



Government of **Western Australia**
Department of **Water**

Environmental flow regime for the lower Collie River, Wellington reach

Environmental flow regime for the lower Collie River, Wellington reach

Looking after all our water needs

Department of Water

Environmental water report series

Report no. 22

August 2011

Department of Water
168 St Georges Terrace
Perth Western Australia 6000
Telephone +61 8 6364 7600
Facsimile +61 8 6364 7601
National Relay Service 13 36 77
www.water.wa.gov.au

© Government of Western Australia 2011

August 2011

This work is copyright. You may download, display, print and reproduce this material in unaltered form only (retaining this notice) for your personal, non-commercial use or use within your organisation. Apart from any use as permitted under the *Copyright Act 1968*, all other rights are reserved. Requests and inquiries concerning reproduction and rights should be addressed to the Department of Water.

ISSN 1833-6582 (print)

ISSN 1833-6590 (online)

ISBN 978-1-921907-82-1 (online)

Acknowledgements

This report was prepared by Katherine Bennett and Adam Green, Water Resource Use, Department of Water.

The department would like to thank the following for their contribution to this publication.

- Jacqui Durrant (Surface Water Hydrology section, Department of Water) for hydrological advice and support
- Dr Andrew Storey (University of Western Australia) and Rob Donohue (Environmental Water Planning section, Department of Water) for advice on river ecology and the modelling.

This project is part funded by the Australian Government's *Water for the Future* initiative.

For more information about this report, please contact Katherine Bennett Phone: 08 6364 6567
Email: Katherine.Bennett@water.wa.gov.au

The recommended reference for this report is:

Bennett K & Green A 2011, *Environmental flow regime for the lower Collie River – Wellington reach*, Environmental water report series, Report no. 22, Department of Water, Western Australia.

Disclaimer

This document has been published by the Department of Water. Any representation, statement, opinion or advice expressed or implied in this publication is made in good faith and on the basis that the Department of Water and its employees are not liable for any damage or loss whatsoever which may occur as a result of action taken or not taken, as the case may be in respect of any representation, statement, opinion or advice referred to herein. Professional advice should be obtained before applying the information contained in this document to particular circumstances.

This publication is available at our website <www.water.wa.gov.au> or for those with special needs it can be made available in alternative formats such as audio, large print, or Braille.

Contents

Contents	iii
Summary	vii
1 Introduction.....	1
1.1 Background: development of a new environmental flow regime	2
1.2 Objective of this study	3
2 The Collie River catchment	5
2.1 Climate.....	6
2.2 Water use and reservoir operations	7
2.3 Hydrology.....	8
Streamflow information and gauging stations	8
Contributions and streamflow volumes in the Wellington reach.....	9
Drying climate and effects on streamflow in the south-west	9
The impact of Wellington Reservoir on streamflow.....	10
Water quality of dam releases	11
3 Ecological values of the lower Collie River	13
3.1 Vegetation.....	13
3.2 Aquatic invertebrates	15
3.3 Fish	16
3.4 Amphibians	18
3.5 Mammals	19
3.6 Carbon sources and ecosystem productivity	20
4 Components of the flow regime and their ecological functions.....	21
4.1 Summer low flows.....	21
4.2 Autumn and winter low flows	22
4.3 Active channel flows	22
4.4 Winter high flows	23
5 Determination of the environmental flow regime	24
5.1 Overall approach	24
Wellington reach.....	26
5.2 Development of daily flow records	26
Dam inflow.....	26
Undammed flow.....	27
Historical flow	27
Modelled environmental flow (potential flow regime)	27
5.3 Aim of the EF regime study	27
5.4 Demand scenarios.....	28
5.5 Ecological and flow objectives.....	29
5.6 Identification of ecological flow thresholds	29
Cobbler nesting habitat.....	31
Summer minimum flow for pool water quality and connectivity.....	31
Macroinvertebrate habitat	31
Inundation of the active channel and trailing vegetation	32
Upstream migration of native fish, small and large bodied	32
Channel maintenance – winter high flows	33

Maintenance of riparian vegetation and organic matter input – overbank flows	34
6 Modelling the environmental flow regime	36
6.1 Evaluation of environmental flow regime	37
Cobbler nesting habitat.....	38
Pool water quality, connectivity and summer macroinvertebrate habitat	38
Winter riffle inundation	39
Winter spawning habitat, active channel and small-bodied fish passage flows	40
Cobbler migration	43
Channel maintenance – winter high flows	44
Maintenance of riparian vegetation and organic matter input – overbank flows	45
Intermediate winter flow thresholds – 50 ML/day and 200 ML/day	47
7 Replacing the existing scour releases with an environmental flow regime	49
Reliability of supply and annual environmental flow regime.....	52
8 Conclusion.....	56
8.1 Future studies and monitoring.....	57
Appendices.....	58
Western minnow (<i>Galaxias occidentalis</i>).....	59
Nightfish (<i>Bostockia porosa</i>).....	59
Swan River goby (<i>Pseudogobius olorum</i>).....	60
Western pygmy perch (<i>Edelia vittata</i>).....	61
Freshwater cobbler (<i>Tandanus bostocki</i>).....	61
Shortened forms	64
Glossary	65
References	67

Appendices

Appendix 1: Information on fish species of the lower Collie River.....	59
Appendix 2: Comparison of reliability of supply for RESYM and TwoRES.....	63

Figures

Figure 1: Location of the lower Collie River	2
Figure 2: Map showing the location of the Wellington reach (Wellington Reservoir to Burekup Weir) and gauging stations.....	6
Figure 3: Rainfall record (mm) at Wokalup station (009642).....	7
Figure 4: Total annual streamflow into Wellington Reservoir and mean annual flows. Flows are gauged flows from Mungalup Tower gauging station (612002) above Wellington Reservoir plus modelled catchment inflow to Wellington Reservoir below Mungalup Tower gauging station.	10
Figure 5: Daily flows above (red) and below (green) Wellington Reservoir for a dry (1987), wet – with overflow (1988) and medium year (1989). Dam inflow is gauged flow from Mungalup Tower (612002) plus modelled catchment inflow below Mungalup Tower. Flow below the dam is gauged flow at Mt Lennard (612006)	11
Figure 6: Riparian vegetation of the lower Collie River, Wellington reach.	14

Figure 7: Representative hydrograph for a south-west stream, with different flow components labelled.....	21
Figure 8: Flow chart showing steps in the Proportional Abstraction of Daily Flows (PADFLOW) method.....	25
Figure 9: The frequency and duration of flows from 1975–2007 above 0 ML/day in the ‘modelled EF’ regime (blue bars) compared with the ‘undammed flow’ (red bars) and ‘historical flow’ (green bars) regimes. The charts show the final EF regime selected.	38
Figure 10: The frequency and duration of flows from 1975–2007 above 2.25 ML/day in the ‘modelled EF’ regime (blue bars) compared with the ‘undammed flow’ (red bars) and ‘historical flow’ (green bars) regimes. The charts show the final EF regime selected.	39
Figure 11: The frequency and duration of flows from 1975–2007 above 14.5 ML/day in the modelled EF regime (blue bars) compared with the ‘undammed flow’ (red bars) and ‘historical flow’ (green bars) regimes. The charts show the final EF regime selected.	40
Figure 12: Frequency and duration of flows from 1975–2007 above 406 ML/day in the ‘modelled EF’ regime (blue bars) compared with the ‘undammed flow’ (red bars) and ‘historical flow’ (green bars) regimes. The charts show the final EF regime selected.....	42
Figure 13: The frequency and duration of flows from 1975–2007 above 518 ML/day in the ‘modelled EF’ regime (blue bars) compared with the ‘undammed flow’ (red bars) and ‘historical flow’ (green bars) regimes. The charts show the final EF regime selected.	42
Figure 14: The frequency and duration of flows from 1975–2007 above 728 ML/day in the ‘modelled EF’ regime (blue bars) compared with the ‘undammed flow’ (red bars) and ‘historical flow’ (green bars) regimes. The charts show the final EF regime selected.	44
Figure 15: The frequency and duration of flows from 1975–2007 above 3456 ML/day in the ‘modelled EF’ regime (blue bars) compared with the ‘undammed flow’ (red bars) and ‘historical flow’ (green bars) regimes. The charts show the final EF regime selected.	45
Figure 16: The frequency and duration of flows from 1975–2007 above 4752 ML/day in the ‘modelled EF’ regime (blue bars) compared with the ‘undammed flow’ (red bars) and ‘historical flow’ (green bars) regimes. The charts show the final EF regime selected.	47
Figure 17: Frequency and duration of flows from 1975–2007 above 50 ML/day in the ‘modelled EF’ regime (blue bars) compared with that of the ‘undammed flow’ (red bars) and ‘historical flow’ (green bars).....	48
Figure 18: The frequency and duration of flows from 1975–2007 above 200 ML/day in the modelled EF regime (blue bars) compared with the ‘undammed flow’ (red bars) and ‘historical flow’ (green bars) regimes. The charts show the final EF regime selected.	48
Figure 20: The plot shows the reservoir storage levels (upper plot), and the target and available draw (lower plot) in ML/day, for the modelled demand scenario of 85.1 GL/year without environmental releases. Where available draw (blue) does not plot over target draw (red), total consumptive demand has not been met. Total demand has not been met five years out of the 33 plotted (85 per cent reliability) from 1975 to 2007.....	54

Figure 21: The plot shows the reservoir storage levels (upper plot), and the target and available draw (lower plot) in ML/day, for the modelled demand scenario of 85.1 GL/year with the modelled environmental release regime. Where available draw (blue) does not plot over target draw (red), total consumptive demand has not been met. Total demand has not been met eight years out of the 33 plotted (76 per cent reliability) from 1975 to 2007.55

Tables

Table 1:	Habitat and breeding biology of frogs likely to occur in the Wellington reach between Wellington Reservoir and Burekup Weir. Information sourced from Cogger (2000) and Tyler et al. (2000).	19
Table 2:	Monthly and daily consumptive use pattern for irrigation demand of 68 GL/year, industrial demand of 17.1 GL/year and total demand of 85.1 GL/year.	28
Table 3:	Ecological flow thresholds for the Wellington reach. The flow rates satisfy the ecological and flow objectives (Streamtec 2000; Hardcastle et al. 2003; WRM 2003 & WRM 2010).	30
Table 4:	The number of years and the frequency that thresholds are met in the 'undammed' and 'historical' flow records.	34
Table 5:	The number of years and the frequency that the thresholds are met in the 'undammed' and 'historical' flow records.	35
Table 6:	Flow ranges and proportion of 'dam inflow' that is released (release rule) to develop the environmental flow regime for the Wellington reach.	37
Table 7:	The number of years and the frequency the threshold of 3456 ML/day is met in the 'undammed flow', 'historical flow' and 'modelled EF' regimes.	45
Table 8:	The number of years and the frequency the threshold of 4752 ML./day is met in the 'undammed flow', 'historical flow' and 'modelled EF' regimes.	46
Table 9:	Presents flows at Mt Lennard gauging station site, and releases at the Wellington Reservoir from June to the end of September for the 'undammed', 'historical' and 'modelled EF' regimes.	51
Table 10:	The annual modelled EF regime, target and available draw for the demand scenario of 85.1 GL/year from 1975 to 2007. EF regime includes environmental releases from the dam, dam overflows and catchment inflow below the dam.	53
Table 11:	RESYM average annual results for the modelled EFR compared with the TwoRES results scenario 4.8 (DoW 2011c)	63

Summary

The environmental flow regime is one component considered in the planning and management of water resources. The degree to which environmental flow regime is achieved is balanced with current and future demands for consumptive use as well as water to maintain *in situ* social and cultural values. This report describes the development of an environmental flow regime for the lower Collie River between Wellington Reservoir and Burekup Weir (referred to as the Wellington reach). Wellington Reservoir separates the 'upper' and lower' Collie River in south-west Western Australia. Burekup Weir is located approximately 14 km downstream of the reservoir. Streamflow between the reservoir and weir has a long history of modification, predominantly as a result of damming for public water supply and irrigation.

At present, irrigation water for the Harvey irrigation district is released from Wellington Reservoir and diverted into irrigation channels at Burekup Weir. During the irrigation season (between October and June), flows in the reach are well above what would have occurred in the natural, unregulated system. Outside the irrigation season, flows in the Wellington reach occur largely as a result of releases to scour saline water from the bottom of the dam (scour releases), rather than to maximise the benefit to ecological values.

Despite these modifications, the Wellington reach still supports ecological values such as populations of native fish, crayfish, macroinvertebrates and healthy riparian vegetation. The reach also supports indigenous values as well as social values such as camping, fishing, swimming, marroning and canoeing.

Current water entitlements from the reservoir are 68 GL/year and in the last ten years from 1999 to 2009 the highest level of abstraction for consumptive use from the reservoir was 56.7 GL in 2000–01. Current water entitlements are likely to increase to the allocation limit of 85.1 GL in the next five years. To accommodate this, it is important that releases from Wellington Reservoir are made in a way that maximises the benefits to ecological values and minimises impacts to the water available for consumptive use. The objective of this study is therefore to determine an environmental flow regime for the Wellington reach that will:

- maintain the presence of the current in-stream and riparian native biota
- maximise the water available for consumptive use.

A water balance model called RESYM (River ecologically sustainable yield model) is used to model 'water in' and 'water out' of the Wellington Reservoir and develop an environmental flow regime for the Wellington reach that meets important ecological thresholds.

In this model, the basic 'water in' and 'water out' components are:

- daily flow into Wellington Reservoir from 1975 to 2007 (water in)
- a target for consumptive use of 85.1 GL/year from the reservoir (water out)

- environmental releases from the reservoir into the Wellington reach (water out)
- and water that flows over the dam wall (dam overflow) into the Wellington reach when the reservoir is full (water out)

The environmental release and dam overflow outputs are added to the contribution of runoff from unregulated tributaries between the Wellington Reservoir and Burekup Weir to develop the environmental flow regime. The model outputs for each of the 'water out' components allow us to see what would have been available for consumptive use and the environmental flow regime from 1975 to 2007 if the environmental flow regime had been implemented over this period.

Using RESYM, the environmental release component of the environmental flow regime is generated by releasing a proportion of daily reservoir inflow. The environmental releases are manipulated until the study panel agrees the balance between all three 'water out' components achieves the objectives of the study, and maximises the amount of abstraction from the dam for consumptive use, while still meeting the important ecological thresholds that maintain the current ecology.

The environmental flow regime modelled for the Wellington reach outside the irrigation season (between June and the end of September) averages 43 GL/year and ranges between 3 and 251 GL/year, reflecting the variation in streamflow into the Wellington Reservoir from 1975 to 2007. To achieve the modelled environmental flow regime outside the irrigation season, nearly half of the flow would be provided by environmental releases, while the other 15 per cent would be provided by catchment rainfall and runoff below the reservoir, and 35 per cent from dam overflow events.

Historical flow recorded in the reach between June and the end of September from 1975 to 2007 averaged 57 GL/year, and is a function of the scour regime, dam overflow and actual consumptive use for this period. The modelled environmental flow regime is therefore an average of 14 GL/year lower than the historical flow recorded in the reach. While this means that the modelled environmental flow regime will result in a reduction of water available for ecological purposes, it releases this water in a way that better targets the range of ecological thresholds. In particular, this has improved flows at the start and end of the irrigation seasons that maintain important pool and riffle habitat, providing some ecosystem resilience and therefore minimising the risk to the ecology. It is anticipated that some populations may decrease in size due to decreasing the water available in the Wellington reach during winter, however the environmental flow regime is expected to maintain their presence.

The environmental flow regime enables an extra 14 GL/year to be available for consumptive use for the modelled period. However it does not provide 85.1 GL/year in every year. If consumptive use increases by more than an average of 14 GL/year and/or the current trend of less inflow into the reservoir continues, both the consumptive use target and the environmental flow regime will be met less frequently. Not meeting the environmental flow regime modelled in this study poses a threat to the current ecological values downstream of the reservoir.

Implementing the environmental release regime in this study, in place of the scour regime, will efficiently provide an environmental flow regime that meets ecological objectives and minimises the impact of taking more water for consumptive use. Initial modelling undertaken by the department indicates the new regime would maintain a similar saline scour function (DoW 2011c) and therefore, should not be detrimental to salinity levels in the reservoir. Further salinity modelling is underway to investigate the impacts in more detail.

Since the development of the modelled environmental flow regime (in this study) the *Lower Collie surface water allocation plan* (DoW 2011a) has been developed. During the development of the plan, the flow regimes resulting from various consumptive use, licensing, release and climate change scenarios for the Wellington Reservoir and lower Collie River were modelled (see DoW 2011c). Flow regimes for these scenarios were compared to the modelled environmental flow regime to assess the potential risks to the ecology and subsequently help to:

- define the amount of water available for abstraction in the lower Collie River
- select a licensing scenario for water entitlements from Wellington Reservoir
- develop an environmental water provision and release regime for the Wellington reach that replaces the winter scour regime for Wellington Reservoir.

This is explained further in the *Lower Collie surface water allocation plan methods report* (DoW 2011b) and the *Wellington Reservoir water balance simulation* (DoW 2011c).

1 Introduction

This report describes the development of an environmental flow regime (EF regime) for the lower Collie River between Wellington Reservoir and Burekup Weir, referred to as the Wellington reach (Figure 1). Using this study, the Department of Water aims to formalise winter releases from the dam, replacing the current scour regime with an environmental release regime to maximise the ecological benefit.

The study recently informed water resource planning and management decisions in the *Lower Collie surface water allocation plan* (DoW 2011a), which defined the amount of water available for abstraction in the lower Collie River, developed a licensing scenario for water entitlements from the reservoir and specified an EF regime to replace the winter scour regime for the reservoir.

The environmental flow study considers the aquatic and riparian ecosystem as a whole, and examines the relationships between the water regime and biodiversity, riverine foodwebs, ecological processes and individual species. It also considers the flow-dependency of aquatic taxa such as fish, invertebrates, amphibians and aquatic plants, as well as the importance of surface water to terrestrial and riparian species.

The environmental flow regime was generated using the 'Proportional abstraction of daily flows' (PADFLOW) method. According to the 'natural flows paradigm' which underpins the PADFLOW approach, the natural regime of flow is responsible for the evolution of the observed ecological state of a river (Poff 1997). The flow regime influences which species are present and governs the processes that support a healthy and resilient aquatic ecosystem. Environmental flow studies should therefore consider the total flow environment including the natural duration and frequency of ecologically important flow events, the annual and inter-annual flow regime, seasonal patterns of flow and long-term trends in flow volume.

Further information about how the various components of the flow regime influence ecological processes is given in Section 4.

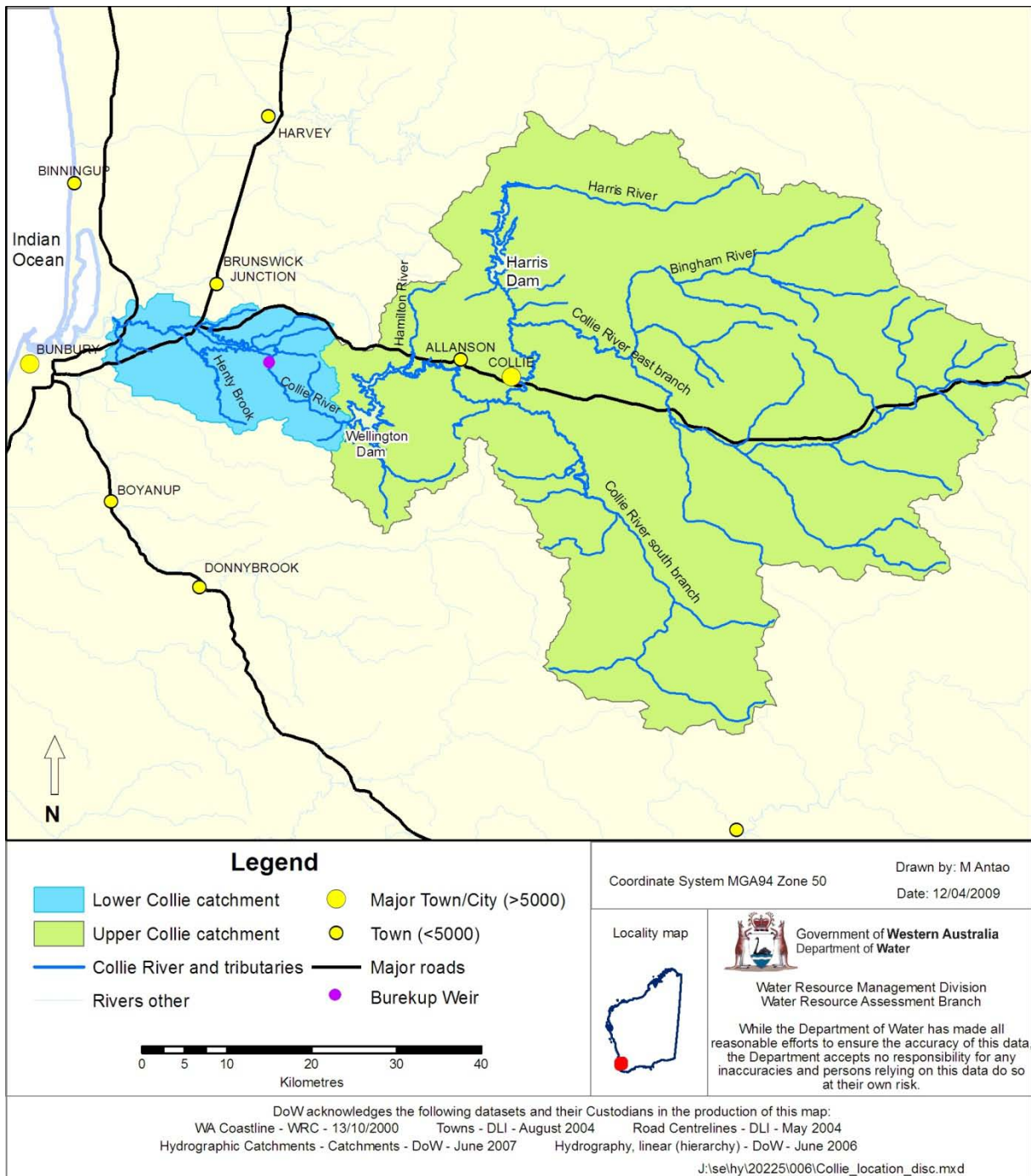


Figure 1: Location of the lower Collie River

1.1 Background: development of a new environmental flow regime

The lower Collie River has a long history of modification through industrial and agricultural practices, as well as damming for public water supply and irrigation. There are two major water supply dams within the catchment: Harris Dam on the Harris River in the upper catchment, and Wellington Reservoir on the Collie River's main channel downstream of the Collie townsite.

Streamflow below the Wellington Reservoir is highly modified compared with the natural, pre-development condition. This is attributed to reduced winter flows resulting from the storage of water behind the reservoir wall and the release of water from the dam during summer to support irrigation. At present, winter flows below the dam are the result of releases to scour saline water from the reservoir to improve the quality of irrigation water, rather than to meet ecological objectives. While the scour releases do provide some ecological benefits, it is expected they could be improved to meet ecological objectives.

It has long been an objective of the Department of Water (formerly the Water and Rivers Commission) to improve the ecological benefits of scour releases from Wellington Reservoir by way of a formal environmental water release strategy. To achieve this, various environmental flow studies have been undertaken; for example, a study of the lower Collie River from below the reservoir to the Leschenault Estuary (Streamtec 2000) that was re-examined three years later by Hardcastle et al. (2003). At the time it was believed the winter scour regime was meeting the environmental flow requirements determined in both studies.

