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Comparison of Optimal Pipe Sizing Designs for Pressurized Flow System

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***Abstract*—** Pipelines are normally designed to deliver fluid at the required head and flow rate in a cost effective manner. The selection of an optimum pipe size for pumping plants and pipelines in pressurized flow pipe network should be based on careful economic analysis. Increase in conduit diameter leads to increase in annual capital costs, and decrease in operating costs. The study presents an optimized pipe diameter selection for the farm located at Hamelmalo Agricultural College (HAC). Relationships were formulated connecting theories and principles of hydraulic and economic analysis of the pipe selection process. These were developed into a computer program, written in Java language, for a high- level precision estimate of the optimum pipe diameter. The optimum pipe diameter design primarily includes three major methods available in literature namely Pipe sizing design using Jack's Cube method, design based on Head Loss Gradient method and design based on Smit's method.

***Keywords*—**Pressurized flow networks, Optimized Pipe diameter, Hydraulic aspects of pipe sizing, Economic aspects of pipe sizing, Java Programming Language.

I. INTRODUCTION

The pressurized irrigation system implies an application of different pipelines in the irrigation fields. These pipelines have a long life and low maintenance costs when properly installed. The purpose of a system pipe network is to supply water at adequate pressure and flow. However, pressure is lost by the action of friction at the pipe wall. The pressure loss is also dependent on the water demand, pipe length, gradient and diameter. The optimal selection, design, and managing of irrigation systems at farm level is an important factor for rational use of water, economic development of the agriculture, and its environmental sustainability [1].

In the system of water distribution, invariably there are fundamental equations which govern the fluid flow problems. For incompressible flows involving Eulerian description of motion of the fluid particles, in which the density remains constant between the entrance and exit and the velocity being uniform, the law of conservation of mass assumes the simplified form of the Continuity Equation [2]. The integrated differential form of the Continuity Equation results in the Bernoulli's Equation. The Reynolds number Re relates the physical and geometric properties of fluid velocity, pipe diameter and viscosity. The Reynolds number decides the flow regimes through the pipe network namely the laminar flow, turbulent flow or the transition zone between the two.

The frictional head loss (h_f) in the pipe network is generally calculated using the Darcy-Weisbach Equation which is given by

$$h_f = \frac{flv^2}{2gd} \qquad (1)$$

where, h_f is the head loss due to friction in units of energy per unit length, the friction factor f is in general a function of Reynolds number and the relative roughness (e/d) of the pipe. For laminar flow, the head loss due to friction can be obtained theoretically in the form of Hagen-Poiseulle's Equation.

The laminar flow is a region in which the relative roughness has no influence of the friction factor. The Colebrook–White equation (or Colebrook equation) expresses the Darcy friction factor f as a function of Reynolds number and pipe relative roughness. The equation provides an iterative solution or a trial and error solution for the Darcy–Weisbach friction factor f for both turbulent and laminar flow. The behaviour of friction factor can be observed from Moody's diagram. The Moody's Chart is a graphical representation in non-dimensional form that relates friction factor f, Reynolds number Re, and relative roughness for fully developed flow in a pipe with certain limitations [3]. Swamee and Jain proposed the following equation for 'f' which is valid for laminar, turbulent and the transition flow in a pipeline as [4].

$$f = 0.25\log\left(\frac{e}{3.7d} + \frac{5.74}{Re^{0.9}}\right)^{-2} \quad (2)$$

Head losses, in addition to those due to pipe roughness are always incurred at pipe bends, junctions, valves etc. These are known as local or minor losses, and are insignificant especially in long pipes with few fittings. Losses at bends, junctions and valves are caused by separation and turbulent eddy formations. Local losses for different fittings and bends are determined experimentally using the general equation $h_l = k_l \left(\frac{v^2}{2g}\right)$ (3)

Where h_l represents the minor head loss, v is the velocity of water flow and g represents the gravity component.

