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Fitting Hazen-Williams Roughness Coefficient to the Head Loss Obtained by Darcy-Weisbach Equation in PVC Pipes

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ABSTRACT

There are still today discussions about what formula shall be used to calculate head loss in water pipelines. Especially in academic circles, the Darcy-Weisbach (DW) equation is highly recommended, with a series of articles and scientific evidence on the subject. In the context of water supply companies, the Hazen-Williams (HW) equation gains a lot of strength, possibly even because, within the speed ranges that the systems operate, it can provide acceptable results. Thus, the present research provides a series of curves to adjust the HW roughness coefficients C, in order to make the obtained head loss results to be very similar to those derived from the DW equation. For the diameters of 50, 75, 100, 150, and 200 mm, spreadsheets were prepared, which indicated which value of C was generated for each flow rate, whose variation ranged from 0.05 to 287.00 L/s. It was verified in the spreadsheets, for each same value of C, which were the combinations of flow and diameter that produced it, and the same procedure was repeated for all C. Thus, each curve of C could be plotted. In order to assess the accuracy of the fit curves, points generated by the combination of flow and diameter outside the Hazen-Williams region of application were taken. Such points were plotted in the curves to obtain the adjusted C. This procedure made the results of HW much closer to those of DW, which when such a comparison was made using the values of C from the literature.

Keywords:

Head loss equation, Hazen-Williams, Darcy-Weisbach, Fitting curves, Water pipelines.

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1. Introduction

In the design of a pipeline, the main issue is determining the amount of energy needed to flow the desired amount of water between the intended points. Engineers and researchers who dealt with the issue always sought to find a practical formula that would allow the problem to be solved (Azevedo Netto et al. 1998) [1]. From the point of view of conservation of mechanical energy, it is possible to verify, from Bernoulli's theorem applied to a pipe flowing a certain fluid, through the contrast between the sums of the energies of velocity, pressure and position, referring to any point, situated upstream, and the other, downstream, the occurrence of a loss of energy, translated by loss of pressure. In sanitation systems, where speeds are limited in the pipelines in general, this energy loss can be attributed, partially or totally, depending on the situation, to the geometric difference between the feeder distribution point (for example, a reservoir) and the points of consumption. There is a wide variety of equations, which relate such energy loss to flow parameters, such as flow, pipe diameters, and others, and, ultimately, flow parameters can be related to geometric differences (verified or necessary), providing the sizing of the system. Such energy loss in question is, in the context of hydraulics and supply systems, commonly referred to as head loss.

1.1. Overview

The determination of the head loss in the supply and distribution pipelines is one of the most important steps in the design of water supply systems. Brown (2002) [2] investigates the historical evolution of the Darcy-Weisbach equation for pipe flow resistance. From its genesis to the present, a succinct overview of the history of the equation and the Darcy friction factor is offered. The contributions of Chézy, Weisbach, Darcy, Poiseuille, Hagen, Prandtl, Blasius, von Kármán, Nikuradse, Colebrook, White, Rouse, and Moody are discussed. The association of the Darcy-Weisbach formula (1857) with the results of investigations by Reynolds (1883), Prandtl (1904), von Kármán (1930), Nikuradze (1933) and others, the semi-empirical equation of Colebrook-White (1938), resulted in the well-known universal head loss equation, presented in (1). This equation, which has great dimensional consistency, is considered to be the “correct” expression of the hydraulic parameter to be determined (Heurich et al. 2005) [3].

$$h_f = f \, \frac{L}{D} \frac{V^2}{2\,g} \tag{1}$$

Where h_f is the head loss (m), f is the friction coefficient (dimensionless), L and D respectively are the length and diameter of the pipe (m), V is the average flow velocity (m/s), and g is the acceleration due to gravity (m/s2). According to Azevedo Netto et al. (1998) [1], the universal formula has dimensional consistency, so much so that it is applicable to the flow problems of any liquid and, with certain restrictions, it also applies to the movement of aeriform fluids. In order to raise the indeterminacy of the coefficient of friction f in (1), C. F. Colebrook and C. M. White developed, in 1938, the equation considered the most accurate for this purpose to date. This takes the name of the authors themselves and is expressed in (2).

$$\frac{1}{\sqrt{f}} = -2{,}0 \log\left(\frac{\varepsilon/D}{3{,}7} + \frac{2{,}51}{Re\sqrt{f}}\right) \tag{2}$$

