Remote real-time pressure control via a variable speed pump in a specific water distribution system

Philip R. Page, S'bonelo Zulu and Matome L. Mothetha

ABSTRACT

Pressure management (PM) in a water distribution system (WDS) can be accomplished by setting the pressure to be low and constant at remote consumer locations, through the use of a controller. The controller adjusts the speed of a variable speed pump (VSP) in real time. To study the implementation of these concepts, the installation of a VSP for PM in a real-world WDS in South Africa is investigated with a hydraulic model, to show how this can assist in addressing challenges and to determine the adequacy of various controllers. In this study, a suitable pump is installed which is sized to supply the required set pressure at maximum demand. Previously existing pressure deficiency challenges are solved. PM with recently proposed controllers, which depend on hydraulics theory, is performed for the first time for a WDS which exists in the real world. Since these controllers need to be studied under realistic conditions, stochastic water consumption is used. All controllers, including conventional proportional control, perform well. A consequence of this is that a controller without a tunable parameter can initially be used safely, and a related controller can then be tuned slowly to improve performance. Criteria for selecting an appropriate controller are given.

Key words | hydraulic modelling, pressure management, remote real-time control, variable speed pump, water distribution system

Philip R. Page (corresponding author)
S'bonelo Zulu
Matome L. Mothetha
Built Environment,
Council for Scientific and Industrial Research (CSIR),
P.O. Box 395, Pretoria, 0001,
South Africa
E-mail: *pagepr7@gmail.com*

INTRODUCTION

The pressure management (PM) technique which is studied is called remote real-time control (RRTC). With this technique the adjustment of actuators allows the pressure at several remote nodes to be kept low and constant in real time (Campisano *et al.* 2010; Giustolisi *et al.* 2015; Vicente *et al.* 2015; Abu-Mahfouz *et al.* 2016). Examples of actuators used are pressure control valves (PCVs), turbines, pumps-as-turbines and variable speed pumps (VSPs). Here, the latter is used. Commonly, as is done here, the pressure is kept constant (at a desired set-point) at individual nodes (Campisano *et al.* 2010). However, keeping the average pressure of a set of nodes constant has been studied for VSPs (Page 2015).

A rotodynamic pump, considered here, is a device where the head is produced by a rotating impeller. For a VSP, the pump impeller's rotational speed n (revolutions per second) can be adjusted, as opposed to a conventional pump (fixed speed).

VSPs can be adjusted to set the pressure at several remote nodes to be low and constant, while at the same time, high enough to satisfy the needs of consumers. There are two expected advantages of such PM: (1) when the water distribution system (WDS) has lower pressures, the water leakage and possible pipe bursts decrease, while consumer water consumption may decrease (in the case of pressure deficient conditions) (Vicente *et al.* 2015); (2) pumping with VSPs can ensure that the consumer pressure is just high enough to satisfy consumer requirements, without making the pressure higher than needed, typically resulting in energy savings (Bakker *et al.* 2014; Gao *et al.* 2017; Darweesh 2018; Monsef *et al.* 2018). However, long-term

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costs associated with VSPs are sometimes higher than with other design solutions (Walski & Creaco 2016).

In order to minimize the difference between the pressure and the desired set-point, an algorithm is used to adjust the VSPs in response to the pressure sensor readings at the remote nodes. This algorithm is referred to as a controller. Electronic controllers can be located in a laboratory test-bed or real-world WDS, without the need for a hydraulic model. This work models the installation of a VSP and the operation of the controllers with the help of a hydraulic model.

Laboratory test-beds which study RRTC in a WDS with a VSP by the use of generic controllers, which do not use any hydraulics theory, have been studied (Bezerra *et al.* 2012; Madonski *et al.* 2014; Silva *et al.* 2015; Filho *et al.* 2018). Recently, the first VSP controllers which explicitly depend on a theoretical understanding of the hydraulics of a pump for their derivation were proposed (Page *et al.* 2017). This research describes the initial application of the recent controllers to a real-world WDS. Another related controller was subsequently conceived (Creaco 2017).

A summary of findings appears in the sections 'Summary of study' and 'Conclusion'.

