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

Ecological water requirements of Cowaramup Brook

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Report no. 10
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Cowaramup Brook

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Disclaimer

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Preface

The purpose of this study was to determine the ecological water requirements (EWRs) of Cowaramup Brook, a small stream flowing west from the Dunsborough fault to the Indian Ocean. The study is part of the South-West Environmental Water Provisions Project, which is being delivered by the Department of Water in partnership with the South West Catchments Council (SWCC). During this project, the EWRs of seven river systems in Western Australia's south-west will be determined. The seven waterways and their catchments, which include the Capel, Brunswick and Margaret rivers and the Wilyabrup, Cowaramup, Chapman and Lefroy brooks, are priorities for research due to the high demand for water for irrigated agriculture, mining and water supply, and declining rainfall in the state's south-west.

These studies have been funded by the Australian and the Western Australian governments as part of the National Action Plan for Salinity and Water Quality and administered through SWCC. Among others, the Cowaramup Brook study will support water resource planning in the south-west. The region's rivers have come under increasing pressure due to decreasing flows caused by below-average rainfall and increases in the abstraction and/or interception of water to meet demands for water supply and irrigated agriculture. The project's primary objective is to inform water resource planning decisions by providing estimates of the river systems' ecologically sustainable yields.

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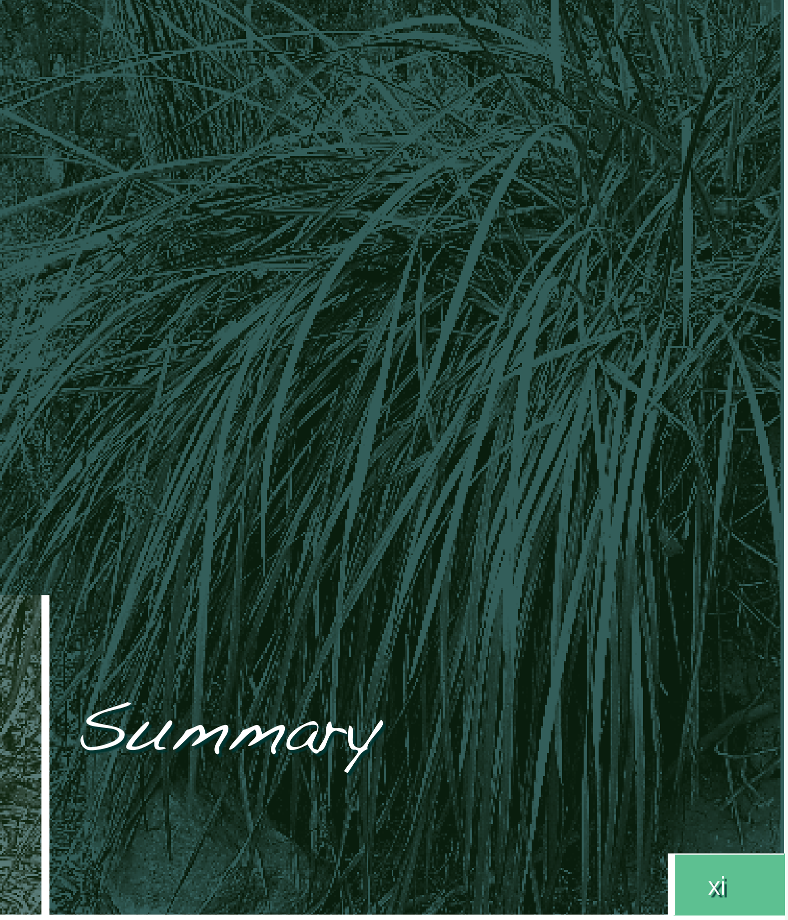


Summary

The ecological water requirement (EWR) of a river is the water regime needed to maintain the ecological values of water-dependent ecosystems at a low level of risk. This report describes the development of an EWR for Cowaramup Brook, a small system arising south-west of the town of Cowaramup and draining west into the ocean at Cowaramup Bay. The EWR for Cowaramup Brook used the Proportional Abstraction of Daily Flows (PADFLOW) method, a new approach developed by the Department of Water for the highly variable streams in the south-west region.

PADFLOW is supported by the River Ecologically Sustainable Yield Model (RESYM). RESYM progressively removes proportions of daily flow from an existing flow record until the duration and frequency of flow spells represent an EWR at a low level of risk to river ecology. The flows abstracted represent the ecologically sustainable yield (ESY) of the stream. The PADFLOW process increases rigour and transparency in water resource planning.

Flows to achieve the desired depth of water in key habitats and corresponding flow rates to achieve these thresholds were identified using the hydraulic analysis module in the River Analysis Package (RAP). These threshold flows provide key ecological functions, such as:

- water depth in river pools
- summer flows required to maintain pool water quality
- depths that allow for fish migration upstream
- inundation of breeding habitat
- flows needed to scour the channel of sediment and maintain a diversity of habitat.

The flow thresholds were used to produce a modelled EWR flow regime that achieves each of a series of ecological objectives. The modelled EWR flow was evaluated by an expert panel using the frequency and duration of flows above each threshold in the EWR compared with that of the 'natural' gauged flow (1975–2003). In Cowaramup Brook, the modelled annual EWR was approximately 80 per cent of the natural yearly flow. The modelled EWR also retains much of the variability present in the natural flow.

Based on the EWR, Cowaramup Brook's ESY averaged 0.67 GL/year and varied between a minimum of 0.41 GL/year and a maximum of 0.89 GL/year. However, given the brook's small size it is recommended that water allocation for consumptive uses should remain at present levels or be only marginally increased.

Chapter one
Introduction

The Department of Water defines the ecological water requirement (EWR) of a river as the water regime required to maintain its ecological values at a low level of risk. This study used a holistic approach to assessing the EWR of Cowaramup Brook. Holistic methods consider the aquatic and riparian ecosystem as a whole, and examine the relationships between water regime and biodiversity, riverine food-webs, ecological processes and individual species. EWR studies consider the flow-dependency of aquatic taxa such as fish, invertebrates, amphibians and aquatic plants, as well as the importance of surface water to terrestrial and riparian species.

According to the 'natural flows paradigm', the natural regime of flow is responsible for the evolution of the observed ecological state of a river (Poff 1997). The flow regime influences which species are present in rivers, and governs the processes that support a healthy, resilient aquatic ecosystem. The natural flows paradigm suggests that an EWR must consider the total flow environment including the natural duration and frequency of ecologically important flow events, the annual and inter-annual flow regime, seasonal patterns of flow and long-term trends in flow volume. Further information about how the flow regime's components influence ecological processes is given in Section 2.5.

This report presents the results of a study designed to determine the EWR of Cowaramup Brook, which is located in Western Australia's south-west. The results of EWR studies allow water managers to identify the ecologically sustainable yield (ESY) of the water resource, as well as implement an appropriate water allocation limit that takes into consideration the economic, social, cultural and ecological values of the system. The Department of Water is Western Australia's primary water resource management agency. This EWR study was undertaken with the aim to support water resource planning in the Whicher resource management area.

1.1 Objective of this study

This study's objective was to identify the volume of water able to be abstracted from the river system while maintaining the current ecological values of the aquatic and near-channel (riparian) environment at a low level of risk. A more detailed description of the EWR is provided in Section 3. EWR studies often have various aims, such as:

- maintaining current, modified ecological values
- enhancing or restoring pre-existing ecological values
- providing for a combination of key current and pre-existing ecological values.

In relatively undisturbed environments, an EWR study will be based on a natural regime, and will identify the flow regime needed to maintain the ecological values of the natural river environment. For ecosystems modified by flow regulation, catchment clearing and land-use changes, the EWR study will use a flow regime derived from existing data collected from the modified system, or from a modelled data set correlated with 'natural' conditions.

Large areas of the Cowaramup Brook catchment have been cleared of native vegetation and developed for agriculture, and a number of dams have been established for agricultural use. For these reasons, the aim of the Cowaramup Brook EWR study was to determine an EWR that would maintain the ecological values of Cowaramup Brook in their present, post-development condition.

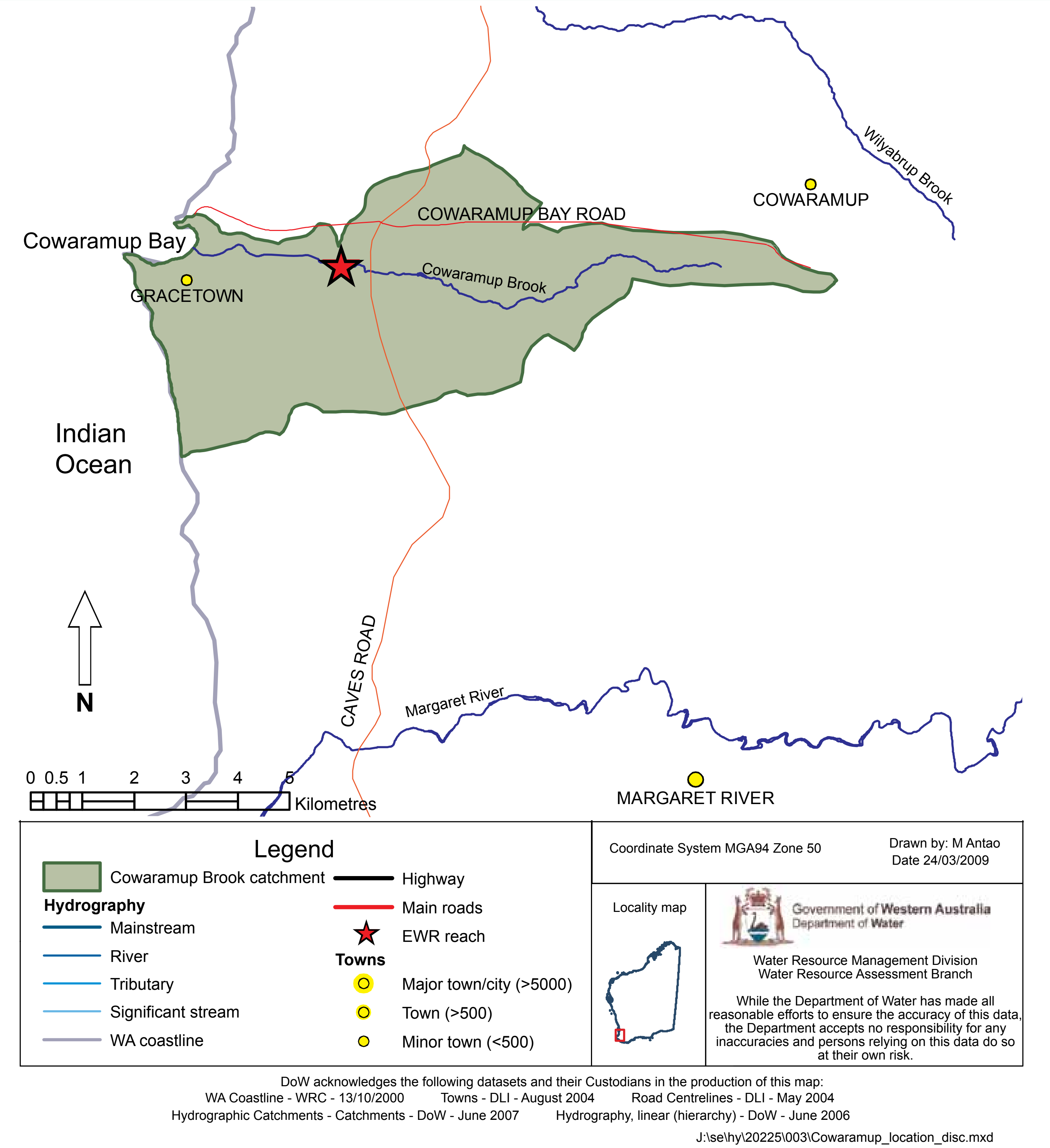
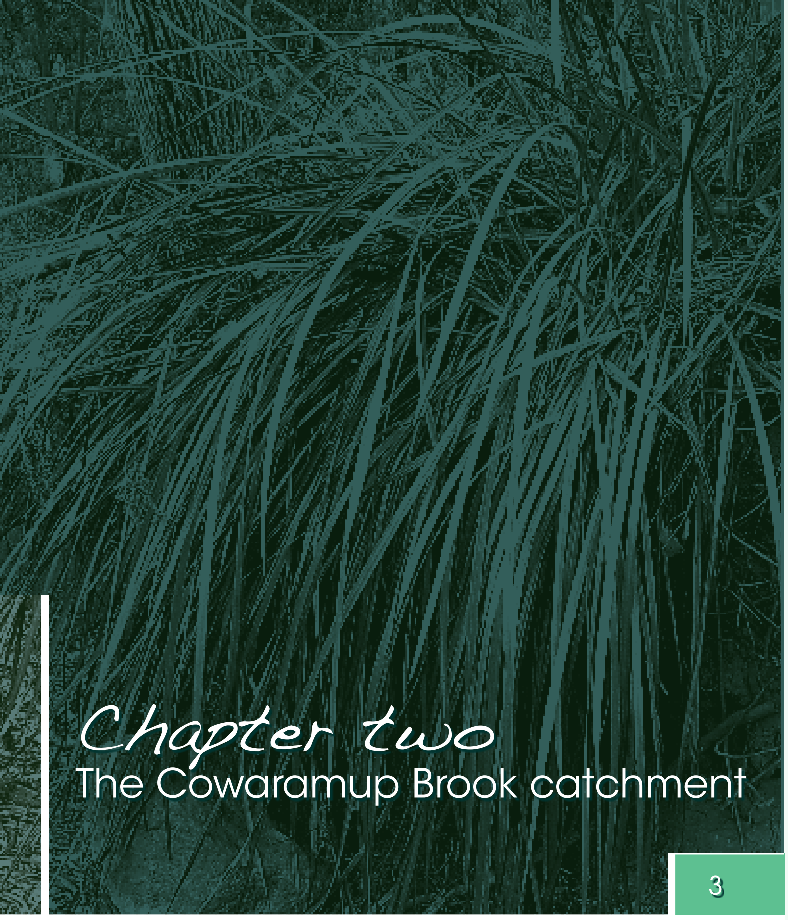


Figure 1

Location of Cowaramup Brook and the EWR study reach



Chapter two

The Cowaramup Brook catchment

Cowaramup Brook is located in the Leeuwin-Naturaliste region of Western Australia's south-west, approximately 280 km south of Perth and 10 km north of the town of Margaret River (Figure 1). It is a very small stream with a total length of only 10 km and drains a catchment of about 24 km^2

The brook originates near the town of Cowaramup, at an elevation of around 80 m above sea level and flows west to the ocean at Cowaramup Bay, near the township of Gracetown. A large proportion of the catchment occurs on the gently undulating Margaret River plateau, which is dissected by a series of shallow valleys. The superficial soils of the valley slopes tend to be well-drained gravels that overlay the granite and gneissic bedrock of the Leeuwin Block (Tille & Lantzke 1990). The valley slopes also have isolated areas of deep sand and gravel over limestone. Large areas of the upper catchment consist of flats and low-gradient slopes with duplex soils of gravels and more structured, grey soils, as well as some more incised v-shaped valleys. The valley floors tend to be poorly drained.

