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Hydraulic performance of knife-cut drainpipes without envelope[1]

Desempenho hidráulico de tubos de drenagem ranhurados sem revestimento

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HIGHLIGHTS:

Knife-cut drains maintain comparable water admission despite smaller orifices.
The elongated geometry appears to restrict larger particle intrusion.
Knife-cut drainpipes offer practical and economic advantages for envelope-free drainage systems.

ABSTRACT: Subsurface drainpipes with narrow, elongated orifices can be designed to operate without envelope material, reducing costs and simplifying system installation. However, their hydraulic performance remains poorly studied. This study evaluated a drainpipe engineered for use without an envelope (Drainpipe KC) and compared it with a conventional orifice drainpipe with (Drainpipe E) and without (Drainpipe NE) an envelope. Laboratory tests under varying hydraulic heads assessed flow rate, inlet resistance, effective radius, and the applicability of the orifice equation. The geometric characteristics of each drainpipe's orifices were also determined. Flow rates increased with hydraulic head for all systems. The NE Drain exhibited statistically higher flow rates. For pressure heads ranging from 0.1 to 0.3 m.w.c. and 0.9 to 1.1 m.w.c., the flow rates of the KC and E drains were statistically equal. Drainpipe KC demonstrated superior drainage capacity while dispensing with envelope material, highlighting its technical effectiveness. The orifice equation accurately represented the hydraulic behavior of Drainpipes NE and KC, and was suitable for Drainpipe E only when both the discharge coefficient and the head exponent were adjusted.

Key words: agricultural drainage, corrugated pipes, envelope-free drainage, drainpipe clogging, sediment control

RESUMO: Tubos de drenagem subterrânea com orifícios estreitos e alongados podem ser projetados para operar sem material envoltório, reduzindo custos e simplificando a instalação do sistema. No entanto, seu desempenho hidráulico ainda é pouco estudado. Este estudo avaliou um dreno projetado para uso sem envoltório (Dreno KC) e comparou-o com um dreno de orifício convencional com (Dreno E) e sem (Dreno NE) envoltório. Testes laboratoriais sob diferentes cargas hidráulicas avaliaram a vazão, resistência de entrada, raio efetivo e a aplicabilidade da equação do orifício. As características geométricas dos orifícios de cada dreno também foram determinadas. As vazões aumentaram com a carga hidráulica em todos os sistemas. O Dreno NE apresentou estatisticamente as maiores vazões. Para cargas hidráulicas entre 0,1 e 0,3 m.c.a. e 0,9 e 1,1 m.c.a., as vazões do Dreno KC e do Dreno E foram iguais. O Dreno KC demonstrou capacidade de drenagem superior, dispensando o material de envoltório, destacando sua eficácia técnica. A equação do orifício representou com precisão o comportamento hidráulico dos Drenos NE e KC, e foi adequada para o Dreno E apenas quando o coeficiente de descarga e o expoente de carga foram ajustados.

Palavras-chave: drenagem agrícola, tubos corrugados, drenagem sem envoltório, colmatação de drenos, controle de sedimentos

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Introduction

Drain clogging remains one of the costliest maintenance challenges (Yannopoulos et al., 2020; Ghane et al., 2022; Meng et al., 2023). A common approach to address this problem is the use of envelope material between the drainpipe and the porous medium. Under field conditions, envelopes play a fundamental role not only as a mechanical filter but also as a transition layer that mediates the hydraulic and physical interaction between the soil and the drainpipe. To perform this role, envelope materials must exhibit higher hydraulic conductivity than the surrounding soil, which helps maintain low hydraulic gradients near the drain, thereby reducing water velocity and minimizing particle transport into pipes (Batista et al., 2002; Bahçeci et al., 2018; Vlotman et al., 2020; Yannopoulos et al., 2020; Ghane, 2022).

Envelopes work well initially, but they have limitations, as installation costs rise significantly. More critically, their pores trap fine particles, organic matter, and chemical precipitates over time, gradually clogging the system (Stuyt et al., 2005; Guo et al., 2020; Alavi et al., 2021; Byrne et al., 2023a; Ghane, 2023). Ironically, envelopes can worsen clogging. By altering flow patterns around the pipe, they increase water velocity in nearby soil. This intensifies drag forces on particles, carrying more sediment toward the envelope and accelerating its deterioration (Bahçeci et al., 2018; Byrne et al., 2023b). When clogging occurs, complete system replacement is often required, involving reopening trenches, replacing the envelope material, and reinstalling the drainage system. In agricultural areas, this procedure demands production stoppage, which can lead to significant economic losses. Installation machinery also struggles with envelopes. Equipment must be carefully adapted to avoid damaging them, adding operational complexity and expense (Stuyt et al., 1999; Vlotman et al., 2001; Yannopoulos et al., 2020).

These limitations highlight the need for drainpipe technologies that eliminate the use of envelope materials while reducing water inflow velocity to minimize particle transport risks (Bahçeci et al., 2018); thus, a question can be raised: can drainpipes work without envelopes at all? A few North American manufacturers think so and started producing what they call 'knife-cut' or 'sand-slot' pipes. These pipes feature narrow orifices, approximately 0.381 mm wide, which restrict water flow and increase hydraulic resistance, slowing water intake from the soil into the drain. This design reduces erosion and sediment transport into the pipes. Additionally, the small orifice width limits the entry of larger solid particles. Together, these characteristics eliminate the need for envelope materials, lowering installation costs (Ghane, 2022; Ghane et al., 2022).

However, this technology is still little widespread, possibly due to concerns regarding the system's drainage capacity compared to those that use drainpipes with conventional orifices and envelope material. In this context, laboratory bench-scale experiments provide a controlled and reproducible framework to isolate and evaluate the intrinsic hydraulic behavior of drainpipe designs, allowing direct comparison of inflow rates and discharge performance under standardized porous media conditions (Skaggs et al., 1978; Ritzema et al., 2006; Ghane et al., 2022). Laboratory and scaled physical experiments are widely adopted in hydrology, soil science, and irrigation engineering to investigate process–structure interactions under controlled conditions prior to field validation, including reduced operational complexity, and lower costs, before more demanding and costly field-scale investigations (Skaggs et al., 1978; Blume et al., 2016; Yannopoulos et al., 2020; Romero, 2024).

Therefore, the present study does not aim to replace field-scale testing, but rather to provide an initial assessment of whether a knife-cut drainpipe can achieve hydraulic performance comparable to that of conventional systems. Furthermore, an additional question is raised: do drainage systems consisting of conventional drainpipes with envelopes exhibit hydraulic behavior similar to that of drainpipes without envelopes? Accordingly, given the complexity and relevance of artificial drainage in water resources management and agricultural productivity (Minnes et al., 2020; Yannopoulos et al., 2020; Kaur et al., 2023), this study evaluated a novel corrugated drainpipe engineered for use without an envelope (Drainpipe KC) and compared it with a conventional orifice drainpipe with (Drainpipe E) and without (Drainpipe NE) an envelope.

Material and Methods

The morphometric characterization of the drainpipes' orifices was performed in the Department of Biology, Botany Section, of the Universidade Federal de Lavras (UFLA), in Lavras, Minas Gerais state, Brazil. All the other experimental procedures were performed in the Department of Water Resources - UFLA.

