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Abstract: The use of chlorine to disinfect water produces a series of by-products, particularly trihalomethanes. This is important given that there is a recognized association with different types of cancer after prolonged exposure, as well as with probable adverse effects on reproduction, especially in relation to offspring. The concentrations of these organic compounds vary greatly depending on the season and the conditions involved in providing water for consumption. This study was aimed at determining the geographic distribution pattern of chloroform in the city of Montevideo, and correlating that with the characteristics of the water distribution network. A total of 400 samples were taken from a sampling network between 2009 and 2015. Chloroform was identified by analyzing these samples using the head-space gas chromatography/mass spectrometry method. Data regarding piping length, diameter, and type of material were obtained. A geographic information system was constructed and hot spots were analyzed using the Getis-Ord G* statistic. A neighborhood piping density index was also proposed. The analysis found two zones in the city: hot and cold spots. The proposed index showed an increase in the G* statistic as the neighborhoods’ piping density increased, with a strong correlation. In addition, the highest G* statistic values corresponded to

ABOUT THE AUTHOR
An interdisciplinary group was formed of professionals with extensive research experience, consisting of chemists, geographers, epidemiologists, and engineers. From the perspective of their disciplines, each has contributed to addressing the complex issue of the quality of water for human consumption. Specifically, the working group has been researching organic byproducts formed by the chlorination process used to disinfect water, and possible effects on health. To understand how THMs behave in a drinking water system, a dense monitoring network was developed in the city of Montevideo, the capital of Uruguay. Advances in the development of geostatistical models have made it possible to delimit zones in the city according to the presence of organic byproducts in water for consumption. In order to address the problem, this working group aims to use this methodology in other cities in the country where the sources of raw water and the management of the supply networks vary.

PUBLIC INTEREST STATEMENT
Providing people with water that is suitable for consumption is increasingly challenging for all societies due to larger populations as well as a gradual deterioration in the sources of the raw water that is extracted for the treatment process. Compounding this are growing urban centers that have aging supply networks alongside networks with new characteristics, creating a complex maze that needs to be characterized. In the case of Uruguay, the disinfection process is performed by chlorinating water. Trihalomethanes are some of the known by-products from this process, which must be properly monitored in order to be maintained at acceptable levels, thereby reducing the risk of health disorders. This work contributes to understanding the formation of trihalomethanes in the network and to determining the geographic zones that show a capability of reaching higher levels of these compounds over time. Mitigation and control plans can be developed based on this data, which will have an impact on population health.
larger amounts of iron piping in neighborhoods. This work was able to determine that the hot spots were associated with the piping density in the neighborhoods as well as with the type of piping material, particularly iron.

Subjects: Environmental Health; Urban Studies; Cities & Infrastructure; Cities & Infrastructure; Urban Studies; Urban Geography; Environmental Geography; Geographic Information Systems; Environmental Modeling; Environmental health

Keywords: Trihalomethanes; chloroform; disinfection by-products; geostatistic; water distribution network

1. Introduction

A total of 700 by-products are known to be produced as a result of using chlorine to disinfect water for human consumption (as is done in Uruguay). The most abundant of these are trihalomethanes (THMs), whose association with health problems has been recognized (Bove, Rogerson, & Vena, 2007a, 2007b; Wang, Deng, & Lin, 2007). Exposure to these by-products can occur in different ways, including ingestion, inhalation, and skin absorption (Botton et al., 2015).

Epidemiological investigations have studied a likely association between prolonged exposure to disinfection by-products (DBP) in chlorinated water and the risk of cancer (Villanueva et al., 2004; Wang et al., 2007). Studies have specifically reported on colorectal cancer (King, Marrett, & Woolcott, 2000; Chen, Weiping, Xinyan, Yao, & Jiang, 2005; Bove et al., 2007b; Kuo, Tiao, Trong-Neng, & Yang, 2009; Kuo, Chen, Shi-Chen, Wang, & Yang, 2010; Md, Bayzidur, & Tim, Villanueva et al., 2017) and bladder cancer (Bove et al., 2007a; Chang, Shi-Chen, Wang, & Chun-Yuh, 2007; Goebell, Villanueva, Rettenmeier, Rubben, & Kogevinas, 2004; Michaud et al., 2007; Villanueva et al., 2004, 2006; Villanueva, Kogevinas, & Grimalt, 2001).

Adverse reproductive effects have also been the subject of attention (Chisholm, Cook, Bower, & Weinstein, 2008; Grellier et al., 2010; Nieuwenhuijsen et al., 2009; Nieuwenhuijsen, Toledano, Eaton, Fawell, & Elliott, 2000).

In Uruguay, the national norm (UNIT Norm 833:2008) is based on 2008 guidelines published by the World Health Organization (WHO (World Health Organization), 2008), although a more recent guide has been published (WHO (World Health Organization), 2017).

THMs are formed by a reaction between the organic matter present in water and chlorine used for disinfection (Guilherme & Rodriguez, 2015). This produces chloroform (CHCl3), chlorodibromomethane (CHClBr2), bromodichloromethane (CHBrCl2), and bromoform (CHBr3). Chloroform is the most abundant of these compounds (Baytak, Sofuoglu, Inal, & Sofuoglu, 2008; Jang, Choi, Ro, & Ka, 2012; Ristoiu et al., 2009; Uyak, Ozdemir, & Toroz, 2007) (Knight, Watson, Carswell, Comino, & Shaw, 2011; Gomez-Camponovo et al., 2014), representing as much as 80% of THMs, on average (Rodriguez, Vinette, Jean-B., & Bouchard, 2003).

The concentration of these compounds depends on several factors, including the source and type of raw water, the concentration of organic matter, the pH of the water (Cool, Lebel, Sadiq, & Rodriguez, 2015; Guilherme & Rodriguez, 2015), bromide and iodide levels, water temperature (Guilherme & Rodriguez, 2015; Ristoiu et al., 2009), initial chlorine concentration (Brown, Bridgeman, & West, 2011), and contact time with the disinfectant agent (Sadiq & Rodriguez, 2004) (considered to be positively correlated with the amount of time it remains in the piping) (Guilherme & Rodriguez, 2015; Loyola-Sepulveda, Lopez-Leal, Jorge., Bravo-Linares, & Mudge, 2009). THM levels also increase as the distance from the chlorination point increases (Rodriguez et al., 2003). This set of parameters affects the decay of chlorine, which occurs due to reactions with compounds present in the bulk water (known as bulk decay), and which previous works on this subject have recognized as the principal determinant of the formation of THMs (Krasner et al., 2006).
Several researchers are currently considering other variables, including those that affect the reaction of chlorine at the pipe wall (known as wall decay).

