Water Practice & Technology

IWA PUBLISHING

 Water Practice & Technology Vol 18 No 8, 1991 doi: 10.2166/wpt.2023.117

Coefficients and curves of hourly and daily variations of water demand for improved operation of potable water distribution systems: a case study of Chihuahua City, Mexico

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ABSTRACT

Maintaining a constant flow in a potable water distribution hydraulic system is challenging due to fluctuations caused by changes in user demand and seasonal factors. This study aimed to calculate the coefficients and curves of hourly and daily variation of water demand in the water distribution system of Chihuahua. It is crucial to understand the hydraulic system's behavior during peak demands and assess its capacity. The methodology involved calculating coefficients and curves of variation of demand based on flow data measured at the inlet of various hydrometric sectors using flanged electromagnetic flowmeters of various diameters and models. The results showed that the variation curves and coefficients of water demand are valuable tools for modeling, designing, and operating water networks. Incorporating these curves into hydraulic simulations during the planning and design stage can improve the accuracy of these models and better reflect the network's actual behavior. The proposed method is suitable for application in cities with similar demographic and social characteristics. The study concludes that accurate supply area information for hydrometric sectors is essential in constructing the curves and coefficients of demand variation, which can lead to opportunities for improving water service by informing more effective network design and operation.

Key words: daily variation, hourly variation, network operation, water demand

HIGHLIGHTS

- This study provides valuable insights into hydraulic system behavior during peak demands.
- Incorporating demand variation curves improves system behavior predictions.
- Generalizable outcomes for similar urban areas' water distribution challenges in maintaining a constant flow.
- Understanding demand patterns enables opportunities for water service improvement.
- Novel approach to calculating water demand variation curves.

INTRODUCTION

In a potable water distribution hydraulic system, maintaining a constant flow is a challenging task as it experiences fluctuations at different timescales such as hourly, daily, and yearly (Mala-Jetmarova *et al.* 2018; DOH 2020). The demand for water can also be seasonal, as observed in the city of Chihuahua, where the demand for water rises during summers due to the use of air-conditioning equipment such as backwash coolers. These variations in the water supply are a consequence of the hydraulic system's response to users' needs for domestic activities and the cyclical changes in their consumption patterns. Coefficients and curves of variation are typically used to describe these fluctuations (Alcocer *et al.* 2004; Ilaya-Ayza *et al.* 2016; Tzatchkov & Alcocer-Yamanaka 2016).

The variation coefficients represent the ratio between the average and maximum potable water demand within a specific timeframe (Paredes & Caiza 2019; Suárez 2019). On the other hand, the permanence curves illustrate the variations in water supply concerning the users' requirements. These curves are useful for understanding the hydraulic system's behavior during peak demands and for assessing its capacity to provide potable water. The study addresses the challenge of achieving a balanced and sustainable water supply by improving the assessment of water usage patterns and losses. In particular, it highlights the challenges of inadequate water pressure and intermittent supply, emphasizing the need to consider consumption, supply, and demand separately during the design phase to avoid inconsistencies between the system's design and its operation. Analyzing each component individually and understanding their interplay is crucial for ensuring a reliable and sustainable water supply system in the region (Polli de Oliveira *et al.* 2020; Delgado *et al.* 2022; Preeti *et al.* 2023).

To accurately analyze flow variations in a hydraulic system of drinking water distribution, it is crucial to consider the hourly variations in demand, as they significantly impact the operational performance of the supply system. Several key factors should be considered, including:

- Urban areas typically experience the highest water consumption during the early hours of the day, before work, and/or school activities.
- Average consumption patterns are influenced by users who are either away from home or engaging in daily domestic activities such as cleaning, laundry, and cooking.
- A second spike in consumption occurs in the evening when individuals return home from work.
- Consumption is reduced, almost to zero, during the night, when most users sleep.

The daily demand for drinking water exhibits variations that are influenced by several factors, including the day of the week, the season of the year, and calendarized holidays. These variations are also observed in hourly patterns throughout the year (Zhao *et al.* 2018).

As mentioned above, demand during the week is established in four phases. Weekends, however, present a different consumption dynamic, depending generally on the residential areas and the socio-economic level of the user. It should be noted that, in this study, the possibility of higher demand on weekends by users of upper socio-economic status was considered.

Elevated temperatures in arid or semi-arid zones, as in the case study presented here, mark the most relevant seasonal variations in demand, since they mean drastic changes in consumption and require the water system to have a continuous and more efficient supply.

In Chihuahua, particularly during the summer, the temperature rises significantly, resulting in a surge in water consumption to meet the user's needs, including increased water intake, garden watering, and air-conditioning systems. The latter, commonly known as 'wash air' in this region, requires a significant amount of water to operate efficiently due to the high temperatures that cause some of the liquid to evaporate.

It is important to note that the endowment variable includes physical losses, such as leaks, which vary inversely with demand. According to hydraulic principles, physical losses are mainly driven by the flow pressure in the network (VAG Germany 2011; Mohamed *et al.* 2021). As demand increases, pressure decreases since higher flow rates result in faster water velocity in the pipes, leading to lower pressure in accordance with Bernoulli's principle. The impact of increasing demand on physical losses in the distribution network is significant. As demand rises, the average pressure within the network decreases, which reduces the volume of physical losses. However, this reduction is not proportionate; the amount of water saved by reducing physical losses is considerably less than the quantity of water demanded by the increase in consumption. Usually, the weekly variation of the demand is not considered in the modeling and design of drinking water supply networks. Since its variation is smaller than the seasonal variation, it is included in the latter. However, it should be considered in the operational area since it is important for the supply network operators to consider the possibility of an increase in demand during the weekend (Velmurugan *et al.* 2023).