METHODS AND PRESSURE MANAGEMENT FRAMEWORK

A real-world South African WDS is studied, and its design is altered to solve pressure challenges faced by the community. After the changes are made, the proposed sub-network studied consists of a single VSP supplying water to a reticulation system. This proposed sub-network is called the 'Borkum WDS' and is investigated by using a hydraulic model.

One of the reasons PM is needed at Borkum is that there is considerable pipe leakage. Care is taken to use a water consumption variation which incorporates pulses each second, since this influences the precise behaviour of the controller. The pump curve used for the VSP is discussed. PM is subsequently implemented. The various controllers are defined, and their performance discussed. Selection criteria for the controllers are then introduced, which are used to select controllers for use at Borkum.

A positive head $\tilde{H}$ is imparted to the liquid by the VSP (the pump head), accompanied by a positive pump discharge flow rate Q (at the pump outlet). A WDS node where the head at the node changes sensitively as $\tilde{H}$ changes and, if possible, also has the lowest pressure, is called a critical node (CN) (Campisano *et al.* 2010). For a WDS with one pump, RRTC is accomplished by requiring a constant target set-point pressure at one CN (Campisano *et al.* 2010, 2012; Creaco & Franchini 2013; Giustolisi *et al.* 2015, 2017). The controller then attempts to set the pressure at the CN near to the low set-point value. By doing so, the part of the WDS influenced by the pump tends to have low pressure, and the pressure variation during the day tends to be small.

To study the VSP controllers, numerical simulations employ an extended-period simulation (EPS) hydraulic solver, based on a custom program in C++ implementing the EPANET2 toolkit. In these simulations, the pump speed is changed (according to a controller rule) as water demand varies, in such a way that the pressure head at the CN remains near a target set-point of 30 m. This value is consistent with site requirements. In response to the changing demand, the pump speed changes every $T_c = 5$ min (also used in Campisano *et al.* (2012), Creaco & Franchini (2013) and Giustolisi *et al.* (2015, 2017)). The pressure head and the target set-point pressure head are compared at the CN.

Leakage is modelled according to a method where leakage flow in pipes is represented by a pressure-dependent consumption at the nodes. The leakage flow rate q_n at node n is (Tucciarelli *et al.* 1999):

$$q_n = p_n^{\gamma} \sum_{j \in M_n} c_j \frac{L_j}{2} \tag{1}$$

where p_n is the pressure head. M_n indicates the group of pipes connected to this node and j is a pipe belonging to this group. The leakage flow is proportional to the lengths L_j of the pipes connected to the node. The value of c_j determines the size of the leakage flow on each pipe. A representative value $\gamma = 1.18$ is used (Araujo *et al.* 2006).

INSTALLATION OF A VSP IN THE BORKUM WDS

Several hydraulic models of South African WDSs have recently been studied (Page 2015; Osman *et al.* 2016; Yoyo *et al.* 2016). Here, a different South African site is studied, where the addition of a VSP has the potential to yield several benefits. Senwabarwana, located in the Capricorn district municipality in Limpopo province, is approximately 1 km^2 and is made up of predominately low income housing. The local water distribution scheme supplies several areas. Of these, this specific study focuses on Borkum suburb, and other areas such as Desmond Park, Extension 1 and the town centre are excluded.

Elevations roughly increase from the western to the eastern part of Borkum (Figure 1(b)). The installation of a new VSP pumping out of an existing reservoir which

