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Master of Science in Petroleum Engineering

ROBUST OPTIMIZATION OF PUMPING SYSTEMS IN PIPELINE OPERATIONS

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ABSTRACT

Pumping systems are required in most transport systems that utilizes pipelines as a mode of transport and these systems occasionally experience failure due to a host of factors. In Pipeline systems, careful selection of the pumps with respect to head requirements and the pump configuration have to be made to avoid impacting the flow performance negatively. This study is concerned with the study of centrifugal pumps and their relation to flow optimization in pipeline systems. The study will analyse various scenarios considering different pump configurations at pump stations to calculate reliability. At the end of the analysis, this study will be able to predict and also calculate reliability more efficiently as a result of design.

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INTRODUCTION

Pumps are important to the successful operation of pipeline systems and with increasingly complex network of piping systems a need for a highly effective and versatile pump station configuration grows higher.

Pump stations are facilities that house pumps and various equipment important for the pumping of liquids from one place to another. Pumps are basically classified into two, based on their mode of operation; Positive displacement and Centrifugal pumps. However, due to the fact that centrifugal pumps are the most preferred in the hydraulic world, (Guyer 2012) this study will focus on centrifugal pumps. “Centrifugal pumps principally are used to raise pressure of a liquid or induce flow by converting rotational kinetic energy into hydrodynamic energy of the fluid flow”. At the heart of the system lies the impeller, which is always immersed in the liquid. When the impeller rotates, it makes the surrounding liquid rotate. (Pumps and Systems 2017)

This study is concerned with the assessment and calculation of reliability of pumping systems. Modelling of the reliability of a system is important in the design and operation of mechanical systems that involve movement of fluids, as it analyses the performance of a system based on the probability of a component or a set of components being able to perform their function or not.

The analysis carried out, builds on studies that have been carried out by M.P. Gimo, and G. Sassi who worked to determine the relationship between reliability and flow rate in a pipeline system in Mozambique. However, this work takes the previous analysis further by developing a *"conditional reliability density"*

Reliability of a system is the probability that it will complete a required function within a given period of time. It is important in system design and can be a basis to judge the flexibility and robustness of a system. Its application is important in engineering due to its effectiveness in predicting and detecting failures in all phases of a system's operation. (Billinton e Allan 1992)

This study is concerned with analysing various pump schemes using the same nominal performance in a pipeline system using the Escravos-Kaduna Pipeline located in Nigeria as the case study. The analysis will focus on the effect of various pump schemes on flow efficiency, the design of pumping stations, how they impact flow performance and influence system optimization.

The aim is to show that different reliability values can be obtained from designing for the same nominal performance but using different pump schemes. The analysis will be carried out using publicly available data from the Nigerian National Petroleum Corporation with the use of analytical equations, established methodology and performing pressure and flow rate simulations using a spreadsheet software such as Microsoft Excel.

The novelty of this work is primarily predicting reliability based on flow rate as a function of frequency of flow. The goal is to generate a ***conditional reliability density*** that shows how the reliability of the pumping system changes with every change in flow rate, a shift from the logical RBD based method.

Objectives of the Study

1. To re-evaluate the Escravos-Kaduna Pipeline analysing pumping stations using publicly available data and calculated values of critical parameters essential to pump station design like head requirement, altimetry, pipeline length, friction factor, density and pressure drop to design various schemes of pumping stations within the same nominal performance.

2. To show that different reliability values can be obtained using different pump schemes with the same nominal performance.

3. To propose a new design methodology that will allow for flexible operation of pump stations and allow for the optimisation of flow systems.

Chapter 1

Materials and Methods

The general concepts of the reliability theory will be introduced in this chapter as it relates to the performance of pumping systems. To better understand the concept, we will begin by looking at failure rates.

Reliability & Availability

The probability of malfunction of a component can be regarded to as unreliability or in some cases unavailability of the expected performance/function. The unreliability/unavailability is usually required to be determined in the evaluation of failure modes of several components.

Availability usually refers to scenarios where the component is able to perform the required function anytime it is required to do so while reliability focuses more on the ability of the component to function and complete the required task and/or mission without failure. To repair in this work will mean to re-establish the function of a component, i.e. return the component to a state where it is considered as good as new. In some cases, changing a failed component can be regarded as repair. (Barringer 1997)

Component failure modes

Unrepairable: Components that have a failure mode in this category are components requiring a cancellation of the mission before a repair can be done. (E.g. the plane engine during a flight)

Repairable: Components classified as repairable are those whose repair can be carried out without cancelling the mission of the system.

- Tested: Components whose failure cannot be detected without a test which reveals the failure
- Repairable when failed: In this category, the failure is immediately discovered when it occurs and the repair can be carried out. (Barringer 1997)

Failure Rate λ (t)

Failure rate is the expected number of times a component will fail within a given period of time given that it was good and functioning at time t = 0. The value provides a measure of reliability and is usually expressed as failure/time. For further classifications of failure rate, the concept of the “mean time to failure”, “mean time to repair” and “mean time between failures” will be introduced here.

Mean time to failure (MTTF)

MTTF is a reliability measure used for un-repairable components, in the case of repairable systems MTTF is the time from repair to the next failure. Basically, it is the mean time until the first failure of a component. It is a statistically derived value and is the inverse of the failure rate (λ). (Barringer 1997)

$$MTTF = \frac{1}{\lambda(t)} \quad (1.1)$$

Mean time to repair (MTTR)

MTTR is the expected time between component failure and the repair or restoration of the failed component.

Mean time between failures (MTBF)

MTBF is the time passed between one failure of a component and its next failure.

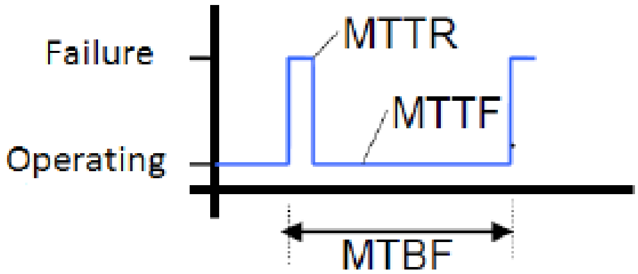

Figure 1.1: Failure vs time relation

The Bathtub curve of failure rate

The bathtub curve is a curve that describes the evolving nature of λ (t) through the lifetime of a component. It is named so due to the shape derived when λ (t) is plotted against time.

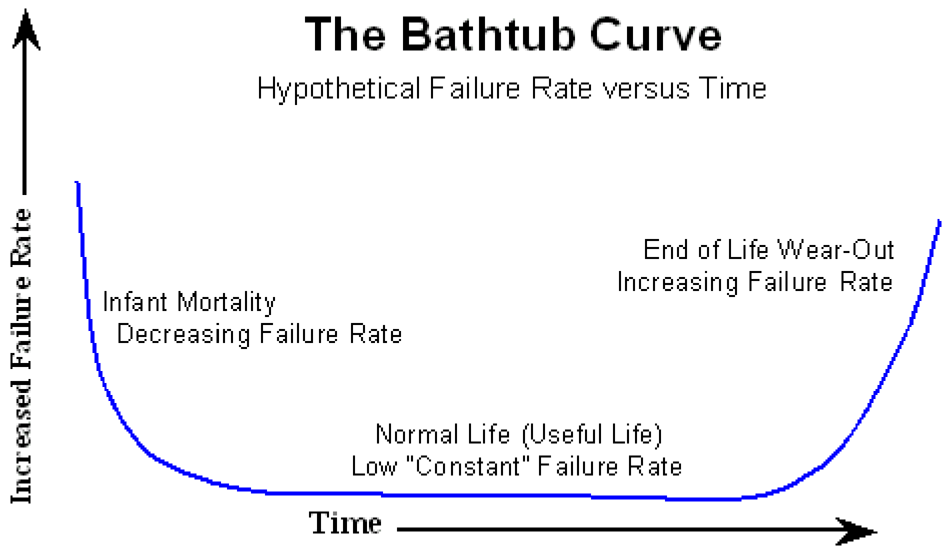

Figure 1.2: The Bathtub Curve

The first region of the graph labelled “Infant Mortality” is the early stage of the component before the active life begins. At this stage the failure rate decreases during debugging. The second region, “Normal life” refers to the active life of the component when the failure rate is more or less constant. The third region “End of life” is the time when the component has aged and has experienced a significant amount of wear. At this period the failure rate could increase significantly. This graph shows the criticality of replacing components before they get to their “End of life” period so as to reduce the risk of failure. (Weibull 2017)

Estimation of Unreliability and Unavailability

Unrepairable components have the same value for unavailability $Q(t)$ and unreliability $F(t)$ due to the fact that it is not possible to repair a failed component during the mission.

$$F(t) = 1 - R(t) = 1 - A(t) \quad (1.2)$$

For components with a constant failure rate, the unreliability at a time t can be written as:

$$F(t) = 1 - e^{-\lambda t} \quad (1.3)$$

The equation above holds for all failure modes, unrepairable, repairable when failed and repairable when tested. In cases where the product of $\lambda.\mathrm{t}$ is less than 10%, the equation above can be written as:

$$F(t) = 1 - e^{-\lambda t} = \lambda.\mathrm{t} \quad (1.4)$$

If the components are unrepairable, then the unavailability will also have the same expression as equation 1.4:

$$Q(t) = F(t) = 1 - e^{-\lambda t} = \lambda.\mathrm{t} \quad (1.5)$$

Unavailability for repairable components has a different expression. It is written as:

$$Q(t) = \frac{\lambda}{\lambda + \mu} \quad (1.6)$$

If the failure rate is much smaller than the repair rate (μ) which usually occurs, the unavailability can be written as:

$$Q(t) = \frac{\lambda}{\mu} \quad (1.7)$$

For repairable when tested components, the unavailability is evaluated taking into consideration the test interval (θ) $Q(t)$ becomes:

$$Q(t) = \frac{1}{2}\lambda\theta + \frac{\tau}{\theta+\tau} \quad (1.8)$$

In equation 1.8, τ represents the time necessary to perform the test. Usually τ << θ, and because of this the last part of the equation is most times discarded and the new equation becomes:

$$Q(t) = \frac{1}{2}\lambda\theta \quad (1.9)$$

The modelling of reliability is an important part of system design. Manufactures and designers are able to achieve this through statistical modelling and probability. The analysis is usually dependent on the probability of specific nodes in the system and not on the entire system. The entire system is usually split into smaller systems and the reliability of the smaller systems evaluated as dependent on the success and/or failure of other smaller systems. (Billinton e Allan 1992)

To be able to do this usually, there is always a logical diagrammatic representation of the system in a way that shows the dependency of the success or failure of the system on the smaller nodes. The diagrams can show the smaller systems arranged in series, parallel or a combination of both. However, there could be complex systems where the simple logical representation of smaller systems or nodes in series and/or parallel will not be sufficient to properly analyse the system. The diagram that shows the dependencies of the nodes in series and parallel conditions is known as the reliability block diagram.

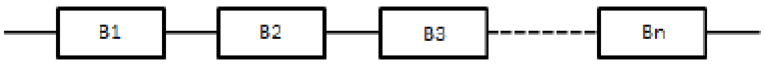

Figure 1.3: Reliability Block Diagram in Series

Series arrangement is used for a system where all components are required for the system to function. In series arrangement, the probability of success or the reliability reduces as the number of components increase. The probability of success of a system arranged in series can be given with the following expression.

$$R_{series}(t) = Prob\big(B_1(t) \cap B_2(t) \dots B_n(t)\big) = \prod_{i=1}^{n} R_i(t) \quad (1.10)$$

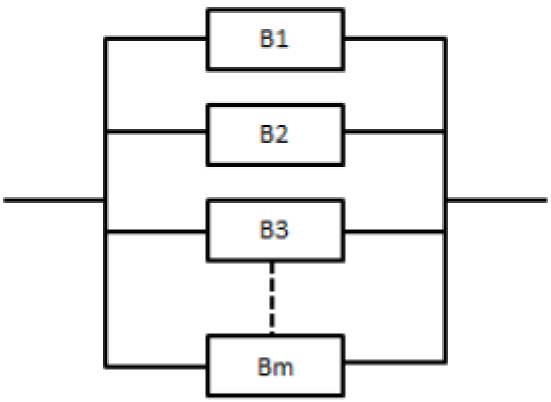

Figure 1.4: Reliability Block Diagram in Parallel

Parallel block diagram is for cases where the system will continue to function in the event of one of the components failing. For a system like this to fail, it'll require all the components to fail. The probability of success of a system arranged in parallel can be given with the following expression

$$R_{series}(t) = Prob\big(B_1(t) \cup B_2(t) \ldots B_m(t)\big) = \prod_{i=1}^{n} R_i(t) \quad (1.11)$$

In most real scenarios, the series and parallel logic explained here does not account for the functionality of the system. A typical example is a pumping station with pumps arranged in series, parallel or a combination of both. For a series connection it can be deduced from the logical arrangement above that the failure of one pump will lead to a failure of all the system however this is mostly never the reality. (Hamdi 2014)

Design Considerations

The transport of oil from one terminal to another will take place with some pressure losses. To accurately predict this, it is necessary to acquire the topographic data, we used the Google Earth software to achieve this goal. Before proceeding to pump station design, the system characteristics have to be designed. some assumptions about the characteristics of the fluid being transported, pump station location, flow rates, supply and delivery pressure need to be established, to enable optimum operation values, which will be considered for the life time of the system.

Fluid Transport in Pipelines

In the case study, this work will be analysing, the principal factor upon which every other design criteria are based is the demand. The demand is based on the daily processing ability of the refinery supplied by the pipeline. Flow rate and pressure requirements are determined by a combined analysis of the supply, pumping and distribution systems.

Pressure Requirements

The pressure requirements for the system depends on a host of factors. The steel grade of the pipe, the operating temperature, the maximum and minimum delivery pressure, all of which are derived from the ANSI/ASME Standard.

For this system, the average operating temperature is estimated to be 40 ^{o}C. This operating temperature will determine the minimum operating pressure with reference to the true vapour pressure (TVP) of Bonny Light Crude and applying a safety factor of 3. The maximum operating pressure is inferred from the ANSI/ASME Standard where the maximum allowable pressure a pipe can withstand is usually stated. The pressure distribution in this study have the following criteria

- Maximum operating pressures. (50 atm)
- Minimum operating pressure.   (0.22 atm)

To better analyse the system, a pressure contour map will be created based on topography and hydraulic analysis.

Bonny Light Oil

The oil that is transported in the pipeline is the low-sulphur and low-density Bonny Light oil which is produced from Nigeria's Niger delta region. The oil has an average density of 800kg/cm^3. After the oil is produced it is pumped to a processing facility at the edge of the Escravos river, where the light components predominantly $C_1 – C_3/C_4$ are stripped to have a more stable oil to be sent through the pipeline.

Pumps

Pump selection is heavily influenced by its capacity and the head anticipated. The daily capacity of the refinery served by the Escravos- Kaduna pipeline (Kaduna Refinery) formed the basis for determining the flow rate and the sizing of each component.

Pump Stations

Pump stations require an infrastructure of their own. They require holding facilities for transfer in batches, and most times the handling and injection of additives often occurs at pump stations. Pumps are typically driven by electric motors; however, engines operating on a variety of fuels (but typically obtained from sources other than the pipeline itself) can also be used to drive the pumps (Todinov 2013). Depending on location, power may be an issue, pump stations are typically equipped with sufficient emergency power generation to support monitoring and control systems to accomplish optimal operating conditions (Dragon 2002).

Centrifugal Pumps

Centrifugal pumps transport fluids by converting rotational kinetic energy into hydrodynamic energy of the fluid flow by accelerating the fluid to the outer rim of an impeller. The amount of energy transferred to the liquid is related to the velocity of the impeller. An impeller that revolves faster or is bigger will result in higher fluid velocities due to the greater energy imparted to the liquid (Pumps and Systems 2017).

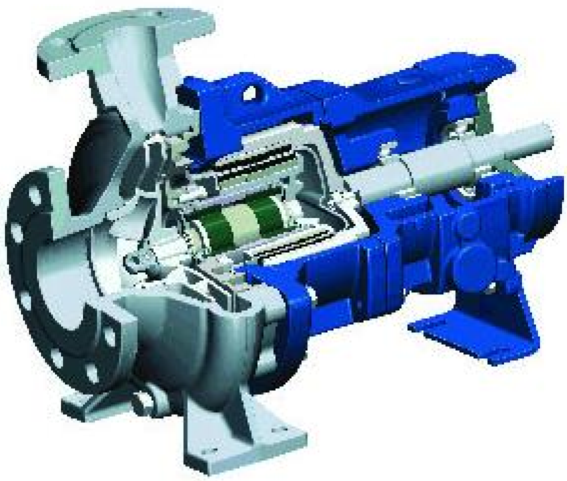

Figure 1.5: A cross section of a centrifugal pump

Head—Resistance to Flow

The term head is a measure of the kinetic energy that a pump creates, it measures the height of a liquid column created by the pump as a result of kinetic energy transferred to the liquid. To create a clearer picture, if a jet of water is shot from a pipe straight into the air, the maximum height that the water reaches is the head.

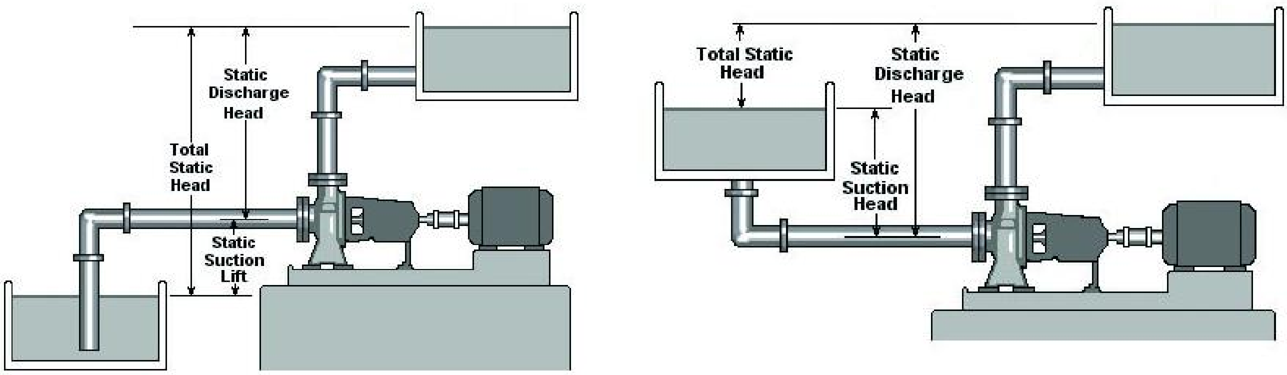

Figure 1.6: Representation of total head

Static discharge head is the vertical distance in feet between the pump centreline and the point of free discharge or the surface of the liquid in the discharge tank.

Total static head is the vertical distance in feet between the free level of the source of supply and the point of free discharge or the free surface of the discharge liquid.

Head is broadly used to measure a centrifugal pump's energy in place of pressure due to the fact that pump pressure will change if the specific gravity of the liquid it pumps changes, however head doesn't change regardless of fluid type.

All the forms of energy involved in a liquid flow system can be expressed in terms of feet of liquid. The total of these heads determines the total system head or the work that a pump must perform in the system. The various forms of head are defined in this section. (Dragon 2002)

Friction Head (h_f)

Friction head is the head required to overcome the friction in the pipe and fittings. It depends on the flow rate, nature of the liquid, size and type of pipe.

Velocity Head (h_v)

This is the energy of a liquid due to its motion at a particular velocity. It is the head necessary to accelerate the water. Velocity head can be calculated using the following formula:

$$h_v = \frac{V^2}{2_g} \quad (1.12)$$

Pressure Head

Pressure head is a parameter that must be considered in scenarios where a pumping system begins or empties into a tank that isn't under atmospheric pressure conditions. If there is a vacuum in the suction tank or a positive pressure in the discharge tank, it should be added to the system head, whereas if there is a positive pressure in the suction tank or vacuum in the discharge tank it must be would be subtracted from the system head.

Pump Performance Curve

Pump characteristic, such as pressure, flow, and efficiency are usually indicated graphically on a pump characteristics curve provided by the manufacturer. The first item of interest in this curve is the pump size. The size of the pump, (2x3-8) in the chart below is shown in the upper section of the graph. The numbers indicate:

- An outlet of 2 inches.
- An inlet of 3 inches.
- An impeller with a diameter of 8-inches.

