

PERFORMANCE ANALYSIS OF LARGE PRESSURIZED IRRIGATION NETWORKS: EFFECT OF HEAD LOSSES EVALUATION

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ABSTRACT

Collective pressurized irrigation networks operating on-demand are extensively used for the distribution of irrigation water. The calculation of the head losses is an integral procedure for the performance analysis of such networks. In the current work, the effect of the head losses formula on the performance analysis of a large pressurized irrigation network operating on-demand is examined. To this end, six equations and formulas are compared in terms of a network's indexed characteristic curves. The examined formulas are compared with Darcy-Weisbach equation combined with Colebrook-White formula for the determination of the friction factor. The examined formulas are applied in the performance analysis of a Greek collective irrigation network operating on-demand, which is located in the prefecture of Argolida, in east Peloponnesus.

1. INTRODUCTION

Large-scale pressurized irrigation networks operating on-demand have been widely used in the distribution of irrigation water over the last decades. The calculation of friction head loss is a central part of both design and analysis of collective irrigation networks. Mathematical modelling is widely used for their analysis, there are generally two approaches; the first one uses the indexed characteristic curves of the network in order to provide analysis at network level, while the second one implements the performance analysis at hydrant level. The most common software implementing such analysis is ICARE and COPAM. ICARE (CEMAGREF, 1983) is a commercial program developed by CEMAGREF in MS-DOS environment. COPAM (Combined Optimization and Performance Analysis Model) is a free distributed programme, developed by FAO and CHIEAM-Bari Institute in Windows environment (Lamaddalea and Sagardoy, 2000). ICARE and COPAM implement both approaches.

For both analysis, computation of the head losses is a vital step. Each of the

available analysis software incorporates a different formula for the calculation of head losses. ICARE uses Calmon and Lechapt formula, and COPAM uses the Darcy equation in combination with Bazin roughness parameter (γ).

In this work, the effect of the formula used for the calculation of head losses on the determination of the indexed characteristic curves is examined. In particular, the Darcy–Weisbach equation with the Colebrook – White (DW-CW) and with the Swamee and Jain formulas (DW-SJ) for the calculation of friction factor, the empirical equation of Hazen-Williams (HW), the Darcy equation with Bazin roughness coefficient (Darcy-Bazin), the Calmon and Lechapt (CL) formula and the most recent Valiantzas (2008) explicit power formula are compared in terms of the indexed characteristic curves of large-scale pressurized irrigation networks operating on-demand.

2. FRICTION LOSS FORMULAS

Friction loss evaluation in pipe systems is crucial, not only for the design procedure but also for their successful operation and for the evaluation of their operation. In the analysis of collective irrigation networks, the calculation of friction loss is an essential procedure. The Darcy-Weisbach equation is a fundamental equation used for calculating the friction loss:

$$S_f = \frac{f}{D} \frac{V^2}{2g} \quad (1)$$

where S_f is the friction slope of the energy grade line, f is the friction factor, D is the pipe diameter, V is the discharge velocity and g is the acceleration of gravity.

The dimensionless friction factor f , under transitional turbulent flow, is a function of relative roughness (ε/D) and Reynolds number Re , and thus varies with pipe material and fluid turbulence. Moody diagram facilitates the determination of friction factor f , otherwise implicitly calculated with Colebrook-White formula. Darcy-Weisbach equation is rational, dimensionally homogeneous and applicable to other fluids as well as water (Liou, 1998).

Various formulas have been proposed and evaluated for the prediction of the Darcy-Weisbach friction factor f . Colebrook and White (1937) and Colebrook (1938) presented formulas for predicting the friction factor between smooth pipe flow and fully turbulent flow (Allen, 1996). The Colebrook-White formula, relates the friction factor to the Reynolds number and relative roughness, and is a highly accurate pipe flow resistance equation (Liou, 1998; Valiantzas, 2005). For turbulent flow, Colebrook-White implicit formula is:

$$\frac{1}{\sqrt{f}} = -2 \log \left(\frac{\varepsilon}{3.72D} + \frac{2.51}{Re \sqrt{f}} \right) \quad (2)$$

where ε is equivalent roughness, D is the pipe diameter, f is the Darcy-Weisbach friction factor and Re is Reynolds number.

