Environment and Ecology Research 12(4): 456-466, 2024 http://www.hrpub.org
DOI: 10.13189/eer.2024.120410

Demographic and Geographical Variations in Residential Drinking Water Consumption: A Case Study through Data Disaggregation in Ecuador

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Received May 11, 2024; Revised August 2, 2024; Accepted August 28, 2024

Cite This Paper in the Following Citation Styles

(a): *[1] Alfonso Arellano, Nadia Benalcázar, Gabriela Arias, Israel Ramírez , "Demographic and Geographical Variations in Residential Drinking Water Consumption: A Case Study through Data Disaggregation in Ecuador," Environment and Ecology Research, Vol. 12, No. 4, pp. 456 - 466, 2024. DOI: 10.13189/eer.2024.120410.*

(b): *Alfonso Arellano, Nadia Benalcázar, Gabriela Arias, Israel Ramírez (2024). Demographic and Geographical Variations in Residential Drinking Water Consumption: A Case Study through Data Disaggregation in Ecuador. Environment and Ecology Research, 12(4), 456 - 466. DOI: 10.13189/eer.2024.120410.*

Abstract This study investigates household monthly drinking water consumption (HMDWC) across different regions and demographic segments in Ecuador. By disaggregating data and clustering according to homogeneous characteristics, the study ensures that average values are more accurate and representative of specific population groups. Data were collected from 65 towns and cities in the Ecuadorian Sierra and Amazonian regions, resulting in a comprehensive dataset of approximately 28 million records after outlier removal. The analysis reveals significant differences in monthly water consumption across five demographic ranges, confirmed by ANOVA (p-value < 0.001) and Tukey's Test. Medium-sized (8,000-30,000 inhabitants) and large towns (30,000-150,000 inhabitants) show higher average HMDWC compared to other ranges. Additionally, regional disaggregation highlights distinct consumption patterns between the Sierra and Amazonian regions. In the Sierra, larger towns exhibit stable consumption throughout the year, while smaller towns show peaks during the rainy season. Comparing regions, the Amazonian towns consistently demonstrate higher HMDWC than their Sierra counterparts. For instance, small towns (500-8,000 inhabitants) in the Amazonian region average 14.155 m³/month, whereas in the Sierra, they average 13.607 m³/month. This trend persists across medium and large towns, emphasizing the need for regional-specific water supply planning. The findings underscore the necessity of disaggregating data by region to achieve accurate planning of water supply systems. Without regional breakdown, the Amazonian region's water supply systems would be undersized, leading to poor resource management. Conversely, towns in the Sierra region would be misrepresented if their data were combined with those from the Amazonian region. This study provides critical insights for optimizing water resource management and planning in Ecuador. By illustrating the importance of detailed data analysis and regional disaggregation, it supports the sustainable management of water resources based on historical consumption patterns, ensuring effective and efficient water supply systems tailored to regional needs.

Keywords Demographic Geographical Disaggregation, Monthly Water Consumption

1. Introduction

Potable water systems serve a wide range of users, including residential, commercial [1], tourism [2], industrial [3], educational, health, and administrative sectors. These users exhibit diverse characteristics that vary significantly around the world. Understanding these variations in household drinking water consumption is crucial for designing efficient and effective potable water systems tailored to the specific needs of different user groups. This study aims to analyze the variation in household drinking water consumption across different regions, providing insights for optimizing water system design and ensuring a sustainable water supply.

Ecuador, located in the northwest of South America and bordered by Colombia, Peru, and the Pacific Ocean, experiences minimal seasonal variation due to the Equator traversing the country from east to west. This geographic positioning gives rise to two primary seasons: a wet season (winter) and a dry season (summer), with the length of these seasons varying regionally. The climate of the country is significantly influenced by its diverse topography. Ecuador is geographically divided into four distinct regions, each possessing unique climatological characteristics. The Andes Mountains, traversing the country from north to south, split into two branches, enclosing an Inter-Andean Valley. This valley houses numerous towns and cities within the Sierra Region. The mountains in this area boast an average elevation of 2,000 meters and feature a variety of slopes and altitudes, including several volcanoes that rise above 5,000 meters. West of the Andes lies the Coastal Region, which borders the Pacific Ocean and descends to sea level. To the east, the Eastern or Amazonian Region experiences varied climatic conditions. The northern Amazonian area has a rainy season from March to November and a dry season from December to February, while the climate in the rest of the region mirrors that of the Sierra. Elevations in this region range from 1,048 to 722 meters above sea level [4], [5], [6]. The fourth geographic region of Ecuador is the Insular Region, also known as the Galápagos Archipelago, located in the Pacific Ocean. This region is renowned for its unique biodiversity and distinct ecological characteristics that have been pivotal in evolutionary studies.

