WATER PIPELINE NETWORK ANALYSIS OF USM ENGINEERING CAMPUS USING WATERGEMS

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By

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ABSTRAK

Hidraulik model adalah salah satu alat untuk menganalisis rangkaian saluran air yang komplex. Penyelidikan ini menggunakan model WaterGEMS untuk menganggar tekanan, halaju dan kehilangan turus air dalam rangkaian saluran paip Kampus Kejuruteraan, Universiti Sains Malaysia (USM). Model WaterGEMS yang diaplikasi termasuk 9.882 km panjang paip, 132 nod (52 nod permintaan) yang terpasang di 34 jenis bangunan yang berbeza dan satu titik tap dimana aliran air bermula. Analisis rangkaian saluran paip menunjukkan 43.6% daripada halaju air di dalam paip tidak memenuhi halaju minimum dan maksimum. 3.8% daripada nod tidak memenuhi tekanan minimum. Hal ini menyebabkan kehilangan kepala turus yang sangat tinggi. Pengoptimuman rangkaian saluran paip telah dilaksanakan dengan mengambil kira reka bentuk yang murah dengan mengurangkan diameter paip. Rangkaian yang dioptimumkan menunjukkan 100% daripada nod mencapai tekanan minimum yang dibenarkan, iaitu 15 meter, manakala 87.9% paip mencapai halaju minimum dan maksimum. Akhir sekali, kos penggunaan tenaga operasi pam Kampus Kejuruteraan USM telah dibincangkan. Hasil pengiraan bil menunjukkan jumlah kadar penggunaan tenaga pam untuk sebulan ialah RM 121,026.43 dan RM 1,452,317.16 untuk setahun. Hal ini menyumbang kepada 28.01% daripada keseluruhan jumlah penggunaan elektrik. Oleh itu, penggunaan elektrik melalui operasi pam adalah tinggi, menjadikannya salah satu kos dominan dalam rangkaian saluran paip Kampus Kejuruteraan USM. Secara keseluruhan, dapatan kajian ini menunjukkan bahawa dengan pengoptimuman saiz paip, perbelanjaan untuk paip air dapat dikurangkan dengan capaian halaju dan tekanan yang diperlukan. Selain daripada perbelanjaan paip, penggunaan elektrik melalui operasi pam adalah salah satu kos marginal tertinggi untuk utiliti air di Kampus Kejuruteraan, USM.

ABSTRACT

The complexity of water pipeline networks is managed using hydraulic models. Utilising the WaterGEMS model, the pressure, flow velocity, and head loss of the USM Engineering Campus pipeline network was estimated. The WaterGEMS model includes 9.882 km pipelines, 132 nodes (52 demand nodes) that spread over 34 different types of buildings, and a tapping point where outflow starts. The pipeline network analysis reveals that 43.6% of the flow velocity in the pipeline does not meet the allowable, minimum, or maximum velocities, and 3.8% of the nodes do not meet the minimum residual pressure. Thus, it causes exceedingly high head losses. Optimisation of the pipeline network had been done to the least-cost design by reducing the pipe diameters. A comparison of results showed that in the optimised networks, 100% of the nodes reached the minimum allowable pressure, which is 15 meters above the platform level of a building, without the use of a pump. 87.9% of pipelines achieve the allowed minimum and maximum velocity. Lastly, costs for energy consumption due to pump operation are discussed. The bill calculation results show that in the USM Engineering Campus, the total consumption rate of pumps for one month is RM 121,026.43. For one year, it is RM 1,452,317.16, contributing to 28.01% of the overall total usage of electricity. Thus, electricity consumption by pump operation is considered high, making it one of the dominant costs in USM Engineering Campus's pipeline network. Overall, the finding of this study indicated that by optimisation of pipe size, pipeline expenses can be reduced with the satisfaction of required velocity and residual pressures. Other than pipeline expenses, electricity consumption by pump operation is one of the highest marginal costs for water utilities at USM Engineering Campus.

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LIST OF ABBREVIATIONS

GA	Genetic Algorithm
LOP	Linear Optimisation Programming
MLD	Mega Litres per Day
MOGA	Multi-Objective Genetic Algorithm
MWA	Malaysian Water Association
PBAPP	Perbadanan Bekalan Air Pulau Pinang
REDAC	River Engineering and Urban Drainage Research Centre
SECS	Science and Engineering Research Centre
SPAN	Suruhanjaya Perkhidmatan Air Negara
USM	Universiti Sains Malaysia
WDS	Water distribution systems
WHO	World Health Organization

CHAPTER 1

INTRODUCTION

1.1 Background of the study

Water distribution systems (WDS) are essential for transporting water from its source to its consumers. It has been developed to supply sufficient potable water with sufficient pressure at the point of consumption, especially in residential, industrial, institutional, and commercial areas (Tevfik Akdoğan, 2005). This system consists of elements such as pipes, valves, pumps, tanks, and reservoirs. The most crucial factor in designing and managing a water distribution system is satisfying consumer demands under various quantity and quality considerations during the entire lifetime for the expected loading conditions.

