Caen Hill Pumping Station

PUMP AUDIT SUMMARY REPORT

NICK TAYLOR

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PUMP AUDIT SUMMARY REPORT

Author: Nick Taylor **Organisation:** Arcadis

Checker: Jermaine Bernard

Approver: Niklas John

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Content

1 Introduction

This report summarises the key findings of the desktop and site system audits for Caen Hill Pumping Station (PS). The review is based upon the following inputs:

- data provided by Canal and River Trust (CRT)
- a preliminary site visit undertaken on 4th June 2019
- a site investigation by Arcadis and Samatrix on 11th September 2019.

The report aims to cover the following areas:

- Derivation and analysis of the existing system curves and pump curves
- Measurement and analysis of Net Positive Suction Head (NPSH) and compliance with currently installed equipment
- Report on current available pumped volumes under both single and dual pump operation at variable frequencies
- Report on current condition and defects including indicators of significant wear or performance issues
- Highlight non-conformance and potential risk areas for equipment or infrastructure damage
- Review and comment on current civils arrangements
- Identify and present potential areas for improvement

Figure 1 – Photo of Caen Hill PS Dry Well

2 System Description

2.1 Pumping Station

Caen Hill PS is situated near Devizes, Wiltshire, UK. Its purpose is to supply water up from Lock 22 to Lock 50 on the Kennet and Avon Canal. Constructed in 1996, it is of a dry well construction, housing 2 no. Xylem dry well submersible pumps normally operating in a duty/assist configuration.

Table 1 – Pump Details

Parameter	Description
Pumps	Xylem (Flygt) CT3240
No. of Pumps	2
Duty Configuration	Duty / Assist
Rated Motor Output	215 kW
Impeller Diameter	535 mm
Drives	Variable Speed (Mitsubishi)
VSD Operation	30 s ramp & 48.0 Hz Operating Frequency
Pipework	300 mm diameter
Non-Return Valves	Ball
Wet Well Level Sensor	Ultrasonic
Wet Well Level	55.5 mAOD
Pump Centre Line	54.3 mAOD

2.2 Rising Main

The rising main is approximately 3600 m in length and manufactured from Ductile Iron. There are no reports of bursts arising since construction. The rising main comprises 2no. intermediate discharge points, with in-line non-return valves (NRVs) complete with a return bypass. The NRVs are situated immediately downstream of each discharge point. The condition and operational effectiveness of the two NRVs is not known. CRT have not inspected them recently and this task would represent a significant intervention given that they are covered with large area concrete infill covers and in remote locations in the towpath of the canal.

Table 2 – Rising Main Details

Parameter	Description
Length	3602 m
Elevation Rise	72 m
Pipe Diameter	600 mm
Discharge Level	127.6 mAOD
Pipe Material	Ductile Iron
Intermediate NRV #1	1270 m from Caen Hill PS
Intermediate NRV #2	2410 m from Caen Hill PS

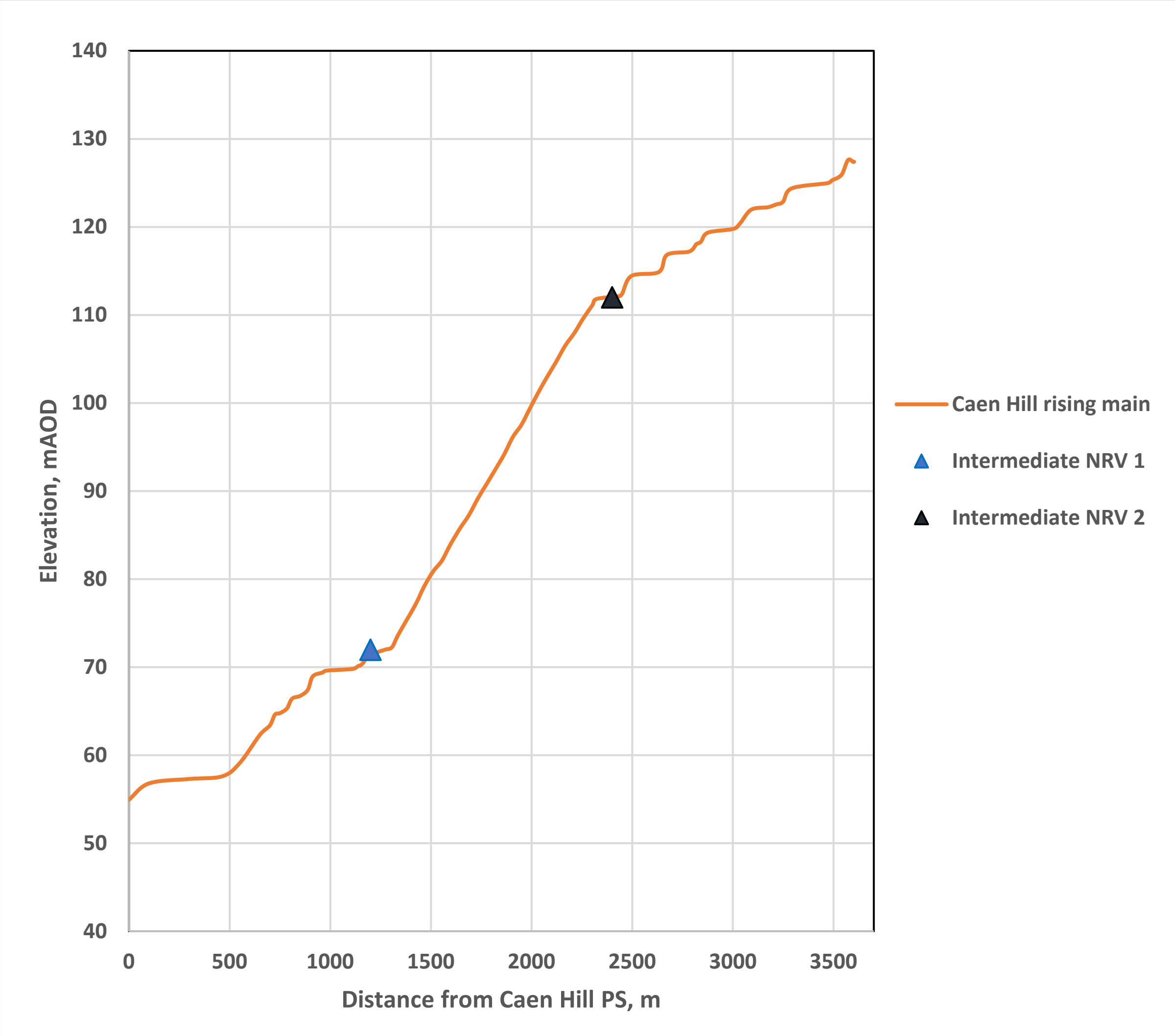


Figure 2 – Caen Hill PS Elevation Profile

2.3 Particular Issues

CRT have reported that the pumping station has the following issues, which are to be investigated as part of this study.

- Poor pump reliability, notably bearing life, suspected to be from high vibration levels
- Impeller damage from cavitation, suspected related to NPSH or poor intake design
- Cracks and Spalling of Pump plinths (supporting bases)
- Pipework flange leaks

These issues are covered further within this report.

3 System Curves

Site testing of pump performance was undertaken with a SME, Samatrix, on the 11th September 2019. The following parameters were measured and logged as part of the test.

- Input Power to each drive (via a portable "Fluke" power meter)
- Pumping Station Flow rate (via the existing installed flowmeter)
- Wet well depth (via a portable ultrasonic)
- Elevation via GPS
- Suction and Delivery Pressures (via pressure transducers)
- Spot vibrations in RMS velocity (via magnetic vibration accelerometer)
- Dimensions and levels of the pumping station.

Based upon the test results, system curves have been derived for the following three operating scenarios:

- Pumps P1 and P2 operating in parallel
- Pump P1 operating only
- Pump P2 operating only

The suction and delivery elevations, pipe roughness values have been based on recorded site measurements in addition to the desktop SCADA data provided.

