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Understanding domestic water consumption in Betania's jurisdiction, Panama City through smart water meter technology powered by LoRaWAN

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Abstract – Panama, being the fifth country with most annual precipitation is facing immense challenges regarding its water management. An aging distribution network and dated regulations in the sector have created an environment where it's estimated that around 39% of the water produced is unaccounted for as "Non-Revenue Water". This presents a major challenge for the main and only water utility company, Instituto de Acueductos y Alcantarillados Nacionales (IDAAN), which faces multiyear operational deficits and is actively seeking new ways to aid in the reduction of operational losses. A solution can be found through the application of Automatic Meter Reading (AMR) technology to enhance the information obtained by the water service provider from consumers and their water usage. This research, performed in the Betania jurisdiction, district of Panama, a mostly residential neighborhood from the 1950's located in Panama City intends to show the operation, future and results provided by a metering network enabled with Long Range Wide Area Network (LoRaWAN). Through the application of LoRa, the data obtained from several dwellings equipped with Smart Water Meters using AMR technology can be analyzed to determine water demand behavior and peak factors of water consumption to support changes in current water distribution system design. Preliminary analysis of the data shows an average consumption of 407.5 ±98 liters/person/day with hourly and daily peak factors of 1.9 and 1.3, respectively.

Keywords—Non-Revenue Water, LoRaWAN, Peaking Factors, Automatic Meter Reding, Water Management.

I. INTRODUCTION

Panama boasts one of the highest average annual precipitations occupying the fifth place in the world. This allows the country to possess a high availability of water resources, numbering on average 126,560.86 Mm^3 per year which also establishes it as one of the richest water countries per capita [1], [2], [3]. Despite these facts it is typical for sectors of the most populated metropolitan areas to go without a reliable potable water supply for multiple days. Climate Change also plays an important role in the countries' freshwater supply. Irregular precipitation patterns and prolonged dry seasons (e.g. 2023-2024 - ENSO) have previously strained the capacity for potable water production from the main reservoirs which are also used by the Panama Canal Authority for navigation purposes. In an attempt to keep up with an ever-growing population demand and to help bring supply to communities that lack it, Panama's government and its main drinking water provider, IDAAN (Instituto de Acueductos y Alcantarillados Nacionales; by its acronym in Spanish) have concreted plans to increase daily potable water production capacity by 0.95 Mm^3 through new potable water treatments plants concentrated around the county's interoceanic region which houses approximately 55% of Panama's 4.0 million inhabitants[4], [5].

Despite the efforts to increase production capacity, Panama also faces problems with high amounts of non-revenue water (NRW) registered by IDAAN, an issue not simply solved by increasing capacity. NRW is all water that is not billed by the service provided as a result of leaks in the network, inaccurate or non-existing metering and both unbilled authorized and unauthorized consumption (see Table I). IDAAN estimated in 2022 that 39.7% of the potable water production is accounted for as NRW, with some estimates that suggest that up to 25% is due to leaks. This situation coupled with a low rate of monitored water meters (17.7 %) contributes to produced water that IDAAN cannot bill [6], reducing available resources for management and investment purposes. It is also important to add that IDAAN has a client's debts of up to 100 million dollars, further reducing available funds to contribute maintenance efforts[7].

TABLE I
STRUCTURE OF WATER BALANCES [8]

Revenue Water	Authorized consumption	Billed authorized consumption	Billed metered consumption
			Billed unmetered consumption
Non-revenue water		Unbilled authorized consumption	Unbilled metered consumption
			Unbilled unmetered consumption
	Water Losses	Apparent losses	Unauthorized consumption
			Metering inaccuracies
			Data handling errors
		Real losses	Leakages on transmission, tanks and connections

In 2023, the water utility company announced its plan to increase client metering coverage and stop billing average consumption to transition into billing the actual volume of water consumed by each client. This is a decision that according to institution executives and supported by studies will help reduce overall water consumption by up to 20% [9], [10]. As of 2024, IDAAN has also opened a bid to acquire water meters equipped with automatic meter reading (AMR) technology. This initiative aims to address the previously presented issues but will also aid in eliminating third party contracts for meter reading and bill distribution, freeing up funds for other projects as well as bolstering billings as a stream of revenue by reducing the unmetered aspect of NRW[11].

