

# Centralised and Decentralised Control of the Broken River

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**Abstract**—In this paper centralised Model Predictive Control (MPC), tuned in two different ways, and a decentralised control scheme are proposed for the control of the Broken River in Victoria, Australia. The control objective is to improve water resource management for the benefit of irrigators and the environment. The controllers are designed based on simple time delay and integrator delay models. The controllers are evaluated in realistic simulation scenarios and compared to manual operation. The use of control offers increased operational flexibility with a significant potential for substantial water savings, improved level of service to irrigators and improved environmental benefits.

## I. INTRODUCTION

Water is a scarce resource in many parts of the world, and good management of the available water resources is becoming increasingly important. Modelling and control have important parts to play in water management since well designed control and monitoring systems will allow for a more efficient distribution of water without creating undesirable environmental or ecological conditions along a river. Potential benefits include accurate and timely delivery of water to irrigators and the environment, water can be ordered by irrigators on a shorter notice leading to more flexible farming, improved environmental outcomes, and a larger amount of water can be commanded for targeted use, e.g. for irrigation or flooding of wetlands.

The application of modelling and control to improve the operations of irrigation channels in Australia has been a large success (see e.g. [1], [2]). However, there are major differences between rivers and irrigation channels. For example, compared to an irrigation channel, there are much less possibilities for in-stream storage of water in a river.

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For an irrigation channel there are few or no ecological or environmental constraints, while they can be very important in a river. For an irrigation channel one would typically aim at minimising releases subject to satisfying demand. This may partly be an objective for a river, but minimising releases may mean that a downstream river is starved for water. For a river, due to the fewer points where the flow can be regulated, there are much larger time delays between the points of supply and the points of demand, and this makes it much more difficult to satisfy demand for water on a short notice.

In this paper we consider the control of a river for the purpose of improving the service to the irrigators and the environment. There are a number of works on control of rivers with the focus on optimisation of the operation of hydro-electric power plants, minimising the energy cost of pumping or ensuring that the river is navigable etc (see e.g. [3] - [10]). In this paper we consider both decentralised control and centralised Model Predictive Control (MPC). MPC is ideally suited for this problem due to its ability to handle constraints (see e.g. [11]). The MPC is tuned in two different ways. In the first case the weights in the optimisation criterion are found based on the control objectives, physical insight and a bit of trial and error, while in the second case the decentralised controller is reversed engineered as an MPC (see [12], [13]). The performance of the control system is assessed through a year long simulation scenario based on recent historical data suitably adjusted for anticipated future trends.

The paper is organised as follows. In the next section, a description of the Broken River is given. The control objectives are described in Section III. A brief description of the models is given in Section IV. Section V covers control design, while the simulation scenario is presented in Section VI. The performance of the control systems are discussed in Section VII. Concluding remarks are given in Section VIII.

## II. BROKEN RIVER

Figure 1 shows a map of the Broken River. The river originates from Lake Nillahcootie which is lake-dam. It flows north for about 45km before turning west at Casey's Weir and flows into the Goulburn River after another 55km. The two main tributaries are Lima Creek and Hollands Creek which flow into the upper part of the Broken River. Broken Creek flows out from the river just upstream of Casey's Weir. The study area we consider is from Lake Nillahcootie (HS1) to Gowangardie Weir (HS4) and covers 2500km<sup>2</sup> of the catchment area.

Within the study area there are four weirs, Broken Weir, Benalla Weir, Casey's Weir and Gowangardie Weir. The last

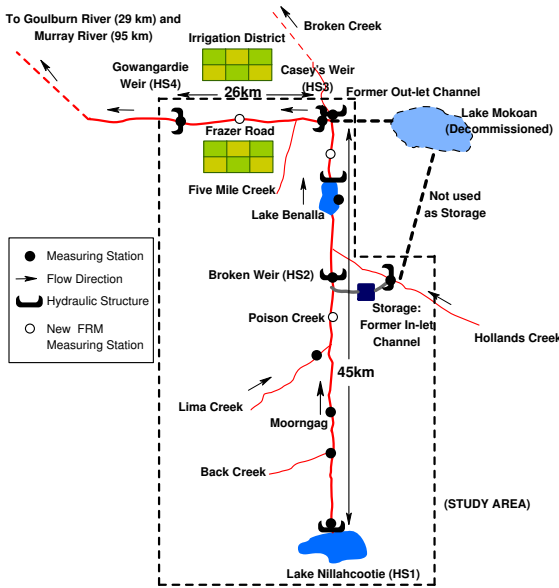


Fig. 1. Approximate top view of the Broken River (not to scale).

