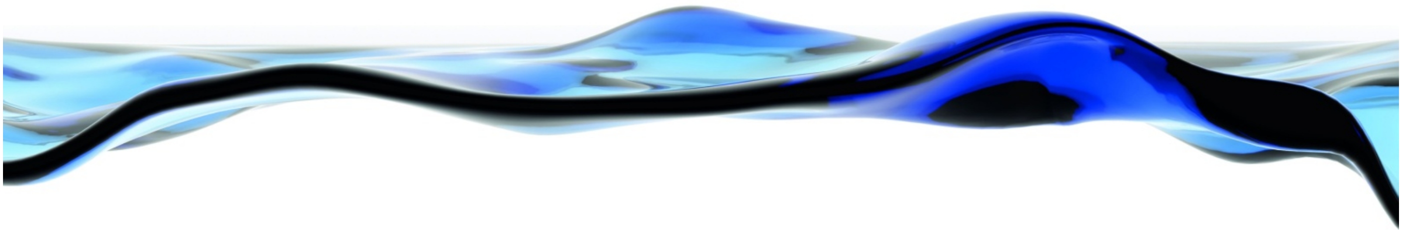
River Murray Channel Environmental Water Requirements: Ecological Objectives and Targets

Goyder Institute Project E.1.9

Part 1 of 2



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Contents

Executive Summary

Background

The Murray Darling Basin Plan requires the development of Long Term Watering Plans (LTWPs) that identify priority assets and functions, ecological objectives and targets for these assets and functions, and environmental water requirements (EWRs) to meet these objectives and targets. The LTWP's will be instrumental in supporting the allocation of environmental water to South Australian River Murray environmental assets. This project contributes to development of the first draft of the Long-Term Watering Plan (LTWP) for the South Australian River Murray water resource plan area.

Prior to commencing this project, some work had been completed for the River Murray in South Australia, including the identification of (i) approximately 130 key environmental assets, and (ii) a suite of targets and Environmental Water Requirements (EWRs) for the broader floodplain and the Lower Lakes, Coorong and Murray Mouth asset. Independent reviews considered that there was:

- a lack of riverine targets to account for hydraulic connectivity and explicitly address the requirements of native fish,
- limited representation of ecological complexity for evaluating the ecological outcomes of hydrologic scenarios, and
- little regard for the requirements of the floodplain landscape between the two asset sites.

This project addresses the need for Ecological Targets and EWRs relating to in-channel habitats and ecological processes (functions).

Scope

Key tasks were to:

- Develop conceptual models outlining hydro-ecological relationships for in-channel assets and functions for QSA (flow to South Australia), ranging from entitlement flows (3,000-7,000 ML day^{-1}) to 40,000 ML day^{-1},
- Develop relevant Ecological Objectives and Ecological Targets, and
- Identify EWRs required to meet these objectives and targets.

Spatial boundaries for this project are the South Australian Border and Wellington, and the upper discharge limit is QSA = 40,000 ML day^{-1}.

Report Structure

Due to the large amount of information generated by this project, the reporting is presented in two parts. The present document *Ecological Objectives and Targets* (Part 1 of 2) includes information on:

- Background,
- Approach,
- Impacts of river regulation,
- Ecological Objectives and Targets,
- Environmental Watering Requirements, and
- Weir pool manipulation.

The accompanying report, *Hydrodynamic Modelling Results and Conceptual Models* (Part 2 of 2) provides information on:

- Hydrodynamic modelling results, and
- Conceptual models.

An overview of the content of both documents is provided below.

Hydrodynamic Modelling

MIKE 21 2D numerical hydrodynamic modelling was used to convert flow (discharge) in the river to spatial distribution in water level and velocity. The model is based on a computational grid that covers the Lock 3-4 reach (91 km). This reach was selected because:

- It has the longest period of pre-lock construction water levels (January 1921 to April 1926), indicating pre-development conditions, and
- There is a significant amount of ecological information available.

This does not mean that results for the Lock 3-4 reach are directly transferrable to all reaches. However visual assessments of data, with previous modelling assessments of velocity in other reaches, (e.g. Lock 6–downstream of Rufus River) indicate that the discharge-velocity relationships are sufficiently representative to be fit-for-purpose. The outputs are voluminous, and are presented in an accompanying report, *Hydrodynamic Modelling Results and Conceptual Models*. The results include conditions under modelled natural (no weirs) conditions, existing conditions and weir pool manipulations.

Conceptual Models

Detailed hydrological–ecological response relationships (conceptual models) based on a review of existing literature, empirical data and expert knowledge were developed for:

- Ecosystem processes,
- Biofilms,
- Phytoplankton (diatom v. cyanobacterial-dominated communities),
- Fish,
- Aquatic and understorey vegetation,
- Long-lived vegetation (floodplain eucalypts, lignum), and
- Temporary wetlands.

Frogs, waterbirds and invertebrates were not considered individually, as they require habitat within wetlands to achieve targets set for them. The focus is on providing the water to generate and maintain supporting habitat, rather than providing water for species that might utilise the habitat. However, the timing and duration of flows are consistent with the breeding/recruitment requirements of frog species known to occur in the region. The conceptual models are included in the accompanying *Hydrodynamic Modelling Results and Conceptual Models* report. The conceptual models developed were used to develop Environmental Water Requirements (EWR). These describe flow pulses from 10,000 to 40,000 ML day^{-1}, with metrics for average and maximum return interval, timing and duration. The return intervals were informed by comparisons with modelled natural conditions, existing and potential return intervals.

Impacts of river regulation

A summary of the impacts of river regulation, including alteration of flow resulting from upstream diversions and regulation of flow into South Australia, and the influence of the 11 low level on the Murray between Mildura and Blanchetown is provided (see section 3 of this document). The weirs have little impact on discharge (ML day^{-1}) but have a significant impact on water levels, velocity and surface water-groundwater interactions. The hydrologic components that require consideration in planning and delivery of water; flow magnitude, timing, duration, frequency, rate of change, sequence, connectivity, spatial scale, hydraulic complexity and flow components are also outlined.

Ecological Objectives and Targets

From the understanding developed *via* the conceptual models, Ecological Objectives and Ecological Targets were developed (see section 4 of this document). Where practical, the targets are structured within a SMART (Specific, Measurable, Achievable, Realistic, Time-bound) framework. Well-defined Ecological Objectives provide a clear articulation for managers, scientists, stakeholders and the wider community of what planned deliveries of environmental water are intended to achieve. Clearly defined, specific and measurable Ecological Targets are a means of (i) assessing and reporting condition over time, (ii) determining the need for management action, and (iii) assessing the outcomes of applied management actions. Ecological Targets streamline monitoring and reporting needs for both short-term (event-specific) and longer-term outcomes, and will allow for plain-language reporting on progress towards Ecological Objectives. An example of an Ecological Objective related to Riparian Vegetation, and the relevant Ecological Targets is provided in Table E1.

Table E.1. Example Ecological Objective and associated Ecological Targets.

Ecological Objective	Ecological Target
Throughout the length of the river channel asset (i.e. SA border to Wellington), establish and maintain a diverse native flood-dependent plant community in areas inundated by flows of 10,000–40,000 ML day^{-1}.	In standardised transects spanning the elevation gradient in the target zone†, 70% of river red gums have a Tree Condition Index score ≥ 10.
	A sustainable demographic is established to match the modelled profile for a viable river red gum population in existing communities spanning the elevation gradient in the target zone.†
	Species from the Plant Functional Group 'flood-dependent/responsive' occur in 70% of quadrats spanning the elevation gradient in the target zone† at least once every 3 years.

†The target zone is the area inundated by flows of 10,000-40,000 ML day^{-1}

Environmental Water Requirements

Seven Environmental Water Requirements (EWR's) spanning the flow range 3,000-40,000 ML day^{-1} were developed (see section 5 of the accompanying report *Ecological Objectives and Targets*), as it is anticipated there are step-points at which changes will occur in hydrology (e.g. discharge, hydraulics, velocity), lateral connectivity (e.g. area inundated) or ecology (e.g. spawning). A summary is shown in Table E2, with information on the magnitude and variation of discharge ($MLday^{-1}$), duration of flow, frequency, Maximum allowable return interval and timing (e.g. season). Each EWR is expected to contribute towards achieving the Ecological Objectives and Ecological Targets, and are considered hypotheses to be tested by delivering flows in a manner that achieves variability in timing, duration, frequency and rate of change, and by measuring responses in terms of progress towards the Ecological Targets.

Table E.2. In-channel Environmental Water Requirements for the lower Murray.

EWR #	Median discharge (ML day^{-1})	Discharge (ML day^{-1})	Duration (days)	Preferred timing	Average return frequency (years)	Percentage of years flow is required	Maximum return interval (years)	Percentage of years that discharge and duration are likely under BP2800 scenario
IC1	10,000	7000 - 12,000	60	Sep-Mar	1.05	95	2	90
IC2	15,000	15,000 -20,000	90	Sep-Mar	1.33	75	2	77
IC3	20,000	15,000 - 25,000	90	Sep-Mar	1.8	55	2	67
IC4	25,000	20,000 - 30,000	60	Sep-Mar	1.7	59	2	67
IC5	30,000	25,000 - 35,000	60	Sep-Mar	1.8	55	2	59
IC6	35,000	30,000 - 40,000	60	Sep-Mar	1.8	55	2	46
IC7	40,000	35,000 - 45,000	90	Sep-Mar	2.1	48	3	31

Conceptual models for in-channel Environmental Water Requirements

Conceptual models for each of the seven EWR's outlined in the table above are presented (see section 6 of this document). These include a description of (i) high level objectives for each EWR, (ii) conditions that may be expected to occur during, or as a result of that flow scenario, and (iii) example hydrographs of how environmental water could be delivered to complement existing flow, mimic the modelled natural hydrograph and achieve the EWR.

Weir pool manipulation

The effects of weirs on in-channel hydraulics are demonstrated by modelling described in the companion report, *Hydrodynamic Modelling Results and Conceptual Models*. The analysis shows that most impact on velocity occurs in the lowermost third of the weir pool. An assessment of how weir manipulation could contribute to achieving In-Channel Ecological Objectives and Targets was undertaken (see section 7 of this document). Reinstating variability *via* re-operation of weirs has potential to restore, in part, seasonal patterns of water level, lateral connectivity and hydraulic diversity in impounded areas. Weir-pool lowering is a mechanism to increase water velocity at all discharges. Weir-pool raisings have the capacity to increase water levels and areas inundated, and the impact on upstream water levels is greatest at low flows. Weir-pool raising trials in the lower Murray already have demonstrated positive outcomes for understorey vegetation and riparian trees. However, at flow to South Australia <20,000 ML day^{-1}, the reduction in velocity associated with a weir pool raising and associated impacts on in-stream processes needs to be taken into account.

1. Background

1.1. Basin Plan

The Murray-Darling Basin Authority's (MDBA) Basin Plan establishes a new framework for managing the Basin's water resources, including new roles and responsibilities for the MDBA, the Commonwealth Government and the Basin States. It will be put into effect through a number of key mechanisms, including an environmental watering plan as a framework for the use of water to achieve key environmental outcomes. Implementation of the Plan is a key priority within the South Australian Department of Environment, Water and Natural Resources (DEWNR) Corporate Plan.

1.2. This project

This project contributes to development of the first draft of the Long-Term Watering Plan (LTWP) for the South Australian River Murray water resource plan area. An LTWP is a requirement under Chapter 8 (Environmental Watering Plan) of the Basin Plan, and will be instrumental in supporting the allocation of environmental water to South Australian River Murray environmental assets. The Basin Plan requires LTWPs to identify priority assets and functions, ecological objectives and targets for these assets and functions, and environmental water requirements (EWRs) to meet these objectives and targets.

Prior to commencing this project, some work had been completed for the River Murray in South Australia, including the identification of approximately 130 key environmental assets (KEAs) based on criteria provided in the Basin Plan, and the identification of a suite of targets and EWRs for the broader floodplain and the Lower Lakes, Coorong and Murray Mouth asset. The MDBA also identified 18 hydrologic indicator sites, believed to be of greatest significance in defining the environmental water requirements for KEAs in the Murray Darling Basin (MDBA, 2010). Two indicator sites are located in South Australia: (i) Riverland–Chowilla Floodplain and (ii) the Coorong, Lower Lakes and Murray Mouth.

Both the MDBA and SA have defined EWRs for these sites (CLLMM) (MDBA, 2012b), and a summary of SA's EWRs is provided by Gibbs et al. (2012b). Pollino et al. (2011) and Lamontagne et al. (2012) considered the main limitations to be:

- Lack of riverine targets to account for hydraulic connectivity and explicitly address the requirements of native fish,
- Limited representation of ecological complexity for evaluating the ecological outcomes of hydrologic scenarios, and
- Little regard for the requirements of the floodplain landscape between the two asset sites.

1.3. Objectives

This project addresses the need for Ecological Targets and EWRs relating to in-channel habitats and ecological processes (functions). Clearly defined, specific and measurable Ecological Targets will streamline monitoring and reporting needs for both short-term (event-specific) and longer-term outcomes, and will allow for plain-language reporting on progress towards the relevant

Ecological Targets. Well-defined Ecological Objectives provide a clear articulation for managers, scientists, stakeholders and the wider community of what planned deliveries of environmental water are intended to achieve. The Ecological Objectives need to be consistent with the criteria used to identify the channel as a KEA (per Section 8.49 of the Basin Plan).

Accordingly, this project:

- Contributes to development of the long-term watering plan for the South Australian River Murray water resource area (SA River Murray LTWP), required under Chapter 8 (Environmental Watering Plan) of the Basin Plan,
- Ensures that the SA River Murray LTWP gives consideration to in-channel habitats and functions and the environmental water requirements needed to support these habitats and functions, and
- Provides information to assist with the annual and real-time management of environmental water in response to changing river flow conditions.

Key tasks are to:

- Develop conceptual models outlining hydro-ecological relationships for in-channel assets and functions for QSA (flow to South Australia), ranging from entitlement flows (3000-7000 ML day^{-1}) to 40,000 ML day^{-1},
- Develop relevant Ecological Objectives and Ecological Targets, and
- Identify EWRs required to meet these objectives and targets.

Note that conceptual models for out-of-channel (overbank) flows are being developed as part of Goyder Institute Research Project E1.7 (*River Murray Research Requirements*).

2. Approach

Riparian and aquatic vegetation and fish are easily-recognised ecological attributes that are highly valued by the broader community. They are also sensitive to hydrologic disturbance and are useful indicators of ecosystem 'health' (Arthington et al., 2012). However, rather than focus immediately on selected attributes and their habitat requirements, as in most environmental flow assessment projects (Tharme, 2003), we pursue a more holistic approach *via* a modification of the process presented by Arthington et al. (2012). The Environmental Watering Requirements presented here are hypotheses to be tested by delivering flows in a manner that achieves variability in timing, duration, frequency and rate of change, and by measuring responses in terms of progress towards the Ecological Targets.

2.1. Spatial boundaries and discharge limits

Spatial boundaries for this project are the South Australian Border and Wellington, and the upper discharge limit is QSA = 40,000 ML day^{-1}. These limits were defined *a priori*, in the Project Brief.

2.2. Modelling hydrology, velocity and surface water levels

The hydrology of the lower River Murray has changed markedly as a result of regulation (Maheshwari et al., 1995). An overview is presented in section 3. In this project, a combination of hydrologic modelling and hydrodynamic modelling is used to assess the relationships between discharge, velocity and depth. This provides a quantitative basis to compare natural (pre-regulation) and current conditions. Hydrologic modelling undertaken by the MDBA for the Basin Plan was used to assess the frequency of occurrence of events over long periods (114 years) under different conditions. MIKE 21 2D numerical hydrodynamic modelling was used over shorter time periods to convert flow (discharge) in the river to spatial distribution in water level and velocity. The model is based on a computational grid that covers the Lock 3-4 reach (91 km). This reach was selected because:

- It has the longest period of pre-lock construction water levels (January 1921 to April 1926), indicating pre-development conditions, and
- There is a significant amount of ecological information available.

This does not mean that results for the Lock 3-4 reach are directly transferrable to all reaches. Visual assessments of data with previous modelling assessments of velocity in other reaches (e.g. Lock 6–downstream of Rufus River) indicate that the discharge-velocity relationships are sufficiently representative to be fit-for-purpose. The model takes discharge (flow) as an input to calculate velocity and water level for each cell of the grid (15 $\times$ 15 m cells). The outputs are voluminous, and are presented in an accompanying report, *Hydrodynamic Modelling Results and Conceptual Models*.

2.3. Conceptual models

Figure 2.1 shows a generic conceptual model of the influence of management of the Murray-Darling Basin at the landscape scale for multiple outcomes, including reinstating a flow regime (a long-term, statistical generalization of the hydrograph) with frequencies and durations of in-channel flow pulses and small floods closer to modelled natural conditions. The model is not fully comprehensive, but identifies (i) key processes required to achieve outcomes at the higher trophic levels, and (ii) flow-on benefits of achieving outcomes for vegetation, in terms of habitat and food resources. Hydrological–ecological response relationships (conceptual models) were developed for some of the KEAs and processes identified in Figure 2.1. These are based on a review of existing literature, empirical data and expert knowledge, and outline the expected response to management actions. Models have been developed for:

- Ecosystem processes,
- Biofilms,
- Phytoplankton (diatom v. cyanobacterial-dominated communities),
- Fish,
- Aquatic and understorey vegetation,
- Long-lived vegetation (floodplain eucalypts, lignum), and
- Temporary wetlands.

Frogs, waterbirds and invertebrates are not considered individually, as they require habitat within wetlands to achieve targets set for them. The focus is on providing the water to generate and maintain supporting habitat, rather than providing water for species that might utilise the habitat. The timing and duration of flows are consistent with the breeding/recruitment requirements of frog species known to occur in the region. The conceptual models are included in the accompanying *Hydrodynamic Modelling Results and Conceptual Models* report.

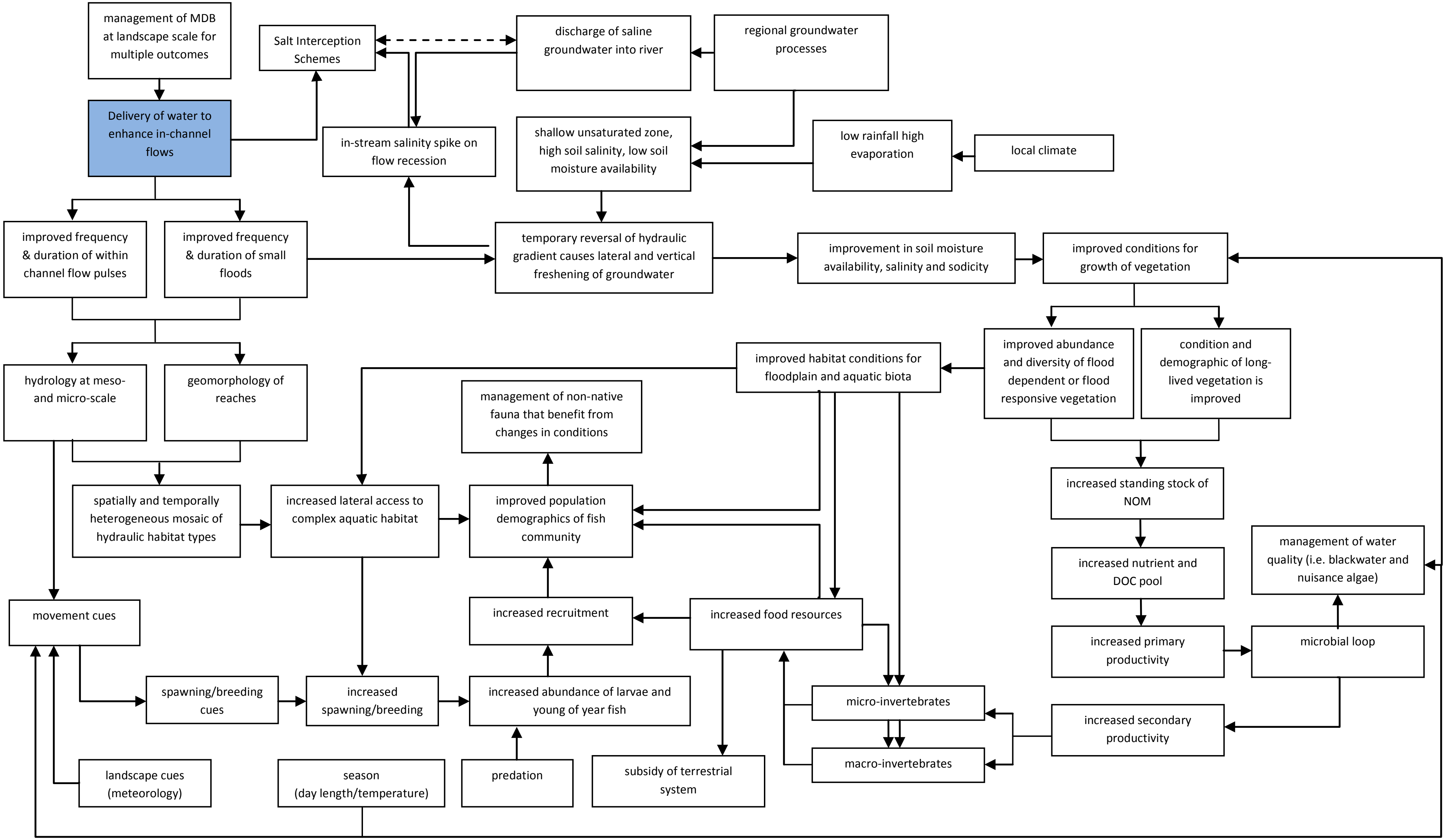


Figure 2.1. Conceptual model of the influence of reinstating a flow regime (a long-term, statistical generalization of the hydrograph) with frequency and duration of in-channel flow pulses and small floods closer to modelled natural conditions.

2.4. Ecological Objectives and Targets

From the understanding developed *via* the conceptual models, Ecological Objectives and Ecological Targets were developed (see section 4). Where practical, the targets are structured within a SMART (Specific, Measurable, Achievable, Realistic, Time-bound) framework.

2.5. Development of Environmental Water Requirements

The conceptual models described above (section 2.3) were used to develop Environmental Water Requirements (EWR). These describe flow pulses from 10,000 to 40,000 ML day^{-1}, with metrics for average and maximum return interval, timing and duration. The return intervals were informed by comparisons with modelled natural conditions, existing and potential return intervals.

3. Impacts of river regulation

3.1. Background

Alteration of hydrology is the main continuing threat to the ecological sustainability of rivers and their floodplain wetlands (see Bunn and Arthington, 2002; Arthington et al., 2010; Vörösmarty et al., 2010). Changing the character of natural flow patterns can directly or indirectly influence water quality, energy sources and processing, physical habitat and biotic interactions (Poff et al., 1997; Boulton and Brock, 1999). Removal of floods and altered hydraulic conditions (depth, velocity, turbulence) can have effects on the entire food web and not just individual species (Lytle and Poff, 2004).

3.2. Effects on lower Murray hydrology

3.2.1. Discharge

The *Murray-Darling Basin Agreement 2008* (the 'Agreement') sets out the arrangements for the sharing and management of the Basin's water resources, particularly the River Murray System. This is the primary determinant of the volume, pattern and quality of water delivered to South Australia.

Under the Agreement, South Australia is entitled to a *maximum* of 1850 GL year^{-1}, regardless of water availability in the Basin. The 1850 GL comprises two volumes:

1. A *variable* 'Consumptive' Entitlement of *up to* 1154 GLyear^{-1} (clause 88a), which may be reduced under Special Accounting (Subdivision E). It is provided over a water year, in proportional monthly quantities that co-vary with consumptive (irrigation) demands. Lesser volumes are provided in the cooler months (April to September), and peak volumes are delivered in the warmer months (December and January).
2. A *fixed* Entitlement of 58 GL month^{-1} (696 GL year^{-1}) that is for 'Dilution and Loss' purposes only (clause 88b) and cannot be reduced, even in Special Accounting, except by a special decision of the MDB Ministerial Council.

Water in excess of entitlement may be provided to South Australia as:

- Interstate water trade,
- Deliveries of deferred water,

- Environmental water,
- Additional Dilution Flow (a volume of 3000 ML day^{-1} that is released once storage volumes in Hume and Dartmouth Reservoirs and Menindee Lakes exceed specified triggers), or
- Unregulated flow (flow not captured by Murray-Darling Basin storages, which may be because storages are full (or, in the case of Menindee Lakes or Lake Victoria, the inlet capacity is exceeded), and is not available for consumptive diversion.

Unregulated flows generate large-scale longitudinal and lateral connectivity and floodplain inundation. They may be supplemented with environmental water allocations to improve hydrographs *via* increases in flow magnitude and duration or the shape of the rising and falling limbs of the hydrograph.

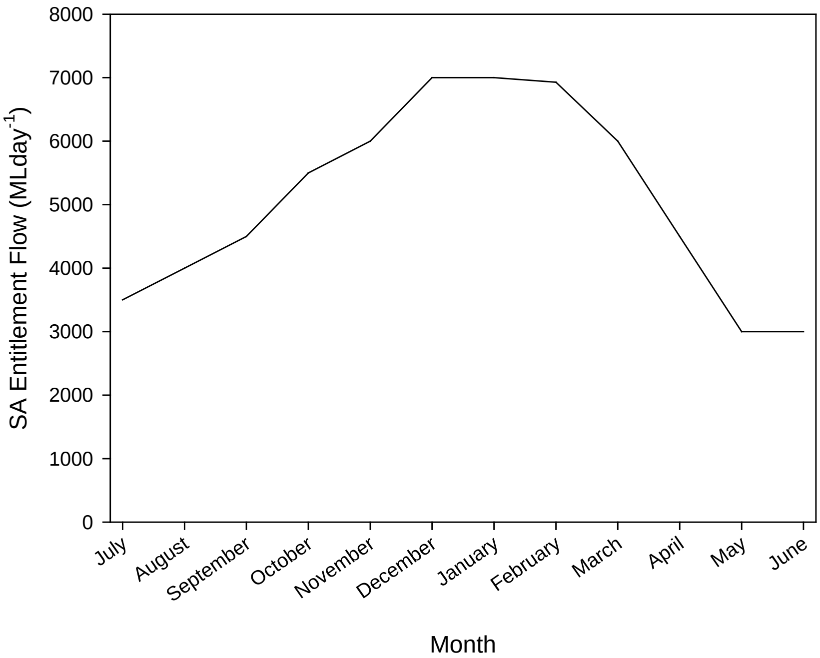


Figure 3.1. Monthly distribution of SA entitlement flow.