During development of the *Upper Collie water allocation plan* (DoW 2009), the Department of Water determined that the methods used by Streamtec (2000) and Hardcastle et al (2003) could be improved by applying more current methods such as the Proportional Abstraction of Daily Flows (PADFLOW) (e.g. see Donohue et al. 2009a & b). PADFLOW is an approach we have developed to determine EF regimes that capture the intra- and inter-annual variability of streamflow in south-west rivers.

More recently, interest in taking water from Wellington Reservoir has increased. Water entitlements from the reservoir are likely to increase from the current entitlement of 68 GL/year to the allocation limit of 85.1 GL/year in the next five years. Increasing use, together with the current trend of less inflow into the reservoir, means less water will be available for winter releases. This poses a threat to the current ecological values downstream of the reservoir, and without effective environmental releases, this risk will be greater. It is therefore increasingly important that winter releases from the reservoir maximise the benefit to ecological values and minimise impacts to the reliability of supply.

This study used the PADFLOW approach to define a new EF regime for the Wellington reach of the lower Collie River (Figure 1). The new regime acknowledges the need to maximise the reliability of supply, while minimising the risks to ecological values.

1.2 Objective of this study

The EF regime presented in this study represents a balance between environmental and economic demands and recognises that due to the high value of consumptive use from Wellington Reservoir, releasing the volume of water needed to satisfy all environmental values at a low level of risk may not be attainable.

In developing the EF regime for Wellington reach, and the release regime that helps to maintain it, the overarching objectives were to:

- maintain the presence of the current in-stream and riparian native biota
- maximise the water available for consumptive use.

The objective to maximise the water available for consumptive use means the EF regime represents a higher risk to the ecology than would have been the case if consumptive use from the reservoir was not increasing. It is therefore recognised that some populations of native biota may decrease, however as stated in the first objective, we aim to maintain their presence in the system.

2 The Collie River catchment

The Collie River catchment is located in south-west Western Australia (Figure 1). The catchment covers an area of 3068 km² and has two major water supply dams:

- Wellington Reservoir (capacity 186 GL), which separates the Collie River's upper and lower reaches and has a catchment area of more than 2800 km²
- Harris Dam (capacity 72 GL), with a catchment area of 382 km².

Other major rivers in the Collie catchment include the Bingham River, Collie River East and Collie River South.

Burekup Weir is located approximately 14 km below Wellington Reservoir along the Collie River (Figure 2). At the weir, irrigation releases from the reservoir are diverted into the irrigation channels for distribution to agricultural users. The stretch of river between the reservoir and weir is referred to as the Wellington reach in this report (see Figure 2). Another EF regime for the 'Shentons Elbow reach' which lies between the Burekup weir and the Leschenault Estuary, has been determined in Green and Bennett (2010)

The Wellington reach's catchment is 60 km² and 98 per cent native forest. Most of the native forest is national park managed by the Department of Environment and Conservation. There are restricted areas for camping and the river is used for recreational activities such as fishing, swimming, marroning and canoeing. The remaining land is privately owned.

The landscape consists of steep hillsides and streams falling around 200 m in elevation on their way to the main channel. The river channel includes deep pools separated by low waterfalls and turbulent rapids (WRM 2003). There is a relatively narrow band of riparian vegetation along the river channel, reflecting the steep banks and valley sides of the area.

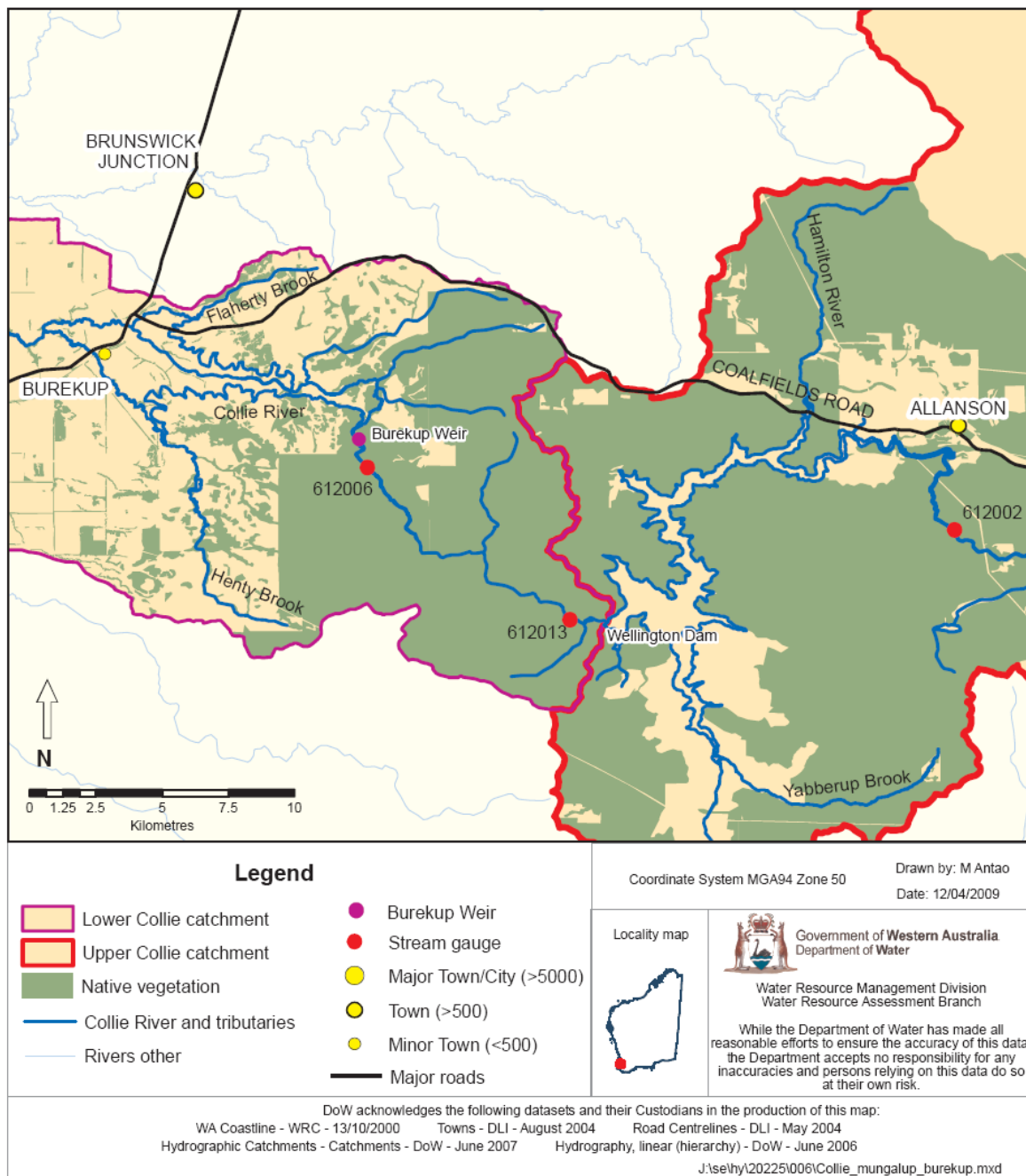


Figure 2: Map showing the location of the Wellington reach (Wellington Reservoir to Burekup Weir) and gauging stations.

2.1 Climate

The region's climate is temperate, with warm dry summers and cool wet winters. Average daytime temperatures can range from 16.5°C in winter to around 30.4°C during summer (Weatherzone 2010). Rainfall in the lower Collie River catchment is seasonal and highly predictable. It is typically derived from cold fronts crossing the coast in winter, although high-intensity summer storms occasionally occur as a result of ex-tropical cyclones bringing rain from the north-west (DoW 2011d).

Longterm rainfall data for the Wokalup rainfall station, north of Wellington reach on the same rainfall isohyet, shows there is a decreasing trend in the annual rainfall record with the short-term (1975–2009) mean 14 per cent lower than the long-term average (1900–2009). The decline in rainfall has continued with the mean annual rainfall from 2000 to 2009 decreasing by a further 9 per cent compared to the short-term average (DoW 2011d).

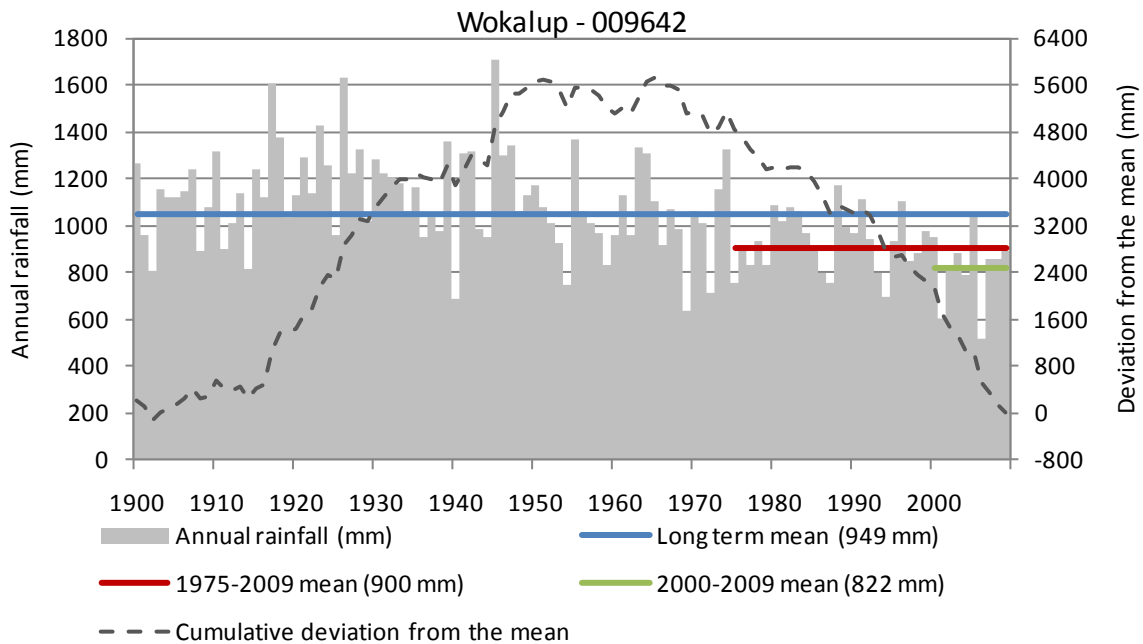


Figure 3 Rainfall record (mm) at Wokalup station (009642)

2.2 Water use and reservoir operations

Wellington Reservoir was built in 1933 and the dam wall raised to its current height in 1961. The reservoir supports an important irrigation industry, the majority of which is irrigated pasture for dairy and beef cattle. Harvey Water presently holds a licence to divert up to 68 GL/year from the reservoir for irrigation and industrial use. This entitlement is not fixed and the exact volume to be abstracted is decided before 1 October each year, based on the dam storage level. Water diverted at Burekup Weir by Harvey Water from 1999 to 2009 has ranged from 42.5 GL in 2004–05 to 56.7 GL in the dry season of 2000–01 (Harvey Water 2009).

In 2008–09, Harvey Water customers used 27.5 GL for irrigation and 0.9 GL for industrial purposes, while 2.4 GL went into the Brunswick, Henty and Ferguson rivers for social, stock and domestic use. The irrigation season typically runs from October to May/June, although use is highest from November to mid-April. Irrigation of pasture for beef and dairy cattle made up 78 per cent of the irrigated area and 86 per cent of the water used in 2008–09 (Harvey Water 2009).

The total allocation limit for Wellington Reservoir set by the *Upper Collie water allocation plan* (DoW 2009) is 85.1 GL. As such, an additional 17.1 GL of water can

be allocated for entitlements above those taken by Harvey Water. Given the region's current level of development it is likely the remaining entitlements will be taken up by industrial use in the next five years.

At present, there is no direct take from Wellington Reservoir and all the water used is released from the bottom of the reservoir into the Collie River and diverted into irrigation channels at Burekup Weir.

Outside the irrigation season, water is released to scour saline winter inflows from the bottom of the reservoir to reduce salinity levels. Scour releases typically occur between June and September and begin when criteria to determine the optimum scour time are triggered. These criteria depend on the reservoir's current storage volume, salinity level in the bottom layer of the reservoir, and the salinity difference between the top and bottom layers of the reservoir (DoW 2011c).

During the summer irrigation period some leakage and overflow occurs at Burekup Weir due to operational constraints when diverting water into the irrigation channel. Winter scour releases are not diverted and flow over the weir and through the lower reaches of the Collie River into Leschenault Estuary.

2.3 Hydrology

Streamflow information and gauging stations

The main gauging stations near the Wellington reach include Mungalup Tower (612002), Wellington Flume (612013) and Mt Lennard (612006) (Figure 2).

Mungalup Tower gauging station is located on the Collie River's main channel above Wellington Reservoir and has recorded streamflow data from 1969. Flows at Mungalup Tower remain relatively natural in terms of seasonality. Streamflow was modelled for the tributaries that flow into the reservoir below the Mungalup Tower gauging station.

Wellington Flume gauging station is located on the Collie River's main channel below Wellington Reservoir and has recorded streamflow data from 1973. This station is located downstream of the confluence with Falcon Brook, which is the first tributary to enter the Collie River downstream of the reservoir. This station measures flows released at the dam wall, dam overflows and tributary flows from Falcon Brook.

Mt Lennard gauging station is located downstream of the Wellington reach and measures dam releases, dam overflows and catchment inflows below the dam wall. The streamflow record for this gauge is 1973 to 1997.

Flow from tributaries running into the river between Wellington Reservoir and Burekup Weir were modelled. Catchment flows between the Wellington Flume and Mt Lennard gauging stations were added to represent flow at the Mt Lennard gauging station from 1975 to 2007. The location of the Mt Lennard gauging station is the point of reference against which all flow regimes were compared for this EF regime study.

Details on which streamflow regimes were used to develop the EF regime can be found in Section 5.6.

Contributions and streamflow volumes in the Wellington reach

Surface water flow in the Wellington reach consists of flow from rainfall and runoff into tributaries that feed into the reach, overflows not captured by the reservoir, and water releases from the reservoir for irrigation and scouring purposes. The tributaries that flow into the Wellington reach only flow in winter and contribute a mean annual flow of 6.3 GL/year (1975–2007). Tributary flows contribute about 10 per cent of the winter flows below the reservoir and help maintain some seasonal variation and fresh water contribution. An analysis of historical streamflow at Mt Lennard gauging station (Figure 2) shows the remaining 90 per cent of flow between June and September (inclusive) is half scour releases and half overflows from the reservoir. Overflow events have occurred about 40 per cent of years from 1994 to 2010. Inflow into Wellington Reservoir from 1975 to 2007 averaged 119 GL, ranging between 18.3 GL in 2001 to 392.2 GL in 1996.

Drying climate and effects on streamflow in the south-west

Post-1975 May to July rainfall in south-west Western Australia has declined by 10 to 15 per cent (from the 1900–74 average) (Bates et al. 2008). The rainfall decline has contributed to a severe reduction in runoff, with an average change in runoff of two to three per cent for every one per cent change in rainfall (Fu et al. 2007). With reduced rainfall in recent years, the mean annual inflow to Wellington Reservoir fell 30 per cent, from 119 GL (1975–2007) to 83.5 GL (1998–2007) (Figure 4).

Almost all global climate models used by the Intergovernmental Panel on Climate Change predict that south-west Western Australia will experience a drier and warmer climate in the future (CSIRO 2009).

The Department of Water used climate and runoff data from the CSIRO south-west Western Australia sustainable yields project (CSIRO 2009) to predict changes to rainfall and runoff in the Collie region to 2030. Wet, median and dry future climate scenarios were compared with the average across the lower Collie catchment from the 1975 to 2007 (DoW 2011d). The changes are as follows:

- wet scenario: -2% change in mean annual rainfall and a -6% change in mean annual runoff
- median scenario: -9% change in mean annual rainfall and a -23% change in mean annual runoff
- dry scenario: -16% change in mean annual rainfall and a -40% change in mean annual runoff

This shows that surface water resources in the Wellington Reservoir catchment are expected to continue to decline.

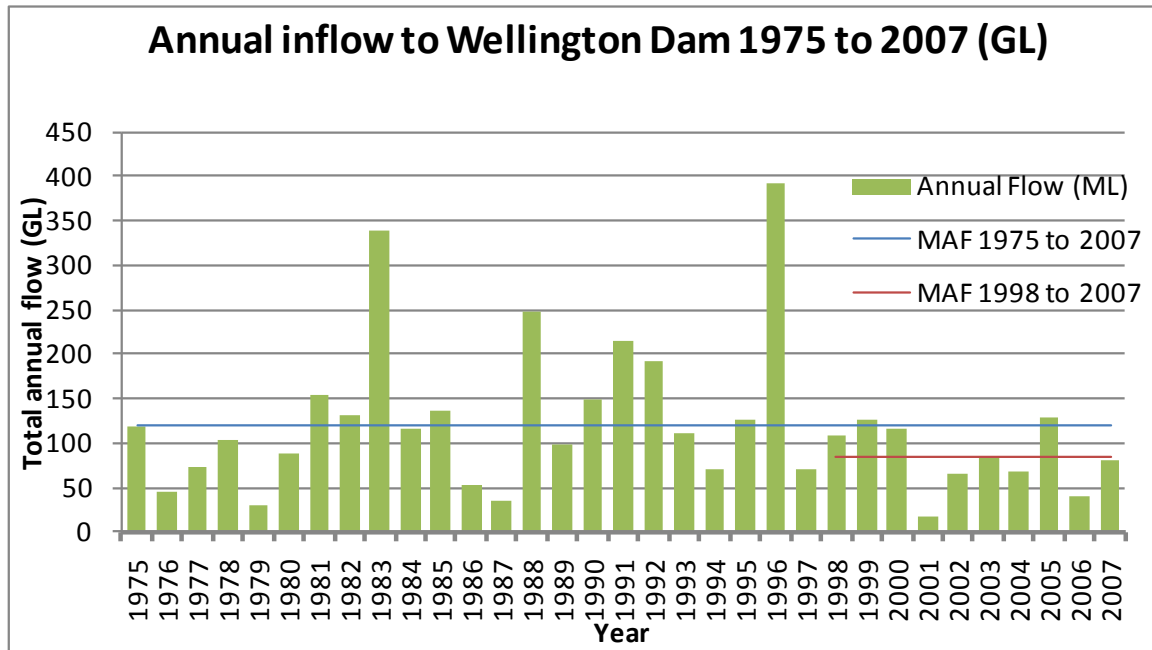


Figure 4: Total annual streamflow into Wellington Reservoir and mean annual flows. Flows are gauged flows from Mungalup Tower gauging station (612002) above Wellington Reservoir plus modelled catchment inflow to Wellington Reservoir below Mungalup Tower gauging station.

The impact of Wellington Reservoir on streamflow

From 1975 to 2007 about half the inflow into Wellington Reservoir was released into the Wellington reach to supply the irrigation industry in summer, and the other half as scour releases or reservoir overflows in winter.

The timing and magnitude of releases is very different to the natural flow regime. The summer irrigation releases (which are diverted at Burekup Weir) are much larger than what the natural summer flow regime of the Wellington reach would be.

Winter catchment flow, overflow and scour releases are not diverted, and flow over the weir and into the Leschenault Estuary. The timing of scour releases is not representative of the magnitude and variability of winter flows into the dam and the onset of winter flows below the dam is often delayed by two to three months compared with dam inflow. Once scour is triggered, it is generally a fixed release rate of around 500 ML/day.

Figure 5 shows winter flows are delayed from about May to August, when scour releases begin. Winter flow below the dam only reflects flow into the dam when the dam fills and overflows. This can be seen in 1988 (see Figure 5). Since 1975, Wellington Reservoir has overflowed about once every three years.

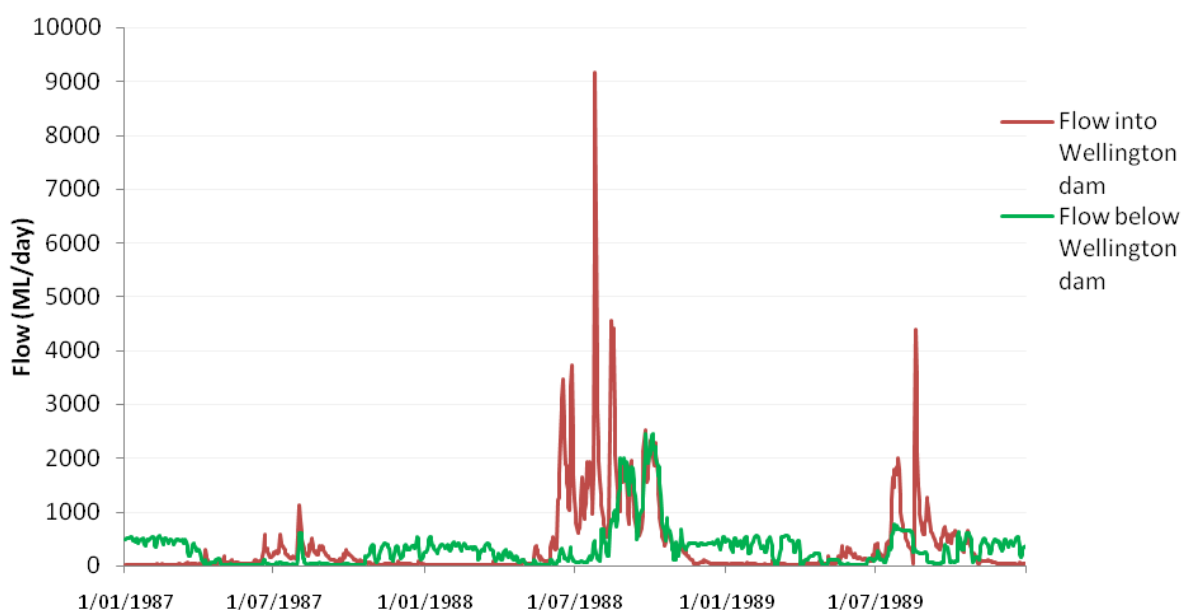


Figure 5: Daily flows above (red) and below (green) Wellington Reservoir for a dry (1987), wet – with overflow (1988) and medium year (1989). Dam inflow is gauged flow from Mungalup Tower (612002) plus modelled catchment inflow below Mungalup Tower. Flow below the dam is gauged flow at Mt Lennard (612006)

Water quality of dam releases

Releases from low off-take or scour valves in large dams are known to be very low in dissolved oxygen (DO). However, sampling from sites just below Wellington Reservoir has indicated the releases are well oxygenated within a short distance downstream of the release point (WRM 2003). This is possibly the result of a large rocky riffle section at the release point. Further, it is assumed the releases improve DO levels in pools by preventing stratification. In 2010, the Department of Water contracted Wetland Research and Management (WRM) to undertake a trial release study to determine the flow required to maintain DO levels above 5 mg/L and prevent stratification.

The study (WRM 2010) found the releases did not have a detrimental impact on the DO in pools and were therefore effective for preventing stratification, maintaining connectivity in pools and maintaining DO. It recommended a minimum flow of 2.25 ML/day be maintained at the Wellington Flume gauging station (Figure 2) to keep DO levels above 5mg/L, prevent stratification and promote connectivity between pools.

