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Analysis of the relationship between the compactness of urban forms and the patterns of water supply in cities

Análise da relação entre a compacidade de formas urbanas e os padrões de abastecimento de água em cidades

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Abstract: This article aims to analyze the relationship between the compactness of urban areas and the patterns of water supply in the area of cities through the study of minimum flows for distribution networks. In this sense, we sought to statistically correlate geometric, demographic and water supply/distribution parameters in a city, through a case study in the urban area of Uberlândia/MG, a typical medium-sized Brazilian city. Using the Google Earth Professional software, the geometric contours, perimeters and areas of all neighborhoods and geographic areas of the municipality were determined. In addition, through data provided by the municipal government, the total populations of each neighborhood were determined. Thus, the compactness index and the population density of the units in the urban area were determined. In addition, based on ABNT NBR 12211/1992, the average water consumption and minimum supply flows were calculated for each neighborhood and its respective zones. These data were correlated and the results obtained were specialized in the form of thematic maps. It was observed that the minimum flow of demand supply is inversely populational to the population density, while this flow is directly proportional to the population and the compactness index of the urban area.

Keywords: Water supply; Compacity index; Urban morphology.

Resumo: Este artigo objetiva analisar as relações entre a compacidade de manchas urbanas e os padrões de abastecimento de água na área das cidades por meio do estudo das vazões mínimas para redes de distribuição. Neste sentido, buscou-se correlacionar estatisticamente parâmetros geométricos, demográficos e de oferta/distribuição de água em uma cidade, por meio de um estudo de caso na mancha urbana de Uberlândia/MG, uma típica cidade de médio porte brasileira. Por meio do software Google Earth Professional, foram determinados os contornos geométricos, os perímetros e as áreas de todos os bairros e zonas geográficas do município. Além disso, através de dados disponibilizados pela prefeitura municipal, foram determinadas as populações totais de cada bairro. Assim, determinou-se o índice de compacidade e a densidade populacional das unidades da mancha urbana. Além disso, com base na ABNT NBR 12211/1992, calculou-se o consumo médio de água e as vazões de abastecimento mínimas para cada bairro e suas respectivas zonas. Estes dados foram correlacionados e os resultados obtido foram especializados na forma de mapas temáticos. Observou-se que a vazão mínima de abastecimento de demanda é inversamente populacional à densidade demográfica, enquanto esta vazão é diretamente proporcional à população e ao índice de compacidade da mancha urbana.

Palavras-chave: Abastecimento de água; Índice de compacidade; Morfologia urbana.

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1. Introduction

Water is an essential natural resource for human life, without which most human activities cannot be fully developed. In this sense, whether for personal consumption, for irrigation of agricultural crops, for supplying livestock, for industrial processing, for transportation by waterways and for recreation and leisure, water is structured as a circumstantial element for humanity. (UNESCO, 2008; ANDRADE, BLUMENSCHEIN, 2013, AGUIAR et al., 2020).

However, most of the fresh water on the planet does not meet adequate standards of potability and availability for immediate human consumption. In this way, it becomes necessary to provide systems for capturing, treating and distributing raw water from riverbeds and reservoirs to final disposal and consumption units (HILL, 2009; BOTELHO, 2011; KUSTERKO et al., 2018) .

To ensure the best functioning of these systems, it is necessary, at first, to determine the minimum supply flows required by the water distribution network. In the case of cities, these flows are configured as the minimum values required by law in order to guarantee the access of an urban population to sufficient quantities of water for the development of their daily activities and for their consumption (TUCCI, MENDES, 2006 ; TUCCI, 2008; AGUIAR et al., 2020).

Traditionally, the calculation of these flows is done through a mathematical relationship between the population of a given urban space, the average daily consumption per inhabitant of this space, and by two empirical coefficients associated with the day and time of greatest consumption over a period of time. year (ABNT, 1992). Of these, it can be seen that the population is the most influential parameter in determining the minimum supply flows.

However, the contemporary scientific community has realized that several other factors can significantly influence the demand for water in an urban population. In this context, it has been noticed that characteristics associated with the morphology of cities play an important role in the patterns of use and use of water resources (RUEDA, 2000; WSUD, 2008; ANDRADE, BLUMENSCHEIN, 2013).

In this sense, the present work aims to analyze the existing relationships between urban form and water consumption in cities. Thus, a study was developed that seeks to correlate the compactness index of urban spots with their respective populations, demographic densities and minimum water supply flows. To this end, a case study was carried out along the urban area of the Brazilian municipality of Uberlândia/MG, an important city in the interior of the country.

2. Recursos hídricos e o ambiente urbanizado

Throughout human history, the management of water and water resources has proven to be a highly dynamic, complex process that involves technical, social, economic, cultural and political issues, especially within the urbanized environment (ZHANG, 2013; MARINHO, 2018). In cities, it is observed that the main uses of water are associated with domestic supply, industrial supply, irrigation of small urban crops and watering animals (SOUZA, 2015, LOUSADA et al., 2019; AGUIAR et al., 2020).

However, in general terms, only the first two uses are directly associated with the provision of systems for capturing, treating and distributing water within acceptable potability standards for human consumption (ANDRADE, BLUMENSCHEIN, 2013; KUSTERKO et al., 2018). In this context, the scientific community proposes a network of processes known as the urban hydrological cycle, also called the artificial water cycle in cities.

Traditionally, water is captured from riverbeds and/or reservoirs and transported through penstocks to a treatment plant. After the due physical and chemical processes, the treated water is then disseminated through a public distribution network until it reaches the points of use in the various buildings of a city (CARVALHO, GUIMARÃES, SILVA, 2007; LOUSADA et al., 2019).

After use, the water is called liquid effluent and is sent through a network of specific free conduits to a sewage treatment plant. From then on, after new physical, chemical and biological treatments, the treated effluent is discharged into water courses, thus concluding its flow in the urbanized environment (CARVALHO, GUIMARÃES, SILVA, 2007; BOTELHO, 2011; LOUSADA et al., 2019).

