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COMPARISON BETWEEN HAZEN-WILLIAMS AND DARCY-WEISBACH EQUATIONS TO CALCULATE HEAD LOSS THROUGH CONVEYANCING TREATED WASTEWATER IN KERBALA CITY, IRAQ

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Reuse of wastewater has been widespread in this era to support the water sustainability process. Therefore, treated wastewater should be conveyed to suitable places and adopted for different uses. This study presents an empirical relationship between the Darcy-Weisbach and Hazen-Williams equations for four types of pipe material (ductile iron, GRP, concrete, and plastic) by using WaterCAD Version 8i. Two hydraulic models were developed to estimate the head loss in pipes by using different diameters: first, using pipe diameters from 800 mm to 1,200 mm for a flow rate of 1.16 m^3/s, second, adopting pipe diameter from 1,600 mm to 2,000 mm for a flow rate of 4.63 m^3/s. The study results are the head loss values obtained from the Darcy-Weisbach and Hazen-Williams equations, which were used to correlate them using IBM SPSS Statistics. The correlation coefficient between both equations turned out to be 0.991, 0.990, 0.990, and 0.990 for ductile iron, GRP, concrete, and plastic pipe materials. Additionally, the relationship between head loss and pipe diameter is negatively proportioned for both equations. Also, both head loss equation results are the same. The head loss values in the Darcy's equation were higher for ductile iron and GRP materials, while being lower for concrete and plastic materials for both models. Selecting concrete or plastic pipes to convey treated wastewater is better than other pipe materials. Another conclusion is that the pipe diameter affects the head loss magnitude irrespective of the kind of equation whether Darcy-Weisbach or Hazen-William equation. Finally, this relationship is very useful for designers in converting the head loss values obtained using these equations

Keywords: Hazen-Williams equation, Darcy-Weisbach equation, WaterCAD V8i, head loss, correlation coefficient

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1. Introduction

Throughout the last ten years, our country has been suffering from decreasing of fresh water that is received through our rivers, so it is important to redistribute available quantities with new goals to satisfy our irrigation requirements.

To carry out this mission, in our country (Iraq) it is the first time of implementing the reuse techniques in our municipality's services with such big diameters for the four types of pipe material (ductile iron, GRP, concrete, and plastic), which are frequently used in our infrastructures system.

Studying these relations in such big diameters is important for designers and engineers to minimize the length, diameter and cost of pipes.

When designing systems for supplying and moving water in pressure conduits, it is necessary to know the hydraulic losses.

This is the basis for the subsequent selection of pipe sizes and the necessary hydromechanical equipment to ensure the operation of the pipeline system [1]. The Hazen-Williams (*H-W*) and Darcy-Weisbach (*D-W*) formulas are the two most common drag equations for pressurized flow. Although the application of the former is quite widespread in practice, the latter has a much more reasonable basis and is acceptable for determining a critical case through water distribution [2], however, both friction formulas have approximately the same results [3]. The empirical equation (*H-W*) uses a clear factor (*C*) for each type of pipe material. However, the coefficient of friction (*f*) of the dimensionally consistent equation (*D-W*) is a function of material property (absolute roughness) and Reynolds number (Re) in turbulent flows, the most common flow regime in water networks [4]. Consequently, the manufacturer must verify the pipe performance using both equations to assure his customers that the product meets all applicable codes and standards. However, the frequency of using both equations varies. As mentioned by [5], the *H-W* equation was developed only for water and is applicable for a pipe with a turbulent flow, while the *D-W* equation is applicable for all flow regimes and can be used for any type of fluid. However, the *H-W* equation is fairly easy to use compared to the others due to many reasons. Studies used both of the equations to calculate friction in different fields like irrigation [6], water supply [7], pipe age [8], pipe size [9], pipeline design [10], friction factor estimation [11], water distribution technique [12] and software engineering programming [13]. Although the mentioned studies used the *H-W* equation, there is a scientific gap represented by using another head loss equation, particularly the *D-W* equation to show the difference between them, and it gives us a wide picture of the magnitude of head loss through transfer for many kilometers. Therefore, recent studies are devoted to using one type of head loss equation, however, some of them used different hydraulic models.

