How does the Degree of River Regulation Influence the Impact of Climate Change on Downstream Flow Regimes?

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Abstract
The Australian Murray-Darling Basin (MDB) faces increasing competition between economic and environmental water use. This occurs against a backdrop of high climate variability. Here we explore how the impacts on downstream flow regimes (a surrogate for environmental impact) and the response to climate change depend on the degree of river regulation. We have used a water allocation simulation modelling approach to share the available water between these two sectors and to explore the economic and ecological responses. The modelling approach is based on a generic catchment with storage, an irrigation area and a tributary joining between the storage and irrigation area. The storage size and irrigated area are varied to represent different degrees of regulation. The results show that the increase in river regulation results in marked changes in the hydrograph both upstream and downstream of the irrigation area. The impact of climate change was analysed by running the model using stream flows under the 'C_{dry}" scenario and testing the reliability of supply to irrigation. The analysis of the results concluded that the reliability of supply to irrigation and environment are severely affected.

Keywords
Murray-Darling, water sharing, climate change, water allocation.

1. Introduction

Most rivers in the MDB are regulated to some degree to meet human demands. Demands from consumptive users reached such high levels that a "Cap" was imposed limiting further growth in diversions in 1995. The ecosystem which relies on the water flowing through the river is under considerable pressure due to this unsustainable growth in diversions. Climate change scenarios suggest that anthropogenic emission of greenhouse gases are likely to result in global warming which may have profound impacts on the availability of water resources in the future. With ever increasing water scarcity, decisions about water allocation become ever more important. In the study region the most important hydrological impact is due to decreased rainfall.

Both agriculture and the environment are viewed as valid and important water uses by the community. In managing water for these two purposes, the first order question is typically how much should be allocated to each; however, there are also important issues that go beyond volumes of water consumed, such as the seasonality of flow and some incompatibility in the timing of demands. Balancing the water requirement of these two sectors is an extremely challenging problem. It is likely that climate change will differentially impact these uses and that the level of streamflow regulation will also affect these impacts. Here we examine this issue using a water allocation simulation modelling approach combined with considering a range of storage sizes and irrigation areas to examine the hydrological impact of regulation.

2. Methodology

The modelling approach used to explore the hydrological impacts of regulation consisted of:

1. Developing a representative generic catchment;
2. Developing development scenarios that varied in terms of the storage size, agricultural entitlement, and hence in the division of water between agriculture and the environment;
3. Water allocation modelling to allocate water to agriculture and the environment in each development scenario, driven by both water availability and demand;
4. Analysing the hydrological response of water allocated to agriculture and environment;

5. Comparing the outcomes over the range of development scenarios; and
6. Analysis for climate change scenarios.

There are a wide range of levels of regulation in the major river valleys of the MDB, from the almost unregulated Ovens River to heavily regulated rivers such as the Goulburn. To avoid the issue of varying geographic characteristics, we developed a simplified generic catchment with storage on the main river, an irrigation area and some tributaries joining the main river between the storage and the irrigation area (Figure 1**Error! Reference source not found.**). This represents a lumped and simplified version of the typical situation in most of the major river valleys in the southern MDB where there are major storages in the mountains or foothills, additional inflows downstream of the storages and the major irrigation areas are located on the riverine plains. In terms of impacts on the river, this configuration allowed us to examine the extremes of hydrological changes by examining flows upstream and downstream of the irrigation area.

We loosely based the location of the storage relative to tributary inflows on the Goulburn River, where 2/3 of the flow is generated upstream of Lake Eildon and 1/3rd is generated between Lake Eildon and Goulburn Weir. The irrigation area is assumed to be supplied exclusively from the storage. Releases were made from the storage to meet agricultural demands and also to maintain flows at or above an environmental flow demand downstream of the irrigation area. This environmental minimum varied seasonally and between years and included a range of high flow events.