Safety and efficiency are also critical, and digital tools are vital approaches that can help support decisions. Monitoring, modelling, and optimisation are digital control strategies that do not necessitate significant investments, renovations, or changes. (Luna *et al.*, 2019). According to the scientific literature, the usage of hydraulic models to characterise WDS is expanding. Hydraulic models are used to manage the complexity of WDSs, and numerous optimisation strategies have been developed to enhance the performance of these infrastructures (Ramos, *et al.*, 2012). Most optimisation programs of WDS characterize the design problem as minimising the pipe cost while satisfying (1) velocity and pressure limits and (2) satisfaction of nodal demands.

Bentley WaterGEMS software will be utilised in this research project to construct a model of the existing pipeline networks at the USM Engineering Campus, to estimate the network's pressure, flow velocity, and head loss. This study also presents the network optimisation by finding the optimal pipe diameter to supply adequate water at satisfactory pressures and velocity to the end-users. Lastly, costs for energy consumption due to pump operation of the USM Engineering Campus will be discussed.

1.2 Problem Statement

When it comes to constructing and analysing pipeline systems, determining pipe flow, pressure, and velocity can be difficult, especially when there is a complex network of pipelines. Several academics have focused on hydraulic and water quality modeling methods for analysing piping systems.

Pipelines are a significant expense for WDS. Over the past few decades, optimisation strategies for WDS have been the subject of extensive discussion. Two challenges must be resolved to optimise WDS: design and operations (Bello *et al.*, 2015). Design optimisation usually deals with pipe sizes. Optimised WDS should be implemented to minimise costs and satisfy required water flow velocities and pressure on the nodal.

Furthermore, the energy consumption associated with pumping system is also a crucial component of water pipeline systems, accounting for more than 60% of the energy consumed by the whole supply system. (Sarbu, 2016).

Thus, this research aims to estimate the pipeline network's pressure, flow velocity, and head loss in the USM Engineering Campus using WaterGEMS Software. This study also presents the network optimisation by finding the optimal pipe diameter to supply adequate water at satisfactory pressures and velocity to the end-users. Lastly, costs for energy consumption due to pump operation of the USM Engineering Campus will be discussed.

1.3 Objectives

1. To estimate the pressure, flow velocity, and head loss in the USM Engineering Campus pipeline network using WaterGEMS software.
2. To optimise the diameter of the pipeline network of USM Engineering Campus.
3. To estimate the energy cost for pump operation in the USM Engineering Campus.

1.4 Scope of Work

This research aims to estimate the flow parameters in the USM Engineering Campus pipeline network and optimise the diameter of the pipeline network using WaterGEMS software. The layout pipeline systems of the USM Engineering Campus covered all areas of the campus, including six engineering schools currently in operation, research institutions, service centers, halls, and hostels. Only six hostels were considered in the pipeline network for the hostel: three in Desasiswa Lembaran and three hostels in Desasiswa Jaya. Hostel in Desasiswa Utama was not considered as the building is located outside the campus.

The study of the pipeline network of USM Engineering Campus was performed using WaterGEMS software. Due to data constraints, the analysis is limited to a steady-state run, and the presence of control devices such as the pump and valve are not considered in the model.

For estimating the energy cost for pump operation, the consumption charge is based on the kilowatt-hours of electric energy consumed by pumps during the billing period. The pump cost, the pricing, and the tariff are based on TNB's tariff rate.

1.5 Dissertation Outline

The dissertation for this project comprises five chapters: Introduction, Literature Review, Methodology, Results and Discussion, and Conclusion. Chapter 1 provides an insight into the background of the study, problem statements, objectives, scope of work, and dissertation outline.

Besides, Chapter 2 breaks the research topic into several components while past studies and research findings related to each segment are discussed. Next, the approaches adopted to conduct this project are discussed in Chapter 3. All the assumptions in the analysis were based on the reference to the Uniform Technical Guidelines for Water Reticulation and Plumbing by Suruhanjaya Perkhidmatan Air Negara (SPAN) and are listed with sufficient explanation. In contrast, data collection, analysis, and presentation flow are included.

Later, Chapter 4 covers all the research outcomes while the discussion is made accordingly to identify the fundamental reasons behind this project. Finally, Chapter 5 summarises the overall accomplishment of this initiative in terms of its initial goals. For individuals who want to improve this study further, suggestions and recommendations are provided as a guide.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter provided an overview of the water supply system in Malaysia and the optimisation techniques of water distribution networks. It also briefly explains the principles and devices used in Water Distribution Systems. Besides, the hydraulic modelling software used in this study is also discussed.

2.2 Water supply in Malaysia

Malaysia is a fortunate country that receives a lot of rain each year and has a lot of water resources. Surface water accounts for 97 percent of Malaysia's water resources, whereas groundwater accounts for 3 percent. In developing countries such as Malaysia, water use climbed to 10,786 Mega Litres per Day (MLD) in 2017, with residential usage of 201 L per capita per day (National Water Service Commission, 2017). Thus, making the country one of Southeast Asia's largest consumers of potable water (Nur Imani, 2015). The amount consumed is still significantly above the World Health Organization's (WHO) recommended daily water consumption of 165 litres per day. Penang had the most water use per day in 2013, at 296 litres, according to the Malaysian Water Industry Guide 2014.

