Managing environmental flow objectives under uncertainty

The case of the lower Goulburn River floodplain, Victoria, Australia

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Abstract

The regulation of river systems to meet water demands for irrigation in the southern Murray Darling Basin has changed the timing and the volume of the natural pattern of flows. Australian governments have committed to restoring, in part, winter and spring flow regimes to preserve and enhance the riverine environment. These changes will involve trade-offs against the foregone returns to agriculture and between different environmental objectives.

To better understand these trade-offs, environmental flow objectives are specified as a change in the inter-arrival time distributions of winter and spring flow events, ranging from brief flooding events to the inundation of flood plains and wetlands over several weeks. Expected costs, and hence the trade-offs, depend on the required volume, the threshold inter-arrival time between environmental watering events, and the acceptable probability of exceeding that threshold time.

The economic costs of meeting environmental flow objectives will depend on prevailing climatic conditions. The key to minimising costs to other water users is to time the environmental release to avoid periods of low water availability and take advantage of periods of high availability while still meeting the flow objectives. In doing so, an environmental manager must weigh current environmental condition against the likelihood of more or less favourable conditions in the future.

A stochastic optimisation model is used to develop release strategies based on a known set of stream inflows and evaluated against a randomised sequence of unknown flows. The model is used to elicit the economic trade-offs associated with environmental flow objectives and the threshold inter-arrival time between events. The model was also used to examine how different institutional arrangements affect the economic efficiency of delivering these objectives.

1. Introduction

The purpose of the Commonwealth Water Act 2007 is “to promote the use and management of the Basin water resources in a way that optimises economic, social and environmental outcomes” (Section 3 (c)). The Act established the Murray Darling Basin Authority (MDBA) and charged it with preparing, implementing, monitoring and enforcing a Basin Plan that will provide for the long term integrated management of the Basin’s water resources.

- This paper presents an economic analysis of the direct economic costs of securing adequate water to fulfil environmental objectives under uncertain climatic conditions by considering:
- How to quantitatively represent environmental flow objectives in a robust and meaningful way;
- The trade-off between the level of reliability with which these objectives can be achieved and the economic cost to government and irrigated agriculture;
- How different institutional arrangements can affect the economic efficiency of delivering these objectives.

A model with two components, hydrologic and economic, is developed to estimate the economic trade-offs of different levels of reliability where reliability refers to the acceptable probability of exceeding the threshold inter-arrival time between environmental events.

2. Background

2.1 The Water Act 2007

Passed in 2007 and amended in 2008, the Commonwealth Water Act established to oversee (but not deliver) water resource planning in the basin. The basin states retain autonomy to manage water shares and to manage natural resources within their catchments in way that is consistent with the requirements of the Basin Plan[3].

2.2 Describing environmental outcomes and objectives

The Water Act 2007 requires that assessment of environmental water needs of the basin must encompass key environmental assets, including water-dependent ecosystems, ecosystem services, and sites with ecological significance; key ecosystem functions; the productive base; and key environmental outcomes for the water resource. Reports published by the MDBA described the method used to assess key environmental assets, recognising that there is little or no information or scientific evidence to determine water requirements for a significant number of the environmental assets (MDBA 2010a, MDBA 2010b, MDBA 2010c). These reports indicate that environmental flow objectives will be specified with attributes to meet desired outcomes that protect and restore the key environmental assets, as has been the case for other environmental watering programs in Australia (see, for example, MDBA 2009).

These flow objectives are generally specified in terms of:

- a minimum duration and rate of flow or total flow volume
- the required frequency of events, and
- the seasonality or timing of the event.

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[3] A guide to draft of the Basin Plan, and supporting technical documentation, was publicly released by the Murray Darling Basin Authority in October 2010 (MDBA 2010a, MDBA 2010b, MDBA 2010c). A revised Basin Plan is due to be released for public consultation in mid to late 2011.

However, the inter-arrival time between environmental events is shaped by extended periods of high and low rainfall that typifies the climate of the basin. Characteristics of the tail end of the distribution of inter-arrival times between events, such as the probability of a prolonged period between events, can be more important than the average frequency of an event.

In this paper, the required frequency of events is specified as the threshold inter-arrival time between events. The threshold time should characterise the most relevant parts of the inter-arrival time distribution. The level of reliability is specified as acceptable probability that the threshold inter-arrival time will be exceeded. Taken together, the objective is to shape of the frequency distribution of threshold inter-arrival times at specific percentiles. For example, given a threshold inter-arrival time of, say, five years:

- A 50 per cent exceedence probability targets the median or 50th percentile; and
- A 10 per cent exceedence probability targets the 90th percentile.

Another way to consider the above is:

- The objective is to create an event every five years with an acceptable level of reliability of 50 per cent; and
- The objective is to create an event every five years with an acceptable level of reliability of 90 per cent.

The cost of meeting a flow objective is a direct function of the frequency of the event and the prevailing conditions when the environmental manager creates the event by releasing water from the storage. The cost minimisation problem is therefore largely about the timing of the event. That is, to exceed threshold inter-arrival times when prevailing conditions are adverse and to intervene on time or early when conditions are favourable while still meeting the targeted point or points of the frequency distribution of threshold inter-arrival times.

Importantly, the forward sequence of prevailing climatic conditions is uncertain and unknown to the environmental manager when making release decisions. It is possible to meet environmental objectives at least cost based on historical climate sequences. Given climatic variability is a key determinant of the availability and price (or opportunity cost) of water, the higher the level of reliability needed to meet the attributes of the environmental objectives, the less certain will be the economic costs of doing so and visa versa.

3. Approach

A model is developed to estimate the costs of meeting specific environmental objectives with different levels of reliability. The model optimises a set of heuristic decision rules to minimise the cost of meeting the environmental flow objectives. Historical data on inflows and rainfall is randomly sampled to train and evaluate the decision rules to create an environmental event by releasing water from storage, or waiting until conditions are more favourable. A case study area, the lower Goulburn River floodplain, is used to demonstrate the method and to estimate the cost and reliability trade-offs for three environmental flow objectives that were identified by the MDBA.

