Comparison of traditional methods with the Dayton Equation in the determination of minor friction losses in irrigation systems

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Abstract: Traditional methods principally used for determination of secondary (minor) losses in irrigation design are Equivalent Length, Resistance Coefficient and Valve Flow Coefficient method. Challenge with using methods during design is the unreliability of accuracy considering shortfalls identified; fixed flow coefficient (bend length, L, to pipe diameter, D ratio), thorough knowledge of development of coefficients required for application, and reliance on conversion parameters, respectively. Study provides comparison of traditional methods to the Dayton Equation considering their shortfalls for extent of error involved in estimation of minor losses. Accuracy of each traditional method was assessed by calculating percentage difference between frictional losses yielded to the 19.05 mm diameter pipe, expanded to different friction coefficients on same pipe diameter for corresponding values from the Dayton Equation as reference. Choice of pipe diameter was mainly due to availability of data points (friction coefficients) for comparison. Equivalent Length method was found to be fairly accurate, tolerance for short radius: 53.23% to 50.41%, standard radius: -35.09% to 62.27%, long radius: -32.33% to 35.34%, provided L/D ratio relative to flow velocity was considered in determination of equivalent lengths. Resistance Coefficient method was confirmed to be the best method due to closeness of published friction coefficients to Dayton Equation values, tolerance for short radius: 0.27%, standard radius: 1.42% to 35.23%, long radius: 0.25% to 25.31%. Valve Flow Coefficient method was largely dependent on values from Equivalent Length and Resistance Coefficient for conversion if not found with respect to changing pipe diameter, curvature, and flow velocity. Tolerance for standard radius: -0.54% to 32.77%, long radius: -1.57%. Frictional loss estimation with all traditional methods was generally poor for bend angles less than 90°. Comparison of Dayton Equation to traditional methods was achieved and recommended for accurate and efficient irrigation design for different L/D ratios.

Keywords: Equivalent Length, Resistance Coefficient, Valve Flow Coefficient, minor, secondary loss, Dayton Equation.

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1 Introduction

Calculating frictional losses in the design of irrigation systems is important because it brings about the ideal sizing and selection of pumps, pipes and fittings, which essentially reduces the capital cost of the irrigation schemes and possible failures of

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irrigation systems. By minimizing the energy losses due to friction, pumping is improved leading to lower energy consumption systems as well as the reduced operating costs (Venter and Grové, 2016; Tagwi et al., 2022). This also translates to sustainable systems with savings over the lifespan of the irrigation systems, particularly for large scale irrigation systems wherein pumping is often continuous (Loureiro et al., 2024). The precise calculation of frictional losses contributes largely to the stability of a system also ensuring uniform distribution across the pipe networks and cuts back on possible pressure fluctuations which may cause pipe bursts or under irrigation in some sections of the irrigation system (Wang and Chen, 2020). This again improves system reliability and reduces the chances of downtime and maintenance costs, all together enhancing overall efficiency of the system, an approach we desire in designing irrigation systems. In essence this research supports cost effective designing and promotes sustainable energy use and ensures long term operational stability which collectively strengthens agricultural productivity and resource conservation.

In the design of irrigation systems, there are two main components of frictional losses. These are mainly due to the fluid interactions with the straight pipe lengths and secondarily the fittings, that is major (primary) and minor (secondary) losses, respectively (Berger et al., 1983). In the determination of primary losses, there are many methods that can be used depending on the straight pipe parameters and field of application for the designer, and these methods give generally the same measure of frictional losses (ARC, 2003). These methods, the Darcy-Weisbach developed in 1845, Hazen-Williams developed in 1906, Newton-Raphson developed in 1911 or Colebrook-White developed in 1939, Moody chart developed in 1944, Lamont equation developed in 1945, Wood developed in 1966, Swamee-Jain developed in 1976, Barr developed in 1981, Haaland developed in 1983 and General Exponential equation developed in 1998, on comparison give reasonably similar results and cater for different fields of application such as irrigation design, water supply and reticulation (ARC, 2003).

When determining the secondary losses, there are, however, three traditional methods: the Equivalent Length, Resistance Coefficient and Valve Flow Coefficient methods, all used in similar fields of application, but there is considerable variability in the frictional losses determined (Markl, 1957; Marossy et al., 2018). The Equivalent Length and Resistance Coefficient methods are used mainly for calculating the minor losses while the Valve Flow Coefficient method is mainly used for determining frictional losses in valves (Co, 1988). Conversion is often done between the Resistance and Valve Flow Coefficient methods. Experimental data from these methods are often used to avoid the cost involved in the testing of all valves and fittings for use. Equivalent lengths and coefficients are available from published tables, diagrams and online from various writers as well as valve manufacturers, and are associated with pipe diameters. Despite the variability in the frictional loss values as determined by the different traditional methods, they all meant to determine the best approximate of the velocity head multiplier (equivalent length or friction coefficient) for determining secondary losses (Markl, 1957; Wilson, 2012; Neutrium, 2016; Marossy et al., 2018).

The Equivalent Length method is based on observations made on the determination of the primary losses wherein the frictional loss component is proportional to the velocity head. As a result an equivalent straight pipe length's pressure drop is used to represent frictional loss due to pipe bending or curvature, hence its name (Wilson, 2012). The Equivalent Length technique, a simple strategy that is often effective also for turbulent flow with conventional fittings, loses accuracy for non-standard geometries and fittings with large flow separations, such as rapid expansions (Hooper, 1981; Idelchik, 1987; Co, 1988). Determination of this equivalent length to be used for an extent of bending is often determined experimentally for close approximation of length. However, when using the Equivalent Length method, the approach assumes that the relative proportions of the fitting size remains constant as the pipe diameter varies (Neutrium, 2016; Baiamonte, 2020). This is rarely the case in irrigation systems and as a result, there is some level of error in the estimation of the frictional loss due to bending or curvature. Since the flow coefficient (L/D ratio, where L = bend length and D = pipe diameter) decreases as the fitting size increases, the pressure drop would be overestimated at pipe sizes greater than those for which the fittings Equivalent Length was calculated (Neutrium, 2016; Baiamonte, 2020). The pressure drop would also be underestimated at smaller pipe sizes than those for which the Equivalent Length was measured and often the resistance coefficient (equivalent length) used is constant for changing bend length, L/D ratio (Ntengwe et al., 2015). Despite these shortfalls, the Equivalent Length method has the advantage of being very easy to apply.

The Resistance Coefficient method is characterised against quite a number of varying pipe diameters, making it more reliable compared to the Equivalent Length method for use in irrigation systems design (ARC, 2003). The Resistance Coefficient approach is applicable to both laminar and turbulent flow regimes, as well as a variety of fitting geometries such as sudden contractions and mitered bends, provides the greatest accuracy for all fitting types by explicitly accounting for frictional losses (Crane, 1957; Hooper, 1981; Idelchik, 1987; Tullis, 1989; Darby, 2001). However, it does not support different or changing pipe geometries for fittings with various sizes (Ntengwe et al., 2015; Neutrium, 2016). The Resistance Coefficient method sums up the resistance coefficients and has the objective of using a resistance coefficient as though it is the same for different diameters, again introducing inaccuracies (Perry, 1950). It was found generally that though the resistance coefficient decreased as the fitting size increased, the K value (Crane Coefficient) used was in the fully turbulent flow conditions and not on laminar flow by Perry (1950) to date (Wilson, 2012). In a bid to improve the friction factor K, the Crane 2 friction factor was introduced with a range of K factors for each fitting, with the provision of adjusting the K values per fitting (Hooper, 1981). This further complicated the use of the Resistance Coefficient method since a thorough knowledge of how the K value was developed was needed for use with varying pipe diameters. It was also discovered that at Reynolds numbers less than 2 000, there was an express increase in the K values (Silverberg, 2001).

