Theoretical Insights into Pressure Reducing Valve Mechanics and Control for Perth's Water Supply

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Abstract

Water Corporation utilizes many Pressure Reducing Valves (PRVs) in the Perth Water Supply (PWS). Many of these operate with a high-pressure differential to reduce the probability of a failure mode known as hydraulic lockout. In preparation for delivering a new major water source, Water Corporation seeks to improve the hydraulic capacity of the PWS by lowering the operating pressure of the PWS trunk mains, which risks causing hydraulic lockout. This project's objective is to provide an analysis of the operation, mechanics, and operational risks of PRVs and provide recommendations to reduce trunk main pressure. By conducting a data analysis on data acquired from Water Corporation pump stations, the project has identified an estimated energy cost related savings between $150,000 to $300,000 AUD by reducing trunk main pressures, depending on several scenarios. The project deliverables include a review of PRV mechanics, a definition of the control strategies, an analysis of PRV operational risks, and a recommendation for the best performing control strategies.

1. Introduction

Water Corporation must reduce trunk main pressures in the Perth Water Supply (PWS) to achieve the hydraulic capacity required to efficiently transfer water from a new water source. Reducing pressure without addressing limitations on existing Pressure Reducing Valves (PRVs) could cause total loss of operational control through a mechanism called 'hydraulic lockout'.

PRVs are valves used to lower the pressure of fluid transported through a pipeline to a targeted downstream pressure level. Hydraulic lockout, also known as hydraulic lock-open, is known to occur when the upstream pressure at the inlet of the PRV becomes equal to the downstream pressure at the outlet of the PRV. In this situation, the valve is designed to fully open, to raise the declining downstream pressure. A PRV can become stuck open in this position when the differential pressure used to force the valve closed is insufficient to overcome the friction forces within the valve. Without differential pressure across the valve, the force available to change the valve's position is insufficient, and it is unable to perform its pressure control function.

Currently, the Water Corporation policy regarding the at-risk PRVs identified by this project, dictates that the difference between the upstream and downstream pressure heads must be at least 20 m (H_2O), or approximately 0.2 MPa. The main reasoning is to reduce the chance that the PRV fully opens, avoiding the risk of the valve becoming hydraulically locked out. This policy requires additional energy consumption from Water Corporation pumps, and leads to lower accuracy in PRV operation. Implementing an external pressure source to simulate higher upstream pressure could be a solution to hydraulic lockout, but future testing will be conducted to verify this.

The objectives of this project include:

- descriptions of PRV operation, mechanics, and control strategies,
- a summary of the current PWS energy consumption with an estimate of energy costs saved by reducing trunk main pressure,
- a recommendation for PRV control system testing based on a risk analysis.

2. Process

Microsoft Excel has access to a module called "Pi Datalink", which allows historical sensor data to be extracted from Water Corporations data historian software. For use in this project, Microsoft Excel was found to be inefficient for large data sets. Python was used to model data after raw data had been extracted and cleaned in Excel. Python's "Pandas" module allows Excel documents to be imported into Python as an array. Input data can then be filtered to sort data by specific time periods before functions are applied.

Four models were generated in Python, two for PRV modelling, and two for pump station modelling. The input data sets for these models were acquired from Pi Explorer. Each PRV has a dimensionless valve flow coefficient, K_v, defined as flow[m^3/3600·s] at 1 bar at 15 degrees Celsius. K_v values required for the modelling of PRV flow rate and power were acquired from the manufacturers engineering data sheets for each PRV. The K_v of a PRV can change over time due to wear, maintenance, or the configuration of the PRV, and due to conflicting records on older PRV models, K_v values obtained are not always reliable. A Python model was made to be able to verify K_v values of a PRV but required PRV flow sensor data to operate.

To control a PRV's position externally, an amount of water must be added to the PRV control chamber to add pressure to the diaphragm. To identify how much water is required for this, the relationship between valve position and PRV bonnet volume is to be determined via a field test. This test was conducted during a scheduled maintenance of a PRV, which involved the disassembly of the PRV411. The PRV, once isolated from the PWS, was filled with water, such that the position sensor indicated the PRV was 100% open. Water was then removed from the PRV control chamber in set intervals, with the volume of water released, and the position reading being recorded, until the control chamber was emptied.