This research intends to study the viability of the implementation of a smart metering network monitoring system using the Internet of Things (IoT) and AMR to collect drinking water consumption data from urban areas of Panama City. This data is collected to determine water consumption patterns to later obtain key parameters used in the design and management of the drinking water supply infrastructure. By using smart meters and storing data for later processing, water demand can be estimated to derive Peak Hourly Factors (PHF) and Peak Daily Factors (PDF) and obtain values to compare with current design codes and accepted practices. Additionally, a visual dashboard developed using open-source platforms eases the display of the collected data and aids in monitoring.

II. Materials and Methodology

A. Data collection infrastructure

The proposed metering network is composed of four main components: the meters, the gateways, cloud services and the dashboard applications connected through a LoRaWAN network. The selected meters for this study use ultrasonic technology in accordance with AWWA 715 standards to measure water flow, avoiding the use of any moving parts. These meters are equipped with LoraWAN modules, allowing for the wireless transmission of data packets to LoRaWAN gateways[12]. The water meters were acquired in both 20 mm (3/4-inch) and 15 mm (5/8-inch) threads which are the most common sizes in domestic use and can achieve readings as low as 0.06 liters per minute. These meters also needed to comply with IDAAN's Common Constructive Practice Guidelines which required a connection length of 190 mm (7.5 - inch) for the 15 mm variant and 229 mm (9 - inch) for the 20 mm variant[13], [14]. The meters also required testing by IDAAN in accordance with ISO 4064 to guarantee their operational accuracy at low, medium and high flow.

In a LoRaWAN network, the gateway plays a vital role by serving as the communication link between end devices, such as water meters, and the server network. It is crucial for receiving and transmitting data packets, as it captures the radio frequency signals sent by the end devices and converts them into data packets that can be sent over the internet to a server. Additionally, LoRaWAN gateways can handle communication with multiple devices simultaneously (in the order of hundreds or even thousands), supporting network scalability, which is especially important for large-scale projects spanning wide geographical areas. This feature is particularly beneficial in applications like water consumption monitoring, where collecting data from numerous households simultaneously is essential. The Things Outdoor Gateway (TTOG) (Fig. 1) was chosen for its durability and efficiency in outdoor settings, making it well-suited to withstand Panama's environmental conditions, and operates in the designated LoRa frequency of 915 MHz for North America. The gateway also offers flexible connectivity options, including Ethernet and LTE connections [12].

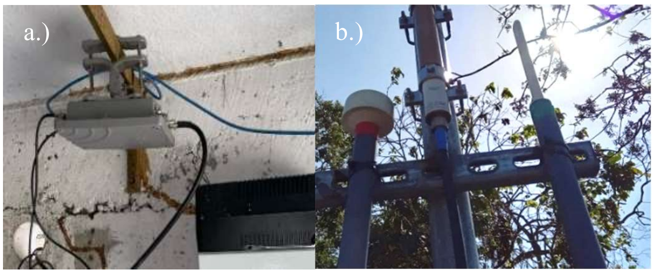

Fig. 1 The Things Outdoor Gateway. (a) shows installed gateway. (b) shows antenna array connected to gateway. From left to right: GPS antenna, LoRa antenna and LTE antenna.

The final parts of the network are the cloud services which collect, process and store the information generated by the water meters. The Things Network performs the initial processing which is decrypting of the data packet and reformatting the data for proper interpretation [12].

The data is then uploaded into the platform InfluxDB which organizes the data into a time series database for ease of access for both users and other applications. The platform Grafana is an example of such an application and was chosen to display a dashboard that showcases instant and cumulative flow in a more visual (graphical) and intuitive manner that helps interpretation of the data. This dashboard also allows the monitoring of battery status and signal strength for each meter in near real-time[12].

B. Site selection

Equipment requirements and conditions in the country demanded certain criteria to be thought of carefully for the placement of the gateways. Firstly, due to the nature of the research and considering that IDAAN's residential clients account for 77% of all water distributed, a residential area needed to be selected to conduct the study [15]. Previous research performed utilizing TTOG suggested that the meter to gateway communication was most effective within a 500-meter radius of the gateway due to the nature of the urban environment and its surroundings [12]. Other LoRaWAN test conducted in urban environments suggest that coverage ranges of up to 800 meters can be reached, however t is noted that signal strength and the amount of received packages drop sharply from 500 meters and beyond [16], [17].The gateway also needed to be installed in an elevated area to improve connectivity. Additionally, equipment security was a concern that needed to be addressed due to certain instances of vandalized equipment (Fig. 2).