Despite the efforts to correctly quantify the secondary losses, friction factors smaller than those obtained by the Moody, Prandtl, White-Colebrook, or Nikuradse smooth pipe rule (or Blasius law) have been calculated in large diameter pipes, according to findings in literature (Berlamont, 2014). It was shown that a small amount of rotation or swirl, such as that induced by curvature, continued downstream of the straight pipe, decreasing the apparent friction factor premeditated or predicted using the nominal Reynolds number (Spedding et al., 2004; Blanckaert, 2009; Hellström et al., 2013; Kim et al., 2014). The Blasius rule can also hold true if the friction factor is measured using the real Reynolds number and rotation of fluid downstream of a 90° bend is considered. For rotation numbers less than 1 to 2 (A dimensionless parameter describing the impact of rotational effects on a fluid system), the reduction in friction factor is usually in the 5% to 10% range. Only large diameter pipes and/or high Reynolds numbers are prone to experience this phenomena (Berlamont, 2014).

The Valve Flow Coefficient method, though mainly used for valves C_v (A_v in the S.I. units, defined as the number of US gallons per minute of water at 60°F flowing through a valve with a pressure decrease) values can be easily converted to K values. The Equivalent Length and the Resistance Coefficient outlined earlier above use the multiplier with the velocity head term giving a likelihood of the same results with the Valve Flow Coefficient method (Wilson, 2012; Zhou et al., 2017). The Valve Flow Coefficient approach, ideal for analysing control valves provides excellent accuracy when backed by manufacturer data. However, it is valve-specific and cannot be generalized to other system components

(Idelchik, 1987). The methods use the same or similar velocity head multiplier when predicting the frictional losses, allowing conversion between the two, considering the fitting dimensions are known in either case.

The C_v and K_v (amount of water that can travel through a valve in m^3 $hour^{-1}$ with a pressure decrease of one bar) methods are used to characterize all kinds of fittings and are the most general for control valves (Neutrium, 2016). Both equations are dependent on one flow rate and apply to the same properties, which enable one to estimate the characteristics of flow at other flow rates. The conversion is such that $C_v = 1.157*K_v$ and $K_v = 0.8646*C_v$. For calculating the head loss using the k value; $h_L = 0.0295*k*(Q^2/d^4)$ and $k = f(L/D)$ (Crane, 1957).

In an effort to improve on the shortfalls found in the traditional methods, the Dayton Equation, an empirically derived equation, was developed to try and precisely calculate secondary losses due to bends in smooth pipes, particularly for irrigation system design. It is based on the resistance coefficient approach but specifically caters for characteristics like the relative radius of curvature (R_c), bend length-to-pipe diameter ratio (L/D), and friction coefficient. The equation dynamically calculates pressure losses for bend angles ranging from 0° to 90°, as it tries to address the errors in traditional approximation and/or the fixed coefficients (Tagwi et al., 2022). The equation, developed through experiments, provides designers with a useful tool for calculating fairly accurate pressure drop without also needing comprehensive knowledge on bend characteristics. The Dayton Equation allows for more effective determination of the friction coefficient by taking into consideration the essential elements impacting fluid flow in curved pipes, decreasing uncertainties and improving pump and pipe sizing for increased energy efficiency (Tagwi et al., 2022).

The combined mathematical relationship for the homogenous equation for the pressure loss or frictional losses, ΔP, due to a bend was then expressed as follows (Division, 1978; Pritchard, 2011; Munson et al., 2013):

$$\Delta P = k * \frac{V^2}{2g} \tag{1}$$

wherein; V - flow velocity; g - acceleration due to gravity.

And the friction factor (Tagwi et al., 2022):

$$k = f(\theta, D, L, r) \tag{2}$$

Where,

θ - bend angle;

D - pipe diameter;

L - bend length ;

r - radius of curvature.

With k composed of functions that cater for the bend L/D ratio:

$$k = \frac{g(D)_{new\ pipe\ diameter}}{g(D)_{wrt\ 19.05mm, R_c=1, 90^\circ}} \times h(R_c)_{wrt\ R_c=new, 90^\circ} \times g(D)_{wrt\ 19.05mm, R_c=1, 90^\circ} * \frac{p(\theta)_{wrt\ \theta}}{p(\theta)_{wrt\ 90^\circ}} \tag{3}$$

And

$$\Delta P = \left(\frac{g(D)_{new\ pipe\ diameter}}{g(D)_{wrt\ 19.05mm, R_c=1, 90^\circ}} * h(R_c)_{wrt\ R_c=new, 90^\circ} * g(D)_{wrt\ 19.05mm, R_c=1, 90^\circ} * \frac{p(\theta)_{wrt\ \theta}}{p(\theta)_{wrt\ 90^\circ}} \right) \frac{V^2}{2g} \tag{4}$$

Wherein the mathematical relation of the pressure drop with change in bend angle, θ:

$$p(\theta) = 4.869e^{-5}\theta^2 + 0.0032870\theta + 0.0493 \tag{5}$$

And the function for the friction coefficient with changing pipe diameter, D , and bend angle:

$$g(D) = 1.487D^{-0.2862} + 0.09968 \tag{6}$$

And the friction coefficient with changing, R_c (relative radius of curvature = radius of curvature, r / pipe diameter for bend, D; which is unit less) and bend angle:

$$h(R_c) = \frac{(4.02R_c^2 - 11.07R_c + 29.93)}{(R_c^2 + 18.53R_c + 11.41)} \tag{7}$$

With a condition with respect to a theoretical 19.05mm pipe diameter, at R_c = 1 and 90°:

$g(D)_{wrt\ 19.05mm, R_c=1, 90^\circ} = 1$;

and $\frac{g(D)_{new\ pipe\ diameter}}{g(D)_{wrt\ 19.05mm, R_c=1, 90^\circ}}$ remains applicable only when $D = 19.05\ mm$ and R_c remains 1.

The argument however, pertaining to the Equivalent Length and the Resistance Coefficient methods is how the Equivalent Length L_e for a pipe diameter D, (L_e/D) and the resistance coefficient (k) (loss coefficient is often employed in the Darcy-Weisbach equation) are compared with different

Reynolds numbers and pipe roughness (Miller, 1990; Swamee and Sharma, 2008; Wilson, 2012). When determining the secondary losses with the above three methods, there is a lot of variability in the determined frictional losses when considering the published results (Blevins, 1984; Idelchik, 1987; Larock et al., 1999; Spedding et al., 2004; Vaughn, 2019). The resulting problem in the use of the traditional methods during the irrigation design process is this variability, leading to uncertainty of the accuracies or approximation of the methods, considering the shortfalls identified in each method. This research aims at comparison of the three traditional methods for specific curvature (0° to 90°) to determine their accuracy, repeatability, and reliability in the estimation of secondary losses with changing pipe diameters with reference to (compared to) the Dayton Equation (Tagwi et al., 2022) when using smooth pipes for irrigation design. This will allow for an appreciation of the extent of error due to the shortfalls identified in each case in the use of the traditional methods with reference to the Dayton Equation. It is hypothesised that minor frictional losses estimated by the traditional methods overstate or understate compared to those estimated by the Dayton Equation.