Nevertheless, the iterative solution of Colebrook-White formula is time consuming and for this reason several explicit formulas have been proposed instead of Colebrook-White formula. One of the most popular explicit formulas that approximate the Darcy-

Weisbach friction factor for turbulent flow was introduced by Swamee and Jain (1976):

$$f = 0.25 \cdot \left[\log \left(\frac{\varepsilon}{3.7D} + \frac{5.74}{\text{Re}^{0.9}} \right) \right]^{-2} \quad (3)$$

where D is the pipe diameter, ε is equivalent roughness and Re is the Reynolds number.

This explicit formula approximates the implicit Colebrook-White formula within $\pm 1\%$ over the entire range of practical interest: $10^{-6} < \varepsilon/D < 10^{-2}$ and $5 \cdot 10^3 < \text{Re} < 10^8$ (Provenzano, 2005).

Apart from Swamee and Jain, several explicit formulas have been proposed for the Colebrook-White formula (Churchill, 1973; Barr, 1972; Chen, 1985; Terzidis, 1992). The friction coefficient f which is explicitly calculated using these formulas has an accuracy of about $\pm 1.5 - 2.0\%$ (Valiantzas, 2008).

Although Darcy-Weisbach equation provides great accuracy, many engineers use empirical relationships the popularity of which is due to the simple calculation resulting from a single smoothness factor for any pipe size or velocity. Furthermore, the use of such power law explicit forms facilitates their integration into numerical models for optimization of pipe networks. Such equation is the Hazen-Williams formula which is widely used in water delivery systems for closed conduits. In contrast to Darcy-Weisbach equation, it is not dimensionally homogeneous and its range of applicability is limited. In SI units the Hazen-Williams formula is:

$$S_f = K \frac{Q^{1.852}}{D^{4.871}} \quad (4)$$

where S_f is the friction slope of the energy grade line, Q is the volumetric flow rate, D is the pipe diameter, and K is an empirical coefficient, $K = 10.675 / (C_{HW})^{1.852}$, where C_{HW} is the friction coefficient for Hazen-Williams. The value of C in Hazen-Williams formula ranges from 80 for extremely rough pipes to approximately 150 for smooth pipes.

Although Hazen-Williams formula has been successfully used in cases of transitional turbulent flow in smooth pipes, the comparison between DW and HW equations in several papers (Provenzano et al., 2005; Hughes and Jeppson, 1978; Kamand, 1988; Liou, 1998; Bagarello and Pumo, 1992) has highlighted the limitations in applying Hazen-Williams formula.

Allen (1996) compared the friction estimated with Hazen-Williams and with Moody diagram. According to his results friction factors predicted by Hazen-Williams for $C=150$ follow the Moody smooth pipe turbulent flow curve closely for $30\,000 < \text{Re} < 10^8$, and generally underestimate f for $\text{Re} < 30\,000$. Moreover, according to his results Darcy-Weisbach equation is more accurate than the Hazen-Williams for both low velocity and high temperature conditions. Liou (1998) points out that HW equation compared to DW-CW equation may exceed 40% error if applied outside its applicability range. In particular, the relative error of HW equation compared to DW-CW equation is $\pm 8\%$ for smooth pipes and increases to 40% for rough pipes. On the

other hand Christensen et al. (2000) state that HW formula is valid only between smooth and transitional turbulent flow. Allen (1996) states that adjustment of C is necessary with changing pipe velocity and diameter, since it represents a specific relative roughness in the fully turbulent region, and changes with Re and velocity. Valiantzas (2005) indicated that there is a strong dependence of C coefficient on pipe diameter and therefore it cannot be considered constant.

Despite the nondimensional homogeneity and the abovementioned limitations, the HW equation remains the most popular pipe flow resistance equation among users.

A more recent formula was proposed by Valiantzas (2008). It is an explicit power law formula that approximates the Darcy-Weisbach combined with the Colebrook-White formula. The maximum relative error of the proposed formula is about $\pm 4\%$ when compared to Darcy-Weisbach with Colebrook-White equation. The proposed formula is extended for all three turbulent regimes and is of the form:

$$S_f = \left(\frac{k_0 Q^2}{D^{5.3}} \right)^m \quad (5)$$

where $k_0 = 0.0126\varepsilon^{0.3}$, ε is the equivalent roughness of the pipe, $m = 1 - 0.133(1 + \varepsilon/\varepsilon_0)^{-1}$ and $\varepsilon_0 = 0.0439 \cdot 10^{-3}$ in m.

