



# Agricultural drainage pipe in *Guadua angustifolia*: implications of Manning roughness in Pitalito forest stands

M. Duarte-Toro<sup>1</sup> · J. M. Silva-Chavarro<sup>1</sup> · J. A. Gil-Hernandez<sup>2</sup>

Received: 14 April 2023 / Revised: 2 January 2024 / Accepted: 6 March 2024  
© The Author(s) 2024

## Abstract

Water extraction in agricultural fields with high saturation levels requires drainage systems that increase land preparation costs, so looking for new options for materials that function as drainage pipes that provide a better technical–economic relationship is crucial. In this study, Manning roughness values were analyzed in the culms of *Guadua angustifolia* considering three factors: flow, section, and location site of the forest stands. This study was carried out in the rural area of the municipality of Pitalito; the characterization of culms was made based on the Colombian technical standards (NTC) 5726 and 5727, the cutting and elaboration of test pieces according to the NTC 5525, and finally, the hydraulic tests were carried out. The roughness values oscillated between 0.1089 and 0.0337 according to the different flow evaluated values in the laboratory tests, between 0.1004 and 0.0356 for the sections analyzed, and between 0.0909 and 0.0533 according to the sample extraction area. The multifactor ANOVA established a significant relationship for the flow and section on the Manning n roughness, while the zone was insignificant.

**Keywords** Manning roughness · *Guadua angustifolia* · Piping · Drainage

## Introduction

Land preparation plays an essential role in transforming the soil to obtain favorable crop conditions. In areas with high rainfall during the year and soils with high water movement resistance, it is necessary to implement actions that allow drainage problems to be corrected. The municipality of Pitalito has a relatively stable temperate climate between 18 and 21 °C, and it is estimated that it has rainfall between 1200 and 1600 mm annually in its valley (Ochoa et al. 2021); therefore, rainfall is considered significant, even during the driest month. Besides, the municipality valley has drainage difficulties because soils have poor capability to evacuate the water coming from irrigation and rainfall, which makes the implementation of agricultural drainage systems necessary.

According to the Territorial Planning Plan of the municipality of Pitalito, the majority of Pitalito falls within the pre-montane humid forest life zone, and approximately 28.5% of the total area consists of soils classified as USDA capability classes IVSHE and IVSH2 (Mendez Pedroza and Montealegre Torres 2017). These lands can be used for agriculture but require special management practices to overcome limitations such as poor drainage and susceptibility to erosion. The soils have high clay content and limited effective rooting depth for plants, leading to waterlogging and the presence of salts in the area. Specifically, class IVSH2 soils have limitations associated with excess moisture and shallow effective depth. While suitable for temporary crops like rice, sorghum, and sesame, these soils require the implementation of agricultural drainage practices.

In areas with high precipitation throughout the year and soils with high resistance to water movement, both externally and internally within the soil profile, it is necessary to implement actions to address drainage problems (Pizarro Cabello 1985). In this regard, it is necessary to mitigate shallow water tables high soil salinity levels, combat fungal disease formation, prevent a decrease in biological activity, halt soil structure degradation, address low fertility and a low air–water ratio, maintain access to the plots for farming

---

Editorial responsibility: Shah Fahad.

✉ J. A. Gil-Hernandez  
jackson.gil@usco.edu.co

<sup>1</sup> Program of Agricultural Engineering, Universidad Surcolombiana, Neiva, Colombia

<sup>2</sup> Program of Civil Engineering, Universidad Surcolombiana, Neiva, Colombia



activities, and crop harvesting, among other measures (Polón Pérez et al. 2011).

The implementation of drainage systems represents an increase in the land preparation costs for farmers, modifies the agroecological conditions, and requires the application of scientifically validated techniques and materials (Cortez Mejía et al. 2016). Such systems for mitigating the drainage problems have been developed with conventional materials, but it is essential to search for new piping options with favorable hydraulic properties that replace conventional materials; for above, the use of bamboo as drain pipe can be one alternative that is environment-friendly, more economical, and at the same time, becomes an additional income for the rural enterprises having stands near agricultural fields (Yannopoulos et al. 2020).

The hydraulic properties of piping are a determining factor in choosing the design material for a drainage system since they allow us to know the material characteristics and behavior of the passage of fluid (Pizarro Cabello 1985). *Guadua angustifolia* is a species of bamboo native from South and Central America, belonging to the subfamily *Bambusoideae*, that grows very well in the southern area of the Huila department due to the agroecological conditions (Duarte Toro et al. 2016). In this sense, this vegetable material is intended to be used as an economical alternative that can be transformed into agricultural drainage piping, taking advantage of its morphology and hollow, circular, tube-shaped stem.

For this material to fulfill drainage piping conditions, the hydraulic characteristics must be determined; one of them is the Manning  $n$  roughness factor. Several recent studies have investigated the influence of various parameters in the design of stormwater drainage pipes using a variety of materials. Abdulla et al. (2023) examined the relationship between the Manning coefficient and the design of high-density polyethylene (HDPE) stormwater drainage pipes, whereas Sun et al. (2023) focused on the behavior of the Manning coefficient in sediment-laden drainage pipes made of polyvinyl chloride (PVC). Tarakanov (2022) investigated the performance of drainage pipes manufactured from polypropylene and reinforced concrete, considering various hydraulic parameters, including roughness. Additionally, Quang et al. (2022) conducted simulations of urban stormwater drainage pipes, varying key parameters such as the Manning coefficient.

On the other hand, Chen et al. (2022) delved into the study of the roughness coefficient in circular drainage pipes with sedimentation under open channel flow conditions. These studies have concluded that proper pipe design, considering the correct parameters, is essential to ensure optimal operation and long service life in these drainage systems.

To date, various research studies have examined perforated bamboo irrigation systems; however, there are no specific studies on Manning's roughness coefficient ( $n$ -value) for *Guadua angustifolia* in subsurface drainage systems. Therefore, this study aims to fill this research gap by providing the necessary data to understand this variable in this type of material for use in the design of subsurface drainage systems, serving as a reference for comparison. For this reason, this study evaluated how the flow rate, cross-sectional area, and geographical location of the stand affect Manning's roughness coefficient. Therefore, this study was designed to estimate the Manning's roughness coefficient of *Guadua angustifolia* pipes concerning flow rate (Q1: low, Q2: medium, and Q3: high), culm section (lower, middle, and upper), and four stand location zones (Z1, Z2, Z3, and Z4). Lastly, using a multifactorial ANOVA analysis, it aims to determine the interaction between the factors: flow rate, culm section, and stand location.

## Background

Considering that there are currently no specific studies on Manning's roughness coefficient ( $n$ -value) for perforated *Guadua* in subsurface drainage systems, it is necessary to gather data on this variable from other types of materials commonly used in drainage systems. These data can serve as a reference for comparison in the absence of specific values for *Guadua*.

Lipangile (1985) documented the inclusion of *Guadua* as a waterpipe for rural life as a government policy in Tanzania in 1985, where irrigation and water supply systems were installed in some villages, and found that using *Guadua* as an alternative to PVC pipe is economically and logistically viable.

Monge Freile et al. (2019) evaluated bamboo as an alternative pipe for a multi-door irrigation system for local farmers; the study considered laboratory tests where the optimal slopes, pressure heads, and roughness values were determined according to the Colebrook–White and Hazen Williams equations.

Almeida Neto et al. (2000) studied the parameters of bamboo as a water pipe in pressurized and non-pressurized systems; the study to obtain the Hazen–Williams coefficient, Manning coefficient, and absolute roughness by Hopf and Colebrook; on the other hand, they head energy losses according to Darcy–Weisbach, Hazen–Williams, and Manning were determined.

In other studies, the Concrete Pipe Association of Australasia (2017) described the importance of roughness coefficients in calculating the hydraulic capacity and the piping diameter. Currently, the most used equations for the roughness coefficient calculation are found in Hazen–Williams, Manning, and Colebrook–White.