2 Methodology on the Comparison of the Dayton Equation to the Traditional Methods

Derivation of the Dayton Equation was based on experimental data and the published data on the Resistance Coefficient method for validation. The Dayton Equation catered for the change in the bend length per diameter (L/D) ratio and ease of application, which was deemed to be missing in the traditional methods. The Dayton Equation took into account the changes in the relative radius of curvature, R_c, for the smoothed or ideal conditions, which ensured repeatability and reliability of the measured friction coefficient, thereby asserting a reasonable degree of accuracy compared to friction coefficients as determined by all other traditional methods (Tagwi et al., 2022). In the comparisons, the Dayton Equation was made the reference or point of departure in determining secondary losses to show the extent of variation involved in the use of each of the traditional methods, as well as the possible conversion between the three methods.

The use of the Dayton Equation allowed for determination of frictional losses due to bending within ranges outside and between the pragmatic tests and the published literature (ARC, 2003; Spedding et al., 2004; Neutrium, 2016). This allowed for comparison of the different equivalent lengths and coefficients published. Comparison of the traditional methods was, however, undertaken using the same pipe diameter and curvature as those in the published data, since the friction coefficient was found to be constant for a fixed pipe diameter and relative radius of curvature, R_c (Itō, 1959; Berger et al., 1983; Idelchik, 1987). The 19.05 mm pipe diameter was chosen for comparison since it had the most data sets from published literature on all traditional methods, giving more information on the comparisons made. Table 1 shows the friction coefficients with the Dayton Equation in the determination of frictional losses for flow velocities within and above the allowable in irrigation systems for comparison.

Table 1 Dayton Equation (Empirical equation) friction coefficients (k) for the 19.05 mm diameter pipe used for comparison of the frictional losses (Tagwi et al., 2022)

Short radius						Standard radius					Long radius				
0°	22.0°	22.5°	45°	67.5°	90°	0°	22.5°	45°	67.5°	90°	0°	22.5°	45°	67.5°	90°
0.060	0.176	0.180	0.359	0.598	0.898	0.049	0.148	0.296	0.493	0.739	0.027	0.080	0.160	0.266	0.399

Comparison with the Dayton Equation was done individually for each of the traditional method to give the percentage difference (for smooth pipes with roughness of 0.03) in the frictional losses determined for the chosen 19.05 mm diameter, mathematically expressed as

$$\left(\frac{\text{Frictional loss as determined by traditional method} - \text{Frictional loss by Dayton Equation}}{\text{Frictional loss by Dayton Equation}}\right)\%$$

, that is also equivalent to

$$\left(\frac{\text{Frictional coefficient by traditional method} - \text{Frictional coefficient by Dayton Equation}}{\text{Frictional coefficient by Dayton Equation}}\right)\%$$

when friction coefficients area involved. This was then expanded to the different published equivalent lengths or coefficients for the same pipe diameter. Based on these comparisons, it could then be deduced to what extent correction of the traditional methods would need, and the possible error in the derivation of the equivalent lengths and friction coefficients was compared to the Dayton Equation. Tables 2 to 4 show the published equivalent lengths and friction coefficients for the traditional methods later used for comparisons with the Dayton's equation.

Table 2 Equivalent lengths (L/D values) for the 19.05 mm diameter pipe used for comparison of the frictional losses (h_f) wherein $h_f = f\,(L/D)V^2/2g$

Short radius						Standard radius						Long radius						Source
0°	22.0°	22.5°	45°	67.5°	90°	0°	22°	22.5°	45°	67.5°	90°	0°	22°	22.5°	45°	67.5°	90°	
-	9	-	18	-	45	-	7	-	14	-	34	-	5	-	9	-	18	(ARC, 2003)
-	-	-	-	-	-	-	-	-	16	-	30	-	-	-	-	-	16	(Spedding et al., 2004)
-	-	-	-	-	-	-	-	-	16	-	30	-	-	-	-	-	16	(Neutrium, 2016)

Note: -, values not found in literature.

Table 3 Resistance coefficients (k values) for the 19.05 mm diameter pipe used for comparison of the frictional losses (h_f) wherein $h_f = kV^2/2g$

Short radius					Standard radius					Long radius					Source
0°	22.5°	45°	67.5°	90°	0°	22.5°	45°	67.5°	90°	0°	22.5°	45°	67.5°	90°	
-	-	-	-	0.90	-	0.15	0.30	-	0.75	-	-	-	-	0.40	(ARC, 2003)
-	-	-	-	-	-	-	0.40	-	0.75	-	-	-	-	0.40	(Spedding et al., 2004)
-	-	-	-	0.90	-	-	0.35	-	0.75	-	-	0.2	-	0.45	(Neutrium, 2016)

Note: -, values not found in literature.

Table 4 Valve flow coefficients (k values) for the 19.05 mm diameter pipe used for comparison of frictional losses (h_L) wherein $h_L = 0.0295\,kQ^2/d^4$; $C_v = 1.157K_v$, $K_v = 0.8646C_v$

Short radius					Standard radius					Long radius					Source
0°	22.5°	45°	67.5°	90°	0°	22.5°	45°	67.5°	90°	0°	22.5°	45°	67.5°	90°	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(ARC, 2003)
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(Spedding et al., 2004)
-	-	-	-	-	-	-	1.1	-	2.06	-	-	-	-	1.1	(Neutrium, 2016)

Note: -, values not found in literature.

3 Results and Discussion

The variances found for the Equivalent Length, Resistance Coefficient, and the Valve Flow Coefficient Method in the determination of minor or secondary losses in comparison with the Dayton Equation (as reference point), are presented and discussed in the following subsections.

3.1 Equivalent Length Method

Looking at the comparisons made on the minor loss as generated by the Dayton Equation and the Equivalent Length method (Comparison or difference, the meter/meter of frictional loss as calculated by the Equivalent Length method compared to the Dayton Equation, expressed as a percentage (%)) summarised in Table 5 for the available published experimental data, there are generally huge differences in the estimation of the frictional loss when looking at the 90° bends. Clearly there were over-estimations when coming up with the equivalent length as derived from the principle of pressure loss as in the straight pipe looking at the R_c, relative radius of curvature, that is the radius of curvature, r per pipe diameter for bend, D (unit less).