On some other charts the number could be displayed as 3x2-8. The larger of the first two numbers is the inlet. The Pump speed in rpm, is also shown in the upper section of the graph and indicates performance at a speed of 3,560 rpm. Flow capacity is shown at the bottom of the curve. The flow levels for the operating speed of 3,560 rpm are shown. (Guyer 2012)

The left side of the performance curve shows the head (feet) generated at the different flow rates. There are multiple flow versus head curves are shown on the graph with each one representing a different impeller size. For the pump represented on this chart, the range of impeller size is 5.5 inches to 8.375 inches. (Emerson 2009)

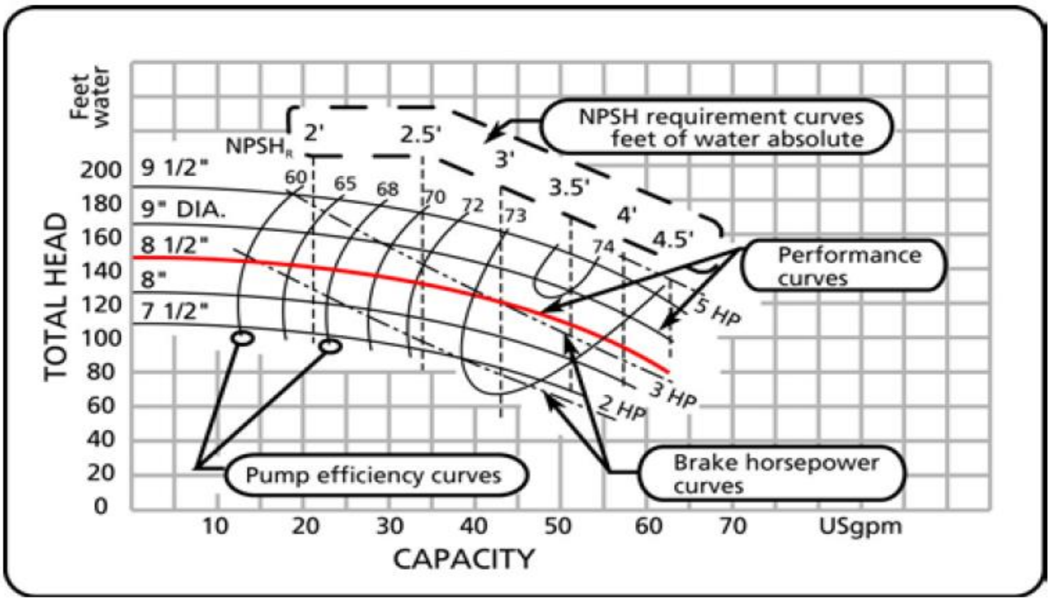

Figure 1.7. A Pump performance curve

Efficiency curves are displayed by the vertical lines overlaid on the graph and indicate from 64 to 45% efficiency for this pump. Flow capacity and efficiency decrease generally decrease as head is increased.

System Characteristic Curve

The pump characteristic curve (PCC) is a function of the physical characteristics of the pump. The system curve is completely dependent on the operating system which relates to the pipe size, pipe length, the presence of elbows, and other factors. The point where the system curve intersects with the PCC is considered the natural operating point. This is where the pump pressure matches the system losses and everything is balanced.

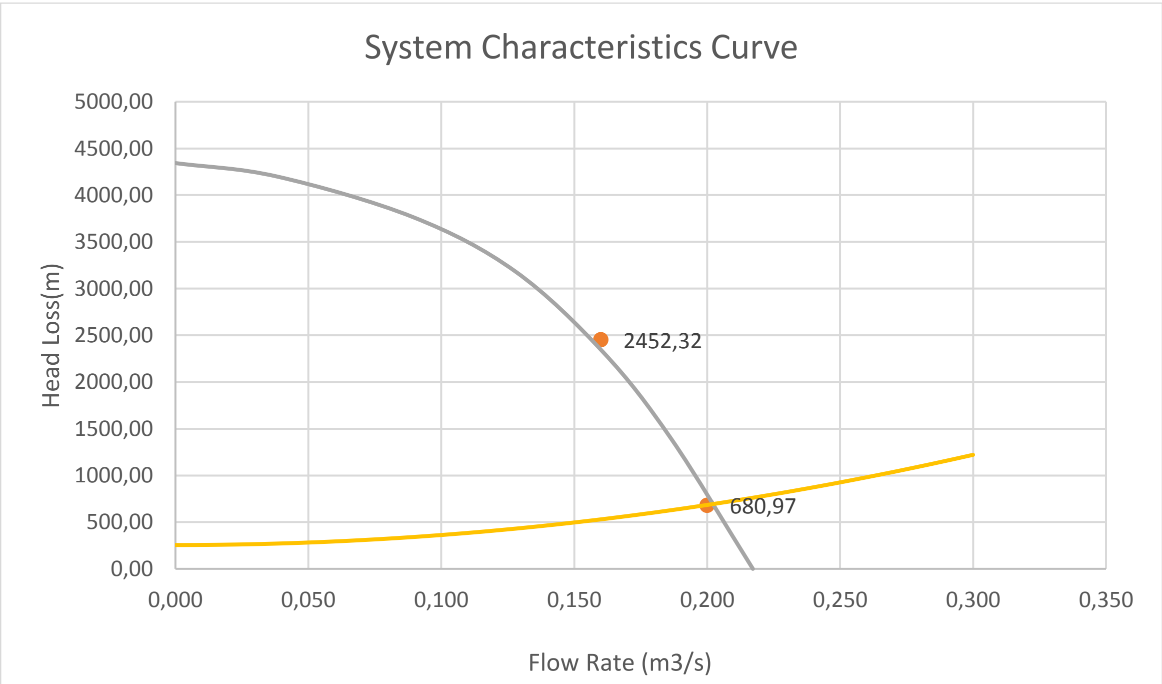

Figure 1.8. Sample pump system curves

If the system is one that changes constantly, then it is necessary to have in place a method of altering the pump characteristics or the system parameters. This can be accomplished principally by two methods; throttling, which changes the system curve by use of a control or throttling valve and varying the speed of the pump, which modifies the pump curve (Dragon 2002). For the purpose of this study emphasis will be placed on latter method.

Valves

Valves are installed at carefully selected locations along the pipeline to serve as a control mechanism for flow rate and pressures within the pipe. Valves are also needed to isolate sections of the pipeline in the event of a breach. Valves should be closely monitored and periodic maintenance should be carried out based on guidelines established by the manufacturer and/or observed deterioration.

Chapter 2

Results

Case study Design

The Escravos Kaduna pipeline is a 674-km pipeline that runs from the Escravos terminal in Warri, southern Nigeria, and terminates at the Kaduna Refinery in Kaduna Northern Nigeria (Theodora 2017) .

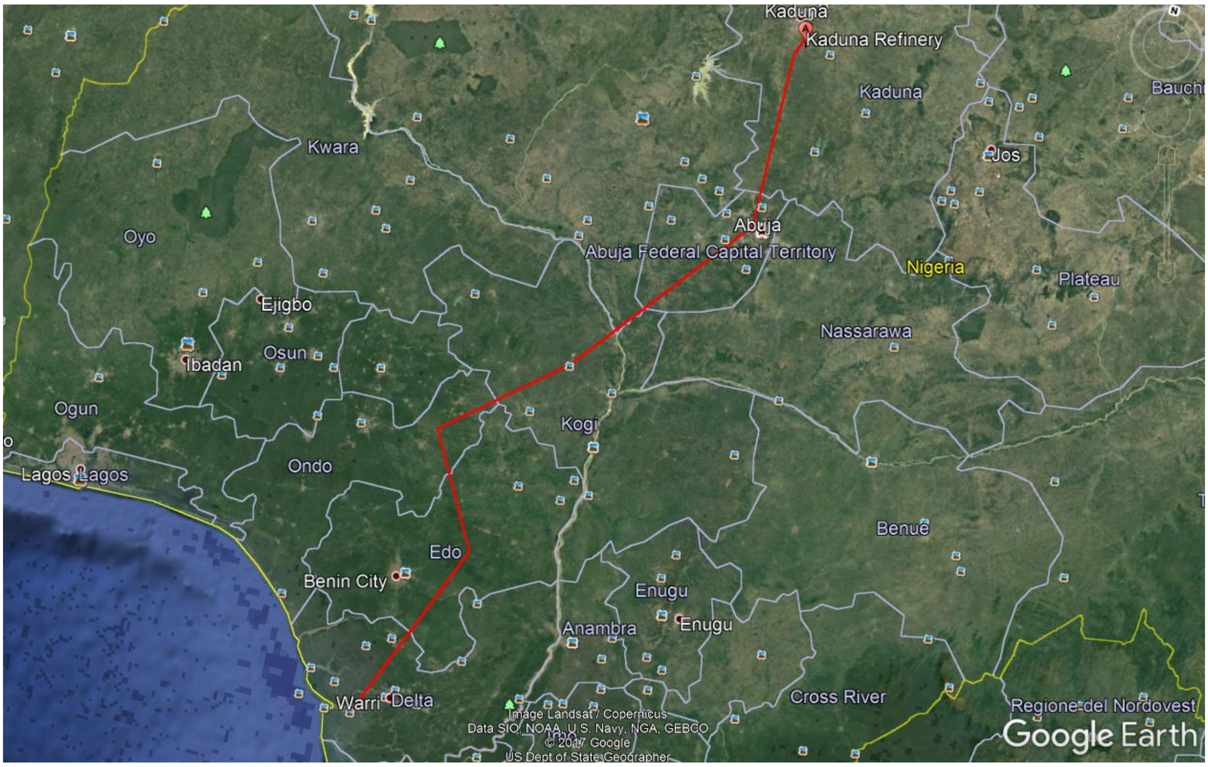

Figure 2.1: A graphic representation of the Escravos Kaduna Pipeline Path.

Elevation Data

The terrain is not uniform. The elevation data is key to calculating the head requirement and is useful for this study. For the purpose of simplification, data about elevation has been taken from google earth taken the start point in Escravos as the reference point

Length (km)	Height(m)
0	2
50	30
75	28
100	70
125	50
150	40
175	28
200	35
225	75
250	100
275	110
300	130
325	135
350	140
375	150
400	170
425	195
450	225
475	235
500	247
525	250
550	285
575	320
600	355
625	390
650	425
674	460

Table 2.1: Elevation profile of the pipeline

To proceed, we need to define the system in terms of flow capacity and also go through the process of defining the system based on thermodynamic and pressure requirements to create a model that closely mimics the physical system already in place.

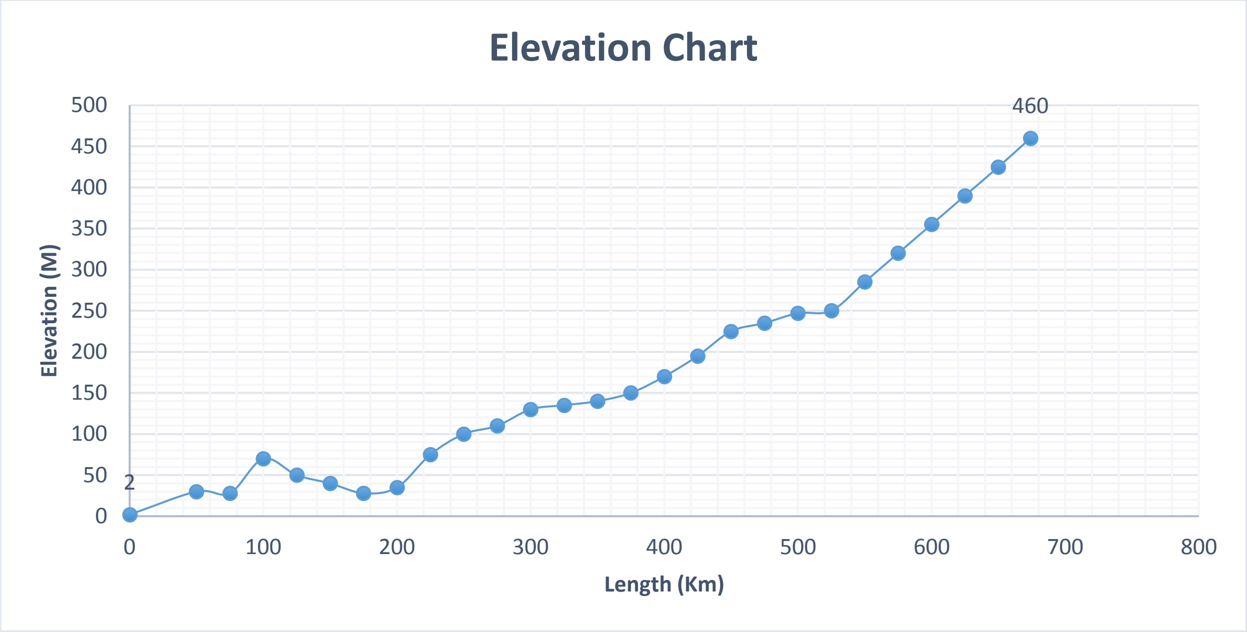

Figure 2.2: Elevation Profile

The Kaduna refinery has a maximum processing capacity of 110,000bbl/d of crude oil. The crude is the low Sulphur Bonny light crude produced from Nigeria's Niger delta region. For the system to be considered optimal, the minimum flow rate required is considered to be 98000bbl/d, a 12% decrease from the maximum. However, to give the analysis a broad range and to allow for some form of sensitivity analysis to see results in different conditions, we will consider three scenarios.

Scenario 1 is the closest to the real system with the same flow range and nominal pipe of 18 inches. In scenario 2, there will be a variation of flow rate with respect to the minimum allowable flow rate on the same pipeline with no changes to pipe size. This is to show the effects a drop in flow rate can have when there is failure of pumps. The third scenario will keep the range of scenario 1 but will vary the diameter to allow for less pumping stations which will ultimately reduce the cumulative probability of failure for the whole system.

2.1. Scenario 1

Daily Capacity				**Flow Rate**
bbl/d	**m^3/d**	**m^3/h**	**m^3/min**	**m^3/S**
110000	17488	729	12.14	0.20
98000	15580	649	10.82	0.18

Table 2.2: Flow Rate Values

The processing capacity gives the information required to calculate the flow rate. With the flow rate determined, the diameter of the pipes can be calculated using the already stated velocity range. (Velocity value was assumed as the velocity data from NNPC was not readily available)

	Velocity (m/s)		
	0.50	1.50	**Flow Rate (m^3/s)**
Diameter(m)	0.71	0.41	0.20
Diameter(m)	0.64	0.37	0.16

Table 2.3: Velocity Values

From the diameter value gotten in the table above, we turn to standard tables to find the ranges of possible diameters that the piping could have keeping in mind that the design of the real system has a nominal size of 18-inches. From the ASTM standards:

Nominal Size (in)	18	18	18
Thickness (in)	0.25	0.31	0.38
Inner Diameter (in)	17.50	17.38	17.24
Max Allowable P (Mpa)	3.50	4.10	5.80
Max Operating P (MPA)	3.30	3.80	5.50

Table 2.4: ASTM Pipe Specifications

The maximum allowable pressure is provided by the pipe manufacturer and indicates the maximum pressure the pipe is allowed to experience before failing.

This system is defined by two flow rates, thus successful operation will be having a flow rate that is between the minimum and maximum desired flowrate.

To further develop this model as close to reality as possible, some other factors like pressure drop, Reynolds number, and friction factor need to be calculated.

Reynolds number and Moody friction factor

Reynolds number is a dimensionless parameter that is used to characterize the degree of turbulence in a flow regime. It is also needed to determine the Moody friction factor (MFF) (Moody 1994).

$$Re = \frac{\rho v D}{\mu} \quad (2.1)$$

The MFF, f, is a function of the Reynolds number and the internal surface roughness of the pipe and is given by the moody chart (L. F. Moody 1944).

Pressure drop for liquid flow can be expressed in terms of internal diameter by the following expression;

$$\Delta P = \frac{f.*\rho*L*v^2}{2*ID} \quad (2.2)$$

With the parameters above defined, we can derive a table for the maximum and minimum flowrates showing all the critical parameters defined above. (Moody 1994)

Energy Loss

Fluid flow in a pipeline is usually accompanied by energy loss as a result of the pipe's flow resistance. This energy loss is usually attributed to friction and elevation differences. The pressure drop per unit length is calculated using:

$$\frac{\Delta P}{L} = \frac{f\varepsilon V^2}{2*ID} \quad (2.3)$$

Flow Data 18 inch Pipe		
	Qmin	**Qmax**
Internal Diameter (in)	17.32	17.32
Velocity (M/S)	1.06	1.19
Reynolds	37204	46505
Friction Factor	0.02	0.02
Pressure Drop (Pa/M)	17.5	25
Com Steel (mm)	0.05	0.05
μ_o (kgM/s)	1.00E-02	1.00E-02
Density (kg/m^3)	850	850

Table 2.5: Minimum Flow Rate Data

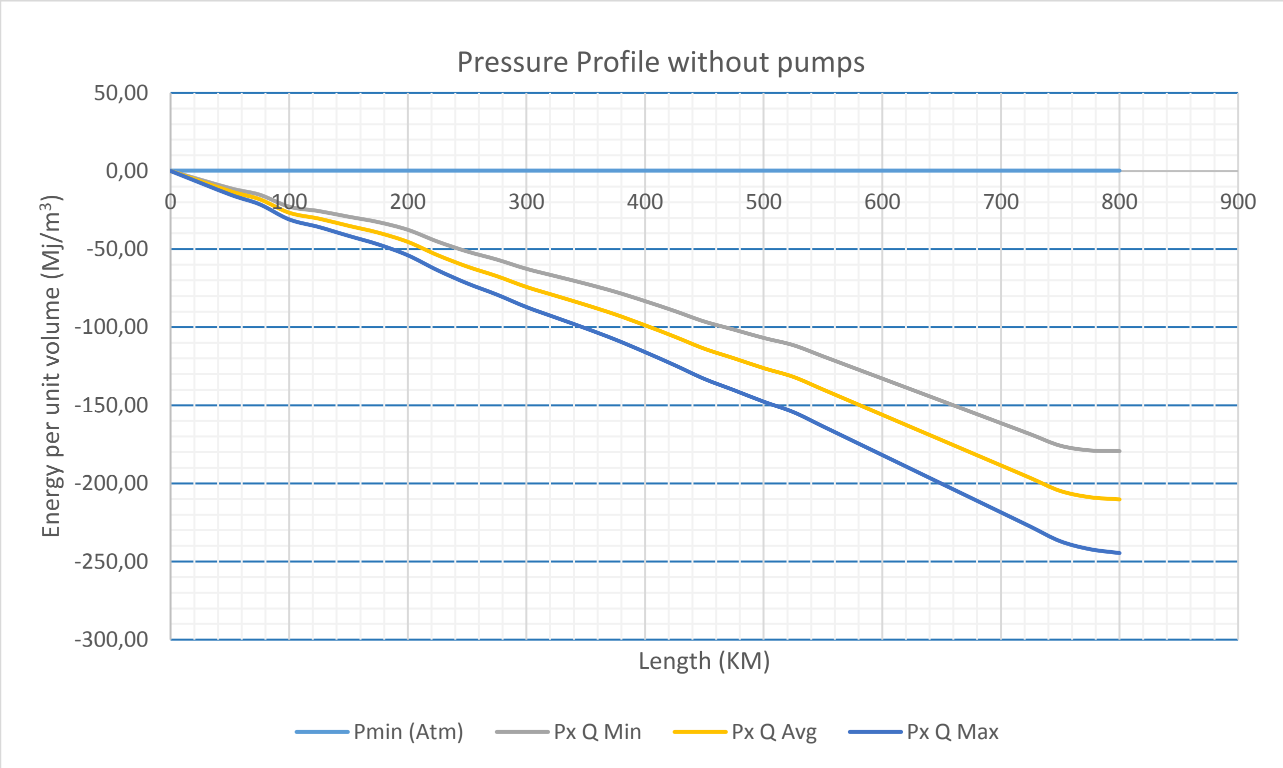

Figure 2.3: Pressure profile of the system

The system which this study is modelled after has a nominal pipe diameter of 18inches which is what we have also decided to use for our system modelling. To be able to fulfill the goal of delivering crude oil from one end to the other, the system will need to be fitted with pumping stations. For optimal performance, this diameter requires 5 pumping stations. The pumping stations are located at 0 km, 175 km, 325 km, 475km, 600 km and. Each pump is fitted with valves to control pressure and flow rate.