2. Literature review and problem statement

This study analyzed the recent studies, which mentioned both Hazen-Williams (*H-W*) and Darcy-Weisbach (*D-W*) head loss equations. Despite advances in computing technology and derivation of explicit approximation formulas, the experimentally verified and widely applicable Colebrook-White friction factor formula is often rejected in favor of the limited and less accurate Hazen-Williams equation. The comparison between the head loss equations is not mentioned, which could be due to inaccurate results. Until now, converting *C* to *ks* required knowledge of both the Reynolds number and pipe diameter originally used to determine *C*. The current effort derives implicit equations relating *C* to *ks* that do not require additional information and compare well with published data. The exact solution is approximated with a single explicit equation, accurate to within 4 % error [1]. These results need more explanation to know the reasons behind their ratios.

Three issues concerning the iterative solution of the nonlinear equations governing the flows and heads in a water distribution system network are considered. Zero flows cause a computation failure (division by zero) when the Global Gradient Algorithm of Todini and Pilati is used for the steady state of a system in which the head loss is modeled by the Hazen-Williams formula. The proposed regularization technique overcomes this failure as a solution to this first issue. The second issue relates to zero flows in the Darcy-Weisbach formulation. They used both head loss equations in different cases, thus they should refer to the advantages and disadvantages of both of them. The third issue relates to a new convergence stopping criterion for the iterative process based on the infinity norm of the vector of nodal head differences between one iteration and the next. This test is recommended because it has a more natural physical interpretation than the relative discharge stopping criterion that is currently used in standard software packages such as EPANET [2]. However, they did not put suitable reasons to use this type of software program.

The Darcy-Weisbach and Hazen-Williams equations are systematically compared, yielding a Hazen-Williams coefficient correction form. A more precise technique for the Darcy-Weisbach equation along irrigation laterals is also suggested, assuming a power function form. The friction loss through laterals was calculated by using the Darcy-Weisbach equation, which closely follows a discharge-power form function. This study used the power function's two empirical parameters, which are determined by the pipe's specific properties as well as the lateral's specific range of discharge values. The proposed analytical solution is expanded to include sprinkler and trickle irrigation laterals, as well as local head loss, velocity head variation, and outflow non-uniformity [6]. They mentioned that the Darcy-Weisbach equation is more precise than the other method, however, both of them are approximately the same.

Water flows through plastic pipes according to an empirical relationship between the Darcy-Weisbach and Hazen-Williams equations for cold and hot water. Five hydraulic models were constructed to estimate the head loss in pipes for varied pipe diameters (15 mm to 50 mm) and volume flow rates for different water temperatures and discharges. The correlation coefficient between the Darcy-Weisbach and Hazen-Williams equations' head loss was 0.999, while the R^2 value for the trend line of head loss values obtained by these equations was 0.9993 [7]. Although they used five hydraulic models, the size of pipe diameters was limited.

Samrahan transformed from a small village into an education hub for the past 2 decades. Rapid development and population growth in Samrahan had led to speedy growth in water demand. The situation is getting worse as the pipes are deteriorating due to pipe aging. Therefore, there is a need to study the adequacy of water supply and relationships among roughness coefficient (*C*) values in the Hazen-Williams equation with head loss and water pressure due to pipe aging at Uni-Central, a residential area located at Samarahan Sarawa. Investigations were carried out with ductile iron, asbestos cement and cast iron pipes at different age categories from 0 to 70 years. Six critical nodes named were selected to study the water pressure and head loss. The model was developed with InfoWorks Water Supply (WS) Pro software. Results showed that asbestos cement pipe has the least impact on head loss and water pressure, followed by ductile iron pipe and lastly cast iron pipe. Simulation results demonstrated that head loss and water pressure have a negative relationship [8]. This paper focused on a small scale of search by using once the model and head loss equation, however, they should expand their search to give us more realistic results but they selected different pipe types.

When compared to the Darcy-Weisbach and Coolbrook-White equations, the proposed power-form formula yields a maximum relative error of roughly +/–4.5 percent. The friction formula in its power form makes it easier to formulate the problem, leading to the derivation of a simple equation from which the economic diameter may be computed explicitly [10]. Their results and conclusions need more comparison between head loss equations. Therefore, the unresolved part is using each head loss equation individually with building one or more hydraulic models.