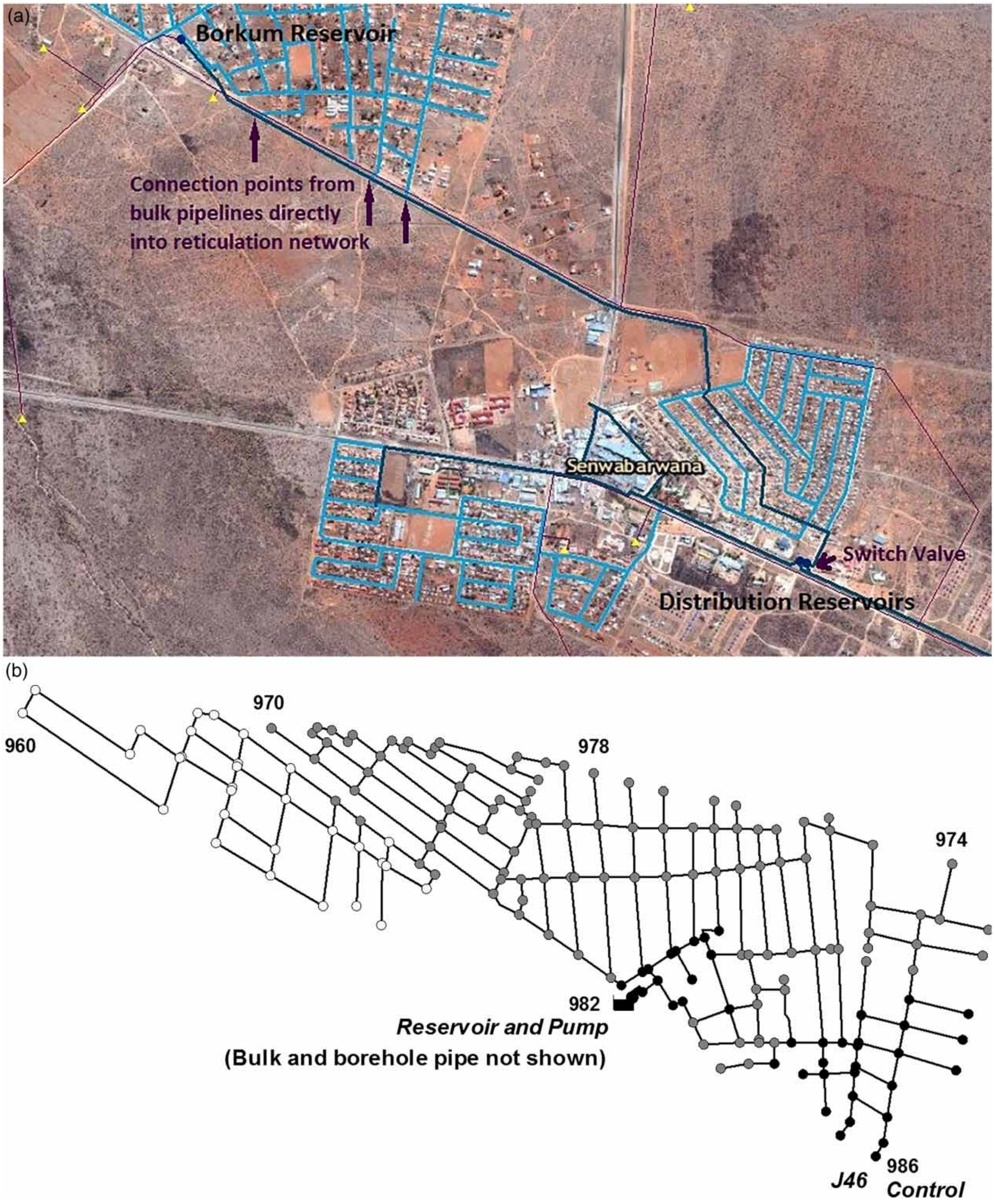

Figure 1 | (a) The bulk pipeline. No VSP at Borkum reservoir. North is towards the top. (b) Borkum WDS with VSP. Three node elevation ranges are indicated: less than 970 m (white), 970–980 m (grey) and more than 980 m (black). Additionally, the elevations of some nodes are indicated in metres.

supplies Borkum (called Borkum reservoir here), in order to increase the insufficient pressure within the south-eastern side of the settlement, would bring significant benefits to the community.

Borkum reservoir is supplied directly by water pumped from a borehole. In addition, Borkum reservoir is fed by water from a distant distribution reservoir (located south-east of Borkum) via a bulk pipeline indicated in Figure 1(a). A switch valve located at the distribution reservoir determines whether the bulk pipeline is open or not. In addition, the bulk pipeline connects to the Borkum reticulation system at three connection points shown in Figure 1(a). The purpose of these three connections is to supply water to a part of the Borkum reticulation system which has an elevation higher than the Borkum reservoir level, when the switch valve is open. However, when the switch valve is closed, Borkum's high-elevation area does not receive water.