Two flexible and corrugated high-density polyethylene (HDPE) drainpipes with a nominal pipe size (NPS) of 100 mm were evaluated. Key dimensions were measured with a 0.01 mm caliper: external radius of 48.70 mm (Ro), internal radius of 43.00 mm (R_i), and drain ring width of 0.72 mm (β_v). Each ring had eight longitudinal orifices (N) spaced 12 mm apart.

The two drainpipe types differed mainly in orifice geometry. Techdreno KC® features narrow knife-cut slits (Figure 1A), while Techdreno NBR® has conventional rounded perforations roughly 6.8 times larger in area (Figure 1B). The standard 100 mm diameter used in most agricultural

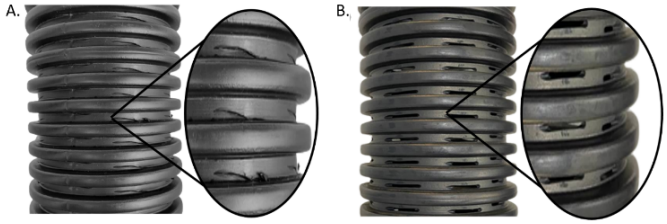


Figure 1. Drainpipes used in the experiment: (A) drainpipe with smaller orifices, in knife-cut shape (Drainpipe KC); and (B) drainpipe with larger orifices, in rectangular shape (Drainpipe NE)

installations was chosen (Gaj & Madramootoo, 2021; Wu et al., 2022).

Additionally, the performance of Drainpipe NE was evaluated in the presence of envelope material, and this condition was referred to as Drainpipe E. This last configuration was Drainpipe NE wrapped with a 100 mm non-woven polyester drainage blanket. This procedure was not performed for Drainpipe KC since it was designed to work without envelopes. The envelope material had the following hydraulic characteristics, as specified by the manufacturer: permittivity of 2.5 s^{-1}, water flux of 0.1262 m^3 s^{-1} m^{-2} and permeability of 0.0040 m s^{-1}.

To reduce water requirements, only three consecutive rings were left unsealed (24 orifices total). All other openings were sealed with silicone and verified leak-proof after 24 hours. The length, width, opening area for water flow, perimeter, circularity, elongation, and compactness of the orifices were determined by processing macroscale-produced digital images, using a Nikon stereomicroscope, model SMZ745T, coupled with an Infinity 1 camera (5x zoom ratio).

Photographs were taken of all the orifices in three rings of each drain, which were chosen randomly. Each orifice was extracted using precision blades to fit the stereomicroscope table, resulting in 24 samples from each draining tube. The specimens were photographed on graph paper, serving as a standard scale for the readings.

The images were processed and analyzed using the ImageJ software (Schneider et al., 2012). This software aids the calculation of the specimens' dimensions by counting the selected regions' pixels (Rasband, 2011). Therefore, after calibrating the standard scale, the images were converted into 8 bits, and the user established the limits of the specimens to determine the values of the morphometric variables analyzed. Finally, the mean and the coefficient of variation of the values obtained for each type of drainage pipe were calculated.

Circularity, also named rounding or angularity, correlates the area by perimeter and describes the object's shape as to its circularity. The values that can be obtained for this variable range from 0 to 1 (1 when the sample is a perfect circle and 0 when the sample is an infinite and elongated polygon). Compactness enables the measurement of circularity, and the more distant its value is from 1, the less circular the object. Elongation is the ratio of the minor axis to the major axis of the sample. If its value is 1, it is inferred that the object is approximately circular or square. The object becomes more elongated as its value deviates from 1 (Ferreira & Rasband, 2012; Viana et al., 2016).

The hydraulic characterization of the drainage pipes was performed by quantifying the flow rate of drained water as a function of the variation of the system's hydraulic head and the opening area of the orifices, for each drainpipe model. Thus, an experimental hydraulic apparatus was developed, consisting of a PVC pipe that involved the drain, allowing the variation of the system's hydraulic head (Figure 2) and presenting a discharge point for conducting and collecting the drained water, which was connected to a water supply system.

The PVC pipe had a nominal diameter of 150 mm, a length of 2.0 m, and 12 orifices equidistant along its length. These orifices have the function of a spillway that, through their opening or individual sealing with cork stoppers of the same diameter, allows varying and maintaining the hydraulic head steady. The orifices were drilled using a 22 mm hole saw coupled with an impact drill. The first perforation was performed at 0.45 m from the lower base of the pipe, and from there, the other perforations were 0.10 m apart from each other. At the bottom of the PVC pipe, a NPS 150 mm sewage PVC Cap was fixed. Using 32 mm hole saw, its center was perforated and connected to NPS 32 mm PVC weldable inlet adapter for reservoirs. The layout of this structure is presented in Figure 2.

A NPS 32 mm PVC weldable inlet adapter for reservoirs was coupled to a NPS 150 cap, then connected to a set of weldable NPS 32 PVC pipes and fittings to conduct the drained water to a collection point. The evaluated drainage pipe was sleeved by a NPS 150 mm PVC pipe and connected to the discharge system (Figure 3). A NPS 100 mm cap was attached to the lower base of the drainpipe, which had its center drilled using a 32 mm hole saw. In this orifice, a NPS 32 mm PVC weldable inlet adapter for reservoirs was installed and coupled to the adapter that connects the PVC 150 mm pipe and the discharge system. The zone of unobstructed drain orifices was subsequently distanced 0.35 m from its base, so the first orifice of the NPS 150 PVC pipe provided a hydraulic head of 0.10 m on the first

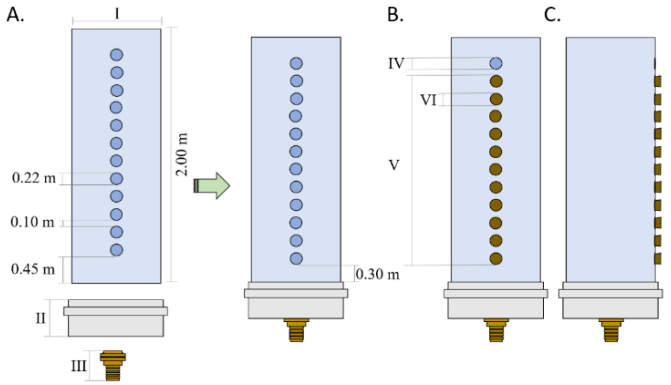


Figure 2. Layout of the structure that involves the drainpipe and allows the variation of the hydraulic head over the pipe: constituent parts (A); and structure with the 12th orifice opened and the others sealed, in front view (B) and side view (C)

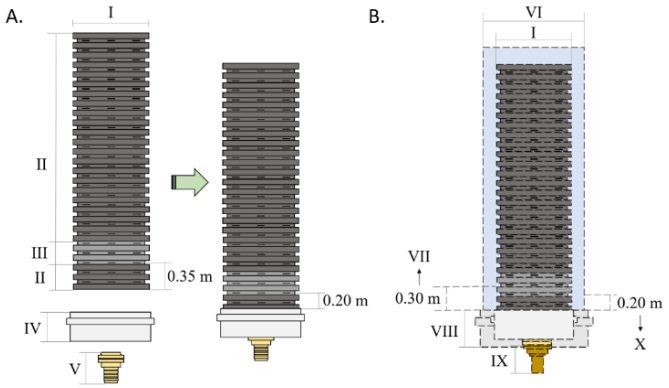


Figure 3. Layout of the drainpipe sleeving process: preparation of the drainpipe (A) drainpipe sleeved by NPS 150 mm PVC pipe and connected to the discharge system (B)

unobstructed drain ring. Figure 3 shows this structure's layout and the drain's sleeve.