This type of decay involves corrosion reactions with the wall material itself, as well as with adhering biofilms and accumulated sediments. It depends on multiple factors, such as pipe material, diameter (and water velocity), service age, inner coating and the presence of attached biofilms, corrosion (Kiene, Lu, & Levi, 1998), and initial chlorine concentrations (Brown et al., 2011). It is important not to underestimate the effect of the material and the pipe service age (which are related to corrosion). These factors can cause chlorine consumption to vary from one distribution system to another (Al Jasser, 2007). In addition, material on the pipe wall, such as corrosion products and biofilm slime, is known to exert significant chlorine demand (Rossman, Brown, Singer, & Nuckols, 2001). Similarly, since iron is highly reactive, it is known to have a higher free chlorine demand than PVC piping (Wang et al., 2012). Also, iron tubercles have been shown to contain organic material, including precursors of DBP (Rossman et al., 2001). And the effect of service age on effective wall decay constants is most evident in cast iron pipes. For these pipes, the effect of service age on chlorine demand should also be considered, especially when there is enough wall decay to render the bulk decay negligible (Al Jasser, 2007).

In addition, iron rust not only increases pipe surface porosity and roughness but also acts as a nutrient, thereby contributing to the formation of biofilm (Wang, Masters, Edwards, Falkinham, & Pruden, 2014; Wang et al., 2012). In iron pipes, the higher chlorine demand associated with non-DBP reactions with corrosion products (ferrous corrosion) and biofilm decreases the amount of chlorine available to react with the residual natural organic matter in the water, thereby decreasing the formation of DBPs. However, Rossman et al. (2001) reported that organic material attached to the walls of these pipes can actually (moderately) increase THM levels, which would otherwise be produced by bulk solution reactions.

In this context, drinking water systems have been evaluated over the past 20 years based on the structural integrity (Charisiadis et al., 2015) of the systems, the characteristics of the networks, the materials with which they are made (Baird, 2012; Hallam, West, Forster, Powell, & Spencer, 2002; Legay, Rodriguez, Sérides, & Levallois, 2010; Rossman et al., 2001; Wang et al., 2012), the age of the piping (Al-Jasser, 2007; Baird, 2012), its diameter (Bassey & Egbe Jerome, 2016; Hallam et al., 2002), and the size of the network (Legay et al., 2010).

While evidence of medium- and long-term effects on health has been mounting, significant difficulties and questions have arisen as to how to assign and evaluate exposure (Hinckley, Bachand, Nuckols, & Reif, 2005), and how to predict organic pollutant levels in drinking water distributed throughout a territory.

While it is challenging to identify and delimit areas with differences in the variability of THMs, doing this would enable the establishment of a prediction system and the eventual implementation of timely actions. The importance of linking the presence of these compounds with the territory has also been reported (Cool et al., 2015), which needs to take into account the surrounding conditions and the way in which water is provided in a locality (Cool et al., 2015; Guilherme & Rodriguez, 2015).

One solution to this problem is to identify the spatial pattern of the geographic distribution of the compounds and delimit the areas that have a certain uniformity in the contents of THM in drinking water, and then analyze these trends in terms of the structure of the network, type of materials, and diameter of the pipes. Specifically, this work analyzes the spatial distribution of THMs in the drinking water network in the city of Montevideo.

It has been recommended that all the variables mentioned above be integrated into a geographic information system (GIS) (Charisiadis et al., 2015; Legay et al., 2010; Sandoval, Lucio, Jaime, León, & Bruno, 2013) so that the data and their georeferenced attributes can be computationally treated.
(Montoya et al., 2009). Based on this, a geostatistical analysis can be performed in order to predict the spatial distribution of a phenomenon, in this case the pollutants of interest (Diggle, 2003; Wernec, 2008).

Geostatistics provides indicators that make it possible to identify whether the levels of a particular phenomenon are higher in certain parts of a territory. These include global indicators, such as spatial autocorrelation measurements (Tsai, Lin, Chu, & Perng, 2009), as well as local indicators.

Sometimes the process needs to be analyzed at the local level (Getis & Ord, 1992), as is the case of the present study.

This particular case used the $G(d)$ (Ord & Getis, 1995) indicator of autocorrelation. This indicator is disaggregated at the level at which the measurements are taken, in this case the neighborhood, which represents the geographic unit. By using this indicator, dependence can be determined in different areas based on data from neighboring areas, which can be used to compare the various neighborhoods (Tsai et al., 2009). This technique can detect hot spots as well as cold spots (Buehler et al., 2015).

An extensive sampling network in the city of Montevideo provided data for the present study, which was based on 51 points (Gomez-Camponovo et al., 2014) and a total of 8 sampling campaigns. In addition, new variables provided by the water supplier (Obras Sanitarias del Estado [OSE] [http://www.ose.com.uy/]) were gradually incorporated into the analysis, specifically: the formation of THM, hydraulics, structures, the type of piping material, and pipe diameter.

Based on the results that have been obtained thus far (Gomez-Camponovo et al., 2014), some hypotheses can be proposed about the distribution of chloroform in drinking water. The present study includes new data from recent sampling campaigns and uses geostatistical tools to generate additional knowledge about variations in chloroform and its spatial relationship in a drinking water network. Thus, the present study is aimed at determining the geographic distribution pattern of chloroform in the city of Montevideo based on (1) the analytical data that were available from the years 2009–2015 and (2) the physical characteristics of the drinking water network, that is, the density of the network and piping diameter and materials. It also aims to simplify the analysis and facilitate the transfer of technology by consolidating the data from the network and constructing an index.

2. Materials and methods

Uruguay is a country in South America with an area of 318,413 km$^2$ and a population of 3,440,157, with 1,377,617 people living in its capital, Montevideo (NIS (Uruguay National Institute of Statistic), 2014). This city is a geographically large city in relation to the total population, with a total urban area of 230 km$^2$. It is divided into 63 neighborhoods with an average area of 3.64 km$^2$ each.

