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AN IMPROVED CONTROL STRATEGY FOR HIGH-PRESSURE PUMPING IRRIGATION SYSTEMS

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Abstract

Pumped irrigation systems are critical infrastructure that supply water from water sources to rural users through interconnected pressurized water pipes. To supply enough pressure head to all the irrigation outlets located in the irrigation network, it is required to have an appropriately high pressure head supplied by the pump station. Therefore, the energy consumption related to pumping could be correspondingly high, which may lead to significant operating costs. With the aid of real-time flow data available from each irrigation outlet, the proposed improved pump head setpoint selection algorithm can locate the most critical outlet in terms of the smallest downstream pressure head and therefore guarantee to deliver the minimum pressure required for all active outlets in the network. By using the proposed algorithm, it has been demonstrated with a two-day simulation that a 4.74% savings in pumping energy cost as well as a reduction in the associated greenhouse gas emissions can be achieved.

Keywords
Pump pressure setpoint, Energy cost savings, Greenhouse gas reduction, High-pressure pumping irrigation systems.

1 INTRODUCTION

Pressurized irrigation water networks supply water to municipal (industrial, commercial and residential) and rural (irrigation and residential) users through pipes [1], [2]. The growth in water demand has led to increased pumping and correspondingly larger energy costs, as well as increased greenhouse gas (GHG) emissions (when electricity is sourced from fossil fuel sources). The water sector in Victoria, Australia has committed to reducing its emissions by 42% by 2025 and to net-zero emissions by 2050, under Victoria's water plan, Water for Victoria [3]. For Lower Murray Water (LMW) - a local water authority in Victoria, this objective translates to a total reduction of 15,535 tonnes of GHG emissions by 2025 [4], [5].

Pumping energy cost often makes up a large portion of the operating cost in a pressurized irrigation water network. Within the LMW's four irrigation systems, the Robinvale High-Pressure System (RVHPS) accounts for approximately 60% of the total electricity cost. During the peak demand season, the RVHPS pump station will often run at close to full capacity for 24 hours a day. As a result, the energy cost and associated GHG emissions from this system are very large. The energy cost savings and GHG reduction can be achieved by improving the pump head setpoint selection strategy and applying better pump operations [6]. Currently, the pump station of the

RVHPS is operated using a proportional-integral (PI) controller with a pressure setpoint found from a pressure-setpoint curve. However, depending on the demand and the location of the active irrigation outlets at times this curve may give a setpoint value that is too high, leading to unnecessary energy costs; while at other times the setpoint may be too low, leading to a pressure below the service requirement at some irrigation outlets.

In this paper, we investigate an improved real-time control strategy to find pump pressure setpoints. This new strategy takes advantage of the flow measurement information from all the irrigation outlets and a well-calibrated hydraulic simulation model [7] to identify the most critical irrigation outlet in terms of pressure. Then, a new pump pressure setpoint can be determined based on this critical outlet. The improved control strategy can potentially lead to energy cost savings, GHG emissions reduction and an improved level of service to irrigators.

With a case study of the Robinvale irrigation network, we have demonstrated that the proposed strategy can obtain 4.74% savings in pumping energy cost as well as a reduction in the associated greenhouse gas emissions. The economic and environmental benefits that can be achieved using the new strategy for selecting pump setpoints are demonstrated using historical data from 28th and 29th Dec 2019. The current pump setpoints are for most of the time higher than the setpoints produced using the proposed selection strategy. The average reduction in pump setpoint values is 4.50 m. This shows that the new strategy can lead to lower energy consumption and lower associated GHG emissions while delivering the minimum service pressure head downstream to all the active irrigation outlets.