Table 5 Comparison of minor (secondary) head losses as determined by the Dayton Equation and the Equivalent Length method for the 19.05 mm diameter pipe

Short radius						Standard radius						Long radius						
0°	22.0°	22.5°	45°	67.5°	90°	0°	22°	22.5°	45°	67.5°	90°	0°	22°	22.5°	45°	67.5°	90°	
-	9	-	18	-	45	-	7	-	14	-	34	-	5	-	9	-	18	Equivalent Length (ARC, 2003)
-	53.231%	-	50.406%	-	50.409%	-	41.986%	-	41.986%	-	37.932%	-	-6.018%	-	-32.332%	-	35.336%	Comparison/Difference (meter/meter) %
-	-	-	-	-	-	-	-	-	16	-	30	-	-	-	-	-	16	E*qui*valent Length (Spedding et al., 2004)
-	-	-	-	-	-	-	-	-	62.270%	-	-35.091%	-	-	-	-	-	20.298%	Comparison/Difference (meter/meter) %
-	-	-	-	-	-	-	-	-	16	-	30	-	-	-	-	-	16	Equivalent Length (Neutrium, 2016)
-	-	-	-	-	-	-	-	-	62.270%	-	-35.091%	-	-	-	-	-	20.298%	Comparison/Difference (meter/meter) %

Note: $h_f = f*L/D*V^2/2g$, (L/D) values and the following corresponding difference in comparison with the Dayton Equation.

Since the flow coefficient (L/D ratio) decreases as the fittings size increases, the pressure drop was generally overestimated at pipe sizes greater than those for which the pipe equivalent length was calculated by the Equivalent Length method (Table 5), though the effect was reduced with increase in the radius of curvature. This is shown by the fairly large percentage differences on comparison of the highest and lowest values. It also means that most pipes tested for the published data were limited to the small diameter pipes (less than 19.05 mm). This left the bigger pipe diameters (larger than 19.05 mm) subject to scaling up to get the equivalent lengths. As pipe diameter decreases, the accuracy of test-based loss predictions also deteriorates, leaving users and others to scale down the equivalent lengths again. Generally, this resulted in the underestimating of the equivalent length at pipe sizes smaller than those for which the equivalent length was calculated with the pragmatic tests conducted.

From the results (Table 5), more deviation is seen with the standard radius bend. Approximation of the minor losses is much poorer as we reduce the bend angle (from the 90° to the 45° bends shown for each R_c). The converse is seen on the long radius, giving the lesser or least difference of the three sets of data available on comparison. It is clear there was no consideration of the change in the L/D ratio considering the R_c values, introducing significant percentage differences, some from a high positive (over estimation) to a fairly high negative (underestimation) with the use of the Equivalent length method.

From the 90° standard and long radius results, though scaled without the consideration of the L/D ratio (seen to introduce the inaccuracies in the traditional method) but using only roughness and Reynolds number (likely to vary from the conditions used to characterize the fitting), the approach can be considered fairly reliable as deemed by Perry (1950), Crane (1957), Co (1988), Spedding et al. (2004) and Neutrium (2016). While Tullis (1989) indicates that the Equivalent length method 's dependability is determined by flow conditions and that it is most accurate for totally turbulent flow with common fittings. This is particularly so in the case when the

L/D ratio or R_c is nearly the same for a pipe diameter in question as that for which the equivalent length would have been derived.

The Equivalent Length method however has the advantage of being very easy to use when calculating the minor loss component, provided the pragmatic values (equivalent lengths) are available. Each pipe run, (straight pipe sections) and fittings (bends), can be added together to form a single total length, from which the overall pressure loss can be determined. Unfortunately, despite this advantage, incorrect determination of the equivalent length due to the constant L/D ratio as seen in the comparison, renders the method erroneous. Mott (2006) also recommended the equivalent length is reasonably accurate for most engineering applications, although it is recommended to cross-check with experimental data for important systems. Iterations or goal seeking can however be done with reference to the use of the Dayton Equation to deduce the correct equivalent length for use in the event that there is need to use an equivalent length repeatedly elsewhere (See Appendix B).The uncertainty in the use of the Equivalent Length method to date has left irrigation designers to apply the general rule of thumb which states that for 90° bends, pressure drop due to a pipe bend is equal to a pipe length of 30 to 50 diameters in excess of the length of the straight pipe as given by Co (1988), Perry (1950) and Spedding et al. (2004). Idelchik (1987) attests that in turbulent flow, the equivalent length of a 90° bend with R/D = 1.5 is between 32 and 40 diameters. Sharper bends (R/D = 1) might approach 50 diameters. This, however, introduces gross inaccuracies or errors as seen by the results of the comparisons.

3.2 Resistance Coefficient Method

On comparison, there was nearly insignificant variation of the frictional losses as determined by the Resistance Coefficient method (published) when compared to the Dayton Equation. Results for the comparison are given in Table 6.

Table 6 Comparison of minor (secondary) head losses as determined by the Dayton Equation and the Resistance Coefficient method for the 19.05 mm diameter pipe

Short radius					Standard radius					Long radius					
0°	22.5°	45°	67.5°	90°	0°	22.5°	45°	67.5°	90°	0°	22.5°	45°	67.5°	90°	
-	-	-	-	0.90	-	0.15	0.30	-	0.75	-	-	-	-	0.40	Friction Coefficient (ARC, 2003)
-	-	-	-	0.272%		1.418%	1.419%	-	1.420%	-	-	-	-	0.249%	Comparison/Difference (meter/meter) %
-	-	-	-	-	-	-	0.40	-	0.75	-	-	-	-	0.40	Friction Coefficient (Spedding et al., 2004)
-	-	-	-	-		-	35.225%		1.420%			-		0.249%	Comparison/Difference (meter/meter) %
-	-	-	-	0.90	-	-	0.35	-	0.75	-	-	0.2	-	0.45	Friction Coefficient (Neutrium, 2016)
-	-	-	-	0.272%		-	18.322%	-	1.420%	-	-	25.309%	-	12.780%	Comparison/Difference (meter/meter) %

Note: $h_f = kv^2/2g$, *k* values following corresponding difference in comparison with the Dayton Equation

With the exception of the standard and long radius 45° bends as deemed by Spedding et al. (2004) and Neutrium (2016), the closeness of the theoretical Dayton Equation frictional loss to the published Resistance Coefficient method results reaffirms the reliability of the Resistance Coefficient methods compared to all the other methods, also making it a good reference for comparison. It can also be seen that there was consideration of the changing bend parameters on the published coefficients that is the changing curvature as considered by the Dayton Equation.

Looking at the lowest and highest differences in the table, the relatively high deviation from the Dayton Equation occurred for coefficients on the 45° bends for the standard radius and long radius. This flagged the possibility of the possible error in the published coefficients since the other dynamically determined coefficients (through scale up with consideration of the R_c) outside the 19.05 mm diameter pipe size (less than or greater than the 19.05 mm diameter) were in closed agreement with the Daton Equation (See Appendix B). Using the published resistance coefficients has proven to give good close estimates of the minor frictional losses due to bending when designing irrigation systems when compared to the Dayton Equation. The only limitation was the availability of the published coefficients with changing pipe diameters, curvature (R_c). This was however catered for with the use of the Dayton Equation as seen with relatively close agreement with the few available published coefficients outside of the 19.05 mm diameter pipe size (pipe diameters less than or greater than the 19.05 mm diameter).

3.3 Valve Flow Coefficient

Based on the comparisons for standard and long radius 90° bends, the method can be considered fairly reliable, although it tends to underestimate the losses. Results are tabulated Table 7.

Table 7 Comparison of head losses as determined by the Dayton Equation and the Valve Flow Coefficient Method for the 19.05 mm diameter pipe.