The city has only one source of water, which is treated by a plant owned by Obras Sanitarias del Estado (OSE, Spanish acronym). Booster chlorination stations are also located in the city.

2.1. Sampling network

Environmental samples were collected from private homes, schools, and shops near the sampling points belonging to the OSE, where routine controls are performed.

Since the locations of the sampling points were determined so as to encompass the entire distribution network in the urban area, an extensive sampling network was established throughout the city. Fifty-one samples were taken in each campaign, as presented in Figure 1, which shows the Montevideo metropolitan area, the drinking water supply network, and the distribution of the sampling points throughout that space.

2.2. Sampling procedures

Tap water was collected in 250 mL glass amber bottles with tapered PTFE caps. The bottles were previously washed with phosphate-free detergent, rinsed with deionized water and acetone, and
placed in an oven overnight at 60°C. When sampling, the bottles were completely filled, leaving no headspace. The samples were stored at 4°C until analysis (Ristoiu et al., 2009).

2.3. Analytical method
Certified reference material ERS-06 (2,000 μg/mL each component, in acetone) from a Cerilliant THM mix and Milli Q-water were used for the THM calibration curve.

The samples were analyzed at certified (ISO 9001:2015) laboratories belonging to the Water Analysis Unit (Unidad de Analisis de Agua) at the University of the Republic's School of Chemistry (Facultad de Química, Universidad de la Republica).

The methodology used was similar to EPA method 524.2 for GC/MS (Cho, Kong, & Seong-Geun, 2003), with slight modifications, which were validated based on ISO 17025:2005.

Headspace-gas chromatography/mass spectrometry (HS-GC/MS) was used to detect TMH (Caro, Serrano, & Gallego, 2007).

The samples were stored at 4°C and were allowed to reach room temperature before conducting the analysis. Then, 10.0 mL of each sample were transferred into 20 mL headspace vials and immediately sealed with Teflon-coated septa and aluminum crimp caps.

The vials were incubated at 60°C for 10 min, with agitation 30 s on and 30 s off, and then 1 mL of the vapor phase was injected in splitless mode.

HS-GC/MS (GC/MS Focus DSQII, Triplus Thermo) equipment was used. The GC was equipped with a capillary column (Agilent HPMS-5: 25 m, i.d. 0.25 mm, and 0.25 mm film).

The temperature program was isothermal at 35°C for 5 min, followed by a ramping up to 150°C at a rate of 10°C/min and holding for 2 min. Helium was used as a carrier gas (grade 5.0, flow rate 1.5 mL/min).

The mass spectrometer conditions were electron impact ionization (70 eV), source temperature at 200°C, and interface temperature at 230°C, in scan mode.
Xcalibur GC-MS software was used to analyze the data. The chloroform was quantified according to their respective area, which was obtained with single-ion extract ion monitoring. Calibration curves were generated with the standard 200 mg/mL Cerilliant ERS-062. Chloroform (m/z 83) was quantified using ion, and the limit of quantification was 1µg/L; the linearity was good, with a correlation coefficient ($r^2$) of 0.9996.

By employing this analytical methodology, the various volatile organic components (THM) found in the water were efficiently separated for their correct identification (Culea, Cozar, & Ristoiu, 2006) using mass spectrometry.

2.4. Geographic information system

ArcGIS software (ESRI (Environmental Systems Research Institute, Inc.), 1996) was used to construct a GIS. The GIS integrated the primary sampling information and the secondary information obtained from the Montevideo Geographic Information Department (Montevideo City Council 2009) (IMM, Spanish acronym). Information about the water distribution network and the piping distribution, diameter, and material was obtained from the drinking water supplier (OSE). The projection of the different layers was corrected and standardized using georeferenced control points (important crossings, notable points) distributed throughout the city. UTM reference system zone 21S was used. The sampling points were incorporated into a point vector layer based on the information collected with the GPS during sampling.

2.5. Spatial analysis

With the chloroform data obtained from the different samples, an analysis of hot spots was performed using ArcGIS® software (https://www.arcgis.com/). Specifically, the $G^*$ statistic was used, which is a global method that quantifies the degree of spatial autocorrelation in an area. The $G^*$ statistic measures the local variation in the autocorrelation corresponding to a study area and calculates a value for each geographic entity (neighborhood). The intention is to identify points having a statistically significant local deviation from the global mean of the set. For example, consider points with a Gaussian distribution and values distributed across space. We have three sets of values: points well below the mean, points close to the mean value, and points well above the mean. While a single point with a high or low value may be interesting, for the geographic entity to be statistically significant it must be surrounded by other values that are also high or low. The local mean of a geographic entity and its neighbors is compared proportionally to the mean of the entire set. The local mean is calculated based on a weighting matrix, which is a function of the distance, $d$, between the point of interest and its neighbors. In this matrix, $\omega_{ij}(d)$, points at a distance less than $d$ are assigned a value of 1 and those that are further away are assigned a value of 0. The $G^*$ statistic uses the spatial dependence relationship with distance to calculate the weights $\omega_{ij}(d)$. This boundary parameter $d$ thereby defines the distance within which regions are considered to be neighbors and the regions outside of which they are not considered neighbors. An intuitive version of the Getis-Ord $G^*$ statistic (Getis & Ord, 1992) is calculated according to Equation (1):

$$G_i^*(d) = \frac{\sum_{j=1}^{n} \omega_{ij}(d) \cdot x_j}{\sum_{j=1}^{n} x_j}$$  

(1)

This describes a set of $n$ entities $x_i$ each of which represents a value or attribute associated with spatial position $i$. The $G_i^*(d)$ is the local statistic, $G$, for the entity located at position $i$ within distance $d$. The spatial contiguity matrix $W$ contains the elements $\omega_{ij}(d)$, which only select the sum of the neighbors with a distance less than $d$. In order to improve the test statistic, Ord and Getis (1995) developed a transformed version of the $G^*$ by subtracting the expected value from the $G^*$ statistic and dividing by the standard deviation and a normalization, which depends on the number of neighbors at distance $d$. This transformation, called the standardized $G^*$, is given by Equation (2):
Here, \( n \) is the total number of observations, \( \bar{x} \) represents the mean value, and \( S \) is the standard deviation calculated for the overall set. The standardized \( G_i^* \) returns a positive Z-score when the local mean is larger than the global mean and a negative score when it is not. Its value is measured in \( S \) units, which is the distance from the local mean in standard deviations.

