An Online Optimised Pump Scheduling System

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Abstract

A common problem facing the suppliers of bulk drinking water is how to minimise the cost of supply. In a typical potable water distribution network, water is supplied from a number of water treatment plants into a mains network. From there it can either be directly piped into domestic reticulation or pumped into a load balancing municipal reservoir. The cost of supply has several aspects: the chemical cost of treating water, the cost of pumping water into the mains network and the cost of pumping water from the mains network into the municipal reservoirs. The demand of water varies seasonally and by time of day so it is uncommon for water treatment plants and reservoir pumping stations to operate at their peak capacity continuously. The goal of optimisation is to find a schedule of water treatment plant outputs and pump running times that will minimise the cost of supplying the demand while meeting operational constraints. This paper describes a solver called *Derceto* which solves the pump scheduling problem for the Wellington Regional Council (WRC)'s Wainuiomata-Waterloo potable water distribution network. Since installation, WRC have reported a 10% reduction in the cost of supplying water to the Wainuiomata-Waterloo network.

1 Introduction

Pump scheduling problems are computationally difficult. The difficulties are caused by the non-linearities of the physical system, resource constraints, operational constraints and varying power and chemical charges. To solve this problem, Beca Carter Hollings & Ferner have created an online pump scheduling software package called *Derceto*. *Derceto* was implemented for Wellington Regional Council's Wainuiomata-Waterloo potable water distribution network.

This paper discusses some of the modelling issues involved in scheduling a water distribution network. It also discusses the complications involved when the schedule is applied to a real time system. This paper then describes the different stages of the solution method used by *Derceto*. The physical network is described, along with the implementation requirements and the control system for this network. Finally, the cost savings experienced since implementation are reported.

2 Design Considerations

In a generic water distribution network, water is produced by water treatment plants (WTPs) and pumped into a mains network. From the mains network, water is pumped into a reservoir for temporary storage or flows directly into the reticulation (the supply network to individual customers). The demand for water out of a reservoir or reticulation point will vary seasonally and over the course of the day. Water treatment plants and pumping stations do not normally run at capacity continuously. Because they do not run continuously, there is scope to schedule the output and running times instead of load-following the demand.

It is desirable to find a schedule that will supply the water demand for the lowest cost possible.

2.1 Modelling

A typical water distribution network is not easy to model.

A typical structure inside a distribution network is that of a fixed speed pump supplying water to a municipal reservoir. The most common way of controlling the level in a reservoir of this nature is to place low and high level switches in the reservoir which will trigger the pump to start and stop. When operating under level control, the pumps are most likely to be running during times of high water demand. This is unfortunate, since many water companies are billed time-of-use energy costs. The cost of energy is high at the same time that water demand is high, since peak electricity use and peak water use tend to coincide.

It is also possible for water in the mains network to be pumped directly into reticulation. When water goes directly into reticulation, it is important that the pressure stays within acceptable bounds to avoid pipes bursting or customers running out of water.

