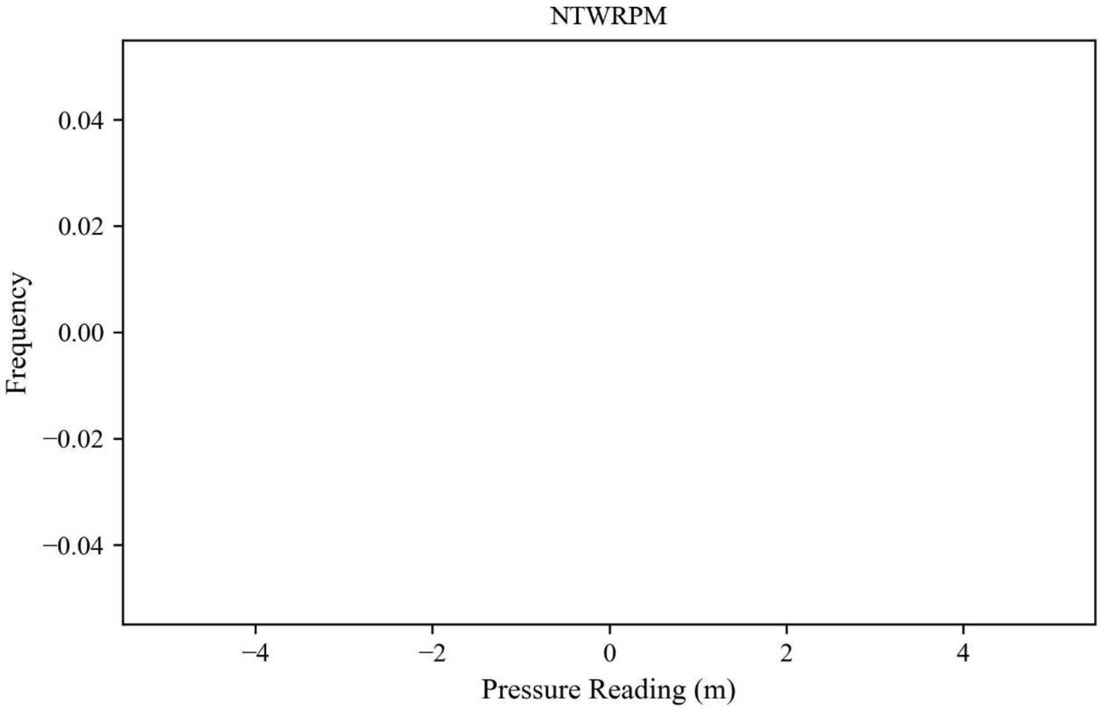

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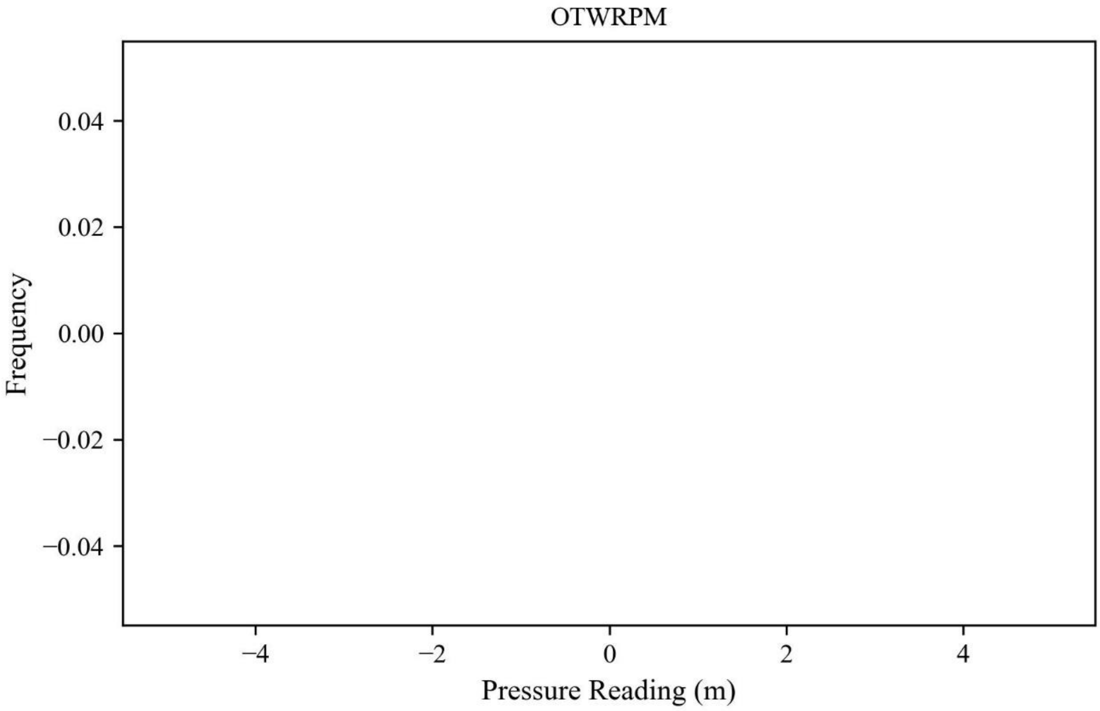

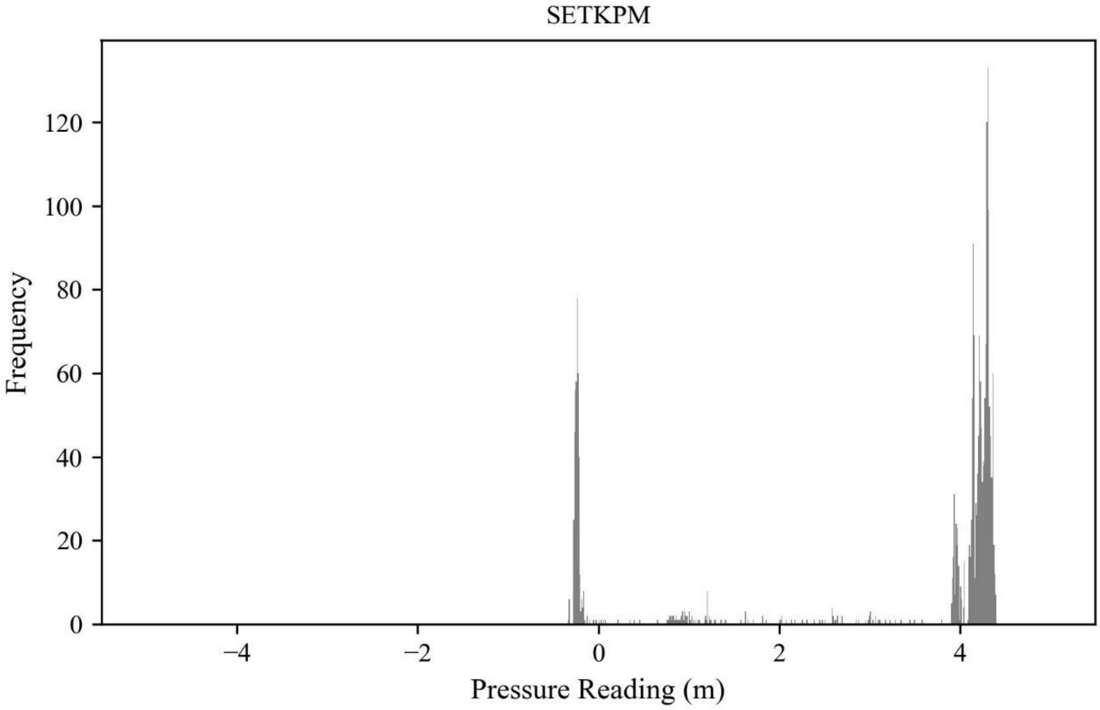

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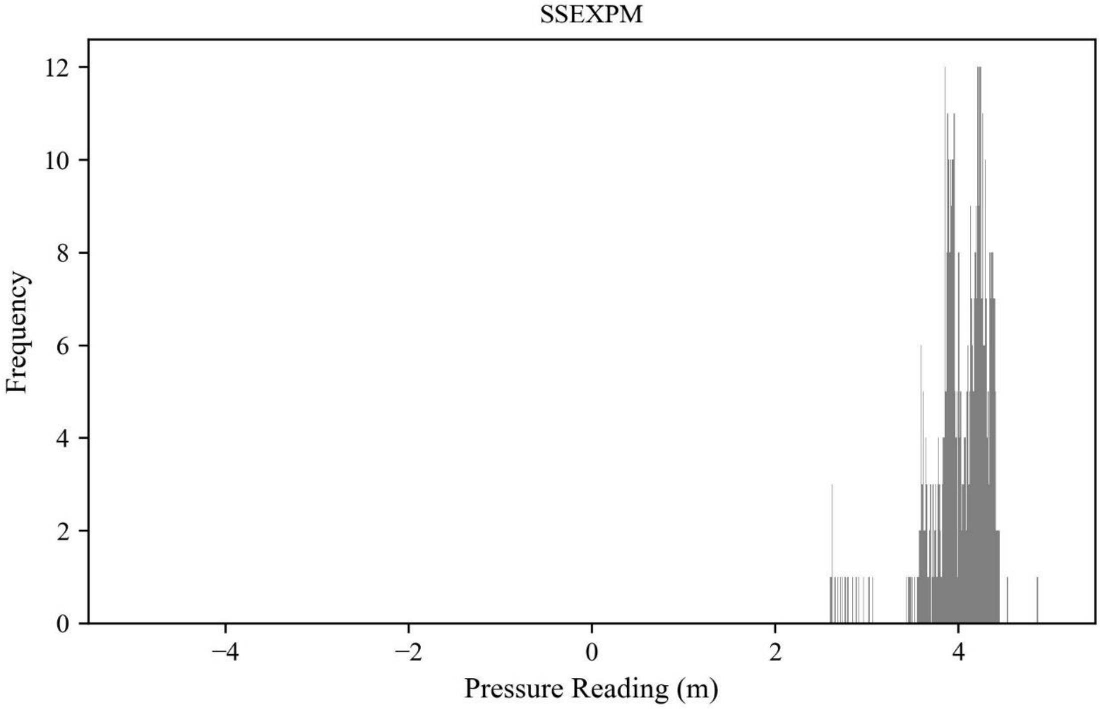