On the other hand, Sabah has the lowest daily water use (109 litres). Most people in metropolitan areas have relatively excellent living standards, with good infrastructure, power, telecommunications, and safe drinking water. (Shahbaz *et al.*, 2015).

According to Luna *et al.* (2019), water resources provide a wide range of essential functions for long-term development. Population growth, industrialization, food and energy security policies, and changing production and consumption patterns have all influenced its ever-ending needs.

2.3 Water Supply System and Hydraulic Concept

This section explains the water supply system, its main elements, the hydraulic concepts, and its fundamental principle.

2.3.1 General Overview

Generally, a water supply system comprises three processes: raw water extraction, water treatment and storage, and clearwater transport and distribution. (N Trifunovic, 2008):

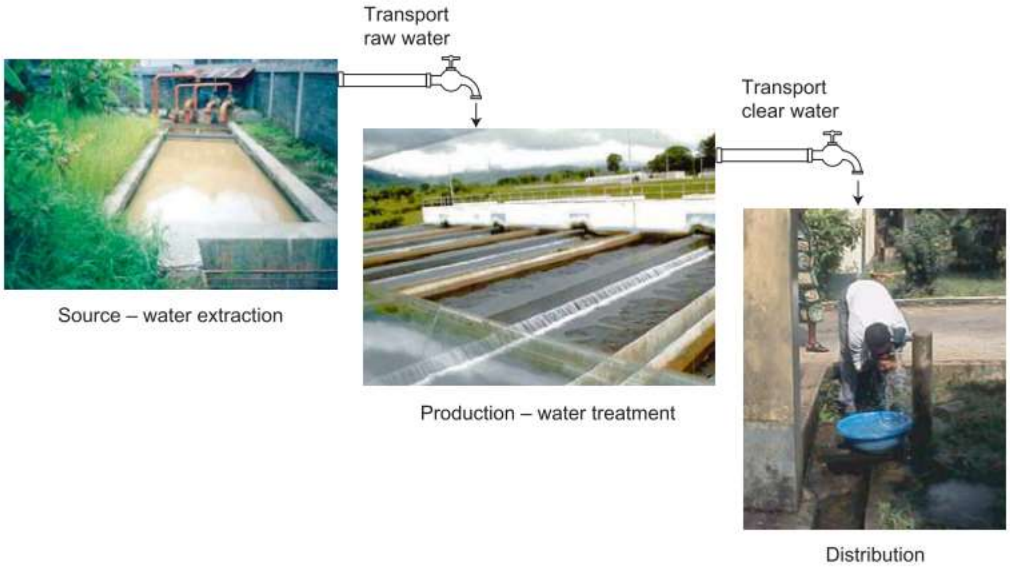

Figure 2.1: Water Supply System Processes (N Trifunovic, 2008)

Transport and distribution are identical procedures in which water is transported through a network of pipes, stored intermittently, and pumped as needed to satisfy system demands and pressures; the difference between the two is their purpose, which determines the system layout decision (N Trifunovic, 2008). On the other hand, water distribution systems provide a means of delivering drinking water to individual homes, businesses, and community taps (WHO, 2004).

2.3.2 Piping

Pipes are one of the most critical components of water networks. They allow water to be delivered from point A to point B and finally to the end-user. Pipes can be composed of various materials, diameters, and service connections or valves. The eventual purpose will determine the pipe specs.

2.3.3 Pump

Pumping systems in WDS generally operate by one of two mechanisms, trigger levels or pump scheduling. Using trigger levels is a way of dynamically controlling the operation of pumps. Upper and lower trigger levels are set up in one of the storage tanks such that when certain levels are reached, this trigger pump starts or stops. Pump scheduling necessitates the estimation of daily total water consumption. The schedule guarantees that the appropriate amount of water is pumped throughout the day. (Kazantzis *et al.*, 2002).

2.3.4 Valves

Another vital component of the WDS is the valve. Many valves are available, and each application may necessitate a specific kind. Valves have three primary roles. First is flow and pressure regulation (flow control valves, pressure reducing or pressure sustaining valves, etc.). The second is to isolate network segments to perform maintenance or emergency operations (section valves). Lastly is to protect the reservoirs and pumps (e.g., float valves, non-return valves) (N Trifunovic, 2008).