Considering the previous criteria, a decision was made to install the gateway at an IDAAN water tank facility which was gated, located at Parque La Gloria, Betania. Betania is a jurisdiction located in Panama City which is a predominantly working-class neighborhood with an aging population. By inspecting the client database provided by IDAAN, it was identified that the zone had 1804 potential clients (Fig. 3b), mostly residential, that could have smart meters installed withing the effective gateways radius.

C. Meter Location

To determine meter location for effective data collection, a parameter called received signal strength indicator (RSSI), which is a measurement of signal quality, was monitored during a pilot program performed at Universidad Tecnológica de

Fig. 2 Damaged water meter (32862702) installed at a home in Betania

Panama. Meters appeared to be communicating reliably in an RSSI threshold that is greater than -110 dbm. A survey with a LoRaWAN field tester, a device that could replicate the signal produced by the end node, was conducted around the area enclosed by the 500 meters radius. By projecting the RSSI measurement in different areas using Geographical Information Systems (GIS), suitable locations for 5 water meters (32862702, 32862705, 32862704, 32862707, 32862708) were identified (Fig. 4).

D. Data collection

Previous trials revealed the meters did not always communicate in the interval required to calculate hourly peak factors, so a more frequent time interval had to be chosen. The water meters were configured through the manufacturer's software to send data packets every 15 minutes to minimize data loss and reduce the need to fill in missing values. These data packets contain vast information related to the operation of the water meter. However, for this study only the time and date of the reading, device number, battery voltage, instant flow, accumulated volume, RSSI - sound to noise ratio (SNR) and the receiving gateway that the water meter connected to was extracted.

E. Measurement period

Data was intended to be collected for at least a year from the five meters installed. However, from July to August 2024, almost no data was captured due to poor signal strength caused by the metal casing the meters were installed in (Fig. 5a). The antennas in the meters were extracted from the casings (Fig 5b) to bolster signal strength, solving the latter issue. Another data gap was later identified, caused by an administrative process with the LTE network provider that left the gateways without connection to the servers through September 2024. From October 2024 until January 2025, meter operations continued regularly without any need of intervention. Nonetheless, several meters have suffered damage from vandalism or were installed in locations with poor signal strength without previous consultation from the service provider, severely reducing the sample size for the study. As of the publication of this investigation, data gathering has continued to ensure the collection of at least the 12-month period which was set as the minimum testing time to produce representative results for a whole year worth of demand data for residential clients.

Fig. 3 Gateway's radius around la Gloria Park. (a) shows the 500-meter radius on a satellite map. (b) shows clients according to IDAAN's client database. Every dot represents a client.

Fig. 4 Installation site of water meter 32862704. (a) Normal aspect of meter casing with protruding antenna from metal casing. (b) Meter casing opened for service.

Fig. 5 Typical metal casing utilized in Panama City. (a) metals casing before installation. (b) a meter antenna protruding from metal casing after intervention.

F. *Data management and analysis*

The data collected and stored in the cloud platforms needed to be processed to extract the relevant information. A CSV file with all the data organized in a time series was downloaded from InfluxDB and processed with Excel into a readable format for other platforms. It is at this point that a tool and a method to fill in missing data was required. Matlab was selected as a software and programming language that was both faster and easier to program for the applications needed. A code was written that allowed for the construction of a uniform 15-minute interval time series that filled in the missing data points using linear interpolation. Using this time series, the accumulated volume corresponding to each hour was employed to estimate the corresponding hourly flow. This hourly flow was calculated as the quotient of the difference in accumulated volume at the start and end of each hour and the elapsed time between these two points as described in (1).

$$Q_{\text{hour i}} = \frac{\text{Vol}_{\text{hour i}} - \text{Vol}_{\text{hour i}-1}}{\Delta t} \quad (1)$$

where $Q_{\text{hour i}}$ is the hourly flow rate for hour "i" in liters per person per hour, $\text{Vol}_{\text{hour i}}$ is the accumulated volume for hour "i" in liters per person, $\text{Vol}_{\text{hour i-1}}$ is the accumulated volume for hour "i-1" in liters per person and Δt is the time difference between data points in hours.