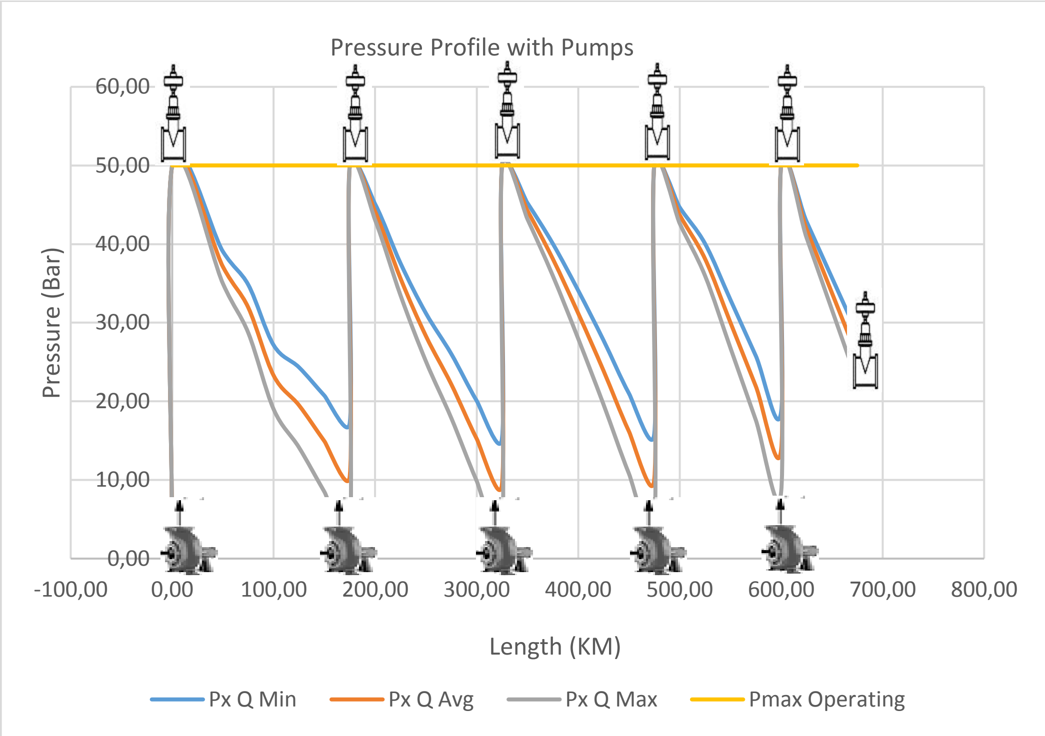

Figure 2.4: Pressure Profile Showing Pumping Stations

System Characteristic Curves

The ideal operating conditions for pumps is where the pump curve and the system characteristics curve intersect. The reliability of pumps is improved when they are sized closely enough to the required flow rate.

The system characteristic curve is gotten by plotting the total dynamic head versus flow rate, while the pump curve can be gotten from plots of pump head versus flow rate. Pump selection is largely based on proper interpretation of centrifugal pump curves. The system modelled in this study has 5 pumping stations with calculated head listed in the preceding tables.

Pump Station 1	Minimum Rate	Maximum Rate
ΔP (Valve) Bar	104.85	15.51
Head Loss by Valve (km)	1.34	0.19
Head Required (km)	0.64	0.64
Pump Head (km)	1.96	0.82
Pump Station 2	Minimum Rate	Maximum Rate
ΔP (Valve) Bar	366.96	75.82
Head Loss by Valve (km)	4.67	0.97
Head Required (km)	0.42	0.60
Pump Head (km)	5.09	1.56
Pump Station 3	Minimum Rate	Maximum Rate
ΔP (Valve) Bar	314.54	49.53
Head Loss by Valve (km)	4.87	0.63
Head Required (km)	0.42	0.59
Pump Head (km)	4.45	1.29
Pump Station 4	Minimum Rate	Maximum Rate
ΔP (Valve) Bar	314,538	47,995
Head Loss by Valve (km)	4.01	0.61
Head Required (km)	4.35	0.59
Pump Head (km)	4.44	1.20
Pump Station 5	Minimum Rate	Maximum Rate
ΔP (Valve) Bar	262,115	50,422
Head Loss by Valve (km)	3.33	0.64
Head Required (km)	0.33	0.53
Pump Head (km)	3.74	1.17

Table 2.6: Pump Station Heads

To identify the optimal working point and the number of pumps required in the pump station, we plot the system characteristics curve and the pump characteristics curve. The first pumping station located immediately at origin will need 6 pumps in series and 4 pumps in parallel. The pump arrangement reaches a maximum flow rate of $0.2m^3/s$ with a maximum valve opening of 90%. The resulting curves are shown below.

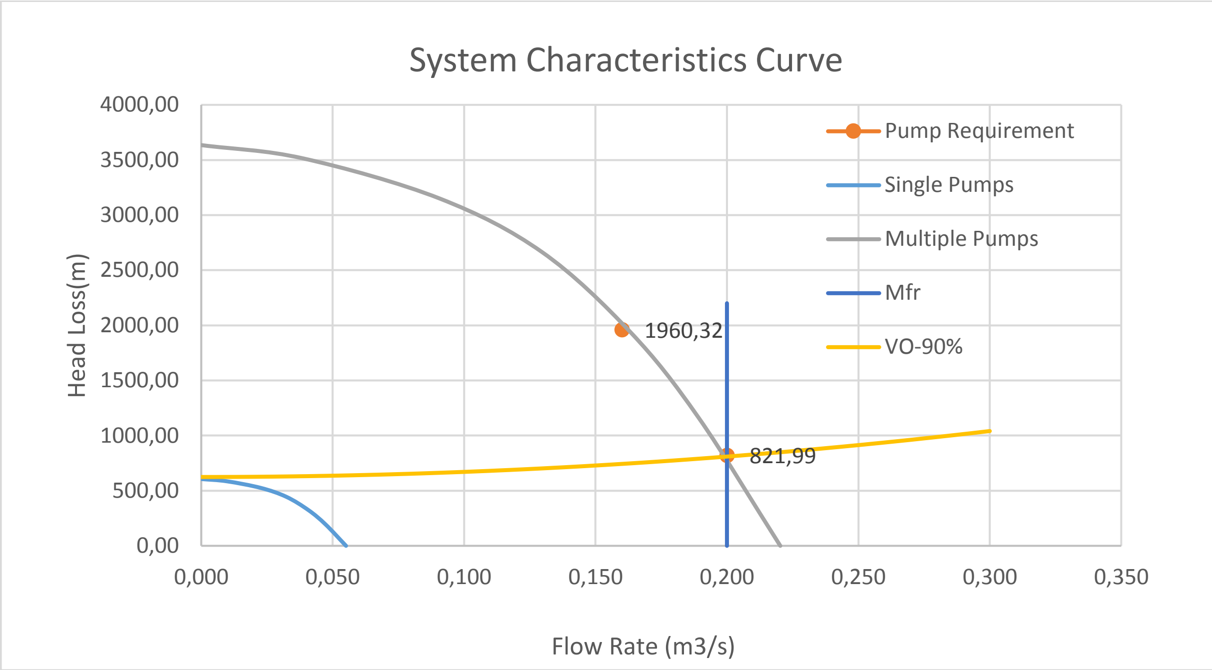

Figure 2.5: Characteristic Curve for Pump Station 1 at 90% Opening

The second pumping station located 175 km from the origin will need 7 pumps in series and 4 pumps in parallel. The pump arrangement reaches a maximum flow rate of 0.2m^3/s with a maximum valve opening of 90%. The resulting curves are shown below.

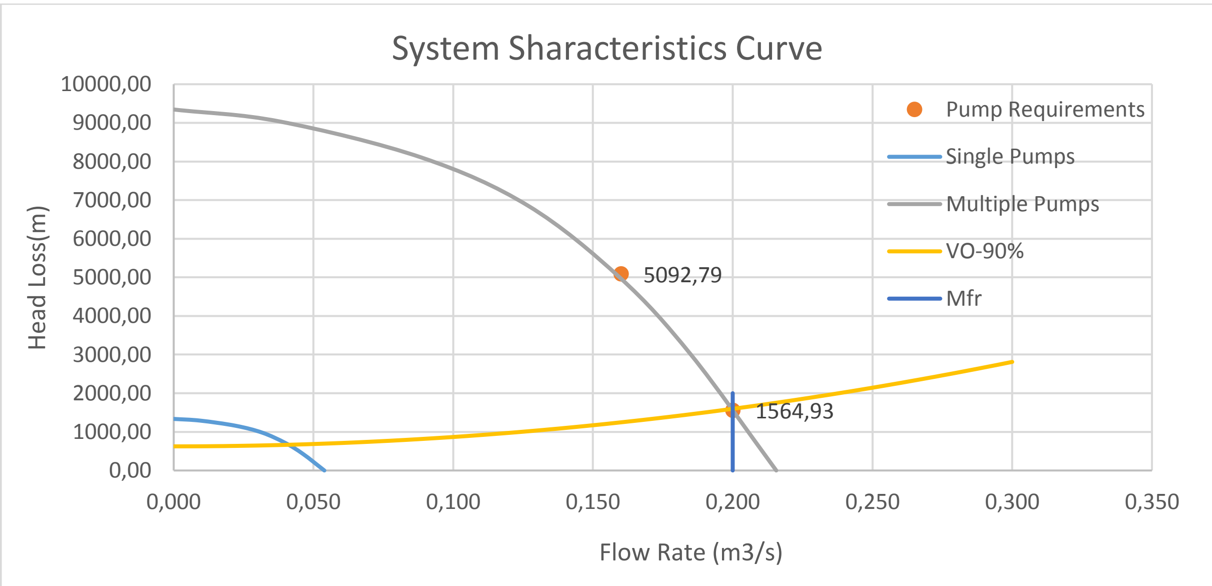

Figure 2.6: Characteristic Curve for Pump Station 2 at 90% Opening

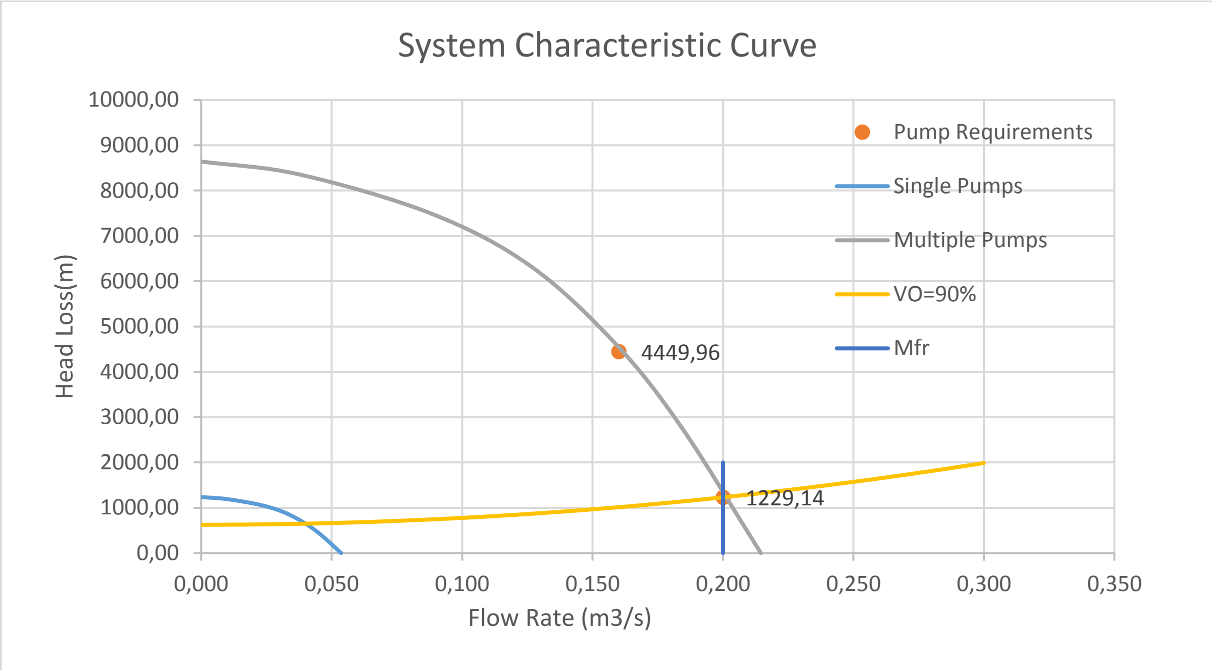

Figure 2.7: Characteristic Curve for Pump Station 3 at 90% Opening

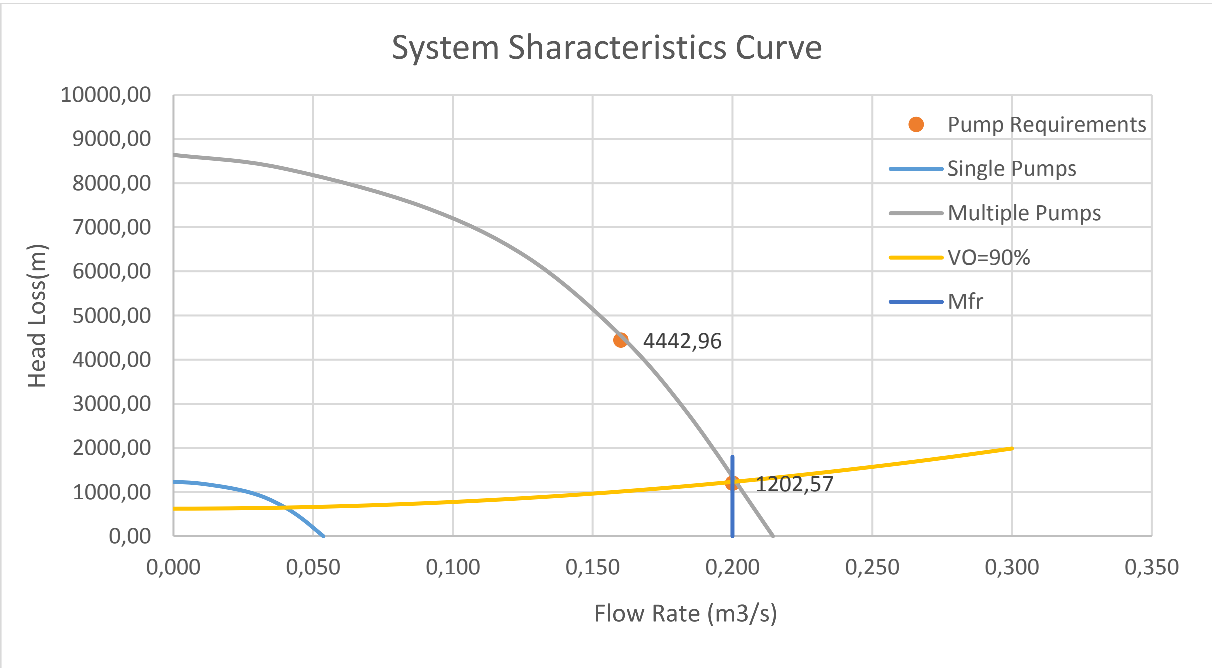

Figure 2.8: Characteristic Curve for Pump Station 4 at 90% Opening

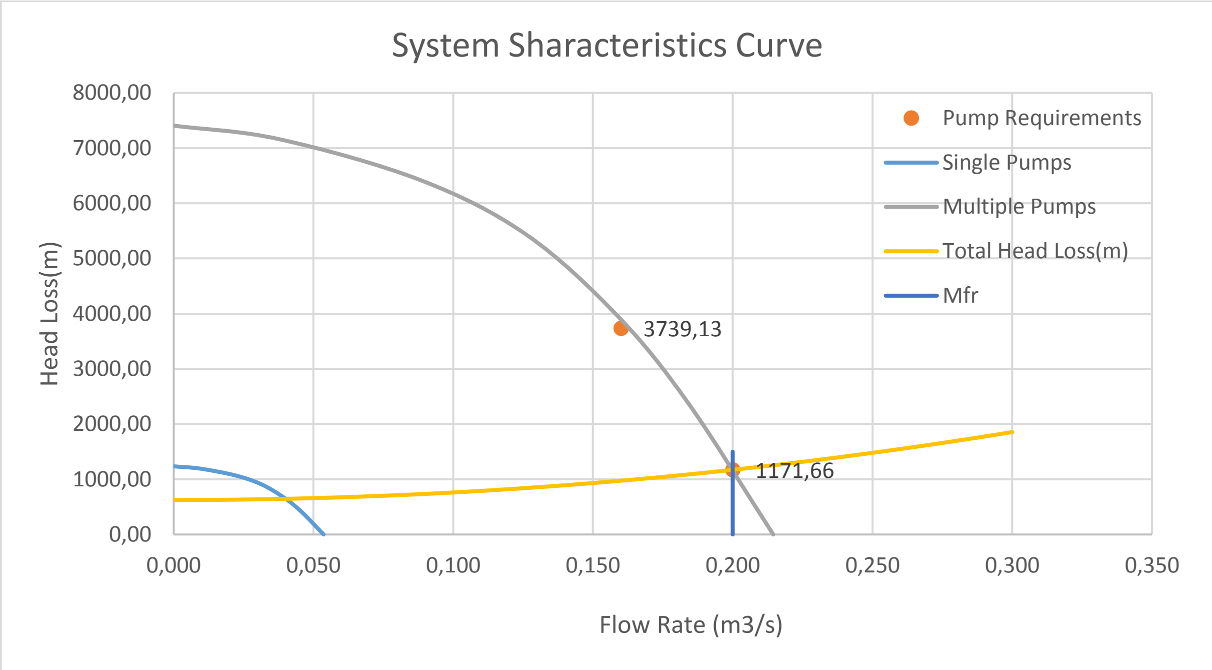

Figure 2.9: Characteristic Curve for Pump Station 5 at 90% Opening

2.2. Scenario 2

The second scenario has the same characteristic as the first scenario, the changes made in this iteration is the minimum flowrate which is pegged at a 24% reduction of the maximum flowrate, double the rate of scenario 1

Daily Need				Flow Rate
bbl/d	**m^3/d**	**m^3/h**	**m^3/min**	**m^3/S**
110000	17488	729	12.14	0.20
84000	13355	556	9.27	0.15

Table 2.7: Flow Rate Data Values

Energy Loss

The tables below show the energy loss calculation for scenario 2

Flow Data 18 inch Pipe		
	Qmin	**Qmax**
Internal Diameter (in)	17.32	17.32
Velocity (M/S)	0.99	1.19
Reynolds	34878	46505
Friction Factor	0.02	0.02
Pressure Drop (Pa/M)	15	25
Com Steel (mm)	0.05	0.05
μ_o (kgM/s)	1.00E-02	1.00E-02
Density (kg/m^3)	850	850

Table 2.8: Minimum Flow Rate Data

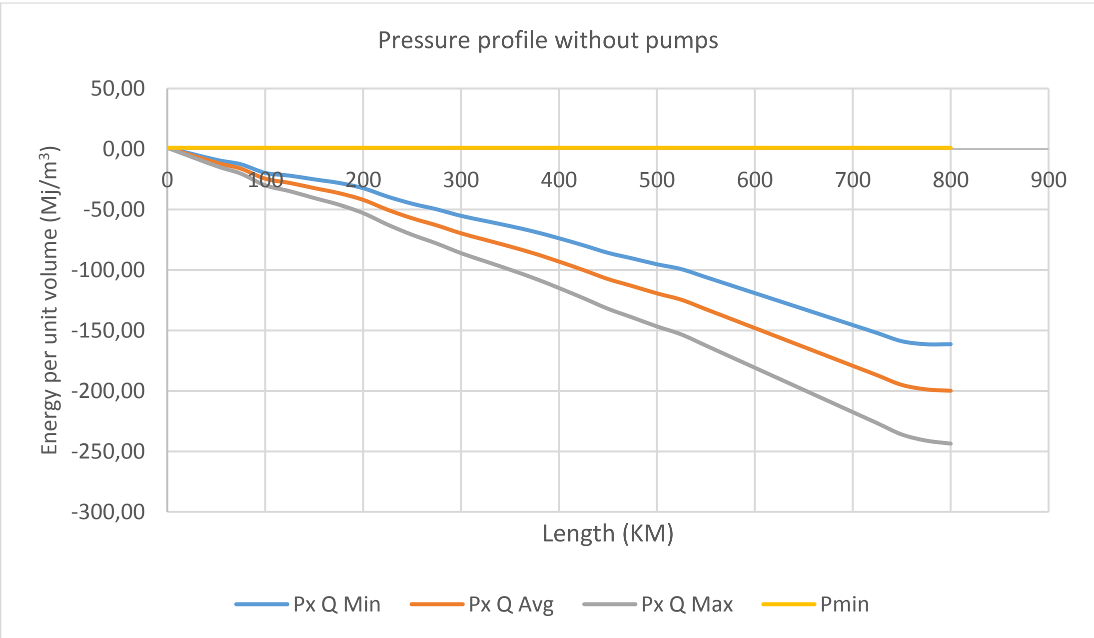

Figure 2.10: Pressure Profile Showing Pumping Stations

The system in scenario 2 has a very similar structure to scenario 1. The number of pumping stations required by both scenarios are the same. The pumping stations are located at 0 km, 175 km, 325 km, 475km, 600 km and. Each pump is fitted with valves to control pressure and flow rate.