Near the coast, the brook flows across a narrow ridge of (discontinuous) limestone running between capes Naturaliste and Leeuwin. The underlying granite and gneissic bedrock is exposed at the surface in places (Hanran-Smith 2004). Soils are deep siliceous sands with some outcropping of the underlying limestone.

Remnant native vegetation covers approximately 35 per cent of the total catchment area, including areas of National Park and other bushland. Figure 2 shows the extent of cleared areas, which includes much of the upper and middle parts of the catchment. Most of the vegetation clearing occurred in the 1920s as part of various settlement schemes. The loss of riparian vegetation typically results in increased surface runoff, leading to flooding and channel erosion, as well as higher nutrient and sediment loads downstream.

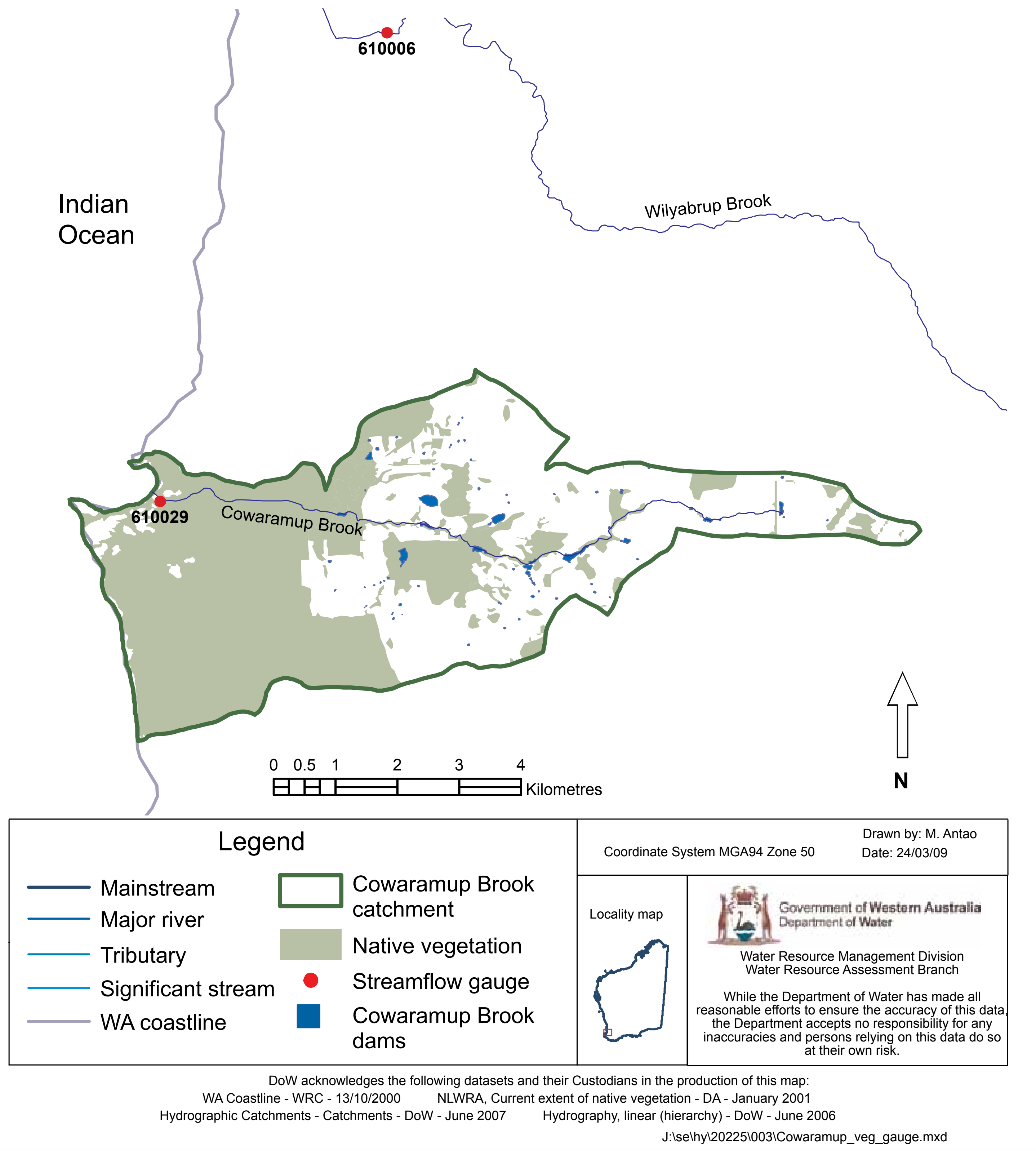


Figure 2

Map showing area of cleared and uncleared land in the Cowaramup Brook catchment

The location of farm dams is also shown

Approximately 65 per cent of the catchment has been cleared for grazing (beef, dairy, deer) and irrigated agriculture (mainly grapes vines, olives and nuts) (CCG 2008). The condition of the brook's riparian vegetation varies considerably along its length. In some areas, the streamline is devoid of native vegetation and the banks are actively eroding. Other parts of the brook's channel have an overstorey of peppermint trees (*Agonis flexuosa*), with little native understorey. Near Cowaramup Bay, a section of approximately 3 km of the brook is in almost pristine condition and supports more than 150 species of native plant (Hunt et al. 2002; CCG 2008).

2.1 Climate

The region's climate is temperate with warm, dry summers and cool, wet winters. Average daytime temperatures can range from 16°C in winter to around 26°C during summer (Weatherzone 2008).

Based on the derived Cowaramup rainfall series (see Section 2.2), the average annual rainfall for the period 1975 to 2006 was 1005 mm (Coppolina 2007). Rainfall is highly seasonal, with around three-quarters of total annual rainfall occurring between May and September (Coppolina 2007) (Figure 3). Winter rainfall is typically associated with the passage of cold fronts over the south-west, which bring moist air from the Southern 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 (Pen 1999).

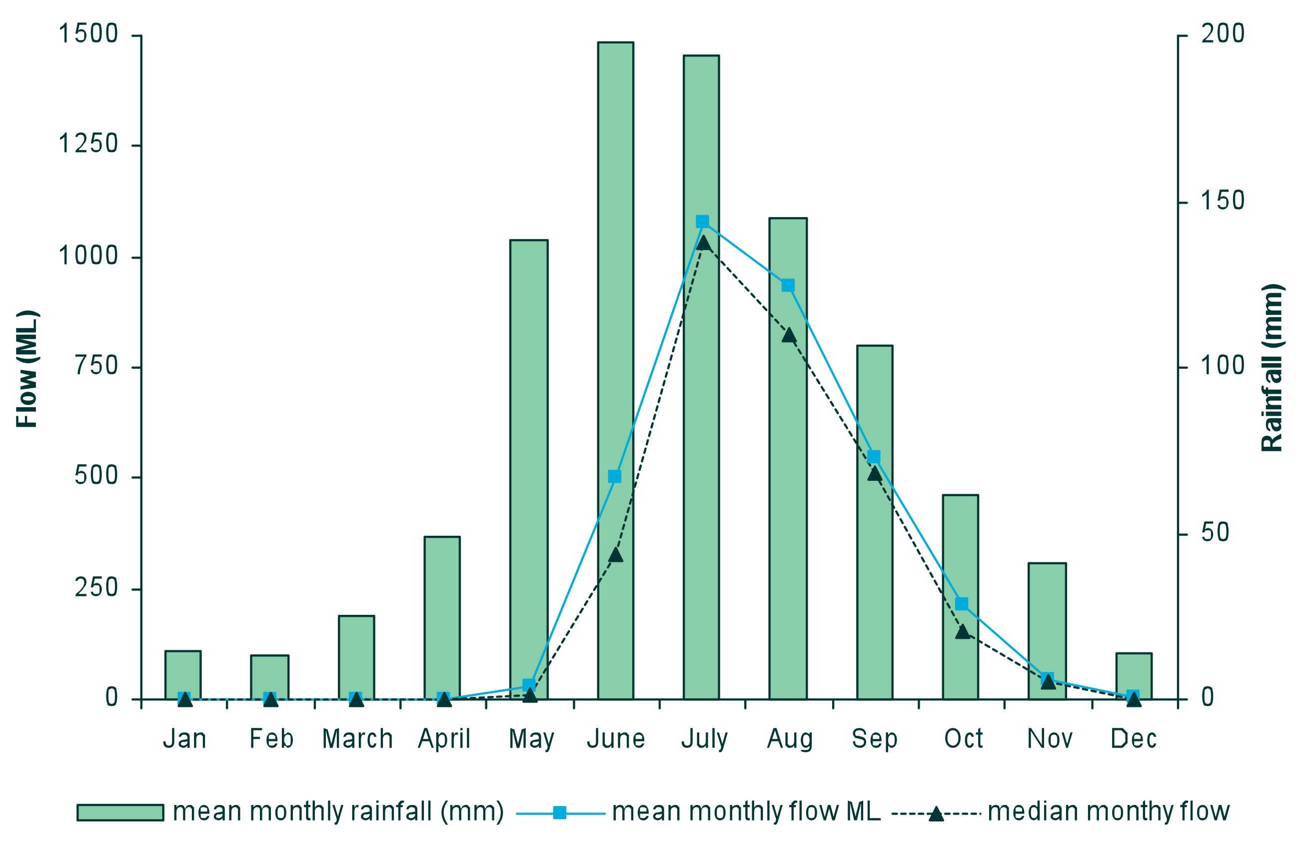


Figure 3
Mean monthly rainfall and streamflow at Gracetown (using modelled data from 1975 to 2003)

Since 1975, there has been a significant reduction in rainfall in Western Australia's south-west, particularly in the winter months (Allan & Haylock 1993; IOCI 2002). Only about 14 per cent of rainfall contributes to runoff and river flow. Overall, the south-west region has experienced a decline of approximately 20 per cent in annual rainfall in the past four decades and a corresponding 30 to 40 per cent decrease in average annual streamflow (WRC 2000). Mean annual rainfall in the Cowaramup Brook catchment has declined by 12 per cent since 1975 (Coppolina 2007) (Figure 4).

Climate models predict a general increase in temperature for the south-west of between 0.4 to 1.6°C by the year 2030 (CSIRO 2001). While the intensity of specific winter rainfall events may increase, the duration of events is expected to decrease. The duration of low rainfall periods and rates of evaporation are also expected to increase.

2.2 Hydrology

The only flow gauging station on Cowaramup Brook (station 610029), is located at the mouth of the brook near Gracetown and has been operating since November 2004. It records drainage from approximately 23.5 km^2 of the catchment. To generate a longer flow record for the EWR study, the data from the Gracetown gauging station was used to derive a linear regression with the data record from the Woodlands gauging station (610006) on the nearby Wilyabrup Brook (Figure 2). The regression model was used to generate a flow data series for Cowaramup Brook for the period 1975 to 2003. The modelled flow suggests that mean annual flow in Cowaramup Brook over the past 29 years was in the order of 3.5 GL/year with annual flow varying between 1.6 and 5.4 GL/year.

Cowaramup Brook is naturally highly seasonal with modelled daily flow varying between 0 ML/day in summer and 380 ML/day in winter during the period 1975 to 2003. More than 95 per cent of annual flow occurs between June and October (Figure 3). The modelled streamflow data over a 29-year period indicates that between January and April, daily flows are less than 0.01 ML for approximately 86 per cent

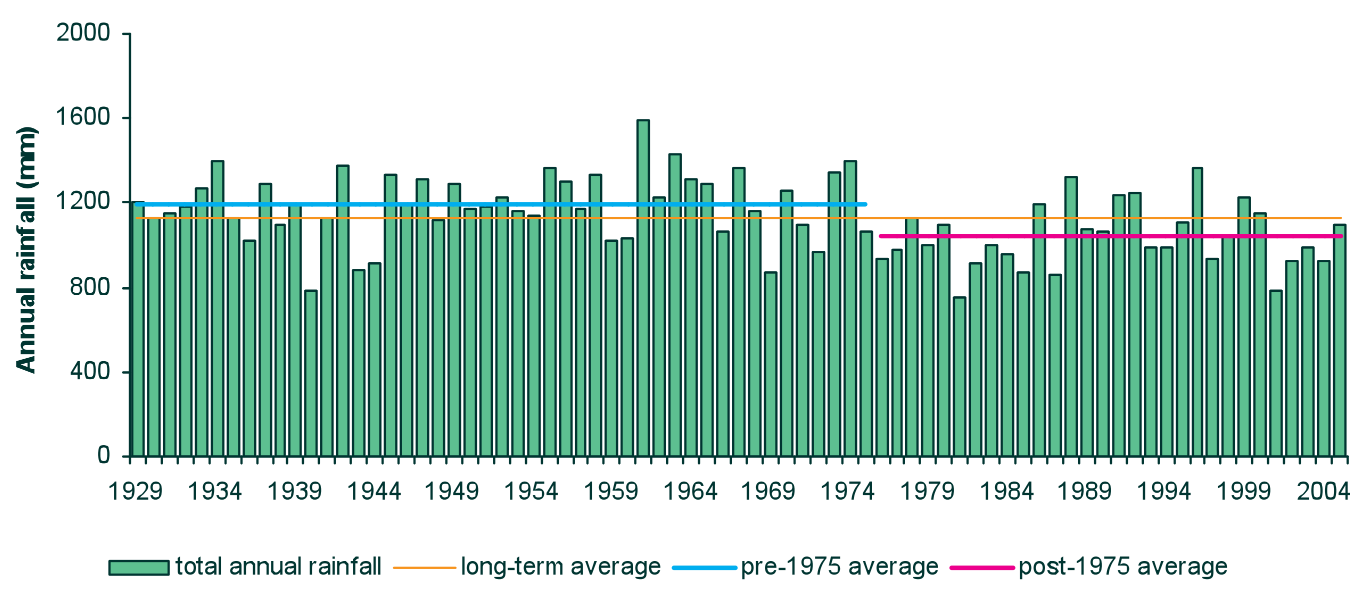


Figure 4

Total annual rainfall and long-term averages for Margaret River post office (station 009547) of the time. Zero-flow days occur in Cowaramup Brook between December and May, with the majority occurring in March (Figure 5). Between 1975 and 2003 there was an average of 56 zero-flow days each year. A general trend of a decreasing number of zero-flow days emerged between 1975 and 2003 (Figure 5). The decreasing number of zero-flow days has been seen in south-west catchments that have many farm dams, and may reflect contributions to summer flow from seepage from on-stream gully-wall dams and irrigation excess (CCG 2008).