According to the author, the proposed formula due to its simplicity can be easily adapted in models of hydraulic analysis and optimum design of irrigation networks.

The most common software for the analysis of large scale irrigation networks operating on demand, namely COPAM and ICARE, incorporate different formulas for the calculation of the friction loss. COPAM software package calculates the friction slope in the pipes using Darcy's equation (Lamaddalena, 2000):

$$S_f = 0.000857(1 + 2\gamma D - 0.5)^2 Q^2 D^{-5} \quad (6)$$

where γ is the roughness parameter of Bazin, expressed in $m^{0.5}$, Q is the discharge flowing into a pipe (in m^3/s) and D the diameter in m. Lamaddalena reports the values of γ for different types of pipes and the corresponding equivalent homogenous roughness ε . COPAM user manual, provides a table that relates the Bazin parameter γ with equivalent roughness and with the description of the pipe material (Table 1).

Table 1: Bazin roughness parameter (γ) for different types of pipes (Lamaddalena and Sagardoy, 2000)

TYPE OF PIPE	Equivalent homogenous roughness ε (mm)	γ (m ^{0.5})
1- Technically smooth tubes (glass, brass, drawn copper, resin)	0 ÷ 0.02	--
2- Steel pipes		
A) Time degradable coverings		
- New pipes, varnished by centrifugation	0.05	--
- Bitumened by immersion	0.1 ÷ 0.015	≤ 0.06
- In current duty with light rust	0.2 ÷ 0.4	0.10
- With asphalt or tar applied by hands	0.5 ÷ 0.6	0.16
- With diffused tubercolisation	1 ÷ 3	0.23
B) Non degradable coverings		
- Cement applied by centrifugation	0.05 ÷ 0.15	≤ 0.06
3- Welded sheet-pipes		
- In good conditions	0.2 ÷ 0.3	0.10
- In current duty with crusting	0.4 ÷ 1.0	0.16
4- Nailed sheet-pipes		
- 1 line of longitudinal nails	0.3 ÷ 0.4	0.10
- 2 lines of longitudinal nails	0.6 ÷ 0.7	0.16
- Idem with crusting	1 till 3.0	0.30
- 4-6 lines of longitudinal nails	2.0	0.23
- 6 lines of longitudinal nails + 4 transversal	3.0	0.30
- Idem with crusting	1 till 5.0	0.36
5- Cast iron pipes		
- With centrifuged-cemented covering	0.1	≤ 0.06
- New, covered internally with bitumen	0.15	0.06
- New, not covered	0.2 ÷ 0.4	0.10
- With light crusting	0.4 ÷ 1.0	0.16
- In current duty, partially rusted	1.0 ÷ 2.0	0.23
- strongly encrusted	3.0 ÷ 5.0	0.36
6- Cement-pipes		
- Asbestos cement	0.1	≤ 0.06
- New reinforced concrete, plaster perfectly smooth	0.1 ÷ 0.15	0.06
- Reinforced concrete with smooth plaster, in work for many years	2.0	0.23
- Tunnels with cement plaster, depending on the degree of finish	2.0 ÷ 5.0	0.23 ÷ 0.36

ICARE software uses Calmon and Lechapt formula for calculating head losses. Calmon and Lechapt, suggested a relationship including three coefficients which vary with the pipe roughness. The suggested formula is presented hereinafter:

$$S_f = L \frac{Q^M}{D^N} \quad (7)$$

where Q is the discharge in m³/s, D is the diameter in m, S_f is the friction slope in (mm/m) and L, M, N are coefficients that depend on the pipe roughness.

The formula is applicable for water of 10°C temperature. Calmon and Lechapt provide a table (Table 2) that presents the correspondence between equivalent roughness ε (used in Colebrook-White formula) and the coefficients used in Calmon and Lechapt formula.