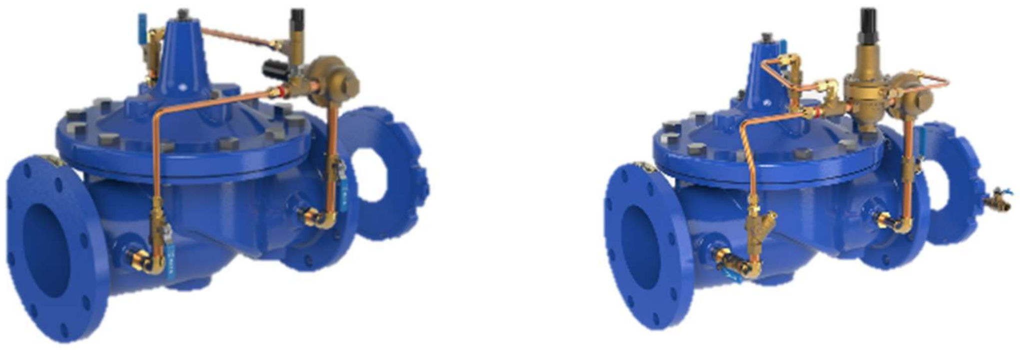

Figure 2.2: Flow Control and Pressure Reducing Valve (Cla-Val, n.d.)

Figure 2.3: Pressure Sustaining Valve and Float Valve (Cla-Val, n.d.)

2.3.5 Basic Hydraulic Concepts

This section explains the principles and concepts underpinning the work's founding concept.

2.3.5.1 Flow

Flow is the amount of a particular fluid that moves across a surface in a given amount of time (Sebastião, 2017). The flow rate can be expressed in terms of velocity and cross-sectional area, as well as time and volume. Incompressible liquids require that the flow rates into and out of a given region be the same since they are incompressible. The continuity equation is the name given to this. It is articulated as:

$$Q = Av = \frac{V}{t} \tag{2.1}$$

Where;
A = Flow Area (m^2)
v = Flow velocity (m/s)
V = Volume (m^3)
t = time (s)

2.3.5.2 Pressure

Pressure is defined as the amount of force exerted on a unit area of a substance or a surface (Mott and Untener, 2019). The equation can state this:

$$p = \frac{F}{A} \tag{2.2}$$

Where;
F = Force (N)
A = Area (m^2)

2.3.5.3 Head

The term "head" refers to the height a pump can elevate a liquid. It is measured in meters and unaffected by the liquid's density. (Sebastião, 2017). Equation 2.3 shows the relationship between pressure and head.

$$H = \frac{p}{\rho g} \tag{2.3}$$

Where;
p = Pressure (N/m^2)
ρ = Liquid density (kg/m^3)
g = Acceleration of gravity (m/s^2)

2.3.5.4 Head Loss

The pipe head loss is the frictional loss in the pipeline, expressed as a fraction of the available head. Water (like any viscous fluid) flowing through a pipe experiences a loss in pressure due to friction. This pressure loss can be expressed as a loss of the head, where the head is the vertical drop through which the fluid flows. Head loss due to friction is examined to understand the effects of pipe size and roughness. Main friction losses through pipelines are calculated using the Hazen-William equation (Radwan, H. G. 2013): -

$$Head\ loss = \frac{10.68L}{D^{4.87}}\left(\frac{Q}{C}\right)^{1.852}\ (m) \tag{2.4}$$

where Q (m^3/s) is the pipe flow, C is the roughness coefficient of the pipe, L (m) is the length of the pipe, and D (m) is the internal diameter of the pipe (Hashemi *et al.*, 2020).

2.3.5.5 Conservation of Energy- Bernoulli Equation

The analysis of a pipeline problem shown in that Figure 2.4 considers all of the energy in the system. Energy cannot be created or destroyed, but it can be converted into another form. This is a statement of the law of energy conservation (Mott and Untener, 2019). Three types of energy are always considered when analysing a pipe flow problem. Consider the example of a fluid element inside a pipe in a flow system, as shown in Figure 2.4.