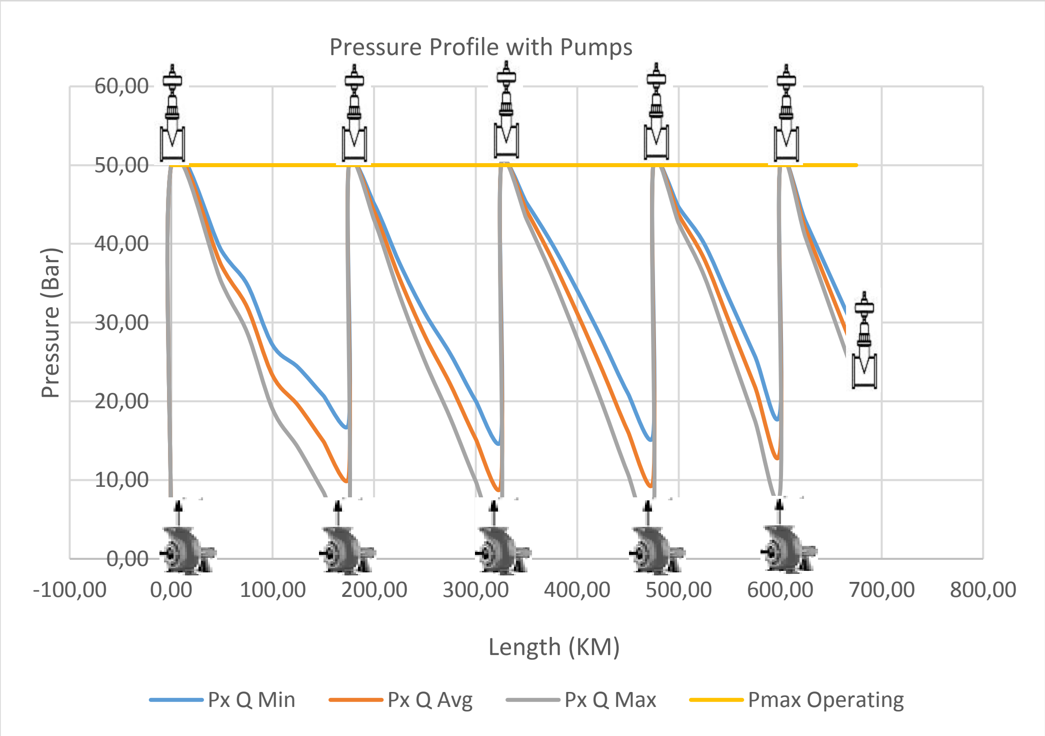

Figure 2.11: Pressure Profile Showing Pumping Stations

System Characteristic Curves

The ideal operating conditions for pumps is where the pump curve and the system characteristics curve intersect. The reliability of pumps is improved when they are sized closely enough to the required flow rate.

The system characteristic curve is gotten by plotting the total dynamic head versus flow rate, while the pump curve can be gotten from plots of pump head versus flow rate. Pump selection is largely based on proper interpretation of centrifugal pump curves. The pump station 2, 3 4 & 5 have the same characteristics so to avoid repetition, only pump station 1 and 2 will be examined.

Pump Station 1	Minimum Rate	Maximum Rate
ΔP (Valve) Bar	97.49	16.41
Head Loss by Valve (km)	1.24	0.21
Head Required (km)	0.62	0.62
Pump Head (km)	1.87	0.83
Pump Station 2	**Minimum Rate**	**Maximum Rate**
ΔP (Valve) Bar	341.22	80.21
Head Loss by Valve (km)	4.35	1.02
Head Required (km)	0.37	0.59
Pump Head (km)	4.71	1.62

Table 2.9: Pump Station Heads

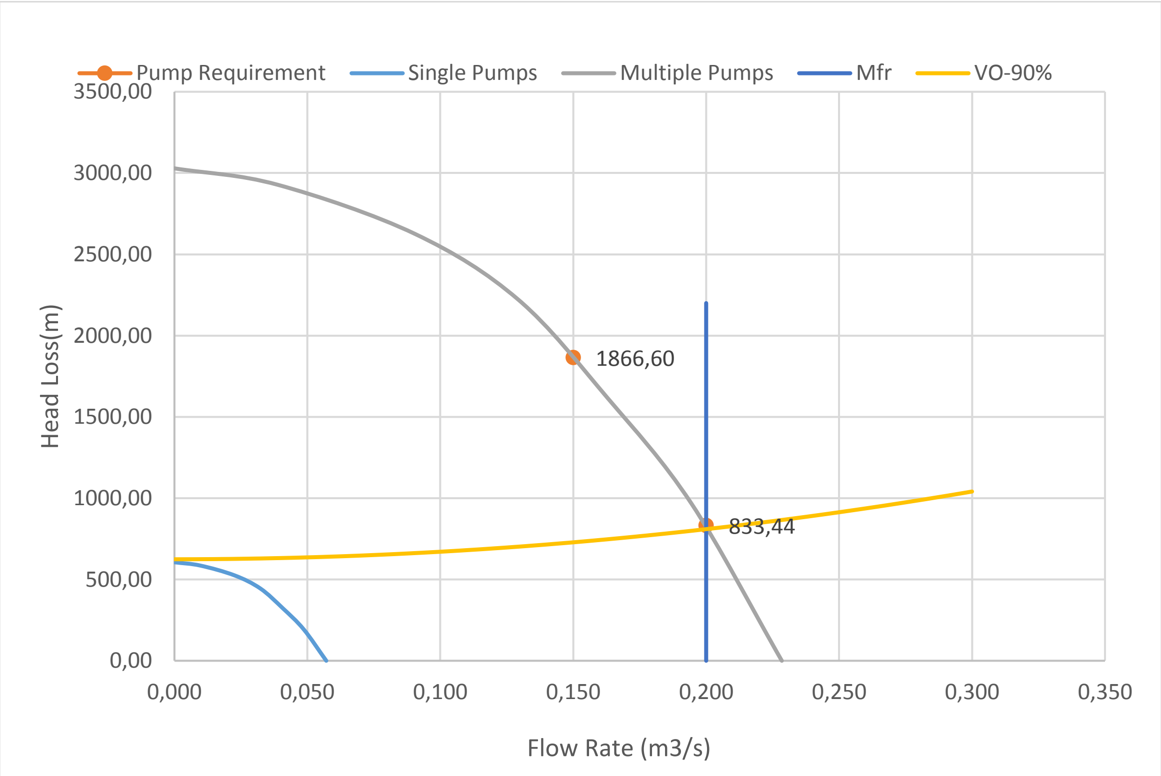

Figure 2.12: Characteristic Curve for Pump Station 1 (Scenario 2) at 90% Opening

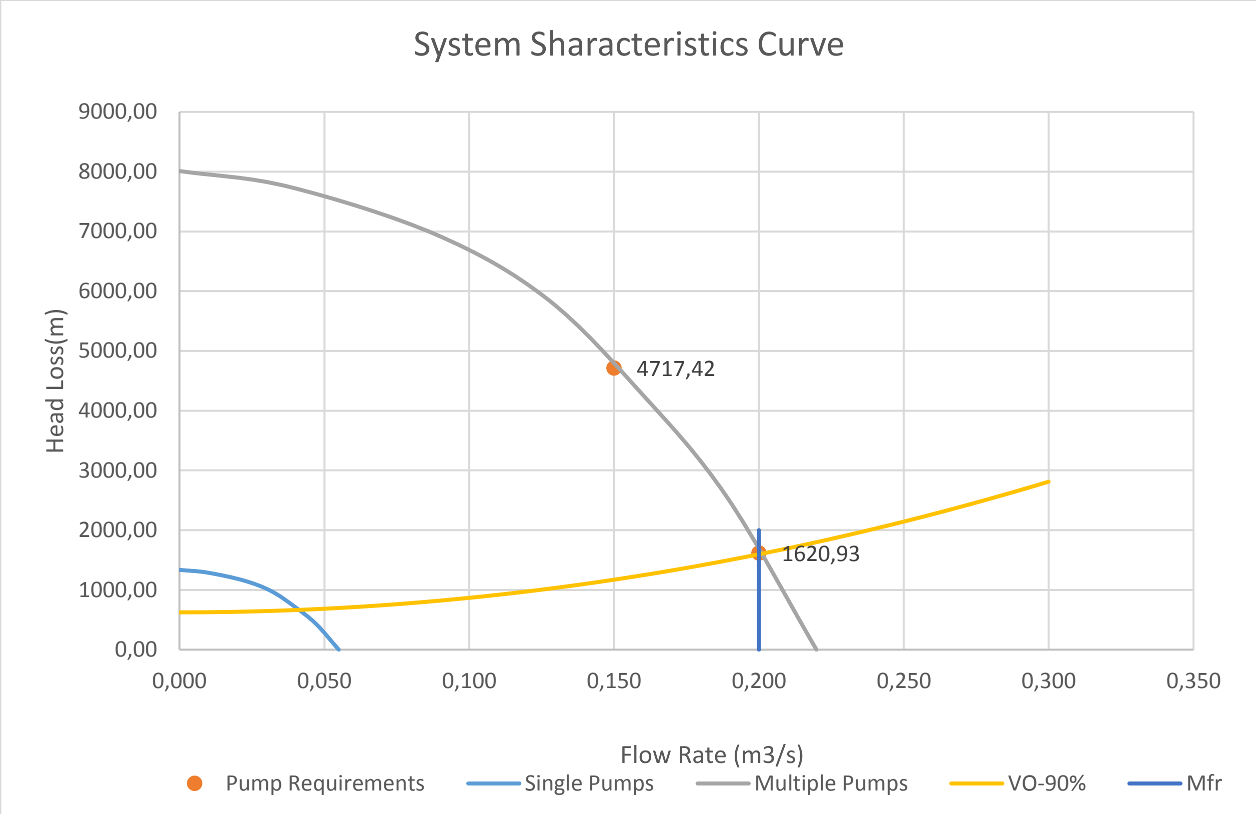

Figure 2.13: Characteristic Curve for Pump Station 2 (Scenario 2) at 90% Opening

2.3. Scenario 3

A third scenario was created to see the effect of nominal size differences. For this scenario a nominal pipe of 20-inches was chosen. The expected velocity was also varied. The flow rate is the same as that used in scenario 2.

Nominal Size (in)	20	20	20
Thickness (in)	0.31	0.37	0.50
Inside Diameter (in)	19.38	19.24	19.00
Max Allowable P (Mpa)	4.80	5.80	7.70
Max Operating P (MPA)	4.50	5.50	7.50

Table 2.10: Pipe Specifications

Energy Loss

The tables below show the energy loss calculation for scenario 3

Flow Data 20 inch Pipe		
	Qmin	Qmax
Internal Diameter (in)	19.38	19.38
Velocity (M/S)	0.95	1.05
Reynolds	39115	38803
Friction Factor	0.02	0.02
Pressure Drop (Pa/M)	27	26
Com Steel (mm)	0.05	0.05
μ_o (kgM/s)	1.00E-02	1.00E-02
Density (kg/m^3)	850	850

Table 2.11: Minimum Flow Rate Data

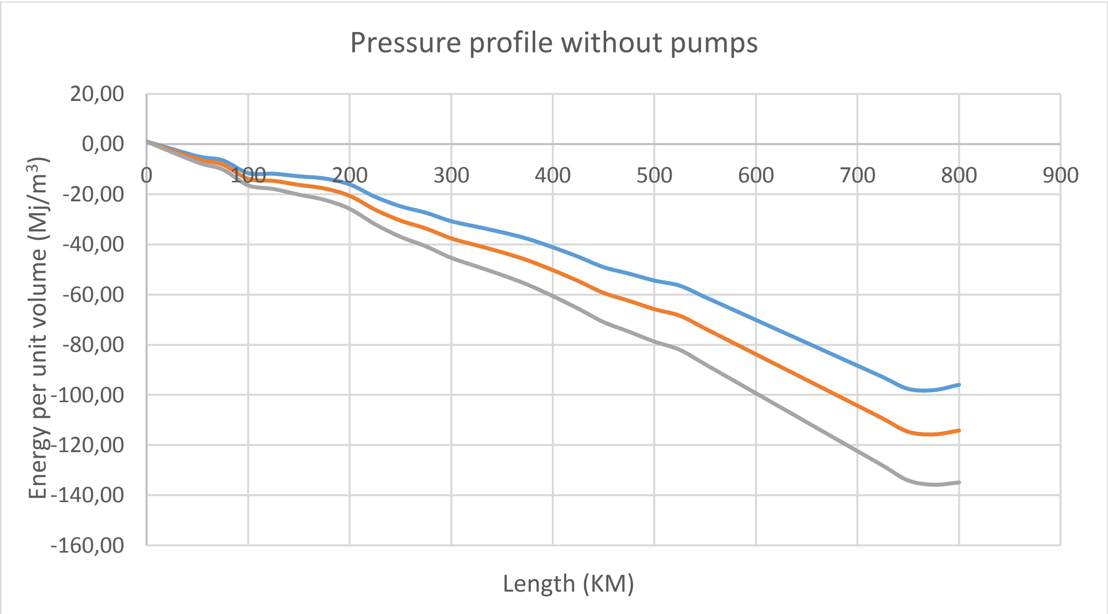

Figure 2.14: Pressure Profile Showing Pumping Stations

The system in scenario 3 will need to be fitted with pumping stations. For optimal performance, this diameter requires 3 pumping stations.

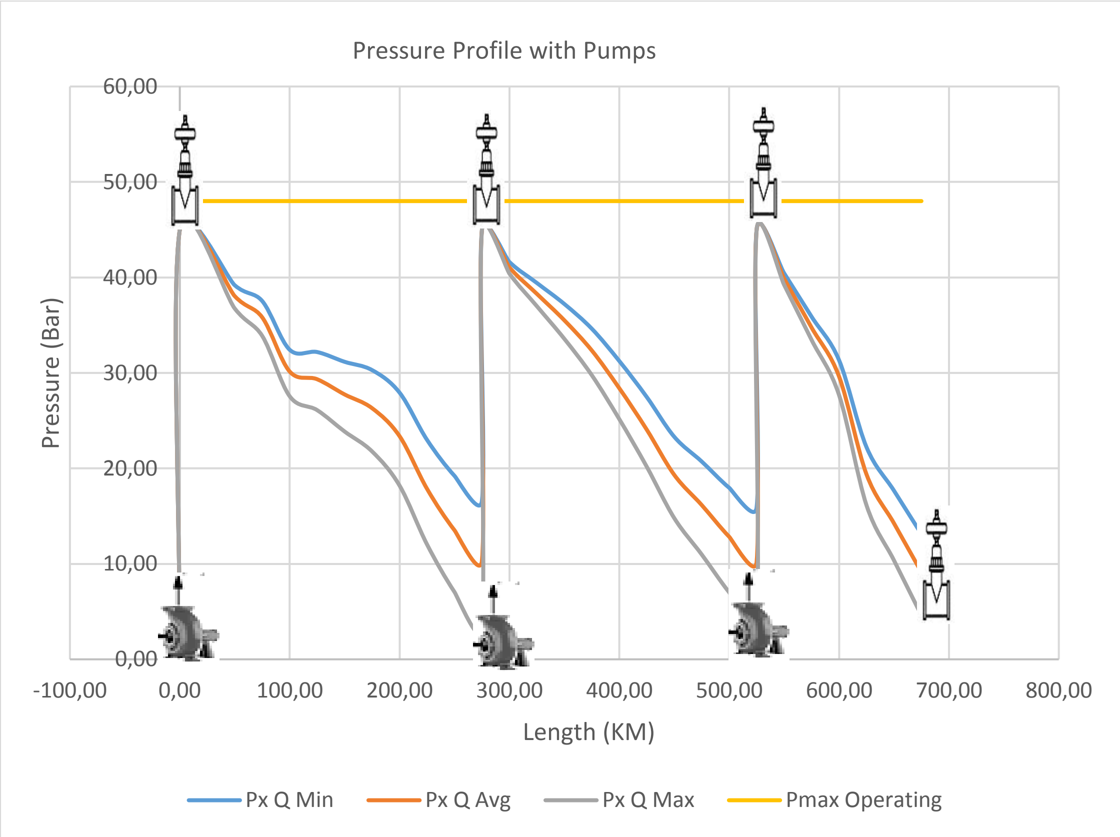

Figure 2.15: Pressure Profile Showing Pumping Stations

System Characteristic Curves

The ideal operating conditions for pumps is where the pump curve and the system characteristics curve intersect. The reliability of pumps is improved when they are sized closely enough to the required flow rate.

The pump station 1 to 3 have approximately the same characteristics. To avoid repetition, only data from pump station 1 will be examined.

Pump Station 1	Minimum Rate	Maximum Rate
ΔP (Valve) Bar	104.85	15.51
Head Loss by Valve (km)	1.34	0.19
Head Required (km)	0.64	0.62
Pump Head (km)	5.99	3.85

Table 2.12: Pump Station Heads

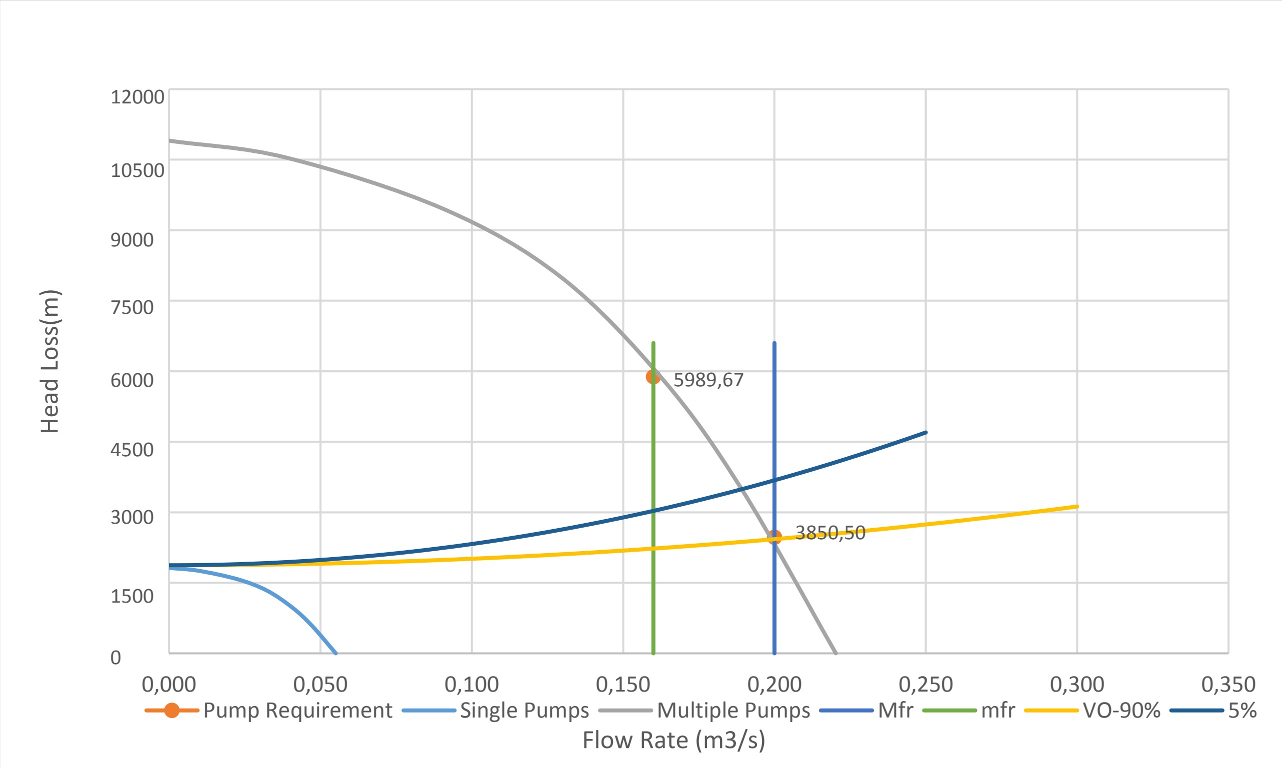

Figure 2.16: Characteristic Curve for Pump Station 1 (Scenario 3) at 90% Opening

The outcome of the analysis above gives strong reason to deduce that in design cases, a larger diameter should be favoured due to the lesser pumping station requirement. Also, larger flow rate ranges allow more room for system flexibility.

Chapter 3

Discussion

Failure Analysis

To analyse our system, we would model our system with the actual working conditions and develop other scenarios by adding additional pumps in series and in parallel.