The solution which is proposed to significantly increase pressure in the Borkum reticulation network and ensure water delivery in its high-elevation part is as follows. The solution leaves the infrastructure intact, but removes the three connections between the bulk pipeline and the Borkum reticulation system, and installs a VSP in the outflow pipe from Borkum reservoir. The removal of the connections between the bulk pipeline and the Borkum reticulation system is necessary because the presence of a VSP will cause water to flow into the bulk pipeline, which is an unwanted side effect. The resultant Borkum WDS depicted in Figure 1(b) is an example of a network where at least one pump must be run at all times or else pressure would be lost (a closed WDS) (Walski & Creaco 2016).

The Senwabarwana WDS hydraulic model was previously constructed from 'as-built' drawings and site visits. The Borkum WDS model is based on this model, considering the origin of the water to be at the Borkum reservoir, with a water level that is constant.

The *base* water consumption (not including leakage) at each node is multiplied by an overall dimensionless demand factor f to obtain the water consumption at that node. f is the same for all nodes. The VSP will be designed for PM with a maximum demand of $f = 2$. When $f > 2$, e.g., for firefighting or pipe breaks, the design will not allow PM. Average demand obtains for $f = 1$ and the minimum demand for $f = 0$. The representative time variation of the overall water consumption used is indicated in Figure 2, nearly reaching the maximum and minimum. The variation drives the change of Q over time. The total base water consumption at all the nodes of the Borkum reticulation system (corresponding to $f = 1$) is 4.604 litre/s.

The consumption in Figure 2 is obtained as follows. The *smooth* consumption pattern is based on an interpolation of 1-hour averages. A stochastic component is then added. Pulses in the demand factor each second are obtained by using data from the example stochastic component of the overall consumption calculated in Creaco *et al.* (2017a). These pulses vary over 1 day with a magnitude of on average 4% (with maximum 20%) when f without pulses is 1.

To calculate the adjusted pump speed, a hydraulic calculation with a temporal step of 5 min should be used. It was shown in Creaco *et al.* (2017a, 2017b) that EPS with a temporal step larger than 2 min (in the case study) can accurately model the effect of transients, when independent stochastic consumption is assumed at each node. These references argue that the average of the stochastic consumption over the temporal step must be used for the EPS modelling. Here, this has been done over a time step T_c to obtain the consumption in Figure 2. In the figure the stochastic component appears small because it is obtained from the averaging of the pulses over the time step. The EPS calculation in this work is expected to accurately take

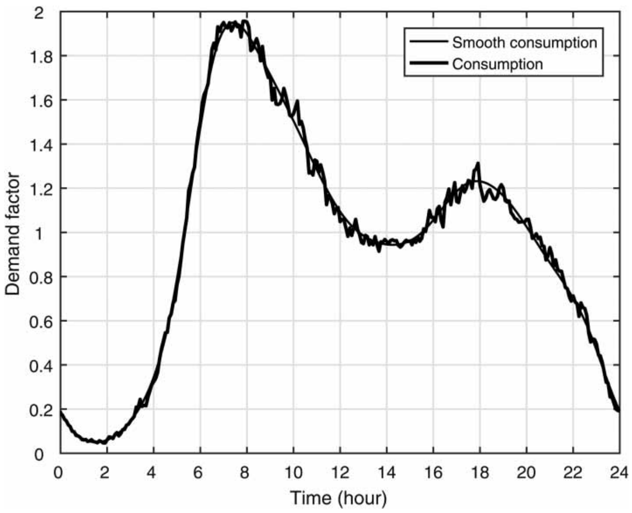

Figure 2 | Time dependence of the demand factor over 1 day. The thin line indicates the smooth consumption.

into account the effect of transients and stochastic consumption. The limitation is that a stochastic component is only assumed for f, i.e., not for each individual node independently.

Leakage throughout the WDS is added to the water consumption mentioned above. Leakage at average demand with PM is chosen to be 35% of water supply (by fitting c in Equation (1)) (Mckenzie *et al.* 2012).

Node J46, at the endpoint on the south-eastern edge of the WDS (near to the VSP), has numerically been identified as having the lowest pressure for minimum up to maximum demand (Figure 1(b)). Moreover, it is calculated to be sensitive. Hence, node J46 is chosen as the CN.