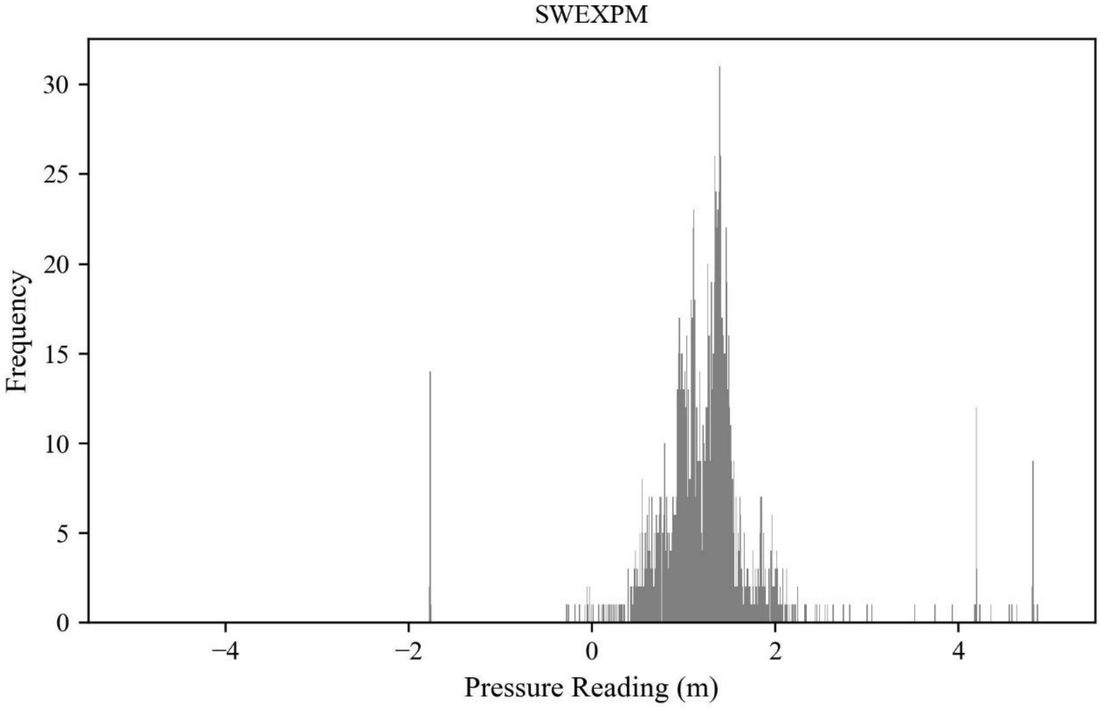

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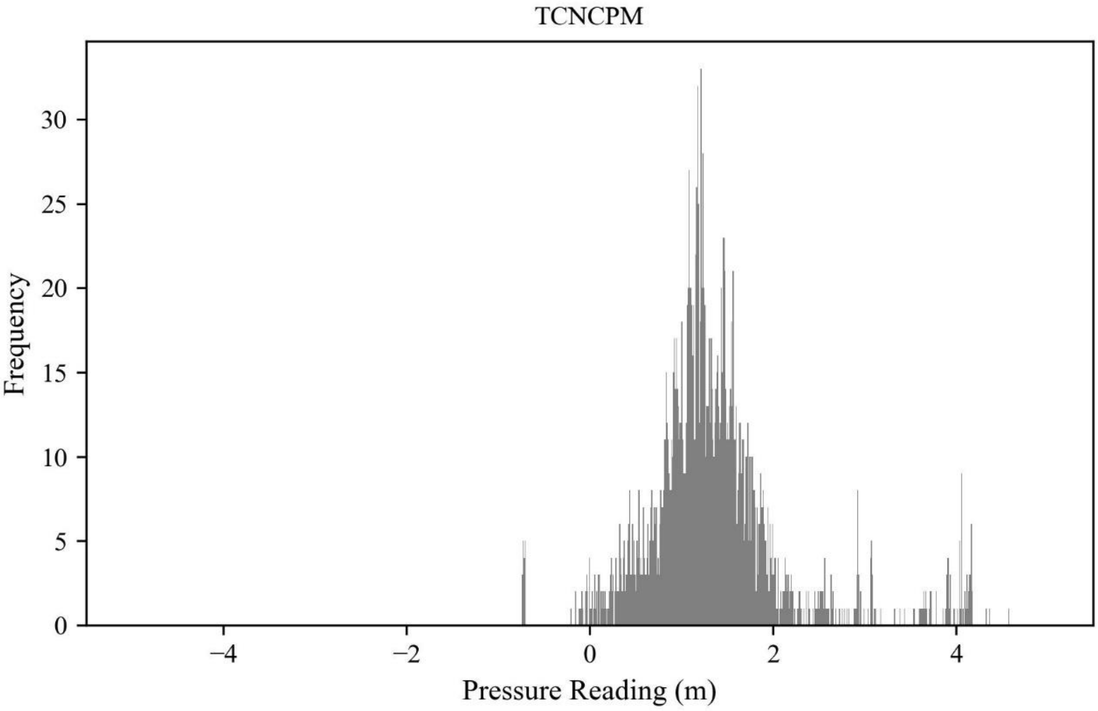


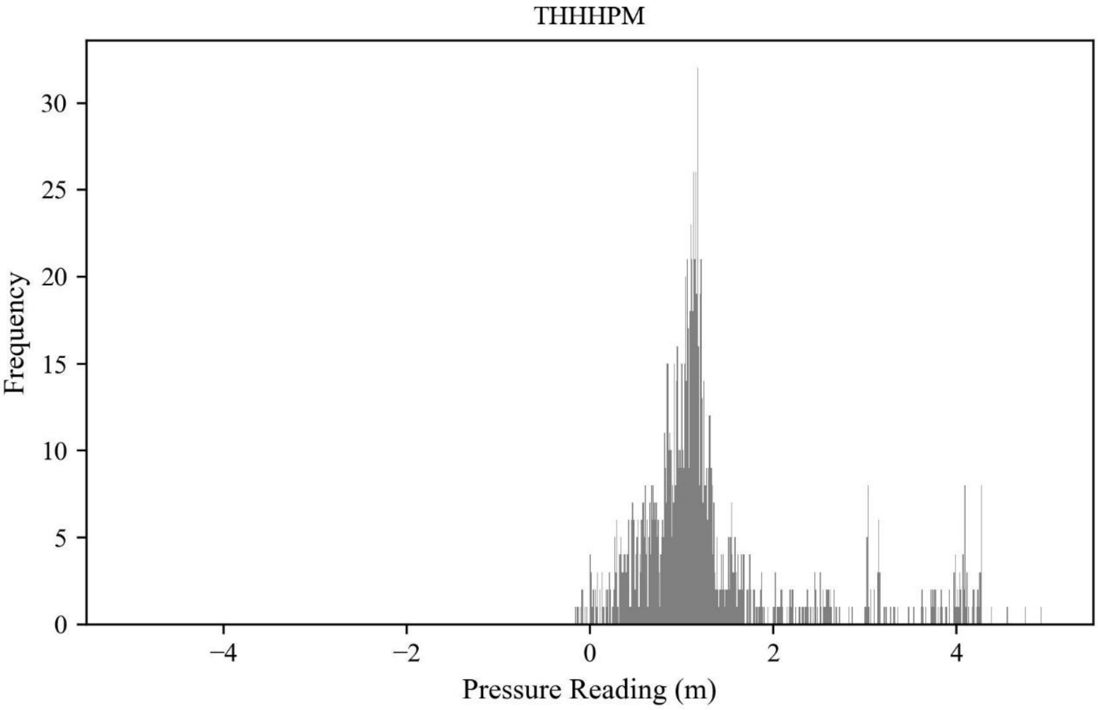


Figure 12.4: Histograms of the low readings (-5 to 5m) of all pressure loggers indicating if a zero error was present

vi. Calibration of Household Smart Meters

The plots below show comparisons between the mechanical dial reading and online data records of the household smart meters that required calibration. The mechanical readings were obtained from site visit following their installation while the online readings were obtained from the server records. The trend lines were used to obtain the calibration parameters.

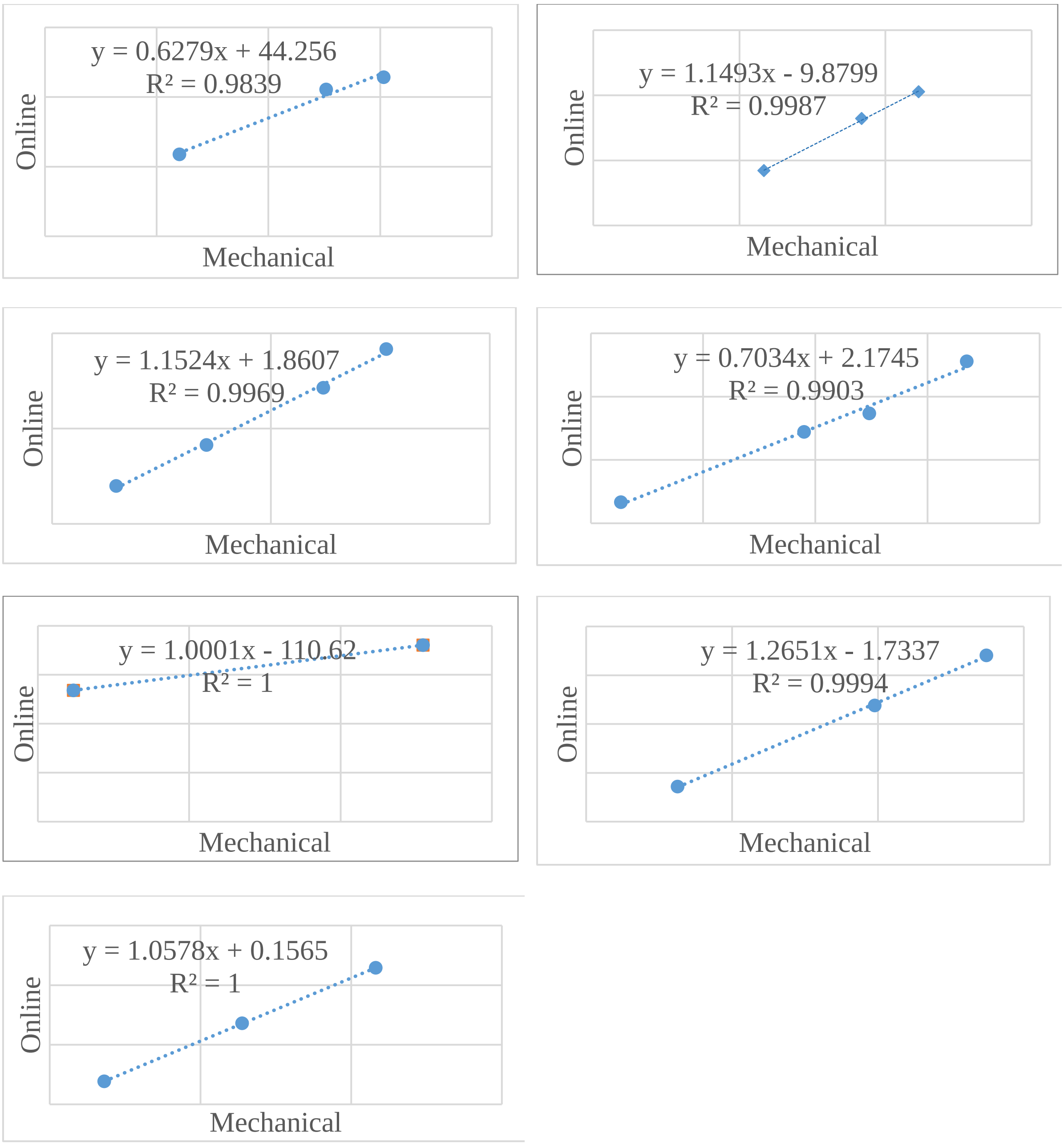


Figure 12.5: Comparison between the mechanical dial reading and online data records of the household smart meters that required calibration

vii. Tests Regarding Air Passing through Meters

The table below assesses the volumes recorded by all household meters in the study that are associated with high flowrates that may be indicative of air passing through the meters. Threshold 1 is flowrates more than 5 times the 90th percentile flowrate; threshold 2 is flowrates above 25L/min. Meters highlighted in red have the greatest associated percentage under threshold 1 and correspond to the plots following the table.

Table 12.2: Volumes recorded by household meters that are associated with high-flowrates (i.e. flowrates 5x 90th percentile or above 25L/min)

Total Volume Used (Litres)	**90th percentile flowrate when the flow is on (Litres/min)**	**Total Volume above threshold 1 (Litres)**	**Percentage above threshold 1 (%)**	**Total Volume above threshold 2: (Litres)**	**Percentage above threshold 2 (%)**
93434	10	0	0	62	0.1
108071	12	0	0	0	0
335204.7	7.7	3377.7	1	21909.5	6.5
398404	9	51	0	425	0.1
377628	9	1574	0.4	2229	0.6
171765	8	0	0	0	0
139702	4	0	0	0	0
121586	7	0	0	0	0
88202.9	10.4	1934.2	2.2	7454.9	8.5
103181	9	0	0	30	0
189508	6	9823	5.2	11371	6
143650	8	0	0	0	0
87356	8	0	0	0	0
136636	8	0	0	125	0.1
34455	6	0	0	0	0
383394	22	0	0	1284	0.3
89809.5	20.6	0	0	6942.5	7.7
88339	11	0	0	0	0
89219.5	8.5	7146.7	8	8168.9	9.2
138884	12	0	0	0	0
162932	5	0	0	0	0
91412	3	0	0	0	0
100963	3	0	0	0	0
9856	5	0	0	0	0
348717	22	0	0	38756	11.1

42068	3	0	0	0	0
299211	8	0	0	0	0
53275	7	82	0.2	162	0.3
20576	4	0	0	0	0
220837.6	15.1	846.1	0.4	5482.1	2.5
175088	15	0	0	159	0.1
195972	10	0	0	0	0
100374	4	0	0	0	0
241046	10	0	0	0	0
93627	6	0	0	0	0
134330	5	0	0	0	0
87020	10	0	0	0	0
96880	11	0	0	0	0
88634	5	0	0	0	0
20582	8	647	3.1	850	4.1
123547	5	0	0	0	0
345695	9	0	0	0	0
352437	12	0	0	0	0
38798	6	0	0	0	0
119868	9	0	0	0	0
141493	9	67	0	95	0.1
207600	6	6220	3	6955	3.4
38149	3	0	0	0	0
96084	11	0	0	0	0
91436	10	0	0	0	0
58652.2	8.7	0	0	0	0
116980	5	0	0	0	0
247941	5	0	0	0	0
291977	16	0	0	149	0.1
101999	5	0	0	0	0
182691	5	0	0	0	0

The Plots below show the flowrate recordings associated with the two highlighted meters in the table above. The daily flowrates across January - December 2023 are included.

