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Geostatistical analysis to identify characteristics involved in sewer pipes and urban tree interactions

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Abstract

Tree roots cause significant and costly damage to sewer systems. However, the contributions made by tree and sewer characteristics to sewer system damage are not yet well understood. Previous research has proved inconclusive and there is a lack of agreement on the importance of the variables involved, which means that the results cannot be extrapolated globally. This study presents a methodology to improve the understanding of tree root-sewer conflicts through a geostatistical analysis of a tree inventory and CCTV video fault reports. The methodology is applied to a 11 km² case study in Bogotá, Colombia. The analysis used tree and sewer pipe georeferenced data, principal component analysis, and linear, Logit, and Poisson regression models. The proposed methodology identifies the pipe characteristics and the tree species most responsible for the root intrusion events into sewers. As expected, larger trees are prone to cause more pipe damage; therefore tree-pipe distance is a relevant parameter control for reducing potential deterioration. Cumulative precipitation and pipe length showed no effect on observed root intrusion events, and pipes made from brick had higher odds to present root intrusion in contrast with concrete pipes. The presented methodology uses readily available information and software, and can be modified depending on the requirements of each particular case study. This approach will therefore allow for more efficient use of costly, site-specific pipe investigations, and is especially useful for cases where there is a general lack of knowledge regarding the characteristics that favour the negative interactions between pipes and tree roots.

Keywords

Logit and Poisson models, Pipe characteristics, Root intrusion, Sewer system, Urban Trees

Introduction

Addressing blockages and structural failures has become a high priority in the maintenance of sewer system functionality (Rodríguez et al. 2012). It is necessary to maintain an adequate sewer operational performance based on an understanding of the processes involved in the sewer system's deterioration. Root intrusion has been identified as a major factor influencing blockages

(Marlow et al. 2011) and as a potential cause of flooding (Stål 1998). Tree root growth interaction with urban infrastructure has been described and identified in several previous studies (e.g. Östberg et al. 2012; Rolf & Stål 1994).

Although underground structures are difficult to survey, some cities and towns have carried out censuses of intruded pipes (e.g. Kuliczowska & Parka 2017; Randrup 2000; Stål 1998), and have shown that root intrusion is a considerable problem. For example, a survey conducted in Denmark noted that 97% of the surveyed towns and cities had root intrusion events (Randrup 2000). In Sweden, 99% of the urban centres studied had pipe intrusions (Stål 1998). McPherson (2000) estimated that in 1996, Californian cities were spending \$1.64 per capita on tree root-related problems (repairing street pavements, curbs, gutters, and sidewalks). In addition to the costs associated with the damage and maintenance of infrastructure (which also includes activities like root removal, pipe replacement, and pipe renewal), there are also high costs related to the damage to trees or their removal (Randrup et al. 2001a). Urban trees provide a range of benefits, the value of which is often under-appreciated (Bartens et al. 2008; Mullaney et al. 2015; Moore 2009).

Rolf and Stål (1994) concluded that tree roots are attracted by the high moisture gradient generated by sewers, making pipes even more vulnerable than other types of urban infrastructure. Root-pipe interactions may cause, among others, structural and sediment-related failures (i.e. surcharged sewer pipes caused by the accumulation of sediments). Structural failure leads eventually to collapse of the structure (Schrock 1994) and sediment-related failures may cause flow problems and the entrapment of suspended solids (Sullivan et al. 1997). In some cases, roots may not cause the initial crack, but they may expand existing openings, speeding up the weakening of the structure (Schrock 1994). Roots also have a detrimental effect on sewer hydraulic conditions by generating a local flow restriction, which reduces flow velocity and favours the screening out of solids (Randrup et al. 2001a).

Studies carried out to understand the most relevant characteristics involved in the root-intrusion process have led to diverse and inconsistent conclusions. Some examples of these contradictory results include conclusions regarding pipes and trees. Rolf & Stål (1994) stated that PVC and glass reinforced plastic pipes are resistant to root intrusion (not considering pipe and joint construction and installation procedures), while Ridgers *et al.* (2006) stated that modern PVC and concrete are vulnerable to tree root-pipe interaction. In addition, while some studies suggest that interactions are more likely to occur at small pipe-tree distances (e.g., Randrup (2000) who defined small as up to 6 m), other studies suggest there is no correlation between pipe-tree distances and the frequency of damage (Kopinga 1994). Some studies concluded that large and fast-growing tree species have a higher risk of root intrusion (e.g. Randrup 2001b). However, Östberg *et al.* (2012) found that slow and moderate-growing tree species cause intrusion to the same extent as fast-growing trees. Conversely, consistent results have been found with other pipe variables. For example, studies have consistently found a positive correlation between tree root intrusion and pipe diameter, (Rolf & Stål 1994), pipe age and depth (e.g. Pohls et al. 2004), and number of joints (Ridgers et al. 2006).

