RIVER RESEARCH AND APPLICATIONS
River Res. Applic. (in press)

ANALYSIS AND MANAGEMENT OF UNSEASONAL FLOODING IN THE BARMAH–MILLEWA FOREST, AUSTRALIA

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ABSTRACT

The Barmah-Millewa Forest is the largest red gum forest in the world and lies adjacent to the middle reaches of Australia's River Murray. Regulation of the River Murray, to supply water for irrigation, has changed the watering regime of the forest and thus is degrading its environmental values. The watering regime has been changed in two ways: (1) there are now fewer large winter/spring events that inundate extensive areas because these floods are mitigated by irrigation storages; and (2) there are more small summer/autumn events that flood low-lying areas and are caused by the way the river is operated to supply irrigation demand. The increased frequency of these small unseasonal floods is the subject of this paper.

During the irrigation season, water to meet irrigation requirements must be released four days in advance to allow for travel time from storages to irrigation areas upstream of the Barmah-Millewa Forest. If there is heavy summer rainfall, irrigators cancel their orders so the flow that would have been diverted, remains in the river and causes a small 'rain rejection' flood. At the same time, river freshets from unregulated tributaries can also increase river flows. The River Murray channel in this area has low capacity and these high flows result in water spilling into the forest. Based on analysis of pre-regulation conditions (1908–1929) and current conditions (1980–2000), forest flooding has increased from 15.5% of days to 36.5% of days between December and April. In particular, small, localized floods, which cover less than 10% of the forest, occur at least eight times more frequently now, than before regulation. Work by others has related these hydrologic changes to tree death and changes in floristic structure in wetland systems. There are also economic costs because much of the water that spills into the forest is not available for irrigation.

Two solutions to unseasonal flooding are described in this paper. One is to limit the maximum flow in the river during the irrigation season so there is capacity to convey at least some of the rain rejection flows without spilling water into the forest. The other is to maintain airspace in a diversion weir (Lake Mulwala) upstream of the forest to store the surplus water when orders are cancelled. Preliminary economic analysis shows the preferred option is to increase airspace in Lake Mulwala which provides net benefits of at least Aus$1.4 million per year along with unquantified environmental benefits from decreased unseasonal forest flooding.

KEY WORDS: Barmah-Millewa Forest; forest watering; environmental effects of river regulation; River Murray

INTRODUCTION

The Barmah-Millewa Forest comprises approximately 70 000 ha of wetland habitats located on the floodplain of the River Murray between Echuca, Deniliquin and Tocumwal in northern Victoria and southern New South Wales, Australia (Figure 1). This forest complex, consisting of the Barmah Forest (Victoria) and the Millewa group of forests (New South Wales), forms the largest river red gum (*Eucalyptus camaldulensis* Dehnhardt) forest in the world, and is valued for wood products, grazing, conservation and recreation. The area is protected under migratory bird agreements between Australia, China and Japan, and includes the Barmah wetland, which is listed under the Ramsar Convention as having international significance, and the Millewa Forest, which has been proposed for Ramsar listing.

The biota of the Barmah-Millewa Forest has evolved in an environment characterized by natural flooding in the winter and spring months of most years, alternated with dry conditions during the summer and autumn

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Received 26 November 2001
Revised 9 May 2002
Accepted 28 May 2002

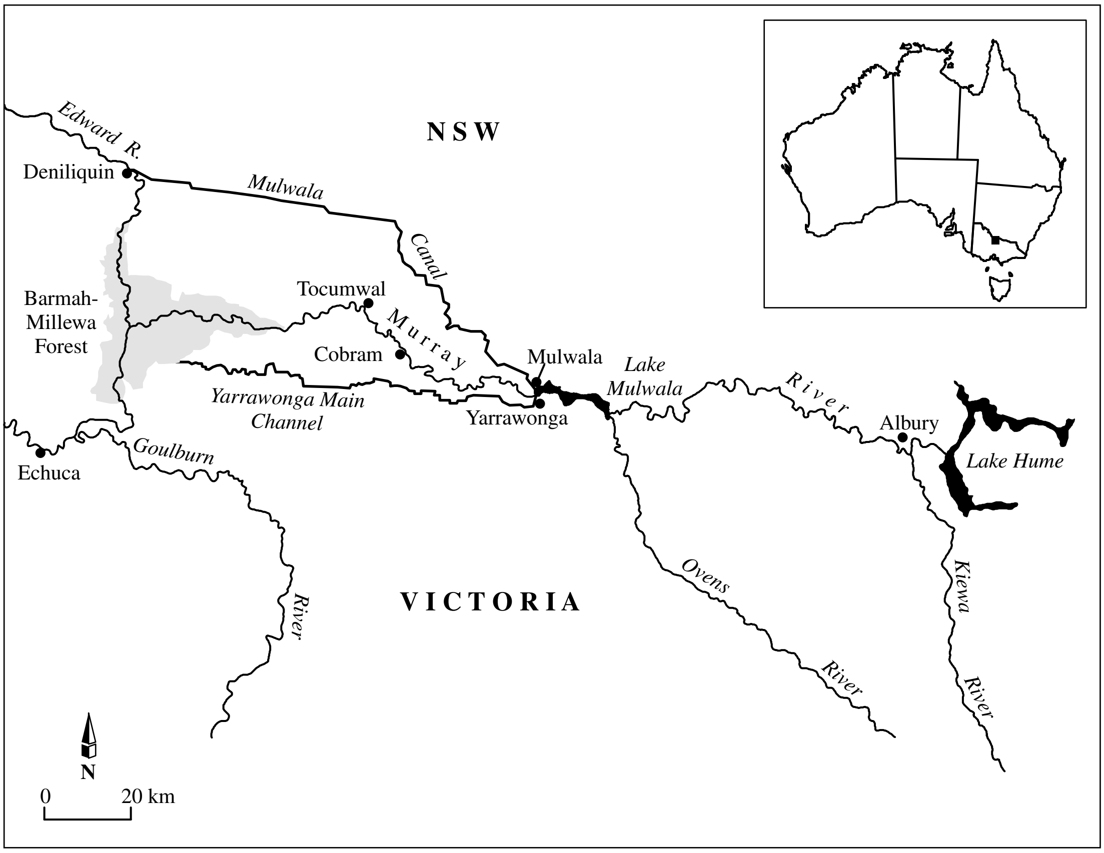

Figure 1. Location of the Barmah-Millewa Forest

months (Bren, 1988a; Maunsell, 1992a). This natural cycle of wetting and drying is required to sustain the ecosystem and its values. However, the natural flow regime of the Barmah-Millewa Forest has been changed by regulation of the River Murray as part of irrigation development. In particular, there are now fewer large winter/spring floods and more small summer/autumn floods.

The reduction in large winter/spring floods and its environmental effects have been analysed elsewhere (e.g. Thoms *et al.*, 2000). For example, hydrologic changes are such that under current levels of development, floods of four months' duration (which are large enough to cover half the forest) now occur in less than 20% of years whereas under natural conditions these floods occurred in 60% of years. Modelling shows that under current development there are periods of up to 13 years without these large floods, compared to a maximum flood-free period of five years before regulation of the river (Lewis, 2000). These hydrologic changes have severe environmental consequences and a set of rules has been developed in order to water the forest with a special allocation of up to 150 Mm^3/year (MDBC, 2001). The impact and management of these winter/spring floods are being addressed by others and will not be discussed further in this paper.

The subject of this paper is the increased frequency of small unseasonal floods that occur in summer and autumn. These floods occur as a consequence of the way the river is operated to deliver irrigation flows during times of peak water demand in the austral summer from November to April. The forest is downstream of Yarrawonga Weir, a major structure on the River Murray from which water is diverted into irrigation areas in New South Wales and Victoria (Figure 1). Water to meet the demand in these irrigation areas must be released four days in advance to allow for travel time from Hume Reservoir. However, if there is heavy summer rainfall, irrigators may cancel their orders after the flow has been released. As there is little airspace at Lake Mulwala, flow intended for diversion instead continues downstream to the forest and causes a small 'rain rejection' flood (Figure 2). The rain can also cause river freshets in unregulated tributaries upstream of the forest. The result is that River Murray flows are increased and can exceed channel capacity through the forest so that water spills into low-lying areas. The economic consequences are that this water has lost potential value as it can no longer be used for further irrigation, nor to provide environmental benefits at a different place or time. The environmental consequences are that low-lying areas near the river are waterlogged which causes tree death and floristic changes to wetlands (Maunsell, 1992a; Chesterfield, 1986). The irony is that while regulation has caused much of the topographically higher areas of the forest to become too dry because there are few large floods, lower areas are now too wet because of excessively frequent small floods.

Throughout this paper flows are listed in SI units along with the units used by river management authorities in Australia, i.e. Ml/day. The conversion is that 1 m^3/s is equivalent to 86.4 Ml/d. These units have been retained to make the management assumptions and implications clear to Australian river managers.

CAUSES AND CONSEQUENCES OF UNSEASONAL FLOODING

The Barmah-Millewa Forest is vulnerable to changed watering regimes caused by river regulation because of its location and the geomorphological history of its development. The forest is formed along a reach of the River Murray which has restricted capacity. In the most restricted part of the forest, called the Barmah Choke, the channel capacity is about 122.7 m^3/s (10 600 Ml/d), the least of any section of the river between the Hume Dam and the South Australian border. Under natural conditions, this low capacity channel led to regular flooding and created a complex system of wetlands, billabongs and lakes along with extensive red gum stands, Moira grass (*Pseudoraphis spinescens)* plains and giant rushlands (*Juncus ingens).*

The Barmah Choke creates operational problems for the regulation of the River Murray. The restricted capacity limits the amount of water that can be delivered to irrigation areas and to meet other entitlements downstream. As a consequence, the river channel through the forest is run at, or near, capacity for much of the year. This results in limited flexibility to deal with flow increases caused by, for example, cancelled orders, without spilling water into the forest.