To detect the degree of local autocorrelation between each geographic entity and its neighbors, a \((G_i^*)Z\) score test was performed, which is the standardized \( G_i^* \) variable. The distribution of the \( G_i^* \) statistic after its \((G_i^*)Z\) standardization follows a standard normal distribution (Cliff & Ord, 1982).

A significant positive \((G_i^*)Z\) value indicates that high values tend to be clustered while significant negative values indicate that low values tend to be clustered, resulting in the rejection of the null hypothesis of no spatial autocorrelation.

When a spatial autocorrelation exists, a cluster of high values are called hot spots and a cluster of low values are called cold spots. When the local mean is very different than the global mean, and that difference is too large to be the result of randomness, a statistically significant \( Z \) score \((G_i^*\) statistic) is obtained.

Thus, the resulting \( Z \) scores indicate where the entities with high and low values are spatially clustered (ESRI 2012). This analysis uses the Getis–Ord \( G_i^* \) statistic (Getis & Ord, 1992) to identify statistically significant hot and cold spots with neighborhoods as the set of entities and chloroform values in the neighborhoods as the field of analysis.

### 2.6. Piping density index for the neighborhood

The sizes of the neighborhoods and the density of their piping are very different. To take this into account, a piping index was constructed to represent the density of the network in each neighborhood. Since the distribution network may contain pipes with different diameters, the index (Equation 3) represents the sum of all possible diameters:

\[
I = \frac{\sum_i \pi D_i^2 L_i}{A \times X T}
\]

where \( L_i \) is the length of piping of diameter \( D_i \), \( X T \) is the total length of the piping in the neighborhood, and \( A \) is the total area of the neighborhood. Thus, the index represents the total volume of the piping in the neighborhood, standardized by geographic area and by total length of the piping in the neighborhood.

### 3. Results

A total of 400 samples were measured as a result of all of the sampling campaigns, which were performed in June, September, and December of 2009, June and November of 2010, April and July of 2011, and November of 2015. Chloroform values varied greatly for the different dates on which the sampling campaigns were conducted (Figure 2). The chloroform concentrations for each sampling campaign are presented.

Given the variability during the seasons, we can see the lack of a repeating pattern during hot months (December, November, April) and cold months (June, July, September), as shown by the different sampling campaigns (Figure 3).

Variability can also be seen when determining the hot and cold spots for each of the sampling campaigns (Figure 3).
However, when considering all the sampling campaigns as a whole (Figure 4), a definite picture emerges.

Since this figure incorporates all the results, zones where high values are likely to be found (hot spots) can be identified, as well as where low values (cold spots) are likely to be located. This makes it possible to draw conclusions about the different areas in the city and to determine which ones require greater attention on the part of the drinking water supplier.

The high values were located in a large area corresponding to the following neighborhoods: Aires Puros (28), Paso de las Duranas (32), Prado (38), Capurro (39), Aguada (40), Reducto (41), Atahualpa (42), Figurita (44), and Brazo Oriental (50). These are old and densely populated neighborhoods.

The water in this area (hot spot) is supplied through a thick branch coming from the treatment plant. A booster chlorination station is also located there, which disinfects the water again before it reaches the final consumer. The cold spots were located in the Buceo (8), Malvin (10), Malvin Norte (11), Las Canteras (18), and La Union (22) neighborhoods. No booster chlorination stations were identified near this area during the sampling period.

In order to analyze the conditions of this network, an index was constructed based on the diameters and lengths of the piping in the neighborhoods. This index reflects the density of the network in each neighborhood. It showed a good correlation with the \((G^*)Z\) score values (see Figure 5).
The higher index values correspond to hot spots and the lower ones to cold spots (see Table 1). Although the construction of the index only included the length and diameter of the pipes, without considering the material or service age, it is important to note that the piping materials in the neighborhoods that appeared as hot spots were primarily iron, which represented the largest percentage, followed by fiber cement, and PVC (see Table 1).

This table shows the iron piping as a percentage of total piping in the neighborhoods, and the piping density index values for the neighborhoods, which are grouped according to expected chloroform concentrations.
In the neighborhoods that appeared as cold spots, the percentage of iron piping was less than 43.3% of the total piping, roughly the same percentage as fiber cement piping.

4. Discussion
The use of the geostatistic made it possible to characterize the neighborhoods in the city of Montevideo as hot spots or cold spots based on chloroform concentrations in the drinking water. Considering that a large variability in the concentrations was found when analyzing each one of

Figure 4. Chloroform hot and cold spots in the drinking water network, considering all the samples, 2009–2015, Montevideo, Uruguay.

Figure 5. Correlation between the \((G^*Z)\) score and the piping density index for the neighborhoods.
Table 1. Percentage of iron piping and density index, according to the \( \hat{G}^* \) Z score, for neighborhoods in Montevideo, Uruguay

| Confidence Level (mean \( \hat{G}^* \pm SD \)) | Neighborhood number* | Pipe wall material | Piping density index |
|---------------------------------------------|----------------------|-------------------|---------------------|
|                                             |                      | Iron (%)           | Cement pipe | PVC | Others |                   |
| −3 to −2 SD                                 | 8, 10, 11, 18, 22   | 43.3              | 42          | 6.2 | 8.5    | 0.94              |
| −2 to −1 SD                                 | 7, 9, 16, 17, 46    | 54.8              | 29.3        | 9.3 | 6.6    | 1.49              |
| −1 SD to mean                               | 3, 4, 5, 6, 12, 15, 20, 21, 23, 31, 49, 52, 56, 57, 58, 59 | 46.9 | 30.8 | 10.9 | 11.4 | 1.82 |
| Mean to 1 SD                                | 0, 1, 2, 13, 14, 19, 24, 25, 26, 27, 29, 30, 33, 34, 35, 36, 37, 43, 45, 47, 48, 51, 53, 54, 55, 60, 61, 62 | 50.3 | 31.7 | 8.3  | 9.7  | 2.98 |
| 1 to 2 SD                                   | 28, 32, 38, 39, 40, 41, 42, 44, 50 | 78.7 | 15.4 | 0.6  | 5.3  | 7.24 |

SD: standard deviation.