Generally the elevation losses, which results from the elevation difference between the pump and the pipe outlet occurs during the flow through a pipeline. These elevation losses can be determined using various types of survey instruments, such as theodolite and GPS. Elevation losses are also included in the local losses. Local losses are usually considered 20-40 % of the major losses.
Pipe roughness generally increases with age due to pitting or etching by sand and corrosion and generally increases with precipitation of salts on the pipe walls. The roughness of pipes also increases with attachment of algae or bacteria to the pipe walls. Roughness of iron and steel pipes increases with formation of rust. Hence PVC pipes are generally suited as they suit most of the benefits and are feasible over the period of years. The roughness coefficient is generally in the range of 0.0005 as compared to G.I. and cast iron whose values are generally 0.0875 and 0.4.

A preliminary study of designing the optimum pipe size based on the discharge of flow through the pipe is given by [5].The preliminary pipe sizing technique based on annual energy cost is given by [6]. Both [5] and [6] proposes the optimum pipe sizing designs based on preliminary pipe sizing techniques where in which complex computations are not required. A case study is presented where the author's studies the formulae which are designed to determine the friction factor present in Moody's diagram without iterations [7].

The equation which can be used to determine the friction coefficient in terms of constants 'a' and 'b' is discussed by [8].The two major equations are described, primarily the Cole-brook White equation followed by the equation given by [8]; in which curve fittings and mathematical operations are applied to determine the friction coefficient of f [9].

Many methods of optimum pipe sizing design are used to design pipes so as to reduce the friction losses and minimum cost. The recommendation to use more than one method for optimum pipe sizing and to compare the results so as to select the better one is discussed in [10]. The various methods of optimum pipe sizing designs generally used are discussed in [11].

The recommendation of the usage of PVC and enlistment of the various benefits of PVC pipes over the rest of the raw materials available for designing is discussed in [12]. Many engineers use the Hazen-Williams Equation to predict friction losses in pipes, primarily due to its simplicity. However, the equation has significant drawbacks. The equation assumes that water temperature is constant about 20^{o}C assumed in the standard Hazen-Williams C factors, the flow is fully turbulent, and that C factors remain constant with increasing Reynolds number, also it does not produce results that agree well with the Darcy-Weisbach equation over a range of flow conditions in rough-walled pipes [13].

In this paper, the rest of the sections are organized as follows. Segment II provides the materials and methods. Segment III provides the results and discussion. Segment IV provides the conclusion and future scope.

II. MATERIALS AND METHODS

II.I Site Description and Topography

The site selected for conducting the case study is the Hamelmalo Agricultural farm which is sub divided into various plots at Hamelmalo Agricultural College (HAC). Hamelmalo Agricultural College is found 15°52'21.23" N latitude and 38°27'41.79" E longitude, at an elevation of about 1285 meters above mean sea level at 12 km North of Keren along the Keren-Nakfa road near Hamelmalo village. It is located adjacent to the Anseba River towards North and North West of Shilaket (tributary of Anseba River). The total area of the college is about 76.3 ha. The landscape of the area is undulating valley plane bounded by chains of mountains. The farm area is estimated to be around 16.3 ha with an average temperature of 29^{o}C. The existing pipe network is a linear type. Currently there are three functioning wells, a hand-dug well constructed during the period of the Italian investor Makelasi, with a location of 15^{0}40′16.47″ N, 39^{0}31′6.86″ E. A bore-hole well dug by the Chinese with a location of 15^{0}40′16.28″ N, 39^{0}31′4.93″ E and another bore hole well with a location 15^{0}52′30″ N, 38^{0}27′50″ E. Their location in proximity of Anseba River ensures their recharge. The bore-hole well dug by the Chinese has a safe yield of 3 l/s and hand-dug well with 8.3 l/s obtained through pump test carried out by the Eritrean Core Well Drilling Company. The second tube well has a safe yield of 18 l/s. The wells recharge water from the Anseba River. The network starts from the two wells and they meet at a junction point. This is done to ensure even if failure of one well or its pumping unit results, it will not cause the crops to suffer from moisture deficit stress since the other well can act as a redundant. The pipelines are used to deliver water from wells to each plot. The pipe network in Hamelmalo Agricultural college farm consist of a mainline, sub mains, manifolds, gate valves and emission devices. The materials in which pipes are made from are steel cast iron and PVC. Some pipes are laid over the ground and others beneath the ground. The farm is divided into different plots. The GIS satellite imaging of the existing pipe network is shown below in order to indicate the above mentioned statistics.