A snapshot study of salinity at the bottom of the reservoir (near the scour valve) sampled on 25 September from 2002 to 2008 showed a salinity range of 1000 to 1214 mg/L. This salt-concentration level is higher than that recommended for freshwater systems in the south-west; that is, total dissolved solid (TDS) of 80 mg/L for upland rivers and TDS of 204 mg/L for lowland rivers (ANZECC/ARMCANZ 2000). However, it is accepted that conductivity less than 1500 $\mu\text{s}/\text{cm}$ (about 1000

mg/L) results in relatively little stress to freshwater ecology (Hart et al. 1991; Horrigan et al. 2005).

The release of cold water from the bottom of dams can be a concern. Because aquatic animals are adapted to a certain temperature range, exceeding this range (unnaturally low or high temperatures) can alter composition and aquatic processes. The ANZECC/ARMCANZ 2000 guidelines suggest the temperature range of releases should remain within the 80th and 20th percentiles of the reference data, but this has not been established for the Wellington reach.

Given the long history of water releases from the reservoir, the aquatic and riparian communities along the Wellington reach must be sufficiently tolerant of the current water quality to survive and recruit. It is assumed that not releasing water from the dam would do greater harm to the reach's ecological values than the continued release of water with the current levels of salt concentration, DO and temperature.

3 Ecological values of the lower Collie River

To develop an EF regime that maintains existing ecological values it is important to:

- describe the existing condition of the river's ecosystem
- define how the various components of the ecosystem depend on the flow regime.

Man-made structures such as Wellington Reservoir and Burekup Weir, as well as the unnatural flow regime, have resulted in a modified aquatic ecosystem in the Wellington reach. Despite these modifications, the area still supports populations of native fish, crayfish, macroinvertebrates, and healthy riparian and aquatic vegetation.

The lower Collie River's ecological values and the relationships between flow and ecological values are discussed in the following sections. These sections draw on information collected for previous environmental flow studies for the Wellington reach, including a vegetation inventory by Syrinx Environmental (2003), a targeted fish sampling program between Wellington Reservoir and Burekup Weir by WRM (2003), and sampling conducted by Storer et al. (2011) on macroinvertebrates, fish and amphibians.

3.1 Vegetation

The catchment surrounding the Wellington reach is 98 per cent native forest and vegetation in the riparian and terrestrial zone is in relatively good condition. The cleared land is privately owned, unirrigated grazing land. Environmental factors influencing plant vigour and affected by river flow include:

- bank soil-moisture content
- proximity of groundwater to the root zone
- period and season of flooding that inundates the floodplain and riparian vegetation.

This section draws heavily on information provided in Syrinx Environmental (2003).

The dominant vegetation complex bordering the banks of the lower Collie River is mixed *Eucalyptus* fringing woodlands, characterised by a narrow fringing sedgeland community (usually less than two metres wide) dominated by *Baumea vaginalis* (twigrush) with *Lepidosperma effusum*. At the interface between riparian and terrestrial vegetation, the most common woodland species in the Wellington reach is peppermint (*Agonis flexuosa*) and blackbutt (*Eucalyptus patens*). Figure 6 illustrates the condition of the vegetation along the Wellington reach.

The vegetation complex most at risk from changes in the flow regime is the fringing sedgeland of *Baumea vaginalis*, as this habitat is limited by steep banks and a long drop to the water. Syrinx Environmental (2003) states: 'anything that results in a bankfull height falling > or = to 10cm' would not allow any recovery potential of *B.*

vaginalis. This has been interpreted to mean that bankfull events should not be reduced in volume or frequency below Wellington Reservoir.

In addition to this, Syrinx Environmental (2003) provides a table that describes the reliance of adult species and seed germination on periodic inundation or seasonal moisture. This information suggests many adult species rely on seasonal inundation (above bankfull flows) and/or permanently moist soil (baseflow) for survival. For germination it suggests most species require seasonal inundation (above bankfull flows) and drying, while some require permanently moist soil. This would indicate that above-bankfull flows are required for germination in many species and a continuous baseflow that maintains soil moisture throughout the year is required for survival of adults and germination in some species.

This is supported by knowledge of Australian riparian zones, in which the greatest numbers of plant species germinate during autumn under waterlogged conditions, while the least number of species germinate during summer (Britton & Brock 1994). Research has found that seed-set, seedling establishment and recruitment for tree species such as flooded gum and swamp paperbark are closely tied to flow events. For example, germination and survival of seedlings can be influenced by infrequent winter high flows, which pick up seeds and move them to open areas in full sunlight. Year-old tree seedlings often do not survive if they are inundated in their first winter after germination (Pen 1999).



Figure 6: Riparian vegetation of the lower Collie River, Wellington reach.

3.2 Aquatic invertebrates

Surveys conducted by WRM (2003) and Storer et al. (2011) within the Wellington reach found marron (*Cherax cainii*) and gilgies (*Cherax quinquecarinatus*) and unclassified freshwater shrimp. Of these three species, marron was the most commonly encountered.

Gilgies are found from Moore River to Bunbury. They exploit almost a full range of freshwater environments from semi-permanent swamps to deep rivers (Austin & Knott 1996). Gilgies dig short burrows into damp bed or banks, retreating into them when water levels are low to prevent their gills drying out and avoid desiccation (WRM 2007; Donohue et al. 2010). Shipway (1951) suggests they are able to tolerate more extreme environmental conditions than marron and may survive longer periods out of water. Gilgies are more commonly found in areas of higher flow velocity and dissolved oxygen (DO) concentrations than marron (Lynas et al. 2006).

Marron require larger, deeper pools as refugia compared with gilgies (Beatty et al. 2006). Before European settlement, the distribution of marron was thought to extend from Harvey to Albany (Morrissy 1978) but now extends from Hutt River (near Geraldton) to Esperance in the south-east (Lawrence & Morrissy 2000; Beatty et al. 2003).

Spring and summer spawning is a common life-history characteristic of aquatic invertebrates in south-west Western Australia. Few species breed in winter, in more than one season, or year-round.

Macroinvertebrates were sampled at two sites between Wellington Reservoir and Burekup in 2009 (Storer et al. 2011). Macroinvertebrates identified to family level, with the exception of oligochaetes (worms) and acarinids (mites) identified to order, chironomids (midges) identified to sub-family and the following identified to genera: *Ephemeroptera* (mayfly), *Odonata* (dragonfly and damselfly), *Plecoptera* (stonefly) and *Trichoptera* (caddisfly). Macroinvertebrate health was scored based on the number of families observed, compared with the number of families expected in an undisturbed system with similar physical and geographical characteristics. The scale of scoring ranges from severely modified (0 to 0.2) to largely unmodified (0.8 to 1). The average of the two site scores is 0.74. This score relates to a large number of macroinvertebrate families being present. Such high diversity can be related to the good condition of the habitat and fringing vegetation.

While WRM 2009 did not sample macroinvertebrates in the Wellington reach, sampling and interpretation has been undertaken in the upper and lower Collie River including sites on Henty Brook and downstream of Harris Dam (WRM 2009). Three-quarters of the species sampled from the upper and lower Collie River were known to breed in spring/summer, 20 per cent were capable of breeding year-round, and less than five per cent bred during winter (WRM 2009). It follows then that seasonal flows reflecting the natural regime should be maintained – in particular spring/summer flows – to provide breeding habitat for these species (WRM 2009).

Studies have found stream permanence to be an overall determinant of the abundance and diversity of aquatic invertebrates (e.g. Bunn et al. 1986 & 1989). Some invertebrates are only found in intermittent streams (Bunn et al. 1989), while other species show large differences in numbers in permanent compared with intermittent streams (Bunn et al. 1986).

Most aquatic invertebrates do not have physiological or life-history strategies that allow them to survive seasonal drying, although some strategies include:

- flying to neighbouring waterbodies (adult insects)
- burrowing into moist sediments (oligochaetes and gilgies)
- a desiccation-resistant stage in their life-cycle (usually as an egg), possibly undergoing diapause during summer (gastropods, cladocerans, copepods and ostracods) (Donohue et al. 2009).

When developing an EF regime for rivers in the south-west, it is important to consider the seasonality of the natural flow regime, including periods of no-flow.

Invertebrate diversity also depends on habitat complexity and diversity, since many species are essentially restricted to particular habitats (Humphries et al. 1996; Kay et al. 2001). Aquatic invertebrates occupy a wide range of habitat types including pools, riffles and sandy runs between pools, and dams of organic debris. Riffles and sandy runs tend to support a higher density and variety of invertebrates than other aquatic habitats. For example, oligochaetes, freshwater crayfish, larvae of dragonfly and damselfly species, chironomid and caddisfly are associated with habitats such as snags, rocks, macrophyte beds and trailing riparian vegetation. To maintain the distribution and abundance of these taxa, it is important to include flows in an EF regime that ensure these habitats are inundated.

Water quality also affects macroinvertebrate assemblages. The freshwater mussel (*Westralunio carteri*) has been found in the lower Collie River downstream of Burekup Weir. Freshwater mussels are believed to be in decline due to secondary salinisation and heavy siltation (WRM 2009).

3.3 Fish

Targeted fish sampling for the Wellington reach was undertaken by WRM (2003) and Storer et al. (2011). Surveys revealed the presence of western minnow (*Galaxias occidentalis*), Swan River goby (*Pseudogobius olorum*), nightfish (*Bostockia porosa*), western pygmy perch (*Edelia vittata*), and cobbler (*Tandanus bostocki*). Ecological and life-history information on each of these species is provided in Appendix 1.

Western minnows were more abundant along the Wellington reach than below Burekup Weir. This difference in abundance has been attributed to the absence of mosquitofish (*Gambusia holbrooki*) within the reach, which could be related to the water released from Wellington Reservoir. WRM 2003 cited Morgan (pers. comm.), who stated that increased flows coupled with cooler temperatures reduced habitat

suitability for mosquitofish, with deaths and population declines often observed during releases.

The breeding ecology of native species is strongly related to flow: migration patterns are triggered by flow events and sufficient water levels are required to provide access to spawning habitat. Native fish species including western minnow, nightfish and western pygmy perch migrate upstream in winter and spring for breeding. With the onset of winter flows in June or July, fish move upstream from summer pools to small side tributaries to spawn on flooded vegetation and submerged reed beds (WRM 2003; Morgan et al. 1998). Cobblers migrate and spawn during late spring and summer (Morrison 1988; WRM 2003; Beatty et al. 2006), however it is presumed they move between pools opportunistically, when flows permit it, to find suitable breeding habitat.

Many natural obstacles can impede the upstream migration of fish, such as steep gradients, logs, shallow riffles and rock bars as well as infrastructure obstacles such as road culverts, weirs and dams. Natural flow regimes include high-flow spells that submerge obstacles, allowing fish to move upstream.

The Wellington reach is steep, with pools separated by waterfalls and granite outcrops. For fish to migrate upstream and pass these barriers, frequent periods of high flow are required.

An important consideration is the length of time that elapses between the onset of cues for breeding and migration (e.g. changes in water temperature and day length) and the submerging of barriers to upstream migration. If flows do not drown out barriers, migrating fish will congregate downstream until the critical flow is achieved. During this time, predation on the congregation of fish may be intense and particularly affect gravid females that are ready to spawn (Donohue et al. 2009a).

For small-bodied fish 10 cm of water over all barriers is considered sufficient for upstream migration. Larger-bodied fish such as freshwater cobbler generally require 20 cm. Fish passage pulses should last 24 hours (Storey 2003). Presumably, a series of winter high-spells is required for fish to navigate upstream in a reach containing a series of barriers, such as a sequence of pools and riffles. Freshwater cobbler also requires pools with a minimum depth of 80 cm in summer for breeding habitat.

The duration and frequency of inundation of trailing and fringing vegetation can influence recruitment success. For example, if water levels fall too soon, or fluctuate greatly, fish eggs may be left above the water line and dry out. Andrew Storey (pers. comm. 2010) suggests a winter baseflow that inundates trailing vegetation interspersed with fish passage pulses would be beneficial for recruitment. Ideally, spawning habitat would be inundated while eggs hatch (72 hours for western pygmy perch) and for a few weeks after spawning to protect fry from predation (Steven Beatty, pers. comm. 2010).

In many south-west rivers, flows that inundate spawning habitat occur for the entire winter, including Lefroy Brook, Margaret River, Wilyabrup Brook and Capel River, or

for the whole year, as in Brunswick River (Bennett & Green 2010). Even in ephemeral streams like Cowaramup Brook, spawning habitat inundation occurs for most of winter (June to September in most years).

Poor recruitment years occur naturally during periods of low rainfall. Given the short breeding life of some native fish (goby may only breed for one year), it is expected that any more than one or two poor breeding years could be detrimental to the population size, resilience and age distribution.

3.4 Amphibians

No specific studies of frogs associated with the Wellington reach were found during a search of the literature. South-west Western Australia has approximately 26 frog species, of which about 20 occupy moist environments adjacent to wetlands and streams.

In the Collie River three frog species were recently recorded: the Glauert's froglet (*Crinia glauerti*), quacking froglet (*C. georgiana*) and slender tree frog (*Litoria adelaidensis*) (WRM 2009). Other frog species thought to inhabit the area include the squelching froglet (*C. insignifera*), Gunther's toadlet (*Pseudophryne guentheri*) and motorbike frog (*Litoria moorei*) (Bamford & Watkins 1983).

All the identified frog species are closely associated with streams and swamps. Spawning generally occurs in winter to spring. Glauert's froglet inhabits marshy areas associated with swamps and damp areas beside pools on small streams, gutters and seeps in forested areas. It lays eggs in shallow water, and tadpoles take about three months to mature in the shallow waters at the edges of rivers and swamps. The slender tree frog lays eggs attached to emergent and submerged vegetation (Tyler et al. 2000).

The breeding requirements and tadpole ecology of these and other species likely to occur in the study area are listed in Table 1. Most species require surface water for egg-laying and then for up to six weeks while tadpoles develop into adult frogs. Frogs tend to be unspecialised opportunistic feeders: adults mainly eat insects while tadpoles tend to graze on algae.

Table 1: Habitat and breeding biology of frogs likely to occur in the Wellington reach between Wellington Reservoir and Burekup Weir. Information sourced from Cogger (2000) and Tyler et al. (2000).

Species	Habitat	Spawning	Tadpole ecology
Glauert's froglet (<i>Crinia glauerti</i>)	Permanent moist areas at the edges of swamps and streams.	<u>Period</u> : mid-winter to spring following rain. <u>Site</u> : lays in shallow water or on moist surface. Eggs sink to bottom.	<u>Habitat</u> : swamps and static areas at the edge of streams. <u>Maturation</u> : >90 days.
Squelching froglet (<i>Crinia insignifera</i>)	Areas of permanent moisture associated with swamps and streams.	<u>Period</u> : winter to early spring following rain. <u>Site</u> : single eggs laid in pools and sink to bottom.	<u>Habitat</u> : swamps and slow-flowing streams. <u>Maturation</u> : 150 days.
Motorbike frog (<i>Litoria moorei</i>)	Riparian areas of permanent wetlands and streams. Arboreal hiding beneath bark and also underneath large rocks and logs.	<u>Period</u> : spring-summer. <u>Site</u> : eggs laid in floating mass attached to vegetation.	<u>Habitat</u> : Permanent wetlands and slow-flowing water. <u>Maturation</u> : 60 days.
Slender tree frog (<i>Litoria adelaidensis</i>)	Dense vegetation in the margins of wetlands and slow-flowing streams.	<u>Period</u> : early spring. <u>Site</u> : eggs in mass attached to vegetation often just below the water surface.	<u>Habitat</u> : wetlands and slow-flowing water. <u>Maturation</u> : not known.
Gunther's toadlet (<i>Pseudophryne guentheri</i>)	Constructs burrows beneath ground cover such as rocks, timber and leaves.	<u>Period</u> : autumn following heavy rain. <u>Site</u> : eggs deposited on damp soil in tunnels.	<u>Habitat</u> : early development in egg capsule and well developed tadpoles emerge when tunnels are flooded. <u>Maturation</u> : not known.

3.5 Mammals

No studies specifically detailing the mammal fauna of the lower Collie River were found during a search of the literature, although some comments can be made based on the results of other studies. Of the mammal species known to inhabit the region through which the river flows, a number rely on the riparian vegetation zone either as habitat or as a food source (Donohue et al. 2009a). Examples of such species include the brush-tailed phascogale (*Phascogale tapoatafa*), quenda or southern brown bandicoot (*Isodon obesulus*), western ringtail possum (*Pseudocheirus occidentalis*), and brushtail possum (*Trichosurus vulpecula*) (Taylor 2006). The two possum species and the brush-tailed phascogale rely on dense vegetation and the availability of hollow-bearing trees, which often occur near rivers and streams. Quenda occur only in areas with dense covering vegetation, such as the margins of wetlands, *Banksia* woodland and jarrah forest. The quokka (*Setonix brachyurus*) and

the western grey kangaroo (*Macropus fuliginosus*) are also likely to inhabit the study area and frequent the riparian zone.

WRM (2009) noted water rats (*Hydromys chrysogaster*) and their burrows at several sites along the lower Collie River. Water rats are found in rivers, swamps, lakes and drainage channels. They have broad, partially webbed hind feet, water-repellent fur and a thick tail. Water rats are water-dependent and known to suffer heat stress without access to water. They construct nesting burrows in banks that are stabilised by riparian vegetation. Water rats restrict their movements to shallower waters less than two metres deep and forage along the shoreline for food such as crayfish, mussels, fish, plants, invertebrates and smaller mammals and birds. They depend on aquatic food webs, the presence of healthy riparian vegetation and the processes that maintain them. The range of water rats has declined in the south-west region due to secondary salinisation and clearing of riparian vegetation (WRM 2007).

3.6 Carbon sources and ecosystem productivity

Aquatic ecosystems rely on energy inputs – in the form of organic carbon – from catchments and riparian zones (WRC 2000). Flow-related processes that control the availability of carbon need to be considered in developing EF regimes. Factors that influence the production of carbon in rivers include light penetration, temperature and nutrient levels.

Some carbon enters rivers as fine particulate matter derived from upstream terrestrial vegetation. This process requires the connection of downstream and upstream river reaches. A significant proportion of organic matter in south-west streams comes from woody debris either washed into the river from the riparian zone or falling directly from overhanging vegetation.

Carbon may also enter river systems as dissolved organic and inorganic carbon in groundwater and soil water. Direct inputs of carbon from in-stream production (phytoplankton and benthic algae) and processing of carbon through fungal, microbial and invertebrate pathways are important in maintaining foodwebs.

The mass of carbon can determine the total standing biomass of aquatic fauna, as well as the biomass of non-aquatic fauna that use the river system as a food source (e.g. piscivorous birds and reptiles that feed on aquatic species). The availability of different types of carbon affects the abundance and biomass of species, competition for resources and, over evolutionary time-scales, speciation and foodweb relationships such as the evolution of functional feeding groups in invertebrates.

4 Components of the flow regime and their ecological functions

A river channel is a highly dynamic system, with a flow regime that varies seasonally and annually (Figure 7). Different components of the flow have particular ecological functions and a direct influence on the structure of aquatic communities and foodwebs in south-west rivers (Pen 1999). Some of the key ecologically-relevant elements of the flow regime in the region's rivers are detailed in the sections below, including periods of no flow, summer low flows, and high winter flows.

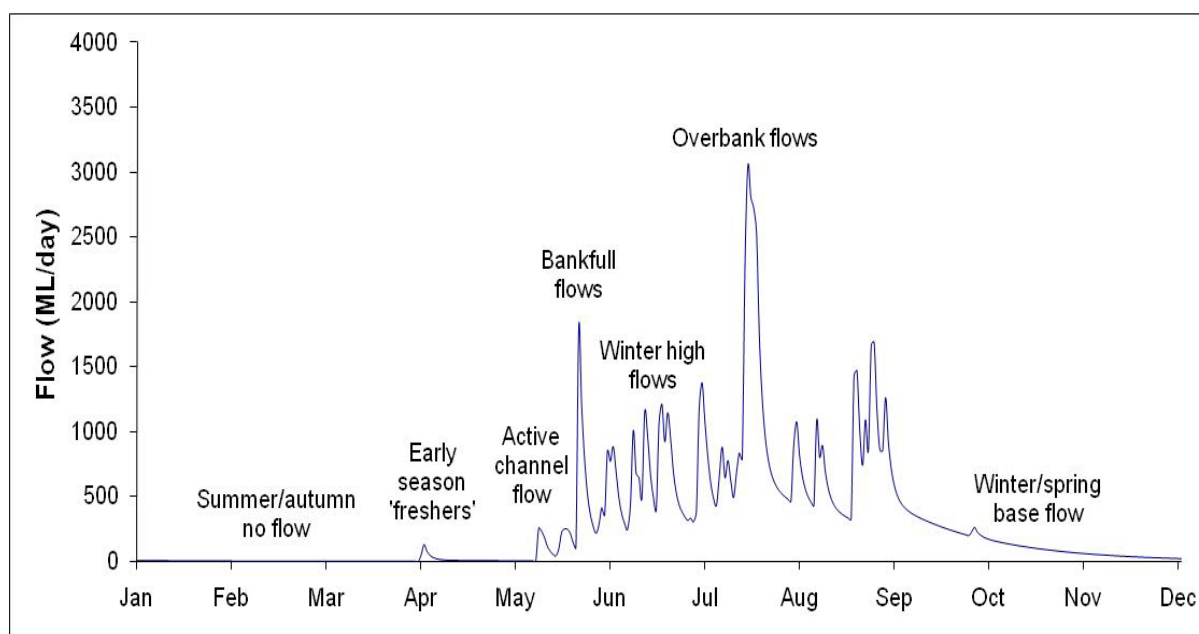


Figure 7: Representative hydrograph for a south-west stream, with different flow components labelled.

4.1 Summer low flows

Summer low flows, including trickle flows, can maintain water levels and depth during the dry period and control water temperature. Summer low flows also maintain circulation and water movement in pools, which prevents stratification and the depletion of oxygen by respiration processes in stream sediments.

In addition, summer low flows maintain habitat in shallow areas of the river, such as riffles and sandy runs, which are important habitat for aquatic invertebrates. The turbulent flow in these areas oxygenates flow and improves the water quality of summer refuges such as pools (Pen 1999). Finally, low flows provide a longitudinal connection between downstream and upstream reaches and pools, and provide for continued downstream carbon movement.

4.2 Autumn and winter low flows

Autumn and winter low flows occur in the early part of the flow season or during winter after prolonged periods of low rainfall and runoff. The magnitude of winter flow in the south-west is variable but highly predictable.

Early-season low flows that occur with the onset of winter rains are particularly important for aquatic fauna, because they relieve late summer stress in pool habitats. As pools dry out, water quality can deteriorate significantly as the temperature rises and dissolved oxygen (DO) levels decline. Also, as the volume of water declines, there is increased competition between species for space and resources. Predatory pressure from birds and other predators also increases owing to the greater density of fish and other aquatic species in the remaining water (Pen 1999).

Early low flows are also a trigger for breeding migrations in some fish species, together with changes in day length and ambient temperature.

4.3 Active channel flows

The morphology of a river channel changes in response to flow events that have the energy to scour the channel, and mobilise and deposit sediment and organic debris. In describing an EF regime it is important to recognise the importance of channel-forming flows and their role in maintaining a healthy and resilient ecosystem. A well-defined low-flow channel is characteristic of many rivers in the south-west and can often be seen as a 'secondary' channel within the wider river channel.