Constraints on the operation of Hume Dam can also exacerbate rain rejection floods. When orders are cancelled, the release from Hume is cut back, but an operational procedure aimed to minimize the risk of bank slumping limits the rate of flow reduction. At Doctors Point, downstream of Hume Dam, decreases in river level are limited to 150 mm per day, which corresponds to a maximum flow change of about 17.4 m^3/s per day (1500 Ml/d) (Maunsell, 1992a). Given that cancelled orders could correspond to diversions of approximately 170 m^3/s (15 000 Ml/d), depending on the extent and duration of summer rainfall and the subsequent weather conditions, it can take several days before the Hume release is reduced sufficiently so that flow can be retained within the channel through the Barmah-Millewa Forest. Work by Green (1999) questions the need for such a stringent control on drawdown rates but this is not considered further in this paper.

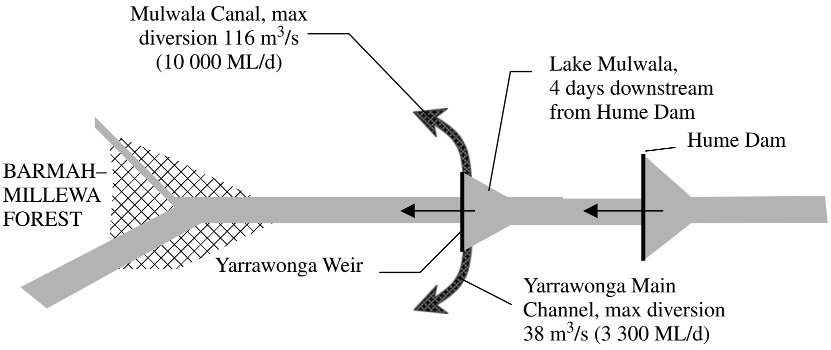

Figure 2. Conceptual diagram of unseasonal surplus flows. If irrigators cancel orders, diversions to Mulwala Canal and Yarrawonga Main Channel are cut back and water that has already been released from Hume remains in the river and can flood the Barmah-Millewa Forest

History of management of unseasonal surplus flows

Concerns about the restricted flow capacity through the Barmah-Millewa Forest probably date to the beginning of large-scale irrigation development. The Hume Dam was first filled in 1936, and Yarrawonga Weir in 1939, and there was rapid expansion of irrigation following the Second World War (Powell, 1989). In 1954 the Government of the Commonwealth of Australia, along with the State Governments of New South Wales, Victoria and South Australia, agreed to amend their River Murray Waters agreement to allow channel clearing works to increase the conveyance in the area of the Barmah Choke (Johnson, 1974). In 1974 the loss of water caused by rain rejection floods was noted by Holmes (1974) who thought that 'reliable forecasting at least four days ahead, may be possible within the next few years, [and] should substantially reduce the frequency of such losses'. In 1980, the River Murray Commission (then the managers of the irrigation system, now called the Murray-Darling Basin Commission, MDBC) noted the problem of rain rejection floods and proposed a number of options including the construction of additional storage capacity along the Mulwala Canal to capture the water that would otherwise be lost when irrigation orders were cancelled. Regulators were constructed that could be operated to control the outflow from the River Murray at low points in levees and at effluent creeks through the Barmah-Millewa Forest (Johnson *et al*., 1980).

There was intensive research on flooding of the Barmah-Millewa Forest and the impact of changed water regimes during the 1980s (Bren and Gibbs, 1986; Bren *et al*., 1987, 1988; Bren, 1988a,b, 1992). By the early 1990s, the environmental problems associated with changed flooding regime of the Barmah-Millewa Forest were recognized but the focus remained on the reduced frequency of large winter/spring floods (DCFL, 1989). Rain rejection floods, which occur in summer and autumn, were seen by some as an environmentally beneficial way of providing water to the forest (Maunsell 1992a,b), despite increasing recognition of the environmental problems caused by this unseasonal flooding.

By 1994 rain rejection flows were beginning to be managed to reduce their impact on the forest. An interim water strategy was developed that recommended rain rejection flows should be directed down the Mulwala Canal or through the least ecologically sensitive areas of the forest (Ward *et al*., 1994). These recommendations reflect the goal of minimizing summer and autumn flooding of the forest, particularly of Moira grass plains. This goal is also emphasized in the *Water Management Plan for the Millewa Forests* (Leslie and Harris, 1996), in which the authors, unlike Maunsell (1992a,b), explicitly state that rain rejection flows should be minimized, rather than used for forest watering.

Unseasonal surplus flows remain an issue. In 1996 the Department of Land and Water Conservation, New South Wales, conducted a preliminary investigation to assess the options for managing unseasonal flows affecting the Barmah-Millewa Forest (DLWC, 1996). The impacts of river regulation exerted through high summer flows and rain rejection floods are also specifically referred to in *The Barmah-Millewa Forest Water Management Strategy* (MDBC, 2000). Furthermore, in a report on flow-related environmental issues along the whole River Murray system, Thoms *et al*. (2000) recommend that the management of unseasonal summer/autumn flooding should receive 'very high priority status'.

Existing approaches to managing unseasonal flooding

Existing approaches to managing unseasonal flooding are mainly focused on attempting to deal with the surplus water rather than preventing the occurrence of floods. At the onset of an unseasonal surplus flow, the MDBC notifies the forest management agencies, which then negotiate on how these flows will be distributed (Maunsell, 1992a). The current *Annual Plan 2000–2001 for water operations and works in the Barmah-Millewa Forest* (BMF, 2000) describes the time-sharing arrangement between the State Forests of New South Wales and the Department of Natural Resources and Environment, Victoria. In situations where floods can be controlled by regulators they are taken by the different states (i.e. the different sides of the river) in alternate years. For example, in 2001 it was Barmah Forest's turn (the Victorian side) to receive rain rejection flows. The effectiveness of this procedure is limited because, despite extensive channel modifications (including raised river levees and the construction of effluent regulators), there is generally limited scope to control unseasonal flows within bank, and outflows into the Barmah-Millewa Forest are common. For example, in the Barmah Forest, Gulf Creek, an effluent stream, carries flows released through the Gulf regulator, and smaller downstream regulators. The wetlands along the Gulf Creek system have high ecological value. However, as the Gulf regulator represents more than 50% of available regulator capacity (57.9 m^3/s, or 5000 Ml/d), its use is necessary when passing larger unseasonal flows into the Barmah forest (DLWC, 1996) which means there is limited protection of these wetlands.

Environmental degradation issues associated with unseasonal surplus flows

Unseasonal flooding has a significant effect on the ecology of the forest. It is degrading wetlands by interfering with the natural drying-out phase and by disrupting nutrient cycling processes. Subsequently, the productivity of the wetlands has been reduced and habitat values have been seriously diminished. Frequent unseasonal flooding is contributing to extensive tree deaths along Moira Lakes and the Edward system (Maunsell, 1992a).

In addition to killing areas of forest, prolonged summer inundation is modifying the floristic structure in major wetland systems (Chesterfield, 1986). The encroachment of Moira grass plains by rushland and red gum, due to the increased frequency of summer flows, is well documented (Chesterfield, 1986; Maunsell, 1992a; Bren, 1992; Ward *et al*., 1994). Chesterfield (1986) estimated that since 1930, 1200 ha (30%) of the Moira grass plain has been lost to red gum regeneration and a further 1200 ha to giant rush encroachment.

Unseasonal flooding also impacts upon commercial operations and recreational use of the forest. Restricted access for logging and stockpiling has significant economic impacts on the timber industry. Access problems also affect bee-keeping, grazing and local tourism activities during the Christmas and Easter peak visitation periods. Fire suppression management in summer is impeded when floods block off access tracks and fuel is too wet to burn.

ANALYSIS OF UNSEASONAL SURPLUS FLOWS

There are clear incentives for better understanding and management of unseasonal flows. In particular, there is potential to reduce the environmental problems in the forest and to save water for other uses. Our investigation began with analysis of the flow record of the River Murray to quantify the flow changes caused by regulation and unseasonal surplus flows. Measured daily flows were used because modelled flow values are not publicly available. The frequency and areal extent of forest flooding was analysed on a month-by-month basis to compare the pattern of forest flooding before regulation (1908–1929) to patterns of forest flooding during 1981–2001. Although water use in the Murray-Darling Basin grew by approximately 20% from 1981 to 2001 (Murray-Darling Basin Ministerial Council, 1995), this period was taken to represent current conditions, which suggests impacts are actually greater than our analysis shows.

Impact of regulation on River Murray flows at Tocumwal

The River Murray flow record at Tocumwal was selected for analysis because it was identified by Bren *et al.* (1987) as the most significant factor relating to the percentage of the Barmah Forest subject to flooding. Various management plans and strategies also cite the flow at Tocumwal as indicative of the restrictive capacity of the Barmah Choke. A record of significant length (1908–present) for mean daily flows is readily available for Tocumwal from River Murray Water. The months November–May were selected because this represents the widest range of months suggested in publications as the season in which rain rejections occur (e.g. DLWC, 1996). The mean daily flows of the River Murray at Tocumwal from 2 January 1908 to 15 March 2001 were divided into flows occurring in these months.