Three NPS 32 PVC pipes with a length of 0.45 m were positioned in the idle space between the drainpipe and the PVC pipe. These pipes were connected to a hydraulic system consisting of NPS 32 mm PVC weldable pipes and connections, connecting the experimental apparatus to a continuous water supply system.

The apparatus was vertically supported by a wooden quadrangular prismatic structure. Figure 4 shows the layout of the lateral section of the drainage pipe sleeved by a NPS 150 mm PVC pipe and the water supply pipes (Figure 4A), as well as the top view (Figure 4B), front view (Figure 4C), and side view (Figure 4D) of the apparatus.

To reach the maximum hydraulic head all the perforations of the PVC pipe with cork stoppers were sealed, except for the twelfth, from ground level, which, at this time, acted as overflow spillway. Subsequently, the water supply system control valve was opened, and the space between the PVC pipe and the drainpipe began to be filled with water until the spillway level was reached. Then, the system hydraulic head became steady, in other words, the water intake by the system was sufficient to sustain steady-state conditions; consequently, the effects of internal flow and pressure distribution could be neglected, thereby isolating the hydraulic characteristics of water intake through the orifices.

The resistance factor of the water inlet through the drainpipe orifices was obtained by the empirical Eq. 1 (Oyarce et al., 2017).

$$\alpha_e = \frac{c}{2\pi^2 R_o}\left[\ln\left(\frac{2c}{\pi \beta_v}\right) - \frac{c}{4\pi R_o}\right] + \frac{c}{2\pi N \gamma_p}\ln\left[\frac{2\,\text{senh}\,\frac{2\pi(R_o - R_i)}{\beta_v}}{\text{sen}^2\,\frac{\pi\beta_s}{2\beta_v}}\right] - \frac{1}{2\pi}\ln\left(\frac{R_o}{R_i}\right) \quad (1)$$

Where:

α_e - resistance factor of water inlet through the drain orifices (dimensionless);

c - distance between the orifices in one ring to the orifices located in the next ring with perforations (m);

R_o - outer radius of the drainpipe (m);

R_i - internal radius of the drainpipe (m);

β_v - width of the drainpipe ring (m);

β_s - width of the drainpipe orifice (m);

γ_p - length of the drainpipe orifice (m); and,

N - number of longitudinal orifices per ring (unit).

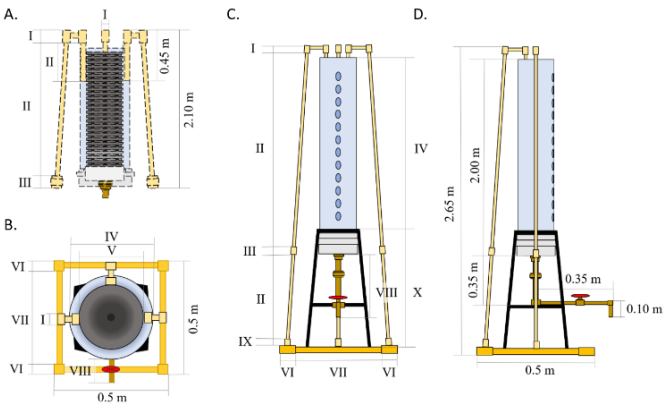


Figure 4. Experimental apparatus: section (A), top view (B), front view (C), and side view (D) of the system

The effective radius of the drainpipes was calculated using Eq. 2 (Dierickx, 1999):

$$R_{ef} = R_o \exp(-2\pi\alpha_e) \quad (2)$$

Where:

R_{ef} - effective radius of the drainpipe (m);

R_o - outer radius of the drainpipe (m); and,

α_e - resistance factor of water inlet through the drain orifices (dimensionless).

The flow rate due to the variation of the system's hydraulic head was quantified by the direct volumetric method (Tucci & Silveira, 2009). The drainpipes were subjected to the hydraulic heads of 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, 1.00, 1.10, and 1.20 m, to simulate the usual maximum depth at which subsurface drainpipes are installed in the field, with three replicates. These hydraulic heads were applied to the drains; however, in the case of the Drainpipe E treatment, the system consisted of a drainpipe plus envelope.

At the beginning of the test, after verifying the condition of steady hydraulic head, a large volume beaker was positioned under the discharge point of the experimental apparatus, allowing the drained water to be collected. This volume was collected at 10-second intervals, and the obtained water mass was measured using an electronic scale with an accuracy of 0.0001 g. Also, water temperature was measured using an infrared thermometer. From the measured mass value, water volume was calculated, and the actual flow rate was calculated using Eq. 3.

$$Qd_r = \frac{P_{(H_2O)}}{\gamma_{(H_2O)}\ t} \quad (3)$$

Where:

Qd_r - actual flow rate ($m^3\ s^{-1}$);

$P_{(H_2O)}$ - mass of the drained solution (kg);

$\gamma_{(H_2O)}$ - density of water as a function of its temperature ($kg\ m^{-3}$); and,

t - collection time of the drained solution (s).

Thus, the average flow rate per orifice Qd_o was obtained by the quotient between the drained flow rate and the number of unobstructed orifices, i.e., 24.

The orifice discharge coefficient was determined by curve fitting based on the relation between the actual flow rate and the maximum flow rate through an orifice (Eq. 4), for each treatment.

$$Cd = \frac{Qd_o}{S\,(2\,g\,h)^X} \quad (4)$$

Where:

Cd - discharge coefficient of the orifice (dimensionless);

S - opening area of the orifice (m^2);

g - acceleration of gravity, considered 9.81 $m\ s^{-2}$;

h - hydraulic head over the orifice (m);

X - head exponent, which is typically adopted as 0.5 (dimensionless); and,

$S\,(2\,g\,h)^X$ - theoretical maximum flow rate ($m^3\ s^{-1}$).

With these coefficients, the flow rate data were estimated and compared to the observed flow rate data to evaluate the suitability of the used model, that is, to evaluate whether the hydraulic behavior of the drains resembled the expected by a hydraulic orifice. The coefficient of determination (R^2) was adopted as the primary goodness-of-fit metric. Following a preliminary assessment of the fitted models, it was observed that, in general, drainpipes for which the calculated R^2 was lower than 70% did not exhibit the expected hydraulic behavior for orifices. In such cases, the discharge coefficient (Cd) and the head exponent (X) were fitted simultaneously to improve model representation, both parameters being presented in Eq. 4. The fitting process was considered convergent when successive iterations resulted in negligible changes in parameter estimates and objective function values. These two R^2 values were subsequently compared.

In addition, to compare the magnitude of the discharge coefficients of each drainage system, the specific discharge coefficient was calculated, which is obtained by calculating the ratio between the discharge coefficient obtained by the single fitting of the orifice equation and the opening area of each drainpipe. The variability of the discharge coefficient due to the hydraulic head variation was then analyzed. This parameter was called the "partial discharge coefficient", and its values were compared with those of the "general discharge coefficient". Thus, Eq. 4 and each treatment's observed flow rate data were used to calculate the discharge coefficient for each evaluated hydraulic head, using an electronic spreadsheet.

Experimental setup and data were analyzed using a completely randomized design with factorial scheme, with two sources of variation: drainage system (3 levels: Drainpipe "KC", Drainpipe "NE", and Drainpipe "E") and hydraulic head (12 levels: 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, 1.00, 1.10, and 1.20 m.w.c.), randomly applied between each assay, with 3 replicates, resulting in 108 observations.