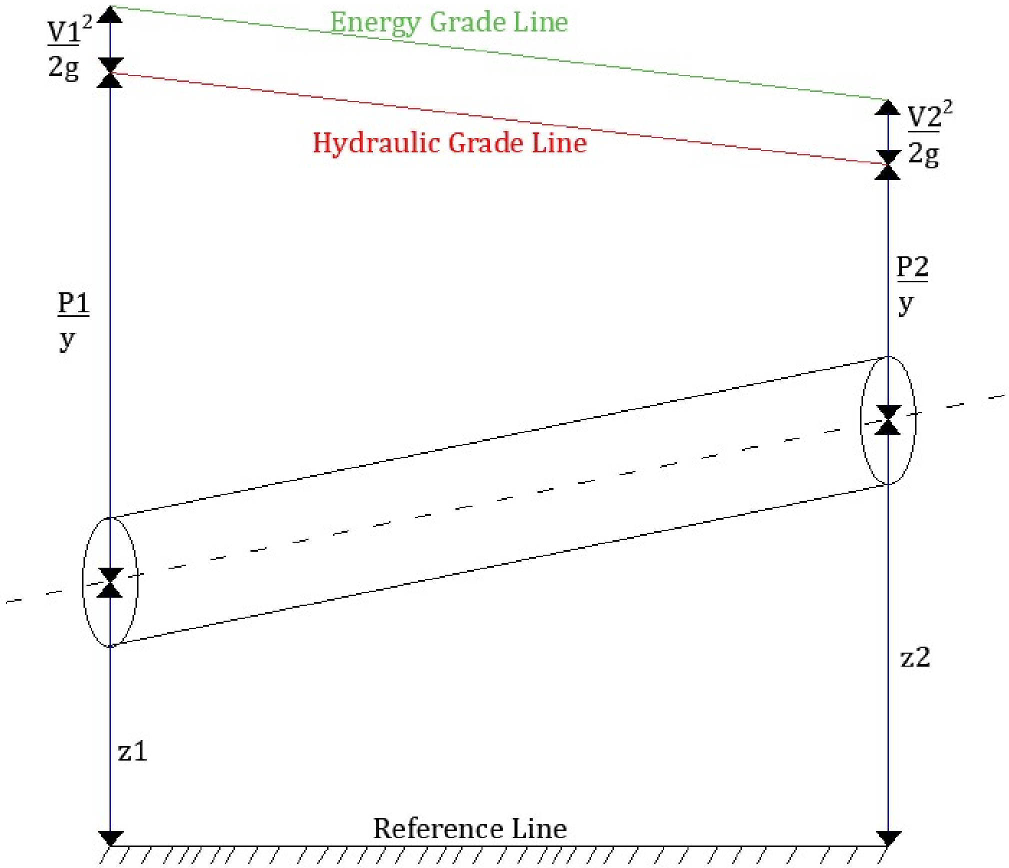

Figure 2.4: Elements inside a pipe

It has a velocity of v and a pressure of p and is placed at a given elevation of z. The following energy types are found in the element fluid:

i) Potential Energy, due to its elevation, the potential energy of an element is relative to some point.

ii) Kinetic Energy, due to its velocity.

iii) Pressure Energy represents the amount of work necessary to move the element of fluid across a particular section against the pressure *p.*

Figure 2.4 shows a fluid element that flows from part 1 to section 2. The value of p, z, and v is different in this two-part. If no energy is added to the fluid or lost between sections 1 and 2, the principle of energy conservation dictates:

$$E_1 = E_2 \tag{2.5}$$

The equation then becomes

$$\frac{\rho_1}{\gamma} + z_1 + \frac{v_1^2}{2g} = \frac{\rho_2}{\gamma} + z_2 + \frac{v_2^2}{2g} \tag{2.6}$$

The equation above is referred to as Bernoulli's equation. Each term in Bernoulli's equation was derived from dividing energy by the weight of a fluid element. As a result, each component in Bernoulli's equation represents one form of the fluid's energy per unit weight of fluid flowing in the system. Each phrase is measured in "energy per unit weight." N.m/N is the SI unit. In contrast, the force (or weight) unit occurs in both the numerator and denominator and can be cancelled.

The metre (m) is the output unit, translated as height. In fluid flow analysis, the terms are commonly presented as "head," referring to an elevation above a reference level. Specifically, $\frac{\rho}{\gamma}$ is called pressure head, z is called elevation head and last, $\frac{v^2}{2g}$ is called velocity head.

The total head is the sum of these three terms. Because each component in Bernoulli's equation corresponds to a height, Figure 2.4 can assist in visualising the relationship between the three energy sources. The magnitude of each phrase may alter in value as the fluid flows from point 1 to point 2. If no energy is lost or added to the fluid, the total head, on the other hand, remains constant. Bernoulli's equation determines how the fluid's pressure, elevation, and velocity heads vary as it moves through the system.

2.3.6 Malaysian Regulation

This section will describe the Malaysian legislation and the applicable standards for water distribution networks.

2.3.6.1 Legislation

Malaysia's water distribution networks are governed by the Suruhanjaya Perkhidmatan Air Negara (SPAN) Uniform Technical Guidelines for Water Reticulation and Plumbing. Suruhanjaya Perkhidmatan Air Negara (or the Commission) develop uniform technical guidelines. This guideline simplifies the planning and design of water distribution systems, including supply mains, pump stations, service reservoirs, external reticulation systems, and water fittings (internal plumbing systems) throughout Peninsular Malaysia the Federal Territories of Kuala Lumpur, Labuan, and Putrajaya.

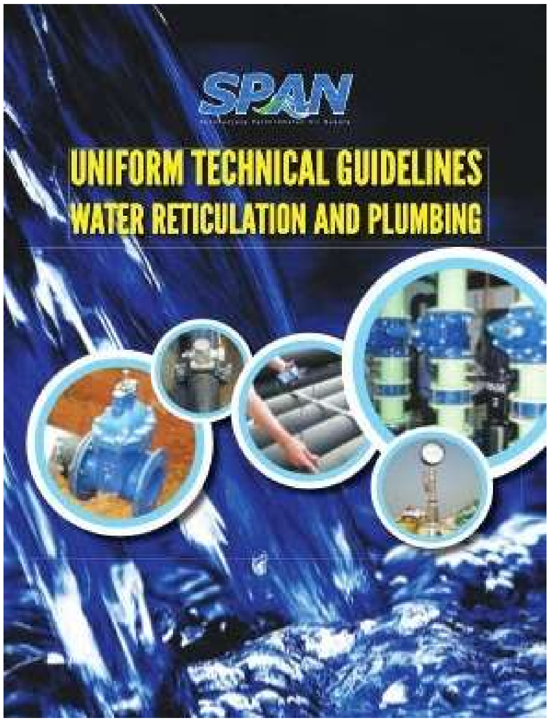

Figure 2.5: SPAN - Uniform Technical Guideline Water Reticulation and Plumbing Book