Ecuador's geographic positioning on the equator results in nearly consistent day lengths throughout the year, with each day featuring approximately 12 hours of daylight. This equatorial location also ensures a steady influx of solar radiation, which stabilizes the average annual temperature across the region, exhibiting a maximum monthly variation of only 3°C, notably in the arid southwestern areas. In contrast, daily temperature fluctuations are more pronounced across different elevations and regions; coastal and low-lying areas in the Amazon experience temperature changes of up to 10°C, while mid to high elevations in the Sierra can undergo temperature shifts of up to 20°C within a single day. Additionally, the annual temperature extremes tend to correlate with the defined wet and dry seasons [6]. The Sierra region’s climate exhibits a diverse range of conditions, including very humid tropical weather in transitional zones adjacent to the coast and the Amazon, semi-humid to humid temperate climates in the inter-Andean zone, warm and dry conditions in the inter-Andean valleys, and cold high-mountain climates in the moors above 3,000 meters in altitude. This region's climate is significantly influenced by alternating oceanic and Amazonian air masses, as well as the oscillations of the Intertropical Convergence Zone, leading to two distinct rainy seasons with a bimodal rainfall distribution during March-April and October-November. Annual precipitation in the Sierra averages between 800 and 1,500mm. Temperature variations are closely linked to altitude; in elevations ranging from 1,500 to 3,000 meters, average temperatures fluctuate between 8 and 20°C, with a temperature gradient of approximately 5°C per 1,000 meters of elevation. The highest temperatures typically occur between December and January, with the lowest temperatures from April to June [6] .The Amazonian region of Ecuador is marked by a persistently very humid tropical climate throughout the year, a condition sustained by the extensive moisture retention capabilities of the vast Amazonian forests. Precipitation in this region remains relatively constant, though it exhibits a slight increase from March to July and decreases in August and January, influenced by the shifts in the Intertropical Convergence Zone. Storms are a frequent occurrence. The average temperature in this region maintains a steady range of 24-25°C, with occasional peaks reaching up to 40°C in May [6].

This study has collected household monthly drinking water consumption (HMDWC) records from 65 towns and cities located in the Ecuadorian Sierra and Amazonian regions. The country's political division is illustrated in Figure 1.

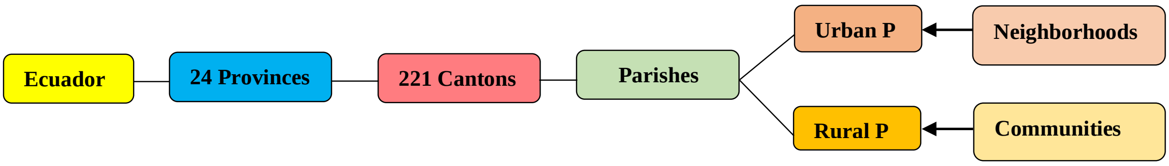


Figure 1. Political division of the Ecuadorian state

When a town has recently obtained its status as a Canton or Parish, there will be little or no demographic information available to reflect its historical growth as such and probably there will only be drinking water consumption data from recent years. The smallest towns are Communities and the largest ones are Cantons, also named Cities [7]. The Parishes are larger than the Communities, and depending on their geographical proximity, they can be urban or rural and they belong to a Canton. In this study, we will refer to them generically as towns to include Communities, Parishes, or Cantons (cities). Ecuador's overall drinking water coverage is 63%, with 83% coverage in urban areas and only 39% in rural areas [8], [9].

The factors influencing drinking water consumption in Ecuador were identified through an analysis of monthly per capita consumption over a semester period reported by Arellano et al. [10]. Multiple linear regression models were employed to develop predictive equations, revealing the significance of various factors in forecasting per capita water consumption. Demographic factors and water quality were the most significant factors within semester per capita consumption, while climatological factors (maximum atmospheric humidity and temperature) were more significant in monthly analyses. Huaquisto Cáceres et al [11] reported average daily per capita water consumption in Puno, Peru. Their results fall below the levels recommended by the World Health Organization, emphasizing the impact of socio-economic [12] and demographic factors [13]. Additionally, that study documents the relationship between family size and household water consumption. The authors also reference per capita water consumption in various American cities and include a figure illustrating monthly variations in per capita consumption across five socio-economic strata, based on data from the INEI's National Household Survey. This information from Peru parallels findings by Arellano et al. [14] in Ecuador. Recent updates in Ecuadorian demographic variables have enhanced predictive modeling, with demographic groups segmented based on per capita water consumption similarities in a macro-demographic analysis. Izurieta et al. [15] conducted a micro-demographic analysis identifying significant correlations between family size and socioeconomic strata, providing insights into typical household compositions in Ecuadorian towns of varying sizes.