The low-flow channel is maintained by winter flows that have sufficient energy, frequency and duration to regularly scour banks. Within this is what is known as the 'active channel' (an actively eroding channel created by flows that occur in most years) (Pen 1999).

The low-flow and active channel are important structural features of rivers and streams. The low-flow channel contains the bulk of functional habitats in rivers, such as riffles, aquatic vegetation and the pools that are so important as deep-water habitat and summer refugia.

The active channel is often overhung by fringing plants and fringing aquatic vegetation. The extent of the active channel can be seen in places as a line of scoured bare earth within the low-flow channel, below which vegetation is less dense or completely absent. The flows that produce and maintain low-flow channels also tend to be those that inundate overhanging and fringing vegetation, and provide cover for fauna such as macroinvertebrates, as well as spawning habitat for native fish such as pygmy perch (Pen 1999).

Flow events that reach the top of the low-flow channel occur two or three times a year in south-west river systems (WRC 2000) and reach the active channel regularly in winter after rainfall events. The duration of active channel flows following rainfall is also influenced by the storage capacity of soils, soil porosity and seepage to channels from saturated soil profiles.

4.4 Winter high flows

Winter high flows include the range of flows that are responsible for creating and maintaining the morphology of the whole river channel and shape the extent of the floodplain. Winter high flows inundate the middle and higher sections of a river channel and are responsible for the creation of channel features such as benches.

Winter high flows fulfil a variety of ecological functions. By scouring channels they control encroachment of riparian vegetation into the river. Winter high flows also scour sediment and organic matter, creating deep pools that provide summer refugia for fish and other fauna as flow declines in summer (Pen 1999). Scouring organic matter from pools also decreases biological oxygen demand, and therefore helps to maintain oxygen levels within the range tolerated by dependent species.

Winter high flows inundate the entire width and depth of the channel, equalling or exceeding bankfull height (i.e. the highest vertical extent of the main river channel). The magnitude of a bankfull flow generally increases with distance downstream within a catchment, as more water is discharged into the main channel from tributaries. Flood flows (i.e. flows that reach or exceed bankfull height) occur in mid-winter due to heavy rain on saturated soils. Flood flows are generally of short duration and occur at a frequency of about one flood every one, two or three years in south-west Western Australia. Due to the damming of the lower Collie River, bankfull and flood flows in the Wellington reach are far less frequent (about one event in every 10 years). Flows that result in water depths greater than the bankfull height inundate floodplains and fill wetlands that are habitat for frogs and native fish. Riparian and floodplain vegetation require occasional inundation to disperse seed, help seed-set and soak soil profiles to promote successful germination.

5 Determination of the environmental flow regime

5.1 Overall approach

The EF regime for the Wellington reach was determined using an approach called the Proportional Abstraction of Daily Flows (PADFLOW). The PADFLOW approach ‘constructs’ an EF regime by removing a proportion of daily flow from an existing flow record. The volume of daily flow abstracted is calculated with reference to known ecologically important flows.

PADFLOW is based around use of the River Ecological Sustainable Yield Model (RESYM), which the Department of Water developed in 2007. RESYM is a water-balance program used to model EF regimes given certain model inputs (or parameters) such as dam storage characteristics, flow into the dam, consumptive use, and the proportion of daily flow released for the environment. The model outputs can include daily dam storage levels, streamflow volumes, overflow volumes and release volumes. These outputs enable us to determine an EF regime downstream of a dam and whether the desired consumptive demand targets have been achieved.

RESYM allows us to manipulate and display potential EF regimes with reference to known ecologically important flow thresholds. A panel can use RESYM in a workshop setting to develop an EF regime by manipulating model parameters and assessing changes in the frequency and duration of flows above ecologically important thresholds (e.g. Donohue et al. 2009a, 2009b, 2010).

The flow chart in Figure 8 shows the steps taken to generate the EF regime for Wellington reach using RESYM and the PADFLOW approach. Steps 1 to 8 are the same as the flow events method (e.g. WRM 2005; Stewardson & Cottingham 2002) and other approaches used in similar ecological water requirement (EWR) studies in Western Australia (e.g. Davies & Creagh 2000). Steps 9 to 10 are associated specifically with the PADFLOW approach and the modelling process using RESYM.

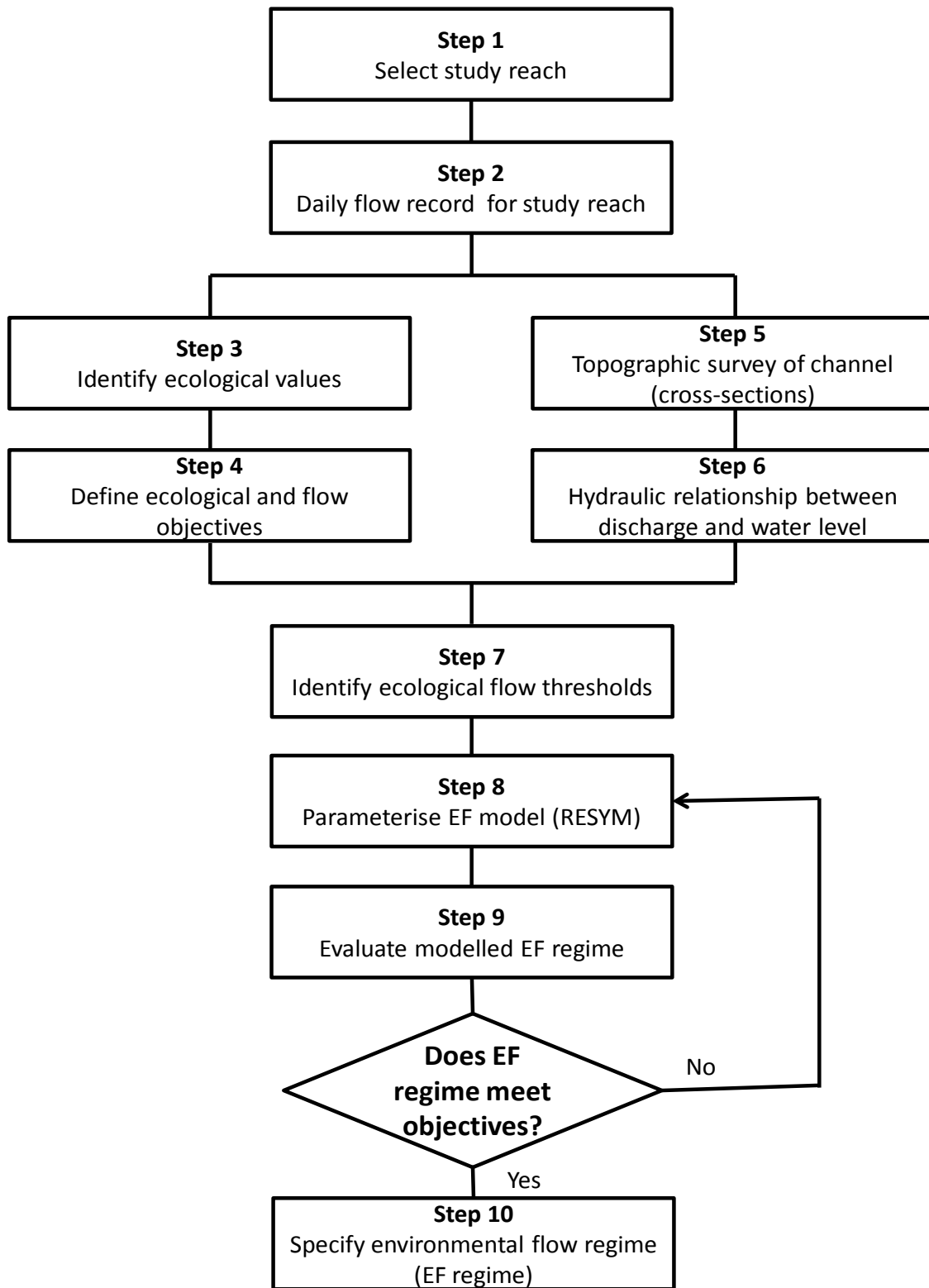


Figure 8: Flow chart showing steps in the Proportional Abstraction of Daily Flows (PADFLOW) method

Wellington reach

EF regime studies are based on detailed research carried out at particular sites. Study sites are selected to represent the hydraulic characteristics and ecology of river reaches. The channel form largely determines the magnitude of flows needed to inundate important habitats.

The Wellington reach is distinct from the lower Collie River below Burekup Weir because of the influence of summer irrigation water (released from Wellington Reservoir and diverted into irrigation channels at the weir). The Wellington reach is approximately 14 km in length, and flows through intact native forest, interspersed with very small disturbed areas. The river reach consists of long, deep well-scoured pools, with sandy and rocky substrates, interspersed with granite rock waterfalls and rapids. The banks and valley sides are steep, with the result that the riparian belt is relatively narrow.

A number of other environmental flow studies have been undertaken for the Wellington reach during the past 10 years (e.g. Streamtec 2000; WEC & Streamtec 2002; Hardcastle et al. 2003), but these reports no longer reflect the most up-to-date method for developing EF regimes. The reasons for this include:

- the EF regimes developed didn't capture and mimic the variability of natural flows from year to year
- the hydraulic methods used to estimate the flow to meet key ecological objectives were not as accurate as current methods.

When thresholds and information in these reports and others (WRM 2003; WRM 2010) was considered accurate, they were used in this report. This is discussed in more detail in Section 5.6.

Particular areas throughout the 14 km reach were identified, such as pools, riffles and waterfalls. These areas were observed and surveyed to identify key habitats and the flows required to maintain them in their current condition (see Section 5.6).

5.2 Development of daily flow records

To model an EF regime, RESYM requires a daily flow series that covers a period representing the variation in annual and daily flows found in the river's flow regime. Three daily flow time-series were generated for this study to develop the EF regime, and gain an insight into past, current and future flow regimes for the Wellington reach. The flow records are described below.

Dam inflow

The 'dam inflow' record is a modelled daily flow time-series for flow into Wellington Reservoir between 1975 and 2008. The flow record was constructed by combining the daily flow datasets of the gauged flow at Mungalup Tower (612002) (Figure 2) and modelled catchment flow into the dam below Mungalup Tower.

This is an input into the RESYM model (see Section 6).

Undammed flow

The 'undammed flow' record is a modelled daily flow time-series, representing flow at the Wellington reach between 1975 and 2007 if Wellington Reservoir had not been present. The flow record is a combination of the 'dam inflow' time-series (above) and modelled flow generated by catchment rainfall and runoff between the Wellington Reservoir wall and the Mt Lennard gauging station (612006) (Figure 2). The 'undammed flow' record is indicative of a natural flow regime at the Wellington reach.

Historical flow

The 'historical flow' record is a daily flow time-series for the lower Collie River below Wellington Reservoir. This record reflects the historical pattern of flow below the dam resulting from dam releases and overflows, as well as contributions from the catchment downstream of the dam. The record combines gauged flow at the Wellington Flume gauging station (612013) immediately below the dam wall (Figure 2) and modelled catchment inflows between the Wellington Flume and Mt Lennard gauging stations. The 'historical flow' daily time-series is for the period 1975 to 2007.

Modelled environmental flow (potential flow regime)

The 'modelled EF' regime is the term used to describe the flow regime developed by an expert panel using RESYM. The daily time-series for this flow consists of the modelled ecological releases from Wellington Reservoir, plus modelled catchment inflow between the reservoir and Mt Lennard gauging station. This time-series runs from 1975 to 2007. The 'modelled EF' regime is developed for a retrospective time period, thus demonstrating how ecological releases from the dam would have affected flow along the Wellington reach in the years 1975 to 2007. It is, however, used to make decisions on how water is released to meet ecological objectives in the future. The 'undammed', 'historical' and 'modelled EF' regimes are all estimated/measured at the Mt Lennard gauging station so the benefit of catchment flows is included in the assessment.

5.3 Aim of the EF regime study

After the summer irrigation season, flows in the Wellington reach are a function of catchment inflow below the dam, scour releases to remove saline water from the dam, and dam overflows. While these flows contribute to the reach's winter flow regime, the timing and magnitude of scour releases is not linked to the river's ecological requirements and could be improved to meet them. Autumn/early winter and spring flows in particular are diminished under the current release regime compared with the natural variability of flow (i.e. 'dam inflow' and 'undammed flow'). The flow regime should be altered to more closely match the timing of flows into the dam and better reflect the system's ecological requirements.

With inflow into Wellington Reservoir predicted to decline in response to a drying climate, and consumptive demand for water likely to increase, less water will be available for environmental water releases.

With this in mind the study has the following aims:

- a. Identify a release regime for Wellington Reservoir that best meets the water requirements of the current in-stream and riparian native biota aquatic and, where possible, restore some of the natural timing and variability of the flow regime.
- b. While achieving a), maximise the water available for consumptive use, acknowledging that the reservoir is a significant state water supply dam.
- c. Provide information to support licensing and allocation decision making processes.

5.4 Demand scenarios

Given the current allocation limit for Wellington Reservoir is 85.1 GL (DoW 2008), a potential consumptive use (demand) pattern for a fully allocated situation was designed to parameterise the RESYM model. The scenario represents a future level of demand of 85.1 GL/year, comprising 68 GL for irrigation and 17.1 GL for industrial use. This was chosen as a possible scenario given that Harvey Water has a licence for 68 GL and the remaining 17.1 GL is likely to be taken up for industrial use in the future. Table 2 illustrates a potential monthly and daily consumptive use pattern for this scenario.

Table 2: Monthly and daily consumptive use pattern for irrigation demand of 68 GL/year, industrial demand of 17.1 GL/year and total demand of 85.1 GL/year.

Month	Irrigation demand (ML)		Industrial demand (ML)		Total demand (ML)	
	Monthly	Daily	Monthly	Daily	Monthly	Daily
January	13045	421	1452	47	14497	468
February	11865	424	1312	47	13177	471
March	11762	379	1452	47	13214	426
April	6785	226	1405	47	8190	273
May	1873	60	1452	47	3326	107
June	1072	36	1405	47	2478	83
July	0	0	1452	47	1452	47
August	0	0	1452	47	1452	47
September	0	0	1405	47	1405	47
October	0	0	1452	47	1452	47
November	9932	331	1405	47	11337	378
December	11666	376	1452	47	13118	423
Annual demand (ML)	68000		17100		85100	

5.5 Ecological and flow objectives

The PADFLOW method's fourth stage involves describing both the ecological and flow objectives for the Wellington reach to maintain in-stream and riparian vegetation; habitat for aquatic invertebrates, native fish, amphibians and mammals; ecological processes (carbon sources) and channel morphology (Figure 8). Ecological and flow objectives that meet ecological values for rivers in the south west have been developed and refined using research and expert panels for over ten years. The most current objectives have been adopted for values identified within the Wellington reach.

Table 3 contains the important ecological and flow objectives considered for the EF regime, as well as the corresponding flow rates (ecological flow thresholds, see Section 5.6) estimated for meeting the objectives.

5.6 Identification of ecological flow thresholds

The flow thresholds (ML/day) for meeting the Wellington reach's ecological objectives were estimated by Streamtec (2000), WRM (2003), Hardcastle et al. (2003) and WRM (2010). In these studies the thresholds were based on field observations and flow calculations for individual cross-sections.

The flow rates that achieve the Wellington reach's ecological and flow objectives are listed in Table 3. The methods used to determine individual flow thresholds are discussed in the sections below. For more information see Streamtec (2000), WRM (2003), Hardcastle et al. (2003) and WRM (2010).

Table 3: Ecological flow thresholds for the Wellington reach. The flow rates satisfy the ecological and flow objectives (Streamtec 2000; Hardcastle et al. 2003; WRM 2003 & WRM 2010).

Ecological objective	Flow objective	Ecological flow threshold	
		m ³ /s	ML/day
1 #Maintain pools as spawning habitat for cobbler	Minimum pool depth of 80 cm	0	0
2 *Inundate gravel runs and riffles as summer habitat for aquatic invertebrates	Riffles inundated to a depth of at least 5 cm over 50% of total riffle width	0.026	2.25
3 *Maintain water quality and DO levels in pools as summer refuge for aquatic fauna. Maintain upstream/downstream carbon transfer.	Maintain DO above 5 mg/L. Maintain connectivity.	0.026	2.25
4 *Inundate gravel runs and riffles as winter habitat for aquatic invertebrates	Riffles inundated to provide sufficient winter habitat	0.168	14.5
5 #Maintain active channel morphology, scour pools and prevent incursion of terrestrial vegetation	Sufficient water levels to fill the active channel	4.7	406
6 - #Inundate aquatic and trailing vegetation as habitat for invertebrates and vertebrates, and as spawning sites for fish and amphibians	Sufficient water depth to begin inundation of fringing vegetation	4.7	406
7 %Allow upstream migration of small-bodied fish during spawning season	Water depth of at least 10 cm over obstacles	6	518
8 +Allow upstream migration of cobbler during spawning season	Water depth of at least 20 cm over obstacles	8.43	728
9 +Maintain channel morphology and scour pools	High-flow events	40	3456
10 xProvide overbank flows to aid seed dispersal and germination of riparian vegetation, and flush organic matter into river system	1:3 year event (undammed flow regime)	55	4752

Notes to Table 3

Method of threshold estimation:

Observation/measurement – Bennett and Green 2009

*Observation/measurement – WRM 2010

- Observation/measurement – WRM 2003

% Calculation – Hardcastle 2003

+ Calculation – Streamtec 2000

x Streamflow analysis – this report

Ecological flow thresholds 1 to 6 are measured at the Wellington Flume gauging station (612013); 7 to 10 are measured at the Mt Lennard gauging station.

Cobbler nesting habitat

Cobbler requires a pool depth of 80 cm over summer so it can build nests for breeding. Throughout the Wellington reach there are pools two to three metres deep (WRM 2003). Some pools are deeper, although they have never been measured. Given the deep permanent pools within the reach, it is assumed no flow would be required over summer to maintain pools more than 80 cm deep.

The estimated flow threshold to maintain cobbler breeding habitat is:

- 0 ML/day.

Summer minimum flow for pool water quality and connectivity

Permanent pools are both a summer refuge habitat for native fish and aquatic invertebrates and a source of water and food for a variety of riparian vertebrates.

To maintain pool water quality and aquatic fauna diversity in periods of low flow, a minimum average bulk water velocity of 0.01 m/s in pools is recommended to prevent stratification and maintain dissolved oxygen (DO) at more than 4 mg/L (WRM 2009).

Streamtec (2000) estimated that 36 ML/day (or 1100 ML/month) was required to maintain pool water quality, although it is unclear how this figure was calculated. This flow appears to be a higher summer flow than that found in the 'undammed flow' regime, and therefore it would be unrealistic to maintain this as a minimum flow during summer.

To improve the integrity of this threshold, the Department of Water contracted WRM to undertake a trial release study. Based on this study (WRM 2010), the recommended daily summer minimum flow at the Wellington Flume gauging station to maintain DO above 5mg/L, prevent stratification and promote connectivity between pools is:

- 2.25 ML/day.

Macroinvertebrate habitat

Riffle zones provide habitat for a broad range of fauna and tend to support a diversity of macroinvertebrate species. The turbulence of flow over riffles also oxygenates water and improves the quality of downstream habitat such as pools.

To maintain the value of riffles as habitat, the following flow criteria are used:

- 50 per cent of the width of riffle cross-sections inundated to a depth of 5 cm in summer
- 100 per cent of the width of riffle cross-sections inundated to a depth of 5 cm in winter.

Streamtec (2000) estimated the ecological flow threshold for winter riffle habitat below Wellington Reservoir as 65 ML/day using Manning's n equation and field measurements of discharge. The study did not estimate an ecological flow threshold for summer riffle inundation.

Hardcastle et al. (2003) later recommended an ecological flow threshold for summer riffles of 64.8 ML/day and winter riffles of 73.4 ML/day in June and October, and 86.4 ML/day in July and August.

To improve the accuracy and transparency of macroinvertebrate habitat thresholds for summer and winter, the Department of Water contracted WRM to undertake a trial release study.

Based on this study (WRM 2010), the recommended flow rate at Wellington Flume gauging station to inundate 50 per cent of the width of riffle habitat to a depth of 5 cm in summer is:

- 2.25 ML/day.

To establish a winter macroinvertebrate threshold, WRM observed riffle inundation at flows of up to 82 ML/day measured at the Wellington Flume gauging station. Flows of 82 ML/day inundated 80 per cent of the width of riffles to a depth of 5cm. However, WRM considered these flows were higher than necessary to maintain winter macroinvertebrate habitat in the Wellington reach (WRM 2010). Based on these observations of the riffles at various flow rates (WRM 2010), the recommended flow at the Wellington Flume gauging station to preserve winter macroinvertebrate habitat is:

- 14.5 ML/day.

Inundation of the active channel and trailing vegetation

The ecological flow threshold to maintain an open low-flow channel was defined as the flow required to fill the depth of the active channel. The elevation of the active channel is evident on the bank as the point above which vegetation is stable and below which the bank is bare and without extensive vegetation (WRM 2008). At this point, trailing or overhanging vegetation also becomes inundated, providing habitat for spawning and protection of fish and macroinvertebrates.

Using cross-sectional data and discharge measurements, Hardcastle et al. (2003) found flow rates ranging from 5.95 to 21.2 m³/s were required to inundate the active channel (and trailing vegetation) in the Wellington reach. However, observational data collected during field visits indicated that trailing vegetation was inundated at lower flow rates of 4.3 m³/s (A. Green and K. Bennett, DoW, 2010 pers. obs.), 4.7 and 5 m³/s (WRM 2003) as measured at the Wellington Flume gauging station.

The average of the observational data was used to determine the ecological flow threshold to inundate the active channel and trailing vegetation, and was determined as:

- 406 ML/day (4.7 m³/s).

Upstream migration of native fish, small and large bodied

The water-level objective for upstream migration of small-bodied native fish is a minimum depth of 10 cm over barriers to migration. Given the presence of granite outcrops within Wellington reach, there are significant barriers to fish migration such

as rocky waterfalls; thus fish passage flows are higher than would be expected in rivers without rocky barriers. Hardcastle et al. (2003) estimated peak flows of up to 518 ML/day (equivalent to 6 m³/s) would be required to enable small-bodied fish passage in the Wellington reach. The flow was determined by analysing natural catchment flow hydrographs from Mt Lennard gauging station (612006). Field observations by WRM (2003) confirmed that small-bodied fish passage was probably possible at observed flow rates of 4.7 to 5 m³/s at Wellington Flume gauging station.

Based on the assessment of hydrographs (Hardcastle et al. 2003) and observed flows, the flow rate at Mt Lennard gauging station that achieves a depth of at least 10 cm throughout the entire reach for migration of small-bodied fish is:

- 518 ML/day (6 m³/s).

The only large-bodied native fish in the Wellington reach is cobbler (*Tandanus bostocki*). The water-level objective for upstream migration of large-bodied native fish is a minimum depth of 20 cm over barriers to migration.

Streamtec (2000) used this depth over barriers to determine the flow rate required for upstream migration of small-bodied fish. This was done by developing ratings curves using Manning's *n* equation and river cross-sections that were possible barriers to fish migration. Streamtec provided a monthly flow volume in its report that included a number of fish passage pulses. The daily fish passage flow rate was subsequently interpreted by WRM (2003) to be 728 ML/day. The threshold is applied to large-bodied fish in the current study.