In conclusion, demand for drinking water in the hydraulic distribution system is not constant over time, and its main variations occur periodically throughout the day and/or seasonally during the year. The modeling and design of drinking water supply networks should consider the temporal variability of demand to ensure that the system operates efficiently and effectively.

USE AND APPLICATION OF DEMAND VARIATION CURVES AND COEFFICIENTS

Demand variation curves are mainly used for the design of water distribution system performance in hydraulic modeling (Ilaya-Ayza *et al.* 2016). The use and application of demand variation curves and coefficients are crucial to calibrate theoretical models with real-world scenarios, which can be achieved through dynamic simulation models. These models enable the evaluation of pressure variations caused by changes in stream velocity due to fluctuations in demand and the water mass in the network. Therefore, an adequate schematization of pressure variability over time using hydraulic simulation is essential in determining the quality of service during the planning and design stages (Polli de Oliveira *et al.* 2020). Furthermore, this information can be utilized to optimize existing networks through sectorization and the application of pressure management techniques during operation, as suggested by Tzatchkov *et al.* (2014).

The hydraulic behavior of a hydrometric sector is influenced by several variables, such as topographic elevation and the distance from the supply center. These variables have a significant impact on the variation of pressure with respect to demand, particularly at the critical point of the sector. The critical point is determined by the geographical location of the sector in relation to the water intake point and affects sectors with the greatest topographic unevenness, resulting in either a decrease or an increase in inlet pressure. Additionally, the distance between the supply and entry points also contributes to pressure variation as flow takes longer to enter the sector than to keep the system pressurized. Proper consideration of these variables is crucial for the accurate modeling and design of hydrometric sectors and for the implementation of effective pressure management strategies (VAG Germany 2011).

While hourly and daily demand variation curves do not capture variations in flow and pressure in the secondary lines of a distribution network (such as household taps), they are essential in dynamic simulation models. This is because these curves accurately reflect the demand variation in the primary pipes and subsequently determine the pressure variation at the critical point of a hydrometric sector (Tzatchkov *et al.* 2014).

OBJECTIVE

The objective of this study is to establish hourly and daily demand variation curves and coefficients for the hydrometric sectors of Chihuahua City. This information is intended to be used in hydraulic modeling, design, review, and optimization of the sectors. Moreover, it aims to facilitate decision-making processes aimed at enhancing the operation of the distribution network and ensuring an adequate supply of drinking water.

STUDY AREA

To estimate the curves and coefficients of daily and hourly variation of demand, data from various hydrometric sectors of the drinking water network of the city of Chihuahua, Mexico, were used. The city of Chihuahua is located in northern Mexico and is the capital of the state of Chihuahua (Figure 1). Due to its geographic location, it is classified as a semi-arid temperate climate zone, with mild winters but cold nights and hot summers (Sánchez *et al.* 2022b). The average temperature ranges between 17–37 °C in summer and 10–17 °C in winter. Typically, from June to August, the temperature reaches the highest levels during the day, resulting in changes in the users' consumption patterns. During the summer month of June to August, the temperature reaches its peak during the day, resulting in changes in users' consumption patterns. The total population of Chihuahua City according to the 2020 census of the National Institute of Statistics and Geography (INEGI 2020) is 925,762. The Chihuahua Municipal Water and Sanitation Board (JMAS for its acronym in Spanish) is responsible for supplying drinking water to the city.

The urban water supply in Chihuahua City is primarily sourced from 167 wells (99%) with only 1% or less coming from the Chihuahua Reservoir. As of 2018, only 12% of drinking water accounts received continuous service (CWS), with the remaining 88% receiving intermittent service (IWS). However, improvements have been made in recent years through the implementation of sectorization, pressure management techniques, and the use of user demand pattern data (Figure 1), resulting in an increase in CWS to approximately 35% of accounts (Sánchez *et al.* 2022a).

METHODS

The calculation of coefficients and curves of daily and hourly variation of demand was obtained based on flow data measured at the inlet of various hydrometric sectors of the city of Chihuahua (Figure 1). Flanged electromagnetic flowmeters of various diameters and models were used to measure the hourly flow rates.