2.1 Modelling Equations

The first model uses the equation for hydraulic power to estimate power removed by PRV as:

$$P = \Delta h * Q * \rho * g \tag{1}$$

Where:

P = Hydraulic power in Watts [W]

Δh = differential pressure in metres head [m H_2O], given as the difference between the upstream and downstream sensor readings of a PRV

Q = flow rate in cubic metres per second [m^3/s]
ρ = density of water in kilograms cubic metre [kg/m^3], (assumed = 1000 for water)
g = acceleration due to gravity [m/s^2] (assumed = 9.81)

This equation was also used in the second Python model to generate a second value for pump station power consumption for comparison with the power data extracted from Pi explorer. It was assumed that the Pi Explorer power readings consider pump hydraulic efficiencies, as the power consumption readings are generally slightly larger than those calculated using the above equation. This difference was generally observed to be around 5%. As no flow sensor was available for the majority of PRVs, flow rate Q was calculated based on the following equation (Bermad Waterworks (2016)):

$$Q = pos * K_v/3600 * \sqrt{\Delta h/10.2} \quad (2)$$

Where:
pos = the position reading of the PRV [percentage expressed as a decimal]

The second python model use the following equations to predict the power saved from a trunk main pressure reduction or new setpoint. For a regular pump station, with only one output:

$$P_{saved} = P * (R/\Delta h) \quad \text{or} \quad P_{saved} = P * ((P_{ds} - P_{SP})/\Delta h) \quad (3), (4)$$

Where:
P_{saved} = Power saved in watts [W]
R = Future scenario Trunk main pressure reduction in metres head [m H_2O]
P_{ds} = Downstream pressure in metres head [m H_2O]
P_{SP} = Future scenario Trunk main head setpoint in metres Australian Height Datum [mAHD]

The third Python model used altered equations to account for the pump bank setup of [Pump Station 2]. At this pump station, the pumps are in series, but only the output of the first pump bank flows towards PRVs. The second pump bank outputs towards reservoirs. This means a reduction of trunk main pressures upstream of the PRVs reduces pressure at the input of the second pump bank, increasing the bank's differential pressure, and power consumption, rather than decreasing it. This required the equations to become:

$$P_{saved} = (P_A + P_B) - (\left(P_A * \left(\frac{\Delta h_A - R}{\Delta h_A}\right)\right) + \left(P_B * \left(\frac{\Delta h_B + R}{\Delta h_B}\right)\right)) \quad (5)$$

$$P_{saved} = (P_A + P_B) - (\left(P_A * \left(\frac{P_{SP} - (P_{dsA} - \Delta h_A)}{\Delta h_A}\right)\right) + \left(P_B * \left(\frac{P_{dsB} - P_{SP}}{\Delta h_B}\right)\right)) \quad (6)$$

Where:
$[X]_A$, $[X]_B$ = [X] of pump banks A, B, respectively.

2.2 PRV Modelling

Each of the 15 PRVs identified by an internal Water Corporation project to be modified had their sensor data gathered from Pi explorer, cleaned in Excel, and input into the first Python model. The data from Pi explorer was extracted using an hourly time-weighted average and contained the average hourly recordings for each PRV's upstream pressure, downstream pressure, and position for the years 2022 to 2024. Using this hourly average was important to provide an even distribution of sensor data, although some precision was lost. This Python model was used to identify relationships between position measurements and differential pressure across the PRVs, and between hydraulic power removed from PWS by a PRV and time. This model required the specific K_v value of each valve to be input, to generate flow rate estimates. These K_v values were supplied by the PRV manufacturer.

A second PRV Python model was developed, as a modification to the first model, which takes PRV data that includes data all inputs of the first model, in addition to data collected from a flow sensor. The purpose of this model was to verify the flow rate estimation of the first model and compare the K_v value used in the first model, to the K_v value calculated based on sensor data. This model compared the means and ranges of the two flow rate data sets and predicted the effective K_v value. Once an estimated K_v value was generated, the theoretical flow rate was recalculated using this new K_v and plotted on the same graph as the flow sensor data.