Where ε is the equivalent roughness of the pipe (m) and *Re*, the Reynolds number (dimensionless). The Reynolds number is given by (3).

$$Re = \frac{V\ D}{\nu} \tag{3}$$

Where ν is the kinematic viscosity (m2/s). However, as it is not possible to explain the friction coefficient f in the Colebrook-White equation (2), it is mandatory to use some numerical method or similar for its determination, for example, via iterative processes. This motivated many researchers, from different parts of the world, to strive to find explicit equations that could be used as alternatives to the Colebrook-White equation. In addition, several alternative equations to the Darcy-Weisbach equation (1) were deduced to determine the head loss, which were much easier to use at that time, considering that in the period they were discovered, microcomputers had not yet appeared, capable of optimizing numerical solutions. One of them, the Hazen-Williams equation, was highly accepted, possibly due to its ease of application and acceptable accuracy at the time. It continues to enjoy great prestige in certain circles to this day, as well as being the target of much criticism, including its users.

1.2. General aspects, discussions and experiments related to the Hazen-Williams equation

In 1903, Allen Hazen and Gardner Williams, through a careful statistical study, proposed an empirical formula for the calculation of head loss, which bears their own name, and is presented in (4).

$$h_f = 10{,}643\ Q^{1{,}85}\ C^{-1{,}85}\ D^{-4{,}87}\ L \tag{4}$$

Where Q is the flow rate (m3/s) and C is the Hazen-Williams roughness coefficient, and the other quantities and units were mentioned previously.

According to Lamont (1981) [4] the Hazen-Williams formula, although far from ideal, was used with relative success in the past, mainly because engineers, quite accustomed to its use, acquired good knowledge in estimating the roughness coefficient to be applied to each use. Thus, it is proposed a careful study on the value of this coefficient, which mitigates the negative effect of empirical formulas not taking into account the diameter influencing the roughness coefficient, even if the type of flow is properly considered. Then the results obtained would be sufficiently accurate for practical purposes. With more emphasis, Assy (1977) [5] states that the use of empirical formulas can lead to two essential errors. The first, due to the inadequate choice of the numerical coefficient, representative of the roughness of the tube, and the second, due to the possible incompatibility of such coefficients with the flow regime verified in the conduit. It also states that the Hazen-Williams formula is very imprecise, especially in hydraulic networks formed by conduits of different diameters, where the adoption of a single roughness coefficient for all conduits can lead to important errors. These errors are more unpredictable when, in the analysis of networks, the final distribution of flows is quite different from the one initially adopted.

Sharp and Walski (1988) [6] point out the Hazen-Williams formula, theoretically speaking, as correctly applicable only to the case of hydraulically smooth flow, where the roughness of the pipe does not exceed the laminar layer, formed along the walls of the pipe. The equation starts to get imprecise in transitional flow, and becomes even more inadequate for rough (full turbulence) flow. Even so, according to the researchers, the equation continues to be applied to water distribution systems, even for rough flow, because the error presented is not significant, except in cases of long conduits with high velocities. In order to circumvent this problem Diskin (1960) [7] derives the Hazen-Williams formula's application boundaries in a way analogous to the Darcy-Weisbach formula and then superimposes the equation thus converted on the Moody diagram. Thus, it determines the maximum and lowest values of the friction resistance coefficient that are appropriate for use with the Hazen-Williams formula, as well as the ranges of Reynolds numbers beyond which the formula is not likely to yield any valid results.

Azevedo Netto et al. (1998) [1] admit the Hazen-Williams expression as theoretically correct and possible to be satisfactorily applied to any type of conduit and material, between the diameters of 50 and 3,500 millimeters. Another recommendation is that speeds be less than 3.0 m/s. They also point out that it has been used for water and sewage pipes, since it does not take into account the variation of viscous effects. Porto (2006) cited by Rocha et al. (2017) [8] suggests the adoption of the Hazen-Williams formula with restrictions, since the roughness coefficient, in addition to depending on the diameter and state of the internal roughness, is affected by the degree of turbulence, not characterizing a category of tubes as specified in the tables accompanying the formula.