The dependence of $\tilde{H}$ on Q is called the *pump curve*. The curve is specified for rated conditions $n = n_R$, where R denotes 'rated'. The dimensionless pump speed can be defined as $\alpha \equiv n/n_R$. A suitable VSP is assumed to be available, which has a pump curve with the physically reasonable form $\tilde{H} = c - aQ^b$, with a and c positive constants, and $b = 2$. The choice $a = 373{,}000\,\mathrm{s}^2/\mathrm{m}^2$ and $c = 90.77$ m is made. With the pump operating at maximum capacity (at $\alpha = 1$), and with maximum demand $f = 2$, these values of a and c yield a pressure head at the CN of exactly 30 m.

As demand varies from minimal to maximal, any pump operates along a line of points specified by Q and $\tilde{H}$. For a fixed speed pump (operating by definition only at $\alpha = 1$), the line of points $(Q, \tilde{H})$ is specified by the pump curve determined above (dashed line in Figure 3).

For both a fixed speed pump and a VSP, the operating point $(Q, \tilde{H})$ is the same for maximal demand (when $\alpha = 1$). (This is the point where the two lines in Figure 3 cross.) For a fixed speed pump, $\tilde{H}$ increases for average and minimal demand, yielding a pressure head higher than 30 m at the CN. (For the water consumption variation depicted in Figure 2, the pressure head at the CN varies in the range 31–72 m, reaching a maximum of 97 m at the far western end of Borkum.) This is not the desired behaviour for PM, hence the need for a VSP.

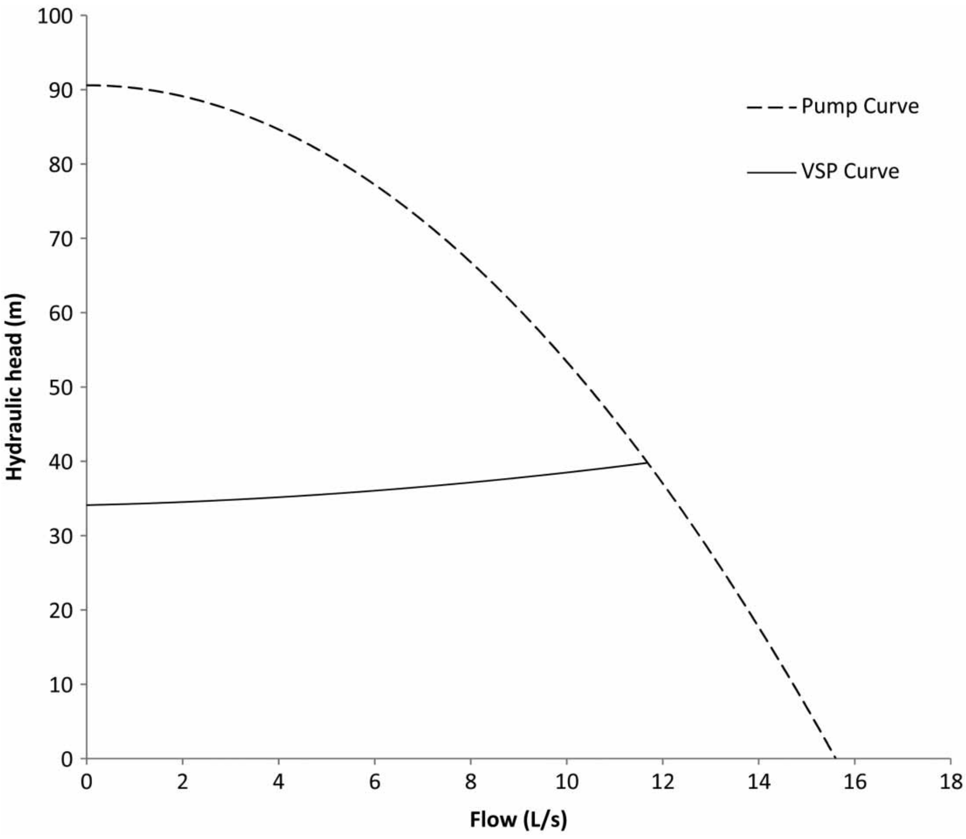

Figure 3 | Pump curve $\tilde{H} = c - aQ^b$ (dashed line). The line of points along which the VSP operates when the pressure head at the CN is exactly 30 m (continuous line).