The widely used Todini and Pilati method for solving the equations that model water distribution systems were originally developed for pipes in which the head loss is modeled by the Hazen-Williams formula. Rossman's popular program EPANET implements elements of the Todini and Pilati algorithm, but when the Darcy-Weisbach head loss formula is used, it does not take into account the dependence of the friction factors on the Reynolds number, and therefore flow, in computing the Jacobian matrix. We present the correct Jacobian matrix formulas, which must be used in order to fully account for the friction factor's dependence on the flow when the Todini and Pilati method is applied with the Darcy-Weisbach head loss formula. With the correct Jacobian matrix, the Todini and Pilati implementation of Newton's method has its normally quadratic convergence restored [12]. They did not mention the reason for the difference between the head loss magnitudes when using the Hazen-Williams and Darcy-Weisbach equations.

The scarcity of water becomes one of the main issues around the world. Therefore, some studies mentioned the possibility of saving water by applying deficit irrigation technique [14] and this study also did it within the same region to support this approach.

The problem statement is how to find the best friction loss equation to apply it with selecting the best type of pipe material to transfer treated water. This study focuses on selecting the best equation of friction losses, which should be adopted to transfer treated wastewater from a treatment station, and choose the best pipe type. Therefore, this study is unique to use software engineering programming (WaterCAD), and used different diameters with two hydraulic models. No study has been carried out by other authors on selecting friction loss equation with pipe type. The scientific gap is why there is a difference between both friction loss equations mentioned herein. Another scientific gap is using both different pipe diameters and materials to transfer treated water.

3. The aim and objectives of the study

The aim of the study is to find an empirical relationship between the Hazen-Williams and Darcy-Weisbach equations for various types of project pipes for transporting treated wastewater in the city of Karbala (Iraq) using the WaterCAD V8i program.

To achieve this aim, the following objectives are accomplished:

– calculation of head losses using the Hazen-Williams and Darcy-Weisbach equations for four types of pipes and for both models;

– finding the correlation coefficient for the head losses obtained from the two mentioned equations.

4. Materials and methods

4. 1. Building models

The flow characteristics and frictional losses of the pipe must be within the specified range to make it suitable for commercial use. Various equations are available in recent studies for calculating pressure losses in pipes. However, the Darcy-Weisbach and Hazen-Williams theory has gained widespread acceptance in fluid mechanics due to its proven accuracy compared to other equations.

Williams and Hazen (1933) empirically derived the equation and this formula is often used in the analysis of pressure pipeline systems (such as water distribution networks and sewers) [15]:

$$h_f = \frac{KL}{D^{4.87}}\left(\frac{Q}{C}\right)^{1.85}, \tag{1}$$

where h_f – head loss (m); Q – section flow rate (m^3/s); C – Hazen-Williams «capacity» coefficient, C value ranges from 80 for very coarse pipes to about 150 for smooth pipes; k – constant (0.85 for SI units, 1.32 for US units); D – pipe diameter (m); L – pipe length (m).

Due to its non-empirical origin, the Darcy-Weisbach equation is considered by many engineers as the most accurate method for modeling friction losses. Most often it takes the following form:

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

where h_f – head loss (m); f – hydraulic resistance coefficient (Darcy-Weissbach friction coefficient); D – pipe diameter (m); L – pipe length (m); V – flow velocity (m/s); g – constant of gravitational acceleration (m/s^2).

We denote:

$$f = 2f\left(\text{Re}, \frac{\Delta}{d}\right), \tag{3}$$

$$R_e = \frac{\rho v d}{\mu}, \tag{4}$$

where R_e – Reynolds number (dimensionless); ρ – flow density (kg/m^3); V – average flow rate (m/s); d – length index or pipe diameter (m); μ – dynamic viscosity (kgm/s); Δ – wall roughness (m).

Recall that in the laminar flow regime:

$$f = \frac{64}{R_e}. \tag{5}$$

However, for the transitional and turbulent flows for which Re≥2000, the friction factor is the main issue in the D-W equation. An implicit equation (6) for the solution of f, which is known as the Colebrook-White equation that is recognized to be the most accurate for the solution of Darcy's friction factor:

$$\frac{1}{\sqrt{f}} = -2.0\log\left(\frac{\frac{\varepsilon}{D}}{3.72} + \frac{2.51}{R_e\sqrt{f}}\right), \tag{6}$$

where f is the friction factor (dimensionless), ε is the roughness height, D is the pipe diameter (m) and Re is the Reynolds number (dimensionless).