3.1 The lower Goulburn River floodplain

The case study area, the lower Goulburn River Floodplain and its associated wetlands, extends for approximately 150 kilometres along the Goulburn River between the Goulburn Weir and its junction with the Murray River. This area has been well studied and documented through Australian and state government processes including the *Sustainable Rivers Audit*, a Scientific Advisory Panel convened to provide expert advice for the development of the Victorian Government Northern Region Sustainable Water Strategy (NRSWS) (Victorian Department of Environment and Sustainability 2009) and a number of independent studies (see for example Cottingham *et al* 2004, Cottingham *et al* 2005). The authors were also able to draw on hydrological modelling undertaken by the Victorian Department of Sustainability and Environment.

Map 1. The Murray Darling Basin, Australia

Source: Rivermurray.com

The Heritage-listed Goulburn River is Victoria's largest – flowing in a northwesterly direction for more than 570 kilometers to the Murray River at Echuca (map 1). The lower Goulburn River Floodplain supports 70 separate wetland sites and a network of 'flood runner' water courses. The floodplain consists of river red gum open forest woodlands with smaller areas of grey box open forest woodland and associated yellow box, white box and black box (MDBA 2010c). The floodplains support vulnerable and threatened wildlife, and significant native fish diversity including Murray cod habitat (Victorian Department of Sustainability and Environment 2008). The Sustainable Rivers Audit reported that the Goulburn River ecosystem is in very poor condition with risks to water quality, native fish populations and floodplain tree species (Davies *et al* 2008).

In addition to its environmental significance, the Goulburn River is valued for tourism and recreation activity and is highly regulated to support irrigated agriculture through the management of the timing and volume of flows through the Eildon and Goulburn Weirs. Winter and spring flows are captured behind Eildon Weir in Lake Eildon and diverted for irrigation use, mainly in the summer, reversing seasonal flow patterns along much of the river.

The main irrigation districts within the Goulburn-Broken region are the Central Goulburn Irrigation region and the Shepparton Irrigation Area. The largest, the Shepparton Irrigation Area, covers more than 500,000 hectares or one third of the Goulburn-Broken catchment. The gross value of irrigated agricultural production in the Goulburn-Broken region was estimated to be $800 million in 2008-2009 – around one quarter of the Victorian total (ABS 2011). Irrigated industries are predominantly dairy and horticulture, valued at around $335 million and $320 million respectively in 2008-2009, followed by mixed grazing and broadacre cropping (Ashton, Hooper and Oliver 2009, ABS 2011). More than 300,000 megalitres of water was applied to these crops in the same year (ABS 2011).

Based on its assessment of available science including the CSIRO Sustainable Yields Project, the MDBA concluded that one of the major impacts of flow regulation on the Goulburn River has been to alter the frequency and duration of regular flooding events (CSIRO 2008). The MDBA reports that this is likely to have changed the filling and drying pattern of floodplain billabongs and anabranches that are important habitats in the Goulburn River (MDBA 2010c).

3.2 Environmental flow objectives for the lower Goulburn River floodplain

Environmental flow objectives identified by the MDBA are used to illustrate the method developed in this paper (MDBA 2010a, 2010b, 2010c). While these flow objectives are under consideration by the MDBA, they serve the purpose as a case study. The environmental outcomes and objectives for the lower Goulburn River floodplain are presented in table 1. Two flow regime frequencies were identified by the MDBA to accommodate the scientific uncertainty associated with defining environmental objectives. These environmental objectives are ordinal; for example, a 60,000 megalitre flow for seven days (outcome 5) would meet the objectives for outcomes 1, 2 and 4.

Table 1. Environmental flow objectives for the lower Goulburn River floodplain

(Source: MDBA 2010c)

Environmental outcome	Flow requirement[A] (Ml/day)	Duration (Days)	Seasonality	Probability (%)			
				Target[C]		Development	
				Low	High	Pre	Post
1. Improve wetland condition	25,000	7[B]	Winter Spring	60	50	72	36
2. Improve wetland condition	30,000	7	Winter Spring	50	40	65	32
3. Improve red gum condition	30,000	14	Winter Spring[D]	40	33	50	23
4. Improve red gum condition	45,000	7	Winter Spring[D]	35	25	44	13
5. Improve red gum condition	60,000	7	Winter Spring[D]	20	15	26	6
6. Bird breeding event	30,000	30	Winter Spring	30	30	35	11

A. Refers to river flow at McCoys Bridge gauging station. It should be noted that these flow requirements are part of a broader flow regime and that multiple flow rules will contribute to meeting environmental objectives.

B. Days are the total for the period, not consecutive. The minimum duration for any flow event is a full day.

C. Low and high are based on the level of scientific uncertainty.

D. "Preferred" rather than required period due to the high flow requirements.

3.3 Formalising environmental flow objectives

The targets in table 1 can be interpreted as the desired frequency of flow events over a finite number of years; say 5 out of 10 years. However, it is recognised that the distribution of these events through time is also important, as there are longer-term trends in weather patterns that create dependence in the probability of a flow event occurring over time. The probability of an extended period between events is important given the potential for extreme or irreversible damage to environmental assets. For example, watering events to support bird breeding must occur within a timeframe that is compatible with the birds' lifecycle. To recognise the importance of the time between events, environmental flow objectives can be recast in terms of limits on the probability that the inter-arrival time would exceed a critical threshold.

For simplicity, the case study focuses on the subset of environmental objectives 2, 3 and 6 (shaded in table 1). The flow requirements and representative reliability targets are presented in table 2.

Table 2. Environmental objectives: Inter-arrival times for the lower Goulburn River floodplain

Event	Environmental outcome	Flow requirement Ml/day	Duration (Days)	Threshold inter-arrival time (Years)	
				Median	90th percentile
Event 1	Improve wetland condition	30,000	7	2	4
Event 2	Improve red gum condition	30,000	14	3	6
Event 3	Bird breeding event	30,000	30	5	10

4. Modelling framework

The modelling framework has a hydrological component that uses historical inflow data for Eildon Dam on the Goulburn River and the downstream tributaries to estimate the water deficit, if any, required to meet environmental flow objectives with different levels of reliability, and; an economic component that is used to estimate total direct costs – comprised of costs to government (represented by the environmental manager) and the foregone value of agricultural production or industry surplus. The components are brought together in a stochastic optimisation framework that seeks a set of release, water market and storage rules that minimise the total economic cost of meeting the environmental flow objectives.