The daily flow is calculated as the quotient of the difference in accumulated volume at the start and end of each day and the elapsed time between these two points as described in (2).

$$Q_{\text{day i}} = \frac{\text{Vol}_{\text{day i}} - \text{Vol}_{\text{day i}-1}}{\Delta t} \quad (2)$$

where $Q_{\text{day i}}$ is the hourly flow rate for day "i" in liters per person per day, $\text{Vol}_{\text{day i}}$ is the accumulated volume for day "i" in liters per person, $\text{Vol}_{\text{day i-1}}$ is the accumulated volume for day "i-1" in liters per person and Δt is the time difference between data points in days.

The previous steps result in two time series, an hourly and a daily one. These data sets are then split into a new series for each month that was collected to analyze hourly and daily trends corresponding to each month. All flow data was then averaged to obtain and average daily flow, as calculated in (3), and average hourly flow, as calculated in (4).

$$\overline{Q}_{\text{daily month "i"}} = \frac{\sum Q_{\text{day -month "i"}}}{\text{n}} \quad (3)$$

where $Q_{\text{daily month i}}$ is the average daily flow rate for the month "i" in liters per day per person, $Q_{\text{daily month i}}$ is the daily flow for every day of month "i" and n is the number of the days in month "i".

$$\overline{Q}_{\text{hourly month "i"}} = \frac{\sum Q_{\text{hour -month "i"}}}{\text{n}} \quad (4)$$

where $Q_{\text{hourly month i}}$ is the average hourly flow rate for the month "i" in liters per day per person, $Q_{\text{hour month i}}$ is the hourly flow for every hour of month "i" and n is the number of the hours in month "i".

To study hourly trends, all data points for each hour in the interval from hour 00:00 to 23:00 were grouped into their own set with their respective flow, date, month and day (see Table II). For each hour of the day all the hourly flow rates were average throughout the month (5), resulting in an average flow rate for every hour of the day. For daily trends, data points were grouped for each day in the interval comprised from Monday through Sunday (see Table III). All daily flow rates were then averaged, resulting in an average daily flow for each day of the week (6).

$$\overline{Q}_{\text{hour(i)}} = \frac{\sum Q_{\text{hour "i""}}}{\text{n}} \quad (5)$$

where $Q_{\text{hour i}}$ is the average hourly flow rate for hour "i" in liters per hour per person, $Q_{\text{hour i}}$ is the hourly flow for every hour "i" of month and n is the number of the hours "i" in month.

$$\overline{Q}_{\text{day (i)}} = \frac{\sum Q_{\text{day "i""}}}{\text{n}} \quad (6)$$

where $Q_{day\ i}$ is the average daily flow rate for day "i" in liters per day per person, $Q_{day\ i}$ is the daily flow for every day "i" of month and n is the number of the days "i" in month.

Finally, the daily and hourly peak factors (PF) were calculated by dividing each average hourly and daily flow rate by the average daily and hourly flow for the entire month, as in (7). The maximum values resulting from this analysis are the Peak Hour Factor (PHF) and the Peak Day Factor (PDF). These factors are used to design water distribution networks and other parts of the distribution infrastructure for the most critical time of the day and the week. Having performed all calculations, it is important to note that all water consumption data was managed to represent consumption per person, based on the observed number of people residing in the household.

$$PF = \frac{Daily\ or\ hourly\ averageflow}{Average\ daily\ or\ hourly\ flow} \quad (7)$$

III. RESULTS AND DISCUSSION

A. Water demand curves

The Panamanian design code establishes an average demand per capita of 100 gallons per person per day, equivalent to 378.54 liters per person per day for urban areas. This value has been in use as the accepted practice for more than 60 years without any publicly available research to back it up as a value that reflects the reality of the country. There are even studies that suggest that most households use less water than the suggested average[18]. From the initial meters installed for the trial, only one meter, 32862704, was able to gather information throughout the described period. The data collected from meter 32862704 indicates an average daily demand of 407.5 ± 98 liters/person/day, slightly higher than the design value (Fig. 6). A study perfomed in 1976 in Panama City which surveyed six neighborhoods in the capital city. Three of this neighboords, Villa Caceres, Santa Maria and Los Angeles are within Bethania's jurisdiction and should reveal a similar reality as the one present in the neighborhood subject area of study. The study calculated an average demand of 327.4 L/person/day for Los Angeles, 247.49 L/person/day for Villa Caceres and 184.96 L/person/day for Santa Maria [19]. According to this study as well, across all three neighboordhoods only 29 households where found to have a demand that exceeded 378.54 liters per person per day design value. Comparisions cant be drawn across both studies due to the single houselhold examined in this study, however there is the possibilities for two scenarios to highlight which are eithering examining a household with an above average demand or the demand in the area has grown over the last 50 years.