Key periods were identified to represent the intervals between successive, major changes to regulation of the Murray upstream of the forest. The following time periods were used in the analysis:

- 1908–1929: before the construction of the Hume Dam (pre-regulation conditions);
- 1936–1960: after the construction of the Hume Dam, and before its enlargement;
- 1961–2001: after the enlargement of the Hume Dam;
- 1981–2001: ‘Present’ level of regulation (representing current irrigation demand conditions).

For each month between November and May, flows were analysed to understand the pattern of change with regulation (for the complete analysis see Chong, 2002). As an example, the flow duration curve for March, the most impacted month, shows large changes in flows which are about the capacity of the Barmah Choke (Figure 3). Flows that exceed 115.7 m^3/s (10 000 Ml/d) have increased in frequency from 7.8% to 79.7%. The demands of downstream users have grown such that, over the period 1929–2000, flows have been held near channel capacity for an increasing proportion of each year. This has increased the risk of forest flooding from even small increases in flow that may occur when orders are cancelled.

From the analysis, the months December–April most closely match the description of the time when there are ‘unseasonal surplus flows’ caused by regulation. In particular, the flow records for these months exhibit a trend towards maintenance of high (>115.7 m^3/s, 10 000 Ml/d) River Murray flows. Flows in November and May do not closely match the description of unseasonal surplus flows as analysis of the flow records indicates that regulation has actually lowered river flows during these months, because water is stored for later release. Therefore, the irrigation season, December to April (approximately 151 days), is used in the following analysis.

Results of our analysis suggest that regulation has reduced the variability of daily flows in December–April. In particular, it has decreased the frequency of flows under 70 m^3/s (6000 Ml/d) and over 185 m^3/s (16 000 Ml/d), with flows more likely to lie within this range. Present flows are more likely to be over 116 m^3/s (10 000 Ml/d) than those before regulation, but less likely to be over 140 m^3/s (12 000 Ml/d).

Frequency of forest flooding

The analysis of forest flooding required investigation of the ‘threshold Tocumwal flow’ at which forest flooding commences. This threshold has changed over time, due to activities such as channel clearing, and construction of levees and regulators. Various publications cite values for threshold flows, including 108.6 m^3/s (9386.8 Ml/d) derived for the period 1963–1984 (Bren *et al.*, 1987); 127.3 m^3/s (11 000 Ml/d) (RMC, 1980; Johnson *et al.*, 1980); and 122.7 m^3/s (10 600 Ml/d) (Thoms *et al.*, 2000). Chong (2002) discusses the sensitivity of the calculation of flooding frequency (the percentage of days during which the forest flooded) to the selection of the threshold. In general, a higher threshold results in the calculation of a smaller impact of regulation on flooding frequency, but does not alter the conclusion that regulation has increased the frequency of forest flooding.

To illustrate the extent to which regulation has increased forest flooding, ‘factor increases/decreases’ were calculated. For example, when using 122.7 m^3/s (10 600 Ml/d) as the threshold, regulation has increased the

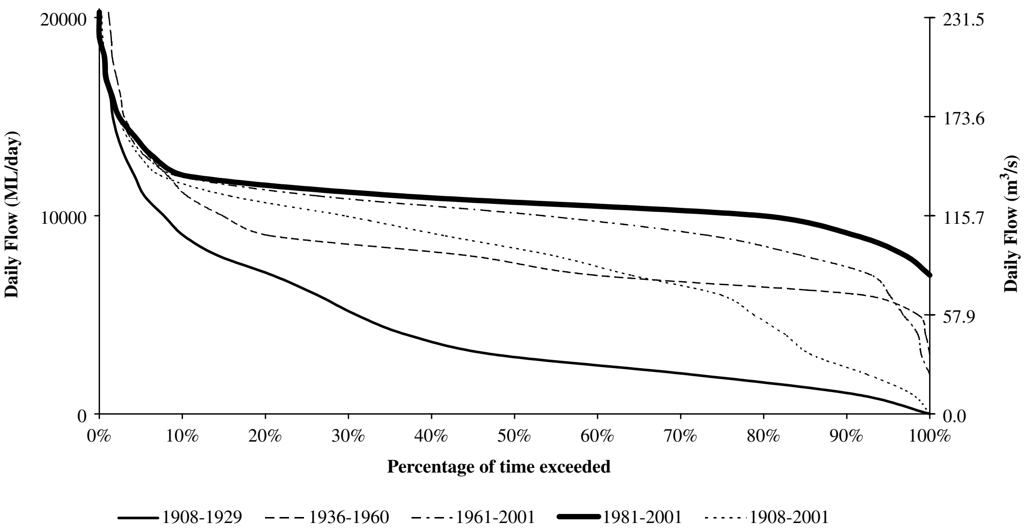

Figure 3. Flow duration curve of the River Murray at Tocumwal: March flows

Table I. Summary effects of regulation on frequency of forest flooding (flooding threshold is a flow of 122.7 m^3/s (10 600 Ml/d) at Tocumwal)

	Frequency of forest flooding (% of days forest is flooded)		
Period	Pre-regulation 1908–1929	Current 1981–2001	Factor change[a]
November	75.0%	51.0%	0.7
December	32.0%	40.6%	1.3
January	21.2%	41.7%	2.0
February	9.8%	37.7%	3.8
March	6.7%	59.8%	9.0
April	4.4%	20.0%	4.6
May	75.0%	51.0%	0.5

[a] Factor change <1.0 = decreased flooding frequency; factor change >1.0 = increased flooding frequency.

frequency of flooding in March from 6.67% to 59.83% of days. This is equivalent to a factor increase of $59.8/6.7 = 9.0$. These factor changes are illustrated in Table I. Regulation has increased the flooding frequency during December–April, with the greatest impact during March and the smallest impact during December. At the threshold of 122.7 m^3/s (10 600 Ml/d), the forest flooded 36.5% of the time during 1981–2001 (compared with just 15.5% of the time in 1908–1929).

Areal extent of forest flooding

The areal extent of forest flooding is related to topography, with low-lying areas close to the river being more susceptible to flooding. Repeated inundation of these areas has the greatest ecological impact with regards to tree deaths and changes in patterns of vegetation. Therefore, a large increase in the frequency of flooding of a small forest area is likely to be more damaging than small increases in the frequency of flooding of a greater area. This flooding extent analysis uses the relationship derived by Bren *et al.* (1987), which relates proportion of Barmah Forest flooded ($P\%$) to the daily flow at Tocumwal, Q (m^3/s), for the period 1963–1984:

$$P = -223.16 + 47.6 \ln(Q) \quad Q < 792.8\ \mathrm{m^3/s}\ (68\,500\ \mathrm{Ml/d})$$

We used the mean daily flow at Tocumwal as the 'Q' in Bren's relationship, rather than the peak flow, as this is more conservative and appropriate for the multi-day duration of flooding which is of interest here. We have also assumed that the relation (although derived from the period 1963–1984) is applicable for the period 1908–2001. The relationship was also only derived for the Barmah Forest (the Victoria side of the river), as data were not available for flooding in New South Wales, although flooding regimes are similar in the two forests (Bren *et al.*, 1987). Consequently, the results provide general illustrations of the trends in area of forest flooded, rather than exact values.

In summary, regulation has increased the proportion of days during which 0–30% of the forest is flooded by a factor of 6.2. In particular, forest floods that cover less than 10% of the Barmah Forest have increased in frequency by a factor of over 8.1. This corresponds to field evidence that in particular areas of the forest, overwatering has caused tree deaths and changes in vegetation association. However, forest floods that cover more than 30% of the forest are now 3.6 times less frequent which corresponds to evidence that higher parts of the forest have been affected by drought.

BETTER MANAGEMENT OF UNSEASONAL SURPLUS FLOWS

Two options are presented that would decrease the frequency and magnitude of unseasonal flows. The first option involves limiting the maximum flow of the River Murray at Tocumwal during the season when water is supplied for irrigation. This would enable larger flows caused by rain rejections or river freshets to pass through the forest without causing flooding. The second option involves increasing the airspace at Lake Mulwala by lowering the water level at Yarrawonga Weir. This would enable storage of some of the water that has been released from Hume Dam for irrigators, but which remains in the river when orders are cancelled.

The research presented in this section comprised two steps. First, individual unseasonal surplus flow events were identified using daily flow data from December 1980 to April 2000 inclusive (20 seasons). The analysis was assisted by the assumption that events are independent. Second, for each management option, 1980–2000 flow data were analysed to determine the extent to which these options would affect forest flooding characteristics (frequency, event duration, total excess volume, and number of events per season). Specifically, the data were analysed to quantify the changes required to decrease the frequency of unseasonal flooding in the Barmah-Millewa Forest (proportion of days in season during which flooding occurs) from 38.3% (current) to 15.5% (pre-regulation).

Identification of unseasonal surplus flow events

In this paper, the method for identifying unseasonal surplus flow events was to use the flows at the Tocumwal gauge to predict forest flooding with a begin-to-flood threshold flow of 122.7 m^3/s (10 600 Ml/d). This method is supported by Thoms *et al.* (2000, p. 102) and Bren *et al.* (1987). The advantages and disadvantages of other methods identified in recent literature are discussed in Chong (2002).

The period December 1980 to April 2000 was selected to provide a 20-year data set that represented current conditions. We excluded the major floods which occurred over the summer of 2000/2001, as they were due to unusual operating circumstances, where water was released to water the forest, rather than rain rejections or river flushes. The use of this method revealed that during the period 1980–2000, there were 82 surplus flow events (4.1 per year), which caused flooding in the forest in 38.3% of days in December–April. The average event duration was 14.1 days (median 10 days); mean peak excess flow was 25.6 m^3/s (2211 Ml/d), with a median of 13.1 m^3/s (1133 Ml/d); and average total flow per event was 17.8 Mm^3 (median 8.0 Mm^3). Information on individual unseasonal flow events is listed in the appendix to this paper, and analysed in greater detail in Chong (2002).