Root barriers can be used for preventing tree root-pipe interaction; these techniques are designed to avoid or delay the impact on infrastructure (Randrup et al. 2001b). The barriers are installed

in the planting hole to reduce lateral growth, deflecting roots down below the depth of the barrier (Costello et al. 1997). Experiments carried out by Costello et al. (1997) showed that the number of roots found outside the barriers were 35 to 55% less than in controls. However, other studies have shown that root barriers are not always effective in protecting infrastructure (Kopinga 1994).

These diverse and inconsistent results may be explained by the differences in the experimental designs used, which range from surveys or questionnaires (e.g. Randrup et al. 2000) to *in-situ* visits (e.g. Rolf & Stål 1994), experimental setups (e.g. Pohls et al. 2004; Costello et al. 1997; Ridgers et al. 2006), or GIS spatial analysis (Cook et al., 2008). Site variability may also account for these incongruences; for example, differences in construction quality, pipe and joints material, tree species under study, and type of root barriers tested. The lack of agreement in previous findings has precluded the extrapolation of results to other case studies.

There are additional characteristics that may affect the tree root-infrastructure conflicts, for example urban soil characteristics, environmental conditions, and geology (Sydnor et al. 2000; Pohls et al. 2004; Randrup et al. 2001b). Recent studies have shown that tree-related blockages are affected by seasonal variations (Marlow et al. 2010). In addition, irrigation of urban trees promotes additional root growth, increasing the roots propensity to penetrate pipes (Phene et al. 1991). Construction quality is also important; a deficiency in pipe construction will eventually lead to leaky joints and inadequate connections, enhancing the moisture gradient and direct root growth into the pipe (Schrock 1994; Stål & Rolf 1998). These variations make it difficult to extrapolate research findings to other sites with different characteristics. In big cities, such as Bogotá (Colombia), soil characteristics and other environmental variables present a high heterogeneity; also, drainage network pipes present a large range of diameters, materials, depths and ages. In order to obtain meaningful results, the present study focus on a relatively small (approximately 11 km²) and homogeneous area. Understanding which pipe and tree characteristics control the process of root intrusion would contribute to the development of a tree root-intrusion prediction tool. An improved understanding of tree-sewer interactions is especially useful for urban planners, water utilities, and tree planting authorities. An improved understanding may also assist the development of proactive sewer system rehabilitation and maintenance strategies, inform construction advice to mitigate tree root-pipe interactions, and facilitate vulnerability and hazard assessments in urban drainage safety plans (e.g. Möderl et al. 2015).

The methodology presented in this study can be applied where CCTV videos, sewer pipe cadastre and tree inventory records are available. To the best knowledge of the authors of this paper, no studies have yet been conducted using a complete and comprehensive tree inventory, which enables the analysis of large areas reducing the costs of in-situ visits (e.g. to identify the tree species or to determine the tree size). Therefore, this research significantly advances the understanding of: (i) the pipe characteristics that make the sewer system more vulnerable to tree root intrusion, and (ii) the tree characteristics that make tree root intrusion events more likely.

The paper is structured as follows. In the next section, the case study is described. After, in the Methodology section, the proposed methodology to relate pipe and trees to tree-root

intrusion events is presented. Then, in the following section, the results are presented. Finally, the results are discussed and the more relevant conclusions of this study are presented in the Discussion and Conclusions section.

Case Study

The water utility of Bogotá operates approximately 8,000 km of sewer pipes (including stormwater, foul and combined systems) and serves nearly 8.5 million inhabitants. Because of the city extension and the heterogeneity of the sewer system characteristics, the water utility subdivided the city in five management units, which are operated, maintained and surveyed independently. Currently, one of the utility's main concerns is to better understand the characteristics that make the sewer system more vulnerable. One of the issues of which the environmental authority is aware is the one related to the conflict between trees and pipes that is responsible for a considerable percentage of sewer system failures. Yet there is a general lack of information regarding root intrusion events; more specifically, in what regards the limited availability of CCTV videos that evidence root intrusion events.