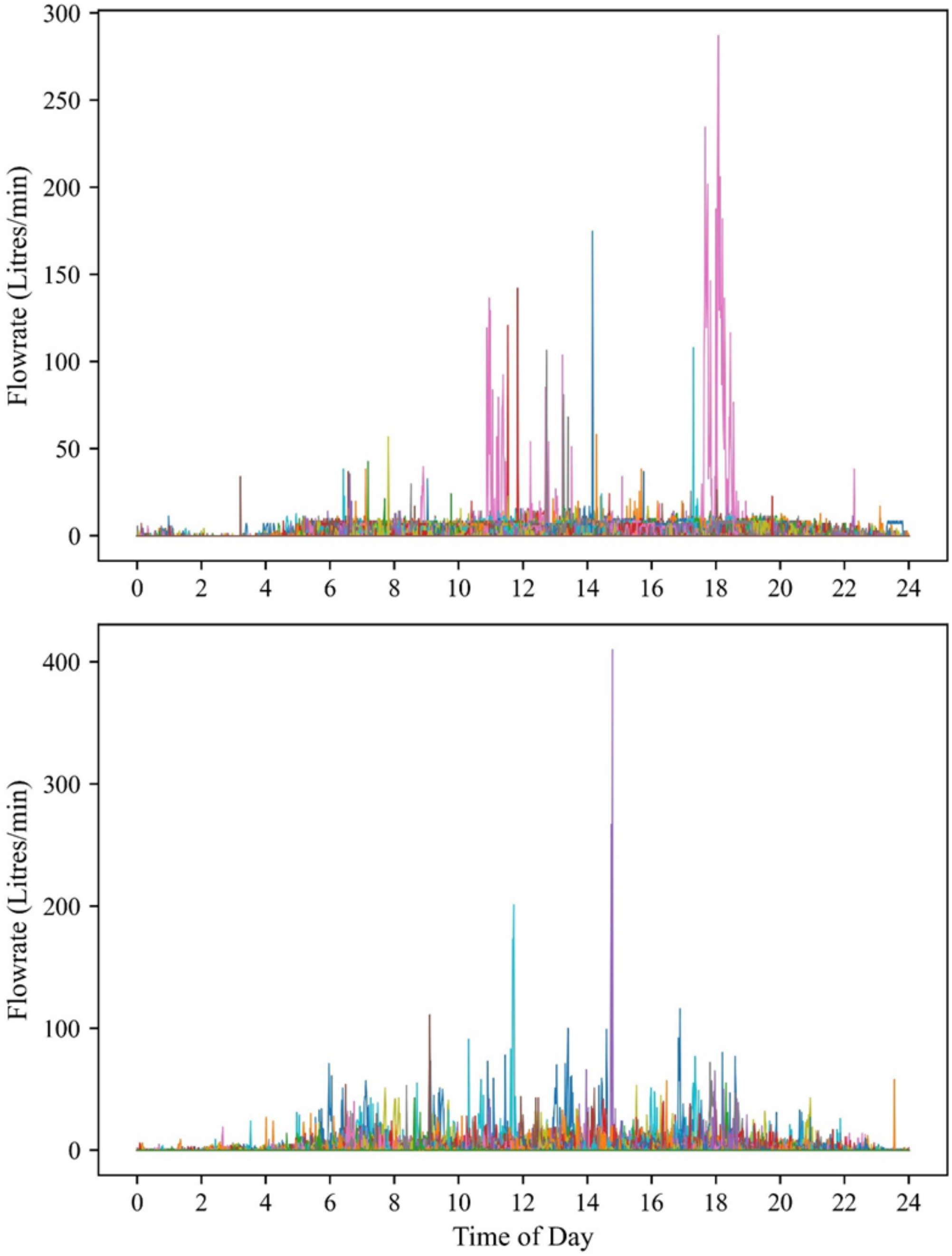
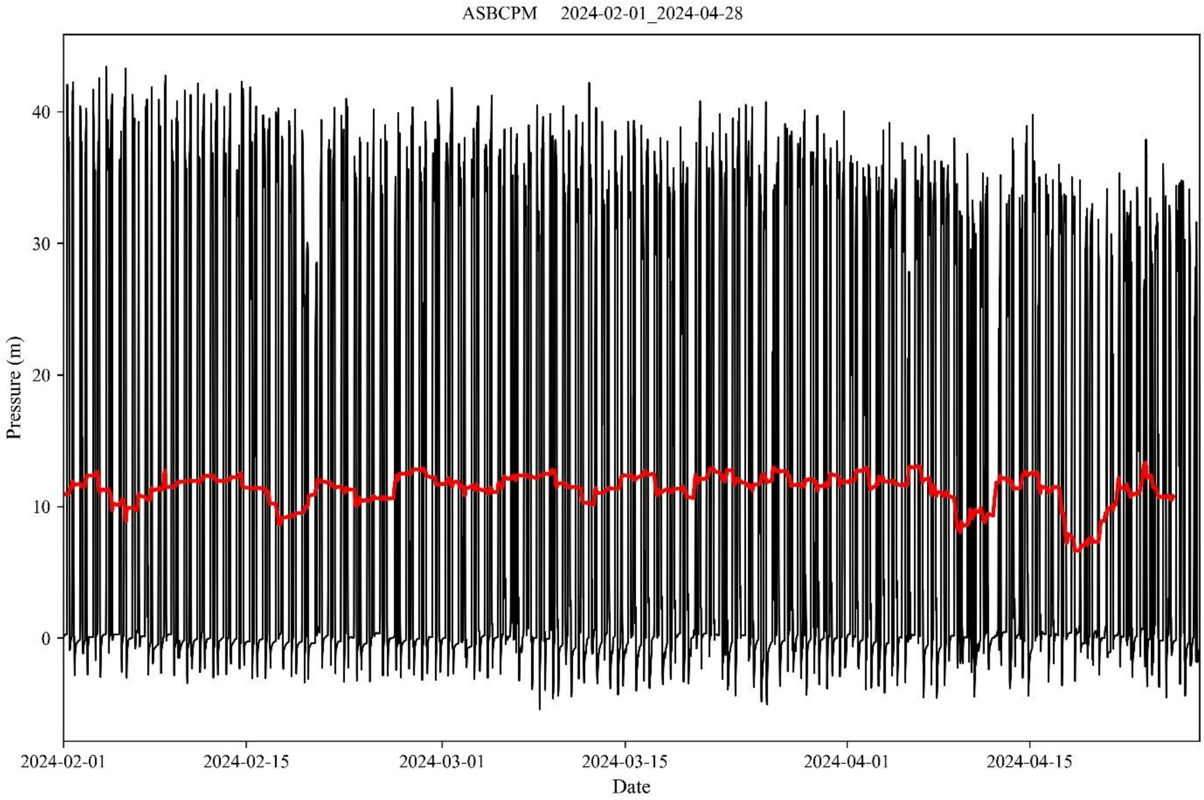


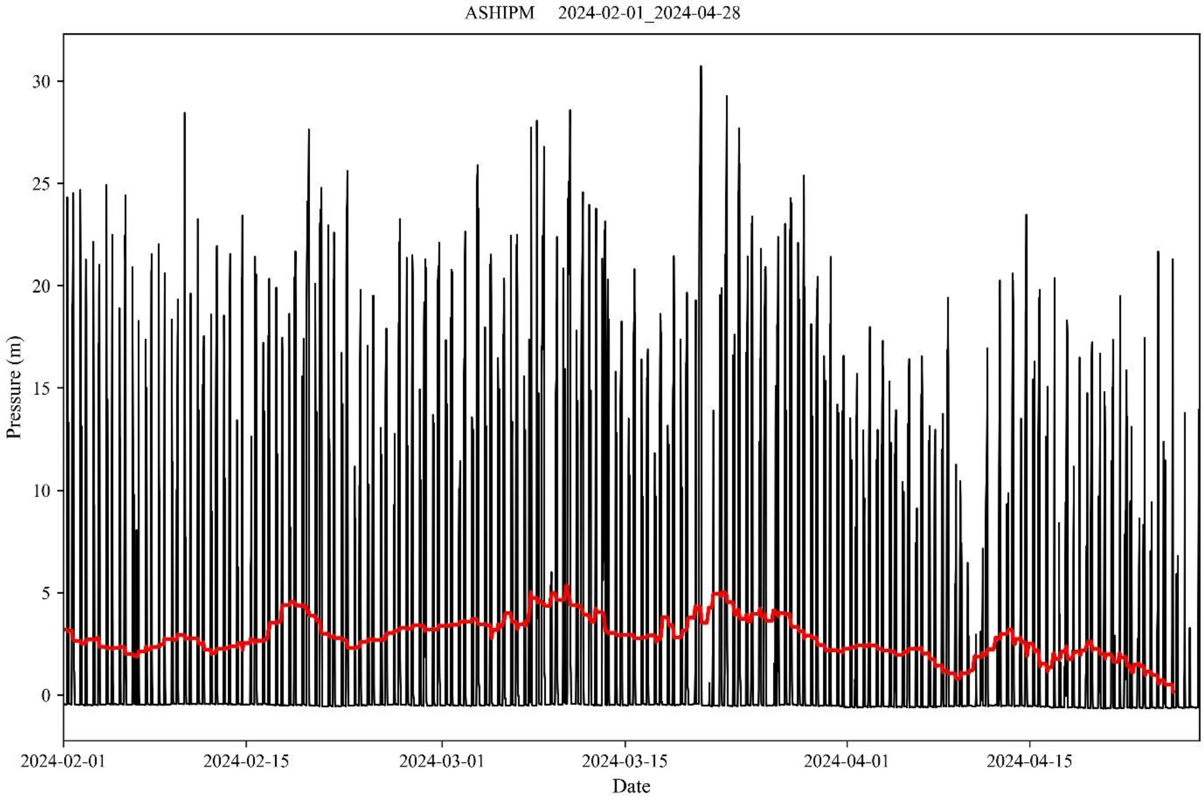
Figure 12.6: Flowrate recordings of two households that were identified as having significant high flowrate instances

Appendix B – Supplementary Results

i. Pressure Logger Timeseries: February – April 2024

The following plots show the pressure logger data between February to April 2024 (the red line represents the 3-day rolling average). They were used to help assess whether there is a notable and consistent change following the altered network configuration on 8th March 2024.





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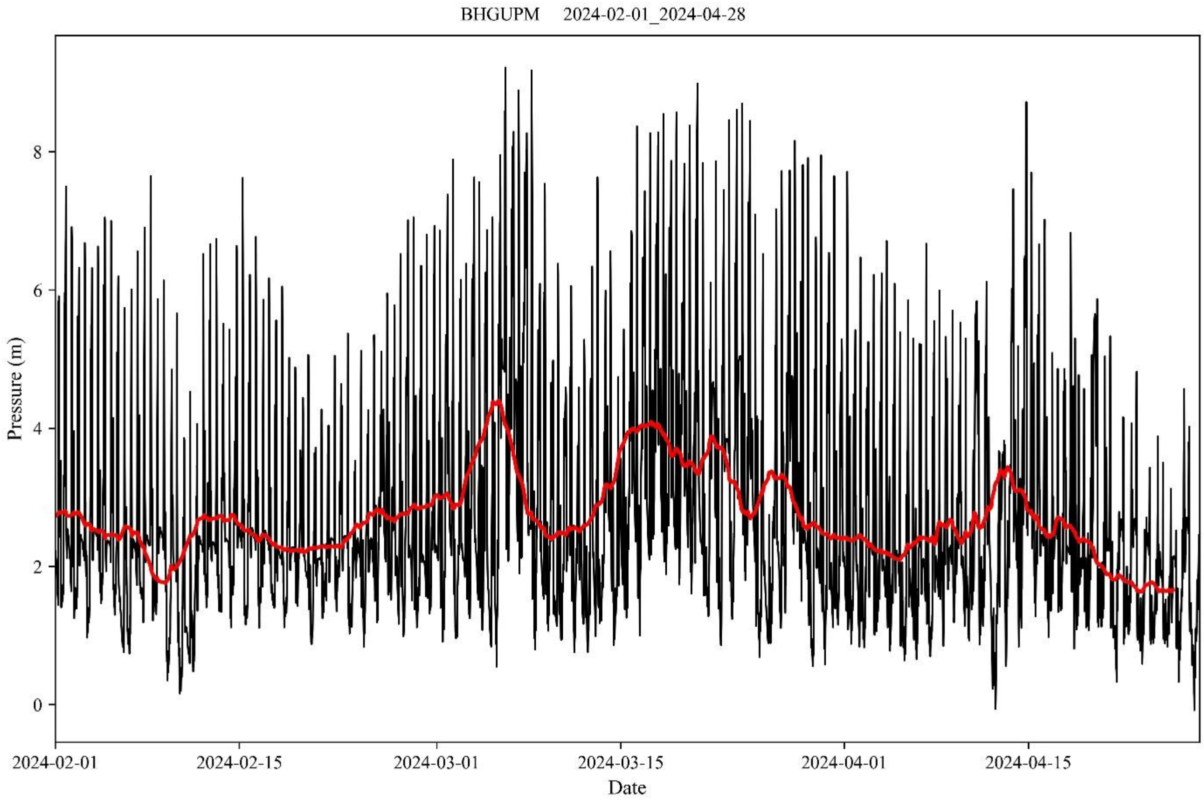