In a study conducted by Perrero (1968), a roughness coefficient applicable to concrete pipes will be determined by comparing experimental results with data from Spanish sanitation regulations and other literature on channel calculations. The report concludes and recommends using the Manning roughness coefficient “n” with a value of 0.015. However, it suggests that this value should be subject to consideration in cases of aged concrete, and an additional safety factor should be applied.

In the final report of Cortez Mejía et al. (2016) determined through an experimental study the piping roughness coefficients, whether pressure or free surface, especially for PVC and HDPE (high-density polyethylene piping) for sewage, they concluded as follows:

- (a) Manning’s n cannot be taken as a constant as is done in practice but depends on flow variables such as Reynold’s Number.
- (b) Full pipe (without pressure) Manning’s n depends on the diameter, increasing for greater diameters.

Araya et al. (2018) analyzed variation in Manning’s roughness coefficient of closed channel PVC piping with respect to the slope, where variation was obtained of Manning’s number in relation to the wetted perimeter and, therefore, to the flow depth. Likewise, they demonstrated that the slope is not a variable affecting Manning’s roughness coefficient in 315 mm PVC piping.

Likewise, Rivera Benítez and García Jacho (2019) proposed considering the capabilities of the reinforced concrete tube with an internal coating of high-density polypropylene HDPE for use in urban drainage since it allows the concrete to be protected from corrosive attacks, optimizing the mechanical and hydraulic characteristics of the pipeline by 30%.

In the field, agricultural drainage is concerned with the control of waterlogging and soil salinization in agricultural lands. Additionally, agricultural drainage aims to timely remove or withdraw excess water to ensure an adequate moisture content in the root zone of plants, promoting optimal growth, maintaining aeration conditions, and allowing nutrient access to ensure proper production (Calvache-Ulloa 1970; Martínez Beltrán 1999; Herrera-Puebla et al. 2009; Génova et al. 2015).

Currently, plastic corrugated pipes are the most commonly used for agricultural drainage. They offer several advantages, including their lightweight nature, which makes transportation and installation easier, as well as being durable, corrosion-resistant, and resistant to the effects of agrochemicals. These pipes can be used in various soil types, ranging from heavy clay soils to those with high organic matter content. PAVCO manufactures in Colombia these piping (with or without filter) with diameters of 65, 100,

160, and 200 mm; besides, it produces 5 m pipes without filter, with their respective joints and the same diameters used for rolls. Pipe bores oscillate between 5 to 8 mm long, and 1.3 mm width (depending on the diameter), with pipe or roll wall thicknesses of 0.5 mm (PAVCO 2005).

Piping bores can be circular in smooth piping or slots in corrugated piping. The number and size of bores will depend on the drilled area density per meter of piping length. This leads to the conclusion that the larger the bore size, the more water can be drained, but with the problem of carrying fine material (Suárez Díaz 2009).

ICONTEC (2013) states in the NTC 6028 that the minimum water inlet area per square meter must be 8 cm<sup>2</sup>. The slots for the water inlet must be uniformly arranged in at least 5 lines on the pipe circumference. They must be so constituted that the water flow inlet through the pipe is not obstructed by residual material. The slot width for the water inlet is equal to the minor axis length, with a width of 0.8 ± 0.2 mm in thin length, a width of 1.2 ± 0.2 mm for medium length, and a wide length width of 1.7 ± 0.3 mm. The minimum bore width could be 0.01 inches, with the disadvantage that it will be susceptible to clogging, which will require regular cleaning, and therefore, it will raise the maintenance costs of the drainage system (Burns 2006). The raw materials specifications with which drainage pipes are manufactured (ceramics, concrete, plastic) are described in the standards for drainage piping (Stuyt et al. 2009).

For the research, the minimum water inlet area per meter of pipe length was considered, which should be greater than 8 cm<sup>2</sup>, and the perforation distribution was done as specified in NTC 6028 (ICONTEC 2013). Regarding the shape of the perforations, they were made circularly. This choice was made because Guadua is a straight, non-corrugated duct, and circular perforations facilitate the transformation of the Guadua material for drainage purposes.

Drainage piping has multiple physical properties that allow appreciating the benefits of different materials and making decisions in the engineering area. In this sense, Manning’s roughness is a fundamental property in deciding the kind of material and necessary works for a land preparation project. The Irish Engineer Robert Manning developed in 1889 an alternative for the Chézy equation that became commonplace for the calculation of flow velocities in channels and piping. In the International System of Units, the Manning’s Eq. (1) is written:

$$v = \frac{1.00}{n} * R^{2/3} * S^{1/2} \quad (1)$$

where v = flow average velocity (m/s), n = Manning’s roughness coefficient (dimensionless), R = Hydraulic Radius (m), S = Slope gradient (m/m).

“n” refers to a resistance coefficient that is occasionally called Manning’s n. In conduction channels, the condition





of such channel surface directly influences the value of “ $n$ .” Therefore, it may be likened to the roughness of a pipe wall (Mott 2006).

However, when applying Manning’s equation, the difficulty arises in determining the  $n$  roughness coefficient in open channels (streams and rivers) because there is no exact manner to find this coefficient. This being said, it is necessary to analyze the factors affecting Manning’s  $n$ , which are surface roughness, vegetation, irregularity of the surface to be analyzed, and sediments that will remain in the duct (Chow 1999).

## Materials and methods

### Research approach

This study was framed within the quantitative approach and the deductive paradigm because the variation of Manning’s roughness in *Guadua angustifolia* piping was determined considering the flow, the section, and the geographical location of the site of the stands. The quantitative component was based on developing a multivariate experiment to estimate Manning’s roughness.

Considering that experimental designs fall within the explanatory level of research, in this context, by controlling various factors, the goal is to estimate the cause-and-effect relationship concerning the response variable, which is Manning’s roughness coefficient ( $n$ -value). These experimental designs are structured to provide insights into how different factors influence the response variable and to establish causal relationships between them.

The study was carried out with *Guadua angustifolia* found in the municipality of Pitalito, department of Huila—Colombia (see Fig. 1), covering the Laboyos valley at an altitude range of 1250–1350 m.a.s.l. The above-considering studies on the physical–mechanical properties of the species were carried out by Universidad Surcolombiana (Takeuchi et al. 2012, 2014; Sapuyes et al. 2018).

There is no current estimation of vegetative and normatively usable *Guadua angustifolia* in the municipality of Pitalito because no general inventory of the species has been conducted. However, the project “Characterization of eco-systemic services of *Guadua angustifolia* Kunth in the lower basin of Guarapas River” by Noriega Ome and Valbuena Calderón (2019) was taken as the reference.

Table 1 shows the selected stands per zone and the area, altitude, longitude, and elevation above sea level. The