three are free overfall weirs where the flow cannot be regulated. The places where the flow in the river can currently be regulated are at the out-let of Lake Nillahcootie and at Broken Weir. The flow into Broken Creek just upstream of Casey's Weir can also be regulated.

A 300 Megalitres (ML)\* off-stream storage in the former in-let channel to the now decommissioned Lake Mokoan is currently being built, and the flow into the storage upstream of Broken Weir will be regulated as well as the flow out of the storage through Hollands Creek into the Broken River.

The environment is protected through minimum flow requirements ranging from the natural flow to 25 ML/day on a fortnightly average [14] at a number of locations along the river. Irrigators pump water directly from the river, and most of the demand for water is downstream of Casey's Weir. Hence, there is a large distance between the point of supply (Lake Nillahcootie) and where the demand is<sup>†</sup>. The system is a demand driven system and under current practice, the irrigators order water four days in advance. All the water orders from irrigators and the environment are added up and another 20-30 ML/day is added as a safety margin before the flow is manually released from Lake Nillahcootie taking into account the approximate travel time to the place where the water is needed.

There is obviously a potential for improved operational efficiencies by applying feedback control. However the performance of the control system will necessarily be limited by the long time delay between the point where the flow can be regulated and the point of demand. One possibility in order to overcome this difficulty is to install regulation

\*We have used the unit ML rather than the SI unit of  $m^3$  since ML is commonly used in the rural water industry.

<sup>†</sup>The time delays for different reaches in the Broken River from Lake Nillahcootie to Gowangardie Weir (see Figure 1) ranges from 500-2250 minutes, while the total time delay is about 6500 minutes.

gates at Casey's Weir which is closer to where most of the demand is, and in this paper we will assume that the flow can be regulated at Casey's Weir.

### III. CONTROL OBJECTIVES

The control objectives are summarised as follows:

- 1) Satisfy the demand for water from the irrigators and the environment.
- 2) Maintain the volume of the off-stream storage at 50% of full capacity.
- 3) Maintain the flows over Broken Weir and Casey's Weir above 22 ML/day to satisfy environmental minimum flow requirements.
- 4) Maintain the water levels at Broken Weir, Casey's Weir and Lake Benalla within  $\pm 15$  cm of setpoints.
- 5) Maintain the flow over Gowangardie Weir at a desired setpoint in order to satisfy downstream demands and the environmental minimum flow requirements.
- 6) Release as little water from Lake Nillahcootie as possible.
- 7) Reduce the water ordering time for irrigators.
- 8) Keep the flow from early spring to mid summer under 120 ML/day in order to create slackwater pockets [15].
- 9) Limit the average daily flow to be between 0.76 and 1.50 of the previous day's flow in all reaches [16].

### IV. MODELS

The time delay and integrator delay models are used for the reaches. They are obtained using system identification techniques and they respectively have the following form,

$$Q_D(t) = Q_U(t - \tau) \quad (1)$$

and

$$\dot{V}_D(t) = Q_U(t - \tau) - Q_D(t) \quad (2)$$

where  $Q$  is the flow, the subscripts 'U' and 'D' denote the upstream and downstream end respectively,  $V$  is the volume and  $\tau$  is the time delay. The flows and volumes can be further approximated in terms of water levels and gate positions.

By calibrating and testing the models against real data it has been shown that the time delay and integrator delay models represent the dynamics of the reaches relevant for control very well. (see [17] and [18] for details).