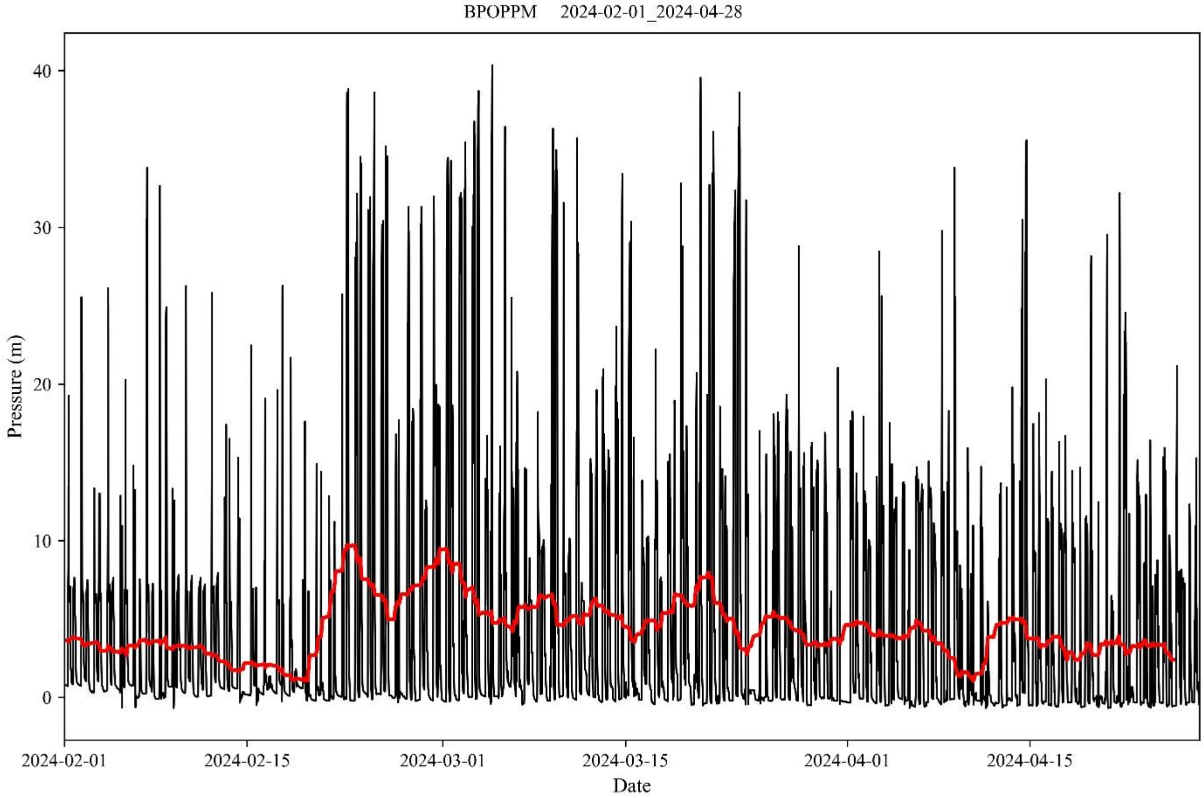

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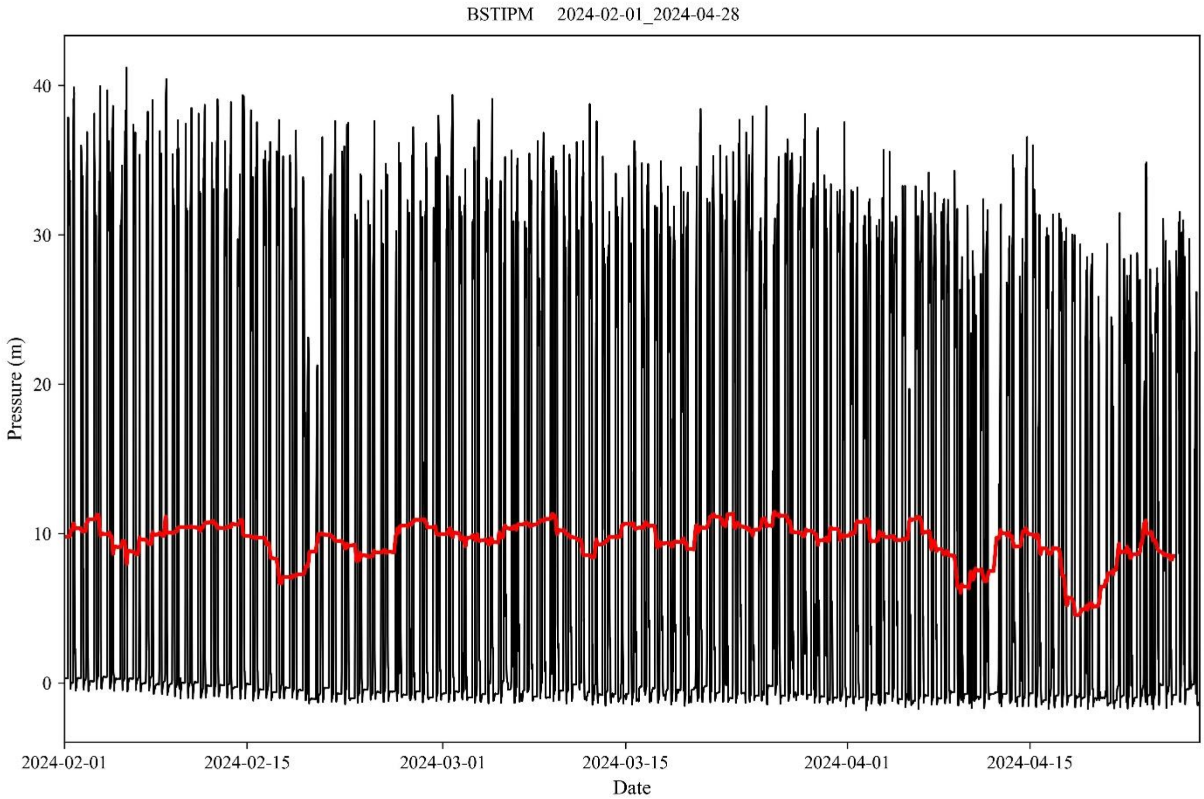

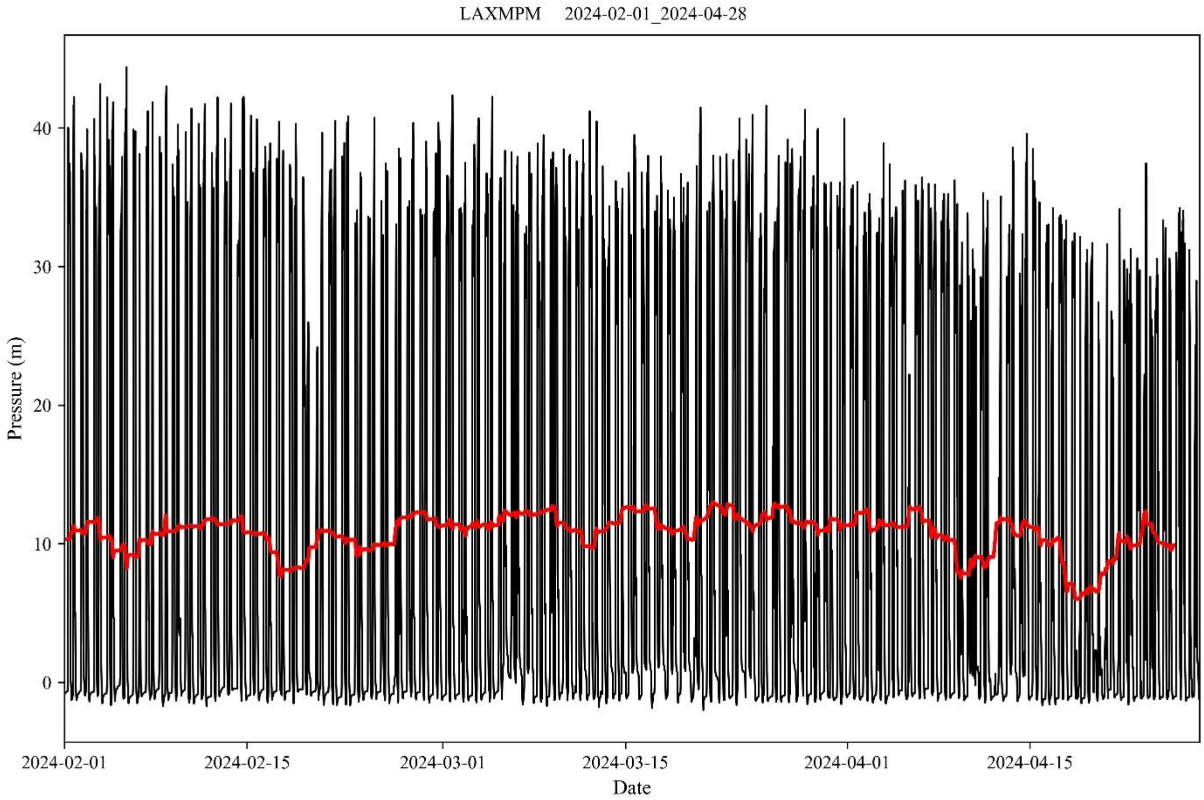

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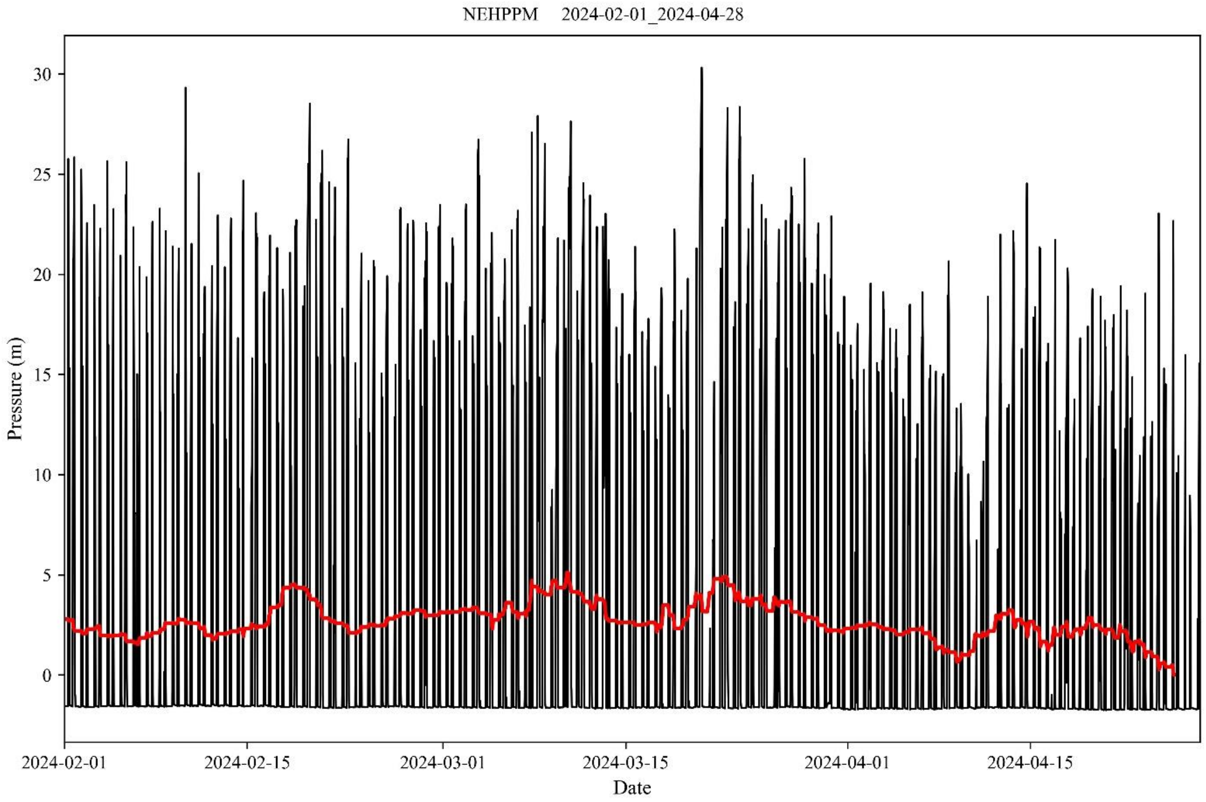