The estimated ecological flow threshold required to achieve a thalweg depth of at least 20 cm throughout the entire reach for migration of large-bodied fish (using Manning's *n* equation) is:

- 728 ML/day (8.4 m³/s).

To allow for the benefit of catchment flow in meeting this threshold, the flow needed to meet fish passage is assessed at the Mt Lennard gauging station site.

Channel maintenance - winter high flows

Winter high flows are important to scour pools and maintain channel form. These flows are often associated with bankfull flows. Flows that reach or exceed bankfull height in south-west rivers typically occur at a frequency of about one flood event every one, two or three years (Green et al. 2011). Streamtec 2000 estimated bankfull flows below Wellington Reservoir were above 159 m³/s, or 9568 ML over 24 hours. This magnitude was adopted by WEC 2002 and Hardcastle et al. 2003 as a channel-maintenance flow threshold. However, analysis during this study showed these flows were infrequent, occurring about 1:8 years in the 'undammed flow' regime (suggesting the threshold was too high). Streamtec (2000) suggested a flow of 40 m³/s (3456 ML/day) once every three years would be sufficient to scour pools. In the 'undammed' regime (1975–2007) flows of this magnitude occurred approximately 1:2 years. While this flow threshold may not achieve a bankfull flow, it occurs at a suitable frequency and is thus likely to be enough to scour pools and maintain channel form.

Table 4: The number of years and the frequency that thresholds are met in the 'undammed' and 'historical' flow records.

Threshold (ML/day)	No. of years and frequency threshold is met	
	Undammed	Historic
3456	18 – (1:2)	5 – (1:6)
9568	4 – (1:8)	3 – (1:10)
No. of years in the record	33	31

Frequency = no. of years threshold is met / no. of years in record.

For the purpose of this assessment, the flow threshold to maintain channel form is based on the recommendation in Streamtec (2000) of:

- 3456 ML/day (40 m³/s)

Compliance with this threshold will be assessed at Mt Lennard gauging station site.

Maintenance of riparian vegetation and organic matter input - overbank flows

Overbank flows that inundate the floodplain and promote germination in riparian vegetation should occur one in every two years, according to Streamtec (2000), WEC (2002) and Hardcastle et al. (2003). They suggest flows above 167 m³/s (a 24-hour event of 10 345 ML in the Wellington reach is required to inundate riparian vegetation). Flows of this magnitude rarely occur in the undammed regime (1:11 years) and only occurred twice below the dam wall between 1975 and 2007. Given riparian vegetation in the Wellington reach is healthy, it is unlikely this infrequent flow event is maintaining the vegetation.

Overbank flows also flush organic matter into the stream, providing a source of carbon. A significant proportion of organic matter in south-west streams comes from woody debris either washed into the river from the riparian zone or falling directly from overhanging vegetation.

The availability of different types of carbon affects the abundance and biomass of species, competition for resources and, over evolutionary time scales, speciation and foodweb relationships such as the evolution of functional feeding groups in invertebrates.

Field observation of flood events should be undertaken to refine the estimate of the flow required to inundate riparian zones in the Wellington reach. In the absence of such information, the flow required to maintain riparian vegetation is based on analysis of the 'undammed flow' regime from 1975 to 2007 and a flow event with a frequency of 1 in 3 years.

Table 5: The number of years and the frequency that the thresholds are met in the 'undammed' and 'historical' flow records.

Threshold (ML/day)	No. of years and frequency threshold is met	
	Undammed	Historic
4752	11 – (1:3)	4 – (1:8)
10 345	3 – (1:11)	2 – (1:15)
No. of years in the record	33	31

Frequency = no. of years threshold is met / no. of years in record.

The flow threshold for an event that occurs on average once every three years in the 'undammed' regime, measured at the Mt Lennard gauging station site, is:

- 4752 ML/day (55 m³/s).

Compliance with this threshold will be assessed at Mt Lennard gauging station site.

6 Modelling the environmental flow regime

The River Ecologically Sustainable Yield Model (RESYM) is a water-balance model designed to be used with the Proportional Abstraction of Daily Flows (PADFLOW) approach when developing EF regimes. The following information was used to parameterise the RESYM and guide the modelling panel in generating an EF regime:

- flow thresholds in Table 3
- demand scenario in Table 2
- 'dam inflow' record
- proportion of dam inflow released (Table 6)
- total storage capacity of Wellington Reservoir (186 000 ML)
- maximum release capacity of the reservoir scour valve (500 ML/day).

Using RESYM, the panel produced an EF regime for the Wellington reach by releasing a proportion (Table 6) of the daily 'dam inflow' in a way that best balanced the ecological objectives identified in Section 5.6 with the reliability of supply for consumptive use. The desired proportion of daily inflow is to be supplied to the environment via releases (up to 500 ML/day) from the Wellington Reservoir scour valve. To produce the EF regime, the releases from the reservoir were added to dam overflows and catchment rainfall and runoff between the reservoir and Mount Lennard gauging station.

The panel then produced what it considered to be the optimal EF regime achievable for the given demand scenario (Section 5.4). It did this by adjusting the proportion of 'dam inflow' released and assessing the resulting EF regime using bar charts. The bar charts in Section 6.1 allowed the panel to compare the frequency and duration of flows above the ecological flow thresholds in Table 3: for the 'modelled EF' (blue bars), 'undammed flow' (red bars) and 'historical flow' (green bars) (see Section 5.2). The panel evaluated each of the ecological flow thresholds listed in Table 3 individually, assessing the frequency and duration of flows above the ecological flow threshold both within years and across years.

The proportion of flow released was adjusted accordingly and the model re-run if the panel considered the frequency and duration of flows above a particular ecological flow threshold:

- did not maintain the ecological objective of that ecological flow threshold
- was likely to cause a risk to the ecological values of the river
- differed significantly from the 'undammed' or 'historical' regime.

The final EF regime was produced when the panel felt the best ecological outcome had been reached given the constraints of the demand scenario.

The final proportion of 'dam inflow' released from the Wellington Reservoir to generate the final EF regime is shown in Table 6. The flow ranges shown came from the record of daily dam inflow into the reservoir.

Table 6: Flow ranges and proportion of ‘dam inflow’ that is released (release rule) to develop the environmental flow regime for the Wellington reach.

Flow range (ML/day)	Release rule
0 – 8 ML/day	100%
8 – 43.5 ML/day	30%
43.5 – 148 ML/day	20%
148 – 734 ML/day	15%
*Above 734 ML/day	40%

*The maximum release capacity for the Wellington Reservoir is currently 500 ML/day, therefore if dam inflow is above 1250 ML/day, only 500 ML/day can be released. The maximum release capacity of 500 ML/day was set as a parameter in RESYM.

6.1 Evaluation of environmental flow regime

The bar charts shown in figures 9 to 18 compare the frequency and duration above the ecological flow thresholds (listed in Table 3) in the final EF regime for Wellington reach for the 85.1 GL/year demand scenario. The EF regime is made up of the proportion of daily ‘dam inflow’ released from the scour valve, dam overflows and catchment rainfall and runoff between the reservoir and Mount Lennard gauging station.

All bar charts are presented for flows (‘modelled EF’, ‘undammed’ and ‘historical’) at the Mt Lennard gauging station. Although ecological flow thresholds 1 to 6 in Table 3 are measured at the Wellington Flume gauging station and thresholds 7 to 10 are measured at the Mt Lennard gauging station (see Figure 2 for locations), there is little difference in the lower flows (and therefore bar charts for lower thresholds) between the Mt Lennard and Wellington Flume sites. The lower thresholds occur as a result of releases from the scour valve and generally at times when there are no catchment flows. There is, however, a large difference in the higher flows (and therefore bar charts for higher thresholds) between the Mt Lennard and Wellington Flume sites because of the impact of winter catchment rainfall and runoff. Therefore, for simplicity, all plots were presented for flows at Mt Lennard to accurately represent the impacts of catchment flows on the higher thresholds (7–10).

It is important to note that within this reach, irrigation water is released from Wellington Reservoir and diverted at Burekup Weir between October and May/June. These irrigation releases have not been included in the ‘modelled EF’ regime because they do not represent an environmental flow. In reality, flows during the irrigation season will be higher than the modelled EF regime in the Wellington reach, and will more closely reflect the ‘historical flow’.

The timing, frequency and duration of the ‘modelled EF’, ‘undammed’ and ‘historical’ flow regimes for the Wellington reach (for each ecological flow threshold in Table 3) are discussed in the following sections.

Cobbler nesting habitat

Due to the deep pools in the Wellington reach, no flow is required to maintain a depth of 80 cm and provide cobbler breeding habitat. As the threshold is 0 ML/day, the cobbler breeding objective is met at all times (Figure 9). If flow were to cease for an extended period of time, evaporation and seepage might eventually dry the pools to the extent that pool depths for cobbler would be affected; but this would only happen if releases to meet all the other thresholds ceased.

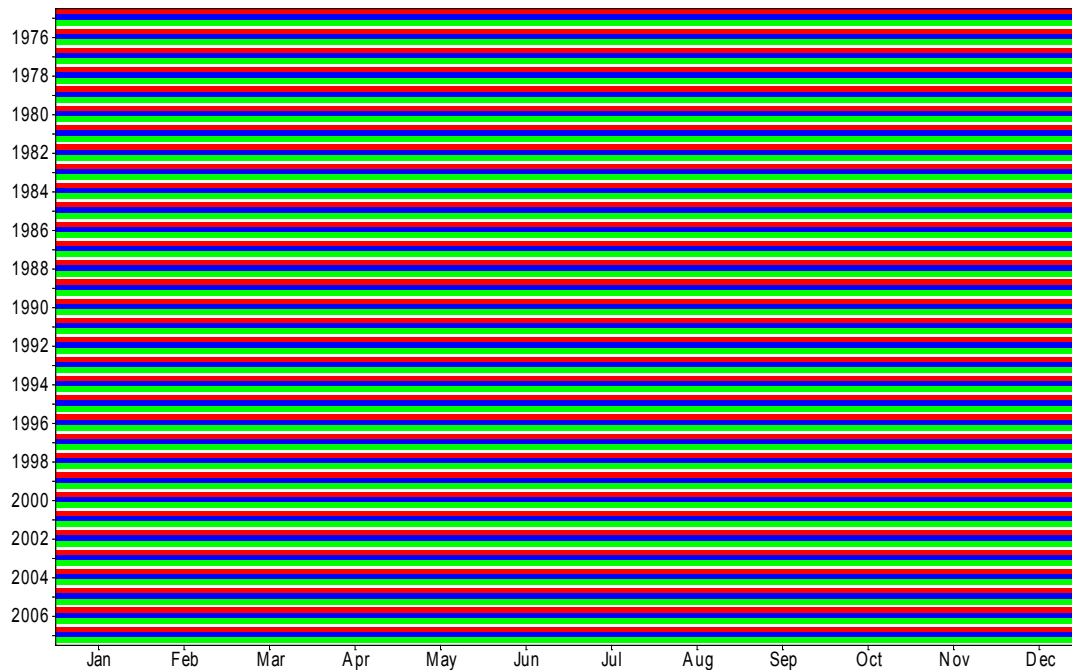


Figure 9: The frequency and duration of flows from 1975–2007 above 0 ML/day in the ‘modelled EF’ regime (blue bars) compared with the ‘undammed flow’ (red bars) and ‘historical flow’ (green bars) regimes. The charts show the final EF regime selected.

Pool water quality, connectivity and summer macroinvertebrate habitat

A flow of 2.25 ML/day is required to maintain DO, prevent stratification, inundate riffles for summer macroinvertebrate habitat and promote downstream carbon movement through connectivity between pools (Table 3). These low-flow requirements are critical to provide habitat, reduce in-stream stress and enable survival of aquatic fauna during periods of low flow (sections 0 and 0). It is therefore a high priority, even as irrigation and industrial demand from Wellington Reservoir increases, that ecological objectives are not affected. Figure 10 shows that below 2.25 ML/day, the ‘undammed flow’ and ‘modelled EF’ match exactly because RESYM was set up to release 100 per cent of the daily dam inflow in the 0 to 8 ML/day range (Table 6).

Given that irrigation releases exist through most of summer, low flows during this period are not likely to occur very often. However, it is evident from the historical flow record that at the end of the irrigation season, flow drops below the minimum

threshold until winter catchment flows below the dam increase or scour releases begin. This has occurred around May, June and July, particularly during the past 10 years. In the ‘undammed flow’ regime, flows only drop below 2.25 ML/day in the summer periods between January and April. It is important that outside the irrigation season, low flows are not diminished beyond what would have occurred naturally (i.e. in the ‘undammed flow’ record).

During the past 10 years the ‘modelled EF’ regime (blue line) shows an improvement in the minimum flow compared with the ‘historical flow’ at the end of the irrigation season. Therefore the modelled EF regime is likely to improve the critical riverine environment during that month.

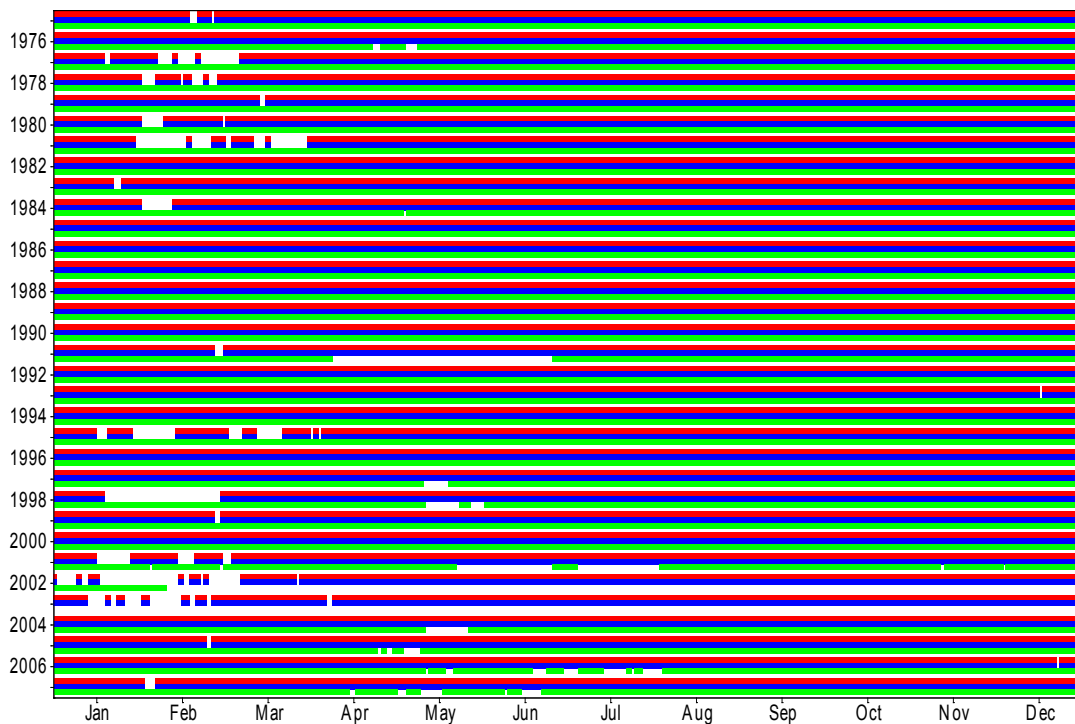


Figure 10: The frequency and duration of flows from 1975–2007 above 2.25 ML/day in the ‘modelled EF’ regime (blue bars) compared with the ‘undammed flow’ (red bars) and ‘historical flow’ (green bars) regimes. The charts show the final EF regime selected.

Winter riffle inundation

Flows above 14.5 ML/day are required to maintain macroinvertebrate winter habitat. Flows of this magnitude would be met naturally in the Wellington reach from about April/May to the end of November (see ‘undammed flow’ regime in Figure 11). In the ‘historical flow’ record for the reach, flows above 14.5 ML/day have occurred throughout the irrigation season (November to April/May) and during the winter months as a result of scour releases and catchment inflow below the dam. After the iterative modelling process the panel agreed that releasing 30 per cent of dam inflows in the 8 to 43.5 ML/day range (Table 6) would meet the requirements for winter riffle inundation.

Although the onset of winter flows above the threshold in the 'modelled EF' regime is delayed by up to nearly two months in some years (e.g. 1989) when compared with 'undammed flow', it generally remains above the threshold during the critical period for winter macroinvertebrate habitat of May to October.

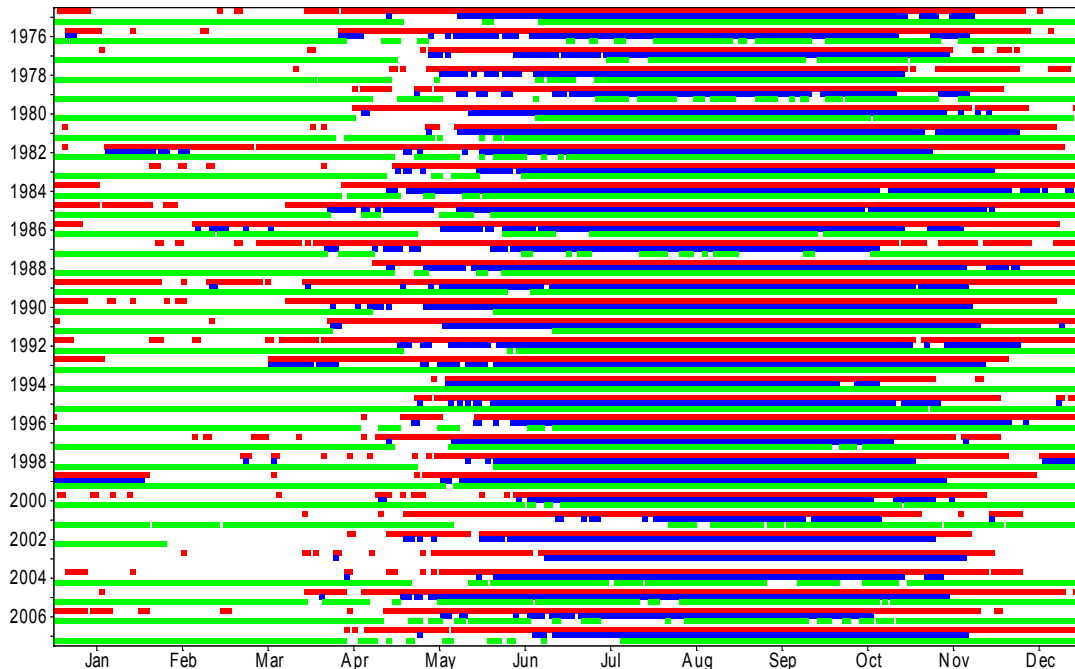


Figure 11: The frequency and duration of flows from 1975–2007 above 14.5 ML/day in the modelled EF regime (blue bars) compared with the 'undammed flow' (red bars) and 'historical flow' (green bars) regimes. The charts show the final EF regime selected.

Winter spawning habitat, active channel and small-bodied fish passage flows

The timing, duration and magnitude of flows required to inundate overhanging vegetation for winter spawning habitat, maintain the active channel and facilitate upstream migration of small-bodied fish are similar in the Wellington reach; therefore these flow requirements have been discussed together. The ecological flow threshold for winter spawning habitat and active channel maintenance is 406 ML/day, and the ecological flow threshold for upstream fish migration is 518 ML/day (Table 3). After the iterative modelling process, the panel agreed that 15 per cent of dam inflows in the range of 148 to 734 ML/day should be released for the EF regime (Table 6).

Flows sufficient to inundate spawning habitat and maintain the active channel occur regularly throughout the irrigation season and indicate that the active channel in this system is as much defined by the summer irrigation releases as it is by winter flows. Typically, if flows were diminished by use or a drying climate, vegetation would encroach to a new level as reductions in winter flow occurred, establishing a new active channel and a lower level of flow to achieve inundation of spawning habitat. This will not occur in this system with the current magnitude of irrigation releases. If winter flows decrease, spawning habitat will be inundated less often during the

critical winter period. In this system it is therefore important to try to preserve the frequency and duration of these events.

During the winter period, flows sufficient to support fish passage and spawning habitat, as well as maintain the active channel in the 'undammed flow' regime (red), generally start in mid-June and continue until the end of September. Flows of this magnitude are generally delayed in the 'modelled EF' regime by a week or two when compared with the 'undammed flow' regime.

When compared with the 'historical flow' record, the EF regime meets the ecological flow threshold around the same time (Figure 12). In many years, however, the flows above the threshold in the 'modelled EF' regime were intermittent compared with both the 'undammed' and 'historical' flows, especially in years when large volumes of scour water were released (1985 and 1999). This is unlikely to be a problem for fish passage as events do not need to be continuous and spells of one to two days throughout winter are enough for migration past obstacles.

However, fish and amphibians would likely benefit from more stable and prolonged events to inundate spawning habitat (of 3 to 14 days) throughout winter. In general, spawning events are less frequent and of shorter duration in the 'modelled EF' than the 'historical' regime because of the increase in demand from 68 to 85.1 GL, and potentially pose a higher risk to the existing ecological values of the river system.

An important observation is that during the dry sequence of the past 10 years, fish have persisted and bred; however, the panel recommends the EF regime should not depart any further from the 'historical' and 'undammed' flow regimes. As such, during this dry sequence the 'modelled EF' regime provides a similar and in some cases slightly improved duration and frequency of flows above the thresholds than the 'historical flow' record. But the EF regime does affect the reliability of supply in the dryer years.

Given the high level of demand modelled for the Wellington Reservoir in this scenario (85.1 GL/year) compared with historic demand (average of 62 GL/year since 1975), as well as a drying climate reducing dam storage levels, the 'modelled EF' regime is proposed as a sufficient fish spawning and migration regime. Monitoring of fish populations should take place to assess the effectiveness of these releases in maintaining fish diversity and populations.

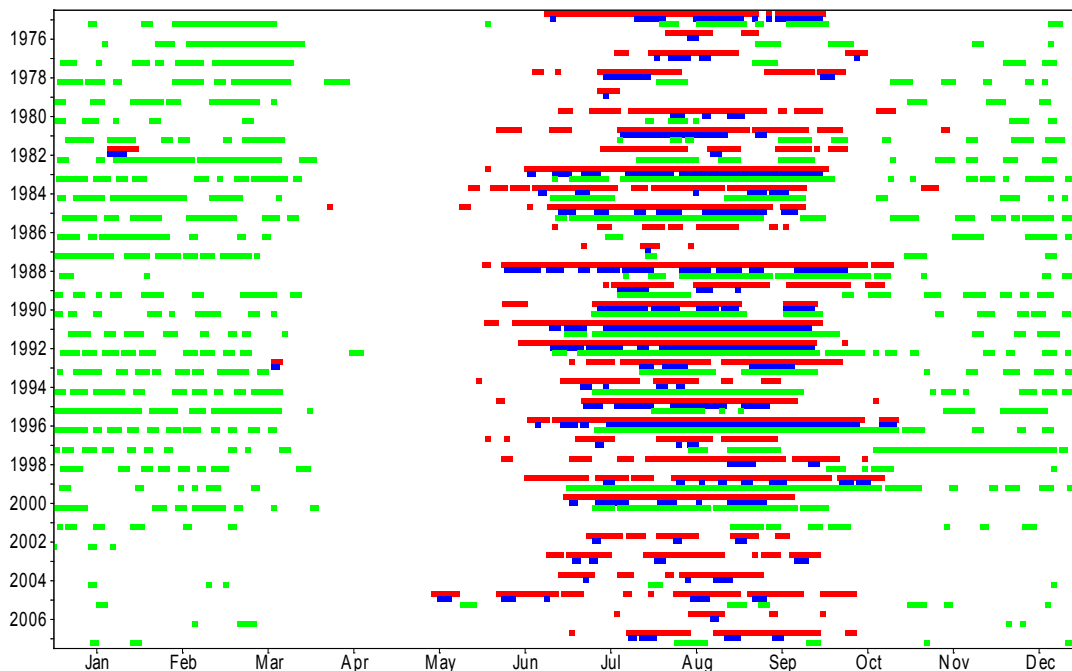


Figure 12: Frequency and duration of flows from 1975–2007 above 406 ML/day in the ‘modelled EF’ regime (blue bars) compared with the ‘undammed flow’ (red bars) and ‘historical flow’ (green bars) regimes. The charts show the final EF regime selected.

