Ecological Water Requirements of Cowaramup Brook

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Department of Water
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by

Wetland Research & Management

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Report Prepared for:

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Final Report

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Frontispiece: Cowaramup Brook within the EWR survey reach (photo by Jess Lynas/WRM, November 2007).

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1 INTRODUCTION

1.1 Background

The purpose of this report is to determine the water required to protect the existing ecological values of Cowaramup Brook. It is part of the South-West Ecological Water Provisions Project being delivered by the Department of Water (DoW) in partnership with the South-West Catchments Council. The project has identified seven key catchments where water resources are under particular pressure from development for agricultural, urban and mining uses and supply pressure from reduced regional rainfall. The Ecological Water Requirement (EWR) will be determined for each of the seven catchments as part of the process of allocating water to competing uses. The DoW have commissioned ***Wetland Research & Management*** to determine the EWRs of four of the catchments, with this report addressing the EWRs of Cowaramup Brook.

1.2 Ecological water requirements

EWRs are the flow regime necessary to sustain key ecological values at a low level of risk. To support water resource planning, the DoW carries out studies to determine the ecological water requirement of rivers with the aim of identifying how much water can be abstracted from a river system without adversely impacting the aquatic and near-channel (riparian) ecology. The results of EWR studies allow the DoW to identify the ecologically sustainable yield of the water resource.

EWRs are determined using the best scientific information available. Key ecological values usually include 'healthy' or undisturbed ecosystems, biodiversity and rare or endangered species. In undisturbed catchments, the usual purpose of the EWR is to protect the existing 'natural' ecological values. In catchments that have been disturbed by land clearing and/or modified flow regimes, the situation is more complex and the purpose of the EWR can be to maintain or in some situations enhance the current key ecological values. Some value judgements need to be made when determining which key ecological values are to be sustained and guiding principles for making these judgements have been developed (WRC 2000).

EWR studies usually consider the water requirements of aquatic and riparian flora and fauna, for example, endemic fish species, macro-invertebrates, amphibians and mammals such as the semi-aquatic water rat. Holistic approaches to EWR assessments (such as the Flow Events Method used in this study) consider the ecosystem as a whole, including biodiversity, food-web interdependencies and water-dependent ecological processes that support food webs. While many terrestrial species in the higher rainfall zones in the south west may also be seasonally dependant on surface water found in river systems, EWR studies do not normally consider the importance of rivers to terrestrial ecology at the landscape scale.

1.3 Environmental water provisions

An environmental water provision (EWP) is the volume of water that is allocated for environmental purposes before water is allocated to future consumptive uses. An EWP is the outcome of a decision-making process that weighs the economic benefits of water abstraction against the environmental and social costs. An EWP defines the total consumptive pool of the water resource which is put into effect by the setting of an allocation limit. The DoW will consider approving requests for water while the sum of licensed entitlements for the resource is below the allocation limit.

In catchments where water use is relatively low, the aim of resource planning may be to maintain the 'natural' water-dependent ecology. With this as the management objective, an EWP and its associated allocation limit, would be set to equal the EWR and therefore meet environmental requirements in full. If an EWP meets or exceeds the ecological requirements the resulting consumptive pool is considered ecologically sustainable.

If the economic benefits of water use in a catchment are high, an allocation limit may be set so that the consumptive yield is greater than the river's ecologically sustainable yield (ESY). Consumptive allocations that are greater than the ESY place water-dependant ecological values at increasingly greater risk of change from the 'natural' condition.

Ecological change will depend on the volume and pattern of water abstraction. Minor deviations above the ESY may involve small changes in abundance, distribution and biomass of sensitive taxa. Large unsustainable abstraction may cause severe degradation to aquatic and riparian ecology involving stressed riparian vegetation, loss of species, decreasing biodiversity and often an increase in the abundance of exotic species.

In situations where the consumptive pool is greater than the ESY (such as downstream of large dams), the management objective is to minimise environmental impacts through careful specification and operational management of environmental flows. Environmental releases (or EWPs) may be required as licence conditions that specifies how and when water can be abstracted, and how much should be forgone or released to maintain ecologically important flows. These conditions may be based on the findings of EWR studies conducted as part of the impact assessment process.

In catchments where current water use is low and the river's EWR is unknown, a conservative allocation limit may be set that is known to be well below the systems ecological sustainable yield. Conservative allocation limits (which are usually based on flow statistics), are useful only in catchments where current water use is less than about 20% of mean annual flow. Where water use approaches or exceeds a conservative limit, EWR studies are conducted with the aim of identifying the system's ESY and setting new allocation limits.

1.4 Water resource planning in the south west of WA

Water resource management plans are currently being developed for the Whicher and Warren surface water sub-regions in the south west of WA. As part of this process, plans will be released in 2008 that specify conservative allocation limits based on the sustainable diversion limit (SDL) approach used in Victoria. The aim of the South West Environmental Water Provisions Project is to provide information needed for water resource management and planning in the south west of Western Australia. This includes information on unlicensed water use, available supply of water and EWRs for the regions priority river systems.

As part of this project, EWRs are being determined for seven rivers in the south west, including the Brunswick River, Capel River, Wilyabrup Brook, Cowaramup Brook, Margaret River, Chapman Brook and Lefroy Brook. The primary objective of the EWR studies is to establish the ESY of rivers in the south west and therefore support ongoing planning, especially in areas where water demand is high or increasing. When this information has been collated, new allocation limits will be recommended that reflect the rivers' ESY. This report presents the results of an EWR study carried out on the Cowaramup Brook.

1.5 Ecological risk

Historically, in WA, the EWR of rivers have been determined at a low level of risk. The low level of risk is a useful aim for assessing a proposal to develop a new resource (or to increase an existing entitlement) as there is an expectation of a reasonable yield through the management of ecological risk.

To support allocation decisions in areas of high demand, there is a need to describe how alternative water allocation scenarios will change the regime of flow in rivers, and the associated level of ecological risk associated with each scenario-related change in flow. There is also a need to predict the expected ecological state or condition at each allocation scenario and risk level.

When EWR studies are conducted on rivers where there is no immediate proposal to develop the resource, there may be no need to address the level of risk. To support future resource planning, the only requirement is to describe the characteristics of the flow regime that support the river's 'natural' ecology, which represents the EWR at no risk. This work also provides the data necessary to analyse the change in flow associated with a future allocation scenario and ascribe a level of risk to the EWP associated with that scenario.

This study describes the EWRs for the Cowaramup Brook. The future EWP can then be determined by either fulfilling the EWR in total, which essentially infers a low level of risk, or by reducing the EWR to meet consumptive demands, thereby increasing the levels of ecological risk making a compromise between ecological, social and economic demands for water.

2 THE COWARAMUP BROOK CATCHMENT

2.1 Location

Cowaramup Brook is located in the southwest of the State (Figure 1), approximately 280 km south of Perth, near Gracetown. It is a small system; being only 10 km long with a catchment area of 24 km^2. The brook arises southwest of the town of Cowaramup, and flows west where it drains into the ocean at Cowaramup Bay (Gracetown). The creek has two main channels and many small tributaries.

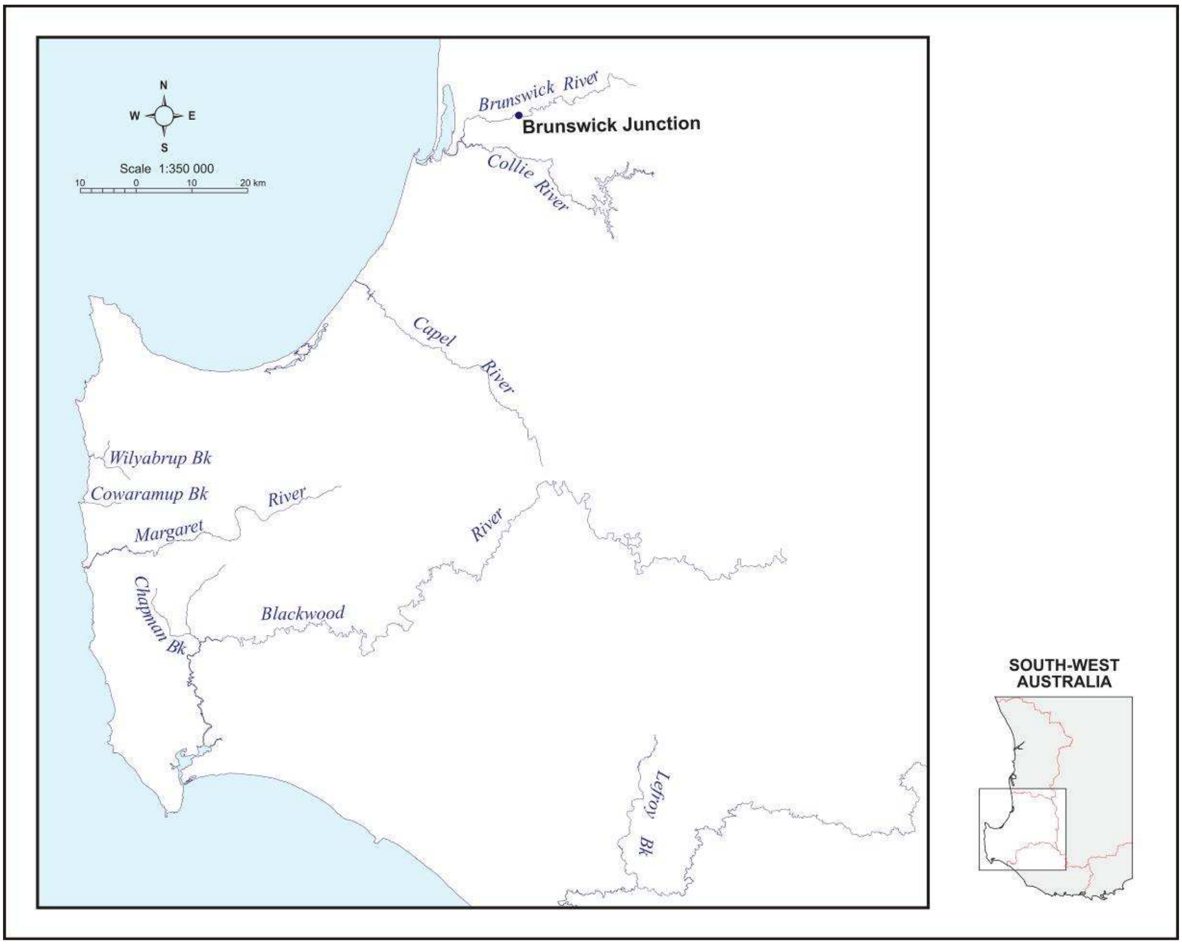

Figure 1. Location of Cowaramup Brook in the southwest of the State.

Approximately 58% of the catchment has been cleared of native vegetation for farming, grazing and viticulture (Hunt *et al.* 2002). Most of the clearing occurred in the 1920s as part of settlement Schemes (Tille and Lantzke 1990). A loss of riparian vegetation results in increased nutrient and sediment loads downstream, coupled with increased surface runoff, resulting in flooding and channel erosion. The condition of the brook varies greatly along its length. In some areas, the creekline is totally devoid of native vegetation and in parts is actively eroding (Hunt *et al.* 2002). Other areas have an overstorey of peppermint trees with little understorey except introduced grasses. Downstream near the mouth, the last 3 km of creek is in pristine condition having suffered very little disturbance. Over 150 species of plants are found in this section of Cowaramup Brook.

This study concentrated on a survey reach which was chosen to be representative of the system. The survey reach was located south of Cowaramup Bay Road and west of Caves Road, approximately 2.5 km upstream of Gracetown (Figure 2).

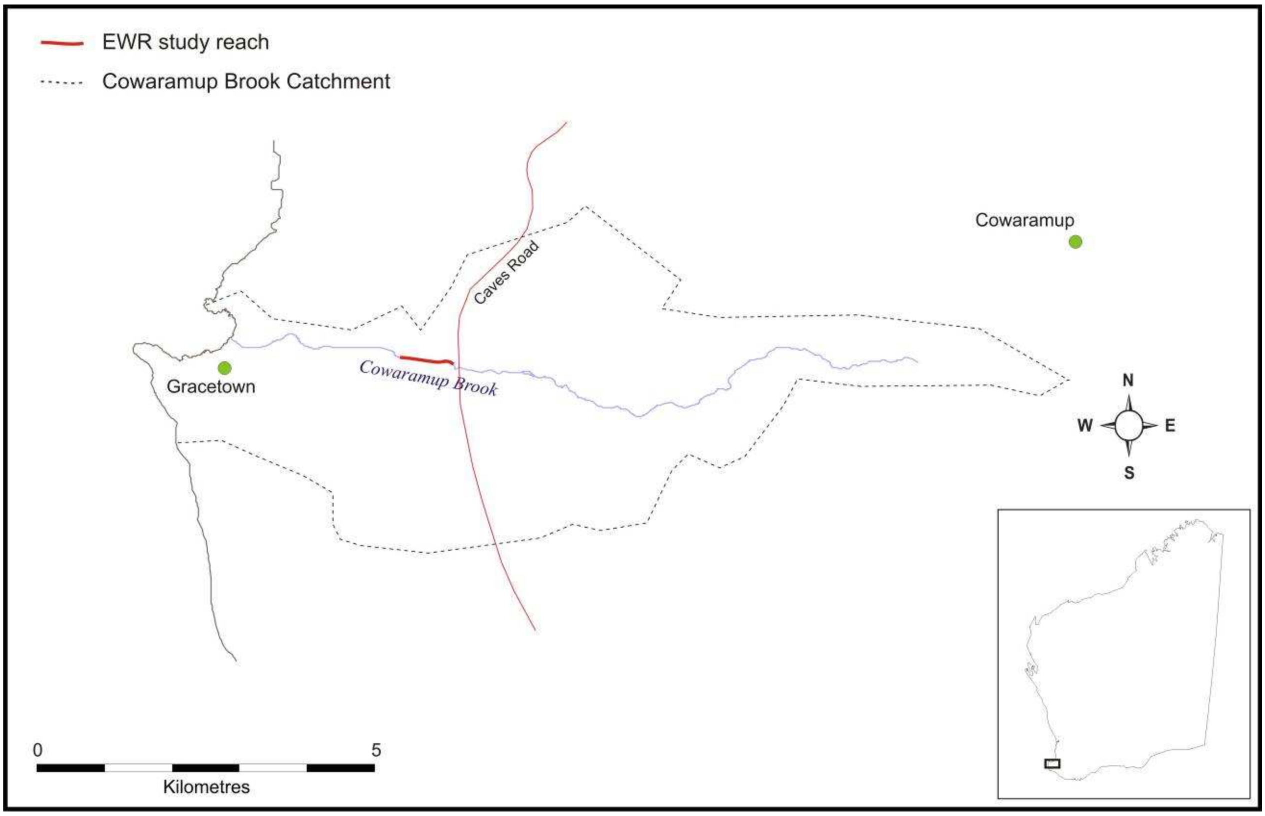

Figure 2. Cowaramup Brook catchment, showing location of the survey reach.

2.2 Climate and hydrology

There are no rainfall stations operating within the Cowaramup Brook catchment. Therefore, the Department of Water analysed data from ten stations within close proximity (within a 13 km radius) to develop a rainfall series for the catchment (Coppolina 2007). These stations are listed in Table 1.

There is one streamflow gauging station along the brook, which is located at Gracetown near the outlet of the catchment (610029). This station has been in operation since November 2004. The Department of Water used a correlation with nearby Woodlands Gauging Station (610006) on Wilyabrup Brook to generate a daily streamflow series for Cowaramup Brook from 1975 to 2003 (Coppolina 2007).

The climate of the region is temperate with warm, dry summers and cool, wet winters (BOM 2006). Average daytime temperatures can range from 16 °C in winter to around 26 °C during summer (Anon 2008). Rainfall is highly seasonal, with 77% of annual rainfall occurring between May and September (Coppolina 2007) (Figure 3). The seasonal rainfall is typically derived from cold fronts in winter which bring moist air from the ocean. These fronts are blocked by high pressure systems in summer, resulting in reduced summer rainfall. Decaying tropical cyclones from the north-west can bring occasional widespread heavy rain to the region during summer (Penn 1999). Average annual rainfall (1975-2006) using the derived Cowaramup series was 1005 mm (Figure 4).

Table 1. Gauging stations in the vicinity of Cowaramup Brook for which data has been used in the current report.