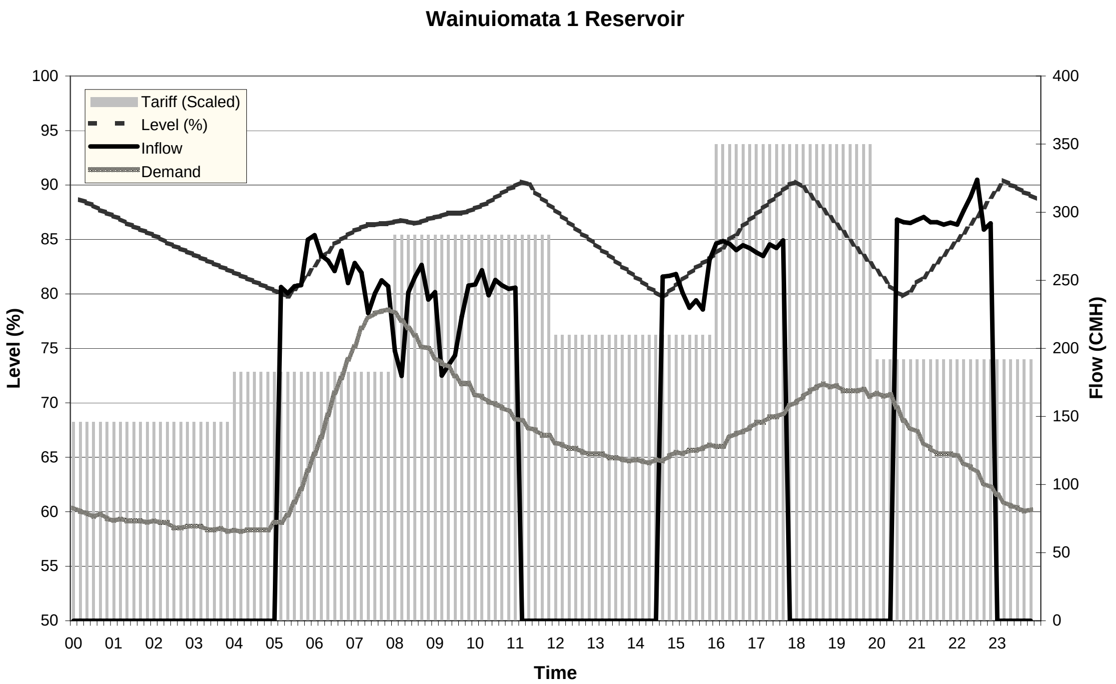

Figure 1. A Typical Reservoir under Level Control

The easiest way to model this is as a mass-balance problem. The water that goes into reticulation over the course of the day is mass removed and the water pumped in is mass added. The flow-head characteristic of a pump is non-linear, but the flow of water pumped in can be assumed constant if the acceptable level range of the reservoir is slight (1-2m) and the pressure on the suction side of the pump does not vary. The control variable is the scheduled times at which the pump is running. The schedule is constrained so that the pump must supply enough water to equal the demand. The pump must also fill the reservoir by a nominated time, without allowing the reservoir level to go outside its set limits.

The biggest assumption is that the suction pressure of the pump is constant. This is not a good one, unless every reservoir pump is completely independent of every other reservoir pump, which often is not the case. The pressure in a closed pipe is dependent on the flow through it. As the water supply into the network increases, the head difference across the pump decreases. The change in head across the pump changes the flow that the pump can produce when running.

If a schedule examines every reservoir independently, it is likely to turn many pumps on at the same time of day because the demand and tariff patterns will be similar. Running many pumps at the same time will change the pumps' flow-head characteristics and invalidate the mass-balance. Pushing a lot of water into the network will increase the pressure at reticulation points. Furthermore, the water available to the system from water treatment plants (WTP) is normally limited and each running pump is competing for its share of the water.

Any schedule must also account for the operational constraints of the water treatment plants. Some types of water treatment plants provide better quality water when their flowrate is constant. The allowable flowrate of a water treatment plant can also be limited by environmental factors such as extremes of rainfall.

2.2 Real Time Control Systems

The most important issue in a real time control system is robustness. *Derceto* is installed to run with or without supervising operators for 24 hours a day. At all times, *Derceto* must be able to cope with unusual situations gracefully. Events that have occurred include:

- Lightning strikes.
- Pump failure.
- Pipe maintenance.
- Telemetry failure.
- Telemetry time delays.
- Extremely high demand out of a reservoir.
- Flow and level meters developing systematic errors.

In order to cope with unexpected events *Derceto* needs to be able to adapt quickly to changes. *Derceto* adapts by re-solving every half-hour and taking advantage of updated level and demand data. If the new data is such that *Derceto* is unable to solve the current system, the previous half-hour's solution is adopted.

Derceto also needs to check data validity by reality checking all incoming data.

3 Solution

There are four main phases in *Derceto's* operation.

1. Initialisation
2. Solve the mass-balance (First Stage Solution)
3. Solve the schedule (Second Stage Solution)
4. Check the answer (Simulation)

Derceto typically runs through these stages several times obtaining a more accurate solution with each new iteration. When the solution is accurate enough, it *Derceto* passes it to the telemetry or plant control system.

3.1 Initialisation

Derceto begins by initialising its data. Some of the data are known in advance such as the current levels of the reservoirs and the operator set limits on the water treatment plants. The rest of the data are predicted, such as the flow through the pumps and the demand for the rest of the day.

The pump flows (if the pump runs) are assumed to be constant for each half-hour period and independent of whether other pumps are running or not. They are preloaded with good first guesses taken from a hydraulic simulation of the network. In subsequent iterations (see section 3.4), the predicted pump flows are taken from a hydraulic simulation that uses the previous iteration's schedule. The use of an iterated simulation accounts for the interactions between pumps and the changes in pump flow caused by varying network pressures.