Table 2: Values of Calmon-Lechapt parameters for different types of pipes (CEMAGREF, 1983)

ε (mm)	L	M	N	Comments
2	1.863	2	5.33	Uncoated steel (corrosive water)
1	1.601	1.975	5.25	Uncoated steel (slightly corrosive water)
0.5	1.400	1.96	5.19	Steel with cement coating
0.25	1.160	1.93	5.11	Steel with bitumen coating
0.1	1.100	1.89	5.01	Rolled steel
0.05	1.049	1.86	4.93	Steel centrifugally coated
0.025	1.010	1.84	4.88	Asbestos cement coated
0	0.916	1.78	4.78	$0.05 \leq D \leq 0.2$ Hydraulically smooth pipes
0	0.971	1.81	4.81	$0.2 < D < 1$ (D in m) Hydraulically smooth pipes

3. COLLECTIVE IRRIGATION NETWORK ANALYSIS WITH INDEXED CHARACTERISTIC CURVES (C_I)

The method of indexed characteristic curves (C_I) offers an overall view of the operation efficiency of a collective irrigation network. For each value of Q at the head of the network (ranging between 0 and $Q_{\max}$) the value of the requested piezometric elevation Z is determined, for each combination of open hydrants that need a total discharge Q (Dercas and Karantounias, 2003). Afterwards the distribution of the piezometric elevation can be calculated in order to operate successfully a percentage of open-closed hydrants' combinations that request a discharge Q , e.g. 10%, 20%, ..., 90%.

Experience has shown that pressurized networks operating on-demand, designed with Clément method for the calculation of the discharges and the discontinuous Labye method for the economic optimization of the diameters, present their optimum operation point ($Q_{\text{clément}}$, Z_{opt}) near the characteristic curve of C_{50} . At this point it should be clarified that the characteristic curve C_{50} does not represent a small percentage of satisfaction, since for the design of the characteristic curves a strict criterion is used. In particular, each combination of open hydrants that present even a small pressure deficiency is assumed unsuccessful (Dercas, 2001).

4. APPLICATION

In the current paper the operation of a Greek collective irrigation network designed to operate on-demand was analysed in terms of its overall operational efficiency. For this reason, the indexed characteristic curves of the network were designed. In order to design the characteristic curves, the formulas mentioned hereinafter were used to calculate the friction losses: Darcy-Weisbach equation with Colebrook-White formula for the calculation of the friction factor, Darcy-Weisbach equation with Swamee and Jain formula, Hazen –Williams formula, Darcy's equation with Bazin γ coefficient, Calmon et Lechapt formula and Valiantzas (2008) formula.

The network under study is located at the southeast side of the prefecture of Argolida, at Iria district. It is equipped with 318 hydrants and irrigates a total area of 954 ha. The nominal discharge of the hydrants is 6 l/s and the minimum required pressure head at the hydrant is 20m. There is a water reservoir that supplies water to the network. The piezometric elevation at the head of the network is 46.7m and the respective Clément discharge is 482 l/s. The cumulative discharge at the head of the network is 1908 l/s.

The aim of the current work is to examine the effect of the various friction loss formulas on the design of the indexed characteristic curves of a collective irrigation network operating on-demand. For this reason, the network under study was analyzed twice. In the first case the network was assumed to be equipped with PVC pipes while on the second case, the network was assumed to be equipped with steel pipes. Although this assumption is not usually implemented in practice for economic purposes (in practice PVC is usually used for small diameters and steel for large diameters), it was used in order to present separately the results for PVC and for steel.

The values of the various coefficients for the friction loss formulas that were used for each pipe material are presented in Table 3.

Table 3: Friction factor coefficients adopted for Iria network.

	DW-CW and DW-SJ and Valiantzas (2008)	Hazen-Williams	Calmon et Lechapt	Darcy -Bazin roughness parameter γ
PVC	$\varepsilon=0.013$ mm	C=150	L=0.971 M=1.81 N=4.81	$\gamma=0,06$
Steel (old)	$\varepsilon=1.52$ mm	C=100	L=1.601 M=1.975 N=5.25	$\gamma=0,23$

For the DW-CW, DW-SJ, HW and Valiantzas formulas, the coefficients were adopted according to Keller and Bliesner (1990). For Calmon and Lechapt and for the Darcy combined with Bazin parameter, the values for the respective coefficients were taken from the software manuals of ICARE and COPAM that use the abovementioned formulas (Table 1 and Table 2).

5. RESULTS AND DISCUSSION

For the network under study, the indexed characteristic curves were designed for PVC and steel network pipes.