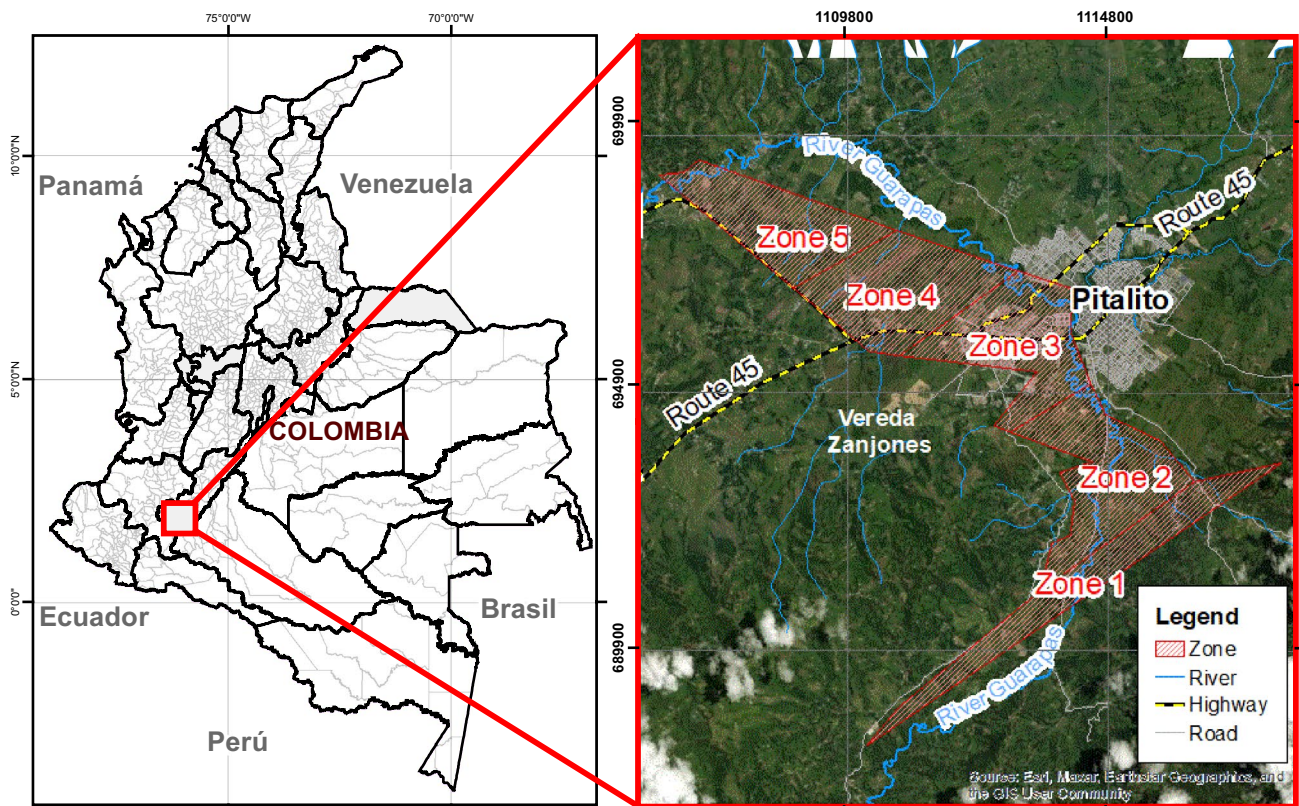


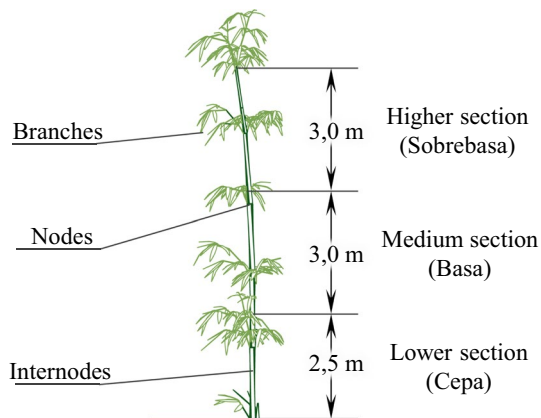
Fig. 1 General location and zones



**Table 1** Selected stands per zone

Zone	Stand	Area m <sup>2</sup>	Latitude	Longitude	Elevation-m.a.s.l
Z1	Rural settlement Zanjones	9496	694,348.2490 N	1,112,605.5260 E	1287
Z2	Universidad Surcolombiana	3580	693,808.0040 N	1,115,918.8780 E	1277
Z3	Santa Rosa	5524	693,429.2590 N	1,117,990.3930 E	1284
Z4	Villa Fátima	6015	692,485.4710 N	1,114,237.6280 E	1263
Z5	–	–	–	–	–

Morphologically, within the Coordinate system, MAGNA Colombia West EPSG:3115



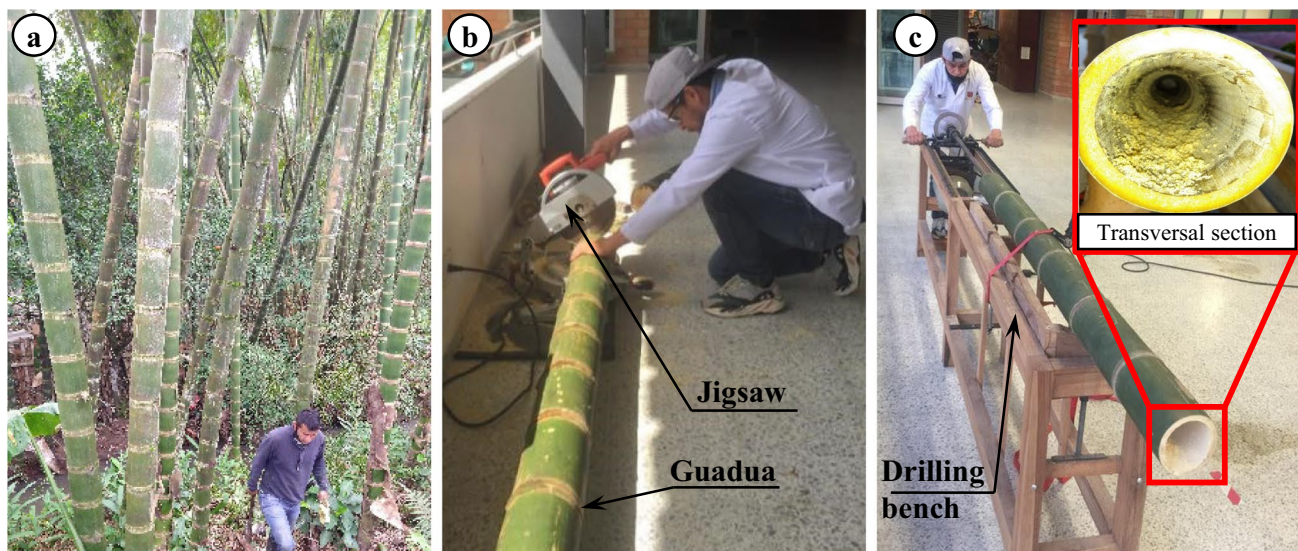
**Fig. 2** *Guadua* conditioning process

height-above-sea-level review found that stands belonging to Zone 5 are below the previously established range; therefore, no stand was selected from this zone.

### Experimental setup and procedure

Once stands were referenced, three culms per stand were chosen (Fig. 2a). Such culms were characterized in accordance with the NTC 5726 standard, “Inventory of *Guadua angustifolia* Kunth stands for commercial purposes” (ICONTEC 2009a). This standard took into account diameters at breast height ranging from 60 to 100 mm (commercial diameters for agricultural drainage pipes), maturity level (*Guadua* “Hecha” or mature, between 4 and 6 years), health status, and stem quality.

The cutting of the culms in the stands was carried out following NTC 5300, “Harvest and post-harvest of *Guadua angustifolia* kunth culm,” cutting them flush above the first or second node to prevent water accumulation (ICONTEC 2008). After cutting, the culms underwent a bleeding or Vinagre process in the Guadual (moisture loss) for two (2) weeks in accordance with NTC 5301, “Preservation and drying of *Guadua angustifolia* Kunth culm” (ICONTEC 2007a). Vinagre is a man-induced fermentation process that involves cutting *Guadua* and leaving it at the cutting site (in the shade) for at least two weeks. It is a natural preservation



**Fig. 3** Parts of the *Guadua*



**Table 2** Labeling of test pieces

Z1	N	1	I
a	B	c	d

process for *Guadua* against deterioration caused by biotic and abiotic agents (ICONTEC 2009b).

Once this process was completed, the culms were cut into 3 longitudinal sections: lower (2.5 m), middle (3.0 m), and upper (3.0 m) (Fig. 3). The selection of the lower, middle, and upper sections was considered according to NTC 5525, “Test methods to determine the physical and mechanical properties of *Guadua angustifolia* kunth” (ICONTEC 2007b). Similarly, the lengths of each section were determined, and efforts were made to ensure that the diameters were as uniform as possible since *Guadua* culms have a conical shape. Additionally, the hydraulic bench used had limitations with longer lengths.