2 CONTROL SYSTEM DEVELOPMENT

2.1 Current Control Strategy

A proportional-integral (PI) controller is currently employed for the operational management of the pumps for the high-pressure irrigation system. A control input can be generated using the PI controller so that the output pressure of the pump station can track a desired pressure setpoint $r(t)$ at each sampling time t. In general, a PI controller can be formulated below as shown in equation (1):

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau, \tag{1}$$

where $e(t)$ is an error signal obtained by $e(t) = r(t) - p(t)$ with the measured pressure head at the exit of the pump station. Furthermore, K_p and K_i are proportional and integral gains, which are tuning parameters. In equation (1), the proportional term $K_p e(t)$ contributes to a response adjusted by multiplying the error signal by a constant gain K_p, while the integral term $K_i \int_0^t e(\tau) d\tau$ contributes to an adjusted accumulated error offset over time that can accelerate the setpoint tracking and eliminate steady state setpoint errors.

The pump pressure setpoint $r(t)$ has been normally selected based on a pressure-flow curve. For instance, as shown in Figure 1, a pump pressure setpoint can be selected by using the measured system total flow at the exit of the pump station. Considering that the system flow is in the range between 0 L/s and 3500 L/s, the corresponding pressure setpoint varies from 81.9 m to 102.3 m. Since irrigation outlets are located in each branch of the network, some outlets far away from the pump station (e.g., critical outlets at the end of a certain branch as shown in Figure 2) may suffer low pressure heads but the outlets near the pump station may have exceeded minimum required pressure heads. To meet the minimum required pressure head (i.e. 35 m) at all active irrigation outlets, the pressure setpoint selected from the pressure-flow curve in Figure 1 is usually conservative and even in this case, there is no guarantee that the minimum required pressure can always be satisfied for all the irrigation outlets.

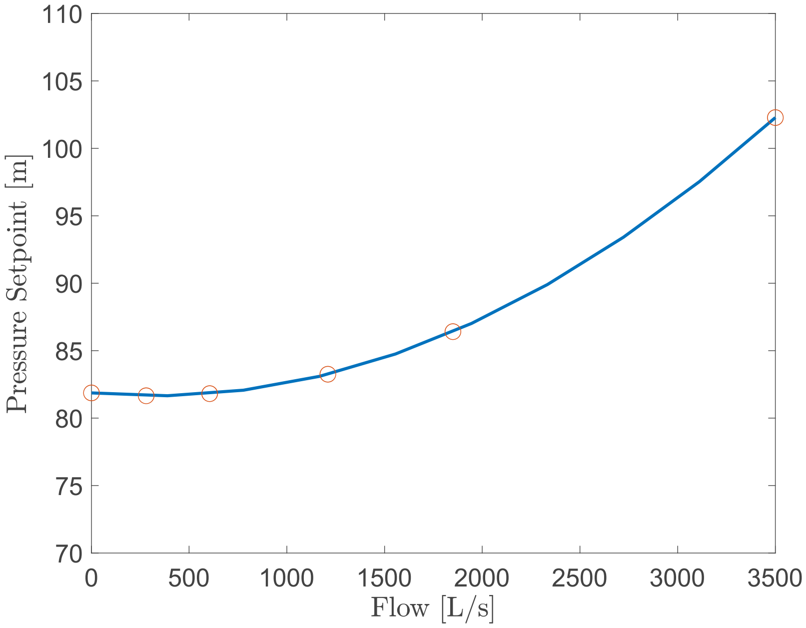

Figure 1. The Pump Pressure Setpoint Curve used by LMW.