South Australia generally receives more than its entitlement flow of 1850 GL year^{-1}, with annual mean and median flows of 6750 GL and 4600 GL, respectively. In the mid-reaches of the Murray, managed water releases for summer irrigation have altered the seasonal pattern of flow, shifting high-flow events from a winter and spring to summer pattern. Although discharge in the mid-Murray is regulated by upstream storages, there are long, free-flowing reaches between weirs. In contrast, annual flows in the lower Murray are much reduced in volume. The seasonality of flows is retained, with flows peaking in spring/summer, but their magnitude is less, reducing the extent and frequency of floodplain inundation (Walker and Thoms, 1993; Maheshwari et al., 1995). Tables 3.1–3.4 show the differences in occurrence of flow into South Australia (QSA) of different magnitudes and durations for (i) modelled natural conditions and (ii) existing conditions, with (iii) The Living Murray Water and Environmental Works and (iv) Basin Plan 2800 scenarios.

Table 3.1. Proportion of years (out of 118 years) that QSA exceeds stated flow: modelled natural system (without development) using historic climatic data. MSM BIGMOD run 11030000. From Gibbs et al. (2012b).

Duration	Percentage of years that flow to SA (QSA ML day^{-1}) was						
	>10,000	>15,000	>20,000	>25,000	>30,000	>35,000	>40,000
>30 days	0.99	0.99	0.98	0.91	0.88	0.84	0.80
>40 days	0.99	0.99	0.96	0.89	0.87	0.82	0.78
>50 days	0.99	0.96	0.94	0.89	0.86	0.82	0.73
>60 days	0.97	0.96	0.93	0.88	0.82	0.81	0.70
>90 days	0.97	0.96	0.90	0.82	0.78	0.68	0.57
>120 days	0.96	0.93	0.89	0.75	0.63	0.54	0.49

Table 3.2. Proportion of years (out of 118 years) that QSA exceeds stated flow: Current system (BSL) using historic climatic data. MSM BIGMOD run 11026000. From Gibbs et al. (2012b).

Duration	Percentage of years that flow to SA (QSA ML day^{-1}) was						
	>10,000	>15,000	>20,000	>25,000	>30,000	>35,000	>40,000
>30 days	0.89	0.73	0.64	0.54	0.46	0.42	0.36
>40 days	0.83	0.68	0.57	0.49	0.45	0.39	0.34
>50 days	0.80	0.66	0.54	0.45	0.42	0.38	0.30
>60 days	0.74	0.59	0.46	0.44	0.39	0.30	0.26
>90 days	0.61	0.46	0.39	0.37	0.28	0.23	0.20
>120 days	0.46	0.36	0.30	0.25	0.22	0.17	0.11

Table 3.3. Proportion of years (out of 118 years) that QSA exceeds stated flow: Basin Plan 2800 GL scenario. From Gibbs et al. (2012b).

Duration	Percentage of years that flow to SA (QSA ML day^{-1}) was						
	>10,000	>15,000	>20,000	>25,000	>30,000	>35,000	>40,000
>30 days	0.97	0.91	0.86	0.80	0.71	0.65	0.48
>40 days	0.96	0.89	0.84	0.75	0.68	0.58	0.45
>50 days	0.92	0.88	0.80	0.70	0.64	0.53	0.42
>60 days	0.90	0.84	0.77	0.67	0.59	0.46	0.40
>90 days	0.86	0.77	0.67	0.54	0.45	0.39	0.31
>120 days	0.79	0.63	0.50	0.40	0.32	0.27	0.18

3.3. Impact of weirs

Impacts on surface water levels

The 11 low-level (c. 3 m head) weirs on the Murray between Mildura and Blanchetown have dramatically altered the hydrology of the lower river. Six of these weirs are within South Australia. The combination of relatively short distance between weirs, gentle gradient (50 mm km^{-1}), low regulated flows and intensive river management has produced a shift from highly variable riverine conditions to more stable conditions, as in a string of connected lakes (Walker and Thoms, 1993; Baker et al., 2000; Walker, 2006). The weirs have little impact on discharge (ML day^{-1}), because (i) discharge is primarily controlled *via* management of storages and (ii) the weirs offer little scope to re-regulate discharge due to the low storage within each weir pool (from 64 GL at Lock 1 to 13 GL at Lock 7). However, they do have a significant impact on water levels (river stage) (Cooling et al., 2010). The data in Table 3.4 show surface water levels at Lock 3 and in the uppermost reach of that weir pool (downstream of Lock 4) under routine operations.

Table 3.4. Look-up table for Surface Water Level (SWL, m AHD) at Lock 3 and the uppermost reach of the weir pool.

QSA ML day^{-1}	Normal Pool Level	
	SWL (m AHD)	
	At Lock 3	Upper Pool
3000	9.80	10.08
5000	9.80	10.27
7000	9.80	10.51
10,000	9.80	10.85
12,000	9.80	11.12
15,000	9.80	11.41
20,000	9.80	11.84
25,000	9.80	12.29
30,000	9.80	12.73
35,000	9.80	13.12
40,000	9.80	13.49

Prior to river regulation, river levels underwent sustained rises and falls over days to weeks. Under current operations, the weirs are managed to maintain relatively stable water levels upstream of the structures. The consequences of stabilisation include:

- Losses of flow-dependent aquatic fauna,
- Declining condition of long-lived vegetation (floodplain trees), with consequences for dependent fauna and flora,
- Change in river-edge productivity and habitat value due to establishment of cumbungi (*Typha* spp.),

- Channel invasion by common reed (*Phragmites australis*) and other wetland plants,
- Permanent inundation of previously temporary wetlands, leading to reduced productivity and habitat value,
- Reductions in flow-related cues for fish migration and reproduction,
- Reductions in water-level fluctuation related cues for soil propagule banks,
- Reductions in lateral access between the river, temporary wetlands and floodplain habitats,
- Reductions in salt export from the floodplain, hence retention in soil,
- Reductions in energy (carbon) and nutrient movement between the floodplain and river,
- Reductions in velocity and hydraulic diversity in the impounded area,
- Interrupted downstream sediment transport and redistribution of sediment in weir pools *via* erosion and deposition, and
- Re-distribution of species between channel and floodplain habitats.

Differences between modelled natural and existing conditions in the velocity matrix

The impact of weirs on in-channel velocity is described in the *Hydrodynamic Modelling Results and Conceptual Models* report. The results show that the impact is substantially higher in the lower and middle reaches than in the upper reach. The relative abundance of habitat in different velocity classes in the lower third of the Lock 3-4 weir pool is shown in Figure 3.2. In this analysis, the velocity (in 0.01 m s^{-1} increments from 0.0 to 2.0 m s^{-1}) in each 15 × 15 m grid cell in the MIKE 21 model is shown. The assessment is summarised in Table 3.5, with the data condensed into six velocity classes:

- 0–0.05 m s^{-1} (very slow)
- 0.05–0.1 m s^{-1} (slow)
- 0.1–0.15 m s^{-1} (slow-moderate)
- 0.15–0.18 m s^{-1} (moderate)
- 0.18–0.25 m s^{-1} (moderate-fast)
- >0.25 m s^{-1} (fast).

The data in Figure 3.2 and Table 3.5 show that the weir creates many slow-flowing habitats, particularly under low-moderate flows. For example, with existing weir conditions and QSA = 3000 ML day^{-1} there is essentially no habitat with velocity >0.15 m s^{-1}. In contrast, at this discharge under modelled natural conditions, 36.4% of the reach has velocity >0.15 m s^{-1}. It is only when flows increase to >20,000 ML day^{-1} that the distribution of hydraulic habitat in modelled natural and existing conditions becomes roughly similar. Even at these relatively high flows, the distribution is skewed. The comparative abundance of very slow flowing habitats under modelled natural conditions may represent complex habitat diversity that is not present under existing conditions.

Influence of weirs on groundwater and soil condition

The Lower Murray is a natural drain for the highly saline regional groundwater systems of the Murray Basin (Evans and Kellett, 1989). A large proportion of the groundwater passes through the floodplain (Barnett, 1989), and as a result the soils are saline and accumulate more salt through evapotranspiration (Jolly, 1996). Prior to regulation, salt that accumulated in dry periods was leached or flushed by flooding, creating a long-term, quasi-stable equilibrium, evidenced by the numbers of mature floodplain trees older than 100 years (Slavich, 1997).

Weir operations have altered surface water levels and altered the head difference between surface water and groundwater, and caused saline groundwater to rise nearer the surface in some areas, leading to increased salt accumulation (Jolly, 1996). At Chowilla Floodplain groundwater levels have risen by 2-3 m (Akeroyd et al., 1998). Irrigation has also contributed to a decrease in depth to the water table. Further, regulation has reduced the frequency and duration of the floods that leach salt from the plant root zone. The combined effects are long-term salt accumulation in floodplain soils, causing dieback of vegetation (Jolly et al., 1993; Cunningham et al., 2011).

Table 3.5A. Percentage of the lower third of the Lock 3-4 weir pool in the respective velocity classes for modelled natural conditions, at QSA from 3,000–40,000 ML day^{-1}. Cells shaded grey are the most abundant classes.

Flow (ML day^{-1})	**3000**	**5000**	**7000**	**10,000**	**12,000**	**15,000**	**20,000**	**25,000**	**30,000**	**35,000**	**40,000**
very slow	30.08	28.15	24.27	21.38	20.57	18.08	15.85	14.10	12.06	10.01	8.03
slow	11.08	8.70	6.50	4.58	4.11	2.47	1.75	1.27	1.03	1.01	0.97
slow-moderate	22.45	16.11	9.53	5.16	4.63	3.49	2.70	2.20	1.89	1.75	1.41
moderate	13.28	14.13	8.54	4.23	3.52	2.07	1.82	1.57	1.36	1.30	1.14
moderate-fast	11.71	18.57	25.93	16.20	13.13	6.00	3.95	3.63	3.24	2.92	2.79
fast	11.39	14.34	25.23	48.44	54.05	67.89	73.93	77.23	80.42	83.01	85.65

Table 3.5B. Percentage of the lower third of the Lock 3-4 weir pool in the respective velocity classes for existing conditions, at QSA from 3,000-40,000 ML day^{-1}. Cells shaded grey are the most abundant classes.

Flow (ML day^{-1})	**3000**	**5000**	**7000**	**10,000**	**12,000**	**15,000**	**20,000**	**25,000**	**30,000**	**35,000**	**40,000**
very slow	56.70	20.40	11.89	7.77	5.68	4.19	3.13	2.56	2.16	1.90	1.69
slow	43.06	76.48	42.07	13.35	8.54	6.60	4.71	3.29	2.50	1.76	1.45
slow-moderate	0.24	2.95	44.11	41.92	18.50	8.37	5.14	4.15	3.38	2.86	2.34
moderate	0.00	0.17	1.39	30.55	22.33	9.93	3.91	2.54	2.11	1.84	1.71
moderate-fast	0.00	0.00	0.55	5.89	42.30	42.85	17.58	8.38	5.55	4.32	3.72
fast	0.00	0.00	0.00	0.52	2.65	28.06	65.52	79.08	84.31	87.32	89.09

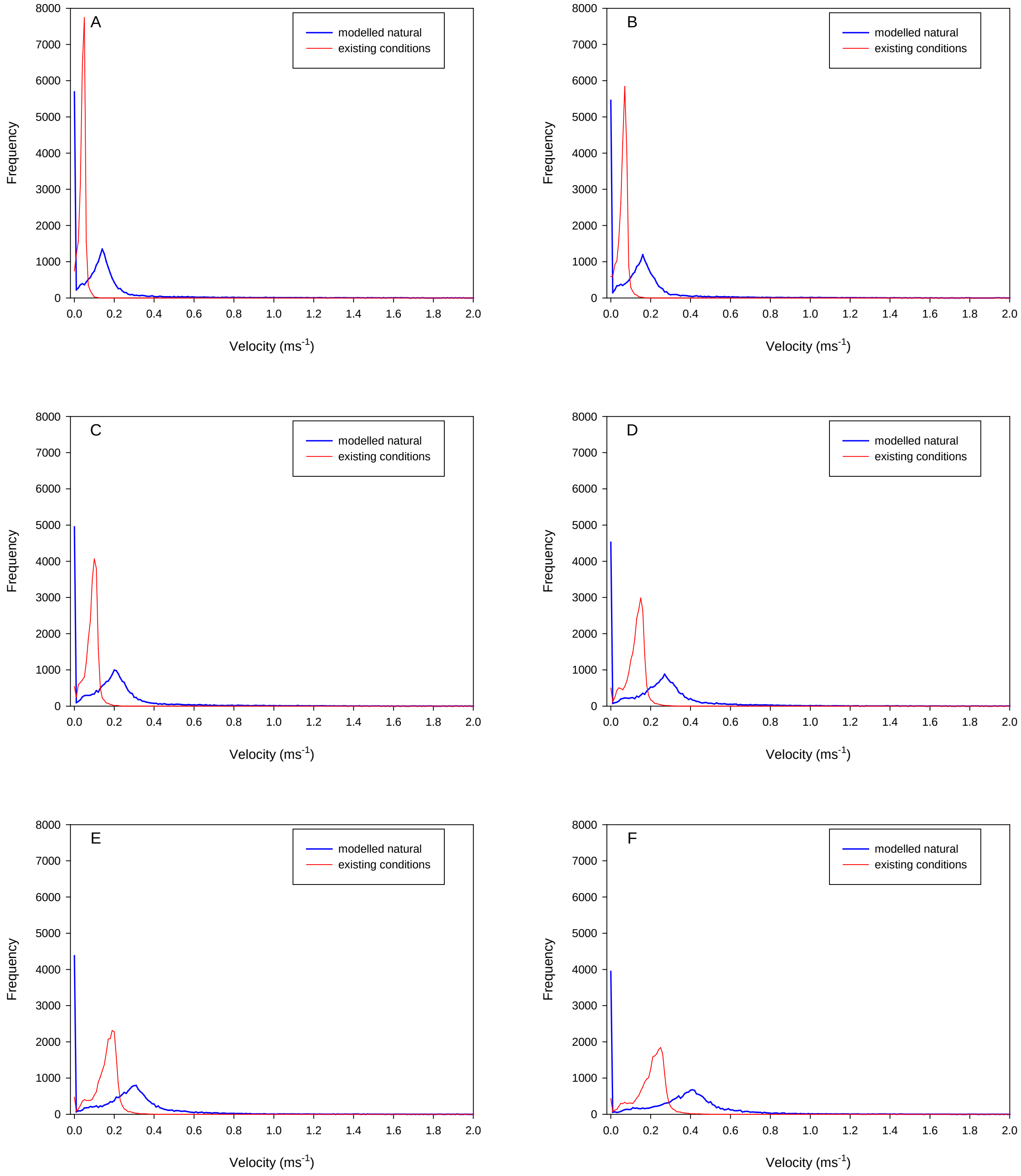


Figure 3.2. Influence of Lock 3 on the velocity frequency-distribution in the lower third of the Lock 3-4 weir pool. Frequency = number of 15 × 15 m grid cells where a given velocity is recorded at a prevailing QSA of [A] 3000 ML day^{-1}, [B] 5000 ML day^{-1}, [C] 7000 ML day^{-1}, [D] 10,000 ML day-1, [E] 12,000 ML day^{-1} and [F] 15,000 ML day^{-1}. Velocity is in 0.01 m s^{-1} increments from 0.0 to 2.0 m s^{-1} in each cell in the MIKE 21 model.

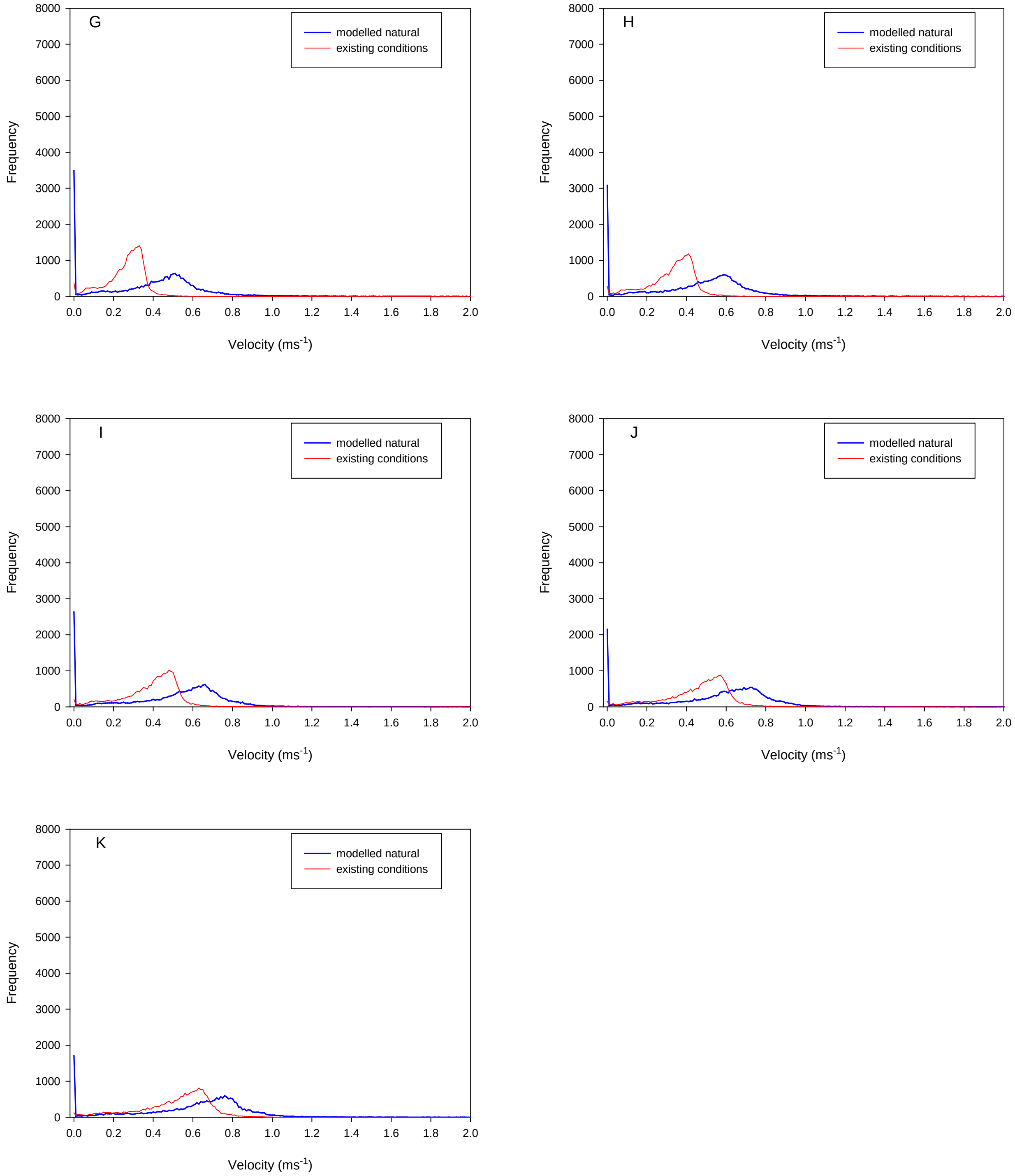


Figure 3.2 continued

Influence of Lock 3 on the velocity frequency-distribution in the lower third of the Lock 3-4 weir pool. Frequency = number of 15 × 15 m grid cells where a given velocity is recorded at a prevailing QSA of [G] 20,000 ML day^{-1}, [H] 25,000 ML day^{-1}, [I] 30,000 ML day^{-1}, [J] 35,000 ML day^{-1} and [K] 40,000 ML day^{-1}. Velocity is in 0.01 m s^{-1} increments from 0.0 to 2.0 m s^{-1} in each cell in the MIKE 21 model.

3.4. Rehabilitation of a more natural flow regime

The terms 'flow' and 'flow regime' have varying definitions, particularly in literature related to the Flood Pulse Concept (Junk et al., 1989). The following definitions are adopted here (Walker et al., 1995; Puckridge et al.,1998):

- Flow regime: a long-term, statistical generalization of the hydrograph,
- Flow history: the sequence of pulses before any point in time,
- Flow pulse: defined not in terms of a threshold (e.g. overbank flow or flood), but as a rise and fall in discharge (or stage) at scales of space and time appropriate to the observer’s frame of reference.

Hydrological behaviour within and between these scales supports ecological functions such as nutrient spiralling, organic matter processing and food web dynamics (Bunn and Arthington, 2002; Bond et al., 2008), and flow thereby is seen as a ‘master variable’(Power et al., 1995) or ‘maestro’ (Walker et al., 1995) in river ecology. Flow variability is a key feature of dryland rivers (Thoms and Sheldon, 2000b), and is acutely important in arid and semi-arid river systems where hydrology is determined by upstream rather than local conditions (Thoms and Sheldon, 2000a). Changes in discharge influence hydrodynamics, biogeochemistry and habitat connectivity. There are five principles to show how changes to hydrology influence aquatic biodiversity (Bunn and Arthington, 2002; Wallace et al., 2011):

- Hydrology is a major determinant of physical habitat (habitat diversity is important as biota are associated with different habitat types),
- Hydrology influences natural patterns of longitudinal and lateral connectivity (maintaining the viability of populations of many species),
- Hydrologic regimes have influenced the evolution of life-history strategies by aquatic species,
- Hydrology is a driver of nutrient and carbon cycles in riverine ecosystems (these govern productivity and food web structure), and
- Hydrologic changes may facilitate the invasion and establishment of alien species.

Regulation of the Murray has substantially reduced flow and water-level variability (sections 3.2, 3.3), but there is general agreement among scientists and water resource managers that hydrologic variability is required to protect biodiversity and ecosystem services (Arthington et al., 2012). Attributes that characterise hydrological behaviour and influence biogeochemical and ecological processes include magnitude, timing, duration, frequency, rate of change and sequence (Poff et al., 1997; Lytle and Poff, 2004). Variability in each is crucial in structuring aquatic communities (Leigh et al., 2010). For example, variation in stage (water level) combined with local geomorphology (e.g. bankfull or wetland commence-to-flow levels) and instream structures (removal or drown-out thresholds) controls longitudinal and lateral connectivity. A dynamic habitat mosaic of wet, wetting, dry, drying, lotic and lentic habitats with adjacent and remote areas inundated and exposed for different times provides increased biodiversity (Ward and Stanford, 1995; Ward et al., 1999; King et al., 2003; Leigh et al., 2010).

The terms river ‘restoration’ and ‘rehabilitation’ are often used interchangeably, but it is useful to make the following distinctions (Aronson et al., 1993):

- Restoration *sensu stricto*: return of a degraded system to the pre-existing (natural) state,
- Restoration *sensu lato*: redirection in trajectory towards one presumed to have existed before the disturbance, and

- Rehabilitation: resumption of damaged or blocked ecosystem functions to increase productivity.

Globally, there is increasing use of environmental flows, or "the quantity, timing and quality of water required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend upon these ecosystems'' (Brisbane Declaration, 2007). The 'natural flow paradigm' of Poff et al. (1997) provides a template for riverine restoration and emphasises the need to re-establish natural variability in hydrology. This ideal is often impractical, or precluded by the conflicting demands of society (Meredith and Beesley, 2009; Hall et al., 2011). As a compromise, there have been calls to 'downsize' river systems (Overton and Doody, 2008; Hall et al., 2011; Pittock and Finlayson, 2011).

In essence, 'downsizing' means that delivery of flows of sufficient magnitude, duration and frequency to maintain the high-elevation floodplain in 'good' condition is not operationally feasible. High-elevation floodplain areas will be inundated occasionally, when flows cannot be regulated or captured in storages, but the frequency and duration of inundation are less than under natural conditions and are unlikely to sustain existing flood-dependent vegetation. Therefore, a shift towards non-flood dependent vegetation and changes in ecological function may occur. Under this approach, a significant effort would be made to reinstate low-moderate flow components of the natural hydrograph (events that would have occurred under similar climatic conditions if the catchment had not been developed) (Watts et al., 2009; Hall et al., 2011; Zampatti and Leigh, 2013). This approach is reflected in the Basin Plan (Commonwealth of Australia, 2012).

The influence of the Basin Plan on increasing the frequency of flow pulses towards natural conditions is demonstrated in Table 3.1 (modelled natural conditions), Table 3.2 (existing conditions) and Table 3.3 (Basin Plan 2800 scenario). Analysis of the potential outcomes of the Basin Plan indicates that the BP2800 scenario does not generate benefits for flows >80,000 ML day^{-1} (Lamontagne et al., 2012), whereas flows of 140,000 ML day^{-1} are needed to inundate about 95% of river red gum (*Eucalyptus camaldulensis*) and black box (*E. largiflorens*) woodlands. An ongoing decline in tree condition therefore is expected for high-elevation areas of the floodplain. This is consistent with the suggestion by Holland et al., (2005) that the boundary for the 'active' floodplain in the lower River Murray is now about 70,000 ML day^{-1}. Thus, the BP2800 scenario represents a 'downsizing' of the floodplain (Lamontagne et al., 2012).