The contribution of baseflow to total streamflow in Cowaramup Brook was modelled by Coppolina (2007) for the period 1975 to 2005. This work suggested that groundwater discharges make a significant contribution to streamflow between September and December, when baseflow comprises over 60 per cent of total monthly streamflow.

Groundwater within the Cowaramup system tends to be brackish to saline, with some areas of freshwater (i.e. total dissolved solids or TDS of less than 500 mg/L) (Coppolina 2007). The groundwater table is generally low yielding (Marnham et al. 2000). Rapid channel flows occur within the limestone of the Quindalup and Spearwood systems that underlie the area, and as such, the depth to the watertable and its relationship with the brook is often not well defined (Marnham et al. 2000).

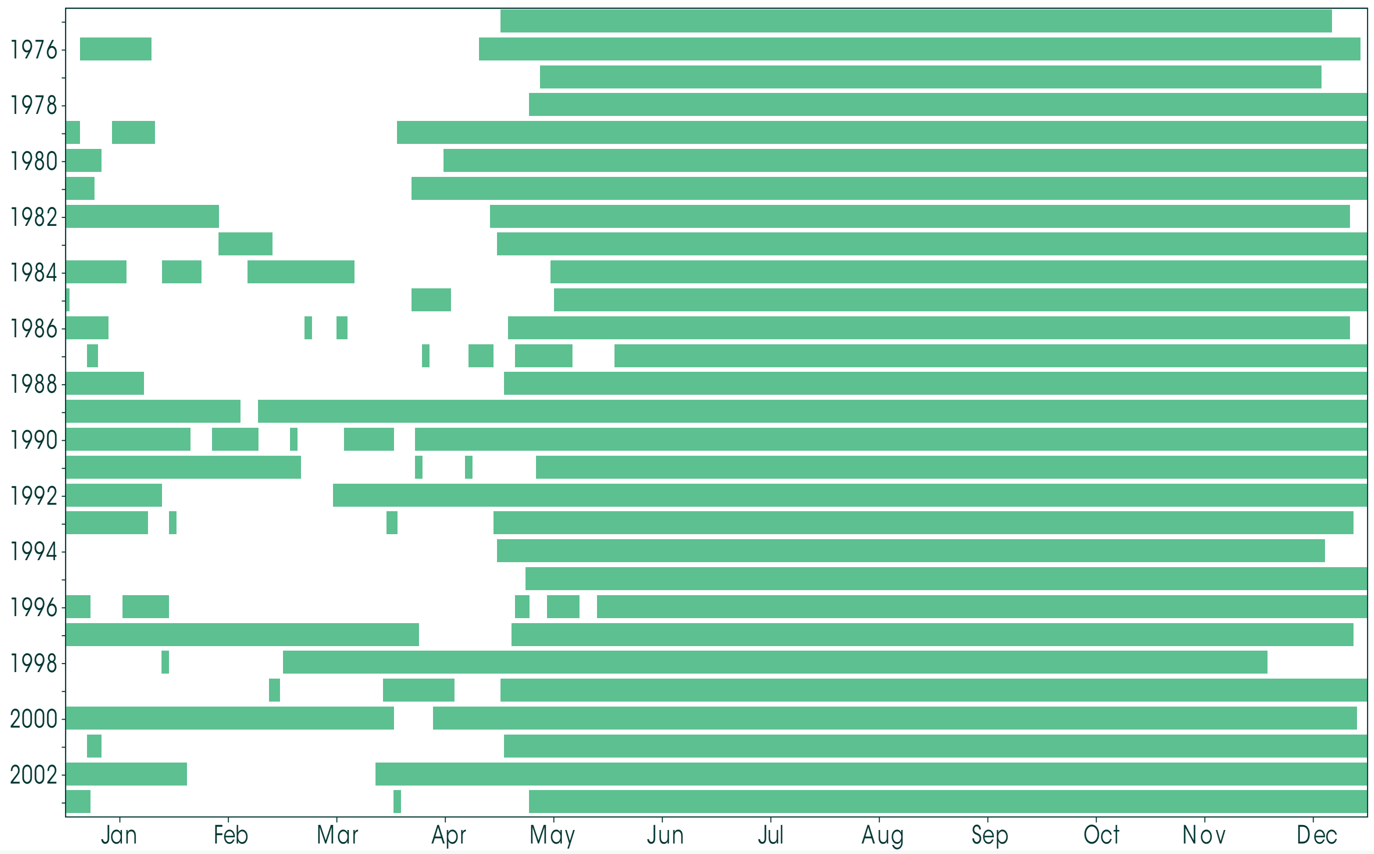


Figure 5

Number of days of zero-flow per year between 1975 and 2003 in Cowaramup Brook

The green bars show when flow in Cowaramup Brook was above zero

2.3 Water resource development

The dominant land use within the Cowaramup Brook catchment is agriculture, with approximately 57 per cent of the total catchment area dedicated to a range of land uses including grazing for cattle (beef and dairy), sheep and deer. There are about 80 farm dams in the Cowaramup Brook catchment, of which the vast majority have a storage capacity of less than 8 ML and are used mostly for stock and domestic purposes (DoW 2009).

This 'self-supply' irrigation industry is characterised by a dependence on water stored in relatively small (on a regional comparison) farm dams. The 13 commercial dams in the catchment store between 10 and 70 ML and have a combined storage of 300 ML (Table 1). These dams are used to irrigate crops such as olives, wine grapes and nuts. The estimated total catchment demand for crops such as these is about 230 ML/year (Table 1).

These numbers suggest the aggregate storage is low compared with crop demand and sufficient only for the next irrigation season (from about December to April). They also indicate the dependence of irrigators on winter runoff and their vulnerability to significant change in rainfall associated with climate change.

There are numerous private bores across the catchment, with the first recorded drilling in 1920. Most private bores are used for livestock and/or domestic or household use but some may be used to irrigate crops. The aquifers are generally low yielding (Marnham et al. 2000).

The on-stream dams are usually completely filled by catchment runoff by mid-May to mid-June, depending on the timing and magnitude of early season rains. Flow gauging and numerical models suggest the dams have a relatively small impact on the magnitude of mid-winter flows (Sinclair Knight Merz 2007). However, models also show that interception of catchment runoff by on-stream dams can reduce the magnitude of summer flows and flows in the seasonal 'shoulder' periods between April and June, and November to January, especially in years of low rainfall.

Table 1

Statistics on commercial* farm dams and water use in the Cowaramup Brook catchment compared with other catchments in the Cape to Cape region

System	Catchment area (km^2)	Mean annual flow (ML)	Runoff (ML/km^2)	Crop irrigation demand (ML/yr)	Number of dams	Storage in dams (ML)	Storage density (ML/km^2)
Wilyabrup Brook	89	23 632	266	1337	66	3102	35
Cowaramup Brook	30	3356	112	227	13	300	10
Margaret River	487	84 707	174	2785	43	1733	4
Chapman Brook	184	54 687	297	1326	56	2297	12

* Data assumes that commercial farms dams are those with a storage capacity of greater than 8 ML.

2.4 Ecological values of Cowaramup Brook

The Cowaramup Brook catchment has been greatly altered, primarily as a result of agricultural development (CCG 2008). Large sections of the brook are unfenced and stock have access to the brook channel. This has resulted in the degradation and loss of native riparian vegetation, invasion of the riparian areas by weeds, erosion and destabilisation of the river banks. In these areas much of the fringing vegetation is either absent or has been severely degraded. The riparian vegetation in many areas of the brook consists of an overstorey of mature trees (peppermints and marri) with little or no native understorey. In the lower reaches, the brook runs through National Park and shire reserve and the riparian vegetation is largely healthy and in relatively good condition (CCG 2008).

The existing environmental attributes and ecological values of Cowaramup Brook were described by WRM (2007, 2008a) and the CCG (2008). The ecological values of Cowaramup Brook and the relationships between flow and ecological values are discussed in the following sections. These sections draw heavily on the work described in the cited reports. For detailed information about the life-history characteristics of flora and fauna species, their degree of water dependence, management options and other general biological information, please refer to these reports.

2.4.1 Vegetation

Native vegetation in and downstream of the EWR study reach (see Section 3.2) is generally in excellent condition (Hanran-Smith 2004). The dominant trees in the reach are karri (*Eucalyptus diversicolor*), marri (*Corymbia calophylla*) and peppermint (*Agonis flexuose var. flexuose*) over a diverse understorey comprised of soapbush (*Trymalium floribundum*), karri oak (*Chorilaena quercifolia*), various wattle species (including *Acacia divergens, A. myrtifolia, A. pulchella, A. scalpelliformis, A. subracemosa* and *A. urophylla*), hibbertia (*Hibbertia cuneiformis, H. cunninghanii, H. furfuracea, H. hypericoides*), sedges (*Lepidosperma* spp.), and rushes (*Baumea* spp., *Juncus pallidus*) (CCG 2008). Figure 6 shows an area of riparian vegetation in excellent condition.

Figure 6

Riparian vegetation of Cowaramup Brook

Source: Gracetown Progress Association

A number of orchid species occur in the study reach such as the mantis orchid (*Caladenia attiingens*), cowslip (*C. flava*), funnelweb spider (*C. infundibularis*) and pink fairy orchid (*C. latifolia* and *C. reptans*). Two species of the rare and endangered spider orchid (*C. huegelii* and *C. excelsa*) have been collected from reaches just upstream of the study site. The karri wattle (*A. subracemosa*) and parrot bush (*Dryandra sessilis var. cordata*) both occur at the study site and are listed as priority species (WRM 2007).

Common introduced species in the Cowaramup Brook area include kikuyu (*Pennisetum clandestinum*), weedy rushes (*Juncus microcephalus* and *Isolepis prolifera*), tree ferns (*Sphaeropteris cooperi*) and dock (*Rumex crispus*). There are scattered infestations of blackberry (*Rubis ulmifolius*) and arum lily (*Zantedeschia aethiopica*) (CCG 2008; Hanran-Smith 2004).

Relatively little is known about the magnitude and duration of flows that maintain the health and vigour of riparian vegetation. Environmental factors that influence plant vigour and are affected by river flow include bank soil moisture, the proximity of groundwater to the root zone and the duration and timing of flood events. In Australian riparian zones, the greatest numbers of plant species germinate during autumn under water-logged conditions, while the least number of species germinate during summer (Britton & Brock 1994).

Research has shown that seed set, seedling establishment and recruitment for tree species such as flooded gum (*E. grandis*), swamp paperbark (*Melaleuca ericifolia*) and modong (*M. preissiana*) are closely tied to flow events. For example, germination and survival of seedlings can be influenced by infrequent winter high flows, which pick up seeds and move them to open areas in full sunlight. Year-old tree seedlings often do not survive if they are inundated again in their first winter after germination (Pen 1999).

2.4.2 Aquatic invertebrates

A number of studies have been undertaken on the aquatic invertebrate fauna of Cowaramup Brook (e.g. Morgan & Beatty 2005; WRM 2008a). As part of this study the macroinvertebrate community was sampled in the autumn and spring of 2007 (WRM 2008a). This sampling collected 44 taxa of macroinvertebrates, of which 34 were insects from the orders Ephemeroptera (four taxa), Odonata (four taxa), Coleoptera (five species), Trichoptera (three taxa) and Hemiptera (one taxa). The dipterans were the richest group, in which 14 taxa of Chironomidae were collected, along with representatives of the families Ceratopogonidae, Empididae and Tipulidae.

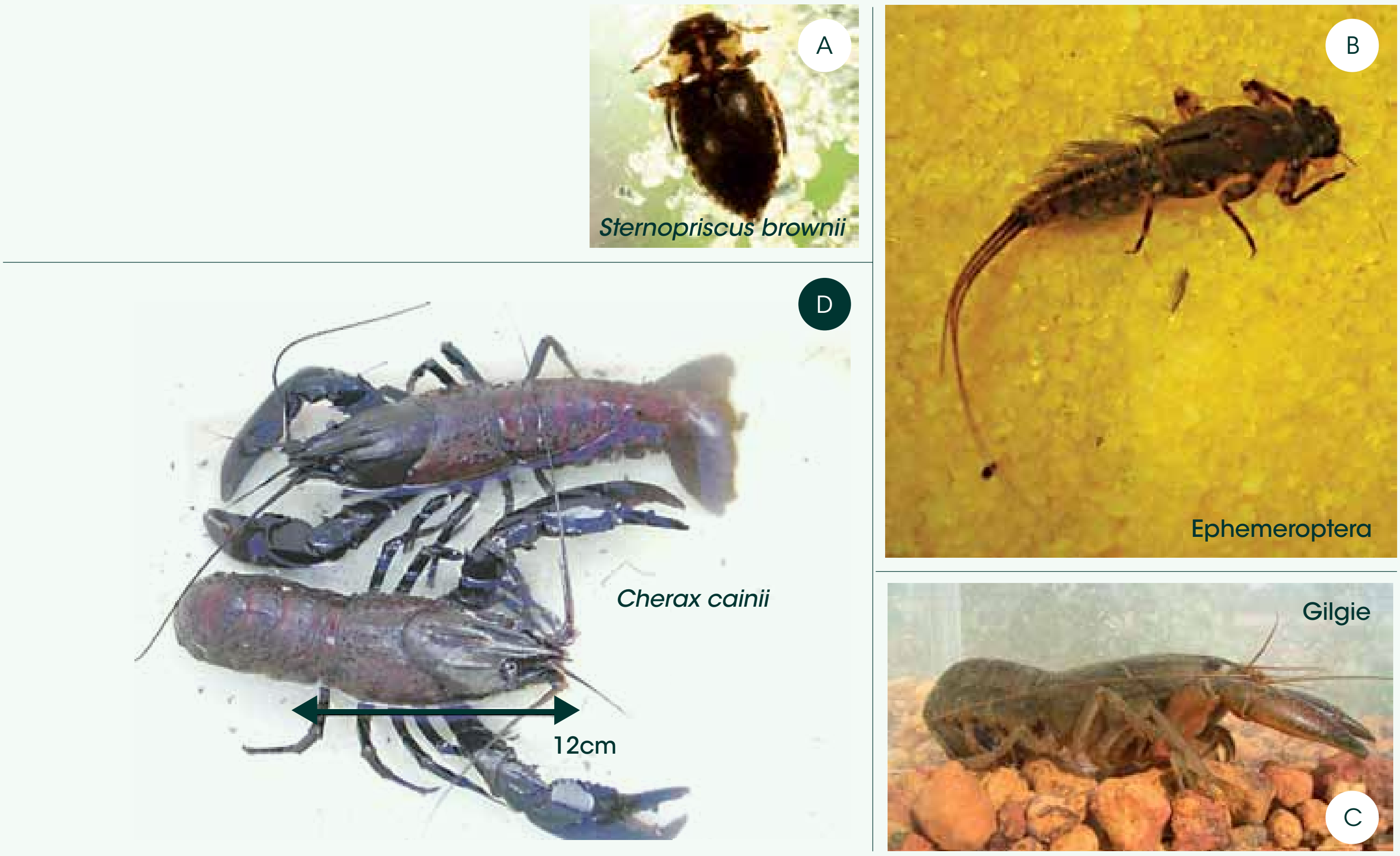


Figure 7

Macroinvertebrates of Cowaramup Brook

Source: (A, B, C) Wetland Research and Management (WRM). (D) John J.S. Bunn.