### V. CONTROL

#### A. Manual operation

Under current manual operation, the flow out of Lake Nillahcootie is adjusted daily by adding up future water orders which are known 4 days in advance. An extra 20 ML/day is added to account for uncertainties and transmission losses.

#### B. Decentralised control

PI and I controllers are considered in the decentralised configurations. Due to the long time delays, feedforward of the known future orders of water is necessary. For demand driven systems, the most appropriate control configuration is distant downstream control, where the water level or flow at

the downstream end of a reach is controlled by a gate at the upstream end. The distant downstream control configuration with feedforward is shown in Figure 2. The feedforward term is calculated as follows: all orders for water downstream of a gate including water orders in the downstream reaches are converted into an equivalent flow time series. The time series are shifted forward with the nominal time delay between the gate and the offtake point and then summed together to arrive at the feedforward flow. This feedforward action will compensate for the offtakes in a reach and for the outflows at the downstream end of the reach. The feedback

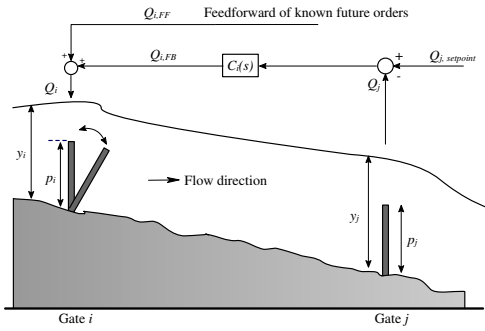


Fig. 2. Distant downstream control configuration with feedforward.

controller  $C_i(s)$  (usually a PI controller) will adjust for any discrepancies in the flow (or the water level). The feedforward and the feedback are added together to produce the required flow  $Q_i$  and the upstream gate  $i$  is positioned to release the flow. In decentralised control the flows in the creeks are treated as disturbances. For further details, see [19]. The whole decentralised control configuration for the Broken River is shown in Figure 3.

**Remarks:** (i) In flow mode, the controller aims at maintaining the constant pre defined flow by adjusting the height of gate,  $p_B$ . (ii) The PI and I controllers are tuned using classical frequency response method with Phase Margin between 51-68° and Gain Margin between 10-23 dB. (iii) The reach between Casey's and Gowangardie Weirs is modelled using a pure time delay. There is not much improvement in using a PI controller, so the simpler I-controller is used instead. (iv) The storage is modelled using a simple integrator, i.e.  $V_S(t) = Q_{Sin}(t) - Q_{Sout}(t)$ .

### C. MPC tuning

The standard way of tuning MPC is to select the appropriate weights in the criterion function based on the control objectives and physical insight. We call the resulting controller **MPC Designed from Scratch (MPC-DS)**. An alternative is to use the idea of reverse engineering. The idea is to first design a simple to tune controller (e.g. a PI controller), and then reverse engineer this controller as an MPC in the sense that we find the weighting matrices in the criterion function such that, in the absence of constraints, the MPC would behave like the simple controller. This MPC controller is much easier

to tune since the weights are automatically generated in the reverse engineering process. Moreover, the performance of the simple controller is maintained and we may potentially obtain the constraint handling capability of MPC as well. This controller is called **MPC Reverse Engineered (MPC-RE)**. For details, see [12] and [13].

1) *State space model:* The time delay and integrator delay models in Section IV are rewritten in state space form. In all control schemes the control variables are flow at Lake Nillahcootie,  $Q_{LN}$ , in-flow to the off-stream storage,  $Q_{Sin}$ , out-flow of the off-stream storage,  $Q_{Sout}$ , flow at Broken Weir,  $Q_B$  and flow at Casey's Weir,  $Q_C$ . The controlled variables are water level at Broken Weir,  $y_B$ , volume of the off-stream storage,  $V_S$ , water level at Casey's Weir,  $y_C$ , water level at Lake Benalla,  $y_{LB}$  and flow at Gowangardie Weir,  $Q_G$ .