The variables were individually analyzed using the F-test at $p \leq 0.01$. The effect of the qualitative source of variation was compared by the Scott-Knott test, with significance levels of $p \leq 0.05$, while the effect of the quantitative source of variation was evaluated by regression analysis, using the SISVAR software (Ferreira, 2011).

Results and Discussion

The geometric characterization, for drainpipes KC and NE orifices, is presented in Table 1.

The values presented in Table 1 indicate that the magnitude of all the analyzed variables referring to the geometric quantities of the Drainpipe NE orifices, in absolute terms, are larger than those of Drainpipe KC, except for the elongation and length, which are inferior. The values regarding circularity, elongation, and compactness indicate that the Drainpipe KC orifices have more elongated shape and that Drainpipe NE orifices are more rounded (Ferreira & Rasband, 2012; Viana et al., 2016), which can be visualized in Figure 1. In addition, the coefficients of variation obtained for Drainpipe KC are higher than those of Drainpipe NE. Therefore, the orifices of Drainpipe NE show greater geometric uniformity.

The inlet resistance factors obtained for Drainpipes KC and NE were 0.39 and 0.32, while the effective radius values were 0.42 and 0.65 cm, respectively. Therefore, the difference between the obtained values for these variables is minimal, despite the discrepancy between the orifices' opening areas for Drainpipes KC and NE, mainly due to the difference between their widths (Table 1).

These results corroborate with Ghane et al. (2022), who studied the effects of employing corrugated drains with different orifice patterns in subsurface agricultural drainage. The author noticed that, although the increase in the orifices' width or length also increases the water flow, a considerable increase in the effective radius occurs only when there is a relevant increase in the length of the orifices.

This occurs due to the longitudinal proportion of the space occupied by the perforations in the concave portion of the drain corrugations also increases by increasing the length of the orifices, which reduces the convergence of the flow lines towards the perforations since the travel distance of water, to the orifice, is smaller. In addition, the authors warn that the increase in the width of the orifices of subsurface drainpipes may not be interesting since the risk of carrying solid particles and subsequent system obstruction is greater (Ghane et al., 2022).

Likewise, Gaj & Madramootoo (2020) argue that the inlet resistance that affects corrugated drains with more rounded orifices tends to be higher than that of corrugated drains with orifices with the same opening area but with more elongated geometry. The authors explain that the water flow lines tend to follow a planar convergence pattern of radial path (2D in the XZ plane) in drainpipes with more elongated orifices. In contrast, the convergence of the flow lines occurs in the XYZ dimensions in drains with more rounded orifices, which causes a more significant hydraulic head loss compared to more elongated orifices. However, the water flow rate into drainpipes

Table 1. Geometric characterization of the orifices for water flow from drainpipes with smaller (Drainpipe KC) and larger (Drainpipe NE) orifices

Drainpipe	S (mm²)	P (mm)	W (mm)	L (mm)	C (-)	St (-)	Cn (-)
KC	2.63	26.06	0.19	13.90	0.06	45.13	0.02
NE	17.83	27.55	1.64	13.47	0.33	7.30	0.14
CV KC (%)	34.50	19.48	63.54	18.78	28.02	25.57	27.91
CV NE (%)	21.11	15.65	18.64	18.72	21.34	22.90	23.38

Caption - Average values obtained using the ImageJ software for water passage area (S); P – Perimeter; W – Width; L - Length, C – Circularity; St - Aspect ratio, and Cn – Roundness of the orifices for the passage of water from drains with smaller (Drain KC) and larger (Drain NE) orifices, and the coefficient of variation (CV) of each of them

with more rounded orifices is generally higher for the same conditions. Finally, the authors conclude that using corrugated drains with more elongated orifices for the same opening area is hydraulically more advantageous.

Inlet resistance can be defined as an additional head loss caused by the partial permeability of a drainpipe. In short, this phenomenon occurs because the water flow lines in the soil tend to converge as they approach drainpipe orifices, which, for being finite, generate head loss and reduce drainage flow velocity. This parameter depends on the diameter and type of drainpipe, the soil, the used envelope material, and the characteristics of the corrugated drainpipe (Dierickx & van der Molen, 1981; Dierickx, 1999; Ghane, 2022a).

Effective radius is understood as the radius of a fictitious pipe whose walls are completely open (Skaggs, 1978) and is related to the inlet head loss caused by the convergence of the flow lines towards the orifices (Dierickx & van der Molen, 1981). This variable depends on the morphometric attributes and distribution of the orifices in the drainpipe wall and, if used, on the envelope material features (Dierickx, 1999; Gaj & Madramootoo, 2021; Ghane, 2022). Oyarce et al. (2017) indicate that the lower the inlet resistance, the greater the effective radius of the drain.

The summary of the analysis of variance (ANOVA) performed to evaluate the drainpipe orifices' flow rate, due to the applied sources of variation, can be seen in Table 2.

The experimental coefficient of variation (CV) was 2.45% (Table 2), and according to Gomes (2022), the obtained value is considered low (< 10%), and the experimental accuracy is classified as optimal (< 10%) (Ferreira, 1991). Thus, the flow rate drained per orifice, for each drainage system evaluated, can be seen in Table 3.

Table 2. Summary of the analysis of variance (ANOVA) of water flow rate of the evaluated drainpipes systems

Source of variation	DF	Flow rate drained per orifice
		F
Drainage system (DS)	2	115647.663**
Hydraulic head (HH)	11	1302.551**
DS × HH	22	542.728**
Error	72	-
Corrected Total	107	-
CV (%)	2.45	-

CV - Coefficient of variation; DF - Degrees of freedom; F- Value from ANOVA (F); ** - Significant at $p \leq 0.01$ by the F-test

Table 3. Flow rate per orifice means obtained for the drainpipes with knife-cut orifices (Drainpipe KC) and for a conventional shape, under the condition of absence (Drainpipe NE) and presence (Drainpipe E) of envelope material

Drainage system	Flow rate drained per orifice ($m^3\ h^{-1}$)
Drainpipe KC	0.01014 b
Drainpipe NE	0.12823 a
Drainpipe E	0.00953 c

Means followed by the same letter do not differ significantly by the Scott–Knott test at $p \leq 0.05$

The results presented in Table 3 were determined considering the drainpipes' physical quantities, i.e., 167 rings per unit of pipe length, totaling 1336 orifices. The flow rate per unit of pipe length was calculated for each draining system based on this data. The values obtained for Drainpipe KC, NE, and E were 13.55, 171.32, and 12.74 $m^3\ h^{-1}$, respectively. Therefore, the average flow rate per length unit obtained for Drainpipe NE was approximately 13 times higher than that of Drainpipe KC, which can be explained by the higher values of Drainpipe NE orifices' geometric dimensions compared to Drainpipe KC, thus allowing a higher rate of water flow into the system.

Mohamed & Abouzeid (2005) studied water flow behavior through drainage pipes with different ratios of opening areas exposed to different hydraulic heads. These authors found that the rate of water flow into the drains is directly proportional to the ratio of the orifices' opening area for all applied hydraulic heads, which supports the average flows obtained for the different drainage systems (Table 3) in this study. These authors reported that the drainpipe inlet resistance decreases with the increase in the ratio of the opening area of their orifices, which, although not very expressive, was also found in this study. These positive correlations between opening area, inlet resistance, and flow rate were also found by Yang et al. (2023), who indicated that the distribution pattern of the orifices along the pipe walls could influence the drained flow rate for drainpipes with the same opening area.