It is assumed an environmental manager knows the volume of water allocated against their entitlement for environmental purposes as well as river flows in the current year. Prevailing conditions in future years are unknown. The use of an optimal decision rule, rather than an optimal set of releases, allows an environmental release strategy to be tested under these conditions.

The primary decision rules are discrete: to make a release sufficient to achieve any one of the three environmental flow objectives or make no release. The required rule structure fits a multinomial choice problem. There is a score, *s*, which is a function of covariates and a set of parameters to be optimised. The maximum scores determine the release strategy at each point in time. The scores are relative so the event scores can be compared to an arbitrary constant k_1 that corresponds to no release.

$$\begin{aligned}
&s_0 = k_1 \\
&s_{it} = \beta_{01} + \beta_{1i} p_t + \beta_{2i} v_{it} + \beta_3 d_{it} \qquad i = 1,3 \\
&S_{it} = \begin{cases} 1 & if \;\; s_{it} = \max(s_t) \\ 0 & otherwise \end{cases} \\
&where \\
&\begin{cases} S_0 = 0 \;\Rightarrow & \text{no release} \\ S_1 = 1 \;\Rightarrow & \text{meet requirement one} \\ S_2 = 1 \;\Rightarrow & \text{meet requirement two} \\ S_3 = 1 \;\Rightarrow & \text{meet requirement three} \end{cases}
\end{aligned}$$

Where *p* is the price of water in the temporary or physical market, *v* is the proportion of *i*th downstream flow requirements that is met by natural inflows and dam spills and d_i is the elapsed time since the *i*th flow event. The release rules are optimised through the choice of the β parameters.

An ancillary rule is used to manage any water allocations that have not been used in the current period by the environmental manager to deliver an environmental objective. This is a choice to:

- Carry water over to the next period up to the maximum allowed and selling the balance on the temporary market in the current period; or
- Sell all of the water available on the temporary market in the current period given the environmental manager has access to the water market.

The structure is intentionally rigid to prevent the decision rule from exploiting a dominant position in the temporary water market. While the decision to buy or sell is influenced through the decision to release or carry over water, the volume purchased or sold does not depend on the effect of the transaction on marginal cost or revenue.

The ancillary decision rule is constructed as a price threshold:

$$if \begin{cases} p_t^* - \alpha > 0 \Rightarrow W = 1 & \text{(carry over)} \\ else \qquad\qquad W = 0 & \text{(sell)} \end{cases}$$

The price, p*, is the market price given the chosen release strategy. The optimisation is now over α as well.

The price of water in the temporary market also needs to be specified. The price of water is taken to be a multiplicative function of the current total water allocation less the net purchases made by the environmental manager and effective rainfall after Brennan (2010):

$$p_t = \exp\left\{\gamma_0 + \gamma_1\left[A_t - \sum_{i=1}^{3} S_i\left(r_i - v_t\right) - \Delta c_t\right] + \gamma_2 Rainfall\right\}$$

Where γ_i is an exogenous parameter, A is the total allocation, r is the flow requirement, Δc is the net change in carry over. The functional form imposes that the elasticity of demand fall as the quantity demanded declines. The market demand function is discussed in greater detail in Appendix A.

The objective is to minimise total economic costs of meeting environmental flow objectives. These costs include the direct costs to the environmental manager and any loss in industry surplus. Direct costs are calculated as the product of release volumes and market prices. The change in industry surplus is calculated between p_t and $P(A_t)$, the prevailing price if there was no environmental releases given the current allocation:

$$\Delta Surplus_t = \frac{P_t - P\left(A_t\right)}{\gamma_1}$$

The final component of the model is a simple annual accounting model of water availability and allocations. The model was developed in Brennan (2010) in consultation with the Victorian Department of Sustainability and Environment. An outline of the accounting model is given in Appendix B.

For a given a sequence of inflows into Eildon Dam and downstream tributaries, and allocations the cost minimisation problem can be specified as:

$$\underset{\alpha,\beta}{Min} \sum_{t=1}^{n} \frac{1}{\left(1+\delta\right)^{t-1}} \left[p \sum_{i=1}^{3} S_i\left(r_i - v_t\right) + \Delta Surplus_t \right]$$

Subject to

$$\left(\sum D_{j_i} \leq T_i\right) \geq \phi_i$$

$$if\ \ S_i = 1\ then \begin{cases} D_{j_i} = d_{it} \\ d_{it} = 0 \\ j_i = j_i + 1 \end{cases}$$

$$else\ \ d_{it} = d_{it} + 1$$

$$c_t = \begin{cases} \max\left(c_{t-1} + a_t - r_t, 0\right) & if\ w \leq 0.5 \\ 0 & otherwise \end{cases}$$

$$c_0 = 0$$

$$d_{i,0} = 0$$

$$j_0 = 1$$

Where δ is the discount rate, α is the environmental manager's allocation, T is the threshold time between events, φ is the level of reliability and c is carry over.

The model was coded and solved in Matlab. The problem is nonlinear with discontinuities at the points where the release rules switch. As a consequence the model is solved using direct search methods. A genetic algorithm proved to be the most robust method. The following strategy was adopted to initiate the search and to limit the susceptibility of the algorithm to local minima: An initial feasible string was provided by calibrating the rule parameters for the time since the last release to the threshold times. The balance of two sub-populations of 100 strings were generated randomly about the feasible string. The algorithm migrated the sub-population every 20 iterations. The optimal solution was then randomly perturbed and the model resolved.

5. Model parameters and scenarios

Inflows to Eildon Dam and tributary inflows downstream of the dam and above the gauging station at McCoys Bridge were obtained from the Victorian Department of Sustainability and Environment from a simulation of the Resource Allocation Model (REALM) from 1891 to 2004 (Victorian Department of Sustainability and Environment 2005). The data was randomly sampled to obtain a set of candidate release rules from the optimisation model.