The state variables are the deviation of the controlled variables from their setpoints, e.g.  $x_{e,C}(n) = y_C(n) - y_{C,sp}(n)$  for the water level deviation at Casey's Weir, where  $y_{C,sp}(n)$  is the setpoint. Let  $u_j(n) = Q_j(n)$ , where  $j = LN, Sin, Sout, B$  or  $C$ . Due to the time delays, we need a number of states to remember the past flows. The model can be written as

$$x(n+1) = Ax(n) + Bu(n) + d(n) \quad (3)$$

where  $d(n)$  incorporates offtakes, setpoint changes, flows in creeks and terms due to the linearisation. The sampling time is  $T_s = 360$  minutes. Note that we have access to all states, and there is no need to design an observer<sup>‡</sup>.

In order to ensure zero steady state error in the presence of disturbances, the integral of the setpoint errors are included in the state vector, i.e.

$$x_{int,l}(n) = x_{int,l}(n-1) + T_s x_{e,l}(n-1) \quad (4)$$

where  $l = B, S, C, LB$  and  $G$ .

2) *Optimisation criterion and constraints:* Based on the control objectives in Section III, using the standard MPC formulation, for MPC-DS, the criterion to be minimised is given by

$$J_{DS} = \sum_{n=0}^{N_p} [x^T(n)Q_{DS}x(n) + u^T(n)R_{DS}u(n) + s_L^T(n)Q_{DS,s,LSL}(n) + s_H^T(n)Q_{DS,s,HS}(n)] \quad (5)$$

while for MPC-RE the criterion contains cross terms between states and inputs, i.e.

$$J_{RE} = \sum_{n=0}^{N_p} [x^T(n)Q_{RE}x(n) + u^T(n)R_{RE}u(n) + x^T(n)S_{RE}u(n) + u^T(n)S_{RE}^T x(n) + s_L^T(n)Q_{RE,s,LSL}(n) + s_H^T(n)Q_{RE,s,HS}(n)] \quad (6)$$

<sup>‡</sup>In some situations, a state estimator may still be needed as the measurements could be corrupted by noise and sensor errors. In this paper, we assume the effect of noise is negligible.

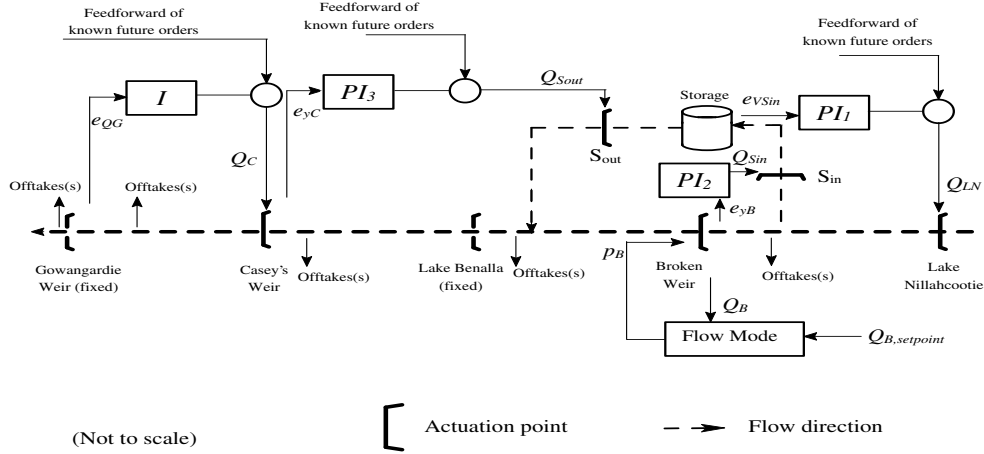


Fig. 3. Decentralised control configuration.

The matrices  $Q_{DS}$  and  $R_{DS}$  are chosen based on the control objectives, while the matrices  $Q_{RE}$ ,  $R_{RE}$  and  $S_{RE}$  are obtained by reverse engineering the decentralised control scheme in Figure 3. For both MPC designs, the matrices  $Q_{DS,s,L}$ ,  $Q_{DS,s,H}$ ,  $Q_{RE,s,L}$ ,  $Q_{RE,s,H}$  are used to handle the soft constraints.  $s_L$  and  $s_H$  are slack variables which are zero when the constraints are satisfied and non-zero when the constraints are violated.