The CSIRO Murray-Darling Basin Sustainable Yields (MDBSY) project summarises estimates the proportion of water diverted under the then current level of development and historic climate. In this research we aimed to cover a wide range of levels of diversion in our scenarios. Specifically, five scenarios were run with storage sizes varying from zero (natural flows) to 240GL (Table 1). The storage sizes and irrigation areas were manipulated to gain reasonably consistent steps in the proportion of water diverted, while fully meeting agricultural demands in 95% of years. The diversion to agriculture varies from 0 to 76 GL/year (45% of end-of-valley flow) (Table 1). It was assumed that there was no harvesting of unregulated tributary inflows.

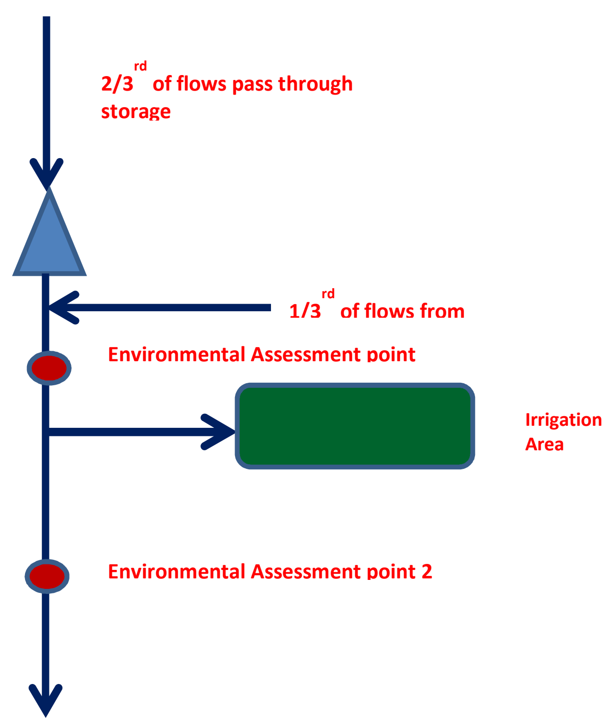

Figure 1: The generic catchment

In this research we used two climate scenarios: the historic climate and the 2030 dry climate as used in the MDBSY study (CSIRO, 2008b; Chiew et al., 2009). Rainfall and PET data from the 'C_{dry}" scenario have then been used as forcing data in the hydrologic model to estimate flows to the Goulburn River under a warmer climate.

In order to assess the hydrologic response of water available for agriculture and environment we have used several models:

1. A hydrological model to generate the available resources;
2. Demand models to estimate the agriculture and environmental demand;
3. An allocation model to distribute water to different demand centres.

AWBM, which is a catchment water balance model that calculates runoff from rainfall at daily or hourly time increments (Boughton, 2004), was used for modelling the catchment inflows. The model was calibrated and validated and then was used to simulate long-term sequences of discharge from the catchment using climate data (Current climate and 'C_{dry}" scenario) for the period 1895 to 2006. More details about these models are provided in Western et al. 2011.

A number of approaches have been applied in irrigation demand modelling which include time series approaches, quasi economic approaches and methods based on biophysical crop water requirements. In this work, a two-stage process was used to generate time series of agricultural demands. This involved 1) using the farm economic models (Farms Rivers and Markets, 2012) to generate monthly irrigation demands and then 2) disaggregating those demands to daily values based on the Program for Regional Irrigation Demand Estimation (PRIDE) (Department of Sustainability and Environment, 2007).

Table 1: Results of the selected scenarios under historical climate.

Scenario	Storage capacity (GL)	Average Irrigation demands (GL/y)	% end-of-valley flow diverted	Irrigation reliability[1]	Environment reliability[1]
1	240	76	45.2	95.2	92.3
2	140	63	35.6	94.2	90.4
3	90	50	27.7	94.2	90.4
4	40	30	16.4	94.2	88.5
5	0 (natural)	0	0	-	-

Notes. [1]Reliability is defined as the proportion of years in which demand is fully satisfied.