To estimate the coefficient of variation of daily demand (CVDD) and the coefficient of variation of hourly demand (CVHD), hydrometric sectors with continuous supply (fixed set point) were preferred to avoid variations in flow pressure, both for users and for the network in general. However, two sectors with intermittent supply were also analyzed using an hourly/pressure table obtained with the methodology of the hourly demand variation

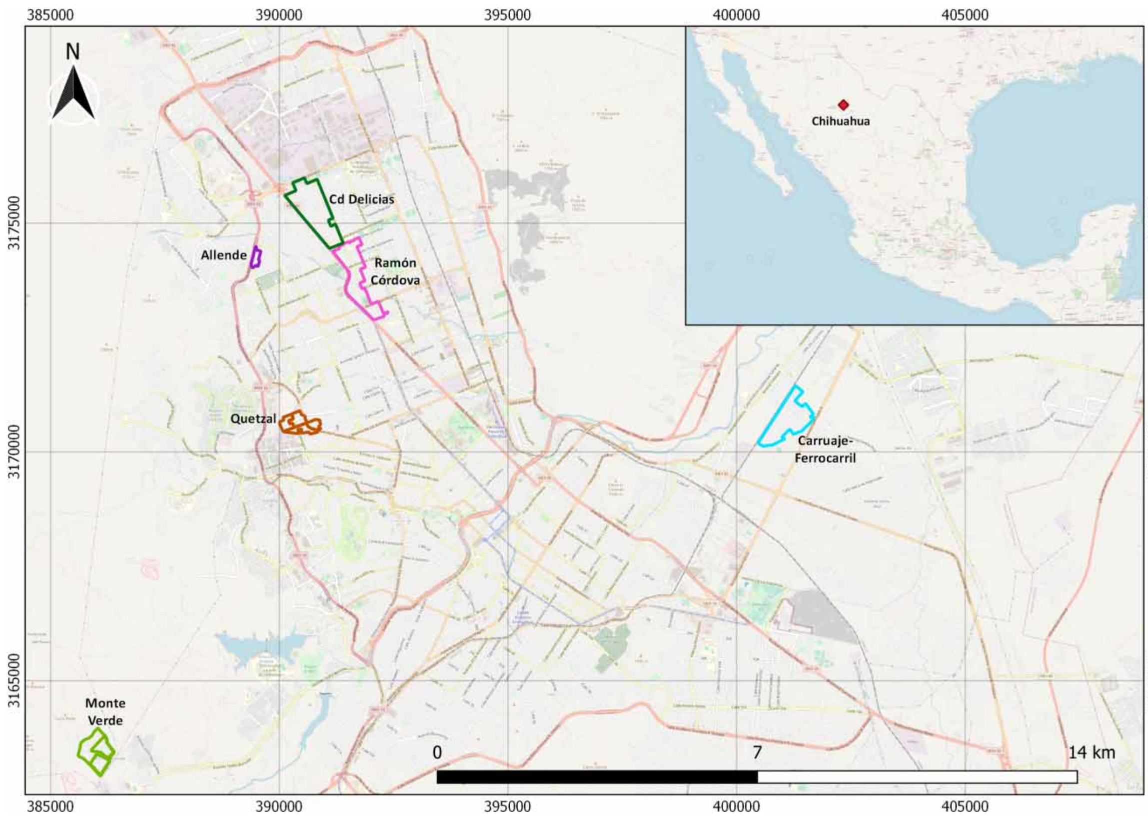

Figure 1 | Macro-location of the city of Chihuahua and the placement of the hydrometric sectors analyzed.

curve designed for the sectors analyzed previously. This approach allowed us to analyze the hourly demand variation of the selected sectors, even in the absence of a fixed set point.

It is important to clarify that some of those sectors in which the hourly variation in demand was calculated did not operate in continuous service. The supply to these sectors was intentionally changed to an uninterrupted mode during the measurement days. To estimate the coefficients and daily variation curves of demand, two sectors were selected for analysis. The first sector had a constant inflow pressure, while the second had semi-intermittent service, characterized by high and low pressure. These sectors were chosen due to their complete 1-year recorded flow data, with no significant operational changes. The duration of measurements for hourly and daily demand variation estimation varied across the sectors analyzed and is presented in Table 1. The measurement period for hourly variation ranged from 11 to 50 days, while the daily variation was estimated based on data recorded for 329–365 days for each sector.

Table 1 | Characteristics of the hydrometric sectors analyzed

Sector	Number of households	Type of service	Start date	End date	No. of days	Average flow rate (l/s)	Indicator
Monte Verde	1,219	Continuous	19-Oct-20	12-Sep-21	329	6.80	CVDD
Carruaje	2,605	Semi-continuous	25-May-21	24-May-22	365	10.76	CVDD
Monte Verde	1,219	Continuous	15-Oct-20	29-Nov-20	46	7.43	CVHD
Ramón C.	1,872	Continuous	13-May-21	23-May-21	11	26.55	CVHD
Allende	128	Continuous	04-May-21	19-May-21	16	1.30	CVHD
Cd. Delicias	1,499	Intermittent	11-Dec-21	23-Dec-21	13	13.04	CVHD
Quetzal	1,050	Intermittent	25-May-21	13-Jul-21	50	8.83	CVHD

CVDD, coefficient of daily variation of demand; CVHD, coefficient of hourly variation of demand.

The flow data were subjected to a comprehensive analysis in this study by plotting both the hourly and daily averages. The resulting information was then compared to the daily and annual averages, in accordance with the recommendations outlined by CONAGUA (2015a, 2015b). Through this analysis, the daily and hourly variation of the flow data in relation to the average flow in unit form was established and presented in Figure 2. In the Monte Verde sector, daily flows were analyzed weekly for 1 year, obtaining the coefficient of variation day/week by dividing the daily/week flow by the average daily flow of the analyzed period.