To estimate the demands, standardised demand curves were constructed for each reservoir. These curves show the average flow out of the reservoir for different types of days. (For instance, Weekend Summer, Weekday Winter.) The correct standard curve is identified each time *Derceto* runs and progressively scaled up or down according to the real-time data that has been logged for the day.

3.2 First Stage Solution

The first solver stage of *Derceto* determines the mass-balance required to get every reservoir full by the end of the day while:

- Keeping the reservoir levels between pre-determined limits.
- Maintaining pressure in the network.
- Not exceeding water treatment plant capacity.
- Minimising the overall cost of supply.

To do this, the day is divided into blocks of time and the reservoir levels are considered only at the boundaries of the blocks. Pump flows and water treatment plant outputs are considered in terms of the volume of water moving in and out of the system in each block. The first stage solver will output for each pump how many hours the pump should run inside each block in order to get the reservoirs full. Inside any given block the instantaneous pump status, reservoir level and water treatment plant output are not considered. Restrictions on pump runtimes and water treatment plant flows are accounted for by semi-continuity constraints.

In the example (see Figure 2), the day is divided into twelve blocks with a duration of two hours each. In the two most expensive blocks of the day, pumping is completely avoided. In addition, the pumping in the next most expensive block is the minimum required to keep the reservoir full. In the blocks in which the pump is only scheduled 'on' for part of the two-hour block, the pumping can be carried out at any time during the block, not just the beginning. The reservoir level is allowed to drop to close to its lower limit by midnight, the beginning of the cheapest tariff window.

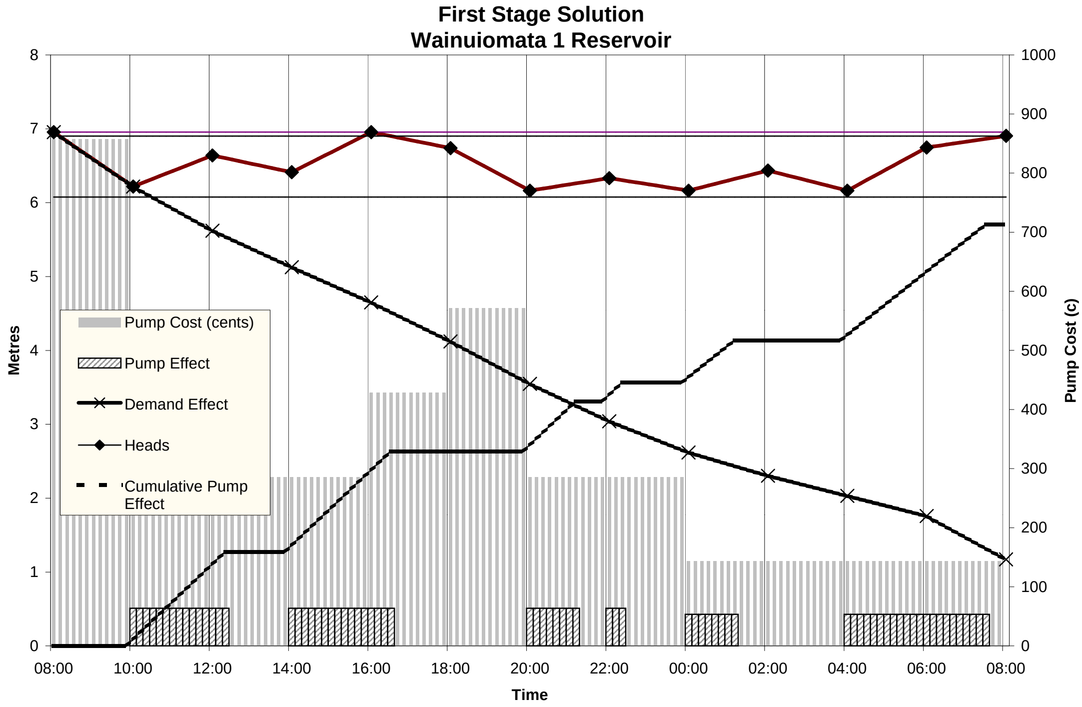

Figure 2. Sample First Stage Solution

3.3 Second Stage Solution

The second *Derceto* solver stage takes the required pump runtimes for each block found by the first solver stage.