The environmental water requirements were estimated on a two stage process. A panel of expert environmental scientists who are familiar with various environmental assets met and set up the environmental objectives and developed flow rules at different locations along the river (Farquharson et al. 2011). They developed seventeen environmental flow rules which were then modelled using *eFlow* predictor (eWater CRC, www.ewater.com.au) to identify the environmental demand at various locations required to maintain a minimum level of ecological health in the river.

Finally, a spread sheet based water allocation model was developed to distribute water to agriculture and the environment on a daily time step. The model functions are based on water balance as the water moves from upstream to downstream. The water allocation model outputs include percentage of demand from agriculture and the environment that is met, volume supplied and daily river flows at different locations. The order of priority of allocation was evaporation losses, agriculture and then environment. Agricultural demands were solely met from the reservoir. Environmental releases were first met from the tributary flows and reservoir releases were then used to meet any deficit in requirement. The percentage of allocation to agriculture and environment is decided at the start of the season based on starting reservoir storage (1st July) and observed inflows until the end of October.

3.0 Results and Discussion

3.1 Hydrological impacts of regulation

The impacts of regulation on the flow regime of the river were analysed for the different storage capacities and irrigation areas described in the scenario section. The reliability of irrigation supply has been kept constant at ≈95 %. Table 2 summarises the four different regulation scenarios. In these the storage capacity varies from 40 GL to 240 GL, resulting in systems having average irrigation demands of 30 to 76 GL at 95% reliability. That is increasing storage size by a factor of 6 increases irrigation supply by 2.5 times. The percentage of natural end-of-valley flow diverted for irrigation varied from 16.4 to 45.2 percent. Typically around 90% of the environmental flow volume specified by the environmental flow rules was met at the time of the demand. The total water going to the environment downstream of the irrigation area obviously varied between scenarios.

The increase in river regulation results in marked changes in the hydrograph both upstream and downstream of the irrigation area. Since the peak irrigation demands were mainly concentrated in the dry period (November to March), the river flows upstream of the irrigation area during these months were high compared to the natural flows (Figure 2). This is mainly because of the releases from reservoir to meet the downstream irrigation demands. Flows during the winter months were lower than natural flows under the regulated conditions. This is because the catchment yield during the wet periods was stored in the reservoir to meet the summer demands. Downstream of the irrigation area flows are generally reduced, with the largest impact occurring in winter as the dam fills.

Table 2: Water allocation under different scenarios (historical climate)

Scenario	Storage capacity (GL)	Average Irrigation Demand (GL/y)	% end-of-valley flow diverted	Irrigation reliability	Environment supply from dam (GL/y)	Environment reliability
1	240	76	45.2	95.2	6.1	92.3
2	140	63	35.6	94.2	6.1	90.4
3	90	50	27.7	94.2	6.2	90.4
4	40	30	16.4	94.2	6.1	88.5

3.2 Impact of climate change on system security

The impact of climate change has been analysed in two ways. First, an analysis was conducted to assess the impact of climate change while holding agricultural water demand constant and allowing the reliability to reduce. Four scenarios were run using streamflows under the 'C_{dry}" scenario to test the reliability of supply to irrigation. The unregulated hydrograph was also simulated. The reliability of supply to irrigation and environment is severely affected (Table 3). The reliability to irrigation drops to 52% from 95% for the 240 GL scenario. The environmental reliability has also dropped to 46.2 % for the same scenario. This set of scenarios represents the highest diversion case and 61% of end-of-valley flow is diverted. Note that given that tributary inflows are not diverted to agriculture, the largest possible diversion is 67%.

A second set of runs was made under the assumption that irrigation entitlements would ultimately be modified in adapting to climate change, the four regulation scenarios (dam volumes), were simulated under a dry climate scenario and irrigation demands modified to achieve ≈95% reliability of supply

(Table 4). Figure 3 compares average irrigation demands that can be supplied with like reliability between the historical inflow and climate change inflow scenarios. The results suggest that the shortfalls due to climate change occur in both agriculture and environmental demands. The average irrigation demand that can be supplied with 95% reliability has declined in all storage capacity scenarios under a drying climate. The analysis suggests that under climate change the largest system can supply only 35 GL to agriculture at 95% reliability, which is approximately 46% of the historical inflow scenario with a 240 GL storage capacity. Under this scenario the increase in storage capacity between scenarios has very little impact on ability to supply irrigation (Figure 3), suggesting that with reduced inflows our large dams could be considered to be over-designed. Percentages of the unregulated end-of-valley flow diverted to agriculture have increased under this scenario compared with historical data.