Gauging station	Number	Type	Period of record	Length of record
Wilyabrup Brook – Harman Rd South	509191	Rainfall	1973 - 1999	27
Wilyabrup Brook - Woodlands	509190	Rainfall	1973 - 1999	27
Cowaramup	009636	Rainfall	1926 - 2007	82
Bramley Res. Stn.	009672	Rainfall	1955 - 1983	29
Margaret River	009778	Rainfall	1995 - 2006	12
Margaret River Post Office	009574	Rainfall	1928 - 2007	80
Margaret River – Willmots Farm	509065	Rainfall	1972 - 2007	36
Margaret River 1	009540	Rainfall	1908 - 1948	41
Prevelly Park	009753	Rainfall	1966	1
Glenbourne	009646	Rainfall	1949 - 1963	15
Cowaramup Brook - Gracetown	610029	Streamflow	2005 - 2007	3

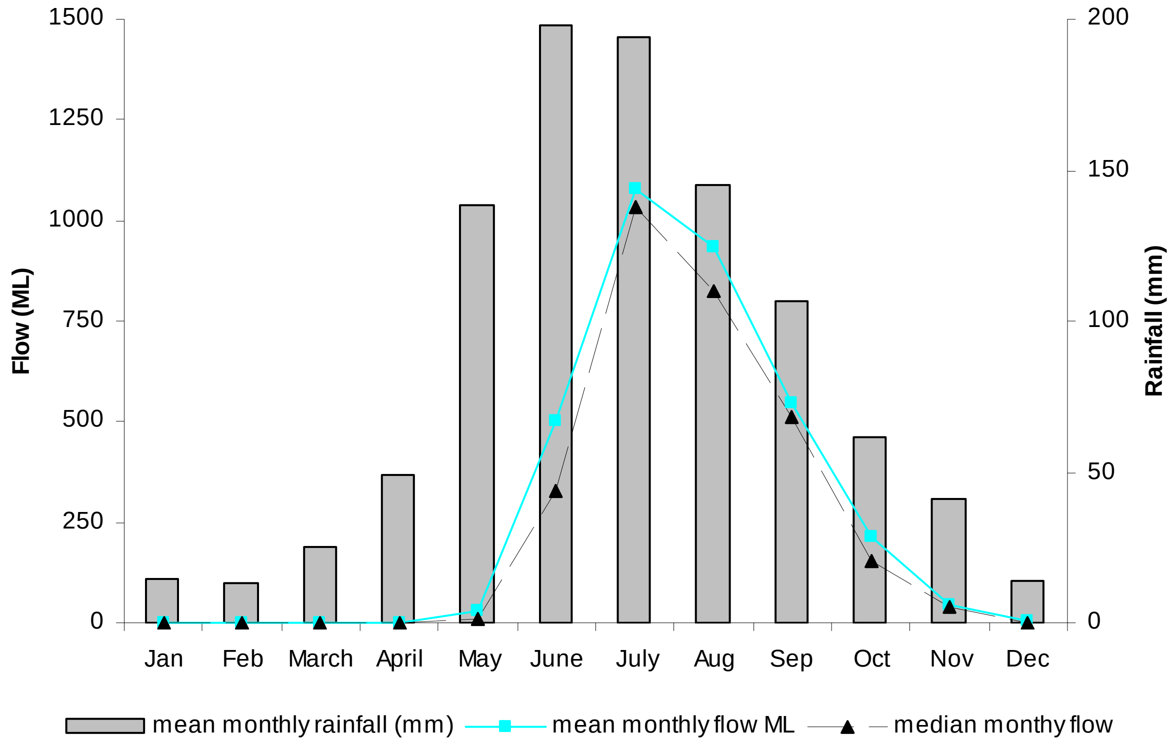

Figure 3. Mean monthly rainfall and stream flow at Gracetown (using the modelled data 1975-2003).

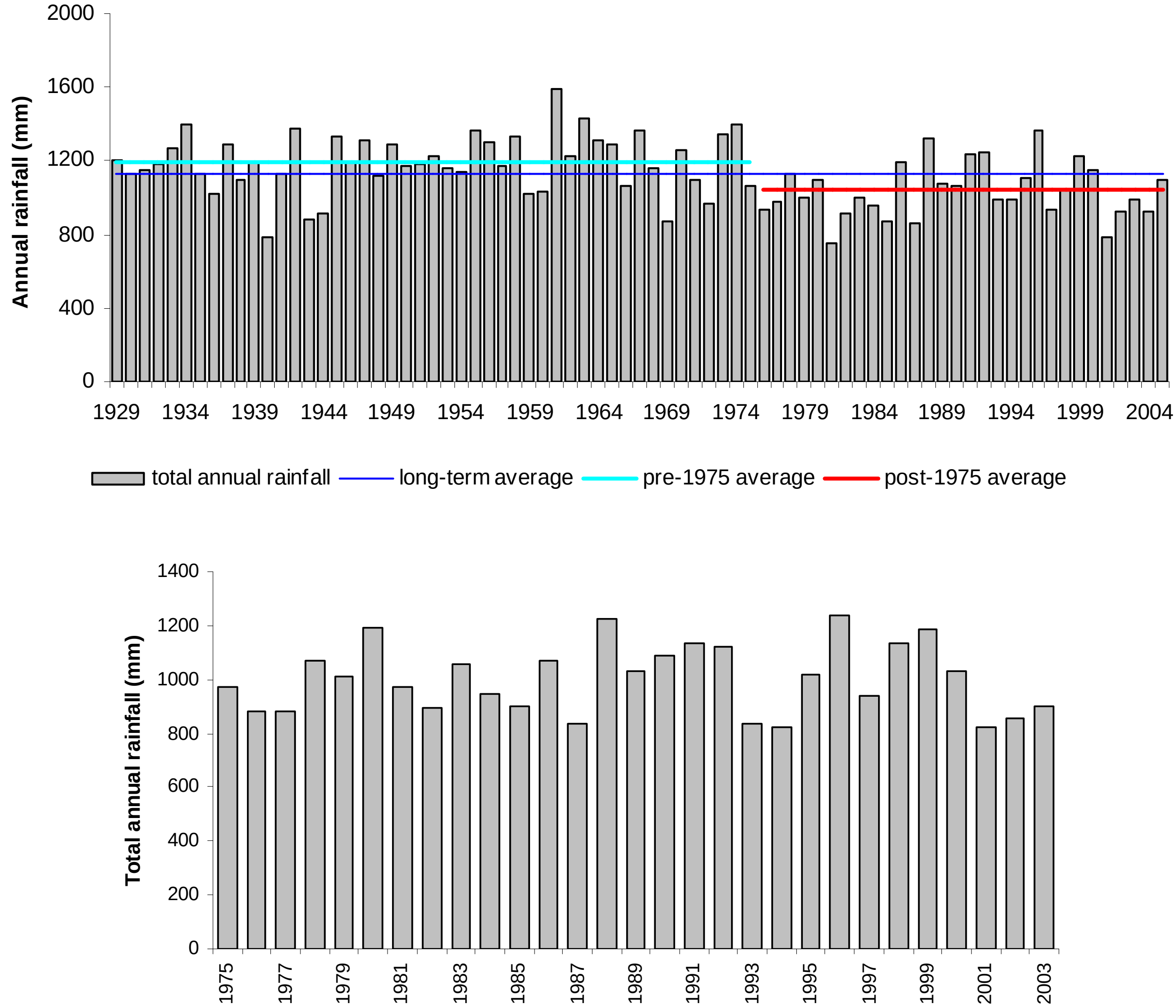

Figure 4. Total annual rainfall and long-term average for Margaret River Post Office 009547 (above) the derived rainfall series for the Cowaramup Brook catchment (below).

Current models (CSIRO 2001) for global warming predict a general increase in temperature for the southwest of between 0.4 - 1.6°C by the year 2030. A decreasing trend (-20% to +5%) in winter and spring rainfall is also predicted and a ±10% change in summer/autumn rainfall. While the intensity of specific winter rainfall events may increase, their duration is expected to decrease. Correspondingly, the duration of drought events and rates of evaporation are also expected to increase. The ~20% decrease in south-west rainfall experienced over the last 30 - 40 years has resulted in a 30 - 40% decrease in annual streamflow (WRC 2000).

Since 1975 there has been a significant reduction in rainfall in the southwest of Western Australia, particularly in winter months (Allan and Haylock 1993, IOCI 2002). The extent of the reduction between the 'Average Climatic Condition' period (pre-1975) and the 'Dry Period' (post-1975) varies regionally. Storey *et al.* (2001) estimated that mean annual rainfall for the Canning Dam area for the period 1975 - 1997 was 18% lower than the long term mean annual rainfall for 1912 - 1997. Similarly, WEC (2004) reported a 20% reduction in rainfall for the Bickley Brook system and WEC (2002) reported an 11% reduction in annual rainfall at Collie. There has been a 12% reduction in mean annual rainfall in the Cowaramup Brook catchment post-1975 (mean = 1055 mm) compared with pre-1975 (Table 2) (Coppolina 2007). Reductions in mean annual rainfall and mean annual streamflow for a number of other south-west river systems are provided in Table 2.

Table 2. South-West regional climate and hydrology.

River	Catchment size	Mean annual rainfall		Mean Annual Flow		Baseflow Index	Runoff Coefficient	90% annual probability flow	1% annual probability flow
		since 1975	Reduction since 1975	since 1975	Reduction since 1975				
	km^2	mm	%	GL	%	%	%	m^3/s	m^3/s
Brunswick	286	911	9	55.1	13	51	27	11	143
Capel	635	735	11	44.8		55	15	12	157
Chapman	184	1148	1	49.1		43	24	5	174
Cowaramup	24	1055	12	3.35		45	14	3.5	35
Lefroy	358	1138	7	57.9	16	66		6.1	60
Margaret	477	1046	8	86.2		57	20	14	102
Wilyabrup	89	1065	7	23.9		51	27	8.3	83

Given the short length of the data series for the one streamflow gauging station on Cowaramup Brook (610029), the DoW used a correlation with nearby Woodlands Gauging Station (610006) on Wilyabrup Brook to generate a daily streamflow series for the period 1975 – 2003 (Coppolina 2007). As with rainfall, streamflow in Cowaramup Brook is highly seasonal and 98% of flows occur between June and October (Figure 3). Using the derived streamflow series, mean annual flow was 3.35 GL and the annual runoff coefficient for the catchment was 14% (Coppolina 2007).

2.3 Hydrogeology

Cowaramup Brook is located within two distinct landform units of the Leeuwin Naturalists Region; the Margaret River Plateau and the Leeuwin-Naturaliste Coast (Tille and Lantzke 1990). Most of the brook occurs within the Margaret River Plateau, a gentle plateau dissected by a series of valley systems. It is formed on granitic and gneissic basement rock of the Leeuwin Block. The system is 5 to 15 km wide and extends from Dunsborough to Augusta.

Closer to the coast, Cowaramup Brook enters the Leeuwin- Naturaliste Coast, which is a discontinuous ridge of Tamala Limestone, with the underlying Leeuwin Block granite being exposed in places (Hanran–Smith 2004). It is between 0.2 and 6 km wide and runs between Cape Naturaliste and Cape Leeuwin.

The main geological feature in the catchment is the Leeuwin Complex which comprises intensely deformed plutonic igneous rocks (Marnham *et al.* 2000). It was formed in the Proterozoic period. A number of regolith-landform systems are known to overlie the Complex, including the Cowaramup, Caves Road, Quindalup, and Spearwood systems. Of these, the Cowaramup system is dominant within the catchment. Low hills and rises with gentle to moderate slopes characterise the Cowaramup regolith-landform system (Marnham *et al.* 2000).

Alluvial deposits in streambeds comprise boulders, silty clayey sand, and fresh to slightly weathered bedrock. Granite and granulite outcrops are more common towards the coast, and are evident where the streambed is incised into the Proterozoic Leeuwin Complex (Marnham *et al.* 2000).

Groundwater within the Cowaramup system (Margaret River Groundwater System) tends to be brackish to saline. It is generally low yielding (Marnham *et al.* 2000). Rapid channel flows occur within the limestone of the Quindalup and Spearwood systems (Leeuwin Naturaliste Coast Groundwater System), and as such, the water table is often not well developed (Marnham *et al.* 2000).

2.4 Vegetation

Flora of the Cowaramup catchment is contained within the Menzies subdistrict of the South West Botanical Province (Beard 1990). Jarrah *(Eucalyptus marginate),* marri *(Corymbia calophylla)* and wandoo *(Eucalyptus wandoo)* are the dominant canopy trees of the area.

Broad vegetation communities along the river were reported by Hanran-Smith (2004) in the Cowaramup Brook Action Plan (draft), and were as follows:

- Peppermint *(Agonis flexuosa),* tea tree *(Taxandria linearfolia),* marri, pale rush *(Juncus pallidus)* –between Cowaramup Bay Road and Ellenbrook Road, south of Cowaramup township
- Spreading sword sedge*(Lepidosperma effusum),* peppermint, marri, weeping grass *(Microlaena stipoides)* and *Trymalium ledifolium*– north of Cowaramup Bay Road to Ellen Brook Road
- Tea tree, pale rush, wonnich *(Callistachys lanceolata), and Centella asiatica* – east of Cinella Road
- Peppermint, marri , swamp paperbark *(Melaleuca rhaphiophylla), Trymalium floribundum, Taxandria linearifolia, Callistachys lanceolata* – north east of Gracetown township
- Peppermint, marri and sparse tea tree - towards Gracetown and the coast.

Plate 1. Cowaramup Brook Riparian Vegetation (Supplied by Gracetown Progress Association).

The main weeds of Cowaramup Brook include kikuyu grasses *(Pennisetum cladestinum),* weedy rushes *(Juncus microcephalus and Isolepis prolifera)*, tree ferns *(Sphaeropteris cooperi)* and dock *(Rumex crispus)* (Hanran-Smith 2004). Scattered in various locations along the riverbank are the blackberry *(Rubis ulmifolius)* and arum lily (*Zantedeschia aethiopica*) (Hanran-Smith 2004).

Two endangered flora species are known to occur close to Cowaramup Brook. These are the grand spider orchid (*Caladenia huegelii*) and the giant spider orchid (*Caladenia excelsa*). Priority species likely to occur within the catchment area are the western karri wattle (*Acacia subracemosa*) and parrot bush (*Dryandra sessilis* var. *cordata*).

2.5 Pressure on water resources

Dominant landuse within the catchment is agriculture, with 1357 hectares of broadacre agriculture and 164 ha of intensive agriculture (Hanran-Smith 2004). Olive growing is the main commercial landuse, with small area of wine grape and nut growing. Numerous dams have been constructed both on and off Cowaramup Brook to accommodate different landuse requirements (Coppolina 2007). Native vegetation, including National Park and remnant vegetation makes up 871 hectares of the catchment.

3 FLOW EVENTS METHOD FOR DETERMINING EWRS

The Flow Events Method (FEM) of determining EWRs was developed by the Cooperative Research Centre for Catchment Hydrology to integrate the various *ad hoc* methods being used throughout Australia at the time. It was designed to provide a standardised, transparent and analytical procedure that was applicable to a wide range of river systems. It advocates a consistent approach, but also allows for expert opinion. The FEM assumes that the various components of a flow regime, for example summer low flow and flood flows, have different ecological functions and that these need to be assessed independently (Figure 5).

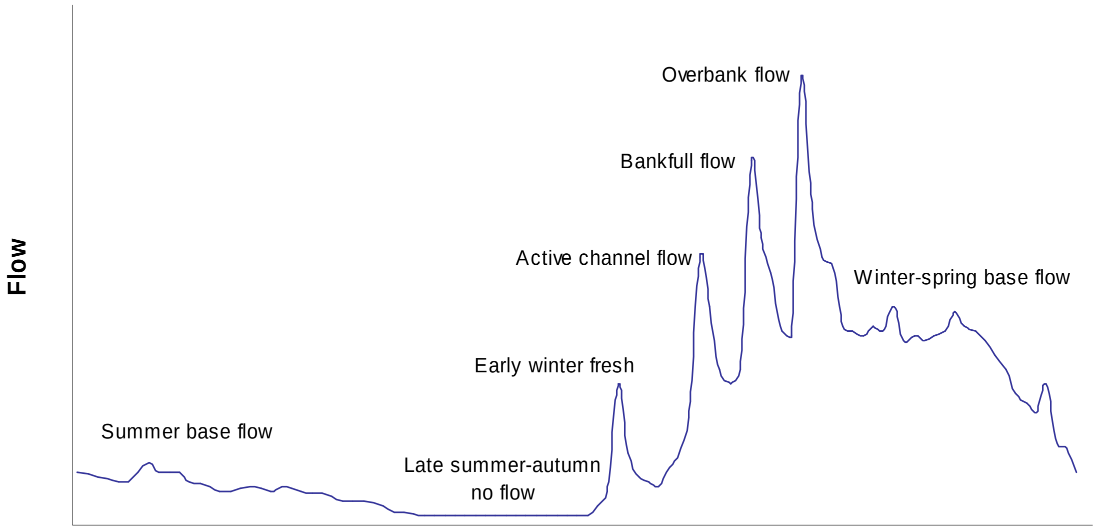

Figure 5. Representative hydrograph with different flow components labelled (after Cottingham *et al*. 2003)

One of the main principles of the approach is that the altered river system needs to retain some of the ecological features of the original system, *i.e.* some of the natural flow variability should remain. FEM is a modification of the FLOWS method developed in Victoria but makes no *a priori* assumptions about the importance of hydrological events without first considering the event's significance for the animals and plants that inhabit the river. FEM is an additive method that allows for as few or as many ecological features to be evaluated as required.

The method is outlined in Figure 6 and described in detail below.

The initial step is to identify the ecological values of the river through a dedicated ecological study or a desktop review of previous work (1). The ecological study identifies critical water levels for an ecological process (2). For example: a particular species of fish may spawn in reed beds, so reed beds would need to be inundated at the appropriate time of year for the population to regenerate.

At the same time, one or more ecologically important reaches of the river are chosen and surveyed (3). Multiple channel cross-sections are surveyed where the channel structure dictates flow and/or there are ecologically important features such as habitat. Distance and elevation between cross-sections is also determined(4). These data are used as input for the HEC-RAS hydraulic model (5), which is calibrated using measured flow rates and water levels. The output of the HEC-RAS model is a relationship between the flow rate in a particular reach and the water level for each cross section. This relationship is called a Rating Curve (6).