Four species are endemic to Western Australia's south-west. A list of the macroinvertebrate taxa collected from Cowaramup Brook is provided in Appendix 1.

There are five species of freshwater crayfish known to occur in the rivers of the state's south-west. Morgan and Beatty (2005) found smooth marron (*Cherax cainii*) and gilgie (*C. quinquecarinatus*) at sample sites on Cowaramup Brook. All sites sampled by Morgan and Beatty (2005) were considered to offer excellent stream habitat and shade for freshwater crayfish.

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

Spring and summer spawning is a common life-history characteristic of aquatic invertebrates in Western Australia's south-west. Few species breed in winter, in more than one season, or year-round. It is therefore important that adequate spring and summer flows be considered in developing an EWR flow regime.

Studies have found stream permanence to be an overall determinant of the abundance and diversity of aquatic invertebrate fauna (e.g. Bunn et al. 1986 & 1989). Most aquatic invertebrates do not have physiological or life-history strategies that allow them to survive seasonal drying. As adults, many insects are capable of flying to neighbouring waterbodies. Some invertebrates are capable of burrowing into moist sediments to avoid desiccation, including oligochaetes and gilgies. Gastropods, cladocerans, copepods and ostracods have some desiccation-resistant stages in their life cycle (usually as an egg) and may undergo diapause during summer.

Figure 8

The Swan River goby

Source: Department of Environment and Conservation

Ephemeral and permanent streams both have distinctive aquatic faunal communities (ARL 1989; Storey et al. 1990). Some invertebrates are found only in intermittent streams (Bunn et al. 1989), while other species show large differences in numbers in permanent compared with intermittent streams (Bunn et al. 1986). When developing an EWR flow regime for rivers in the south-west, it is important to consider the seasonality of the natural flow regime, including periods of no-flow.

2.4.3 Fish

The only native fish species to be found in Cowaramup Brook is the Swan River goby (*Pseudogobius olorum*) (A. Storey pers. obs.). Gobies are fish that have adapted to fast-flowing water and have an excellent climbing ability, due to modifications to their pectoral fins. The Swan River goby does not have physiological adaptations to withstand desiccation, and relies on the presence of permanent water.

Cowaramup Brook does not support populations of native fish such as pygmy perch (*Edelia vittata*) and western minnow (*Galaxias occidentalis*) or other species that are found in good numbers in nearby streams. The reasons for this are not understood. Cowaramup Brook seems to have some habitat for native fish in its lower reaches, including deeper shaded areas and riffles, and vertical structure to habitats with woody debris and in-stream vegetation. It also contains micro-crustaceans and other invertebrates that form a large part of the Swan River goby's diet in other systems.

Most native species are adapted to harsh conditions of high temperatures and low oxygen; yet they do require permanent pools as summer refugia. None have adapted to survive desiccation. The brook may at one time have had deeper permanent pools and supported native fish. However, with reduced flows and sedimentation, Cowaramup Brook no longer has deep pools that are reliably permanent and essential to the survival of native species.

Farm dams provide permanent water and can provide summer refugia for native fish. In Cowaramup Brook, however, the dams support large populations of mosquitofish (*Gambusia holbrooki*) (R. Donohue pers. obs.; Morgan & Beatty 2005; WRM 2008b). Large numbers of mosquitofish result in a high incidence of fin nipping of native species (Morgan et al. 1998) and they are known to generally out-compete native fish, especially in degraded systems with altered flow regimes (WRM 2008a). Given that many of these problems are manageable, it seems prudent to consider the flow requirements of native fish in developing an EWR to support future restoration activities (CCG 2008). Pusey et al. (1989) suggested, for example, that natural winter spates can reduce mosquitofish populations and allow coexistence with small native species with similar habitat and dietary requirements.

The breeding biology of native fish has evolved to synchronise closely with the seasonality of rainfall and flow in the south-west. Some species, such as pygmy perch, undertake upstream breeding migration (Pen 1999) initiated by a combination of change in day length, water temperature and flow rate. At this time, sufficient depth of water is required to drown out obstacles and allow for access to upstream spawning habitat. Many native fish species undertake upstream migrations in winter and spring for breeding. With the onset of winter flows around June or July, fish move upstream from summer pools to small side tributaries to spawn on flooded vegetation and submerged reed beds.

There are many obstacles that can impede the upstream migration of fish, such as steep gradients, logs, rock bars, road culverts, weirs and dams. Natural flow regimes include periods of high flows that submerge obstacles, allowing fish to move upstream. Such spells should last at least several hours to allow upstream migration of fish. Presumably, a series of winter high spells is required for fish to navigate upstream in a reach containing a series of barriers, such as a sequence of pools and riffles.

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

Flows are required for maintaining water depths that inundate trailing and aquatic riparian vegetation – a favoured spawning habitat for some native fish species. Flooded vegetation and shallow, flooded off-river areas also provide sheltered, low-velocity nursery areas for growing juveniles. Flooding in winter and spring must be maintained to ensure breeding success and strong recruitment. The duration and frequency of inundation of trailing and fringing vegetation can influence recruitment success. For example, if water levels fall too soon, or fluctuate greatly, fish eggs may be left above the water line and may dry out. Less successful recruitment may occur in years when reed beds and trailing vegetation are inundated for periods of less than five consecutive weeks. Poor recruitment years occur naturally during periods of low rainfall. However, if conditions that are likely to result in poor recruitment occur more than three years in a row, this may lead to a population age structure skewed towards older individuals.

2.4.4 Amphibians

No specific studies of frogs associated with Cowaramup Brook were found during an extensive literature review (WRM 2007). Western Australia's south-west has approximately 26 species of frog, of which about 20 occupy moist environments adjacent to wetlands and streams. Species recorded in the area include the banjo frog (*Limnodynastes dorsalis*), slender tree frog (*Litoria adelaidensis*), quacking frog (*Crinia georgiana*), Glauert's froglet (*Crinia glauerti*) and the moaning frog (*Heleioporus eyrie*) (WRM 2007).

The breeding requirements and tadpole ecology of these and other species likely to occur in the study area are listed in Table 2. Most species require surface water for egg-laying and then for up to six weeks while tadpoles develop into adult frogs. Frogs tend to be unspecialised opportunistic feeders, eating mainly insects as adults while tadpoles tend to graze on algae.

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

Quacking frog

Moaning frog

Slender tree frog

Glauert's froglet

Western banjo frog

Figure 9

Amphibians of Cowaramup Brook

Source: Department of Environment and Conservation

Table 2

Habitat and breeding biology of frogs likely to occur in the Cowaramup Brook area
Information sourced from Cogger (2000) and Tyler et al. (2000)

Species	Habitat	Spawning	Tadpole ecology
Quacking frog (*Crinia georgiana*)	Swampy areas along streams which are inundated in winter.	**Period:** July to October. **Site:** Large and separate laid in shallow seep water or wet ground that will soon be flooded.	**Habitat:** Tadpoles show lotic adaptions. **Maturation:** 45 days.
Glauert's frog (*Crinia glauerti*)	Permanent moist areas at the edges of swamps and streams.	**Period:** Mid-winter to spring following rain. **Site:** Lays in shallow water or on moist surface. Eggs sink to bottom.	**Habitat:** Swamps and static areas at the edge of streams. **Maturation:** >90 days.
Moaning frog (*Heleioporus eyrei*)	Swampy areas on sandy soils.	**Period:** Winter **Site:** Eggs laid in burrows excavated in sandy soils.	**Habitat:** Not known. **Maturation:** Not known.
Banjo frog (*Limnodynastes dorsalis*)	Vegetation adjacent to permanent water. Inhabits burrows during dry periods.	**Period:** Winter to spring. **Site:** Eggs in foam mass on surface of static or slowly flowing water.	**Habitat:** Not known. **Maturation:** Not known.
Slender tree frog (*Litoria adelaidensis*)	Dense vegetation in the margins of wetlands and slowly flowing streams.	**Period:** Early spring. **Site:** Eggs in mass attached to vegetation often just below the water surface.	**Habitat:** Wetlands and slowly flowing water. **Maturation:** Not known.

2.4.5 Reptiles

Local community members and Department of Environment and Conservation (DEC) staff have recorded a number of reptile species in the brook's vicinity. Reptiles known to occur in the area that rely on aquatic and riparian food webs include the tiger snake (*Notechis scutatus*), King's skink (*Egernia kingii*) and bobtail skink (*Tiliqua rugosa*). The tiger snake is common in the region and is often encountered along rivers, especially in the swampier reaches where it hunts for frogs. It readily takes to water in warm weather and is a strong swimmer. The western glossy swamp skink (*Egernia luctuosa*) inhabits dense ground cover on the margins of swamps, lakes and streams, while the western three-lined skink (*Acritoscincus trilineatum*) can be regarded as semi-aquatic in that it tends to inhabit areas of damp soil (Cogger 2000).

Many reptiles are associated with permanent and seasonal waterbodies, as these habitats provide a water source and a diverse array of prey species. However, the impact on reptile species of changes in the availability of fresh water in Western Australia's south-west has not been studied, and there is little published information on reptile species' tolerance to changes in the availability of water in other geographic regions. In the absence of specific information, it is assumed that terrestrial reptiles depend on elements of the flow regime that maintain riparian vegetation and habitat, as well as ecological processes that protect aquatic biodiversity and biomass. It is also important for the survival of reptile species that permanent pools are maintained as a source of water and food during the dry summer months. Figure 10 shows some of the reptiles likely to be found in the Cowaramup Brook area.

Tiger snake

King's skink

Bobtail skink

Figure 10

Reptiles of Cowaramup Brook

Source: (A,B) Department of Environment and Conservation

2.4.6 Waterbirds

No specific studies on the waterbird fauna of Cowaramup Brook have been undertaken (WRM 2007). However, the DEC, Gracetown Progress Association and Birds Australia have some records of bird sightings. Waterbird species that have been observed frequently in the region include Australian shelduck (*Tadorna tadornoides*), Australian wood duck (*Chenonetta jubata*), Pacific black duck (*Anas superciliosa*), white-faced heron (*Egretta novaehollandiae*), straw-necked ibis (*Threskiornis*

Pacific Black Duck

Hooded Plover

Australian Wood Duck

Australian Shelduck

White Faced Heron

Figure 11

Waterbirds of Cowaramup Brook

Source: Department of Environment and Conservation.

spinicollis), red-capped plover (*Charadrius ruficapillus*), hooded plover (*Thinornis rubricollis*) and the sacred kingfisher (*Tordirhamphus sanctus*).

Other waterbirds that have been observed less frequently, or are thought to occur within the study area, are the mallard duck (*Anas platyhychos*), white-necked heron (*Ardea pacifica*), nankeen night heron (*Nycticoraz calendonicus*), glossy ibis (*Plegadis falcinellus*), royal spoonbill (*Platalea regia*), yellow-billed spoonbill (*P. flavipes*) and the blue-billed duck (*Oxyura australis*) (WRM 2007). Figure 11 shows some of the waterbirds observed in the areas surrounding Cowaramup Brook.

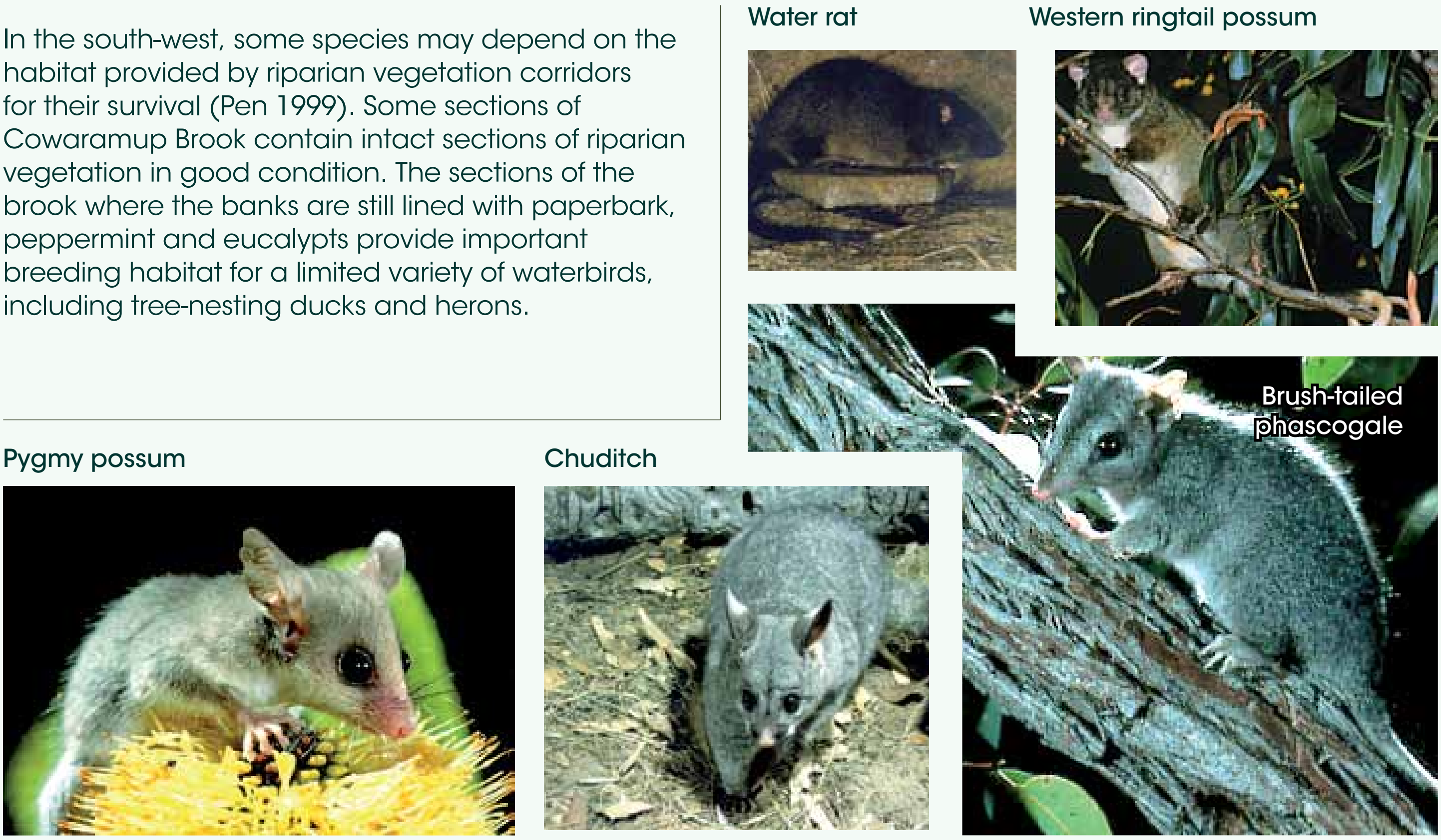
Perhaps more than any other group of vertebrates, the ecology and habitat requirements of waterbirds must be considered at the landscape scale. River habitats are of only marginal value to most of the south-west region's waterbirds (Pen 1999), although many bushland birds use riverine habitats for nesting and as a source of water and food.