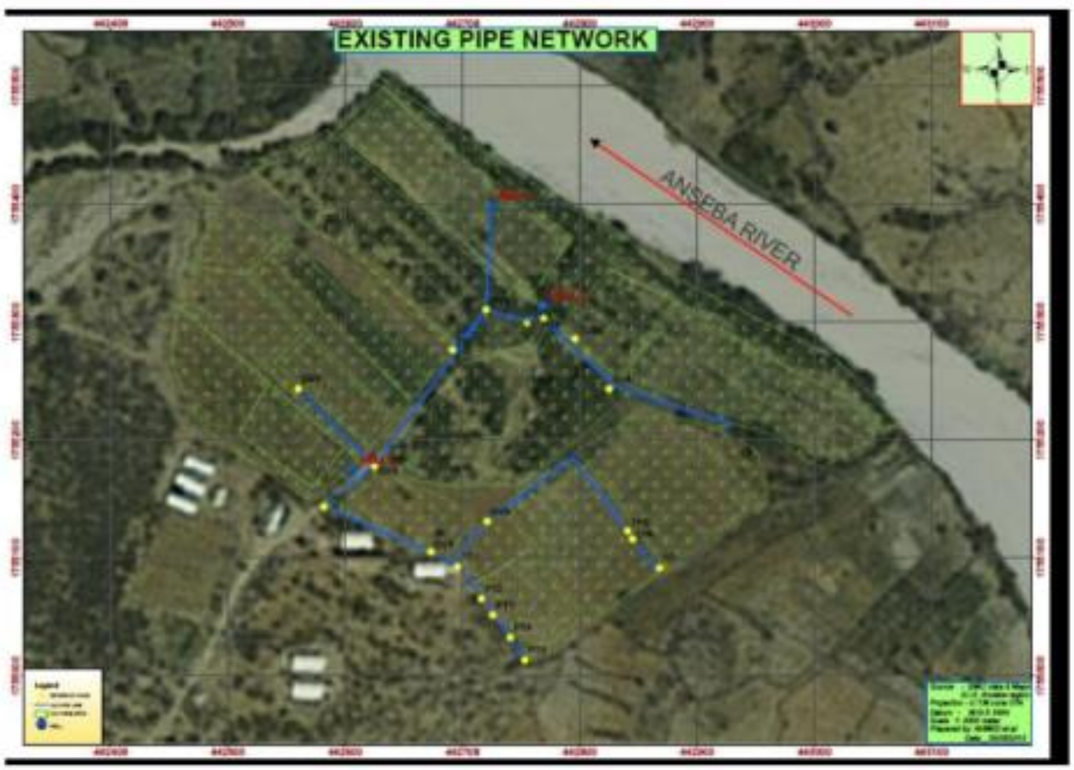

Figure 1 Satellite image of the existing pipe network at HAC

The field is located about 600 meters from the wells with a pipe diameter of 2 inch through the field. The water source for irrigating the farm is a bore hole well (Well 1) with a submersible pump inside it. The pump has the capacity to discharge 18 l/s indicated by the triangle (A). For convenience the pipe system network was divided into 15 pipe links, namely AB, B1, BC, C2,CD, D3, DE, E4, E5, EF, FG, G6, GH, HI and H7 as shown in the Hydraulic Analysis chart. The flow through the network is scheduled for two intervals, such that the flow of liquid is monitored uniformly and regularly. During the primary schedule, the flow of water takes place through the first nine links namely AB, B1, BC, C2, CD, D3, DE, E4, and E5. The second schedule for the flow of water takes place through the next six links namely EF, FG, G6, GH, HI and H7.