The River Analysis Package (RAP) then uses the rating curves for each cross section to determine the flow rate required to satisfy an ecological requirement at each cross section (7 & 8). For example, a flow rate of at least 42 m^3 is required to maintain shallow backwater fish habitat in the Lower Ord River (Braimbridge & Malseed 2007). RAP is then used to analyse historical flow data to determine how many times per year the critical flow rate has been observed and how long the flow exceeded the rate. This process is known as time series analysis (10). In streams with no historical flow data, or gaps in the data set, modelled data are developed and used (9). When time-series analysis is performed, the link between flow and ecology (2) that was determined in the ecological studies is kept in mind and may be modified. For example, if the required flow rate has never been achieved, then the link must be reconsidered.

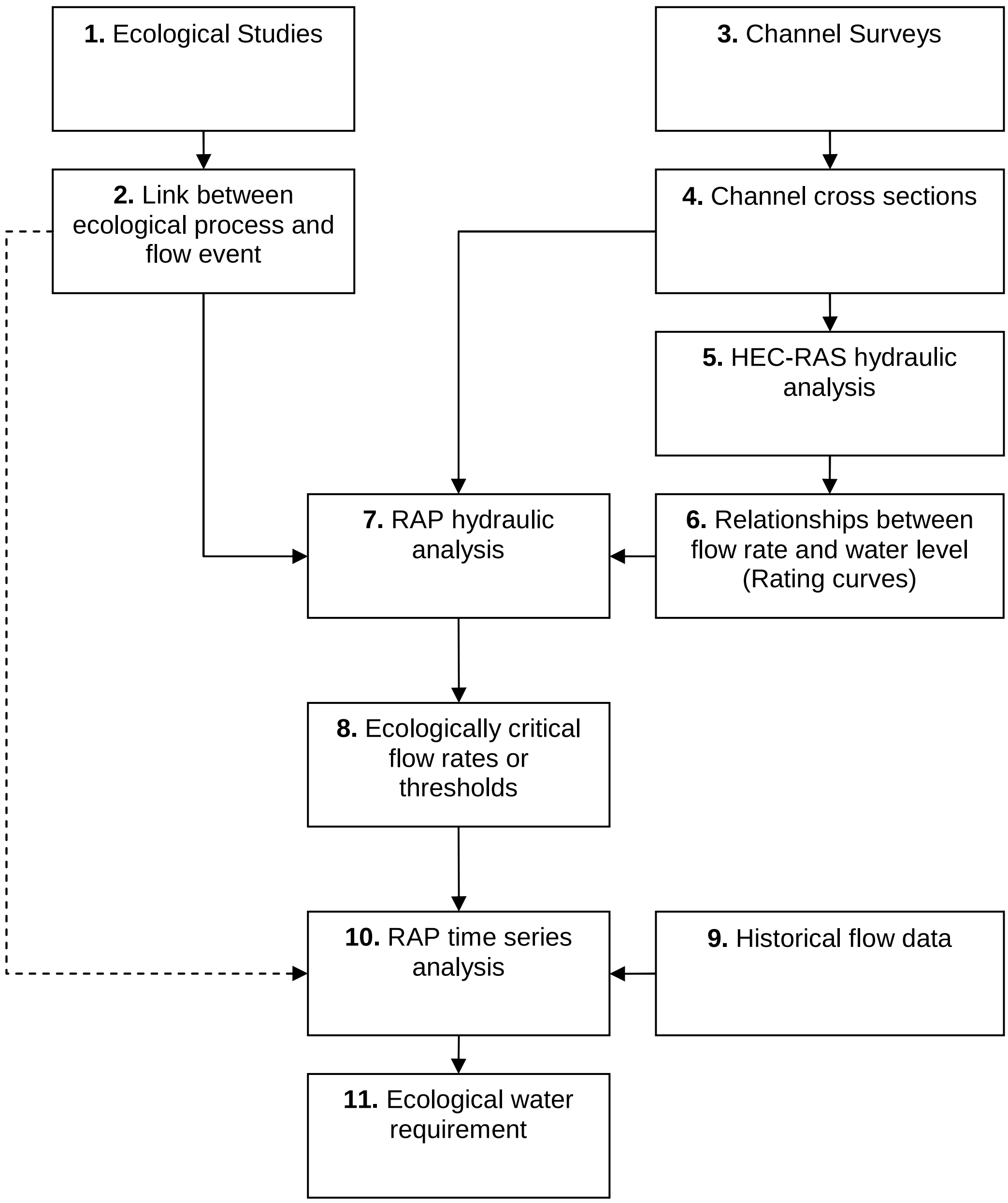

Figure 6. Flow Events Method for determining EWRs.

4 WATER-DEPENDENT ECOLOGICAL VALUES

4.1 Ecological values of the Cowaramup Brook

Plate 2. The slender tree frog, *Litoria adelaidensis* (Rob Davis 2001).

A critical step in the determination of EWRs for an aquatic system is the identification of key water-dependent ecological values. In undisturbed environments, the usual aim in establishing EWRs is to protect the existing 'natural' ecological values at a low level of risk. However, for ecosystems that have been modified (i.e. through regulation and/or land use changes), EWRs can be established to:

- maintain and/or enhance current key ecological values,
- identify the likely pre-existing ecological values and determine the key values which the EWRs should aim to re-establish, or
- provide for a combination of current key ecological values and key pre-existing natural ecological values.

Identification of past and present ecological values, therefore, is an important part of any EWR study. Current ecological values were detailed in a desk-top review (WRM & DoW 2007) and a targeted sampling programme undertaken in autumn and spring 2007 (WRM 2008). The ecological values identified in these studies are provided in Table 3. For information pertaining to life history characteristics, degree of water dependence, and other general biological information refer to WRM (2008) and WRM & DoW (2007).

Table 3. Water-dependent ecological values of Cowaramup Brook (identified in WRM & DoW 2007; WRM 2008).

	Water-dependent ecological value
Aquatic macroinvertebrates	
	44 taxa of macroinvertebrates known
	4 species endemic to the southwest
Freshwater crayfish	
	Smooth marron, *Cherax cainii*
	Gilgie, *Cherax quinquecarinatus*
Fish	
	Swan River goby, *Pseudogobius olorum*
Frogs	
	Banjo frog, *Limnoynastes dorsalis*
	Slender tree frog, *Litoria adelaidensis* (Plate 2)
	Quacking frog, *Crinia georgiana*

	Water-dependent ecological value
	Glauertsfrog, *Crinia glauerti*
	Moaning frog, *Heleioporus eyrei*
Riparian fauna	
	Tiger snake, *Notechis scutatus*
	Bobtail skink, *Tiliqua rugosa*
	Mourning skink, *Egernia luctuosa*

4.2 Flow requirements of key values and processes

Channel morphology

In-stream flows influence the size, shape and condition of the channel through physical processes such as scouring (Arthington *et al*. 1993). Elevated winter flows are often required to maintain existing (or active) channel dimensions, and prevent the accumulation of sediment and organic debris, and prevent encroachment by riparian vegetation. Disturbances from these events can also be important in structuring benthic macroinvertebrate communities and biofilms, and may have a profound influence on ecosystem function (e.g. primary production, nutrient spiralling and decomposition) (see Resh *et al*. 1988). In addition, scour of river beds, and undercutting of banks is essential for producing and maintaining diversity of habitat, especially for fish. These high winter flows are commonly referred to as 'channel forming' or 'active channel' flows, and are required in winter with the objectives of channel maintenance, riparian vegetation inundation, inundation of higher benches for energy transfer and flushing of pools. It is generally accepted that active channel flows events occur on a 1:2 to 1:3 year frequency for south-west river systems (WRC 2001).

Unseasonal and/or high velocity flows however, can result in excessive scouring, destabilisation of banks and subsequent increased sediment loads downstream. The erosional power of a system increases disproportionately with its discharge, thus 1:100 year floods or runoff events are extremely important in forming landscapes. Such floods and events carry the largest quantities of sediment and nutrients. Prior to European settlement, natural vegetation provided a high level of resistance to flows throughout south-west river systems. In many catchments, the clearing of vegetation for urban and rural development has made river systems sensitive to flooding, to the extent that 10-year or similar sized floods may now cause catastrophic erosion (Lovett & Price 1999). The associated practices of de-snagging and channelisation resulted in increased current velocity and thus also lead to increased bank and bed erosion, increased sedimentation and more severe flooding of downstream reaches (Lovett & Price 1999).

Riparian vegetation

Calculation of EWRs for riparian vegetation normally assumes there is water-dependent (i.e. dependent on water from the river channel) vegetation on the floodplain, which requires regular (annual) inundation to a shallow depth to disperse seed and to saturate soils to promote successful seedset. In these conditions, EWRs usually recommend overbank flooding.

Vegetation of the riparian zone can either intercept groundwater or directly extract channel water. Determination of the extent to which riparian vegetation is reliant on groundwater was beyond the scope of the current study. Since the water-dependent vegetation was within the channel, EWRs for riparian vegetation were calculated assuming a total reliance on surface flows to inundate the riparian zone.

Specific flow volumes to meet riparian vegetation EWRs need to consider duration, frequency and depth of flooding as these will have varying effect on germination, recruitment and successful colonisation by plant species. Changes in biodiversity through succession of one plant assemblage by another is a natural progression, however interruption or loss of any one successional stage can degrade the efficiency of the vegetation system as a whole (Pen 1983).

In Australian riparian zones, greatest numbers of plant species germinate during autumn under water-logged conditions and fewest germinate over summer months (Britton & Brock 1994). Decreased winter flows may thus have greater impact on the germination of fringing vegetation, than increased summer flows.

Aquatic macroinvertebrates

Life histories of aquatic species are intrinsically linked to flow regimes (Bunn 1988). There are two main features of flow regimes that influence aquatic fauna community structure in southwest rivers. These are **seasonality** and **predictability** of flows.

The variation in the degree of seasonality can lead to changes in invertebrate community structure (Bunn *et al.* 1989) and changes in life history patterns. Stream permanence has been found to be an overall determinant of the aquatic invertebrate fauna. Streams with intermittent flows show distinctive aquatic faunal communities compared to permanently flowing streams (ARL 1989; Storey *et al.* 1990). Some macroinvertebrate species are found only in intermittent streams (Bunn *et al.* 1989), while other species show large differences in abundances in permanent compared to intermittent streams (e.g. Bunn *et al.* 1986). Native fish require permanent water, only colonising seasonal and ephemeral streams during wet season flows.

Analyses of extreme flow events have shown that low-flow events have a far more pronounced effect on the river biota than high-flow events, although in streams of the northern jarrah forest, there is a linkage between near-bed water velocities and macroinvertebrate community structure (ARL 1988a, b, 1990). The problems associated with low flow include desiccation, de-oxygenation of the water column, and accumulation of leaf leachates (phenols, tannins etc) (Resh *et al.* 1988; Boulton & Lake 1992).

There are marked seasonal changes in the structure and functional organisation of communities in upland streams in south-western Australia (ARL 1986, 1989; Bunn 1986; Bunn *et al.* 1986). This has been attributed to the influence of a highly seasonal and predictable Mediterranean climate with high winter and low summer flows. Some fauna may be influenced by seasonal differences in water temperature, however, it appears that stream flow and/or flow-related variables are the important underlying factors. Flow results in major seasonal differences in benthic organic matter, depth, width and aspects of substrate composition (ARL 1986, 1988c, d; Bunn *et al.* 1986; Storey *et al.* 1991). These seasonal patterns mean that in many systems, aquatic fauna can be grouped into typically 'dry' (summer/autumn) and 'wet' (winter/spring) season communities (Bunn 1986, Bunn *et al.* 1986, Storey *et al.* 1990).

The other major influence on aquatic fauna is the degree of temporal concordance of the flow regime; i.e. the degree to which a flow regime is not only seasonal but also predictable year-to-year (McMahon 1989, Bunn & Davies 1990, Bunn 1995). The high temporal concordance of south-western streams contrasts with streams elsewhere in Australia. Stable flows are a distinctive feature of lowland rivers during the dry season. Species that are susceptible to high and variable flows can synchronise life cycles so that the sensitive stages (e.g. the larvae of crustaceans or pupating stages of some insects) occur only during the dry season. As a consequence, unusually high discharge events during the dry season may be detrimental to the persistence of these species. It is important, therefore, that dry season flows below proposed impoundments remain benign without dramatic changes in flow rate.

Freshwater crayfish

Although gilgies are capable of burrowing to avoid summer drying, soils must be moist to ensure their gills remain hydrated. Neither marron nor gilgies have any resistant stage in their life cycle. Therefore, permanent flows or access to pools or shallow groundwater are required to maintain marron and gilgie populations, with EWRs for freshwater crayfish being met by flows set for macroinvertebrates.

Frogs

Tadpoles would require seasonal water in the form of backwaters, shallows, still pools and/or flooded vegetation on the floodplain. In Cowaramup Brook, flows retained to meet EWRs of macroinvertebrates and floodplain inundation flows would be sufficient to ensure survival of frog eggs and tadpoles.

Fish

Components of the biology of native fish species most likely to be affected by altered flow regimes are migration and reproduction/access to spawning habitat. Western minnows and nightfish migrate up tributaries to spawn during winter months. Thus, maintenance of winter flows is necessary to allow movement of these fish over riffles, snags and other possible barriers. In past EWR studies a depth of 10 cm over perceived obstacles was considered the minimum threshold depth for small-bodied fish to allow upstream migration (see WRM 2005a, a, 2007b). However, this value was derived for native fish such as western minnow and western pygmy perch. The only fish known from Cowaramup Brook is the Swan River goby (Andrew Storey pers. obs.). Given the climbing ability of gobies, a lower minimum threshold depth of 5 cm was considered more appropriate than the 10 cm used for other natives. Gobies are a group of fishes which have adapted to fast flowing water and have an excellent climbing ability due to their modified pectoral fin creating a suction device. Some species of goby elsewhere have been reported to climb out of the water on vertical, wet rock faces to move upstream (Plate 3).

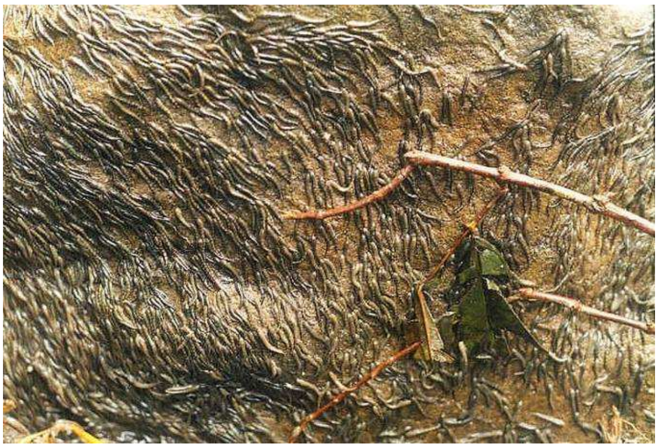

Plate 3. The goby *Stiphodon semoni* climbing rocks on the Tatarloka River, southern Sumbawa, Indonesia (photos taken by Keith Martin and Muhammad Yani).

Predictable winter/spring flooding must also be maintained to ensure breeding success and strong recruitment. The mode of delivery of winter flows to provide for fish passage is also a critical issue. It is generally acknowledged that flows should be delivered in pulses to provide sufficient depth to maximise the ability of accumulated fish to traverse natural and man-made obstacles. Generally, fish will wait below a barrier until a spate allows them to negotiate upstream. The duration of the higher flows required for fish to negotiate an obstacle is open to conjecture. To maintain fish passage in Cowaramup Brook it would be necessary to maintain the current frequency and duration of fish passage events.

WEC (2002) suggested that increased flows do not need to be continuous, but should be maintained, as pulses to simulate spates, for at least ten days during each of the months of August and September. This aspect of EWRs for fish requires review and further development. Ideally, the number of passage flow events should be based on the natural frequency of events, which will be related to the frequency of rainfall from south-westerly frontal systems from early winter through to spring. Native fish start to migrate upstream as soon as winter flows commence (i.e. late May - early June; A.W. Storey, pers. obs.), therefore, passage flows need to start earlier in the winter (i.e. June) and continue through winter. Late winter/spring flows may be lower as fish are able to move downstream over obstacles in considerably less water than required to move upstream.

The introduced mosquitofish is prolific in the Cowaramup Brook system. Pusey *et al.* (1989) suggested that natural winter spates regularly reduce the population density of mosquitofish to low levels, thus permitting the coexistence of this exotic species and small indigenous species with similar habitat and dietary requirements. Conversely, flow regulation, and the absence of large flushing flows in winter in the Canning seemed to favour the prevalence of mosquitofish; a relatively poor swimmer (Pusey *et al.* 1989). The breeding strategy of mosquitofish is extremely effective; they bear live young and out-compete native fish, especially in degraded systems. High densities of mosquitofish result in a high incidence of fin damage (fin nipping) in native species (Morgan *et al.* 1998; Storey 2000).

Modifications to flow regimes may have significant implications for the dynamics and management of *Gambusia holbrooki* populations. A combination of flow regimes is required to control mosquitofish. It is suggested that the maintenance of winter spates is necessary to restore/maintain natural habitat characteristics in the lower reaches and provide increased flows which are unfavourable for these poor swimmers. In addition, a period of zero flow days in summer would also be required. These flow recommendations would reduce the suitability of the system for proliferation of the mosquitofish.