Liou (1998) [9] proposes a method to estimate the relative roughness of a conduit, from values of the Hazen-Williams roughness coefficient, valid for specific conditions. He reports that this is an expressive function of Reynolds number and tube size, pointing out that, when applied outside specific ranges, the Hazen-Williams formula can produce significant errors. In the discussion of Liou’s paper, Swamee (2000) [10] states that the Hazen-Williams formula is conceptually incorrect. Its strangeness is evident because this is the most popular head loss formula among users, and the Darcy-Weisbach formula, with a much more consistent basis, is restricted mainly to the academic environment. Complementing, Christensen (2000) [11] points out that there is a hydraulic region where the Hazen-Williams formula is perfectly applicable, but he himself concludes that, in practice, most flows are outside this region.

In a study on explicit friction factor relationships and the Darcy-Weisbach equation, Mohan (1986) [12] provides a dimensionally homogeneous and reliable method for estimating surface resistance in pipes. Modified Hazen-Williams formula is the name given to the new connection. The coefficient of roughness values for commercial pipes have been empirically calculated, and a reasonable method has been proposed to account for the decline in transport capability of pipelines with time. Following the same idea, Pallepati (2014) [13] provides a very didactic construction of the Hazen-Williams formula for pressurized ducts, mentioning its dimensional inaccuracy and a number of other restrictions. To handle such problems, a variation of the Hazen-Williams formula based on the Darcy-Weisbach and Colebrook-White formulas is given. It indicates that the roughness parameters should not be dependent solely on the pipe wall when employing Hazen-Williams equation.

As recommended by the Associação Brasileira de Normas Técnicas (Brazilian Association of Technical Standards) (2017) [14, 15] for the hydraulic dimensioning of supply and distribution pipes, the Hazen-Williams coefficient or equivalent of the Darcy-Weisbach equation must be considered for the project horizon, as well as, aging, scaling and deposition on the pipe walls. The coefficients must be collected in the field or, in the impossibility of carrying out the evaluations in the field, values explained in the theory of hydraulic manuals must be adopted. A differentiated study of the coefficient for raw water and for treated water is recommended. Still, for water temperatures very different from the ambient temperatures, it is recommended to apply the Darcy-Weisbach equation, or apply criteria defined by the operator/contractor.

According to Bombardelli and García (2003) [16], despite its limitations, the Hazen-Williams method is commonly employed for the design of big dimension pipelines. This approach can have a significant negative impact on pipe design and may result in problems. According to the research, the formula is only correct when the pipe is operating in the intermediate or smooth, turbulent flow states. Many water supply pipe operating ranges are typically outside of such circumstances. The work gives an overview of the usage of the Hazen-Williams equation for the design of big dimension pipe systems, highlighting the likely consequences. Allen (1996) [17] claims that the Hazen-Williams *C* coefficient vary with Reynolds number and average flow speed. He provides numbers for calculating tube roughness elevations or relative roughness proportions that are equal to Hazen-Williams *C* coefficients. The findings make it easier to combine friction data from the Hazen-Williams model with data from the Darcy-Weisbach equation. *C* factors that are equal to known or observed tube roughnesses were also established. The Churchill formula is contrasted to other recognized friction factor formulae for directly determining the Darcy-Weisbach friction factor. The Churchill formula reliably predicts surface roughness in systems throughout all ranges of Reynolds number, roughness of the tube, and temperatures observed, such as the laminar and transition flow patterns.

Field measurements from thirty center pivots with PVC laterals were used to analyze and compare friction head loss formulas and roughness adjustment aspects. Darcy-Weisbach, Hazen-Williams, and Scobey equations, as well as a suggested equation valid for smooth and rough pipe types and all turbulent flow types, are among the friction head loss equations. The suggested equation was created by merging the Darcy-Weisbach and Hazen-Williams equations, as well as the multiple nonlinear regression approach. The roughness adjustment aspects were determined using the Christiansen, modified Christiansen, Anwar, and Alazba equations. The assessment was based on statistical error approaches, with observed values serving as a comparison. The results showed that the magnitudes of friction head loss computed using the Darcy-Weisbach, Hazen-Williams, and suggested equations were in accord with field data when employing a composite of modified Christiansen, Anwar, and Alazba formulas. The results for root mean square deviation varied from 1.6 to 1.7 m. The findings demonstrated poor agreement between observed and calculated friction head loss estimates when the usual Christiansen friction correction factor was applied with the Darcy-Weisbach, Hazen-Williams, and suggested equations, as predicted. The high root mean square deviation readings, which ranged from 5.4 to 5.9 m, clearly demonstrated this. When paired with the standard Christiansen formula, however, there was agreement between measured friction head loss numbers and those estimated using the Scobey equation, which is invalid for PVC pipe type. This intriguing discovery resulted in enhanced Scobey equation findings via a generated roughness coefficient suitable for PVC pipe type by analytically math analysis; as a consequence, the root mean square deviation value decreased from around 8.6 to 1.6 m (Alazba et al. 2011) [18].