Within this cycle, an extremely important parameter for the good use of water resources is the water distribution flow in the distribution network (BOTELHO, 2011; KUSTERKO et al., 2018). This flow, also called demand flow, is a direct function of the resident population in a given urban area and its consumption patterns (TUCCI, 2008). According to ABNT NBR 122211/1992, this parameter can be calculated as shown in Equation 1.

$$Q = \frac{k_1.k_2.C.P}{86400} \tag{1}$$

Where: Q = minimum demand flow (L/s); k_1= coefficient of the day with the highest consumption; k_2= coefficient of the hour of greatest consumption; C= average daily consumption per capita (L/s.day); and P=population of the supplied area.

The coefficients shown in Equation 1 are empirical dimensionless values that work to adapt the calculation of demand flows to hourly and daily fluctuations in consumption, considering peaks in water use for the most diverse purposes (GUIMARÃES, CARVALHO, SILVA, 2007; AGUIAR et al., 2020).

Theoretically, the coefficient of the day with the highest consumption is calculated through the ratio between the average flow of the day with the highest consumption by the annual average daily flow. Analogously, the coefficient of the hour of greatest consumption is obtained through the quotient between the highest hourly flow of the day and the average hourly flow of the day. However, for engineering design purposes, these values can be adopted as being equal to 1.20 and 1.50, respectively (ABNT NBR 12211/1992).

Over many decades, the equation set out in Equation 1 was widely used by the scientific and professional community to develop studies associated with the design of water distribution networks (ANDRADE, BLUMENSCHEIN, 2013; DA SILVA et al., 2020). However, currently, it is clear that the relationship between demand flows and the population served is not one-dimensional.

Thus, it is observed that variables associated with the structure and behavior of the urbanized environment influence the determination of supply flows and, consequently, the use of water resources in a city RUEDA, 2000; ZHANG, 2013; SOUZA, 2015; KUSTERKO et al., 2018).

Since the end of the first decade of the twentieth century, international studies have discussed the importance and influence that the urban morphological configuration has on the dimensioning, distribution and use of natural resources (HILL, 2009; ANDRADE, BLUMENSCHEIN, 2013; ZHANG , 2013). In this context, researchers have observed that the geometric shape with which a city is structured is intimately and systemically related to the water consumption of its population (MARINHO, 2018; LOUSADA et al., 2019; DA SILVA et al., 2020).

Conventionally, water distribution networks in cities develop below the street grid axis (TSUTIYA, 2005). Thus, penstocks that carry water from their treatment plants to distribution points in buildings are designed, sized, built and operated underground in urban roads (BOTELHO, 2011).

In a practical way, the greater the distances on urban surface roads to be covered in a water distribution network, the greater the expenses with material, operation and management of the penstock system. Similarly, the greater the population residing in the area where the roads are developed and, consequently, the greater the consumption of water by these inhabitants.

With greater water consumption, when analyzing Equation 1 above, there is also an increase in the minimum supply flows. This increase tends to cause, among other situations, the following (THÉRIAULTE, LAROCHE; 2009; VAN LEEUWEN et al., 2012; SOUZA, 2015; RENOULF et al., 2017):

- Larger volumes to be removed from natural watercourses, thus being able to cause imbalances in the fauna and flora of ecosystems;
- Higher expenses with materials for the distribution network, which must be designed to be able to withstand higher flows and, consequently, higher static and dynamic pressures, thus demanding more resistant materials;
- Increase in the cost of acquisition, operation and maintenance of equipment in pumping stations, such as pumps and booster systems, when the water needs to be distributed through pumping, and not just by gravity; It is,
- Greater fluctuations in consumption in case of interruption of the water supply to the population.

Based on this, several researchers and professionals associated with the urban environment have encouraged the development of studies and recommended new paradigms for the design, construction and management of cities and their morphological elements. With this, it is possible not only to better understand how cities, their populations and their phenomena develop, but also to mitigate the negative impacts caused by the geometric structuring and by the functioning of the urbanized geographic space in an ecosystemic way (HILL, 2009; RENOULF et al., 2017, DA SILVA et al., 2020).

In this sense, the conceptual discussion of the so-called “Water Sensitive Cities” (WSC) has become frequent at the international level. This term refers to a set of design, construction and operation practices of the urban fabric and its infrastructure equipment whose main objective is based on the following aspects (MARE, 2008; UNESCO, 2008; LIMA et al., 2013; AGUIAR et al., 2020; DA SILVA et al., 2020):

- Ensure the smallest possible interventions in the natural environment, in order to intensely preserve the original ecosystems of a given geographic space;
- Effectively minimize the impacts caused by buildings on the urban water cycle;

- Ensure that the geometric and morphological structure of cities is resilient in the face of disasters and natural catastrophes of water origin, such as floods and extreme rainfall events; It is,
- Provide a conscious use of water within the urbanized environment, in order to optimize the use of water resources in all its instances.

Within this scenario, one of the most unique characteristics of water-sensitive cities is their urban compactness. By definition, the compactness of an urban area is understood as the quantitative parameter that measures the relationship between its perimeter and the area of a fictitious circle inscribed in the real area occupied by the city (LI, YEH, 2004; CRUZ, MARINS, 2017). In other words, it is a parameter that measures the degree of compactness of a given city.

Thus, the compactness of an urban area is obtained by calculating the so-called Compactness Index (CI), as shown in Equation 2 (LI, YEH; 2004; Lu, Y, 2015).

$$IC = 2\left(\frac{\sqrt{\pi.A}}{P}\right) \tag{2}$$

Where: IC= compactness index (dimensionless, by definition); A= area of the urban area (km²); and P= perimeter of the urban area (km).

From the values obtained by Equation 2, a certain urban area can be classified according to its compactness index. Table 1 presents these classifications (LI, YEH, 2004; LU, Y, 2015; CRUZ, MARINS, 2017).