Literature documents various factors influencing drinking water demand across regions and countries. Although some variables are consistently identified, their quantitative measurements and influence within complex mathematical models vary significantly [16], [17], [18], [19].

In developing nations like Ecuador, the collection and monitoring of data present significant challenges. These difficulties are exacerbated when data must represent variations over extended periods for conducting robust statistical analyses that yield dependable results with credible predictive adjustments [20]. Therefore, this study provides an analysis based on several years of monthly consumption records from the residential sector, ranging from very small towns to large cities.

Towns without their own data, but with geographic and demographic similarities to those exhibiting significant patterns, can utilize these results to project their potable water systems, ensuring components are adequately dimensioned to provide the service. Incorrect flow rates could lead to under-dimensioning or over-dimensioning of the components in a potable water system [21], [22] and assist in devising sustainable water resource management strategies [12], [23].

This study has two goals. The first aim is to demonstrate a methodology for the segregation and clustering of geographical and demographic data, presenting the results comparatively so they can be replicated according to the reader's convenience. The second aim is to disseminate historical potable water consumption data for use by service managers in both the sampled and unsampled communities, through interpolations. Consequently, this study provides compelling information for the sustainable management of water resources based on historical potable water consumption across different regions.

2. Materials and methods

2.1. Sampling

On the right side of Figure 2, the names of 13 provinces from where the samples were collected are depicted by pink dots within the figure. Provincial boundaries are indicated by black lines. Provinces within the Sierra region are predominantly represented by whitish and bluish colors, indicating cooler temperatures, while Amazonian provinces are situated to the right. The Sierra region exhibits higher demographic density compared to the Amazonian region, resulting in a higher sample yield. Figure 2 also illustrates variations in environmental temperature across Ecuador's continental regions on April 5, 2024, between 1:00 p.m. and 4:00 p.m., presented on a horizontal scale in degrees Celsius [24].

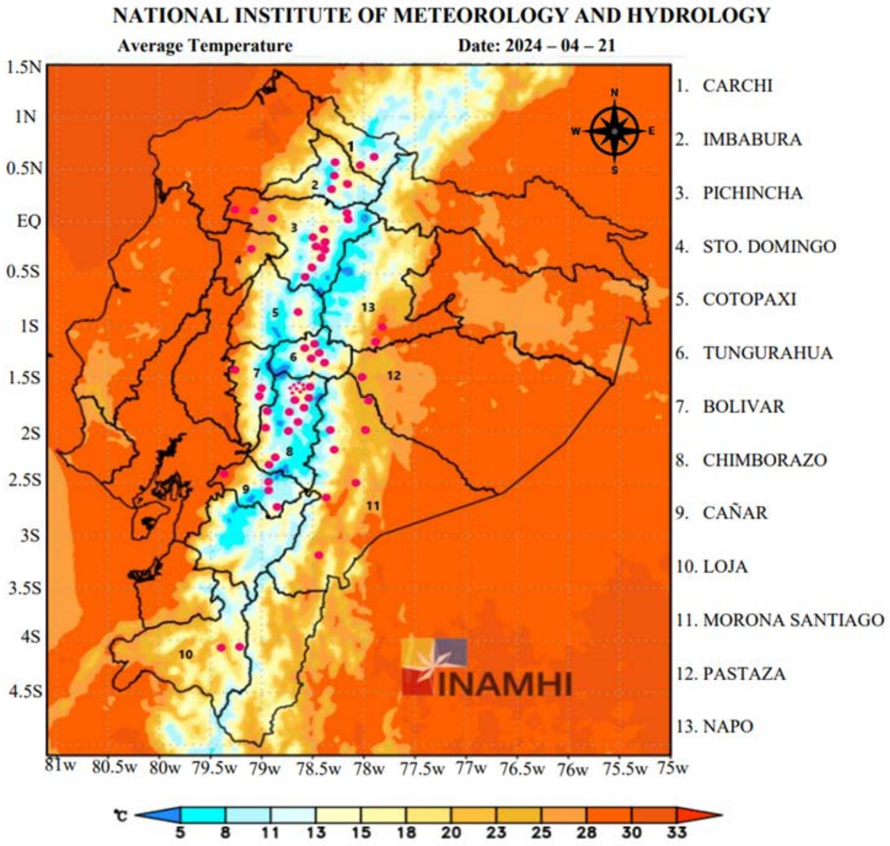


Figure 2. Sample locations and thermal variations in three Ecuadorian regions. Adapted from [24]

HMDWC data were collected from the service managers of entities known as Communal Boards, Parish Boards, or Canton´s Decentralized Autonomous Governments (Figure 1). Some managers possess records dating back to 2004, while others have data spanning approximately five years. The initial dataset comprised 32,647,495 monthly records. From these, 4,842,363 records were manually excluded due to their irrelevance to residential consumption or because they indicated zero consumption. The HMDWC data derives from micrometer records taken from distribution networks [25]. The towns studied vary significantly in population size; the smallest Community has 205 inhabitants and the biggest city has 450,000 inhabitants. They were selected randomly from the Sierra and Amazonian regions.