3.1. Reliability Analysis Scenario 1

The system begins at the Escravos terminal and terminates at the Kaduna refinery. 674 km in length with a nominal diameter of 18 inches. There are five pumping stations with pumps arranged in series and parallel. Each Pumping station is fitted with valves to regulate pressure and in turn control the rate. For the purpose of this study it was assumed that the valves were operating at a maximum of ***90%*** opening to produce a conservative result which would be valid should the operating conditions change.

For the reliability analysis, our focus was solely on pumps with spurious stop assumed to be the failure mode. The refinery is also assumed to function all year round so this gives our pumps an operating time of ***8670 hours***. In the analysis, we assumed that the MTTR a critical part of our analysis is 10 days equivalent to **240 hours**. Another factor critical to our analysis is the **λ**, which has a value of **6.26×10^{-6}**. Referencing equation 1.3, the reliability can be calculated with the equation below:

$$R(t) = e^{-\lambda t} \quad (3.1)$$

In the case of our system, the reliability one pump using the equation above is **0.98**.

3.1.1 Failure Analysis at Pump Station 1

Here, we are analyzing the first pumping station in the system. Located almost immediately at the starting point. The mission of this pumping station is to ensure flow continues at maximum flow rate until the next pumping station. This pumping station consists of 6 pumps arranged in series and 4 arranged in parallel (***6x4 configuration***) making a total of 24 pumps. The analysis will look at several possible arrangements and consider various scenarios involving the failure of different pumps. At normal conditions, it is assumed that the pumping station is operating between the maximum required rate and the minimum without any pump failing.

The method of analysis will lead to two failure modes, ***working/not working,*** each pump failure will lead to a new characteristics curve due to the change in the pump arrangement that will be caused by a failure. In our analysis, for failure locations, we considered two directions relating to the pump failure horizontal and vertical.

3.2.1. Pump Station 1 without Failure

Without any pump failure, the system is assumed to operate at regular condition.

The system operates at the maximum flow rate of 0.2 m^3/s while the valve is considered to be 90% opened at full capacity. The 90% valve opening is to ensure a conservative figure and a fully flexible system.

3.2.2. Pump Station 1 with One Pump Failure

The system is assumed to experience its first failure at one of the installed 24 pumps. This failure will lead to a drop in the maximum flow rate of this system to be lowered whereas the minimum flow rate will still be achieved. I the presence of one failure the system configuration changes from a ***6x4*** to a ***5x4*** and ***6x3*** configuration. This new configuration will bring about a decrease in the pump head curve and will cause a new maximum flow rate, commensurate to the new configuration, to be realized. This kind of scenario leads to a ***non-working*** failure of the system since the system continues to function but the mission has been altered and affected by the failure of one pump. Where Nmfr represents new maximum flow rate under failure which is equal to 0.195m^3/s. The blue dot represents the new operating condition under mFR with VO of 35% and NMFR of 0.195m^3/s.

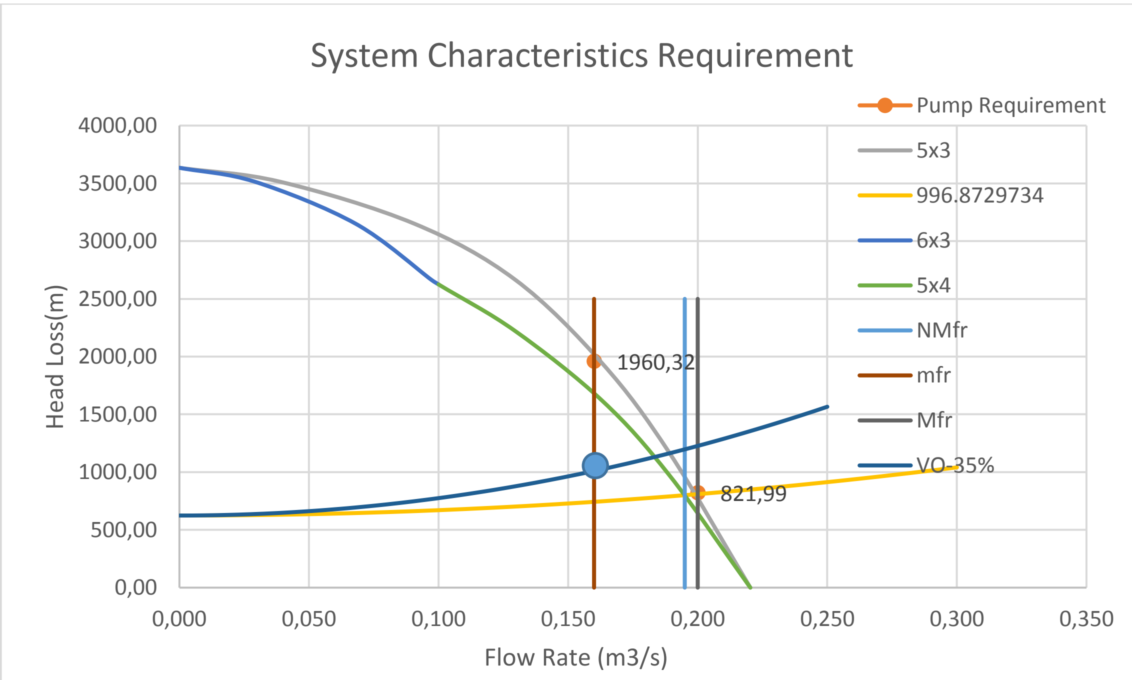

Figure 3.1: Pump Station 1 with 1 Pump failed

3.2.3. Pump Station 1 with Two Pumps Failure

To give our system a huge flexibility and to get a conservative value, the assumption in this scenario is that two pumps fail simultaneously without any warning system. The failure mode here is also a ***non-working*** failure mode. We can have two scenarios of failure with 2 pumps failing in series or two failing in parallel leading to a 6x3 and a 4x4 configuration or a 5x3 and 6x2 configuration.

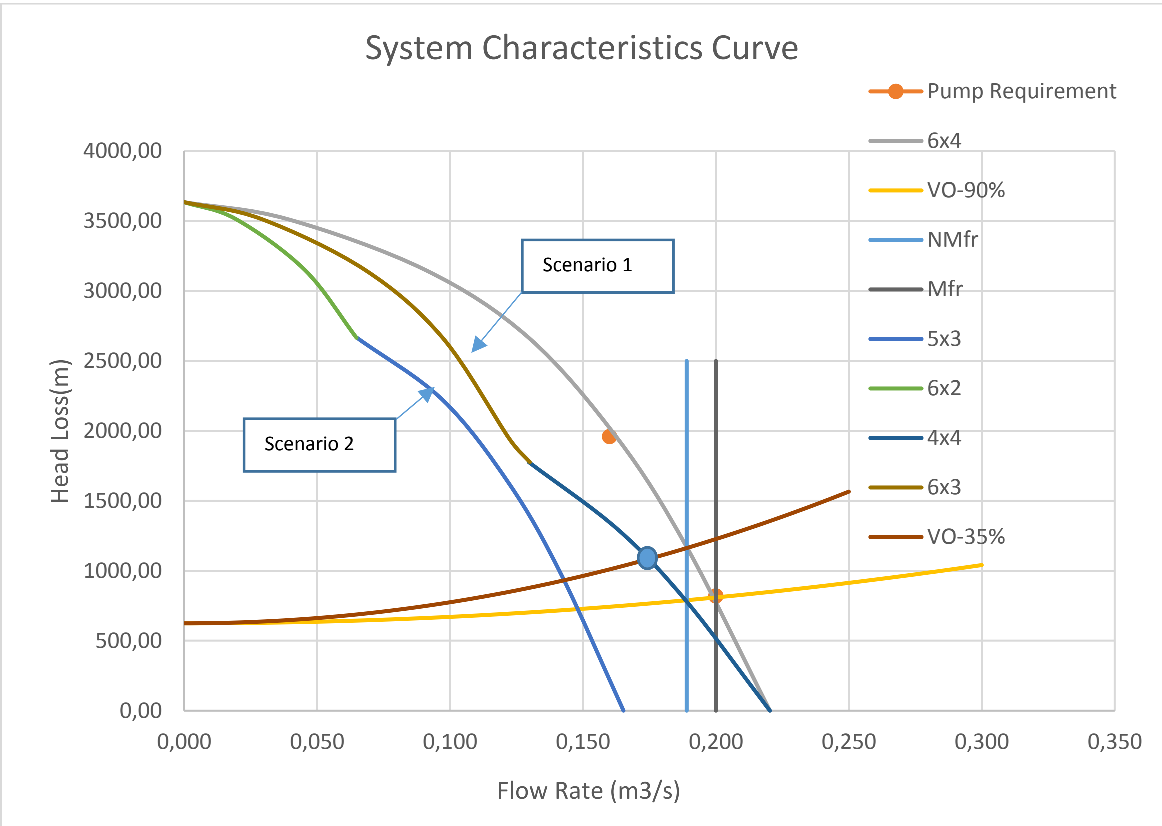

Figure 3.2: Pump Station 1 with 2 Pump failed

From the characteristic curve above, it can be seen the failure of two pumps will cause the pump curve to drop below the original system head leading to a NMfr in both scenarios. The minimum flow rate is only achieved in the first scenario and a new minimum rate is defined in the second scenario.

3.2.4. Pump Station 1 with Three Pumps Failure

Here also, to get a conservative value and give our system a huge flexibility, it is assumed that all three failures occur simultaneously. Just as in the previous case, the failure of three pumps will lead to a reduction in the pump curve causing a ***non-working*** failure mode.

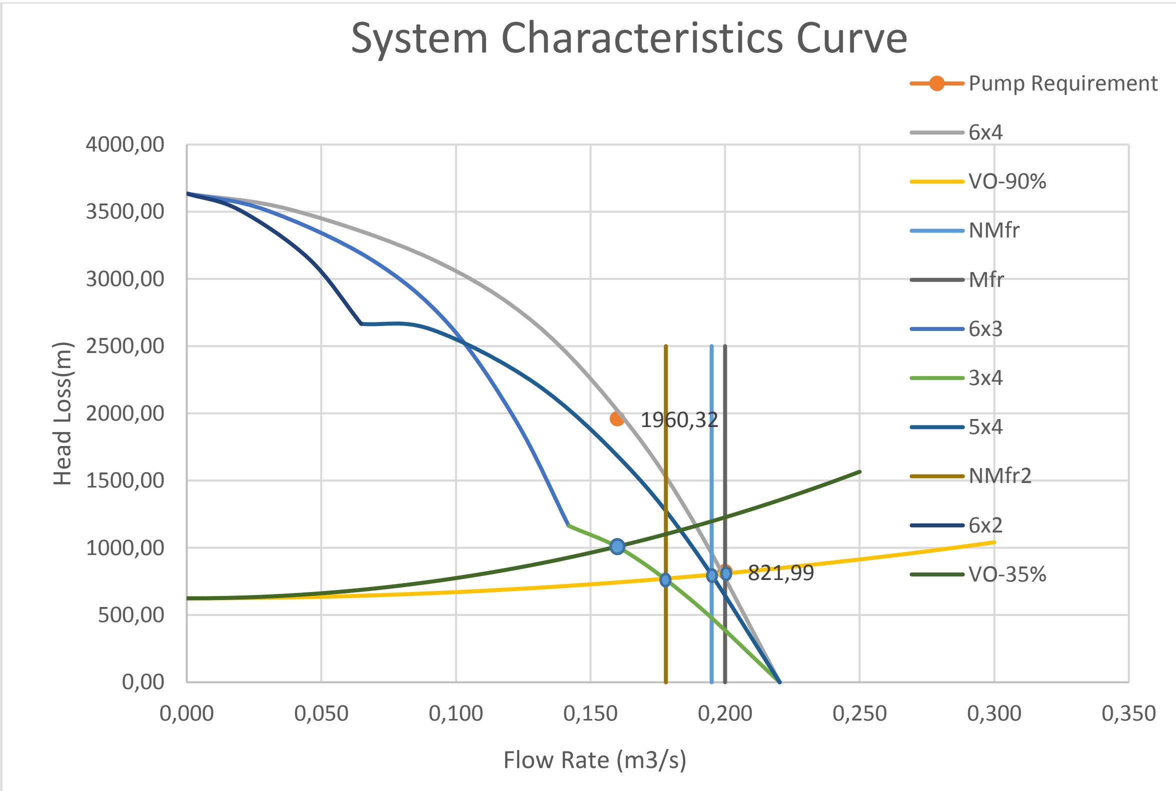

Figure 3.3: Pump Station 1 with 3 Pumps failed

In the case of three pump failures, the minimum rate is still achieved however there is a drop in the maximum rate with the scenario 1 (6x2 and 5x4) giving a 0.195 m^3/s and scenario 2 (6x3 and 3x4) achieving a rate of 0.178 m^3/s.

3.3. Failure Analysis at other Pump Stations

The pump stations 2, 3, 4 and 5 have similar requirements and thus require the same pump configuration. The analysis will be conducted for one of the pumping station (pump station 2) and the result will be extended to be valid for others. As is the case of the first pumping station, the mission of the successive stations is to ensure flow continuity within the stipulated range until the refinery. This pumping stations consist of 7 pumps arranged in series and 4 arranged in parallel (***7x4 configuration***) making a total of 28 pumps. The analysis will look at several possible arrangements and consider various scenarios involving the failure of different pumps. At normal conditions, it is assumed that the pumping station is operating between the maximum required rate and the minimum without any pump failing.

The method of analysis will lead to two failure modes, ***working/not working,*** each pump failure will lead to a new characteristics curve due to the change in the logical pump arrangement that will be caused by a failure.

3.3.1. Pump Station 2 without Failure

Without any pump failure, the system operates at regular condition. The system operates at the maximum flow rate of 0.2 m^3/s and a minimum of 0.16m^3/s while the valve is considered to be 90% opened at full capacity. The 90% valve opening is to ensure a conservative figure and a fully flexible system.

3.3.2. Pump Station 2 with One Pump Failure

The system is assumed to experience its first failure at one of the installed 28 pumps. This failure will lead to a drop in the maximum flow rate of this system to be lowered whereas the minimum flow rate will still be achieved. In the presence of one failure the system configuration changes from a ***7x4*** to a ***7x3*** and ***6x4*** configuration. This new configuration will bring about a decrease in the pump head curve and will cause a new maximum flow rate, commensurate to the new configuration, to be realized. This kind of scenario leads to a ***non-working*** failure of the system since the system continues to function but the mission has been altered and affected by the failure of one pump. Where Nmfr represents new maximum flow rate under failure which is equal to 0.198m^3/s.

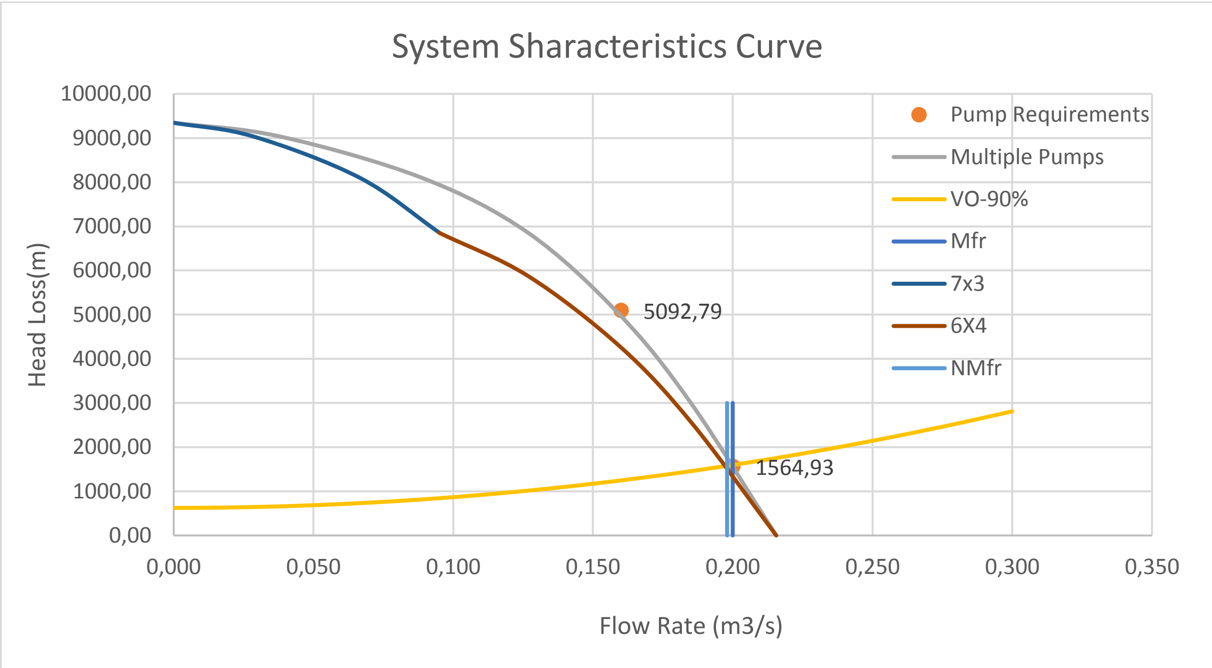

Figure 3.4: Pump Station 2 with 1 Pumps failed

3.3.3. Pump Station 2 with Two Pumps Failure

To give our system a huge flexibility and to get a conservative value, the assumption in this scenario is that two pumps fail simultaneously without any warning system. The failure mode here is also a ***non-working*** failure mode. We can have two scenarios of failure with 2 pumps failing in series or two failing in parallel leading to a 5x3 and a 7x2 configuration or a 6x2 and 7x1 configuration.

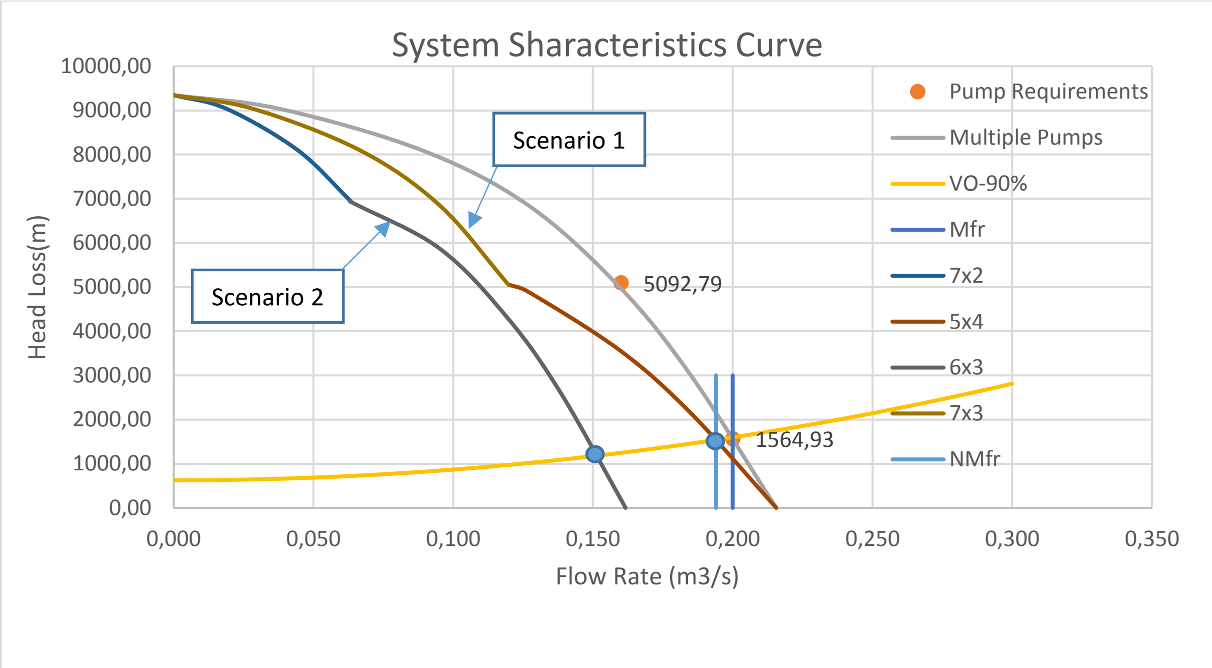

Figure 3.5: Pump Station 2 with 2 Pumps failed

The failure in the scenario analysed here finds a reduction in the maximum operating flow rate from 0.2m^3/s to 0.198 m^3/s for scenario 1 and 0.151 for scenario 2. While the minimum flow rate of 0.16 m^3/s is achieved in scenario 1 that value is greatly reduced in scenario 2 to an Nmfr of 0.103 m^3/s.