Figure 1 shows the case study area with nearly 11 km² in the central-east zone of Bogotá, which belongs to the Salitre and the Fucha catchments. The area has both commercial and residential uses and around 45,000 inhabitants. The sewer pipe network of the study area is of combined type and comprises about 245.3 km of pipes.

[Fig 1 near here]

Urban tree inventory

The current tree inventory for Bogotá was compiled in 2007 and lists 1.3 million trees and 324 species planted in urban areas (Secretaría Distrital de Ambiente [SDA], 2010). Along with the location of each tree, the census contains tree species, total height, physiology, equatorial diameter, basal perimeter, height and perimeter of the trunk, and a brief description of the leaves and the site location (Escobedo et al. 2015). From the 324 species identified, the urban tree planting authority has identified 54 species capable of causing root intrusion based on observations of visible infrastructure (sidewalks and ways). These species are classified, for this study, as intrusive species; among these species are *Pinus spp.*, *Croton spp.*, *Ficus spp.*, *Acacia spp.*, *Myrsine guianensis* (Aubl.) Kuntze, *Magnolia grandiflora* L., and *Querus humboldtii* Bonpl., which are all fast-growing species. The area of study counts on 28,428 trees, from which 9,363 (33%) correspond to intrusive trees. Tree variables are described in Table 1.

[Table 1 near here]

CCTV records

The CCTV videos used in this study were recorded in 2011 and were processed by water utility operators to extract observed anomalies (such as root intrusion, sediments, structure collapse, exfiltration, FOG (fat, oil and grease), or rupture) and generate a sewer pipe failure database. The database is fed with a new record each time that an anomaly is observed, even if the

observations are separated by short distances – e.g. in the order of centimetres. The nature of the anomaly is reported along with the pipe ID, the distance from the pipe inlet in which the observation was found, the CCTV recording direction (with the flow or against the flow), and a condition qualifying score according to water utility standards (Empresa de Acueducto y Alcantarillado de Bogotá [EAAB], 2001).

A total of 917 sewer pipes (45.5 km length) were inspected and 17,423 observations were collected. The information gathered was filtered to obtain only those records that reported root intrusion. Almost 10% of the CCTV inspected pipes (corresponding to 88 pipes) showed at least one root intrusion event. In this set of pipes, one of the pipes was found to report up to 10 root intrusion events; this was an especial case of a long pipe with reported observations considerably close to each other.

Methodology

In the study presented in this paper, two different methods to explore the relation between trees' and pipes' characteristics are presented (Figure 2). Each of the methods leads to a database that is afterwards fitted using three statistical tools: linear, Logit and Poisson regressions. Method I aims at explaining root intrusion events based on pipe characteristics, while the main objective of Method II is to explain root intrusion events based on tree characteristics. All spatial data is handled and analysed using ArcGis 10.3 (ESRI 2014).

As the first step of the two methods, tree root intrusion events are extracted and geo-referenced based on the CCTV videos (Figure 2a, "CCTV data preprocessing"). XY coordinates are obtained by identifying the pipe and measuring the distance from the inlet to the length in which the root intrusion was recorded. Taking into account that a single tree can cause several root intrusions, root intrusion events distanced by less than 0.5 meters are merged and counted as a single event. As a result of this step, a root intrusion events point vector layer is generated and later used as input for the two methods.

[Figure 2 near here]

Method I: explaining tree root intrusion events based on pipe characteristics

In this method tree root intrusions are counted for each pipe, resulting in a file that relates each pipe ID with the number of observed root intrusion events. Then, this file is joined (using *pipe ID* attribute) with the sewer pipes' vector layer attributes to obtain a database that is used in the statistical models described below (see Figure 2b, "Method I").

In order to identify the pipe characteristics that are more relevant for tree root intrusion, two statistical models were used: (a) A linear regression model is used considering the number of tree intrusion events as the response variable; (b) A Logit model is also used but it requires the conversion of the response variable "Observed number of root intrusion events" to 'presence/absence' of root intrusion records. Linear regression coefficients, Odds Ratios (OR) (the OR represents the odds of an outcome given a particular exposure, compared to the odds of the outcome occurring in the absence of that exposure), and Incidence Rate Ratios (IRR) (the IRR is the ratio of two incidence rates, which can be defined as the number of events divided by a

particular exposure) are then obtained from the statistical models. To obtain OR and IRR values the STATA 12 statistical package (StataCorp. 2011) was used.