In the south-west, some species may depend on the habitat provided by riparian vegetation corridors for their survival (Pen 1999). Some sections of Cowaramup Brook contain intact sections of riparian vegetation in good condition. The sections of the brook where the banks are still lined with paperbark, peppermint and eucalypts provide important breeding habitat for a limited variety of waterbirds, including tree-nesting ducks and herons.

In the absence of species-specific information on water-dependency, it is assumed that waterfowl associated with Cowaramup Brook depend on the health of riparian vegetation, regular inundation of the floodplain and its wetlands, and the ecological processes that maintain food webs and aquatic species diversity.

2.4.7 Mammals

No studies specifically detailing the mammal fauna of Cowaramup Brook were found during a search of the literature. The riparian zone of the nearby Wilyabrup Brook is a known habitat for brushtail possum (*Trichosurus vulpecular*), western ringtail possum (*Pseudocheirus occidentalis*), brush-tailed phascogale (*Phascogale tapoatafa*), chuditch (*Dasyurus geoffroii*), water rat (*Hydromys chrysogaster*) and pygmy possum (*Cercatetus concinnus*) (Jury 2006).



Water rat

Western ringtail possum

Brush-tailed phascogale

Pygmy possum

Chuditch

Figure 12

Mammals found in the Cowaramup Brook region

Source: Department of Environment and Conservation.

A number of the mammal species inhabiting the region rely on the riparian vegetation community both as habitat and food source. The brush-tailed phascogale, southern brown bandicoot or Quenda (*Isoodon obesulus*), western ringtail possum and brushtail possum have all been seen in the Cowaramup Brook area (CCG 2008). These mammals rely on dense vegetation and the availability of hollow-bearing trees, which often occur near rivers and streams. Quenda only occur in areas with dense covering vegetation, such as the margins of wetlands, banksia woodland and jarrah forest. The western grey kangaroo (*Macropus fuliginosus*) has also been seen in the riparian areas of the brook (CCG 2008).

Cowaramup Brook is within the known range of the water rat (*Hydromys chrysogaster*), which is found in rivers, swamps, lakes and drainage channels. Water rats have broad, partially-webbed hind-feet, water-repellent fur, and a thick tail. They are completely dependent on the presence of water to the extent that they are known to suffer heat stress without access to water. They construct nesting burrows in banks that are stabilised by riparian vegetation.

Water rats restrict their movements to shallower waters less than 2 m deep and forage along the shoreline for food such as crayfish, mussels, fish, plants, invertebrates and smaller mammals and birds. Thus they depend on aquatic food webs, the presence of healthy riparian vegetation and the processes that maintain them. The range of water rats has declined in the south-west region due to salinisation and clearing of riparian vegetation (WRM 2007).

2.4.8 Carbon sources and ecosystem productivity

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

Some carbon enters rivers as fine particulate matter derived from upstream terrestrial vegetation. This process requires the connection of downstream and upstream river reaches. However, given the length of Cowaramup Brook, upstream sources are probably not critical to maintaining food webs. A significant proportion of organic matter in south-west streams comes from woody debris that is either washed into the river from the riparian zone or from direct litter fall from overhanging vegetation.

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

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

2.5 Components of the flow regime and their ecological functions

A river channel is a highly dynamic system, with a flow regime that varies seasonally and annually (Figure 13). Different components of the flow have particular ecological functions. For example, high flows scour pools and influence the distribution of sand bars, woody debris, and the complexity and distribution of habitat. As a result, high flows have a direct influence on the structure of aquatic communities and food webs in the south-west region's rivers (Pen 1999). Early-season flows relieve summer stress (high temperatures and low oxygen), provide cues for breeding migrations of native fish, and provide habitat for micro-crustaceans, aquatic insects, waterbirds, and larval stages of some terrestrial insects. Some of the key ecologically-relevant elements of the flow regime in the region's rivers are detailed in the sections below, including periods of no flow, summer low flows, and high winter flows.

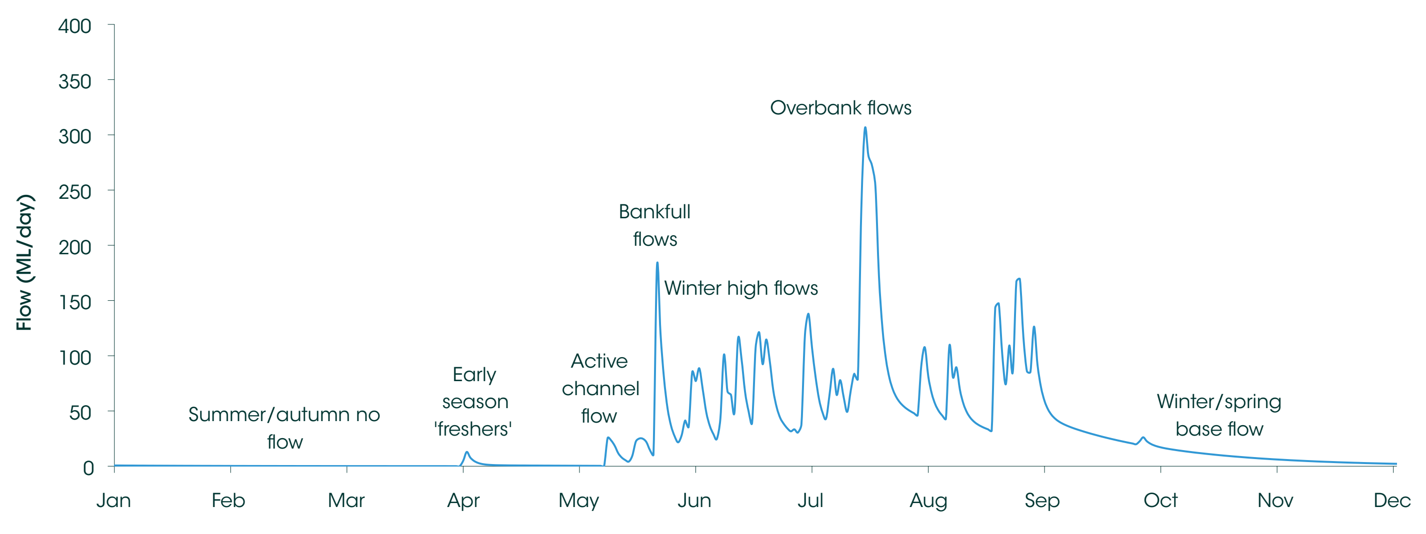


Figure 13

Representative hydrograph with different flow components labelled

2.5.1 Periods of no flow

Many rivers in Western Australia's south-west cease to flow in the dry period between December and April, especially during periods of below-average rainfall when regional groundwater tables fall below the base level of river channels. For example, Cowaramup Brook is typically an ephemeral system, with very low or no flow during much of the dry summer period between December and April.

As seasonal drying is part of the natural flow regime, endemic and other native fauna have adapted to periods when rivers recede to a series of disconnected pools. As a result, native fish have evolved to tolerate the high water temperatures and low oxygen levels that characterise the pools in late summer. Exotic species, such as mosquitofish, are less tolerant of such conditions. In order to survive, aquatic fauna move from ephemeral tributaries and upstream reaches to river pools or perennially-flowing lower reaches of rivers. Permanent pools form critical habitat in ephemeral reaches of rivers, especially in ephemeral streams (Pen 1999). Many of the more permanent pools in Cowaramup Brook have been lost due to climate change and reduced flows and sedimentation caused by clearing and erosion (CCG 2008).

To maintain the adaptive capacity of native species to variations in rainfall and flow, the EWR flow regime must include the periods of no flow that are part of the historic flow regime. These periods also help to control populations of non-native species such as mosquitofish.

2.5.2 Summer low flows

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

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

2.5.3 Autumn and winter low flows

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

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

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

2.5.4 Active channel flows

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

The low-flow channel is maintained by winter flows that have sufficient energy, frequency and duration to regularly scour banks. It is also known as the active channel, because the flows that maintain an open channel occur in most years and the channel is therefore actively eroding (Pen 1999).

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

The active channel is often overhung by fringing plants and fringing aquatic vegetation (CCG 2008). The extent of the active channel is not always obvious, but can be seen in places as a line of scoured bare earth within the low-flow channel – below which vegetation is less dense or completely absent. The flows that produce and maintain low-flow channels also tend to be those that inundate overhanging and fringing vegetation, and provide cover for fauna such as macroinvertebrates, as well as spawning habitat for native fish such as pygmy perch (Pen 1999).

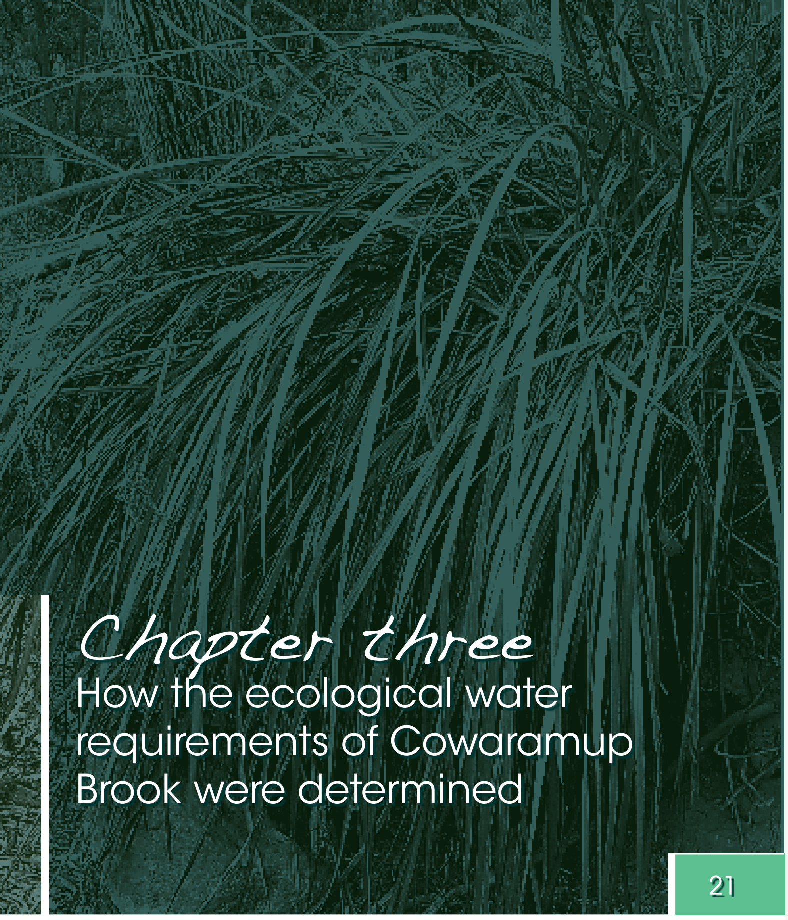
The frequency and duration of active channel flows is related to rainfall patterns. Flow events that reach the top of the active channel occur two or three times a year in south-west river systems (WRC 2001). The duration of active channel flows following rainfall is also influenced by the storage capacity of soils, soil porosity and seepage to channels from (saturated) soil profiles.

2.5.5 Winter high flows

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

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

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



Chapter three

How the ecological water requirements of Cowaramup Brook were determined

3.1 Overall approach

The ecological water requirement (EWR) of Cowaramup Brook was determined using an approach called the Proportional Abstraction of Daily Flows (PADFLOW). PADFLOW was developed to better define the EWR flow regime needed to maintain the ecological values of rivers (at a low level of risk). The approach evolved out of experience with using other methods, such as the 'flow events method' to determine EWRs for rivers (e.g. WRM 2005a, 2005b). The PADFLOW approach 'constructs' an EWR flow regime by removing a proportion of daily flow from an existing flow record. The volume of daily flow abstracted is arrived at with reference to known ecologically important flows.

PADFLOW is based around the use of the River Ecological Sustainable Yield Model (RESYM), which the Department of Water developed to estimate the EWRs of rivers. An expert panel can use RESYM in a workshop setting to assess changes in the frequency and duration of flows in a measured 'natural' flow above ecologically important thresholds compared with that of a modelled EWR flow (e.g. Donohue et al. 2009a, 2009b). For the Cowaramup Brook study, the expert panel included experts in water resource management, channel morphology, vegetation and aquatic ecology (Appendix 2).

The flow chart in Figure 14 shows the steps taken to generate an EWR flow for Cowaramup Brook using RESYM and the PADFLOW approach. Tasks set out from steps 1 to 8 are the same as for the flow events method (e.g. WRM 2005b; Stewardson & Cottingham 2002) and other approaches used in EWR studies in Western Australia (e.g. Davies & Creagh 2000). Steps 9 to 10 are associated specifically with the PADFLOW approach and the modelling process using RESYM.