*Ciudad Vieja, 1. Centro, 2. Barrio Sur, 3. Cordón, 4. Palermo, 5. Parque Rodó, 6. Punta Carretas, 7. Pocitos, 8. Buceo, 9. Pique Battle, 10. Malvín, 11. Malvín Norte, 12. Punta Gorda, 13. Carrasco, 14. Carrasco Norte, 15. Bahiados de Carrasco, 16. Marañas, 17. Flor de Marañas, 18. Las Canteras, 19. Punta Bieles, 20. Jardines del Hipódromo, 22. Union, 23. Villa Española, 24. Mercado Modelo, 25. Castro, 26. Cerrito, 27. Los Acacias, 28. Aires Puros, 29. Casavalle, 30. Pedras Blancas, 31. Manga, 32. Paso de las Duranas, 33. Peñarol, 34. Cerro, 35. Casabo, 36. La Paloma, 37. La Teja, 38. Prado, 39. Capurro, 40. Aguada, 41. Reducto, 42. Atahualpa, 43. Jocinto Vera, 44. Figurita, 45. Larrága, 46. La Blanquera, 47. Villa Muñoz, 48. La Comercial, 49. Tres Cruces, 50. Brazo Oriental, 51. Sayago, 52. Conciliación, 53. Belvedere, 54. Nuevo Paris, 55. Tres Ombues, 56. Paso de la Arena, 57. Colon, 58. Colón Centro, 59. Lezica, 60. Villa García, 61. Manga, 62. Puerto.
the sampling campaigns, it can be said that the identification of hot and cold spots was possible because of the availability of numerous sampling points that were correctly distributed throughout the different geographic units of analysis (neighborhoods) in the urban space, with data covering a long time period (2009–2015).

The index proposed by this study reflects the density of the piping networks at the neighborhood level.

The study found that the standardized $G_i^*$ levels increased as the proposed index increased. For future studies, this index can provide an early indication of points that may behave as hot spots and cold spots as long as the sampling points are selected in a manner that produces efficient measurements.

In addition, the hot spots were found to be related to a higher percentage of iron piping (Chang, Guo, Shu, Chiang, & Huang, 2010), which is consistent with previous findings showing that old cast iron pipes are one of the main causes of chlorine decay.

Larger piping diameters result in larger cross sections, which contributes to slower flows, while slower flow velocities decrease chlorine levels (due to bulk decay) (Chang et al., 2010; Ozdemir & Metin, 1998) and the wall decay rate (Hallam et al., 2002). In addition, the effect of flow conditions on the formation of THM varies and greatly depends on other factors such as residence time (which increases the formation of THM) (Hallam et al., 2002), the condition of the piping, and the piping material (iron can increase or decrease the formation of THM depending on service age) (Rossman et al., 2001).

In our case, the index increasing along with the standardized $G_i^*$ values was related to a higher percentage of iron piping, which for the city of Montevideo suggests that piping conditions and materials are important factors in the formation of THMs. This explains why hot spots were not found at the end of the network (which would correspond to increased THM formation at points further from the water chlorination point in the treatment plant) but rather in neighborhoods that had a higher piping density and a higher percentage of iron piping (Chang et al., 2010; Guilherme & Rodriguez, 2015; Loyola-Sepulveda et al., 2009). These results are similar to findings by other studies (Al-Jasser 2007; Baird, 2012; Hallam et al., 2002; Legay et al., 2010; Rossman et al., 2001; Wang et al., 2012).

In terms of the service age of the iron piping, although information was not available, iron is known to be one of the earliest materials (OSE (National Sanitary Administration), 2017) used to build the water supply network, and therefore the service age is likely to be considerable.

This work was able to describe a relationship between chloroform levels and the conditions related to the distribution of water, specifically, the piping density as well as the type of piping material in each geographic unit (neighborhood).

While booster chlorination stations existed in the city and the quantity increased during the study period, it is worth mentioning that the analysis provided important results even without data about the presence and location of those points.

Since the hot spots were located in Montevideo’s older neighborhoods, and given that iron was one of the first materials used (OSE (National Sanitary Administration), 2017) in the distribution system (Marlow, Gould, Beale, & Lane, 2015), the structure and integrity may have been affected over time (Al-Jasser 2007; Marlow et al., 2015) by factors such as corrosion, the presence of biofilms, and ruptures (unlined pipes) (Baird, 2012; Marlow et al., 2015). This reaffirms the importance of ongoing maintenance and rehabilitation programs (Baird, 2012; Marlow et al., 2015).

It would be useful to conduct other studies using this methodology in other localities where the management of the supply network varies and where water for human consumption is obtained from different sources. This can contribute to the development of a more extensive prediction
system and will undoubtedly provide a more precise evaluation of the population risk of health disorders, which are still being studied.

5. Conclusions
New techniques are needed for the early detection of zones that may have unsafe levels of organic pollutants in water used for human consumption.

With the use of a geostatistical technique (Getis–Ord G*), this study was able to detect sets of neighborhoods with high stable chloroform values over time. It was also able to detect sets of neighborhoods with low values.

Neighborhoods with hot spots and others with cold spots could be identified. And it was possible to associate these values with a neighborhood piping density index. The highest values corresponded to neighborhoods in the city that had a higher percentage of iron.

The results obtained by this work suggest the need for processes to transfer technology and knowledge from academic institutions to water management organizations, which can contribute to improving the efficiency of managing drinking water systems, optimizing control systems, and developing the measures needed to minimize risk from organic pollutants. A more detailed analytical process needs to be developed so that the maintenance and rehabilitation of drinking water distribution networks can be adjusted.

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Cover Image
Source: The cover photos were taken by the authors at the Santa Lucia River and the Aguas Corrientes dam in the department of Canelones.