According to Achour and Amara (2020) [19], despite its application limitations, the Hazen-Williams equation is still commonly employed today. The equation includes a constant roughness coefficient *C* that is solely determined by the pipe's material. Many studies, however, have claimed that *C* should be proportional to both the relative surface of the pipe and the Reynolds number. This dependency of *C* on relative roughness and Reynolds number was emphasized by Liou, in particular, via a connection that is of importance to their research. A modification of Liou's connection resulted in an implicit dimensionless equation, which was converted into a *C* dimensionless diagram. Additionally, the dimensionless relationship produced from the conversion of the Hazen-Williams equation, together with the dimensionless graphic, accelerates the computation of the gradient of the energy line. For a particular degree of relative roughness, the dimensionless *C* relationship approaches a peak. A thorough examination of this connection resulted in the successful demonstration of the explicit reliance of *C* peak value on relative roughness.

As pointed by Taş et al. (2019) [20] plastic pipes, particularly polyethylene pipes, have developed to be one of the most often used materials in pipeline systems due to its corrode, microbiological, and chemical stability advantages over traditional metal pipes. The design of a polyethylene pipeline system, like any other material, necessitates a thorough and rigorous friction head loss study. There are two primary approaches advocated in the literature for measuring friction head loss. The known Darcy-Weisbach formula is one, and the Hazen-Williams equation is an empirical solution. The Darcy-Weisbach equation is affected by the Darcy friction factor, whereas the Hazen-Williams equation is affected by the Hazen-Williams coefficient. Pipe surface elevation must be determined to derive Darcy friction factor. Head losses in polyethylene and plastic pipes are routinely approximated in recent research by applying certain constant factors for pipe roughness height and the Hazen-William equation. However, experimental tests indicated that these values are highly dependent on pipe diameter and the flow regime defined by Reynolds numbers. As a result, for all dimension and flow velocity ranges on polyethylene pipes, a single fixed number cannot be employed. The authors evaluated experimental investigations for energy losses on polyethylene tubes and suggested some strategies for hydraulic design of polyethylene pipelines. The findings revealed a scarcity of experimental investigations for plastic pipes, especially for larger polyethylene pipe diameters.

Seifollahi-Aghmiuni et al. (2013) [21] analyzes network effectiveness throughout an operating cycle while accounting for pipe roughness unpredictability (2013). During the operating cycle of the two ring systems, an analysis is done by creating a stochastic sequence of tube roughness using Monte Carlo methodology. The analysis reveals that increasing the unpredictability in surface roughness induces a deterioration in network effectiveness over the operating time. Moreover, the network's efficiency is only desired in the first ten years. As a result, the suggested design technique, which takes into account the variability of model parameters, is an efficient way for evaluating system performance. Another research was conducted to evaluate the head loss in commercial pipes consisting of zinc-plated steel, galvanized iron, and PVC of several diameters in order to develop corrections for the Hazen-Williams formula as a factor of total solids content in swine farming effluent. The findings suggest that the head loss has a linear trend as a function of the total solids content of the swine industry effluent; the head losses obtained from the partial and global corrections were, on average, 0.7 and 13% overestimated and underestimated, respectively (Sampaio et al. 2007) [22].

Due to its simplicity, the Hazen-Williams equation is commonly employed by watering systems designers. The Darcy-Weisbach equation, on the other hand, is more precise and stable. The latter's accuracy is owing to its friction coefficient, which is affected by both flow parameters and pipe surface condition. Hazen-Williams' coefficient, on the other hand, is simply affected by pipe material and age. A simple iterative model was used to undertake a comparative examination of both models. The drip laterals real-estate design approach was used in the analysis. More precise roughness coefficient *C* values were proposed for use in constructing drip laterals. *C* was calculated using a simple equation based on emitter flow rate, emitter flow exponent, and pipe diameter. The results show that *C* ranges from 132 to 138 for drip laterals, whereas *C* equal to 150 is appropriate for manifold design (Alazba and ElNesr 2011) [23].