The data were sampled in random sized blocks ranging from one to seven years to preserve the correlation structure between years. The starting point for each sequence was selected at random. If the block size extended beyond the historical data series the starting point was adjusted so that the sequence terminated with the last historical observation.

The modelling approach taken in this paper uses a “training run” and an “evaluation run”. In the training run, a random sample was used to determine a set of decision rules as specified in section 4. The rules were then evaluated against 500 randomly generated samples to establish the average and variability in the performance of the rule (the evaluation run). Different environmental objectives were evaluated using the training and evaluation samples.

5.1 Model Parameters

The environmental manager is assumed to hold 15 per cent of total entitlements. This is to allow the valuation of access to carry over provisions and access to the temporary water trading market but does not have a direct impact on costs. It also allows an assessment of the size of the entitlement required to manage the environmental flow objectives. The initial carry over limit for the environmental manager is set at 25 per cent of allocation in the current year and water carried over is assumed to be lost when dam capacity is exceeded. The environmental manager is initially given complete access to the temporary trade market.

The discount rate is seven per cent. Initial storage levels are taken from the first year of any given random sample. The initial time since the last flow event is set to zero for each of the three flow events.

The environmental objectives are set in terms of threshold times and acceptable exceedence probabilities or reliability. Increasing the threshold inter-arrival time between events or lowering the level of reliability for each event can reduce the economic costs of releases to meet environmental objectives. Alternatively trade-offs may be made between the events by, for example, lowering the reliability for a particular event. Model scenarios were developed to estimate changes in cost to the environmental manager and industry of different threshold times between events and different levels of reliability.

Three sets of modelling runs are undertaken:

- Changing the median or 50th percentile threshold inter-arrival time (scenario A and scenario B)
- Reshaping the tail of the distribution by changing the level of reliability (scenario C, scenario D and scenario E), and
- Targeting multiple points within the inter-arrival time distribution by changing threshold inter-arrival times and levels of reliability (scenario F, scenario G and scenario H).

These scenarios are presented in table 3 and discussed in the following section. In addition, the following institutional arrangements were examined: the ability of the environmental manager to access carry over facilities, and; the ability of the environmental manager to trade water on the temporary market.

When interpreting the outcomes it is important to consider two points. First, the rule is a feasible approximation to the problem of finding a least cost set of releases that meets the flow objectives specified in the constraints. The rules will not always meet a constraint with equality even though the constraint serves to bound the solution. Second, in evaluation, the rules may under or over perform with respect to the flow objectives and this will have an influence on costs. While this is a valid reflection of the uncertainty in future climatic conditions, the results should be viewed as indicating orders of magnitude.

Table 3. Environmental scenarios modelled

	Threshold inter-arrival time (Years)			Reliability (%)		
Scenario	Event 1	Event 2	Event 3	Event 1	Event 2	Event 3
Median based scenarios						
A	2	3	5	50	50	50
B	3	4	6	50	50	50
Reshaping the tail scenarios						
C	4	6	10	90	90	90
D	4	6	10	70	70	70
E	4	6	10	70	80	90
Multiple threshold scenarios						
F	2, 4	3, 6	5,10	50, 90	50, 90	50, 90
G	2, 4	3, 6	5,10	40, 90	40, 90	40, 90
H	2, 4	3, 6	5,10	40, 70	40, 70	40, 70

6. Modelling results

The median threshold inter-arrival times for each environmental objective identified by the MBDA and presented in table 3 are considered first to construct a point of reference (table 4, scenario A).

The total economic cost of attempting to meet the median inter-arrival times is estimated to be around $800 million (table 4). The cost to government, represented by the environmental manager, is $350 million. Under scenario A the environmental manager is a buyer in the temporary water market with a net value of water purchases of around $60 million. The net cost to industry is estimated to be $450 million. The median threshold inter-arrival time for each event has been increased by one year in scenario B. This leads to a reduction in total economic cost of almost 25 per cent.

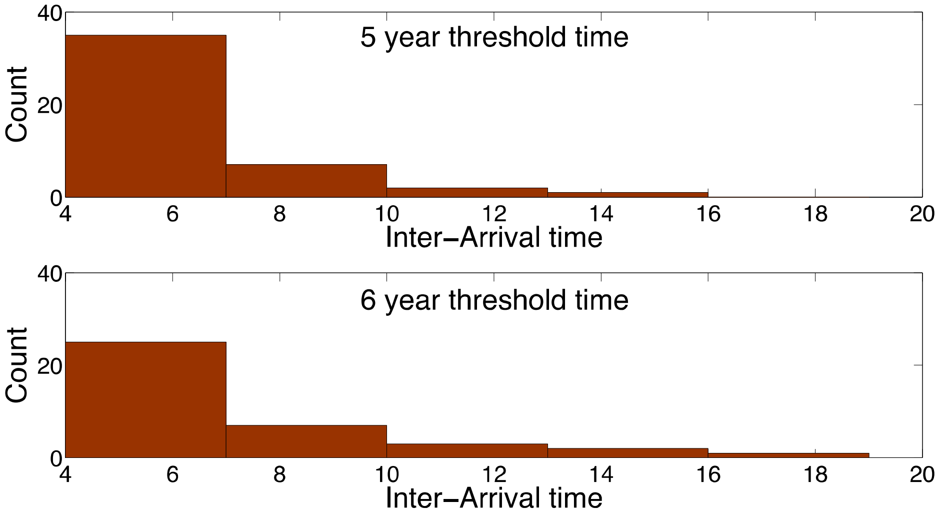
These results show that attempting to shift the central portion of the inter-arrival time distributions requires frequent intervention by the environmental manager and can impose large costs. A small increase in the threshold inter-arrival times can generate substantial cost savings. The latter is reflected in the shape of the inter-arrival time distributions presented for event 3, scenario A and scenario B, in figure 1. Under scenario A, a large part of the inter-arrival time distribution is between four and six years. A substantial portion of this part of the original distribution is shifted to the right with a change to a six-year threshold under scenario B.