A key assumption in environmental water management is that reinstating components of the natural hydrology of rivers or wetlands will promote ecosystem recovery *via* recruitment and growth of biota and partial restoration of ecosystem processes (Poff et al., 1997; Arthington et al., 2006). Hydrological variability is a driver of the distribution and diversity of aquatic flora and fauna *via* its effects on physical habitat (Poff and Allan, 1995), and many fish and other biota have evolved life-history strategies (including spawning and feeding requirements) to match hydrological conditions and the availability of habitat (Baumgartner et al., 2013). Consequently, planning and delivery of environmental water must be underpinned by understanding of the relationships between the desired ecological outcome and the hydrology that drives the processes involved. Knowledge from empirical data (as opposed to conceptual models and expert opinion) is not yet sufficient to produce modelling tools to (i) link the bioenergetic processes that affect individuals to spatially-explicit population dynamics or (ii) predict whole-of-system responses to spatial and temporal variability (Anderson et al., 2006).

Interactions and feedbacks within and between biotic and abiotic components, lateral and longitudinal connectivity and temporal and spatial scales are important factors. Positive and negative responses may occur either as linear, curvilinear or step-changes (Anderson et al., 2006). The latter are sudden and/or unexpected outcomes that result in transition to an alternate state, and may not be easily reversible (Scheffer et al., 2001; Scheffer and Carpenter, 2003). It is important to note that delivery and management of environmental water allocations may have short- and long-term effects. Wallace et al. (2011) described a hierarchy of temporal phases associated with environmental watering, namely *instantaneous* (effects within minutes-hours of inundation), *fast* (hours-weeks), *slow* (weeks-months), *delayed* (months-years) and *cumulative* phases (responses that occur only after a series of events). The time lags may cause outcomes to cascade, so that different responses may occur within or between sites for similar flow delivery regimes.

3.5. Hydrologic components in planning and delivery of environmental water

3.5.1. Magnitude

The magnitude of a flow event is the discharge recorded over a specified time, and affects physical variables including flow velocity and stage (water level). Flow velocity indicates the energy available for geomorphic processes (e.g. scour, transport and deposition of sediments) and the re-arrangement of biotic (e.g. macrophytes) and structural (e.g. woody debris, rocks, gravel) habitat, dispersal of material including biological propagules, and mixing energy to maintain non-buoyant propagules in suspension and prevent stratification. In addition, the magnitude of any given event may directly or indirectly influence migration and spawning/breeding behavioural responses.

Weirs on the lower Murray have little effect on discharge but they do have significant impacts on flow velocity and stage. Prior to regulation, river levels underwent sustained rises and falls over days–weeks whereas the weirs are managed to maintain relatively stable pool levels. In these circumstances, reinstating a more natural pattern of discharge may not reinstate corresponding natural variability in depth, velocity and other ecological processes and responses.

3.5.2. Timing

Temperature and day length affect fauna and flora through life-history adaptations (Lytle and Poff, 2004), behavioural traits and metabolic (energetic) and endocrine (e.g. circadian rhythm) pathways (Bunn and Arthington, 2002). Their effects on biogeochemical rates also shape ecological patterns and processes in riverine ecosystems (Arthington et al., 2010; Lytle and Poff, 2004). Changes in the timing of events may have more effect on life-history responses than behavioural responses, but there are boundaries for responses within seasons. For example, rising flows combined with appropriate temperatures and day length may cue reproduction (Bunn and Arthington, 2002). Further, biogeochemical processes are likely to be slowed if the water temperature is <15°C.

3.5.3. Duration

The number of days a flow event remains at or above a specified level influences the ability of biota to exploit the longitudinal and lateral connections created by the event. Long periods of high flow may promote productivity and access to feeding, breeding and nursery habitats (Bunn and Arthington, 2002), although protracted inundation can cause waterlogging of soils and death of some floodplain/wetland vegetation types.

3.5.4. Frequency

Frequency refers to the number of cycles (events) of given magnitude within a specified period. It is a function of flow magnitude and duration, with small flows typically having a relatively high return frequency. Events at different frequencies affect different biogeochemical and biological functions. Small to moderate events at high frequency are critical for maintaining connectivity, migration, dispersal, vegetation, sediment and nutrient exchange and water quality. Less-frequent high flows may also reset ecological processes (Leigh et al., 2010). Extreme events (floods, droughts) are key processes driving mortality and recruitment (Lytle and Poff, 2004).

3.5.5. Rate of change

The rate of change (mm day^{-1}) in water level on the rising and falling limbs of the hydrograph is important for a variety of biota and processes. An increase in river level stability (the time taken for a change in water level to occur) may substantially alter the response of ecological processes in the river (Thoms and Sheldon (2000b). Thus, a managed slow change in water level will have a different effect from the same change at a faster rate. Rapid changes (days) are likely to have more effect on maintaining biofilms in a desirable state than slow changes (weeks). Rates of rise are less critical for the establishment of flood-dependent plants, as many species germinate only as water levels recede, leaving areas with high soil moisture (Nicol, 2004). However, established stands of low-growing and emergent amphibious macrophytes are vulnerable to rapid increases in water depth, as many species cannot maintain sufficient rates of photosynthesis and gas exchange to tolerate extended inundation (Siebentritt and Ganf, 2000). 'Top flooding' can have drastic effects on littoral plants like river clubrush (*Bolboschoenus* spp.). Drawdown rates of 10-30 mm day^{-1} (<50 mm) have most benefit for amphibious and floodplain plant communities (Nicol, 2004) and breeding waterbirds (Rogers and Paton, 2008), and minimise bank slumping (Gippel et al., 2008) and the risk of stranding fish in connected wetlands (Mallen-Cooper et al., 2008).

Rapid recessions induce saline inflows and may reduce the dilution capacity of the river when these occur (Telfer et al., 2012). Modelling of the potential salinity impacts of managed inundations at Chowilla Floodplain indicates that the peak salt load is influenced by the extent and duration of inundation and the rate of drawdown, suggesting that a managed slow drawdown could be used to mitigate saline inflows on the falling limb of high-flow events (Li et al., 2012).

3.5.6 Sequence

Antecedent conditions govern the ecological outcomes from any flow event. For example, frequent small floods maintain soil moisture and water levels in wetlands, increasing the potential for subsequent flows to travel further downstream and/or inundate larger areas (Leigh et al., 2010). Further, sequential floods have cumulative positive effects on recruitment to populations of native fish (Puckridge et al., 2000; Arthington et al., 2005) and waterbirds (Kingsford and Porter, 1993; Kingsford et al., 1999).

Although germination and establishment of river red gums are not completely dependent on flooding (Jensen *et al.*, 2008b), regeneration (recruitment success) is enhanced by appropriate flood regimes (follow-up flooding: Bacon *et al.* 1993, Roberts and Marston 2000, MDBC 2001) or substantial rainfall following a flood (George, 2004; cited by Jensen et al., 2008a). Repeated watering is required to maintain initial responses in stressed trees and ensure that tree health continues to improve (Overton and Doody, 2008; Souter et al., 2013).

3.5.7. Connectivity

Hydrological connectivity refers to the water-mediated movement of materials (carbon, nutrients, propagules, biota) within and between habitats (Pringle, 2001; Douglas et al., 2005). A hierarchical relationship between connectivity and movements of organisms and resources between habitats was outlined by Wallace et al. (2011):

- Passive movement:
  1-dimensional (1D) and 2-dimensional (2D) movements of carbon, nutrients, phytoplankton, plant propagules, micro-invertebrates and fish eggs and larvae (e.g. by downstream drift)
- 1D active movement:
  longitudinal movements by fish and macro-Crustacea (crayfish, prawns, shrimps)
- 2D active movement:
  lateral movements by fish, macro-Crustacea (crayfish, prawns, shrimps) and turtles
- 3D active movement:
  movements by birds and macro-invertebrates able to fly.

In this hierarchy, the importance of the flow regime as a driver of connectivity and longitudinal and lateral movements becomes evident. The ability of a population to persist in a river reach depends on (i) the length of the reach and (ii) flow conditions, consumer-resource interactions and the organism's life-history strategy (Anderson et al., 2006). Longitudinal barriers in rivers (e.g. weirs, dams) and lateral barriers between rivers and floodplains (diversion and flood protection levees) disrupt connectivity, reducing the length of reaches. This can lead to reduced transport of nutrients, organic matter and biota, isolation of populations, failed recruitment and losses of biodiversity (Bunn and Arthington, 2002; Arthington and Pusey, 2003; Anderson et al., 2006). The close links between river and floodplain suggest that they should not be regarded as separate food webs (Douglas et al., 2005).

3.5.8. Spatial scale

The response length of a system (or management action) is the scale at which local disturbances (management actions) influence distant populations (Anderson, 2006). For organisms that have long response lengths (i.e. highly mobile/migratory species), management actions that influence microhabitats (e.g. snags, aquatic macrophytes, substrata) or mesohabitats (e.g. individual anabranches, wetlands, or floodplains) may have less influence than those that occur at the macrohabitat (e.g. river reach) scale. Actions at the site scale (i.e. managed inundation of floodplains and/or wetlands) achieved independently of the landscape-scale processes that would normally accompany and/or drive those outcomes (i.e. rainfall and high discharge) may achieve reduced outcomes.

3.5.9. Hydraulic complexity

Understanding hydraulic habitat is a challenge for river management (Kilsby and Walker, 2012), and often is overlooked when determining environmental flow needs (Bice et al., 2013). Kilsby and Walker (2012) proposed that temporal and spatial hydraulic diversity that provides for a range of species should be a management goal, and may provide a tool to enhance biodiversity in regulated rivers (Dyer and Thoms, 2006). This may be particularly important in the lower River Murray, where management for stable water levels creates a disconnect between hydraulic diversity (depth, velocity, turbulence) and changes in discharge. It may also be important during low-flow periods when there is little opportunity to manipulate discharge (Kilsby and Walker, 2012).

Hydraulic habitat represents the 'dynamic' components of the water column (depth, velocity, turbulence), influenced by interactions between discharge and channel form (geomorphology) and submerged habitat. Spatial hydraulic diversity in a reach is driven by local structure/channel features, and temporal variability is driven by changes in discharge/depth, maintaining heterogeneity within and between macrohabitats (e.g. channel), mesohabitats (e.g. backwaters, anabranches) and microhabitats (e.g. snags, aquatic macrophytes, substrata) (Bice et al., 2013). Selection of hydraulic habitats by fish is influenced by age, activity, migration, season, competition and predation, availability of habitat and swimming ability, so that a spatially-diverse hydraulic habitat is likely to support many species (Kilsby and Walker, 2012). The provision or maintenance of conditions that provide sufficient turbulence (water-column mixing) to maintain negatively-buoyant propagules is another consideration. For example, downstream drift of eggs and/or larvae and juveniles is an important life-history phase for riverine fish (Brown and Armstrong, 1985), including Murray cod, golden perch and silver perch (Humphries et al., 1999). Thus, management should strive to generate hydraulic diversity similar to that under natural conditions.

Microfaunal communities (e.g. zooplankton) differ between slackwater and fast-flowing habitats (Nielsen et al., 2010), reflected in a higher density and diversity of microcrustaceans relative to rotifers. Fish larvae benefit from the increased food availability in these zones (e.g. Ning et al., 2010). Although slackwaters break down and re-form with changes in velocity and depth, community composition in new slackwaters approaches that in existing slackwaters within days. Further, the lower abundance and diversity of microfauna in fast-flowing habitats may not occur in slackwater habitats. Rotifers dominate in lotic habitats (as part of the 'potamoplankton' community) and microcrustaceans dominate in lentic habitats ('limnoplankton'). In the lower Murray, the zooplankton community varies with inputs from rivers that do/do not have significant floodplain wetlands. For example, the Darling contributes mainly rotifers, and the Murray and its tributaries contribute mainly copepods and cladocerans (Shiel et al., 1982).

3.5.10. Flow components

The Basin Plan (http://www.comlaw.gov.au/Details/F2012L02240) identifies seven flow components:

1. cease to flow,
2. low-flow season base flows,
3. high-flow season base flows,
4. low-flow season freshes,
5. high-flow-season freshes,
6. bankfull flows,
7. overbank flow.

Under regulated conditions, the lower Murray does not experience cease-to-flow conditions, and as a result of the stabilisation of water levels the delivery of managed entitlement flows represent the base flows. The following components may be more applicable (the first four, shown bold, are relevant to in-channel Environmental Water Requirements):

1. **Regulated entitlement flows** (<7000 ML day^{-1}),
2. **In-channel low flows** (7000-15,000 ML day^{-1}),
3. **In-channel moderate flows** (15,000-30,000 ML day^{-1}),
4. **Bankfull flows** (30,000 - 40,000 ML day^{-1}),
5. Small overbank flows (40,000 - 60,000 ML day^{-1}),
6. Moderate overbank flows (60,000-80,000 ML day^{-1}),
7. Large overbank flows (>80,000 ML day^{-1}).

3.6. Environmental water management and Basin Plan water quality targets

Chapter 9 of the Basin Plan (Commonwealth of Australia, 2012) establishes the Water Quality and Salinity Management Plan (WQSMP) for the Murray-Darling Basin. As part of the implementation of the WQSMP, river operators and holders of environmental water are required to have regard to 'Targets for managing water flows' (section 9.14 of the Basin Plan) when making flow-management decisions. The targets include:

- To maintain dissolved oxygen at a target of at least 50% saturation (section 9.14(5c) of the Basin Plan),
- The water quality targets for water used for recreational purposes are that the values for cyanobacterial cell counts or biovolume should meet values in Chapter 6 of the Guidelines for Managing Risks in Recreational Water (NHMRC, 2008) (section 9.18 of the Basin Plan), and
- The levels of salinity at the reporting sites in Table 3.6 should not exceed the values set out in the table, 95% of the time (section 9.14(5c) of the Basin Plan).

3.6.1. Dissolved oxygen

The influence of water temperature on the solubility of dissolved oxygen (percent saturation) relative to the concentration (mg O_2 L^{-1}) and the Basin Plan target (50% saturation) is shown in Figure 3.2.

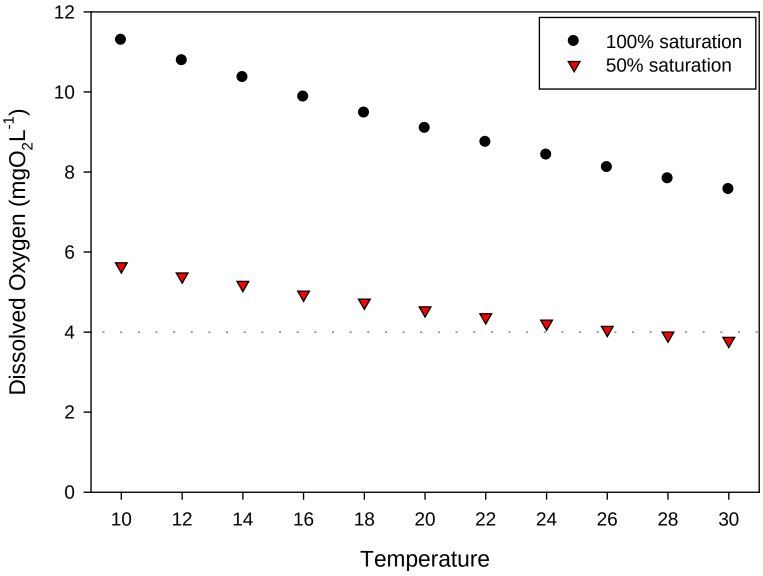


Figure 3.2. The influence of water temperature on solubility of dissolved oxygen in fresh water. Note that solubility decreases as salinity increases. The Basin Plan target is ≥50% saturation. The horizontal line is a 4 mg L^{-1} critical threshold identified by Wallace and Lenon (2010). Data from Eaton et al. (1995).

3.6.2. Cyanobacteria

The NHMRC guidelines (2008) state that freshwater recreational bodies should not contain:

- More than 10 µg L^{-1} total microcystins; or ≥50,000 cells mL^{-1} toxic *Microcystis aeroginosa*; or biovolume equivalent of ≥4 mm^3 L^{-1} for the combined total of all Cyanobacteria where a known toxin producer is dominant in the total biovolume; or
- More than 10 mm^3 L^{-1} for total biovolume of all cyanobacterial material where known toxins are not present; or
- Persistent cyanobacterial scums.

3.6.3. Salinity accounting

Basin Plan salinity targets are shown in Table 3.6. "Time" is defined as the current water accounting period and the previous four water accounting periods (a rolling five-year average).

Table 3.6. Salinities at reporting sites should not exceed these values 95% of the time. Adapted from the Basin Plan (2012). EC: Electrical Conductivity at 25°C.

Reporting Site	Target (EC, $\mu S\ cm^{-1}$)
Murray at Lock 6	580
Murray at Morgan	800
Murray at Murray Bridge	830
Lower Lakes at Milang	1000

4. Ecological Objectives and Targets

4.1. Scope of Ecological Objectives and Ecological Targets

Ecological Objectives and Targets for the channel are shown in Table 4.1. They have not been developed for lignum (*Duma florulenta*) or black box (*Eucalyptus largiflorens*), as the effects of flows up to 40,000 ML day^{-1} are slight for these species (see sections 7.6–7.7, *Hydrodynamic Modelling Results And Conceptual Models*).

4.2. Condition relative to Ecological Targets

Ecological Targets are a means of assessing and reporting condition over time, indicating the need for management action and assessing the outcomes of those actions. Condition scores that do not meet the Ecological Target in any given year are not an indication of failure, as the condition and trajectory of each attribute or process are dynamic in time and space. The focus of management should be not to attain stable conditions, but to maintain the condition of biota and abiotic processes within responsive ranges.

A hypothetical example is shown in Figure 4.1. In this example, the condition of the population of trees is poor in the first year of a 10-year period of assessment. The black circles indicate a successful outcome over the 10-year period, whereby management actions have supported an improvement in condition between years 1 and 5, such that the target is exceeded in years 5 and 6. Although the trajectory is negative between years 5 and 9, the population remains in a condition where there is a rapid positive response to management actions, and the target is almost met in year 10. In contrast, the red triangles indicate a ‘fail’ scenario, where the decline in condition over the 10 years is likely to lead to loss of the population.

Timeframes for assessment and 'fail' points will vary between assets and functions. As a rule, the timeframes need to be relevant to (i) the life cycle of the organisms (including longevity of seed banks) and/or (ii) the time scales of the biogeochemical processes involved. Detail on these timeframes and 'fail' points are not provided in this report, but the Basin Plan SDL Adjustment Project (Overton et al., 2013) includes this information for many of the assets for which Ecological Targets have been developed here. In addition, thresholds for management action for some Ecological Targets corresponding to those in Table 4.1 have been proposed for the Chowilla Floodplain Icon Site (MDBA, 2014). Refining these values for application to in-channel Ecological Targets warrants a high priority.

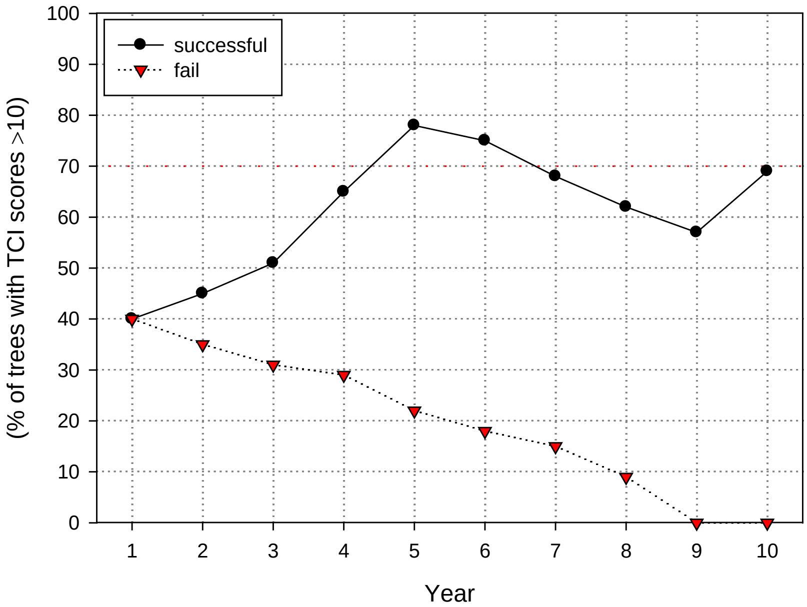


Figure 4.1. A hypothetical example of tree condition measured annually, relative to the Ecological Target '70% of trees in standardised transects spanning the elevation gradient within the target zone will have a Tree Condition Index (TCI) score ≥10' (indicated by the red broken line). The black circles indicate a successful outcome over 10 years, and the red triangles indicate a 'fail' outcome over the same period.

Table 4.1. Ecological Objectives and Targets.

Type	Asset or Function	Ecological Objective	Ecological Target
Ecosystem processes	Function	Provide for the mobilisation of carbon and nutrients from the floodplain to the river to reduce the reliance of instream foodwebs on autochthonous productivity.	Open-water productivity shows a temporary shift from near zero or autotrophic dominance (positive Net Daily Metabolism) towards heterotrophy (negative Net Daily Metabolism) when QSA >30,000 ML day^{-1}.
	Function	Provide diverse hydraulic conditions over the range of velocity classes in the lower third of weir pools so that habitat and processes for dispersal of organic and inorganic material between reaches are maintained.	Habitat across the range of velocity classes is present in the lower third of weir pools for at least 60 consecutive days in Sep–Mar, at a maximum interval of 2 years.
	Function	Maintain a diurnally-mixed water column to ensure diverse phytoplankton and avoid negative water quality outcomes.	Thermal stratification does not persist for more than 5 days at any time.
	Function	Ensure adequate flushing of salt from the Murray to the Southern Ocean.	Basin Plan Target: Salt export, averaged over the preceding 3 years, is ≥2 million tonnes per year.
Water Quality	Function	Maintain water quality to support aquatic biota and normal biogeochemical processes.	Biovolume <4 $mm^3 L^{-1}$ for all Cyanobacteria, where a known toxin producer is dominant.
			Biovolume <10 $mm^3 L^{-1}$ for all Cyanobacteria, where toxins are not present.
			Basin Plan Target: Maintain dissolved oxygen above 50% saturation throughout water column at all times.
Biofilms	Asset	Promote bacterial rather than algal dominance of biofilms and improve food resource quality for consumers.	Annual median biofilm composition is not dominated (>80%) by filamentous algae.
			Annual median biofilm C:N ratios are <10:1.

Table 4.1 continued. Ecological Objectives and Targets.

Type	Asset or Function	Ecological Objective	Ecological Target
Riparian vegetation	Asset	Throughout the length of the river channel asset (i.e. SA border to Wellington), establish and maintain a diverse native flood-dependent plant community in areas inundated by flows of 10,000–40,000 ML day^{-1}.	In standardised transects spanning the elevation gradient in the target zone†, 70% of river red gums have a Tree Condition Index score ≥ 10.
			A sustainable demographic is established to match the modelled profile for a viable river red gum population in existing communities spanning the elevation gradient in the target zone.†
			Species from the Plant Functional Group 'flood-dependent/responsive' occur in 70% of quadrats spanning the elevation gradient in the target zone† at least once every 3 years.
Wetland vegetation	Asset	Throughout the length of the river channel asset (i.e. SA border to Wellington), establish and maintain a diverse macrophyte community in wetlands inundated by flows up to 40,000 ML day^{-1}.	Native macrophytes from the emergent, amphibious and flood- dependent functional groups occur in 70% of quadrats spanning the elevation gradient in the target zone† at least once every 3 years.
Wetlands	Asset	Maintain habitats and provide for dispersal of organic and inorganic material and organisms between river and wetlands.	Inundation periods in temporary wetlands have unrestricted lateral connectivity between the river and wetlands in >90% of inundation events.

†The target zone is the area inundated by flows of 10,000-40,000 ML day^{-1}

Table 4.1 continued. Ecological Objectives and Targets.

Type	Asset or Function	Ecological Objective	Ecological Target
Groundwater and soil	Asset	Throughout the length of the river channel asset (i.e. SA border to Wellington), establish and maintain groundwater and soil moisture conditions conducive to improving riparian vegetation.	Establish and maintain freshwater lenses in near-bank recharge zones.
			Maintain soil water availability, measured as soil water potential > -1.5 MPa at soil depth 20–50 cm, to sustain recruitment of long-lived vegetation across the elevation gradient in the target zone.†
			Reduce soil salinity (measured as EC 1:5) to <5000 $\mu S\ cm^{-1}$ to prevent shifts in understorey plant communities to salt-tolerant functional groups across the elevation gradient in the target zone.†

†The target zone is the area inundated by flows of 10,000-40,000 $ML\ day^{-1}$

EC = Electrical Conductivity at 25°C.

Table 4.1 continued. Ecological Objectives and Targets.

Type	Asset or Function	Ecological Objective	Ecological Target
Fish	Asset	Restore the distribution of native fish.	Expected[1] species occur in each mesohabitat (channel, anabranch, wetlands) in each weir pool/reach.
		Restore resilient populations of Murray cod (a long-lived apex predator).	Population age structure[2] of Murray cod includes recent recruits[3], sub-adults and adults in 9 years in 10.
			Population age structure of Murray cod indicates a large recruitment[4] event 1 year in 5, demonstrated by a cohort representing >50% of the population.
			Abundance (CPUE[5]) of Murray cod increases by ≥50% over a 10-year period.
		Restore resilient populations of golden perch and silver perch (flow-dependent specialists).	Population age structure of golden perch and silver perch includes YOY with sub-adults and adults in 8 years in 10.
			Population age structure of golden perch and silver perch indicates a large recruitment event 2 years in 5, demonstrated by separate cohorts representing >30% of the population.
			Abundance (CPUE) of golden perch and silver perch increases by ≥30% over a 5-year period.

[1] Expected species are those that were historically abundant (e.g. silver perch, freshwater catfish) and would not be considered beyond their extant range (e.g. trout cod), vagrants (i.e. spangled perch) or not expected to occur (e.g. mature Murray cod in temporary wetlands)

[2] Population age structure is inferred from length-frequency distributions and validated by otoliths where appropriate

[3] 'Recent recruits' are fish <2 years old

[4] 'Recruitment' refers to survival and growth of the larvae and juveniles to YOY (young of year).