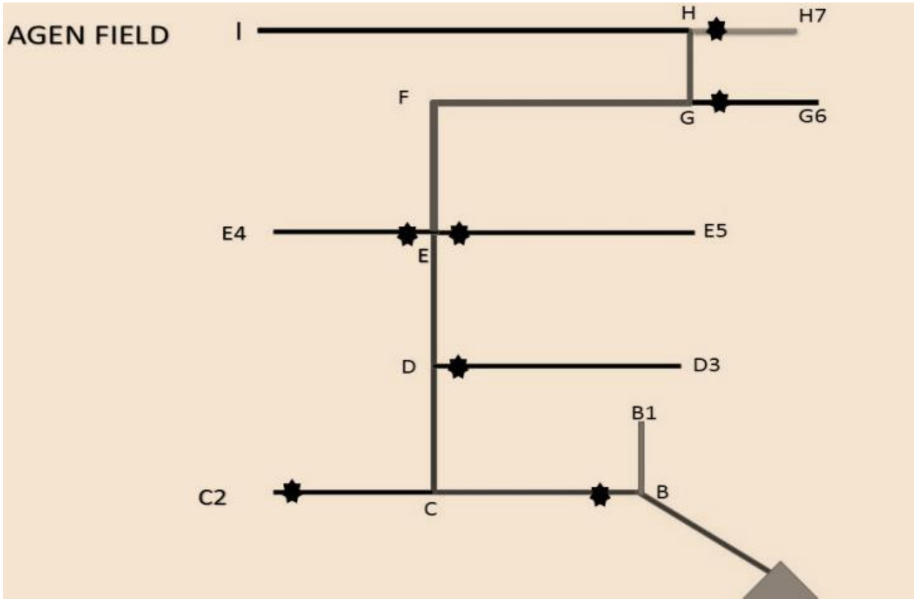

Figure 2 Hydraulic Analysis chart of Hamelmalo Agricultural College

II.II Estimation of Pipe Sizes for Liquid Flow

II.II.I. Adams Method: Estimation of Pipe size with "Jack's Cube"

J.N.Adams [5] developed two mathematical equations which describes the pressurized flow of liquids in typical pipes within the realm of normal supply pressures. They offer a simple way to do preliminary pipe sizing. They provide a quick size determination for typical flow situations for normal fluids. The Adams equations in their original form are cubic in terms of pipe diameter, and as such are more suited for determining the approximate flow corresponding to a known nominal pipe size. However, with manipulation they can provide a quick means to determine an approximate nominal pipe size. A least squares geometric regression analysis of Adams equation for flow rates yield the correlation equations. For lower flow rates, the equation is given by

$$d = 0.25\sqrt{Q} \quad \left[\text{For } Q < 100 \ \frac{gal}{min}\right] \qquad (4)$$

For higher flow rates, the equation is given by,

$$d = \left(\frac{Q}{1.2}\right)^{\frac{1}{3}} - 2 \ [\text{For Q} > 100 \ \frac{gal}{min}] \qquad (5)$$

Where, 'Q' is system discharge in gal/min and'd' is the required inside pipe diameter in inches.

Pipe sizing using Jack's cube generally applies to a typical liquid pipe with a normal supply pressure, such as a pump to provide the motive force. Sizes provided by this rule of thumb are a conservative estimate. The method also warns the user regarding its application on processes which involves high viscosity, minimum slurry velocity, abrasive or crystal slurries having a restriction on maximum velocities and pressure drops. Hence the rule is not meant to be used as the final engineering design, but merely to give a reasonable estimate for sizing pipe.

II.II.II. Head Loss Gradient Method

This method of pipe selection generally suggests about setting a limit on the head loss per unit length. The usual limit of the head loss per unit length in a pipe network is suggested to be in the range of 2.0 m/ 100 m or (2.0 ft. / 100 ft.).

Generally classical methods of design involve a procedure of iteration in order to determine the value of the unknown. The advanced automated computational methods provide solution for designing the diameters of the pipe network. In order to determine the friction factor ' f ' without the methods of trial and error and the usage of Moody's chart the following two mathematical equations are used such that they directly yield the final solution . The two equations required to model the design of the diameter of the pipes using the head loss gradient method are the Colebrook-White equation and Konakov apud

Nekrasov equation. By several curve fittings and mathematical operations of the below equations, the final design of the diameter is obtained. The pictorial flow chart for the determination of the optimum diameter is given below.

$$(f)^{-0.5} = -2log[\,2.51(Re\sqrt{f})^{-1}] \qquad (6)$$

$$(f)^{-0.5} = -2log[\,a(Re)^{-b}\,] \qquad (7)$$

Where, ‘a’ and ‘b’ in (7) represents numerical constants of Konakov’s formula.