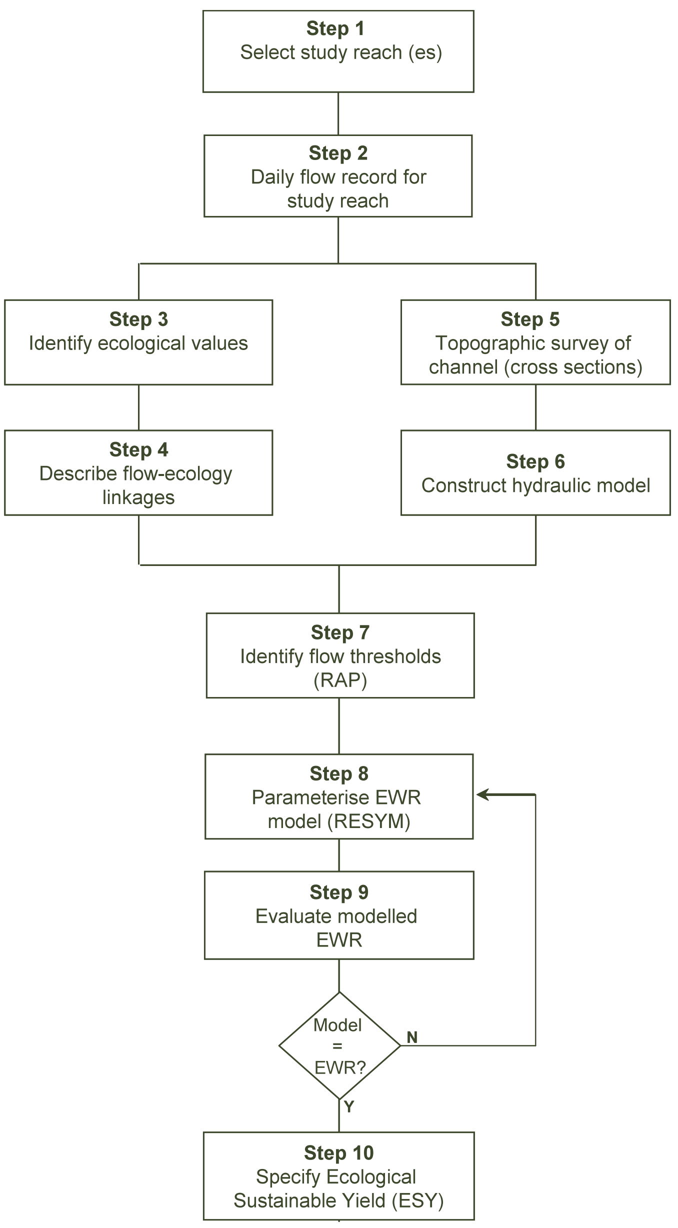


Figure 14

Flow chart showing steps in the proportional abstraction of daily flows method (PADFLOW)

In this report, the term 'EWR flow' will be used to describe the RESYM-generated EWR flow regime. The term 'natural flow' will be used to refer to the historical flow record derived for Cowaramup Brook. The term 'natural' is used here only to differentiate between the modelled EWR data series and the flow data from which the EWR was derived. It should be understood that the 'natural' flow for a large period of time was generated from a regression model with gauged flow data from nearby Wilyabrup Brook (see Section 2.2). In addition, the so-called 'natural' flow includes the impacts of catchment clearing and interception of flows by on-stream dams in both the Cowaramup and Wilyabrup brooks

3.2 Selection of study sites

EWR studies are based on detailed research carried out at particular sites. Study sites are selected to represent the hydraulics and ecology of river reaches. The most important consideration in the selection of a study site is the 'naturalness' of the channel morphology, as it is the channel form that largely determines the magnitude of flows needed to inundate important habitats. Highly modified channels, such as those that have been cleared of vegetation, are often deeply incised and simplified in terms of habitat types (CCG 2008; Pen 1999). Consequently, highly modified reaches are not usually selected for EWR studies because it is often difficult to identity critical hydraulic points and habitat types.

The Cowaramup Brook study site is a 155 m length of river approximately 2.5 km upstream of the township of Gracetown, where the brook runs adjacent to National Park and shire reserves (Figure 1 or Figure 15). Riparian vegetation within the study site has been described as pristine to slightly disturbed (CCG 2008). The morphology of the river channel appears to be intact and representative of the natural condition of the river channel from the study site to the coast. The middle and upper reaches of Cowaramup Brook have been cleared of native vegetation and the river channel is highly modified.

3.3 Development of daily flow record

To model an EWR flow, RESYM requires a daily flow time-series covering a period that represents the variation found in the natural flow regime. There is one streamflow gauging station on Cowaramup Brook at Gracetown (station 610029),

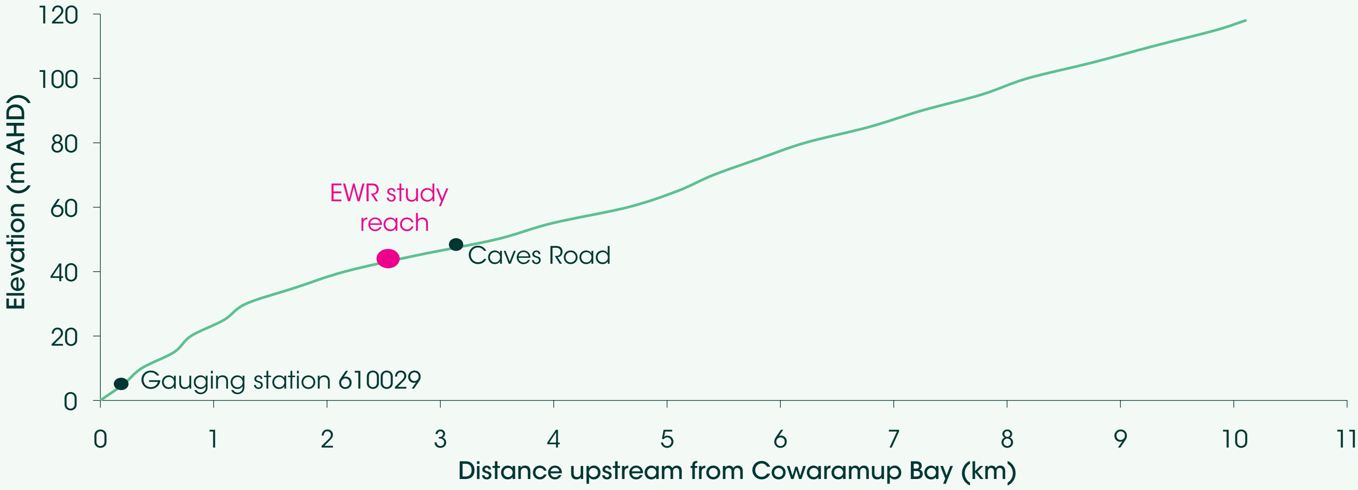


Figure 15

Elevation of Cowaramup Brook from Cowaramup Bay, upstream to its origin which has been operating since November 2004. To generate a longer time-series, a relationship was developed between the Cowaramup Brook data record (November 2004 to July 2006) and a flow record from the Woodlands gauging station on Wilyabrup Brook (station 610006) – a nearby catchment with similar rainfall, soils and vegetation types (Coppolina 2007).

A comparison of the flow data from Cowaramup Brook (610029) and Wilyabrup Brook (610006) between 2004 and 2006 showed the two daily flow records were correlated and closely matched in terms of the magnitude and timing of flow events. Using the Woodlands flow record, flow data was generated for Cowaramup Brook for the period January 1973 to December 2003 (Coppolina 2007).

3.4 Aim of the EWR study

CCG (2008) describes in detail the sort of management actions required to improve the health of Cowaramup Brook in different reaches. It lists stock access, loss of fringing vegetation, weeds and lack of environmental flows as major problems for the brook's health. The impact of dams and abstractions of water on the quantity and timing of flows is of particular concern.

In September 2007, many catchments in the region were proclaimed under the *Rights in Water and Irrigation Act 1914* (WA). This means that water use in the region is now subject to licensing, including water from Cowaramup Brook. In March 2009, the Department of Water released a draft water allocation plan for the region, in which the department undertook to license all current water use (as of September 2007) and to identify the water available for consumptive purposes (if any). It estimated that current use in Cowaramup Brook is about 300 ML/year (DoW 2009, in prep.).

The aim of this study is to support the planning position by identifying if and when water may be available for allocation while meeting the brook's EWR. In keeping with the undertaking to license current use, the environmental objectives are to maintain existing values and where possible provide for restorative activities such as those set out by the CCG (2008).

3.5 Flow-ecology linkages

The fifth stage of the PADFLOW method (Figure 14) involves describing the water depths and related flow rates in Cowaramup Brook that maintain in-stream and riparian vegetation, habitat for aquatic invertebrates, native fish, amphibians, reptiles, waterbirds and mammals, ecological processes (carbon sources) and channel morphology (WRM 2005a, 2005b).

The key ecological objectives considered in the determination of the brook's EWR, and the corresponding depth criteria, are listed in Table 3. The objectives are listed in ascending order of the daily rate of flow required to fulfil the depth criteria.

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 (WRM 2005a, 2005b). However, this value was derived for native fish such as the western minnow and western pygmy perch. The only native fish found in the Cowaramup Brook is the Swan River goby. Gobies are known to have good climbing ability, enabling them to navigate obstacles in shallow water. For this reason, a minimum threshold water depth of 5 cm was considered more appropriate than the 10 cm depth used for other small-bodied native fish species.

The flow criteria listed in Table 3 were used to develop a set of flow-ecology 'rules' that define the components of the flow regime required to maintain the ecological values in Cowaramup Brook. These rules were used as defining criteria for hydraulic modelling carried out to identify the flow rate needed to achieve the ecological depth criteria in Table 3. The process is described in greater detail in Section 3.8.

Table 3

Ecological objectives and flow criteria for Cowaramup Brook.

Ecological objective	Flow criteria	Flow component
Provide summer minimum flow to maintain water levels, water quality and dissolved oxygen levels in pools, and maintain upstream/ downstream connectivity for carbon transfer	Minimum average discharge of 0.01 m/s	Summer low flows
Inundate gravel runs and riffles as summer habitat for aquatic invertebrates	Riffles inundated to a depth of at least 5 cm over 50% of total riffle width	Summer low flows
Inundate gravel runs and riffles as winter habitat for aquatic invertebrates	Riffles inundated to a depth of at least 5 cm over 100% of total riffle width	Winter low flows
Allow upstream migration of gobies	Water depth of at least 5 cm over obstacles	Winter and spring low flows
Inundate aquatic and trailing vegetation as habitat for invertebrates and vertebrates, and as spawning sites for fish and amphibians	Sufficient water depth to begin inundation of low benches	Autumn, winter and spring low flows
Inundate low benches to flush organic matter into river and provide habitat	Sufficient water depth to begin inundation of low benches	Winter high flows
Inundate medium-elevation benches to flush organic matter into river, provide habitat and inundate vegetation	Sufficient water depth to begin inundation of medium-elevation benches	Winter high flows
Maintain active channel morphology and scour pools	Sufficient water levels to fill the depth of the active channel	Winter high flows
Provide overbank flows to inundate floodplain, recharge floodplain wetlands, provide fauna habitat and aid seed dispersal and germination of riparian vegetation	Sufficient water levels to exceed top of bank	Winter high flows (flood event)

3.6 Cross-section survey of the river channel

To construct a hydraulic model of the Cowaramup Brook channel, a topographic survey of the study site was carried out on 21 November 2005, on which the flow rate was an estimated 0.96 ML/day (Step 5 in Figure 14). To characterise the shape and variability of the channel profile along the study site's 155 m, a total of 15 channel cross-sections were surveyed (Figure 16). The cross-sections were taken at key hydraulic and ecological features such as rock bars, backwaters, pools, riffles, large woody debris and channel constrictions. Figure 17 shows a schematic of how the locations of cross-sections were selected and point data collected on each cross-section.

To allow for the calibration of the hydraulic model described in Section 3.7 below, discharge measurements were taken during the surveys and related to measured water depths on the cross-sections. The cross-sectional profiles of the river channel are shown in Appendix 3.

3.7 Construction of hydraulic model

The cross-sections from the study site were used to construct a hydraulic model of the river channel using the US Army Corps of Engineers' Hydrologic Engineering Center's River Analysis System (HEC-RAS). Observed relationships of discharge to stage height were used to calibrate the model. A diagram of the hydraulic model created for the Cowaramup Brook study site is shown in Figure 18.

Figure 16

Location of the 15 surveyed cross-sections in the Cowaramup Brook study site

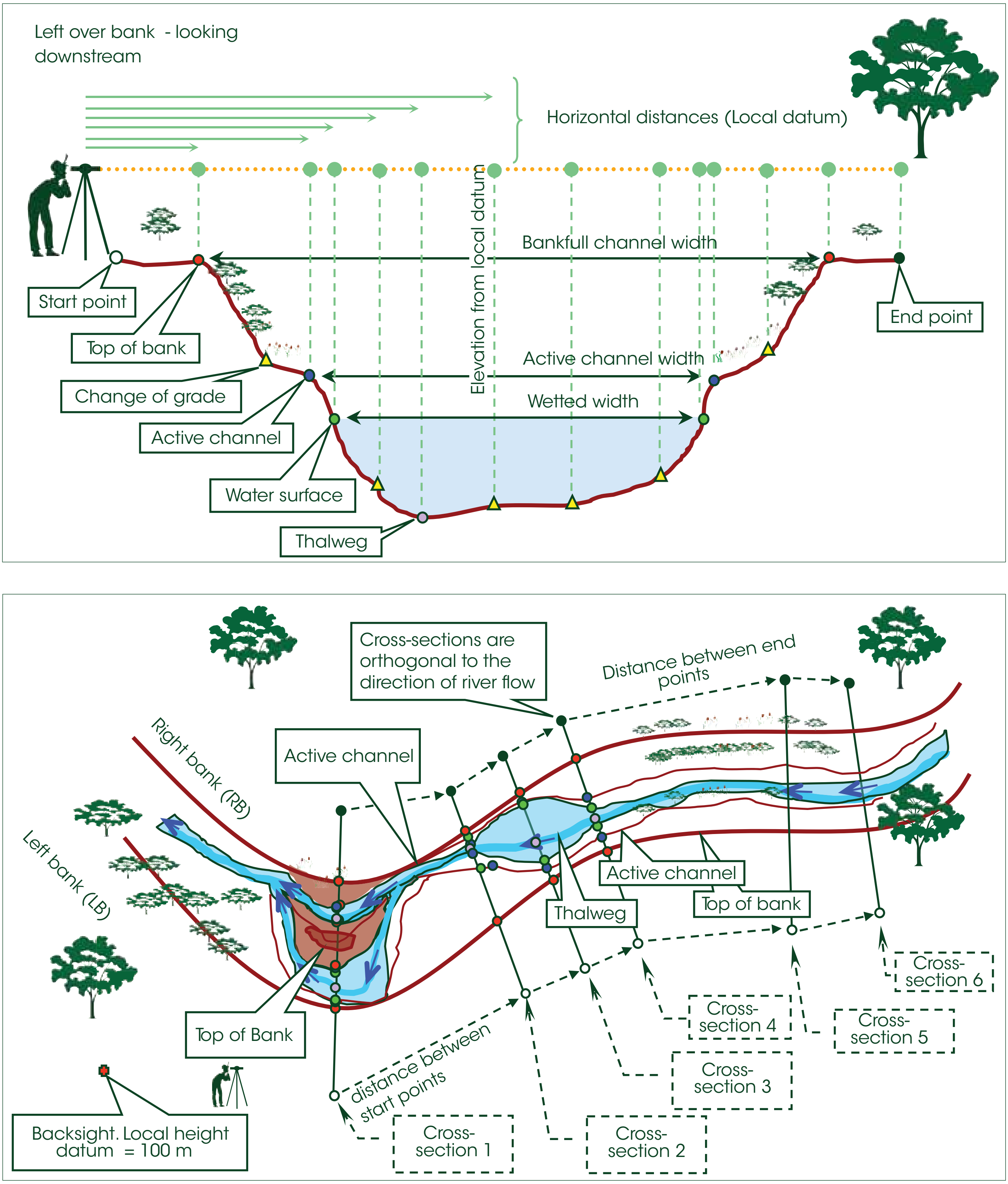


Figure 17

Schematic diagram of a river reach

The upper diagram shows the point data surveyed as part of a cross-section. The lower diagram shows the longitudinal layout of cross-sections along a river reach.