Method II: explaining tree root intrusions events based on tree characteristics

To analyse only the tree species within a sensible distance of the sewers, a 10 meter buffer parallel to the sewer pipes was applied. An area of influence was drawn for each tree using 1.3 times the equatorial diameter of the individual's crown as the diameter (Figure 2c, "Method II"). This additional 30% was used to account for (i) the year difference in the databases (the trees that caused the root intrusion reported in 2011 are bigger trees than those measured in the 2007 tree census), and (ii) because of pruning activities, the natural equatorial diameter is expected to be bigger than what is reported in the tree census.

Conducting a *Spatial Join* (i.e. a GIS operation that relates data from one feature layer to another from a spatial perspective) between the root intrusion events and the tree buffer area, the root intrusion events were associated to each tree; Figure 3 illustrates how these spatial elements are related. To avoid excessive 0-observations (trees with 0 root intrusion events), only those trees whose buffer intersects with inspected pipes were included in the method; otherwise, trees located far away from inspected pipes introduce bias in the analysis.

[Figure 3 near here]

In addition to the tree variables, two environmental variables were included in Method II, namely groundwater table depth and cumulative precipitation for the year previous to the tree census (2006). Because of groundwater table depth inter- and intra-annual variability, the multi-year mean was calculated using information from 1961 to 2011. Kriging interpolation of 3,384 groundwater table depth point data obtained from drilling studies, that were carried out by the water utility, were used for this purpose (CHIA, 2015). Calculated groundwater table depths were always found below pipe invert levels. Cumulative precipitation was determined from cumulative daily precipitation records for 2006, gathered from 28 rainfall stations operated by the water utility. To take into account the low tree growth, rainfall was extracted from 2006 data, and applied to the 2007 information to obtain a meaningful assessment of conditions that could explain tree measurements in 2007. The environmental variables were extracted directly from raster layers using tree coordinates.

[Table 2 near here]

Principal Component Analysis (PCA) (Jolliffe 2002) was applied to six tree variables (excluding dummy and categorical variables) (see Table 2) in order to reduce the dimension of the dataset, yet retaining as far as possible the variation present originally; correlation coefficients were calculated prior to PCA to ensure that the variables are interrelated. After the PCA analysis, Logit, Poisson, and linear regressions were done using the STATA 12 statistical package. The response variable for linear and Poisson regressions is the number of root intrusion events lying on each tree influence area. The Logit model required the conversion of the response variable to 'presence/absence' of root intrusion records within the tree influential area.

Results

Method I resulted in a database with 917 observations, each compiling the characteristics summarized in Table 2. Method II collected 238 observations, which correspond to trees located within the 10 meters buffer and whose influence area intersects a root intrusion point event or a pipe that reported root intrusion. Table 3 describes the data set range, mean and standard deviation for both pipe and tree characteristics. Table 4 summarises the results obtained using the two methods (Method I and Method II) and the three implemented statistical models: (i) linear regression coefficients, (ii) Logit regression (OR values), which compare the odds of having a root intrusion event between two different situations, and (iii) Poisson regression model (IRR), which establishes the root intrusion event incidence ratio under two situations.

[Table 3 near here]

Method I

From the values in Table 4, pipe length variable showed no effect on the observed intrusion events: the linear coefficient is near zero and the OR and IRR are very close to one. This means that there is no statistical evidence to support differences in odds or incidence rates for this variable. In contrast, pipe depth variable has a positive effect in the observed root intrusion events, a linear regression coefficient of 0.11 and an OR of 1.5 were obtained. This result indicated that the odds to present a root intrusion events increase by 1.5 when the pipe is buried one additional meter; this is a counterintuitive result taking into account that shallower pipes can be more easily reached by tree roots than pipes laid deeper.

It is noteworthy that construction quality can also play an important role in preventing root intrusion. If the pipe is not installed correctly, the probability of a tree root intrusion will be higher, no matter how resistant the material is or how deep the pipe is installed. Also, considering that root intrusion is expected to occur in pipe joints, simply knowing the pipe material is not sufficient for a complete analysis. Unfortunately, the construction quality and the joint material information were not available and could not be included in the analysis.