2.2. General Methodology

The resulting dataset, approximately 28 million records, underwent outlier detection and removal using the Box and Whisker Test (Minitab), leaving 26,036,281 valid HMDWC records for this study. The geographic and demographic heterogeneity, coupled with the abundance of data, enables detailed disaggregation into analyzable clusters to minimize result dispersion while maintaining temporal consistency across other factors [16], [26]. Given the stochastic nature of drinking water consumption [23], temporal variability has been incorporated into the analysis. Monthly disaggregation was chosen to systematically capture historical consumption records, allowing a detailed and accurate representation of consumption patterns over time [27].

Analysis of Variance (ANOVA) was conducted using Minitab Software, set at a 95% confidence level to determine variance in means. Statistical significance among HMDWC means was determined using Tukey's Test to identify means that are significantly different from each other. It was applied to identify which specific groups' means differ. These groups are identified by letters or groups of letters (e.g., A, B, C, D, or AB, BC...), where means sharing a common letter are not significantly different from each other, while means not sharing any letters are significantly different.

This research reports results from three approaches. The first approach analyzes monthly consumption variations across five demographic ranges (Table 1) for the entire sample. The second approach divides the sample into Sierra and Amazonian towns, maintaining the analysis with the same demographic ranges (Figure 3). The third approach calculates annual mean consumptions for each demographic range and compares these values between the Sierra and the Amazonian regions. These calculations undergo statistical analysis as described above.

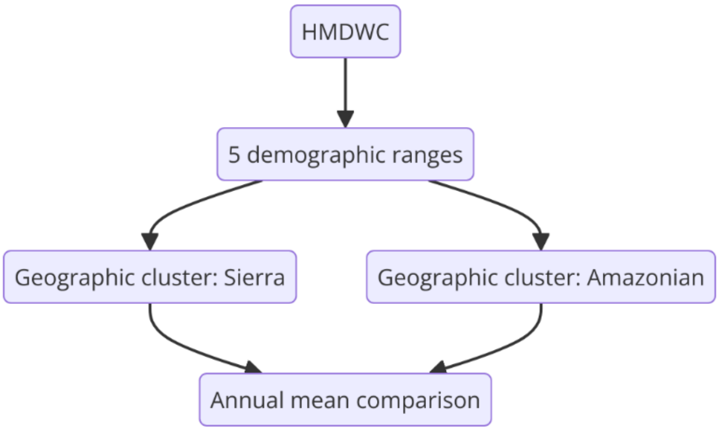


Figure 3. Data processing flowchart

Table 1. Demographic ranges

Range	1	2	3	4	5
Town size	Very small	Small	medium	big	Very big
inhabitants	< 500	500-8,000	8,000-30,000	30,000-150,000	>150,000

Source: Zuñiga et al. [28]

2.3. Demographic Approach

In the Amazonian region, there were no samples from ranges 1 and 5, whereas the Sierra region included all ranges. Variations in HMDWC for each demographic range were plotted in a single figure to distinguish their patterns and differences when geographic regions are not separated, aiming to illustrate the implications of conducting less detailed analyses.

2.4. Geographic Approach

The data were disaggregated into two clusters corresponding to the Sierra and Amazonian regions [16]. Within each cluster, HMDWC variations across demographic ranges throughout the year were analyzed. ANOVA was then applied to observe monthly variations in each demographic range using interval plots. These plots display vertical bars representing confidence intervals for monthly means of different groups. The overlap of these intervals indicates whether the group means are significantly different from each other. Non-overlapping intervals suggest significant differences between those specific groups.

2.5. Comparison of Means between the Sierra and the Amazonian Regions

Annual mean HMDWC values were obtained for each demographic range within the Sierra and Amazonian regions separately. ANOVA was applied, and interval plots were used again to identify differences among demographic groups, comparing Sierra and Amazonian means with their respective confidence intervals.

3. Results and Discussion

3.1. Household Monthly Drinking Water Consumption (HMDWC) from both Regions Together

In Figure 4, the X-axis represents the months, while the Y-axis displays the HMDWC from all samples. The initial data was disaggregated into five demographic ranges, revealing five distinct trends. The application of ANOVA revealed significant differences in monthly consumption ($p\text{-value} < 0.001$). The demographic ranges R3 (medium-sized towns, green line) and R4 (large-sized towns, red line) display parallel consumption trends in August, September, October, November, and December. They exhibit very similar values in February and May, but their HMDWC differs in March and June.