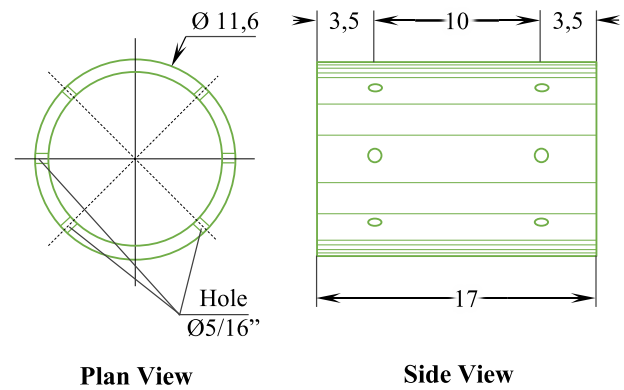
Once the culms were selected, the washing and elaboration of test pieces were carried out considering the stand location and culm section, resulting in 3 test pieces per culm and a total of 36. Each culm was cut into 2-m sections (Fig. 2b). Subsequently, the labeling of the test pieces (Table 2) was conducted following the guidelines outlined in NTC 5525 (ICONTEC 2007b) as follows: where Stand location zone (Z1, Z2, Z3, Z4); Property to test Manning’s  $n$  (N); Test piece number (1, 2, 3); *Guadua* section (I: lower, M: medium, S: Higher).

The *Guadua* test pieces drilling was made in two stages:

The initial stage involves the drilling of the transversal septum. Morphologically, within the *Guadua*, and especially in the node, a transversal septum (membrane) grows that interrupts the cavity called intranode, which is necessary to break it to give continuity to the duct. The drilling bench (Fig. 2c) was used for this, designed and built by Carantón García and Molina Gordillo (2021). The second stage involves the lateral drilling of the pipe. In the lateral drilling of the pipe, the PAVCO bore distribution of agricultural drainage piping was considered, which establishes six (6) lines in total, three on the left side, and three on the right side, at 45° vertically between lines and horizontal spacing of 10 cm between bores per line. A space free of bores of 90° was left on the lower and higher surfaces (Fig. 4).

A drilling diameter of 5/16 inches was used for the water inlet bores (Fig. 5a), resulting in 26.72 cm<sup>2</sup> of total area per linear meter, which is a water inlet area per linear meter higher than the minimum required by ICONTEC (2013) in the NTC 6028, indicating that the minimum water inlet area for drainage is 8 cm<sup>2</sup> per linear meter (Fig. 5b). Later, the physical characterization of test pieces was carried out, considering the external diameter, thickness, internal diameter, number of nodes, and distance between nodes to determine Manning’s  $n$  and its influence.

Note: Measures in centimeters



**Fig. 4** Diagram of bores in test pieces. Source: Modified from (Burbano Ibarra and Ortiz Claros 2021)

The measuring instrument used to determine the variability of Manning’s roughness in *Guadua angustifolia* piping is a physical model called a hydraulic test bench. The equipment has a rectangular, horizontal channel in galvanized sheet, a metallic structure, a stilling section in 6 mm thick glass, a spillway in acrylic with limnimetric needle (0.1 mm accuracy), a 1000-L plastic supply tank, 1.5 inches polyethylene conduction piping with gate valve, a 500 L plastic reception tank, and a Powermaster motor pump with 1.5 inches of input and output diameter, gasoline-fueled, model MG168R-KBPM15H, 300 l/min maximum flow, and 3.5 HP of power (Fig. 5c).

For the calculation of Manning’s  $n$  roughness, the area of the internal transversal section of the culm was calculated, obtained from the averages of the external diameter and the test piece thickness in the initial and final sections. The slope “S” used in the project was 1 percent for all the tests. The flow was determined considering the reading of the limnimetric needle of the spillway. The water depth (refers to the water film inside the test piece) was obtained through piezometers along the piping, which is indispensable for determining the hydraulic radius (Mott 2006). The hydraulic bench spillway was calibrated following the method proposed by Portillo España (2012).

Lastly, the determination of Manning’s  $n$  was obtained by Eq. (1). With the estimated Manning’s  $n$  data, the multifactor analysis of variance, according to Table 3, proceeds.

## Results and discussion

### Estimation of Manning roughness for flow

Manning’s  $n$  descriptive statistic for Q1 (low), Q2 (medium), and Q3 (high) flows shows that an increase in the flow



Fig. 5 Assembly of the test pieces

Table 3 Levels per assessed factor for Manning’s n roughness

Factor	Factor levels	Response variable
1. Zone	Z1	Manning’s n Roughness
	Z2	
	Z3	
	Z4	
2. Section	Lower	
	Medium	
	Higher	
3. Flow	Q 1	
	Q 2	
	Q 3	

Table 4 Confidence intervals for the mean of Manning’s n roughness in the flow levels

Level	Lower	Higher
Q1	0.0911	0.1089
Q2	0.0600	0.0778
Q3	0.0337	0.0527

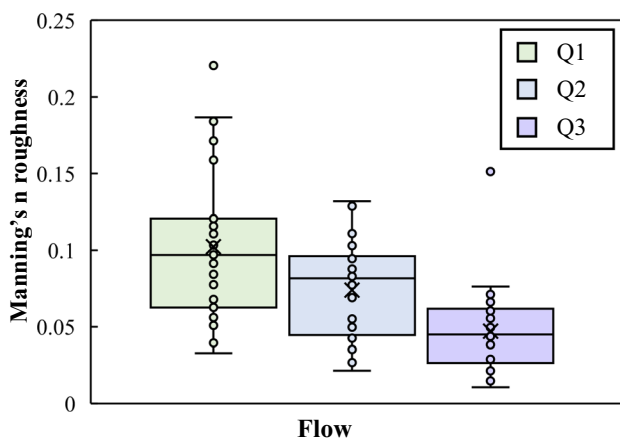


Fig. 6 Flow variable box and whisker plot

decreases Manning’s n roughness; for instance, the mean for Q1 (low flow) Manning's n is 0.0975, for Q2 (medium flow) is 0.0689 and for Q3 (high flow) is 0.0472. The median in Q1 and Q3 is lower than the mean; however, in Q2 the

median is greater than the mean (Fig. 6). Regarding the dispersion measurements, the standard deviation and variance are higher in Q1, and there is lower variability in Q3. In kurtosis, Q1 and Q3 are leptokurtic and show a high concentration around the central values, while Q2 is platykurtic, namely, data are not concentrated around the central values. The flow asymmetry is positive, indicating that the median is lower than the mean. In Q1, there is moderate positive asymmetry; in Q2, the positive asymmetry is slight; and in Q3, the positive asymmetry is high.

The normality test in flow levels through the Shapiro–Wilk test with a 0.05 significance level showed a *p*-value of 0.0114 (Q1), 0.1104 (Q2), and 0.0001 (Q3), meaning that the null hypothesis is rejected for Q1 and Q3, proving non-normality in the data distribution, and accepting normality only for Q2.

Table 4 shows the confidence intervals with a reliability of 95 percent for the levels’ mean of the flow factor. It can be deduced that Manning’s n roughness mean oscillates between 0.1089 and 0.0337 concerning the flow.