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References
Al-Jasser, A. O. (2007). Chlorine decay in drinking-water transmission and distribution systems: Pipe service age effect. Water Research, 41, 387–396. doi:10.1016/j.watres.2006.08.032
Baird, G. M. (2012). The epidemic of corrosion, Part 2: The importance of communication. Journal - American Water Works Association, 104, 20–24. doi:10.5942/jawwa.2012.104.0018
Bassey, G. I., & Egbe Jerome, G. (2016). Residual chlorine decay in water distribution network. International Journal of Scientific Research and Engineering Studies, 3, 1–6. Retrieved from http://www.ijsrres.com/2016/vol-3_issue-3/paper_1.pdf
Baytok, D., Sofuoglu, A., Inal, F., & Sofuoglu, S. C. (2008). Seasonal variation in drinking water concentrations of disinfection by-products in IZMIR and associated human health risks. Science of the Total Environment, 407, 286–296. doi:10.1016/j.scitotenv.2008.08.019
Botton, J., Kogevinas, M., Gracia-Lavedan, E., Patelarou, E., Roumeliotaki, T., Ilifuez, C., … Villanueva, C. M. (2015). Postnatal weight growth and Trihalomethane exposure during pregnancy. Environmental Research, 136, 280–288. doi:10.1016/j.envres.2014.09.035
Bove, G. E., Jr, Rogerson, P. A., & Vena, J. E. (2007a). Case-control study of the effects of Trihalomethanes on urinary bladder cancer risk. Archives of Environmental & Occupational Health, 62, 39–47. Retrieved from http://www.tandfonline.com/doi/abs/10.3200/AEOH.62.1.39-47
Brown, D., Bridgeman, J., & West, J. R. (2011). Predicting chlorine decay and THM formation in water supply systems. Reviews in Environmental Science and Bio/
Technology, 10, 79–99. doi:10.1007/s11157-011-9229-8
Buehler, C. P., Blevins, M., Ossemane, E. B., González-Calvo, L., Ndatimana, E., Vermund, S. H., … Moon, T. D. (2012). Assessing spatial patterns of HIV knowledge in rural Mozambique using geographic information systems. Tropical Medicine and International Health, 20, 353–364. doi:10.1111/tmi.12437
Gomez Camponovo, M., Seoane Muniz, G., Rothenberg, S. J., Umpierrez Vazquez, E. & Marcel, A. B. (2014). Predictive model for chloroform during disinfection of water for Consumption, City of Montevideo. Environmental Monitoring and Assessment, 186, 6711–6719. doi:10.1007/s10661-014-3884-5
Caro, J., Serrano, A., & Gallego, M. (2007). Sensitive headspace gas chromatography–mass spectrometry determination of Trihalomethanes in Urine. Journal of Chromatography B, 848, 277–282. doi:10.1016/j.j Chromb.2006.10.034
Chang, C.-C., Shu-Chen, H., Wang, L.-Y., & Chun-Yuh, Y. (2007). Bladder cancer in Taiwan: Relationship to Trihalomethane concentrations present in drinking-water supplies. Journal of Toxicology and Environmental Health, Part A, 70(12), 1757–1775. doi:10.1080/15287390701459031
Chang, E. E., Guo, H. C., Shu, L. I., Chiang, P. C., & Huang, C. P. (2010). Modeling the formation and assessing the risk of disinfection by-products in water distribution systems. Journal of Environmental Science and Health, Part A, 45, 1185–1194. doi:10.1080/10934529.2010.493776
Charisiadis, P., Andra, S. S., Makris, K. C., Christophi, C. A., Skarlatos, D., Vasilis, V., … Stephanou, E. G. (2015). Spatial and seasonal variability of top water disinfection by-products within distribution pipe networks. Science of the Total Environment, 506–507, 26–35. doi:10.1016/j.scitotenv.2014.10.071
Chen, K., Weiping, Y., Xinyan, M., Yao, K., & Jiang, Q. (2005). The association between drinking water source and colorectal cancer incidence in Jiangshan County of China study. European Journal of Public Health, 15, 652–656. doi:10.1093/eurpub/ck027
Chisholm, K., Cook, A., Bower, C., & Weinstein, P. (2008). Risk of birth defects in Australian communities with high levels of brominated disinfection by-products. Environmental Health Perspectives, 116, 1267–1273. doi:10.1289/ehp.10980
Cho, D.-H., Kong, S.-H., & Seong-Geun, O. (2003). Analysis of Trihalomethanes in drinking water using headspace-SPME technique with gas chromatography. Water Research, 37, 402–408. doi:10.1016/S0043-1354(02)00285-3
Cliff, A. D., & Ord, J. K. (1981). Spatial processes. Models and applications. Population, (37)63Retrieved from http://www.persee.fr/doc/pop_0032-4663_ 1982_num_37_6_17407
Cool, G., Lebel, A., Sadiq, R., & Rodriguez, M. J. (2015). Modelling the regional variability of the probability of high Trihalomethane occurrence in municipal drinking water. Environmental Monitoring and Assessment, 187, 746. doi:10.1007/s10661-015-4969-5
Culeo, M., Cozor, O., & Ristoiu, D. (2006). Methods validation for THMs determination in drinking water. Journal of Mass Spectrometry, 41, 1594–1597. doi:10.1002/jms.1149
Diggles, P. J. (2003). An Introduction to model-based geostatistics. Chap. 2. In J. Moller (Ed.), Spatial statistics and computational methods. Lecture notes in statistics (Vol. 173, pp. 43–86). New York, NY: Springer. doi:10.1007/978-0-387-21811-3_2
ESRI (Environmental Systems Research Institute, Inc) 2012. ArcGIS resources: Hot spot analysis (Getis-Ord G’I*) (Spatial Statistics). Retrieved from: http://resources.arcgis.com/en/help/main/10.2/index.html#//005p00000010000000
ESRI (Environmental Systems Research Institute, Inc) 1996. ArcGIS 10.1 spatial analysis.Retrieved from: http://www.esri.com/
Getis, A., & Ord, J. K. (1992). The analysis of spatial association by use of distance statistics. Geographical Analysis, 24, 189–206. Retrieved from http://resources.esri.com/help/93/arcgisengine/ova/GeoTools/spatial_statistics_tools/how_hot_spot_analysis_colon_getis_ord_g_i_star.spatial_statistics_works.htm
Goebell, P. J., Villanueva, C. M., Rettenmeier, A. W., Rübben, H., & Kogevinas, M. (2004). Environmental exposure, chlorinated drinking water, and bladder cancer. World Journal of Urology, 22, 424–432. doi:10.1007/s00334-003-0389-1
Grellier, J., Bennett, J., Patelarou, E., Smith, R. B., Toledano, M. B., Rushton, L., … Nieuwenhuijsen, M. J. (2010). Exposure to disinfection by-products, fetal growth, and prematurity: A systematic review and meta-analysis. Epidemiology, 21, 300–313. doi:10.1097/ede.0b013e3181d16f1d
Guilherme, S., & Rodriguez, M. J. (2015). Short-term spatial and temporal variability of disinfection by-product occurrence in small drinking water systems. Science of the Total Environment, 518-519, 280–289. doi:10.1016/j.scitotenv.2015.02.069
Hollam, N. B., West, J. R., Forster, C. F., Powell, J. C., & Spencer, I. (2002). The decay of chlorine associated with the pipe wall in water distribution systems. Water Research, 36, 3479-3488. doi:10.1016/S0043-1354(02)00056-8
Hinckley, A. F., Bouchard, A. M., Nuckols, J. R., & Reif, J. S. (2005). Identifying public water facilities with low spatial variability of disinfection by-products for epidemiological investigations. Occupational and Environmental Medicine, 62, 494–499. doi:10.1136/oem.2004.017798
IMM (Montevideo City Council) 2009. Geographic Information, City of Montevideo. Retrieved from: http://intgis.montevideo.gub.uy/
ISO (International Organization for Standardization) 2005. ISO/IEC 17025:2005(es). Requisitos generales para la competencia de los laboratorios de ensayo y de calibración. Retrieved from: https://www.iso.org/obp/topic.do?��=17025_es-d2x1e
Jang, H. J., Choi, Y. J., Ro, H. M., & Ka, J. O. (2012). Effects of phosphate addition on biofilm bacterial community and water quality in annular reactors equipped with stainless steel and ductile cast iron pipes. Journal of Microbiology, 50, 17–28. doi:10.1007/ s12275-012-1169-8
Kiene, L., Lu, W., & Levi, Y. (1998). Relative importance of the phenomena responsible for chlorine decay in drinking water distribution systems. Water Science Technology, 38, 219–227. doi:10.2166/wst.1998.0255
King, W. D., Marrett, L. D., & Woolcott, C. G. (2006). Case-control study of colon and rectal cancers and chlorination by-products in treated water. Cancer Epidemiology, Biomarkers & Prevention, 9, 813–818.
Knight, N., Watson, K., Carswell, S., Comino, E., & Shaw, G. (2011). Temporal and spatial variation of Trihalomethanes and haloacetic acids concentration in drinking water: A case study of Queensland, Australia. Air, Soil and Water Research, 4, 1–17. doi:10.4137/ASWR.S55618
Krasner, S. W., Weinberg, H. S., Richardson, S. D., Pastor, S. J., Chinn, R., Scrimlent, M. J., … Thruston, A. D. (2006).
Occurrence of a new generation of disinfection by-products. Environmental Science & Technology, 40, 7175–7185. doi:10.1021/es060353j