The runtimes are turned into a specific schedule of On/Off times for each pump. The schedule must account for any conflicts between pumps that must not run at the same time. The schedule must also determine the water treatment plant output so that capacity is not exceeded and the flow does not ramp up too quickly. Additional considerations are the points at which pressure is restricted and the total instantaneous power use. *Derceto* returns the lowest cost schedule that will satisfy these constraints.

3.4 EPAnet Simulation

EPANET is a program for analysing the hydraulic and water quality behaviour of pressurised pipe networks.

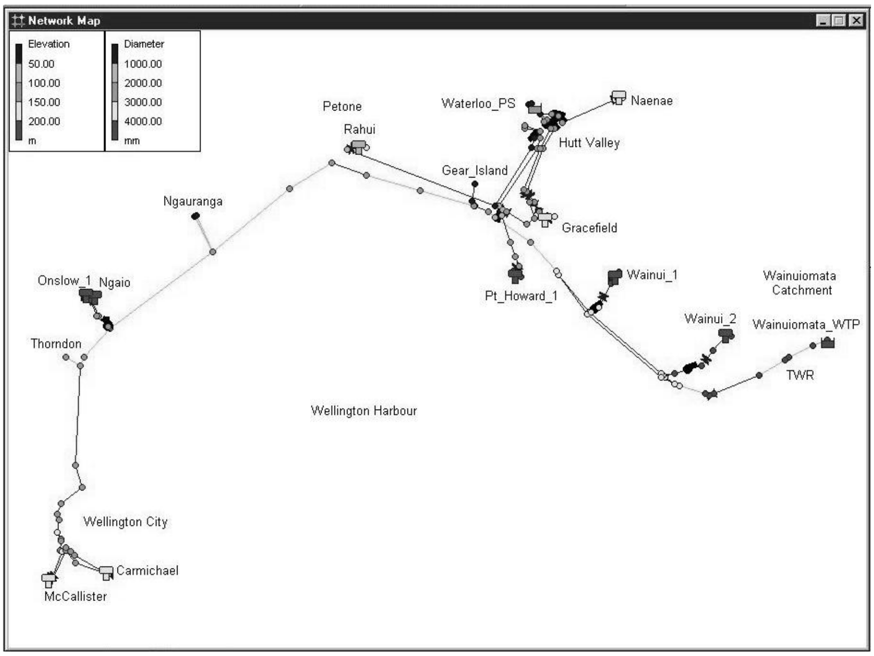

Figure 3. EPAnet Model of Wainuiomata-Waterloo System

The EPAnet simulation takes as inputs:

- The predicted demand for the day.
- The current levels of the reservoirs.
- The scheduled flow out of the water treatment plants.
- The schedules for the pumps.

The EPAnet simulation outputs are:

- Half-hourly reservoir levels for every period from the start of the simulation until the end of the day.
- The average flow and head for each pump calculated for each half-hour from the start of the simulation until the end of the day.

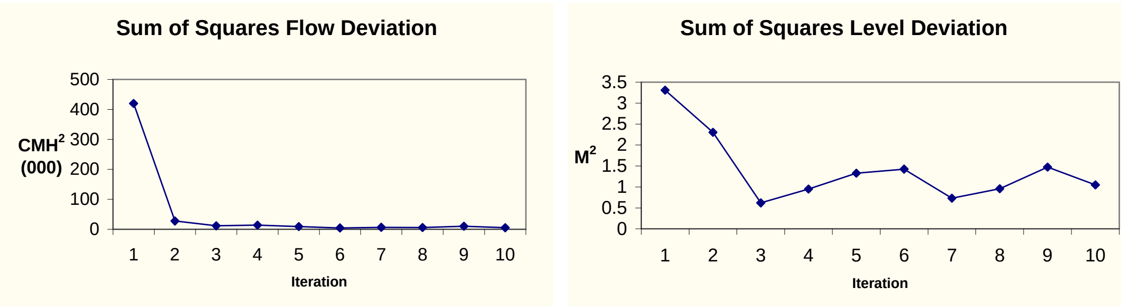

Figure 4. Head and Flow Deviation per EPAnet Iteration

The updated flows and heads are then used as the basis for new solver iteration. This iteration will be able to solve with more accurate mass-balance and cost information. This process continues until convergence is reached.