This has implications for prices in the temporary water market. Overall prices are around four per cent lower under scenario B with a threshold inter-arrival time of six years compared with five years. The distribution of water prices, shown in figure 2, is shifted to left with a consequent reduction in the likelihood of very high prices. However, the general pattern of price variability is the same for both scenarios and is primarily a reflection of climatic conditions. Despite the relatively small shift in price distributions under the two scenarios, the difference in loss in industry surplus is substantial. The increase in the threshold inter-arrival time of one year reduces the loss in industry surplus by almost 30 per cent.

Table 4. Summary results for the decision rule optimisation runs

	Reliability achieved (%) (Training/evaluation)			Costs ($m)[4] (Evaluation)			
Scenario	Event 1	Event 2	Event 3	Net Purchases	Environmental manager	Industry surplus	Total economic
			Median based scenarios				
A	52/57	53/49	52/52	63	351	450	801
B	51/59	75/79	50/51	67	263	351	614
			Reshaping the tail scenarios				
C	96/96	91/89	91/87	94	289	390	679
D	71/74	81/70	76/68	-103	131	205	336
E	70/72	89/91	93/89	-3	259	324	583
			Multiple threshold scenarios				
F	63/65 91/93	52/51 937/90	50/53 95/95	129	379	463	842
G	53/66 92/93	52/57 91/89	41/46 93/92	119	361	472	833
H	55/74 79/91	59/82 85/97	44/52 72/89	-87	146	203	349

Figure 1. Inter-arrival time distributions for event 3, scenario A and scenario B



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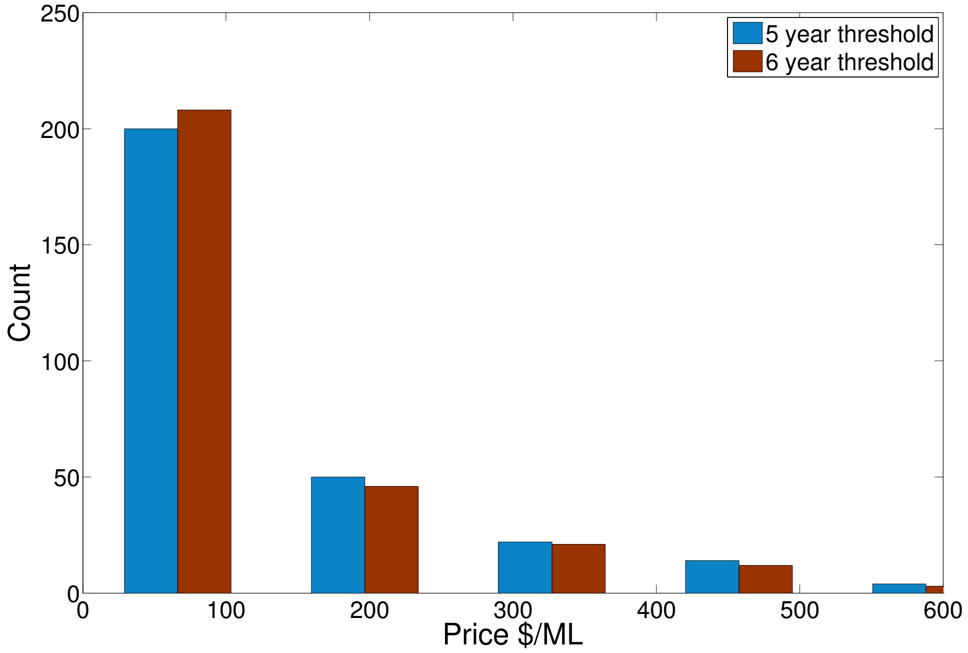
[4] All economic costs are presented as net present values.

Figure 2. The distribution of prices in the temporary water market for event 3, scenario A and scenario B



6.1 Reshaping the tail of the inter-arrival time distribution

An alternative goal of an environmental flow regime may be to preserve environmental assets by attempting to avoid protracted periods between watering events. Targets may be based on longer or critical threshold times with greater levels of reliability. Here the doubling of the median threshold inter-arrival time is used as an illustration of a set of critical thresholds. The trade-offs associated with different levels of reliability are explored.

The scenarios examining the costs of meeting critical threshold times with high levels of reliability show how the costs to the environmental manager and industry can be lowered if acceptable levels of reliability are reduced (scenario C, scenario D and scenario E) (table 4). The estimated cost of attempting to achieve 90 per cent reliability for the three events is almost $700 million with the loss in industry surplus approaching $400 million (scenario C). The costs reflect the need to intervene at times when water availability is low to meet tight reliability constraints. The decision rule underperforms with respect to event 3 so the costs of meeting the level of reliability are to some extent underestimated. Dropping the level of reliability to 70 per cent reduces the estimated total economic cost by half (scenario D). The environmental manager switches from being a net purchaser in the temporary water market to a net seller as the level of reliability is reduced from 90 per cent to 70 per cent under scenario D.

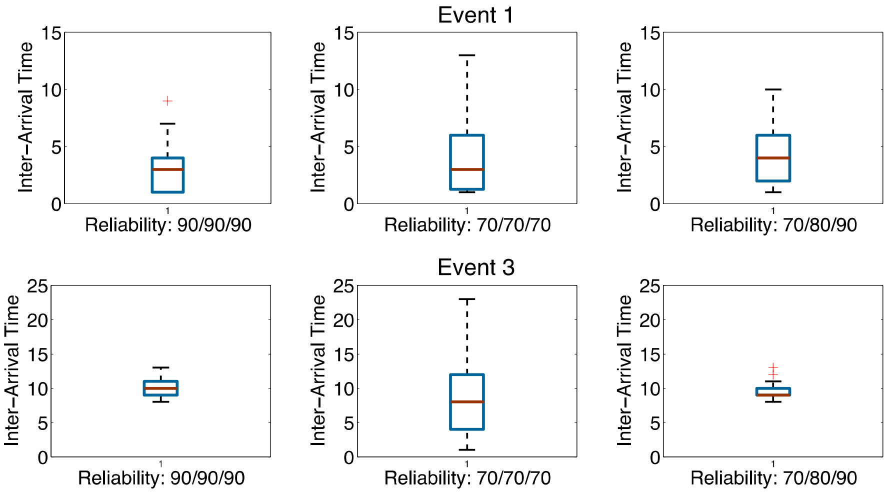
Trading off the level of reliability of event 1 and event 2 against event 3 also generates a significant reduction in costs (scenario E). Maintaining the reliability of event 3 at 90 per cent and dropping event 1 and event 2 to 70 and 80 per cent, respectively, reduces the estimated total economic cost by almost 15 per cent. The environmental manager’s purchases and sales in the temporary water market are evenly balanced in terms of value. The original capital outlay on the permanent entitlement is sufficient to meet but not exceed environmental requirements over the longer term.