The control objectives 6) is to keep the releases from Lake Nillahcootie small, thus  $u_{LN}$  is assigned a weight 2.5. In order to ensure that most of the water to be used downstream is supplied from the off-stream storage rather than from the weir pool at Broken Weir,  $u_B$  is assigned a weight 10. The remaining control actions are assigned a weight of 1. The integral of the setpoint errors are penalised with the weights in the range from  $1 \cdot 10^{-7}$  to  $150 \cdot 10^{-7}$ . The setpoint errors themselves are not penalised since they are taken care of by the constraints.

Control objectives 3), 4), 5) and 8) are treated as soft constraints while control objective 9) is regarded as hard constraints. For the off-stream storage, the hard constraint  $0 \text{ ML} \leq V_S(n) \leq 300 \text{ ML}$  is applied.

Known future orders from irrigators are easily handled by including them directly in the prediction model [11]. All the flows and water levels setpoint changes are also known in advance, and this information is also included in the prediction model. The in-flows from the creeks are assumed constant over the prediction horizon and equal to the last available measurement. The prediction horizon,  $N_P$  is chosen to be 4 days (5760 minutes)<sup>§</sup>. The control problem is a quadratic programming problem, which is formulated using YALMIP [20] in MATLAB<sup>®</sup> and solved using the commercial package CPLEX 12.2 [21].

<sup>§</sup>We considered prediction horizons up to 10 days, but no significant improvement was observed. In order to keep the computational load small, we chose the prediction horizon of 4 days.

## VI. SIMULATION SCENARIO

Here we describe the simulation scenario which is used to assess the performance of the control systems. Current practice is that once an irrigator has placed an order for water and it has been approved, then the irrigator can pump water from the river regardless of whether sufficient water has been released. For the evaluation of the control system this practice will be followed, and a failure to supply sufficient water will manifest itself in water levels in weir pools going below minimum levels or that changes in the daily flows are too large.

As the study area we consider ends at Gowangardie Weir, all demand for water downstream of Gowangardie Weir including environmental water and water to be delivered to the Goulburn River are aggregated into a desired flow over Gowangardie Weir. As for in-flows from creeks, only the two main tributaries, Lima and Hollands Creeks, are considered.

For the external inputs to the simulation, a brief description is described here. For more details see [18].

- 1) *Demand for irrigation water.* The orders for irrigation water are based on the historical water orders in the period from 2006 to 2008.
- 2) *Minimum environmental flows.* The minimum environmental flows are taken from [14].
- 3) *In-flows from creeks.* The historical in-flows from Lima and Hollands Creeks scaled down with 65% to account for a possible drier future are used.
- 4) *Evaporation.* In [23] it is estimated that on average 2310 ML evaporate yearly from the Broken River. The daily evaporation losses have been modelled as half a period of a sinusoid starting at 9am, reaching its maximum at 3pm and finishing at 9pm, and the amplitude has been scaled linearly with the maximum daily temperature in 2006 and 2007.

## VII. EVALUATION OF THE CONTROL SYSTEMS

Manual operation is considered as the baseline case, and in the simulation 30920 ML of water is released from Lake

TABLE I

TOTAL WATER RELEASED, EXCESS WATER, NUMBER OF DAYS WITH FLOW BREACHES FOR DIFFERENT ORDERING TIMES AND CONTROL STRATEGIES.