4 Implementation

4.1 Wainuiomata-Waterloo Network

In the Wellington region, water is supplied by the Water Group of the Wellington Regional Council (WRC) to the four cities. WRC maintains the water levels in the municipal reservoirs between set limits at all times. Every reservoir is target filled by 8am in the morning.

Four water treatment plants supply water: Te Marua, Wainuiomata, Waterloo and Gear Island. While technically any supply point may provide water to any demand point, under normal operation the Te Marua system will behave as a separate network with only one linkage to the Wainuiomata-Waterloo system. This linkage is at the Ngauranga Pumping Station. Water may be transferred between systems by running pumps and/or opening a control valve at the Ngauranga Pumping Station. The Gear Island water treatment plant is used as an emergency supply only.

Derceto was implemented for the Wainuiomata-Waterloo system. This network comprises:

- 3 water treatment plants (Wainuiomata, Waterloo, Gear Island)
- 12 primary reservoirs
- 5 fixed pumps (4 standby)
- 2 variable speed pumps (1 standby)
- 1 dual speed pump (1 standby)
- 1 control valve
- 1 pressure control point where water enters the reticulation

This network has an average annual daily demand (AAD) of 85 megalitres per day (MLD). The approximate average annual power costs are $900,000.

4.2 Implementation Issues

The operators need to be able to schedule pumps and water treatment plants on or off at any time of day to schedule maintenance. It is also desirable for operators to be able to schedule the water transferred between networks via the Ngauranga Pumping Station.

Power costs are from three principal charges. Energy use (kWh) is charged for every site (pumping stations and plants) by the time of day. The tariff structure at the time of implementation was two-tier, however WRC wanted the ability to optimise to a structure where the tariff changes every half-hour. Network costs make up the other two charges. For each site the highest recorded energy use over a half-hour period for the entire month is given an additional charge called the Anytime Maximum Demand (AMD) charge. The highest recorded energy use over a half hour period between 8-10am and 5.30-7pm for the entire month is given an additional charge called the

Coincident Maximum Demand (CMD) charge. Typically AMD and CMD charges account for approximately half the total power costs.

While most of the reservoirs in the network are supplied by dedicated pumps, two large reservoirs (Macalister Park and Carmichael) are terminal reservoirs. In addition, Macalister Park and Carmichael are linked by reticulation and their levels are interdependent. Another reservoir (Rahui) is controlled by a flow control valve so that it can only be supplied water when the Waterloo WTP Wellington pumps are supplying water.

The Wainuiomata WTP is a surface water DAF (dissolved air flocculation) plant. The plant ramp rates are set. The plant requires manual intervention to start and so always needs to supply at least its minimum flow into the network when not being directly controlled by operators. The Waterloo WTP supplies Wellington using two variable speed duty pumps. *Derceto* is required to select the most efficient combination of one or two duty pumps at all times.

4.3 Control System

Derceto is implemented on a PC linked to the Waterloo Plant control system. The control system retrieves real-time level, pressure and flow information via telemetry and the control system for every 'solve'. The *Derceto* 'solve' returns pump and water treatment plant schedules to the control system.

The existing operator interface is a Supervisory Control and Data Acquisition (SCADA) system called Citect. Citect was used to implement the *Derceto* interface. Citect provides a graphical interface that gives insight into the system operation and makes control intuitive. Using the existing system means that linking *Derceto* to the