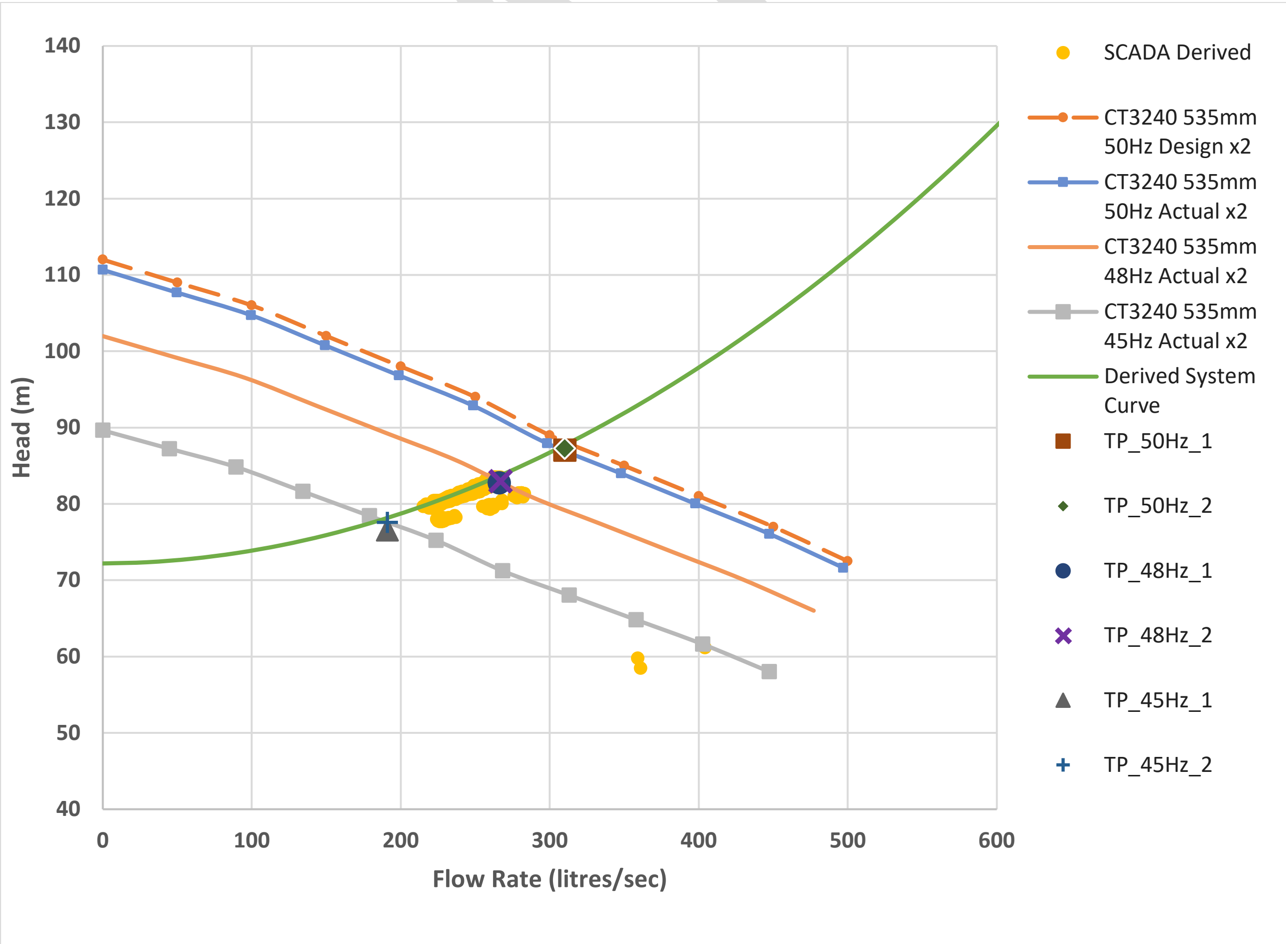


Figure 3 – Derived System Curves for 2-Pump Operation

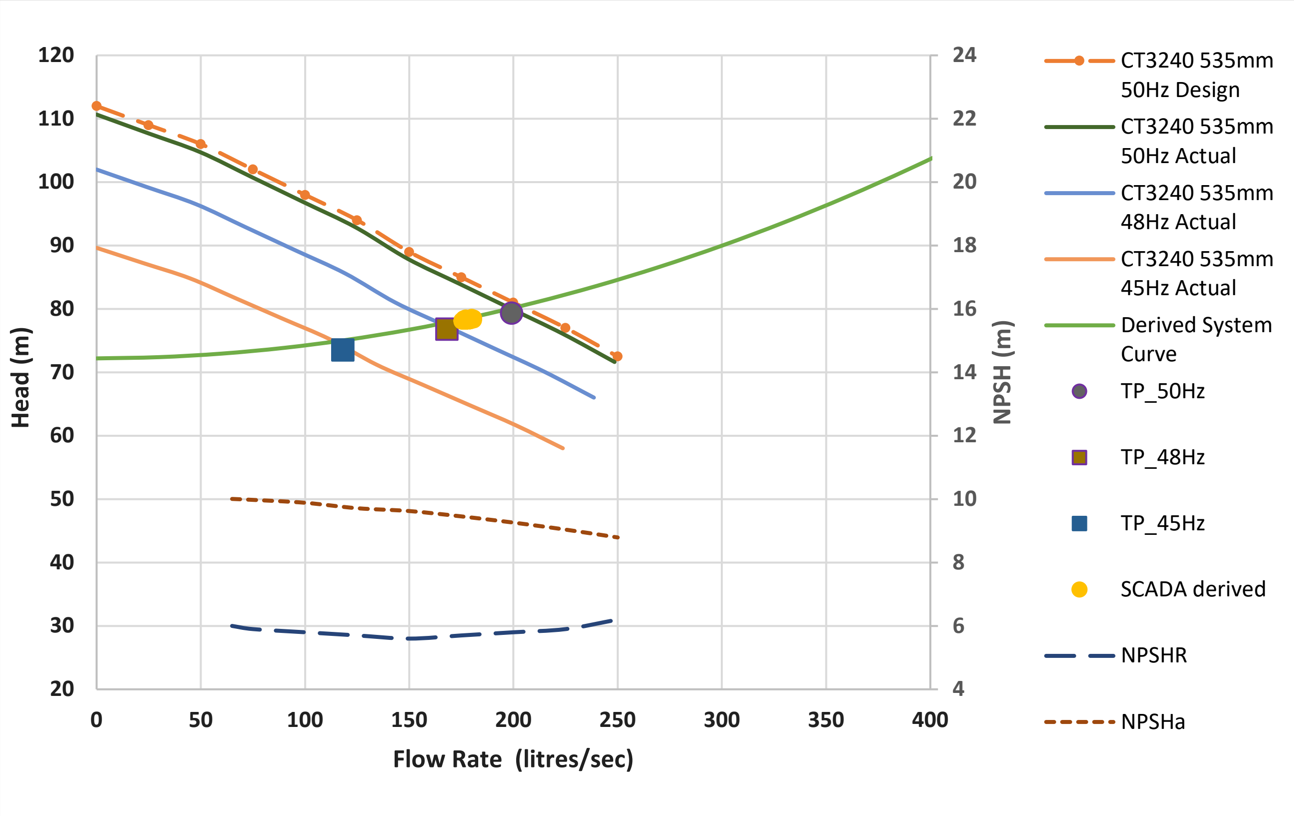


Figure 4 – Derived System and NPSH Curves for Pump 1 Only Operation

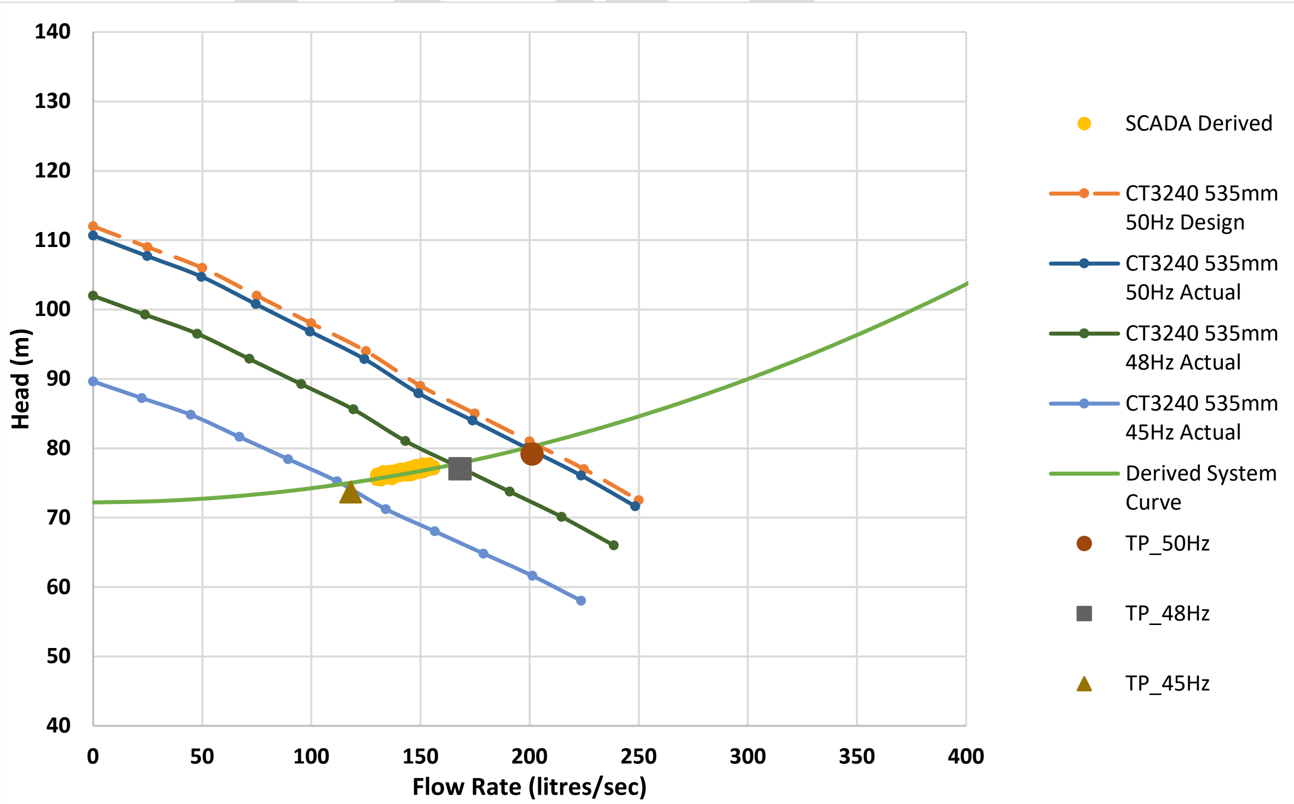


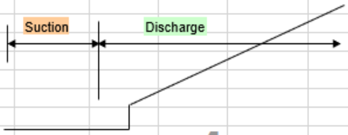
Figure 5 – Derived System Curves for Pump 2 Only Operation

The system curve calculation sheet is shown in Figure 6. In order to correlate the rising main losses with the SCADA delivery pressure data, high values for loss coefficients were required in the system curve head loss calculation, as highlighted.

1 INPUT DATA

Gravity, g	9.81	m/s2
Atmos pressure	101.3	kPa
Fluid	Water	[select]
Temperature	3	°C
Kinem. viscosity	1.62E-06	m2/s
Density	1000.0	kg/m³
Vap pressure	0.0766	m

Sump levels		
TWL	55.5	mAOD
Design	55.5	mAOD
BWL	55.5	mAOD



Pump level:	54.3	mAOD
Pump station located before reach:	2	[select]

Assumed Hydraulic Discharge levels		
TWL	127.7	mAOD
Design	127.7	mAOD
BWL	127.7	mAOD

Static lift			
	Minimum	72.2	m
	Design	72.2	m
	Maximum	72.2	m

Reach:		1	2	3	4	5	6	7	8	9	10	11	12	13
Description		CAEN HILL PS	CAEN HILL Main	CAEN HILL Main										
Length (m)		2	6	3600										
Diameter (m)		0.3	0.3	0.6										
Flow area (m²)		0.070686	0.070686	0.282743	0	0	0	0	0	0	0	0	0	0
Roughness (mm)	Low	0.03	0.03	0.03										
	Design	0.3	0.3	0.3										
	High	0.3	0.3	0.3										
Proportion of station flow		1	1	1										

Global head loss factor 0 % (added to friction and fittings losses throughout)

	Fittings Losses:	k-value	Number of fittings:												
1	Inlet (slightly rounded)	0.25	1												
2	Short R 90˚ bend	0.75	2	1											
3	Swing check valve	1		1	2										
4	Gate valve	0.12	1	1	2										
5	T straight through	0.35		1	2										
6	Short R 45˚ bend	0.3			10										
16	Outlet	1			1										
	Additional K (other devices)			0.1	120.0										
	Total K		1.87	2.32	126.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
			Equivilient Headloss		3.06	m									

Figure 6 – Hydraulic Calculation Input Data

The key observations from the derived system curves are as follows:

a) The site test results backed up by the SCADA data raised a concern with the rising main losses. For a relatively new pipeline main of less than 25 years' service, an additional head loss coefficient of 120 was necessary for the calculations to obtain an equivalent head loss performance. This creates an additional 6m at 300l/s. To put this into a physical context, a restriction equivalent to an orifice of 224mm create the same loss within the system.

b) From the 2018 SCADA data, Pump 2 experienced some hydraulic issues and performance below its curve. This was explained by AMCOs recent maintenance and removal of blockage items, after which the pump delivery performance was reported to have improved from 121l/s to 169l/s once returned to operation. This performance improvement was confirmed at the site test.