### Estimation of Manning roughness for the section

In the Manning’s n roughness descriptive statistics for the section, in the mean (average) is observed that the greater Manning’s n occurs in the lower part (0.0915) and the lower in the higher (0.0466) (Fig. 7). The above can be explained because the lower section has greater external diameters, the lower distance between nodes, and a therefore greater

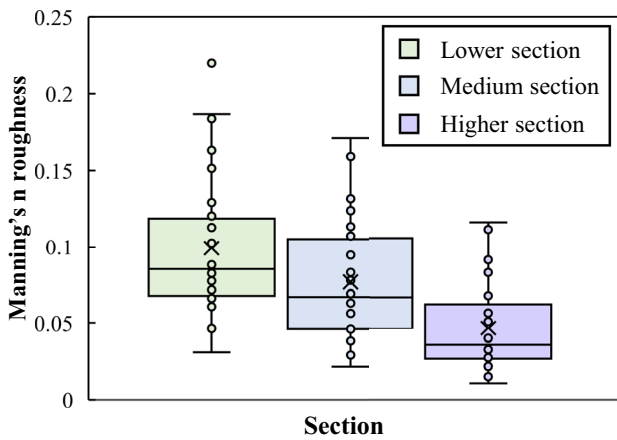


Fig. 7 Section variable box and whisker plot

Table 5 Confidence intervals for the mean of Manning's n roughness according to the section

Section	Lower	Higher
Lower	0.0827	0.1004
Medium	0.0667	0.0844
Higher	0.0356	0.0546

number of nodes, which would originate greater losses. Regarding the median, it shows slightly lower values with respect to the mean in all the sections. Kurtosis showed positive values, namely a high concentration around the central values (leptokurtic) in the lower and higher sections, while in the medium section, there is a lower degree of concentration. In the asymmetry, the values for the sections are positive; however, there is a higher concentration in the higher section, indicating that the distribution is lengthened to the right for values greater than the mean and minimally concentrated to the left.

The normality test in section levels through the Shapiro–Wilk test with a 0.05 significance level showed a *p*-value of 0.0180 (lower), 0.0148 (medium), and 0.0040 (higher), meaning that the null hypothesis is rejected for the sections, showing non-normality in the data distribution.

Table 5 shows the confidence intervals with a reliability of 95 percent for the levels' mean of Manning's n roughness for the section factor. It is evinced that Manning's n roughness oscillates between 0.1004 and 0.0356 concerning the section factor.

### Estimation of Manning roughness for the zone

In Manning's n descriptive statistics for the factor zone, the mean that shows the greatest Manning's coefficient is in the Z2 zone (0.0825) and the lowest in the Z4 zone (0.0670). In

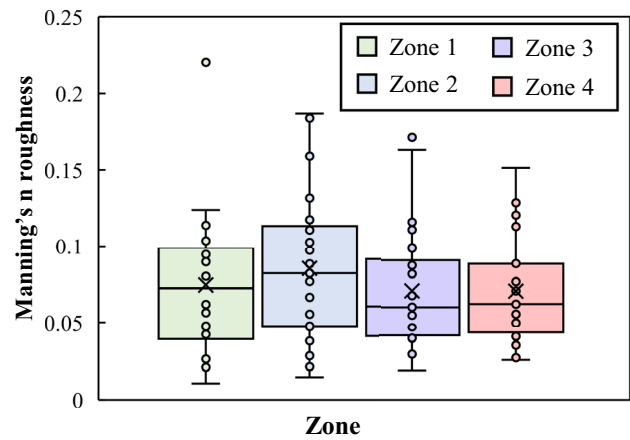


Fig. 8 Zone variable box and whisker plot

Table 6 Confidence intervals at 95% for Manning's n roughness mean according to the zone

Zone	Lower	Higher
Z1	0.0597	0.0802
Z2	0.0700	0.0910
Z3	0.0580	0.0785
Z4	0.0533	0.0751

zones Z1 and Z3, roughness is very similar (Fig. 8). Regarding the median, it shows slightly lower values than the mean in all the zones. Kurtosis showed positive values indicating a concentration of data (leptokurtic), with the greatest value in Z1 (shows very thick tails) and the lowest value in Z2. In the asymmetry, the values for the four zones are positive, namely the median is lower than the mean, evincing distribution lengthening to the right.

The Shapiro–Wilk test with a significance level of 0.05 showed a *p*-value of 0.1683 in Z2 zone; therefore, the null hypothesis is accepted, which is normality in the distribution. For the other zones, the *p*-value is lower than 0.05; therefore, the null hypothesis is rejected, which evinces non-normality in the data distribution.

Table 6 shows the confidence intervals at 95 percent for Manning's n roughness factor zone mean. It can be seen that Manning's n roughness oscillates between 0.0910 and 0.0533.

When reviewing Figs. 6, 7 and 8, atypical Manning's n roughness data are appreciated for each factor: the flow variable, data 2, and 83; in the section variable, data 2, 4, 2, 4, 6, 30, and 32, and in the zone variable, data 2, 8, 19, and 83. Field verification of the physical and mechanical measurements carried out in the data collection confirms that these data cannot be excluded because they belong to the process.



**Table 7** Analysis of Variance for 1/n—Sum of Squares Type III

Source	Sum of Squares	Gl	Mean Square	F-Ratio	P-value
<i>Main effects</i>					
A: flow	1.7941	2	0.9705	37.18	0.0000
B: section	1.7318	2	0.8659	35.88	0.0000
C: zone	0.0589	3	0.0196	0.81	0.4907
<i>Interactions</i>					
AB	0.0573	4	0.0143	0.59	0.6683
AC	0.0281	6	0.0047	0.19	0.9774
BC	0.3038	6	0.0506	2.10	0.0651
ABC	0.0758	12	0.0063	0.26	0.9931
Residues	1.5926	66	0.0241		
Total (corrected)	5.7160	101			

### Interaction between factors flow, culm section, and site location

The ANOVA multifactor variance analysis was used in the flow, culm section, and site location factors. To do so, the normality assumption was verified in the roughness data. Based on the findings in Manning's  $n$  estimation per factor, it can be concluded that it does not behave as a normal distribution according to the Shapiro–Wilk test with a significance level of 0.05 ( $p$ -value = 0.0000486), and therefore the transformation of the Manning's  $n$  response variable through the logarithm function was proposed. Once the transformation of Manning's  $n$  response variable was carried out, the normality was obtained with a 0.05 significance level through the Shapiro–Wilk test ( $p$ -value = 0.880). Later, the multifactor analysis of variance was carried out through the R Software, with the graphic interface RStudio (Version 1.3.1073, © 2009–2020 RStudio, PBC) (Table 7). To do that, the type III sum of squares was used, where the contribution of each factor is measured by eliminating the effects of the other factors.

There were no statistically significant differences in ANOVA in the three-way interaction (Zone: Section: Flow). It is evident that the section and flow factors, whose significance level is 0.05, are statistically significant for Manning's  $n$  roughness, showing a  $p$ -value of 5.98e-08 and 1.81e-09, respectively; in turn, the site location did not show significance with a  $p$ -value > 0.05. Likewise, by reviewing the effect of the two-way combinations between factors, it was found that they are greater than the significance level (0.05).

All F-ratios are based on the mean square of the residual error.

From the above, it can be confirmed that in the section factor, the Guadua's physical variables, such as the external

diameter, the internode distance, and the number of nodes, directly affect the response variable, showing that the lower diameter and the longer internode distance (higher section), the lower Manning's  $n$ . For the flow factor, as previously said in the descriptive statistics analysis, it is evident that the higher the flow, the lower the Manning's  $n$  roughness.

### Verification of assumptions

Zero mean: With the t-student test, the null hypothesis is accepted  $H_0$ : zero mean (0) with  $p$ -value 1.

Normality of residues: With the Shapiro–Wilk test (0.2131), the  $H_0$  is accepted: normal distribution in the residues.

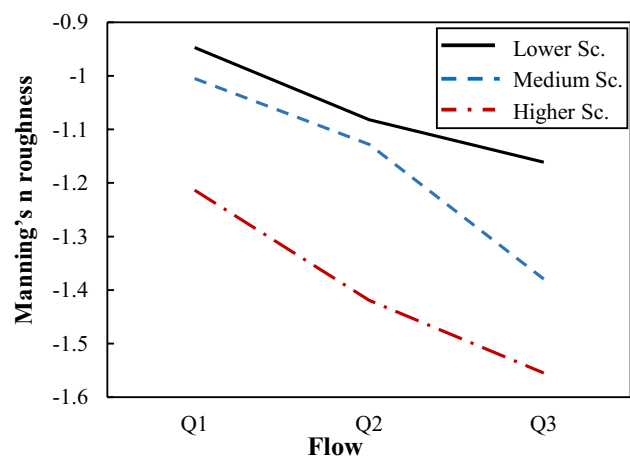
Constant variance test: Through Levene's test, the variance equality was confirmed, yielding a  $p$ -value of 0.8063. Therefore, the null hypothesis  $H_0$  is accepted: Constant variance, namely, there is homoskedasticity.