Limiting maximum River Murray flows at Tocumwal

If the flow through the Barmah-Millewa Forest could be limited to below the flooding threshold there would be some ability to convey surplus flows without exceeding channel capacity. To determine the impact of limiting the flow of the River Murray at Tocumwal to below 122.7 m^3/s (10 600 Ml/d), each unseasonal surplus flow event was analysed on a day-by-day basis.

To illustrate, an imaginary event is described in Figure 4. Under current operating procedures, flooding would occur on days two to six, when flows exceeded 122.7 m^3/s (10 600 Ml/d). In Figure 4, excess flow is represented by the dark portion of the bars. The total excess flow is 2 Mm^3. Figure 5 illustrates the scenario where flow is limited (on day one) to 116.9 m^3/s (10 100 Ml/d). Given the same upstream conditions as the scenario in Figure 4, flows on subsequent days will be less, and surplus flows (totalling 0.4 Mm^3) will now only occur on days three and four.

Thus limiting the maximum flow at Tocumwal to 'B', where $B < 122.7$ m^3/s (10 600 Ml/d) effectively captures all events with peak flow < (Flowday_0—B), where Flowday_0 is the flow at Tocumwal the day before an event starts, i.e. limiting the maximum flow at Tocumwal to 'B' reduces the number of surplus flow events.

Limiting the flow decreases the flooding frequency, the number of events, the excess flow per event and the surplus volume per season although the benefits are subject to diminishing marginal returns. For example, limiting flow from 122.7 m^3/s to 115.7 m^3/s (10 600 Ml/d to 10 000 Ml/d) reduces flooding frequency by 26 days per season (38% to 21%). However, a further 7 m^3/s (600 Ml/d) reduction in maximum flow only reduces flooding frequency by an additional 12 days per season (Figure 6).

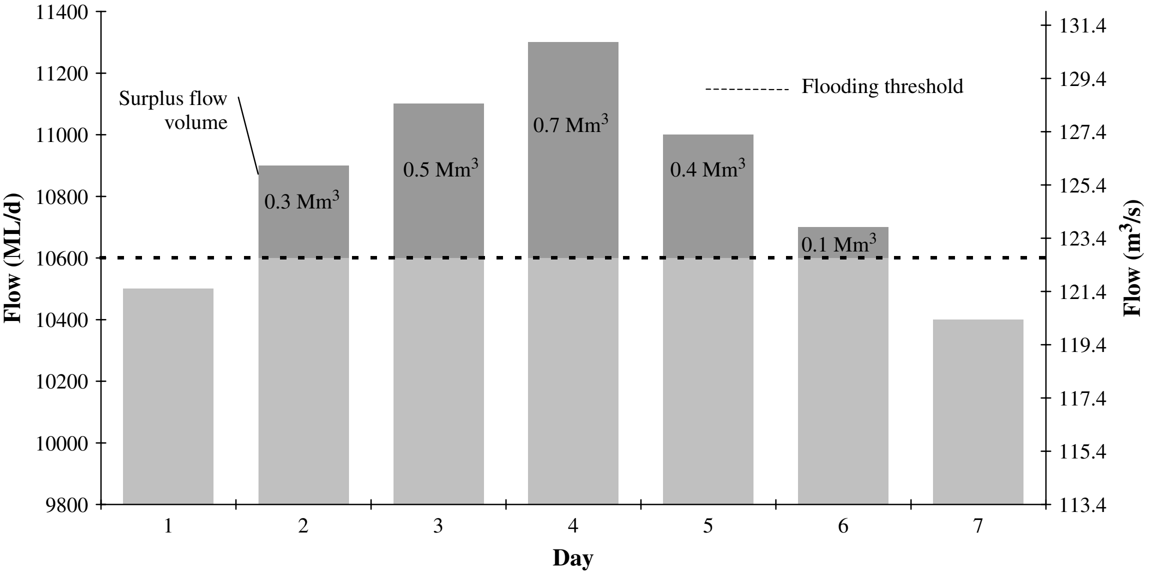

Figure 4. Imaginary unseasonal surplus flow event, to illustrate ‘do-nothing’ management option

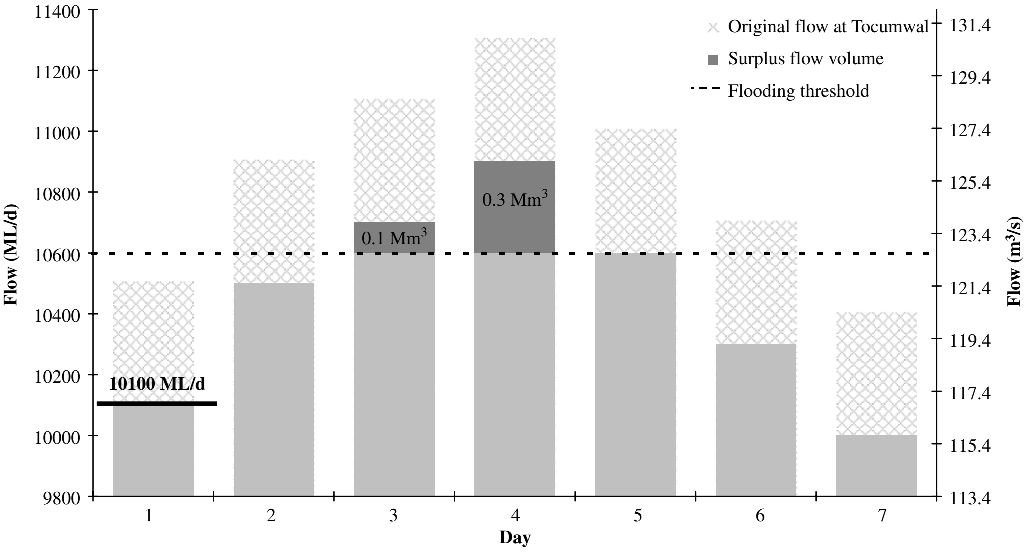

Figure 5. Imaginary unseasonal surplus flow event, to illustrate effect of limiting the maximum flow of the River Murray at Tocumwal to 117 m^3/s (10 100 Ml/d)

Increasing airspace at Lake Mulwala

A second way to reduce unseasonal forest flooding is to operate Lake Mulwala at a generally lower level to allow for the storage of at least part of the surplus flows when they occur. To determine the impact of increasing the airspace at Yarrawonga Weir (by 0.5, 1, 1.5… 2 Mm^3), each unseasonal surplus flow event was analysed on a day-by-day basis. The threshold for forest flooding was maintained as a flow at Tocumwal of 122.7 m^3/s (10 600 Ml/d).

To illustrate, consider the same imaginary event described in Figure 4. If airspace at Yarrawonga is increased by 1 Mm^3, there is the potential to contain the first 1 Mm^3 of an unseasonal surplus flow event whilst

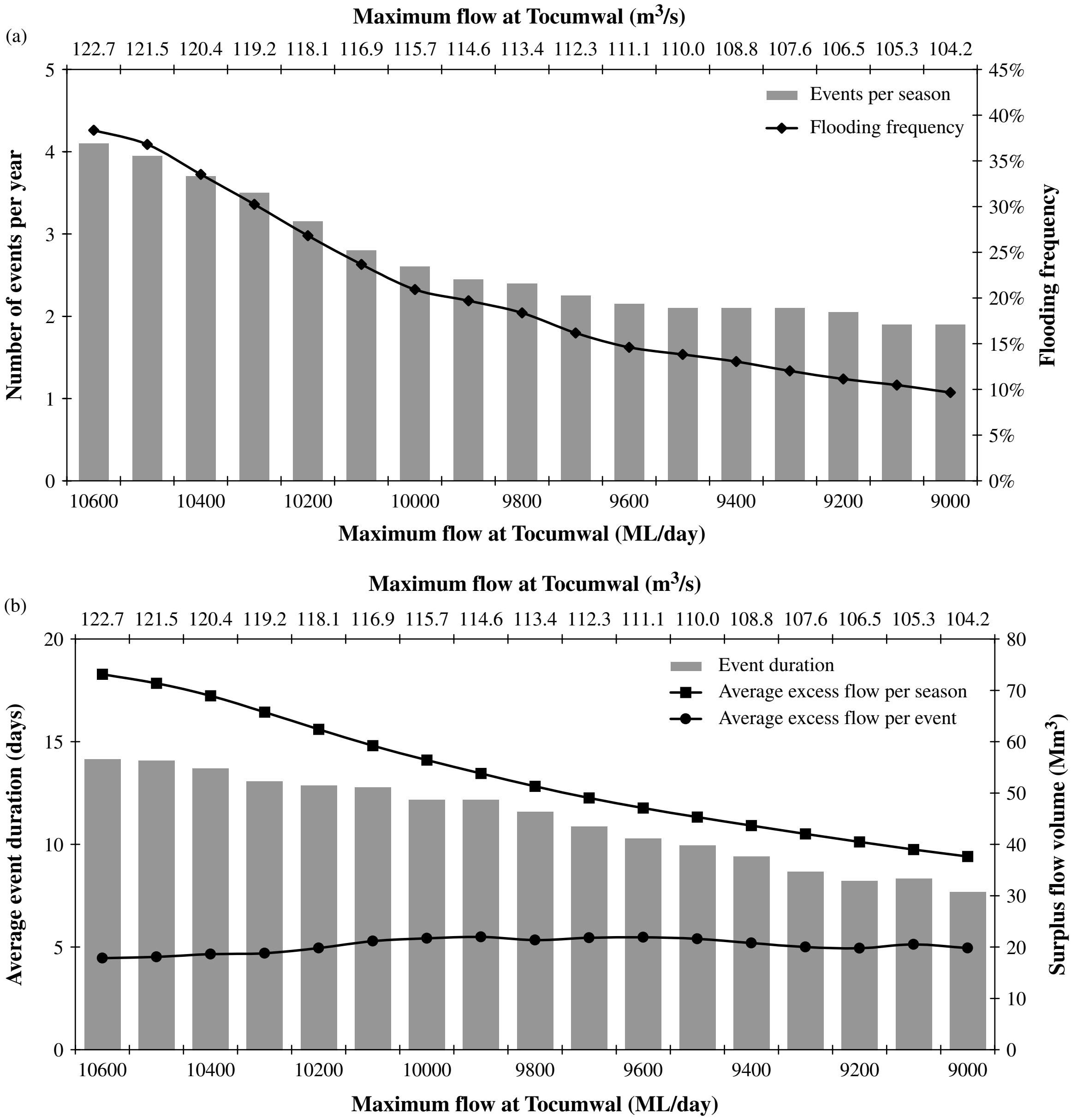

Figure 6. Effect of decreased River Murray flow on (a) frequency of unseasonal surplus flows and (b) surplus flow volumes