c) The performance of the pump curves were adjusted down from the manufacturers published performance curves in order to align with site results. The reduction being an equivalent of 0.3 Hz on a VSD. It is noted that impeller impact damage is present on Pump 2 as discovered from the recent AMCO maintenance visit, which may have had an impact. It is also noted that this curve is still within "as new" manufacturers tolerances[1] .

d) The best efficiency point (BEP) of the installed CT3240 pump is just to right hand side of the pump curve extents as shown in the system curves i.e., 262l/s @ 70m for 1-pump and 524l/s @ 70m for 2-pump operation.

[1] *BS EN9906:2012 and assuming a 2B Test acceptance grade*

4 Net Positive Suction Head (NPSH) and Submergence

NSPH calculations have been undertaken and the results indicate there is a sufficient margin between NPSH required and NPSH available of approximately 4 metres, as shown on Figure 4. In addition, the volute of the pump is located at a level lower than canal level so should always remain fully primed.

It is unlikely given the calculated suction head available that this is the root cause for the cavitation issues seen on the pumps. Other possible reasons for the presence of cavitation marks as found in the pump impeller include:

- A significant partial blockage within the inlet pipe or pump impeller
- Heavy siltation in wet well

5 Energy Analysis

At the pump audit visit by Samatrix, a temporary "Fluke" power meter was connected at the individual pump start compartment to record power into the pump VSD. From the measured power, flow rate, and pressure undertaken at the Samatrix audit visit, an analysis of pumping efficiency and energy has been undertaken.

Table 3 summarises the measured VSD input power, efficiency and derived specific energy findings.

Table 3 – VSD Input power, Efficiency and Specific Energy

Pump Configuration	Measured Flow rate (l/S)	VSD FREQUENCY (Hz)	Measured Power Factor	Measured power (kW)	STRING Efficiency *	Specific energy (kWh/1000 m^3)
Pump 1 Only	199	50	0.92	224.0	69%	312.7
	168	**48**	**0.90**	**187.5**	**68%**	**310.0**
	118	45	0.87	137.5	62%	323.7
Pump 2 Only	201	50	0.90	214.5	73%	296.4
	168	48	0.90	179.0	71%	296.0
	118	45	0.89	133.0	64%	313.1
Both Pumps (Power Measured at Pump 1)	310	50	0.92	201.0	66%	352.2**
	266	**48**	**0.91**	**170.0**	**64%**	**347.6****
	191	45	0.88	126.0	57%	360.7**
Both Pumps (Power Measured at Pump 2)	310	50	0.92	192.0	69%	352.2**
	267	**48**	**0.91**	**163.5**	**66%**	**347.6****
	191	45	0.89	122.0	60%	360.7**

* String Efficiency is overall "wire to water" efficiency including the VSD

** Averaged from both Pump 1 and Pump 2 individually measured power readings

The normal running frequency of each pump at Caen Hill PS is 48 Hz. From Table 5, running at 48 Hz results in a lower specific energy and therefore energy cost than running at 50 Hz or 45 Hz on a VSD. It can also be seen that 2-pump operation results in a higher specific energy and a lower overall operating efficiency.