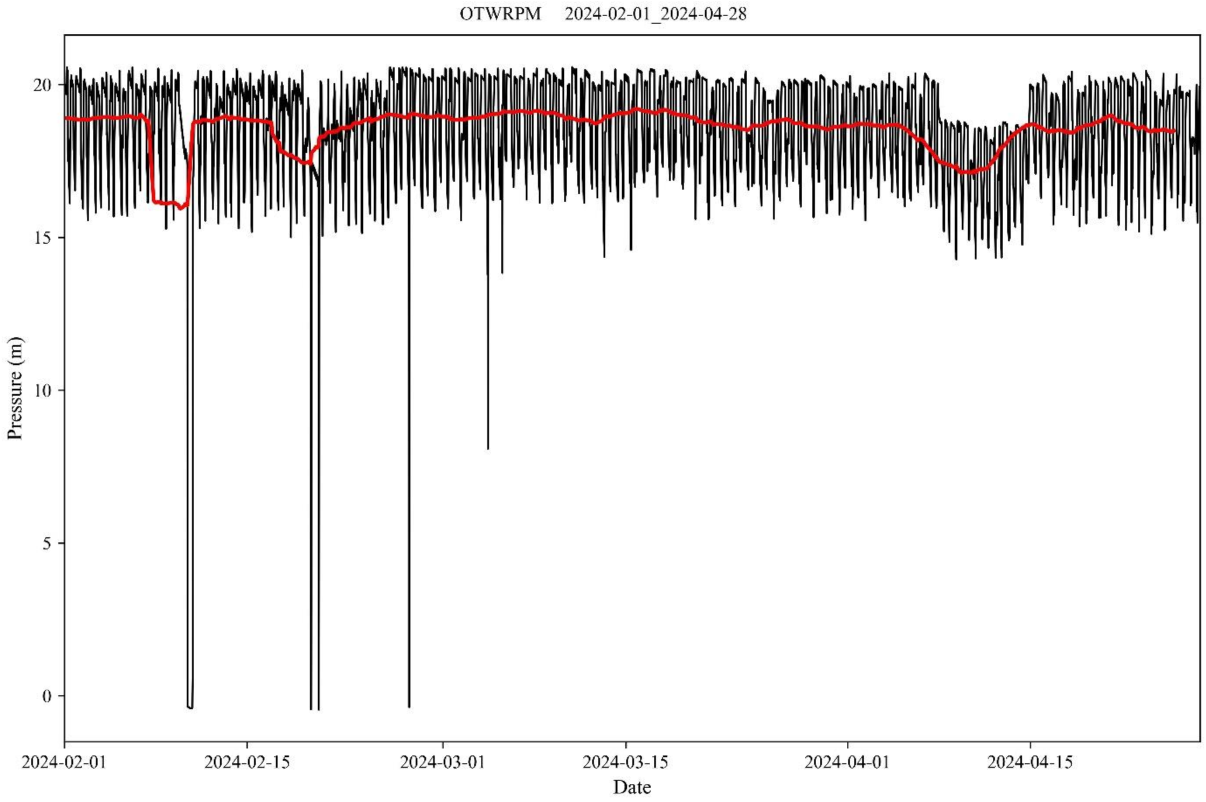

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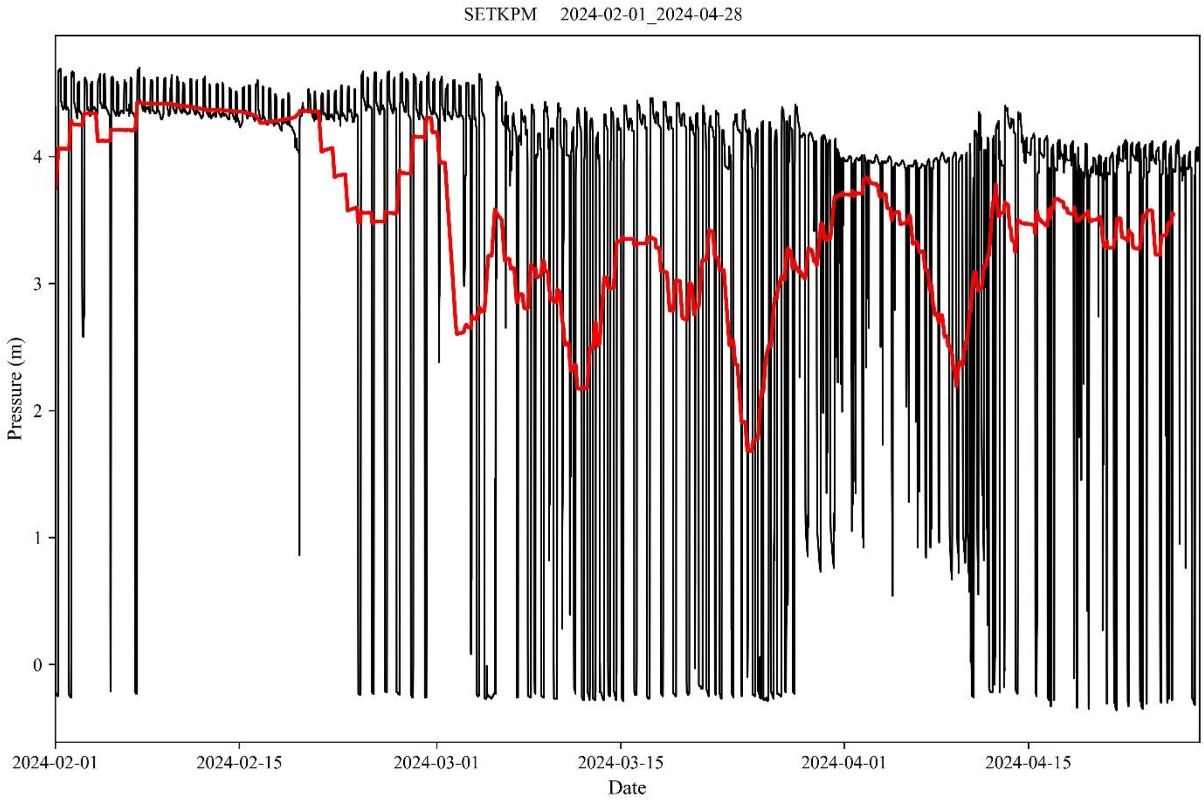

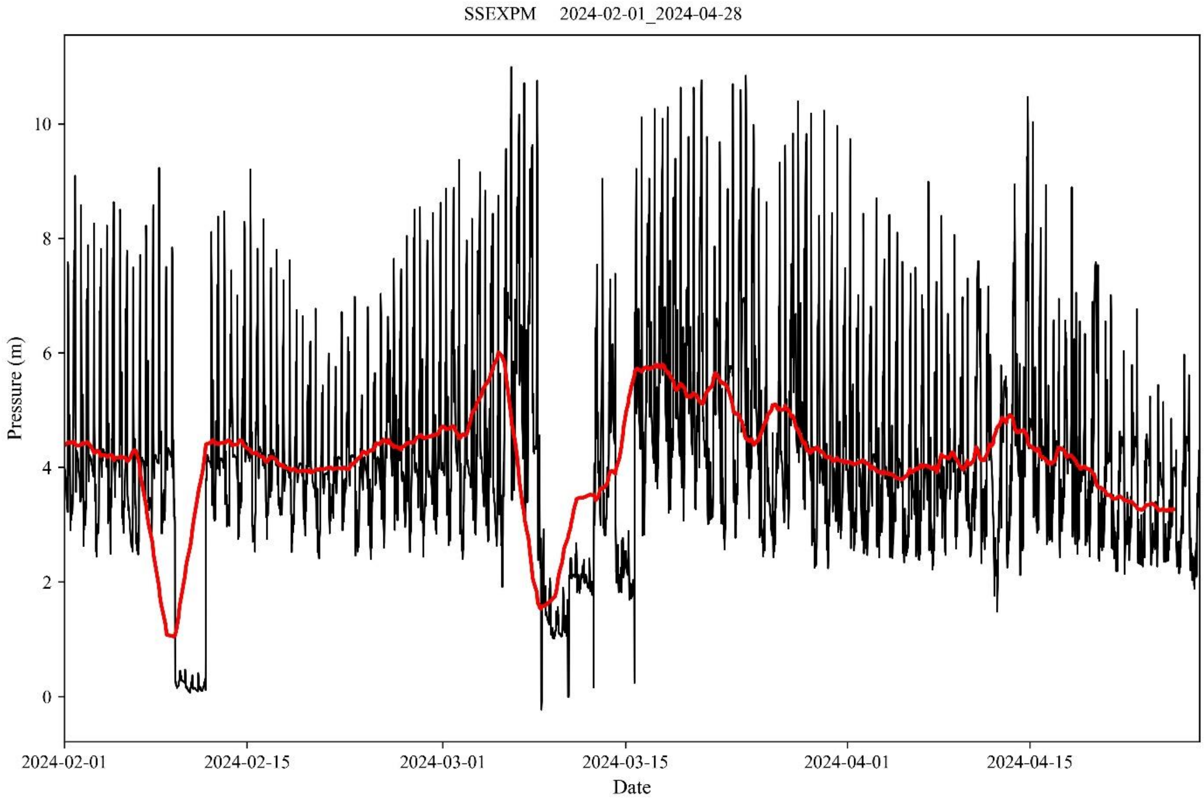

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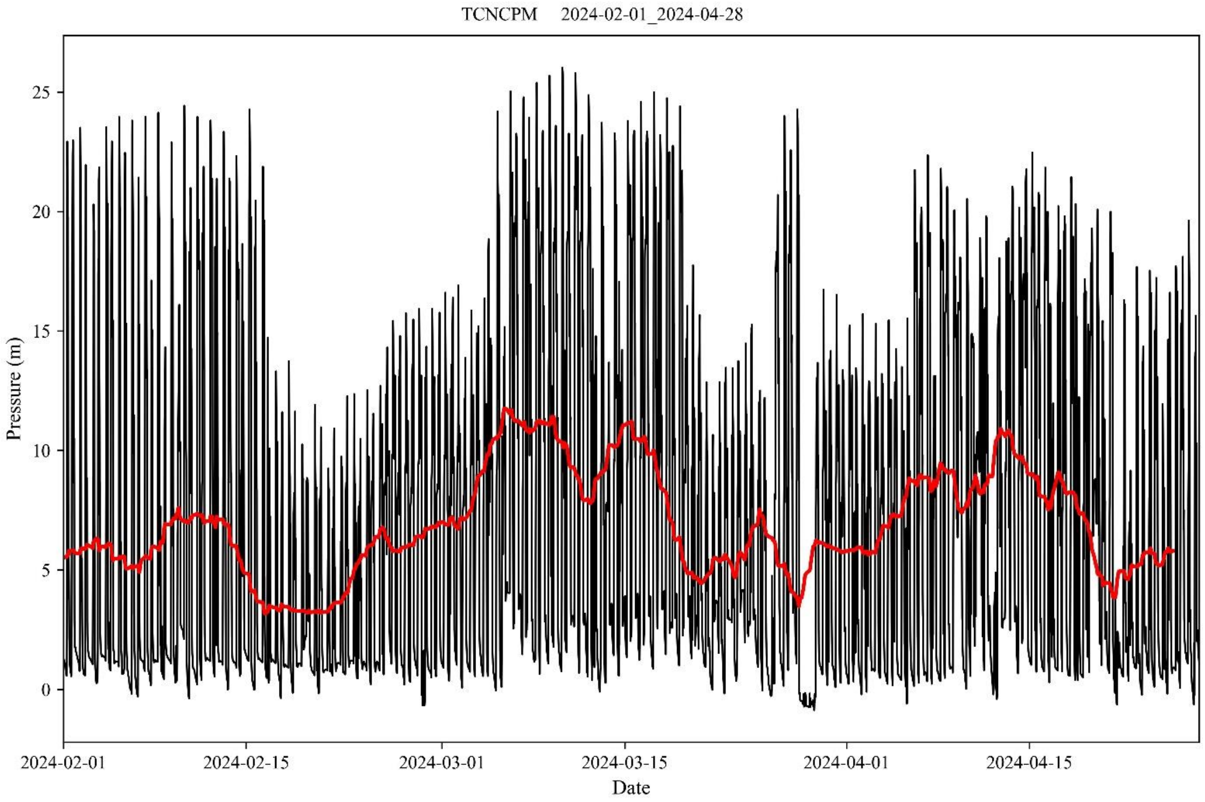

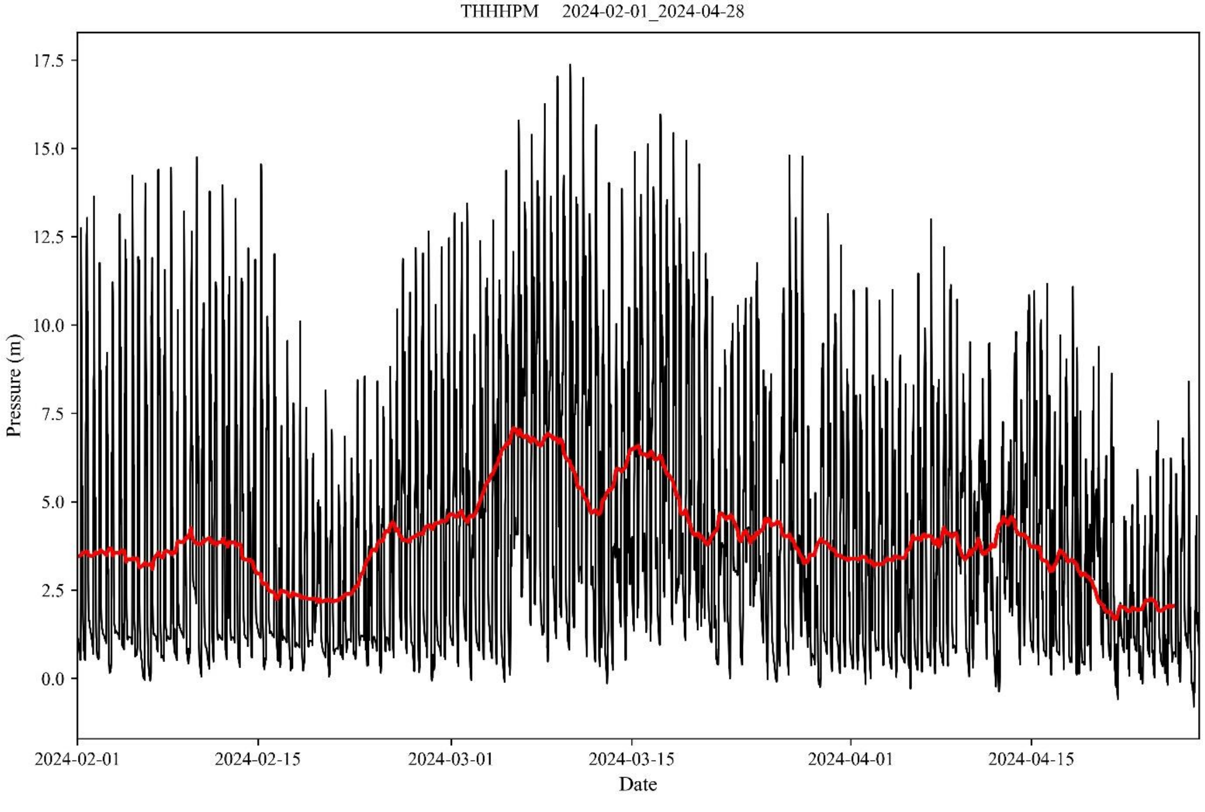

Figure 12.7: Pressure logger data between February to April 2024 (the red line represents the 3-day rolling average) of all functioning pressure loggers

ii. Analysis of the change in monthly withdrawal volumes which is illustrated in Figure 7.35