[5] CPUE is 'catch per unit effort' resulting from formal surveys using standard techniques (e.g. boat-mounted electrofishing, fyke nets)

Table 4.1 continued. Ecological Objectives and Targets.

Type	Asset or Function	Ecological Objective	Ecological Target
Fish	Asset	Restore resilient populations of freshwater catfish.	Population age structure of freshwater catfish includes YOY, with sub-adults and adults in 9 years in 10.
			Population age structure of freshwater catfish indicates a large recruitment event 2 years in 5, demonstrated by separate cohorts representing >30% of the population.
			Abundance (CPUE) of freshwater catfish increases by ≥30% over a 5-year period.
		Restore and maintain resilient populations of foraging generalists (e.g. Australian smelt, bony herring, Murray rainbowfish, unspecked hardyhead, carp gudgeons, flathead gudgeons).	The length-frequency distributions for foraging generalists include size classes showing annual recruitment.
		Minimise the risk of carp recruitment.	The relative abundance and biomass of common carp does not increase in the absence of increases in abundance and biomass of flow-dependent native fish.

YOY = Young of Year.

5. Environmental Watering Requirements

5.1. Pre-existing requirements

Both the MDBA and SA have defined EWRs for the Riverland–Chowilla Floodplain (MDBA, 2012a, c) and the Coorong, Lower Lakes and Murray Mouth (CLLMM) (MDBA, 2012b), and a summary of SA's EWRs is provided by Gibbs et al. (2012b). Pollino et al. (2011) and Lamontagne et al. (2012) considered the main limitations in these EWRs to be:

- Lack of riverine targets to account for hydraulic connectivity and explicitly address the requirements of native fish,
- Limited representation of ecological complexity for evaluating the ecological outcomes of hydrologic scenarios, and
- Little regard for the requirements of the floodplain landscape between the asset sites.

To address these issues, two preliminary EWRs relating to recruitment by large-bodied native fish were defined in August 2012. The suite of pre-existing EWRs is shown in Table 5.1. The focus here is on flows in the range relevant to in-channel flows, namely 3000–40,000 ML day^{-1}.

5.2. In-channel requirements

Environmental Water Requirements have been identified for in-channel flows and various ecological attributes and functions, with indications of variation about the mean discharge. This reflects the fact that (i) under natural conditions, flows are inherently variable, and (ii) maintaining a static flow for prolonged periods is not desirable. Seven EWRs are presented, as it is anticipated that within the flow range (3,000-40,000 ML day^{-1}) there are several points at which step-point changes will occur in hydrology (e.g. discharge, hydraulics, velocity), lateral connectivity (e.g. area inundated) or ecology (e.g. spawning). A summary is shown in Table 5.2, with information on the magnitude and variation of discharge (ML day^{-1}), duration of flow, frequency, Maximum allowable return interval and timing (e.g. season).

Each EWR is expected to contribute towards achieving the Ecological Objectives and Ecological Targets.

Note:

- Flows of a higher magnitude will meet the requirement for lower events. For example, achieving the metrics for the 20,000 ML day^{-1} EWR means that the metrics for the 10,000 and 15,000 ML day^{-1} EWRs will have been met.
- The magnitude of outcomes from meeting the metrics of a given EWR depend on the antecedent conditions.
- Cumulative outcomes from multiple events will be required to achieve the Ecological Targets (i.e. no one EWR represents a ‘silver bullet’).

Conceptual models outlining the expected ecological responses from delivering a flow pulse that matches the metrics for each EWR are described in section 6. A matrix to allow a rapid appraisal of the ability of each EWR to contribute towards achieving Ecological Targets is shown in section 5.3.

Table 5.1. Pre-existing EWRs with discharge (ML day^{-1}) corresponding to in-channel flows (3000–40,000 ML day^{-1}). Adapted from Lamontagne (2012) and Gibbs et al. (2012a).

Origin	EWR #	Discharge (ML day^{-1})	Duratio n (days)	Timing	Average return frequency (years)	Maximum interval (years)	Description
MDBA Riverland–Chowilla Floodplain	MDBA 1	20,000	60	-			Freshes
	MDBA 2	40,000	30	Jun–Dec			Maintain 80% of the current extent of wetlands in good condition.
	MDBA 3	40,000	90	Jun–Dec			Maintain 80% of the current extent of wetlands in good condition.
SA Riverland–Chowilla Floodplain	SA-q (FV)	Pool to 40,000		Variable			Provide variability in flow regimes at lower flow levels.
	FSr	15,000	60	Oct–Feb	1 in 3	5	Support spawning and recruitment by flow-dependent spawners (golden perch, silver perch).
	MCr	40,000	60	Sep–Dec	1 in 4	5	Support spawning and recruitment by Murray cod.
	SA-p (TW2)	40,000	90	Aug–Jan	1 in 2	3	Maintain and improve majority of lower elevation (20%) temporary wetlands in healthy condition, providing for small-scale bird-and fish-breeding and microbial decay/export of organic matter.

Table 5.2. In-channel Environmental Water Requirements for the lower Murray.

EWR #	Median discharge (ML day^{-1})	Discharge (ML day^{-1})	Duration (days)	Preferred timing	Average return frequency (years)	Percentage of years flow is required	Maximum return interval (years)	Percentage of years that discharge and duration are likely under BP2800 scenario
IC1	10,000	7000 - 12,000	60	Sep-Mar	1.05	95	2	90
IC2	15,000	15,000 -20,000	90	Sep-Mar	1.33	75	2	77
IC3	20,000	15,000 - 25,000	90	Sep-Mar	1.8	55	2	67
IC4	25,000	20,000 - 30,000	60	Sep-Mar	1.7	59	2	67
IC5	30,000	25,000 - 35,000	60	Sep-Mar	1.8	55	2	59
IC6	35,000	30,000 - 40,000	60	Sep-Mar	1.8	55	2	46
IC7	40,000	35,000 - 45,000	90	Sep-Mar	2.1	48	3	31

5.3. Ability of EWRs to contribute to Ecological Targets

A matrix to allow rapid appraisal of the anticipated ability of each EWR to contribute towards achieving the Ecological Targets was developed using a ranking system (Table 5.3), and scores were generated (Table 5.4) with reference to the conceptual models (section 6). It is intended that the table be used to support decisions about the potential benefits and/or trade-offs of either:

- Temporarily increasing flow to the next flow band (i.e. increasing flow by up to 10,000 ML day^{-1}), or
- Maintaining prevailing flows at a lower magnitude for a longer period.

The table should be used with reference to the conceptual models for each EWR. Due to the coarse nature of the ranking system, a result of 'no change' in ranking between flows of similar magnitude does not imply no improvement in ecological condition from increased flow/duration. Further, it is important to note that the table must be interpreted with due caution, as outcomes from any flow pulse will be dependent on antecedent flows, and prevailing ecosystem condition.

Table 5.3. A system for rapid appraisal of the contribution of management actions towards Ecological Objectives and Targets.

Rank	Requirements or processes met	Contribution towards Ecological Objectives and Targets
1	All or most	Large positive contribution
2	Some	Moderate positive contribution
3	Very few or none	Contribution unlikely to be detectable or expected

Table 5.4. Ranked ability of the suggested EWRs (see table 5.2) to contribute to Ecological Targets. Scores refer to the system in Table 5.3. EF = Entitlement Flows.

Type	Ecological Target	EWRs (Table 5.2: discharge, duration, timing, frequency)							
		EF	IC1	IC2	IC3	IC4	IC5	IC6	IC7
Ecosystem processes	Open-water productivity shows a temporary shift from near zero or autotrophic dominance (positive Net Daily Metabolism) towards heterotrophy (negative Net Daily Metabolism) when QSA >30,000 ML day^{-1}.	3	3	3	3	2	2	1	1
	Habitat across the range of velocity classes is present in the lower third of weir pools for at least 60 consecutive days in Sep–Mar, at a maximum interval of 2 years.	3	3	3	2	1	1	1	1
	Thermal stratification does not persist for more than 5 days at any time.	3	1	1	1	1	1	1	1
	Basin Plan Target: Salt export, averaged over the preceding 3 years, is ≥2 million tonnes per year.	3	3	2	2	2	1	1	1
Water quality	Biovolume <4 $mm^3 L^{-1}$ for all Cyanobacteria, where a known toxin producer is dominant, **or** <10 $mm^3 L^{-1}$ for all Cyanobacteria where toxins are not present.	3	2	1	1	1	1	1	1
	Basin Plan Target: Maintain dissolved oxygen above 50% saturation throughout water column at all times.	3	3	3	2	2	2	1	1
Biofilms	Median biofilm composition is not dominated (>80%) by filamentous algae.	3	2	2	2	1	1	1	1
	Median biofilm C:N ratios are <10:1.	3	2	2	2	1	1	1	1
Riparian vegetation	In standardised transects spanning the elevation gradient in the target zone†, 70% of river red gums have a Tree Condition Index score ≥ 10.	3	3	2	2	2	2	2	1
	A sustainable demographic is established to match the modelled profile for a viable river red gum population in existing communities spanning the elevation gradient in the target zone.†	3	3	3	2	2	2	2	1
	Species from the Plant Functional Group 'flood-dependent/responsive' occur in 70% of quadrats spanning the elevation gradient in the target zone† at least once every 3 years.	3	3	3	2	2	2	2	1

Table 5.4 continued. Ranked ability of the suggested EWRs (see table 5.2) to contribute to Ecological Targets. Scores refer to the system in Table 5.3. EF = Entitlement Flows.

Type	Ecological Target	EWRs (Table 5.2: discharge, duration, timing, frequency)							
		EF	IC1	IC2	IC3	IC4	IC5	IC6	IC7
Wetland vegetation	Native macrophytes from the emergent, amphibious and flood- dependent functional groups occur in 70% of quadrats spanning the elevation gradient in the target zone† at least once every 3 years.	3	3	3	3	2	2	2	1
Wetlands	Inundation periods in temporary wetlands have unrestricted lateral connectivity between the river and wetlands in >90% of inundation events.	3	3	3	3	2	2	2	1
Groundwater and soil	Establish and maintain freshwater lenses in near-bank recharge zones.	3	3	2	2	2	2	1	1
	Maintain soil water availability, measured as soil water potential > -1.5 MPa at soil depth 20–50 cm, to sustain recruitment of long-lived vegetation across the elevation gradient in the target zone.†	3	3	3	2	2	2	2	1
	Reduce soil salinity (measured as EC 1:5) to <5000 µS cm^{-1} to prevent shifts in understorey plant communities to salt-tolerant functional groups across the elevation gradient in the target zone.†	3	3	3	2	2	2	2	1
Fish	Expected[1] species occur in each mesohabitat (channel, anabranch, wetlands) in each weir pool/reach.	3	3	3	3	3	2	1	1
	Population age structure[2] of Murray cod includes recent recruits[3], sub-adults and adults in 9 years in 10.	3	3	3	2	2	2	2	2
	Population age structure of Murray cod indicates a large recruitment[4] event 1 year in 5, demonstrated by a cohort representing >50% of the population.	3	3	3	3	3	3	3	2
	Abundance (CPUE[5]) of Murray cod increases by ≥50% over a 10-year period.	3	3	3	2	2	2	2	2

Table 5.4 continued. Ranked ability of the suggested EWRs (see table 5.2) to contribute to Ecological Targets. Scores refer to the system in Table 5.3. EF = Entitlement Flows; YOY = Young of Year.

Type	Ecological Target	EWRs (Table 5.2: discharge, duration, timing, frequency)							
		EF	IC1	IC2	IC3	IC4	IC 5	IC6	IC7
Fish	Population age structure of golden perch and silver perch includes YOY with sub-adults and adults in 8 years in 10.	3	3	2	2	2	2	2	1
	Population age structure of golden perch and silver perch indicates a large recruitment event 2 years in 5, demonstrated by separate cohorts representing >30% of the population.	3	3	2	2	2	2	2	1
	Abundance (CPUE) of golden perch and silver perch increases by ≥30% over a 5-year period.	3	3	3	2	2	2	2	1
	Population age structure of freshwater catfish includes YOY, with sub-adults and adults in 9 years in 10.	3	3	3	2	2	2	2	1
	Population age structure of freshwater catfish indicates a large recruitment event 2 years in 5, demonstrated by separate cohorts representing >30% of the population.	3	3	3	3	3	2	2	1
	Abundance (CPUE) of freshwater catfish increases by ≥30% over a 5-year period.	3	3	3	3	3	2	2	1
	Length-frequency distributions for foraging generalists include size classes showing annual recruitment.	1	1	1	2	2	2	2	2
	Relative abundance and biomass of common carp do not increase in the absence of increases in abundance and biomass of flow-dependent native fish.	1	1	2	2	2	1	1	1

6. Conceptual models for in-channel Environmental Water Requirements

The conceptual models here are a synthesis of details (with provenance of statements and assumptions) provided in *Hydrodynamic Modelling Results and Conceptual Models*.

Ideally, flow deliveries should attempt to mimic the modelled natural hydrograph. However, forecasts of equivalent natural flow currently are not provided with the 4-week operational forecast routinely provided by the MDBA. This limits the ability to manage the hydrograph to match or mimic the hydrograph that would have occurred under 'modelled natural conditions' in that particular scenario. Forecasts of modelled natural conditions may soon become available, but in the interim the general patterns of a natural hydrograph should be mimicked.

The Resource Availability Scenarios (RAS) relevant to determining priorities for applying environmental water defined by MDBA (2012d) are outlined in Table 6.1. Alignments between these priorities and each in-channel EWR are shown in the respective conceptual models.

Table 6.1. Management outcomes for Resource Availability Scenarios (adapted from MDBA, 2012d).

	Resource Availability Scenario				
	Very dry	Dry	Moderate	Wet	Very wet
Management Outcomes	**Avoid irretrievable loss or damage to environmental assets**	**Ensure environmental assets maintain basic functions and resilience**	**Maintain ecological health and resilience**	**Improve health and resilience of water-dependent ecosystems**	**Improve health and resilience of water-dependent ecosystems**
	Avoid critical loss of species, communities and ecosystems. Maintain critical refuges. Avoid irretrievable damage or catastrophic events. Allow drying to occur, where appropriate, but relieve severe unnaturally prolonged dry periods.	Support the survival and viability of threatened species and communities. Maintain environmental assets and ecosystem functions, including by allowing drying to occur consistent with natural wetting-drying cycles. Maintain refuges.	Enable growth, reproduction and small-scale recruitment for a diverse range of flora and fauna. Promote low-lying floodplain-river connectivity. Support medium-flow river and floodplain functions.	Enable growth, reproduction and large-scale recruitment for a diverse range of flora and fauna. Promote higher floodplain-river connectivity. Support high-flow river and floodplain functions.	Enable growth, reproduction and large-scale recruitment for a diverse range of flora and fauna. Promote higher floodplain-river connectivity. Support high-flow river and floodplain functions.

6.1. Entitlement flows: 3000-7000 ML day^{-1} (base-case)

6.1.1. Background

The *Murray-Darling Basin Agreement 2008* ('the Agreement') sets out the arrangements for sharing and management of the Basin's water resources, particularly of the River Murray System. It is the primary determinant of the volume, pattern and quality of water delivered to South Australia. Under the terms of the Agreement, South Australia is entitled to a *maximum* of 1850 GL year^{-1}, regardless of water availability in the Basin. Further detail on the seasonal pattern of delivery of entitlement flows is provided in section 3.2. The variable 'Consumptive' Entitlement is provided over a water year, in proportional monthly quantities that co-vary with consumptive (irrigation) demands; lower volumes (3000 ML day^{-1}) are provided in the cooler months, and peak volumes (7000 ML day^{-1}) are delivered in the warmer months (see Figure 3.1).

Comparison between modelled natural and existing conditions

Under pre-development conditions, (modelled natural) flows of 3000 ML day^{-1} for 60 days occurred every year. Flows of 7000 ML day^{-1} occurred for 60 days in 99.1% of years. Under existing conditions, these flows occur in 90.4% of years.

6.1.2. High level objectives

Dry condition resource availability scenario

Flows of this magnitude maintain low-flow, refugia-style conditions during very dry conditions. Within the Basin Plan Guidelines, the management objectives for this scenario are to avoid irretrievable loss or damage to environmental assets:

- Avoid critical loss of threatened species, communities and ecosystems,
- Maintain key refuges,
- Avoid irretrievable damage or catastrophic events, and
- Allow drying to occur, where appropriate, but relieve severe unnaturally prolonged dry periods.

6.1.3 Velocity and surface water levels

Velocity

Under modelled natural conditions, all velocity classes are present at flows ≥3000 ML day^{-1}. Under existing conditions, at QSA = 3000 ML day^{-1}, effectively all (99.8%) of the lower pool reach has velocity <0.1 m s^{-1} and there is no habitat with velocity >0.15 m s^{-1} (Figure 3.2). Even at QSA = 7000 ML day^{-1}, 54% of the lower reach has velocity <0.1 m s^{-1} and <2% has velocity >0.15 m s^{-1} (Table 3.5, Figure 3.2).

Surface water levels

The modelled data indicate that with QSA = 7000 ML day^{-1} and normal Lock 3 pool level (9.80 m AHD), the tailwater effect elevates the surface water level (SWL) in the last kilometre of the upper reach 0.44 m above that at 3000 ML day^{-1} (Table 3.4). Modelled backwater curves are shown in Figures 7.1–7.2.

6.1.4. Expected ecological conditions

Carbon and nutrients and primary productivity

It is anticipated that carbon and nutrient concentrations will depend on upstream inputs and in-channel retention, so that the lower Murray will be a sink for these resources and the system will be dominated by autotrophic production. Changes in carbon and nutrient concentration and availability are likely to be driven by water source. The difference in SWL between minimum and maximum entitlement flows will alter the light environment for biofilms, but any potential benefit towards reducing the dominance of filamentous algae in biofilms is negated by the slow rate of change in discharge and extended periods of stable discharge and water levels. Therefore, the influence of SWL variation on the light regime for biofilms will be greatest in periods of high turbidity (e.g. Darling River inflows), when the photic depth is shallow.

Low water velocity (<0.1 $m\ s^{-1}$) and high solar radiation in summer mean that the development and persistence of thermal stratification will depend upon wind conditions. In warm periods with low wind speed there is a risk of persistent stratification in some reaches that may support the development and persistence of harmful or nuisance algal blooms. The shift in spatio-temporal distribution of velocity mosaics and microhabitats (e.g. formation and breakdown of slackwater habitats) associated with changes in water level will have more impact on ecological outcomes than is suggested by the velocity values.

Fish

Foraging generalist fish species are likely advantaged under low-flow conditions in the channel. Low flows allow proliferation of submerged vegetation, favoured habitat for small-bodied generalist species, and may also enhance the recruitment of these species. Species that prefer or require higher flow conditions (apex predators, flow-dependent specialists, freshwater catfish) are likely not to breed.

Vegetation

Submergent aquatic vegetation: Submergent aquatic plants will be restricted to permanent and semi-permanent habitats.

Emergent aquatic vegetation: Emergent aquatic plants will be restricted to a narrow band around permanent habitats with a slightly wider distribution in the upper weir pools due to greater variation in water levels compared with the lower weir pool.

Floodplain understorey: Floodplain understorey will be restricted to the narrow band around permanent habitats subject to wetting and drying. As for emergent aquatic plants, the distribution will be slightly wider in the upper weir pool due to greater variation in water levels.

Long-lived floodplain vegetation: Lateral recharge to generate near-bank freshwater lenses is likely to be minimal except in localised areas where soil conditions and surface water and regional groundwater levels are conducive to the development/maintenance of losing reaches. The condition of long-lived species outside of the aforementioned areas is likely to decline in the absence of higher flows.

Invertebrates

Many invertebrate species along the pool margins are associated with emergent and submerged plants (e.g. insects, spiders, crustaceans), so that invertebrate diversity depends indirectly upon the effect of water-level changes on littoral plants. Submerged plants are a refuge for invertebrates (and small fish and other vertebrates). Slow-moving molluscs (most snails, freshwater mussels) can be stranded by rapid falls in water level.

Wetlands

At these flows, there will be little lateral connectivity to temporary floodplain wetlands and habitat diversity will be low.

6.2. IC 1: median QSA = 10,000 ML day^{-1}

6.2.1. Suggested EWR

Median discharge (ML day^{-1})	Range in discharge (ML day^{-1})	Duration (days)	Timing	Average return frequency (years)	Percent of years flow is required	Maximum return interval (years)	Percentage of years that discharge and duration are likely to be met under BP2800
10,000	7000–12,000	60	Sep–Mar	1.05	95	2	90

Example hydrographs indicating how environmental water could be delivered to complement existing flow, mimic the modelled natural hydrograph and achieve this EWR are shown in Figures 6.1 A-B.

Comparison to modelled natural and existing conditions
Under modelled natural conditions, QSA would have exceeded 10,000 ML day^{-1} for 60 days in 97.4% of years. Under 2009 conditions, this discharge occurs in 73.7% of years.

6.2.2. High level objectives

Flows of this magnitude provide variation to within-channel, low-flow conditions during dry resource availability scenarios. In the Basin Plan guidelines, the objectives for this water resource availability scenario are to ensure that environmental assets maintain their basic functions and resilience:

- Support the survival and viability of threatened species and ecological communities,
- Maintain environmental assets and ecosystem functions, allowing drying that is consistent with natural wetting-drying cycles, and
- Maintain refuges.

6.2.3. Velocity and surface water levels

Velocity
Under modelled natural conditions, all velocity classes are present at QSA = 10,000 ML day^{-1}. Under existing conditions, approximately 21% of the lower pool reach has velocity <0.1 m s^{-1}. This is the minimum flow at which the modelling indicates that fast (>0.25 m s^{-1}) habitat begins to appear, but the proportion is extremely low (<1%) (Table 3.5, Figure 3.2).

Surface water levels
The modelled data indicate that at 10,000 ML day^{-1} and normal Lock 3 pool level (9.80 m AHD), the SWL level in the upper pool is 10.85 m AHD (Table 3.4). This is 0.34 m above that which occurs at 7000 ML day^{-1}. Modelled backwater curves are shown in Figures 7.1–7.2.

6.2.4. Expected ecological conditions

Carbon and nutrients and primary productivity
It is anticipated that carbon and nutrient concentrations will depend on upstream inputs and in-channel retention, so that the lower Murray will be a sink for these resources and the system will be dominated by autotrophic production. Changes in carbon and nutrient concentration and availability are likely to be driven

by water source. It is unlikely that persistent stratification and conditions conducive to harmful algal blooms will occur. The 0.61 m variation in SWL in the upper pool between 7000 and 12,000 ML day^{-1} will substantially alter the light environment for biofilms in the upper section of the weir pool. This has the potential to promote bacterial rather than algal dominance of biofilms and improve food quality for consumers. Very slow rates of water level change and extended periods of stable flow conditions need to be avoided to maximise outcomes.

Fish

Foraging generalist fish species are likely to benefit under low-flow conditions in the channel. Low flows allow proliferation of submerged vegetation, favoured habitat for small-bodied generalist species, and may enhance the recruitment of these species (Humphries et al., 1999). Species that prefer or require higher flow conditions (apex predators, flow-dependent specialists, freshwater catfish) are likely not to breed.

Vegetation

Submergent aquatic vegetation: Submergent aquatic plants will be restricted to permanent and semi-permanent habitats and under the proposed scenario the distribution is unlikely to change.

Emergent aquatic vegetation: Emergent aquatic plants probably will be restricted to a narrow band surrounding permanent habitats, with a slightly wider distribution in the upper weir pools. The 0.34 m increase in water level in the upper weir pool may facilitate recruitment of emergent species in this zone.

Floodplain understorey: Floodplain understorey will be restricted to the narrow band around permanent habitats subject to wetting and drying under the scenario. The distribution will be slightly wider in the upper weir pool, due to greater variation in water levels, and recruitment would be expected in areas inundated after water levels recede.

Long-lived floodplain vegetation: Variation in surface water levels will increase potential for lateral recharge to generate near-bank freshwater lenses in the upper reaches of the weir pool, which may result in an improvement in the condition of long-lived species close to the edges of permanent habitats.

Invertebrates

Many invertebrate species along the pool margins are associated with emergent and submerged plants (e.g. insects, spiders, crustaceans), so that invertebrate diversity depends indirectly upon the effect of water-level changes on littoral plants. Submerged plants are a refuge for invertebrates (and small fish and other vertebrates). Hence there will be a marginal expansion of habitats available to species associated with littoral plants. Slow-moving molluscs (most snails, freshwater mussels) can be stranded by rapid falls in water level.

Wetlands

At these flows, there will be little lateral connectivity to temporary floodplain wetlands and creeks and habitat diversity will be low.