2.3 Pump Station Modelling

The pump station Python model used data gathered from sensors on pump stations within the PWS. The pressure output, differential pressure, power consumption and flow rate data were extracted in Excel, cleaned, and input into the second Python model. This model also took the electricity cost [in $ AUD/kWh] per hour, per month (as an array) as an input. The model sorted each data input from each pump station and combined each with its corresponding electricity cost value to estimate how much was spent on each pump station annually. This model had additional modes and was used to predict how much of this expenditure can be saved by reducing trunk main pressure by an amount, or to a setpoint.

A second pump station Python model was developed, as a modification to the first model that accounted for the specific conditions of [PUMP STATION 2]. This model was mostly the same as the previous model, but the input data file included data sets for both pump station banks.

These two models were used to predict the energy cost savings to be achieved from reducing trunk main pressures. For the estimation of savings, calculated as the power conserved multiplied by time and the cost of energy, two values for power were used in the modelling; the power consumption from Pi explorer (P_{Pi}), and the hydraulic power required from the power equation in Section 2.1 (P_{calc}). The amount of trunk main pressure reduction was estimated based on the downstream pressure setpoints of PRVs within the PWS. For each of the PRVs, the hourly average upstream data from 2024 was collected, and the tenth percentile value was selected as an estimate for how low the upstream pressure typically reaches. The difference between these minimum upstream pressure estimates (Min. P_{us}) and the downstream head setpoints ($P_{ds.SP}$) was calculated to estimate the tolerable trunk main pressure drop allowable while maintaining downstream pressure supply.

Four trunk main pressure reduction scenarios have been identified; an 11m pressure reduction based on the minimum tolerance among all Perth PRVs, a 29.7-metre pressure reduction based on the minimum tolerance of only PRVs within the upgrade project, a 20-metre reduction based on the minimum PRV differential pressure policy, and a reduction of trunk main head to 80 mAHD based on predicted future Water Corporation operations plans.

3. Results and Discussion

3.1 PRV Modelling

The graphs below represent the average differential pressure, power consumption and flow rate across PRV411, for Summer and Winter from 2020 to 2024. From the graphs, it can be observed that the flow rates through PRV411 increase in summer, and during peak times, in the morning around 8am and evening at 7pm. These peaks coincide with peaks in hydraulic power removed by the PRV, where a differential pressure reduction would have the most effect.

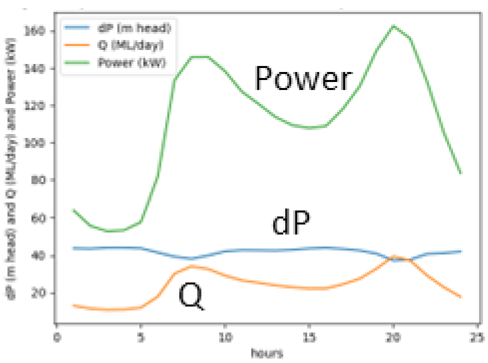

Figure 1 - PRV411 dP (Δh), Q, Power cons vs hour Summer

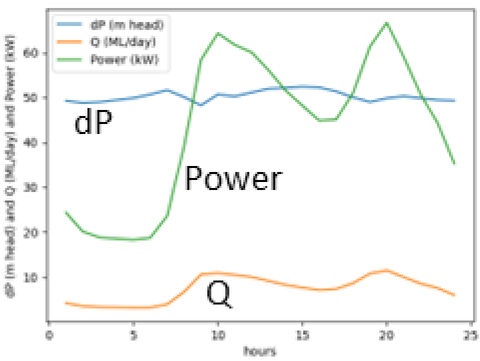

Figure 2 - PRV411 dP (Δh), Q, Power cons vs hour Winter

3.2 Pump Station Modelling

Pump Station	11m red	20m red	29.7m red	80m SP
[Pump Station 1]	$81,981	$149,057	$216,133	$145,349
[Pump Station 3]	$70,649	$128,454	$186,258	$147,357
[Pump Station 2]	-$2,128	-$3,869	-$5,610	$843
Total	**$150,502**	**$273,642**	**$396,781**	**$293,549**

Table 1 Annual savings in AUD using P_{pi}.