Experiments show that the energy loss in a turbulent fluid flow in pipes of constant cross-section (i.e., frictional head loss) is significantly higher than in a laminar one. This increase in hydraulic losses is caused by the formation of large vortices and their disintegration, turbulent mixing of significant masses of liquid and curvature of the trajectories and streamlines of motion of liquid particles. If, in a laminar flow regime, friction head losses increase in proportion to the velocity (and also to the flow rate) to the first degree, then during the transition to the turbulent regime, a certain jump in resistance is noticeable and then a steeper increase in the value of h_f along a curve close to the second degree parabola [1].

In this paper, information has been collected on the treated wastewater treatment plant in Karbala (Iraq), where the current flow is 1.16 m^3/s, and it is hoped that 4.63 m^3/s will complete the construction of the sewer network for the entire period. The two hydraulic models have been designed with these flow rates in mind and pipe diameters ranging from 800 mm to 1,200 mm and 1,600 mm to 2,000 mm using WaterCAD V8i software. The head loss was estimated for each model for all the considered pipe materials and diameters. The Re values calculated for the above flow conditions ranged from 1,050,735 to 1,584,063 for the first model and from 2,905,443 to 3,645,734 for the second model, indicating that the flow was turbulent in each model. This satisfies the condition of applicability of both equations (*D-W* and *H-W*), justifying a common basis for comparing the results of both equations. In addition, the head loss of the relationship between the two equations was found using IBM SPSS Statistics. Fig. 1 shows the methodology of work.

The methodology was built by using two hydraulic models with four different types of pipes. This method is unique because other studies adopted only plastic pipes [7], and other researchers used metal and plastic pipes [16]. Therefore, this study is the first of its kind to use four different types of pipes to transport treated sewage water, depending on the results of head loss values, through which it is possible to find the optimal diameter and material [17].

Also, the method adopted the WaterCAD Version 8i software and statistical analysis to obtain the results, however, [18] used the Matlab program to calculate friction losses by using the Darcy-Weisbach equation.

As shown in Fig. 1, both models will build up. Therefore, this flow chart represents the steps of building our models.

5. Results of research on the calculation of head losses and the relationship between Darcy-Weisbach and Hazen-Williams equations

5. 1. Calculation of head losses using Hazen-Williams and Darcy-Weisbach equations

The model was built using the WaterCAD V8i software with all the necessary initial data. Fig. 2 shows a model built for pumping water from a new water treatment plant through the main transport pipe to the city of Karbala.

Fig. 3 shows the difference of head loss obtained using *D-W* and *H-W* equations versus pipe diameter for four materials and two hydraulic models.

The relationship between the diameter and head loss can be separated to two categories; one with small discharge, which is affected by the head loss but the second category is not highly affected by head loss due to the difference in both of discharge and pipe size.

5. 2. Relationship between Darcy-Weisbach and Hazen-Williams equations

In general, an increase in head loss can be observed as the pipe diameter decreases for both equations. The results also showed that the head loss values in the Darcy's equation were higher for ductile iron and GRP materials, while they were lower for concrete and plastic materials for both models.

The main part of data analysis is to determine the relationship between both head loss equations. Consequently, the head loss values for a pipe of four materials obtained from the two models were plotted as shown in Fig. 4.