However, the values presented in Table 3 show that, although the dimensions and distribution pattern of the orifices for Drainpipes NE and E are the same, the average flow rate drained by the latter drainage system was lower. Such behavior may, at first, seem contradictory due to the envelope's effect on the water flow previously presented and because one of the objectives of using envelope materials in subsurface drainage systems is to facilitate the water flow from the soil through the drainpipes' orifices (Ghane et al., 2022; Byrne et al., 2023b; Yang et al., 2023).

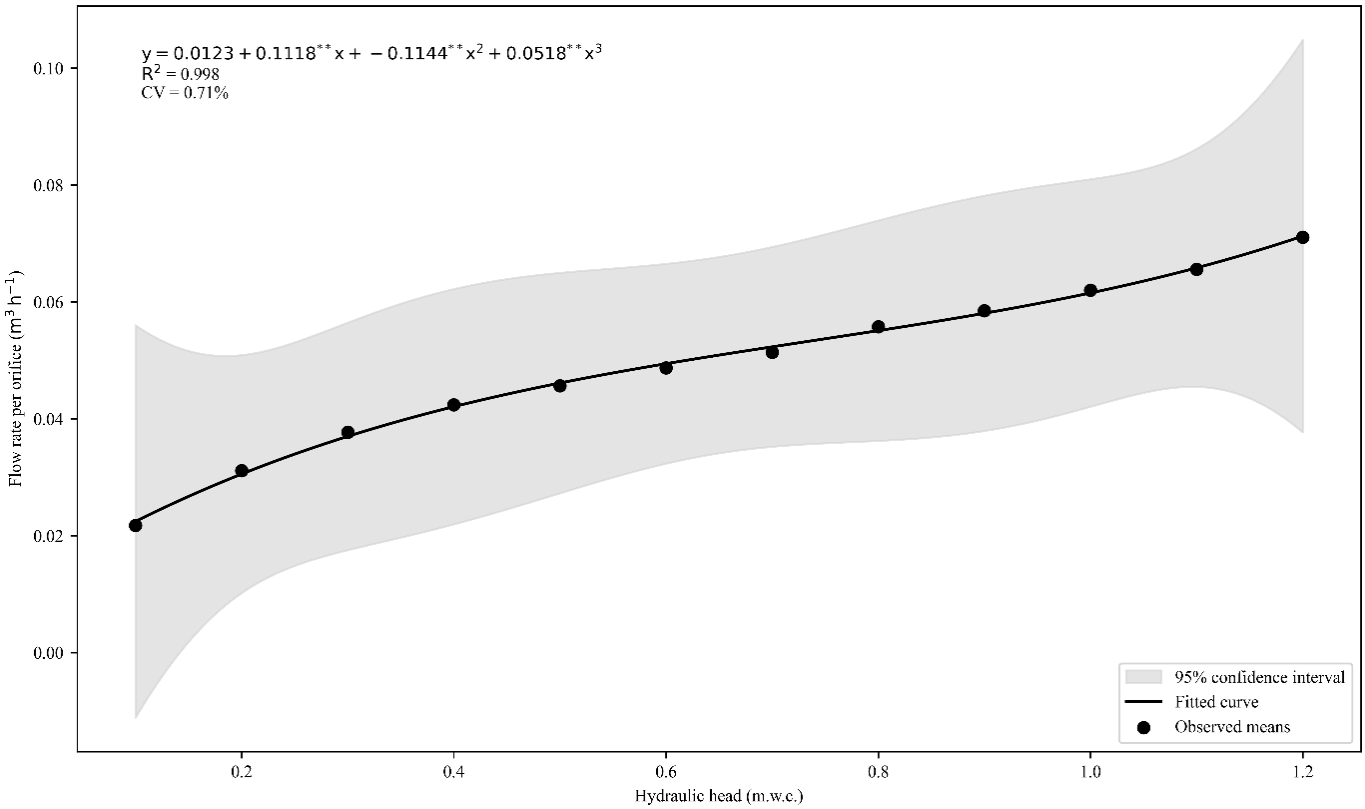
However, the envelope material is expected to act as a flow-facilitating agent only when subsurface employed, since its efficiency is associated, above all, with its ability to restrict the unwanted input of solid particles into the pipes and, mostly, to keep the hydraulic gradient of the soil adjacent to the drainpipe low (Ding & Chang, 2020). In the absence of a porous medium, it is inferred that the envelopes act as a reducing factor of the potential for water inlet through the drainpipe orifices since they have their own porosity. Thus, for the water inlet, it must first cross the pores of the envelope, a physical barrier that, although permeable, generates additional hydraulic resistance compared to the drainpipe without this material. This resistance increases the occurrence of head loss along the path travelled by water, which reduces the water influx, explaining the flow rate results obtained in this study (Table 3).

Figure 5 shows the simple effect of the source of variation "hydraulic head" on the mean flow rate drained per orifice. The estimation of this effect was best represented by a cubic function, with a coefficient of determination (R^2) of 99.83%.

Figure 5 indicates that the flow rate through the orifice increases as the hydraulic head applied to the drainage systems increases. This effect can be explained by the hydrostatic law, which establishes that the pressure of a static fluid system, with

constant density, varies linearly with depth, and by the orifice equation, which is obtained by applying Bernoulli's equation and relates the flow velocity through a hydraulic orifice with the hydraulic head acting over the orifice (Qin & Duan, 2017; Azevedo Netto & Fernández, 2018; Ramos et al., 2020; Hansen, 2023). Thus, since the absolute pressure acting on the unobstructed drain orifices in the experimental apparatus results from the sum between atmospheric pressure and the pressure exerted by the water column, upon reaching hydraulic balance, the greater the water column (i.e., the hydraulic head), the greater the pressure exerted on these orifices. The fluid flow velocity through the perforations increases by increasing the pressure on the orifices, which have a constant opening area. Therefore, there is an increase in the drained flow rate.

Table 4 presents the mean flow drained per orifice due to the source of variation "draining system" within each level of the "hydraulic head" factor. For all applied hydraulic heads, the mean flow rate drained per orifice of Drainpipe NE was



** - Significant at p ≤ 0.01 by t-test

Figure 5. Flow rate drained per orifice as a function of the hydraulic head

Table 4. Flow rate per orifice for each drainage system at different hydraulic head levels, comparing drainpipes with knife-cut orifices (Drainpipe KC) and conventional drainpipes without (Drainpipe NE) and with (Drainpipe E) envelope material

Hydraulic head (m.w.c.)	Mean flow rate drained per orifice (m³ h⁻¹)		
	Drainage system		
	Drainpipe KC	Drainpipe NE	Drainpipe E
1.2	0.01688 c	0.16953 a	0.02677 b
1.1	0.01619 b	0.16357 a	0.01697 b
1.0	0.01513 b	0.15739 a	0.01347 b
0.9	0.01357 b	0.15080 a	0.01112 c
0.8	0.01225 b	0.14565 a	0.00941 c
0.7	0.01105 b	0.13512 a	0.00941 c
0.6	0.00989 b	0.12968 a	0.00658 c
0.5	0.00854 b	0.12268 a	0.00573 c
0.4	0.00709 b	0.11521 a	0.00481 c
0.3	0.00555 b	0.10325 a	0.00435 b
0.2	0.00365 b	0.08611 a	0.00363 b
0.1	0.00190 b	0.05977 a	0.00359 b