In general terms, adult native fish species in south-western Australia appear to be able to withstand relatively high salinity during low flows in summer. However, it is likely that eggs, larvae and juvenile life history stages have a considerably lower salinity threshold. Freshwater species would undoubtedly require fresher water in winter/spring to ensure successful reproduction and recruitment of these more sensitive life stages. This may be in the form of maintaining access to seasonal freshwater tributaries for spawning, or maintaining river channel winter flows comprised of freshwater runoff.

EWRs for fish species can be grouped into four categories:

- Predictable winter/spring flooding must be maintained to ensure breeding success and strong recruitment in the western minnow and nightfish. For example, sufficient water is required to inundate trailing riparian vegetation, a favoured spawning habitat of the western minnow during winter.

- Management of the introduced mosquitofish by maintaining winter spates and zero flow days in summer.

- Fish passage flows maintained at the current frequency and duration of fish passage events.

Energy flows

Stream and river ecosystems are an integral component of the landscape, where ecological boundaries are often the entire catchment. Catchments provide water (surface, groundwater), nutrients and food for aquatic fauna (*e.g.* leaf litter). Therefore, any disruption within the catchment will be translated to impacts to the stream and river ecosystem.

Existing models of ecological processes differ in the interaction between a river and the catchment. The River Continuum Concept (RCC) (Vannote *et al.* 1980) emphasises an upstream-downstream linkage in energy flow, where material derived from forested regions supports downstream ecosystems. Reservoirs inhibit this upstream-downstream linkage in carbon flow. In these circumstances, the input from the riparian zone and tributaries below reservoirs are important to maintain the connectivity between forested and lower reaches.

An alternative model is the Flood Pulse Concept (FPC) (Junk *et al.* 1989) which emphasises the links between the river and its floodplain. These links occur during large flood events and material from the floodplain is transported back into river channels when floods recede.

A third concept, the River Productivity Model (RPM; Thorp & Delong 1994) may also apply to some rivers. This model emphasises the importance of local carbon inputs in providing energy (carbon) to the system. These local inputs consist of in-stream primary production (i.e. autochthonous sources; phytoplankton, benthic algae, other aquatic plants) and direct carbon inputs from the adjacent riparian zone (i.e. allochthonous sources; leaf litter, terrestrial insects). Inundation of in-channel benches is an important mechanism for the movement of leaf litter and terrestrial fauna into the aquatic ecosystem.

Analyses conducted in other south-west river systems (Davies 1993; Davies *et al.* 1998) have shown upland reaches to be reliant on the input of terrestrial carbon from forested lands, whilst Coastal Plain reaches are more dominated by algal-based production. It is likely that carbon derived from the upstream, forested catchments drives the algal-based food webs in the lower reaches on the Coastal Plain however, anthropogenic sources of nutrients also likely support coastal plain food webs.

Storey *et al.* (2001) and Streamtec (2002) consider that baseflows recommended for macroinvertebrates are adequate to maintain upstream-downstream energy linkages (autumn through to spring). Higher winter flows provided for fish passage and to inundate riparian values will also be adequate to flush the channel and inundate benches and riparian vegetation and thereby maintain floodplain linkages respectively. EWRs to maintain energy linkages therefore, will be met within the EWRs for macroinvertebrate baseflows, combined with fish passage flows and riparian inundation flows.

Energy flows in Cowaramup Brook may be summarised as:

- Winter flows to maintain upstream-downstream linkages and therefore transport of energy/carbon

- Flows to maintain riparian vegetation as an energy source for the RPM

- Flood flows to maintain carbon/energy linkages between the channel and its floodplain by inundating low, medium and high benches.

Ecological flow objectives

Ecologically critical flow events that maintain crayfish, macroinvertebrates, carbon flows, water quality, vegetation and channel morphology were determined based on methods previously used by the authors (WRM 2005a, b, WRM 2007). A series of critical flows were identified for each ecological component in different seasons. These are outlined in Table 4.

Table 4. Ecological values and objectives for Cowaramup Brook.

Flow component	Ecological attribute / Value	Ecological objective	Season (duration)	Time series (pulse/spells)	Hydraulic metric	Consequence of not meeting objective
Summer low flows		Gravel runs & riffles maintained in summer as biodiversity 'hotspots'.	Summer	Baseflow	Minimum stage height during summer to maintain current area of gravel runs & riffles to a depth of 0.05 m. 50% lateral coverage in summer.	Reduced biodiversity as obligate gravel run/rapid dwelling species will be lost from the system.
Stress relief flows	Pool ecology	Maintain oxygen, temp, flush contaminants	From late spring, through summer, and late autumn early winter	Small events	Maintain frequency, timing, duration of early season freshers (minimum velocity of 0.01 m/sec in pools)	Reduced flow period and extended period of summer stress conditions – threats to ecological values in pools.
Fish Passage Flow	Fish diversity	Passage for small bodied fish moving upstream from late autumn through into early spring across natural obstacles (i.e. rock bars shallow riffles and LWD).	Late autumn through into early spring	Events (size and frequency) / duration	Minimum depth over obstacles of 0.05 m for gobies. Late May to late August.	Loss of migratory species from parts of the system if passage restricted. Reduced connectivity.
Winter Low Flow	Process	Seasonal inundation of benches for allochthonous litter transfer. Predictions of Riverine Productivity Model; seasonal inundation & recession 'collects' detrital material in main channel which supports food webs.	Winter	medium wet season events	Inundate lower benches in winter. Combination of lateral gradient and wetted width	Detrital material important in food webs. Loss of this material may limit abundance and/or presence of some species.
	Invertebrates	Gravel runs & riffles maintained in winter low flow.	Winter	Flow duration	Inundate riffles in winter. 100% lateral coverage to 0.05m.	Loss of biodiversity
	Vegetation	Inundate emergent macrophytes and aquatic plants	Winter	Flow duration	Inundate emergent macrophytes in winter	Loss of biodiversity
	Process	Downstream movement of C to drive food webs (RCC)	Winter	Baseflow	Maintain connectivity (satisfied by riffle inundation objective)	Loss of C supply to downstream foodwebs. Decrease in biomass and biodiversity.

Flow component	Ecological attribute / Value	Ecological objective	Season (duration)	Time series (pulse/spells)	Hydraulic metric	Consequence of not meeting objective
	Vegetation	Riparian vegetation - main channel bank & emergent vegetation. Seasonal inundation of emergent and main channel bank vegetation.	Winter	Flow duration	Flood lower banks in winter.	Change from historic water regime = change in plant community (terrestrialisation) with associated change in structure. Enhanced opportunity for terrestrial weeds (e.g. grasses) and terrestrial encroachment. Riparian vegetation supplier of LWD as aquatic habitat & of material to support detrital food webs. Regulator of nuisance algal growth, through shading.
Winter Medium Flows	Frogs	Stage height to ensure rushes and reeds are trailing (provide habitat)	Winter	Flow duration	Duration of base flow sufficient to inundate trailing veg	Loss of frog species
Winter High Flow	Channel morphology	Maintain pools & channel form. Pools provide refugia for fauna in summer & require regular scouring to prevent excessive build up & infilling.	Winter	Event magnitude / frequency	Channel forming flows – flows to active channel stage height. Average depth of Thalweg depth to active channel for riffles and run cross sections.	Loss of pool depth = reduced carrying capacity and summer refugia for fish, tortoise, water rats etc greater encroachment by riparian vegetation, higher BOD with associated risk of low DO in summer, loss of benthic fauna due to smothering by fine sediment build up, smothering of snags in pools = reduced habitat.
		Prevent incursion of riparian vegetation into channel. There is a dynamic relationship between flow, sediment deposition & vegetation encroachment on the channel.	Winter	Event magnitude / frequency	Channel forming flows – flows to active channel stage height.	Area of active channel will decrease. Peripheral velocities will be reduced resulting in more sediment deposited & weed incursion.
	Predictions of Flood pulse concept	Seasonal inundation of high benches	winter	Medium to high magnitude events of low duration	Inundate high benches in winter	
Annual Low Flow	Process	Flow connectivity of upstream to downstream reaches is required for energy transfer.	All year	Flow duration	Flows to maintain longitudinal connectivity at all times	Disruption of flows may inhibit downstream subsidy of food webs. This may limit biodiversity particularly of detritivores and filter feeders.
Over bank	Riparian zone	Maintain overbank flows to inundate	winter	high magnitude	Over bank flows to inundate	Possible reduced seed dispersion,

Flow component	Ecological attribute / Value	Ecological objective	Season (duration)	Time series (pulse/spells)	Hydraulic metric	Consequence of not meeting objective
flows	condition	the floodplain vegetation		events of low duration	floodplain riparian zone. Lateral gradient plus wetted width (greater than active channel width)	possible enhanced invasion by exotic grasses, territorialisation of plant communities with assoc change in structure
	Riparian zone condition	Maintain overbank flows to inundate the floodplain and maintain vertebrate and invertebrate diversity	winter	high magnitude events of low duration	Over bank flows to inundate floodplain riparian zone. Lateral gradient plus wetted width	Loss of biodiversity (species dependent on riparian condition)

5 FLOW EVENTS MODELLING FOR COWARAMUP RIVER

5.1 Hydraulic modelling

A critical aspect of determining EWRs to protect key water-dependent environmental values and processes is the accurate surveying of the hydraulic geometry of the river channel. This is necessary to build hydraulic models which are then used to calculate the flows required to achieve specific water levels/discharges that drive important hydraulic and ecological processes.

Methods

Based on system hydrology, location of major tributaries, catchment morphology and extent of clearing, one main reach was selected on Cowaramup Brook:

- South of Cowaramup Bay Road and west of Caves Road, approximately 2.5 km upstream of Gracetown (see Figure 2).

Fifteen channel cross-sections were surveyed within the ~ 500 m reach in November 2005 (see Figure 7). Survey methods followed those previously used by the authors in EWR studies of river systems in Western Australia (i.e. ARL 2005; WRM 2005a, b). Cross-sections were located to characterise the shape and variability of the channel over the reach and were positioned to include key hydraulic and ecological features such as controlling features, backwaters, pools, riffles, large woody debris and channel constrictions. These features, together with elevations of bankfull[1] and active channel (depth & width) were surveyed by a commercial surveying company contracted by DoW. Discharge was also measured on several occasions and related to depths on cross sections to assist in calibrating the hydraulic model to be developed for each reach.

All data, including width and depth measurements of surveyed cross-sections, was entered into the Hec-Ras hydraulic model ((**H**ydrological **E**ngineering **C**entre, United States Army Corps of Engineers, **R**iver **A**nalysis **S**ystem). Observed relationships of discharge to stage height were then used to calibrate the model. Different cross-sections control flows at different rates, so the hydraulic model developed by Hec-Ras was calibrated at higher flows.

Figure 7 shows the longitudinal section of the EWR survey reach (Hec-Ras output). Cross-sections 3, 4, 11, and 14 were control points, and cross-sections 2, 5, 6, 8, 12 and 15 represent pools (Figure 7). Controlling cross-sections usually contain riffles at low flows where water flow is turbulent and macroinvertebrate diversity is high. Water velocity in pool cross-sections is slower and less turbulent and provides habitat for some macroinvertebrates, particularly crayfish, and larger vertebrates.

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[1] Bankfull level is the bank height to which waters rise to top of channel bank without flowing out onto the floodplain. Active water level is also referred to as the 'Channel Forming Flow' and is a flow that occurs frequently enough to shape the channel. Active level may be at bankfull level (i.e. floodplain level) or at some point below the top, particularly if the channel is incised (deepened) or has been physically modified (channelised and straightened). Both these levels may be determined by looking for features such as upper edge of exposed soil, lowest extent of annual grasses, grooves in the bank, changes in vegetation type and upper edge of water stains on the bank or on vegetation (WRC 2001).

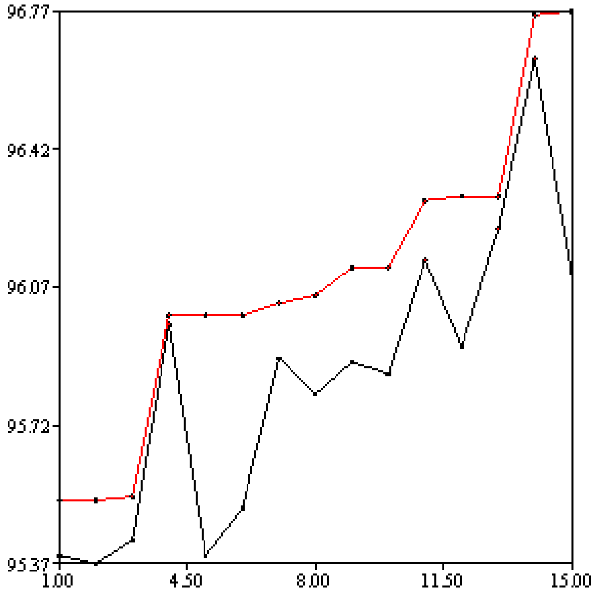


Figure 7. Longitudinal section of the EWR survey reach on Cowaramup Brook. Cross-section number is on the x-axis and elevation (metres above arbitrary datum) is on the y-axis.

5.2 Hydraulic Analysis (RAP)

The River Analysis Package (RAP) was used to determine flow rates that would satisfy the ecologically critical water levels detailed in section 4.

The ecologically critical flow rates for Cowaramup Brook are summarised in Table 5.

Table 5. Ecologically critical flow rates for Reach 1 that satisfy the rules detailed in Table 4.

Season	Flow rate (m^3/sec)	Ecological objectives satisfied
Summer	0.01	• Habitat for macroinvertebrates (summer riffles)
	0.02	• Low flows for stress relief and maintenance of pool water quality (for crayfish and macroinvertebrates) • Downstream carbon movement maintained by connectivity between pools
Winter	0.04	• Habitat for macroinvertebrates (winter riffles)
	0.04	• Low benches inundated to flush detritus and leaf litter into channel • Inundate trailing veg
	0.06	• Small-bodied fish migration
	0.12	• Medium benches inundated to flush detritus and leaf litter into the channel (carbon sources) • Riparian vegetation
	0.33	• Channel morphology (active channel)
	3.27	• Flows to inundate floodplain and riparian vegetation

Season	Flow rate (m^3/sec)	Ecological objectives satisfied
		(top of bank flows)

Pool water quality

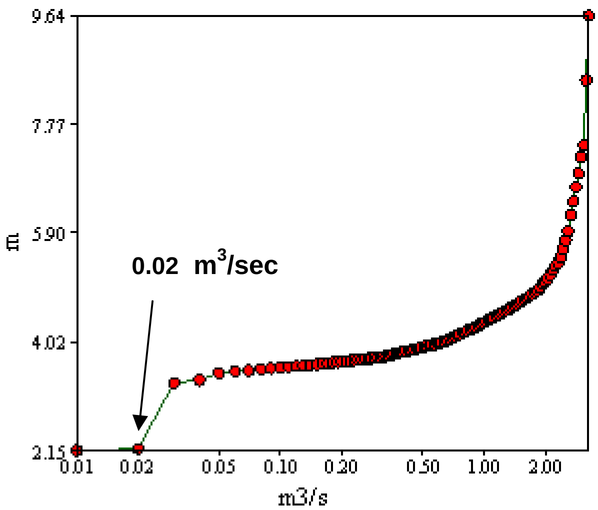


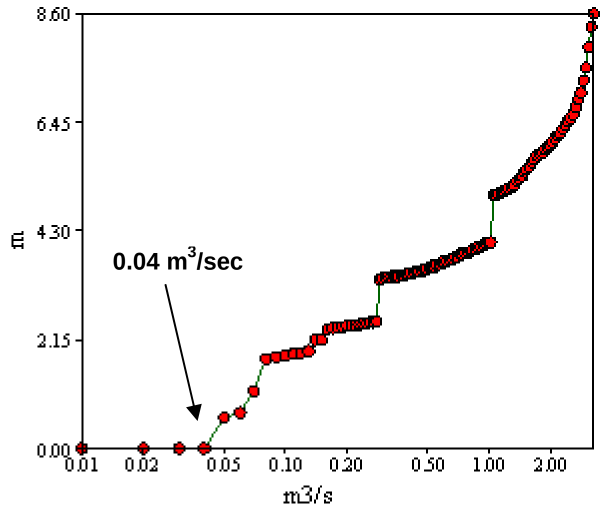
Figure 8. Rating curve for pool water quality (cross-sections 2, 5, 6, 8, 12 and 15).

In order to maintain pool water quality and fish diversity following summer dry periods, a minimum average bulk water velocity of 0.01 m/sec in pools is recommended. To determine the flows required to achieve this threshold, a rule was applied in RAP of 0.01 m/sec bulk flow velocity, incorporating only those cross-sections with pools. The discharge was then calculated in RAP as the average threshold flow across pools for the reach, and the value read from the rating curve. The critical flow to maintain pool water quality was calculated as 0.02 m^3/sec (Figure 8).

Habitat for macroinvertebrates

Riffle zones provide habitat for a broad range of aquatic macroinvertebrates and tend to be biodiversity 'hotspots'. In order to maintain this ecological value, 100% of the riffle cross-section must be inundated in winter, and 50% in summer, to a depth of 5 cm. From the channel surveys, the mean width of the riffles (cross-sections 3, 4, 11, and 14) was 3.68 m. The flow rate required to achieve coverage of riffles in winter was calculated in RAP by applying the rule of at least 0.05 m local depth and at least 3.68 m surface width. Only cross-sections with riffles were included. The discharge required to meet the objective was then read as the inflection point on the rating curve (i.e. the point at which there is only a small change in the width of the water surface for a given increase in flow rate). The flow rate required to inundate riffles in winter at Cowaramup Brook was 0.04 m^3/sec (Figure 9).