Kuo, H.-W., Chen, P.-S., Shu-Chen, H., Wang, L.-Y., & Yang, C.-Y. (2010). Trihalomethanes in drinking water and the risk of death from rectal cancer: Does hardness in drinking water matter? Journal of Toxicology and Environmental Health, Part A, 73, 807–818. doi:10.1080/15287391003689267

Kuo, H.-W., Tiao, M.-M., Trong-Neng, W., & Yang, C.-Y. (2009). Trihalomethanes in drinking water and the risk of death from colon cancer in Taiwan. Journal of Toxicology and Environmental Health, Part A, 72, 1217–1222. doi:10.1080/15287390901129176

Legay, C., Rodríguez, M. J., Sérides, J. B., & Levallois, P. (2010). The assessment of population exposure to chlorination by-products: A study on the influence of the water distribution system. Environmental Health, 9, 59. doi:10.1186/1476-056X-9-59

Loyola-Sepulveda, R., Lopez-Leal, G., Jorge, M., Bravo-Linares, C., & Mudge, S. M. (2009). Trihalomethanes in the drinking water of Concepción and Talcahuano, Chile. Water and Environment Journal, 23, 286–292. doi:10.1111/j.1747-6593.2010.01608.x

Marlow, D., Gould, S., Beale, D., & Lone, B. (2015). Rehabilitation of small-diameter cast-iron pipe: US, UK, and Australian perspectives. Journal - American Water Works Association, 107, E12–E21. doi:10.5942/jawwa.2015.107.0003

Rahman, Md, Bayzidur, D., & Tim, C. Christine, and Armstrong, Bruce K. (2010). Disinfection by-products in drinking water and colorectal cancer: A meta-analysis. International Journal of Epidemiology, 39, 733–745. doi:10.1093/ije/dyp371

Micheud, D. S., Manolis, K., Cantor, K. P., Villanueva, C. M., Garcia-Closas, M., Nathaniel, R., … Silverman, D. T. (2007). Total fluid and water consumption and the joint effect of exposure to disinfection by-products on risk of bladder cancer. Environmental Health Perspectives, 115, 1569–1572. doi:10.1289/ehp.10281

Montoya, C., Loaiza, D., Cruz, C., Torres, P., Escobar, J. C., Torres, P., … Levallois, P. (2007). Propuesta metodológica para localización de estaciones de monitoreo de calidad de agua en redes de distribución utilizando sistemas de información geográfica. Revista Facultad De Ingenieria, 49, 129–140. Retrieved from http://apren.deileenaa.udea.edu.co/revistas/index.php/ingeniera/issue/view/18

Nieuwenhuijsen, M. J., Martinez, D., James., G., Bennett, J., Best, N., Nina, I., … Toledano, M. B. (2003). Occurrence of a new generation of disinfection byproducts in water and their association with cancer: Distributional issues and an application. Environmental Health, Part A:1025811021502

Rossman, L. A., Brown, R. A., Singer, P. C., & Nuckols, J. R. (2001). DBP formation kinetics in a simulated distribution system. Water Research, 35, 3483–3489. doi:10.1016/S0043-1354(01)00059-8

Sadig, R., & Rodríguez, M. J. (2006). Disinfection by-products in drinking water and predictive models for their occurrence: A review. Science of the Total Environment, (321), 21–46. doi:10.1016/j.scitotenv.2003.05.001