PRESSURE MANAGEMENT: CONTROLLERS, RESULTS AND CRITERIA

The controllers determine the pump speed α at the next iteration $i+1$ from the current iteration i, separated by a time-step T_c, using (Page *et al.* 2017):

$$\text{PC: } \alpha_{i+1} = \alpha_i - k_\pi \ (H_i - H_{sp}) \quad (2)$$

$$\text{PCM: } \alpha_{i+1} = \alpha_i - \frac{k'_\pi}{\alpha_i} \ (H_i - H_{sp}) \quad (3)$$

$$\text{Others: } \alpha_{i+1} = \alpha_i - \frac{K}{2c}\frac{1}{\alpha_i} \ (H_i - H_{sp}) \quad (4)$$

where $H_i - H_{sp}$ is the difference of the pressure head and target set-point pressure head at the CN. Equation (4) incorporates the specific form of the pump curve used (determined by c), and

$$\text{DCF: } K = K_\pi$$

$$\text{LCF: } K = 1 \quad (5)$$

Note that k_π, k'_π and K_π are tunable parameters. The acronyms for the controllers mean 'proportional control' (PC), 'pump proportional control modified' (PCM), 'parameter-dependent P-controller with known constant pump flow' (DCF) and 'parameter-less P-controller with known constant pump flow' (LCF).

Because the water consumption in Figure 2 is averaged over time periods of length T_c, the deviation $H_i - H_{sp}$ calculated in EPS should be interpreted as an average deviation during a time period T_c. Let Δ and δ, respectively, measure the average and maximum of the absolute values of $H_i - H_{sp}$ for all i relevant to 1 day. Hence, they respectively measure the mean and maximum daily deviations. (The original definitions are in Creaco & Franchini (2013) and Page *et al.* (2016)).

When a controller has a tunable parameter k, it is said to be optimally converged when $\Delta(k)$ and $\delta(k)$ are minimal. Since different WDS conditions usually require different parameters for optimal convergence (Madonski *et al.* 2014), the parameter should best be considered to lie in a range. For comparison purposes to parameter-less controllers, a criterion used here is to consider parameters which yield $\Delta(k)$ within a factor of two of its minimum, called the effective range of the parameter (Campisano *et al.* 2012). This is the range of k which satisfies $\Delta(k) \leq 2\Delta_{min}$.

PM in the Borkum WDS is studied for the water consumption pattern in Figure 2. The results for the new VSP controllers, compared to conventional PC, are shown in Table 1. Pressure head deviations smaller than about 0.5 m are unlikely to have important consequences for PM. In this sense, all controllers perform well on average, consistent with what was found for a non-real-world WDS with a smooth water consumption pattern (Table 1 in Page *et al.* (2017)). Even though the parameter-less controller does not have the freedom of a tunable parameter, it also performs well. At the far western end of Borkum the pressure head is the highest, and varies between 54 and 56 m. The time variation of α is shown in Figure 4; it closely follows the consumption in Figure 2.

Table 1 shows that not including the stochastic component in the water consumption pattern leads to an underestimate of the deviation of the pressure from the set-point (Creaco *et al.* 2017a). This can be seen by comparing Δ obtained with and without the stochastic component.

The pressure head at the CN is shown in Figures 5 and 6 for all controllers. Figure 5 shows the optimally converged

Table 1 | Efficacy of controllers

Controller			**Parameter**	Δ **(m)**	δ **(m)**	Δ_s **(m)**
PC	Conventional	N	$k_\pi = 0.0084 - 0.0114\text{m}^{-1}$	≤ 0.089	≤ 0.054	
PCM	–	N	$k'_\pi = 0.0068 - 0.0093\ \text{m}^{-1}$	†	†	
DCF	Known Q	Y	$K_\pi = 1.24 - 1.69$	≤ 0.085	≤ 0.63	
LCF	Known Q	Y	Parameter-less	0.198	1.18	0.129

† Same values as for DCF (only true for the pump curve assumed). Δ_s is obtained from the smooth water consumption pattern in Figure 2.