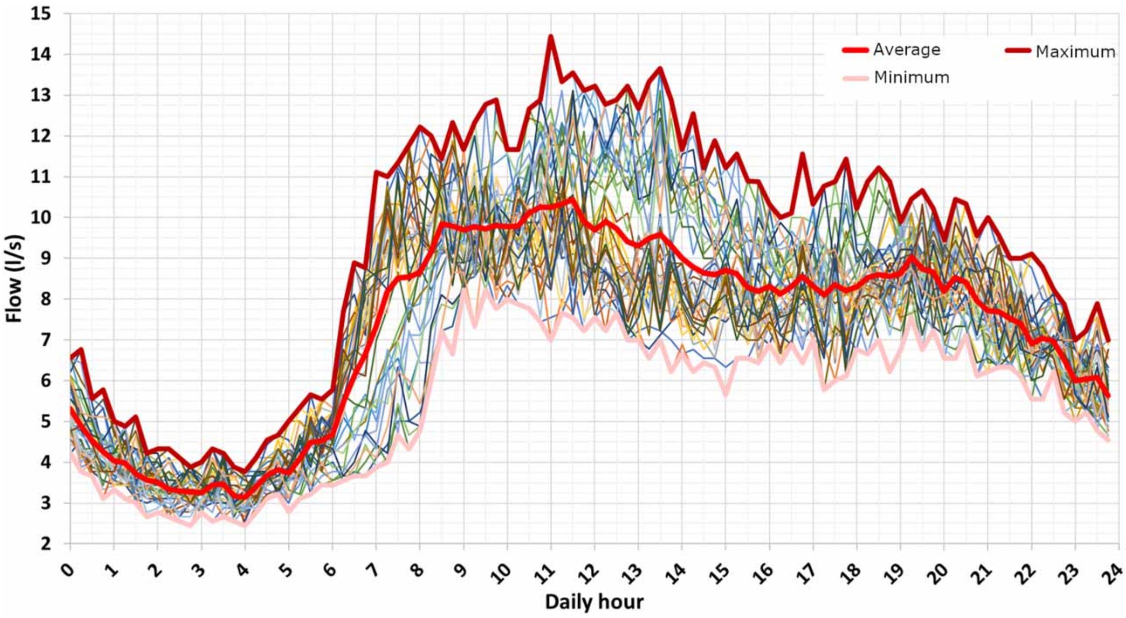

Figure 2 | Hourly flow rates, Monte Verde sector.

RESULTS AND DISCUSSION

The hourly variation curves of drinking water demand, which depict the analysis results of the inflow rate to the sectors, are presented in Figure 3.

The maximum and minimum hourly variation coefficients of demand, ranging from 1.259 to 1.635 and 0.079 to 0.586, respectively, are presented in Table 2. Additionally, the coefficient of daily variation throughout the year ranges from 0.756 to 1.18. The minimum daily variation coefficients are observed at 0.756 and 0.86, while the maximum values are recorded at 1.11 and 1.18.

According to the hourly variation of demand curves (Table 2), the minimum consumption values occur between 3:00 and 4:00 a.m., after which there is an increase in values between 4:00 and 6:00 a.m. The first peak in consumption, which corresponds to the maximum value, is observed between 8:00 and 12:00 p.m. and gradually decreases in the afternoon. The second peak in consumption is recorded between 5:00 and 8:00 p.m.

The distinction between sectors with a fixed set point and those with pressure management is evident (Figure 4). In the latter, the flow variation is more significant, resulting in higher maximum and minimum values. The hourly variation coefficient's minimum values were 0.079/0.159 in sectors with pressure management, while the minimum was 0.463 in other sectors. In contrast, the maximum values of hourly variation in the sectors with programed supply were 1.635/1.576, whereas, in those with continuous supply, they ranged between 1.259 and 1.424, indicating a difference of up to 0.394. Alternatively, the maximum difference between the maximum and minimum values of the hourly demand variation coefficient was 0.961 in the continuous pressure service and 1.556 in the pressure management service.

In contrast, the minimum night flow exhibited significant differences between the sectors with pressure management and those with fixed set points. Sectors with pressure management in continuous supply showed a minimum night flow of 11.9% with respect to the average flow, while sectors with fixed set points exhibited a minimum night flow of 53.6%. This disparity indicates a 77.8% reduction in total volume, including the amount attributed to leaks. Additionally, there was a 41.7% increase in hydraulic performance of sectors with pressure management compared to those with fixed set points. Overall, this underscores the significant impact of pressure management on hydraulic performance as stated by Polli de Oliveira *et al.* (2020).