5.1 Network equipped with PVC pipes

In the first case it was assumed that the network was equipped with PVC pipes. Thus according to Keller and Bliesner (1990) the equivalent roughness ε equals to 0.013mm and C coefficient of Hazen-Williams is 150. From ICARE software manual it was chosen the PVC values for the parameters of eq. (7): L= 0.971; M=1.81; N=4.81 (Table 2). The value of the Bazin roughness parameter γ ($\gamma=0.06$) was determined according to

the equivalent roughness ($\epsilon=0.013\text{mm}$, Table 1).

In Figure 1, the indexed characteristic curve C_{50} is presented when various friction loss formulas are used.

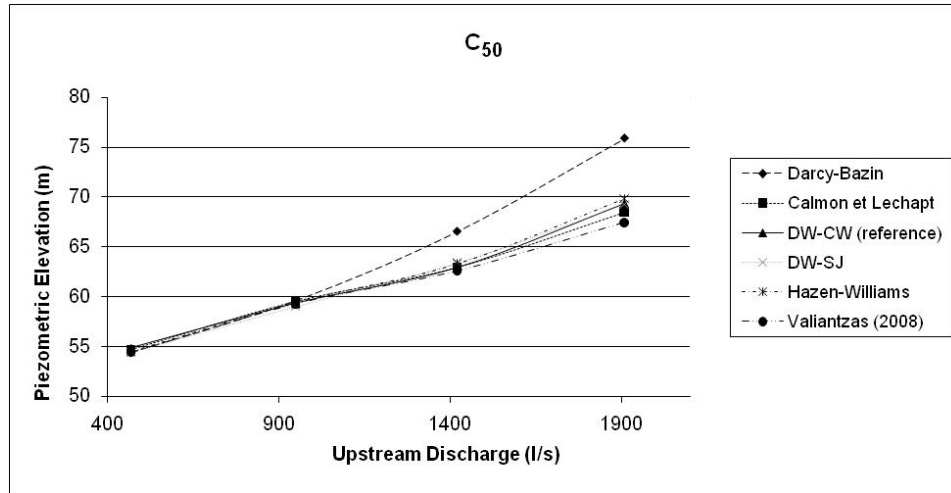


Figure 1. Indexed characteristic curve C_{50} of the PVC network for the various examined friction loss formulas (Iria network).

All C_{50} curves seem to perform well for upstream discharges around the Clément discharge, however there are important deviations for greater upstream discharges. In particular, Darcy with Bazin parameter seems to overestimate head losses, and the deviation from DW-CW equation is greater as the examined upstream discharge increases. The other examined formulas, namely DW-SJ, Calmon and Lechapt and Valiantzas (2008) slightly underestimate head losses. The HW formula slightly overestimates head losses for discharges near the maximum upstream discharge.

Table 4: Deviation (%) of piezometric elevation at the head of the Iria network for various upstream discharges and for PVC pipes, based on the indexed characteristic curve C_{50} .

	Darcy-Bazin	Calmon et Lechapt	DW-CW (reference)	DW-SJ	Hazen-Williams	Valiantzas (2008)
$Q=470\text{l/s}$	-0.83%	-0.35%	-	-0.83%	-0.61%	-0.86%
$Q=950\text{l/s}$	0.46%	0.31%	-	-0.55%	0.20%	-0.12%
$Q=1420\text{l/s}$	5.78%	0.09%	-	0.77%	0.67%	-0.52%
$Q=1908\text{l/s}$	9.47%	-1.16%	-	-0.06%	0.79%	-2.73%

After taking into account Figure 1, the deviation of the piezometric elevation for all friction losses formulas and for all examined upstream discharges, namely 470l/s, 950l/s, 1420l/s, and 1908l/s, is presented in Table 4,. The latter is the cumulative discharge $Q_{\max}$ of the network under study. The reference for this comparison, was the piezometric elevation resulted from DW-CW equation.

According to the above table, as expected, DW-SJ approaches very closely the

results from DW-CW (less than 0.8% difference for all examined upstream discharges). The results from H-W, Calmon-Lechapt, and Valiantzas (2008) also present a maximum difference less than 1% for upstream discharges near the Clément discharge. Darcy's formula with Bazin roughness parameter γ for the determination of friction loss seem to deviate with the increase of the examined upstream discharge at the head of the network, reaching about 9.5% deviation for $Q_{\max}$ (i.e. 1908 l/s).