[Table 4 near here]

On the other hand, domestic sewer pipes result in 1.7 higher odds of root intrusion when compared to combined sewer pipes. The effect of pipe material on tree root intrusion was evaluated by comparing concrete (the most common material used in Bogotá sewer system) with those obtained for the other two pipe materials present in the case study: stoneware and brick. p-values obtained using the complete dataset does not allow to draw conclusions for any of the materials. To tackle this problem, a sub-selection of pipes installed after 1960 was analysed. For this new sample, linear regression coefficients and OR values indicated that the odds of root intrusion events are almost 13 times higher when the material of the pipe is brick instead of concrete.

Method II

Preliminary analysis using T statistics showed that each tree species has to be treated as a distinct group because they are statistically different from each other. For example, observations of *Pinus* had to be split into: *Pinus radiata* D.Don, *Pinus patula* Schiede and Deppe in Schlecht., and *Pinus montezumae* Lamb. PCA showed that in most cases, 90% or more of the variability of the original variables could be described by the first two principal components. This first PCA analysis was developed using all numeric variables listed in Table 2. The species identified to cause tree root intrusion events are:

- *Prunus serotina* ssp.
- *Lafoensia speciosa* Kunth DC
- *Ficus soatensis* Dugand
- *Croton funckianus* Müll. Arg.
- *Tecoma stans* (L.) Juss. ex Kunth
- *Salix humboldtiana* Willd
- *Quercus humboldtii* Bonpl.
- *Phoenix canariensis* Chabaud
- *Acacia melanoxylon* R.Br.
- *Fraxinus chinensis* Roxb.

After each species was analysed independently, all the observations were used to analyse all environmental variables, as well as tree setting, tree physiology and root exposure (these last three under the assumption that they are independent of tree species).

A new PCA analysis was then conducted with the complete data set using three variables: Equatorial diameter, total height and trunk height. These variables were selected because their records in the tree inventory census were the most complete (95% or higher). The first principal component explained 85% of the variability of the original variables and was used for the regression analysis; this component was named *Measurement of the tree*. The weight of each original tree variable was in the order of 0.5, which means that all variables are contributing in similar proportions to the component. As observed in Table 4 the variable *Measurement of the tree* was significant and indicates that an increase 1 unit will increase the number of root intrusions by 0.32. In other words, the number of observed root intrusion events will increase by 1 for each 2.9 units that *Measurement of the tree* augments. *Measurement of the tree* variable can be calculated using the following linear expression (in meters).

$$\text{Measurement of the tree} = 0.59 * \text{Equatorial Diameter} + 0.60 * \text{Total High} + 0.54 * \text{Trunk High}$$

From the original 11 tree and environmental variables proposed, conclusions could be drawn for seven variables, three of them grouped by PCA. The IRR and OR of precipitation variable is very close to one, and the linear regression parameters are nearly zero, meaning that there is no effect on the observed root intrusion events. Groundwater table depth variable was significant for the tree statistical models, as positive coefficients were obtained. This outcome suggest that an increase of one meter in water table depth the odds of presenting an intrusion event increases by

2.2; and that the incidence rate increases by 1.3 for each additional meter depth. The obtained OR and IRR values are lower for trees that expose the roots over ground in contrast to those trees that do not exhibit roots. Based on the linear regression coefficient (OR), the number of observed root intrusion events is decreased by 0.5 when a tree exhibits its roots.

Additionally, it was also found that for trees lower than 12 meters high, the tree-pipe distance has an effect on the root intrusion events. An increase of one meter on tree-pipe distance, decreases the root intrusion events by 0.3; in other words, each increase of 3.4 meters in such distance decreases by 1 the observed root intrusion events. An interesting finding was that when the regression model was limited to smaller trees, the tree-distance coefficient was more negative. For trees up to 11 meters high, each increase of 3.2 meters in tree-pipe distance decrease by 1 the observed root intrusion events, while for trees up to 7 meters high, the increase of 1.8 meters decrease by 1 the observed root intrusion events. Table 5 summarizes these findings.