This is as expected as the individual pump duty points under parallel operation are further to the left of its Q-H curve and further away from its best efficiency point which is exacerbated with a reduction in drive frequency. (Figure 8)

6 Pump Control

Under normal operation, the pumps operate automatically via level control. The lock flight level at the discharge location (Lock Flight 50) is monitored and transmitted to Caen Hill PS via telemetry. Upon this level falling to a pre-set low level, the pumps are started. Each pump ramps up to a manually set VSD speed of 48 Hz and both pumps operate in parallel (duty/duty) at fixed speed. When the discharge lock flight 50 level rises to a pre-set high level, the pumps both ramp down and stop.

Flow rate is measured via an on-site electromagnetic flowmeter, but it is not utilised for control. Additionally, both pumps have relay protection by means of a MAS 711 unit and low level (suction) protection.

Key pumping station data is available on CRT's central SCADA facility.

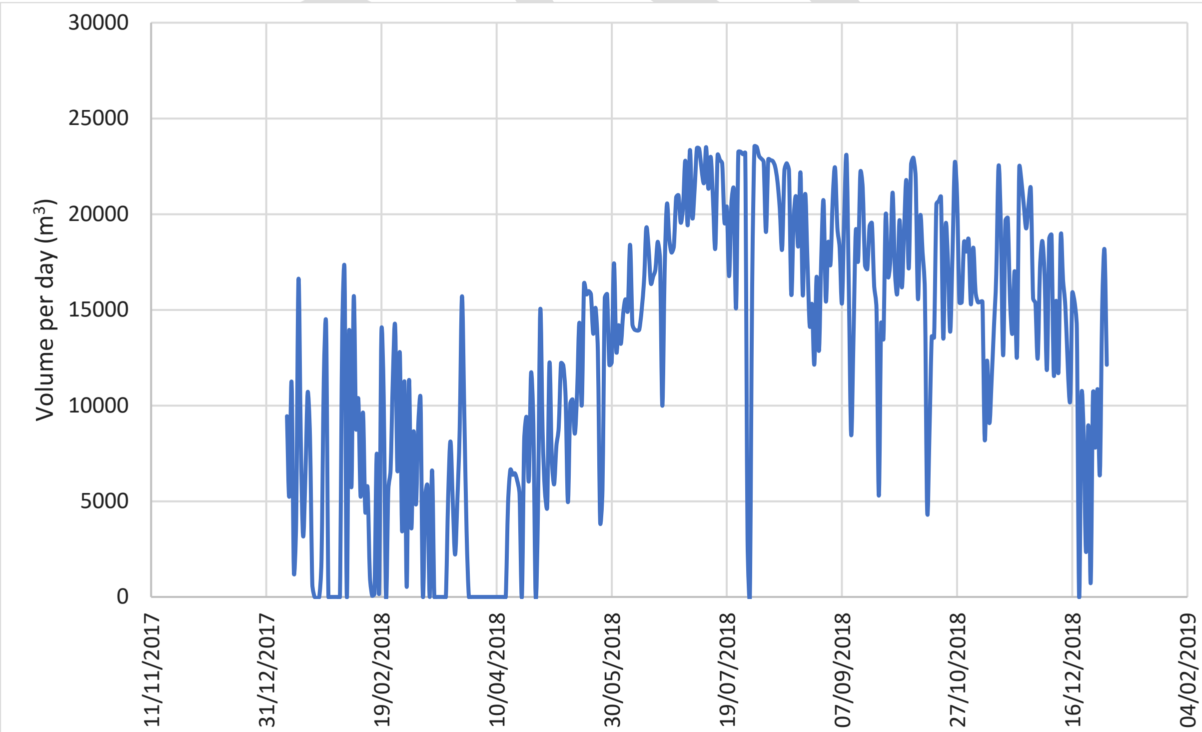


Figure 7 –Daily Volume Pumped during 2018 (Estimated from SCADA data)

The daily output volumes taken from the 2018 SCADA data in Figure 7 suggest that opportunities may exist for optimising control.

7 Vibration Issues

7.1 Pump Vibration

The pumps have poor reliability and Pump No.1 recently was removed following a failure and reinstalled. During the site visit it was noted that Pump 1 was leaking glycol coolant fluid from the top seal. This could be due to incorrect reassembly during recent refurbishment or alternatively it could indicate the start of another bearing failure.

The Pump Service centres inspection report stated the following findings:

- Pump was seized solid due to failed bearings
- Both seals had also failed causing some oil to pass into the stator housing
- Some water ingression into the oil housing causing the oil to emulsify
- There is some pitting in the centre of the impeller around the sleeve/cover possibly caused by cavitation; this has caused water to pass into the locking assembly.

It is understood that the typical bearing life for both pumps generally is short at between 2,000 to 3,000 hours, against a design life expectation of 50,000 hours. This is indicative of excessive vibration.

Figure 8 shows the manufacturer's pump curve. From the system curve the relative operating points for Operation at Caen Hill PS for single and dual pump operations have been derived.

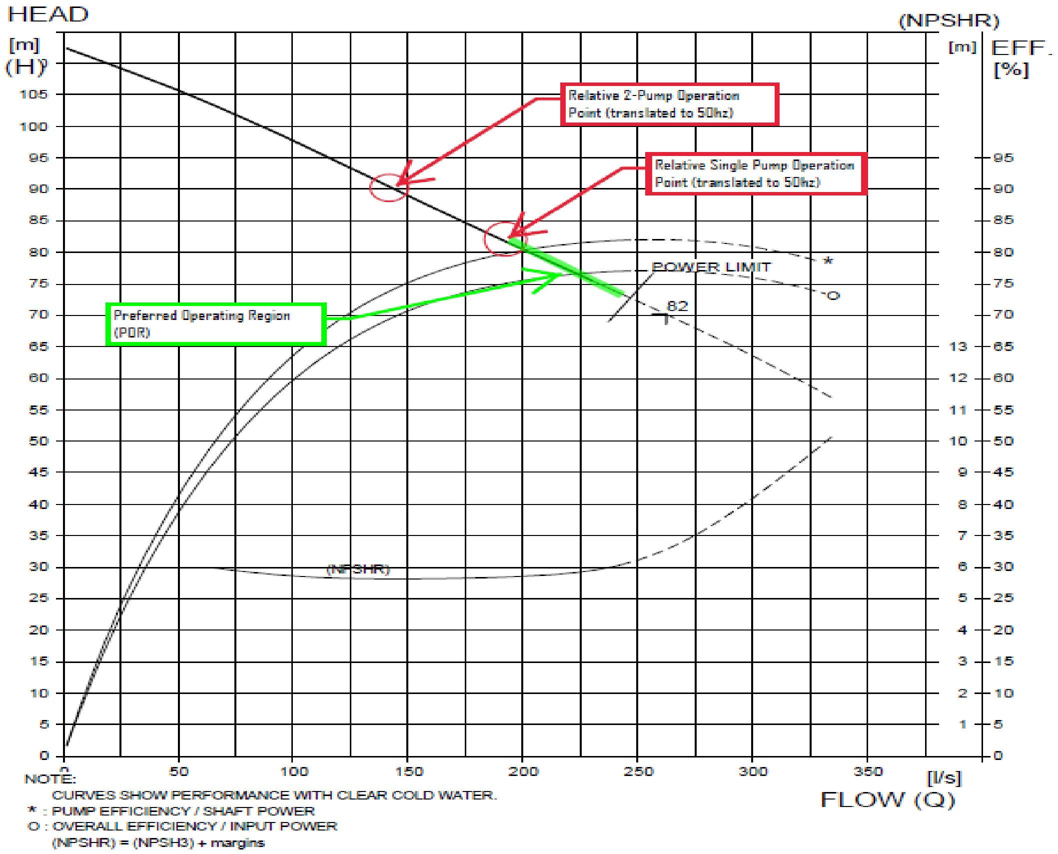


Figure 8 – Manufacturer's Pump Curve and Relative Operating Points at Caen Hill

The pump curve has a preferred operating region (POR), defined by being 70% to 120% of flow rate at the best efficiency point (BEP), where vibration should be lowest. This is highlighted in green in

Figure 8 and shows that single pump operation is within the POR but falls to the left of POR under 2-pump operation, which may be an indicator of higher vibration.

7.2 On-Site Vibration Measurement

Vibration measurements were taken at the pumping station at the site audit visit of 11th September 2019 and carried out generally in accordance with the guidance BS ISO 10816 Part 7.

The measurement was taken via the temporary in-situ placement of a magnetic transducer on the X, Y and Z axes at the drive bearing end (just above volute casing), and at the corner of the mounting plate.