An empirical relationship for fluxes via plastic pipes between the Darcy-Weisbach and Hazen-Williams equations is established by Jamil and Mujeebu (2019) [24]. According to them, it can be very useful for designers. Five hydraulic models were constructed to predict the head loss in tubes for several dimensions (15 mm to 50 mm) and volume flow rates related to water temperatures varying from 20°C to 60°C. (0.25 L/s to 2 L/s). The Darcy-Weisbach and Hazen-Williams estimates of head loss were utilized to build a connection between them. The autocorrelation between both equations was determined to be 0.999, and the adjusted R-squared for the pattern of head loss data produced by both equations was determined to be 0.9993.

As stated per Niazkar et al. (2017) [25] even though the Darcy-Weisbach formula has been acknowledged as a conventional resistance model in pressured flow, some academics and engineers still choose to analyze water distribution networks using the Hazen-Williams formula. The fundamental distinction between the friction coefficients of these two resistivity formulas is that the Darcy-Weisbach friction coefficient changes with the Reynolds number of the fluid domain, but the Hazen-Williams coefficient is commonly thought of as a constant value for a certain material. They analyze discrepancies in the solutions of pipelines using these equations. The systems were calculated with variable roughness levels assumed. Similar friction factors dependent on two resistant formulas have been utilized to compare the findings. Various approaches for calculating comparable friction coefficient from the literature were chosen in this aspect. A first category converts Darcy-Weisbach friction factors to Hazen-Williams coefficients using Reynolds number and pipe dimension data. The second, from the other side, is solely determined by the diameter of the pipe. The obtained findings show that mistakes in computing systems with Hazen-Williams parameters are not considerable when compared to the Darcy-Weisbach equation outcomes. More crucially, the approach that solely uses pipe diameter to convert roughness appears to be unreliable in several of the circumstances studied.

In the opinion of Valiantzas (2008) [26], although the Darcy-Weisbach formula coupled with the Colebrook–White semi-theoretical equation for determining the friction factor yields an extremely precise generalized network head loss equation, many users adopt simple, clear and direct simple linear shape equations. The empirical formula of Hazen-Williams and Manning continue to be the main head loss formulae used in everyday hydro engineering fields due to its easiness despite their restrictions. A novel basic law form equation is constructed in his study to approximate the general Darcy-Weisbach paired with the Colebrook-White solution. The suggested formula included explicit references to the two basic pipe flow parameters, such as flow or speed and dimension. When contrasted to the Darcy-Weisbach and Coolebrook-White equations, the proposed formula has a maximum relative inaccuracy of roughly ± 4.5 percent. It is proposed that the formula is spatially homogeneous and has adequate precision for engineering work. For the fluctuation in kinetic viscosity, an adjustment function is calculated. The formula's use is proven in a case study involving the best style of a network including boosting. The phrasing of the issue is aided by the structure of the friction equation, which leads to the development of a simple concept from which the optimal size is directly computed.

As maintained by Travis and Mays (2007) [27], in spite of the progress in computers and the development of explicit estimation equations, the observationally validated and generalizable Colebrook–White roughness factor formula is frequently replaced by the restricted and less precise Hazen-Williams formula. The overall reticence of practitioners to adopt the Colebrook-White equation could be attributed to the relatively vast existing dataset of Hazen-Williams roughness coefficient values in presence of the comparatively small dataset of absolute quantities needed by the Colebrook-White formula. Until now, translating the roughness coefficient (C) to absolute roughness (ε) requisite skills of both Reynolds number and the pipe size used to calculate C. They present a research that generates implicit equations connecting C to that do not require any extra data and match up with available data. The precise answer is approximated by a simple explicit expression that is precise to within 4% deviation.

Despite the fact that the Darcy-Weisbach and Hazen-Williams equations and the corresponding conclusions of head losses they produce have been balanced against each other, the experimental approach is still widely used by professionals and researchers, even beyond its applicability range. In this way, they present a paper that evaluates the discrepancies between using the Darcy-Weisbach formula versus the Hazen-Williams, particularly on sizable pipe network model types where the roughness parameters haven't been adjusted, i.e. models of ongoing construction systems used for development purpose. The findings reveal that even after adjusting the Hazen-Williams parameter estimates, the discrepancies might be considerable (Uribe, Saldarriaga, and Páez 2015) [28].