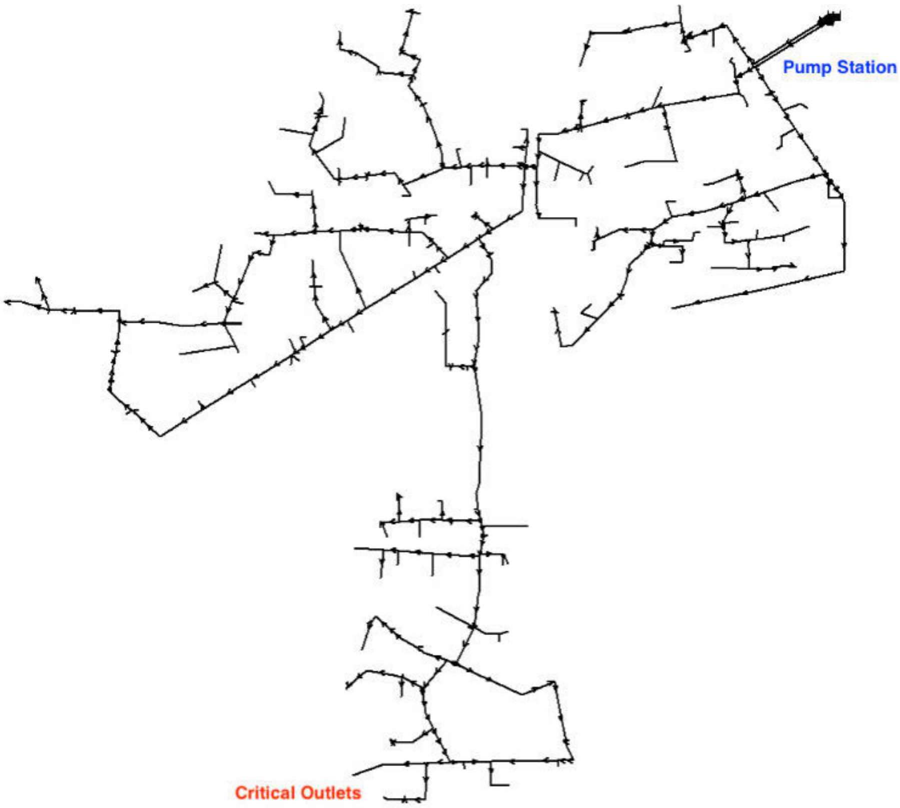

Figure 2. Robinvale High-Pressure Irrigation Network Layout.

2.2 Improved Pump Pressure Setpoint Selection

The new pump setpoints for the proportional-integral controller are adjusted considering actual irrigation deliveries. In principle, all irrigators who have placed an irrigation water order will receive at least the agreed minimum level of service (35 m of pressure head) regardless of what other irrigators do. Meanwhile, no specific attempt will be made to provide sufficiently high pressure to irrigators who are taking irrigation water but who have not ordered water.

Based on these principles, the steps for finding the pump setpoints based on a new method can be summarized as follows:

1. Initialize the pump setpoint with an arbitrarily selected value (e.g. 100 m of pressure head).
2. At every 15 minutes, for each outlet
    a. Obtain the ordered demand and measured irrigation delivery flows at active outlets (the outlets actually ordered and takes water from the network); and
    b. If both flows are greater than zero (indicating an active irrigation outlet), then
        i. Obtain the pressure head at the upstream side of each irrigation outlet from the EPANET hydraulic model simulation;
        ii. Compute the head loss across the irrigation outlet based on the minimum of the ordered demand and actual measured flow (also taking into account different diameters of irrigation outlets); and
        iii. Obtain the outlet downstream pressure head by subtracting the outlet head loss from the upstream pressure head obtained from EPANET.
3. Find the most critical active irrigation outlet by finding the minimum downstream pressure head.
4. Obtain the difference in pressure head by subtracting the downstream pressure head at the most critical irrigation outlet from the required minimum pressure head.
5. Adjust the pump setpoint by adding (or subtracting) the computed difference in pressure head to the pump setpoint 15 minutes ago.
6. Repeat Step 2.

3 CASE STUDY AND RESULTS

3.1 System Description

The Robinvale area had a population of 3,313 at the 2016 census. The Robinvale population includes people living in the Robinvale township and the surrounding rural area, some within the Robinvale Irrigation District. As shown in Figure 2, the RVHPS consists of one pump station and pipelines to supply water from the River Murray to 244 irrigation outlets across a 2700 ha area.