Independence of residues: With the Durbin Watson,  $H_0$  is accepted. Therefore, the presence of self-correlation is rejected because of  $p$ -value (0.08802) > 0.05.

### Interaction graphs

Figure 9 shows the interaction between the flow and section factors concerning Manning's roughness, confirming that Manning's  $n$  decreases as the flow increases and the diameter decreases.

Figure 10 evinces that in all zones between Q1 and Q2 flows, the decreasing trend of Manning's remains; however, between flows Q2 and Q3, that trend remains for Z1, Z2, and Z3 zones, but in the Z4 zone, there is a slight decrease in roughness.



**Fig. 9** Manning's  $n$  interaction graph between the flow and section factors

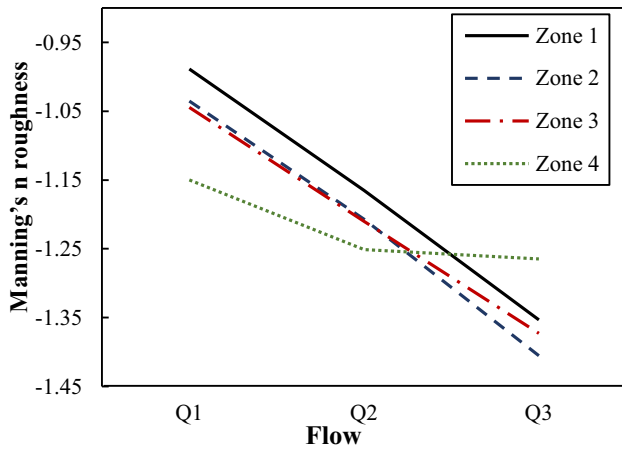


Fig. 10 Manning's n interaction graph between the flow and zone factors

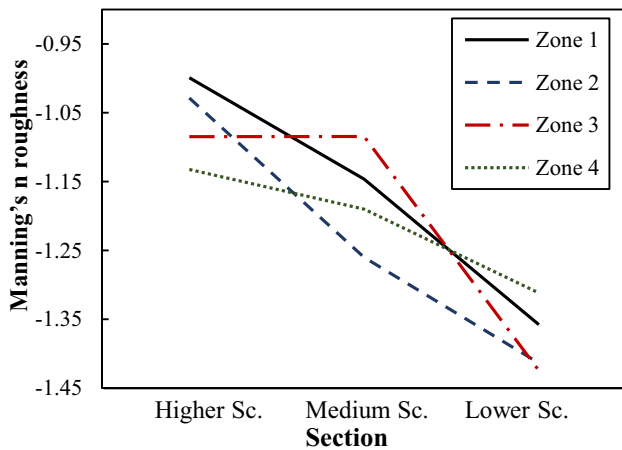


Fig. 11 Manning's n interaction graph between the zone and section factors

Table 8 Multiple ranges test for flow

Groups according to the probability of means differences and alpha level (0.05) Treatments with the same letter are not significantly different		
Flow	logM	Groups
Q1	-1.0547	a
Q2	-1.2100	b
Q3	-1.3533	c

Figure 11 evinces that in zones Z1, Z2, and Z4, the decreasing trend of roughness remains as the diameter (section) decreases, however in the Z1 zone, between the lower

Table 9 Multiple range tests for sections

Groups according to the probability of means differences and alpha level (0.05) Treatments with the same letter are not significantly different		
Section	logM	groups
Lower	-1.0579	a
Medium	-1.1705	b
Higher	-1.3758	c

Table 10 Multiple range tests for the zone

Groups according to the probability of means differences and alpha level (0.05) Treatments with the same letter are not significantly different		
Zone	logM	groups
Z2	-1.1623	a
Z1	-1.1943	a
Z3	-1.2144	a
Z4	-1.2192	a

and medium sections, the roughness remains almost constant and begins to decrease between the medium and higher sections.

**Test of multiple ranges for flow**

In Table 8, the HSD Tukey's multiple comparison procedure is applied to determine which of the medians are significantly different from others. The letters ("a," "b," "c," "d") indicate that combinations between flows show statistically significant differences with a confidence level of 95.0% for levels Q1, Q2, and Q3. This would prove that the sample in the three groups is homogeneous.

**Multiple ranges test for section**

In Table 9, the same test used for the flow factor was applied for the mean comparison. It shows that there are statistically significant differences ("a," "b," "c") with a confidence level of 95.0% between levels. The above indicates how in sections, as external diameters decrease, and internode distances increase (lower number of nodes per section), Manning's n roughness decreases.

**Multiple ranges test for zone**

As with the section and flow variables, the mean comparison for the factor zone was applied with the HSD Tukey's test. Table 10 shows that there are no statistically significant differences between any couple of means of the zone-related

levels (letter “a”), all done with a confidence level of 95.0%. This complements what was shown in the multifactor ANOVA, namely that the zone factor does not influence the n-Manning values.

### Discussion on roughness concerning the factors

Determining Manning’s roughness coefficient (n-value) for perforated Guadua to design subsurface agricultural drainage systems is an innovative approach. The values obtained allow the pipe diameter calculation, assuming that flow occurs with the pipe filled but without pressure. While the values found may be higher than those established for other types of pipes, such as PVC, the advantage of Guadua is that it is an environmentally friendly plant-based material readily available in the region. This makes it an economical alternative for farmers, who can potentially sell or use it for their benefit. Guadua thus becomes a sustainable and cost-effective choice for agricultural drainage systems, offering both ecological and economic benefits.

Since, to date, there are no reported studies that have measured the roughness of perforated Guadua as drainage pipes in filter systems, the results of this research will be compared with roughness values reported by tests where Guadua or other materials were used as non-perforated conduction pipe.

Starting from the Manning roughness results obtained in the flows Q1, Q2, and Q3, it can be established that the null hypothesis is rejected; therefore, there is a statistically significant difference between them because as the flow increases, Manning’s roughness decreases (inverse relationship), as referenced in Eq. (1) and presented in Table 3.

This study found values of roughness (0.1089 and 0.0337) lower than those reported by Monge Freile et al. (2019), who studied the use of Guadua as a pipe in an irrigation district with sections diameters of 60 and 80 mm and determined that roughness oscillated from 0.0175 to 0.0283, with an average of 0.0232 for different flow rates evaluated. Similarly, a study carried out by Almeida Neto et al. (2000) evaluated parameters in bamboo pipes of 90 and 130 mm and characterized their Manning roughness as ranging from 0.0124 to 0.0250, with an average of 0.0154, both of which are lower than the value found in this study; nevertheless, the results of this study match with what Andes University and PAVCO report stated; however, this study was carried out with sanitary PCV piping with 250 mm of fixed diameter (González Vega et al. 2009).

Likewise, Vatankhah (2015) found that Manning’s roughness coefficient, under the condition of partially complete flow, varies with the flow film for circular channels. Therefore, it confirms that when varying the flow, Manning’s roughness varies.

Based on the results obtained for Manning’s roughness for the culm section, it can be established that the null hypothesis is rejected; therefore, there is a statistically significant difference between the section levels—as the diameter decreases (higher section), the Manning’s roughness decreases (direct relationship). The above can be understood because the morphology of the Guadua (Fig. 2) in the lower section presents a larger diameter and hydraulic radius; furthermore, in the same section, there are shorter distances between nodes, and therefore, a higher number of nodes, which would result in greater losses. Although there are no records that mention Manning’s roughness with agricultural drainage piping regarding the culm section, the results of this study are related to what was reported by Araya et al. (2018), establishing that an increase in the flow depth and the wetted perimeter, increase the values of Manning’s roughness coefficient. The above was carried out with 315 mm diameter sanitary PVC piping.