Following an examination of the simulation results and friction factor connections for isothermal single stage movement, Genić e Jaćimović (2019) [29] use statistics tools to assess the veracity of very well relationships. Throughout this procedure, it was proven that some of the most known and often used roughness formulae may be modified. Furthermore, for practical engineering applications, some formulas are constructed in order to span the complete spectrum of laminar, critical, and turbulent movement. In a study carried out by Taş et al. (2020) [30] the equations of Darcy-Weisbach, Hazen-Williams, Manning, and Chezy were utilized to determine the head loss in an 80-km offshore water supplier pipe. The MATLAB software was used to develop the routine in order to perform the calculations. The results were contrasted with each other, indicating a good approximation between the data obtained by Manning and by Chezy to those derived from Darcy-Weisbach, while the values of the deviation between the head losses calculated by Hazen-Williams and by Darcy-Weisbach were a little larger than the previous ones. These were, respectively, 0.66%, 0.61%, and 2.55%.

2. Theoretical Modeling

The purpose of the present work is to provide curves for adjusting the Hazen-Williams roughness coefficient as a function of the flow parameters, such as flow rate and pipe diameter, so that the value expressed by this equation approaches, as much as possible, the head loss value obtained by the Darcy-Weisbach equation. In order to operate to obtain such curves, the Darcy-Weisbach equation (1), placed in terms of flow, as presented in (5), is equated to the Hazen-Williams equation (4), generating (6), which is a relationship that provides the value of the Hazen-Williams *C* coefficient so that the head losses calculated by both formulas are the same.

$$h_f = 0{,}0827\,\frac{f\,L\,Q^2}{D^5} \tag{5}$$

$$C = \left(\frac{128{,}694\,D^{0,13}}{f\,Q^{0,15}}\right)^{0,54} \tag{6}$$

All quantities were previously defined. The diameters evaluated were 50, 75, 100, 150 and 200 mm, as they are the most common in water distribution networks, and the equivalent roughness of the pipe ε was taken to be 0.06 mm given that it is an average value for PVC pipes in the available literature. The kinematic viscosity of water ν was adopted as referring to an average temperature of 20°C, representative of practice, and corresponds to a value of 1,007 x 10^{-9} m2/s. The flow rates tested ranged from 0.05 to 160 L/s. The Darcy-Weisbach friction factor f was computed using the Enio Tourasse formula (1986) [31], presented in (7).

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$$f = \left(1{,}4\,\frac{\varepsilon}{D} + 0{,}1004\right) . \left(\frac{\varepsilon}{D} + 5\,.\,10^{-5} + \frac{72}{Re}\right)^{0{,}24} \quad (7)$$

Making use of (6), spreadsheets were prepared referring to each of these diameters, aiming to obtain *C*. In Figure 1 it is possible to have a partial view of the process of obtaining the values of *C*.

Q (L/s)	*V* (m/s)	*Re*	*f*	*C*
0.05	0.01	843	0.056	121.05
0.10	0.02	1,686	0.048	125.03
0.20	0.05	3,372	0.041	128.99
0.30	0.07	5,058	0.037	131.24
0.40	0.09	6,743	0.035	132.77
0.50	0.11	8,429	0.033	133.90
0.60	0.14	10,115	0.032	134.77
0.70	0.16	11,801	0.031	135.48
0.80	0.18	13,487	0.030	136.05
0.90	0.20	15,173	0.029	136.53
1.00	0.23	16,859	0.029	136.94
1.20	0.27	20,230	0.03	137.57
1.40	0.32	23,602	0.03	138.04
1.60	0.36	26,974	0.03	138.39
1.80	0.41	30,345	0.03	138.65
2.00	0.45	33,717	0.03	138.84
2.50	0.57	42,146	0.02	139.11
3.00	0.68	50,576	0.02	139.18
3.50	0.79	59,005	0.02	139.13
4.00	0.91	67,434	0.02	139.01
5.00	1.13	84,293	0.022	138.62
6.00	1.36	101,151	0.022	138.14
7.00	1.58	118,010	0.021	137.62
8.00	1.81	134,868	0.021	137.09

50 mm / **75 mm** / 100 mm / 150 mm / 200 mm / Curves / Equivalences

Figure 1. Process of obtaining values of *C*.