Table 4 –Vibration measurements recorded on 11 September 2019

	Frequency	Flow (l/s)	Vibration X Axis Vel. (mm/s)			Vibration Y Axis Vel. (mm/s)			Vibration Z Axis Vel. (mm/s)			Vib. Mtg. Plate Vel (mm/s)		
Pump No. (s)	(Hz)	Average	Min	Max	Average	Min	Max	Average	Min	Max	Average	Min	Max	Average
1+2	48	266	10.80	14.30	12.60	11.30	17.60	13.50	14.50	17.90	16.40			
1+2	45	191	10.10	16.90	12.60	10.00	16.30	11.90	16.80	21.20	19.00			
1+2	50	310	14.80	20.80	17.00	16.60	23.80	19.00	10.60	15.30	12.20			
1	50	199	24.00	37.50	29.40	20.00	30.00	23.40	12.00	19.50	13.90	21.20	27.80	23.60
1	48	168	15.90	26.60	18.90	19.20	26.10	22.50	19.80	35.40	25.50	14.80	19.20	16.70
1	45	118	10.50	15.90	12.50	11.00	13.50	12.10	10.80	16.00	11.90	9.80	12.50	10.80
2+1	45	191	10.20	16.80	12.30	10.70	14.80	12.20	17.90	28.70	21.90			
2+1	48	267	11.40	23.60	14.20	10.60	15.40	12.40	17.20	26.50	20.90			
2+1	50	310	14.30	23.20	18.10	10.40	17.00	12.10	17.10	26.80	20.00			
2	50	201	12.50	22.30	15.50	N/R	N/R	N/R	17.50	22.10	19.10	16.50	26.10	19.40
2	48	168	11.40	16.60	13.20	10.30	16.60	12.20	14.80	20.00	17.50	16.20	21.40	17.90
2	45	118	8.90	20.60	12.40	11.20	20.60	13.80	15.80	20.00	17.70	14.70	18.90	16.90

7.3 Discussion

BS ISO 10816 Part 7 defines the requirements for the measurement and evaluation of rotodynamic pumps. This suggests that risk of damage occurs at vibration velocities of above 9.5 mm/s RMS. However, it should be noted that submersible pumps are excluded from the scope of this standard.

The scope of the Water Industry Mechanical and Electrical Specification (WIMES) 1.03 covers dry well submersible pumps as installed at Caen Hill. The applicable clauses for vibration are stated in the capture below:

7.2.3 Vibration Testing (Where Required) (Refer to Clause 7.1.1)

Refer to Guidance Notes.

1. Vibration velocity measurements shall be taken on the bearing housing in accordance with BS ISO 10816-7, with the pump unit operating in the range 70-120 % of the BEP. For variable speed pump units, testing shall be performed across the full range of pump unit operating speeds.

2. For pump units with multivane or vortex impellers, the maximum value of the Root Mean Squared (RMS) vibration velocity shall be 7.1 mm/s. For pump units with a single channel or screw centrifugal impeller, the maximum value of the RMS vibration velocity shall be 11.2 mm/s.

The model of pump installed at Caen Hill PS has a 2-vane (or 2-channel) impeller, which falls outside the definitions stated above on a technicality as it is not classed as a multivane impeller (≥ 3 vanes) nor a single channel impeller. Given this situation, applying the higher vibration limit of 11.2 mm/s RMS to the 2-channel impeller pump is a reasonable acceptance limit.

As can be seen from Table 4, both pumps significantly exceed the 11.2 mm/s RMS value under all tested operation scenarios. Therefore, it is safe to conclude that vibration is excessive and a probable reason for premature pump failure.

Finding the root cause of high vibration can often be difficult. However, the following points are noted.

The vibration levels on the mounting plate were also measured and indicated comparable levels of excessive vibration to the pump. This suggests that the concrete supporting plinths are not providing a firm anchored foundation. The evidence of cracking and groundwater/clay seepage at the plinth- floor joint suggests that the plinths are not adequately secured to the PS floor structure.

The spalling of concrete and further cracking within the concrete plinths is of concern and should be investigated as a priority.

Visually the pump baseplate and plinth appear in keeping with Xylem's recommendations (Figure 9). The interfacing of the plinths to the PS floor could not be seen, but it was noted that the floor itself near the plinths had a noticeable reduction in vibration from the plinths to the touch.

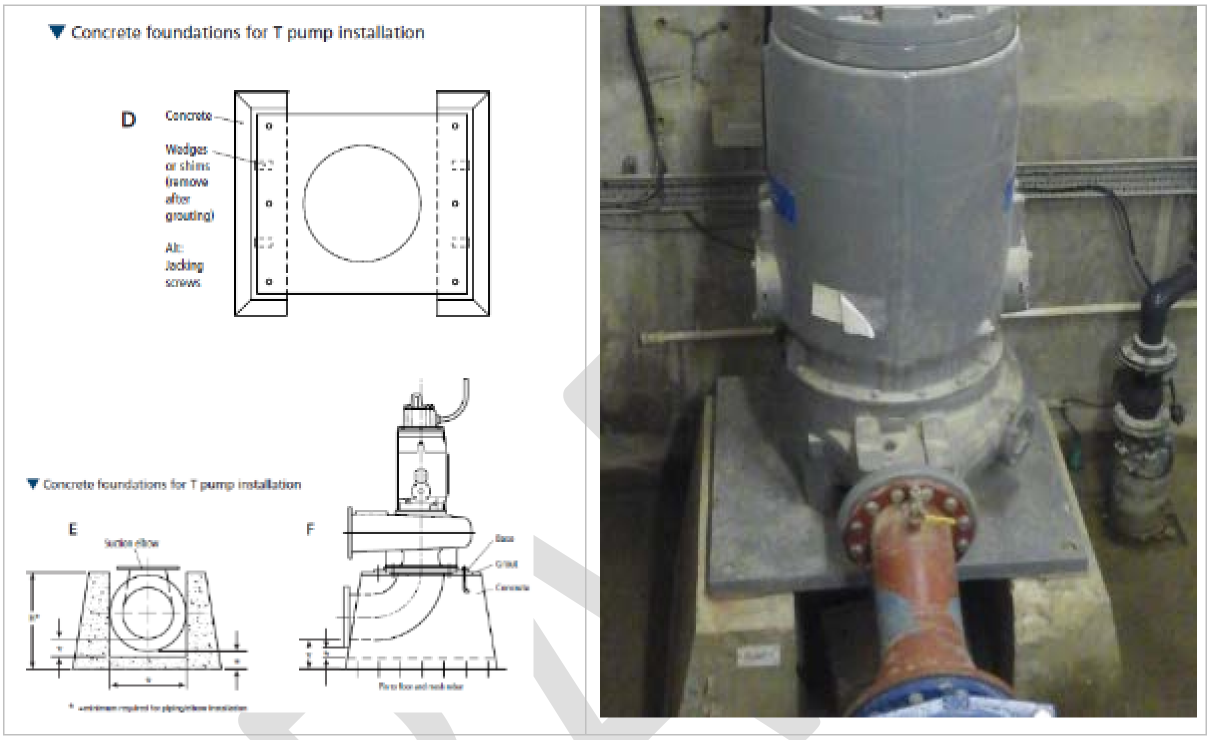


Figure 9 – Pump Installation Recommendations and Photo of As Built Installation

The pump unit itself when mounted vertically is anchored at its base with the motor unsupported. This would naturally lead to a lower natural frequency or stiffness of installation which is exacerbated further in combination with poorly anchored plinths. Supporting the pump at the motor end (such as in a typical horizontal configuration) may assist in vibration control.

Xylem have published recommendations on pump and pipework mechanical installation. A comparative assessment of the as built design with the design recommendations has been taken

High vibration levels may be a symptom of adverse hydraulic pumping conditions, either from any intake flow instability or pumping duty outside the preferred operating region, as axial thrusts increase further from the BEP. At Caen Hill they may be secondary contributors, given that under 2 pump operation the pumps operate outside the 70% to 120% BEP range.

The pump is sewage type dry well submersible pump, with a 2-vane impeller, and a generated head of up to 85 m head. The pump delivery head is high for a solids handling, centrifugal pump impeller. In comparison to a low head or multivane impeller pump, significant imbalanced axial thrusts are expected. Nevertheless, it would also be expected that the pump design from Xylem should produce vibrations within the WIMES limits on a well anchored installation.