[Table 5 near here]

Discussion and conclusions

The study presented herein took advantage of the extensive information available for the city of Bogotá (Colombia) to develop a statistical analysis to identify pipe and tree characteristics that are involved in tree-root intrusion process. The proposed methodology makes use of CCTV video data, pipe cadastre and tree inventory. Two methods that spatially relate pipes, trees and root intrusion events were developed; each of the methods implementing three different statistical tools (linear regression, Logit, and Poisson). These analyses allowed the identification of the key variables (pipe and tree characteristics) that are relevant for the process of root intrusion in sewer pipes. A major advantage of this methodology is that it is based on georeferenced tree data which are more readily available in contrast with the exact knowledge of which tree caused the root intrusion event. In addition, the geostatistical method is versatile because the area of influence can be adjusted according to the case study needs. Also, the methodology does not require major investments and can be developed with any available statistical package. A limitation of the proposed methodology is that it does not distinguish between the effect of a single tree and the combined effect of trees located close to each other.

According to the results obtained when applying the proposed methodology to the city of Bogotá, the total tree height, trunk height and equatorial diameter variables were positively correlated with observed root intrusion events. These results support the findings of Wagar and Baker (1983), who observed that larger trees tend to cause more damage than small trees. In contrast to previous findings, such as Ridgers *et al.* (2006), pipe length did not affect the occurrence of observed root intrusion events. Also, statistical evidence showed that precipitation is not an influential variable in the occurrence of intrusion events. A counterintuitive result obtained was that deeper pipes have higher odds of presenting a root intrusion event. These results can be explained by the fact that in the presented case study the groundwater level is lower than the sewers elevation, and because of this tree roots are predominately directed downwards to reach water and nutrients. Nevertheless, as tree root growth is not necessarily straight downwards, the angle of growth may put deeper pipes at longer distances at higher root intrusion risk. Other

characteristics not considered in this study due to their unavailability, such construction quality, soil compaction, and soil type, may need to be considered in future studies.

The ultimate goal of the methodology proposed is to support the managers of the drainage system and the urban trees deciding (i) the best conditions to install the pipes, and (ii) the most suitable tree species to be planted. As a conclusion of this study, and for Bogotá case, decision-makers should avoid construction of sewer pipes in the surrounding of trees more than six meters high; and they should be especially aware of big trees. Finally, Bogotá's wastewater utilities should regularly inspect brick pipes. These recommendations should be included in the holistic and complex sewer system design process in order to reduce maintenance costs in addition to other design objectives, e.g. increase wastewater/ stormwater collection and transport performance and reduction of investment costs. Consequently, the recommendations should also have a positive impact on reducing the total life cycle cost of sewer systems.

The study also showed, that the bigger the tree, the longer the distance required to reduce the observed intrusion events. This result can be explained by the fact that bigger trees have a higher capacity to laterally extend their roots to reach water and nutrients. Bogotá's planting authority should avoid planting tree species from the *Ficus*, *Salix*, and *Prunus* genera in the proximity of urban infrastructures. Pohls *et al.*, 2004 and Stål (1998) have also identified these genera as highly intrusive. All species identified as responsible for causing tree intrusion events share the characteristics of fast-growing, strength and longevity. Except for the specie *Phoenix canariensis* Chabaud, these species share root system special features: medium or high depth and high root strength. The species *Phoenix canariensis* Chabaud belongs to the palm family *Arecaceae*, and have not been identified as an intrusive tree in previous studies. More CCTV videos and field information is required to verify this finding.

The methodology used in this investigation can be replicated for other case studies. However, because of the great number of variables involved in the process of root intrusion, the global validity of the results of different case studies is not clear. We strongly suggest to apply the methodology in homogeneous areas, i.e. areas that share similar pipe, soil and environmental characteristics. The inclusion of soil properties and traffic loads in further research is highly recommended. These variables might have an important effect on the number of root intrusion events. Understanding how they interact with tree root growth (e.g. directing roots in a particular direction) and pipe stability, will clarify their importance in the tree root-intrusion process. Also, a method to model how tree characteristics change with time would be valuable; this significantly would augment the certainty of trees measurements on years after the census was elaborated.