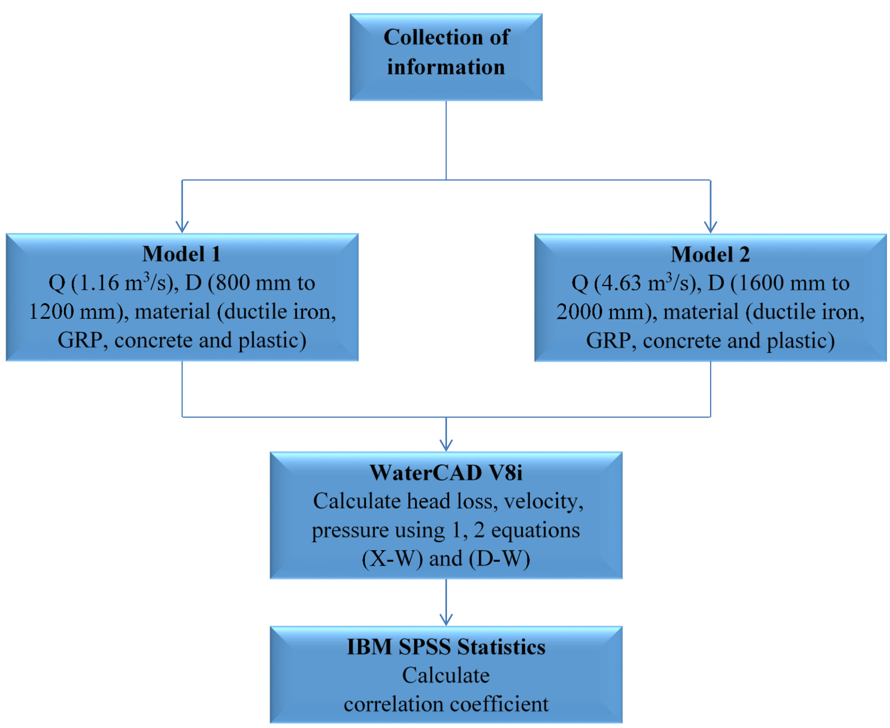


Fig. 1. Methodology of work