In accordance with the Xylem recommendations, our preliminary calculations suggest that the critical pipework length is between 6 m and 7 m, with the recommended distance to the first support at no greater than 2.3 m and subsequent supports at 4.8 m. The as built installation has pipe supports at frequencies which fall within these distances, and so should be acceptable and not a cause of vibration disturbances.

In summary, the most likely cause is considered to be poorly anchored pumping installation. The level of degradation suggest that remedial works should be a high priority.

8 Additional Observations

8.1 Debris

Figure 10 – Photos following Pump No.2 Inspection – July 2019

Based on the AMCO's maintenance records since 2017, there were two other occasions since November 2017 when significant debris was found in the pumps and necessitated reactive maintenance removal.

The impeller design has a twin passage design with a 78 mm throughlet. Impellers with larger throughlets and/or single passage designs would be expected to provide improved solids handling. However, these would not be possible on a lower head system.

8.2 Pipework

From the site visit, it was noted that pipe flange gasket failures have occurred at Caen Hill PS. The following items were also observed:

- Each pump delivery branch has ball check valves. These typically have a poor dynamic response and may create pressure spikes under a phenomenon known as "check valve slam" following pump trips and stops.
- The non-return valves are located close to the pump delivery (i.e. not achieving 3 or 5 diameters typically recommended by manufacturers) but this is largely dictated by the available space.

- Each branch has untied flange adaptors. The manifold itself has supported off the floor and back wall by several fabricated bracing supports, although a tied coupling is present the manifold assembly. There could be a potential for residual resultant forces/moments may exist which may be contributing factor.

8.3 Pressure Transients

Based on the above observations a basic hydraulic transient model was constructed in VariSim to understand if any high or excessive surge pressures could arise under normal operation.

The following simulations were then studied using the model, based on the current set up (48 Hz):

- Uncontrolled 2-Pump Trip/Power failure
- Uncontrolled 1-Pump Trip (when two running)
- Controlled pump stopping (Ramp rate of 30 secs)

The simulations were conducted based on the intermediate non-return valves at the diversion points not working (i.e. open at all times) and also working.

Initial findings suggest high pressure transients may be present (assuming intermediate NRVs are not operational)

Table 5 – Estimated Surge Pressures at PS Manifold

Transient Event	**Calculated Peak Pressure (bar.g)**
Uncontrolled 2-Pump Trip/Power failure	17.5
Uncontrolled 1-Pump Trip (when two running)	20
Controlled pump stopping (ramp rate of 30secs)	13

8.4 Wet Well and Intakes

Arcadis were requested to review the wet well and intakes as concerns were raised on potential cavitation marks upon the impellers during recent pump refurbishments by AMCO.

This investigation has found that the intake at Caen Hill generally conforms with known pump intake standards and there are no submergence issues around the bellmouths. One notable exception being the height of the bellmouth intake above the wet well floor. ANSI/HI 9.8 gives an ideal bellmouth elevation of between 0.3D and 0.5D (D = Bellmouth diameter) off the wet well floor to limit the deposition of silt/debris. The volume of the wet well is relatively large with a wide aspect ratio which would produce low velocity and dead spot zones inevitably resulting in solids deposition.

It is noted that during August 2019 the wet well (Figure 11) was inspected and cleaned and it was reported that:

- Both pump intake screens had 30% loss due to silt build up with the well.
- Total volume of silt, brick, concrete rubble and vegetation removed was circa 40 tonnes.
- Pipework was inspected for blockages and confirmed clear.

Partially clogged trash screens can create skewed flow patterns, which may have led to possible air entrainment or vorticity. It would be advised that these screens are cleaned regularly to maintain regular flow patterns to the pumps.

The design of the intake with the floating trash baffles appears satisfactory. Reducing the bar spacing would help with debris ingress but would increase the risk of screen blockage. The impact of this trade-off is generally dependent on local characteristics, and the feasibility of reducing bar spacing would depend on the experience of the CRT operations.

Figure 11 – Photos during Caen Hill wet well cleaning – August 2019

Whilst 40 tonnes of debris is a significant amount, lowering the pump intake bellmouths or raising benching to achieve the bellmouth to floor clearance as based on ANSI/HI 9.8, may potentially bring unintended consequences. Caen Hill is already susceptible to blockages even with the trash screens, reducing the bellmouth clearance would effectively diminish a "buffer" zone for debris build up, potentially making it more likely (in frequency) for incoming debris to be pulled into the impellers.

The option introducing benching as per Figure 12 would reduce the volume of the wet well and silt deposition and maintain the existing access points. It is unlikely that the improvements would result in avoidance of silt build up, but it would result in lower amounts of debris being removed in a single visit.

In summary, the action of increasing the benching needs to be balanced against the risk of higher frequency of blockages / desilting operations based upon an assumption that the rate of debris ingress remains consistent.

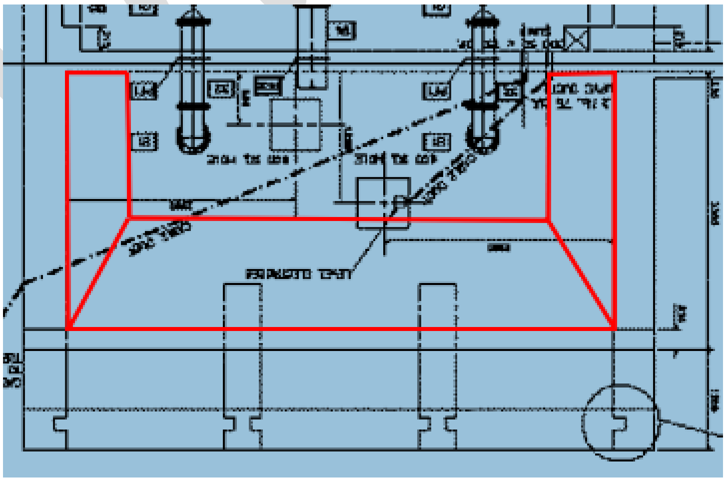


Figure 12 – Potential benching possibility in wet well

9 Potential Areas for Improvement

9.1 Pipeline Losses

The results of the audit suggest that the rising main pipeline is subject to an unknown high head loss. For pumped flow rate of 300 l/s we estimate that there is a potential to reduce the pumping head by approximately 6 m, which is equivalent to 7% of the total head loss. Assuming all other aspects being equal then any lowering in pumping head will result in an equivalent saving in energy.

It is suggested that CRT investigate the 2no. Intermediate NRVs – it is possible that at least one of these valves are in poor condition and causing a restriction to flow path in the main or are shut with flows passing via the NRV bypass pipework.

9.2 Alternative Pump Selection

On a duty/assist 2-pump operation the current Xylem pump selection is considered a good selection. The duty conditions cannot be achieved by Hidrostal pump selection nor ABS or KSB from their standard ranges.

There is a separate centrifugal pump and motor solution (i.e., not submersible) using a Bedford pump although this would result in taller installation, with knock on construction, accessibility, and potential lifting issues. At this stage we have considered alternative Xylem selections.

A preliminary search for alternative selection from Xylem, based on the duties calculated, has suggested the following selections, as based on the existing pipeline losses.

From Table 6, in terms of reducing energy consumption, the optimum configuration from Xylem is the section of the same model pump with larger impeller and motor operating in duty/standby configuration. However, this would require new supporting MCC, cabling etc. to drive the larger motor and these would attract higher CAPEX costs. The flow rates would also reduce for a duty/standby option, and at present this option does not cover peak flows within the system. Therefore, its viability would depend on this solution providing a sufficient flow rate.

Given the current vibration issue, the adoption of a larger motor and flow rate per pump exacerbating the vibration risk cannot be ruled out.

Operating duty/assist pumps using fixed speed drives also generates energy consumption savings. However, it is understood that this site is subject to a “frequency response” agreement with the Network Operator, and thus requires VSDs.