The discharge required to achieve coverage of riffles in summer was calculated in the same manner, with the rule being at least 0.05 m local depth and at least 1.84 m surface width (i.e. 50% lateral coverage) for the riffle cross-sections. The flow rate required in summer was found to be 0.01 m^3/sec (Figure 9).



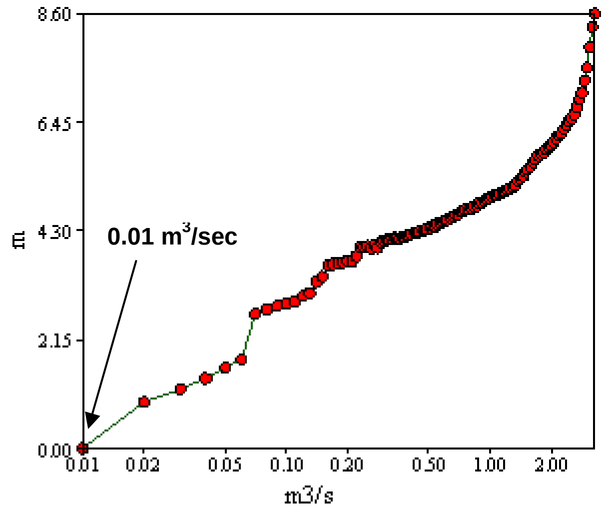


Figure 9. Rating curve for inundation of riffles in winter (left) and summer (right) (riffle cross-sections 3, 4, 11 and 14)

Fish migration

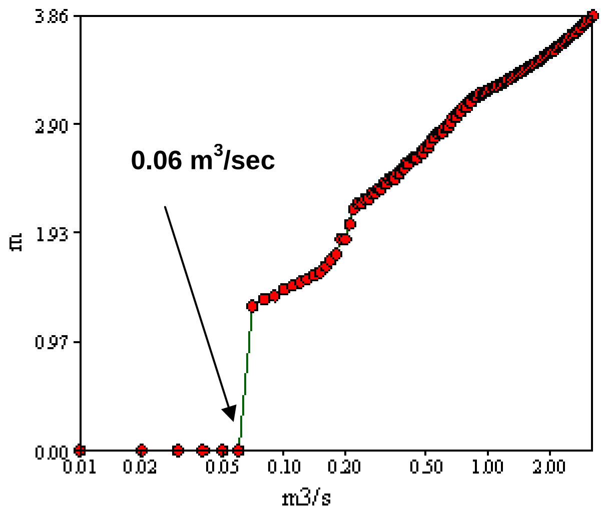


Figure 10. Rating curve for small-bodied fish passage.

Gobies were observed in Cowaramup Brook during cross-section surveys (Andrew Storey, WRM, pers. obs). In past EWR studies a depth of 10 cm over perceived obstacles was considered the minimum threshold depth for small-bodied fish to allow upstream migration. However, this value was derived for native fish such as western minnow and western pygmy perch. Given the climbing ability of gobies, a lower minimum threshold depth of 5 cm was considered more appropriate. Therefore, to determine the flows needed to achieve this threshold, a rule was applied in RAP of at least 5 cm thalweg depth over all cross-sections. The discharge was then calculated as the minimum threshold flow for the reach, and the value read from the rating curve. This rule was used under the assumption that no other native fish occur in Cowaramup Brook. Surveys have only reported the introduced mosquitofish *Gambusia holbrooki*. Fish passage flow for small-bodied fish was calculated as 0.06 m^3/sec (Figure 10). The critical cross-section was # 4 (the rock bar).

Bench inundation

A number of ecological objectives are satisfied by inundating benches, including flooding of emergent macrophytes, provision of trailing vegetation as cover and spawning habitat for fish, and the provision of inputs of autochthonous (algal production) and allochthonous energy (leaf litter/detritus) from benches, which support components of in-stream foodwebs.

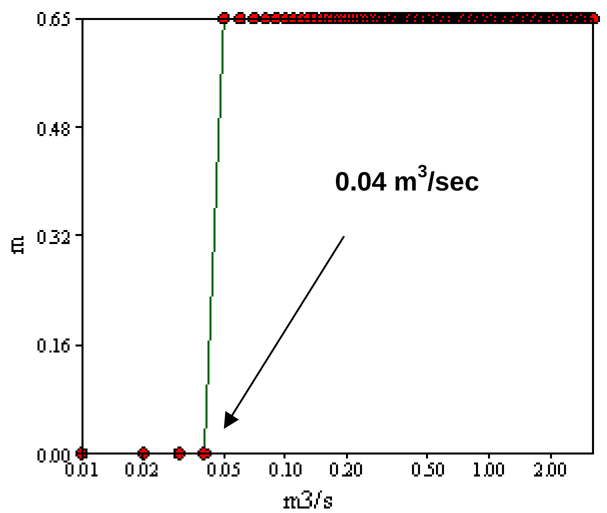


Figure 11. Rating curve for winter low bench inundation (cross-sections 3 and 8).

Low benches were surveyed in cross-sections 3 and 8 in Cowaramup Brook. The flow required to inundate these benches was determined by applying a rule in RAP of a lateral gradient greater than 0.01 m/m to these cross-sections. The discharge was then calculated as the average threshold flow for the reach, and the value read from the rating curve. The critical flow was 0.04 m^3/sec (Figure 11). At this flow, the lower benches on cross-section 3 and 8 just begin to be inundated (see Figure 12).

Two medium level benches were surveyed in Cowaramup Brook (cross-sections 9 and 14). The rule used for low benches did not work for medium benches, probably reflecting differences in lateral gradient. Therefore, the flow required to inundate these benches was determined using the water level function in RAP. That is, the water level was physically increased until the point at which the medium bench was inundated for each individual cross-section with the feature surveyed. The critical flow to inundate medium benches was then taken as the average flow for the two cross-sections. This flow was calculated as 0.12 m^3/sec (Figure 13). EWRs were not determined for high benches, as none were surveyed in Cowaramup Brook.

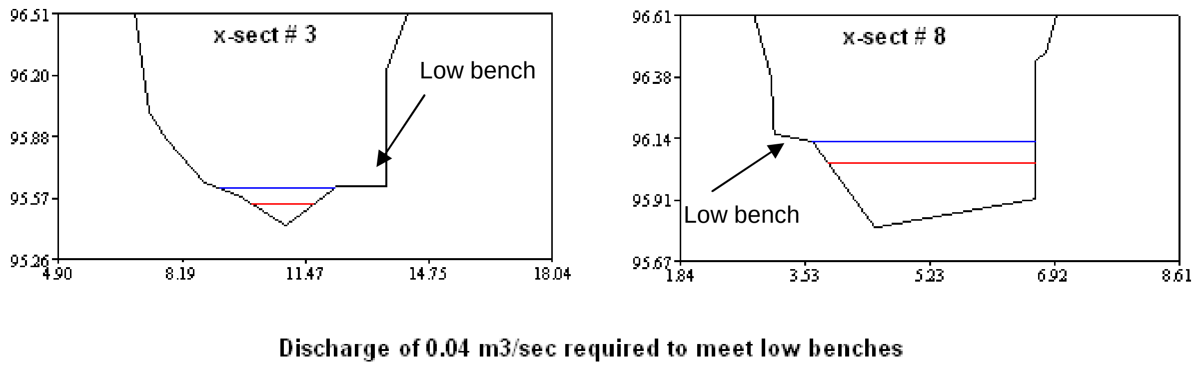


Figure 12. Channel cross-sections with a low bench, showing that this feature begins to become indundated at the critical flow of 0.04 m^3/sec (blue line).

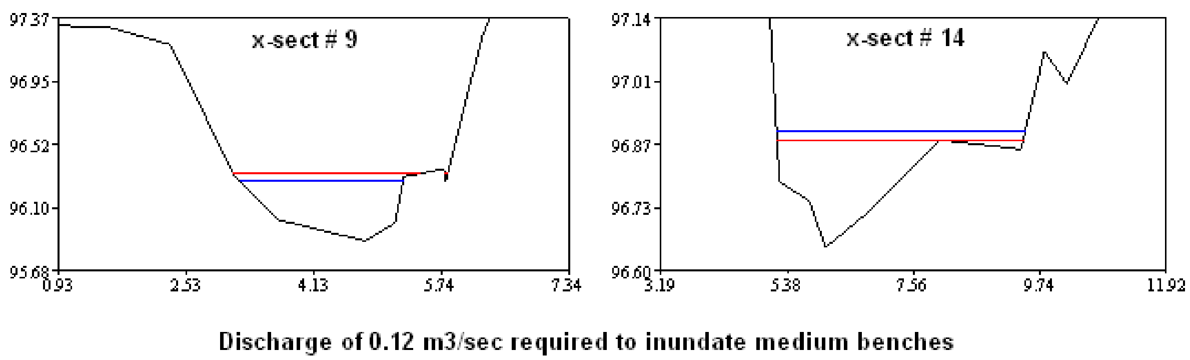


Figure 13. Channel cross-sections with a medium bench, showing the discharge required to meet each bench individually (red line) and the average discharge required to inundate both medium benches (blue line)

Channel morphology (active channel)

Active channel, or channel forming flows, assist in maintaining the shape of the channel by mobilising sediment, scouring pools and preventing riparian vegetation encroaching into the channel. These flows also inundate trailing vegetation to provide cover and spawning habitat for fish, and provide inputs of autochthonous (algal production) and allochthonous energy (leaf litter/detritus) from banks.

The current active channel was surveyed during cross-sectional surveys (*i.e.* the level on the banks above which vegetation is stable and below which the bank is eroding/bare, and without extensive riparian vegetative growth). Using the riffle cross-sections (cross-sections 3, 4, 11, and 14), the average depth of the bed to active channel height, taken as the deepest part of the channel (thalweg depth) to the level approximated as active channel, was calculated as 0.48 m. Using this stage height, a rule was applied in RAP to calculate the flow required to inundate thalweg depth to at least 0.48 m. The rating curve produced by hydraulic analysis calculated a discharge of 0.33 m^3/sec to achieve active channel flows (Figure 14).

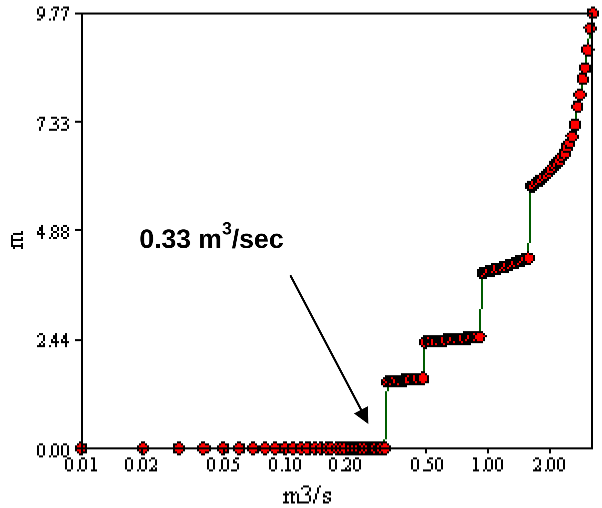


Figure 14. Rating curve for channel forming flows (active channel) (cross-sections 8 and 13) at Reach 1.

Top of bank flows

Flows to meet TOB were calculated individually for each cross-section using the water level function in RAP. Flows were only determined for cross-sections with a well defined TOB (i.e. obvious level on the cross-section above which the bank profile started to decline onto a flatter floodplain; cross-sections 7, 10, 11, 12, and 14). The average value was then taken to be the ecologically critical flow rate. The critical flow for top of bank inundation was 3.27 m^3/sec (Figure 15).

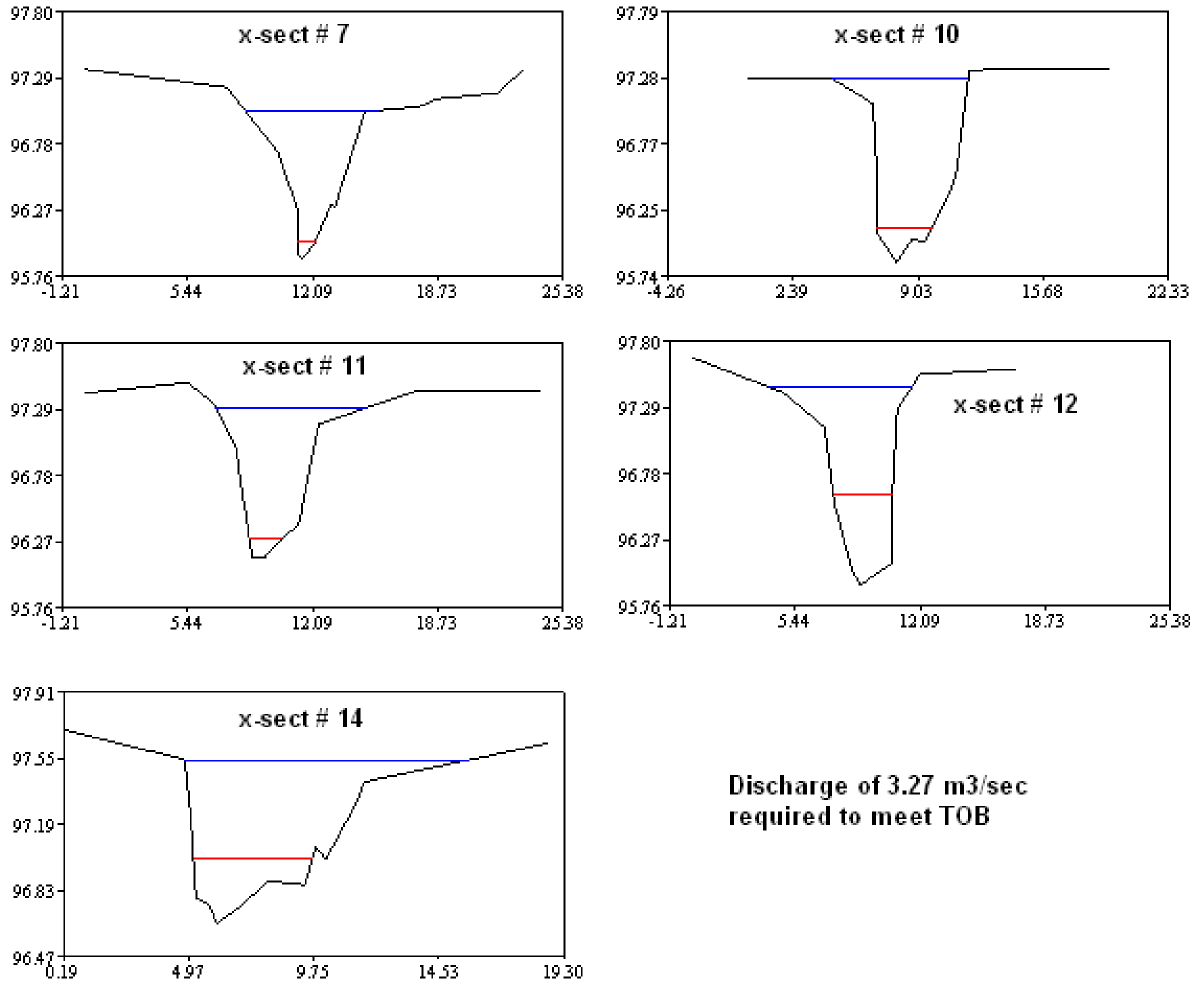


Figure 15. Channel cross-sections with a well defined TOB, showing the average flow required to inundate TOB ($3.27\ m^3/sec$).

Overbank flows – floodplain inundation

The objective of overbank flows was to commence inundation of the floodplain and associated riparian vegetation. The floodplain often supports shallow wetland/sump areas that are likely important feeding and nursery areas for frogs and provide habitat in which juvenile stages with poor swimming ability may avoid high flows. Overbank flows are required to inundate and recharge these wetlands. Similarly, riparian vegetation on the floodplain (*i.e. Eucalyptus rudis* and paperbarks) also require occasional inundation to disperse seed, assist seed set, and soak soil profiles to promote successful germination. To achieve the above objectives, a flow above TOB is required. These flows usually occur as a result of larger rainfall events, principally in winter, and occur infrequently and for short durations.

Overbank flows were calculated individually for each cross-section using the water level function in RAP. Flows were only determined for cross-sections with a well defined TOB and floodplain area (i.e. obvious level on the cross-section above which the bank profile started to decline onto a flatter floodplain; cross-sections 7 and 10). The average value was then taken to be the ecologically critical flow rate. The critical flow for overbank flows/floodplain inundation was $3.73\ m^3/sec$ (Figure 16).