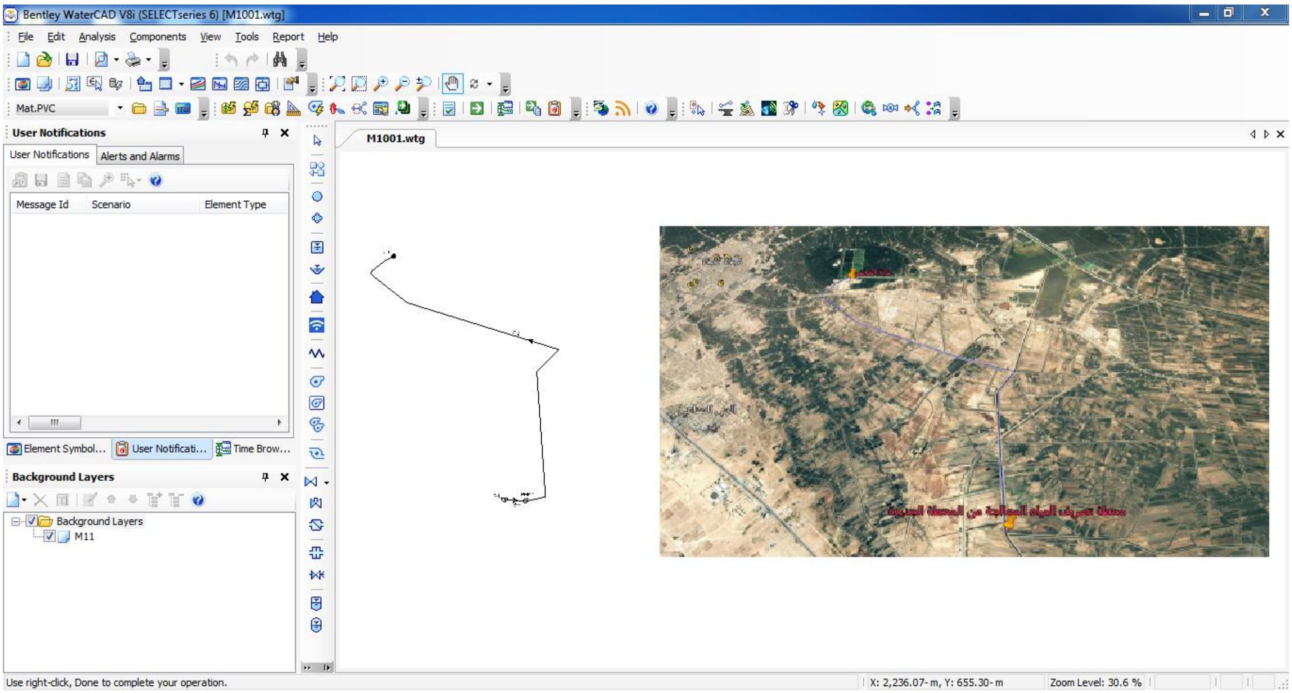
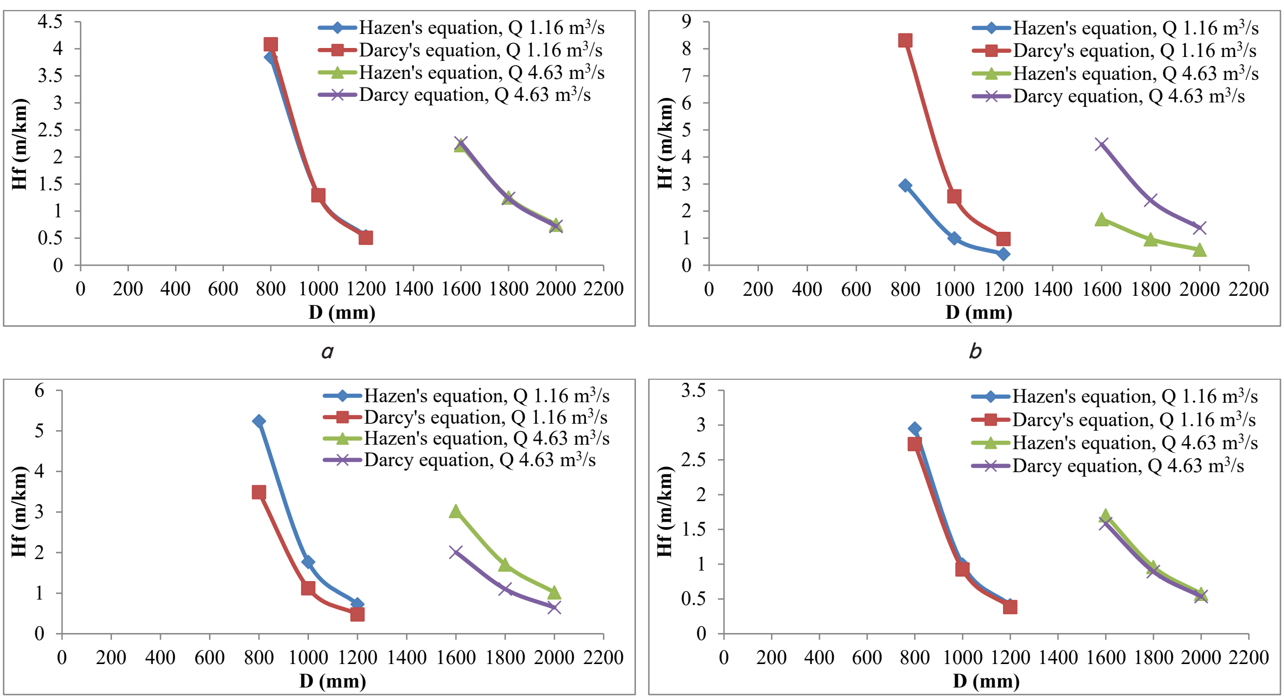