Table 6 – Alternative pump selections from Xylem

Configuration	Selection (Xylem)	Flow rate (l/s)	Input Power (kW)*	Pump and Motor Combined Efficiency (%)	Assumed VSD Efficiency (%)	Estimated Specific Energy* (kWh/1000 m³)	Saving on Specific Energy (kWh/1000 m³)
Duty/Assist (2-pumps) VSD + standard motor	*CT3240 /805 (215kW) 535 mm Impeller***	*316*	*189*	*71.8*	*96*	*347*	-
Duty/Assist (1-pump) VSD + standard motor	*CT3240 /805 (215kW) 535 mm Impeller***	*205*	*212*	*75.6*	*96*	*300*	-
Duty/Assist (2-pumps) VSD + IE3 Motor	CT3240 /806 (215kW) 535 mm Impeller	317	185	73.7	96	339	8
Duty/Assist (1-pump) VSD+ IE3 Motor	CT3240 /806 (215kW) 535 mm Impeller	205	208	77.4	96	293	7
Duty/Assist (2-pumps) Fixed speed+ IE3 Motor	CT3240 /806 (215kW) 525 mm Impeller	293	169	72.7	-	321	26
Duty/Assist (1-pump) Fixed speed+ IE3 Motor	CT3240 /806 (215kW) 525 mm Impeller	188	189	76.8	-	279	21
Duty/Standby VSD (50Hz) + IE3 motor	CT3240 /866 (375kW) 585 mm Impeller	279	300	79.8	96	311	36
Duty/Standby VSD (45Hz)+ IE3 motor	CT3240 /866 (375kW) 585 mm Impeller	198	200	77.6	96	292	8
Duty/Standby VSD (50Hz)+ IE3 Motor	CT3240 /836 (290kW) 565 mm Impeller	259	290	79.7	96	302	45
Duty/Standby VSD (45Hz)+ standard motor	CT3240 /836 (290kW) 565 mm Impeller	169	170	75.8	96	291	9

* To Pump and Motor (excluding VSD)

** As existing installed units for comparison with alternative selections

9.3 Pump Controls

The existing control does not automatically vary duty configuration or flow rate based on lock flight level. It is suggested that pumping configuration could be tailored according to a level scale, rather than a simple ON/OFF type operation to improve energy consumption. However, the practical feasibility would depend on the characteristics of the particular canal system and ensuring the required flow rates needed to safely maintain canal levels for navigation are maintained.

For example, introducing a modified PLC control based upon two level setpoints at lock flight 50 level to reduce energy costs. Under this control a single duty pump at 45 Hz would operate when the canal is relatively high or during low lock use, and 2no pumps would operate during high flow periods (frequent lock usage) as triggered from a lower level setpoint. However, this philosophy also depends on

Using the daily total flow as guideline and a 21 hour per day pumping regime, 2018 results indicate that Caen Hill could operate 1no pump for 157 days of the year (approximately 43% of the time). Although it is noted that averaging out the daily flow over a 21 hour is potential practical it may not be feasible at times to maintain a navigable canal level using this regime and the second pump could be called upon during periods of peak lock activity.

It is suggested that this control regime concept could be tested and evaluated using a simple computer model prior to any physical implementation.

Adopting a smarter, predictive monitoring system that encompasses flow rate, bearing temperature, power, efficiency, vibration specific energy is viable proposition at this and other sites. This could be implemented centrally on SCADA based upon telemetry data and coded to allow automatic adaption/correction of operation, informative data analysis reporting, and preventative fault alarms. It might also be of benefit in peak tariff and triad avoidance reducing both cost and CO_2 output even further.

9.4 Pipework

The following aspects of pipework could be improved:

i. Non return valves (NRVs) – To reduce the secondary surges replace ball check valve with fast acting low maintenance alternative such as a resilient hinge disc check valve.

ii. Thrust restraint – ensure all flexible joints are fully tied.

iii. Common isolation valve – replace knife gate valve externally with gate valve.

9.5 Vibration Mitigation

Possible mitigation options (in addition to pump selection recommendations) as shown in Table 7 have been considered.

Table 7 – Potential vibration mitigation options

OPTION		Description
1	Maintain existing configuration (Xylem "T" configuration) Redesign and construct plinths	Review flooring adequacy and structurally integrate redesigned plinths to building structure, thus creating a more complete anchored foundation adhering to the manufacturer's requirements. In addition, consider additional motor bearing supporting.
2	Reconfigure pump arrangement to horizontal configuration (e.g., Xylem "Z" Configuration see adjacent)	This would allow a larger area plinth to be installed, improving load distribution to the existing floor, with a baseplate supporting both the motor and pump. The intake to the pump will be straight thus improving suction flow presentation. Space constraints apply. 
3	Install an isolated pump foundation (Soft installation)	This comprises the installation on antivibration mounts and flexible pipework couplings. Typically, this would require a plinth mass of 2x pump mass (i.e. ~6 t or 2.5 m^3) which may not be feasible at this site.

As no "as built" design drawings of the present building structure are available, it is suggested that a further structural inspection is undertaken in tandem with the solution design to ensure structural calculations and assumptions are appropriate. The selected mitigation option should also be decided in collaboration with the proposed pump manufacturer.

Site measurements indicate that options 2 and 3 may are not likely to be feasible, leaving Option 1 as the preferred option.

10 Preliminary Conclusions

10.1 Existing Pump Hydraulics Performance and Selection

The installed pumps have been selected appropriately by Xylem. Although they do not operate within 70% to 120% of the pumps BEP they are the best Xylem standard option available for a duty/assist configuration.

A selection for 1-pump duty/standby operation could provide a more energy efficient option but would attract a higher capital investment.

IE3 motors are available for either of the selections above and it would be recommended that this option is explored further to reduce energy consumption.

Replacing the VSD units with soft start/stop drives and revert to back to a fixed speed operation will reduce energy consumption. This would have the additional benefit of reducing electrical losses, simplifying the system and being easier to control and maintain. However, the maintenance of "frequency response" and the income this generates offsets this benefit.

10.2 Pump Control

The specific energy analysis and review of daily pumped volume, the pump control could potentially be optimised to provide energy savings. The review of control would be subject to the hydraulic modelling review being undertaken by University of Liege and agreement form CRT on potential and future requirements.

10.3 Vibration

The pumping station pumps, plinths and local pipework are subject to high vibration, which is probably a major contributing factor in causing the short bearing and seal life.

Resolution can be difficult under such circumstances, but anchorage improvements may benefit the situation. However, further structural evaluation is required, and it is recommended that such a survey is to be completed to understand the floor construction for input into a plinth redesign solution. This needs to be undertaken urgently given the failing current condition of the pump plinths.

At this time the preferred solution would be to replace the plinths under Pump 1 and Pump 2, but this would be subject to a structural survey of the floor/building to inform on the required plinth design and it would be advisable to include Xylem within these discussions to benefit from their expertise and experience on anchoring this model of pump.

10.4 Pumping Station Pipework

It is suspected that transient pressure surges may be contributing factor to gasket failures. The pumping station pipework improvements could be implemented to resolve gasket failure issues by means of additional thrust supports, and potentially additional surge mitigation measures by means of changing the NRV and location (further away from pump).

Stop/start ramp rates could also be increased to "cushion" the return flow and lower the resulting surge pressures.

All flexible pipework joints should be fully tied.

10.5 Rising Main

From the calculations, based on the provided SCADA and pump audit data, an unknown head loss is present within the rising main, equating to an additional 6m of pumping head at 300l/s. The condition and operability of the intermediate NRVs is questionable and requires further investigation to understand if they are a contributing factor to the high dynamic losses.

During the investigation it was noted that there is DN250 return bypass pipework around the intermediate NRV that connects the 600 mm DI upstream and downstream (Figure 13) complete with a 250 mm gate valve for isolation. If the intermediate NRV was damaged and unable to open and the 250 mm gate valve was open the flow would pass through the bypass, which would account for the additional head loss found from the site data.

The overlaid system curves for this scenario and the estimated system curve from the site data can be seen in Figure 14 and it would seem to suggest that this is a possibility that should be explored further as correlation between the system curves is evident.