2.3.6.2 Hydraulic Design

The minimal consumption demand must be considered when designing a water distribution network. The design must view the number of people living there and their demands. SPAN's Uniform Technical Guidelines for Water Reticulation provide some consumer references for specific structures, including schools, hotels, restaurants, hospitals, and emergency networks. The unit rates of demand are different depending on the types of premises.

For hydraulic design, convey flows must be no less than 0.3 m/s. This design flow is to reduce sediment deposition. However, if these criteria cannot be satisfied, explanations for lower flow velocities and related maintenance implications must be presented to the Commission/Certifying Agency. The maximum flow rate is set at 2.0 m/s. Flow velocities along pumping mains within a pump station (i.e., header system) may surpass this amount.

The minimum pipe size is 100 mm in an external reticulation network system. During peak flow conditions, the minimum residual pressure at each node shall be of such magnitude as to enable water to flow straight into a storage cistern located up to 15 metres above a building platform level without the need for pumping. The residual discharge pressure at the highest supply level (HSL) shall not be lower than 7.5 metres.

2.3.6.3 Type of pipe Material

In contexts of pipe material, SPAN regulation states that pipe materials for supply mains and external reticulation pipelines must be chosen based on laying conditions. Such as whether they are in corrosive soils or not, under different terrain conditions, or whether they are subjected to traffic loadings. The tables below summarise the allowable pipe materials under various laying conditions.

Table 2.1: Materials for supply mains (without tapping)

Laying Conditions	Pipe Material
Non-corrosive soil	- Mild Steel - Ductile Iron - HDPE, ABS, GRP, PVC-O
Corrosive soil	- HDPE, ABS, GRP, PVC-O - Ductile Iron - Mild Steel

Table 2.2: Materials for pumping mains

Laying Conditions	Pipe Material
Under roadways	- Mild Steel, Ductile Iron - GRP, PVC-O - HDPE, ABS with RC pipe sleeve
All pumping mains and gravity main in undulating and sloping/ hilly areas	- Mild Steel - Ductile Iron - PVC-O

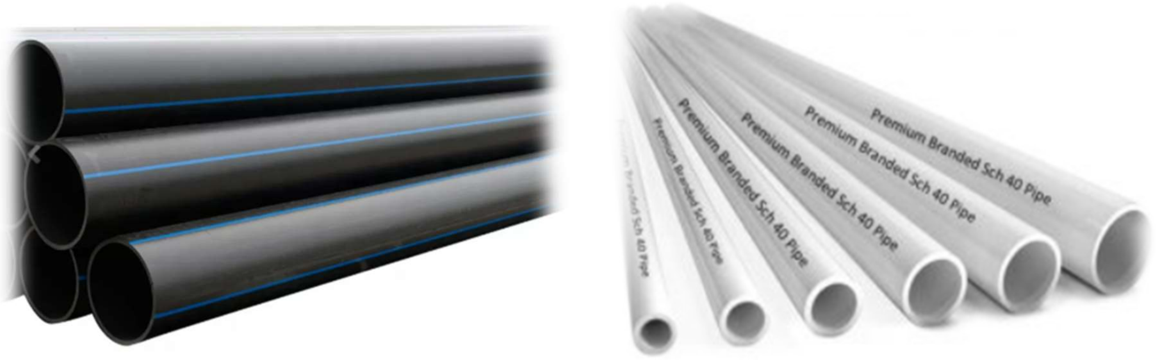

Figure 2.6: HDPE and PVC pipe (Nan Ya Hardware, n.d.)

Figure 2.7: Mild Steel and Ductile Iron Pipe (Metalloy Piping Solution, n.d.)

2.4 Optimisation Studies in Water Distribution System

The general WDS design problem aims to minimise the entire network cost since these systems are costly infrastructures. An optimised WDS should be implemented to reduce the project's total cost and satisfy required water flow velocities and pressure on the nodal. Recently, a significant amount of research has been performed on the optimal design of water distribution networks. Numerous optimisation methods are studied worldwide.

Dhumal *et al.* (2018) investigated continuous water supply systems. Due to its many advantages, continuous water supply systems have generated significant interest in India. Continuously increasing demand can be fulfilled by designing efficient water distribution networks based on advanced computing systems, including modern hydraulic modeling and designing software. WaterGEMS software was used to develop and design the system. Model calibration was performed to minimise the difference between the observed and simulated pressures.