From that point on, it was a matter of verifying, for each value of *C*, which were the one or more corresponding combinations of flow and diameter. It was decided that the roughness coefficients covered a range from 120 to 144, and the intervals were smaller close to the value 140, considering that this is the value indicated by the hydraulic manuals for PVC pipes. Table 1 exemplifies the procedure and summarizes such data.

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Table 1. Data relating flow rate, diameter and *C*.

Diameter (mm)	C 120	C 125	C 130	C 132	C 134	C 136	C 138	C 139	C 140	C 141	C 142
50	0.03	0.07	0.18	0.25	0.40	0.70					
75	0.04	0.10	0.25	0.35	0.50	0.80	1.40	2.30			
100	0.06	0.14	0.32	0.45	0.65	0.98	1.50	2.00	3.00	5.00	
150	0.10	0.22	0.50	0.70	1.00	1.40	2.10	2.60	3.30	4.20	6.00
200	0.13	0.30	0.70	1.00	1.35	1.95	2.80	3.40	4.10	5.10	6.50
	Flow rates										
Diameter (mm)	**C 144**	**C 144**	**C 142**	**C 141**	**C 140**	**C 139**	**C 138**	**C 136**	**C 134**	**C 132**	**C 130**
50								2.50	4.30	6.20	8.30
75						4.00	6.00	10.00	14.00	19.00	25.00
100					9.50	13.00	16.00	23.00	31.00	41.00	53.00
150			22.00	28.00	36.00	43.00	50.00	68.00	89.00	114.00	144.00
200	13.50	28.00	54.00	66.00	78.00	92.00	106.00	140.00	179.00	228.00	287.00
	Flow rates										

Checking the data in table 1, for each value of *C*, it is possible to plot points, referring to that *C*, as a function of flow and diameter. Thus, the procedure is repeated for all *C* values evaluated, that generated from one to five points referring to each roughness coefficient, depending on the observed combination.

3. Results and Discussions

Figure 2 shows the proposed curves, derived from each point generated by crossing the evaluated flow rates and diameters, as available in Table 1. They make it possible to determine values of specific roughness coefficients *C* as a function of flow rate and diameter. Thus, even if the Hazen-Williams equation is chosen to determine the head loss, the results will be very close to those arising from the Darcy-Weisbach equation.

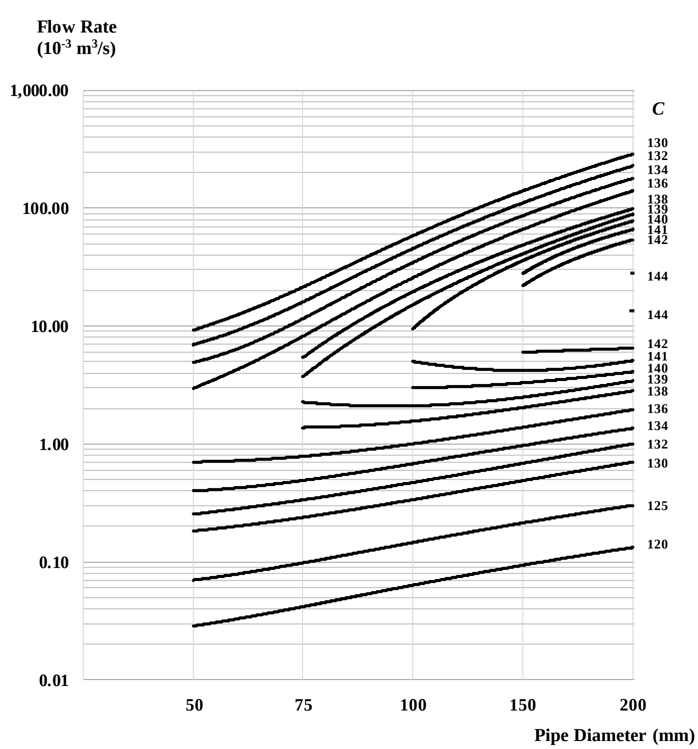

Figure 2. Fitting curves.