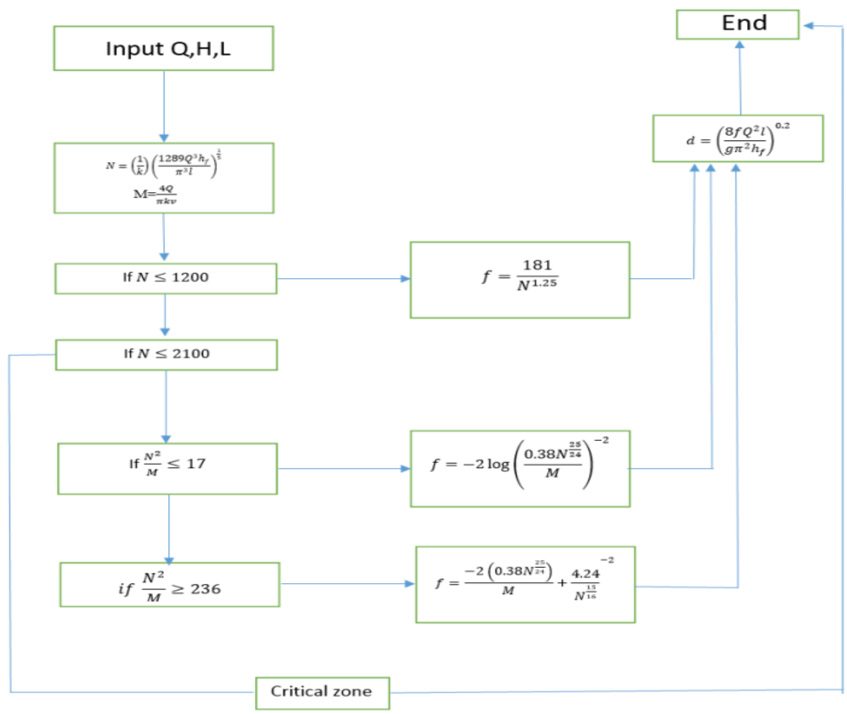

Figure 3 Flow chart to determine optimum diameter using Head Loss Gradient method

II.II.III. Smit’s Method of Optimum Pipe Design

The diameter of the pipe will depend on the flow rate and the friction losses of the different types of pipes for the chosen velocity. This would then affect the annual energy cost. Smit proposed the empirical equation based on the flow rate and a constant k, which depends on the annual pumping hours. This formula applies only to 80% of cases and suggests that it should be used as a first approximation. The optimum diameter d can be modelled using this method by the equation

$$d = k(Q)^{0.37} \qquad (8)$$

Where d is the pipe diameter in mm, Q is the system discharge in m^3/hr and K is the constant value. The values of the constant K for electric and diesel pumping duration are given below in the table:

Table 1. Values of constant K for electric and diesel pumping duration

K	25	27	29	31	34
Electric pumping(hrs/yr)	1500	2000	4000	8000	
Diesel pumping (hrs/yr)		500	1000	2000	4000
Estimated friction (%)	2	1.5	1	0.75	0.5

Smit's method claims that, these norms which are mentioned in the table vary from country to country because of the combined effect of pipe prices and transport and installation cost. Since the raw material for the manufacture of both polyethylene and PVC are petrol derivatives and since a very high percentage of their manufacture cost is the cost of the raw material, the cost of the international price of petrol can affect their prices substantially.

III. RESULTS AND DISCUSSION

The principle of selecting an optimum pipe diameter depends upon two major factors. The pipe size selected should have a minimum frictional loss and at the same time must be cost effective. Considering the above mentioned fact, three methods available in the literature were selected and comparisons were made among them so as to select an optimum pipe size for the proposed model.