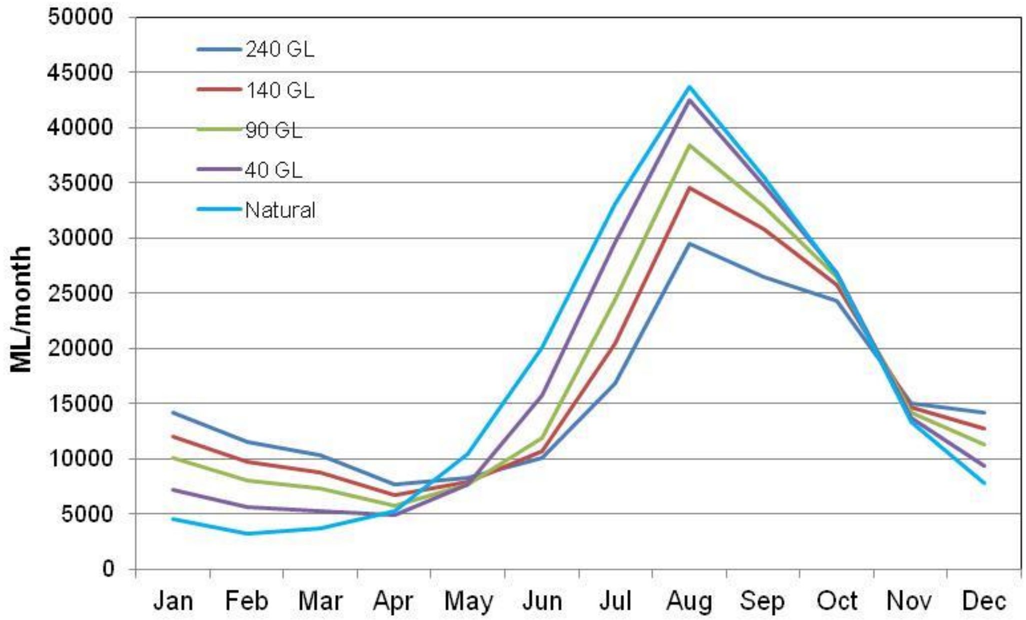

Figure 2: Mean monthly flows upstream of the irrigation area. Scenarios are identified by storage volume.

Table 3: Results of the selected scenarios under dry climate change and "historic" entitlements.

Scenario	Storage capacity (GL)	Average Irrigation Demand (GL/y)	% end-of-valley diverted	Irrigation reliability	Environment supply from Dam (GL/y)	Environment reliability
1	240	76	60.6	51.9	5.1	46.2
2	140	63	55.1	57.7	6.4	54.8
3	90	50	48.1	70.2	8.2	66.3
4	40	30	32.3	84.6	10.5	76.9

Table 3 and 4 provides some insight into the implications of managing entitlements under climate change adaptation. If historic entitlement volumes are maintained, there is a decline in system reliability for consumptive use. In addition the variation in annual volumes supplied is magnified for the larger multiyear storages. This implies increased volatility in the volume of supply farmers can expect. If entitlements are adjusted down to regain system reliability, the inter-annual volatility of supply is significantly reduced and volumes supplied in the 15-25% of years with least supply are significantly increased. These effects are not present in the two smaller storages, which are smaller than the historic mean annual dam inflow.