Ordering Time	4 days				2.5 days			1 day	
	Manual	Decentralised	MPC-DS	MPC-RE	Decentralised	MPC-DS	MPC-RE	MPC-DS	MPC-RE
Total water released	30920ML	25760ML	26409ML	25203ML	31647ML	31081ML	31716ML	31165ML	31599ML
Excess water	8122ML	2235ML	2884ML	1678ML	2165ML	2318ML	1726ML	2403ML	1641ML
$Q_G < 80\%Q_{min}$	1 day	0 days	0 day	1 day	0 day	0 day	0 day	0 day	0 day
$Q_G < 0.76Q_{G,prev}$ or $> 1.5Q_{G,prev}$	52 days	25 days	0 day	0 day	6 days	0 day	0 day	0 day	0 day
$Q_C < 0.76Q_{C,prev}$ or $> 1.5Q_{C,prev}$	12 days	34 days	0 day	0 day	15 days	0 day	0 day	0 day	0 day
$Q_{LB} < 0.76Q_{LB,prev}$ or $> 1.5Q_{LB,prev}$	6 days	9 days	0 day	0 day	4 days	0 day	0 day	0 day	0 day
$Q_B < 0.76Q_{B,prev}$ or $> 1.5Q_{B,prev}$	17 days	0 day	0 day	0 day	0 day	0 day	0 day	0 day	0 day

Nillahcootie under manual operation as shown in Table I. 8122 ML of the released water is excess water which is water leaving the study area at Gowangardie Weir which is neither required by irrigators nor the environment. This water eventually ends up in the Goulburn River, and it is not "wasted" water. As an additional 20 ML/day is released under manual operations there are only a few days where the environmental minimum flows are breached as can be seen from Table I. However, the limits on the daily flow variations are often exceeded, e.g. they are breached on 52 days at Gowangardie Weir. Apart from 10 days at Broken Weir and 5 days at Lake Benalla all water levels are within 15 cm from setpoints. In the period from early spring to summer the flow exceeded 120 ML/day on a total of 18 days across parts of the river, see Table II.

#### A. Decentralised control

In the first scenario, the ordering times are 4 days as before and the emphasis is on minimising the releases from Lake Nillahcootie. The flow setpoint at Gowangardie Weir is set as the sum of the orders placed downstream of Gowangardie Weir plus 30 ML/day which corresponds to the minimum flow requirement of 25 ML/day with an extra 20% added. In this scenario, 25760 ML is released from Lake Nillahcootie and the amount of excess water is 2235 ML. There are no breaches of the minimum environmental flow constraints at Gowangardie Weir but a larger number of days of violations of the limits on the daily flow variations are observed, i.e. 25 days, 34 days and 9 days at Gowangardie Weir, Casey's Weir and Lake Benalla respectively.

In the second scenario, the emphasis is changed to reducing the ordering times for the irrigators. The aim is now to deliver the same amount of water to the Goulburn River as under manual operation. As the amount of excess water is reduced by 5887 ML when using the decentralised control, the flow setpoint at Gowangardie Weir is increased with 16.13 ML/day which over a year adds up to 5887 ML. The ordering time is reduced to 2.5 days. In this case, as expected, a similar volume of water as with manual operation is released but only 2165 ML is regarded as excess water since it is a deliberate operational decision that 5887 ML should be delivered to Goulburn River and not just a byproduct of the operational procedures as it is under manual operation. The number of days the constraints on the flow variations are breached has been reduced.

#### B. MPC

The scenarios above are repeated with MPC-DS and MPC-RE. In this first scenario, for MPC-DS, 26409 ML is released from Lake Nillahcootie and the amount of excess water is 2884 ML. The flow at Gowangardie Weir is below minimum environmental flow for 18 days, but the flow is never less than 80% of the minimum environmental. There are no violations of minimum environmental flows at the other locations. Moreover, there are no violations of the limits on the daily flow variations, all water levels are within 15 cm of setpoints and the flow in spring/summer do not exceed 120 ML/day.

On the other hand, for MPC-RE, 25203 ML is released and the excess water is 1678 ML which is less than MPC-DS. However, the flow at Gowangardie Weir is below minimum environmental flow for 30 days and the flow is less than 80% of the minimum environmental flow for 1 day. The water level at Casey's Weir is below 15 cm for 2 days and at Lake Benalla, the water level is above 15 cm for 5 days. The flow in spring/summer exceed 120 ML/day at Lake Benalla for 2 days with the maximum flow of 136 ML/day.