The four groups identified by Tukey's test (Table 2) with letters A, B, C, and D underscore the mean HMDWC variance across demographic ranges. Range 4 has the highest average consumption (20.251 m^3/month), and Range 3 has the second highest value (19.768 m^3/month). However, these two values do not have a statistically significant difference, which is why Tukey's Test groups them under the same letter 'A', distinguishing them from the other values as the highest. The average consumption in Range 5 (17.267 m^3/month) is lower than those in Ranges 4 and 3, which is why it is grouped with letter B. The value in Range 1 (11.029 m^3/month, grouped with letter D) has the lowest HMDWC value of all.

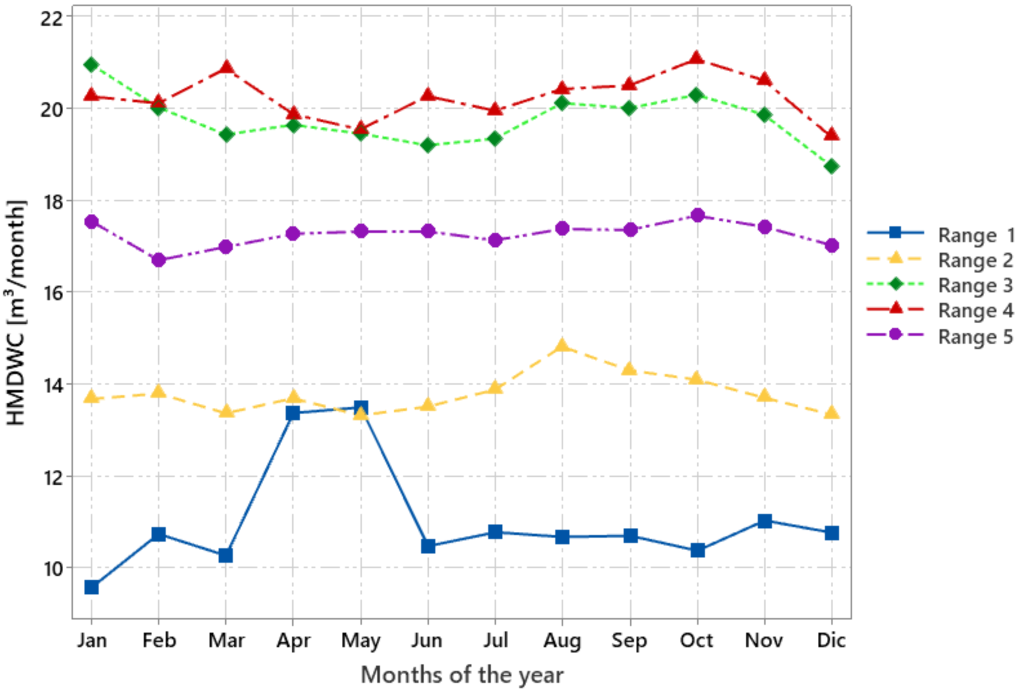


Figure 4. Average HMDWC without regional breakdown

Table 2. The Tukey Test applied to population ranges

Factor	N	Mean Monthly consumption	Groups			
Range 4	12	20.251	A			
Range 3	12	19.768	A			
Range 5	12	17.267		B		
Range 2	12	13.795			C	
Range 1	12	11.029				D

HMDWC increases as the size of the population grows up to a limit of 150,000 inhabitants. In larger cities (>150,000 inhabitants), water consumption is lower than in towns with population sizes ranging between 8,000 and 150,000 inhabitants. This might be attributed to citizens spending less time at home due to the long distances between their residences and places such as schools or workplaces. This observation aligns with findings from the per capita consumption study where socioeconomic factors were explicitly considered. It further confirms the validity of these demographic ranges [28] for potable water projects.

It is notable that Range 5 shows less variation in monthly consumption compared to the other ranges; it remains quite stable throughout the year. The opposite occurs in Range 1, which shows the highest consumption peaks in April and May, the rainy months in the Sierra region.

3.2. Household Monthly Drinking Water Consumption across 5 Demographic Segments: Disaggregation by Sierra Region

Figure 5 illustrates the variations in HMDWC across different population ranges in Sierra towns throughout the year. The black dashed lines represent the averages of the monthly consumptions, which are comparable to the dashed lines in Figure 4 (without geographical disaggregation).