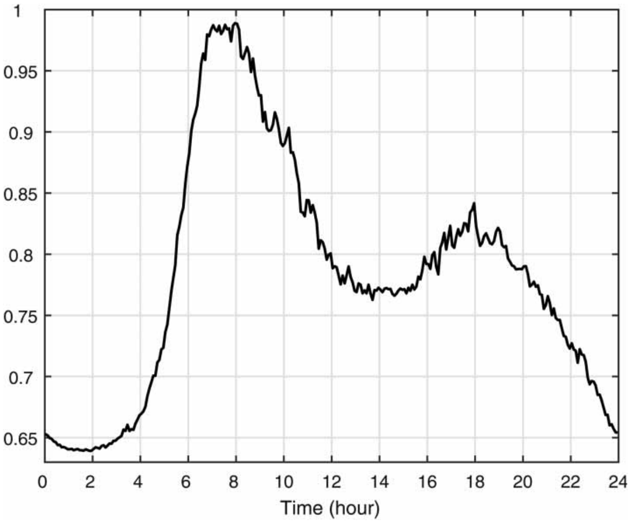

Figure 4 | Time-dependent pump speed for the optimally converged DCF. Other controllers give very similar results.

cases: PC: $k_\pi = 0.0094\ \mathrm{m}^{-1}$ where $(\Delta, \delta) = (0.050, 0.27)$ m; PCM and DCF: $k'_\pi = 0.0077\ \mathrm{m}^{-1}$ and $K_\pi = 1.40$ where $(\Delta, \delta) = (0.043, 0.45)$ m. The stochastic component of the water consumption leads to oscillatory behaviour. Only when the change in water consumption dominates the stochastic component (from 4 to 7 hours) does the pressure head show a less oscillatory behaviour. Because the precise behaviour for the controllers in Figure 5 depends on the tunable parameter, the results for a range of parameters, shown in Table 1, are important.

We define a flow controller as one where Q is present in the definition of the controller, i.e., where Q needs to be known (see Table 1). (Even though DCF and LCF for the pump curve considered in this work do not depend on Q, they do in general.) A flow controller has the following disadvantages and advantage.

Disadvantages:

- Knowledge of Q requires that either (1) a flow meter be present to measure it (Creaco & Franchini 2013; Giustolisi *et al.* 2015) or (2) a hydraulic model be available to predict it (Page *et al.* 2016). An additional financial cost will be incurred by the installation of a flow meter. Non-flow controllers do not have this requirement.
- All flow controllers considered in this work, in principle, depend on the pump curve (Page *et al.* 2017), and hence

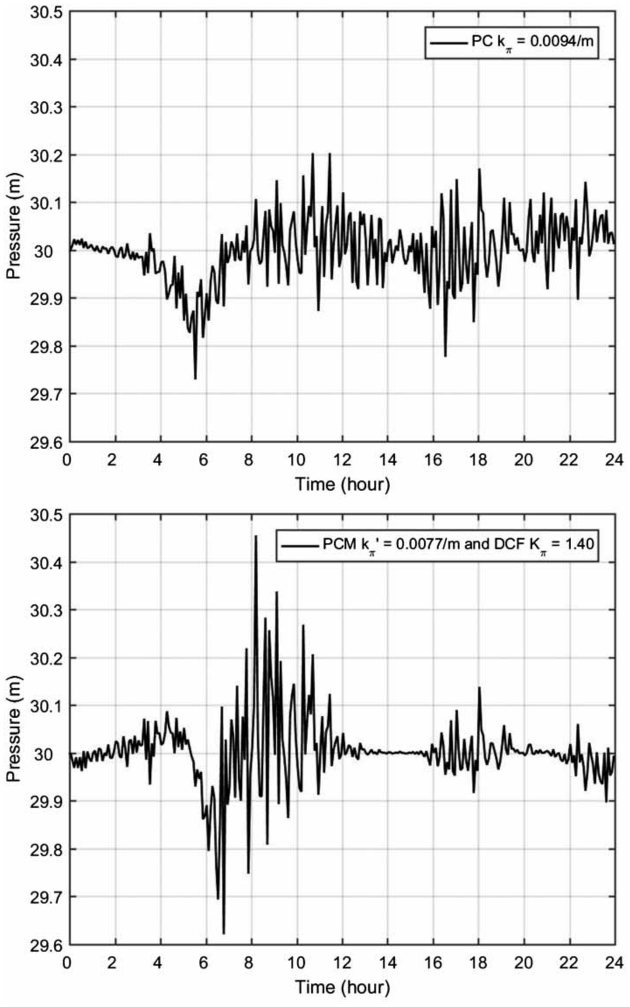

Figure 5 | Time-dependent pressure head at the CN for optimally converged parameter-dependent controllers (on the same scale).