In the second scenario, the ordering times are reduced to 2.5 and 1 day while delivering the same amount of water to the Goulburn River as under manual operation. In order to supply the additional water, the flow setpoint at Gowangardie Weir is increased with 14.35 ML/day, which over a year adds up to 5238 ML for MPC-DS and 17.65 ML/day, which over a year adds up to 6444 ML for MPC-RE respectively. For the ordering times of 2.5 and 1 days, the excess water is 2318 ML and 2403 ML respectively for MPC-DS and 1726 ML and 1641 ML respectively for MPC-RE. The flow at Gowangardie Weir is below the minimum environmental flow on 4 and 6 days respectively for 2.5 and 1 day ordering times for MPC-DS and 2 and 5 days respectively for 2.5 and 1 day ordering times for MPC-RE, which are significantly fewer than before. This is expected since the flow setpoint is increased. For MPC-DS, all water levels are within 15 cm of setpoints on all days but for MPC-RE, there are instances where the water levels at Casey's Weir are above or below 15 cm from setpoint, see Table II. For MPC-DS, the flow is above 120 ML/day for at most 6 days at Lake Benalla, but the maximum flow on these days is only 128 ML/day. While for MPC-RE, the flow is above 120 ML/day for 27 days at Lake Benalla with the maximum flow of 143 ML/day.

#### C. Discussion

From the above results one can see the benefit of control. With control one can either reduce the releases or the

TABLE II

NUMBER OF DAYS THE WATER LEVELS EXCEED 15 CM BELOW/ABOVE SETPOINTS AND THE FLOWS EXCEED 120ML/DAY.

Location	Broken Weir		Lake Benalla		Casey's Weir	
	Level	Flow	Level	Flow	Level	Flow
Manual	0/10	6	0/5	12	0/0	0
MPC-DS (4 days)	0/0	0	0/0	0	0/0	0
MPC-DS (2.5 days)	0/0	0	0/0	3	0/0	0
MPC-DS (1 days)	0/0	0	0/0	6	0/0	0
MPC-RE (4 days)	0/0	0	5/0	2	0/2	0
MPC-RE (2.5 days)	0/0	0	0/0	20	0/2	0
MPC-RE (1 days)	0/0	0	0/0	27	5/3	0
Decentralised (4 days)	0/0	0	0/11	3	0/0	0
Decentralised (2.5 days)	0/0	0	0/1	9	8/1	0

ordering times for irrigators. Most importantly, control allows operators to command a larger volume of water and make operative decisions on how it should be used. In general the results demonstrate the abilities of MPC to deal with constraints when compared to the decentralised control scheme in particular when satisfying the environmental constraints.

In comparing MPC-RE with the decentralised control, we can see the good constraint handling ability of MPC, in particular in the daily flow variation. This comes as no surprise given that this is a hard constraint. For the soft constraints MPC-RE has either similar if not better performance compared to decentralised control. On the other hand, MPC-RE does not allow for a decentralised implementation and must be implemented centrally. However, given the small number of reaches in the Broken River, a centralised control configuration may not suffer much from the common drawbacks of centralised control schemes. The performance of MPC-DS is better than MPC-RE. However, obtaining the weighting matrices in MPC-DS is not as easy as for MPC-RE. The simulation study shows that control systems allow for a more accurate and timely delivery of water to irrigators while ensuring that the environmental and ecological water needs are satisfied. Moreover, a reduction in ordering time will allow for more flexible farming practices and increased productivity for irrigators.

### VIII. CONCLUSION

Management of water resources is becoming increasingly important, and in this paper we have considered a centralised MPC tuned in two different ways and a decentralised control scheme for the the Broken River with the aim of improving the environmental outcomes and the service to irrigators. Through a realistic year long simulation scenario it is found that a control system offers significant advantages compared to current manual operation. In particular, a control system allows the operators to command a larger portion of the water with the benefit that releases and/or ordering times for the irrigators can be reduced. The performance of MPC-RE in particular the constraint handling, is better compared to decentralised control. Not surprisingly the performance of MPC-DS is the best among the three control configurations, but it also requires the largest design effort.

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