The trade-off between reliability and cost has substantial implications for the shape of the inter-arrival time distribution. This is illustrated for event 1 and event 3 for scenario C, scenario D and scenario E in the box and whisker plot shown in figure 3. The red line in the box is the median, the box bounds the inter-quartile range and whiskers extend 1.5 times further than the inter-quartile range. The easing of the reliability constraint allows the upper tail of the distribution to expand as expected. At the same time it allows the decision rule to depend to a greater extent on prevailing water availability conditions. As a result the overall distribution, especially of event 3, is more variable. With a higher reliability constraint the decision rule tends to be locked in more tightly to the time since the last event and the distribution of inter-arrival times is less variable.

The results highlight that achieving a relatively high level of reliability for large events is a significant determinant of the cost to the environmental manager and industry. What trade-offs are welfare improving depend on how the changes in the inter-arrival time distributions affect environmental conditions. It is clear that the most critical aspect of that assessment is with respect to large events.

The relatively high cost and impact of shifting the central part of the inter-arrival time distribution (scenario A and scenario B) needs to be weighed against the possibility that compressing the tails of the distribution may not deliver a sufficient mean level event frequency (scenario C, scenario D and scenario E). It is straightforward to introduce an additional set of constraints. That is, one set of thresholds and reliability profiles near the median of the distribution and a second set near the critical time between events.

Figure 3. Inter-arrival time distribution for event 1 and event 3 under scenario C, scenario D and scenario E

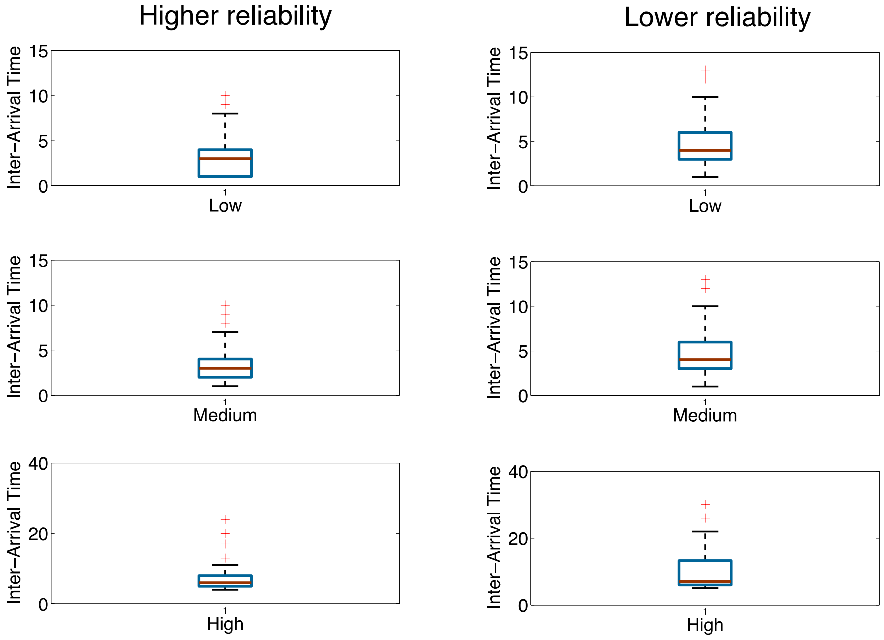


This is explored using scenario F in which threshold inter-arrival times and the acceptable level of reliability are aligned with the first median based scenario (scenario A) and the 90th percentile scenario (scenario C). This targets a comparatively large shift in the overall inter-arrival time distribution for each event. The costs of meeting the targets in scenario F are of the same order of magnitude as those for the individual median and 90th percentile targets on which it is based. This suggests that, with higher levels of acceptable reliability, meeting the target at one point on the distribution can largely serve to meet other constraints on the distribution. This is evident in figure 3 where the 90 per cent reliability constraint on event 3 compresses the entire distribution quite tightly.

In scenario G the acceptable level of reliability associated with the median threshold inter-arrival times is decreased to 40 per cent. That is, the 50th percentile is shifted to the 60th percentile. The 90th percentile is unchanged. There is no substantiative decline in total costs or loss in industry surplus, around $830 million and $470 million respectively. For event 3, this suggests that setting a high level of reliability for the tail threshold time of 10 years imposes a substantial proportion of the total costs. This is because there is very limited flexibility to shift the timing of an event even when conditions are unfavourable.

In scenario H, the 90 per cent level of reliability of not exceeding the tail threshold inter-arrival time is reduced to 70 per cent and the reliability of meeting the median threshold inter-arrival time is again relaxed to 40 per cent. The estimated total economic costs are more than 50 per cent lower than for Scenario F in which the higher reliability targets are 90 and 50 per cent, respectively. The inter-arrival time distributions for scenario F and scenario H are shown in figure 4. However, this is a similar result to when only the 90 per cent threshold target is reduced to 70 per cent (scenario C and scenario D), which can be seen by comparing figures 3 and 4.