Short radius					Standard radius					Long radius					
0°	22.5°	45°	67.5°	90°	0°	22.5°	45°	67.5°	90°	0°	22.5°	45°	67.5°	90°	
-	-	-	-	-	-	-	1.1	-	2.06	-	-	-	-	1.1	Friction Coefficient (Neutrium, 2016)
-	-	-	-	-	-	-	32.767%	-	-0.544%	-	-	-	-	-1.574%	Comparison/Difference (meter/meter) %

Note: $C_v = 1.157K_v$ and $K_v = 0.8646Cv$; $h_L = 0.0295 K Q^2/d^4$, K values following corresponding difference in comparison with the Dayton Equation

Reliability of the method is seen to underestimate frictional losses as we continue to increase the relative radius of curvature (R_c) from the Standard to the Long radius bend.

Cleary from the 45° Standard radius bend, overestimation is seen for lower levels of bending (smaller bend angle). This again is largely due to the unreliability of conversion of the friction factors with the reduced size (R_c) of the fittings. The Valve Flow Coefficient methods' poor estimates when applied to the bends can again simply be corrected using iterations from values obtained from the Dayton Equation for use in instances wherein it may be required repeatedly (See Appendix B).

Despite the complexity of using the k values published for the Resistance Coefficient method compared to the findings of the Dayton Equation, the reliance of the Valve Flow method for the conversion of the Resistance Coefficient shows that moving to the Valve Flow method slightly underpredicts the determination of minor losses. This leaves room for error and can better be corrected when using the Dayton Equation.

Comparison with all the traditional methods was achieved for the Standard bend despite the limited data. Reasonable agreement was also found for the standard and long radius bends at 90°, even though equivalent lengths and resistance coefficients for bend angles below 90° were largely absent from the literature.

In the comparisons made with reference to the Dayton Equation, generally there were significant differences for the frictional losses estimated with the Equivalent Length method. Losses were nearly the same with the Resistance Coefficient method, accenting the accuracy of the resistance coefficient methods. For the Valve Flow Coefficient method, frictional losses were nearly the same in some instances but quite varied in other instances. Frictional loss estimations were relatively poor for the Equivalent Length and the Valve Flow Coefficient method for bend angles less than 90°.

4 Conclusions

Using the Dayton Equation as a reference gave a strong foundation for assessing the accuracy, reliability and dependability of the three conventional approaches (Equivalent Length, Resistance Coefficient, and Valve Flow Coefficient) for calculating minor (secondary) head losses. This approach permitted comparisons using known equivalent lengths and coefficients, as well as extrapolation and validation for pipe diameter other than 19.05 mm. Notably, published experimental findings for 90° bends were closely aligned with the Dayton Equation, demonstrating that conventional approaches can yield reasonably accurate results in such cases. However, their efficiency is greatly reduced when applied to bend angles less than 90° or when flow coefficients and curvature parameters change.

The Equivalent Length Method, despite its simplicity and convenience of application, showed significant deviations, owing to oversimplification of curvature effects and assumptions of constant L/D ratios. These variables contributed to both overestimation and underestimating of pressure loss, particularly when scaled beyond the initial test circumstances. Although it is still helpful for broad estimates, its accuracy is restricted unless it is corrected iteratively using more accurate reference data from experimental tests or the Dayton Equation.

In contrast, the Resistance Coefficient Method consistently yielded the best agreement with the Dayton Equation. It was reliable for calculating losses across a variety of bend configurations, as long as published resistance coefficients (calculated with curvature and pipe diameter considerations) were available. Minor inconsistencies, such as those detected at 45° bends, were ascribed to potential flaws in published coefficients, but this method emerged as the most reliable of the three conventional ways.

The Valve Flow Coefficient Method produced relatively accurate findings for 90° conventional and long-radius bends, but it consistently overestimated losses as curvature grew. Its dependence on coefficient conversion and restricted application for bends smaller than 90° jeopardized its dependability. However, iterative correction against the Dayton Equation may increase its accuracy for subsequent uses.

Overall, the comparison analysis revealed clear differences in the reliability of the three approaches. The Resistance Coefficient Method was the most accurate, followed by the Valve Flow Coefficient Method, and finally the Equivalent Length Method exhibiting the greatest deviations. Significant estimate errors were observed across all three traditional methods for bend angles less than 90°, highlighting their limits in dynamic design scenarios.

The Dayton Equation is consequently suggested as the preferable approach for computing comparable lengths and resistance coefficients. Its capacity to produce close approximations to experimentally confirmed data, as well as extrapolate values beyond stated limits, making it a better and more reliable tool for predicting minor losses, particularly in precision-critical applications like irrigation system design.

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Appendix A: Frictional losses as determined by Dayton Equation for the 19.05 mm diameter pipe