Table 4: Results of the selected scenarios under dry climate change

Scenario	Storage capacity (GL)	Average Irrigation Demand (GL/y)	% end-of-valley diverted	Irrigation reliability	Environment supply (GL/y)	Environment reliability
1	240	35	50.4	95.2	11.9	91.3
2	140	31	42.6	95.2	12.1	92.3
3	90	26	35.2	95.2	12.2	93.3
4	40	19	24.3	95.2	12.3	93.3

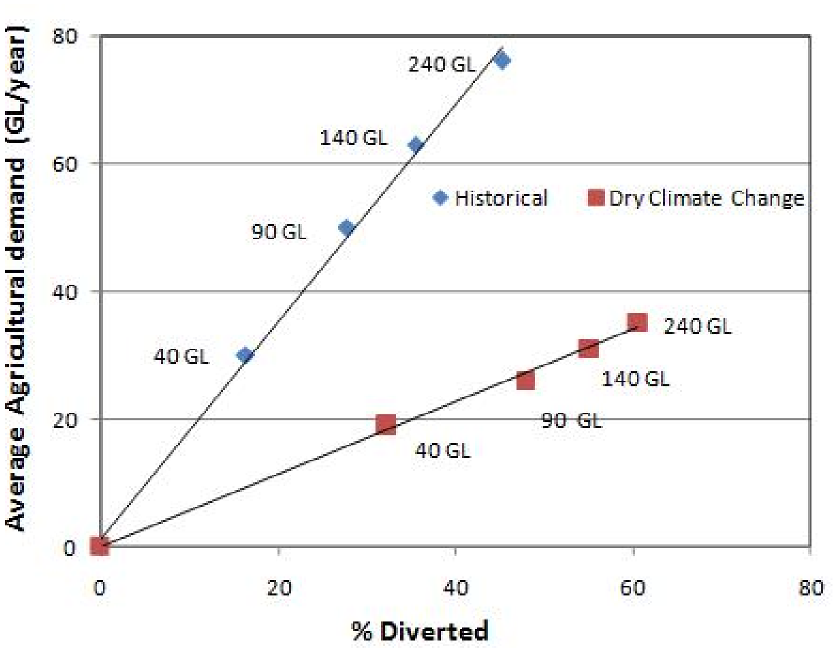

Figure 3: Change in agriculture entitlements under 95% supply reliability

4.0 Summary and Conclusion

In this paper an assessment of the hydrological implications of climate change in regulated river is made by developing a generic catchment with storage in the main river, an irrigation area and some tributaries joining the main river between the storage and the irrigation area. In particular we look across a spectrum of levels of regulation. The approach chosen to undertake this task is a simulation model that allocates water to agriculture and environment by using a water balance approach. The analysis is built on a combination of hydrological, water demand and water allocation modelling.

The hydrologic analysis of the catchment was carried out using AWBM catchment water balance model. The model was then used to generate streamflows. Water demand for agriculture is estimated using a farm economic model which is then disaggregated into daily values using PRIDE model. The environmental demands were estimated using an expert panel approach. Finally, a water allocation model was developed to distribute water to agriculture and the environment. The models were run using two sets of climate data:**:** the historic climate and the 2030 dry climate as used in the MDBSY study.

The impacts of regulation of flow on the flow regime of the river were analysed by changing the storage capacity and irrigation areas. Increases in river regulation result in marked changes in the hydrograph both upstream and downstream of the irrigation area. The model was then run using streamflows under the 'C_{dry}" scenario to test the impact of climate change on system reliability. The reliability of irrigation supply has dropped to 52% from 95% for 240 GL storage scenario, whereas the reliability of supply to the environment has dropped to 46.2 % for the same scenario. Simulations with demand reduced to achieve ≈95% reliability of supply to irrigation were carried out. System demands had to be reduced by up to 54% to maintain 95% reliability. If inflows reduce as expected under climate change, most reservoirs will operate with significantly lower storage levels than previously and if operations are not adjusted through changed entitlements/allocation rules, the proportion of water harvested will increase.

Acknowledgement

The authors would like to thank the National Water Commission, the Victorian Water Trust, the Dookie Farms 2000 Trust (Tallis Trust) and the University of Melbourne for their financial support.

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