In order to determine the total cost for the selection of the optimum pipe diameter, the current market prices of the available pipe diameter was collected from various retail shops. The optimum cost generally consists of two variables namely; the fixed cost which is computed using the capital recovery factor per unit length of the pipe of the present market value and the operating cost which is determined considering the variable diameters, flow rate, head loss due to friction, time of operation per annum, cost of electricity per annum and the efficiency of the power unit. Thus the total cost for the overall pipe network design will be the total sum of the fixed cost and the operating cost which is considered for all the methods of the model designed i.e. ($C_T = C_0 + C_f$). The equation for the determination of the total cost of the optimum pipe diameter is given by the equation [1]

$$C_T = P\left[\frac{i(1+i)^n}{(1+i)^n-1}\right] + \left[\frac{8.103*10^{-4}\, W f Q^3\, t(C_e)}{d^5 * \eta}\right] \qquad (9)$$

Where P= price per unit length of the pipe (Nakfa(NFA)/m), i= interest rate (fraction), n= Life of pipe (years), C_T= Total cost per annum (NFA/ year), C_f= fixed cost per annum (NFA/year), C_o=Operating cost per annum (NFA/year), L= Length of the pipe (m), d=Diameter of the pipe (m), Q=Discharge (l/s), h_f= Head loss due to friction (m), t=Pump use hr/year, c_e= Cost of electricity (NFA/KWH), η=Efficiency of power unit (fraction), W= Unit weight of water(kg/m^3).

III.I. Design of optimum pipe diameter using Adams Method: Estimation of pipe size with "Jack's Cube"

The design of optimum pipe sizing using the Adams method is the preliminary design concept. As per the equations proposed, the amount of water at the inlet discharge is 18 l/s (237.56 gal/min), which is greater than 100 gallon / min. The results obtained where compared with the available pipe sizes collected from the market and the results are tabulated as shown below. The graphical responses shown below signifies the total amount of friction losses incurred during the flow of water through the network among the various links as shown in the hydraulic analysis chart. The total cost incurred for the design of the optimum pipe flow network by the diameter selected using the method is also shown below.

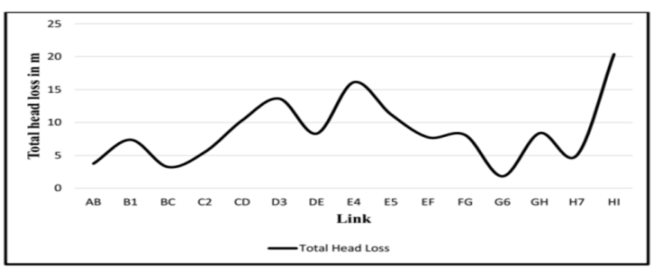

Figure 4 Graphical response of the total head loss estimated using "Jacks Cube Method"

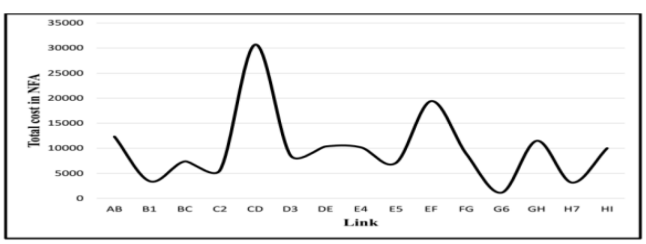

Figure 5 Graphical response of the total estimated cost using "Jack's Cube Method"

Table 2. Determination of optimum pipe diameter using Adams Method

Interval	**Link**	**L (m)**	**Total Head loss (m)**	**d (inch)**	**Q (l/s)**	**Total cost (Nakfa)**
Schedule -1	AB	70	3.74	3.82	17.08	12336.09
	B1	38	7.36	1.28	1.67	3444.67
	BC	42.3	3.23	3.72	15.86	7394.80
	C2	43.3	5.52	1.81	3.54	5643.97
	CD	177.4	10.32	3.58	14.99	30693.45
	D3	89.7	13.60	1.57	2.60	8609.81
	DE	61.2	8.29	3.48	13.20	10360.63
	E4	106.2	16.11	1.57	2.60	10193.56
	E5	74	11.22	1.57	2.60	7102.86
	EF	116.3	7.741	3.25	12.38	19423.18
	FG	53.5	8.07	3.14	10.75	8886.53
	G6	12	1.82	1.57	2.60	1151.81
Schedule- 2	GH	73	8.37	2.40	6.95	11491.79
	H7	33	5	1.57	2.60	3167.49
	HI	65.5	20	1.50	3.02	10015.52
Total			**130.8**			**149916.24**

III.II. Design of optimum pipe diameter using Head Loss Gradient Method

The selection of pipe diameter using the Head loss gradient method is based on the mathematical formulas of Cole-brook White equation and Konakov apud Nekrasov. Curve fittings were used in order to correlate these two equations and the optimum pipe diameter was selected based on the final equation obtained from the two mathematical formulas. The basic concept behind the Head Loss Gradient method is that the usual limit of the head loss per unit length is suggested to be in the range of 2.0 m/ 100 m or (2.0 ft/ 100 ft) as suggested in the literatures available. The optimum diameter was selected based on the above mentioned limits and the incurred friction losses and the total cost prices of the selected pipe diameter has been tabulated and shown graphically below.