Table 1 – Classification and analysis of compactness index values.

Compactness Index Value (CI)	Urban área classification
CI > 0,50	Compact
0,20 < CI < 0,50	Little compacta
0,15 < CI < 0,20	Disperse
CI < 0,15	Very scattered

Source: Adapted from Cruz and Marins (2017).

About to the objective of a water-sensitive city, it is observed that urban areas with a higher CI have greater potential for optimizing the use of water resources. This is due to the fact that compact cities tend to be denser, that is, to have a higher population density (CRUZ, MARINS, 2017).

Thus, a greater number of inhabitants are concentrated in a reduced geographic space. Consequently, the management of urban infrastructure equipment, rainwater drainage systems and water distribution networks for this consumer population becomes easier (TSUTIYA, 2005; ANDRADE, BLUMENSCHEIN, 2013). Thus, a compact urban space implies smaller distances between streets and, consequently, lower expenses with materials for penstocks in underground water distribution networks.

Furthermore, in a distribution network that accompanies an urban area with a high CI, there is a tendency for less use of hydraulic singularities, such as elbows, elbows and curves in penstocks. Thus, it is possible to promote a considerable decrease in head losses (energy dissipated in the form of heat resulting from fluid/wall and fluid/fluid friction in a forced conduit flow) during water distribution (TSUTIYA, 2005; TUCCI, 2008) .

A direct consequence of the reduction in load losses is the reduction in the occurrence of accidents involving distribution pipes, such as water hammer (ABNT NBR 12211/1992). These phenomena are mainly responsible for the loss of efficiency in the functioning of a water supply network, and may act in such a way as to cause intense variations in pressure and/or flow, sudden interruptions in the water supply and, in extreme cases, the total collapse. of the conduits (PORTO, 1999; TSUTIYA, 2005; TUCCI, MENDES, 2006).

Given the above, it is consonant with today's society that the search for the construction of cities sensitive to water and with a compact morphological structure has become a necessity. In this way, it is possible to guide more intelligent and sustainable practices with regard to the use of water resources within the urbanized environment and to establish more conscious standards for water consumption.

3. Method

3.1 Study área characterization

The municipality of Uberlândia is located in the state of Minas Gerais, in the Geographic Mesoregion of Triângulo Mineiro and Alto Paranaíba (Figure 1). It has a territorial extension of 4,115.206km², a population of 706,597 inhabitants and a population density equivalent to 146.78 inhabitants/km² (IBGE; 2021).

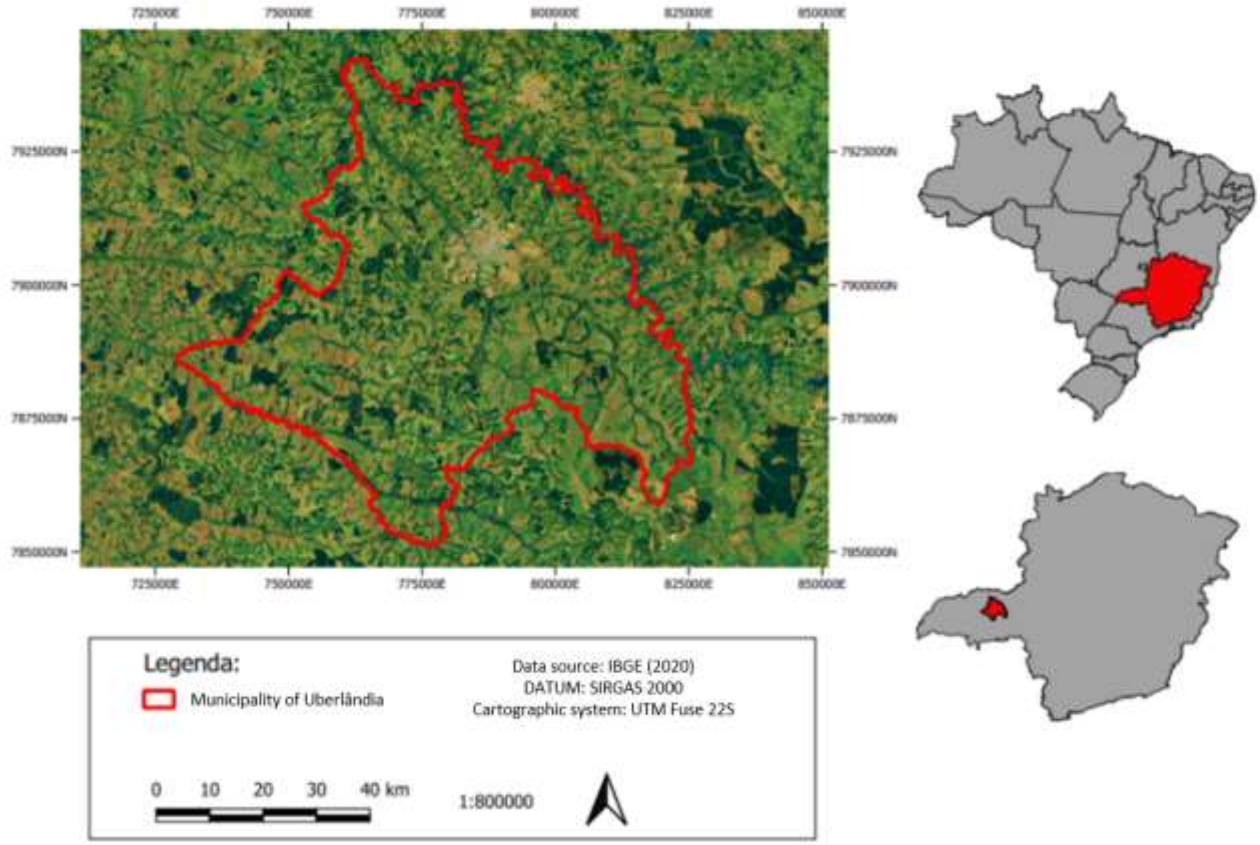

Figure 1 – Geographic location of the study area.
Source: The authors.