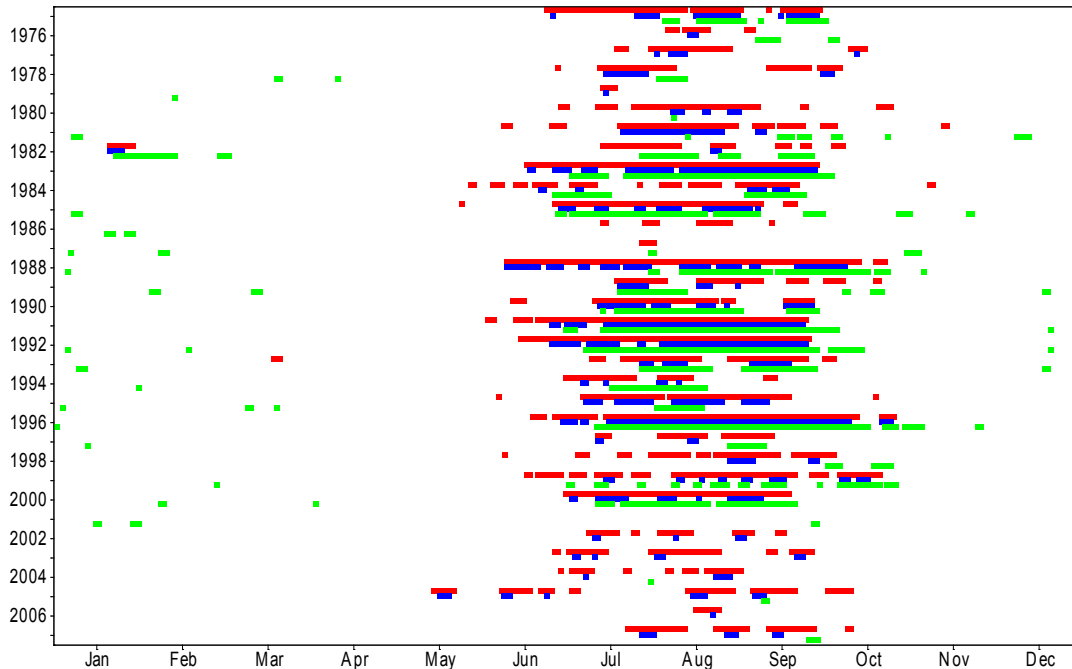


Figure 13: The frequency and duration of flows from 1975–2007 above 518 ML/day in the ‘modelled EF’ regime (blue bars) compared with the ‘undammed flow’ (red bars) and ‘historical flow’ (green bars) regimes. The charts show the final EF regime selected.

Cobbler migration

Cobbler usually breeds in late summer and migrates upstream to find suitable breeding habitats such as deep pools. The estimated threshold flow to allow cobbler to migrate upstream over barriers is 728 ML/day. After the iterative modelling process, the panel agreed that 15 per cent of dam inflows in the range 148 to 734 ML/day, and 40 per cent of dam inflow above 734 ML/day, to the maximum release capacity of 500 ML/day, should be released for the EF regime (Table 6).

In the 'undammed flow' record, intermittent flows sufficient to allow upstream passage for cobbler occurred every year except 2001 and between June/July and September/October. In the 'historical flow' record these flows occur in only about half the years and less frequently in the dry sequence, but the presence of cobbler within the reach suggests the current regime is enough to maintain the population because they continue to breed and survive.

It is possible that because deep pools persist all year around below Wellington Reservoir, migration to find suitable breeding habitat is not as important as it would be in systems with fewer and shallower pools.

In the 'modelled EF' regime, these events occurred in about one third of years, compared with half in the 'historical' and nearly all in the 'undammed' regimes. In the 'modelled EF' regime, cobbler migration events have not occurred since 1998.

Due to the high demand for water from Wellington Reservoir, the panel was not able to maintain the current frequency of cobbler migration events without seriously affecting the reliability of supply. The low mean annual inflow into the dam of 83.5 GL/year from 1998 to 2007 also indicates that overflow events are unlikely to occur (if demand is 85.1 GL/year).

Given the maximum release capacity of the reservoir is currently 500 ML/day, releases alone cannot provide flows of the magnitude required to support upstream migration of freshwater cobbler. Historically, these events occur either as a result of high catchment inflow, together with scour events, and/or dam overflow.

In the future, it may be more realistic to use high-catchment-flow events, perhaps above 200 ML/day, as a trigger to release 500 ML/day from the scour valve for an event of 12 hours. This would ensure at least 700 ML/day is flowing past the Mt Lennard site and thus it is likely cobbler would be able to move between pools. If this method is implemented, cobbler migration events would have occurred in 18 of the 33 years from 1975 to 2007, compared with 10 years in the 'modelled EF' or 20 years in the 'historical flow' regimes.

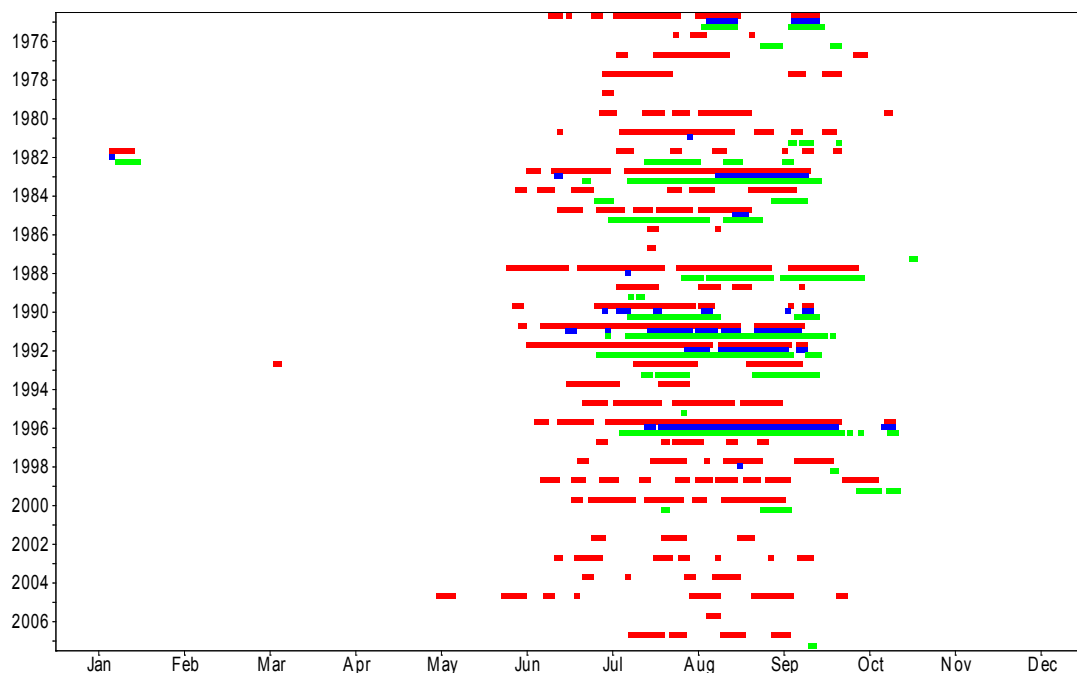


Figure 14: The frequency and duration of flows from 1975–2007 above 728 ML/day in the ‘modelled EF’ regime (blue bars) compared with the ‘undammed flow’ (red bars) and ‘historical flow’ (green bars) regimes. The charts show the final EF regime selected.

Channel maintenance - winter high flows

The ecological flow threshold for channel maintenance is 3456 ML/day (Table 3). After the iterative modelling process, the panel agreed that 40 per cent of dam inflow above 734 ML/day, to the maximum release capacity of 500 ML/day, should be released for the EF regime (Table 6).

Channel maintenance events occurred in 18 of the 33 years in the ‘undammed flow’ record. Flows of this magnitude cannot be released from the Wellington Reservoir. The maximum modelled catchment flows between the reservoir and Burekup Weir were just over 700 ML/day, so without overflow from the dam (and large overflow events at that) flows above 3456 ML/day would not occur. As can be seen from the plot below, these events only occurred in the historical record (since 1975) in 1982, 1983, 1990, 1991 and 1996.

In the ‘modelled EF’ regime, the recommended release rules provided channel maintenance flows in four years (1983, 1991, 1992 and 1996). While these events do not occur as frequently as channel-forming flows typically do in unmodified streams of the south-west (1:1, 1:2 or 1:3), the pools and channel of the Wellington reach remain well scoured. It is probable the combination of intact vegetation, mostly granite bedrock channel and consistently high summer-irrigation releases prevent sediment and organic matter build-up in pools; as such, high winter-flow events may not be as important to maintaining channel form. In addition to this, it is likely to be increasingly difficult to maintain the frequency of large overflow events in a drying

climate and with increasing demand, both of which draw down the storage in the dam. Therefore providing a 'modelled EF' regime with close to the same frequency of channel forming flows as the 'historical' regime is a good result.

Table 7: The number of years and the frequency the threshold of 3456 ML/day is met in the 'undammed flow', 'historical flow' and 'modelled EF' regimes.

	Undammed	Historical	Environmental
No. of years and frequency	18 – (1:2)	5 – (1:6)	4 (1:8)
No. of years in the record	33	31	33

Frequency = no. of years threshold is met / no. of years in record.

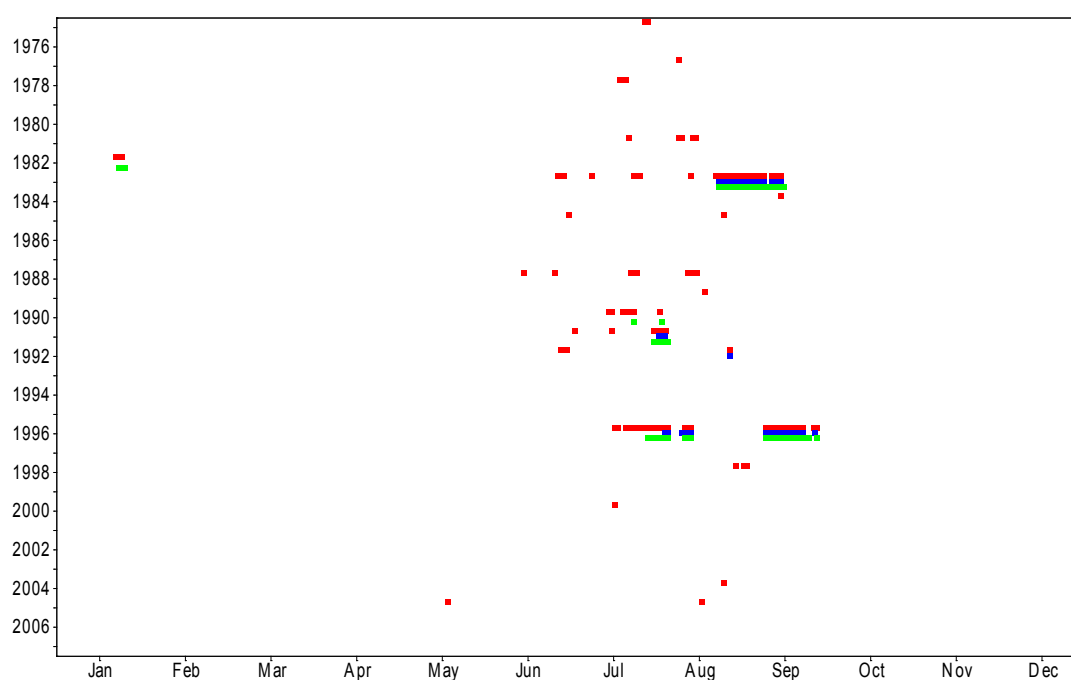


Figure 15: The frequency and duration of flows from 1975–2007 above 3456 ML/day in the 'modelled EF' regime (blue bars) compared with the 'undammed flow' (red bars) and 'historical flow' (green bars) regimes. The charts show the final EF regime selected.

Maintenance of riparian vegetation and organic matter input - overbank flows

The ecological flow threshold for maintaining riparian vegetation and flushing organic matter into the system is 4752 ML/day (Table 3). After an iterative modelling process, the panel agreed that 40 per cent of dam inflow above 734 ML/day, to the maximum release capacity of 500 ML/day, should be released for the EF regime (Table 6).

Like channel maintenance flows, flows expected to flood riparian vegetation and wash organic matter off the riverbank (4752 ML/day) only occur during large overflow events. Overbank flows trigger germination and recruitment of vegetation in the riparian zone by spreading seed and soaking the soil profile. Organic matter washed

into rivers from the riparian zone provides carbon that supports the abundance and biomass of aquatic species.

Overbank flows occur at a frequency of 1:3 years in the 'undammed' record, 1:8 in the 'historical' record and 1:11 in the 'modelled EF' regime. While the events in the 'modelled EF' regime occur at a frequency similar to the historic events, they are far more frequent in the 'undammed flow' regime. Regardless of this, vegetation is in near-pristine condition and Syrinx Environmental (2003) recommends the frequency of bankfull (and presumably overbank flows) should not drop below the 'historical flow' regime below Wellington Reservoir.

It is probable that established vegetation is maintained by soil moisture in the riverbank and therefore irrigation flows in summer aid survival, while overbank flows are of sufficient frequency to maintain recruitment. The condition of the riparian and overhanging vegetation is likely to provide important carbon inputs from direct litter fall into the river, potentially reducing the reliance on overbank flows.

The panel felt that providing overbank flows at the same frequency as the historical flow regime was a good outcome for a dam with a high level of demand. If the climate continues to dry as predicted, it will be increasingly difficult to maintain the frequency of overbank flows without reducing demand.

To make this flow threshold more robust, we need to better understand the flow required to inundate riparian vegetation, as well as the frequency of overbank flows needed for maintaining recruitment in the riparian vegetation.

Table 8: The number of years and the frequency the threshold of 4752 ML./day is met in the 'undammed flow', 'historical flow' and 'modelled EF' regimes.

Threshold (ML/day)	Undammed	Historical	Environmental
No. of years and frequency	11 - (1:3)	4 (1:8)	3 (1:11)
No. of years in the record	33	31	33

Frequency = no. of years threshold is met / no. of years in record.

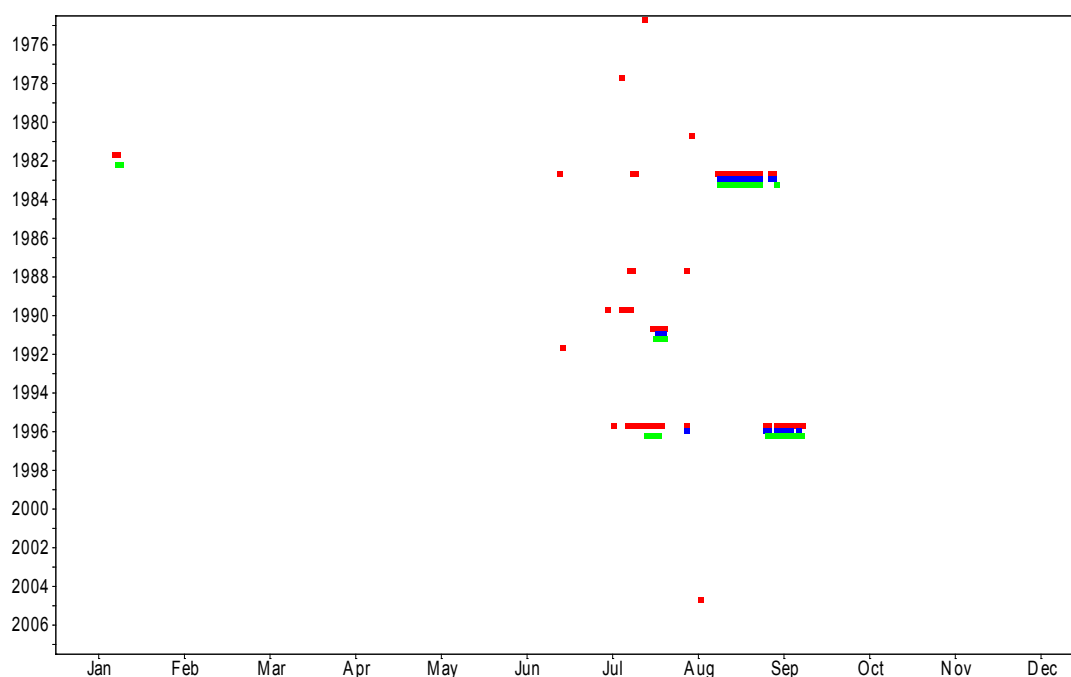


Figure 16: The frequency and duration of flows from 1975–2007 above 4752 ML/day in the ‘modelled EF’ regime (blue bars) compared with the ‘undammed flow’ (red bars) and ‘historical flow’ (green bars) regimes. The charts show the final EF regime selected.

Intermediate winter flow thresholds - 50 ML/day and 200 ML/day

Because the ‘natural flow paradigm’ states the flow regime is responsible for the evolution of a river’s observed ecological state (Poff 1997) and because a large range of flows occurs between the winter macroinvertebrate threshold (14.5 ML/day) and the active channel flows (406 ML/day), two intermediate thresholds of 50 ML/day and 200 ML/day have been chosen to demonstrate the ‘take’ rules (Table 6) provide sufficient flows. Although these flow thresholds don’t have specific ecological objectives, it is likely flows in this range increase the amount and type of habitat available for aquatic flora and fauna by inundating riffles, low benches and in-stream macrophytes, and improve connectivity between some pools and the ability of fauna to migrate – both upstream and downstream.

These plots both show the ‘undammed’ (red) flows have a longer frequency and duration in the winter months than the ‘historical’ (green) flows below the dam. The ‘modelled EF’ regime (blue) improves the frequency and duration of winter flows when compared with the ‘historical’ flow and demonstrates the take rules in Table 4 help restore some of the natural timing and magnitude of flows in winter, particularly during the shoulder periods between the irrigation season and the historical scour release period.

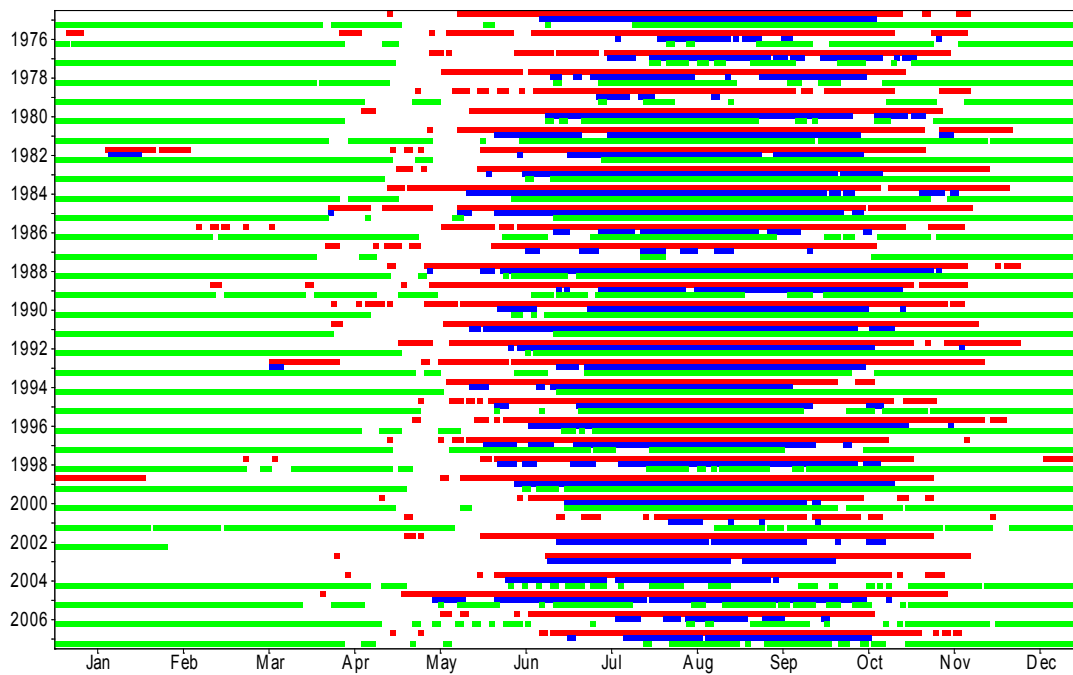


Figure 17: Frequency and duration of flows from 1975–2007 above 50 ML/day in the ‘modelled EF’ regime (blue bars) compared with that of the ‘undammed flow’ (red bars) and ‘historical flow’ (green bars).

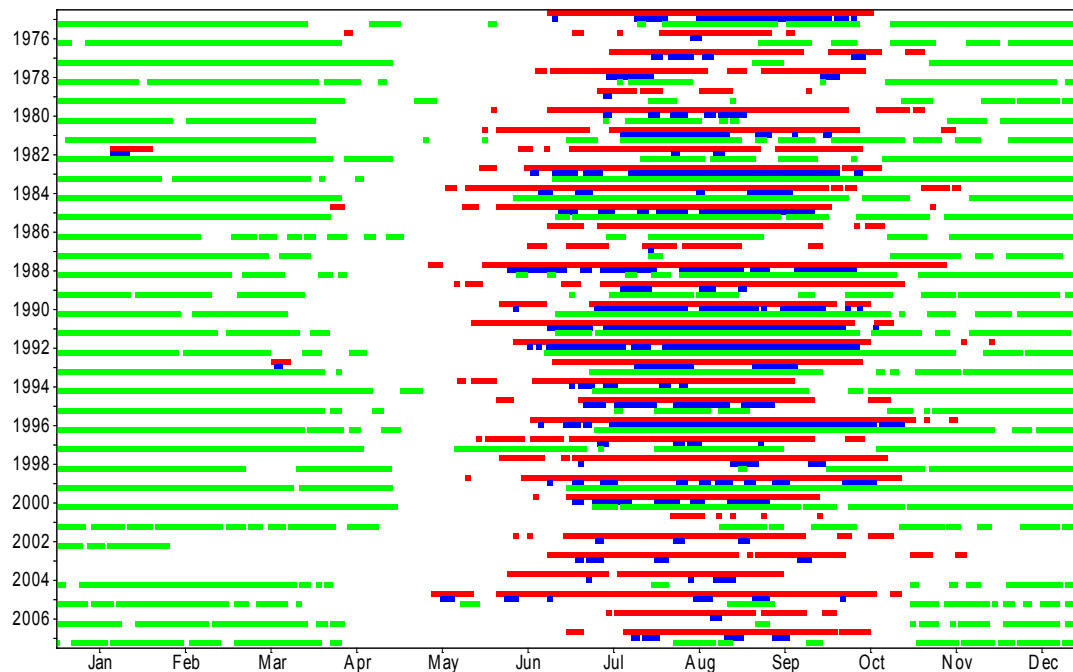


Figure 18: The frequency and duration of flows from 1975–2007 above 200 ML/day in the modelled EF regime (blue bars) compared with the ‘undammed flow’ (red bars) and ‘historical flow’ (green bars) regimes. The charts show the final EF regime selected.