	Velocity (m s^{-1})	**Short radius**						**Standard radius**					**Long radius**				
		0°	**22.0°**	**22.5°**	**45°**	**67.5°**	**90°**	**0°**	**22.5°**	**45°**	**67.5°**	**90°**	**0°**	**22.5°**	**45°**	**67.5°**	**90°**
Allowable flow for irrigation →	0.0328	3.29E-06	9.67E-06	9.86E-06	1.97E-05	3.29E-05	4.93E-05	2.71E-06	8.12E-06	1.62E-05	2.71E-05	4.06E-05	1.46E-06	4.38E-06	8.76E-06	1.46E-05	2.19E-05
	0.0393	4.71E-06	1.39E-05	1.41E-05	2.83E-05	4.71E-05	7.07E-05	3.88E-06	1.16E-05	2.33E-05	3.88E-05	5.82E-05	2.09E-06	6.28E-06	1.26E-05	2.09E-05	3.14E-05
	0.0472	6.78E-06	2.00E-05	2.03E-05	4.07E-05	6.78E-05	1.02E-04	5.59E-06	1.68E-05	3.35E-05	5.59E-05	8.38E-05	3.02E-06	9.05E-06	1.81E-05	3.02E-05	4.52E-05
	0.0550	9.23E-06	2.72E-05	2.77E-05	5.54E-05	9.23E-05	1.38E-04	7.61E-06	2.28E-05	4.56E-05	7.61E-05	1.14E-04	4.10E-06	1.23E-05	2.46E-05	4.10E-05	6.16E-05
	0.0629	1.21E-05	3.55E-05	3.62E-05	7.23E-05	1.21E-04	1.81E-04	9.93E-06	2.98E-05	5.96E-05	9.93E-05	1.49E-04	5.36E-06	1.61E-05	3.22E-05	5.36E-05	8.04E-05
	0.0656	1.31E-05	3.87E-05	3.94E-05	7.88E-05	1.31E-04	1.97E-04	1.08E-05	3.25E-05	6.50E-05	1.08E-04	1.62E-04	5.84E-06	1.75E-05	3.51E-05	5.84E-05	8.76E-05
	0.0707	1.53E-05	4.49E-05	4.58E-05	9.16E-05	1.53E-04	2.29E-04	1.26E-05	3.77E-05	7.54E-05	1.26E-04	1.89E-04	6.78E-06	2.04E-05	4.07E-05	6.78E-05	1.02E-04
	0.0786	1.88E-05	5.55E-05	5.65E-05	1.13E-04	1.88E-04	2.83E-04	1.55E-05	4.66E-05	9.31E-05	1.55E-04	2.33E-04	8.38E-06	2.51E-05	5.03E-05	8.38E-05	1.26E-04
	0.0865	2.28E-05	6.71E-05	6.84E-05	1.37E-04	2.28E-04	3.42E-04	1.88E-05	5.63E-05	1.13E-04	1.88E-04	2.82E-04	1.01E-05	3.04E-05	6.08E-05	1.01E-04	1.52E-04
	0.0985	2.96E-05	8.71E-05	8.87E-05	1.77E-04	2.96E-04	4.44E-04	2.44E-05	7.31E-05	1.46E-04	2.44E-04	3.65E-04	1.31E-05	3.94E-05	7.89E-05	1.31E-04	1.97E-04
	0.1313	5.26E-05	1.55E-04	1.58E-04	3.15E-04	5.26E-04	7.88E-04	4.33E-05	1.30E-04	2.60E-04	4.33E-04	6.50E-04	2.34E-05	7.01E-05	1.40E-04	2.34E-04	3.51E-04
	0.1641	8.21E-05	2.42E-04	2.46E-04	4.93E-04	8.21E-04	1.23E-03	6.77E-05	2.03E-04	4.06E-04	6.77E-04	1.02E-03	3.65E-05	1.10E-04	2.19E-04	3.65E-04	5.48E-04
	0.1969	1.18E-04	3.48E-04	3.55E-04	7.10E-04	1.18E-03	1.77E-03	9.74E-05	2.92E-04	5.85E-04	9.74E-04	1.46E-03	5.26E-05	1.58E-04	3.15E-04	5.26E-04	7.89E-04
	0.2297	1.61E-04	4.74E-04	4.83E-04	9.66E-04	1.61E-03	2.41E-03	1.33E-04	3.98E-04	7.96E-04	1.33E-03	1.99E-03	7.16E-05	2.15E-04	4.29E-04	7.16E-04	1.07E-03
	0.2626	2.10E-04	6.19E-04	6.31E-04	1.26E-03	2.10E-03	3.15E-03	1.73E-04	5.20E-04	1.04E-03	1.73E-03	2.60E-03	9.35E-05	2.80E-04	5.61E-04	9.35E-04	1.40E-03
	0.2713	2.24E-04	6.61E-04	6.73E-04	1.35E-03	2.24E-03	3.37E-03	1.85E-04	5.55E-04	1.11E-03	1.85E-03	2.77E-03	9.98E-05	2.99E-04	5.99E-04	9.98E-04	1.50E-03
	0.5426	8.98E-04	2.64E-03	2.69E-03	5.39E-03	8.98E-03	1.35E-02	7.40E-04	2.22E-03	4.44E-03	7.40E-03	1.11E-02	3.99E-04	1.20E-03	2.39E-03	3.99E-03	5.99E-03
	0.8139	2.02E-03	5.95E-03	6.06E-03	1.21E-02	2.02E-02	3.03E-02	1.66E-03	4.99E-03	9.99E-03	1.66E-02	2.50E-02	8.98E-04	2.69E-03	5.39E-03	8.98E-03	1.35E-02
	1	3.05E-03	8.98E-03	9.15E-03	1.83E-02	3.05E-02	4.57E-02	2.51E-03	7.54E-03	1.51E-02	2.51E-02	3.77E-02	1.36E-03	4.07E-03	8.13E-03	1.36E-02	2.03E-02
	2	1.22E-02	3.59E-02	3.66E-02	7.32E-02	1.22E-01	1.83E-01	1.01E-02	3.02E-02	6.03E-02	1.01E-01	1.51E-01	5.42E-03	1.63E-02	3.25E-02	5.42E-02	8.13E-02
	3	2.74E-02	8.08E-02	8.23E-02	1.65E-01	2.74E-01	4.12E-01	2.26E-02	6.78E-02	1.36E-01	2.26E-01	3.39E-01	1.22E-02	3.66E-02	7.32E-02	1.22E-01	1.83E-01
Above allowable flow ↓	4	4.88E-02	1.44E-01	1.46E-01	2.93E-01	4.88E-01	7.32E-01	4.02E-02	1.21E-01	2.41E-01	4.02E-01	6.03E-01	2.17E-02	6.51E-02	1.30E-01	2.17E-01	3.25E-01
	5	7.62E-02	2.25E-01	2.29E-01	4.57E-01	7.62E-01	1.14E+00	6.28E-02	1.88E-01	3.77E-01	6.28E-01	9.42E-01	3.39E-02	1.02E-01	2.03E-01	3.39E-01	5.08E-01
			R_c at 90°				0.5		R_c at 90°			1		R_c at 90°			1.5
			Pipe diameter (mm)				19.05		Pipe diameter (mm)			19.05		Pipe diameter (mm)			19.05
Theoretical friction coefficients for 19.05mm pipe		**0.060**	**0.176**	**0.180**	**0.359**	**0.598**	**0.898**	**0.049**	**0.148**	**0.296**	**0.493**	**0.739**	**0.027**	**0.080**	**0.160**	**0.266**	**0.399**

Appendix B: Dayton Equation calculator based on the theoretical 19.05 mm diameter pipe