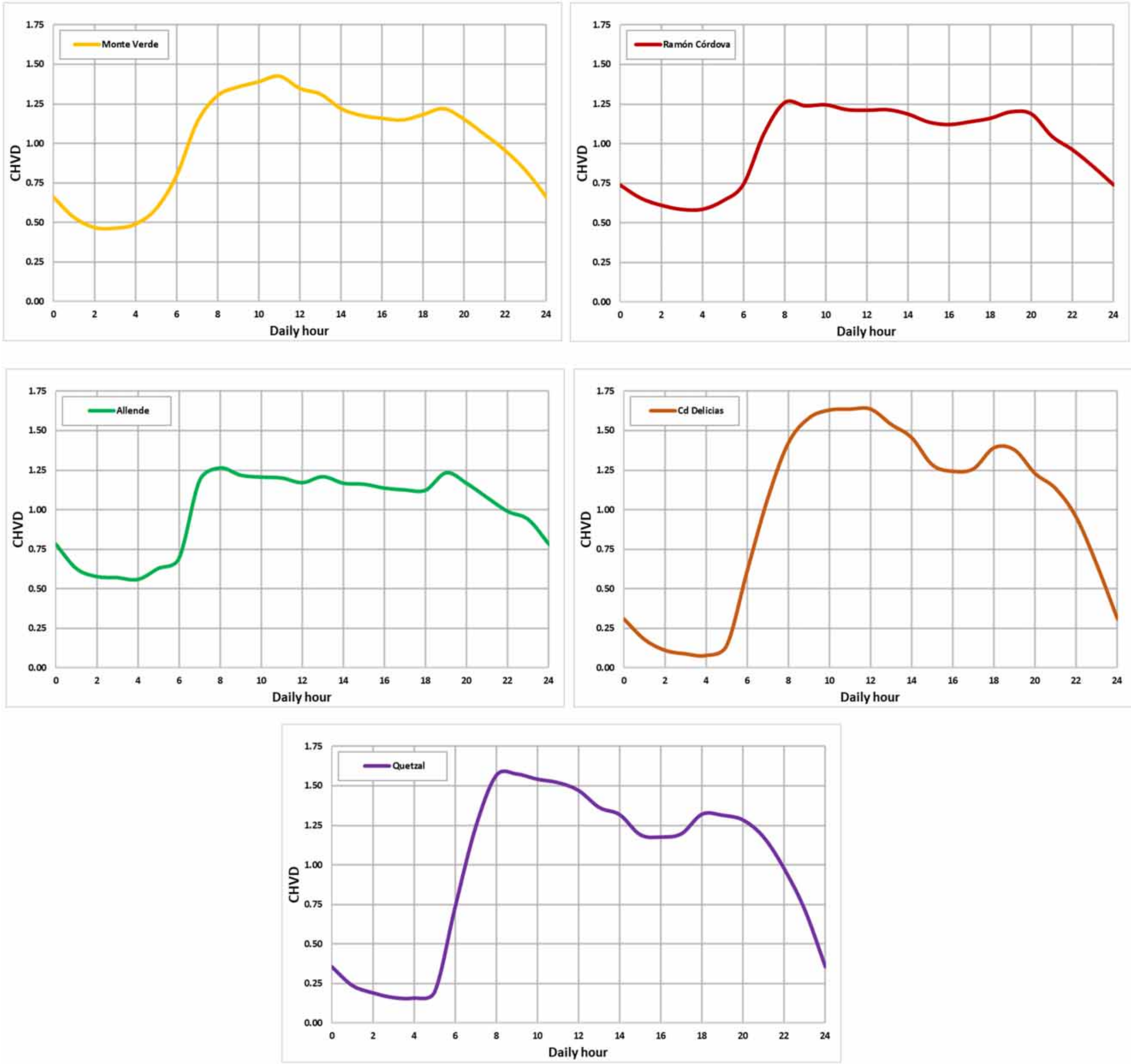

Figure 3 | Hourly variation curve of potable water demand across various sectors.

Upon comparison of the hourly demand variation curves obtained in this study with the theoretical curve proposed by CONAGUA (2015a, 2015b) for design purposes in Mexico, significant differences were observed. Specifically, the theoretical curve fails to account for a second peak demand caused by the increase in water consumption when users return to their homes after work hours. Additionally, the maximum and minimum values of the coefficient of hourly variation of demand proposed by CONAGUA (2015a, 2015b) are 1.372 and 0.61, respectively, although, in other references, CONAGUA reports the maximum coefficient of hourly variation of demand as 1.55 (see Table 2 for details).

Seasonal behavior of daily variation in demand throughout the year is evident in Figure 5, which is likely related to temperature changes. As shown in Figure 5, demand decreases during the rainy days of the year, when temperatures drop after the hottest weeks. The daily variation of demand throughout the year is a critical parameter as it affects the minimum and maximum pressure values registered in the system and serves as an indicator of both satisfactory user supply and potential leaks (Gwoździej-Mazur & Świętochowski 2019).

The daily demand variation in the two sectors analyzed exhibits a similar pattern, with nearly identical minimum and maximum values of 0.756/0.86 and 1.11/1.18, respectively. In contrast, the Monte Verde sector presents a maximum demand variation that is 11% higher than the mean and 14% lower than the minimum, indicating a significant difference of 25% between them. It is worth noting that physical losses account for approximately 46.3% of the volume supplied to this sector, as indicated in Table 2.