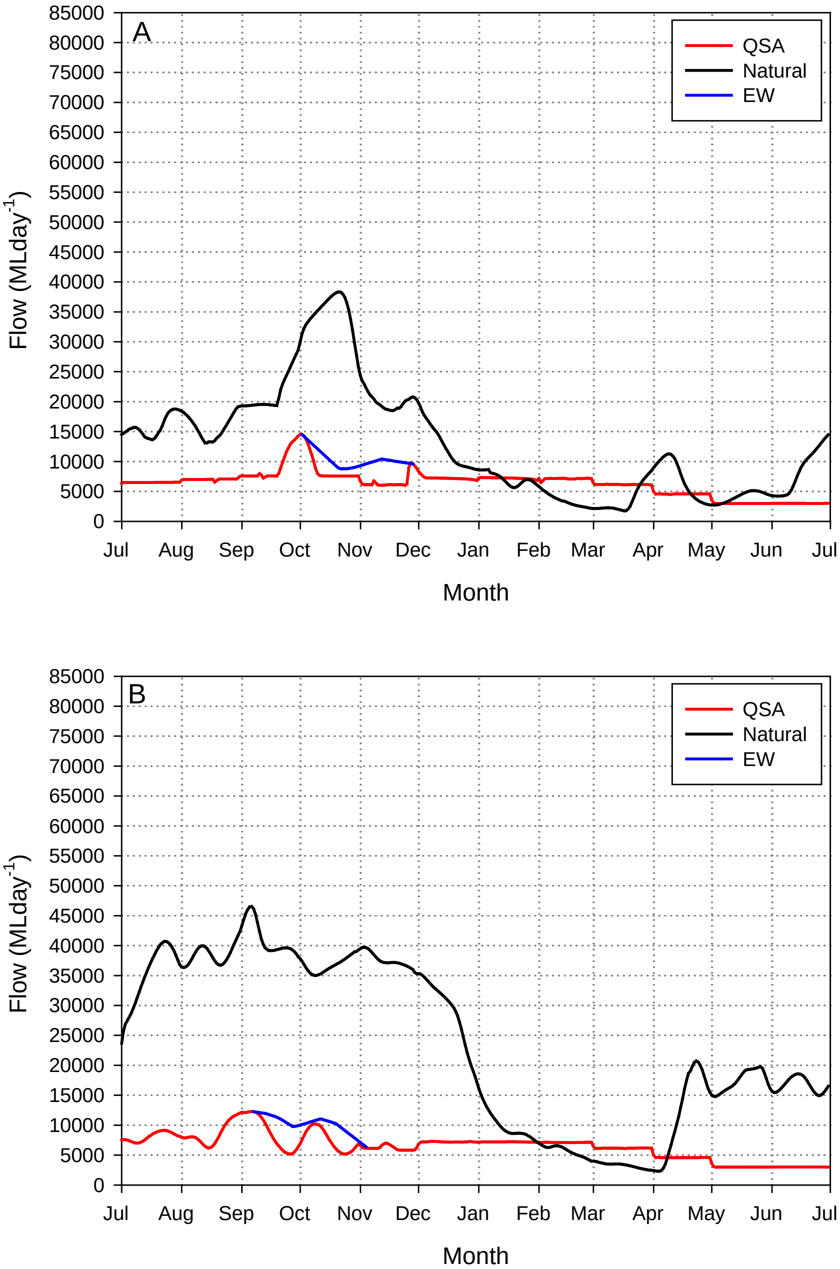


Figure 6.1. Example hydrographs indicating how environmental water could be delivered to complement existing flow, mimic the modelled natural hydrograph and achieve the EWR for this flow band. QSA = recorded flow into SA for year, Natural = modelled natural flow for the year, EW = Environmental Water. Water use for example A and B is 153 GL and 150 GL, respectively. For each event, a decision needs to be made on the best way to augment the hydrographs with environmental water. The decision to (i) extend a peak or (ii) achieve a higher elevation will be driven by the duration over which the hydrograph can be sustained—the peak must be sustained enough to achieve ecological outcomes—the most suitable event is the highest magnitude of flow that can be sustained long enough to meet the EWR duration.

6.3. IC 2: median QSA = 15,000 ML day^{-1}

6.3.1. Suggested EWR

Median discharge (ML day^{-1})	Range in discharge (ML day^{-1})	Duration (days)	Timing	Average return frequency (years)	Percent of years flow is required	Maximum return interval (years)	Percentage of years that discharge and duration are likely to be met under BP2800
15,000	15,000–20,000	90	Sep–Mar	1.33	75	2	77

Example hydrographs indicating how environmental water could be delivered to complement existing flow, mimic the modelled natural hydrograph and achieve this EWR are shown in Figures 6.2 A-B.

Comparison to modelled natural and existing conditions
Under modelled natural conditions, QSA would have exceeded 15,000 ML day^{-1} for 90 days in 96 % of years. Under 2009 conditions, this discharge occurs in 46 % of years.

6.3.2. High level objectives

Flows of this magnitude provide variation to within channel, low-flow conditions during moderate resource availability scenarios. In the Basin Plan guidelines, the objectives for this water resource availability scenario are to maintain ecological health and resilience:

- Enable growth, reproduction and small-scale recruitment for a diverse range of flora and fauna,
- Promote low-lying floodplain-river connectivity, and
- Support medium-flow river and floodplain functions.

6.3.3. Velocity and surface water levels

Velocity
Under modelled natural conditions, all velocity classes are present at QSA = 15,000 ML day^{-1}. Under existing conditions, approximately 11% of the lower reach has velocity <0.1 m s^{-1}. The modelling indicates that at QSA = 15,000 ML day^{-1}, moderate-fast (0.18–0.25 m s^{-1}) habitat is abundant, but fast (>0.25 m s^{-1}) habitat is still scarce compared to modelled natural conditions (Table 3.5, Figure 3.2).

Surface water levels
The modelled data indicate that at 15,000 ML day^{-1} and normal Lock 3 pool level (9.80 m AHD), the SWL level in the upper end of the weir pool is 11.41 m AHD. This is 0.9 m above that which occurs at 7000 ML day^{-1} (10.51 m AHD) (Table 3.4). Modelled backwater curves are shown in Figures 7.1–7.2.

6.3.4. Expected ecological conditions

Carbon and nutrients and primary productivity
It is anticipated that carbon and nutrient concentrations will be dominated by upstream inputs and in-channel retention such that the lower River Murray will be a sink for resources and the system will be dominated by autotrophic production. Changes in carbon and nutrient concentration and availability are likely to be driven by water source. It is highly unlikely that persistent stratification and conditions conducive

to the maintenance of harmful algal blooms will occur. The 0.9 m variation in SWL in the upper pool between 7000 and 15,000 ML day^{-1} will substantially alter the light environment for biofilms in the upper section of the weir pool. This has the potential to promote bacterial rather than algal dominance of biofilms and improve food quality for consumers. Very slow rates of water level change and extended periods of stable flow conditions need to be avoided to maximise outcomes.

Fish

Foraging generalist fish species are likely to be present and common under these conditions, but favourable habitat in the form of submerged vegetation may begin to be lost temporarily, at flows of this magnitude (see vegetation section), although the effect is likely to be relatively minor. Slightly greater stage height may provide greater access to emergent vegetation and other physical structure for spawning.

Flow of approximately 15,000 ML day^{-1} is considered conducive to reproductive activity in the flow-dependent specialists, golden perch and silver perch. Flows of this magnitude, when temperature thresholds (>20°C) are exceeded, may facilitate the drift of larvae from upstream areas as well as potentially eliciting a local spawning response. An event where water temperatures are above the minimum threshold for common carp and goldfish (15°C), but below the minimum threshold for large-bodied native species, may disadvantage regional native fish if there is large-scale recruitment of invasive species.

Flows of this magnitude may be adequate for promoting limited recruitment of Murray cod. Larvae will be present seasonally at all flow volumes, but survival of larvae (hence recruitment) may be improved at flows >15,000 ML day^{-1}. Mechanism for improved recruitment, however, remains unresolved. It should be noted that recent data suggest that detecting recruitment of Murray cod is often delayed by up to two years.

Vegetation

Submergent aquatic vegetation: Submergent aquatic plants will be restricted to permanent and semi-permanent habitats and under the proposed scenario the distribution is unlikely to change. With a water level increase of 0.9 m there may be temporary loss of deeper beds of submergent macrophytes in the upper weir pool due to higher water levels limiting light for photosynthesis.

Emergent aquatic vegetation: Emergent aquatic plants will be restricted to a narrow band around permanent habitats in the lower weir pool; however, there is potential for recruitment higher up the elevation gradient in the upper weir pool in areas inundated by the higher water levels (Blanch et al. 2000).

Floodplain understorey: As for emergent aquatic plants, floodplain understorey will be restricted to a narrow band around permanent habitats in the lower weir pool; however, there is potential for recruitment (after water levels recede) higher up the elevation gradient in the upper weir pool in areas inundated by the higher water levels.

Long-lived floodplain vegetation: Variations in surface water level will provide capacity to increase the width of the riparian zone in the upper reaches due to the comparatively high variability in water level variability in the tail-water. Variation in surface water levels will increase potential for lateral recharge to generate near bank freshwater lens in the upper reaches of the weir pool, which may result in an improvement in the condition of long-lived species close to the edges of permanent habitats.

Invertebrates

Many invertebrate species along the pool margins are associated with emergent and submerged plants (e.g. insects, spiders, crustaceans), so that invertebrate diversity depends indirectly upon the effect of water-level changes on littoral plants (see below). Submerged plants are a refuge for invertebrates (and small fish and other vertebrates). Hence it is expected that there will be a marginal expansion of habitats available to species associated with littoral plants. Slow-moving molluscs (most snails, freshwater mussels) can be stranded by rapid falls in water level.

Wetlands

At these flows, there will be little lateral connectivity to temporary wetlands. Some early commence to flow wetlands will begin to fill at the upper limit of the EWR. Water levels and hence area inundated may be altered in some permanent wetlands, particularly in the upper pool where water levels vary substantially.

6.3.5. Recommendation

Variation in discharge should be managed to produce short-term increases in flow towards 20,000 ML day^{-1}. Downward variation in flow (i.e. short periods of flow of 12,000 ML day^{-1}) may be counterproductive in this case due to the difference in conditions between modelled natural and existing conditions at flow <15,000 ML day^{-1} (Table 3.5).

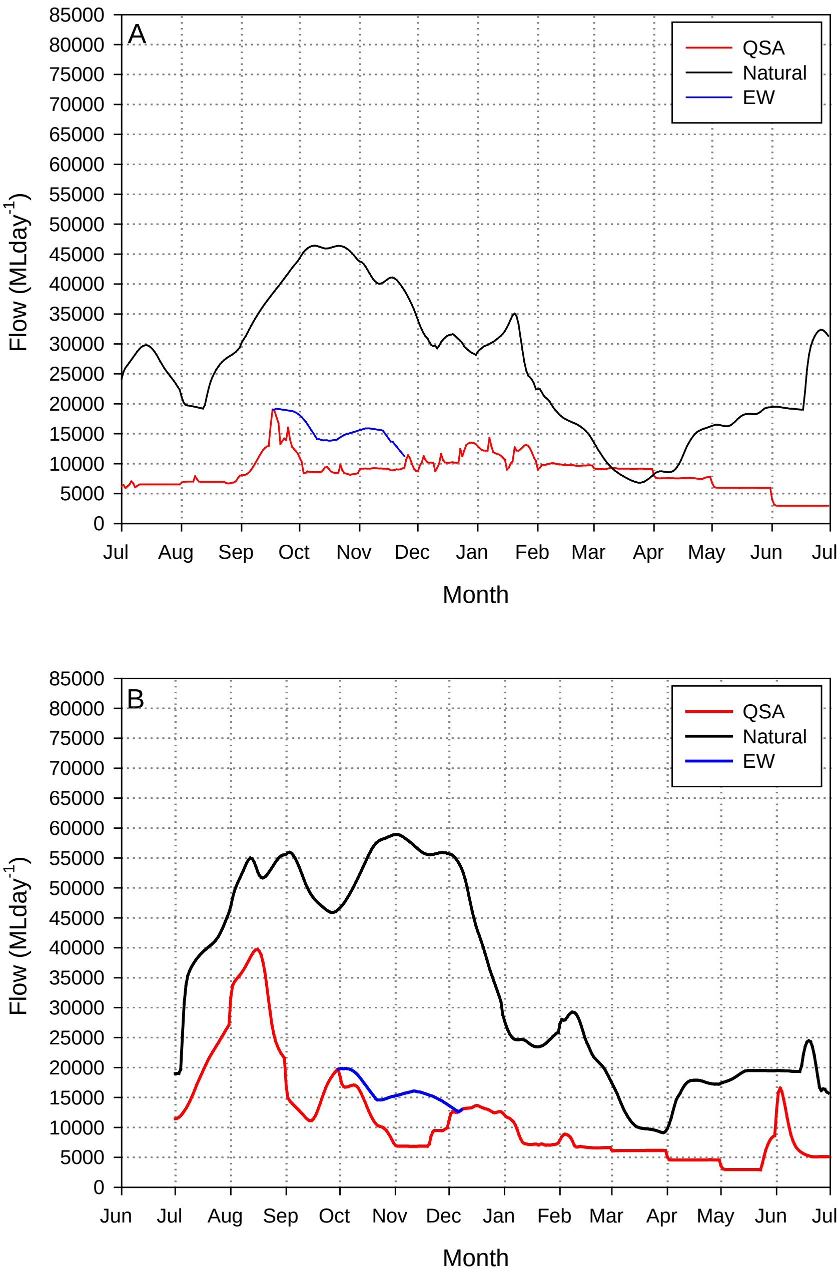


Figure 6.2. Example hydrographs indicating how environmental water could be delivered to complement existing flow, mimic the modelled natural hydrograph and achieve the EWR for this flow band. QSA = recorded flow into SA for year, Natural = modelled natural flow for the year, EW = Environmental Water. Water use for example A and B is 382 GL and 350 GL, respectively. For each event, a decision needs to be made on the best way to augment the hydrographs with environmental water. The decision to (i) extend a peak or (ii) achieve a higher elevation will be driven by the duration over which the hydrograph can be sustained—the peak must be sustained enough to achieve ecological outcomes—the most suitable event is the highest magnitude of flow that can be sustained long enough to meet the EWR duration.

6.4. IC3: median QSA = 20,000 ML day^{-1}

6.4.1. Suggested EWR

Median discharge (ML day^{-1})	Range in discharge (ML day^{-1})	Duration (days)	Timing	Average return frequency (years)	Percent of years flow is required	Maximum return interval (years)	Percentage of years that discharge and duration are likely to be met under BP2800
20,000	15,000–25,000	90	Sep–Mar	1.8	55	2	67

Example hydrographs indicating how environmental water could be delivered to complement existing flow, mimic the modelled natural hydrograph and achieve this EWR are shown in Figures 6.3 A-B.

Comparison to modelled natural and existing conditions
Under modelled natural conditions, QSA would have exceeded 20,000 ML day^{-1} for 90 days in 90 % of years. Under 2009 conditions, this discharge occurs in 39 % of years.

6.4.2. High level objectives

Flows of this magnitude provide variation to within channel, low-flow conditions during moderate resource availability scenarios. Within the Basin Plan Guidelines, the objectives for this water resource availability scenario are to maintain ecological health and resilience:

- Enable growth, reproduction and small-scale recruitment for a diverse range of flora and fauna,
- Promote low-lying floodplain-river connectivity, and
- Support medium-flow river and floodplain functions.

6.4.3. Velocity and surface water levels

Velocity
Under modelled natural conditions, all velocity classes are present at QSA = 20,000 ML day^{-1}. Under existing conditions, approximately 8% of the lower reach has velocity <0.1 m s^{-1}. The modelling indicates that at QSA = 20,000 ML day^{-1}, fast (>0.25 m s^{-1}) habitat becomes abundant (Table 3.5, Figure 3.2).

Surface water levels
The modelled data indicate that at 20,000 ML day^{-1} and normal Lock 3 pool level (9.80 m AHD), the SWL level in the uppermost reaches of the Lock 3 weir pool is 11.84 m AHD. This is 1.33 m above that which occurs at 7000 ML day^{-1} (10.51 m AHD) (Table 3.4). Modelled backwater curves are shown in Figure 7.1-7.2.

6.4.3. Expected ecological conditions

Carbon and nutrients and primary productivity
At flows of 20,000 ML day^{-1} inundation of the riparian zone and early commence to flow wetlands will start to influence the load of carbon and nutrients in the water column. It is estimated that at 20,000 ML day^{-1} and normal weir pool operating heights, the load of FRP and DOC will be ~5.85 and 1100 kilotonnes respectively. Heterotrophic activity will become increasingly important in net ecosystem productivity. Phytoplankton communities are likely to be dominated by diatoms. The 1.33 m variation in SWL in the upper pool between

7000 and 20,000 ML day^{-1} will substantially alter the light environmental for biofilms in this upper section of the weir pool. Velocities in some areas may be approaching the threshold at which scouring of existing biofilms may occur, creating surface area available for colonisation by early successional state taxa. The magnitude of biogeochemical response will be mediated by day-length and water temperature. Very slow rates of water level change and extended periods of stable flow conditions need to be avoided to maximise outcomes.

Fish

Foraging generalist fish species are likely to be present and common under these conditions, but favourable habitat in the form of submerged vegetation may begin to be temporarily lost at flows of this magnitude (see vegetation section), although the effect is likely to be relatively minor and limited to the upper weir pool. Slightly greater stage height may provide greater access to emergent vegetation and other physical structure for spawning. Inundation of temporary wetlands and raised water levels in permanent wetlands may increase off-channel habitat availability for these species. Wetlands that currently support floodplain specialists (Murray hardyhead) may experience hydrological connection with the main channel and variability in water levels. This may have benefits in regards to salinity mitigation, increased habitat availability and enhanced spawning and recruitment.

Flow of approximately 20,000 ML day^{-1} is considered conducive to reproductive activity in flow-dependent specialists, golden perch and silver perch. Flows of this magnitude, when temperature thresholds (>20°C) are exceeded, may facilitate the drift of larvae from upstream areas as well as potentially eliciting a local spawning response. An event where water temperatures are above the minimum threshold for common carp and goldfish (15°C), but below the minimum threshold for large-bodied native species, may disadvantage regional native fish if there is large-scale recruitment of invasive species.

Flows of this magnitude may be adequate for promoting limited recruitment of Murray cod. Larvae will be present seasonally at all flow volumes, but survival of individuals may occur at flows >20,000 ML day^{-1}. Strong age classes of Murray cod have been associated with years of flow volumes >20,000 ML day^{-1} in the lower River Murray. It should be noted that recent data suggest that detecting recruitment of Murray cod is often delayed by up to two years. Thus, while juveniles may be present, they may not be detected for some time.

Vegetation

Submergent aquatic vegetation: Submergent aquatic plants will be restricted to permanent and semi-permanent habitats and under the proposed scenario the distribution is unlikely to change. With a water level increase of 1.33 m, there may be temporary loss of deeper beds of submergent macrophytes in the upper weir pool due to higher water levels limiting light for photosynthesis.

Emergent aquatic vegetation: Emergent aquatic plants will be restricted to a narrow band around permanent habitats in the lower weir pool; however, there is potential for recruitment higher up the elevation gradient in the upper weir pools and the 2284.9 ha of temporary wetlands inundated by higher water levels.

Floodplain understorey: As for emergent plants, floodplain understorey will be restricted to a narrow band around permanent habitats in the lower weir pool; however, there is potential for recruitment higher up the elevation gradient after water levels recede in the upper weir pools and in the 2284.9 ha of temporary wetlands inundated by the higher water levels.

Long-lived floodplain vegetation: At 20,000 ML day^{-1} QSA and normal weir pool operating heights 1580.7 ha of river red gum woodland is inundated, where tree condition will improve. In addition, tree condition just outside the area inundated will improve due to lateral recharge of groundwater and increased soil water availability.

Invertebrates

Many invertebrate species along the pool margins are associated with emergent and submerged plants (e.g. insects, spiders, crustaceans), so that invertebrate diversity depends indirectly upon the effect of water-level changes on littoral plants (see below). Submerged plants are a refuge for invertebrates (and small fish and other vertebrates). Hence it is expected that there will be a significant expansion of habitats available to species associated with littoral plants. Slow-moving molluscs (most snails, freshwater mussels) can be stranded by rapid falls in water level.

Wetlands

The area of temporary wetland inundated in the gorge and valley sections of the lower Murray will be 802.6 and 1468.7 ha, respectively (total 2284.9 ha). Water levels and hence area inundated may be altered in some permanent wetlands, particularly in the upper pool where water levels vary substantially.

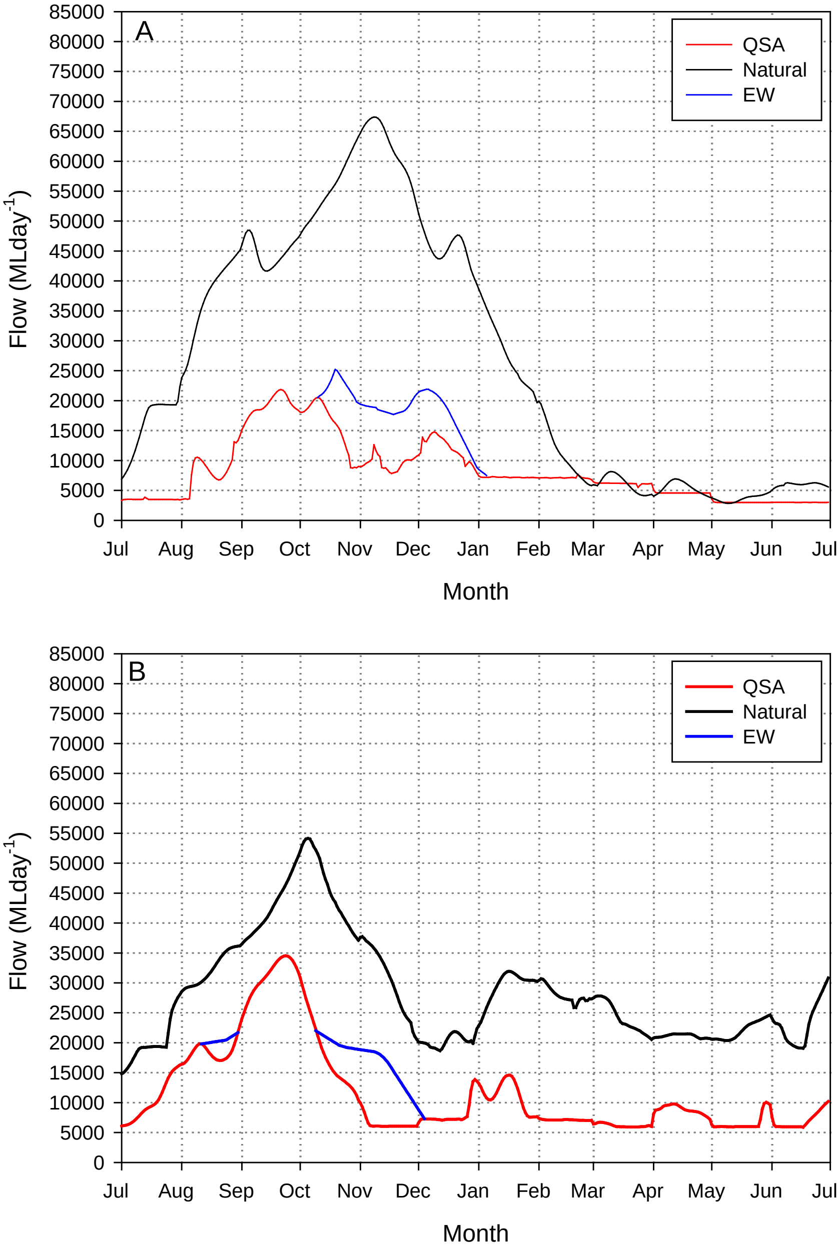


Figure 6.3. Example hydrographs indicating how environmental water could be delivered to complement existing flow, mimic the modelled natural hydrograph and achieve the EWR for this flow band. QSA = recorded flow into SA for year, Natural = modelled natural flow for the year, EW = Environmental Water. Water use for example A and B is 611 GL and 425 GL, respectively. For each event, a decision needs to be made on the best way to augment the hydrographs with environmental water. The decision to (i) extend a peak or (ii) achieve a higher elevation will be driven by the duration over which the hydrograph can be sustained—the peak must be sustained enough to achieve ecological outcomes—the most suitable event is the highest magnitude of flow that can be sustained long enough to meet the EWR duration.

6.5. IC4: QSA = 25,000 ML day^{-1}

6.5.1. Suggested EWR

Median discharge (ML day^{-1})	Range in discharge (ML day^{-1})	Duration (days)	Timing	Average return frequency (years)	Percent of years flow is required	Maximum return interval (years)	Percentage of years that discharge and duration are likely to be met under BP2800
25,000	20,000–30,000	60	Sep–Mar	1.7	59	2	67

Example hydrographs indicating how environmental water could be delivered to complement existing flow, mimic the modelled natural hydrograph and achieve this EWR are shown in Figures 6.4 A-B.

Comparison to modelled natural and existing conditions
Under modelled natural conditions, QSA would have exceeded 25,000 ML day^{-1} for 60 days in 88 % of years. Under 2009 conditions, this discharge occurs in 44 % of years.

6.5.2. High level objectives

Flows of this magnitude provide variation to within channel, moderate-flow conditions during moderate resource availability scenarios. In the Basin Plan guidelines, the objectives for this water resource availability scenario are to maintain ecological health and resilience:

- Enable growth, reproduction and small-scale recruitment for a diverse range of flora and fauna,
- Promote low-lying floodplain-river connectivity, and
- Support medium-flow river and floodplain functions.

6.5.3. Velocity and surface water levels

Velocity
Under modelled natural conditions, all velocity classes are present at QSA = 25,000 ML day^{-1}. Under existing conditions, less than 6% of the lower reach has velocity <0.1 m s^{-1}. The modelling indicates that at QSA = 25,000 ML day^{-1}, fast (>0.25 m s^{-1}) habitat is dominant (Table 3.5, Figure 3.2).

Surface water levels
The modelled data indicate that at 25,000 ML day^{-1} and normal Lock 3 pool level (9.80 m AHD), the SWL level in the upper pool is 12.29 m AHD. This is 1.78 m above that which occurs at 7,000 ML day^{-1} (10.51 m AHD) (Table 3.4). Modelled backwater curves are shown in Figures 7.1–7.2.