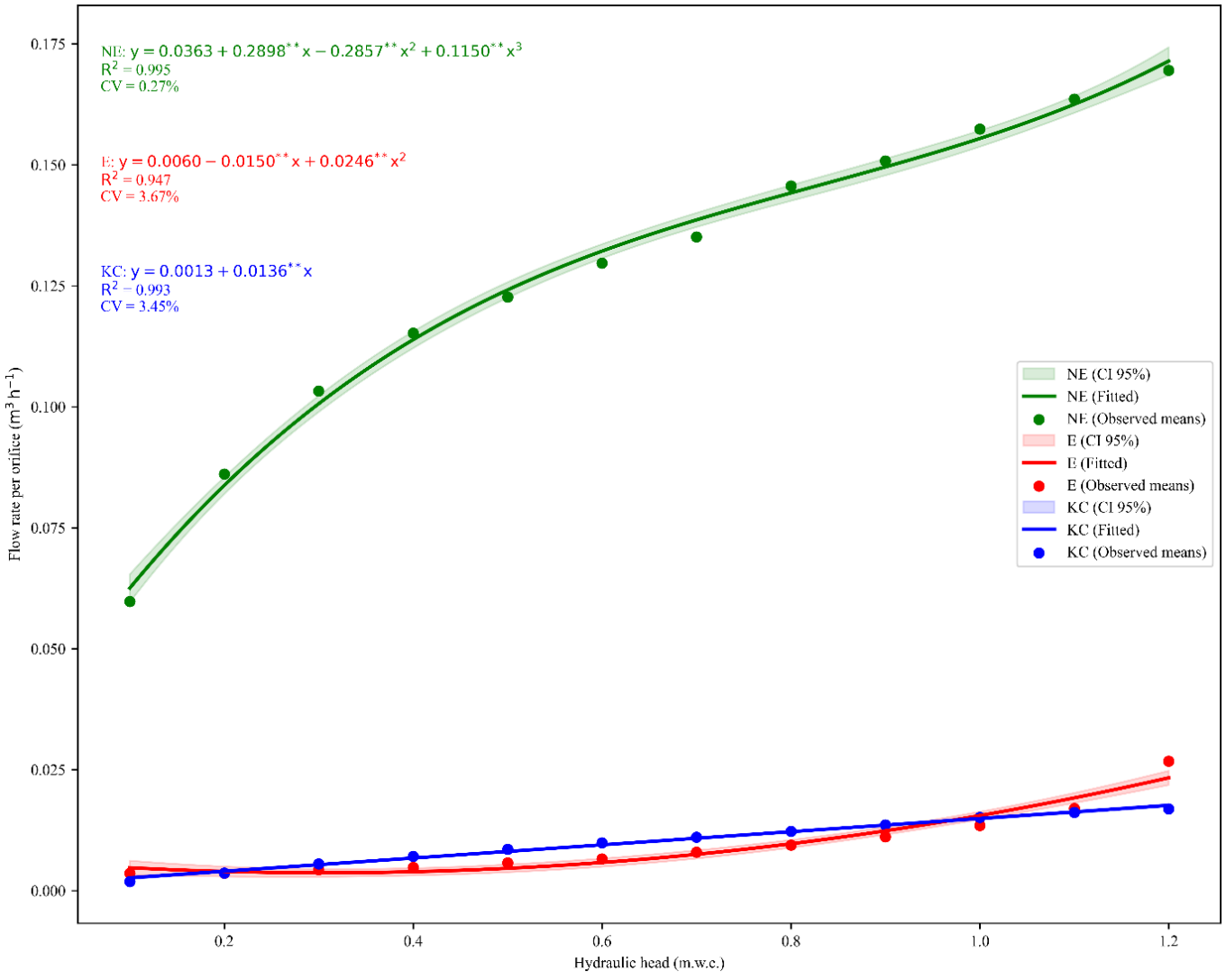
Means followed by the same letter in the row do not differ significantly according to the Scott-Knott test at p ≤ 0.05

statistically different from and higher than those for the other drainage systems. The means obtained for Drainpipes KC and E were statistically equal for the hydraulic heads of 1.1, 1.0, 0.3, 0.2, and 0.1 m.w.c. However, although close in magnitude, the means obtained for Drainpipe KC were mostly higher, except for the 1.2 m.w.c. hydraulic head, which may indicate a change in the hydraulic behavior of the conventional drainpipe with the presence of envelope material.

On the other hand, Figure 6 shows the "hydraulic head" effect within each level of the "drainage system" factor. In this evaluation, significant differences were found for all the interactions performed. For Drainpipe KC, the equation that best fit the observed data was the first-degree polynomial, with an R^2 of 99.3%; for Drainpipe E, it was the second-degree polynomial equation, with R^2 of 94.7%; and for Drainpipe NE, a third-degree polynomial, with an R^2 of 99.5%.

Figure 6 indicates that the magnitude of the flows drained per orifice by Drainpipes KC and E are similar and lower than the magnitude of the flows drained by Drainpipe NE, which, once again, corroborates the results previously obtained. In addition, the behavior of the increase in the flow rate through the orifice due to the hydraulic head increase for Drainpipe KC is similar to the behavior observed for Drainpipe E, and these increases are more tenuous than those observed for Drainpipe NE. Therefore, it is concluded that the variability of the drained flow rate due to the hydraulic head over Drainpipe NE is greater than the variability of the drained flow rate shown by the other drainpipe systems. Finally, the higher the hydraulic head applied, the higher the average flow rate drained per orifice for all drainage systems.

The values obtained by the single fitting of the Cd and their respective R^2 for each drainage system were 0.328 and 99.33% for Drainpipe KC, 0.575 and 98.84% for Drainpipe NE, and 0.046 and 69.64% for Drainpipe E, respectively. This coefficient is a dimensionless parameter that expresses the relationship between the actual flow rate and the maximum (theoretical) expected flow rate through a hydraulic orifice. Cd is intrinsically related to the head loss in the system due to the narrowing of the flow, which is caused by the resistance to water inlet exerted by the orifice. This parameter describes fluid flow efficiency through a hydraulic orifice (Wadhwa, 2022; Zaiter et al., 2024). Therefore, the drainage capacity of Drainpipe NE is approximately 13 times higher than that of Drainpipe E since, while maintaining all the other variables



** - Significant at p ≤ 0.01 by t-test; CI – Confidence interval

Figure 6. Water flow rate per orifice as a function of hydraulic head within each level of draining systems KC, NE and E

of the orifice equation constant, the higher the discharge coefficient, the greater the flow rate drained into the orifices (Eq. 4). This finding supports the flow rate drained means presented in Table 4 for the evaluated drainage systems.

By analyzing the obtained R^2 values for the orifice equation fittings, it was found that the drainage system best suited for using the orifice equation to describe its hydraulic behavior was Drainpipe KC, followed by Drainpipes NE and E. However, as the value of R^2 for the orifice equation for Drainpipe E was less than 70%, a new regression analysis was conducted, fitting the discharge coefficient and head exponent concurrently (Eq. 4). The new values obtained for these parameters were 1.831×10^{-12} and 1.75, respectively, with an R^2 of 89.50%. This suggests that the simultaneous fitting of the discharge coefficient and the head exponent can result in a mathematical model that represents the hydraulic behavior of the orifices of this drainage system with greater reliability.