Table 12.3: The Difference in Monthly Withdrawal Volume between Equivalent Months in 2023 and 2024 for Households with Available Data. Percentage Differences that are Greater than 20% are highlighted in Blue

House ID	Average Volume Withdrawn per Day (Litres/day)								
	April			May			June		
	2023	2024	% diff.	2023	2024	% Diff.	2023	2024	% Diff.
1	385	318	-17%	224	371	66%	319	572	79%
2	421	438	4%	415	489	18%	453	330	-27%
3	832	148	-82%	881	151	-83%	1103	127	-89%
4	1114	2077	87%	1224	2154	76%	1429	2364	65%
5	1233	1861	51%	1767	2244	27%	1720	2394	39%
6	596	309	-48%	1256	207	-84%	437	198	-55%
7	375	254	-32%	609	459	-25%	506	440	-13%
8	618	7	-99%	676	49	-93%	1171	136	-88%
9	516	500	-3%	504	548	9%	439	599	36%
10	122	223	84%	240	188	-22%	126	275	118%
11	414	538	30%	317	781	146%	385	680	76%
12	338	1093	223%	348	441	26%	522	465	-11%
13	383	321	-16%	378	353	-7%	390	380	-3%
14	443	535	21%	339	416	23%	298	574	93%
15	556	447	-20%	594	500	-16%	452	689	53%
16	309	248	-20%	303	340	12%	386	436	13%
17	548	726	33%	406	608	50%	427	404	-5%
18	358	401	12%	294	326	11%	405	371	-8%
19	735	564	-23%	553	583	5%	323	645	99%
20	1384	1419	3%	792	1167	47%	1221	1208	-1%
21	182	153	-16%	253	191	-25%	231	174	-25%
22	597	918	54%	511	1096	114%	473	818	73%
23	1132	938	-17%	928	1441	55%	1291	136	-89%
24	148	86	-42%	208	108	-48%	176	100	-43%
25	454	356	-22%	438	566	29%	342	515	50%
26	343	403	18%	316	452	43%	392	452	15%
27	234	284	21%	161	260	61%	208	239	15%
28	592	694	17%	1225	1174	-4%	1404	870	-38%
29	1030	1116	8%	1111	1037	-7%	1194	1140	-5%
30	292	285	-2%	343	302	-12%	505	318	-37%

iii. Boxplots of Household Assets vs International Wealth Index (IWI) Score

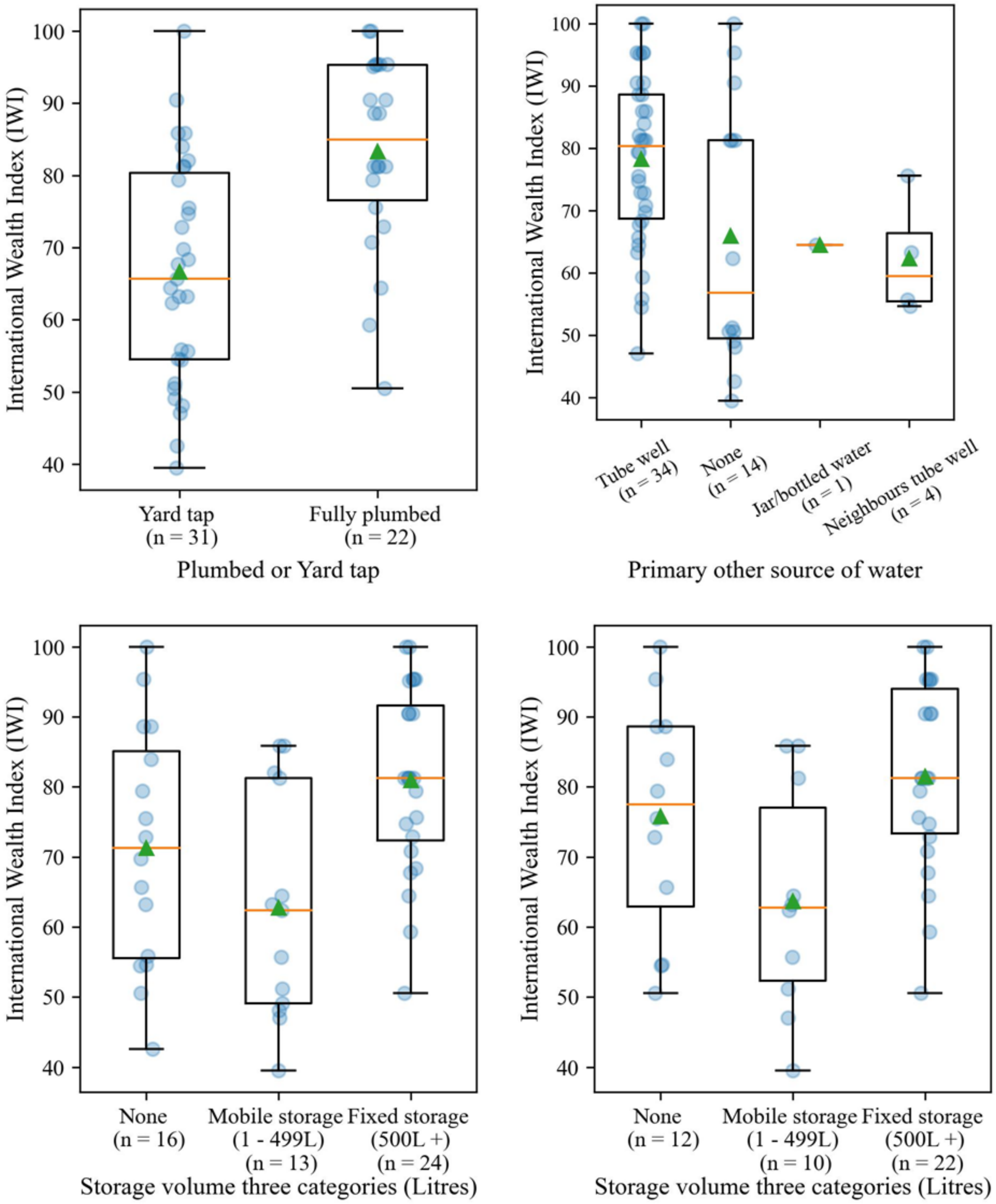

Figure 12.8: Boxplots of household assets vs international wealth index - All households (bottom left), and IWS Households Only (bottom right)

iv. Boxplots of Supply Conditions vs Household Adaptations

The following boxplots compare the effect of Estimated Supply Hours on Whether Households have a Yard tap or are Plumbed

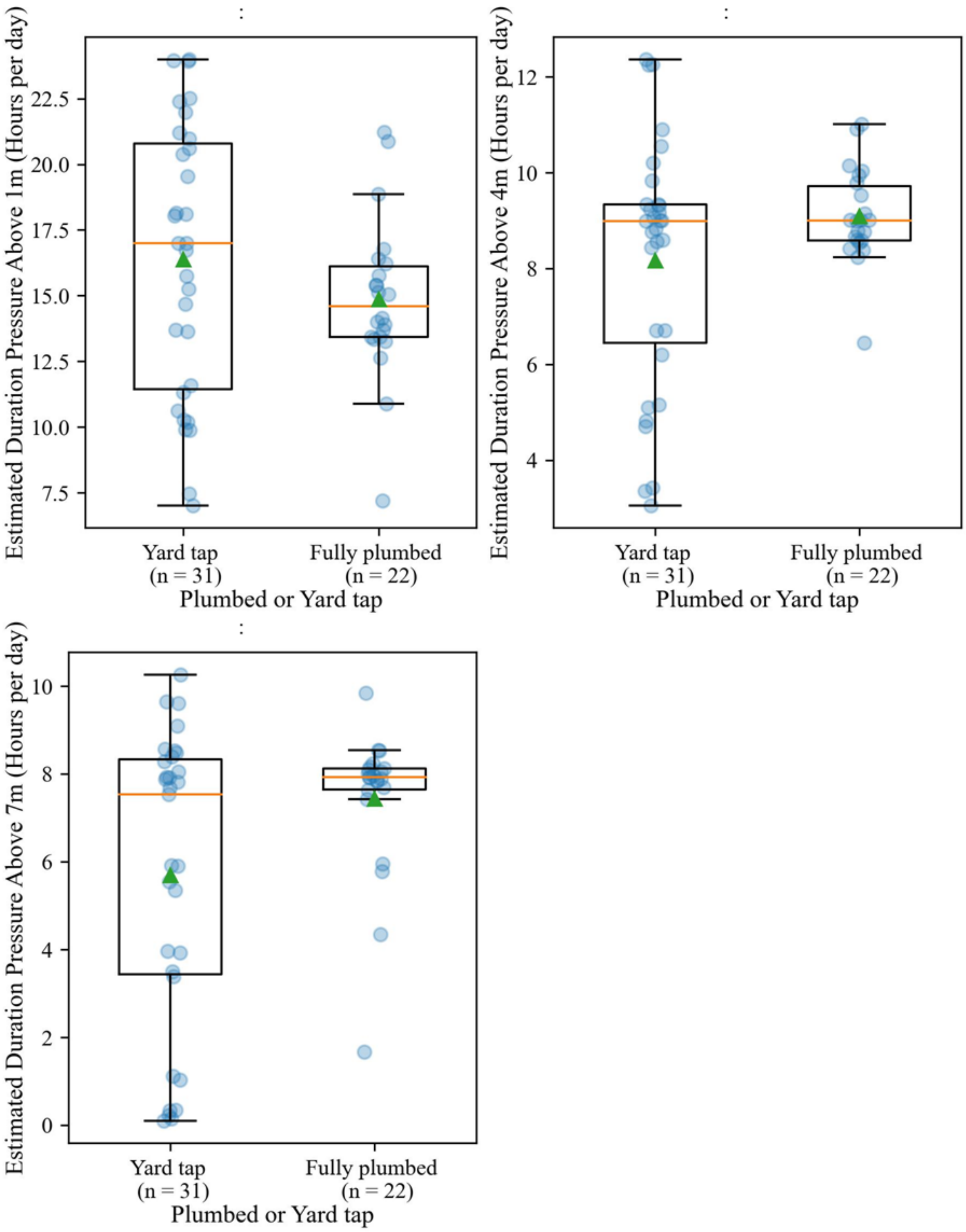

Figure 12.9: Boxplots comparing the Estimated Supply Hours against Whether Households have a Yard tap or are Plumbed

The following boxplots compare the effect of estimated supply hours on household storage volume

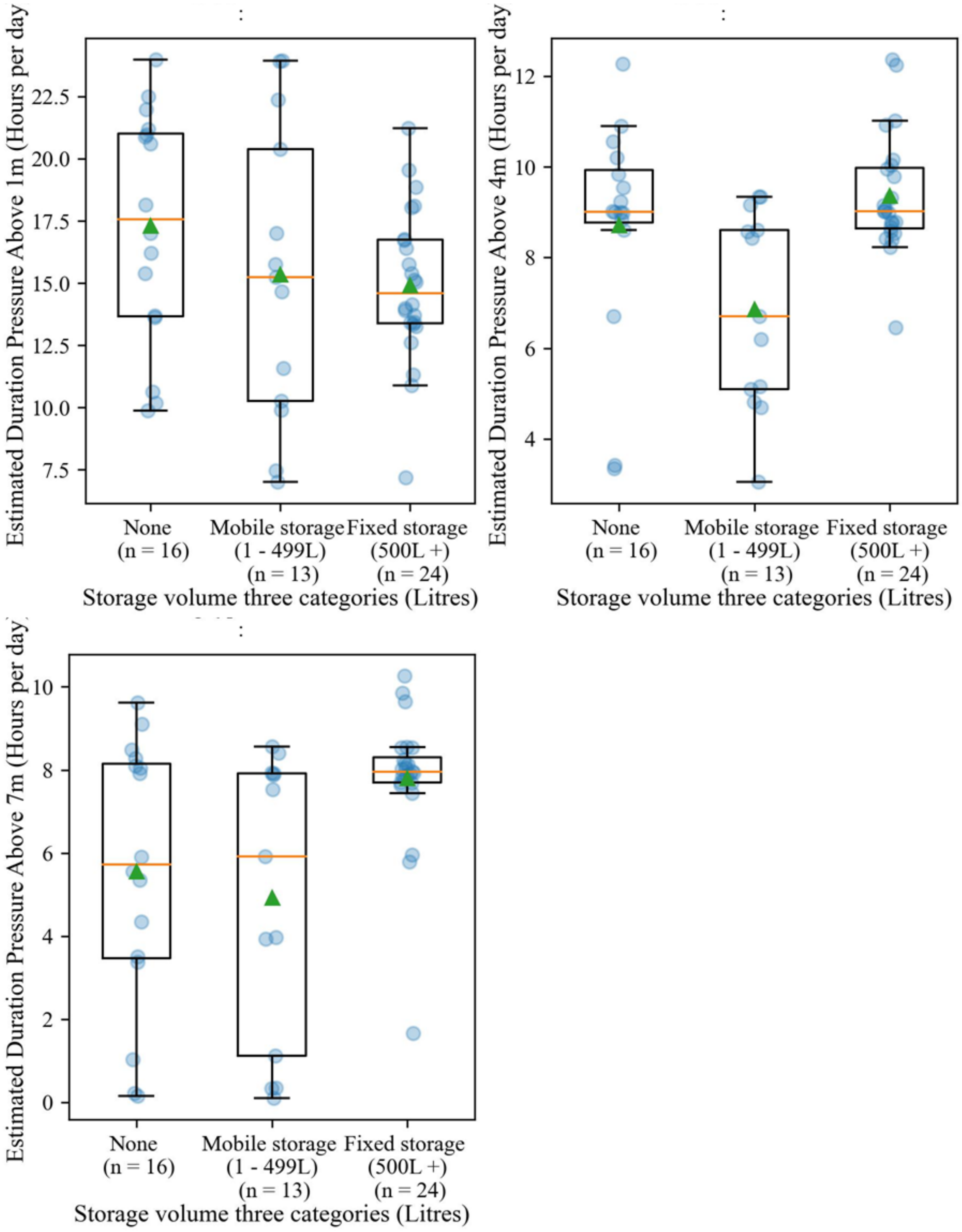

Figure 12.10: boxplots comparing the effect of estimated supply hours on household storage volume