6.5.4. Expected ecological conditions

Carbon and nutrients and primary productivity
At flows of 25,000 ML day^{-1} the influence of inundation of the riparian zone and early commence to flow wetlands will increase the load of carbon and nutrients in the water column. It is estimated that at 25,000 ML day^{-1} and normal weir pool operating heights, the loads of FRP and DOC will be about 6.1 and 1146 kilotonnes, respectively. Heterotrophic activity will become increasingly important in net ecosystem productivity. Phytoplankton communities are likely to be dominated by diatoms. The 1.78 m variation in SWL

in the upper pool between 7,000 and 25,000 ML day^{-1} will substantially alter the light environment for biofilms in the upper section of the weir pool. Velocities in some areas may be approaching the threshold at which scouring of existing biofilms may occur, creating surface area available for colonisation by early successional state taxa. The magnitude of biogeochemical response will be mediated by day-length and water temperature. Slow rates of water level change and extended periods of stable flow conditions should be avoided to maximise outcomes.

Fish

Foraging generalist fish species are likely to be present under these conditions, but favourable habitat in the form of submerged vegetation will be temporarily lost at flows of this magnitude (see vegetation section), particularly in the upper weir pool. Slightly greater stage height may provide greater access to emergent vegetation and other physical structure for spawning. Inundation of temporary wetlands and raised water levels in permanent wetlands may increase off-channel habitat availability and promote lateral movement of these species. Wetlands that currently support floodplain specialists (Murray hardyhead) may experience hydrological connection with the main channel and variability in water levels. This may have benefits in regards to salinity mitigation, increased habitat availability and enhanced spawning and recruitment.

Flow of approximately 25,000 ML day^{-1} is considered conducive to reproductive activity in flow-dependent specialists, golden perch and silver perch. Flows of this magnitude, when temperature thresholds (>20°C) are exceeded, may facilitate the drift of larvae from upstream areas as well as potentially eliciting a local spawning response. An event where water temperatures are above the minimum threshold for common carp and goldfish (15°C), but below the minimum threshold for large-bodied native species, may disadvantage regional native fish if there is large-scale recruitment of invasive species.

Flows of this magnitude may promote limited recruitment of Murray cod. Larvae will be present seasonally at all flow volumes, but survival of individuals may occur at flows >25,000 ML.day^{-1}. Strong age classes of Murray cod have been associated with years of flow volumes >25,000 ML.day^{-1} in the lower Murray. It should be noted that recent data suggest that detecting recruitment of Murray cod is often delayed by up to two years. Thus, while juveniles may be present, they may not be detected for some time. Flows of this volume may stimulate upstream migration of mature fish.

Vegetation

Submergent aquatic vegetation: The water level increase of 1.78 m may result in temporary loss of beds of submergent macrophytes in the upper weir pool due to higher water levels limiting light for photosynthesis.

Emergent aquatic vegetation: Emergent aquatic plants will be restricted to a narrow band around permanent habitats in the lower weir pool; however, there is potential for recruitment higher up the elevation gradient in the upper weir pools and in 2381.4 ha of temporary wetlands inundated by higher water levels

Floodplain understorey: As for emergent plants, floodplain understorey will be restricted to a narrow band surrounding permanent habitats in the lower weir pool; however, there is potential for recruitment higher up the elevation gradient after water levels recede in the upper weir pools and in 2381.4 ha of temporary wetlands inundated by higher water levels

Long-lived floodplain vegetation: At QSA = 25,000 ML day^{-1} and normal weir pool operating heights, 1642.8 ha of river red gum woodland is inundated, so that tree condition should improve. In addition, tree condition just outside the inundated area will improve due to lateral recharge of groundwater and increased soil water availability.

Invertebrates

Many invertebrate species along the pool margins are associated with emergent and submerged plants (e.g. insects, spiders, crustaceans), so that invertebrate diversity depends indirectly upon the effect of water-level changes on littoral plants (see below). Submerged plants are a refuge for invertebrates (and small fish and other vertebrates). Given the expected contraction of submergent vegetation associated with increasing depth in the upper reaches, there may be a proportional contraction of species associated with littoral plants. Slow-moving molluscs (most snails, freshwater mussels) can be stranded by rapid falls in water level.

Wetlands

The area of temporary wetland inundated in the gorge and valley sections of the lower River Murray will be 849.9 and 1571.8 ha, respectively (total 2381.4 ha). Water levels and hence area inundated may be altered in some permanent wetlands, particularly in the upper pool where water levels vary substantially.

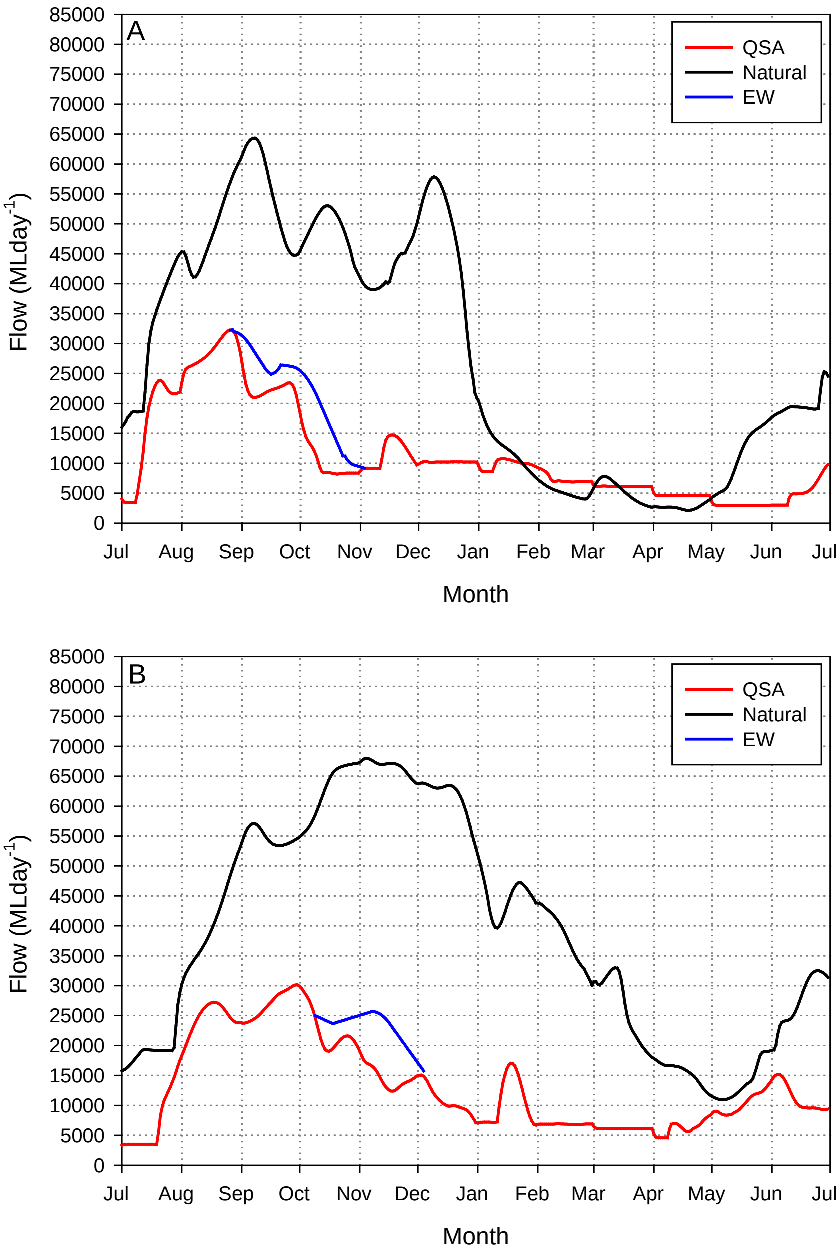


Figure 6.4. Example hydrographs indicating how environmental water could be delivered to complement existing flow, mimic the modelled natural hydrograph and achieve the EWR for this flow band. QSA = recorded flow into SA for year, Natural = modelled natural flow for the year, EW = Environmental Water. Water use for example A and B is 352 GL and 334 GL, respectively. For each event, a decision needs to be made on the best way to augment the hydrographs with environmental water. The decision to (i) extend a peak or (ii) achieve a higher elevation will be driven by the duration over which the hydrograph can be sustained—the peak must be sustained enough to achieve ecological outcomes—the most suitable event is the highest magnitude of flow that can be sustained long enough to meet the EWR duration.

6.6. IC5: QSA = 30,000 ML day^{-1}

6.6.1. Suggested EWR

Median discharge (ML day^{-1})	Range in discharge (ML day^{-1})	Duration (days)	Timing	Average return frequency (years)	Percent of years flow is required	Maximum return interval (years)	Percentage of years that discharge and duration are likely to be met under BP2800
30,000	25,000–35,000	60	Sep–Mar	1.8	55	2	59

Example hydrographs indicating how environmental water could be delivered to complement existing flow, mimic the modelled natural hydrograph and achieve this EWR are shown in Figures 6.5 A-B.

Comparison to modelled natural and existing conditions
Under modelled natural conditions, QSA would have exceeded 30,000 ML day^{-1} for 60 days in 82 % of years. Under 2009 conditions, this discharge occurs in 39 % of years.

6.6.2. High level objectives

Flows of this magnitude provide variation to within channel, moderate-flow conditions during moderate resource availability scenarios. In the Basin Plan guidelines, the objectives for this water resource availability scenario are to maintain ecological health and resilience:

- Enable growth, reproduction and small-scale recruitment for a diverse range of flora and fauna,
- Promote low-lying floodplain-river connectivity, and
- Support medium-flow river and floodplain functions.

6.6.3. Velocity and surface water levels

Velocity
Under modelled natural conditions, all velocity classes are present at QSA = 30,000 ML day^{-1}. Under existing conditions, less than 5% of the lower reach has velocity <0.1 m s^{-1}. The modelling indicates that at QSA = 30,000 ML day^{-1}, fast (>0.25 m s^{-1}) habitat is dominant (Table 3.5, Figure 3.2).

Surface water levels
The modelled data indicate that at 30,000 ML day^{-1} and normal Lock 3 pool level (9.80 m AHD), the SWL level in the upper end of the weir pool is 12.73 m AHD (Table 3.4). This is 2.22 m above that which occurs at 7000 ML day^{-1} (10.51 m AHD). Modelled backwater curves are shown in Figures 7.1–7.2.

6.6.4. Expected ecological conditions

Carbon and nutrients and primary productivity
At flows of 30,000 ML day^{-1} the step point in area inundated will lead to a marked increase in the load of carbon and nutrients in the water column. It is estimated that at 30,000 ML day^{-1} and normal weir pool levels, the loads of FRP and DOC will be about 7.05 and 1,286 kilotonnes, respectively. Heterotrophic activity will become increasingly important in net ecosystem productivity. Phytoplankton communities are likely to be dominated by diatoms. The 2.22 m variation in SWL in the upper pool between 7000 and 30,000 ML day^{-1}

will substantially alter the light environment for biofilms in the upper section of the weir pool. Velocities in some areas may be approaching the threshold at which scouring of existing biofilms occurs, creating surface area available for colonisation by early-successional taxa. The magnitude of biogeochemical response will be mediated by day-length and water temperature. Slow rates of water-level change and extended periods of stable flow conditions should be avoided to maximise outcomes.

Fish

Foraging generalist fish species are likely to be present under these conditions, but the main channel will become increasingly unfavourable to these species. Reductions in submerged vegetation and the resulting loss of foraging areas, increased predation risk and exposure to high water velocities contribute to declines in the abundance of these species in the main channel. Recruitment is likely to be limited relative to low flow years. Significant inundation of temporary wetlands and raised water levels in permanent wetlands may increase off-channel habitat availability and promote lateral movement of these species. Wetlands that currently support floodplain specialists (Murray hardyhead) may experience hydrological connection with the main channel and variability in water levels. This may have benefits in regards to salinity mitigation, increased habitat availability and enhanced spawning and recruitment.

Flow of approximately 30,000 ML day^{-1} is considered conducive to the spawning and recruitment of flow-dependent specialists, golden perch and silver perch. Flows of this magnitude, when temperature thresholds (>20°C) are exceeded, may facilitate the drift of larvae from upstream areas as well as potentially eliciting a local spawning response. An event where water temperatures are above the minimum threshold for common carp and goldfish (15°C), but below the minimum threshold for large-bodied native species, may disadvantage regional native fish if there is large-scale recruitment of invasive species.

Flows of this magnitude may promote limited recruitment of Murray cod. Larvae will be present seasonally at all flow volumes, but survival of individuals may occur at flows >30,000 ML.day^{-1}. Strong age classes of Murray cod have been associated with years of flow volumes >30,000 ML.day^{-1} in the lower Murray. It should be noted that recent data suggest that detecting recruitment of Murray cod is often delayed by up to two years. Thus, while juveniles may be present, they may not be detected for some time. Flows of this volume may stimulate upstream migration of mature fish.

Vegetation

Submergent aquatic vegetation: The water level increase of 2.22 m may result in temporary loss of beds of submergent macrophytes in the upper weir pool due to higher water levels limiting light for photosynthesis.

Emergent aquatic vegetation: Emergent aquatic plants will be restricted to a narrow band around permanent habitats in the lower weir pool; however, there is potential for recruitment higher up the elevation gradient in the upper weir pools and 2791.2 ha of temporary wetlands inundated by the higher water levels. Further, there may be temporary loss of emergent species due to top flooding in the upper weir pools.

Floodplain understorey: As for emergent plants, floodplain understorey will be restricted to a narrow band around permanent habitats in the lower weir pool; however, there is potential for recruitment higher up the elevation gradient after water levels recede in the upper weir pools and in 2791.2 ha of temporary wetlands inundated by the higher water levels (Blanch et al. 2000).

Long-lived floodplain vegetation: At QSA = 25,000 ML day^{-1} and normal weir pool operating heights 1830.8 ha of river red gum woodland is inundated, so that tree condition should improve. In addition, tree condition just outside the area inundated will improve due to lateral recharge of groundwater and increased soil water availability.

Invertebrates

Many invertebrate species along the pool margins are associated with emergent and submerged plants (e.g. insects, spiders, crustaceans), so that invertebrate diversity depends indirectly upon the effect of water-level changes on littoral plants (see below). Submerged plants are a refuge for invertebrates (and small fish and other vertebrates). Given the expected contraction of submergent vegetation associated with increasing depth in the upper reaches, there may be a proportional contraction of species associated with littoral plants. Slow-moving molluscs (most snails, freshwater mussels) can be stranded by rapid falls in water level.

Wetlands

There is a step point in area of wetlands inundated between flows of 25,000 and 30,000 ML day^{-1}, indicating that a marked gain in area of habitat can be achieved by targeting an increase in flows from c. 25,000 to 30,000 ML day^{-1}. The area of temporary wetland inundated in the gorge and valley sections of the lower Murray increases from 849.9 to 1011.8 ha in the gorge region, and from 1517.8 to 1765.7 ha in the valley region (total increases from 2381.4 to 2791.2 ha). Water levels and hence area inundated may be altered in some permanent wetlands, particularly in the upper pool where water levels vary substantially.

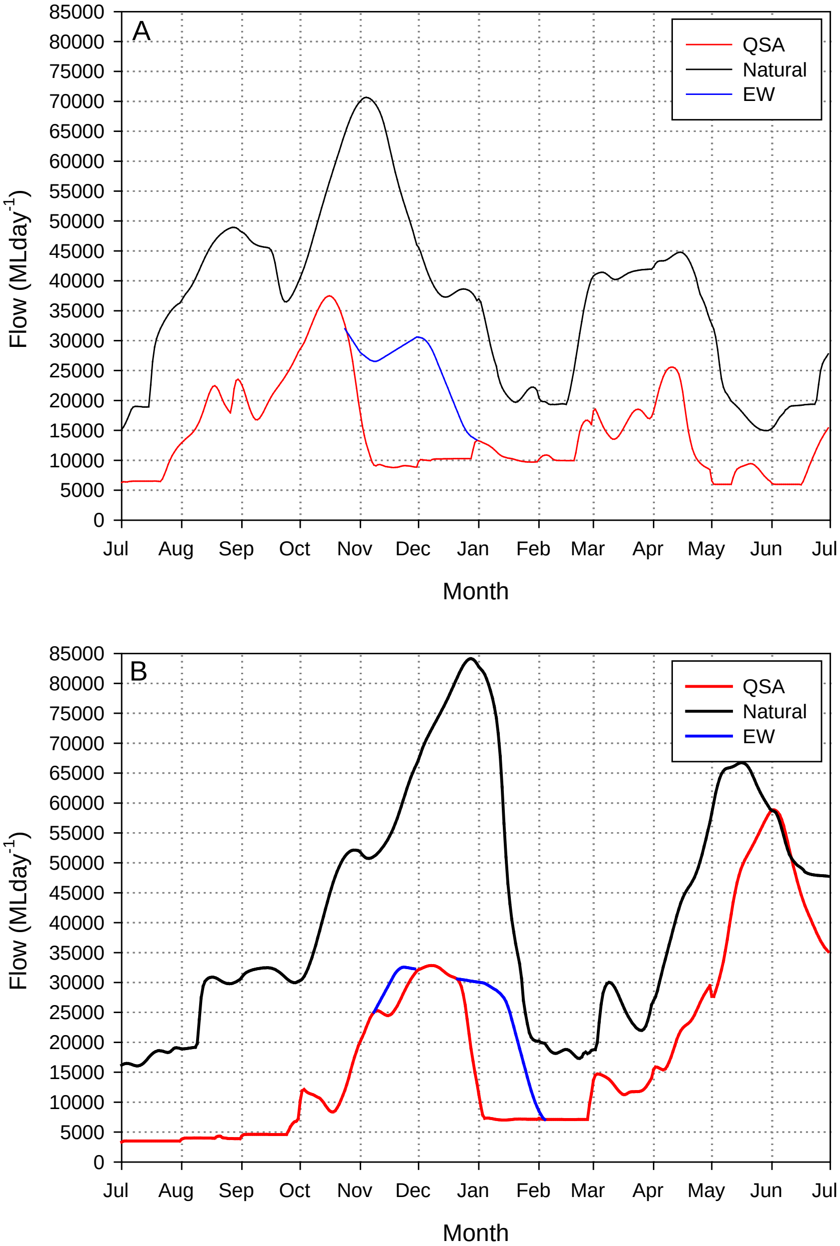


Figure 6.5. Example hydrographs indicating how environmental water could be delivered to complement existing flow, mimic the modelled natural hydrograph and achieve the EWR for this flow band. QSA = recorded flow into SA for year, Natural = modelled natural flow for the year, EW = Environmental Water. Water use for example A and B is 932 GL and 639 GL, respectively. For each event, a decision needs to be made on the best way to augment the hydrographs with environmental water. The decision to (i) extend a peak or (ii) achieve a higher elevation will be driven by the duration over which the hydrograph can be sustained—the peak must be sustained enough to achieve ecological outcomes—the most suitable event is the highest magnitude of flow that can be sustained long enough to meet the EWR duration.

6.7. IC6: QSA = 35,000 ML day^{-1}

6.7.1. Suggested EWR

Median discharge (ML day^{-1})	Range in discharge (ML day^{-1})	Duration (days)	Timing	Average return frequency (years)	Percent of years flow is required	Maximum return interval (years)	Percentage of years that discharge and duration are likely to be met under BP2800
35,000	30,000–40,000	60	Sep–Mar	1.8	55	2	46

Example hydrographs indicating how environmental water could be delivered to complement existing flow, mimic the modelled natural hydrograph and achieve this EWR are shown in Figures 6.6 A–B.

Comparison to modelled natural and existing conditions

Under modelled natural conditions, QSA would have exceeded 35,000 ML day^{-1} for 60 days in 81 % of years. Under 2009 conditions, this discharge occurs in 30% of years.

6.7.2. High level objectives

Flows of this magnitude provide variation to within channel, moderate-flow conditions during moderate resource availability scenarios. In the Basin Plan guidelines, the objectives for this water resource availability scenario are to maintain ecological health and resilience:

- Enable growth, reproduction and small-scale recruitment for a diverse range of flora and fauna
- Promote low-lying floodplain-river connectivity.
- Support medium-flow river and floodplain functions.

6.7.3. Velocity and surface water levels

Velocity

Under modelled natural conditions, all velocity classes are present at QSA = 35,000 ML day^{-1}. Under existing conditions, less than 4% of the lower reach has velocity <0.1 m s^{-1}. The modelling indicates that at QSA = 35,000 ML day^{-1}, fast (>0.25 m s^{-1}) habitat is dominant (Table 3.5, Figure 3.2).

Surface water levels

The modelled data indicate that at 35,000 ML day^{-1} and normal Lock 3 pool level (9.80 m AHD), the SWL level in the upper end of the weir pool is 13.12 m AHD (Table 3.4). This is 2.61 m above that which occurs at 7000 ML day^{-1} (10.51 m AHD). Modelled backwater curves are shown in Figures 7.1–7.2.

6.7.4. Expected ecological conditions

Carbon and nutrients and primary productivity

It is estimated that at 35,000 ML day^{-1}, the loads of FRP and DOC from inundated plant material and soils will be about 7.6 and 1,442 kilotonnes, respectively. Heterotrophic activity will become increasingly important in net ecosystem productivity. Phytoplankton communities are likely to be dominated by diatoms. The 2.61 m variation in SWL in the upper pool between 7000 and 35,000 ML day^{-1} will substantially alter the light environment for biofilms in the upper section of the weir pool. Velocities are likely to be sufficient to generate some scouring of existing biofilms, creating surface area available for colonisation by early-successional taxa. The magnitude of biogeochemical response will be mediated by day-length and water temperature. Slow rates of water-level change and extended periods of stable flow conditions should be avoided to maximise outcomes.

Fish

Foraging generalist fish species are likely to be present under these conditions, but the channel will become increasingly unfavourable to these species. Reductions in submerged vegetation, and potentially emergent vegetation, and the resulting loss of foraging areas, increased predation risk and exposure to high water velocities will contribute to declines in their abundance in the main channel. Recruitment is likely to be limited relative to low-flow years. Significant inundation of temporary wetlands and raised water levels in permanent wetlands may increase off-channel habitat availability and promote lateral movement of these species. Wetlands that currently support floodplain specialists (Murray hardyhead) may experience hydrological connection with the main channel and variability in water levels. This may have benefits in regards to salinity mitigation, increased habitat availability and enhanced spawning and recruitment. Higher levels of connectivity between off-channel and main channel environments may promote dispersal of Murray hardyhead.

Flow of approximately 35,000 ML day^{-1} is considered conducive to the spawning and recruitment of flow-dependent specialists, golden perch and silver perch. Flows of this magnitude, when temperature thresholds (>20℃) are exceeded may facilitate the drift of larvae from upstream areas as well as potentially eliciting a local spawning response. An event where water temperatures are above the minimum threshold for common carp and goldfish (15°C), but below the minimum threshold for large-bodied native species, may disadvantage regional native fish if there is large-scale recruitment of invasive species.

Flows of this magnitude may be adequate for promoting recruitment of Murray cod. Larvae will be present seasonally at all flow volumes, but survival of individuals may improve at flows >35,000 ML.day^{-1}. Strong age classes of Murray cod have been associated with years of flow volumes >35,000 ML.day^{-1} in the lower River Murray. It should be noted that recent data suggest that detecting recruitment of Murray cod is often delayed by up to two years. Thus, while juveniles may be present, they may not be detected for some time. Flows of this volume may stimulate upstream migration of mature fish.

Vegetation

Submergent aquatic vegetation: The water level increase of 2.61 m may result in temporary loss of beds of submergent macrophytes in the upper weir pool due to higher water levels limiting light for photosynthesis.

Emergent aquatic vegetation: Emergent aquatic plants will be restricted to a narrow band around permanent habitats in the lower weir pool; however, there is potential for recruitment higher up the elevation gradient in the upper weir pools and 2935.6 ha of temporary wetlands inundated by the higher water levels. Further, there may be temporary loss of emergent species due to top-flooding in the upper weir pools. Water velocities in the mid- and lower weir pools may flatten stands of emergent plants, leading to top-flooding.

Floodplain understorey: As for emergent plants, floodplain understorey will be restricted to a narrow band around permanent habitats in the lower weir pool; however, there is potential for recruitment higher up the elevation gradient after water levels recede in the upper weir pools and in 2935.6 ha of temporary wetlands inundated by the higher water levels (Blanch et al. 2000).

Long-lived floodplain vegetation: At QSA = 35,000 ML day^{-1} and normal weir pool operating heights, 2073.5 ha of river red gum woodland is inundated, so that tree condition should improve. In addition, tree condition just outside the area inundated will improve due to lateral recharge of groundwater and increased soil water availability.

Invertebrates

Many invertebrate species along the pool margins are associated with emergent and submerged plants (e.g. insects, spiders, crustaceans), so that invertebrate diversity depends indirectly upon the effect of water-level changes on littoral plants (see below). Submerged plants are a refuge for invertebrates (and small fish and other vertebrates). Given the expected contraction of submergent vegetation associated with increasing depth in the upper reaches, there may be a proportional contraction of species associated with littoral plants. Slow-moving molluscs (most snails, freshwater mussels) can be stranded by rapid falls in water level.

Wetlands

The area of temporary wetland inundated in the gorge and valley sections of the lower River Murray will be 1076.9 ha and 1844.9 ha, respectively (total = 2935.6 ha). Water levels and hence area inundated may be altered in some permanent wetlands, particularly in the upper pool where water levels vary substantially.