This sector exhibits an increase in demand of 29.31% compared to the minimum demand. However, the consumption between the minimum and maximum values (winter and summer) shows a significant increase of

Table 2 | Hourly variation coefficients of demand for different sectors in Chihuahua City compared with CONAGUA's variation (CONAGUA 2015a, 2015b)

Daily hour	Monte Verde	Ramón Córdova	Allende	Cd Delicias	Quetzal	CONAGUA
0	0.660	0.740	0.782	0.311	0.357	0.606
1	0.532	0.657	0.627	0.181	0.238	0.616
2	0.467	0.612	0.576	0.112	0.192	0.633
3	0.463	0.586	0.570	0.089	0.162	0.637
4	0.489	0.587	0.558	0.079	0.159	0.651
5	0.586	0.641	0.629	0.142	0.198	0.828
6	0.797	0.745	0.692	0.613	0.736	0.938
7	1.133	1.064	1.185	1.071	1.243	1.199
8	1.302	*1.259*	*1.264*	1.421	1.568	1.307
9	1.356	1.238	1.218	1.578	*1.576*	*1.372*
10	1.389	1.245	1.206	1.629	1.543	1.343
11	*1.424*	1.215	1.200	1.634	1.522	1.329
12	1.347	1.210	1.171	1.635	1.472	1.288
13	1.311	1.214	1.209	1.538	1.365	1.266
14	1.219	1.186	1.167	1.453	1.319	1.216
15	1.176	1.136	1.161	1.283	1.192	1.201
16	1.158	1.120	1.136	1.242	1.178	1.196
17	1.147	1.138	1.125	1.258	1.199	1.151
18	1.182	1.160	1.123	1.390	1.323	1.121
19	1.219	1.200	1.234	1.376	1.316	1.056
20	1.151	1.187	1.166	1.227	1.285	0.901
21	1.055	1.046	1.076	1.133	1.176	0.784
22	0.953	0.961	0.988	0.950	0.976	0.710
23	0.826	0.856	0.937	0.652	0.715	0.651
24	0.660	0.740	0.782	0.311	0.357	0.606

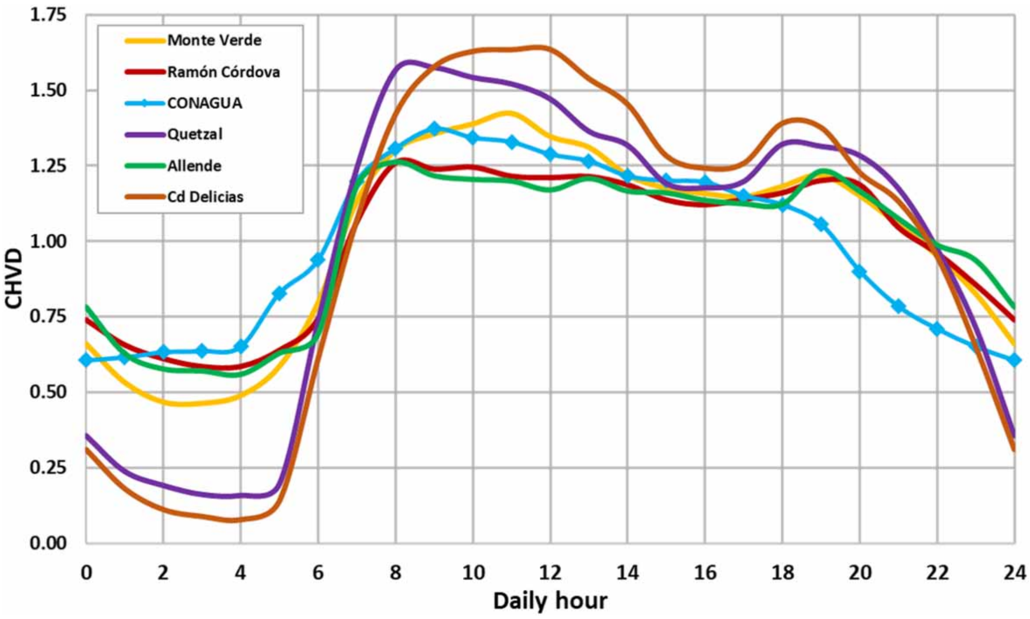

Figure 4 | Comparison of hourly variation curves of the demand of various sectors of Chihuahua City and CONAGUA's variation curve *Source:* own data with data from 'Illustration 2.2' (CONAGUA 2015a, 2015b).