More recent studies applying smart meters across the world have also worked to determine average demand, peak factors and the drivers of these peaks. Reference [20] presents a study which determined an average demand of 154.78 L/person/day by instrumenting 230 residences in South East Queensland with smart meters and data loggers in household appliances. Reference [21], a study conducted in Beni Abbes, Algeria concluded that the average demand for the town sat at 80

TABLE II
EXAMPLE HOURLY DATA SERIES FOR 5:00 AM

Hour: 5				
Date	**Volume (m^3)**	**Month**	**Day**	**Q hour (Liters/person/hour)**
11/11/2024	134.38	Nov	Mon	13.00
11/12/2024	135.00	Nov	Tue	6.50
11/13/2024	135.93	Nov	Wed	4.50
11/14/2024	136.85	Nov	Thu	9.00
11/15/2024	137.96	Nov	Fri	7.00
11/16/2024	138.82	Nov	Sat	2.00
11/17/2024	139.30	Nov	Sun	6.50

TABLE III
EXAMPLE DAILY DATA SERIES FOR MONDAYS

Day: Monday				
Date	**Volume (m^3)**	**Month**	**Day**	**Q hour (Liters/person/day)**
11/17/2024	140.21	Nov	Mon	514.80
11/24/2024	145.72	Nov	Mon	239.50
12/01/2024	152.28	Dec	Mon	505.00
12/08/2024	159.25	Dec	Mon	311.00
12/15/2024	165.87	Dec	Mon	393.00
12/22/2024	171.71	Dec	Mon	379.50

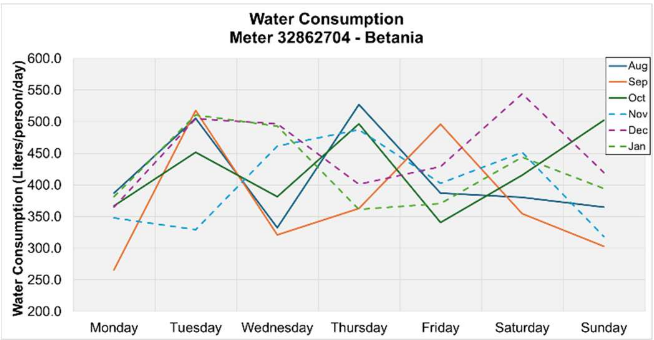

Fig. 6 Daily water consumption for all months organized by weekday

L/person/day. Reference [22] in Hvaler, Norway resulted in an average demand of 133 L/person/ day, which was way lower than the 200 L/person/day that is established in Norwegian design codes for the area. In Lima, Peru, [23], consumption ranges from 234.07 L/person/day on higher income neighborhoods to 115.21 L/person/day on lower income neighborhoods. More studies of residential water consumption throughout the Latinamerican countries need to be investigated in order to have a better picture of the consumption behavior across the region.

The results obtained from meter 32862704 are hardly a representative sample of the studied area. However, these results do help validate the methodology through comparisons with expected values and scenarios. All the previously mentioned studies had a greater sample size ranging from 12 households in [21] to over 1800 households in [22]. This