3.3.4. Pump Station 2 with Three Pumps Failure

Here also, to get a conservative value and give our system a huge flexibility, it is assumed that all three failures occur simultaneously without any warning system in place. Just as in the previous case, the failure of three pumps will lead to a reduction in the pump curve causing a ***non-working*** failure mode.

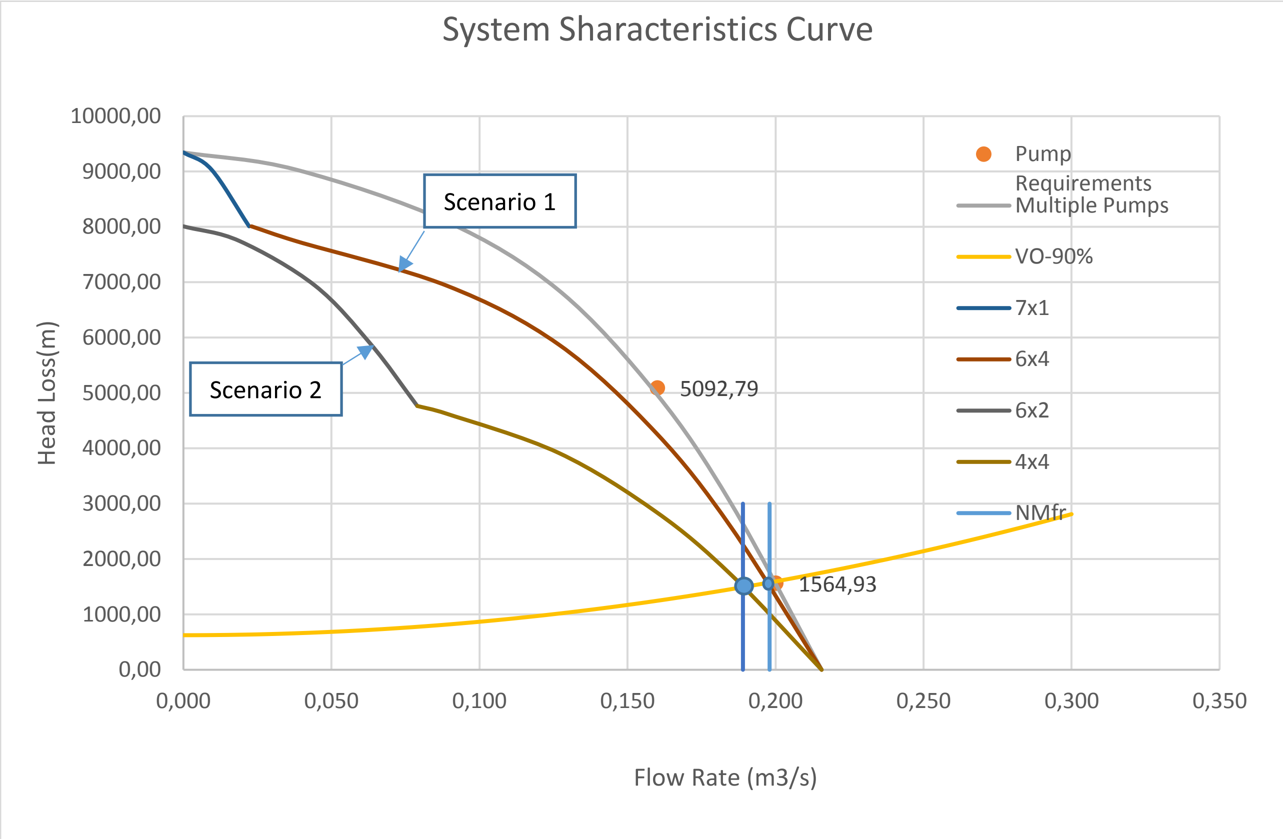

Figure 3.6: Pump Station 2 with 3 Pumps failed

3.4. Probabilities of Failure

To better understand the possibilities of failure and the effects on the flow rate of the system, a probability analysis was conducted to establish a relationship. This is done by analyzing the cases within the number of failures then considering previous cases that already occurred. Possible failures are estimated and distributed among the cases. Possible combinations of the 24 pumps, taking into account the failed one, are calculated and distributed by cases considered. This analysis was conducted for all five pumping stations using a binomial distribution function;

$$P_F = \binom{N}{F} R^F (1-R)^{N-F} \quad (3.2)$$

Where N denotes the total number of pumps in the pump station and F is the number of failed pumps. For each case, a cumulative probability of failure is calculated and from this value we can deduce the range of flow rates lower than the maximum flow rate that can be achieved after experiencing failure. A graph has been generated from the probability values calculated to indicate a case of failure with up to three pumps failing simultaneously and the resulting flowrate that can be achieved with an MTTR of 10 days. When there is no pump failure the system will achieve its maximum flow rate of 0.2 m^3/s. but in the case of failure; the behaviour is observed.

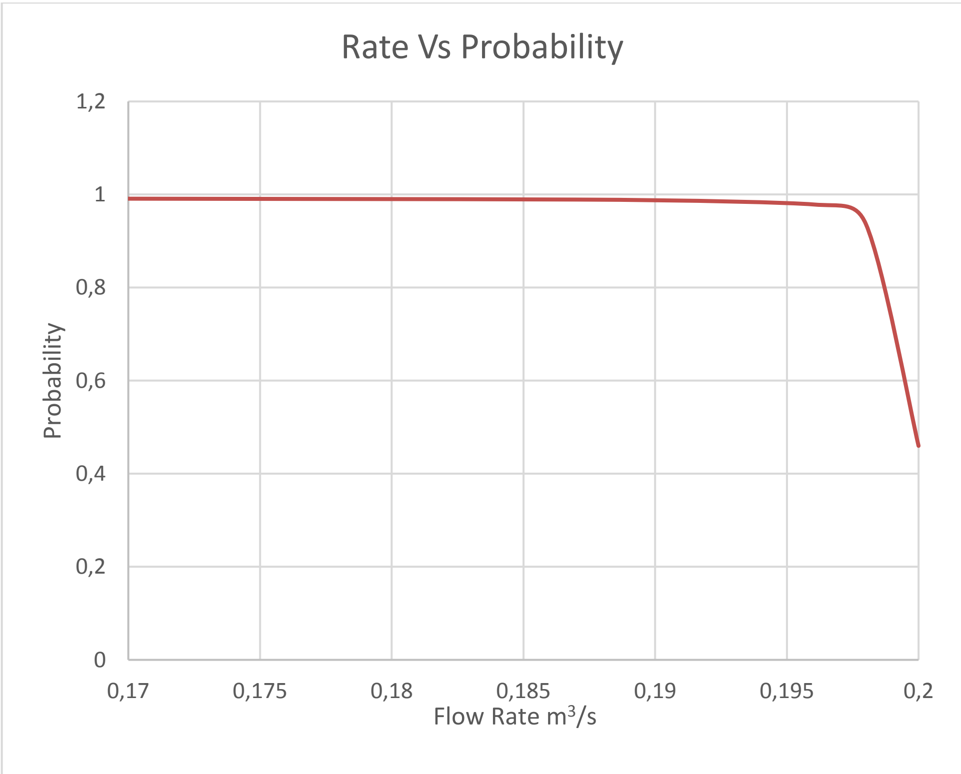

Figure 3.7: The probability of achieving a range of flow rates after failure for pump station 1

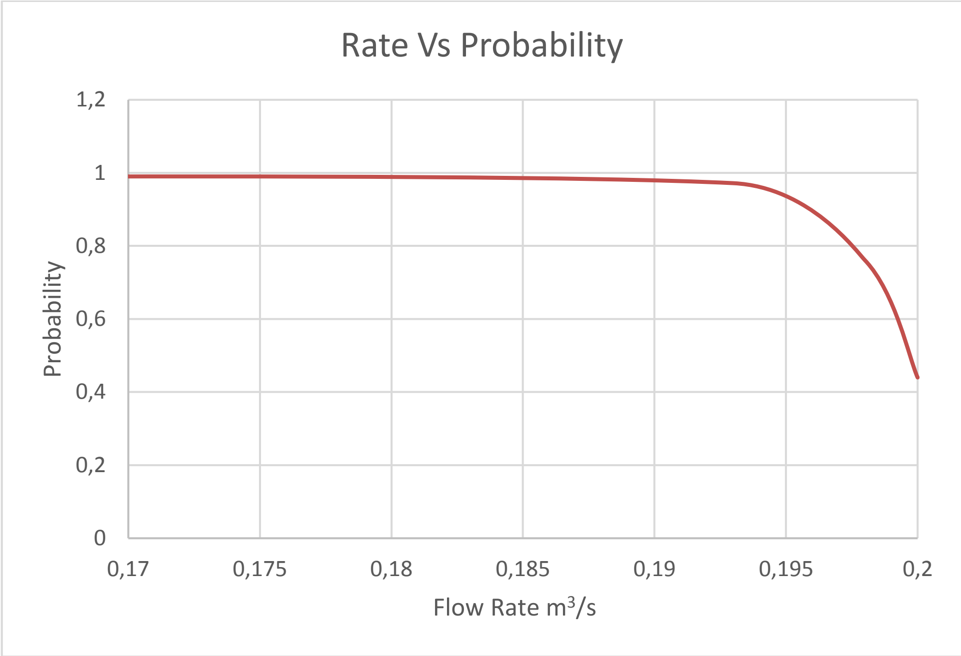

Figure 3.8: The probability of achieving a range of flow rates after failure for pump station 2

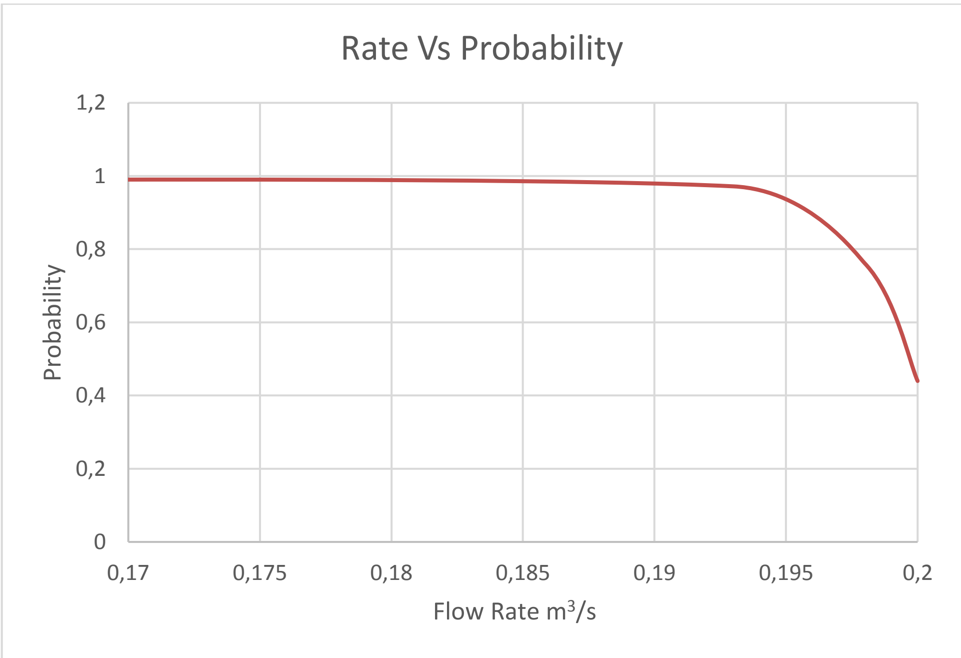

Figure 3.9: The probability of achieving a range of flow rates after failure for pump station 3

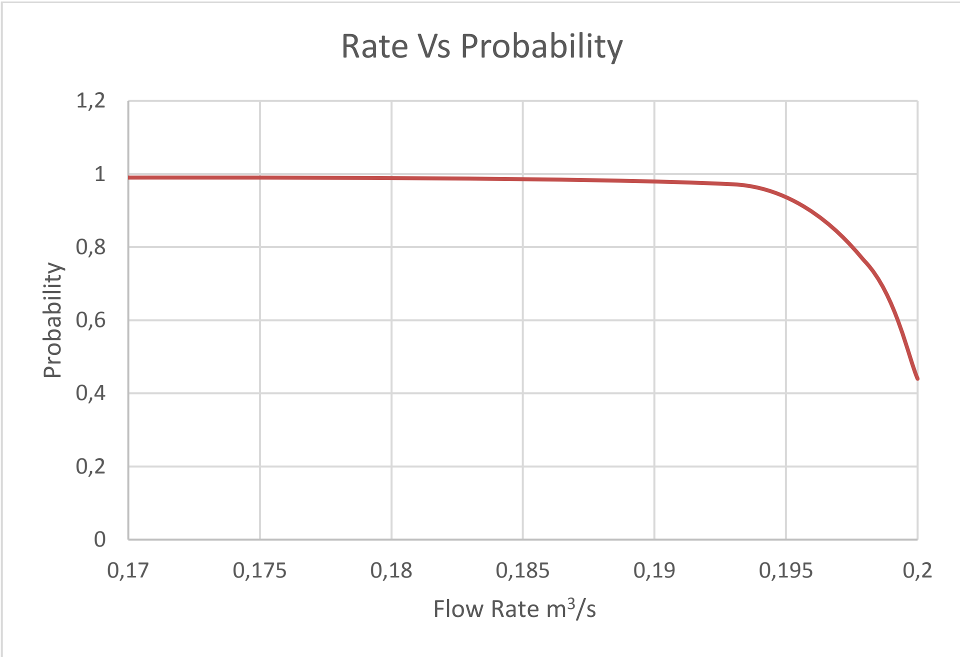

Figure 3.10: The probability of achieving a range of flow rates after failure for pump station 4

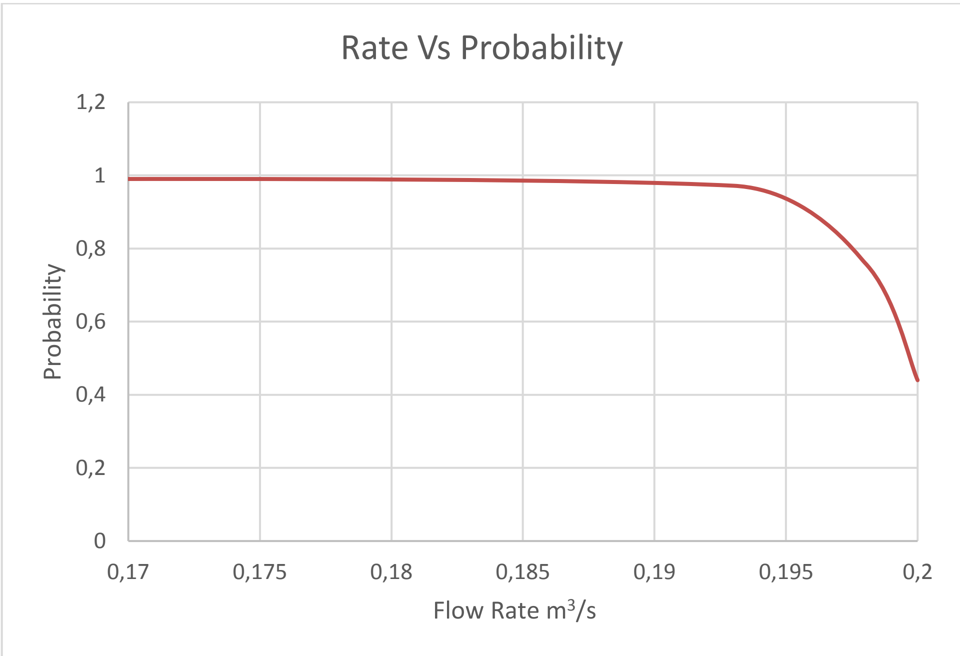

Figure 3.11: The probability of achieving a range of flow rates after failure for pump station 5

An interesting comparison can be drawn from the graph above to calculate the reliability of each pumping station at a given flow rate. A graph of the expected flow rate and the frequency is provided. The reliability of the pumping station can be easily evaluated at a range of flowrates using an integral.

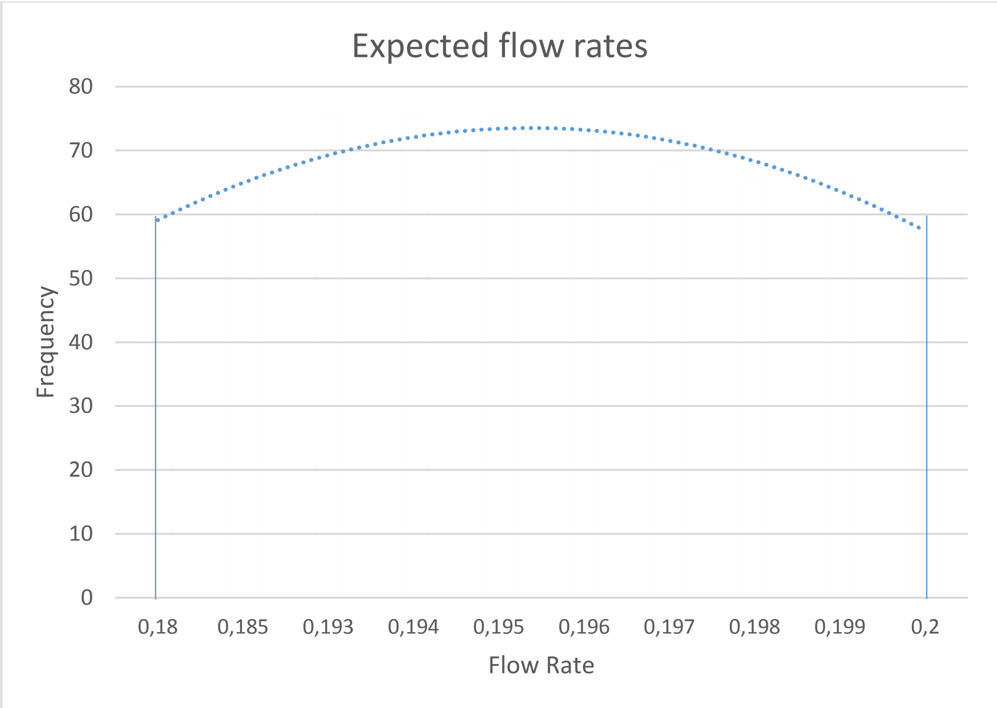

Figure 3.12: Frequency of expected flow rates.

Combining the integral of figure 3.20 above with the reliability values on figures 3.16 to 3.19 a reliability of the pumping station can be calculated taking into account flow rate frequency using equation 3.2 below.

$$R = \int_{Q_{min}}^{Q_{max}} \overline{R}. f. dQ \quad (3.1)$$

3.5. Reliability Analysis Scenario 2

The system begins at the Escravos terminal and terminates at the Kaduna refinery. 674 km in length with a nominal diameter of 18 inches. There are five pumping stations with pumps arranged in series and parallel. Each Pumping station is fitted with valves to regulate pressure and in turn control the rate. For the purpose of this study it was assumed that the valves were operating at a maximum of ***90%*** opening to produce a conservative result which would be valid should the operating conditions change.

For the reliability analysis, our focus was solely on pumps with spurious stop assumed to be the failure mode. The refinery is also assumed to function all year round so this gives our pumps an operating time of ***8670 hours***. In the analysis, we assumed that the MTTR a critical part of our analysis is 10 days equivalent to **240 hours**. Another factor critical to our analysis is the **λ**, which has a value of $\mathbf{6.26 \times 10^{-6}}$. Referencing equation 1.3, the reliability can be calculated with the equation below:

$$R(t) = e^{-\lambda t} \quad (3.1)$$

In the case of our system, the reliability one pump using the equation above is **0.98**.

3.6. Failure Analysis at Pump Station 1

Here, we are analyzing the first pumping station in the system. Located almost immediately at the starting point. The mission of this pumping station is to ensure flow continues at maximum flow rate until the next pumping station. This pumping station consists of 5 pumps arranged in series and 4 arranged in parallel (***5x4 configuration***) making a total of 20 pumps. The analysis will look at several possible arrangements and consider various scenarios involving the failure of different pumps.

At normal conditions, it is assumed that the pumping station is operating between the maximum required rate and the minimum without any pump failing.

The method of analysis will lead to two failure modes, ***working/not working,*** each pump failure will lead to a new characteristics curve due to the change in the pump arrangement that will be caused by a failure. In our analysis, for failure locations, we considered two directions relating to the pump failure horizontal and vertical.

3.6.1. Pump Station 1 without Failure

Without any pump failure, the system is assumed to operate at regular condition. The system operates at the maximum flow rate of 0.2 m^3/s while the valve is considered to be 90% opened at full capacity. The 90% valve opening is to ensure a conservative figure and a fully flexible system.