As can be seen in Figure 1, the municipal urban area develops in the Northeast portion of the municipality. It has a territorial extension of 135.72km², which corresponds to 3.30% of the municipal area. Practically, 97% of the municipality's population lives in the urbanized area (IBGE; 2021).

It is important to point out that Uberlândia is a reference city nationwide in the context of public water supply and the collection, treatment and proper disposal of sanitary effluents. The municipality has 98.5% of its urban area covered with highly efficient sanitation systems, ranking as the second city with the best basic sanitation system in the entire country (IBGE; 2021).

3.2 Data collection

After the initial characterization of the study area, it became necessary to collect fundamental data about the urban area of Uberlândia. In this sense, together with the digital platforms of the Municipality of Uberlândia, data were collected related to the list of neighborhoods that make up the city, as well as their respective populations and geometric contours.

In addition, vectorization of the urban area was carried out using orbital images extracted from Google Earth

Professional, related to the image of the municipal urban area in the year 2020. Using delimited polygons, the geometric parameters of area and perimeter were calculated for each vectorized figure.

3.3 Determination of compactness índices

CI values were calculated based on Equation 2, previously exposed in this text. For this purpose, the perimeters and areas of each geographic zone of the municipal urban area were considered, divided into North Zone, South Zone, East Zone, West Zone and Central Zone. Table 2 presents the neighborhoods belonging to each zoning.

Table 2 – Neighborhoods that are part of each geographic zoning of the urban area.

North	South	East	West	Central
Pres. Roosevelt	Tubalina	Tibery	Jaraguá	Centro
Jd. Brasília	Cid. Jardim	S. Mônica	Planalto	Fundinho
S. José	Nova Uberlândia	Segis. Pereira	Chac. Tubalina	Lídice
Marta Helena	Patrimônio	Umuarama	Jd. Palmeiras	Tabajaras
Maravilha	M. da Colina	Cust. Pereira	Jd. Canaã	Cazeca
Pacaembu	Vigilato Pereira	Morumbi	Panorama	Bom Jesus
S. Rosa	Saraiva	Integração	Jd. Holanda	Brasil
Res. Gramado	Jd. Karaíba	Industrial	Mansour	N. S. Aparecida
N. S. das Graças	Granada	Others	Jd. Europa	Martins
Minas Gerais	S. Jorge		Luizote de Freitas	Osvaldo Resende
Others	Laranjeiras		Jd. Patrícia	Daniel Fonseca
	Ibiporã		D. Zulmira	
	Shopping Park		Taiaman	
	S. Luzia		Guarani	
	Others		Tocantins	
			Morada do Sol	
			Others	

Source: The authors.

It is important to point out that, in Table 2, where it reads "Others", neighborhoods that have not yet been formalized by the City Hall of Uberlândia and/or closed residential areas were included which, although they are structured as exclusively residential neighborhoods, are not considered as residential units. administrative by public management.

In this way, 5 values were obtained for perimeters and areas, corresponding to each of the 5 zonings in Table 1. Consequently, through the application of Equation 2, 5 CI values were obtained, one for each geographic zone of the municipal urban area from Uberlandia.

3.4 Determination of minimum supply flows (demand flows)

The calculation of the minimum supply flows was carried out using Equation 1, previously exposed in this text. For this purpose, the total population of each neighborhood in the city of Uberlândia was considered. The values of k1 and k2, for practical calculation purposes, were taken as being 1.20 and 1.50, respectively (ABNT NBR 12211/1992). Finally, the values of average daily consumption per capita were adopted according to normative recommendations (ABNT NBR 12211/1992).

In this sense, the flow was calculated for each district of the city. These flows were then added up neighborhood by neighborhood by zoning sector of the urban area. Thus, 5 minimum supply flows were obtained, each relative to the demand flow necessary to supply the resident population in a geographic area of the city of Uberlândia.

3.5 Determination of demographic densities

After calculating the CI values and the minimum supply flows, the population density of the geographic zones of the city was calculated. This value was obtained through the ratio between the sum of the population of a certain zone by its respective territorial area. Thus, 5 values of population density were obtained per area of the municipality's urban area.

3.6 Spatialization and analysis of results

After the completion of all calculations, the results obtained were specialized in the form of a thematic map. For that, the geoprocessing software QGIS version 3.16.6 was used, where the acquired results were manipulated graphically. In addition, comparative graphs were also developed in order to analyze, visually and numerically, the existing relationships between demand flow and compactness index.

Finally, the results expressed in the form of the thematic map and the graphics developed were correlated with issues associated with the optimization of the use of water resources. In particular, attention was paid to their relationship with the promotion of water distribution networks in line with the concepts advocated by water-sensitive cities in a context of smart and sustainable urbanization.

4. Results and discussions

4.1 Population, demographic density and supply flows for Uberlândia

At first, population parameters and minimum water supply flows were determined and analyzed considering the population of Uberlândia as a whole. In this sense, we sought to interpret the population growth curve provided by the City Hall, shown in Figure 2.