The deviation of the fitted head exponent from the classical value of 0.5, particularly for the drainage system with envelope material (Drainpipe E), indicates that the dominant hydraulic behavior can not be described solely by ideal free orifice discharge. This suggests the presence of additional energy dissipation mechanisms associated with flow through a permeable interface prior to entering the orifice. Similar deviances from classical pressure–discharge relationships have been reported in studies of flow through porous and semi-porous media, where pore-scale resistance and velocity-dependent effects lead to non-linear pressure–velocity behavior under laboratory conditions (Dierickx, 1999; Gaj & Madramootoo, 2021; Young & Kabala, 2024). In this context, fitted head exponents greater than 0.5 should be interpreted as empirical indicators of complex flow behavior governed by inlet resistance and porous media effects, rather than as a purely theoretical orifice discharge mechanism.

Similar non-classical head–discharge relationships have been reported in systems where flow is influenced by geometric constraints and distributed hydraulic resistance, such as drip irrigation emitters and non-ideal orifice configurations. In these systems, the discharge exponent reflects the sensitivity of flow to pressure variations and may deviate from the classical value of 0.5 due to viscous losses, flow tortuosity, and resistance imposed by control elements or geometric characteristics of the inlet (Farley & Trow, 2003; Greyvenstein & van Zyl, 2007; Chen et al., 2022; Alsaydalani, 2023; Eltoukhy & Alsaydalani, 2023).

Experimental evidence shows that discharge coefficients and pressure–flow relationships can vary significantly with hydraulic head and orifice geometry, reinforcing that such deviations arise from combined hydraulic and geometric effects rather than idealized orifice behavior. Head exponents greater than 0.5, as observed in this study, are interpreted as an empirical representation of the hydraulic response under laboratory conditions, rather than as a strict theoretical description of ideal orifice flow.

The head exponent of the orifice equation expresses the relation between the flow into an orifice and the pressure difference between the two sides of this orifice. This pressure difference is due to the inlet resistance caused by the partial permeability of the drains, since the orifices of these pipes represent, at most, about 1 to 2% of the total wall area (Dierickx, 1999; Gaj & Madramootoo, 2021). Then, by applying Bernoulli's Theorem, due to the reduced flow area, the fluid velocity increases, and the static pressure head decreases.

Thus, this exponent describes how the hydraulic head influences the flow through the orifice; the higher its value, the greater the sensitivity, or even the dependency, of the flow rate drained to variations in the hydraulic head (Farley & Trow, 2003; Greyvenstein & van Zyl, 2007). Therefore, as the value of the fitted head exponent for Drainpipe E (1.75) was higher than the theoretical value that is usual for the orifice equation (0.5), it is inferred that the flow rate drained by this drainage system is more susceptible to hydraulic head variations than that of the other systems studied, under the evaluated laboratory conditions. However, the value presented for the Cd of this drain was low (1.831×10^{-12}), contributing, in absolute terms, to a less expressive variation of the flow rate than the variation of the hydraulic head despite the high head exponent, due to the presence of the envelope material that hinders the full expression of this draining system's potential, from a hydraulic standpoint. In addition, for this drainpipe system, the highest increases in flow rate drained were obtained for the two highest hydraulic heads applied (Figure 6 and Table 4); it is inferred that higher pressure heads, possibly above 1.0 m, could suppress the inflow resistance caused by the envelope. However, as the maximum hydraulic head applied in this study was 1.2 m, it is impossible to fully understand the effects of the envelope's use on the inflow resistance, indicating the need for further investigation beyond the tested head range.

It is important to emphasize that the simultaneous fitting of the discharge coefficient and the head exponent for Drainpipe E should be interpreted as an empirical modeling approach, aimed at improving the representation of the observed laboratory data, rather than as a direct extrapolation of physical parameters to field-scale conditions. This type of bench-scale empirical fitting is consistent with previous hydraulic studies dealing with non-ideal flow conditions and porous interfaces (Farley & Trow, 2003; Greyvenstein & van Zyl, 2007; Chen et al., 2022), in which deviations from classical theoretical formulations are commonly observed due to distributed resistance and porous media effects.

Recent investigations have further demonstrated that pressure–velocity relationships in porous or composite flow systems may deviate from idealized behavior because of pore-scale structure, flow tortuosity, and energy dissipation mechanisms, particularly under controlled laboratory conditions (Singh, 2024; Young & Kabala, 2024); thus, the fitted exponent reflects the combined hydraulic effects of the envelope and the orifice under controlled bench-scale conditions.

Figure 7 shows the observed flow rates and those calculated by the fitted orifice equation for each drainage system, considering the single and concomitant fitting of the discharge coefficient with the head exponent for Drainpipe E system.

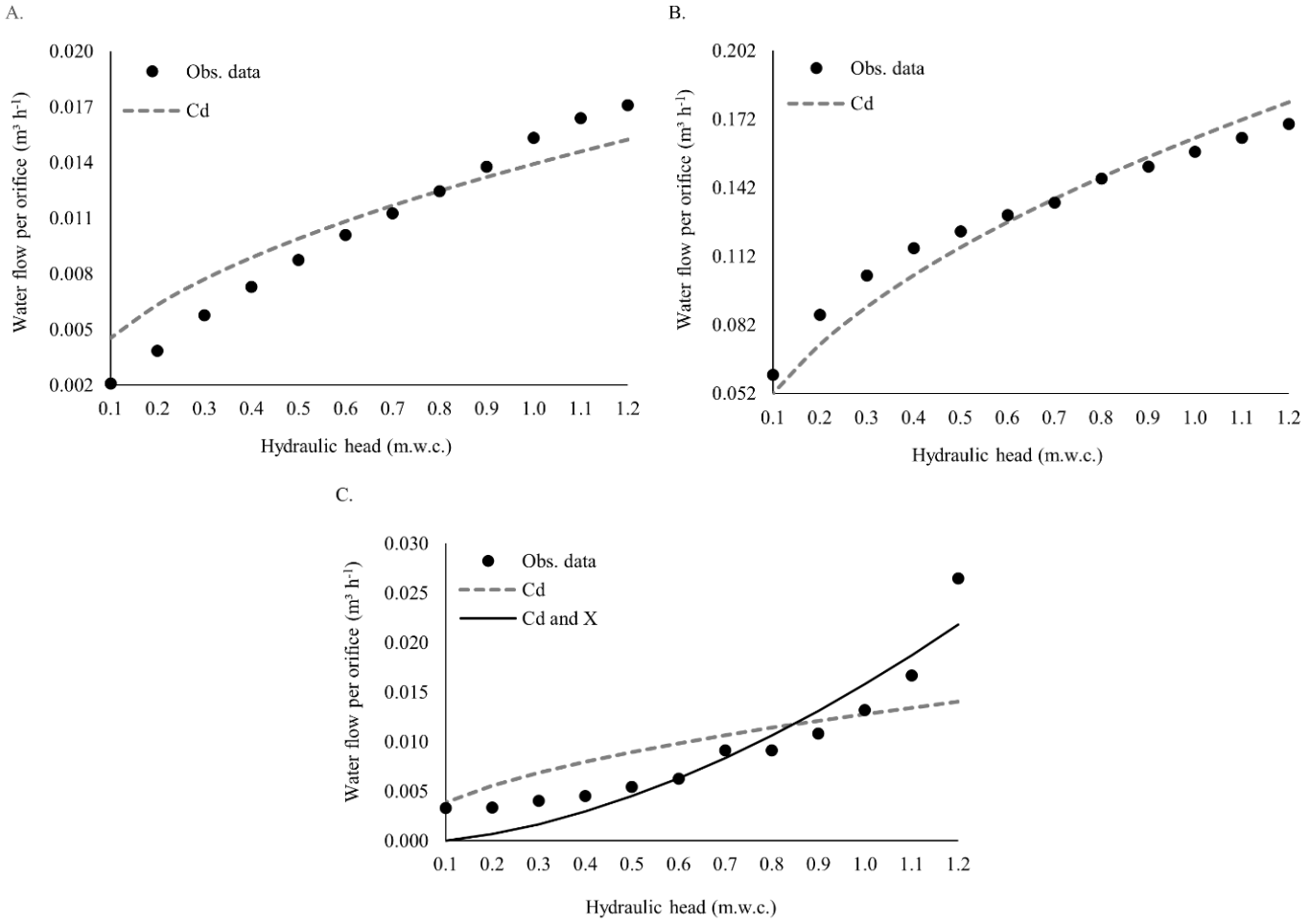
The values obtained for the specific discharge coefficient (m^{-2}) by the single fitting of the discharge coefficient of Drainpipes KC, NE, and E were 126.538, 32.257, and 2.582 m^{-2}, respectively. This parameter normalizes the discharge coefficient by the area of the drain opening. Therefore, the higher its value, the greater the capacity of each drainpipe to allow the water flow in relation to the drainage available area. Thus, the efficiency of Drainpipe KC is approximately four times higher than that of Drainpipe NE and 48 times higher than that of Drainpipe E, which, in turn, has a drainage efficiency approximately 13 times lower than that of Drainpipe NE. However, these results should be interpreted with caution, as they represent the hydraulic efficiency related to the orifice geometry, and not necessarily higher drainage capacity in absolute terms.