3.6.2. Pump Station 1 with One Pump Failure

The system is assumed to experience its first failure at one of the installed 20 pumps. This failure will lead to a drop in the maximum flow rate of this system to be lowered whereas the minimum flow rate will still be achieved. In the presence of one failure the system configuration changes from a ***5x4*** to a ***4x4*** and ***5x3*** configuration. This new configuration will bring about a decrease in the pump head curve and will cause a new maximum flow rate, commensurate to the new configuration, to be realized. This kind of scenario leads to a ***non-working*** failure of the system since the system continues to function but the mission has been altered and affected by the failure of one pump.

Where Nmfr represents new maximum flow rate under failure which is equal to 0.195m^3/s. The blue dot represents the new operating condition under mFR with VO of 35% and NMFR of 0.195m^3/s.

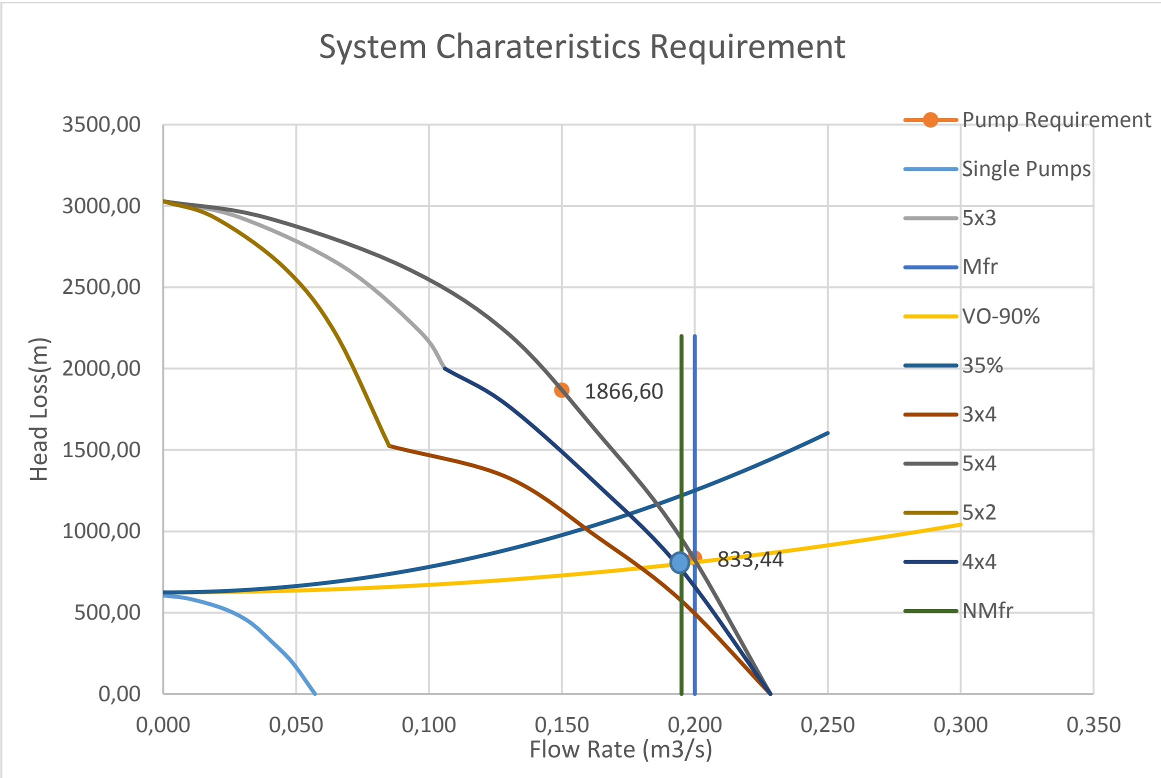

Figure 3.13: Pump Station 1 with 1 Pump failed

3.6.3. Pump Station 1 with Two Pumps Failure

To give our system a huge flexibility and to get a conservative value, the assumption in this scenario is that two pumps fail simultaneously without any warning system. The failure mode here is also a ***non-working*** failure mode. We can have two scenarios of failure with 2 pumps failing in series or two failing in parallel leading to a 5x3 and a 3x4 configuration or a 5x2 and 4x4 configuration.

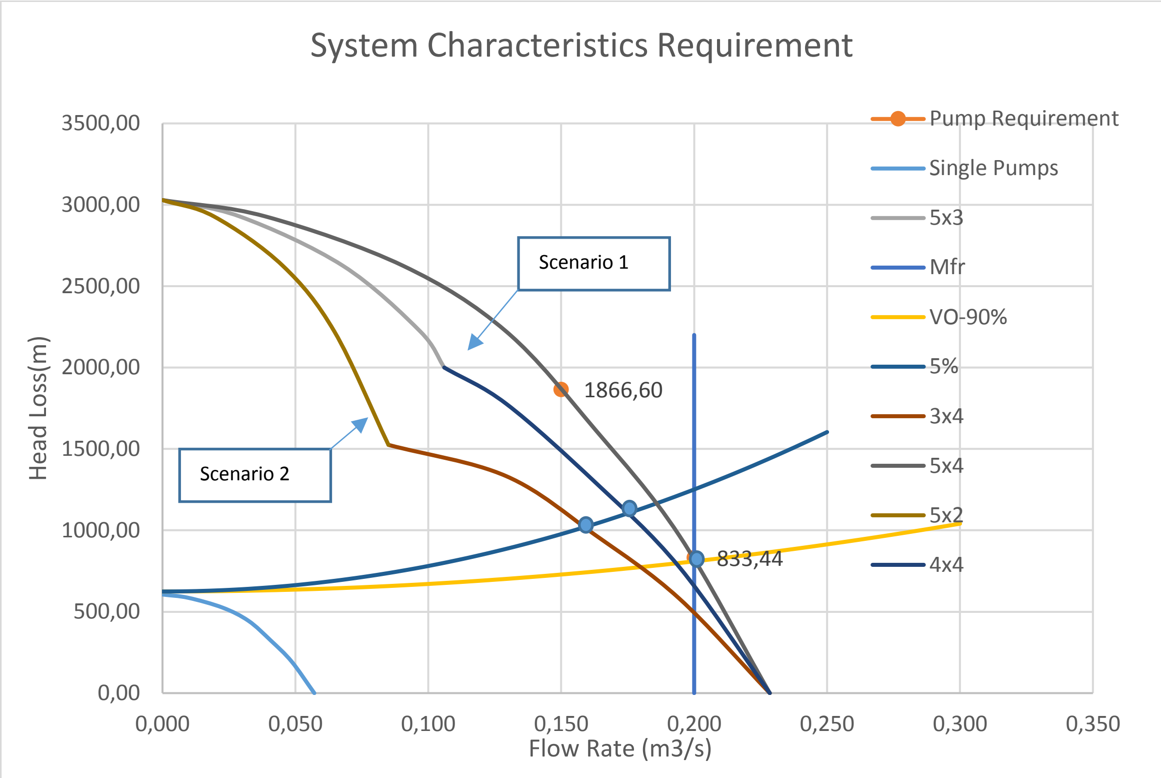

Figure 3.14: Pump Station 1 with 2 Pump failed

From the characteristic curve above, it can be seen the failure of two pumps will cause the pump curve to drop below the original system head leading to a NMfr in both scenarios. The minimum flow rate is only achieved in the first scenario and a new minimum rate is defined in the second scenario.

3.6.4. Pump Station 1 with Three Pumps Failure

Here also, to get a conservative value and give our system a huge flexibility, it is assumed that all three failures occur simultaneously. Just as in the previous case, the failure of three pumps will lead to a reduction in the pump curve causing a ***non-working*** failure mode.

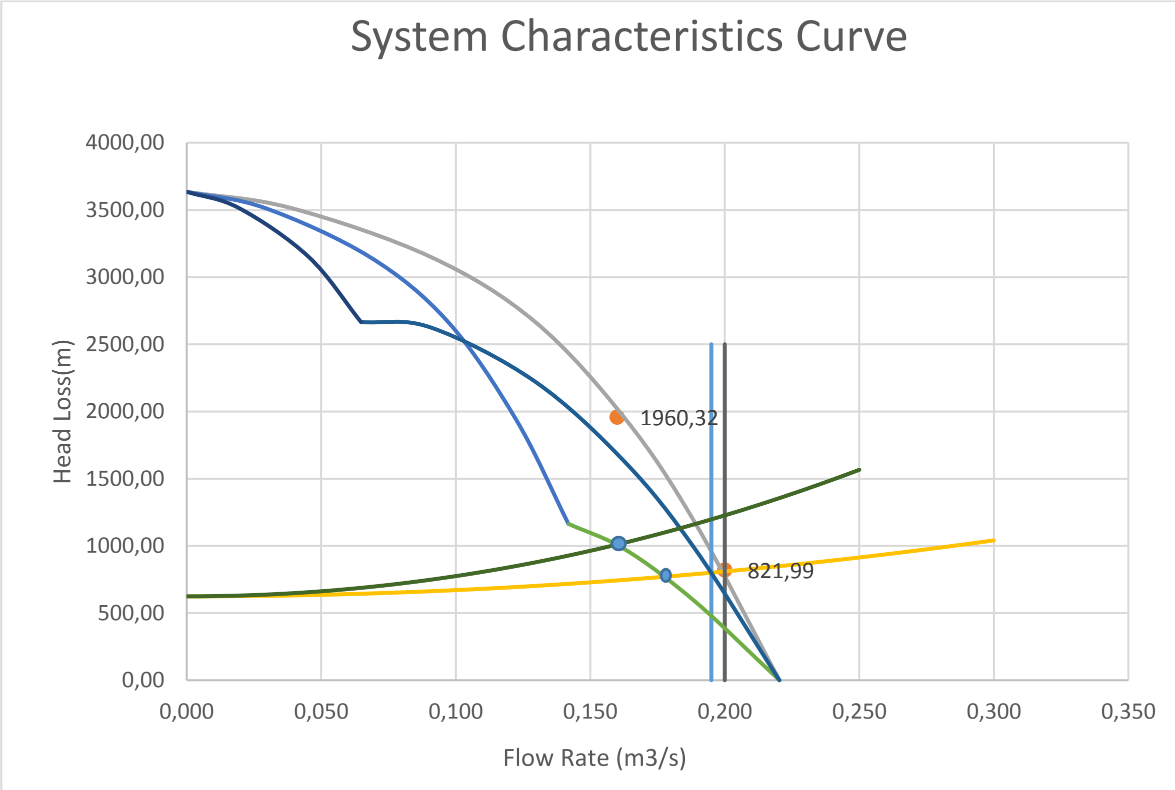

Figure 3.15: Pump Station 1 with 3 Pumps failed

In the case of three pump failures, the minimum rate is still achieved however there is a drop in the maximum rate with the scenario 1 (5x3 and 2x4) giving a 0.195 m^3/s and scenario 2 (5x1 and 4x4) achieving a rate of 0.178 m^3/s.

3.7. Failure Analysis at other Pump Stations

The pump stations 2, 3, 4 and 5 have similar requirements and thus require the same pump configuration. The analysis will be conducted for one of the pumping station (pump station 2) and the result will be extended to be valid for others. As is the case of the first pumping station, the mission of the successive stations is to ensure flow continuity within the stipulated range until the refinery. This pumping stations consist of 6 pumps arranged in series and 4 arranged in parallel (***6x4 configuration***) making a total of 24 pumps. The analysis will look at several possible arrangements and consider various scenarios involving the failure of different pumps. At normal conditions, it is assumed that the pumping station is operating between the maximum required rate and the minimum without any pump failing.

The method of analysis will lead to two failure modes, ***working/not working,*** each pump failure will lead to a new characteristics curve due to the change in the logical pump arrangement that will be caused by a failure.

3.7.1. Pump Station 2 without Failure

Without any pump failure, the system operates at regular condition. The system operates at the maximum flow rate of 0.2 m^3/s and a minimum of 0.16m^3/s while the valve is considered to be 90% opened at full capacity. The 90% valve opening is to ensure a conservative figure and a fully flexible system.

3.7.2. Pump Station 2 with One Pump Failure

The system is assumed to experience its first failure at one of the installed 28 pumps. This failure will lead to a drop in the maximum flow rate of this system to be lowered whereas the minimum flow rate will still be achieved. In the presence of one failure the system configuration changes from a ***6x4*** to a ***6x3*** and ***5x4*** configuration. This new configuration will bring about a decrease in the pump head curve and will cause a new maximum flow rate, commensurate to the new configuration, to be realized. This kind of scenario leads to a ***non-working*** failure of the system since the system continues to function but the mission has been altered and affected by the failure of one pump.

Where Nmfr represents new maximum flow rate under failure which is equal to 0.198m^3/s.

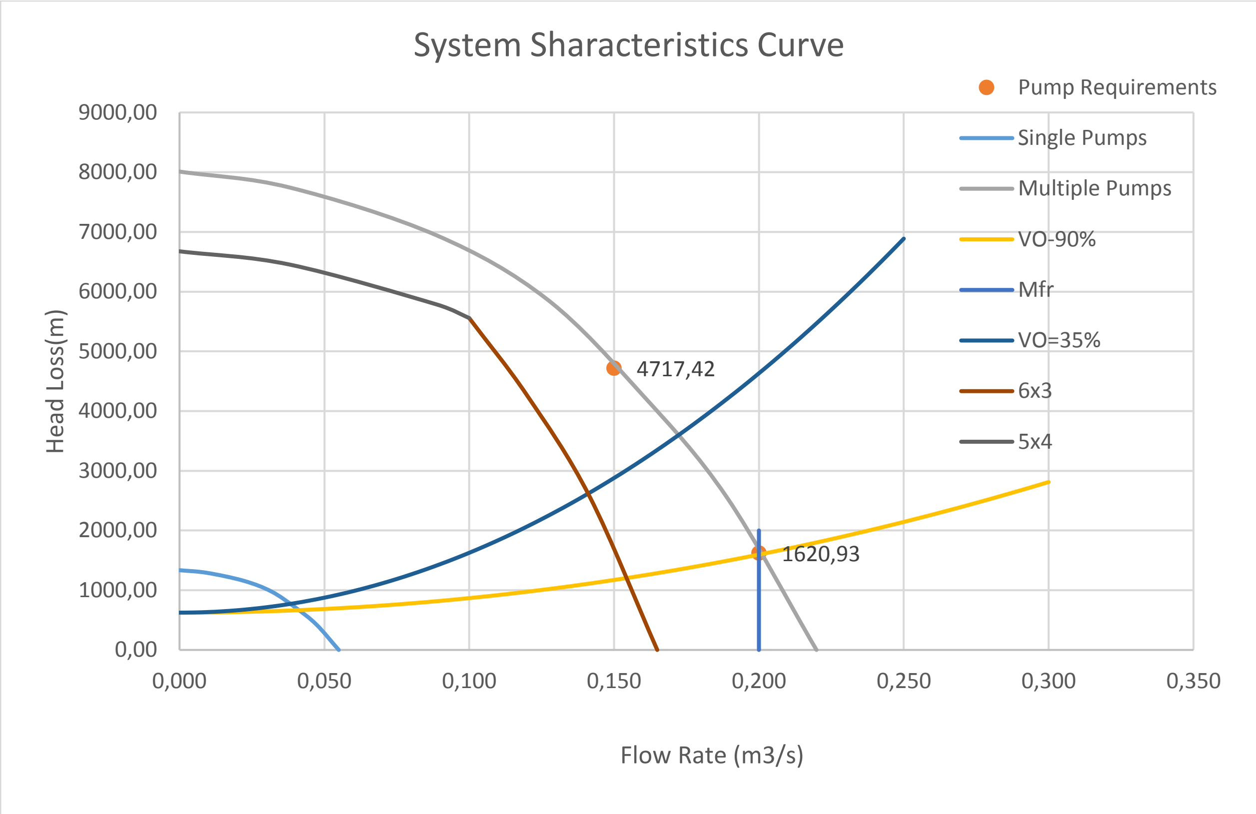

Figure 3.16: Pump Station 2 with 1 Pumps failed

3.7.3. Pump Station 2 with Two Pumps Failure

To give our system a huge flexibility and to get a conservative value, the assumption in this scenario is that two pumps fail simultaneously without any warning system. The failure mode here is also a ***non-working*** failure mode. We can have two scenarios of failure with 2 pumps failing in series or two failing in parallel leading to a 6x3 and a 4x4 configuration or a 6x2 and 5x4 configuration.

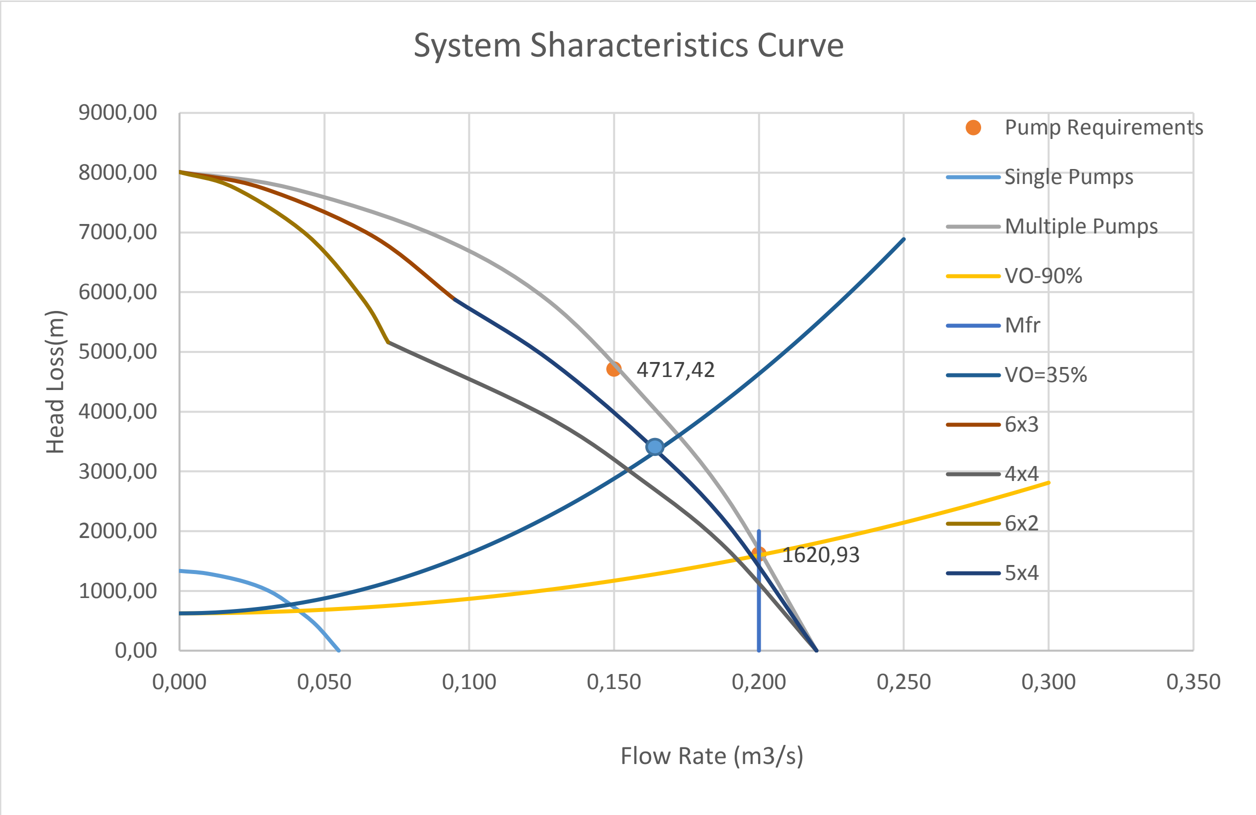

Figure 3.17: Pump Station 2 with 2 Pumps failed

The failure in the scenario analysed here finds a reduction in the maximum operating flow rate from 0.2m^3/s to 0.198 m^3/s for scenario 1 and 0.151 for scenario 2. While the minimum flow rate of 0.16 m^3/s is achieved in scenario 1 that value is greatly reduced in scenario 2 to an Nmfr of 0.103 m^3/s.

3.7.4. Pump Station 2 with Three Pumps Failure

Here also, to get a conservative value and give our system a huge flexibility, it is assumed that all three failures occur simultaneously without any warning system in place. Just as in the previous case, the failure of three pumps will lead to a reduction in the pump curve causing a ***non-working*** failure mode.