Cabrera, referenced by Alarcón and Camacho (2019), found that there is a variation of Manning’s n coefficient concerning the high-density polyethylene (HDPE) piping diameter, obtaining averages of 0.0076 for a 100 mm diameter piping and an n average of 0.0099 for a 150 mm diameter piping, concluding that the greater the diameter, the greater its Manning’s n.

When reviewing the obtained results of Manning’s roughness for the site location of the stands, it can be established that the null hypothesis is not rejected; therefore, there is no statistically significant difference between the different location zones of the stands, indicating that this factor does not affect the Manning’s roughness values, in this sense, it can be observed that the elevation above sea level where the stands are located is very similar, with no difference greater than 24 m (Table 1); therefore, it can be inferred that they maintain the same morphological characteristics. Being this, the first project carried out on the study of *Guadua* as drainage piping, no comparison pattern was found as a reference for the location zones of the stands.

### Conclusion

The laboratory test results indicate that the Manning’s “n” value of Guadua, when used as a drainage pipe, behaves similarly to other commercial materials such as PVC, HDPE, concrete, among others. After a bilateral comparison of the test results, it can be inferred that using Guadua as a drainage pipe would enhance water management in areas like the one studied (Municipio de Pitalito). Additionally, it presents itself as an economically viable alternative, contributing to a reduction in environmental impact due to the nature of the material being utilized.



The parameters considered in these experimental investigations include flow, section, and zone. Based on the experimental results, the following conclusions were drawn,

- Manning's roughness varies between 0.1089 and 0.0337 with respect to the flow factor, demonstrating a decrease as flow rates increase. Statistically significant differences in flow levels were observed. This behavior emphasizes the importance of operating perforated Guadua pipes under full-flow conditions, without pressure, to enable efficient water evacuation.
- Manning's  $n$  roughness fluctuates between 0.1004 and 0.0356 with the section factor. This behavior reveals reduced roughness in smaller diameter sections and confirms statistically significant differences between section factor levels. These findings underscore the superior hydraulic performance of upper Guadua sections, particularly under applied flow conditions.
- Manning's  $n$  roughness varies from 0.0910 to 0.0533 concerning the zone factor. The results demonstrate high homogeneity, indicating no significant differences in roughness among stand locations.
- Manning's roughness for agricultural drainage pipes made of *Guadua angustifolia* exhibited an average value of 0.0719, with a maximum of 0.2197 and a minimum of 0.0116. Compared to values established by Ortega and Salgado (2001), the average roughness of Guadua pipes is higher than that of clay (0.013), concrete (0.015), and PVC (0.015) pipes. However, some values fall below these thresholds, mainly when working with medium and high flows in small-diameter piping. It demonstrates that using appropriately sized perforated Guadua pipes for specific flow rates is a viable and sustainable alternative for subsurface agricultural drainage systems, providing the potential for improved water management and reduced environmental impact; however, it is important to consider the limitations of the physical properties of the Guada and the different care regarding the bio-environmental factors of the area.

## Recommendations

It is suggested to carry out research involving different types of lateral perforations to gain a more comprehensive view of *Guadua angustifolia*'s capabilities as a drainage pipe material. It could include standard circular and oval perforations and designs with a three-bobbin distribution in the pipe. These studies will enable the assessment of Guadua's versatility in different configurations and its adaptability to various drainage needs.

It is important to consider altitude in future research related to *Guadua angustifolia* as a drainage pipe material.

It is recommended to conduct studies in areas where this species naturally grows, such as the inter-Andean valleys of the Magdalena and Cauca rivers, located at altitudes ranging from 500 to 1500 meters above sea level. Studying Guadua under these altitudinal conditions will allow a better understanding of their performance and durability in specific environments.

Expanding the research to address additional variables affecting Guadua's performance as a drainage pipe is recommended. It may include examining the influence of different slope levels on water flow through the pipes using greater lengths than those employed in previous studies and considering the number of nodes present in sections of *Guadua angustifolia* Kunth. These variables are crucial for better understanding Guadua's behavior in diverse conditions and applications.

A specific study on *Guadua angustifolia* as a water conduit material is suggested. It involves evaluating its Chézy roughness coefficient and its ability to transport fluids by gravity without significant energy expenditure. This study would be relevant for water distribution applications in areas where energy is limited or costly, and Guadua could offer an efficient and sustainable solution.

**Acknowledgements** The authors thank the Surcolombiana University for its collaboration during the development of this study.

**Funding** Open Access funding provided by Colombia Consortium.

## Declarations

**Conflict of Interest** The authors have no conflict of interest with anyone related to the material presented in the paper, and we declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

## References

- Abdullah J, Mohd Arif Zainol MRR, Riahi A et al (2023) Investigating the relationship between the manning coefficients ( $n$ ) of a perforated subsurface stormwater drainage pipe and the hydraulic parameters. Sustainability 15:6929. <https://doi.org/10.3390/su15086929>