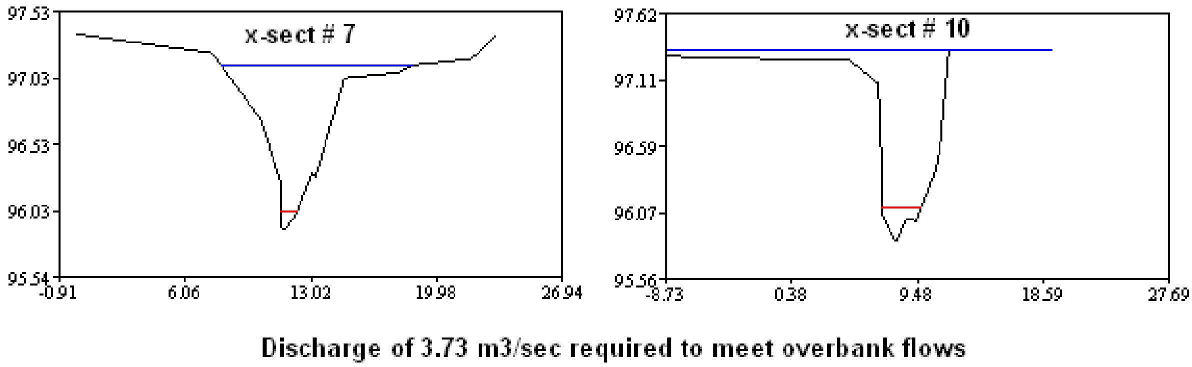


Figure 16. Channel cross-sections with a well defined TOB and floodplain area, showing the average flow required to meet overbank flows/inundate the floodplain (3.73 m^3/sec)

5.3 Time Series Analysis (RAP)

Time series analysis was conducted in RAP and data exported to MS Excel for graphical representation. Output data from RAP showing the inter-annual variability in the flow record for each flow event are presented in Appendix 1 for all critical flows and ecological objectives, and are detailed below.

<u>Summer flows</u>

Cowaramup Brook is an ephemeral system, with an average of 56 zero flow days each year. There appears to be a general trend of decreasing number of zero flow days between 1975 and 2003 (Figure 17). Zero flow days occur in Cowaramup Brook between December and May, with the majority occurring in March (Figure 18). The decreasing number of zero flow days has been seen in other south-west catchments that have many farm dams (i.e. LeFroy) and may reflect seepage from the numerous earthen-wall dams.

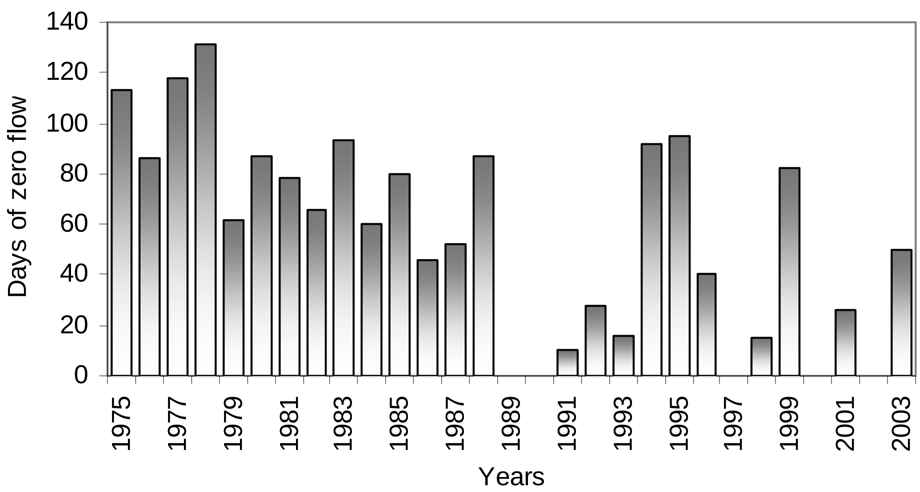


Figure 17. Number of days of zero flow per year between 1975 and 2003 in Cowaramup Brook.

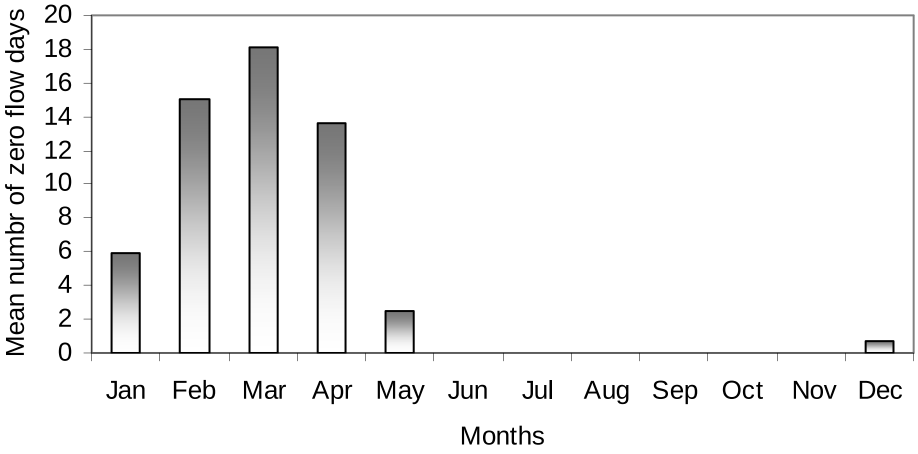


Figure 18. Mean number of zero flow days each month since 1975 (1975 – 2003).

Figure 19 shows the number of days that the summer low flow thresholds (riffle habitat and pool water quality) were met in each month of the historic record. Given the high number of zero flow days in summer, flow events to meet the summer riffle objective did not occur for much of the summer period for most of the years on record. For some of the years on record (90^{th} percentile), summer riffle habitat flows were met for 26 days in November, 2 days in December, 2 days in April and 14 days in May (Figure 19). Figure 20 shows the mean number and mean duration of summer riffle flows. The current regime of summer riffle flows is an event of greater than 0.01 m^3/sec magnitude occurring for a mean total duration of 17.8 days.

The critical flow rate required to meet the pool water quality objective of 0.01 m/sec velocity was 0.02 m^3/sec. This was not met for much of the summer period for most of the years on record (Figure 19). For some years on record, pool water quality flows were met for 17 days in November, 0.2 days in April, and 11.2 days in May. Figure 20 shows the mean number and mean duration of pool water quality flows. The current regime of pool water quality flows is an event of greater than 0.02 m^3/sec magnitude occurring on average 2.8 times per year and lasting 71.4 days.

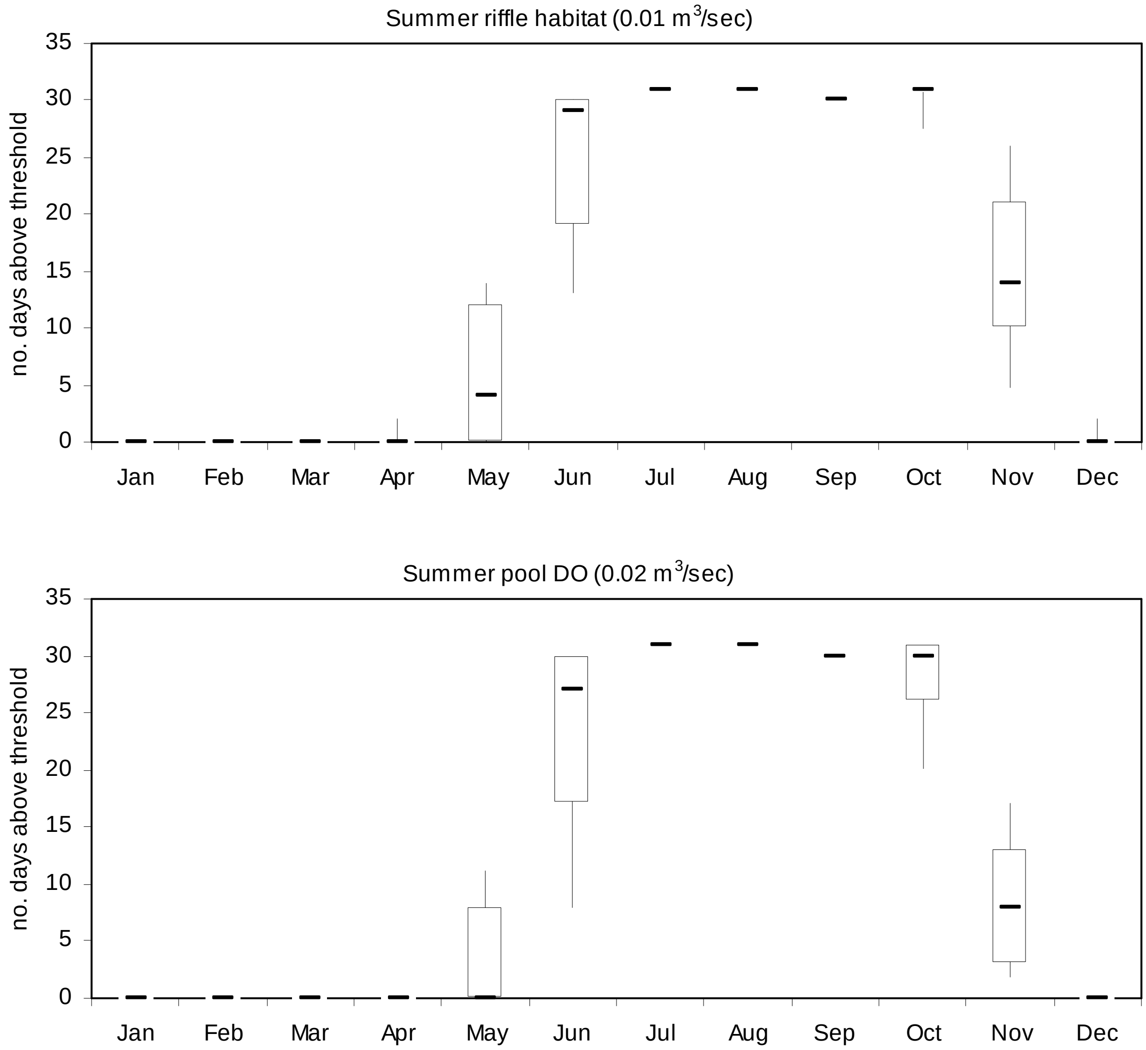
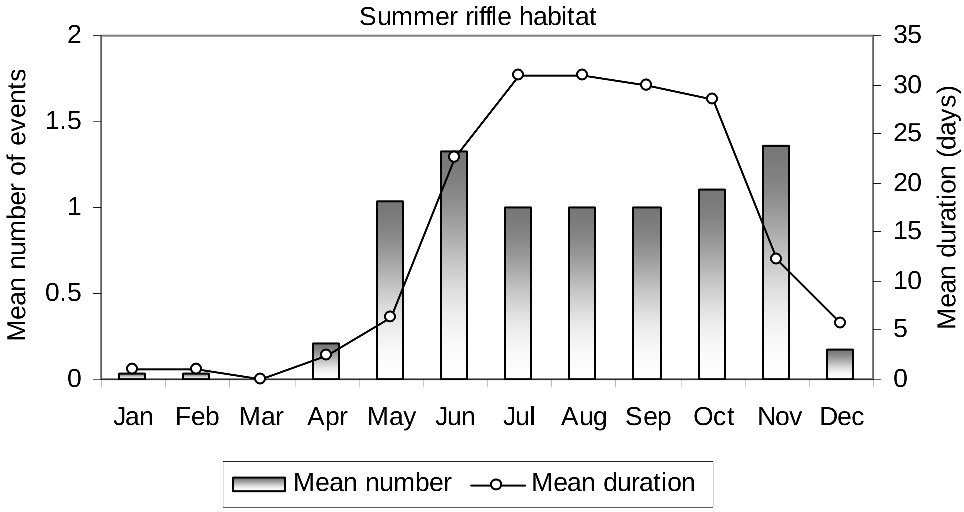


Figure 19. Days in excess of ecologically critical flow rates for summer processes. Horizontal bars represent the median, boxes the 25th and 75th percentile and vertical lines the 10th and 90th percentile.

Winter flows

Figure 21 shows the number of days that the winter low flow thresholds (winter riffle habitat/low bench inundation, small-bodied fish passage, winter medium bench inundation) were met in each month of the historic record. The critical flow for winter riffle habitat and winter low bench inundation was the same, and therefore time series analysis was conducted once for both objectives. The flow rate (0.04 m^3/sec) required to maintain winter riffle habitat and low bench inundation was met for most of the winter period for half of the years on record (Figure 21). Figure 22 shows the mean number and duration of winter riffle and low bench inundation flows. The current regime of winter riffle flows is an event of greater than 0.04 m^3/sec magnitude, with a mean frequency of one event occurring for a mean total duration of 133.4 days. The regime of low bench inundation is an event of greater than 0.04 m^3/sec magnitude occurring on average 3.1 times per year and lasting 59.1 days.



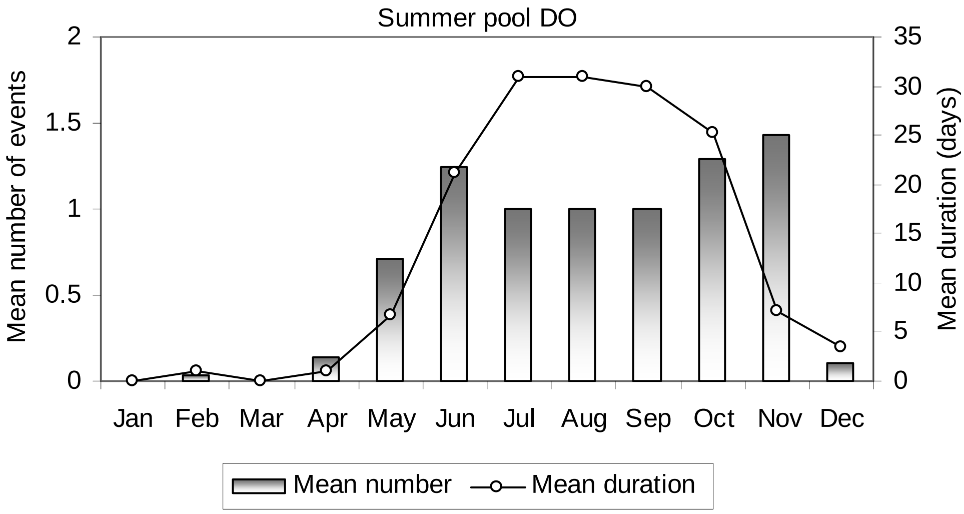
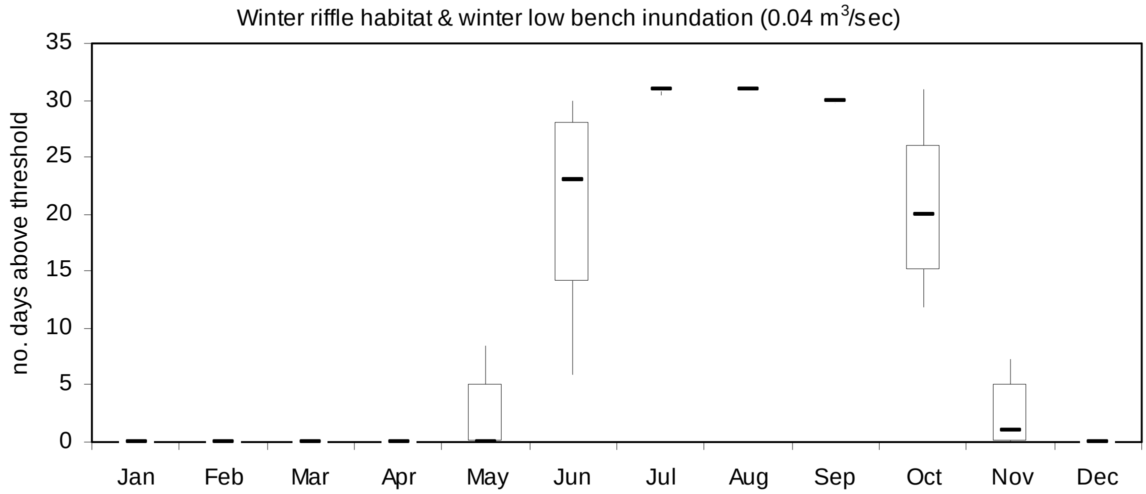
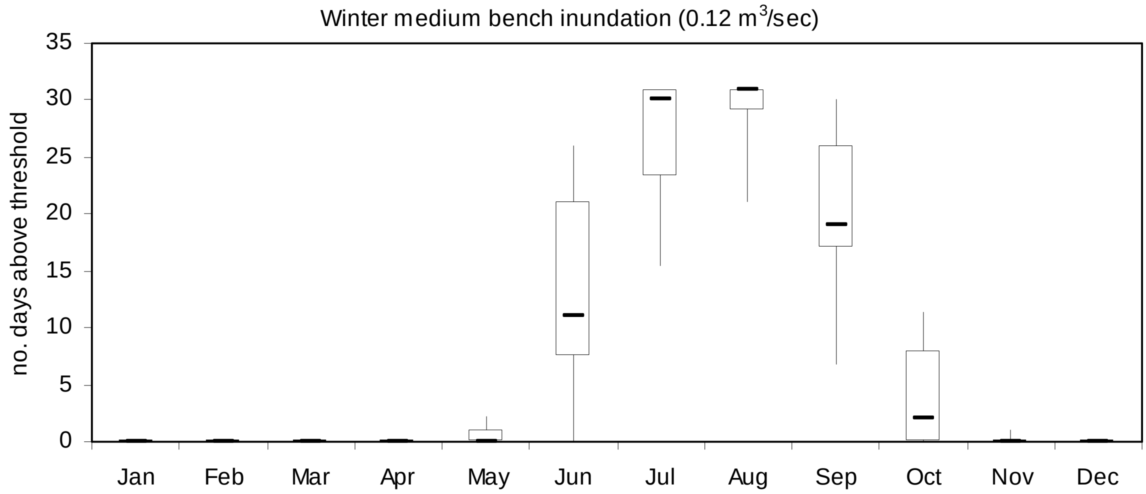


Figure 20. Mean number and duration of summer flow events.