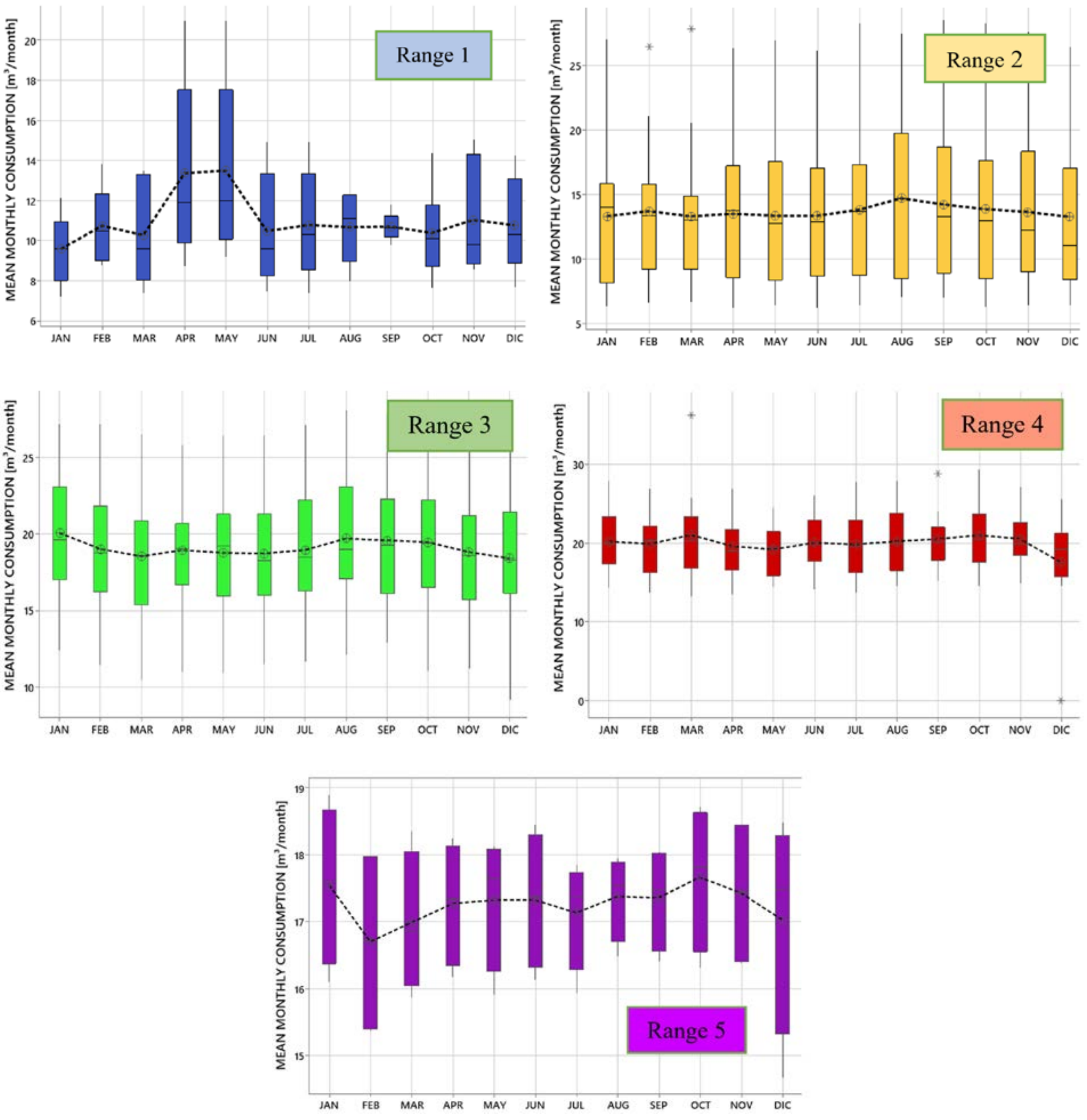


Figure 5. ANOVA Box Plot for Each Demographic Range in the Sierra Region

The average values for Ranges 3 and 4 remain higher than those of the other ranges, as shown in Figure 4, and maintain the same trend. However, there are some quantitative differences between the values in Figure 4 and Figure 5. Consumption peaks occur in different months in the Sierra towns. Some of these months correspond to the rainy season, while others do not. Figures 4 and 5 illustrate poor heterogeneity of patterns from Ranges 3, 4, and 5, probably because there are more samples from the Sierra Region.

When analyzing the monthly values within each range separately, the ANOVA shows no statistically significant differences between the compared groups. The variances (a measure of dispersion) overlap, and the p-values (a measure of the probability that the observed results are due to chance) exceed 0.05, as shown in Table 3. This indicates that there is no significant monthly variation within each analyzed range. The average consumptions remain stable throughout the year.

Table 3. ANOVA results from the Sierra Region

Demographic range	1	2	3	4	5
Value p	0,388	1,000	0,992	0,893	0,994

3.3. Household Monthly Drinking Water Consumption across 5 Demographic Segments: Disaggregation by Amazonian Region

The relatively recent establishment of towns in the

Amazonian Region likely explains why none have populations exceeding 150,000 inhabitants. Additionally, towns with populations lower than 500 inhabitants often do not maintain monthly drinking water records because some of them do not have micrometers or water distribution networks. They depend on water directly sourced from rivers or communal or family wells.