		Empirical Equation (Pressure drop calculator)															
		Short radius						**Standard radius**					**Long radius**				
Flow (LPM)	**Flow (m/s)**	**0°**	**22.0°**	**22.5°**	**45°**	**67.5°**	**90°**	**0°**	**22.5°**	**45°**	**67.5°**	**90°**	**0°**	**22.5°**	**45°**	**67.5°**	**90°**
14.55	0.0328	3.2852E-06	9.6744E-06	9.8561E-06	1.9712E-05	3.2853E-05	4.9280E-05	2.7067E-06	8.1205E-06	1.6241E-05	2.7068E-05	4.0602E-05	1.4604E-06	4.3815E-06	8.7631E-06	1.4605E-05	2.1907E-05
17.43	0.0393	4.7100E-06	1.3870E-05	1.4131E-05	2.8261E-05	4.7102E-05	7.0653E-05	3.8806E-06	1.1642E-05	2.3285E-05	3.8807E-05	5.8211E-05	2.0939E-06	6.2818E-06	1.2564E-05	2.0939E-05	3.1409E-05
24.40	0.0550	9.2317E-06	2.7186E-05	2.7696E-05	5.5392E-05	9.2320E-05	1.3848E-04	7.6060E-06	2.2819E-05	4.5638E-05	7.6063E-05	1.1409E-04	4.1040E-06	1.2312E-05	2.4625E-05	4.1041E-05	6.1561E-05
27.88	0.0629	1.2058E-05	3.5508E-05	3.6175E-05	7.2349E-05	1.2058E-04	1.8087E-04	9.9344E-06	2.9804E-05	5.9609E-05	9.9347E-05	1.4902E-04	5.3603E-06	1.6082E-05	3.2163E-05	5.3604E-05	8.0406E-05
31.37	0.0707	1.5261E-05	4.4940E-05	4.5784E-05	9.1567E-05	1.5261E-04	2.2891E-04	1.2573E-05	3.7721E-05	7.5442E-05	1.2574E-04	1.8860E-04	6.7841E-06	2.0353E-05	4.0706E-05	6.7843E-05	1.0176E-04
34.85	0.0786	1.8840E-05	5.5481E-05	5.6523E-05	1.1305E-04	1.8841E-04	2.8261E-04	1.5522E-05	4.6569E-05	9.3139E-05	1.5523E-04	2.3284E-04	8.3754E-06	2.5127E-05	5.0255E-05	8.3757E-05	1.2563E-04
58.21	0.1313	5.2564E-05	1.5479E-04	1.5770E-04	3.1539E-04	5.2565E-04	7.8847E-04	4.3307E-05	1.2993E-04	2.5985E-04	4.3309E-04	6.4963E-04	2.3367E-05	7.0105E-05	1.4021E-04	2.3368E-04	3.5052E-04
87.32	0.1969	1.1827E-04	3.4828E-04	3.5482E-04	7.0964E-04	1.1827E-03	1.7741E-03	9.7441E-05	2.9234E-04	5.8467E-04	9.7444E-04	1.4617E-03	5.2576E-05	1.5774E-04	3.1547E-04	5.2578E-04	7.8866E-04
101.87	0.2297	1.6098E-04	4.7405E-04	4.8295E-04	9.6590E-04	1.6098E-03	2.4147E-03	1.3263E-04	3.9790E-04	7.9580E-04	1.3263E-03	1.9895E-03	7.1562E-05	2.1470E-04	4.2939E-04	7.1564E-04	1.0735E-03
120.29	0.2713	2.2445E-04	6.6096E-04	6.7338E-04	1.3467E-03	2.2446E-03	3.3668E-03	1.8492E-04	5.5480E-04	1.1096E-03	1.8493E-03	2.7739E-03	9.9779E-05	2.9935E-04	5.9870E-04	9.9782E-04	1.4967E-03
240.59	0.5426	8.9779E-04	2.6438E-03	2.6935E-03	5.3870E-03	8.9782E-03	1.3467E-02	7.3969E-04	2.2192E-03	4.4383E-03	7.3972E-03	1.1096E-02	3.9911E-04	1.1974E-03	2.3948E-03	3.9913E-03	5.9869E-03
360.88	0.8139	2.0200E-03	5.9487E-03	6.0604E-03	1.2121E-02	2.0201E-02	3.0301E-02	1.6643E-03	4.9932E-03	9.9863E-03	1.6644E-02	2.4965E-02	8.9801E-04	2.6941E-03	5.3883E-03	8.9804E-03	1.3470E-02
Tested flows →	1	3.0497E-03	8.9809E-03	9.1496E-03	1.8299E-02	3.0498E-02	4.5747E-02	2.5127E-03	7.5383E-03	1.5077E-02	2.5127E-02	3.7691E-02	1.3558E-03	4.0674E-03	8.1348E-03	1.3558E-02	2.0337E-02
	2	1.2199E-02	3.5924E-02	3.6598E-02	7.3196E-02	1.2199E-01	1.8299E-01	1.0051E-02	3.0153E-02	6.0306E-02	1.0051E-01	1.5076E-01	5.4230E-03	1.6270E-02	3.2539E-02	5.4232E-02	8.1347E-02
	5	7.6243E-02	2.2452E-01	2.2874E-01	4.5748E-01	7.6245E-01	1.1437E+00	6.2817E-02	1.8846E-01	3.7692E-01	6.2819E-01	9.4227E-01	3.3894E-02	1.0169E-01	2.0337E-01	3.3895E-01	5.0842E-01
		R_c value wrt 19.05mm pipe; 90°& R_c =1					0.5	**R_c value** wrt 19.05mm pipe; 90°& R_c =1				1	**R_c value** wrt 19.05mm pipe; 90°& R_c =1				1.5
		Pipe diameter (mm)					19.05	Pipe diameter (mm)				19.05	Pipe diameter (mm)				19.05
		Friction coefficient															
		0.060	**0.176**	**0.180**	**0.359**	**0.598**	**0.898**	**0.049**	**0.148**	**0.296**	**0.493**	**0.739**	**0.027**	**0.080**	**0.160**	**0.266**	**0.399**
		Unit conversion from (×10^2 kPa = bar)					1										

Accuracy / Difference	**Reference**

Short Radius (R = 0.5D)					**Standard Radius (R = 1D)**					**Long Radius (R =1.5D)**					**Reference**	**mm**	**inch**
0°	**22.5°**	**45°**	**67.5°**	**90°**	**0°**	**22.5°**	**45°**	**67.5°**	**90°**	**0°**	**22.5°**	**45°**	**67.5°**	**90°**			

-	**-**	**-**	**-**	**0.90**	**-**	**0.15**	**0.30**	**-**	**0.75**	**-**	**-**	**-**	**-**	**0.40**	**(ARC, 2003)**	**Not given**	**Not given**
-	-	-	-	-	-	-	0.43	-	0.81	-	-	-	-	0.43	**(Spedding *et al.*, 2004)**	12.7	0.5
-	**-**	**-**	**-**	**-**	**-**	**-**	**0.4**	**-**	**0.75**	**-**	**-**	**-**	**-**	**0.40**		**19.05**	**0.75**
-	-	-	-	-	-	-	0.37	-	0.69	-	-	-	-	0.37		25.4	1
-	-	-	-	-	-	-	0.35	-	0.66	-	-	-	-	0.35		31.75	1.25
-	-	-	-	-	-	-	0.34	-	0.63	-	-	-	-	0.34		38.1	1.5
-	-	-	-	-	-	-	0.3	-	0.57	-	-	-	-	0.3		50.8	2
-	-	-	-	-	-	-	0.29	-	0.54	-	-	-	-	0.29		63.5	2.50 to 3
-	-	-	-	-	-	-	0.27	-	0.51	-	-	-	-	0.27		101.6	4
-	-	-	-	-	-	-	0.24	-	0.45	-	-	-	-	0.24		152.4	6
-	-	-	-	-	-	-	0.22	-	0.42	-	-	-	-	0.22		203.2	8.0 to 10
-	-	-	-	-	-	-	0.21	-	0.39	-	-	-	-	0.21		304.8	12.0 to 16
-	-	-	-	-	-	-	0.19	-	0.36	-	-	-	-	0.19		457.2	18.0 to 24
-	**-**	**-**	**-**	**0.90**	**-**	**-**	**0.35**	**-**	**0.75**	**-**	**-**	**0.2**	**-**	**0.45**	**(Neutrium, 2016)**	**Not given**	**Not given**
R = Radius, D = Outside Diameters																	