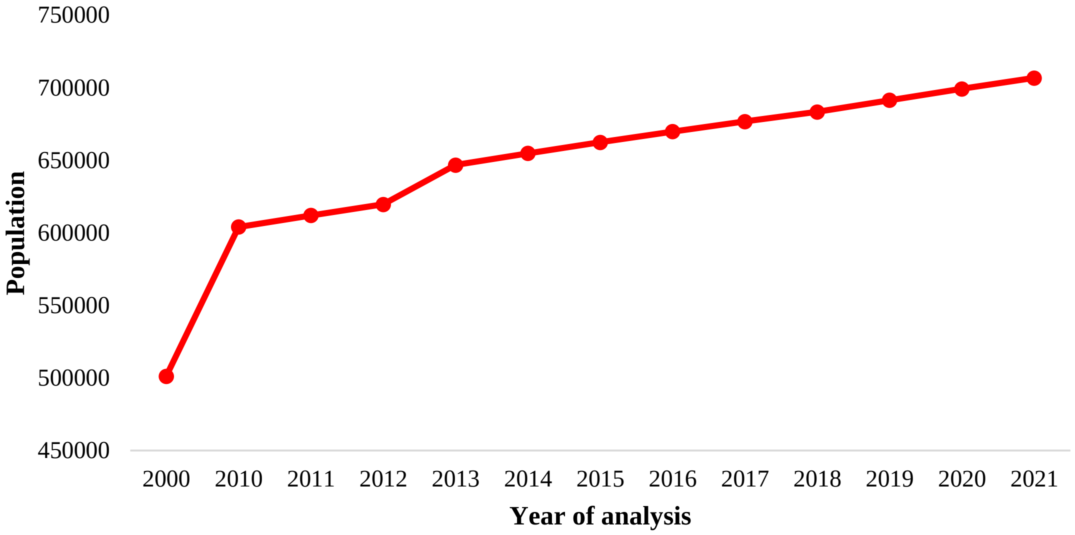

Figure 2 – Uberlândia population growth curve.
Source: Adapted from City Hall of Uberlândia (2022).

Through Figure 2, it is possible to observe that between the years 2000 and 2010, there was a considerable growth in the population residing in the municipality of Uberlândia. However, from 2013 onwards, this growth practically started to show a linear behavior.

Given this population estimate, the values of the minimum supply flow for the general population of the city were determined. In this context, it was decided to determine the flows only for the period of time whose behavior of the population curve was observed and/or estimated as linear, that is, between the years 2013 and 2030. Table 2 presents these values.

Table 2 – Minimum supply flows for the population of Uberlândia as a whole.

Year	Population	k1	k2	q (L/hab)	Q estimated (L/s)	Q estimated (m³/s)
2013	646673	1,2	1,5	300	4041,706	4,042
2014	654681	1,2	1,5	300	4091,756	4,092
2015	662362	1,2	1,5	300	4139,763	4,140
2016	669672	1,2	1,5	300	4185,450	4,185
2017	676613	1,2	1,5	300	4228,831	4,229
2018	683247	1,2	1,5	300	4270,294	4,270
2019	691305	1,2	1,5	300	4320,656	4,321
2020	699097	1,2	1,5	300	4369,356	4,369
2021	706597	1,2	1,5	300	4416,231	4,416
2022	713728	1,2	1,5	300	4460,799	4,461
2023	721135	1,2	1,5	300	4507,091	4,507
2024	728541	1,2	1,5	300	4553,384	4,553
2025	735948	1,2	1,5	300	4599,676	4,600
2026	743355	1,2	1,5	300	4645,968	4,646
2027	750762	1,2	1,5	300	4692,260	4,692
2028	758168	1,2	1,5	300	4738,552	4,739
2029	765575	1,2	1,5	300	4784,844	4,785
2030	772982	1,2	1,5	300	4831,137	4,831

Source: The authors.

Through Table 2 and Figure 2, it is observed that, concomitantly with the linear increase in the resident population, the minimum flows to meet the demand in the water distribution networks in the municipality also grew linearly.

4.2 Population, compactness and supply flows by geographic área

In general, it could be seen that the minimum flows to meet the population demand in water distribution networks have a directly proportional relationship with the amount of population supplied. Mathematically, this becomes evident through Equation 1 and is observed through the graphs shown in Figures 4 and 5 that refer to the population patterns of Uberlândia and their respective demand flows over the years.

However, as explained in the previous sections of this article, it is known that the way in which the urban area develops can also influence these flows due to variations in population density in cities. Furthermore, the degree of compactness of the built environment, measured by the CI, is also an influential parameter in determining supply flows.

In this context, in order to analyze the influence of population density and the compactness of the urbanized environment on demand flows for water supply, it was decided to carry out a sectoral study. Thus, the total population, population density and demand flow were determined for each geographic zone of the city of Uberlândia/MG. These values are shown in Table 3.

Demand flows were calculated separately by neighborhood, taking into account their respective populations. After this calculation, they were added according to the neighborhoods that make up each geographic zone of the municipal urban area of Uberlândia.

In Table 3, the population of each zone was obtained in a similar way, by adding the total population of the neighborhoods that make up each analyzed sector. The population density was obtained through the quotient between the population of each zone and its respective territorial area.

The CI value was determined using Equation 2, previously exposed in the text of this article. Finally, the information presented in Table 3 was also represented using a thematic map, as shown in Figure 3.

Table 3 – Population, population density, compactness and flows by geographic zone.

Zone	**Q demanded (m^3/s)**	**Population**	**Populational density (hab/km^2)**	**CI**
Norte	0,386	93267	3330,964	0,845
Sul	0,498	125851	2125,861	0,814
Leste	0,604	137000	2337,884	0,805
Oeste	0,568	140539	1979,423	0,638
Centro	0,334	84903	6242,868	0,755

Source: The authors.