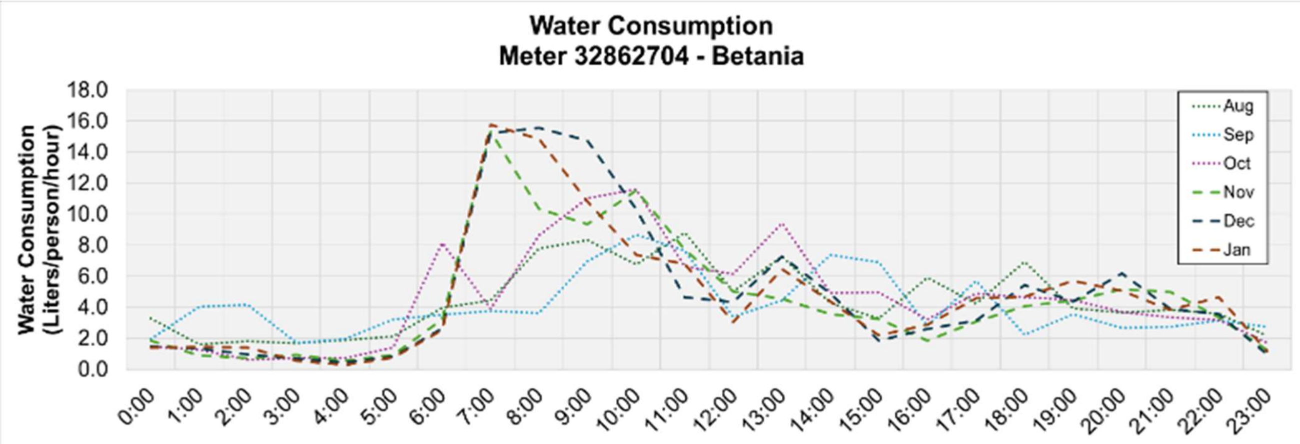

Fig. 7 Hourly water consumption for all months organized by hour

evidences the need to increase sample size by correctly identifying sites that meet the needed wireless communication requirements and a continuing communication and renewing cooperation agreements with IDAAAN which are needed to perform meter installation. Nonetheless, the water consumptions curves elaborated from data between August 2024 and January 2025 start revealing certain patterns (Fig. 7).

Water demand starts ramping up from 5am to 8am when families usually start their day by getting ready for school, work or other activities. The demand then starts falling until midday when it starts ramping up again until a smaller peak near 1pm. Demand then remains below the average for the rest of the series up until a drop off at around 11 pm. Certain explanations can also be given to observed behaviors in the complete data series. By zooming in on the data series between the 8th and 11th of November, a gap of 12 hours on the 10th of November can be identified where no water consumption was detected (Fig.8). The 10th of November is a national holiday in Panama, leaving a possibility that the inhabitants of the dwelling left the residence, thus leading to this behavior. This gap with no consumption registered could also be used as an observation point to determine that there are no leaks present inside the residence. Looking at the complete data set also helps to understand metering behavior (Fig.9). For example, the presence of long horizontal lines and large gaps are indications of very few data packets being delivered. Linear interpolation, used to fill the data, between data points received days apart, lead to a constant demand filling up the data.

B. *Peaking Factors*

The Panamanian design code establishes a PHF of 2.0 for urban environments, however accepted practice also allows for usage of 2.5. PDF is not regulated in codes; however, standard practice is to utilize 1.5. The data collected from the meter 32862704 shows an average PHF of 1.9 occurring at 8:00 am. However, values between 2.0 and 3.4 can be observed through the data series around 7:00 to 11:00 am, the hours where consumption is expected to peak. The average PDF was 1.1, occurring on Tuesdays, with certain days going to PDF as high as 1.9, which was the case for the 5th of October. Other high consumption days were identified, like the 12th of August and 9th of December when consumption peaked at 1.82 and 1.86 times above the average respectively. The Panama City study [19] found that across the three surveyed neighborhoods, PHF around 2.0 to 3.0 and PDF of 1.13 to 1.17 are typical. Additionally, the study concluded that Panama's maximum and minimum consumption days were Sunday and Tuesday respectively. The findings from data provided by meter 32862704 back these results through the average PDF curve, which reaches its maximum value on Tuesdays and falls to its lowest point on a Sunday (Fig. 11). The Southeast Queensland study [20] found that PDF of 1.0 to 1.2 are usual, however extreme cases are shown to go as far 1.7 on particularly demanding days which were driven by external water uses. The Beni Abbess study [21] observed an average PDF of 1.6 and a PHF of 2 with peaks reaching as high as 3.6. The Hvaler study [22] reached a conclusion where a PHF around 1.8 and PDF of 1.3 were found as the average values for the area. It can be observed that although different sample sizes were evaluated, PHF range between 1.8 and 2.0 while PDF usually can be found below 1.3 but presents a higher variability.