Table 3. Determination of optimum pipe diameter using Head Loss Gradient method

Interval	**Link**	**L (m)**	**h_f (m)**	**Total Head loss (m)**	**d (inch)**	**Q (l/s)**	**Total cost (Nakfa)**
Schedule -1	AB	70	1.4	1.68	5.36	17.57	11619.2
	B1	38	0.76	0.91	2.37	1.95	3593.06
	BC	42.3	0.84	1.91	4.72	16.76	8464.51
	C2	43.3	0.86	1.03	3.06	3.90	4616.15
	CD	177.4	3.54	4.25	5.10	15.46	28570.92
	D3	89.7	1.79	2.15	2.75	2.92	9358.54
	DE	61.2	1.22	6.06	3.88	13.92	14926.54
	E4	106.2	2.12	2.54	3.06	3.90	11321.84
	E5	74	1.48	1.77	3.06	3.90	7889.04
	EF	116.3	2.32	2.79	4.96	14.32	18422.37
	FG	53.5	1.07	5.61	3.71	12.65	12795.34
	G6	12	0.24	0.28	2.75	2.92	1251.97
Schedule- 2	GH	73	1.46	2.10	4.12	9.46	9242.14
	H7	33	0.66	0.79	2.75	2.92	3442.94
	HI	65.5	1.31	2.54	3.33	6.14	7925.99
Total				**36.41**			**153440.54**

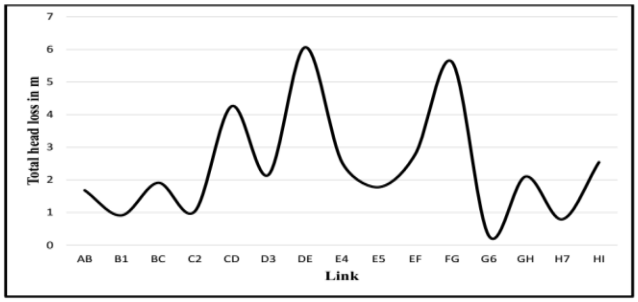

Figure 6 Graphical response of the total head loss estimated using Head Loss Gradient Method

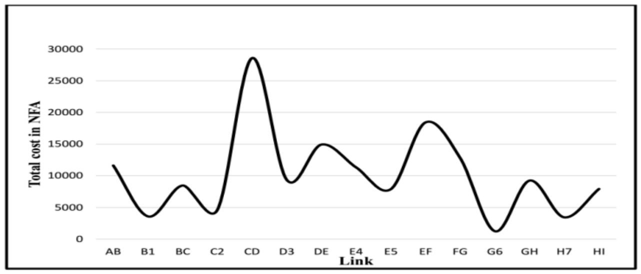

Figure 7 Graphical response of the total estimated cost using Head Loss Gradient Method

III.III. Design of optimum pipe diameter using Smit's Method

The selection of pipe diameter using the Smit's method is based on the annual energy cost. The diameter of the pipe will depend on the flow rate and the friction losses of the different types of pipes for the chosen velocity. This would then affect the annual energy cost. Smit proposed the following empirical equation based on the flow rate and a constant k, which depends on the annual pumping hours. The pump available for the network is a submersible pump, which operates with electric power. The annual pumping hours at HAC was estimated to be 2920 hr/year. Based on the data obtained, the value of K was determined to be 27.92. The total friction losses and the total cost incurred are shown graphically and tabulated below.