	Comparisons																						
	Equivalent length where $h_f = f*L/D*V^2/2g$ (19.05mm diameter pipe)										**Resistance Coefficient method where $h_f = kv^2/2g$ (19.05mm diameter pipe)**							**Valve flow coefficient method where $C_v = 1.157K_v$ and $K_v = 0.8646C_v$; $h_L = 0.0295\ k\ Q^2/d^4$ (19.05mm diameter pipe)**					
	Short radius				**Standard radius**			**Long radius**			**Short radius**		**Standard radius**			**Long radius**		**Short radius**		**Standard radius**		**Long radius**	
Flow (m/s)	**0°**	**22.0°**	**45°**	**90°**	**22°**	**45°**	**90°**	**22°**	**45°**	**90°**	**0°**	**90°**	**22.5°**	**45°**	**90°**	**45°**	**90°**	**0°**	**90°**	**45°**	**90°**	**0°**	**90°**
0.0328	-	9.6744E-06	1.9712E-05	4.9280E-05	8.1205E-06	1.6241E-05	4.0602E-05	8.7631E-06	2.1907E-05	2.1907E-05	-	4.9280E-05	8.1205E-06	1.6241E-05	4.0602E-05	8.7631E-06	2.1907E-05	-	-	1.6241E-05	4.06016E-05	-	2.1907E-05
0.0393	-	1.3870E-05	2.8261E-05	7.0653E-05	1.1642E-05	2.3285E-05	5.8211E-05	1.2564E-05	3.1409E-05	3.1409E-05	-	7.0653E-05	1.1642E-05	2.3285E-05	5.8211E-05	1.2564E-05	3.1409E-05	-	-	2.3285E-05	5.82107E-05	-	3.1409E-05
0.0550	-	2.7186E-05	5.5392E-05	1.3848E-04	2.2819E-05	4.5638E-05	1.1409E-04	2.4625E-05	6.1561E-05	6.1561E-05	-	1.3848E-04	2.2819E-05	4.5638E-05	1.1409E-04	2.4625E-05	6.1561E-05	-	-	4.5638E-05	0.000114093	-	6.1561E-05
0.0629	-	3.5508E-05	7.2349E-05	1.8087E-04	2.9804E-05	5.9609E-05	1.4902E-04	3.2163E-05	8.0406E-05	8.0406E-05	-	1.8087E-04	2.9804E-05	5.9609E-05	1.4902E-04	3.2163E-05	8.0406E-05	-	-	5.9609E-05	0.000149019	-	8.0406E-05
0.0707	-	4.4940E-05	9.1567E-05	2.2891E-04	3.7721E-05	7.5442E-05	1.8860E-04	4.0706E-05	1.0176E-04	1.0176E-04	-	2.2891E-04	3.7721E-05	7.5442E-05	1.8860E-04	4.0706E-05	1.0176E-04	-	-	7.5442E-05	0.000188603	-	1.0176E-04
0.0786	-	5.5481E-05	1.1305E-04	2.8261E-04	4.6569E-05	9.3139E-05	2.3284E-04	5.0255E-05	1.2563E-04	1.2563E-04	-	2.8261E-04	4.6569E-05	9.3139E-05	2.3284E-04	5.0255E-05	1.2563E-04	-	-	9.3139E-05	0.000232843	-	1.2563E-04
0.1313	-	1.5479E-04	3.1539E-04	7.8847E-04	1.2993E-04	2.5985E-04	6.4963E-04	1.4021E-04	3.5052E-04	3.5052E-04	-	7.8847E-04	1.2993E-04	2.5985E-04	6.4963E-04	1.4021E-04	3.5052E-04	-	-	2.5985E-04	0.000649625	-	3.5052E-04
0.1969	-	3.4828E-04	7.0964E-04	1.7741E-03	2.9234E-04	5.8467E-04	1.4617E-03	3.1547E-04	7.8866E-04	7.8866E-04	-	1.7741E-03	2.9234E-04	5.8467E-04	1.4617E-03	3.1547E-04	7.8866E-04	-	-	5.8467E-04	0.001461656	-	7.8866E-04
0.2297	-	4.7405E-04	9.6590E-04	2.4147E-03	3.9790E-04	7.9580E-04	1.9895E-03	4.2939E-04	1.0735E-03	1.0735E-03	-	2.4147E-03	3.9790E-04	7.9580E-04	1.9895E-03	4.2939E-04	1.0735E-03	-	-	7.9580E-04	0.001989477	-	1.0735E-03
0.2713	-	6.6096E-04	1.3467E-03	3.3668E-03	5.5480E-04	1.1096E-03	2.7739E-03	5.9870E-04	1.4967E-03	1.4967E-03	-	3.3668E-03	5.5480E-04	1.1096E-03	2.7739E-03	5.9870E-04	1.4967E-03	-	-	1.1096E-03	0.002773921	-	1.4967E-03
0.5426	-	2.6438E-03	5.3870E-03	1.3467E-02	2.2192E-03	4.4383E-03	1.1096E-02	2.3948E-03	5.9869E-03	5.9869E-03	-	1.3467E-02	2.2192E-03	4.4383E-03	1.1096E-02	2.3948E-03	5.9869E-03	-	-	4.4383E-03	0.011095685	-	5.9869E-03
1	-	8.9809E-03	1.8299E-02	4.5747E-02	7.5383E-03	1.5077E-02	3.7691E-02	8.1348E-03	2.0337E-02	2.0337E-02	-	4.5747E-02	7.5383E-03	1.5077E-02	3.7691E-02	8.1348E-03	2.0337E-02	-	-	1.5077E-02	0.037690917	-	2.0337E-02
2	-	3.5924E-02	7.3196E-02	1.8299E-01	3.0153E-02	6.0306E-02	1.5076E-01	3.2539E-02	8.1347E-02	8.1347E-02	-	1.8299E-01	3.0153E-02	6.0306E-02	1.5076E-01	3.2539E-02	8.1347E-02	-	-	6.0306E-02	0.150763669	-	8.1347E-02
5	-	2.2452E-01	4.5748E-01	1.1437E+00	1.8846E-01	3.7692E-01	9.4227E-01	2.0337E-01	5.0842E-01	5.0842E-01	-	1.1437E+00	1.8846E-01	3.7692E-01	9.4227E-01	2.0337E-01	5.0842E-01	-	-	3.7692E-01	0.942272934	-	5.0842E-01
	R_c at 90°			0.5	R_c at 90°		1	R_c at 90°		1.5	R_c at 90°	0.5	R_c at 90°		1	R_c at 90°	1.5	R_c at 90°	0.5	R_c at 90°	1	R_c at 90°	1.5
	Pipe diameter (mm)			19.05	Pipe diameter (mm)		19.05	Pipe diameter (mm)		19.05	Pipe diameter (mm)	19.05	Pipe diameter (mm)		19.05	Pipe diameter (mm)	19.05	Pipe diameter (mm)	19.05	Pipe diameter (mm)	19.05	Pipe diameter (mm)	19.05
Inputted value	-	5.8735	11.9676	29.9185	4.9301	9.8601	24.6499	5.3202	13.3003	13.3003	-	0.8976	0.1479	0.2958	0.7395	0.1596	0.3990	-	-	0.8285	2.0713		1.1176
ARC (2003)	-	9	18	45	7	14	34	5	9	18	-	0.9	0.15	0.30	0.75	-	0.40	-	-	-	-	-	-
Spedding *et al.* (2004)	-	-	-	-	-	16	30	-	-	16	-	-	-	0.40	0.75	-	0.40	-	-	-	-	-	-
Neutrium (2016)	-	-	-	-	-	16	30	-	-	16	-	0.90	-	0.35	0.75	0.2	0.45	-	-	1.1	2.06	-	1.1
	(L/D) values as found in literature										**k values as found in literature**							**K values as found in literature**					
Output		**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**		**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**			**0.0%**	**0.0%**		**0.0%**