Fig. 2. Constructed model



a *b* *c* *d*

Fig. 3. Relationship between head loss and pipe diameter for different materials: *a* – ductile iron pipes; *b* – GRP pipes; *c* – concrete pipes; *d* – plastic pipes

From Fig. 4, the relationships between head loss values are linear, which is accurate. Direction plotted for the scatter line, whose equation was obtained using the IBM SPSS Statistics program. For ductile iron:

$$y=0.11+1.06\cdot x. \quad (7)$$

(7) can be rewritten in terms of the studied variables as *D-W* and *H-W*:

$$(D\text{-}W)=0.11+1.06\times(H\text{-}W). \quad (8)$$

The same is with the rest of the pipe materials:

For GRP $(D\text{-}W)=0.33+2.85\times(H\text{-}W)$. (9)

For concrete $(D\text{-}W)=0.04+0.67\times(H\text{-}W)$. (10)

For plastic $(D\text{-}W)=7.21E-3+0.92\times(H\text{-}W)$. (11)

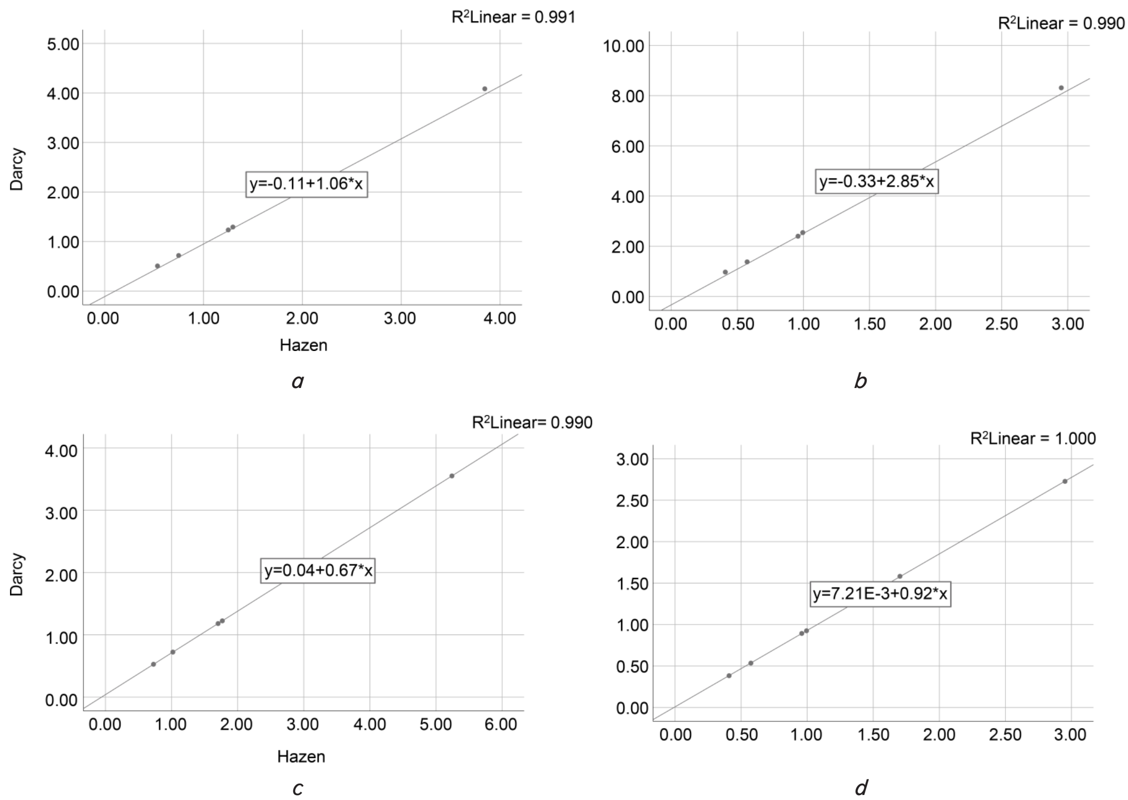


Fig. 4. Darcy-Weisbach vs. Hazen-Williams equation using:
a — iron pipes; *b* — GRP pipes; *c* — concrete pipes; *d* — plastic pipes

In this paper, the head loss resulting from the flow of treated wastewater into the pipe was calculated using the Darcy-Weisbach and Hazen-Williams equations for four kinds of pipe materials and two models.

For the first model, Fig. 3 above shows that the highest recorded head loss values were at 800 mm diameter, this was 8.312 m/km for GRP in the Darcy equation, while the lowest value recorded for the same diameter was 2.727 m/km for plastic in the same equation, because of the difference in the type of pipe material and therefore the difference in the roughness factor, which they consider to be the most important factors. It contains a Darcy correction for calculating the head loss.

For the second model, Fig. 3, 4 showed that the highest recorded head loss values were at 800 mm diameter, which was 4 m/km for GRP in the Darcy equation, while the smallest value recorded for the same diameter was 1.582 m/km for plastic in the same equation.

Where *D-W* and *H-W* are the head losses in meters per kilometer (m/km) of pipe obtained by the Darcy-Weisbach and Hazen-Williams equations, respectively. Equations (8)–(11) are empirical relationships that will evolve in the current research. The trend line R^2 was found to be 0.991, 0.990, 1.00 and 1.00 for ductile iron, GRP, concrete and plastic pipe materials, indicating excellent statistical accuracy.

6. Discussion of the results of calculation of head losses and the relationship between Darcy-Weisbach and Hazen-Williams equations

According to the results of the relationship between head loss and pipe diameter for different pipe materials with both two hydraulic models, referring to Fig. 3, changing pipe diameter from 800 mm to 1,200 mm caused a decrease in head loss.

Referring to pipe material, applying two models on ductile iron with pipe diameters between 800–1,200 mm, the head loss magnitude of 4.0 m/km was similar for both *H-W* and *D-W* head loss equations. However, the head loss magnitude measured by the *D-W* equation was relatively higher compared to the *H-W* equation, whereas the head loss magnitude decreased by half to 2.0 m/km when the pipe diameter increased ranging between 1,600–2,000 mm.