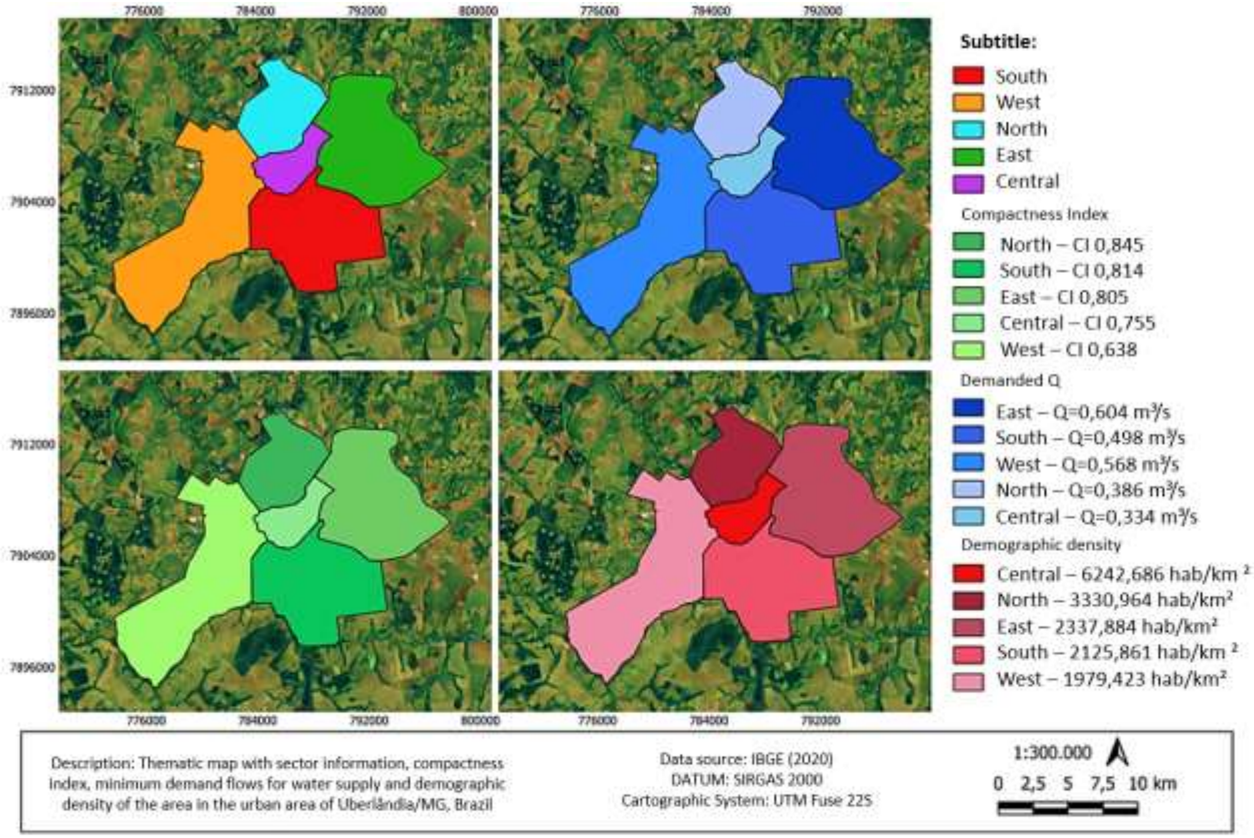

Figure 3 – Zoning, compactness, demand flows and population density in the study area.
Source: The authors.

Regarding the data shown in Table 3 and Figure 3, it can be seen that the relationship between population density, compactness index and demand flows is complex. Therefore, in general, it is not possible to establish direct and/or indirect proportionality relationships between the analyzed parameters.

In this context, it was decided to analyze, in an isolated way, the existing relations between the CI and the supply flows for the geographic zones of Uberlândia. This relationship was possible since both parameters are within the same absolute scale range for analysis (values between 0.00 and 1.00). Figure 7 illustrates, by means of a graph, the relationship between these two variables.

It is important to note that, in general, high values for the CI are associated with lower values for the minimum supply flow in water distribution networks. By Figure 7, it is possible to prove this behavior when verifying that the North, South and Center regions present the highest values of urban compactness and, associated with this, low values of demand flow.

Analogously, the West region obtained the highest demand flow value. Associated with this behavior, through Figure

4, it is observed that the West region had the lowest compactness index value among the other geographic zones of the municipal urban area.

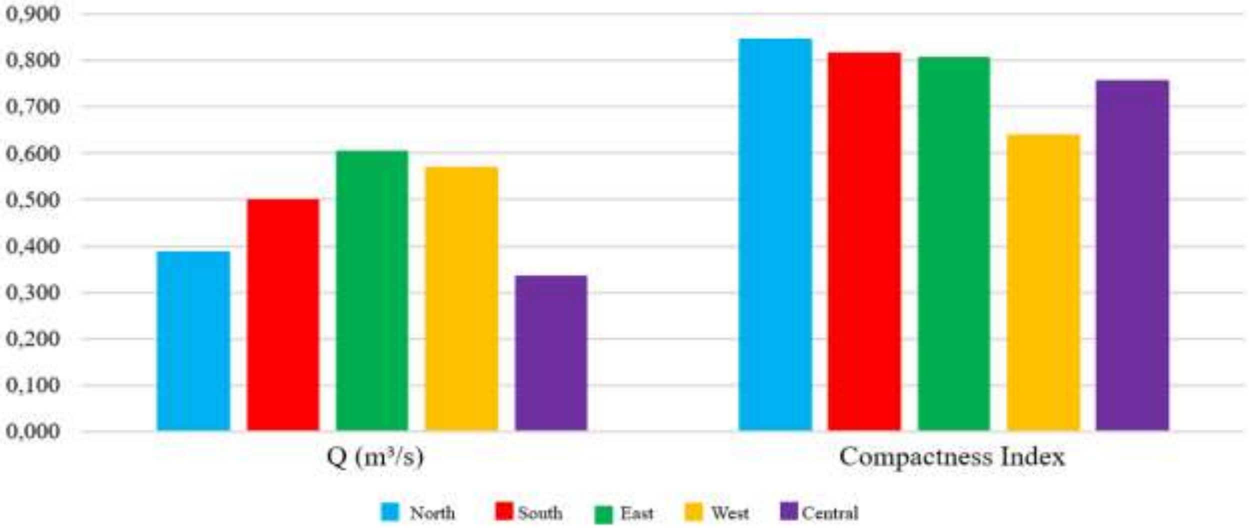

Figure 4 – Relationship between CI and minimum demand flows for water supply.
Source: The authors.

However, it is important to point out that the East zone showed a behavior that differed from the general observed. In this sense, it presented a high CI value and also a high value for the demand flows. This is mainly due to the large population residing in the region, so that the population influence on water consumption becomes greater than the influence of urban morphology. With regard to the relationship between population density and demand flows, Figure 5 illustrates the behavior presented by these variables as a function of their geographic zone. In this sense, it is possible to observe that there is greater complexity in the relationship between these two parameters.