7 Replacing the existing scour releases with an environmental flow regime

This study demonstrates the benefits to the ecology and consumptive use of replacing the winter scour regime with the EF regime.

During the irrigation season, releases and flow below the dam are above what the ecology requires. This is clearly shown in Figure 19. Irrigation flows are recorded in the 'historical' regime and from November to mid-April flow is well above the modelled EF regime.

Outside the irrigation season, at present releases from the dam stop until the salinity gradient and dam storage is such that scour releases of salty water are triggered. This is often late in winter and not linked to ecological needs. As a result, flow below the dam wall is often very low from the end of the irrigation season until late winter (Figure 19).

In 2007 (as an example) higher magnitude 'undammed' flows begin towards the end of June but scour releases don't begin until early August, more than one month later. Replacing the scour regime with the modelled EF regime improves the timing of winter flows, with small fresher flows starting in early July and larger flows in mid-July (Figure 19).

Table 9 presents the volume of flow from June to the end of September (assumed as the period outside the irrigation season) that has occurred between 1975 and 2007 under the scour regime, and those that would have occurred under the modelled EF regime. For the 33 years of record, the EF regime averaged 76 per cent of the historical flow. The reduction is a result of an increase in demand between the historical use and the modelled 'fully allocated' scenario (see Section 5.4).

Although the total volume of water provided for the environment during this period is reduced under the EF regime, it is expected that mimicking the timing of the 'undammed' flows will better meet the ecological objectives (Table 3) and improve the ecology's resilience to the flow reductions resulting from the increased allocation of water and the drying climate.

To meet the Wellington reach's EF regime outside the irrigation season (assumed to be June to September inclusive), on average nearly half the EF regime is provided by environmental releases, while the other 15 per cent is provided by catchment rainfall and runoff below the reservoir, and 35 per cent from dam overflows.

It is worth noting initial TwoRES simulations showed the EF regime acts as a surrogate for the scour by removing the salty winter inflows from the reservoir (DoW 2011c), and therefore the impacts on salinity in the dam of replacing the scour regime with an environmental release regime are minimal. Further salinity modelling is underway to investigate the effects in more detail.

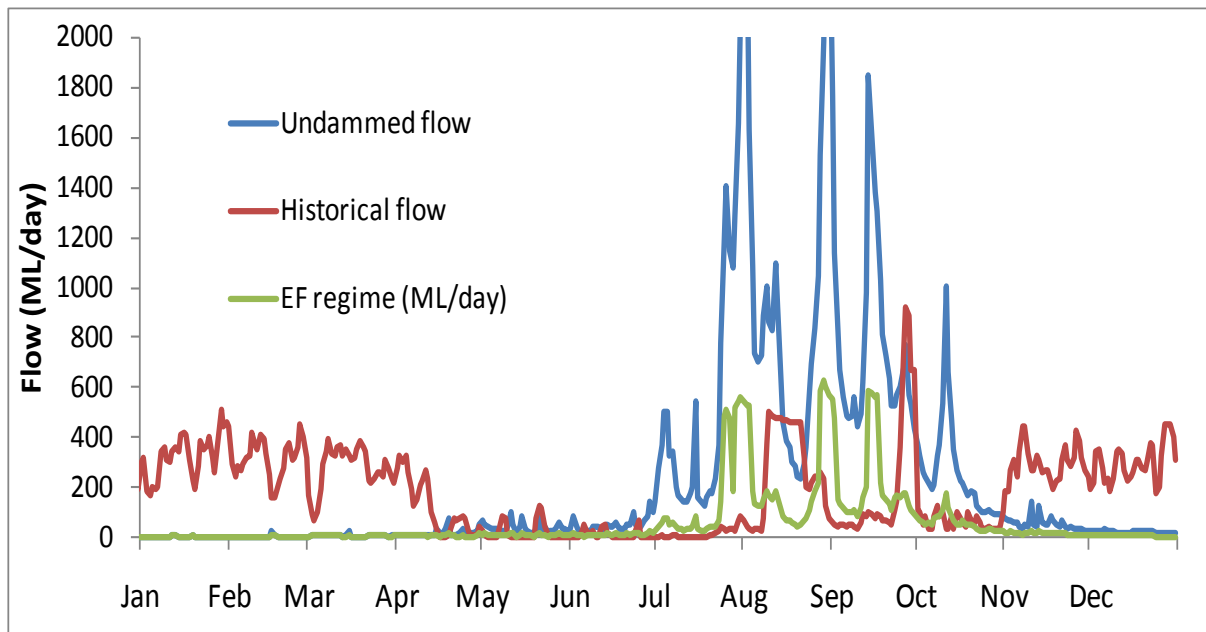


Figure 19: 'Undammed', 'historical' and 'modelled EF' regimes in the Wellington reach for 2007. The 'modelled EF' regime shows the onset of winter flows was earlier than the 'historical flow' regime. The EF regime more closely mimics the 'undammed flow' regime throughout the year.

Table 9: Presents flows at Mt Lennard gauging station site, and releases at the Wellington Reservoir from June to the end of September for the 'undammed', 'historical' and 'modelled EF' regimes.

Year	Undammed flow (GL)	Historical flow (GL)	EF regime (GL)	Historical release (GL)	Environmental release (GL)
1975	112	53	51	25	33
1976	36	13	8	9	7
1977	60	9	15	6	12
1978	90	15	18	11	14
1979	24	5	6	4	5
1980	79	19	22	14	15
1981	144	34	35	24	26
1982	57	40	14	26	9
1983	339	267	220	44	45
1984	101	56	26	41	20
1985	124	74	46	43	34
1986	42	20	8	19	6
1987	29	5	6	3	5
1988	218	88	55	31	43
1989	78	29	19	22	16
1990	144	98	48	42	34
1991	215	167	134	48	48
1992	185	148	105	47	46
1993	93	66	28	36	21
1994	69	43	17	37	13
1995	123	25	37	17	30
1996	377	276	251	41	46
1997	67	33	17	28	12
1998	95	6	20	3	16
1999	96	48	26	42	19
2000	119	56	32	40	25
2001	14	14	3	13	3
2002	59	-	14	-	11
2003	73	-	18	-	15
2004	65	9	15	6	12
2005	95	13	21	10	17
2006	35	7	7	6	6
2007	73	15	18	11	15
Mean GL (June to September inclusive)	109	57	43	24	21
EF regime as % of regime	39%	76%	100%	-	-
Historical release as % of flow regime	22%	43%	-	100%	-
EF release as % of flow regime	19%		49%		100%

Note: The years 2002 and 2003 were excluded from statistical analysis of all flow regimes. This was to ensure consistent time periods for comparisons between flow regimes, because the Wellington Flume gauging station, which measures the historical flow regime, was not functioning during this time.

Reliability of supply and annual environmental flow regime

The annual volumes for the EF regime, target and available draw (1975–2007) and the reliability of supply are shown in Table 10.

Because the EF regime is generated as a percentage of daily dam inflow, its volume varies between years. The annual EF regime ranges from 5 GL to 275 GL from 1975 to 2007 and on average, constitutes 37 per cent of the mean annual inflow.

Reliability of supply is the frequency with which water allocated under a license is able to be supplied in full. For example, if consumptive users receive their full allocation for seven years out of 10, reliability of supply would be 70 per cent.

For the EF regime (Table 10) and proposed release rules (Table 6), the reliability of supply for the target draw of 85.1 GL/year is 76 per cent. The available draw ranges from 24.5 to 85.1 GL/year. In the dry sequence of the past 10 years, reliability of supply drops to 50 per cent.

A comparison of figures 20 and 21 demonstrates the modelled EF regime's impact on dam storage levels and reliability of supply. These figures plot the resulting dam storage level, target draw and available draw under the scenario with no environmental release (Figure 20) and with the modelled environmental release (Figure 21).

Even without environmental releases, the full target draw of 85.1 GL is only met in 85 per cent of years (Figure 20), compared with 76 per cent for the modelled EF regime. In the dry sequence of the past 10 years, reliability of supply is only 70 per cent without environmental releases and 50 per cent with them. This is evidence that the modelled EF regime has relatively little impact on reliability of supply (85 per cent to 76 per cent), and that the reduction in dam inflow during the dry sequence has more impact on reliability of supply (dropping from 76 to 50 per cent under the modelled EF regime).

Given CSIRO's median climate scenario predicts streamflow within the Collie area will reduce by 24 per cent by 2030 from the 1975 to 2007 streamflow regime, it is likely the reliability of supply will fall below 76 per cent for the next 20 years. This indicates that either:

- the allocation limit for Wellington Reservoir will need to be adjusted in the future, using the EF regime modelled above, and modelled using a climate-adjusted flow regime and reliability-of-supply target agreed between the Department of Water and industry, or
- users will need to accept a lower reliability of supply.

Table 10: The annual modelled EF regime, target and available draw for the demand scenario of 85.1 GL/year from 1975 to 2007. EF regime includes environmental releases from the dam, dam overflows and catchment inflow below the dam.

Year	Undammed flow (GL)	EF regime (GL)	EF regime – % of undammed flow	Target draw (GL)	Available draw (GL)	Draw – % of undammed flow
1975	124.0	57.8	47%	85.1	85.1	69%
1976	47.2	11.6	25%	85.1	85.1	180%
1977	77.3	20.2	26%	85.1	85.1	110%
1978	107.6	24.1	22%	85.1	85.1	79%
1979	30.9	8.1	26%	85.1	60.6	196%
1980	95.8	26.8	28%	85.1	24.5	26%
1981	163.4	40.0	24%	85.1	85.1	52%
1982	138.4	22.8	16%	85.1	85.1	61%
1983	352.7	227.1	64%	85.1	85.1	24%
1984	122.6	30.9	25%	85.1	85.1	69%
1985	142.6	51.3	36%	85.1	85.1	60%
1986	55.4	11.7	21%	85.1	85.1	153%
1987	37.3	8.9	24%	85.1	85.1	228%
1988	262.5	66.9	25%	85.1	82.0	31%
1989	101.4	24.1	24%	85.1	85.1	84%
1990	158.1	54.3	34%	85.1	85.1	54%
1991	230.6	141.8	61%	85.1	85.1	37%
1992	201.9	112.8	56%	85.1	85.1	42%
1993	118.5	34.3	29%	85.1	85.1	72%
1994	74.4	19.5	26%	85.1	85.1	114%
1995	132.8	39.4	30%	85.1	85.1	64%
1996	407.8	275.1	67%	85.1	85.1	21%
1997	75.1	19.5	26%	85.1	85.1	113%
1998	112.1	24.3	22%	85.1	85.1	76%
1999	134.5	37.0	27%	85.1	85.1	63%
2000	124.3	33.9	27%	85.1	85.1	68%
2001	19.2	5.3	28%	85.1	85.1	442%
2002	68.8	17.1	25%	85.1	82.8	120%
2003	85.7	20.9	24%	85.1	48.1	56%
2004	72.0	17.5	24%	85.1	65.6	91%
2005	132.3	28.9	22%	85.1	56.5	43%
2006	42.4	9.6	23%	85.1	85.1	201%
2007	85.6	22.2	26%	85.1	47.7	56%
Average	125.3	46.8	37%	85.1	78.7	63%
Minimum	19.2	5.3	28%	85.1	24.5	127%
Maximum	407.8	275.1	67%	85.1	85.1	21%
Reliability of supply				76%		

Note: For comparison with Table 9, excluding the years 2002 and 2003, the average annual EF regime is 48.6 GL/year

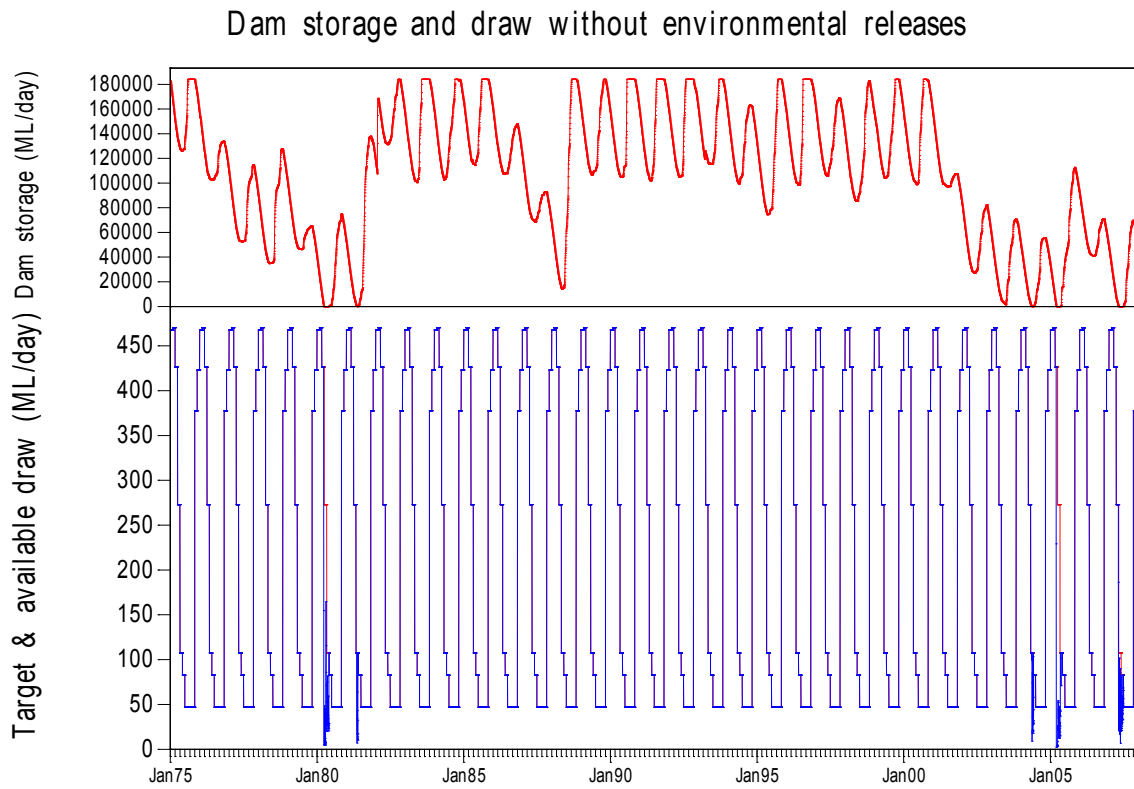


Figure 20: The plot shows the reservoir storage levels (upper plot), and the target and available draw (lower plot) in ML/day, for the modelled demand scenario of 85.1 GL/year without environmental releases. Where available draw (blue) does not plot over target draw (red), total consumptive demand has not been met. Total demand has not been met five years out of the 33 plotted (85 per cent reliability) from 1975 to 2007.

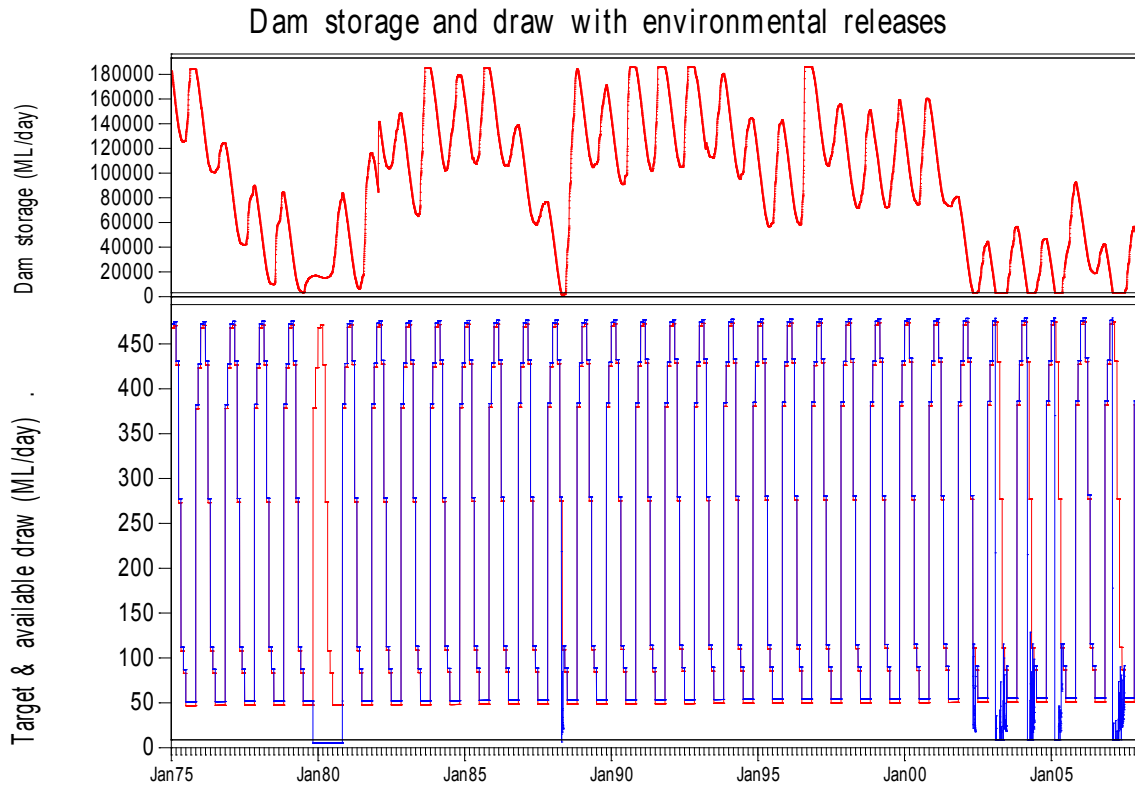


Figure 21: The plot shows the reservoir storage levels (upper plot), and the target and available draw (lower plot) in ML/day, for the modelled demand scenario of 85.1 GL/year with the modelled environmental release regime. Where available draw (blue) does not plot over target draw (red), total consumptive demand has not been met. Total demand has not been met eight years out of the 33 plotted (76 per cent reliability) from 1975 to 2007.

While RESYM is very effective for modelling daily and variable releases from dams or abstraction from rivers, a more accurate model for determining the reliability of supply from Wellington Reservoir is the TwoRES water balance model (see DoW 2011c). A comparison of the results from RESYM and TwoRES (Table 11, Appendix 2) for similar modelling scenarios shows the reliability of supply for the modelled environmental flow regime is likely to be overestimated in RESYM, however the reliability of supply estimates above are accurate enough to be used as a comparison between scenarios in this study.

8 Conclusion

This study's objective was to develop an EF regime for the Wellington reach that would:

- maintain the presence of the current in-stream and riparian native biota
- maximise the water available for consumptive use (from Wellington Reservoir).

The EF regime acknowledges the need to maximise reliability of supply, while minimising risks to the ecological values of the lower Collie River below Wellington Reservoir. The modelled EF regime averages 39 per cent of the 'undammed flow' and 76 per cent of the 'historical flow' (from June to September inclusive); thus it is likely to place the ecology at a higher risk than other recent EF studies for south-west rivers such as Cowaramup Brook (Donohue 2010), Lefroy Brook (Donohue et al. 2009a), Brunswick River (Donohue et al. 2009b) and Margaret River (Green et al. 2011). However, the objective of those reports was to develop an EF regime that protected the existing ecological values at a *low* level of risk.

Ecological thresholds that showed the greatest departure from the 'undammed' and 'historical' flow regimes were the flows required to provide spawning habitat and upstream migration for small- and large-bodied fish. This is the compromise that must be made between consumptive use and providing environmental flows. While these thresholds are not met as often as they were in the 'historical flow' regime, others were improved.

The modelled EF regime, compared with the historical scour regime, is particularly beneficial for winter low-flow thresholds (such as winter riffle inundation) when irrigation releases have ceased in early winter. Overall, the timing and variability of thresholds in the EF regime more closely matches the 'undammed' regime than those provided by the winter scour regime. By more closely matching the EF regime with the 'undammed' flow regime, and better meeting the early winter low-flow ecological thresholds, it is expected the ecosystem will be more resilient to the reduced release volumes.

Dam inflow from 1998 to 2007 (mean annual flow 83.5 GL) has been notably lower than the historical average from 1975 to 2007 (mean annual flow 119 GL) (Figure 4). Lower rainfall and streamflow reduces the frequency and duration of flows above specific ecological thresholds.

The reduction in dam inflow also decreases the reliability of supply of consumptive use from 76 per cent (1975–2007) to 50 per cent during the past decade (1998–2007). It is increasingly important (where possible) that releases from Wellington Reservoir maximise the benefits to ecological values and minimise impacts to the reliability of supply.

This report provides useful information to allocation planners and licensing officers against which to assess new licence applications and the ecological impacts of predicted reductions in dam inflow resulting from a drying climate. The fully allocated demand scenario, EF regimes and corresponding reliability of supply for consumptive

use provide insight into the likely impacts on ecological values and reliability of supply resulting from future changes in demand and reduction in streamflow.

Since this EF regime was developed, further modelling has been undertaken using a water balance model (TwoRES) for Wellington Reservoir. TwoRES was used to produce flow regimes below the reservoir for a variety of different licensing, environmental release and climate change scenarios (DoW 2011c).

The EF regime was used to assess the flow regimes resulting from TwoRES to select a licensing scenario for the Wellington Reservoir and subsequently:

- develop an environmental water provision (EWP) to replace the winter scour regime for Wellington Reservoir
- define the amount of water available for abstraction in the lower Collie River
- select a licensing scenario for water entitlements from Wellington Reservoir.

An EWP is a water regime resulting from a water allocation decision-making process taking into account ecological, social, cultural and economic impacts. It may meet in part or in full the ecological water requirements. This work is explained further in the *Lower Collie surface water allocation plan methods report* (DoW 2011b) and the Wellington Reservoir water balance simulation (DoW 2011c).

8.1 Future studies and monitoring

Given CSIRO's median climate scenario predicts a further 24 per cent reduction in average runoff by 2030, compared to the 1975 to 2007 average in the lower Collie area, the Wellington Reservoir's allocation limit is likely to be reassessed, taking into account the EF regime modelled above, the EWP proposed in the *Lower Collie surface water allocation plan* (DoW 2011a), a dam inflow regime that reflects the climate change predictions and an agreed reliability-of-supply target.

To manage the risks associated with increased allocation of water and a drying climate, the development and implementation of a hydrological and ecological monitoring program would be beneficial. The program should also track the effects of replacing the scour regime with an EF regime. Identification of trends and changes will enable managers to respond (if necessary), and prevent unacceptable risks to the environment.

To improve assumptions about the flows required to meet ecological thresholds, opportunistic field observations should be utilised; particularly for the cobbler migration, bankfull and overbank thresholds.

A better understanding of cobbler migration, and how frequently overbank flows are needed to maintain recruitment in the riparian vegetation, would also improve these thresholds.

Appendices

Appendix 1: Information on fish species of the lower Collie River

Western minnow (*Galaxias occidentalis*)

The western minnow prefers to migrate upstream, moving into streams to spawn between June and September, peaking around August when water temperatures increase (WRM 2003). Given the steep tributaries in the Wellington reach, it is assumed the minnow also breeds in main channels, finding backwaters and slow-flowing pools. Its preferred habitat for spawning is flooded or overhanging vegetation.