The following boxplots compare the effect of estimated supply hours on whether households have a tube well or not

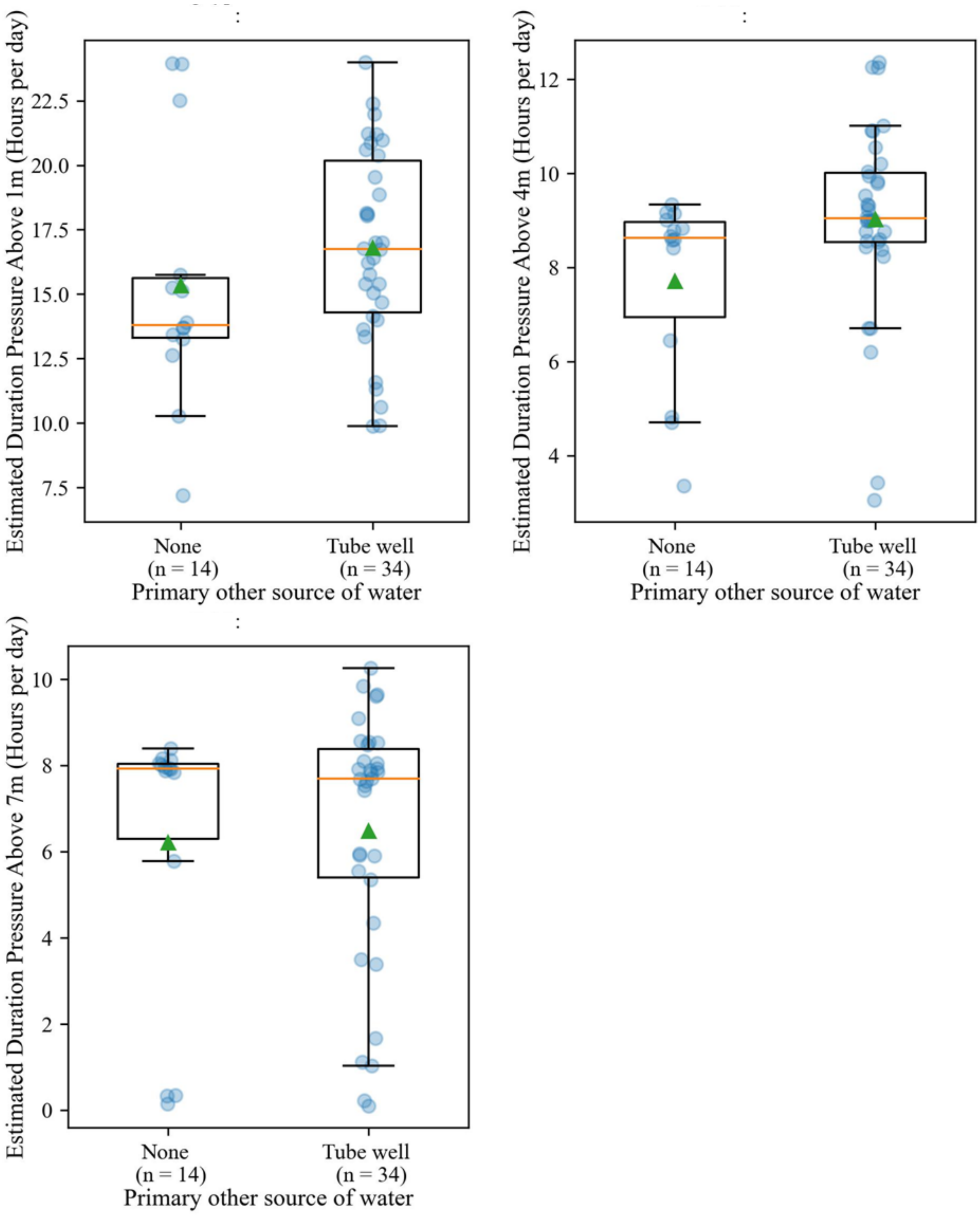

Figure 12.11: Boxplots comparing the effect of estimated supply hours on whether households have a tube well or not

The following boxplots compare categorical variables with HWISE score

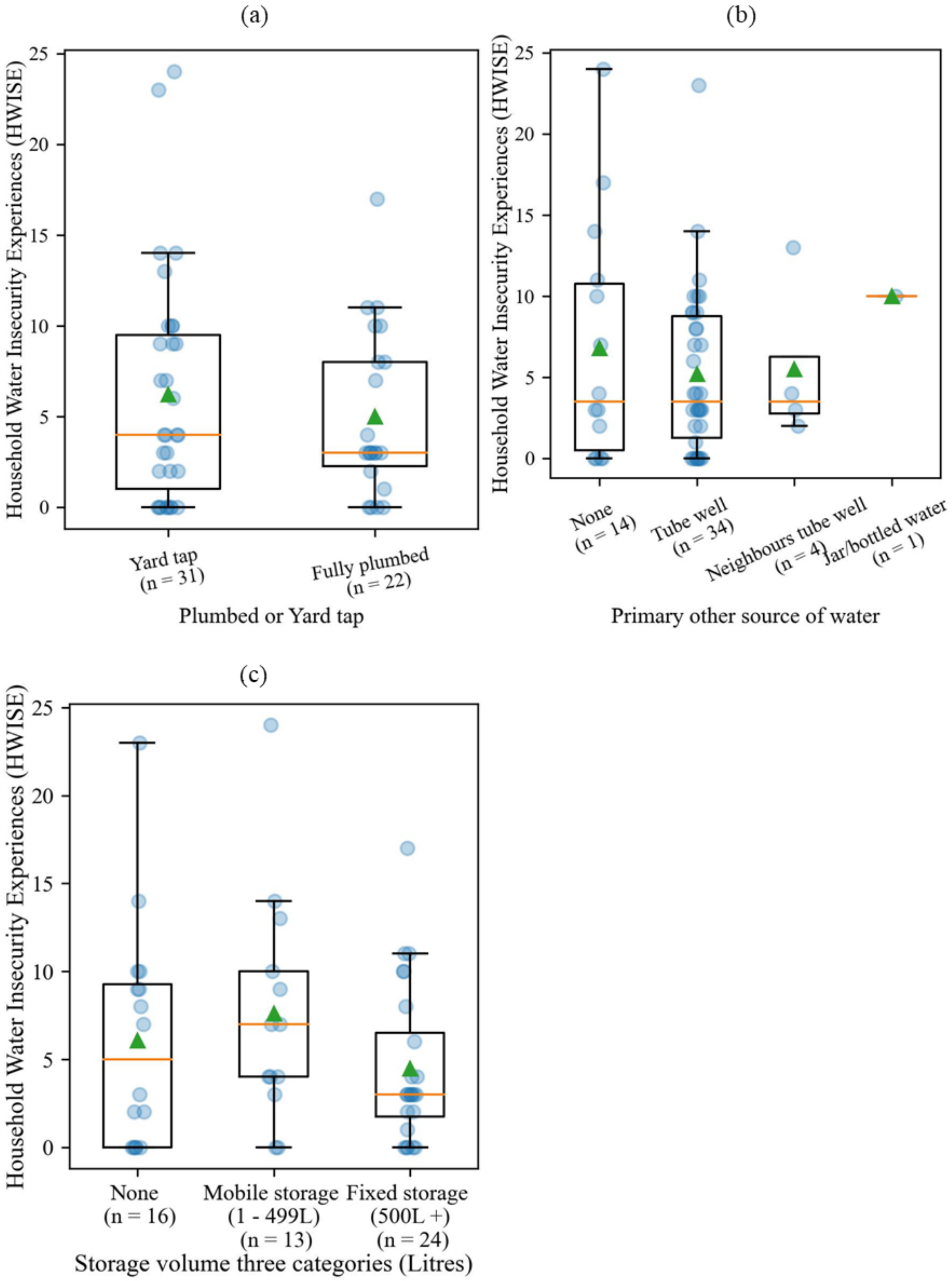

Figure 12.12: Boxplots comparing categorical variables with HWISE score

The following boxplots compare continuous variables against the desire for longer supply hours

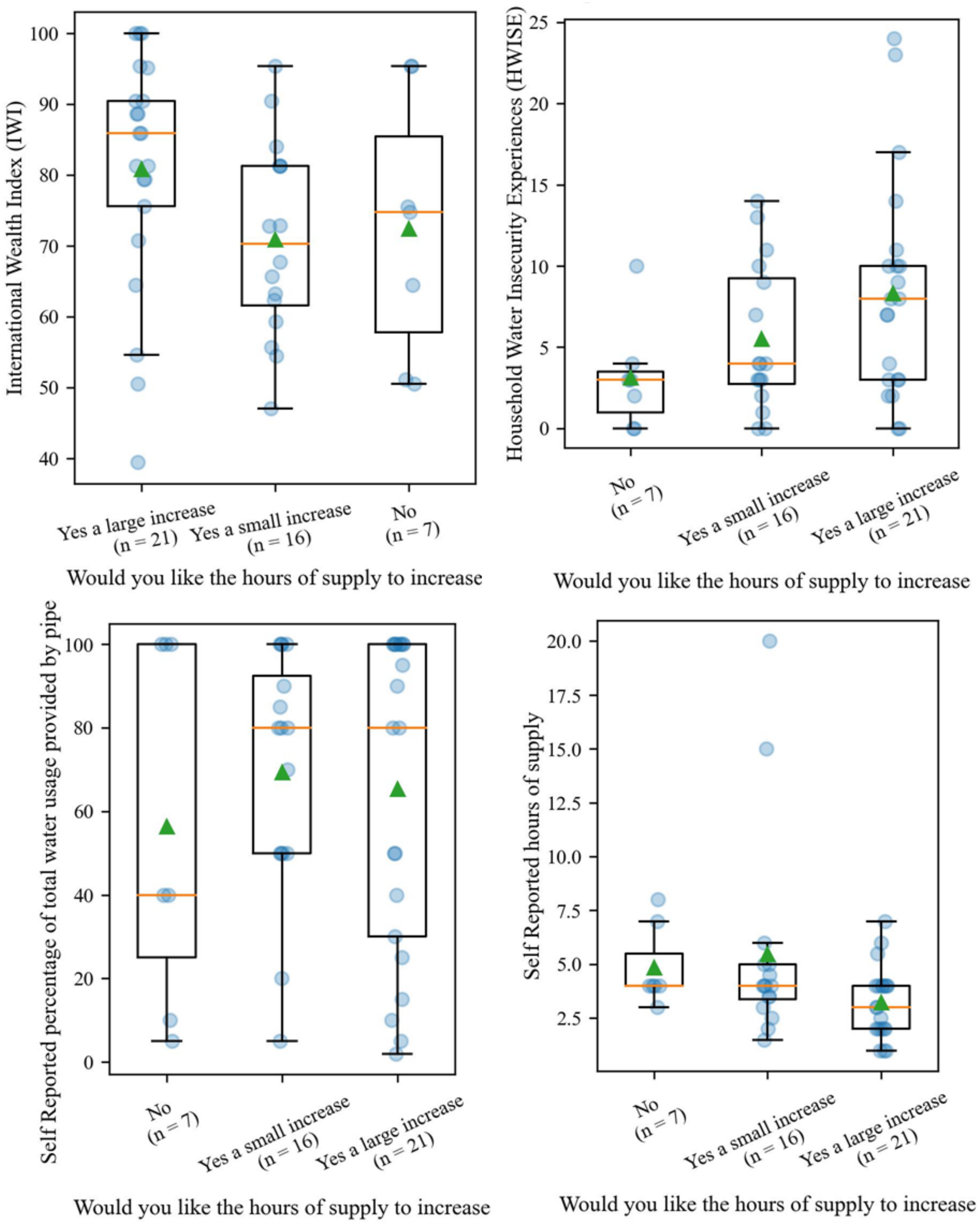

Figure 12.13: Boxplots comparing continuous variables against the desire for longer supply hours