maintaining flow at Tocumwal at 122.7 m^3/s (10 600 Ml/d). Without increasing airspace, this event is five days long, with a total surplus flow of 2 Mm^3. If 1 Mm^3 free storage was available at Yarrawonga, this event would be three days long with a total surplus flow of 1 Mm^3 (Figure 7).

Increasing airspace decreases the flooding frequency, the number of events per season and the surplus volume (Figure 8). However, the benefits of increasing airspace do not accrue linearly. Firstly, considerable benefit is achieved from increasing airspace by 5 Mm^3, as flooding frequency is reduced from 38% (57 days per season) to 20% (30 days per season). However, increasing airspace by a further 5 Mm^3 (to 10 Mm^3) has lower benefits as it only reduces flooding frequency from 20% to 14% (21 days per season). Secondly, 5 Mm^3 extra airspace reduces event frequency from 4.1 to 2.4 per season, but another 5 Mm^3 extra airspace reduces

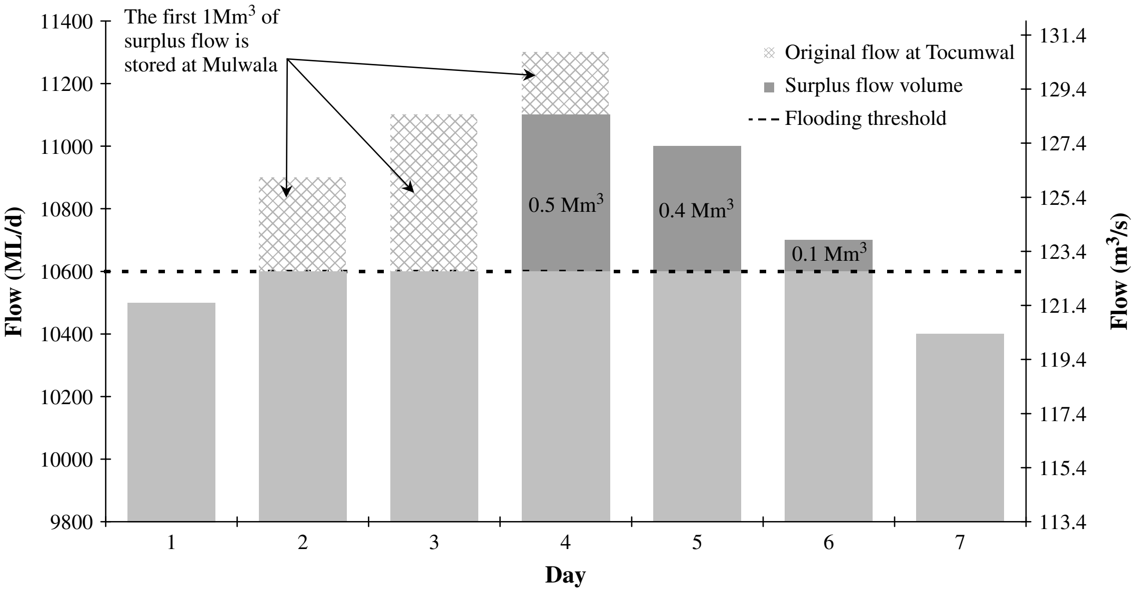

Figure 7. Imaginary unseasonal surplus flow event, to illustrate analysis of increasing airspace at Mulwala by 1 Mm^3

event frequency from 2.4 to 2.0 per season. Thirdly, the surplus flow volume per season decreases from 73 Mm^3 to 58 Mm^3 (with 5 Mm^3 extra airspace) to 48 Mm^3 (with 10 Mm^3 extra airspace) to 34 Mm^3 (with 20 Mm^3 extra airspace). There is no distinct trend between increased airspace and average event duration.

ECONOMIC ANALYSIS

The economic analysis of alternative environmental management strategies is not straightforward as both market and non-market costs and benefits can be identified. The approach taken here was to selectively quantify only the following costs and benefits (collectively defined as 'net conservative cost/benefit') for the two options: (1) limiting maximum River Murray flows at Tocumwal; and (2) increasing airspace at Lake Mulwala. The benefits and costs are:

- benefit of irrigation water 'saved' due to reduced forest flooding (both options);
- cost of irrigation water foregone due to reduced diversions (both options);
- cost of the reduction of hydroelectric generation (increasing airspace only).

Quantifying the 'net conservative cost/ benefit' provides a *lower limit* of the actual net benefit of each option (or an *upper limit* of the actual net cost of each option). The total economic benefit/cost would also include non-market values (such as biodiversity and habitat preservation) as well as other market values (such as benefits from increases in forestry and tourism activities). The quantification of these and other market benefits and non-market costs and benefits is outside the scope of this project. This is because accurate market valuations (e.g. of increased forestry yields) are prohibited without further, detailed investigation of the complex patterns of forest hydrology (in which each vegetation association requires a distinct watering regime). Furthermore, although alternative methods exist which enable the valuation of non-market costs and benefits, significant amounts of information and data are required to prevent biased results (Kahn, 1998). Our simple, conservative approach is justified because the costs of reduced amenity value are likely to be negligible, given the small changes to River Murray and Lake Mulwala levels; the environmental benefits are likely to exceed the environmental costs; and the net operating costs involved with decreasing flooding frequency are likely to be negligible.

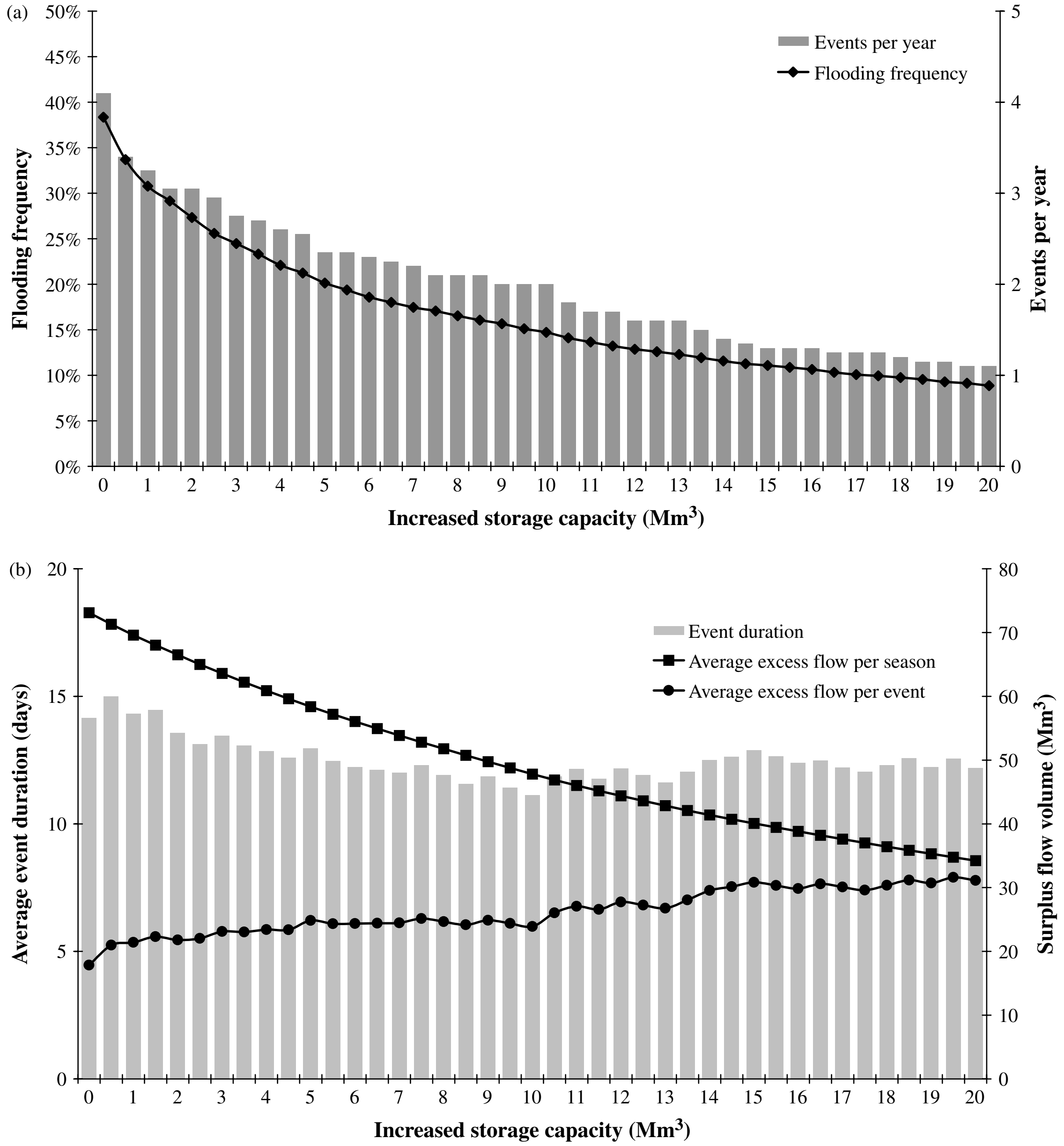

Figure 8. Effect of increased airspace at Lake Mulwala on (a) frequency of unseasonal surplus flows and (b) surplus flow volumes