Although little research exists on how long minnow eggs take to hatch, Beatty (pers. comm. 2010) suggests one day of fish passage flow followed by two to three days of flows that inundate overhanging vegetation and allow eggs to hatch would be beneficial for recruitment. Ideally, spawning habitat would be inundated for a few weeks after spawning so that fry were protected from predation. Andrew Storey (pers. comm. 2010) suggests a winter baseflow that inundates trailing vegetation interspersed with fish passage pulses.

Watts et al. (1995) found two distinct populations of western minnow between the coastal plain and scarp in the North Dandalup and Canning rivers. It is often assumed that fish populations between Wellington Reservoir and Burekup Weir suffer from genetic isolation but the findings of Watts et al. (1995) suggest populations may be restricted regardless of man-made structures and not breed naturally with downstream populations.

Western minnows are sexually mature by the end of their first year and some spawn the following year. While adults may survive one poor breeding year to breed the next year, more than one poor breeding year in a row could be detrimental to the population.

Winter flow is considered to be a trigger for migration and spawning of native fish in south-west Western Australia. Beatty et al. (2006) found migration to be positively correlated to discharge during the major flow periods of August to December in the Blackwood River.

Minnows are considered good swimmers and have been observed jumping through 'V notch' weirs (WRM 2003) and crawling up wet rocks (ARL 1990) to traverse barriers.

Nightfish (*Bostockia porosa*)

Nightfish has a wide distribution in the south-west from Hill River north of Perth to Kalgan River (Morgan et al. 1998). The preferred habitat for nightfish is under ledges, rocks, root mats and inundated vegetation (WRM 2003). They are solitary fish that are more active at night. Nightfish move into streams and slower-flowing water in winter and spawn in late August to November (Stephen Beatty, pers. comm. 2010) when streamflow, temperature and day length have increased (WRM 2003). Given the steepness of tributaries in this reach, it is assumed that nightfish breed in slower-

flowing pools and tributary mouths with low gradients. Nightfish are found in waters 60 cm to 1.6 m deep and prefer slow flows, but they have been observed negotiating waters 1 cm deep with flows up to 2 to 4 m/s (WRM 2003). Beatty et al. (2006) found upstream migration events to be ambiguous, however relatively weak upstream migration was found in the Blackwood system in September. Upstream migration was correlated with mean dissolved oxygen (DO) levels during the flow period in tributaries.

While most males reach sexual maturity by the end of the first year, females mature at the end of their second year. As with western minnows, Pen and Potter (1990) found most nightfish in Collie River (sampled above Wellington Reservoir) were one and two years old, although fish up to six years were also found. This suggests that short sequences of poor breeding years may be tolerated, but any more than one or two poor breeding years would be detrimental to breeding populations.

Swan River goby (*Pseudogobius olorum*)

The distribution and habitat range of the Swan River goby is very widespread in the south-west: from Kalbarri to Esperance it inhabits estuaries, rivers and streams, freshwater and hypersaline lakes, and can tolerate extreme salinities and temperatures (Morgan et al. 1998). It is most commonly associated with muddy bottoms and sometimes weedy or rocky areas (WRM 2003) and is generally abundant throughout its range (Morgan 1998). Within the lower Collie River the Swan River goby was abundant at most sites below Burekup Weir (WRM 2003).

The Swan River goby spawns in autumn and spring, and while some adults survive to breed twice, most only breed once and survive less than one year (Morgan et al. 1998). This means autumn and spring breeding every year is important for population health.

The female lays approximately 150 eggs on the underside of a rock or log. The male fans the eggs during the four-day incubation period. Larvae are planktonic and are swept into estuaries and migrate back into rivers as juveniles (WRM 2003) – although this is not possible in the Wellington reach.

Little is known about the Swan River goby's migratory habits, but given its poor swimming ability it is possible it is relatively sedentary (WRM 2003). In a study on the Blackwood River, no notable migration was noted in the tributaries and little in the main channel (Beatty et al. 2006).

The only periods that upstream movement was greater than downstream movement in the Blackwood River were December at one site and March at another site, when discharge decreased and spawning possibly occurred.

Given this, it is likely the Swan River goby does not require high flows for spawning habitat under rocks and logs, or migration. Together with its tolerance of salinity, it is probably tolerant of salinity levels and reduced winter flows in the Collie River.

Western pygmy perch (*Edelia vittata*)

Although western pygmy perch was not found in the Wellington reach when sampled in 2003 by WRM, sampling in January 2009 found it to be the most abundant fish species in the reach (FARWH unpublished data).

Together with the western minnow, western pygmy perch is a widely distributed endemic fish in the south-west, ranging from the Moore River in Gingin to the Philips River east of Albany (Morgan et al. 1995). Within this range the species is abundant in rivers, streams, lakes and pools. Its habitat requirements are riparian vegetation or other cover provided by submerged macrophytes, algae or snags. Pygmy perch is rarely found in open or deep water (Morgan et al. 1995) and is usually associated with slower-flowing water of approximately 0.2 to 0.3 m/s, a mean water depth of 0.5 m and maximum depth of 1.5 m (Thorburn 1999) Compared with the nightfish and western minnow, pygmy perch shows a greater preference for lateral flooded margins than tributaries (Pen & Potter 1991c).

Western pygmy perch are multiple spawners that breed between July and November, peaking around September to mid-October (Morgan et al. 1995; WRM 2003). Females lay 20 to 60 eggs at six- to eight-week intervals, which stick to flooded vegetation. Shipway (1949) noted eggs hatch after 60 to 72 hours and the larval stage lasts two to three weeks after eggs. Shipway (1949) suggests that individuals spawn from July to January in the Canning River when food is plentiful. Given that high flows extend into summer as a result of irrigation releases from Wellington Reservoir, it is possible pygmy perch breed well into summer if food supplies are plentiful.

Sexual maturity is reached at the end of the first year and adults usually survive for three years or more (WRM 2003). Given that pygmy perch breed repeatedly and for a long season and survive for three years or more, it is likely to be able to withstand poor breeding years better than the western minnow and nightfish, assuming other conditions such as salinity, temperature and food are suitable. However, to be sure of this, information on sensitivity of the species to aspects associated with breeding success (e.g. salinity and temperature) would need to be investigated.

Beatty et al. (2008) investigated salinity tolerances of the western minnow and western pygmy perch in the Blackwood River and found 95 per cent of both species lost equilibrium (i.e. became stressed to the point that they would have died if they weren't removed from the trial) within 72 hours at a median salinity of between 15 600 ppm and 15 800 ppm. This suggests adults of both species are tolerant of salinity levels in the Collie River (~1000 ppm). Beatty et al. (2006) found more pygmy perch in fresher Blackwood tributaries and that 97 per cent of variation between tributaries of upstream migration was explained by DO levels, indicating they like well oxygenated water.

Freshwater cobbler (*Tandanus bostocki*)

Tandanus bostocki is the only catfish in south-western Australia and is restricted to the area between the Franklin (Walpole) and Moore (Gingin) rivers (Allen 1982).

Smaller cobbler feed on insect larvae and ostracods, while older fish feed mostly on marron and fish (Morgan et al. 1995).

Cobbler reach sexual maturity between two and five years of age, at a weight of around 500 g (Morrison 1988). Large cobbler inhabit the deeper pools of a river's main channel, and migrate and spawn between November and February (WRM 2003). In the Blackwood River migration peaks around late spring and summer and is stronger where groundwater discharge is greatest. Migration was positively correlated with both increases in temperature and discharge. Spawning coincided with migration (Beatty et al. 2006).

Morrison (1988) noted spawning between November and January and that females produce around 5000 eggs. The male constructs an oval or circular nest of 0.6 to 2.0 m in diameter made out of gravel and rocks, with sand in the middle. Eggs hatch in about seven days. Anecdotal evidence suggests cobbler spawn and nest in water of about 75 cm depth.

Appendix 2: Comparison of reliability of supply for RESYM and TwoRES

While the exact EF regime could not be modelled in TwoRES to accurately determine reliability of supply for the EF regime developed here, a scenario with a similar allocation and reliability of supply was compared (scenario 4.8, DoW 2011c). To provide some indication of the accuracy of RESYM, the results of RESYM and TwoRES are shown in Table 11. The mean inflow and draw and reliability of supply are similar for both models. However, the EF regime is 6.8 GL less in TwoRES. Evaporation and rainfall figures for RESYM don't exist but the deficit evaporation was 6.5 GL for TwoRES. If the evaporation/rainfall deficit was added to the EF regime in TwoRES it would be similar to the EF regime in RESYM. This indicates that if rainfall and evaporation were accurately modelled in RESYM, the reliability of supply for an EF regime with an average of 46.8 GL/year would be lower than 76% and that for a reliability of supply of 76%, the EF regime is likely to be closer to 40 GL/year than 46.8 GL/year.

Table 11: RESYM average annual results for the modelled EFR compared with the TwoRES results scenario 4.8 (DoW 2011c)

	RESYM	4.8
Total in (dam inflow)	125.3	125.2
EFR (release + spill)	46.8	40
Draw	78.7	79.6
Net evaporation		6.5
Total out (EFR + draw + net evap)	125.5	126.1
Reliability of supply	76%	76%

Shortened forms

ARL	Aquatic Research Laboratory
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DoW	Department of Water
EF regime	environmental flow regime
EWP	environmental water provision
EWR	ecological water requirement
PADFLOW	Proportional Abstraction of Daily Flows (approach)
RESYM	River Ecologically Sustainable Yield Model
WEC	Welker Environmental Consultancy
WRC	Water and Rivers Commission
WRM	Wetland Research and Management

Glossary

Abstraction	The permanent or temporary withdrawal of water from any source of supply, so that it is no longer part of the resources of the locality.
Bankfull	Refers to a discharge of a river that completely fills its channel and the elevation of the water surface coincides with the bank margins. Any further rise in water level would cause water to move into the floodplain.
Biomass	The total mass of living matter in a given unit area.
Biota	All the plant and animal life of a particular region.
Catchment	Area of land from which rainfall runoff contributes to a single watercourse, wetland or aquifer.
Climate change	A change of climate attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.
Diapause	A physiological state of dormancy with very specific triggering and release conditions.
Ecologically sustainable yield	The level of water extraction from a particular system that, if exceeded, would compromise key environmental assets or ecosystem functions.
Ecological water requirement	Water regime needed to maintain the ecological values (including assets, functions and processes) of water-dependent ecosystems at a low level of risk.
Ecosystem	A community or assemblage of communities of organisms, interacting with one another, and the specific environment in which they live and with which they also interact, e.g. a lake. Includes all the biological, chemical and physical resources and the interrelationships and dependencies that occur between those resources.
Environment	Living things, their physical, biological and social surroundings, and the interactions between them.
Environmental flow regime	The environmental flow regime (EF regime) of a river is the timing, magnitude and duration of flows determined to achieve the study objectives.
Environmental water provision	The water regimes that are provided as a result of the water allocation decision-making process taking into account ecological, social, cultural and economic impacts. They may meet in part or in full the ecological water requirements.
Extraction	Taking of water, defined as removing water from or reducing the flow of a waterway or from overland flow.
Flow	Streamflow in terms of m ³ /yr, m ³ /d or ML/yr. Also known as discharge.
Gravid	Bearing eggs or embryos; pregnant.
Groundwater	Water that occupies the pores and crevices of rock or soil beneath the land surface.

Piscivorous	Fish eating.
Riparian	Of or relating to the bank of a river or stream.
Reliability of supply	The frequency with which water allocated under a water access entitlement is able to be supplied in full. Referred to in some states as 'high security' and 'general security'. For example, if consumptive users receive their full allocation for seven years out of 10, reliability of supply would be 70 per cent.
Scour release	Release of water from Wellington Reservoir to manage salinity.
Surface water	Water flowing or held in streams, rivers and other wetlands on the surface of the landscape.
Thalweg	The line joining the lowest points of successive cross-sections of a channel. Usually associated with the path of highest velocity.
Water-dependent ecosystems	Those parts of the environment that are sustained by the permanent or temporary presence of water.
Water regime	A description of the variation of flow rate or water level over time. It may also include a description of water quality.

References

- Allen, GR 1982, *A field guide to inland fishes of Western Australia*, Western Australian Museum, Perth
- ANZEC/ARMCANZ 2000, *Australia and New Zealand guidelines for fresh and marine water quality* <www.ea.gov.au/water/nwqms/index.html>.
- ARL 1989, *Canning Reservoir catchment; lower Canning River catchment; Serpentine/Gooralong Brook catchments; Dirk Brook catchment; North Dandalup Pipehead Dam catchment results and recommendations 1988*, Stream fauna study, Aquatic Research Laboratory, University of Western Australia, report to the Water Authority of Western Australia.
- 1990, *Habitat differences in upland forested streams*, Stream fauna study, Aquatic Research Laboratory, University of Western Australia, report to the Water Authority of Western Australia.
- Austin CM & Knott B 1996, 'Systematics of the freshwater crayfish genus *Cherax* *Erichson* (Decapoda: Parastacidae) in south-western Australia: electrophoretic, morphological and habitat variation', *Australian Journal of Zoology* 44:223–258.
- Beatty S, Morgan D & Gill HS 2003, 'Reproductive biology of the large freshwater crayfish *Cherax cainii* in south-western Australia', *Marine and Freshwater Research* 54: 597–608.
- Beatty S, McAleer F & Morgan D 2006, *Fish and crayfish migrations of the Blackwood River: influenced of surface and groundwater*, unpublished report by Centre for Fish & Fisheries Research, Murdoch University, for the Department of Water.
- Beatty S, Rashnavadi M, Morgan D & Lymbery A 2008, *Salinity tolerances of native freshwater fishes of the Blackwood River*, report by Centre for Fish & Fisheries Research, Murdoch University, for the Department of Water.
- Britton DL & Brock MA 1994, 'Seasonal germination from wetland seedbanks', *Australian Journal of Marine and Freshwater Research*, 45: 1445–1457.
- Bunn SE, Edward DHD & Loneragan NR 1986, 'Spatial and temporal variation in the macroinvertebrate fauna of streams of the northern jarrah forest, Western Australia: community structure', *Freshwater Biology*, 16: 67–91.
- Bunn SE, Davies PM & Edward DHD 1989, 'The association of *Glacidorbis occidentalis* Bunn & Stoddart (Gastropoda: Glacidorbidae) with intermittently-flowing forest streams in south-western Australia', *Journal of the Malacology Society of Australia*, 10: 25–34.
- Cogger HG 2000, *Reptiles and amphibians of Australia*, Reed New Holland, Sydney.

CSIRO 2009, *Surface water yields in south-west Western Australia*, a report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project, CSIRO Water for a Healthy Country Flagship, Australia.

Davies PM & Creagh S 2000, *Lower Collie River including Henty Brook environmental water requirements*, Report 21/99, unpublished report to the Water Corporation of Western Australia, Perth.

DoW 2009, *Upper Collie water allocation plan*, prepared by Department of Water, Government of Western Australia.

—2010, *Surface water hydrology of the lower Collie catchment*, Surface water hydrology series, Department of Water, Government of Western Australia

—2011a, *Lower Collie surface water allocation plan: for public comment*, Department of Water, Government of Western Australia.

—2011b, *Lower Collie surface water allocation plan methods report*, Department of Water, Government of Western Australia.

—2011c *Wellington Reservoir water balance simulation, a summary of the Two Res Model, Western Australia; water availability under a range of possible demand scenarios*, Department of Water, Government of Western Australia.

—2011d, *Surface water hydrology of the lower Collie catchment*, Department of Water, Perth.

Donohue R, Moulden B, Bennett K & Green A 2009a, *Ecological water requirements for Lefroy Brook*, Environmental water report no. 6, Department of Water, Government of Western Australia.

Donohue R, Green A, Bennett K, Pauli N, Lynas J & Storey A 2009b, *Ecological water requirements of the Brunswick River*, Environmental water report no. 7, Department of Water, Government of Western Australia.

Donohue, R., Green, A, Pauli, N, Storey A, Lynas, J & Bennett, K 2010, *Ecological water requirements of Cowaramup Brook*, Environmental water report no. 10, Department of Water, Government of Western Australia.

Green A & Bennett K 2010, *Environmental flow regime for the lower Collie River, Shentons Elbow reach*, Environmental water report series, Report no 21, Department of Water, Western Australia.

Green A, Donohue R, Storey A, Lynas J & Pauli N, 2011, *Ecological water requirements of the Margaret River*, Environmental water report no. 11, Department of Water, Government of Western Australia.

Hardcastle K, Rose T, Pearcey M & Storey A 2003, *Lower Collie River ecological water requirements review: stream morphology, riparian vegetation and fish*

- passage, unpublished draft report by Department of Water, Government of Western Australia.
- Hart B, Bailey P, Edwards R, Hortle K, James K, McMahon A, Meredith C & Swadling K 1991, 'A review of the salt sensitivity of the Australian freshwater biota', *Hydrobiologia* 210: 105–144.
- Harvey Water 2009, *Annual report for the Collie River Irrigation District 2008/9*, prepared by Harvey Water for the Department of Water, Perth.
- Horrigan N, Choy S, Marshall J & Recknagel F 2005, 'Response of stream macroinvertebrates to changes in salinity and the development of a salinity index', *Marine and Freshwater Research*, 56: 825–833
- Humphries P, Davies PE & Mulcahy ME 1996, 'Macroinvertebrate assemblages of littoral habitats in the Macquarie and Mersey rivers, Tasmania: implications for management of regulated rivers', *Regulated Rivers: Research and Management*, 12: 99–122.
- Kay WR, Halse SA, Scanlon MD & Smith MJ 2001, 'Distribution and environmental tolerances of aquatic macroinvertebrate families in the agricultural zone of south-western Australia', *Journal of the North American Benthological Society*, 20: 182–199.
- Lawrence CS, Morrissy NM 2000, 'Genetic improvement of marron *Cherax tenuimanus* (Smith) and yabbies *Cherax* spp. in Western Australia', *Aquaculture Research* 31: 69-82.
- Lynas J, Storey AW, Armstrong K, Prince & Knott B 2006, 'Invasion by the exotic crayfish, *Cherax destructor* Clark (Parastacidae) into habitats of local crayfish near Perth, Western Australia', *Freshwater Crayfish* 15: 176-188.
- Morgan DL, Gill HS & Potter IC 1995, 'Life cycle, growth and diet of Balston's pygmy perch in its natural habitat of acidic pools in south-western Australia', *Journal of Fish Biology* 47: 808-825.
- 1998, *Distribution, identification and biology of freshwater fishes in south-western Australia*, Records of the Western Australian Museum, Supplement no. 56. Western Australian Museum, Perth
- Morrison P 1988, *Reproductive biology of two species of plotosid catfish, Tandanus bostocki and Cnidoglanis macrocephalus, from south-western Australia*, PhD Thesis, University of Western Australia.
- Morrissy NM 1978, 'The past and present distribution of marron, *Cherax tenuimanus*, in Western Australia', *Fisheries Research Bulletin of Western Australia* 22: 1-38.
- Pen L 1999, *Managing our rivers: a guide to the nature and management of the streams of south-west Western Australia*, Water and Rivers Commission, Perth.

- Pen LJ & Potter IC 1990, 'Biology of the nightfish *Bostockia porosa* Castelnau in a south-western Australian river, *Australian Journal of Marine & Freshwater Research* 41: 627–646.
- 1991c, 'Biology of the Western pygmy perch *Edelia vittata* and comparisons with two other teleost species endemic to south-western Australia', *Environmental Biology of Fishes* 31: 365–380.
- Poff LN, Allan JD, Bain MB, Karr JR, Prestegard KL, Richter BD, Sparks RE & Stromberg JC 1997, 'The natural flow regime: a paradigm for river conservation and restoration', *BioScience*, 47, 769–84.
- Shipway B 1949, 'Notes on the natural history of the pigmy perch (*Nannoperca vittata*)', *W. Aust. Naturalist* 2(1):1-9.
- 1951, 'The natural history of the marron and other freshwater crayfishes of south-western Australia', Part 1, *Western Australian Naturalist* 3: 7–12.
- Stewardson MJ & Cottingham P 2002, 'A demonstration of the flow events method: Environmental flow requirements of the Broken River', *Australian Journal of Water Resources*, 5: 33–48.
- Storer, T, White, G, Galvin, L, O'Neill K, van Looij, E & Kitsios, A 2011, *The Framework for the Assessment of River and Wetland Health for south-west Western Australia: project summary and results*, Final report, Department of Water, Western Australia.
- Storey AW, Bunn SE, Davies PM & Edward DH 1990, 'Classification of the macroinvertebrate fauna of two river systems in south-western Australia in relation to physical and chemical parameters', *Regulated Rivers: Research and Management*, 5: 217–232. Streamtec 2000, *Lower Collie River including Henty Brook, Environmental Water Requirements*, report by Streamtec Pty Ltd for the Water and Rivers Commission.
- Syrinx Environmental 2003. *Riparian vegetation requirements – Collie River*, report by Syrinx Environmental for the Water and Rivers Commission.
- Taylor L 2006, *River action plan for the Brunswick River*, unpublished draft report to the Leschenault Catchment Council.
- Thorburn D 1999, *The broad and fine scale habitat associations of the fish fauna of the Blackwood River and its tributaries*, B.Sc. (Hons) thesis, Murdoch University.
- Tyler MJ, Smith LA & Johnstone RE 2000, *Frogs of Western Australia*, Western Australian Museum, Perth.
- WRC 2000, *Environmental water provisions policy for Western Australia*, Statewide policy no. 5, Waters and Rivers Commission, Perth.
- Watts R, Storey AW, Hebbert D & Edward D 1995, 'Genetic and morphometric variability in populations of the western minnow', *Galaxias occidentalis* Ogilby in

streams and rivers of the Darling Range and Swan Coastal Plain', *Journal of Marine and Freshwater Research* 46:769-777.

Weatherzone 2008, www.weatherzone.com.au [accessed 11 March 2010].

WEC & Streamtec 2002, *Lower Collie River and Henty Brook preliminary environmental water provisions: discussion paper*, unpublished report to the Water and Rivers Commission, Perth.

WRM 2003, *Wellington below – EWR review: fish community including migration requirements*, unpublished report by Wetland Research and Management for the Water and Rivers Commission.

—2005a, *Ecological water requirements of Hill River – intermediary assessment*, report prepared by Wetland Research and Management for the Department of Environment and Northern Agricultural Catchment Council.

— 2005b, *Ecological water requirement of Augustus River – intermediary assessment*, report prepared by Wetland Research and Management for Worsley Alumina.

— 2007, *Ecological values of seven south-west rivers: desktop review*, report by Wetland Research and Management for the Department of Water.

— 2008, *Ecological water requirements of Cowaramup Brook*, unpublished report by Wetland Research and Management for the Department of Water.

— 2009, *Collie River ecological values assessment 2008*, unpublished report by Wetland Research and Management for the Department of Water.

— 2010, *Lower Collie River trial environmental releases: Wellington Dam to Burekup Weir*, unpublished report by Wetland Research and Management for the Department of Water.

Department of **Water**

168 St Georges Terrace, Perth, Western Australia
PO Box K822 Perth Western Australia 6842

Phone: 08 6364 7600

Fax: 08 6364 7601

www.water.wa.gov.au

WT7508 0 0811