The pump station capacity is about 3,700 L/s. A total of 3,000 L/s is available for irrigation water orders and 300 L/s is reserved for domestic and stock (D&S) use. The remaining capacity of about 400 L/s accommodates irrigators using flow rate in excess of orders, turning an outlet off late or starting an order early. Better compliance with irrigation orders would allow some of the 400 L/s to be made available for irrigation purposes.

3.2 Economic and Environmental Outcomes

The new pump setpoint selection algorithm has been evaluated in simulation and compared with old setpoints using historical data from 28th and 29th Dec 2019. The comparison result with old and new pump setpoints is shown in Table 1. From this table, it can be seen that an average reduction in pressure setpoints is 4.50 m. In addition, operations with the new pump setpoints over the two days investigated resulted in a 7.08 MWh savings in pumping energy, an $800 savings in pumping energy cost, and a reduction of 7.72 tonnes in GHG emissions. The operations with the new pump setpoints can lead to 4.74% savings in operation related energy consumption and GHG emissions compared to old operations during the chosen summer period (peak demand).

Table 1. Comparison of Economic and Environmental Outcomes (over 2-day Simulation Period).

	With Old Setpoints	With New Setpoints
Average Pump Setpoints [m]	94.0	89.5
Total Energy [MWh]	149.3	142.2
Total Energy Cost [$]	16,300	15,500
Volume Pumped [ML]	464	464
Unit Energy Usage [kWh/ML]	322	306
GHG Emissions [tonne]	163	155

3.3 Comparison: Mismatch between Total Ordered and Delivered Irrigation Flows

Before an irrigator takes water, an order should be placed via a computerised water ordering system. Actual measured irrigation deliveries at some outlets may not match the orders. As shown in Figure 3, total ordered demands and sum of measured irrigation flows are different over the two-day simulation period (28th and 29th Dec 2019). In order to understand the impact of the mismatch between total ordered demands and sum of actual delivered irrigation flows on the operation of the RVHPS, its energy consumption and on GHG emissions, the above comparison and analysis are carried out again for two different operation periods when ordered and delivered flows differ. In operation period 1 (within the 2-day simulation period), the sum of flow rates through irrigation outlets exceeds the sum of irrigation orders; and in operation period 2, the sum of ordered flow rates exceeds the sum of flow rates being used through irrigation outlets. A comparison of the results for the two operation periods is presented in the following two sub-sections.

While the sum of actual flow rates through irrigation outlets may exceed the sum of irrigation orders during a period, the actual flow rate may not have necessarily exceeded the ordered flow rate at every irrigation outlet, and vice versa. Compliance with the ordered flow rate at an irrigation outlet may vary during a period, and an outlet may vary between taking more and taking less than ordered.

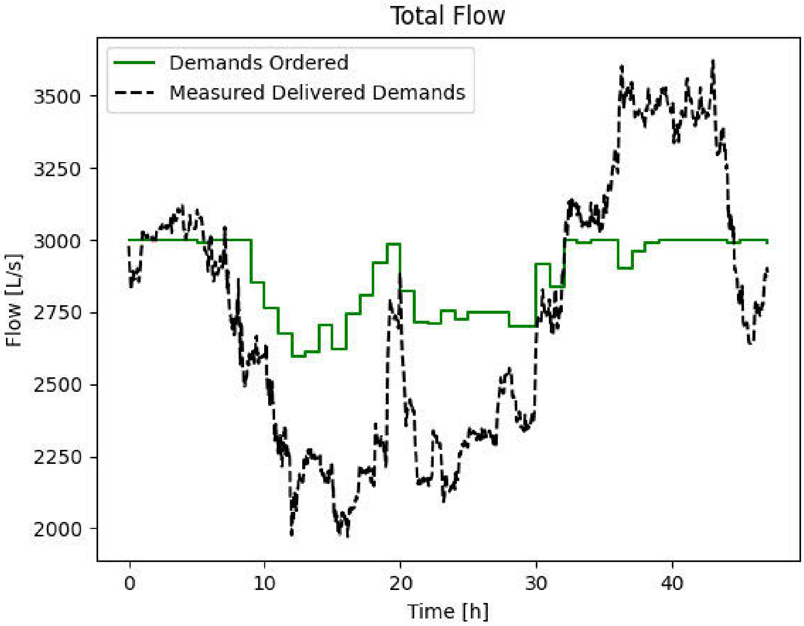

Figure 3. Comparison of Total Pumping Flows with Ordered versus Measured Irrigation Deliveries.