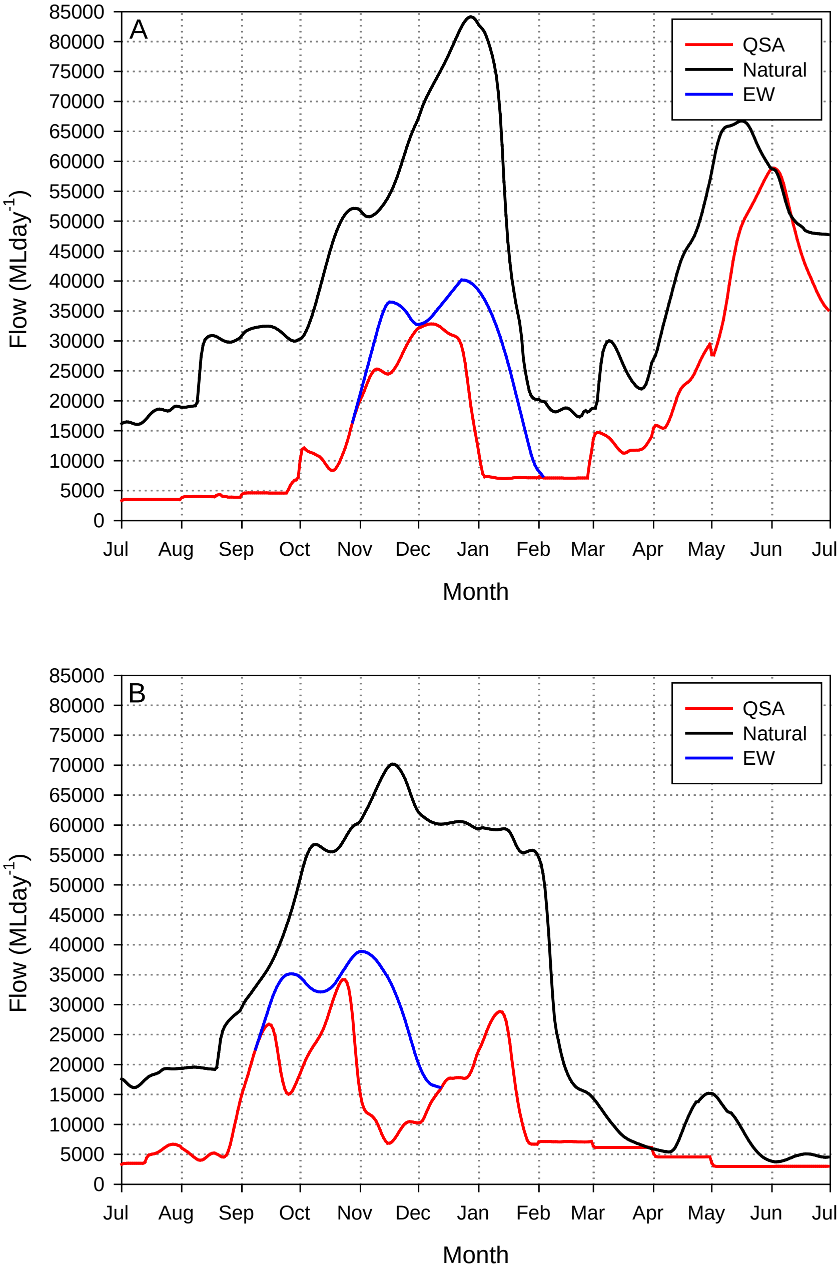


Figure 6.6. Example hydrographs indicating how environmental water could be delivered to complement existing flow, mimic the modelled natural hydrograph and achieve the EWR for this flow band. QSA = recorded flow into SA for year, Natural = modelled natural flow for the year, EW = Environmental Water. Water use for example A and B is 988 GL and 1213 GL, respectively. For each event, a decision needs to be made on the best way to augment the hydrographs with environmental water. The decision to (i) extend a peak or (ii) achieve a higher elevation will be driven by the duration over which the hydrograph can be sustained—the peak must be sustained enough to achieve ecological outcomes—the most suitable event is the highest magnitude of flow that can be sustained long enough to meet the EWR duration.

6.8. IC7: QSA = 40,000 ML day^{-1}

6.8.1. Suggested EWR

Median discharge (ML day^{-1})	Range in discharge (ML day^{-1})	Duration (days)	Timing	Average return frequency (years)	Percent of years flow is required	Maximum return interval (years)	Percentage of years that discharge and duration are likely to be met under BP2800
40,000	35,000–45,000	90	Sep–Mar	2.1	48	3	31

Example hydrographs indicating how environmental water could be delivered to complement existing flow, mimic the modelled natural hydrograph and achieve this EWR are shown in Figures 6.7 A–B.

Comparison to modelled natural and existing conditions
Under modelled natural conditions, QSA would have exceeded 40,000 ML day^{-1} for 90 days in 57% of years. Under 2009 conditions, this discharge occurs in 20 % of years.

6.8.2. High level objectives

Flows of this magnitude provide variation to within channel, moderate-flow conditions during moderate resource availability scenarios. In the Basin Plan guidelines, the objectives for this water resource availability scenario are to maintain ecological health and resilience:

- Enable growth, reproduction and small-scale recruitment for a diverse range of flora and fauna,
- Promote low-lying floodplain-river connectivity, and
- Support medium-flow river and floodplain functions.

The 90 day duration for the 40,000 ML day^{-1} EWR (IC7, Table 5.2) is provided due to the increase in area of wetland vegetation/habitat types that occurs at this flow magnitude. This would support improved outcomes by providing time for wetlands to achieve stable water levels, for habitat and food resources to develop, and for plants/animals to complete their lifecycles. The SA Riverland–Chowilla floodplain objectives for this magnitude and duration of flow are:

- Maintain and improve majority of lower elevation (c. 20%) temporary wetlands in healthy condition; and inundation of lower elevation temporary wetlands for small-scale bird and fish breeding events, and microbial decay/export of organic matter.

6.8.3. Velocity and surface water levels

Velocity
Under modelled natural conditions, all velocity classes are present at QSA = 40,000 ML day^{-1}. Under existing conditions, less than 4% of the lower pool reach has velocity <0.1 m s^{-1}. The modelling indicates that at QSA = 40,000 ML day^{-1}, fast (>0.25 m s^{-1}) habitat is dominant (Table 3.5, Figure 3.2).

Surface water levels
The modelled data indicate that at 40,000 ML day^{-1} and normal Lock 3 pool level (9.80 m AHD), the SWL level in the upper end of the weir pool is 13.49 m AHD (Table 3.4). This is 2.98 m above that which occurs at 7000 ML day^{-1} (10.51 m AHD). Modelled backwater curves are shown in Figures 7.1–7.2.

6.8.4. Expected ecological conditions

Carbon and nutrients and primary productivity
It is estimated that there will be a marked increase in the load of FRP and DOC resulting from the increase in flow from 35,000 to 40,000 ML day^{-1}, with loads estimated to be about 8.6 and 1,788 kilotonnes, respectively. Heterotrophic activity will become increasingly important in net ecosystem productivity. Phytoplankton communities are likely to be dominated by diatoms. The 2.98 m variation in SWL in the upper pool between 7000 and 35,000 ML day^{-1} will substantially alter the light environment for biofilms in the upper weir pool. Velocities are likely to be sufficient to generate some scouring of existing biofilms, creating surface area available for colonisation by early-successional taxa. The magnitude of biogeochemical response will be mediated by day length and water temperature. Slow rates of water-level change and extended periods of stable flow conditions need to be avoided to maximise outcomes.

Fish
Foraging generalist fish species are likely to be present in significantly reduced abundance in the main channel under these conditions. Reductions in submerged vegetation and emergent vegetation cover, and loss of foraging areas, increased predation risk and exposure to high water velocities will contribute to declines in the abundance of these species in the channel. Recruitment is likely to be limited relative to low flow years. Significant inundation of temporary wetlands and raised water levels in permanent wetlands may increase off-channel habitat availability and promote lateral movements. Wetlands that currently support floodplain specialists (Murray hardyhead) may experience hydrological connection with the main channel and variability in water levels. This may have benefits in regards to salinity mitigation, increased habitat availability and enhanced spawning and recruitment. Higher levels of connectivity between off-channel and main-channel environments may promote dispersal of Murray hardyhead.

Flow of approximately 35,000 ML day^{-1} is considered conducive to the spawning and recruitment of flow-dependent specialists, golden perch and silver perch. Flows of this magnitude, when temperature thresholds (>20°C) are exceeded, may facilitate the drift of larvae from upstream areas as well as potentially eliciting a local spawning response. An event where water temperatures are above the minimum threshold for common carp and goldfish (15°C), but below the minimum threshold for large-bodied native species, may disadvantage regional native fish if there is large-scale recruitment of invasive species.

Flows of this magnitude may be adequate for promoting recruitment of Murray cod. Larvae will be present seasonally at all flow volumes, but survival of individuals may improve at flows >40,000 ML.day^{-1}. Strong age classes of Murray cod have been associated with years of flows >40,000 ML.day^{-1} in the lower Murray. It should be noted that recent data suggest that detecting recruitment of Murray cod is often delayed by up to two years. Thus, while juveniles may be present, they may not be detected for some time. Flows of this volume may stimulate upstream migration of reproductively mature fish.

Vegetation
Submergent aquatic vegetation: The water level increase of 2.98 m may result in temporary loss of beds of submergent macrophytes in the upper weir pool due to higher water levels limiting light for photosynthesis.

Emergent aquatic vegetation: Emergent aquatic plants will be restricted to a narrow band around permanent habitats in the lower weir pool; however, there is potential for recruitment higher up the elevation gradient in the upper weir pools and 3193.6 ha of temporary wetlands inundated by the higher water levels (Blanch et al. 2000). Further, there may be temporary loss of emergent species due to top flooding in the upper weir pools. Water velocities in the mid- and lower weir pools may flatten stands of emergent plants, leading to top-flooding.

Floodplain understorey: As for emergent plants, floodplain understorey will be restricted to a narrow band around permanent habitats in the lower weir pool; however, there is potential for recruitment higher up the elevation gradient after water levels recede in the upper weir pools and in 2935.6 ha of temporary wetlands inundated by the higher water levels (Blanch et al. 2000).

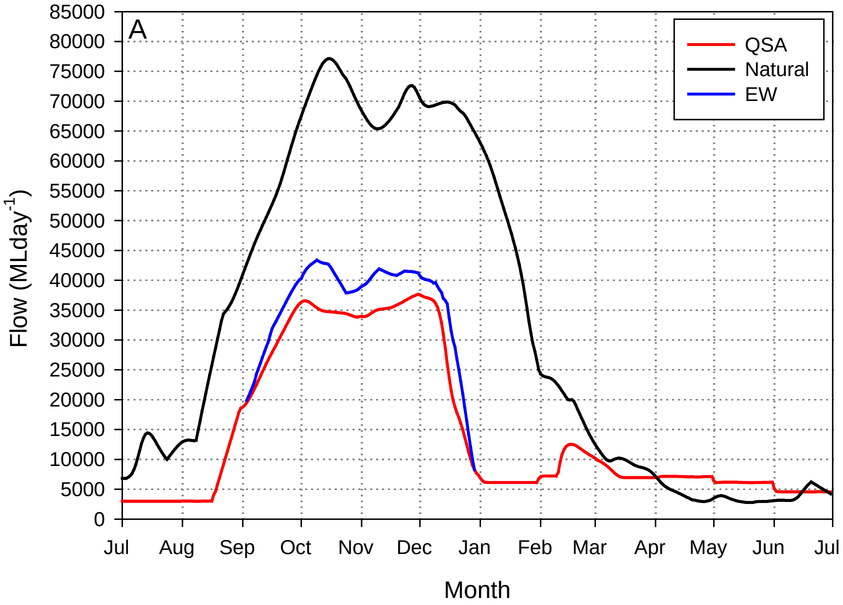
Long-lived floodplain vegetation: At QSA = 25,000 ML day^{-1} and normal weir pool operating heights, 2614.2 ha of river red gum woodland is inundated, so that tree condition should improve. In addition, tree condition just outside the area inundated will improve due to lateral recharge of groundwater and increased soil water availability.

Invertebrates

Many invertebrate species along the pool margins are associated with emergent and submerged plants (e.g. insects, spiders, crustaceans), so that invertebrate diversity depends indirectly upon the effect of water-level changes on littoral plants (see below). Submerged plants are a refuge for invertebrates (and small fish and other vertebrates). Given the expected contraction of submergent vegetation associated with increasing depth in the upper reaches, there may be a proportional contraction of species associated with littoral plants. Slow-moving molluscs (most snails, freshwater mussels) can be stranded by rapid falls in water level.

Wetlands

The area of temporary wetland inundated in the gorge and valley sections of the lower River Murray will be 1225.25 ha and 1946.9 ha, respectively (total = 3193.6 ha). Water levels and hence area inundated may be altered in some permanent wetlands, particularly in the upper pool where water levels vary substantially.



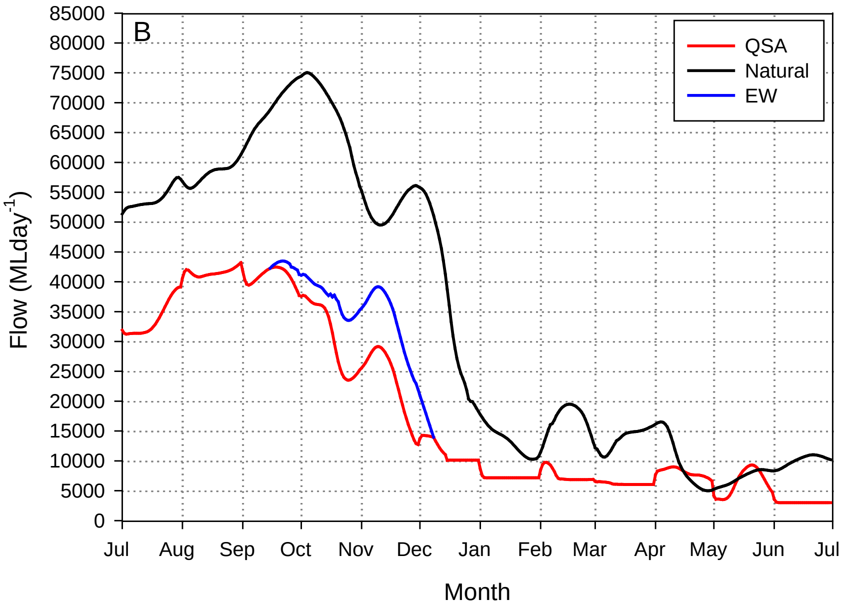


Figure 6.7. Example hydrographs indicating how environmental water could be delivered to complement existing flow, mimic the modelled natural hydrograph and achieve the EWR for this flow band. QSA = recorded flow into SA for year, Natural = modelled natural flow for the year, EW = Environmental Water. Water use for example A and B is 574 GL and 548 GL, respectively. For each event, a decision needs to be made on the best way to augment the hydrographs with environmental water. The decision to (i) extend a peak or (ii) achieve a higher elevation will be driven by the duration over which the hydrograph can be sustained—the peak must be sustained enough to achieve ecological outcomes—the most suitable event is the highest magnitude of flow that can be sustained long enough to meet the EWR duration.

7. Weir pool manipulation

7.1. Background

The effects of weirs on in-channel hydraulics are demonstrated by modelling described in the companion report, *Hydrodynamic Modelling Results and Conceptual Models*. The analysis shows that most impact on velocity occurs in the lowermost third of the Lock 3–4 weir pool (Table 3.10). This section shows how weir manipulation could contribute to achieving In-Channel Ecological Objectives and Targets, and is relevant to a weir-manipulation strategy being developed by DEWNR as part of the *Riverine Recovery Project*.

7.2. Capacity to manipulate water levels

Weirs on the lower Murray are periodically removed for routine maintenance or to maintain structural integrity in periods of high flow (moderate-large floods), but they can also be manipulated to impart variability in water levels, even during normal operations. Within engineering (structural) constraints, the weirs can be re-operated to raise or lower water levels independently of flow and thereby address some of the impacts of routine operations. Weir manipulations including (i) temporarily raising weirs to maximum structural height and increase the area that can be inundated (less velocity and longitudinal connectivity but more lateral connectivity) and (ii) temporarily lowering weirs (less lateral extent but more longitudinal connectivity and velocity).

7.3. Ecological rationale

Reinstating variability *via* re-operation of weirs has potential to restore, in part, seasonal patterns of water level, lateral connectivity and hydraulic diversity in impounded areas. Manipulating water levels in the channel or in weir pools may:

- Lead to increased exchange between near-bank groundwater and surface water to lower near bank groundwater salinity and/or create freshwater lenses and thereby improve soil-moisture availability for riparian vegetation, and
- Benefit many plant species, promoting diversity by restoring a wider range of water regimes.

The goals of the *SA Murray Weir Operation Strategy* (Cooling et al., 2010) are to:

- Increase in-channel water-level variability, to enhance:
    - plant diversity in the riparian zone,
    - temporary seasonal habitats,
    - germination/hatching of plants and invertebrates from sediments, and
    - river and wetland productivity,
- Create (reinstate) a wetting and drying regime in low-level wetlands,
- Improve the hydrological connectivity of anabranch channels,
- Create small-scale flooding events in low-lying floodplain habitats to enable feeding, breeding and recruitment opportunities for flood-dependent biota, and
- Promote cycling of carbon and nutrients within the river, anabranches, floodplain and wetlands.

Weir-pool raising trials in the lower Murray already have demonstrated positive outcomes for understorey vegetation (Siebentritt et al., 2004) and riparian trees (Souter et al., 2013).

7.4. Effects of weirs on surface water levels

The 'backwater curve' (the upstream longitudinal profile of the water surface) influences the magnitude of changes in water level at the weir and upstream in the weir pool. During routine operations, as flow increases the water level at the weir is maintained by increasing flow past the weir, but the level at upstream locations increases. Under current standard operating regimes, the weirs are managed to ensure relatively stable water levels (±50 mm) upstream of the structures, but the stabilising influence diminishes with distance upstream. In the tailwaters below each weir, levels fluctuate daily by ±200 mm (Maheshwari et al., 1995). Further, as flow increases the magnitude of impact on upstream water levels decreases. Thus, weir-pool manipulation has most impact on upstream water levels at low flows. The influence of Lock 3 on surface water levels relative to modelled natural conditions, existing conditions and manipulation of the operating height (+0.5 m raising and -0.25m lowering) of the weir is represented in Figure 7.1.

Table 7.1. Look up table for modelled surface water level (SWL) in the Lock 3-4 weir pool at Lock 3 and at the upper pool for (i) normal pool height, (ii) a -0.25 m lowering and (iii) a +0.5 m raising.

QSA (ML day^{-1})	Normal pool level		Effect of weir manipulation on upper pool SWL			
	SWL (m AHD)		-0.25 m lowering		+0.5 m raising	
	At Lock 3	Upper Pool	SWL (m AHD)	Change (m)	SWL (m AHD)	Change (m)
3000	9.80	10.08	10.00	-0.08	10.42	0.35
5000	9.80	10.27	10.17	-0.10	10.61	0.34
7000	9.80	10.51	10.42	-0.09	10.80	0.29
10,000	9.80	10.85	10.79	-0.06	11.08	0.23
12,000	9.80	11.12	11.08	-0.05	11.29	0.17
15,000	9.80	11.41	11.38	-0.03	11.56	0.15
20,000	9.80	11.84	11.81	-0.04	11.97	0.13
25,000	9.80	12.29	12.26	-0.03	12.40	0.12
30,000	9.80	12.73	12.70	-0.03	12.82	0.09
35,000	9.80	13.12	13.10	-0.02	13.20	0.08
40,000	9.80	13.49	13.47	-0.02	13.54	0.05

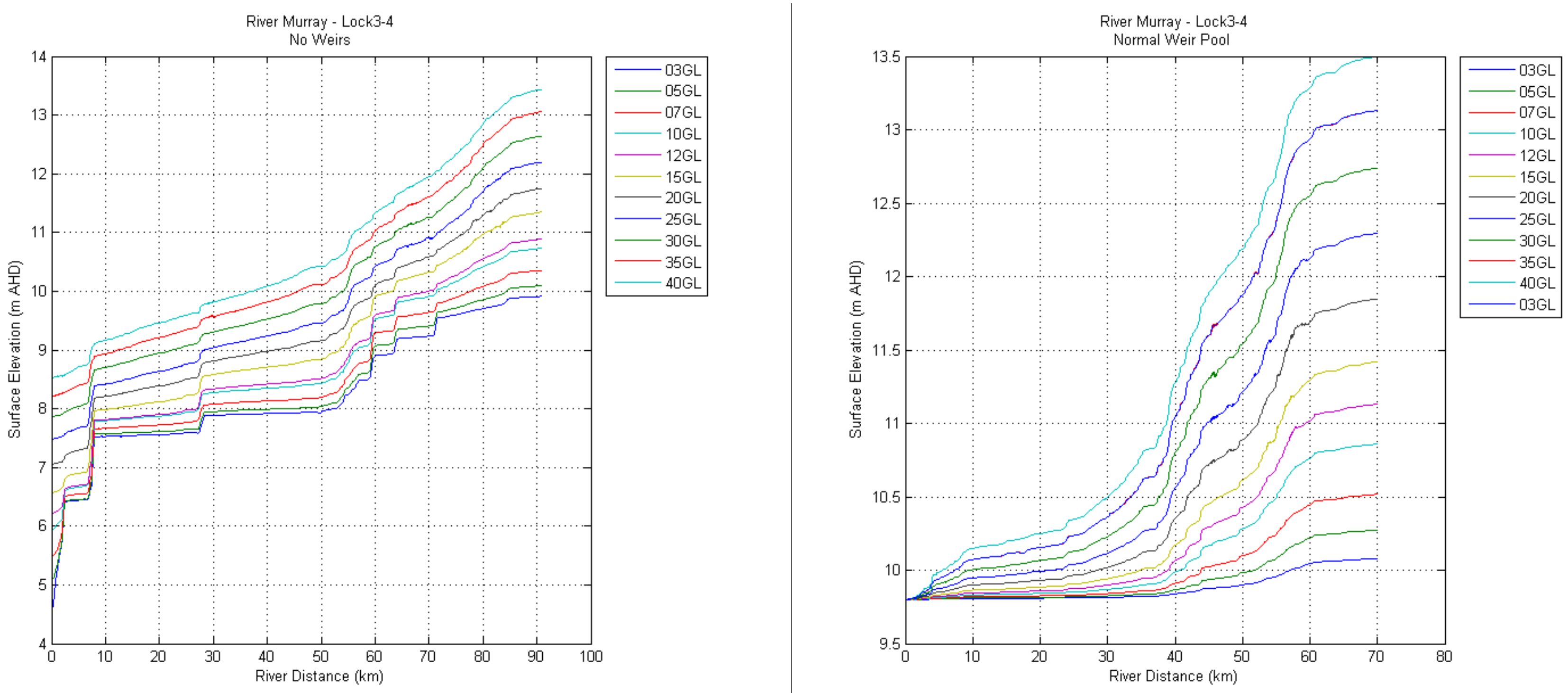


Figure 7.1. Modelled surface elevation (water levels, m AHD) for the Lock 3-4 reach. The left panel is for 'no weirs'; the right panel is normal pool level.

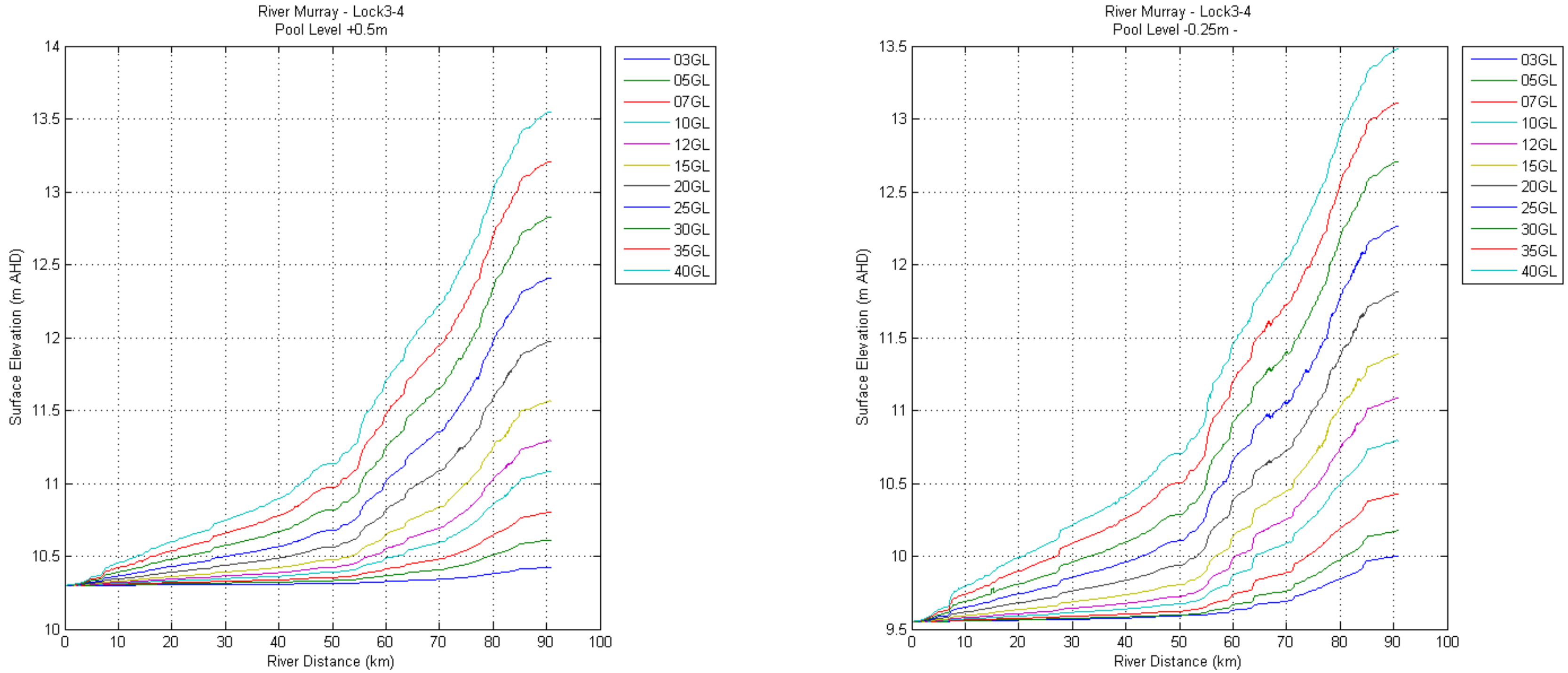


Figure 7.2. Modelled surface elevation (water levels, m AHD) for the Lock 3-4 reach. The left panel is for '0.5 m weir pool raising'; the right panel is for '0.25 m weir pool lowering'.