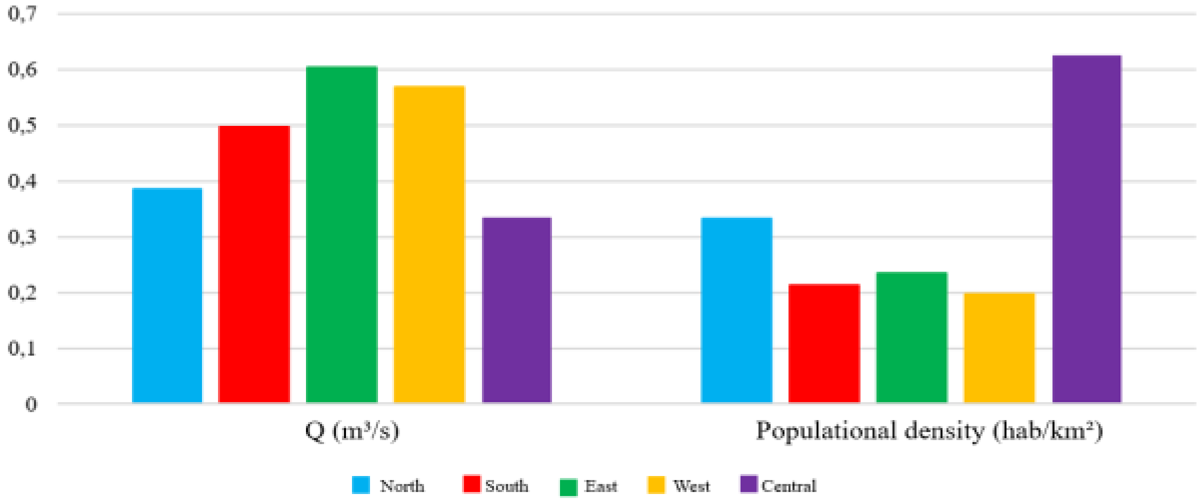

Figure 5 – Relationship between population density and demand flows for water supply.
Source: The authors.

In general, when analyzing the information presented in Figure 5, it is clear that there is an inverse proportionality relationship between the two variables. Thus, as population density increases, supply flows tend to decrease. Analogously, the reduction in population density tends to imply an increase in the minimum demand flows in the supply network.

However, this behavior cannot be taken as fateful and immutable since the demographic density is a quotient function of two variables: one of population order (number of inhabitants residing in an area) and another of morphological order (area in which a population resides). Traditionally, the increase in populations implies a consequent increase in the area occupied by this demographic portion. Thus, the increase in demographic density culminates in an increase in supply flows, since both population and morphological parameters were increased.

In the case of compact cities and water-sensitive cities, this relationship is reversed. Keeping the inhabited area fixed and promoting only the increase in population parameters, there is only an increase in demographic density. This increase, in turn, is usually not enough to cause significant increases in consumption patterns and demand for water in public distribution networks.

The central zone of the urban sprawl of Uberlândia, as can be seen in Figure 5, exemplifies this situation well. The region develops with an inflexible area and with a high consolidated population, which implies the highest population density in the municipality. Despite this, the flow of demand for the region is the lowest when compared to the other geographic areas of the city.

5. Final considerations

Through the results obtained in this research, it was concluded that water consumption in cities, a variable synthesized by the value of the minimum supply flows established by ABNT NBR 12211/1992, is a parameter directly proportional to the urban population. In this way, it is concluded that as the number of residents in a given urbanized area increases, the minimum flows also increase. Similarly, population reduction also causes a reduction in water consumption.

In addition, it was concluded that water consumption in cities tends to be inversely proportional to demographic density and the compactness index of urban areas. In this way, it was concluded that geometric and urban parameters of cities act in a very sensitive way with regard to the determination of minimum design flows in water supply systems.

For the case study developed in this work, it was concluded that the proportionalities described above are applicable, except for the central region of the city of Uberlândia-MG. This region, in turn, presents a particular behavior due to its singularity and urban consolidation.

It is suggested for future work to collect information on the actual exact consumption of water by populations residing in each neighborhood of the study area. With this, one can compare the generated model and the estimated values in this research with exact data and, thus, optimize the statistical analysis of this model.

Finally, it is also suggested the adoption of other cities for the development of new case studies. With this, it is possible to compare different urban scenarios with their respective particularities and optimize the modeling process of water consumption in cities and its relationship with urban, demographic, environmental aspects, among others.

References

AGUIAR, G., TEIXEIRA, T., DE SOUZA, F. P., DOS SANTOS, K. V. Expansão demográfica e abastecimento de água no sistema integrado de Feira de Santana/BA. *Humanas Sociais & Aplicadas*, 10(29), 34-45. 2020.

ANDRADE, L.M.S.; BLUMENSCHEIN, R.N. Cidades sensíveis à água: cidades verdes ou cidades compactas, eis a questão? *Paranoá, Brasília*, n. 10, p. 59-76, 2013.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS – ABNT. NBR 12211/1992. *Estudos de concepção de sistemas públicos de abastecimento de água*. Rio de Janeiro/RJ. Brasil. 54p. 1992.

BOTELHO, R. G. M. Bacias hidrográficas urbanas. In: GUERRA, A. J. T. (org.) *Geomorfologia urbana.* Rio de Janeiro: Bertrand Brasil, 2011.

CRUZ, R. B. C.; MARINS, K. R. C. Avaliação do índice de compacidade nas subprefeituras do município de São Paulo. *Revista Eletrônica de Engenharia Civil*. v.13, n.2, p. 287-298. 2017.

DA SILVA, G. M., SCHWANTZ, P. I., PRESTES, M. M. B., DE QUEVEDO, C. A., PORN, C. M., DE LARA, D. M. Análise per capita do abastecimento de água no município de Soledade (Rio Grande do Sul). *Revista Estudo & Debate*, 27(2). 2020.