On the other hand, when using GRP pipe material with a diameter between 800–1,200 mm, the head loss has doubled to 8.0 m/km when using the *D-W* equation. However, the head loss stays approximately at the same magnitude when measured by the *H-W* equation. Similarly, when using pipe diameters between 1,600–2,000 mm, the head loss increased from 2.0 m/km to 4.0 m/km when using the *D-W* equation, however, the head loss increased to the half magnitude of 2.0 m/km when using the *H-W* equation.

In contrast, head loss results of the *D-W* equation when using a concrete pipe with diameters between 800–1,200 mm showed a decrease in the magnitude compared to GRP and ductile iron materials. However, the head loss magnitude measured by the *H-W* equation was higher than for both GRP and ductile iron materials. Also, when using pipe diameters between 1,600–2,000 mm, the head loss magnitude of 2.0 m/km measured by the *D-W* equation was lower than for GRP pipe material but the same for ductile iron material. However, the head loss magnitude of 3.0 m/km measured by the *H-W* equation was higher than for both GRP and ductile iron materials.

Similarly, when using plastic pipe material with pipe diameters between 800–1,200 mm, the head loss magnitude of 2.8 m/km when using the *D-W* equation was lower than for all other types of pipe material. Consequently, the head loss magnitude of 3.0 m/km when using the *H-W* equation was lower than for both concrete and ductile iron materials, however, it is equal to the head loss value when using GRP material. Similarly, by using pipe diameter between 1,600–2,000 mm, the head loss magnitude when using both head loss equations was lower than for all other types of pipe material.

The results revealed that the head loss magnitude measured by the *D-W* equation was higher compared to the *H-W* equation for all types of pipe material except concrete material. The reason is that the *H-W* equation uses a roughness coefficient, which depends primarily on the height of the interval roughness of each pipe type, and depends secondarily on pipe diameter and size, whereas the *D-W* equation adopts friction factor, which is not mainly affected by the type of pipe material. Another reason explaining the difference in head loss magnitude results is that using a large pipe diameter caused a decrease in head loss magnitude. Another study explained that the increase in pipe size caused a decrease in head loss [15]. Although many studies [7, 16, 19] used both of the head loss equations without mention of the relationship between head loss and pipe diameter. Therefore, this study indicates the gap of the recent studies. Although both head loss equations are important to adopt, some contemporary studies used one head loss equation [18, 20–22].

The results revealed that both Darcy-Weisbach and Hazen-Williams equations are similar with respect to the magnitude of head loss, however, these equations were used at different pipe sizes. These results are similar to [7], however, they used a unique pipe type for flowing cold and hot potable water.

One of the study objectives is calculating head loss by using two head loss equations with four different types of pipe material by applying two hydraulic models. Therefore, head loss results are different due to the different limitations of these equations. Therefore, the *H-W* equation has two limitations relative to the type of flow and water temperature, on the other hand, the *D-W* equation has less limitation than the *H-W* equation because the *D-W* equation uses a friction coefficient, which can be used with any type of flow materials. Therefore, these differences between head loss equations caused the difference in the magnitude of head loss with both models when using four different pipe materials.

The gap of the study is how to select the best head loss equation to achieve the minimum head loss magnitude. Therefore, to use the best head loss equation, this study used both *H-W* and *D-W* head loss equations to apply on two hydraulic models with different discharges, pipe diameters, and pipe materials to recognize the effects of all parameters of the head loss magnitude.

The advantage of the study is selecting four different types of material with two different hydraulic models depending on different discharges. However, this study has a limit to specified discharge and using a software engineering program. Therefore, to develop this study, coming researchers can select more than four types of pipe material and a longer transfer distance from a treatment station to either a storage tank or a temporary storage place for recharging to either a river or a lake.

7. Conclusions

1. Head loss magnitude observed by the *D-W* equation through GRP pipe material with model 1, which has a flow rate of 1.16 m^3/s within pipe diameters between 800–1,200 mm, is the highest magnitude during all study cases. Therefore, GRP material caused a high head loss. From the study results and discussion, both head loss equations have approximately the same effect on head loss. Therefore, pipe diameter and pipe material have a clear effect on the head loss magnitude. Summing up, with respect to pipe materials, plastic pipe material is the best type to adopt with a large pipe diameter ranging from 1,600 to 2,000 mm.

2. The correlation coefficient between the *H-W* and *D-W* equations is very strong because the coefficient of determination between them is approximately equal to one, which is statistically considered a very strong relation.

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