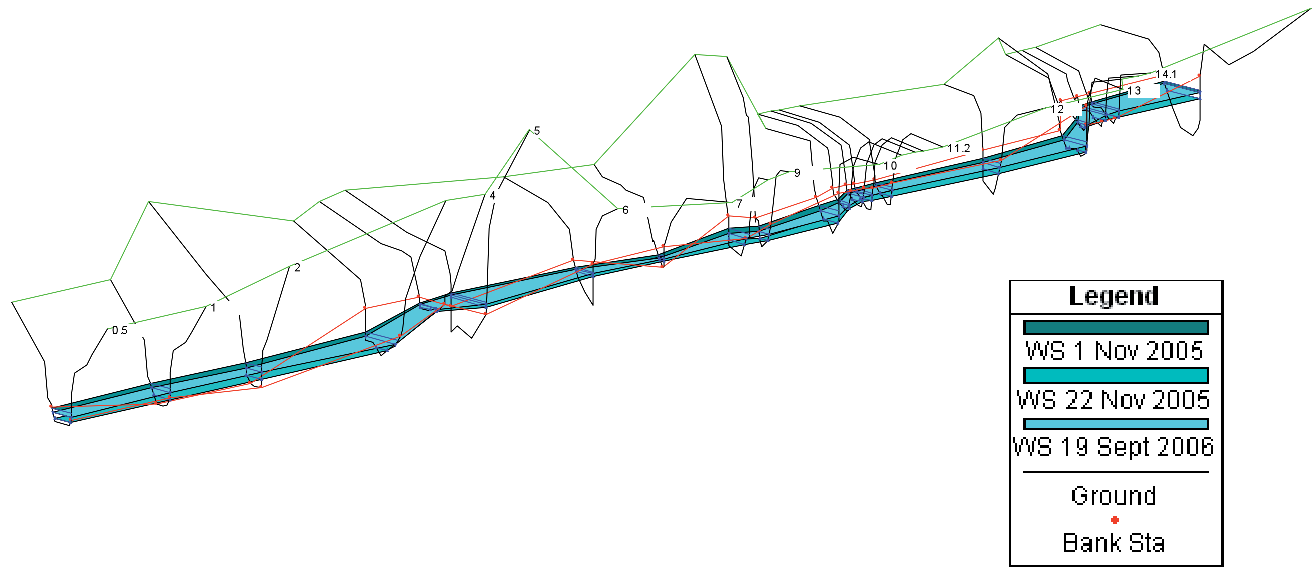


Figure 18

Structure of the HEC-RAS hydraulic model for the representative study reach in Cowaramup Brook.

The blue trace shows the water level at the time of the channel surveys.

Figure 19 shows the longitudinal profile of the study reach. Thalweg depth (measured as the deepest part of the river channel in each cross-section) dropped by approximately 0.8 m over the length of the study site. As the profile suggests, cross-sections 4, 11 and 14 were located on points of the brook's channel that control upstream water depth. The high part of the channel at cross-section 4, for example, 'controls' water depth at points on cross-sections 5 and 6 (see Figure 20 for visual representation). The shallowest points in the study reach were between 0.1 and 0.2 m deep with a flow rate of 0.96 ML/day.

Cross-sections 5, 6, 8, 12 and 15 were located on the channel where water depth is controlled by either points downstream (channel pools) or by flow rate in areas with a relatively steep gradient. The deepest surveyed points within the channel (with respect to water level at the time of the survey) were in the pools located at cross-sections 15 (0.8 m depth), 5 (0.7 m depth) and 12 (0.5 m depth). Assuming these data are representative of the reach, an average of one pool in every 50 m stretch of channel can be expected; and at a flow rate of around 1 ML/day, these pools would be between about 0.5 and 0.8 m deep (Figure 19). When the brook ceases to flow in summer, pool depth would decrease to between only 0.2 and 0.6 m deep. This suggests that pools are probably not a reliable summer refuge for aquatic fauna in this reach of the brook.

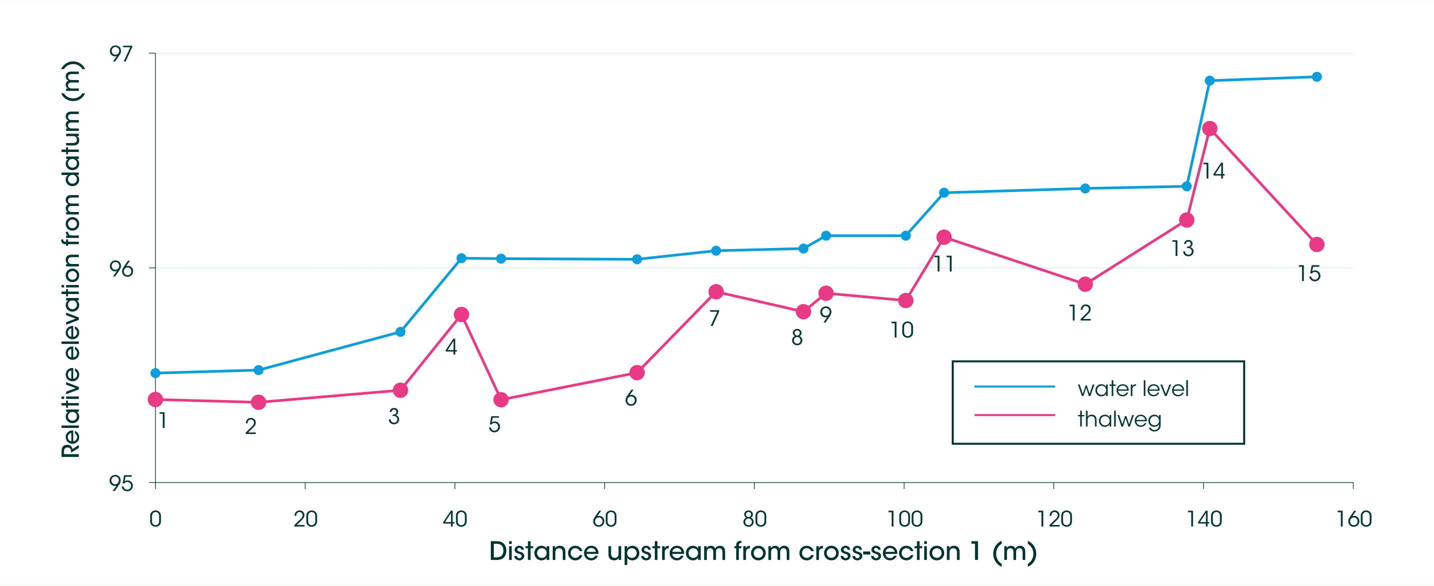


Figure 19

Longitudinal profile of the Cowaramup Brook study reach

The profiles show a series of pools separated by riffles. The thalweg is the deepest continuous line along a river channel and represents the flow path during very low summer flows.

Figure 20

Photograph showing the rock bar at cross-section 11, which is controlling water depth (with flow) in the pool upstream (cross-section 12)

The depth of water at the thalweg over the rock bar was 0.2 m at a flow rate of 0.96 ML/day.

3.8 Identification of flow thresholds

The River Analysis Package (RAP) model was used by Wetland Research and Management (WRM) to identify the flow rates required to achieve the ecological objectives set out in Table 3 (Step 7 in Figure 14) (WRM 2008b). The hydraulic model (HEC-RAS) developed in Step 6 of the PADFLOW process (Figure 14) was used in RAP to determine the relationships between channel geometry, flow rate and water depth at various points of the Cowaramup Brook channel. Depending on the flow-ecology rule applied, such features could include rock bars, benches, pools, riffles or the height of riparian vegetation.

The RAP output includes 'rating curves', which graphically relate changes in discharge to changes in water depth or the wetted width of channel at one or a combination of cross-sections based on user-defined 'queries' of the model (WRM 2008b). Appendices 4 to 6 show the flow rates (as water levels on the cross-sectional profiles) required to inundate various features such as channel benches, the elevation of the top of the bank and riparian vegetation.

Table 4

Ecologically critical flow rates for Cowaramup Brook

Flow-ecology rule	Threshold flow		Ecological functions
	m^3/s	ML/day	
Water depth of 5 cm over 50% of width of riffle runs	0.01	0.9	Provide summer habitat for macroinvertebrates.
Minimum flow velocity of 0.01 m/s	0.02	1.7	Maintain water quality and dissolved oxygen levels in pools. Downstream carbon movement maintained by connectivity between pools.
Water depth of 5 cm over entire width of riffle runs	0.04	3.5	Provide winter habitat for macroinvertebrates.
Inundate low benches	0.04	3.5	Flush organic matter into river system. Inundate trailing vegetation, providing fish cover and spawning sites.
Minimum thalweg depth of 5 cm at shallowest cross-section	0.06	5.2	Allow upstream spawning migration of Swan River gobies.
Inundate medium benches	0.12	10.4	Flush organic matter into river system. Inundate trailing and emergent vegetation. Provide spawning habitat.
Inundate active channel	0.33	28.5	Scour and maintain low-flow channel. Prevent incursion of terrestrial vegetation. Flush organic matter into river system.
Inundate floodplain	3.27	282.5	Inundate and recharge floodplain wetlands. Maintain floodplain wetland nursery areas for fish and tadpoles. Inundate channel and floodplain riparian vegetation. High-energy flows to scour pools and maintain channel morphology.

The ecologically critical threshold flow rates (in ML/day) for Cowaramup Brook that achieve the ecological (depth) objectives listed in Table 3 are summarised in Table 4. The flow rates are thresholds that achieve the particular objectives specified in Table 3. It should be noted, however, that each flow threshold may fulfil multiple ecological objectives including some at flows below the threshold, as well as other ecological outcomes not specifically considered in this study.

The threshold flows described in the following sections are those that satisfy the ecological objectives listed in Table 3.

3.8.1 Summer no-flow period

To maintain the natural permanency of Cowaramup Brook, an ecologically critical flow rate of 0 ML/day (0 m^3/sec) was used to classify periods of no-flow.

3.8.2 Summer minimum flow

To maintain pool water quality and fish diversity following summer dry periods, a minimum average bulk water velocity of 0.01 m/s in pools is recommended. This is the minimum water velocity required to prevent stratification and maintain dissolved oxygen at more than 4 mg/L (WRM 2008b). Summer flows also maintain permanent pools that are an important summer refuge habitat for native fish and aquatic invertebrates, and provide a source of water and food for a variety of riparian vertebrates.

To calculate the flow rate needed to maintain habitat quality in pools, only those cross-sections across river pools (cross-sections 2, 5, 6, 8, 12 and 15) were included in the hydraulic analysis (WRM 2008b). The flow required to achieve a mid-pool water velocity of 0.01 m/s was:

- 1.7 ML/day (0.02 m^3/s).

3.8.3 Macroinvertebrate habitat

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

To maintain the value of riffles as habitat, RAP was parameterised so that the hydraulic model would determine the flow rate (in ML/day) that would inundate:

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

These calculations were done using cross-sections 3, 4, 11 and 14, which were all located on riffles (Figure 19). The mean total width of the riffle habitat at these cross-sections was 1.84 m in summer and 3.6 m in winter. Based on the hydraulic model's predictions, the instantaneous flow rate required to inundate the riffle habitat to a depth of 5 cm was:

- 0.9 ML/day (0.01 m^3/s) to inundate 50 per cent of the riffles in summer
- 3.5 ML/day (0.04 m^3/s) to inundate 100 per cent of the width of the riffles in winter.

3.8.4 Inundation of low and medium benches

A number of ecological objectives are satisfied by inundating benches, including flooding of emergent macrophytes and inundation of aquatic and trailing vegetation (which is good habitat for fauna such as frogs and invertebrates). These flows also wash woody debris into the river, providing structure for habitat and organic carbon to fuel primary and secondary production and support species diversity and food webs (WRM 2008b).

In the Cowaramup Brook study reach, low-elevation benches were surveyed at cross-sections 3 and 8 (Appendix 3). Two medium-elevation benches were surveyed at cross-sections 9 and 14 (Appendix 4).

The flow required to inundate low-elevation benches was determined by identifying the increase in area of channel with a slope of less than 1:100. This defines channel features with a low gradient (i.e. benches) as opposed to steep banks. Using the rule of a slope (of 0.01) identified the flow at which there was a rapid increase in flooded area for a small increase in flow – due to the low-gradient benches being inundated (WRM 2008b).

This change in wet perimeter approach did not work for medium-elevation benches, probably due to the higher lateral gradient at the elevation of the benches in the channel. The flow required to inundate medium-elevation benches was determined using the hydraulic model to calculate a flow rate that would fill the channel to an elevation where the benches became inundated at each cross-section (WRM 2008b). The threshold flow was calculated as the average flow for the two cross-sections.