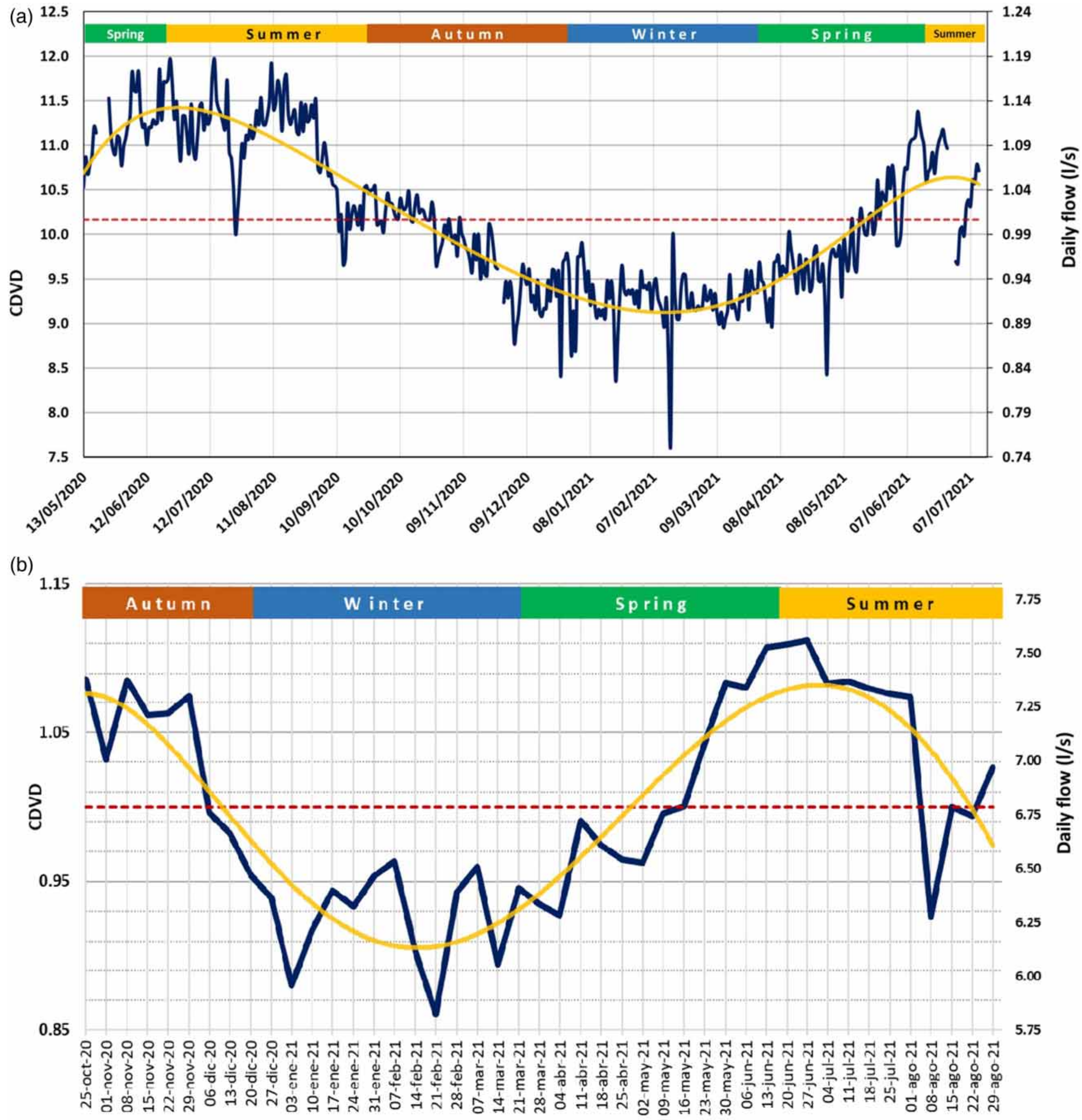

Figure 5 | Daily variation curve of drinking water demand, Carruaje sector (a) and Monte Verde sector (b).

63.5% of the minimum value. In other words, if the users consume a hypothetical flow of 10.0 l/s during the day of lowest demand, during the day of highest demand, the consumption will rise to 16.5 l/s (excluding leaks). This highlights the importance of seasonal variations and their impact on the water demand in this sector as Zhao *et al.* (2018) demonstrated in their study.

The figures depicting the daily and weekly variation of demand are presented in Figure 6. The coefficient of daily variation of demand on different days of the week ranges from 0.995 to 1.02.

Figures 6(b) and 6(c) show that there is a substantial decrease in inflow in the Monte Verde and Carruaje sectors on December 25 and on the first day of the year.

On December 25, the Carruaje sector experienced an 8.4 l/s reduction in flow during the day, representing a 10.24% decrease compared to the average flow between December 15, 2020, and January 10, 2021 (9.36 l/s). Meanwhile, the Monte Verde sector saw an even greater decrease on December 25, with a flow reduction to 5.20 l/s, marking a 16.8% decline from the sector's average flow during the same analysis period (6.25 l/s). These observations suggest that holidays have a notable impact on the water demand, and consequently, the water supply system.