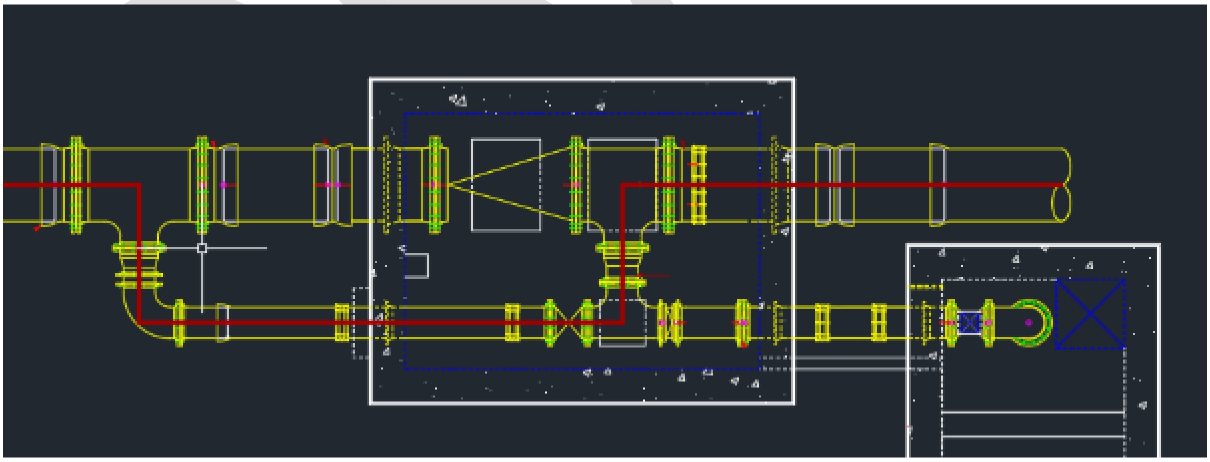


Figure 13 –Intermediate NRV schematic with suspected flow path in red

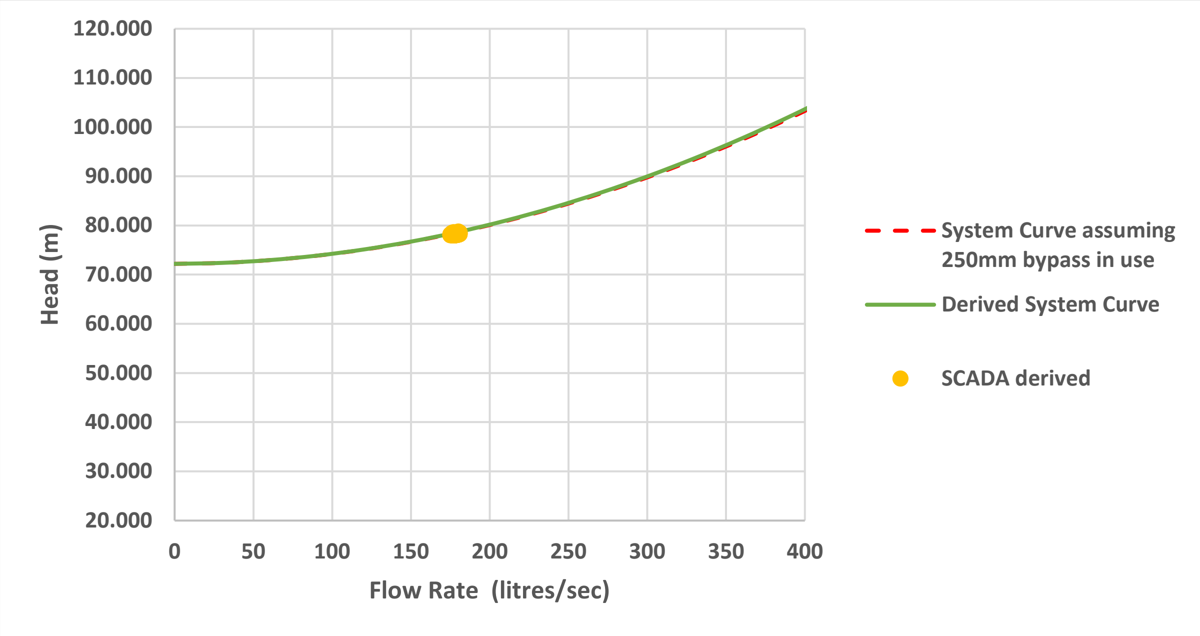


Figure 14 – System curves showing estimated system curve based on site data and system curve if flows pass around the 600 mm NRV and through the 250 mm bypass line

Under ideal circumstances with the flow passing through a fully operational check valve, the losses would be deemed negligible at approximately 60mm per NRV (assuming an operation under 2 pump conditions, producing 310l/s and a C_v across the check valve of 1).

If this head loss can be located and potentially eliminated, the pumps would produce an approximate 15-20l/s increase when operating 2 pumps at 48Hz. This could raise the capacity of the 2 pump operation from 266l/s to 280l/s which would give an approximate 5-7% increase in capacity. (Figure 15)

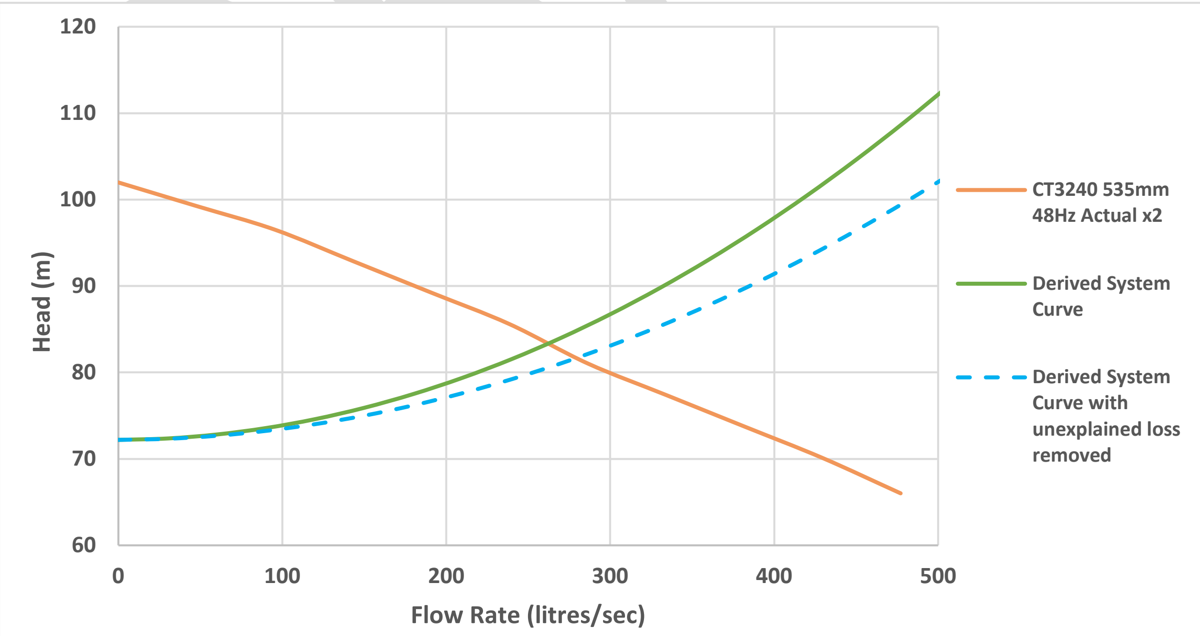


Figure 15 – System curves showing impact of removing the perceived restriction when 2 pumps are operating at 48Hz

10.6 Energy Saving Potential

There is potential here to reduce overall energy usage at this site. There are several possibilities that could be explored in more earnest, using greater level controls, changing impeller diameter using IE3 motors, and potential VSD removal.

Table 8 – Potential energy savings by option/action (based on 2018 flows and 4.6M m3 total volume)

Option/Action	% Saving over Existing	kWh / Annum
IE3 Motors	2.3	36,700
Fixed Speed Drives (+IE3)	7.5	119,700
Larger impeller/motor Duty/Standby Configuration (+ IE3)	10	159,600
Improving Rising Main Headloss*	7	110,000
Changing to 2-Point level Control*	5	80,000

** based on existing pumps*

11 Recommendations

- It is recommended that the vibration issues and the pump plinths are looked into as a matter of priority, including a structural assessment. Resolving this issue would have the potential benefit of increasing the bearing life of the pumps, leading to increased reliability and efficiency. Depending on the existing structural design, the new plinths should be integrated into the existing foundations.
- Contact the pump refurbishment team and investigate the Glycol coolant leak from Pump 1
- Assess the cost-benefit opportunities for duty/standby and fixed speed options.
- The rising main and intermediate check valves should also be further investigated. The site test data suggest that there is a possibility of a partial blockage somewhere in the rising main and a malfunctioning check valve offers the most likely source of head loss.
- Consult with University of Liege and finalise the levels and flowrates required to maintain the system in operation before finalising the pump selection and duty configuration.
- Implement a 2-level pump control system which allows pump flow rate to vary with Lock 50 flight levels. For example, reducing flow rate when levels are approaching the existing "Stop pump" level.
- Assuming the flow rates are not changing, provide new IE3 motor CT3420 pumps and retain existing as boxed spare units.
- Replace the existing ball check valves with a resilient hinge disc check valve and redesign pipework branches to achieve a better separation of pump and NRV.

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