The critical flow for small fish passage flows was not much different from winter riffle habitat and low bench inundation. Therefore, the flow was similarly met for most of the winter period for half of the historic record (Figure 21). Figure 22 shows the mean number and duration of small fish passage flows. At a magnitude of 0.06 m^3/sec, small fish passage flows currently occur at a mean frequency of 3.9 events, with each event lasting a mean duration of 42.2 days.

The critical flow rate for inundation of medium benches (0.12 m^3/sec) was not met for all days throughout the winter months for every year of record (Figure 21). Medium winter bench flows did not occur in May, but occurred for 11 days in June, and increased in July and August (30 and 31 days, respectively), for half of the years on record (Figure 21). The number of days the critical flow was met then decreased in September to 19 days, with only 2 days meeting the flow rate in October for half the length of record (Figure 21). Figure 22 shows the mean number and duration of winter medium bench inundation flows. At a magnitude of 0.12 m^3/sec, winter medium bench inundation flows currently occur at a mean frequency of 6.4 events, with each event lasting for 19.3 days.





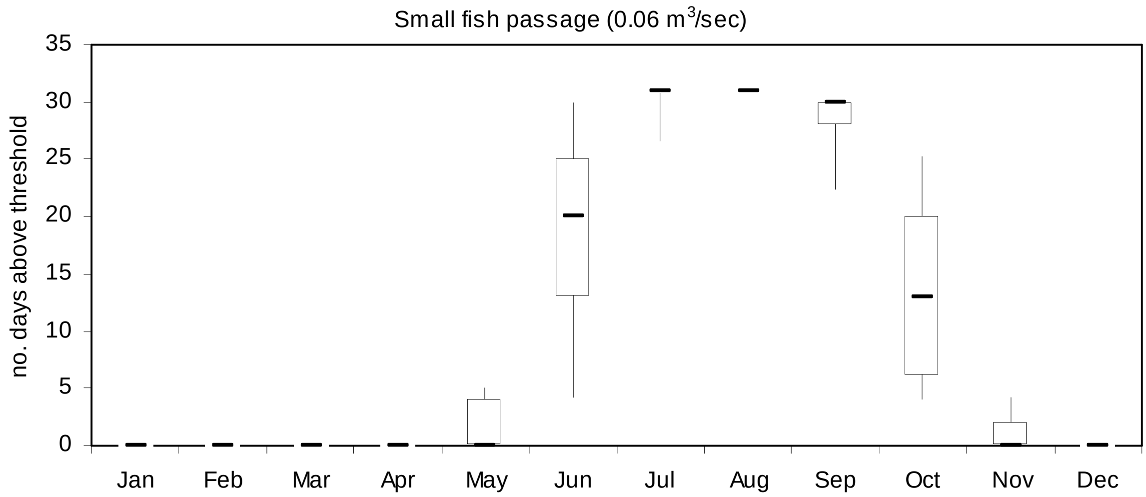


Figure 21. Days in excess of ecologically critical flow rates for winter low flow processes. Horizontal bars represent the median, boxes the 25th and 75th percentile and vertical lines the 10th and 90th percentile.

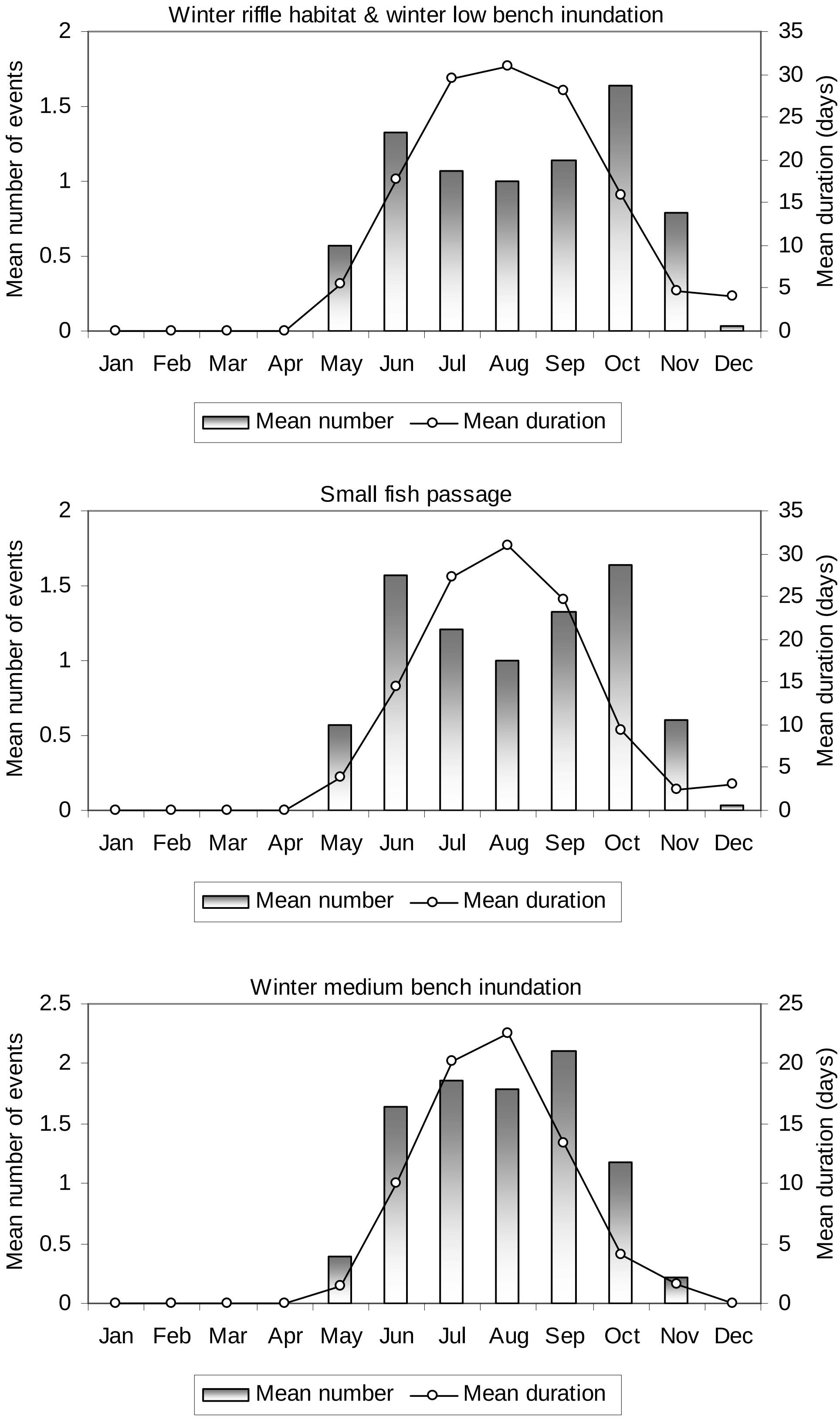


Figure 22. Mean number and duration of winter low flow events.

Figure 23 shows the number of days that the winter medium/high flow thresholds (channel morphology, top of bank, overbank flows) were met in each month of the historic record. For half the years on record, active channel flows were met for 17.1 days in June, 23.2 in July, 22.2 in August, 10.1 in September, and 4.2 days in October (Figure 23). Active channel flows were not met between November and May. Figure 24 shows the mean number and duration of active channel flows. At a magnitude of 0.33 m^3/sec, active channel flows currently occur at a mean frequency of 7.8 events, with each event lasting 4.6 days.

As would be expected, top of bank flows were not met for much of the winter period for most of the period of record (Figure 23). For half the years on record, the critical flow was not met at all throughout the year. Very infrequently (90^{th} percentile), top of bank flows were met for 0.1 days in June and July. Figure 24 shows the mean number and duration of top of bank flows. The current regime of top of bank flows is an event of greater than 3.27 m^3/sec magnitude, occurring on average 0.14 times each winter, for a mean total duration of 1.25 days.

Similarly, overbank/floodplain flows were not met for much of the winter period for most of the years on record (Figure 23). Infrequently (90^{th} percentile), overbank flows were met for 0.1 days in June and July. Figure 24 shows the mean number and duration of overbank flows. The current regime of overbank flows is an event of greater than 3.737 m^3/sec magnitude, occurring on average 0.07 times each winter, for a mean total duration of 1 day.

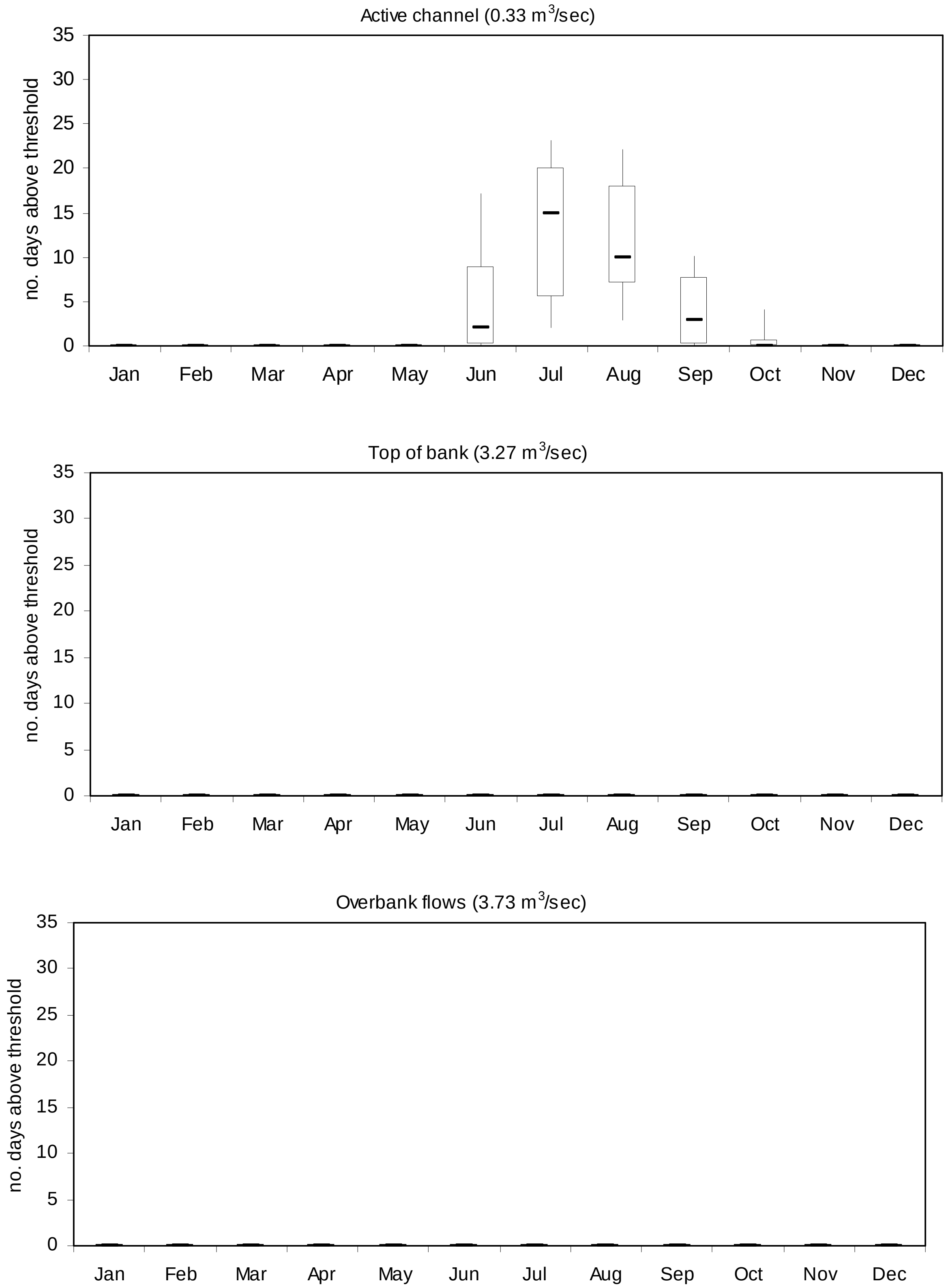


Figure 23. Days in excess of ecologically critical flow rates for winter medium/high flow processes. Horizontal bars represent the median, boxes the 25th and 75th percentile and vertical lines the 10th and 90th percentile.

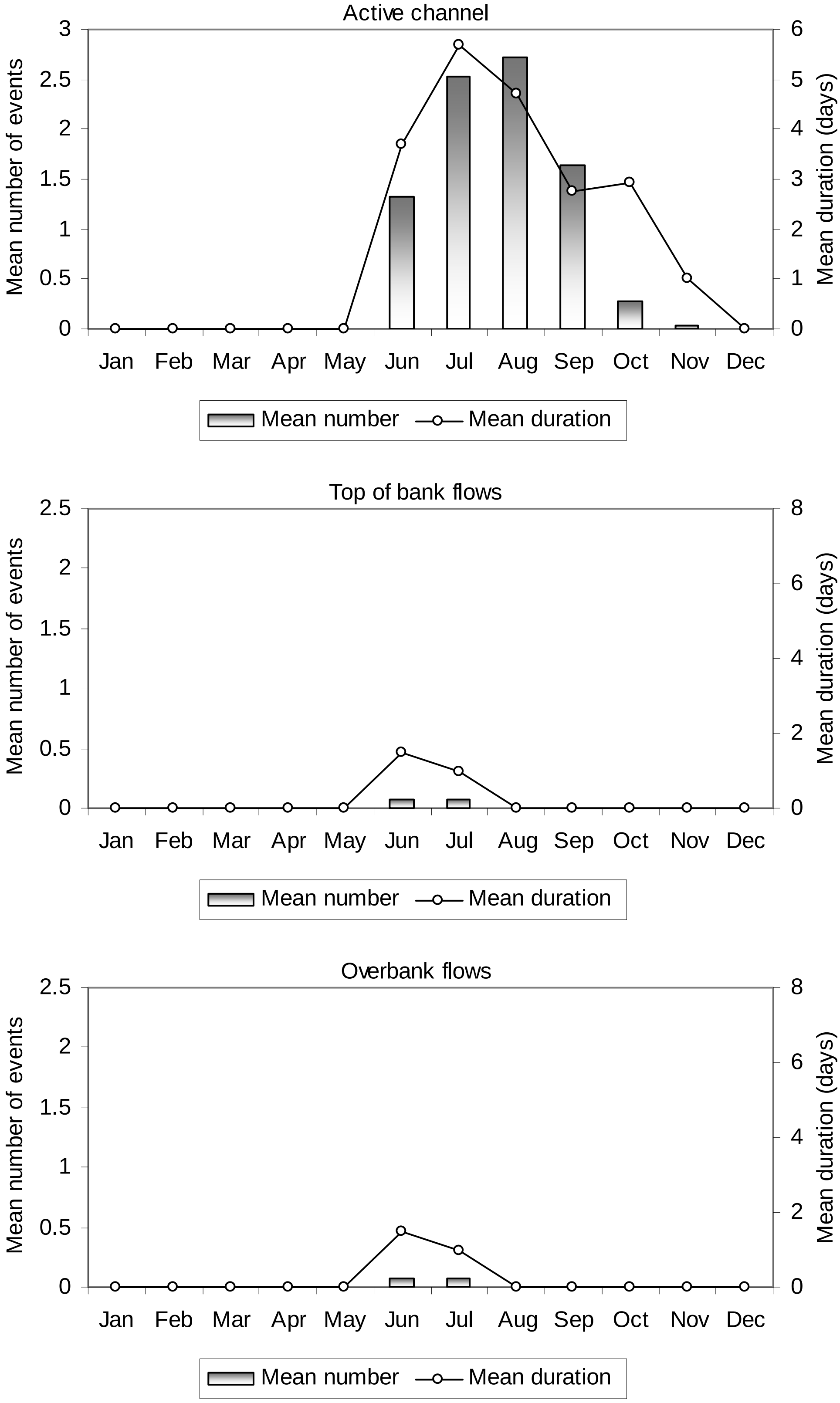


Figure 24. Mean number and duration of winter medium/high flow events.

6 MEAN VOLUMETRIC EWR FOR COWARAMUP BROOK

For the purpose of determining an allocation plan for Cowaramup Brook, it would be necessary to know the total environmental flows required by the different parts of the system, with the difference between the environmental flows and total system yield being potentially available for consumptive uses/diversion. The EWRs for the above reach and ecological values are based on summer and winter base flows and a range of events of varying magnitude and duration (i.e. active channel flows) which may or may not occur each year depending on annual rainfall. It is possible to estimate a total environmental flow by totalling the volumes required to achieve each event, multiplied by the number of events required, added to summer and winter base flows for an "average" year. However, this approach can only be a conservative approximation for several reasons:

- The concept of an "average" year is indicative only, with flows in any year dependent upon rainfall, with the EWR (and licensed diversion) volumes ultimately to reflect and be dependent upon annual rainfall so that flows will mimic natural variability (seasonal and inter-annual) in discharge. As such, aspects such as commencement and termination of winter base flows and number and duration of critical flows will vary between years,
- The EWRs apply to the survey reach, where flow will be a combination of local catchment run-off and groundwater recharge and discharge. The relative proportion of total flow from these sources is unknown, and will vary seasonally and annually.
- The calculated volume in each event will depend on the shape of the flood hydrograph which will vary intra and inter-annually. Therefore it is not possible to definitively define the shape of hydrographs for all events, but approximate shapes for events such as fish passage flows, active channel flows and over bank flows were approximated based on instantaneous flows and previous EWR studies on similar sized channels/catchments.
- Some flows will not occur every year (i.e. overbank flows), and other flows (i.e. winter medium or fish passage flows) may occur with varying frequency between years. As a conservative approach, it is assumed they occur every year at the mean annual frequency calculated by TSA in RAP. This frequency will vary between years.
- In years when a higher flow event occurs, it is assumed it will encompass a range of lower flow objectives. This was provided for in the calculations however, in years when an active channel flow does not occur, then additional winter medium and fish passage flows may need to be added.