Pump Station	11m red	20m red	29.7m red	80m SP
[Pump Station 1]	$77,247	$140,450	$203,653	145,416
[Pump Station 3]	$94,120	$171,127	$248,135	197,462
[Pump Station 2]	-$936	-$1,703	-$2,469	5,497
Total	**$170,531**	**$309,874**	**$449,319**	**348,375**

Table 2 Annual savings in AUD using P_{calc}.

3.3 PRV411 Field Test Results

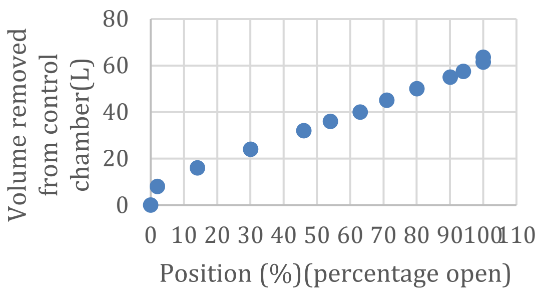

Figure 1 – PRV411 chamber volume (L) vs pos (%)

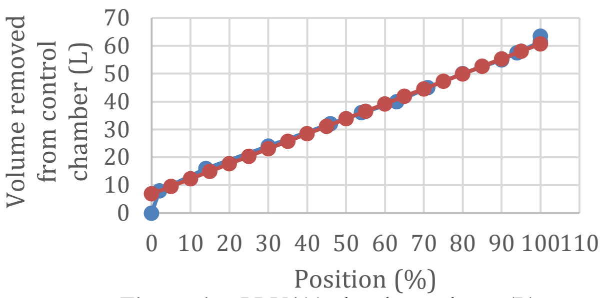

Figure 4 – PRV411 chamber volume (L) vs pos (%) with linear relationship

Using P_{Pi} as the highest confidence calculation method, as it was sourced directly from Water Corporation software, the future operation plan of 80 mAHD trunk main head pressure is expected to result in savings of approximately $293,000 AUD annually, ignoring electronic inefficiency. If Water Corporation Operations finds any issues with this plan and decides to reduce trunk main pressure less, a more conservative estimate for trunk main pressure reduction is offered by the 11m reduction scenario, with approximately $150,000 AUD saved annually. PRV411 has a rated bonnet volume of 56 litres. The relationship between volume and position is required to determine what volume of water a control system would need to add to this PRV's control chamber to produce a desired response in the valve's position, such as would be necessary to alleviate hydraulic lockout.

A linear relationship can be fit as Volume(L) = 0.538*position (%) + 6.92 for position >0 and <100. This curve excludes the data assumed to be deadband outliers. The range of the linear relationship was 53.8 litres, which is less than 4% less than the rated volume. Volume vs position appeared linear, although there seemed to be some excess water above and below the diaphragm, about 7 litres below and 3 litres above. It can be assumed that the volume given by the manufacturer (56L) is the volume from 0-100% (measured as 54L, ~5% difference), and the required volume to change the position can be calculated easily using a simple linear equation. If the position of the diaphragm is to be moved from 100% to 80%, the amount of water added can be estimated from the linear equation(10.8L) plus the deadband above 100% (7L).

4. Conclusions and Future Work

The Pump station modelling presents significant energy savings to be achieved by reducing trunk main pressures. Savings may be predicted more accurately in the final report by increasing the resolution of the data collected from Pi Explorer, at the cost of increased processing times. This would decrease the discrepancy between P_{pi} and P_{calc}. The PRV modelling results could be refined in future study arising from this work by using data from PRVs with flow sensors attached. Recreating these graphs with data sorted into ranges of flow speed may more effectively display the dP vs pos relationship by removing Q as a factor. The PRV field test data provided the relationship between volume and position for valves of this model, but this data may not be applicable to each PRV in the PWS, as their makes and models vary. This simple test is recommended on other PRVs during commissioning of the new control systems. Future work to be completed for this CEED project includes the risk analysis of each PRV control strategy, an analysis of PRV response times, a recommended control strategy setup, and a testing method with criteria for success for a PRV control system.

5. Acknowledgements

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6. References

Bermad Waterworks, Pressure Reducing Valve with Solenoid Control – Model 720-55, (2016) https://www.bermad.com/app/uploads/2016/06/ww-720-55.pdf