Figure 6 shows that in Range 2, the peak occurs in January (around 15 m³/month), while in Figure 4, the peak occurs in August (also around 15 m³/month). The same comparison in Range 3 shows that peaks occur in January in both cases, but the peak is higher in Figure 4. Therefore, the HMDWC is different when comparing those from the Amazonian region with the entire sample, which also includes those from the Sierra.

When comparing Figures 5 and 6, different values and trends are observed in Ranges 2, 3, and 4, indicating that the HMDWCs of the towns in the Sierra are different from those in the Amazonian region.

Table 4 presents ANOVA results for towns within Demographic Ranges 2, 3, and 4 in the Amazonian Region. It reveals no significant variations in average HMDWC (p-value = 1) throughout the year in any Demographic Range.

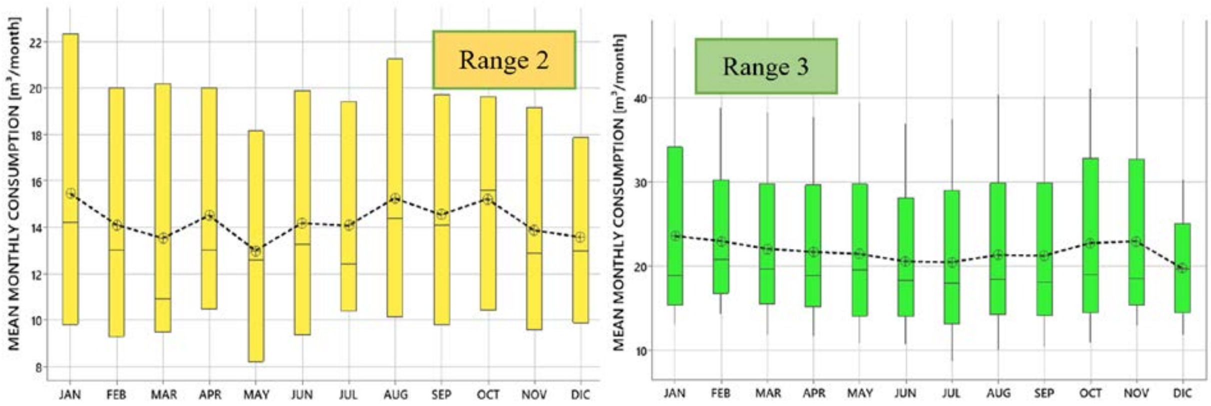
3.4. Comparative Analysis of Household Monthly Drinking Water Consumption across Demographic Ranges in Sierra and Amazon Regions

The quantitative differences and trends in Demographic Ranges 2, 3, and 4, reported in the three analyses above, lead us to a comparison between the average annual consumptions of towns in the Sierra Region and those in the Amazonian Region.

The average annual water consumption of small towns (500-8,000 inhabitants) in the Sierra Region (13.607 m³/month) is lower than the equivalent in the Amazon Region (14.155 m³/month) by 0.55 m³ per family-month (Figure 7). The same occurs in medium-sized towns (8,000-30,000 inhabitants), where the difference is 2.66 m³ per family-month, and in large towns, which show a difference of 0.97 m³ per family-month. The potable water consumption of a family living in the Amazon Region is higher than that in the Sierra Region by these proportions. This could be due to the fact that the settlements in the Amazon region experience higher ambient temperatures compared to those in the Sierra, corroborating the study by Arellano & Peña [10], which reports that per capita monthly consumption is influenced by climatological parameters.

The average annual potable water consumption in medium-sized (green) towns is higher than that in small (yellow) and large (red) towns in the Amazonian Region. In the Sierra Region, large towns (red) consume more than very large (purple), medium-sized (green), small (yellow), and very small towns (blue) (Figure 7). These differences confirm the utility of considering demographic and geographic characteristics to obtain more representative and precise results [16].

There is no statistical significance between monthly consumption throughout the year, likely because the populations are near the equator, resulting in the absence of distinct seasons and minimal variations in temperature, humidity, and precipitation within each town and region.