Sendová, F., Lucio, R. Z.-F., Jaime, R., León, J., & Bruno, A. (2013). Sistema para control y gestión de redes de agua potable de dos localidades de México. Ingeniería Hidráulica y Ambiental, 34, 112–126. Retrieved from http://riho.cujae.edu.ec/index.php/riho/issue/view/18

Tsai, P.-J., Lin, M.-L., Chu, C.-M., & Perng, C.-H. (2009). Chlorination disinfection by-products in drinking water matter? Water and Environment Journal, 125, 9. doi:10.1080/15287391003689267

UNIT (Uruguay Institute for Technical Norms). 2011. Norma 833:2008: Agua potable - Requisitos. Retrieved from: http://www.osm.com.uy/Descargas/Clientes/Reglamentos/norma_833_2008_.pdf

Uyak, V., Ozdemir, K., & Toroz, I. (2007). Multiple linear regression modeling of disinfection by-products formation in Istanbul drinking water reservoirs. Science of the Total Environment, 378, 269–280. doi:10.1016/j.scitotenv.2007.02.041

Villanueva, C. M., Kogevinas, M., & Grimalt, J. O. (2003). Cloración del agua potable en España y cáncer de vejiga. Chlorination of drinking water in Spain and bladder cancer. Gaceta Sanitaria, 15, 48–53. doi:10.1016/S0213-9111(01)71517-8

Villanueva, C. M., Cantor, K. P., Cordier, S., Joaakolla, J. J. K., King, W. D., Lynch, C. F., … Kogevinas, M. (2004). Disinfection byproducts and bladder cancer: A pooled analysis. Epidemiology, 15, 357–367. doi:10.1097/01.de.0000121380.02594.fc

Villanueva, C. M., Cantor, K. P., King, W. D., Joaakolla, J. J. K., Cordier, S., Lynch, C. F., … Kogevinas, M. (2006). Total and specific fluid consumption as determinants of bladder cancer risk. International Journal of Cancer, 118, 2040–2047. doi:10.1002/ijc.21587

Villanueva, C. M., Gracia-Lavedan, E., Bosetti, C., Righi, E., Molina, A. J., Martin, V., … Kogevinas, M. (2017). Colorectal cancer and long-term exposure to trihalomethanes in drinking water: A multicenter case-control study in Spain and Italy. Environmental Health Perspectives, 125, 56–65. doi:10.1289/EHP155

Wang, G.-S., Deng, Y.-C., & Lin, T.-F. (2007). Cancer risk assessment from Trihalomethanes in drinking water. Science of the Total Environment, 387, 86–95. doi:10.1016/j.scitotenv.2007.07.029

Geographical Analysis, 27, 286–306. doi:10.1111/j.1538-4632.1995.tb00912.x

Ozdemir, O. N., & Metin, G. A. (1998). Realistic numerical simulation of chlorine decay in pipes. Water Research, 32, 3307–3312. doi:10.1016/S0043-1354(98)00107-9

Ristoiu, D., von Gunten, U., Mocan, A., Chira, R., Siegfried, B., Kovacs, H., … Sidonia. (2009). Trihalomethane formation during water disinfection in four water supplies in the Somes River Basin in Romania. Environmental Science and Pollution Research, 16(supplement 1), 555–65. doi:10.1007/s11356-009-0100-1

Rodríguez, M. J., Vinette, Y., Jean-B., S., & Bouchard, C. (2003). Trihalomethanes in drinking water of greater Québec region (Canada): Occurrence, variations and modelling. Environmental Monitoring and Assessment, 89, 69–93. doi:10.1023/A:1024881110150

Reseña Historica. Retrieved from: http://www.osm.com.uy/e_historia.html

Ord, J. K., & Getis, A. (1995). Local spatial autocorrelation statistics: Distributional issues and an application.

On the distribution of trihalomethanes in water and their association with cancer: Distributional issues and an application. Environmental Health, Part A:1025811021502

Geographical Analysis, 27, 286–306. doi:10.1111/j.1538-4632.1995.tb00912.x

Ozdemir, O. N., & Metin, G. A. (1998). Realistic numerical simulation of chlorine decay in pipes. Water Research, 32, 3307–3312. doi:10.1016/S0043-1354(98)00107-9

Ristoiu, D., von Gunten, U., Mocan, A., Chira, R., Siegfried, B., Kovacs, H., … Sidonia. (2009). Trihalomethane formation during water disinfection in four water supplies in the Somes River Basin in Romania. Environmental Science and Pollution Research, 16(supplement 1), 555–65. doi:10.1007/s11356-009-0100-1

Rodríguez, M. J., Vinette, Y., Jean-B., S., & Bouchard, C. (2003). Trihalomethanes in drinking water of greater Québec region (Canada): Occurrence, variations and modelling. Environmental Monitoring and Assessment, 89, 69–93. doi:10.1023/A:1024881110150

Reseña Historica. Retrieved from: http://www.osm.com.uy/e_historia.html

Ord, J. K., & Getis, A. (1995). Local spatial autocorrelation statistics: Distributional issues and an application.
Wang, H., Masters, S., Edwards, M. A., Falkinham, J., & Pruden, A. (2014). Effect of disinfectant, water age, and pipe materials on bacterial and eukaryotic community structure in drinking water biofilm. Environmental Science & Technology, 48, 1426–1435. doi:10.1021/es402636u

Wang, H., Masters, S., Hong, Y., Stallings, J., Falkinham, J. O., Edwards, M. A., & Pruden, A. (2012). Effect of disinfectant, water age, and pipe material on occurrence and persistence of Legionella, Mycobacteria, Pseudomonas Aeruginosa, and Two Amoebas. Environmental Science & Technology, 46, 11566–11574. doi:10.1021/es303212a

Werneck, G. L. (2008). Georeferenced data in epidemiologic research. Ciencia & Saude Coletiva, 13, 1753–1766. doi:10.1590/S1413-81232008000600010

WHO (World Health Organization). (2008). Guidelines for drinking-water quality: Fourth edition incorporating the first addendum. Retrieved from: https://www.ncbi.nlm.nih.gov/books/NBK442372/

WHO (World Health Organization). (2017). Guidelines for drinking-water quality: Fourth edition incorporating the first addendum. Geneva: World Health Organization. Licence: CC BY-NC-SA 3.0 IGO.