7.5. Effects on area inundated

Modelling by DEWNR (2012) for the Lock 3 weir pool demonstrates that raising the weir by 0.59 m at flows of 10,000 ML day^{-1} results in an increase in water level of about 0.2 m at the most upstream point of the pool, and inundates an additional 1556 ha (28%) than occurs at routine weir height. In contrast, at flows of 30,000 ML day^{-1}, the same 0.59 m raising has no discernible effect on water level at the most upstream point of the pool, but inundates 1849 ha (29%) more area than occurs at routine weir height.

For QSA = 50,000 ML day^{-1}, a 0.30 m weir pool raising inundates an additional 1212 ha (16%) above routine weir height, although the magnitude of this effect varies between weir pools. This assessment assumes steady-state conditions (river levels are elevated long enough to allow anabranches and wetlands to fill and reach equilibrium). Short-term weir manipulations will not achieve this, so that the area of influence will deviate from anticipated extents.

The relationship between weir-pool heights and areas occupied by vegetation is also explored by Cooling et al. (2010). At flows of 10,000 ML day^{-1}, 0.25 m raisings are ineffective at all weirs. Figure 7.2 shows the influence of weir-pool raising on additional areas of river red gum woodland inundated at QSA = 10,000 ML day^{-1}. This is the most responsive among 10 associations considered by Cooling et al. (2010). Thus, weir-pool raisings need to be in the mid- to maximum possible range to have a substantial ecological impact.

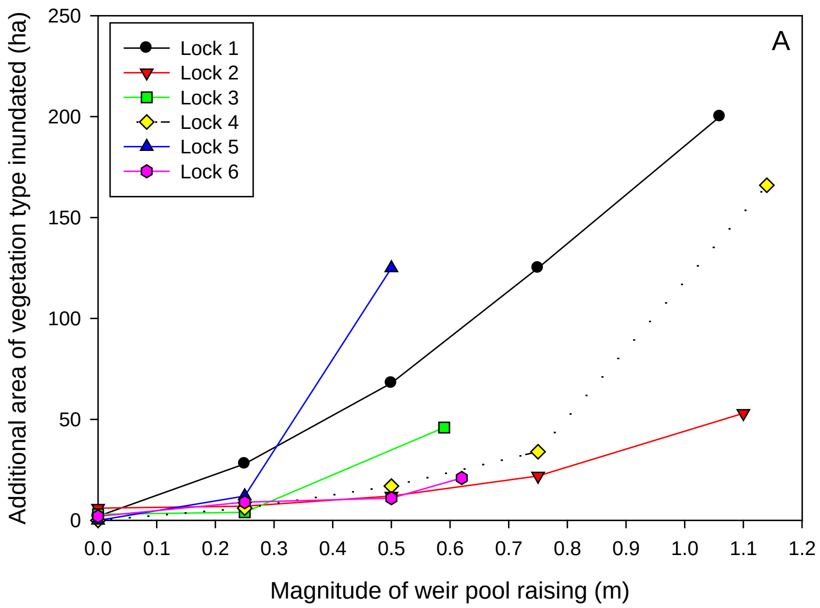


Figure 7.2. Influence of weir pool raising on additional area of river red gum woodland inundated at QSA = 10,000 ML day^{-1}.

7.6. Effects on mean channel velocity

7.6.1. Lock 3-4 reach

Modelling shows that most of the impact of weirs on in-channel velocity occurs in the lowermost third of the weir pools (Table 3.10). The impact of a +0.5 m weir pool raising and a –0.25m weir pool lowering on the relative abundance of hydraulic habitat in the channel is shown graphically in Figure 7.3. This indicates that, for QSA = 3000–5000 ML day^{-1}, a +0.5m weir-pool raising causes a marked increase in very-slow flowing habitat (Figures 7.3 A–B).

A look up-table for the proportions of habitat with velocity ≤0.1 m s^{-1} is shown in Table 7.2. The data show that at 7000 ML day^{-1} there is a substantial increase in slow-flowing habitat relative to that at normal pool level.

Table 7.2. Look-up table for proportion of channel with very slow–slow velocity for normal pool SWL and with weir-pool manipulation.

QSA (ML day^{-1})	Percentage of channel with velocity <0.1 m s^{-1} (very slow–slow)			
	Modelled natural	Normal pool	+0.5 m raising	-0.25 m lowering
3000	41.2	99.8	100.0	98.4
5000	36.8	96.9	98.9	94.0
7000	30.8	54.0	71.7	46.4
10,000	26.0	21.1	28.0	20.4
12,000	24.7	14.2	17.1	14.8
15,000	20.6	10.8	11.8	11.7
20,000	17.6	7.8	8.4	8.9
25,000	15.4	5.9	6.0	6.8
30,000	13.1	4.7	4.6	5.4
35,000	11.0	3.7	3.9	4.3
40,000	9.0	3.1	3.4	3.6

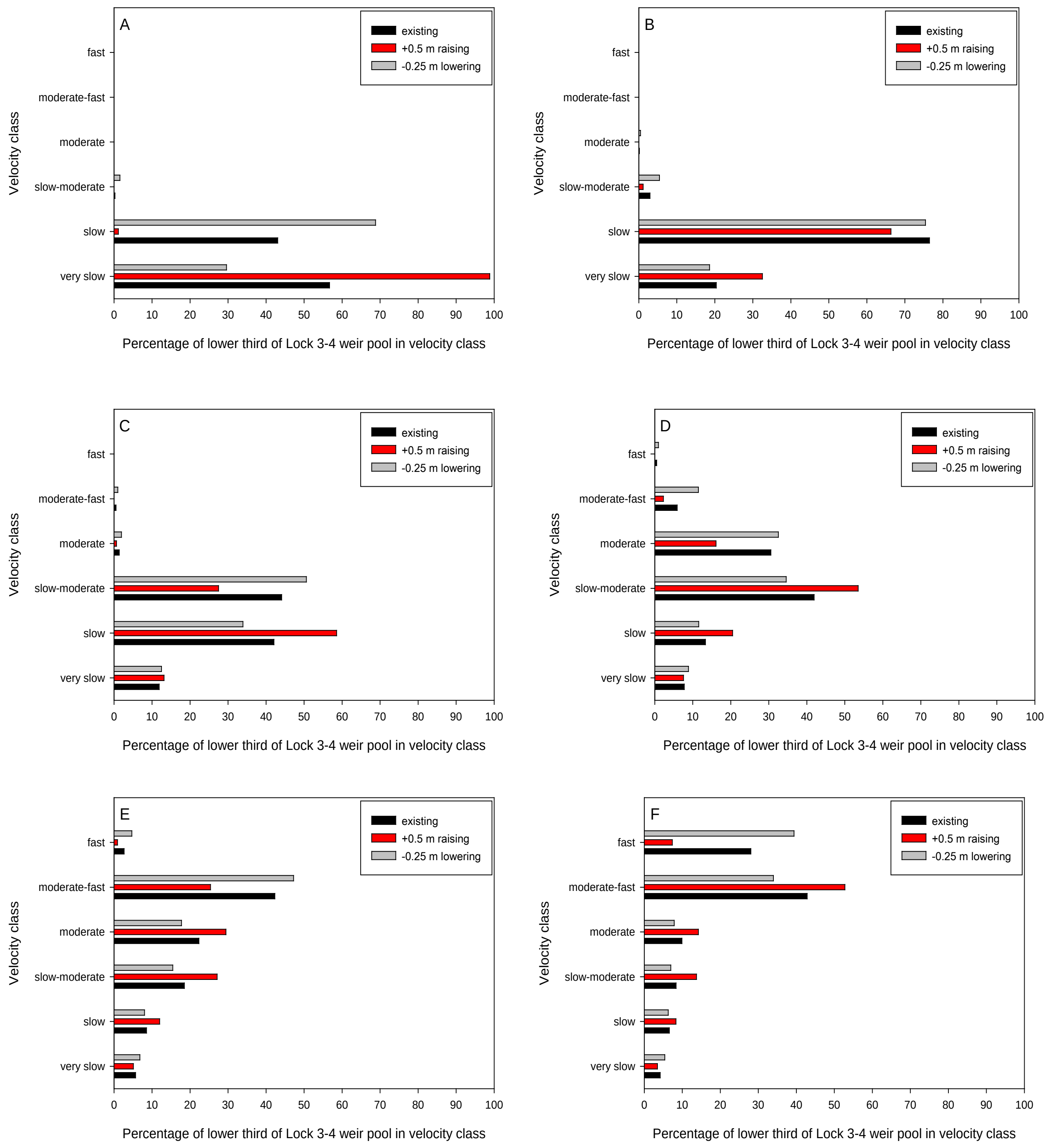


Figure 7.3. Influence of Lock 3 on the percentage of the lowermost third of the Lock 3–4 weir pool with velocity in the respective classes for increasing QSA: [A] 3000 ML day^{-1}, [B] 5000 ML day^{-1}, [C] 7000 ML day^{-1}, [D] 10,000 ML day^{-1}, [E] 12,000 ML day^{-1} and [F] 15,000 ML day^{-1}.

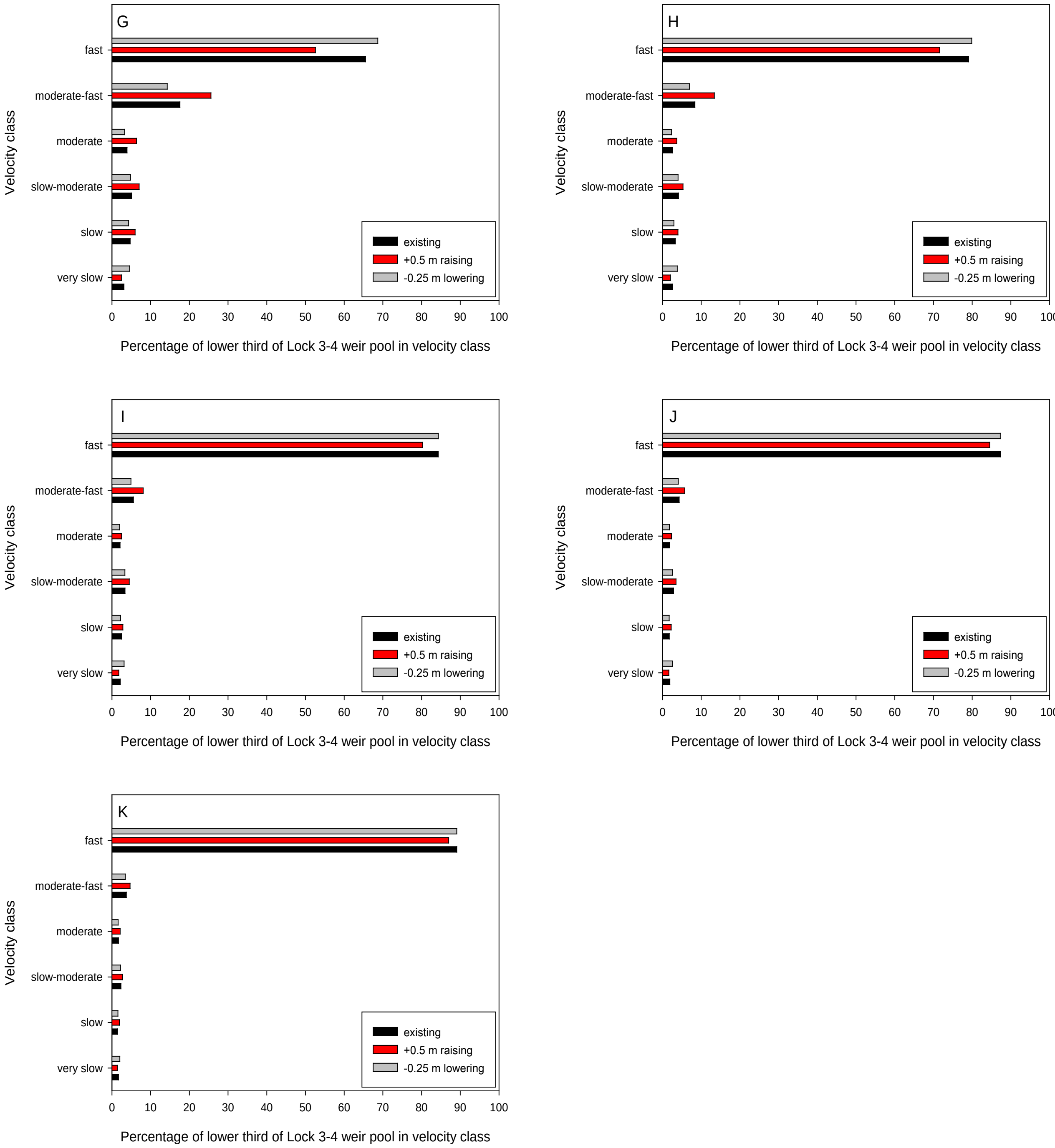


Figure 7.3 continued.

Influence of Lock 3 on the percentage of the lower third of the Lock 3–4 weir pool with velocity in the respective classes for increasing QSA: [G] 20,000 ML day^{-1}, [H] 25,000 ML day^{-1}, [I] 30,000 ML day^{-1}, [J] 35,000 ML day^{-1} and [K] 40,000 ML day^{-1}.

7.6.2. Lock 5-7 reach

Water Technology (2010) used MIKE FLOOD software to investigate the differences between modelled natural and existing conditions for the reach from Lock 5 to downstream of Rufus River. The data demonstrate that for QSA = 10,000 ML day^{-1} (Figure 7.4A) and 20,000 ML day^{-1} (Figure 7.4B) the weirs have a marked impact on the distribution of habitat in velocity classes. The effects of raising the weir from the normal operating height (19.25 m AHD) to 19.87 m AHD (+0.62 m raising), and lowering the weir to 18.75 m AHD (-0.5 m lowering), are also shown.

At QSA = 10,000 ML day^{-1} and 20,000 ML day^{-1}, a +0.62 m raising results in a complete loss of very fast (>0.5 m s^{-1}) habitat, an increase in the proportion of fast (0.31-0.5 m s^{-1}) habitat and a decrease in the proportion of moderate–fast habitat (0.18-0.3 m s^{-1}) compared to normal pool level. At both flows, a 0.5 m weir-pool lowering results in an increase in the proportion of fast and very fast habitat.

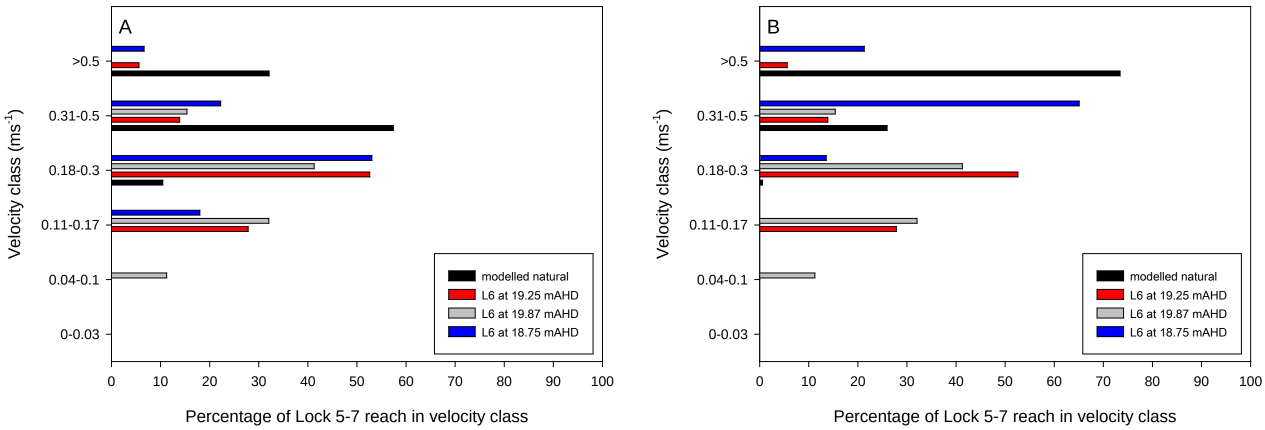


Figure 7.4. Effect of Lock 6 on the percentage of the Lock 5–7 reach with velocity in the respective classes for QSA = [A] 10,000 ML day^{-1} and [B] 20,000 ML day^{-1}.

7.7. Recommendations

Weir-pool lowering is a mechanism to increase the water velocity at all discharges. Weir-pool raisings have the capacity to increase water levels and areas inundated, and the impact on upstream water levels is greatest at low flows. The data in Table 7.2 demonstrate that at 7000 ML day^{-1} there is a high proportion of slow-flowing habitat (72%) relative to normal pool (54%) and modelled natural conditions (31%). This increases the likelihood of persistent thermal stratification, so that weir-pool raisings at these low flows would not be recommended. At QSA = 12,000 ML day^{-1}, there is a very small amount (2.7%) of fast-flowing (>0.25 m s^{-1}) habitat for normal weir pool height. This is increased to 4.7% by a –0.25 m lowering but reduced to <1% by a +0.5 m raising. Thus, a weir-pool raising at QSA ≤12,000 ML day^{-1} would not be consistent with the Ecological Objective, namely to:

- Provide diverse hydraulic conditions within the river channel including the full range of velocity classes from very slow (0.0-0.05 m s^{-1}) to fast (>0.25 m s^{-1}) in the lower third of weir pools, such that habitat and processes for the dispersal of organic and inorganic material between reaches are maintained.

From data presented here, it is suggested that QSA = 20,000 ML day^{-1} is the minimum at which a +0.5m weir-pool raising should be conducted, to minimise negative outcomes related to decreased velocity. During periods of higher discharge, a weir-pool lowering and raising could be combined within the same management action, or as part of a sequence of actions. A lowering would be conducted early in the event so as maximise velocity, and a later return to normal pool level followed by a raising would maximise the area inundated. Examples are included in the following sub-sections.

When planning manipulations, managers need to be aware of the potential impacts on downstream reaches, as flow downstream will decrease following weir-pool raising, as water is taken into storage, and later during the return to normal pool level. It will be necessary to manage rates of change on both the rising and falling limbs of the hydrograph to manage outcomes, including possible erosion and bank failure.

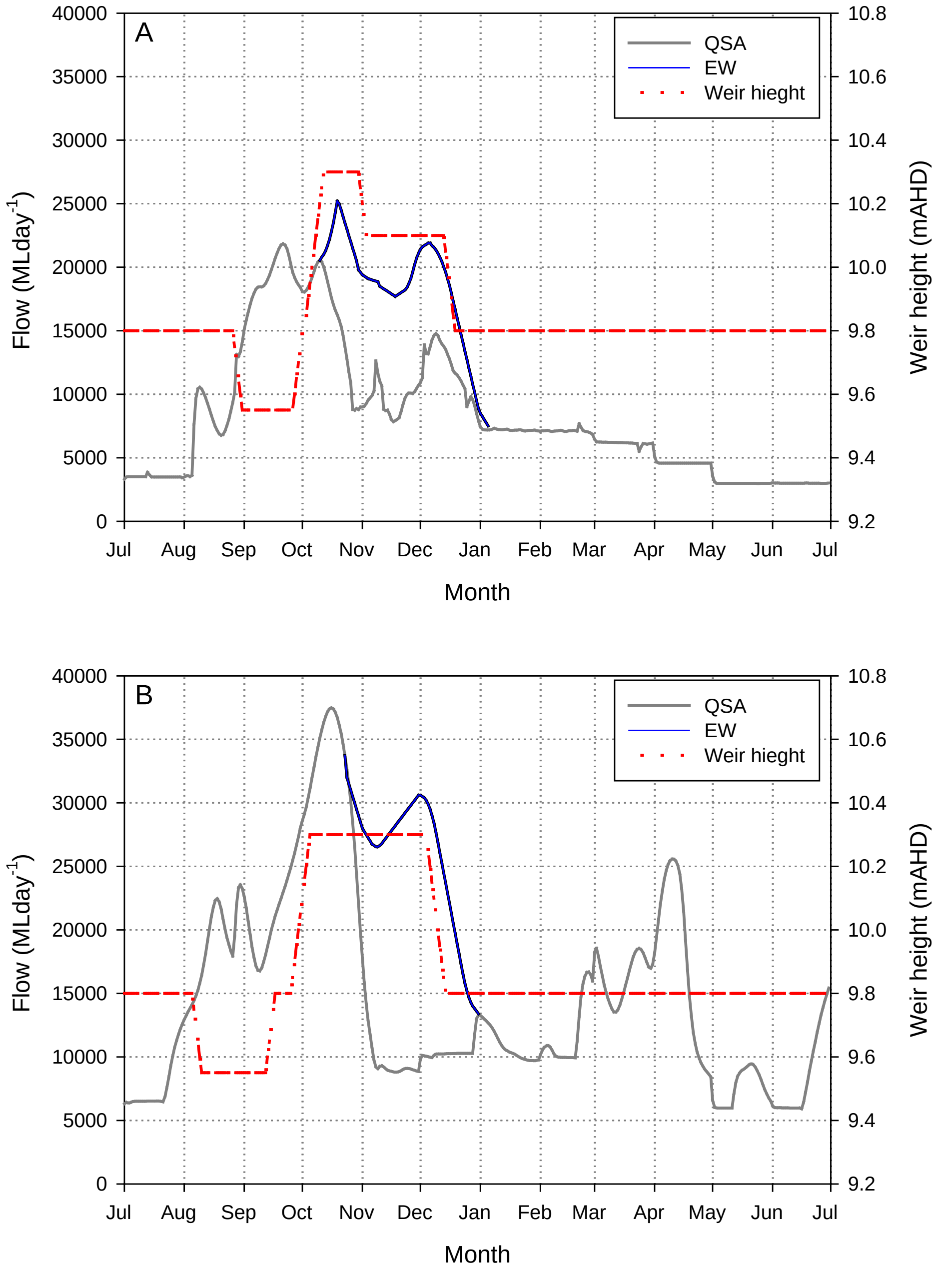


Figure 7.5. Hypothetical example of coordinating weir-pool manipulation with increasing discharge and delivery of environmental water (EW): [A] 20,000 ML day^{-1} for 90 days (compare Figure 6.3A) and [B] EWR for 30,000 ML day^{-1} for 60 days (compare Figure 6.5A).

7.8. Potential weir manipulation scenarios

7.8.1. Entitlement flows: 3000–7000 ML day^{-1} (base-case)

Weir pool lowering is recommended at these flows to increase hydraulic diversity.

7.8.2. Weir manipulation, QSA = 10,000–20,000 ML day^{-1}

From the recommendation in section 7.7, weir pool lowering is recommended at these flows to:

- Increase hydraulic diversity,
- Vary surface water levels, and
- Generate positive contributions towards Ecological Objectives and Targets.

7.8.3. Weir manipulation, QSA = 20,000 ML day^{-1}

To provide hydrodynamic variability, it is recommended that weir pool levels should be lowered by 0.25 m at the low end of the flow band and raised by 0.5 m at the high end of the flow band. A major outcome would be to induce a 0.75 m variation in surface water level (SWL) at the weir (9.55–10.3 m AHD). Assuming that the lowering occurs when flows are c. 12,000 ML day^{-1}, and that raising occurs when flows are c. 20,000 ML day^{-1}, this would produce a 0.89 m variation in SWL at the uppermost section (11.08–11.97 m AHD) (Table 7.1). An example showing how this could be managed in conjunction with delivery of environmental water is shown in Figure 7.5A.

7.8.4. Weir manipulation, QSA = 25,000 ML day^{-1}

Weir lowering at c. 15,000 ML day^{-1} combined with raising at c. 25,000 ML day^{-1} would produce a 1.02 m variation in SWL at the uppermost section (11.38–12.40 m AHD) (Table 7.1).

7.8.5. Weir manipulation, QSA = 30,000 ML day^{-1}

Weir lowering at c. 15,000 ML day^{-1} combined with raising at c. 30,000 ML day^{-1} would produce a 1.44 m variation in SWL at the uppermost section (11.38–12.82 m AHD) (Table 7.1). An example showing how this could be managed in conjunction with delivery of environmental water is shown in Figure 7.5 B.

7.8.6. Weir manipulation, QSA = 35,000 ML day^{-1}

Weir lowering at c. 15,000 ML day^{-1} combined with raising at c. 35,000 ML day^{-1} would produce a 1.82 m variation in SWL at the uppermost section (11.38–13.20 m AHD) (Table 7.1).

7.8.7. Weir manipulation, QSA = 40,000 ML day^{-1}

Weir lowering at c. 15,000 ML day^{-1} combined with raising at c. 40,000 ML day^{-1} would produce a 2.16 m variation in SWL at the uppermost section (11.38–13.54 m AHD) (Table 7.1).

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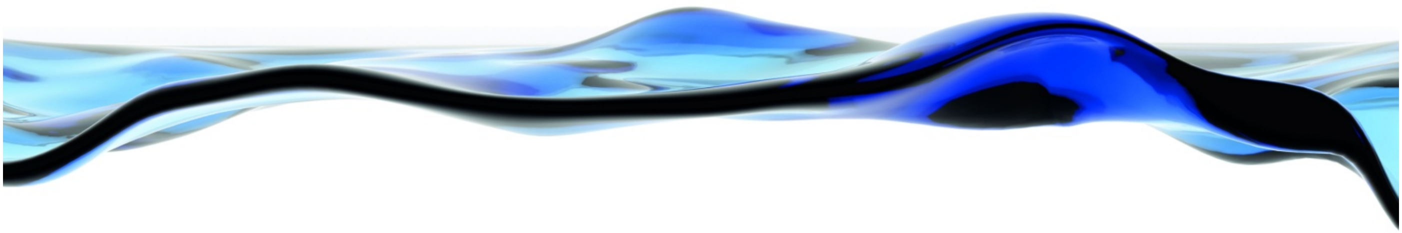

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