- Alarcón JJ, Camacho LJP (2019) Variación del coeficiente de rugosidad de Manning bajo distintos escenarios hidráulicos. Universidad Tecnológica de Pereira, Pereira
- Araya IA, González CV, Jiménez M (2018) Análisis de la variación del coeficiente de rugosidad de Manning con respecto a la pendiente del canal en tubería de PVC de 315 mm de diámetro. *Revista Ingeniería UC* 25:43–49
- Burbano Ibarra LM, Ortiz Claros AV (2021) Determinación de la resistencia a la compresión perpendicular a la fibra y módulo de elasticidad circunferencial de la *Guadua angustifolia* Kunth modificada como tubería de drenaje agrícola en el municipio de Pitalito. Universidad Surcolombiana
- Burns SF (2006) Landslides in practice: investigation, analysis and remedial/preventative options in soils: (Derek H. Cornforth). *Environ Eng Geosci* 12:81–82. <https://doi.org/10.2113/12.1.81>
- Calvache-Ulloa AM (1970) Manejo del Agua de Riego en Zonas de Ladera. *Eidos* 2:32–39. <https://doi.org/10.29019/eidos.v0i2.52>
- Carantón García LA, Molina Gordillo JF (2021) Implementación de la *Guadua angustifolia* Kunth como tubería para el diseño y construcción de drenaje agrícola en la Usco - Pitalito. Universidad Surcolombiana
- Chen S, Sun B, Fang H et al (2022) Analysis of the roughness coefficient of overflow in a drainage pipeline with sedimentation. *J Pipeline Syst Eng Pract* 13:0000668. [https://doi.org/10.1061/\(asce\)ps.1949-1204.0000668](https://doi.org/10.1061/(asce)ps.1949-1204.0000668)
- Concrete Pipe Association of Australasia (2017) Concrete Pipe Facts | General | General. In: Concrete Pipe Facts - Concrete Pipe Association of Australasia. <https://www.cpa.asn.au/General/concrete-pipe-facts.html>. Accessed 27 Mar 2023
- Cortez Mejía PE, Tzachkov V, Rodríguez Varela JM, et al (2016) Estudio del coeficiente de rugosidad de tuberías etapa II proyecto “estudio del coeficiente de rugosidad de tuberías etapa II” CLAVE HC1610.1 Informe final. México
- De Almeida Neto JA, Testezlaf R, Matsura EE (2000) Características hidráulicas de tubos de bambu gigante. *Revista Brasileira De Engenharia Agrícola e Ambiental* 4(1):7. <https://doi.org/10.1590/S1415-43662000000100001>
- de Noriega Ome M, los Á, Valbuena Calderón OE, (2019) Caracterización de servicios ecosistémicos de la *Guadua angustifolia* Kunth en la cuenca baja del río Guarapas en Pitalito, Huila. La guadua, una apuesta al cumplimiento de los objetivos del desarrollo sostenible. Universidad Nacional Abierta y a Distancia, Pitalito, pp 93–123
- Duarte Toro M, Erazo WJ, Barrios RYF, Joven QAN (2016) Actividades de manejo silvicultural asociadas a las propiedades físicas y mecánicas de la *Guadua angustifolia* kunth en el municipio de Pitalito. *Ingeniería y Región* 14:75–85. <https://doi.org/10.25054/22161325.695>
- Génova L, Andreau R, Etchevers P, Etcheverry M (2015) Impacto del riego por goteo superficial y subterráneo y del drenaje en la distribución de la humedad y salinidad edáficas y en el rendimiento del tomate cultivado bajo cubierta. *Cuadernos Del Curiham* 21:1–9. <https://doi.org/10.35305/curiham.v21i0.33>
- González Vega CM, Guerrero Molina E, Gonzáles E, et al (2009) Determinación del coeficiente n Manning y rugosidad absoluta ks de la tubería NOVAFORT de 250 mm. Bogotá
- Herrera-Puebla J, Pujol-Ortiz R, de Jesus López-Canteñs G et al (2009) Hydraulic evaluation of subsurface drainage in rice fields. *Ingeniería Agrícola y Biosistemas* 1:103–108. <https://doi.org/10.5154/r.inagbi.2009.08.017>
- ICONTEC (2007a) NTC 5301 PRESERVACIÓN Y SECADO DEL CULMO DE *Guadua angustifolia* KUNTH. In: Instituto Colombiano de Normas Técnicas y Certificación (ed) Norma Técnica Colombiana. Bogotá
- ICONTEC (2007b) NTC 5525 Métodos de ensayo para determinar las propiedades físicas y mecánicas de la *Guadua angustifolia* kunth. In: Instituto Colombiano de Normas Técnicas y Certificación (ed) Norma Técnica Colombiana. Bogotá
- ICONTEC (2009b) NTC 5727 TERMINOLOGÍA APLICADA A LA GUADUA Y SUS PRODUCTOS. In: Instituto Colombiano de Normas Técnicas y Certificación (ed) Norma Técnica Colombiana. Bogotá
- ICONTEC (2008) NTC 5300 COSECHA Y POSTCOSECHA DEL CULMO DE *Guadua angustifolia* KUNTH. In: Instituto Colombiano de Normas Técnicas y Certificación (ed) Norma Técnica Colombiana. Bogotá
- ICONTEC (2009a) NTC 5726 Inventario de Rodales de *Guadua angustifolia* kunth para aprovechamientos con fines comerciales. In: Instituto Colombiano de Normas Técnicas y Certificación (ed) Norma Técnica Colombiana. Bogotá
- ICONTEC (2013) NTC 6028 TUBERÍAS DE DRENAJE DE POLICLORURO DE VINILO RÍGIDO (PVC-U). DIMENSIONES, REQUISITOS Y ENSAYOS. In: Instituto Colombiano de Normas Técnicas y Certificación (ed) Norma Técnica Colombiana. Bogotá
- Lipangile TN (1985) Bamboo water pipes. *Waterlines* 3:18–20. <https://doi.org/10.3362/0262-8104.1985.018>
- Martínez Beltrán J (1999) CIGR handbook of agricultural engineering, Volume I Land and Water Engineering, Chapter 5 Irrigation and Drainage, Part 5.6 Land Drainage. CIGR Handbook of Agricultural Engineering Volume I Land and Water Engineering pp 430–484. <https://doi.org/10.13031/2013.36307>
- Mendez Pedroza NM, Montealegre Torres WI (2017) Adaptabilidad de biotipos de la guadua (*Guadua angustifolia* Kunth) etapa vivero en bosque húmedo premontano, cuenca hidrográfica río guarapas, predio marengo municipio Pitalito. Huila, Pitalito
- Monge Freile M, Sánchez Delgado M, Huanca Velarde LA, Moreno Llacza A (2019) El bambú (*Guadua angustifolia* spp.) como alternativa de conducción para un sistema de riego por multi-compuertas. *Anales Científicos* 80:. <https://doi.org/10.21704/ac.v80i1.1391>
- Mott RL (2006) *Mecánica de Fluidos*. Sexta edición, Pearson Educación, México
- Ochoa JPM, Mora-Villalobos CA, Coca MMG (2021) Relações entre política e realidade cafeeira: estudo de caso em Pitalito (Huila-Colômbia). *Redes*. <https://doi.org/10.17058/redes.v26i0.17253>
- Ortega L, Salgado L (2001) Drenaje en suelos agrícolas. CNR
- PAVCO (2005) MANUAL TECNICO Tubo sistemas para Uso Agrícola PAVCO
- Perrero JH (1968) Cálculo hidráulico en conductos de hormigón. Análisis del factor de rugosidad. *Inf Constr* 21:63–68. <https://doi.org/10.3989/ic.1968.v21.i202.3864>
- Pizarro Cabello F (1985) Drenaje agrícola y recuperacion de suelos salinos. Agrícola Española, Madrid



- Polón Pérez R, Ruiz Sánchez M, Dell'Amico Rodríguez JM et al (2011) Principales beneficios que se alcanzan con la práctica adecuada del drenaje agrícola. *Cultivos Tropicales* 32:52–60
- Portillo España LE (2012) Calibración de vertederos de pared delgada para plantas de tratamiento de aguas residuales. Universidad de San Carlos de Guatemala, Guatemala
- Quang CNX, Giang NNH, Hoa HV, Hung PQ (2022) Effects of sediment deposit on the hydraulic performance of the urban stormwater drainage system. *IOP Conf Ser Earth Environ Sci* 964:012020. <https://doi.org/10.1088/1755-1315/964/1/012020>
- Rivera Benítez A, García Jacho CA (2019) Evaluación del comportamiento hidráulico y mecánico de tubos de hormigón armado revestidos internamente con polietileno. universidad de especialidades espíritu santo
- Sapuyes E, Osorio J, Takeuchi C et al (2018) Resistencia y elasticidad a la flexión de la *Guadua angustifolia* Kunth de Pitalito, Huila. *Rev Invest* 11:97–111. <https://doi.org/10.29097/2011-639x.182>
- Stuyt L, Dierickx W, Martínez Beltrán J (2009) Materiales para sistemas de drenaje subterráneo. Roma
- Suárez Díaz J (2009) Deslizamientos: Técnicas de Remediación. Universidad Industrial de Santander UIS, Bucaramanga
- Sun B, Yang R, Tong A et al (2023) The changing rules of the composite roughness in drainage pipelines with sediments. *Water Supply* 23:975–995. <https://doi.org/10.2166/ws.2023.040>
- Takeuchi TC, Duarte TM, Capera OAF, Erazo EWJ (2012) Análisis de varianza multifactorial para resistencia última a la compresión paralela a la fibra en muestras de *Guadua angustifolia* Kunth. *Ingeniería y Región* 9:53–61. <https://doi.org/10.25054/22161325.775>
- Takeuchi TC, Duarte TM, Alarcón GJE, Olarte FJF (2014) Estudio multifactorial de resistencia última a tensión paralela a la fibra en muestras de *Guadua angustifolia* Kunth. *Ingeniería y Región* 11:85–90. <https://doi.org/10.25054/22161325.745>
- Tarakanov DI (2022) Plastic pipes and their use in rainwater drainage systems. *IOP Conf Ser Earth Environ Sci* 988:052032. <https://doi.org/10.1088/1755-1315/988/5/052032>
- Te CV (1999) *Hidráulica de Canales abiertos*, 1st edn. McGraw-Hill, Bogotá
- Vatankhah AR (2015) Analytical solution of gradually varied flow equation in circular channels using variable Manning coefficient. *Flow Meas Instrum* 43:53–58. <https://doi.org/10.1016/j.flowmeasinst.2015.04.004>
- Yannopoulos SI, Grismer ME, Bali KM, Angelakis AN (2020) Evolution of the materials and methods used for subsurface drainage of agricultural lands from antiquity to the present. *Water* 12:1767. <https://doi.org/10.3390/w12061767>