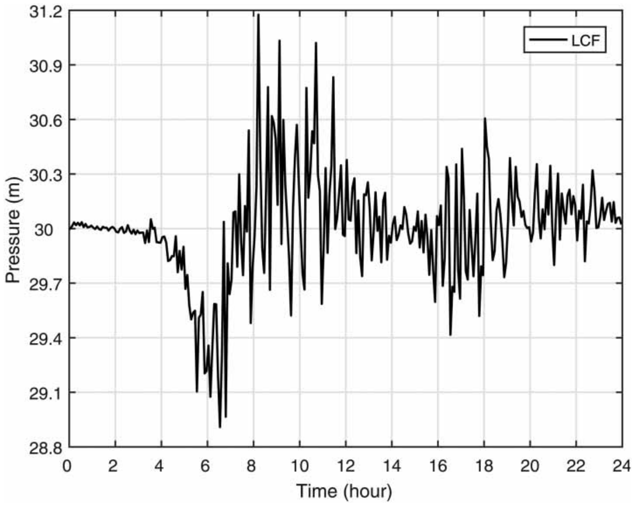

Figure 6 | Time-dependent pressure head at the CN for the parameter-less controller.

the pump curve must be known accurately. Non-flow controllers do not depend on the pump curve.

Advantage:

- Q varies as WDS conditions change. Dependence on Q makes the controller robust under different conditions (indicated by 'Y' for yes, the controller is robust in Table 1). This was numerically demonstrated for an analogous controller to DCF for a PCV (Creaco & Franchini 2013).

How is the appropriate controller selected? The first criterion to consider is whether to use a flow or non-flow controller. The second criterion to consider is that a parameter-less controller may be preferable, because it has no need for tuning a parameter, and accompanying tuning rules (Madonski *et al.* 2014). The third criterion to consider is performance of the controller. This includes favourable ability to maintain the target set-point pressure, e.g., the results for Δ and δ listed in Table 1 and the results in Figures 5 and 6. It also includes ability to deal with rapid water consumption change, and minimization of the amount of pump speed changes.

Assuming that a VSP with an accurately known pump curve, as well as a flow meter at the pump, can be installed at Borkum, a flow controller can be used (first criterion). However, the second and third criteria do not lead to a unique choice of controller at Borkum. A conservative approach is to start with the LCF controller (having $K = 1$). Then change to the DCF controller (with $K = K_\pi$) and ensure reliable operation with K_π increased slowly from 1 over a multi-day period. On the other hand, if a flow meter is not installed at the pump, the easy-to-use PC or PCM controllers can be selected.

In summary, three criteria for the selection of an appropriate controller for PM in any WDS are introduced. At Borkum, the performance of all controllers (third criterion) is comprehensively discussed and is found to be good. Assuming the use of a flow controller (first criterion), it follows in light of the second criterion that a controller without a tunable parameter (LCF) can initially be selected safely, and a related controller (DCF) can then be tuned slowly to improve performance.

SUMMARY OF STUDY

The pressure deficiency in Borkum can be solved via the installation of a VSP at the Borkum reservoir. Because of PM, the minimal amount of pumping is performed, while still keeping pressure at an adequate level. This could bring significant benefits to the community. It is possible to identify a CN in the WDS where the pressure is set to be low and constant. A suitable pump can be installed which is sized to supply the required pressure at maximum demand. Specific controllers are suggested for use at Borkum. PM using a VSP is a promising option at this site.

CONCLUSION

The first variable speed pump controllers, which explicitly depend on a theoretical understanding of the hydraulics of the pump for their derivation, are considered. PM with these controllers is studied for the first time in a WDS which exists in the real world. All controllers, including conventional proportional control, perform well for stochastic water consumption. Three general criteria for selecting a controller for real-world use are highlighted.

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