Costs and benefits of limiting maximum River Murray flows at Tocumwal

The economic impact of limiting the maximum flow at Tocumwal includes: (1) the cost of reduced water supply downstream of the Barmah-Millewa Forest; and (2) the benefit of water saved from reduced flooding. It is necessary to consider the value of this water. Gross margins (activity income minus associated variable costs) associated with irrigated agriculture vary considerably between region and for different land uses, but we have adopted an average farm gross margin (foregone by irrigated agriculture) of Aus\$0.06/m^3 (\$60/Ml), as estimated by Gordon *et al.* (2000).

To calculate the decrease in water available to downstream irrigators, daily flow data at Tocumwal were analysed for each day in December–April from 1980 to 2000 with various flow limits (for an example, see

Figure 5). We have not included the scenario where part of this loss to downstream users could be offset by a gain in irrigation supply to upstream users. We have also assumed that all the water that spills into the forest is lost, which is a reasonable approximation for small events of the size considered here.

Under the current accounting rules of the Murray-Darling cap on diversions, water that floods the forest is not included in the calculation of net diversions. Therefore any water 'saved' by reducing flooding cannot be sold for irrigation purposes. However, this saved water could be used for environmental flows and watering the forest during winter and spring. The gross margins for irrigated agriculture have been adopted as the marginal value of water saved from reduced flooding frequency.

The economic consequences of limiting the maximum flow at Tocumwal are summarized in Table II. The reduction of flooding frequency achieved by limiting maximum flow at Tocumwal incurs a net cost, because the volume of water saved is less than the reduced volume of water available to downstream irrigators. This cost is an 'upper limit' estimate, which does not include analysis of the potential for increased upstream use.

The flooding frequency could be reduced from 38.3% to 15.5% (pre-regulation) by limiting the flow at Tocumwal to 111.1 m^3/s (9 600 Ml/d). This could be achieved at a net cost of Aus$2.2 million, which would comprise a cost of Aus$3.7 million (6.3 Mm^3) in water lost to downstream users and a benefit of Aus$1.5 million (2.5 Mm^3) in water saved from flooding the forest. Significant improvements can also be made at a net cost of Aus$1 million, which would reduce flooding frequency to 21%.

Costs and benefits of increasing airspace at Lake Mulwala

To calculate the costs and benefits of increasing airspace at Lake Mulwala it is necessary to consider: (1) the cost of reduced irrigation supply flexibility; (2) the cost of reduced hydroelectricity power generation; and (3) the benefit of reduced forest flooding, which is the same as for option 1, i.e. the limiting of maximum River Murray flow at Tocumwal.

Irrigation supply flexibility. Yarrawonga weir has been constructed to allow transfer of water to irrigation areas using gravity diversion. Therefore any decrease in lake levels (to provide more airspace) has the potential to affect the flow rate of these diversions. It has been suggested that authorities maintain Lake Mulwala above a minimum level in December–April because they are required to ensure that maximum flows can be released down Yarrawonga Main Channel and Mulwala Canal for irrigation orders. Reportedly, this is a more significant problem at the end of the irrigation season, when weed growth obstructs Yarrawonga Main Channel. Clearly, costs would be imposed by increasing airspace if less water could be provided to irrigators. In fact, our investigation, as follows, shows that this is unlikely to be an issue.

Data provided by River Murray Water (RMW) reports daily height upstream of Yarrawonga Weir from 1 December 1967 and daily volumes of Lake Mulwala from 1 March 1993. A stage–volume curve was constructed to determine the relation between height [m] referenced to the Australian Height Datum (AHD) and available volume using available data from 1 March 1993 to 15 March 2001. The FSL (full supply level) of Lake Mulwala is 124.9 m AHD (GMW, 2001); however, the absolute limit is approximately 125.1 m, when water begins to flood property in nearby low-lying areas and it has been common to operate Lake

Table II. Economic consequences of limiting maximum River Murray flows at Tocumwal

Flow limit (m^3/s)	Flow limit (Ml/d)	Flooding frequency[a] (%)	Cost per year (less water available to downstream irrigators)		Benefit per year (water saved by reducing forest flooding)		Net cost per year	
			Volume (Mm^3)	Value (Aus $ million)	Volume (Mm^3)	Value (Aus $ million)	Volume (Mm^3)	Value (Aus $ million)
115.7	10 000	20.9	33	2.0	17	1.0	16	1.0
111.7	9650	15.8	63	3.7	25	1.5	38	2.2

[a] Under current conditions, the flooding frequency is 38.3% and the flooding threshold is 122.7 m^3/s (10 600 Ml/d).

Mulwala to 125.1 m. The relationship between lake level and available volume is:

$$H = 125.1 - 2.147 \times 10^{-8} \times V \tag{1}$$

where H is the water level height (m AHD) and V is the airspace available in Lake Mulwala (m^3).

In order to reduce flooding frequency to 15.5% (pre-regulation frequency), approximately 9 Mm^3 extra storage space is required at Lake Mulwala or 0.193 m of storage (see Figure 8a). Thus the usual operating level of the lake must be maintained at 125.1–0.193 = 124.9 m AHD.

Historical data were used to determine if this would limit the diversions from Lake Mulwala. Scatter plots were constructed (using data from 1 December 1980) of lake height (m AHD) versus outflow at Yarrawonga Main Channel (Ml/d), and lake height (m AHD) versus outflow at Mulwala Canal (Ml/d). Scatter plots using data from December to April were compared to plots constructed using data from the end of the irrigation season (March–April) when any weed growth restricting outflow would require high lake levels for maximum diversion flow rates to be maintained.

Analysis of the scatter plots (Figures 9 and 10) reveals that even during March–April, nominal maximum flows can pass down both Yarrawonga Main Channel (38.2 m^3/s, 3300 Ml/d) and Mulwala Canal (115.7 m^3/s, 10 000 Ml/d) at a lake height of 124.9 m AHD. Thus, increasing airspace at Lake Mulwala to reduce unseasonal flooding does *not* incur any costs due to reduced irrigation supply flexibility.

Hydropower generation. There is a hydropower station at Yarrawonga weir that generates electricity as water is passed from Lake Mulwala downstream to the River Murray. Increasing airspace at Lake Mulwala will result in a cost as there will be less head and hence less electricity generated. The station's maximum capacity is 9.4 MW, which corresponds to a maximum head differential of 9 m. The average wholesale price of electricity in Victoria over the period 1 December 1999 to 30 April 2001 was Aus$46.36/MWh (NEMMCO, 2001).

A linear relationship exists between maximum generating capacity and maximum head differential (e.g. increasing airspace by 0.1 m reduces maximum generating capacity by 0.1/9.0 × 9.2 = 0.10 MW). Thus a

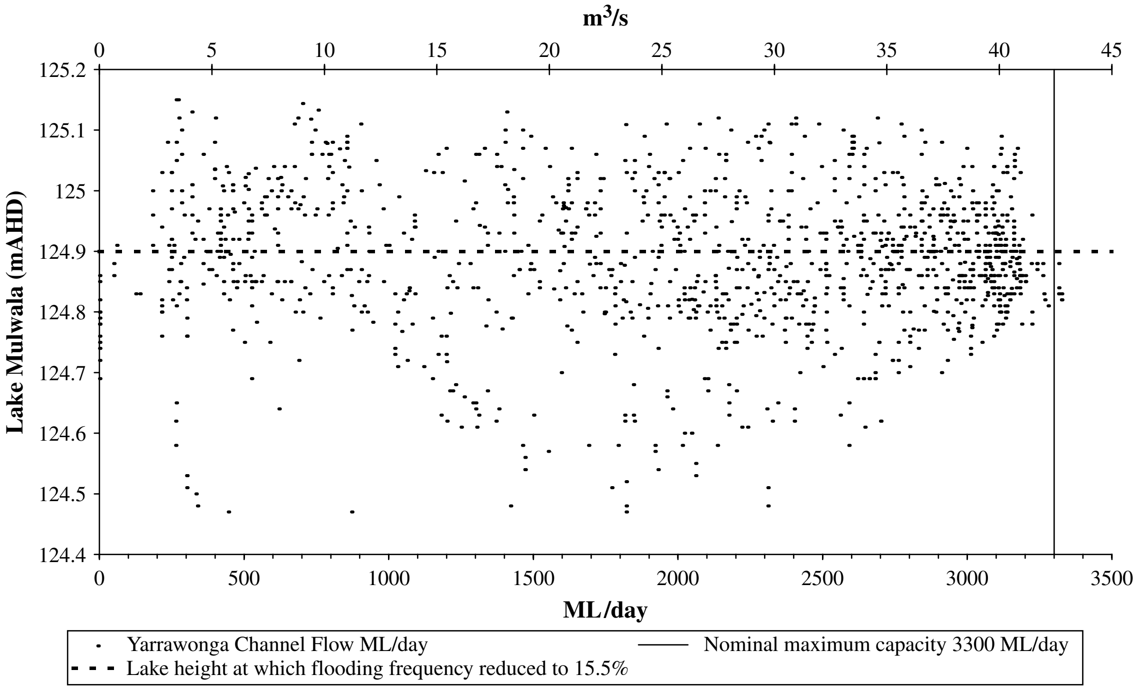

Figure 9. Lake Mulwala scatter plot showing outflows to Yarrawonga Main Channel during March and April and flows may be restricted by weed growth