Figure 4. Inter-arrival time distributions for scenario F and scenario H



The scope to make trade-offs within the distribution of inter-arrival times for an event, that is the ability to meet the reliability of one threshold against the reliability of another, is limited. This is because of the underlying pattern of natural inflows and the relationship between the flow objectives with, for example, a high flow event being a perfect substitute for a medium and low flow event. As a result meeting one criterion for a flow event can have a significant effect on meeting other criteria for this and other flow events. This may not be the case for other inflow regimes and environmental objectives. However, for the stated flow requirements on the Goulburn River, the costs and key characteristics of the inter-arrival time distributions are, to a large extent, determined by how the tail of the inter-arrival time distribution has been altered. Hence, it seems appropriate to focus the specification of flow objectives on limiting the risk of exceeding critical environmental thresholds as opposed to simply trying to restore the average frequency of an event.

6.2 Institutional arrangements

The institutional arrangements governing the environmental manager will have an effect on the level of economic efficiency in meeting environmental outcomes. This is because welfare losses will be incurred if the environmental manager is not able to source water at least cost. There are two instruments that allow an environmental manager to source water source more efficiently: the use of carry over where the manager has access to infrastructure to store unused allocations for use in the next period, and; access to the temporary water market to purchase and sell water in the current period. The two instruments are related in that access to the temporary water market is a substitute for the capacity to physically store water.

Two scenarios were considered to explore the welfare implications of access to carry over and access to the temporary water market. In the first, the environmental manager has access to the temporary market but not carry over facilities. In the second carry over of up to 100 per cent of the allocation is allowed but the environmental manager is not able to trade on the temporary market. The scenarios that were evaluated were for the 90th and 70th percentile targets. These can be compared directly with scenario C and scenario D in tables 3 and 4 in which there was a 25 per cent carry over limit and trade between agricultural and environmental users was not restricted. Summary results for scenarios estimating the costs of alternative institutional arrangements are presented in table 5 and discussed in relation to the comparable scenarios in table 4. The changes in costs are in brackets.

Reducing the carry over limit from 25 per cent of allocations to zero has additional total economic costs of around $75 million. This includes an additional loss of industry surplus of around $20 million for scenario C and $14 million for scenario D. Approximately 20 per cent of the benefits of the carry over facility accrue to agricultural water users. The higher costs under these scenarios reflect the reduced flexibility of the environmental manager to source water at least cost to meet flow objectives. Greater flexibility through carry over yields benefits to all water users and further benefits could be expected if the carry over limit was raised from 25 per cent.

As noted above, the ability of the environmental manager to access carry over and to trade on the temporary market can be substitutes in that they both transfer the physical use of water over time. The environmental manager relies more heavily on the water market in the scenarios with no access to carry over. This is most pronounced in scenario D where the environmental manager switches from a net seller of water to a net purchaser to meet the 70th percentile target.

Limiting access to carry over facilities has implications for the temporary water trading market with higher prices and greater price variability. For example, when comparing the 90 per cent reliability targets of Scenario C, average prices are 6 per cent higher without access to carry over facilities. The relative standard deviation the market price was 9 percentage points higher without environmental carry over.

When access to trade is restricted, the environmental share of total water allocation becomes one of the optimisation parameters. That is the manager must acquire an entitlement that is sufficient to meet the environmental objectives. The objective is still to meet flow requirements at minimum economic cost, and as a consequence the optimal rule will minimise the level of entitlement required subject to the reliability constraints. However, the peak level of demand that must be met determines the minimum requirement.

Table 5. Summary results for the institutional constraint scenarios

	Reliability achieved (%) (Training/evaluation)			Costs ($m) (Evaluation)			
Scenario	Event 1	Event 2	Event 3	Net purchases	Environmental manager	Industry surplus	Total economic
Scenarios with no carry over							
C	91/95	96/89	90/90	124	342 (53)	410 (20)	752 (73)
D	71/72	72/74	72/69	54	188 (57)	222 (17)	410 (74)
Scenarios with no trade							
C	90/83	96/92	90/91	na	377 (88)	821 (431)	1,198 (519)
D	84/82	71/67	72/63	na	154 (23)	289 (84)	443 (107)

Na: Not applicable

The costs of restricting access to trade escalate with the acceptable level of reliability. Total economic costs in scenario D are around $105 million greater than the comparable scenario with trade presented in table 4. The loss in industry surplus accounts for about 80 per cent of the increase between the two scenarios. The difference escalates to more than $500 million in the 90th percentile scenario (scenario C), again with the loss in industry surplus accounting for about 80 per cent of the increase in total economic costs.

The potential gains from trade arise when the marginal return to agricultural and environmental water uses diverge. Within the framework set out here these gains are realised into ways. First, when the environmental manager is holding water in excess of release requirements and has no further access to carryover facilities, the marginal value of water to the environmental manager falls to zero The transfer of water to agriculture generates a net economic gain as long as the marginal value of water in agricultural use is greater than zero. Second, the environmental manager can, with the constraints, delay or bring forward a release when the market value of water is very high or low. The extent to which this inter-temporal arbitrage can be realised is dependent on the reliability requirements and the climatic pattern.

The gains from trade benefit agricultural users more than the environmental manager. Around 80 per cent of the total benefits accrue to agriculture as a reduction in lost industry surplus. This is a reflection of water being transferred to agriculture when prices are generally higher and the functional form of the estimated agricultural water demand curve (see Appendix A). Demand becomes increasingly inelastic as prices rise in response to reduced availability so at the margin, the change in surplus is increasing.

The ability of the rules to meet the level of reliability is also less robust where the institutional arrangements constrain the ability of the environmental manager to source water to meet any shortfall in reserves held in storage. When comparing all the scenarios with trade, for example, the rules fail to meet the acceptable level of reliability by a maximum of 3 per cent (table 4). Without access to trade this increases to between 7 and 10 per cent (table 5).

Access to the temporary trading market by the environmental manager has implications for water prices. Prices are lower but more variable when the environmental manager is able to trade. Again, comparing the 90 per cent reliability targets of Scenario C, restricting access to the temporary trading market increases the average price by more than 75 per cent. The relative standard deviation in prices is more than 40 percentage points.

These results show the importance of trade and, to a lesser extent, carry over arrangements as risk management tools for the environmental manager. The ability to transfer the physical use of water through time reduces the risk that the environmental manager will not be able to meet flow requirements with the acceptable level of reliability. The ability to access both instruments through flexible institutional arrangements reduces the cost of meeting environmental flow objectives to consumptive water users and the government.