5.2 Network equipped with Steel pipes

In the second case it was assumed that the network under study was equipped with steel pipes. In that case, the equivalent roughness ε is 1.52mm and the C Hazen-Williams coefficient is 100 (Keller and Bliesner, 1990).

From ICARE user manual for steel pipes the following values for the parameters of eq. (7) were assumed: $L=1.601$; $M=1.975$ and $N=5.25$ (Table 2).

For the Bazin roughness coefficient γ , the respective table of COPAM software manual that relates the Bazin parameter with equivalent roughness and with the description of the pipe material (Table 1) was consulted. Thus, based on steel equivalent roughness, it was assumed $\gamma=0.23$.

Figure 2 presents the indexed characteristic curve C_{50} as calculated with the various friction loss formulas.

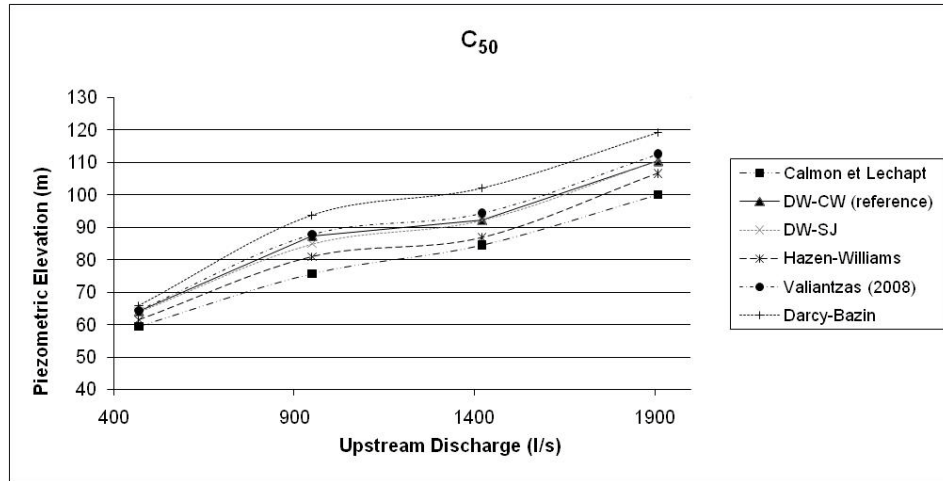


Figure 2. Indexed characteristic curve C_{50} of the Steel network for the various examined friction loss formulas (Iria network).

Figure 2 reveals that DW-SJ and Valiantzas (2008) approximate quite well the curve obtained with DW-CW equation. Furthermore, both HW formula and Calmon and Lechapt formula underestimate the piezometric elevation at the head of the network. The Darcy-Bazin formula overestimates the piezometric elevation at the head of the network.

Furthermore, in Table 5 the differences observed in the above diagram are quantified as a percentage deviation of piezometric elevation at the head of the network,

compared to the reference (DW-CW).

According to Table 5, indeed DW-SJ and Valiantzas (2008) approximate quite successfully the DW-CW results, presenting about 2% or less deviation for all values of examined upstream discharges at the head of the network. Hazen-Williams and Calmon-Lechapt perform better for upstream discharges around the Clément discharge, however Calmon-Lechapt formula presents 9% deviation when the examined upstream discharge approaches $Q_{\max}$. When Darcy with Bazin parameter is examined, the results present deviations up to 10.5%.

Table 5: Deviation of piezometric elevation at the head of the network for various upstream discharges and for Steel pipes, based on the characteristic curve C_{50} (Iria network).

	Darcy-Bazin	Calmon et Lechapt	DW-CW (reference)	DW-SJ	Hazen-Williams	Valiantzas (2008)
$Q=470$ l/s	2.83%	-7.08%	-	-0.12%	-3.87%	0.56%
$Q=950$ l/s	7.40%	-13.25%	-	-2.71%	-7.23%	0.61%
$Q=1420$ l/s	10.68%	-8.37%	-	0.01%	-5.86%	2.32%
$Q=1908$ l/s	7.94%	-9.36%	-	0.19%	-3.46%	2.02%

This deviation suggests that the selection of the appropriate value for Bazin roughness parameter is vital for the credibility of the designed characteristic curves.