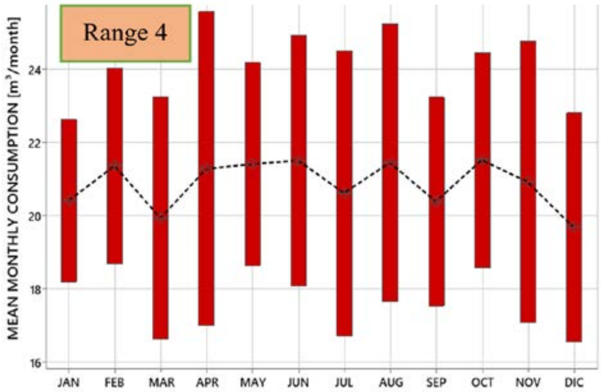


Figure 6. ANOVA Box Plot for Each Demographic Range in the Amazonian Region

Table 4. ANOVA results from towns in the Amazonian Region

Demographic range	2	3	4
Value p	1,000	1,000	1,000

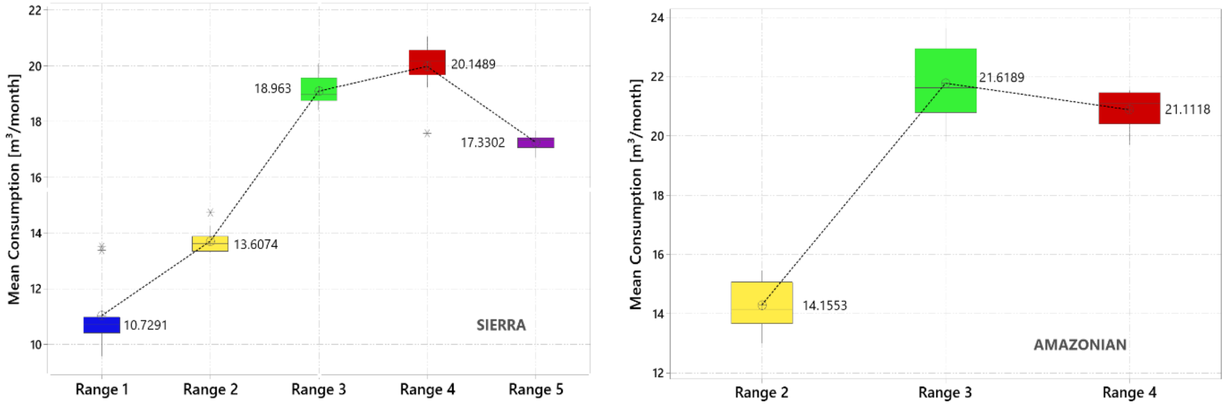


Figure 7. Average HMDWC in the Sierra and Amazonian Regions

4. Conclusions

This study demonstrates the importance and utility of disaggregating data and clustering them according to homogeneous characteristics in new groups, ensuring that their average values are more accurate and representative of their particularities. This extensive dataset forms a solid foundation for identifying consumption patterns applicable to towns not included in this database. Through a detailed examination of HMDWC, we elucidated temporal variations and discerned trends within clusters of towns categorized by their demographic and geographical characteristics. These trends confirm the validity of the five demographic ranges and the utility of the technique for separating the database into homogeneous clusters. Although certain socio-economic, cultural, and water quality variables are not explicitly considered, they do not impact the predictive accuracy of the outcomes, as they are inherently accounted for within the dataset.

Our study also provides monthly consumption values and annual averages in demographic ranges for each geographical region, illustrating the monthly variation within their respective regions based on a robust and extensive historical database. Data on average HMDWC in both the Sierra and Amazonian regions offer valuable insights for towns within this sample and for others with similar demographic profiles, facilitating more informed planning and projections. Temporal disaggregation over the 12 months reveals no distinct trends within any demographic range, indicating no statistically significant variation across the months. This suggests that the monthly water demand per family remains relatively stable.

When data are analyzed without considering regional divisions but are categorized into demographic ranges, the average monthly water consumption (m³/month-family) in small towns (Range 2) is 13.80. This value is slightly higher than its counterpart from the Sierra Region (13.61) but lower than that from the Amazon Region (14.15) when regions are separated. Similarly, in medium-sized towns (Range 3), the average value for both regions combined is 19.80, while it is 18.96 for the Sierra and 21.62 for the Amazon. In large cities (Range 4), the average for the two regions is 20.3, whereas it is 20.15 for the Sierra and 21.11 for the Amazon. In all cases, the average for the two regions is lower than those of the Amazonian Region. HMDWC from towns (8,000-150,000 inhabitants) in the Amazonian Region is higher than that in towns from the Sierra Region.

These findings highlight the necessity of dividing the database by regions to obtain accurate representative mean values. Without regional disaggregation, the planning of water supply systems, especially in the Amazonian Region, would be undersized, leading to deficient management of its water resources. Conversely, towns in the Sierra Region, which have lower average HMDWC, would be inaccurately represented if combined with data from the Amazonian Region.

In conclusion, this study provides compelling evidence for the sustainable management of water resources based on historical potable water consumption across different regions. It underscores the importance of detailed data analysis and regional disaggregation in ensuring the accuracy and applicability of water consumption data for planning and resource management.

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