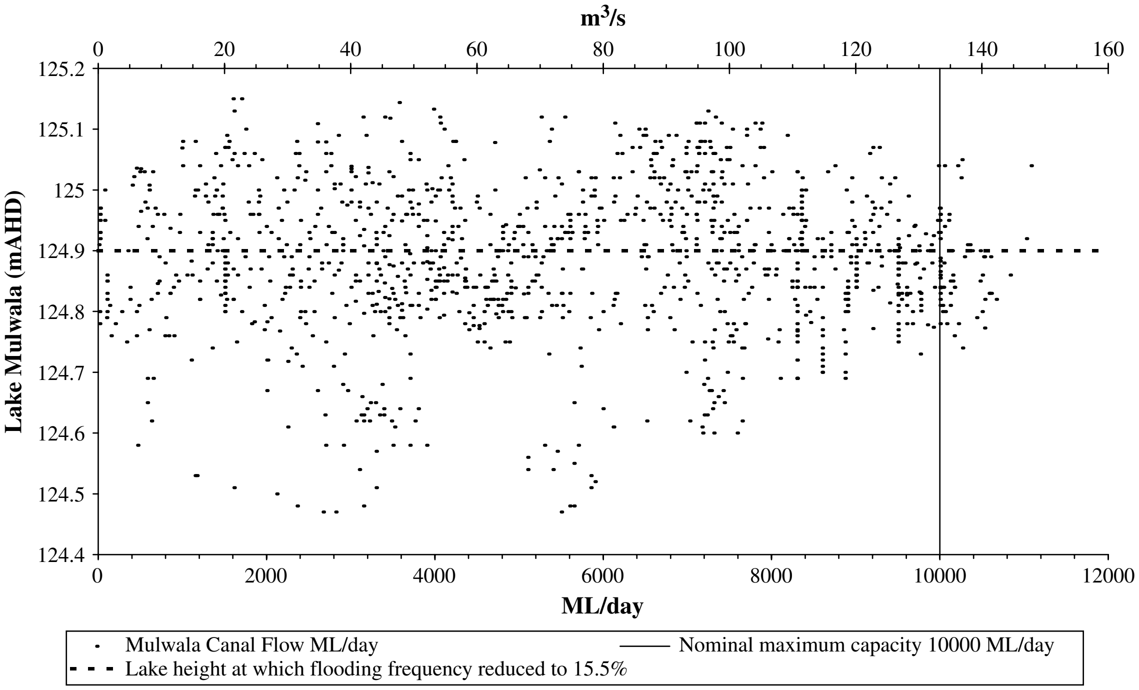

Figure 10. Lake Mulwala scatter plot showing outflows to Mulwala Canal during March and April when flow may be restricted by weed growth

relationship can be constructed linking cost (value of foregone electricity generation) to unseasonal flooding frequency. The main result was that reducing the maximum head differential by 0.2 m to 124.9 m (in order to reduce flooding frequency to 15.5%) reduces energy generation, at a cost of about Aus$8000 per season.

The analysis relied on the assumptions that: (1) if the maximum allowable level at Lake Mulwala is X m AHD, electricity generation is only affected on days where the historical records indicate a level Y m AHD, where $Y > X$; and (2) on days where lake level is $Y > X$, it is assumed that the power facility is running at full capacity (maximum head of 9 m), i.e. $9.4\ \text{MW} \times 24\ \text{hours} = 225.6\ \text{MWh}$. These assumptions mean that the analysis significantly overestimates the costs of foregone electricity because in practice, the system rarely (if ever) runs at full capacity (GMW, 2000).

The costs of decreased hydroelectricity generation are insignificant compared to the benefits of saved water. Thus, net benefits accrue from increasing airspace to reduce flooding frequency. Figure 11 illustrates how the net conservative benefit varies as the airspace at Yarrawonga is increased, and the extent to which this reduces flooding frequency. The benefits of reducing flooding frequency to 15.5% are in the order of Aus$1.5 million per season (current prices).

CONCLUSION

The detrimental impacts of summer/autumn flooding of the Barmah-Millewa Forest have been well documented since the early 1980s. Both the results of analytical research and anecdotal observations point to increased red gum tree death in low-lying areas and the increasing loss of Moira grass plains. The management agencies at state and federal government level pay heed to this problem by highlighting its importance in their published management strategies and plans for the forest. However, recent priorities have concentrated on environmental flows for winter/spring flooding, rather than the management of unseasonal surplus flows. Little analytical work has been conducted to quantify the extent and severity of flooding, or to investigate the feasibility of management options.

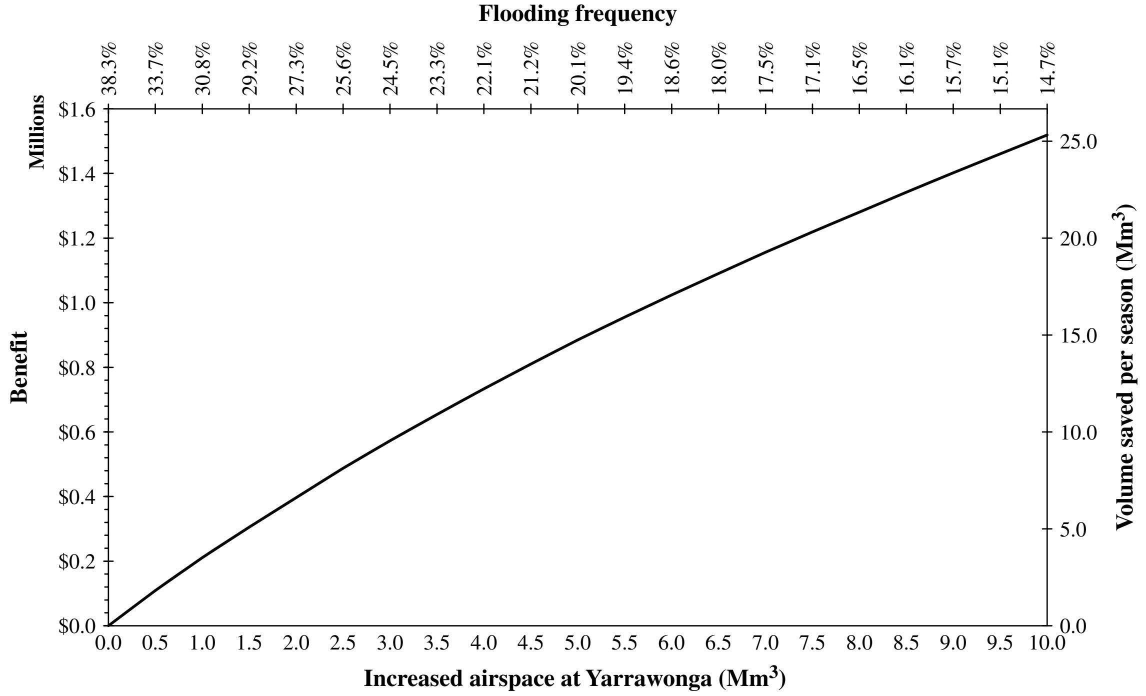

Figure 11. Net benefit per season of increasing airspace at Lake Mulwala

A comparison of historical flow data from 1908 to 1929 (before the construction of the Hume) and 1981 to 2001 (present regulation conditions) revealed that there have been significant changes in the patterns of River Murray flow at Tocumwal during summer and autumn. During December to April (particularly in February and March), flows are far more likely to be above 10 600 Ml/d (the flow at which forest flooding begins) now (36.5% of the time) than before 1908 (15.5% of the time). This means that regulation has increased the number of days in summer/autumn during which flooding occurs in the Barmah-Millewa Forest.

However, an application of the relationship derived by Bren *et al.* (1987) linking flow at Tocumwal to proportion of forest flooded revealed that more extensive floods (in which over 30% of the forest is flooded) are now less frequent. This is because the construction of dams and weirs has enabled mitigation of larger River Murray flows. Consequently, there are some parts of the forest (*c*. 30% of the area) which are flooded more than twice as frequently in summer/autumn now than before 1929, which leads to tree stress and death. However, the remainder of the forest (*c*. 70% of the area) is flooded less frequently now than before 1929. Both these changes have resulted in changes to the 'natural' vegetation associations and patterns in the forest.

Using a flooding threshold of 122.7 m^3/s (10 600 Ml/d) at Tocumwal revealed that during the period 1980–2000, there were 82 surplus flow events (4.1 per season), which caused flooding in the forest on 38.3% of days during December–April. The average event duration was 14.1 days (median 10 days); mean peak excess flow was 25.6 m^3/s (2211 Ml/d), with a median of 13.1 m^3/s (1133 Ml/d); and average total flow per event was 17.8 Mm^3 (median 8.0 Mm^3).