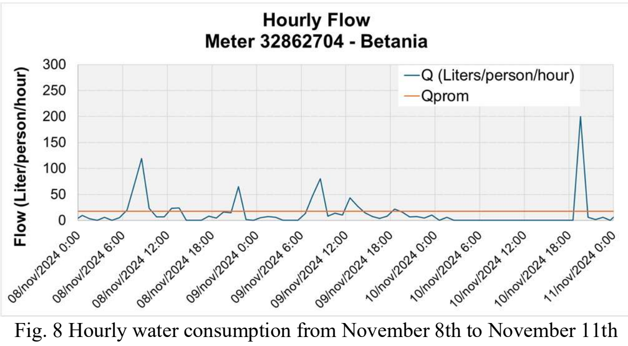

Fig. 8 Hourly water consumption from November 8th to November 11th

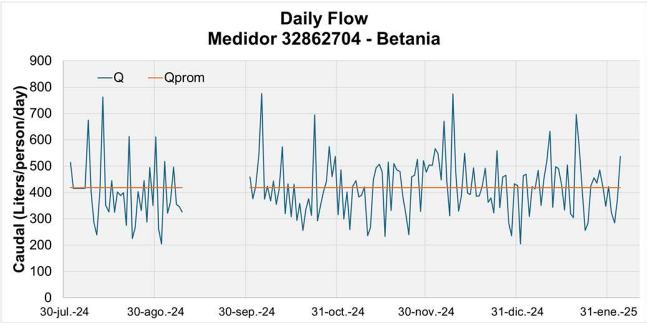

Fig. 9 Complete data set for daily water consumption.

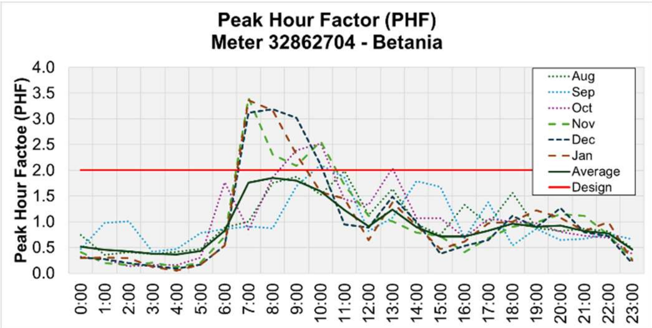

Fig. 10 PHF organized by hour and month, design PHF in Panama highlighted in red.

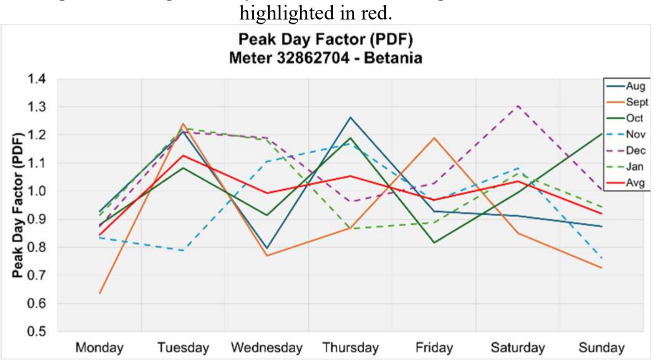

Fig. 11 PDF organized by weekday and month

IV. Conclusion

Implementation of a network capable of AMR in an urban area in Panama was demonstrated to be possible. Although gateway effective communication range is considerably reduced from the publicized value, a considerable number of clients can be found within 500 meters radius that fit the criteria required for effective metering. Although the sample size was severely reduced, proper causes of failure for all meters were identified and documented to avoid future mishaps. Lastly, cooperation with the water utility company needs to be enhanced for further research since is the regent authority to install and modify water meters, as well as providing certifications for any meter that will be used in the Republic of Panama.

External and social factors can influence the pattern of consumption. To better understand the demand patterns created by the measurements, targeted surveys need to be conducted to characterize certain behaviors like extreme peaks or days of no consumptions. Without these surveys, certain inferences could be made from the patterns of consumption without any concrete evidence to support these claims.

Data from one meter is not enough to conclude the need for changes in the design codes, however it is observed that the average parameters gathered for the studied residence do seem to fit with the established design parameters. However, there are certain extreme cases, only visible, when looking closer at some periods, where values do greatly exceed design parameters and will need further examination.

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