Besides, it optimizes the distribution network by optimizing the diameter pipes on the source of performance and cost, which suits the pressure requirements and money availability. It also optimizes the network based on pressure and velocity constraints given. As a result, the researchers concluded that WaterGEMS is a more advanced computing system for hydraulic modelling and software design. WaterGEMS is a versatile tool that can minimise energy costs or energy use.

Bello *et al.* (2015) provide a technique of cost optimisation for the proposed water distribution system using MATLAB and EPANET software. Selection of pipe diameters from a set of commercially available diameters to form a water distribution network of the least capital cost has been shown. The authors used Linear Optimisation Programming (LOP) in MATLAB, which required the EPANET solver's basic input, which covered the flow rate for each pipe, the generated unit head loss, and the length of the pipe. The LOP uses the Hazen William equation to determine the unit head loss for the alternative diameters, which is consonant with the EPANET solver. It then uses the same equation in the analysis. The objective function and constraint equations try to find the best diameters for the pipeline to reach the optimum result.

Electric energy consumption due to water pumping represents the most significant part of the energy expenses in the water industry sector. Among several practical solutions, which can enable the reduction of energy consumption, the change in the pumping operational procedures shows to be very effective since it does not need any additional investment. Still, it can reduce energy costs significantly in the short term. Ramos *et al.* (2012) conducted pump optimisation in their study. The Genetic Algorithm (GA) was the tool chosen that offers excellent flexibility in search space, allied to the possibility of using discrete variables. Besides these advantages, the technique has easy manipulation, which makes its connectivity with simulation models easier. The main goal of the model is to find the configuration of the pumps' status, which proceeds to the lowest energy cost scenario for the operational time duration.

Similarly, Boano *et al.* (2015) focused on optimizing the pump scheduling to minimise pumping energy costs. Mathematical techniques were chosen to be efficiently solved the problem. To this aim, the authors have applied the innovative WDNetXL code to pumping optimisation. WDNetXL is a system tool created to entail the latest research advancements in WDN planning, analysis, and management. In particular, a Multi-Objective Genetic Algorithm (MOGA) approach is used for the optimisation problem. Table 2.3 summarize the optimisation method in WDS.

Table 2.3: Optimisation Method

Optimisation Method	References
Pipe diameter optimisation based on pressure and velocity constraints.	• (Dhumal *et al.*, 2018)
Pipe diameter optimisation using Linear Optimisation Programming (LOP)	• (Bello *et al.*, 2015)
Pump Optimisation using Mathematical techniques.	• (Ramos, Costa and Goncalves, 2012) • (Boano *et al.*, 2015)

2.5 Pumping System in WDS

According to Kazantzis *et al.* (2002), Pumping systems generally operate by one of two mechanisms, trigger levels or pump scheduling. Using trigger levels is a way of dynamically controlling the operation of pumps. Upper and lower trigger levels are set up in one of the storage tanks such that when certain levels are reached, the triggers pump starts or stops.

Trigger levels are used to keep tank levels within an operating range and may be set for the elevated or clear water storage tanks. Pump scheduling controls the system by predetermining the operation of all pumps for all periods of the day. For example, the day may be divided into 96 fifteen-minute periods. In each period, the status of the pumps will be set (i.e., on or off). Pump scheduling requires the prediction of the total water demand for each day. The schedule then ensures that amount of water is pumped over that day.

According to Sarbu (2016), Pumping in water supply systems consumes about 2% to 3% of global electricity consumption. Most water distribution systems rely on pumps to deliver the required water at the appropriate pressure to the final consumers. Water distribution systems equipped with pumping stations consume more than 60% of the energy consumed by the entire supply system of large urban centres. As a result, the energetic system load increases significantly, particularly during peak water consumption hours. On the other hand, pumping systems have been discovered to have a significant potential for energy efficiency improvements. Retrofitting pumping equipment with more efficient solutions, such as variable speed system motors and enhanced control systems, can often result in significant energy savings (Marchi *et al*., 2012).

2.6 Basic Pump Terminology

The Japan Industrial Standards (JIS B 0131) define the technical terms for turbo pumps. Below are some important terms relating to pump performance (Ebara Cooperation, 2013)

2.6.1 Capacity, Discharge

The volume of liquid (m^3/min or m^3/s) that a pump discharges in a unit of time.

2.6.2 Total Head, Total Pump Head

The total head produced by pump operation; Figure 2.8 shows the total head of a pump. When a pump is operated, there are various losses in the suction pump, such as discharge pipe outlet, etc. The Total Head (H) is the sum of the Actual Head (Ha), which represents the head difference between the discharge liquid surface and the suction liquid surface, the pipe line heads loss ($h_{ls} + h_{ld}$), and the discharge flow velocity head ($v_d^2/2g$). The head difference between the discharge liquid surface and the suction liquid surface is the sum of Actual Head (H_a), which corresponds to the pipeline system head loss ($h_{ls} + h_{ld}$); and discharge flow velocity head ($v_d^2/2g$) is the Total Head H, expressed by the following equation.