The mean annual volumetric requirement (VR) for each of the ecologically critical flow events was calculated by the following equation:

VR = days above threshold x (critical flow rate – next lowest critical flow rate)
where, units of flow are expressed in ML/day.

The volumetric water requirements for each of the ecologically critical flow events are provided in Table 6. Considering the above caveats/assumptions, a total annual environmental flow of 2383 ML was determined for an "average" year for Cowaramup Brook. This equates to 75% of the mean annual flow (1975-2003) (Table 6).

Table 6. Ecological water requirements for Cowaramup Brook.

Flow rate	Frequency	Mean event duration	Mean annual volumetric requirement (ML)
Reach 1			
0.01 Summer riffle habitat	1	17.8	174.25
0.02 Pool DO	2.8	71.4	176.06
0.04 Winter riffle & low bench inundation	1	133.4	232.90
0.06 Small fish passage	3.9	42.2	293.66
0.12 Winter medium bench inundation	6.4	19.3	685.95
0.33 Active channel	7.8	4.6	863.29
3.27 Top of bank	0.14	1.25	93.35
3.73 Overbank	0.07	1	6.61
	Mean Volumetric EWR		**2526**
	Mean Annual Flow		**3349**
	EWR as % MAF		**75%**

7 FUTURE STUDIES/MONITORING

To confirm the validity of the calculated flows, it is recommended that monitoring of each reach is conducted to relate flows to ecological and hydrological objectives. Subsequent monitoring then assesses the effectiveness of the EWRs in maintaining ecological values at a low level of risk. A tiered approach to monitoring is recommended, whereby Tier 1 monitoring would test whether the recommended flows achieve the desired stage heights (*i.e.* flow to inundate riffles in winter, flow to give desired depth for fish passage over obstacles), Tier 2 monitoring would then be considered as Compliance Monitoring, used to test whether the specified flows are actually released/provided with the desired frequency and duration and with the appropriate seasonal timing, and Tier 3 monitoring would assess overall effects of the environmental flows on the ecological condition of the system (*e.g.* changes in riparian vegetation, loss of species of aquatic macroinvertebrates, changes in population structure of native fish species). An adaptive context would require revision of flows/management actions in response to results of monitoring. For example, if flows are insufficient to cover riffles in winter (Tier 1), then recommended flows would need to be increased before Tier 2 monitoring is conducted. The monitoring tiers effectively reflect monitoring priorities with Tier 1 monitoring taking highest priority.

7.1 Tier 1 Monitoring: Flow Objective Monitoring

Flow objectives to test are:

- Is summer baseflow adequate to inundate riffles to 5 cm average depth with 50% lateral coverage;
- Is winter baseflow adequate to inundate riffles to 5 cm average depth with average of 100% lateral coverage;
- Is the recommended fish passage flow adequate to give a minimum depth threshold for the reach of of 10 cm for small bodied fish;
- Is the recommended active channel flow adequate to provide a stage height equivalent to active channel stage height;
- Is the recommended winter medium flow event sufficient to inundate lower benches for energy transfer;
- Is the recommended Top Of Bank flow sufficient to achieve TOB flows.

Monitoring will require measurement of discharge at each survey reach under the varying flow conditions (*e.g.* seasonally and during flood and drought events). Stage height (depth) must be measured for each discharge to assess whether the objectives were met, with depth measured relative to the actual objectives (i.e. depth on riffles, benches etc).

7.2 Tier 2 Monitoring: Compliance Monitoring

The aim of Tier 2 compliance monitoring is to determine if the frequency, duration and magnitude (volume) of the various flows requested under the EWR are actually delivered. Tier 2 monitoring would only occur after any adjustments have been made following Tier 1 monitoring (i.e. were requested flows adequate to meet objectives). If agreed flows are not met, then the amount of water released/left in the system after abstraction/diversion will need to increase (or decrease) and Tier 2 monitoring repeated.

7.3 Tier 3 Monitoring: Ecosystem Health Monitoring

The ultimate aim of monitoring is to assess whether the calculated EWR flows maintain the observed ecological values at a low level of risk. This is achieved by monitoring the values and processes to be maintained.

Ecosystem Health objectives to test are:

- Has there been any change in macroinvertebrate community composition, species diversity and occurrence of rare/restricted distribution species following implementation of the revised flow regime;
- Has there been a change in the composition of native (& introduced) fish that may be indicative of increasing/decreasing population health;
- Has there been a change in the distribution of aquatic and riparian plants in and adjacent to the channel in response to the revised flow regime.
- Are fish able to migrate up through the study reach when the required flows are delivered;
- Has abstraction resulted in accumulation of sediment in pools or exposure of riffle areas due to inadequate flow?

Assessing these objectives will require the design of specific short-term programmes to measure attributes such as pool dissolved oxygen levels over 24 hrs during low flows, fish passage through a reach and bed/bank erosion/aggradation. Other Tier 3 objectives will require the design of on-going, low frequency monitoring programmes to sample macroinvertebrate assemblages (to species level), fish communities and population structure and composition and distribution of aquatic and riparian vegetation. Designs must be standardised for on-going monitoring purposes, using accepted methodologies, with frequency of application determined by anticipated rate of change in the attribute being monitored. Initially, monitoring may have a high frequency (*i.e.* annual for fish and macroinvertebrates), but then sampling may be reduced/stopped once there is confidence in there being no observed effect.

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APPENDICES

Appendix 1. RAP output showing inter- and intra- annual variation

Table A1-1. Total duration of high spell for macroinvertebrate habitat in summer (critical flow = 0.01 m^3/sec).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1975					12	30	31	31	30	31	19	
1976	1				3	22	31	31	30	31	12	
1977					5	27	31	31	30	31	15	
1978					17	30	31	31	30	31	14	
1979				3	12	30	31	31	30	31	28	
1980				2	6	30	31	31	30	31	26	2
1981					8	30	31	31	30	31	26	5
1982						27	31	31	30	31	10	
1983		1				16	31	31	30	31	7	
1984					5	30	31	31	30	31	24	
1985				2		26	31	31	30	31	18	
1986					14	30	31	31	30	31	14	
1987						18	31	31	30	26	5	
1988					12	30	31	31	30	31	18	
1989						8	31	31	30	31	19	
1990				9	26	30	31	31	30	31	23	
1991					5	30	31	31	30	31	23	
1992					12	30	31	31	30	31	21	2
1993						4	31	31	30	31	11	
1994					4	30	31	31	30	24		
1995						26	31	31	30	30	13	1
1996						14	31	31	30	31	30	18
1997					1	29	31	31	30	28	4	
1998						24	31	31	30	31	11	
1999					8	30	31	31	30	31	15	
2000						19	31	31	30	23		
2001					14	30	31	31	30	30	7	
2002						18	31	31	30	31	10	
2003						9	31	31	30	31	6	
25 pctl	0	0	0	0	0	19	31	31	30	31	10	0
10 pctl	0	0	0	0	0	13	31	31	30	27.6	4.8	0
mean	0	0	0	1	6	24	31	31	30	30	15	1
median	0	0	0	0	4	29	31	31	30	31	14	0
90 pctl	0	0	0	2	14	30	31	31	30	31	26	2
75 pctl	0	0	0	0	12	30	31	31	30	31	21	0

Table A1-2. Total duration of high spell for summer pool DO (critical flow = 0.02 m^3/sec).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1975					9	30	31	31	30	31	8	
1976					2	13	31	31	30	25	8	
1977						27	31	31	30	31	11	
1978					14	30	31	31	30	31	10	
1979				2	11	30	31	31	30	30	17	
1980				1	4	30	31	31	30	31	13	
1981					8	30	31	31	30	29	13	2
1982						26	31	31	30	31	6	
1983		1				14	31	31	30	25	2	
1984					5	30	31	31	30	26	16	
1985						20	31	31	30	30	6	
1986					14	29	31	31	30	31	3	
1987						17	31	31	30	14	3	
1988					6	30	31	31	30	31	14	
1989						4	31	31	30	31	13	
1990				1	12	30	31	31	30	31	18	
1991					4	30	31	31	30	29	17	
1992					11	25	31	31	30	28	9	
1993						3	31	31	30	31	3	
1994						30	31	31	30	17		
1995						25	31	31	30	26	7	
1996						14	31	31	30	31	30	10
1997						29	31	31	30	21	2	
1998						24	31	31	30	31	3	
1999					6	30	31	31	30	31	6	
2000						18	31	31	30	17		
2001					8	30	31	31	30	29	2	
2002						4	31	31	30	31	8	
2003						9	31	31	30	30	1	
25 pctl	0	0	0	0	0	17	31	31	30	26	3	0
10 pctl	0	0	0	0	0	8	31	31	30	20.2	1.8	0
mean	0	0	0	0	4	23	31	31	30	28	9	0
median	0	0	0	0	0	27	31	31	30	30	8	0
90 pctl	0	0	0	0.2	11.2	30	31	31	30	31	17	0
75 pctl	0	0	0	0	8	30	31	31	30	31	13	0

Table A1-3. Total duration of high spell for winter riffle habitat and low bench inundation (critical flow = 0.04 m^3/sec).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1975					6	27	31	31	30	17		
1976						8	22	31	30	12	5	
1977						22	31	31	29	27		
1978					13	30	31	31	30	26	6	
1979					10	30	31	31	30	25	11	
1980					3	29	31	31	30	29		
1981					5	30	31	31	30	12	5	
1982						24	31	31	30	22		
1983						14	31	31	30	17		
1984					2	25	31	31	30	15	8	
1985						14	31	31	30	15	3	
1986					14	9	31	31	30	21		
1987						15	31	31	21	1	2	
1988					1	30	31	31	30	27	4	
1989						2	31	31	30	31	4	
1990					8	30	31	31	30	31	7	
1991						28	31	31	30	18	6	
1992					6	20	31	31	30	16	2	
1993							28	31	30	23		
1994						23	31	31	24	9		
1995						22	31	31	30	16	1	
1996						13	31	31	30	31	23	4
1997						25	31	31	30	15	1	
1998						24	31	31	30	26		
1999					5	30	31	31	30	31		
2000						18	31	31	30	11		
2001					4	28	31	31	30	23		
2002							25	31	30	16	4	
2003						7	31	31	30	20		
25 pctl	0	0	0	0	0	14	31	31	30	15	0	0
10 pctl	0	0	0	0	0	6	30.4	31	29.8	11.8	0	0
mean	0	0	0	0	3	20	30	31	29	20	3	0
median	0	0	0	0	0	23	31	31	30	20	1	0
90 pctl	0	0	0	0	8.4	30	31	31	30	31	7.2	0
75 pctl	0	0	0	0	5	28	31	31	30	26	5	0

Table A1-4. Total duration of high spell for small fish passage (critical flow = 0.05 m^3/sec).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1975					4	23	31	31	23	4		
1976						5	17	31	23	6	3	
1977						20	31	31	20	21		
1978					10	30	31	31	30	19	1	
1979					5	30	31	31	30	17	5	
1980						25	31	31	30	21		
1981					5	29	31	31	30	6	3	
1982						24	31	31	25	13		
1983						14	31	31	30	7		
1984						20	31	31	30	6	3	
1985						13	31	31	30	8	1	
1986					10	7	31	31	30	15		
1987						14	31	31	14			
1988					1	30	31	31	30	21	1	
1989						1	28	31	30	31	1	
1990					5	27	25	31	30	26	5	
1991						28	31	31	30	12	4	
1992					3	20	31	31	30	10		
1993							27	31	30	16		
1994						18	31	31	18	4		
1995						18	31	31	25	4		
1996						11	31	31	30	25	17	3
1997						20	31	31	30	11	1	
1998						24	31	31	30	20		
1999					5	30	31	31	30	28		
2000						16	31	31	28	1		
2001					4	18	30	31	29	15		
2002							24	31	28	8	2	
2003						6	31	31	30	13		
25 pctl	0	0	0	0	0	13	31	31	28	6	0	0
10 pctl	0	0	0	0	0	4.2	26.6	31	22.4	4	0	0
mean	0	0	0	0	2	18	30	31	28	13	2	0
median	0	0	0	0	0	20	31	31	30	13	0	0
90 pctl	0	0	0	0	5	30	31	31	30	25.2	4.2	0
75 pctl	0	0	0	0	4	25	31	31	30	20	2	0

Table A1-5. Total duration of high spell for winter medium bench inundation (critical flow = 0.12 m^3/sec).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1975					2	18	31	31	10			
1976							13	29	7	1		
1977						10	26	29	2	9		
1978					3	30	30	21	22	11		
1979					1	22	31	25	19	3	1	
1980						21	31	31	17	7		
1981					1	26	25	31	17	1	2	
1982						13	31	21	13	6		
1983						11	30	31	29			
1984						10	25	31	22	1	1	
1985						11	23	31	18			
1986					4	7	31	31	26			
1987						12	22	17	3			
1988					1	30	31	29	30	9		
1989							22	30	22	22		
1990					1	9	24	31	18	6	1	
1991						25	31	31	26	1		
1992						20	31	31	26			
1993							16	29	30	9		
1994						12	31	18	6			
1995						4	27	31	18	2		
1996						9	31	31	29	13	4	
1997						11	19	31	28	1		
1998						23	31	31	30	8		
1999					3	26	31	31	30	17		
2000						9	31	31	18			
2001					1	7	12	23	17	5		
2002							11	29	15		1	
2003						2	30	30	24	2		
25 pctl	0	0	0	0	0	7.5	23.25	29	17	0	0	0
10 pctl	0	0	0	0	0	0	15.4	21	6.8	0	0	0
mean	0	0	0	0	1	13	26	28	20	5	0	0
median	0	0	0	0	0	11	30	31	19	2	0	0
90 pctl	0	0	0	0	2.2	26	31	31	30	11.4	1	0
75 pctl	0	0	0	0	1	21	31	31	26	8	0	0

Table A1-6. Total duration of high spell for channel morphology flow (critical flow = 0.33 m^3/sec).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1975						9	25	8	3			
1976							2	9				
1977						1	5	7				
1978						14	18	2	10	3		
1979						4	15	6				
1980						10	23	19				
1981						2	11	22				
1982						1	17	1	3	1		
1983						2	12	18	15			
1984						2	9	8	8			
1985						2	3	18	2			
1986						4	20	28				
1987							7	1				
1988						17	20	19	5			
1989							7	7	1	6		
1990						1	17	10	5			
1991						20	20	10	5			
1992						16	22	24	6			
1993							2	7	10	2		
1994						3	20	3				
1995							19	19	5			
1996							18	16	11	4	1	
1997						4	5	15	9			
1998						9	8	18	7			
1999						18	23	15	9	7		
2000							25	12	3			
2001						1		5	3	1		
2002							1	7	2			
2003						1	3	9	4			
25 pctl	0	0	0	0	0	0.25	5.5	7	0.25	0	0	0
10 pctl	0	0	0	0	0	0	2	2.9	0	0	0	0
mean	0	0	0	0	0	9	25	23	8	2	0	0
median	0	0	0	0	0	2	15	10	3	0	0	0
90 pctl	0	0	0	0	0	17.1	23.2	22.2	10.1	4.2	0	0
75 pctl	0	0	0	0	0	9	20	18	7.75	0.75	0	0

Table A1-7. Total duration of high spell for top of bank flows (critical flow = 3.27 m^3/sec).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1975												
1976												
1977												
1978												
1979						1						
1980							1					
1981												
1982												
1983												
1984												
1985												
1986												
1987												
1988						2						
1989												
1990												
1991												
1992												
1993												
1994												
1995												
1996												
1997												
1998							1					
1999												
2000												
2001												
2002												
2003												
25 pctl	0	0	0	0	0	0	0	0	0	0	0	0
10 pctl	0	0	0	0	0	0	0	0	0	0	0	0
mean	0	0	0	0	0	0	0	0	0	0	0	0
median	0	0	0	0	0	0	0	0	0	0	0	0
90 pctl	0	0	0	0	0	0.1	0.1	0	0	0	0	0
75 pctl	0	0	0	0	0	0	0	0	0	0	0	0

Table A1-8. Total duration of high spell for overbank flows (critical flow = 3.73 m^3/sec).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1975												
1976												
1977												
1978												
1979						1						
1980							1					
1981												
1982												
1983												
1984												
1985												
1986												
1987												
1988						2						
1989												
1990												
1991												
1992												
1993												
1994												
1995												
1996												
1997												
1998							1					
1999												
2000												
2001												
2002												
2003												
25 pctl	0	0	0	0	0	0	0	0	0	0	0	0
10 pctl	0	0	0	0	0	0	0	0	0	0	0	0
mean	0	0	0	0	0	0	0	0	0	0	0	0
median	0	0	0	0	0	0	0	0	0	0	0	0
90 pctl	0	0	0	0	0	0.1	0.1	0	0	0	0	0
75 pctl	0	0	0	0	0	0	0	0	0	0	0	0