Table 5 shows the values obtained for the partial discharge coefficient. The values obtained for this parameter varied depending on the variation of the drainage system and the hydraulic head for all drainage systems. The lowest index presented for the standard deviation of the partial Cd in relation to the general Cd was obtained for Drainpipe E under the condition of concomitant fitting of Cd and the head exponent, which suggests, once again, the effectiveness of this fitting procedure.

Subsequently, the lowest standard deviations were obtained for Drainpipe E, in the single fitting condition, followed by Drainpipes NE and KC. However, despite being more representative, it is suggested that in cases where the R^2 obtained by the single fitting of the general Cd is low, the concomitant fitting of this parameter with the head exponent should be made since the difference between the R^2 values obtained by these methods and by the partial Cd fitting was not very expressive, being close to 0.7 and 10%, in the case of the best and worst fitting, respectively.

It should be noted that the change in the values of the discharge coefficient reflects the fluid's energy loss when flowing through the orifice. Therefore, this parameter does not have a fixed value since it can be influenced by several factors, such as the material of the pipe, geometry of the orifices, flow regime and velocity, and hydraulic head upstream of the orifice, among others (Alsaydalani, 2023; Zaiter et al., 2024). Thus, orifices with different geometries may have different discharge coefficients, even under the same flow conditions, which is consistent with the results presented in this study.

Considering the values regarding the opening area of the orifices (Table 1) and the average flow drained per orifice of each drainage system (Table 3), it was determined, by the



Obs. data – Observed data; Cd – Orifice equation fitted only for Cd; Cd and X – Orifice equation fitted for Cd and X

Figure 7. Water flow rate per orifice as a function of hydraulic head within each level of draining system for the drainage systems KC (A), NE (B), and E (C), considering, for the latter, the single and concomitant fitting of the discharge coefficient with the head exponent

Table 5. Partial discharge coefficient (Cd) for each hydraulic head and drainage system, comparing drainpipes with knife-cut orifices (Drainpipe KC) and conventional drainpipes without (Drainpipe NE) and with (Drainpipe E) envelope material

Hydraulic head (m.w.c.)	Partial Cd			
	Drainpipe KC	Drainpipe NE	Drainpipe E	
			Single Fitting	Concomitant fitting (x 10^{-10})
1.2	0.369	0.544	0.086	0.0460
1.1	0.368	0.549	0.057	0.0402
1.0	0.361	0.554	0.047	0.0502
0.9	0.342	0.559	0.041	0.0500
0.8	0.327	0.573	0.037	0.0506
0.7	0.315	0.568	0.040	0.063
0.6	0.305	0.589	0.030	0.0808
0.5	0.288	0.610	0.029	0,113
0.4	0.268	0.641	0.027	0.191
0.3	0.242	0.663	0.028	0.305
0.2	0.195	0.677	0.029	0.497
0.1	0.143	0.665	0.040	1.86
General Cd	0.328	0.575	0.046	0.0183
$\sum$ Error^2	6.97×10^{-2}	3.44×10^{-2}	3.47×10^{-3}	4.74×10^{-22}
Standard deviation from general Cd	7.62×10^{-2}	5.36×10^{-2}	1.70×10^{-2}	6.29×10^{-12}

continuity equation, that the average water inlet velocity per orifice of Drainpipes KC and NE are 1.07 and 2.00 m s^{-1}, respectively. So, the chances of obstruction of Drainpipe NE are higher than that for Drainpipe KC, since inflows with higher velocities are associated with a higher probability of erosion and soil particles transport (Oyarce et al., 2017; Bahçeci et al., 2018; Alavi et al., 2021; Ghane et al., 2022). This inference can also be made considering the opening area of the orifices (Table 1) since drains with smaller orifices, especially in terms of width, as is the case with Drainpipe KC, tend to limit the passage of larger sediments, operating as a filter, which also contributes to minimizing the risks of soil particle input and siltation of pipes (Ghane, 2022; Ghane et al., 2022).

Finally, although the water inlet capacity of Drainpipe NE is higher, Drainpipe KC can meet the drainage demand of various types of soil under the evaluated laboratory conditions. Therefore, using tubular drains with narrow orifices and more elongated geometry for the water flow, such as the so-called sand-slot pipes, is a simple and promising alternative, from a hydraulic standpoint, for reducing the risk of sediment entry into subsurface drainage systems, with its practical and economic feasibility requiring further validation under porous media and field-scale conditions (Ghane, 2022; Ghane et al., 2022).

Conclusions

1. The water inlet resistance and effective radius of the non-conventional knife-cut drainpipe and the conventional drainpipe with envelope material were similar, under the tested laboratory conditions, despite the smaller orifice area of the non-conventional knife-cut drainpipe.

2. The conventional drainpipe without envelope material drained more water than the conventional drainpipe with envelope material, while the non-conventional knife-cut drainpipe showed flow rates comparable to those of the conventional drainpipe with envelope material.

3. The use of envelopes was associated with increased hydraulic resistance under the experimental conditions, reducing flow energy and water influx.

4. The non-conventional knife-cut drainpipe showed higher hydraulic performance, from a bench-scale hydraulic perspective, than conventional drainpipes with or without envelope material.

5. The results suggest that the probability of obstruction by soil particles may be higher for the conventional drainpipe without envelope material than for the non-conventional knife-cut drainpipe, considering the tested hydraulic conditions, and the elongated orifice geometry of the latter may limit the passage of larger particles.

6. From a hydraulic standpoint, the non-conventional knife-cut drainpipe showed potential to meet the drainage demand of various soil types, although field-scale studies in porous media and long-term clogging assessments are required to confirm these findings.

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