3.4 Potential Savings for the Period of Ordered Flows Less Than Flows Delivered

Within the two-day simulation, this operation period occurred from 32:05 hours to 44:31 hours (Period 1). The sum of actual flow rates through irrigation outlets exceeded the total ordered flow rates. The comparison of the calculation results of energy, energy cost and GHG emissions is reported in Table 2. As can be seen in Table 2, operations with the new pump setpoints over this period can lead to approximately 2.7 MWh savings in pumping energy, $300 savings in pumping energy cost, and a reduction of 2.9 tonnes in GHG emissions. In summary, the improved operation can lead to 5.21% in operation related energy consumption and GHG emissions, when ordered flows are less than delivered irrigation flows.

Table 2. Comparison of Results for Economic and Environmental Outcomes (Period 1).

	With Old Setpoints	With New Setpoints
Average Pump Setpoints [m]	100.1	95.0
Total Energy [MWh]	50.8	48.1
Total Energy Cost [$]	5,500	5,200
Volume Pumped with Non-compliance [ML]	149	149
Unit Energy Usage [kWh/ML]	340	323
GHG Emissions [tonne]	55.3	52.4

Non-compliance with irrigation orders can result in actual delivered flows being higher than ordered demands and hence larger head losses in pipes. To overcome this, the pressure setpoint at the pump station must be increased in order to guarantee minimum required pressure heads at active irrigation outlets. It is also worth mentioning that non-compliance behavior is not always satisfied. The minimum required pressure head is taken into account the ordered flow if farmer takes more water than ordered. During the operation period from 32:05 hours to 44:31 hours in the two days that were investigated, some irrigators were taking more water than they ordered. The total ordered volume was 134 ML (Table 2) and the actual pumped irrigation volume was 149 ML (Table 3). The compliant behavior considered here is that all the irrigators take water strictly in accordance with orders, that is, staying within the start and stop times and adhering to the magnitude of the ordered flow rate. As can be seen in Table 3 the non-compliant behavior can lead to approximately a $1.50/ML increase in unit energy cost compared with the old pump station setpoint operation. In a similar way, for non-compliant behavior, an approximately $1.70/ML increase in unit energy cost occurs with the new pump station setpoint operation. In summary, non-compliance with irrigation orders can cause a 4.21% and 5.07% increase in unit energy cost taking into account old and new pump operations, respectively.

Table 3. Comparison of Results for Energy Cost with Compliant and Non-compliant Water Use (Period 1).

	With Old Setpoints	With New Setpoints
Average Pump Setpoints [m]	96.1	90.5
Volume Pumped with Compliance [ML]	134	134
Unit Energy Cost with Compliance [$/ML]	35.6	33.5
Unit Energy Cost with Non-compliance [$/ML]	37.1	35.2
Percentage of Cost Increase for Non-Compliance	4.21%	5.07%

3.5 Potential Savings for the Period of Ordered Flows Greater Than Flows Delivered

Within the two-day simulation, this operation period occurred from 05:31 hours to 31:00 hours (Period 2). The sum of actual delivered flow rates through irrigation outlets was less than the total ordered flow rates. The comparison of the calculated energy use, energy cost and GHG emissions is reported in Table 4. As can be seen in the table, operations with the new pump setpoints over this period can lead to 3.4 MWh savings in pumping energy, $300 savings in pumping energy cost, and a reduction of 3.7 tonnes in GHG emissions. In summary, the improved operation can lead to a 5.10% reduction in operation related energy consumption and GHG emissions, when the sum of ordered flows is greater than the sum of actual flows being used through irrigation outlets.