GUIMARÃES, A. J. A.; CARVALHO, D. F. de; SILVA, L. D. B. da. *Saneamento básico*. Disponível em:

<http://www.ufrrj.br/institutos/it/deng/leonardo/downloads/APOSTILA/Apostila%20IT%20179/Cap%201.pdf>. Acesso em: maio/2022.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA – IBGE. Portal cidades. Uberlândia. Disponível em: <https://cidades.ibge.gov.br/brasil/mg/uberlandia/panorama>. Acesso em: junho/2022.

HILL, K. Urban Design and Urban Water ecosystems. *The Water Environment of Cities*. Springer. pp 141-170. 2009.

KUSTERKO, S., ENSSLIN, S. R., ENSSLIN, L., CHAVES, L. C. Gestão de perdas em sistemas de abastecimento de água: uma abordagem construtivista. *Engenharia Sanitária e Ambiental*, 23, 615-626. 2018.

LIMA, B. ANDRADE, L. S. A., HOLLANDA, P. P. T.M., *Padrões de uso e ocupação da Bacia Hidrográfica do Paranoá e seus impactos para o ciclo da água no meio urbano*. In: Anais do ELECS, Curitiba, 2013.

LI, X., YEH, A. Analyzing spatial restructuring of land use patterns in a fast growing region using remote sensing and GIS. *Landscape Urban Planning*, v.69, n.4., (October 2004) p 335– 354. 2004.

LOUSADA, S., SOARES-DA SILVA, P., CASTANHO, R. A., NARANJO-GÓMEZ, J. M. Modelação de sistemas de abastecimento de água. O caso de Ilha da Madeira. *Bitácora Urbano Territorial*, 29(2), 89-98. 2019.

LU, C., Y., L. Effects of China's urban form on urban air quality. *Urban Studies Journal Limited* 2015. DOI: 10.1177/0042098015594080. China. p1–17. 2015.

MARINHO, S. D. A. M. *Planejamento urbano sensível aos recursos hídricos: análise a partir do metabolismo urbano e da produção do espaço em Campina Grande-PB.* Dissertação de mestrado. Programa de Pós-graduação em Engenharia Civil e Ambiental. Universidade Federal de Campina Grande. Campina Grande/PB, Brasil. 89p. 2018.

MARE, C. *An Historical survey of urban densities as a consequence of energy regime: descent into the urban village*. In: Anais do Ecocity, São Francisco, Califórnia 2008.

MENEZES, P. H. B. J. *Avaliação do efeito das ações antrópicas no processo de escoamento superficial e assoreamento na Bacia do Lago Paranoá*. Dissertação (Mestrado). Universidade de Brasília, 2010.

PORTO, R.M. Hidráulica básica. São Carlos: EESC/USP, 1999.

PREFEITURA MUNICIPAL DE UBERLÂNDIA. Mapas e bairros. Disponível em: <https://www.uberlandia.mg.gov.br/prefeitura/secretarias/planejamento-urbano/mapas-e-bairros/>. Acesso em: junho/2022.

PREFEITURA MUNICIPAL DE UBERLÂNDIA. População. Disponível em: <https://www.uberlandia.mg.gov.br/prefeitura/secretarias/planejamento-urbano/populacao-uberlandia/>. Acesso em: junho/2022.

QGIS. Quantum Gis 3.16.6. Software de geoprocessamento. Disponível para download em: < https://www.qgis.org/pt_BR/site/forusers/download.html>. Acesso em: junho/2022.

RENOULF, M. A., SERRAO-NEUMANN, S., KENWAY, S. J., MORGAN, E. A., LOW CHOY, D. Urban water metabolism indicators derived from a water mass balance - Bridging the gap between visions and performance assessment of urban water resource management. *Water Research*, 122, 669-677. 2017.

RUEDA, S. *Modelos de ciudad: indicadores básicos y las escalas de la sostenibilidade*. Barcelona: [s.n.]. Quaderns – D'arquitetura e urbanismo – Collegio D' Arquitetos de Catalunya. 2000.

SOUZA, T. J. *Potencial de aproveitamento de água de chuva no meio urbano: o caso de Campina Grande – PB. Dissertação de mestrado.* Programa de Pós-graduação em Engenharia Civil e Ambiental. Universidade Federal de Campina Grande. Campina Grande/PB, Brasil. 2015.

THÉRIAULT, J., LAROCHE, A. Evaluation of the Urban Hydrologic Metabolism of the Greater Moncton Region, New

Brunswick. *Canadian Water Resources Journal* Vol. 34(3): 255–268, 2009.

TSUTIYA, M.T. *Abastecimento de água*. 2. ed. São Paulo: DEHS-USP, 2005.

TUCCI, C. E. M.; MENDES, C. A. *Avaliação Ambiental Integrada de Bacia Hidrográfica*. Brasília: MMA, 2006.

TUCCI, C. E. M. Águas Urbanas. *Estudos avançados* n.22 v. 63, 2008.

UNESCO – IHP. Urban Water Cycle Processes and Interactions. In: MARSALEK, J., JIMÉNEZCISNEROS B., KARAMOUZ M., MALMQUIST P., GOLDENFUM J. & CHOCAT B. *Urban Water Series*. Taylor & Francis, Londres, 2008.

VAN LEEUWEN, C. J., FRIJNS, J., VAN WEZEL, A., VAN DE VEN, F. H. M. City Blueprints: 24 Indicators to Assess the Sustainability of the Urban Water Cycle. *Water Resour Manage*. 26, 2177-2197. 2012.

WATER SENSITIVE URBAN DESIGN PROGRAM - WSUD. City of Melbourne WSUD guidelines: applying the model WSUD. Melbourne Water, 2008.

ZHANG, Y. Urban metabolism: A review of research methodologies. *Environmental Pollution*, 178, 463-473. 2013.