Boxplots assessing the effect of supply conditions and current withdrawal volume on the desire for longer supply hours

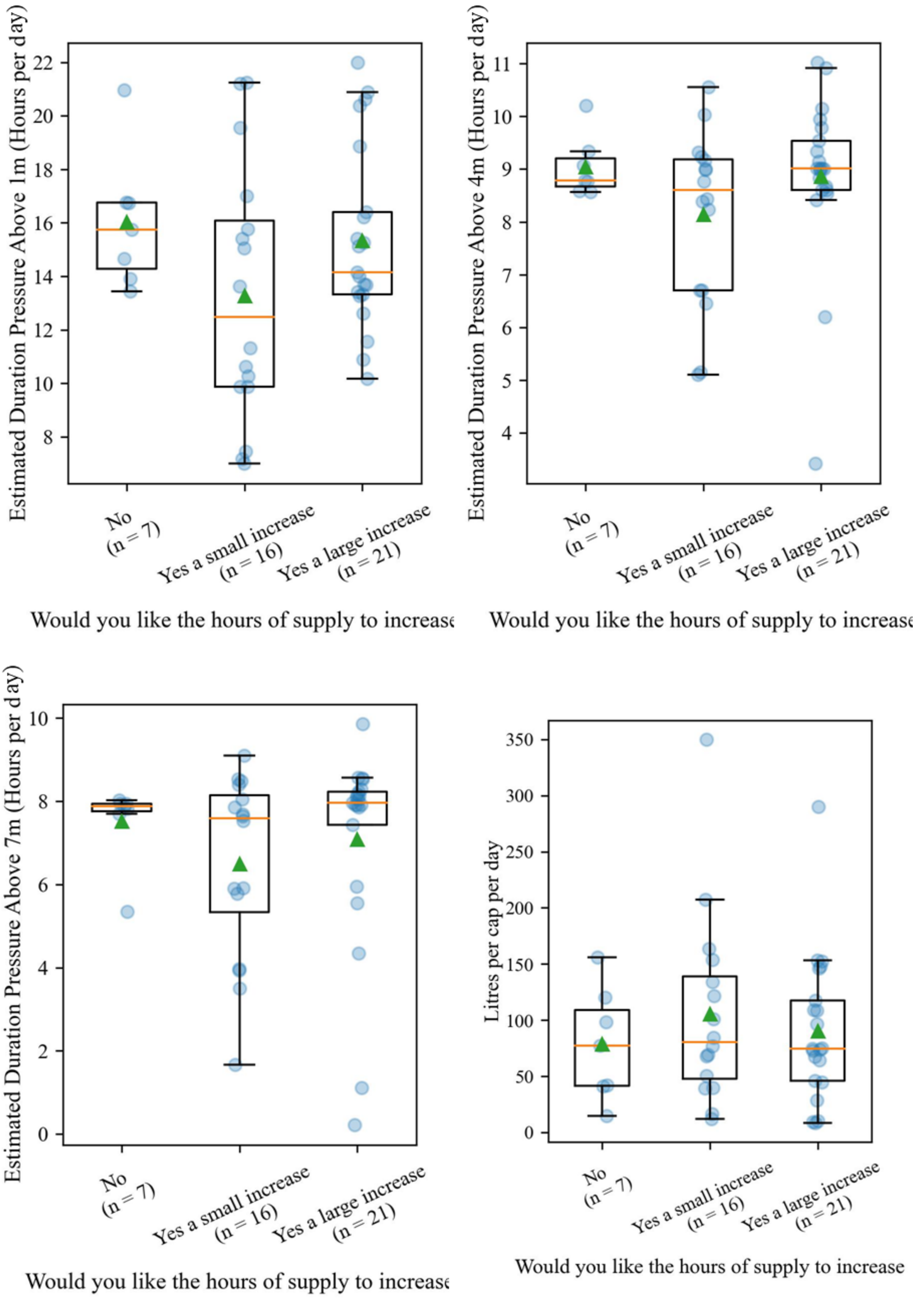

Figure 12.14: Boxplots comparing the supply conditions/current withdrawal volume of different groups depending on their desire for longer supply hours

Boxplots comparing continuous variables against the expectancy that more water would be used if the supply hours increase

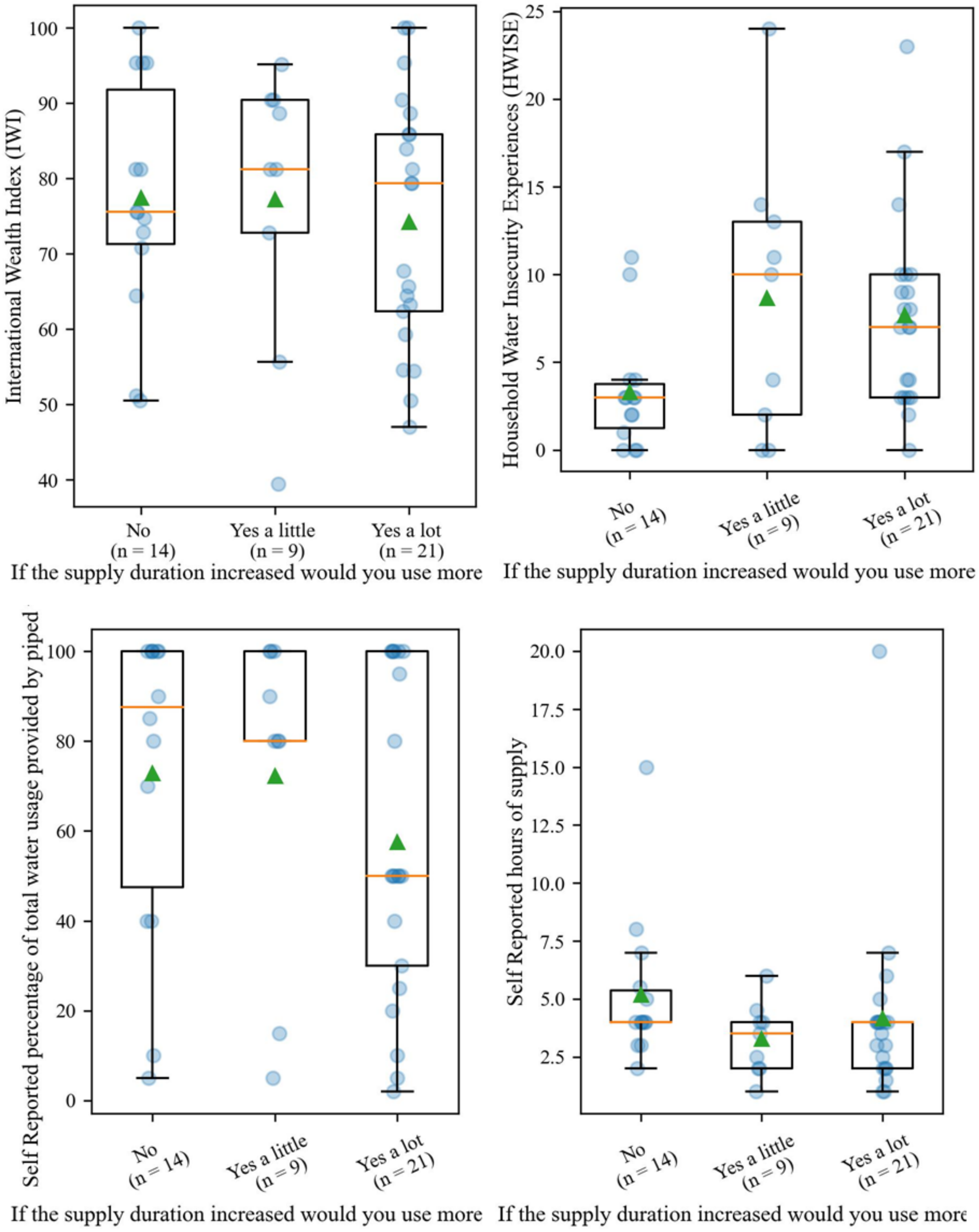

Figure 12.15: Boxplots comparing continuous variables against different groups defined by their anticipation that more water would be used if the supply hours increase

Boxplots assessing the effect of supply conditions and current withdrawal volume on the expectation that more water will be used if the supply hours increase

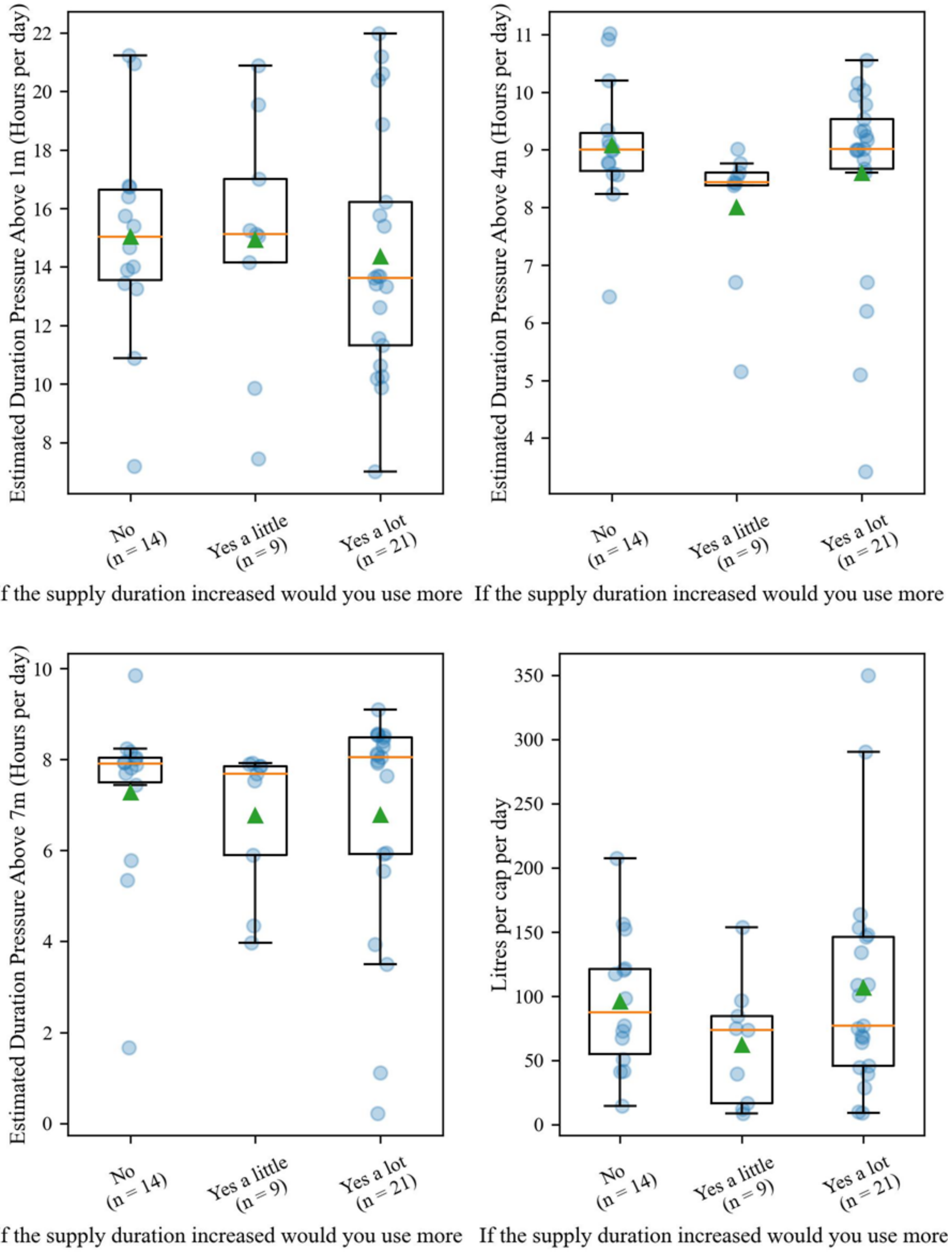

Figure 12.16: Boxplots assessing the effect of supply conditions/current withdrawal volume on the anticipation that more water will be used if the supply hours increase

v. Statistical Tests Comparing Household Variables against the Volume Used per Day

The table below summarises the statistical tests investigating if household variables correlate with the withdrawal volume of the consumer measured in litres per day (not litres per capita per day).

Table 12.4: Statistical tests investigating whether household characteristics are correlated with the total withdrawal volume of the connection

Variable	**Test**	**Statistic**	**P-value**	**Null hypothesis (p-value > 0.05)**	**Outcome**
Plumbed or yard tap	Mann-Whitney	277	0.251	Not rejected	No statistical significance at 95% level
Primary other source of water (Tube well vs None)	Mann-Whitney	222	0.725	Not rejected	No statistical significance at 95% level
Storage volume three categories (Litres)	Kruskal-Wallis	3.79	0.150	Not rejected	No statistical significance at 95% level
Self reported perception of water quality	Kruskal-Wallis	3.10	0.212	Not rejected	No statistical significance at 95% level