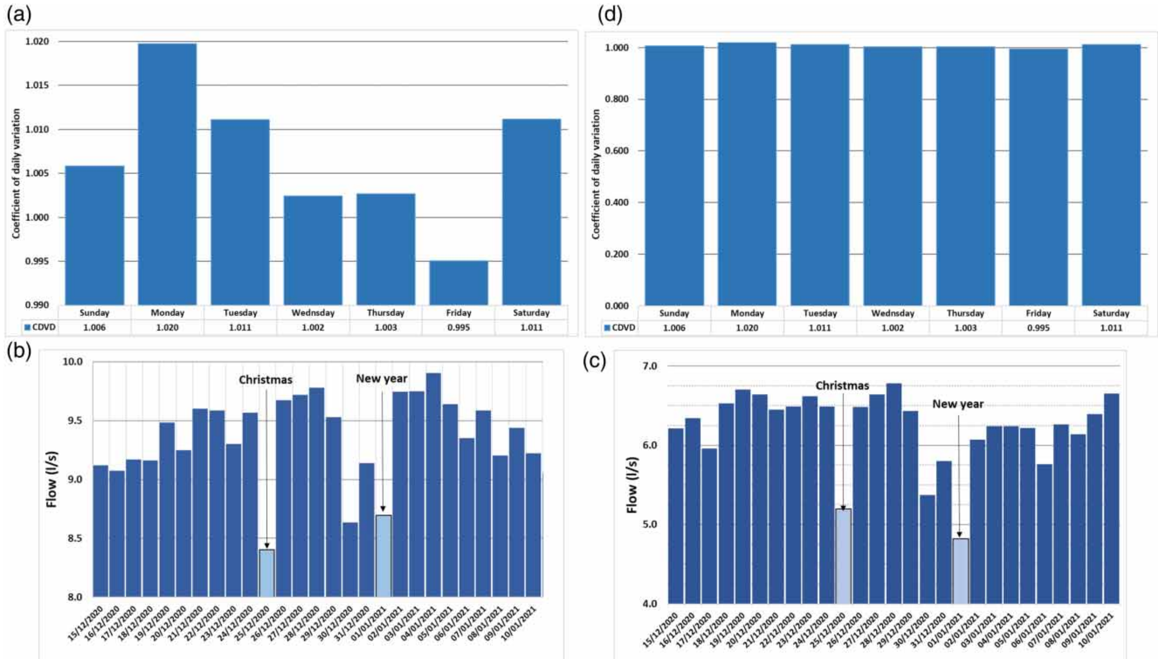

Figure 6 | Daily variation of potable water demand by day of the week, Carruaje sector (a). Reduction in incoming flow observed in the Carruaje sector (b) and Monte Verde sector (c) during Christmas and New Year's Day. Daily variation of potable water demand by day of the week in the Carruaje sector, plotted with the original scale (d).

The daily variation of potable water demand per day of the week is displayed in Figure 5. Although the vertical scale was adjusted to appreciate the variation, it results in relatively low values. To provide a clearer perspective, Figure 6(d) presents the same data rescaled from 0 to the highest value. The coefficient of variation for each day ranges from 0.995 to 1.02, representing a difference of less than 2.50% between them.

Based on the literature review, the hourly and daily variation curves and coefficients of water demand have been identified as valuable tools for modeling, designing, and operating drinking water networks (Ilaya-Ayza *et al.* 2016; Suárez 2019; Delgado *et al.* 2022). Incorporating these curves allows hydraulic simulations to better reflect the actual behavior of the network and serves as a reference for operational decision-making. While the distinction between demand and endowment curves may not be necessary for practical purposes, considering physical losses in the variation curves can be important (Gwoździej-Mazur & Świętochowski 2019).

The construction of reliable curves and coefficients of demand variation relies on accurate supply area information for hydrometric sectors. In this study, the analysis of data from sectors with the highest number of recorded days was conducted to determine the daily variation throughout the year. Additionally, to accurately calculate hourly variation coefficients, some sectors were switched from their usual semi-intermittent operation to a fixed set point service. The use of flow data from hydrometric sectors was crucial for generating reliable curves and coefficients.

The proposed method offers opportunities to improve water service by increasing the number of days for calculating hourly demand variables and providing water in a fixed mode. This 'stabilizes' the water supply system, potentially eliminating the need for water storage and enabling continuous water supply and pressure throughout the day. The method aligns with the existing literature (VAG 2011; Ilaya-Ayza *et al.* 2016; Delgado *et al.* 2022) and demonstrates consistent patterns, making it suitable for application in the metropolitan area of Chihuahua and similar cities with comparable characteristics. Consideration of both continuous supply and pressure management scenarios is essential for hydraulic simulation models in network design and operation, as significant differences exist in the hourly variation curves of these sectors.

The analysis of coefficients of variation of hourly demand reveals that the minimum night flow occurs between 3 and 4 a.m., with nearly all the flow at this time being lost due to leaks in sectors with fixed set point and pressure management. Pressure management leads to higher variability in the hourly variation coefficient compared to continuous supply sectors. However, continuous supply sectors experience substantial physical losses (approximately 53.6%), while intermittent supply shows lower physical losses (approximately 11.9%), resulting in an increase of up to 42% in physical efficiency. These findings have implications for the design and operation of hydraulic systems and can promote better water management practices.

CONCLUSIONS

These findings provide valuable insights for hydraulic system design, operation, and water management practices, highlighting a compensatory relationship between reducing water loss and managing pressure variation. For modeling and designing drinking water networks in Chihuahua City, a recommended maximum hourly variation coefficient of 1.64 and a coefficient of 1.2 for daily variation, aligned with CONAGUA (2015a, 2015b) and Carruaje sector's daily demand variation, respectively.

The analysis of hourly variation curves of demand demonstrates that the decrease in water loss due to leaks in a pressure-managed service compensates for pressure variations experienced by the pipes. These findings significantly contribute to the efficient and effective management of water supply networks, promoting improved water management practices and optimal resource utilization.

ACKNOWLEDGEMENTS

We would like to express our sincere appreciation to the Junta Municipal de Agua y Saneamiento (Municipal Water and Sanitation Board) for their support in providing available data and their contributions to the methodology of this study. We also extend our sincere gratitude to the anonymous editors and reviewers for their invaluable insights and professional comments, which greatly enhanced the quality of this manuscript.

FUNDING

No funding was received to assist with the preparation of this manuscript.

AUTHORS CONTRIBUTIONS

E.H.-S. did data curation, wrote the original draft, and supervised the study. C.N.-G. conceptualized the study, prepared the methodology, investigated the study, did software analysis. D.H.S. wrote, reviewed, and edited the article. J.R.S.-N. did software analysis and validated the study.

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 20 June 2023; accepted in revised form 13 July 2023. Available online 31 July 2023