7. Concluding comments

Coupled with scientific knowledge, an approach to water planning that supports the tailoring of preferences for reliability to environmental outcomes could reduce the costs of meeting those outcomes. For some environmental assets it will be appropriate to have a zero tolerance for exceeding the threshold time between watering events, but for others more flexibility may be possible.

This flexibility should reflect the level of risk the community is prepared to accept that the preferred timing of an environmental watering regime may not be met. Explicit consideration of where flexibility is possible, based on scientific information, will require consideration of the resilience of the environmental asset to extended and sometimes repeated durations between watering events. This may not generate the optimal environmental outcome but would help to ensure that the option to preserve key environmental assets is maintained.

It is shown here that it is possible to evaluate trade-offs between the reliability with which environmental objectives can be met and the economic costs to government and irrigated agriculture. Trade-off decisions can be made on a range of criteria, for example, total budget (maximise the number of successful events subject to a budget constraint), differential rankings of reliability that indicate different preferences for particular environmental outcomes (for example, high levels of reliability for assets that have high community values) or equalising reliability across environmental objectives (implicitly saying that preferences for the probability of success are the same for each environmental asset).

This approach can facilitate adaptive management as it naturally leads to an ongoing and objective assessment of the probability that performance to date is meeting a set of clearly defined environmental objectives. It does not replace the need for monitoring and evaluation of environmental objectives versus outcomes.

Regardless of the economic trade-offs, institutional settings that enable water to be sourced and managed efficiently to meet environmental demands is in the interests of all parties. Allowing an environmental manager access to carry over facilities and the market for temporary trade in water entitlements can lower direct costs to taxpayers and the costs of foregone returns to agriculture and other users. However, given the potential size of an environmental manager’s transactions in the temporary water market, it would be worthwhile investigating institutional arrangements that promote certainty and transparency in environmental management. This is so other water users can understand the likely behaviour of the environmental manager in the market and account for it as a factor when making long and short-term investment decisions. This may involve placing constraints on the environmental manager, for example, rules governing the orderly purchase and disposal of water requirements. However, it might also include the use of call and put options.

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Appendix A: Water market demand

Brennan (2010) constructed a model of the southern connected Murray River catchments including the major irrigation districts on the Murrumbidgee, Murray and Goulburn rivers, as well as private diverters. The purpose of the model is to simulate market prices making it necessary to include water market trading rules, such as those associated with the Barmah Choke, and financial transactions costs imposed by irrigation authorities. The model is used to assess the impact of physical trading constraints, the spatial pattern of water entitlement holdings on the market price of water under historic climate and climate change scenarios, and the Commonwealth entitlement buyback program.

Estimating the demand function for consumptive water

Prices in seasonal markets in each irrigation district are affected by supply (local as well as that imported from other regions) and demand in the same market. Demand depends on local demand and also those bidding from outside the district. As buy and sell decisions made by irrigators will depend on the opportunity cost of water, water will be delivered into the irrigation district as long as the value of consumptive use does not exceed the opportunity cost of that water. This enables the estimation of a district level water demand curve by regressing the market price against the quantity of water delivered to the *j*th district at time *t*. Annual time series of irrigation diversions and weighted average seasonal prices were used to estimate a semi-log demand function:

$$\ln\left(P_{jt}\right) = \gamma_0 + \gamma_1 D_{jt} + \gamma_2 R_{jt} + \varepsilon_{jt}$$

Where:

- P is the average seasonal price in period t for the trading region in $ per megalitre (ML)
- D is diversions in the irrigation district in ML
- R_t represents useful rainfall
- γ_i are the coefficients to be estimated; and
- ε is an error term

For the Goulburn Broken Catchment the estimates were:

- $\gamma_0 = 7.484$;
- $\gamma_1 = -1.308$;
- $\gamma_2 = -0.007$.

Comparing estimated and actual water prices showed that modelled market prices are within 3 per cent of actual prices over a ten year period from 1998-99 for regions three and four. Slight overestimates in market prices for the other two regions may have been due to the influence of the ban on water trade in New South Wales that occurred in 2006-07 (Brennan 2010).

Some caveats with the modelling approach should be noted. The demand curve for consumptive use in any season is a short-run concept; the curve is derived from current decisions about water use given current prices. In reality, the value derived from consumptive use is the result of investment decisions made previously. For example, horticultural producers require water to protect perennial plantings as assets as well as maximise productive yield. Decisions about annual crops are more opportunistic and producers of annual crops will most likely have more flexibility in their water use decisions. Over the longer term, the underlying asset base can change as new investments are made and old investments are abandoned. This may change the demand characteristics of an irrigation region over time if, for example, permanent entitlements are sold and producers rely more on the temporary market to manage water availability requirements for opportunistic crops.

Appendix B: Water accounting and allocation rules

The following describes the water accounting rules used in the optimisation model. Annual variables are in italics, constants are bolded.

1. *October Carry In* = maximum of [(*May Carry In* + *Winter Spring Inflow*) * (1 – ***Evaporation***), **Dam Capacity**);
2. *Spill* = minimum of (*May Carry In* + *Winter Spring Inflow* - Dam Capacity, 0);
3. *Downstream flows* = *Natural inflows below the dam* + *Spills*;
4. *Water Available* = (*October Carry In* + *Balance of Inflows*) * (1 –***Evaporation***) - **critical reserve**;
5. *Allocation = minimum of (2 * Entitlement, Water Available);*
6. *Allocation = minimum of (Entitlement, Average Use Adjustment);*
7. *May Carry In = Water Available – (1+**System Losses**)* Allocation*.

The model parameters were supplied by the Victorian Department of Sustainability and Environment and included:

- Evaporation = 3.64 per cent
- Critical reserve = 146,251 ML
- Total entitlement = 985,865 ML
- System losses = 11 per cent

The adjustment for average use is a function of the allocation given the allocation is above the level of entitlement:

$$Average\ Use = 0.036 + 1.245 InitA - 0.274 InitA^2$$

Where InitA is the initial allocation specified in (5).

Adjustments to the code were made to account for the carry over of environmental allocations.