In Figure 3 the Darcy-Bazin formula was applied twice with different values for γ parameter. In particular, $\gamma=0.1$ (chosen according to the description of the pipe material from the respective table of COPAM software manual) and $\gamma=0.23$ (chosen according to the value of equivalent roughness) were examined. The results indicate that for $\gamma=0.23$ the formula overestimates the piezometric elevation (2-10.5% percentage deviation) while for $\gamma=0.1$ the formula greatly underestimates the piezometric elevation (25% deviation).

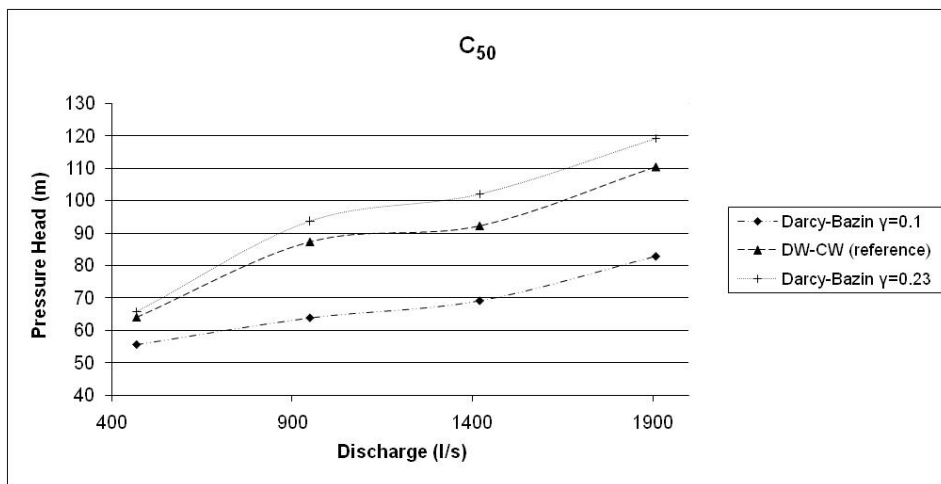


Figure 3. Indexed characteristic curve C_{50} of the Steel network for the $\gamma=0.1$ and $\gamma=0.23$ (Iria network).

6. CONCLUSION

The performance analysis of collective irrigation networks operating on-demand is implemented both at network and at hydrant level. At network level, the indexed characteristic curves give an overall view of the network's performance. The calculation of the head losses is a vital step for the design of indexed characteristic curves and for their reliability in presenting the real behaviour of the network.

In the current work, various head loss formulas and equations were applied, and the indexed characteristic curves of the Iria pressurized collective irrigation network operating on-demand were designed. Six equations and formulas (DW-CW, DW-SJ, HW, Darcy-Bazin, Calmon and Lechapt, and Valiantzas (2008)) were examined among which the formulas used by the most common software for the performance analysis of such networks (i.e. ICARE and COPAM). The results from all examined formulas were compared to those obtained with DW-CW equation.

In the first accomplished analysis, it was assumed that the network was equipped with PVC pipes while in the second it was assumed that the network was equipped with steel pipes. This approach was adopted, in order to have a clear view of the effect of each head loss formula for both materials examined (PVC and steel).

The results for the PVC pipes, illustrate that the characteristic curve C_{50} obtained with DW-SJ, HW, CL, and Valiantzas (2008) present deviation of piezometric elevation up to 2.7%. In opposite, with Darcy-Bazin formula, the requested piezometric elevation at the head of the network presents deviation up to 9.5%.

For steel pipes, the results obtained with the CW-SJ and Valiantzas (2008) present about 2% or less deviation from those obtained with DW-CW equation. The respective deviation of piezometric elevation with CL and HW formulas are greater reaching even 9% for maximum upstream discharge. For the application of Darcy-Bazin formula, there is a difficulty in the determination of the right value for the γ Bazin parameter. From COPAM user manual, two values of the particular parameter were chosen as most appropriate, and the results present up to 25% deviation from those obtained with DW-CW, stressing thus the need for a thorough investigation before the selection of the appropriate value for the Bazin roughness parameter.

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