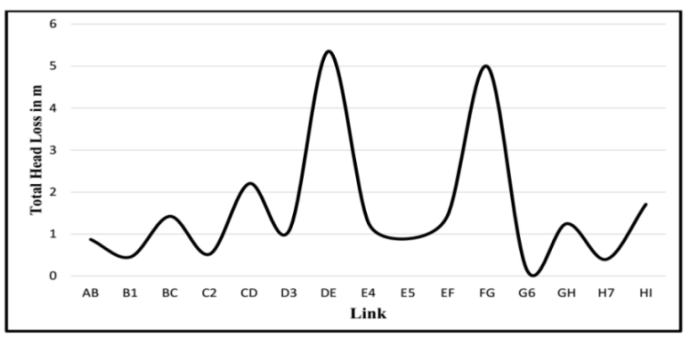

Figure 8 Graphical response of the total head loss estimated using Smit's Method

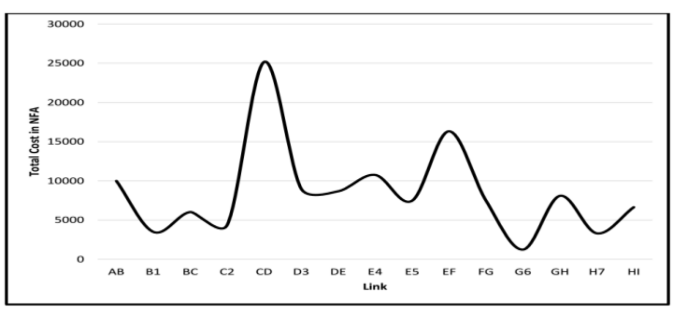

Figure 9 Graphical response of the total estimated cost using Smit's Method

Table 4. Determination of optimum pipe diameter using Smit's Method

Interval	Link	L (m)	Total Head loss (m)	d (inch)	Q (l/s)	Total cost (Nakfa)
Schedule -1	AB	70	0.86	5.18	17.77	9987.58
	B1	38	0.45	2.3	1.97	3491.52
	BC	42.3	1.42	5.16	17.2	6025.92
	C2	43.3	0.51	2.97	3.95	4386.2
	CD	177.4	2.2	5.09	16.99	25168.4
	D3	89.7	1.07	2.67	2.96	9000.18
	DE	61.2	5.35	5.07	15.62	8669.64
	E4	106.2	1.27	2.97	3.95	10757.9
	E5	74	0.88	2.82	3.43	7458.78
	EF	116.3	1.43	4.9	15.43	16315.2
	FG	53.5	4.99	4.88	14.11	7494.99
	G6	12	0.14	2.67	2.96	1234.03
Schedule- 2	GH	73	1.24	4.33	10.92	8086.85
	H7	33	0.39	2.67	2.96	3311.1
	HI	65.5	1.7	2.97	3.89	6635.02
Total			**23.9**			**128023**

From the graphical responses of figure 4, figure 6 and figure 8 the overall estimated head loss using Jack's Cube method is the maximum for the design of an optimum diameter. The head loss estimated by the Head Loss Gradient method is comparatively less as compared to the design of optimum diameter using Adams method. The head loss estimated using Smit's method is the least among the three methods. From figure 5, figure 7 and figure 9 the overall cost estimated using the Adam's method is the maximum among the three methods, where as the cost estimated using Smit's method is the least among the three. The Head Loss Gradient method contributes much higher cost than the Smit's method.

IV. CONCLUSION AND FUTURE SCOPE

The design of optimum pipe diameter using Jack's Cube method is a preliminary technique and has many caveats. The design using Smit's method is also a preliminary technique, where 80% optimum design is preferable as the author suggests. The Head Loss Gradient method is considerably better than Adam's method but contributes more amounts of head loss and estimated cost as compared to Smit's method in the model considered.

On comparison, Smit's method contributes to be a much better method than all the three methods for the model considered. Considering the present cost analysis and the estimated overall frictional losses, the Smit's methods is suggested to be significantly better. The pressurized irrigation system designed using Smit's method for the model would be highly beneficial with better efficiency.

As the authors [7] suggests adopting of more than one method is essential while designing pipe diameters and then to compare the results. Hence on comparison Smit's method yields a better result for the design of the diameter of the current case study.
Various methods available in the literature for designing optimum pipe selection can be adopted so as to design a pipe with minimum losses and optimum cost. The various object oriented programming languages along with Android features also leads to better results when compared to conventional methods which involves complex computations.

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