Furthermore, over this operation period, the average total pumping flow with ordered demands is 2,779 L/s compared to the one with measured irrigation deliveries of 2,384 L/s. The difference between the two average total pumping flows is 394 L/s, which means the network can accommodate delivery to an extra 7.5 irrigators on average (with an assumed ordering capacity of 52 L/s per irrigator) during the same time period of 26 hours.

Table 4. Comparison of Results for Economic and Environmental Outcomes (Period 2).

	With Old Setpoints	With New Setpoints
Average Pump Setpoints [m]	90.6	85.9
Total Energy [MWh]	66.4	63.0
Total Energy Cost [$]	7,200	6,900
Volume Pumped with Non-compliance [ML]	216	216
Unit Energy Usage [kWh/ML]	308	292
GHG Emissions [tonne]	72.4	68.7

3.6 Comparison of Level of Service Delivered by the Old and New Pump Setpoints

A comparison of the level of service has been assessed with irrigators using the ordered demands, as shown in Figure 4. This simulates the case where all irrigators comply with their water orders. In this case, operation with the new pump setpoints ensures that the required minimum pressure head (35 m) is delivered at all the irrigation outlets every 15 minutes when the pump setpoint is recalculated. As a comparison, the operations with the old pump setpoints did not always ensure all the irrigation outlets have enough pressure. As shown in Figure 4, one irrigation outlet has the largest unsatisfied pressure head magnitude was 3.51 m for a duration of approximately 3 hours.

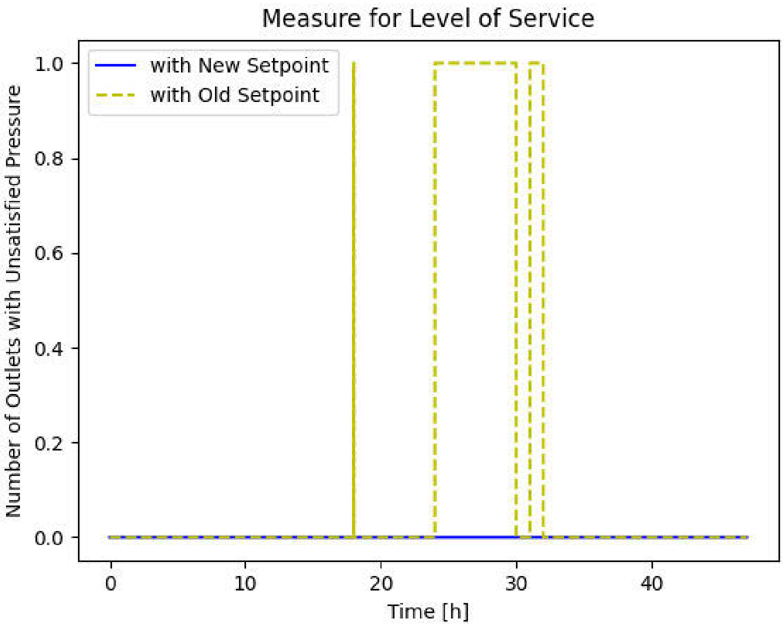

Figure 4. Comparison of the level of service.

4 CONCLUSIONS

In this paper, an improved pump pressure setpoint has been developed for a high-pressure pumping irrigation system. The proposed algorithm can select improved pump pressure setpoint based on real-time measured flows sent from each irrigation outlet to identify the most critical outlet currently active outlets with minimum downstream pressure. From the simulation results, it can be seen that the PI controller with the improved pump pressure setpoint can gain 4.74% savings in pumping energy cost as well as the reduction in the associated greenhouse gas emissions.

Non-compliance with irrigation orders can have a significant impact on pumping energy needed to meet the minimum pressure requirement at all outlets with irrigation orders. The pump setpoint selection can be further incorporated with the water ordering system. Moreover, potential water storage can be designed into the RVHPS network, which gives more degree of freedom to further investigate better control operations leading to more energy savings and GHG emission reduction.

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