This paper investigated the potential for two management options related to increasing system flexibility, namely increasing airspace in Lake Mulwala and limiting the maximum flow at Tocumwal. If 1980–2000 is assumed to represent current water demand conditions, then flooding frequency can be reduced from 38.3% to 15.5% by:

- increasing airspace in Lake Mulwala by 9 Mm^3 (maintaining height at 124.9m); or
- limiting the maximum flow at Tocumwal to 111.1 m^3/s (9600 Ml/d).

Smaller changes can also have a significant impact on reducing flooding frequency, e.g. a frequency of 20% will be achieved by increasing airspace by just 5 Mm^3 or limiting the maximum flow at Tocumwal to 114.6 m^3/s (9900 Ml/d).

Based on a conservative economic analysis, increasing air space at Lake Mulwala is the preferred option. Increasing the airspace by 9 Mm^3 does not limit the outflow into the irrigation areas through Yarrawonga Main Channel and Mulwala Canal. Very minor losses in hydroelectric power generation will be incurred, but they will be more than offset by the value of the water saved from flooding (Aus\$1.4 million). This figure assumes a marginal value of water equivalent to the agricultural gross margin (Aus\$0.06/m^3), which is likely to be an understatement of the value of water if it were used for environmental watering purposes. Furthermore, the Aus\$1.4 million benefit does not include other values accrued from reducing flooding frequency.

The analysis indicates that significant net benefits will accrue from increasing airspace at Yarrawonga to reduce the frequency of summer/autumn forest flooding. However, maintaining the head of water at Lake Mulwala at a lower level is by no means the only avenue by which patterns of forest flooding could be changed. Apart from various supply-side options, the streamlining of water ordering procedures, and perhaps the introduction of economic incentives, could also have great potential to encourage irrigators to order accurately and cancel early.

APPENDIX

Unseasonal surplus flow events

Start date	End date	Duration (days)	Peak date	Peak excess flow (m^3/s)	Total excess flow (Mm^3)	Average excess flow (m^3/s)
2/02/75	5/02/75	4	2/02/75	3.0	0.69	2.0
13/02/75	25/02/75	13	18/02/75	3.7	3.00	2.7
27/02/75	28/02/75	2	28/02/75	2.3	0.30	1.7
11/03/75	13/04/75	34	18/03/75	29.5	39.69	13.5
26/02/77	1/03/77	4	28/02/77	6.2	1.46	4.2
25/03/78	27/03/78	3	26/03/78	8.0	1.70	6.5
3/12/78	14/12/78	12	12/12/78	25.0	13.79	13.3
7/04/79	10/04/79	4	8/04/79	4.9	1.20	3.5
22/04/80	26/04/80	5	24/04/80	8.5	2.64	6.1
17/12/80	23/12/80	7	20/12/80	49.0	16.12	26.7
15/01/81	8/04/81	84	5/04/81	76.0	124.75	17.2
15/12/81	18/12/81	4	17/12/81	22.1	4.94	14.3
31/12/81	8/02/82	40	29/01/82	57.1	37.05	10.7
11/03/82	30/03/82	20	27/03/82	39.4	25.74	14.9
11/12/82	21/12/82	11	16/12/82	4.1	2.84	3.0
2/12/83	14/12/83	13	12/12/83	61.3	45.62	40.6
5/01/84	9/01/84	5	7/01/84	31.6	10.73	24.8
18/01/84	22/01/84	5	20/01/84	83.8	24.50	56.7
15/03/84	21/03/84	7	20/03/84	3.1	1.31	2.2
7/01/85	8/01/85	2	8/01/85	1.2	0.20	1.2
26/01/85	21/02/85	27	19/02/85	4.7	6.24	2.7
10/03/85	1/04/85	23	25/03/85	31.4	21.19	10.7
9/01/86	18/01/86	10	12/01/86	7.1	3.63	4.2
30/01/86	3/02/86	5	31/01/86	1.3	0.29	0.7
8/02/86	25/02/86	18	19/02/86	15.1	14.00	9.0
2/03/86	28/03/86	27	23/03/86	14.5	22.76	9.8
9/12/86	14/12/86	6	12/12/86	48.0	14.50	28.0
20/12/86	27/12/86	8	23/12/86	50.1	20.71	30.0
25/01/87	4/02/87	11	27/01/87	8.5	4.85	5.1
21/02/87	27/02/87	7	26/02/87	2.4	1.23	2.0
2/03/87	10/03/87	9	10/03/87	2.8	0.98	1.3

(*continued overleaf*)

Unseasonal surplus flow events (*Continued*)

Start date	End date	Duration (days)	Peak date	Peak excess flow (m^3/s)	Total excess flow (Mm^3)	Average excess flow (m^3/s)
15/03/87	5/04/87	22	27/03/87	10.3	13.17	6.9
23/11/87	17/12/87	25	5/12/87	6.6	5.78	2.7
25/12/87	8/01/88	15	5/01/88	22.2	8.53	6.6
11/03/88	20/03/88	10	15/03/88	3.0	1.45	1.7
29/03/88	6/04/88	9	4/04/88	6.1	2.71	3.5
10/04/88	13/04/88	4	12/04/88	4.8	1.00	2.9
9/12/88	19/12/88	11	15/12/88	81.5	43.82	46.1
29/12/88	31/12/88	3	30/12/88	12.0	2.27	8.8
11/02/89	28/03/89	46	25/03/89	71.2	67.81	17.1
4/04/89	11/04/89	8	6/04/89	73.7	28.33	41.0
14/04/89	14/04/89	1	14/04/89	1.5	0.13	1.5
16/04/89	20/04/89	5	18/04/89	21.7	7.08	16.4
19/12/89	30/01/90	43	14/01/90	9.7	11.78	3.2
3/02/90	18/02/90	16	14/02/90	33.6	19.43	14.1
5/03/90	8/04/90	35	3/04/90	23.6	17.70	5.9
12/04/90	21/04/90	10	15/04/90	7.2	4.97	5.8
27/12/90	27/12/90	1	27/12/90	0.2	0.02	0.2
6/01/91	12/01/91	7	10/01/91	18.2	9.00	14.9
19/01/91	30/01/91	12	28/01/91	16.3	10.19	9.8
11/02/91	10/03/91	28	7/03/91	6.1	7.39	3.1
17/03/91	26/03/91	10	19/03/91	3.6	2.65	3.1
18/04/91	21/04/91	4	20/04/91	3.9	0.95	2.8
10/12/91	24/12/91	15	20/12/91	30.8	18.34	14.2
30/12/91	8/01/92	10	5/01/92	25.4	13.14	15.2
19/01/92	9/02/92	22	5/02/92	13.0	20.33	10.7
11/02/92	12/02/92	2	11/02/92	5.9	0.97	5.6
14/02/92	14/02/92	1	14/02/92	0.9	0.08	0.9
24/02/92	14/03/92	20	3/03/92	3.0	3.27	1.9
17/03/92	7/04/92	22	27/03/92	7.3	6.87	3.6
20/01/93	5/02/93	17	29/01/93	94.0	92.21	62.8
22/02/93	1/03/93	8	25/02/93	25.3	10.25	14.8
7/03/93	16/03/93	10	13/03/93	9.3	3.70	4.3
26/03/93	9/05/93	45	1/04/93	33.6	32.11	8.3
16/12/93	14/01/94	30	1/01/94	125.1	162.55	62.7
24/01/94	25/01/94	2	25/01/94	1.3	0.16	0.9
27/01/94	28/01/94	2	27/01/94	1.9	0.30	1.7
2/02/94	3/02/94	2	2/02/94	2.1	0.19	1.1
6/02/94	24/02/94	19	17/02/94	111.3	71.88	43.8
26/02/94	23/03/94	26	15/03/94	95.8	95.20	42.4
28/03/94	14/04/94	18	6/04/94	30.0	20.33	13.1
1/12/94	15/12/94	15	3/12/94	13.2	10.17	7.8
24/12/94	2/01/95	10	1/01/95	5.0	2.54	2.9
7/01/95	28/02/95	53	23/01/95	101.9	87.94	19.2
9/03/95	8/04/95	31	28/03/95	5.5	10.49	3.9
13/04/95	13/04/95	1	13/04/95	0.8	0.07	0.8
5/12/95	17/12/95	13	10/12/95	51.9	35.17	31.3
3/01/96	11/01/96	9	7/01/96	34.3	13.71	17.6
14/02/96	14/02/96	1	14/02/96	0.5	0.04	0.5
17/02/96	17/02/96	1	17/02/96	0.9	0.08	0.9
29/02/96	6/03/96	7	4/03/96	27.3	10.91	18.0
19/03/96	22/03/96	4	21/03/96	18.6	4.22	12.2
10/12/96	12/12/96	3	11/12/96	29.3	5.55	21.4
26/12/96	27/12/96	2	26/12/96	2.5	0.33	1.9
5/03/97	10/03/97	6	8/03/97	32.6	11.65	22.5
16/03/97	31/03/97	16	17/03/97	5.6	4.59	3.3

Unseasonal surplus flow events (*Continued*)

Start date	End date	Duration (days)	Peak date	Peak excess flow (m^3/s)	Total excess flow (Mm^3)	Average excess flow (m^3/s)
17/12/98	1/01/99	16	18/12/98	3.5	2.49	1.8
7/01/99	14/01/99	8	12/01/99	1.5	0.46	0.7
29/01/99	30/01/99	2	30/01/99	0.1	0.01	0.1
20/03/99	29/03/99	10	25/03/99	50.1	24.74	28.6
29/12/99	4/01/00	7	1/01/00	45.5	14.96	24.7
19/02/01	19/02/01	1	19/02/01	3.3	0.29	3.3

1 Ml/day = 86.4 m^3/s.

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