3.1. Validation Tests

In order to guarantee the good functioning of the proposed curves, points (Reynolds Number versus diameter) were taken in regions outside the limits of application of the Hazen-Williams equation, following the indication of the graph presented in [11]. Knowing that the absolute roughness ε of the PVC is 0.06 mm, it was possible to know the value of D/ε to be verified in the graph. At the same time, such points must be in the range covered by the curves. From the chosen points, representative of different conditions, the flow rates referring to each one was determined. Then, head loss was calculated by three different ways: by the Darcy-Weisbach equation, by the Hazen-Williams equation with PVC roughness coefficient tabulated according to the literature, where C is equal to 140 for PVC, and by the Hazen-Williams equation with the roughness coefficient adjusted by the curves proposed here. Finally, considering a 1.0 km long pipeline, comparisons and verifications of average deviations between the modular values of the head losses obtained by Darcy-Weisbach and traditional Hazen-Williams equations and by Darcy-Weisbach and Hazen-Williams adjusted by the curves equations are made. As expected, the fit curves made the Hazen-Williams results much closer to those of Darcy-Weisbach. Table 2 summarizes the described procedure.

Table 2. Validation tests of the fitting curves

Diameter (mm)	Re	Q (L/s)	hf_{DW} (m)	$hf_{HW\ Tabulated}$	$hf_{HW\ Curves}$	$Dev_{(DW - HW\ Tabulated)}$	$Dev_{(DW - HW\ Curves)}$
50	1,000	0.040	0.023	0.018	0.023	24.29%	1.05%
	10,000	0.395	1.344	1.251	1.357	7.12%	0.98%
	100,000	3.954	94.734	88.585	94.750	6.71%	0.02%
75	1,000	0.059	0.007	0.005	0.007	24.42%	0.92%
	10,000	0.593	0.391	0.368	0.393	6.21%	0.51%
	100,000	5.932	26.435	26.035	26.738	1.53%	1.14%
100	1,000	0.079	0.003	0.002	0.003	24.65%	0.68%
	10,000	0.791	0.164	0.154	0.165	5.91%	0.82%
	50,000	3.954	2.978	3.029	3.009	1.71%	1.05%
	1,000,000	79.090	923.005	773.122	899.485	17.67%	2.58%
150	1,000	0.119	0.001	0.001	0.001	25.11%	1.74%
	10,000	1.186	0.048	0.045	0.048	5.82%	0.90%
	50,000	5.932	0.859	0.890	0.867	3.59%	0.96%
	1,000,000	118.634	252.301	227.223	253.354	10.46%	0.42%
200	1,000	0.158	0.000	0.000	0.000	25.51%	0.19%
	10,000	1.582	0.020	0.019	0.020	5.95%	0.78%
	50,000	7.909	0.357	0.373	0.360	4.45%	0.92%

Re is the Reynolds Number, *Q* is the flow rate (L/s), hf_{DW}, $hf_{HW\ Tabulated}$, and $hf_{HW\ Curves}$ are the head losses calculated (m), respectively, by Darcy-Weisbach, Hazen-Williams with C tabulated as 140, and Hazen-Williams adjusted by the curves proposed equations. $Dev_{(DW - HW\ Tabulated)}$ and $Dev_{(DW - HW\ Curves)}$ are the average deviations between head losses using Darcy-Weisbach and Hazen-Williams tabulated, and using Darcy-Weisbach and Hazen-Williams with the fit curves.

4. Conclusions

A review of the existing literature about Hazen-Williams head loss equation applications was carried out. Fit curves for the roughness coefficient C were proposed, which make the head losses calculated by Hazen-Williams very similar to those determined by the Darcy-Weisbach equation. Such curves were tested for several points, materialized by the combination between flow rate and diameter, with very satisfactory results. The intention of the present work was not to discuss or deepen the question of the accuracy of the Hazen-Williams equation, as well as its possible acceptable ranges of application. This is a subject discussed by some to this day, fully concluded and closed for many, and not so much for others, which involves researchers, professors, academics, engineers from water supply companies, and the like. The intention was just to suggest some adjustments to the Hazen-Williams roughness coefficient for certain hydraulic situations, in the case that this is the equation chosen for use, in order that the head loss results obtained are as close as possible from those achieved using the Darcy-Weisbach equation, taken in the present work as the values of reference.

5. References

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