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Figure 1. Case Study area in the east-center zone of Bogotá (Colombia) (DOUBLE COLUMN FITTING IMAGE)

Figure 2. Methodology flow chart (2-COLUMN FITTING IMAGE)

Figure 3. Trees (equatorial diameter buffer) and root intrusion events spatially related (SINGLE-COLUMN FITTING IMAGE)

Table 1. Description of the tree variables available in Bogota's tree census (SINGLE-COLUMN FITTING TABLE)

Tree Variables	Description
Total height	Height measured from the base of the tree to the tip of the crown.
Trunk height	Height measured from the base of the tree to the base of the crown.
Perimeter at trunk's height	Length of the contour of the trunk measured at 1.3 m from the base.
Basal perimeter	Length of the contour of the trunk measured at 0.3 m from the base.
Equatorial Diameter	Measure of the crown's orthogonal projection in a horizontal plane.
Polar diameter	Measure of the crown's orthogonal projection in a vertical plane.
Tree sitting	Determines if the tree planting site has or not barriers.
Tree physiology	Determines if the tree is deciduous, semi-deciduous or perennial.
Root exposition	Determines if the roots are exposed overground.

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584 Table 2. Pipe, tree and environmental selected variables to be included in the regressions (2-
 585 COLUMN FITTING TABLE). Pipe variables are used in Method I; while Tree and Environmental variables
 586 are used in Method II.
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Method I	Method II	
Pipe Variables	Tree Variables	Environmental variables
Pipe depth ¹	Total height ¹	Precipitation ¹ (2006)
Pipe material ²	Trunk height ¹	Water table depth ¹
Pipe diameter ²	Perimeter at trunk's height ¹	
Pipe length ¹	Basal perimeter ¹	
Pipe age ¹	Equatorial Diameter ¹	
Pipe type ³	Polar diameter ¹	
	Tree sitting ³	
	Tree physiology ²	
	Root exposition ³	

¹Numerical Variables

²Categorical Variables

³Dummy Variables

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Table 3. Range, mean, and standard deviation for the trees and pipes dataset. (2-COLUMN FITTING TABLE)

Tree Characteristics				Pipe Characteristics			
	Range	Mean	Standard deviation		Range	Mean	Standard deviation
Total Height (m)	[1.2-34.6]	13.9	7.8	Depth (m)	[0.60-7.00]	1.8	0.6
Trunk height (m)	[0.2-14.4]	4.7	3.1	Diameter (mm)	[200-1500]	332.8	156.7
Perimeter at trunks' height (m)	[0.1-3.8]	1.6	0.9	Length (m)	[0.5-132.70]	42.0	28.7
Basal Perimeter (m)	[0.1-4]	1.7	1.0	Age (years) ¹	[6-84]	58.4	25.5
Equatorial Diameter (m)	[0.9-23.8]	11.1	5.8	Groundwater Table Depth (m)	[2.43-13.23]	7.3	2.7
Polar Diameter (m)	[0.2-27.8]	9.3	5.9				

¹Calculated using 1st January 2017 as reference

Table 4. Results for linear regression, logit and poisson models (2-COLUMN FITTING TABLE)

	Variable	Value	Linear regression		Logit regression		Poisson regression	
			β	p-value	OR	p-value	IRR	p-value
Pipe characteristics	Pipe type	(Combined pipes as reference)			1.79	0.08		
	Pipe depth		0.11	0.04	1.58	0.04		
	Pipe length		0.00	0.00	1.02	0.00	1.01	0.00
	Material	(Concrete as reference)						
		Stoneware					1.54	0.05
Trees characteristics		Brick	1.94 ¹	0.00	12.82 ¹	0.10		
	Root exposition	(No root exposition as reference)	-0.49	0.10	0.33	0.06	0.53	0.03
	Measurement of the tree		0.34	0.02	4.56	0.00	1.50	0.00
	Tree-pipe distance		-0.29 ²	0.01	0.72	0.02		
	Precipitation (2006)		-0.01	0.10	0.98	0.00	0.99	0.03
	Water table		0.26	0.07	2.18	0.01	1.37	0.01

¹ Only for pipes installed after 1960

² Only for trees lower than 12 meters

Tree variables coefficients

without ¹ or ² are results for trees lower than 20 meters

Table 5. Linear coefficient regression model for tree-pipe distance variable for trees between 6 and 12 meters high. (SINGLE-COLUMN FITTING IMAGE)

Tree Maximum height	Regression coefficient	p-value	Distance increase required to reduce the observed intrusion events by 1
12	-0.29	0.01	3.45
11	-0.31	0.01	3.23
10	-0.31	0.01	3.23
9	-0.45	0.01	2.22
8	-0.42	0.01	2.38
7	-0.57	0.00	1.75
6	-0.71	0.01	1.41