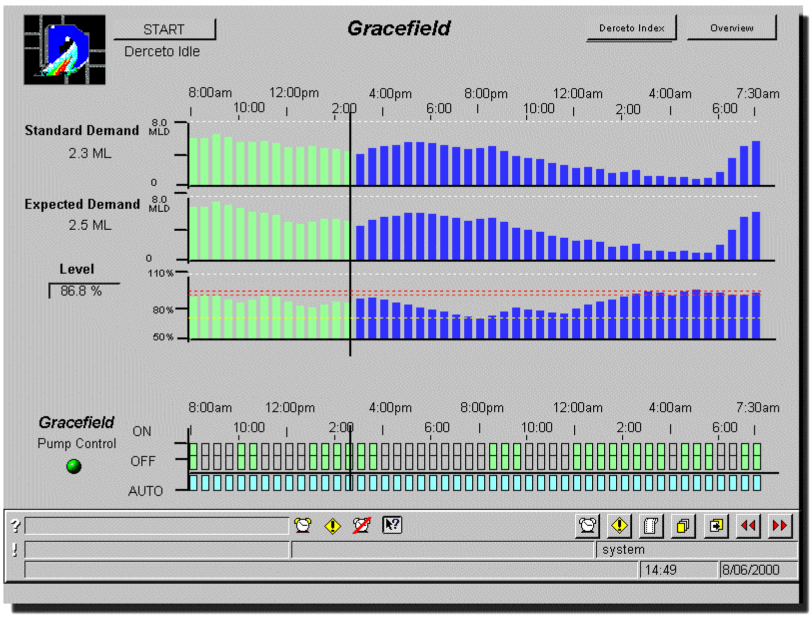

Figure 5. Operator screen for Gracefield reservoir pump schedule

main plant controls was easy and that the operators were already familiar with the mechanics of the system.

Derceto is set to run automatically every half-hour. In addition to the automatic 'solve', the operators can trigger a 'solve' manually if desired. The previous solution is always kept until *Derceto* has returned with a new feasible solution as a fallback.

The control system has multiple layers of redundancy. The topmost layer is the optimisation controlled by *Derceto*. In addition to this, the plant operators have the option of turning *Derceto* off and running some or all of the system manually. (In fact, for a three month trial period, only the Pt Howard reservoir was controlled by *Derceto* to give the operators confidence in the system.) As a final safety measure, the reservoirs have hardwired level controls that will automatically start and stop their reservoir pumps if the levels transgress set bounds.

Derceto was installed on a PC running WindowsNT. A solve of three iterations typically takes less than two minutes.

5 Cost Savings

The cost savings experienced by WRC have been significant. These have three components: energy use, network charges and chemical treatment.
(Note, these figures are quoted from [1].)

5.1 Energy Costs

The energy use of the pumping stations is charged on a two-tier tariff pattern with 8am-Midnight more expensive and Midnight-8am less expensive. The percentage of time spent pumping in the cheaper night period has increased markedly in the first nine months of operation. Savings have been estimated at $40,000 or approximately 10% of the energy bill.

Figure 6. Off-peak energy as a percentage of total energy consumed

Pumping Station	**Before Derceto**	**After Derceto**
Waterloo Water Treatment Plant	23%	40%
Moore's Valley Pumping Station	10%	50%
Wainuiomata Pumping Station	15%	30%
Pt Howard Pumping Station	20%	40%
Kaiwharawhara Pumping Station	17%	30%

5.2 Network Charges (AMD/CMD)

The network charge savings have been chiefly from CMD avoidance. In the first nine months of operation, approximately $35,000 has been saved. At the Waterloo Water Treatment Plant there was a reduction in CMD charges of approximately 80%.

Unfortunately, it has not proved possible to completely avoid the CMD charges, as it requires only one half-hour incursion in a given month to incur the charge. Incursions may be due to operational constraints such as pump breakdowns, scheduled additional flow to Te Marua and the requirement to maintain system pressure.

5.3 Chemical Treatment Costs

Derceto will automatically select the lowest cost source of water permitted. This means reducing the flow taken out of the Wainuiomata Water Treatment Plant and increasing the flow out of the Waterloo Water Treatment Plant except during the CMD time window. This is because Waterloo has a lower cost for chemical treatment and except when CMD charges are applied, its pumping costs were also lower. The savings achieved in nine months were approximately $20,000.

6 Conclusions

In conclusion, the implementation of *Derceto* has been an effective means of controlling the Wainuiomata-Waterloo network. *Derceto* has been able to solve a complex physical system in real-time and cope with unexpected physical events. The solver strategy of solving the mass-balance equations, solving the instantaneous schedule and then checking the result with a hydraulic simulation is effective. *Derceto* is able to model numerous idiosyncrasies of the distribution network and the interface gives the plant operators insight and control of the system. The cost savings experienced have been significant.

Acknowledgements

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Keith Woolley is the Wellington Regional Council project manager in charge of the implementation of *Derceto* whose help has also been invaluable.

References

[1] Bunn S.M., Woolley K., 'Derceto: An Online Pump Schedule Optimisation System', NZWWA Annual Conference 2001