$$H = H_a + h_{ls} + h_{ld} + \frac{{v_d}^2}{2g} \tag{2.7}$$

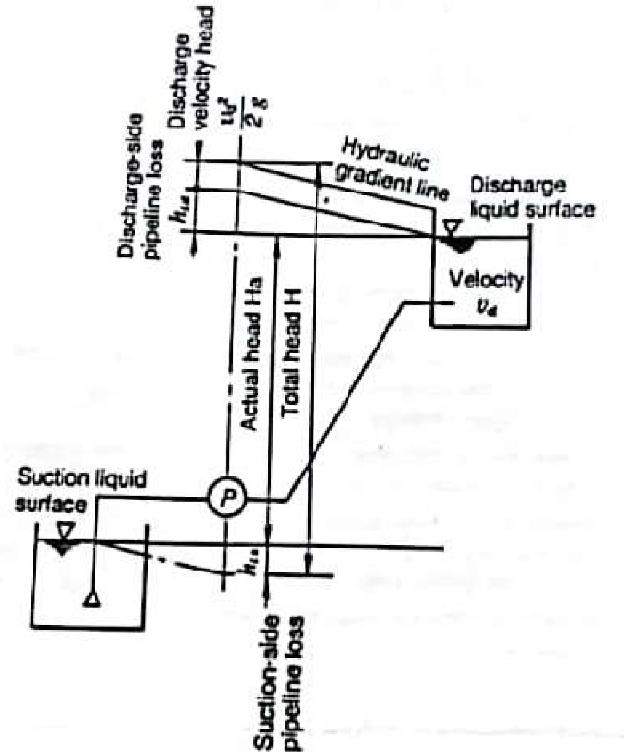

Figure 2.8: Total Pump Head (Ebara Cooperation, 2013)

2.6.3 Liquid Power

The formula expresses the effective energy given to a liquid by a pump in a unit of time.

$$L_w = 0.163\,\gamma Q H\ (kW) \tag{2.8}$$

Where:
L_w = liquid power (kW)
γ = Specific weight of the liquid [density] (kg/l)
Q = Capacity (m^3/min)
H = Total Head (m)

2.6.4 Pump Efficiency

The ratio of liquid power L_w to the shaft power L transmitted to the pump shaft by the motor is called pump efficiency η, and is expressed by the following equation.

$$\eta = \frac{L_w}{L} \times 100 = 0.163\frac{\gamma Q H}{L} \times 100\% \tag{2.9}$$

2.6.5 Specific Speed

The following equation expresses the numeric value derived from the Hydraulic Affinity Law:

$$N_s = \frac{NQ^{\frac{1}{2}}}{H^{\frac{3}{4}}} \tag{2.10}$$

Where;
N_s = Specific speed
N = Speed (min^{-1})
Q = Capacity (m^3/min) (using half the discharge with a double-section impeller)
H = Total head (m) (using the total head for one stage with a multi-stage pump)

Specific speed is obtained by the highest efficiency points of pump capacities N, H, and Q. The value is the same for similar types of pumps regardless of the size and speed.

2.6.6 Suction Specific Speed

The following equation expresses pump suction performance with respect to cavitation.

$$S = \frac{NQ^{\frac{1}{2}}}{{H_{sv}}^{\frac{3}{4}}} \tag{2.11}$$

Where;
S = Suction-specific speed
N = Speed (min^{-1})
Q = Capacity (m^3/min) (using half the discharge with a double-suction impeller)
H_{sv} = Required net positive suction head (m)

The value *S* for most pumps is the flow at the highest efficiency point and is approximately 1,200 – 1,500. The S value is 1900 on some pumps specially designed to increase suction performance. This value drops in partial discharge areas, and care must be used since vibration, noise, and cavitation-erosion dangers increase.

2.7 Pump Types

Since ancient, several types of pumps have been used to transport fluids. Figure 2.9 illustrates their classifications by operating principle.

Figure 2.9: Pump Types (Ebara Cooperation, 2013)

2.7.1 Turbo-type Pumps

Turbo-type pumps are machines that apply energy to liquid using a rotating impeller inside a casing. They are categorized into the following three categories:

a) Centrifugal Pumps

These pumps apply pressure and velocity energy to liquid using an impeller's centrifugal force. Their specific speed, N_s, falls between 100 and 700. "Volute pumps" employ a volute casing to transfer the energy of the liquid, leaving the impeller from velocity energy to pressure energy, whereas "diffuser pumps" use guide vanes.

b) Mixed-flow Pumps

By utilizing the centrifugal force of impellers and the lifting force of vanes, these pumps provide liquids with pressure and velocity energy. Their N_s is approximately a method of converting the velocity energy of the liquid leaving the impeller into pressure energy; however, units using a volute casing are called "volute mixed flow pumps".

c) Axial flow Pumps

These pumps utilize vane lifting force to provide pressure and velocity energy to a liquid, and diffuser vanes to convert velocity energy to pressure energy. Its N_s range between approximately 1,000 and 2,500.

2.7.2 Displacement Pumps

Displacement pumps are machines that use the pushing action of pistons, plungers, or rotors to feed a liquid, and they are divided into the following two classes.