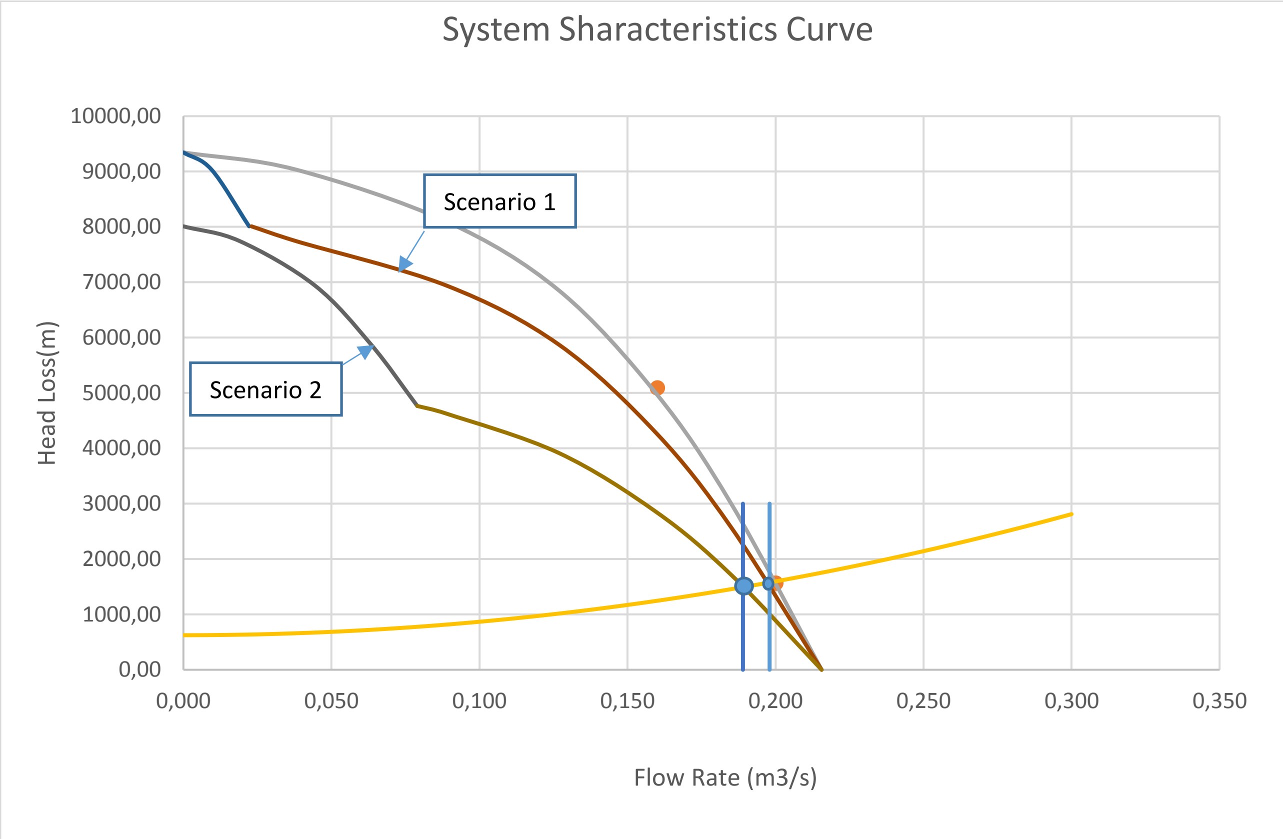

Figure 3.18: Pump Station 2 with 3 Pumps failed

3.8. Probabilities of Failure

To better understand the possibilities of failure and the effects on the flow rate of the system, a probability analysis was conducted to establish a relationship. This is done by analyzing the cases discussed in the previous section and assigning randomly a scenario of possible failures.

A graph has been generated from the probability values calculated to indicate a case of failure with up to three pumps failing simultaneously and the resulting flowrate that can be achieved with an MTTR of 10 days. When there is no pump failure the system will achieve its maximum flow rate of 0.2 m^3/s. but in the case of failure; the behaviour is observed.

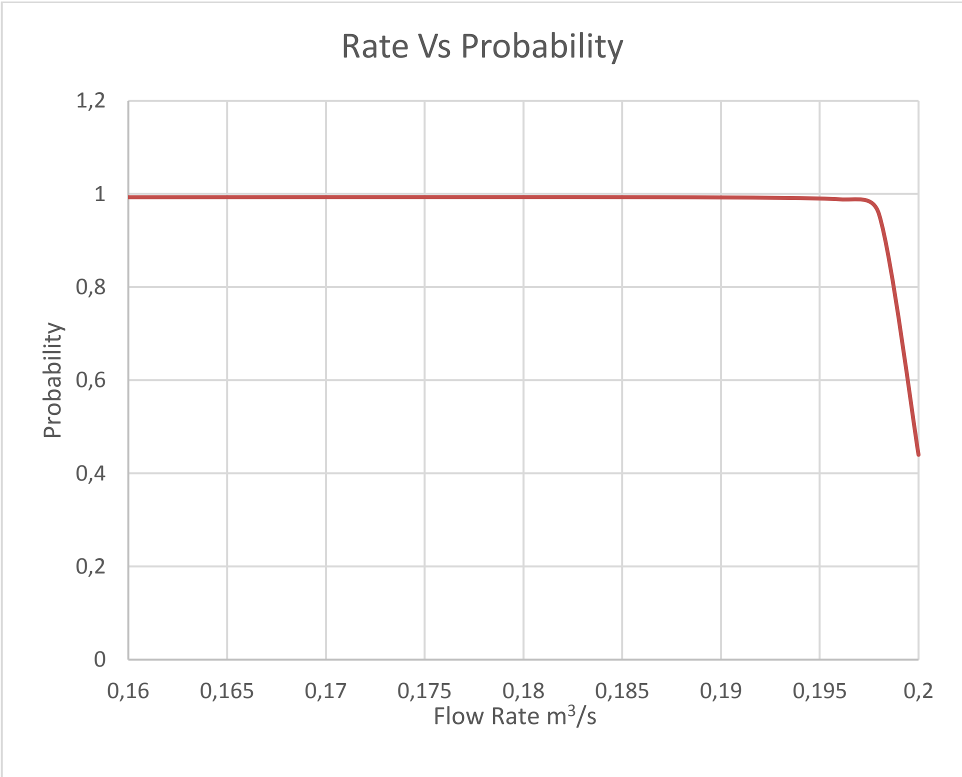

Figure 3.19: The probability of achieving a range of flow rates after failure for pump station 1

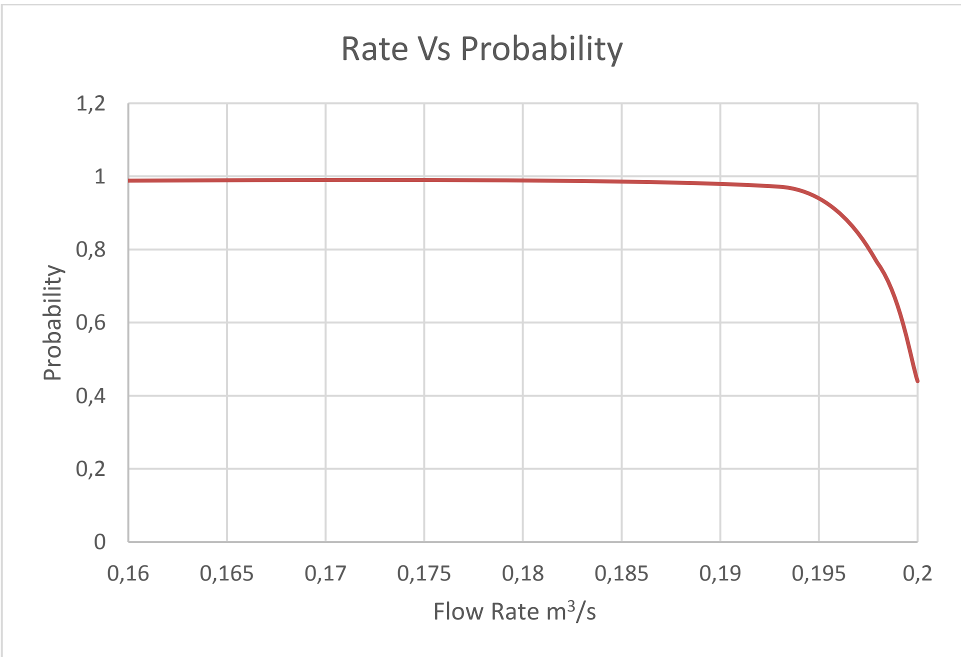

Figure 3.20: The probability of achieving a range of flow rates after failure for pump station 2

An interesting comparison can be drawn from the graph above to calculate the reliability of each pumping station at a given flow rate. A graph of the expected flow rate and the frequency is provided. The reliability of the pumping station can be easily evaluated at a range of flowrates using an integral.

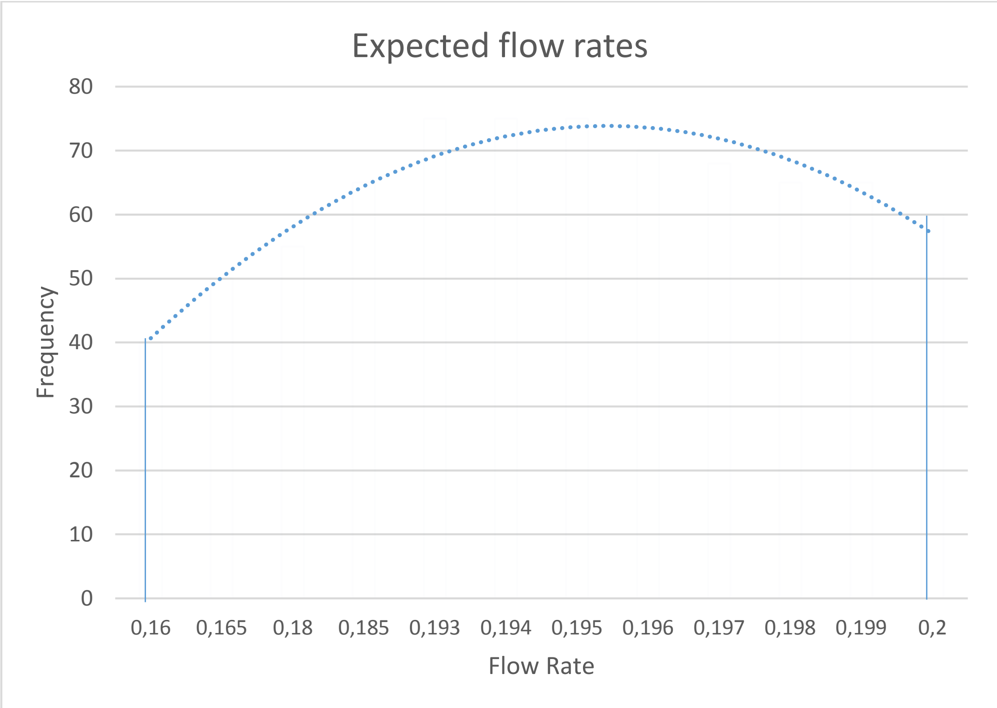

Figure 3.24: Frequency of expected flow rates.

Combining the integral of figure 3.24 above with the reliability values on figures 3.19 to 3.24 a reliability of the pumping station can be calculated taking into account flow rate frequency using equation 3.2

Chapter 4

Discussion & Conclusion

In addition to the failure scenarios studied in the previous chapters, a new scenario was suggested and applied to pump station 1. This new scenario increased the number of pump by adding a new pump in series to the 6x4 setup giving rise to a 7x4 system keeping the same flow rate requirements. For this arrangement, we studied failure of up to four pumps failing simultaneously and calculated the probabilities and the resulting flow rate which are presented below;

Number of Pump Failures	Cases	Cumulative Probability	NMFR
0 Failure	0	0.965	0.200
1 Failure	Failure State 1	0.988	0.198
2 Failures	Failure State 1	0.991	0.195
	Failure State 2	0.996	0.192
3 Failures	Failure State 1	1.000	0.195
	Failure State 2	1.000	0.195
	Failure State 3	1.000	0.195
	Failure State 4	1.000	0.195
4 Failures	Failure State 1	1.000	0.195
	Failure State 2	1.000	0.195
	Failure State 3	1.000	0.195
	Failure State 4	1.000	0.195
	Failure State 5	1.000	0.195
	Failure State 6	1.000	0.195

Table 4.1: Cumulative probability with one more series arrangement for pump station 1

From the figures in the table above, it can be concluded that the system is more reliable in this case and there is a close probability of achieving the required range should pumps fail.

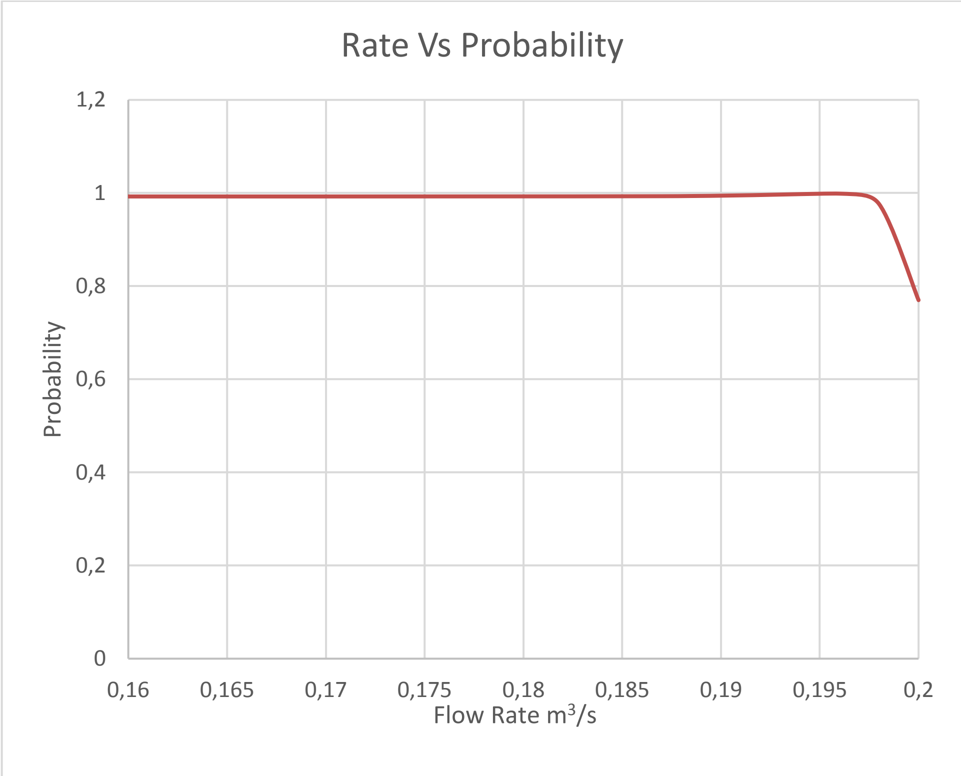

Figure 4.1: The probability of achieving a range of flow rates after failure for pump station 1 with additional pumps in series

4.1. Effect of MTTR on Reliability

The effect of MTTR duration was analysed to see if it increased the probability of failure of the pump station, and an interesting result was obtained. The reliability of the pumping station was higher at lower flow rates suggesting that when designing a pumping station, we can give room for a higher maximum flowrate so that the reliability of the system at the desired flowrate could be much higher. Another interesting result shown here is the fact that the MTTR has an effect on the overall system reliability. The MTTR was varied in the calculations and this indicated naturally that systems with shorter MTTR have are more reliable at higher flow rates.

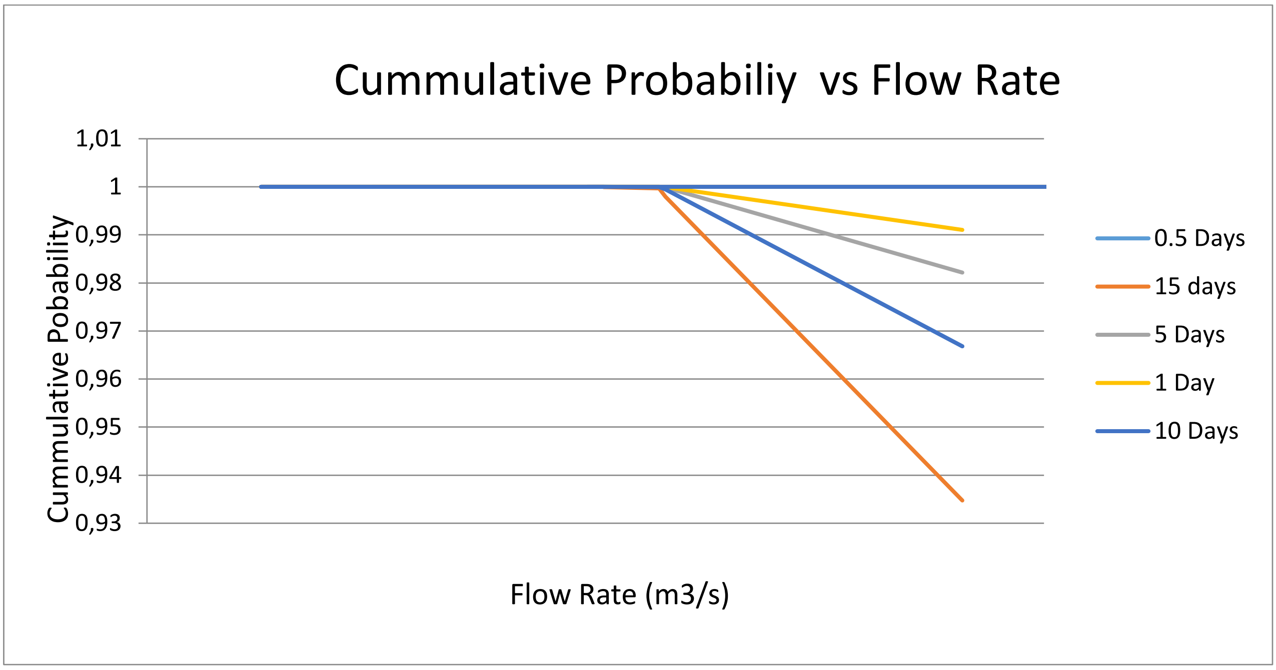

Figure 4.2: Influence of MTTR

4.2. Conclusion

- Increasing the number of pumps has a huge influence on the flow rate achieved.
- Increasing the number of pumps could improve the reliability of the system
- For a pumping stating with an additional set of pumps in series, the flow still operated at the required range even with up to four pumps failing simultaneously
- The probability of success can be increased by reducing the MTTR of the system.
- Flexible design that increases the maximum flowrate of the system without having a negative effect on the desired flow rate could boost system reliability.

Bibliography

Ash, Robert B. 2009. *Basic Probability Theory.* New York: Dover Publications.

Barringer, H. Paul,. 1997. *Availability, Reliability, Maintainability, and Capability.* Texas: Barringer.

Billinton, Roy, and Ronald N. Allan. 1992. *Reliability Evaluation of Engineering Systems: Concepts and Techniques, 2nd Ed.* New York: Plenum Press.

Dragon, Josh. 2002. "Pump Station Design Guidelines, 2nd edition." *AIChE Clearwater Convention.* New York.

Emerson. 2009. "Valve sizing calculation (Traditional Method)."

europipe. 2017. *Europipe.* August. http://www.europipe.de/.

Faber, M. Havbro. 2001. *Basics of Structural Reliability.* Zurich: Swiss Federal Institute of Technology ETH.

Grinstead, Charles M Snell, Laurie J. 2007. *Introduction to Probability.* Hanover: Dartmouth College.

Guyer, J. Paul. 2012. *Introduction to Pumping Stations for Water Supply Systems.*

Hamdi, Hassan O. Ahmed S. 2014. *Reliability Block Diagram.* Rhodes.

J., Smith D. 2001. *Reliability, Maintainability and Risk.*

Marvin, Rausand. 2004. *System Reliability Theory: Models, Statistical Methods, and Applications, 2nd Ed.* NEw Jersey: John Wiley & Sons.

Moody. 1994. *Friction Factors for Pipe Flow.* New Jersey.

Pumps and Systems. 2017. *Centrifugal Pumps.* October. https://www.pumpsandsystems.com .

2003. *Review of Reliability Theory, Analytical Techniques, and Basic Statistics.*

Theodora.com. 2017. *Nigeria Oil and Gas Pipelines.* 12 August. http://www.theodora.com/pipelines/nigeria_oil_gas_and_products_pipelines_map.html .

Todinov, Michael T. 2013. *Flow Networks: Analysis and Optimization of Repairable Flow Networks, Networks with Disturbed, Static Flow Networks and Reliability Networks.* London: Elsevier.

Topside Equipment. 2009. *SINTEF Technology and Society, Offshore Reliability Data Handbook.*

US Tubular. 2017. August. http://www.usstubular.com.

Weibull. 2017. *The Bathtub curve.* September. http://www.weibull.com/hotwire/issue21/hottopics21.htm.