Benches in the Cowaramup Brook channel were inundated using the rules:

- for low-elevation benches, the flow where the rate of increase in wet width was ≥ 100 times the increase in water level
- for medium-elevation benches, the average of the flow rates that inundated medium benches at cross-sections 9 and 14.

The flows needed to inundate channel benches along the study site were:

- 3.5 ML/day (0.04 m^3/s) for low-elevation benches (Appendix 4)
- 10.4 ML/day (0.12 m^3/s) for medium-elevation benches (Appendix 5).

3.8.5 Upstream migration of native fish

The water-level criteria for upstream migration of the Swan River goby, the only native fish found in Cowaramup Brook, was a minimum depth of 5 cm over barriers and shallow sections (WRM 2008b). It is considered that this flow is probably adequate for other native species also. The key period for this flow is the winter breeding period between June and November.

To determine the threshold flow for upstream migration of small fish, RAP was programmed to identify the flow that would:

- maintain a minimum depth of 5 cm over the shallowest cross-section in the reach – a rock bar at cross-section 4.

The critical flow rate required to achieve a depth of at least 5 cm throughout the entire reach was:

- 5.2 ML/day (0.06 m^3/s).

3.8.6 Inundation of the active channel

The critical threshold to maintain an open, low-flow channel was defined as the flow required to fill the depth of the active channel. The elevation of the active channel was surveyed as the point on the bank above which vegetation is stable and below which the bank is bare and without extensive vegetation (WRM 2008b).

Using the four cross-sections that encompassed shallow, depth-controlling riffle features (cross-sections 3, 4, 11 and 14), the average depth from the deepest part of the river bed (thalweg) to the elevation of the active channel was used as the water-level height needed to inundate to the active channel. The average thalweg to active channel height for the four cross-sections was 0.48 m (WRM 2008b).

The flow required to inundate the channel at cross-sections 3, 4, 11 and 14 to a depth of 0.48 m was:

- 28.5 ML/day (0.33 m^3/s).

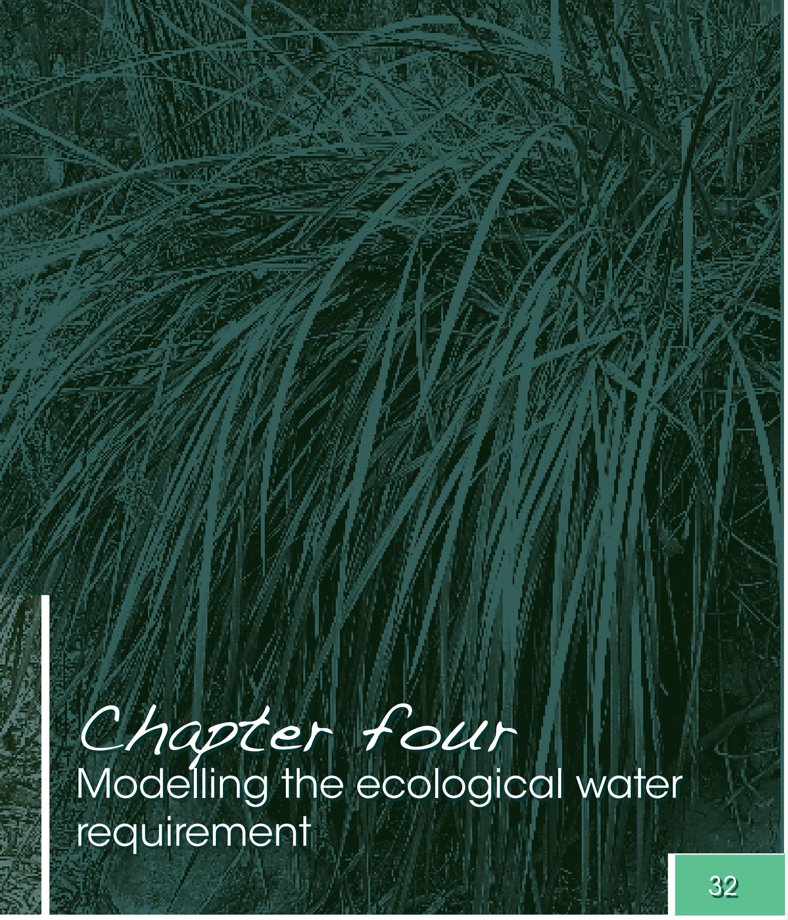
3.8.7 Bankfull and overbank flows

The height of the 'top of bank' was noted during the field survey. Only those cross-sections with a well-defined top of bank were used in the hydraulic analysis of bankfull (or overbank) flows (Appendix 6).

Five of the 14 cross-sections had a well-defined top of bank (cross-sections 7, 10, 11, 12 and 14). The flow required for water levels to reach the height of the top of bank was calculated individually for each cross-section using RAP, and the average flow required to overtop the banks was taken as the ecologically critical flow rate (WRM 2008b).

The average discharge required to achieve a bankfull flow in the study reach was calculated as:

- 282.5 ML/day (3.27 m^3/s) (Appendix 6).



Chapter four

Modelling the ecological water requirement

The flow thresholds in Table 4 were used in conjunction with the 'derived' historical flow record (see Section 3.3) to guide the modelling team in generating an ecological water requirement (EWR) flow using the River Ecologically Sustainable Yield Model (RESYM). RESYM is a water-balance model designed to be used with the Proportional Abstraction of Daily Flows (PADFLOW) approach in developing a modelled EWR (see Section 3.1). A modelled EWR flow series is produced in RESYM by removing a proportion of daily flow from the historical flow record until the remaining water equals or exceeds each of the ecological thresholds identified in Section 3.8. An expert panel (see Section 3.1) parameterises and evaluates the resulting EWR flow with respect to the magnitude and timing of flows and their ecological functions.

Bar charts showing the frequency and duration of flows above each specific ecological threshold (Table 4) – for both the historic and modelled EWR flow – are part of RESYM's graphic output. Using these bar charts, the expert panel compared the EWR flow with the historical flow. If the panel considered that the frequency and duration of flows above each ecological threshold differed significantly between the EWR flow and the historical flow, it was concluded that the modelled output was not consistent with an EWR at a low level of risk (steps 9 and 10 in Figure 14). When this was the case the model parameters were adjusted accordingly, the model re-run, the results evaluated again, and so on until the model parameters produced an EWR flow consistent with a low level of risk.

While the panel evaluated each threshold individually, it must be emphasised that the final EWR flow reflects the panel's evaluation of the frequency and duration of flows above all the ecological thresholds listed in Table 4. In evaluating the various versions of the modelled EWR, the panel considered the frequency and duration of flow spells greater than the thresholds both within years and across years.

The RESYM parameters used to generate the final EWR for Cowaramup Brook are shown in Table 5. The flow ranges shown are generated using the derived 'natural flow' as discussed in Section 2.2. Four flow ranges are used to cover the entire range of flows in the natural flow regime (Table 5). As a result of the way the final set of model parameters are derived, most of the ecologically critical flow thresholds are encompassed within the lowest two flow ranges. The highest flow range covers very infrequent events that occur in Cowaramup Brook far less than once a year.

Table 5

Proportion of the natural daily flow volume that was retained to meet the ecological water requirements within each flow class in Cowaramup Brook.

Flow range (ML/day)	Ecological water requirements as percentage of daily flow
0 ≤ 1.7	100%
>1.7 ≤ 26.6	70%
>26.6 ≤ 337.3	90%
>337.3	100%

4.1 Evaluation of key components of the modelled EWR

The final modelled EWR was determined as a proportion of the natural daily flow within a defined series of flow ranges (Table 5). The EWR flow produced by any set of RESYM parameters was evaluated by the expert panel (Appendix 2) by comparing the frequency and duration of flows above the thresholds in the EWR compared with the natural flow record. The bar charts shown in Figure 21 compare the frequency and duration above the ecological thresholds (listed in Table 4) in the final EWR flow that the panel selected for Cowaramup Brook. Further detail on the flow regimes associated with the threshold flows for Cowaramup Brook is provided in the following sections.

4.1.1 No-flow period

Permanent and ephemeral streams in the south-west have distinctive faunal assemblages and any EWR flow should aim to maintain this fundamental characteristic of the stream.

In modelling an EWR flow, the panel aimed to preserve exactly the natural frequency, duration and inter-annual variation of the summer no-flow period. After the iterative modelling process (Figure 14), the expert panel agreed that retaining 100 per cent of flow in the 0 to 1.7 ML/day range would maintain the natural frequency and duration of the no-flow period in the EWR flow regime (Table 5). Section 4.1.3 discusses the origin of this rule.

Plot 1 of Figure 21 compares the natural no-flow period in Cowaramup Brook with that of the EWR flow. The summer low-flow period typically occurs between January and May, and for the period of record has lasted anywhere between one week and four months annually. The plot shows that the season, frequency and duration of no-flow periods in the EWR flow is identical to that of the natural flow regime.

4.1.2 Summer macroinvertebrate habitat

Hydraulic modelling using RAP showed that a flow rate of 0.9 ML/day is needed to inundate half the width of shallow riffles in the study site to a depth of at least 5 cm (Table 4). The panel members felt that due to the small size of Cowaramup Brook and predictions of decreasing rainfall in the region due to climate change, it was important to maintain the summer low-flow regime in the EWR flow, and that the frequency and duration of flow below 0.9 ML in the EWR flow should match exactly what was found in the natural flow regime.

The panel found that retaining 100 per cent of the natural flow in the 0 to 1.7 ML/day range in the EWR flow was needed to maintain summer riffle habitat (Table 5). Section 4.1.3 discusses the origin of this rule.

Plot 2 of Figure 21 compares the frequency and duration of flows above 0.9 ML/day in the EWR flow with those for the natural flow record from 1975 to 2003. Flows greater than 0.9 ML/day occurred in every year starting from about May and continuing through winter to around November. Once flows reach 0.9 ML/day in late autumn/early winter, they remain above this threshold throughout the winter period for between four and six months a year (during the period of record). The plot shows that the seasonality, frequency and duration of flows above 0.9 ML/day in the EWR flow was identical to what was found in the natural flow for the period 1975 to 2003.

4.1.3 Dry season minimum flow

A minimum flow rate of 1.7 ML/day is required in Cowaramup Brook to maintain pool connectivity, reduce stresses on aquatic fauna and maintain water quality in pools. Below a flow rate of 1.7 ML/day there is a risk that the quality of deeper water habitat may begin to deteriorate earlier, going into summer. Any abstraction when flow is below 1.7 ML/day will increase the length of the no-flow period and the duration of summer stress compared with the natural state.

Because changes in the summer flow regime pose a risk to ecosystems, the panel took the position that the frequency and duration of flows below 1.7 ML in the EWR flow should match exactly what was found in the natural flow regime. Therefore RESYM was set up to retain 100 per cent of the natural daily flow in the 0 to 1.7 ML/day range (Table 5).

Figure 21

Frequency and duration of flows above the ecological thresholds in the modelled EWR (red bars) compared with that of the natural flow (blue bars).

The charts show the results of the final model selected by the expert panel using the parameters in Table 5.

Note also that this rule also achieves the aim of maintaining the natural duration of the no-flow period (Section 4.1.1) and seasonal variation in inundation of riffle habitat (Section 2.1.2) in the EWR flow regime. The threshold flow of 1.7 ML/day should not be interpreted literally as meaning that the EWR flow should not fall below 1.7 ML/day. Summer flows in Cowaramup Brook naturally fall below 1.7 ML/day on a regular basis and, in most summers, the brook stops flowing. The threshold is a guide for the modelling team on the frequency and duration of a low summer flow that should be incorporated into the modelled EWR.

The frequency and duration of flows above 1.7 ML/day in the EWR flow are compared with those of the natural flow record (1975–2003) in Plot 3 of Figure 21. The plot shows summer flows in Cowaramup Brook fall below 1.7 ML/day by the end of November in most years, as flows tend to recede towards 0 and stay below 1.7 ML/day until around the following May. There is some variation between years in relation to flows falling below or increasing above 1.7 ML with the onset of winter rains. As Plot 3 shows, the duration of flows above and below 1.7 ML/day in the modelled EWR is identical to what is found in the natural flow regime.

4.1.4 Winter macroinvertebrate habitat and inundation of low benches

A flow of 3.5 ML/day is required to inundate the entire width of riffles in winter for invertebrate habitat. The same discharge is required to inundate low benches (to flush organic matter into the river system) and trailing vegetation (to create spawning sites for fish and amphibians), as well as provide habitat for a range of vertebrates and invertebrates. As this threshold occurs early in winter when flows are on the rise and continues through to early summer, the panel considered that the ecological functions could be preserved during this period with an EWR flow of lower frequency and shorter duration than the natural flow.

After the iterative modelling process (Figure 14), the expert panel agreed that retaining 70 per cent of natural flow in the 1.7 to 26.6 ML/day range in the EWR would maintain the flow's ecological functions.

Plot 4 of Figure 21 compares the frequency and duration of flows above 3.5 ML/day in the EWR flow with that of the natural flow from 1975 to 2003. Flows greater than 3.5 ML/day have occurred naturally for most of the winter flow period during the 29 years of record. Flows over 3.5 ML/day tend to start between mid-May and late June, and continue until mid-October to mid-November. Following the winter period, the occurrence of flows over the threshold was more sporadic as flow recedes.

The pattern of flow above 3.5 ML/day in the modelled EWR was slightly different to the natural flow, more noticeably at the end of the winter period. The expert panel felt that the differences were not substantial and would not compromise the dependent ecological functions. The expert panel concluded that the RESYM parameters in Table 5 met the ecological objectives of maintaining winter macroinvertebrate habitat and inundation of low benches in Cowaramup Brook.

4.1.5 Upstream migration of small-bodied native fish

The only small-bodied native freshwater fish in Cowaramup Brook is the Swan River goby. A discharge of 5.2 ML/day is required to submerge obstacles to at least 5 cm and allow upstream spawning migration of the goby. After the iterative modelling process (Figure 14), the expert panel agreed that retaining 70 per cent of natural flow in the 1.7 to 26.6 ML/day range for the EWR would maintain the flow's ecological functions.

The frequency and duration of flows above 5.2 ML/day in the EWR are compared with that of the natural record in Plot 5 of Figure 21. Flows above the threshold have occurred during winter in all years between 1975 and 2003. Flows of this magnitude tend to start between May and June, and continue to around late September to late October. At the end of the winter period, flows over 5.2 ML/day tend to become discontinuous, with flows falling below the threshold for one to three weeks, before rising above the threshold for short periods of less than a week.

The EWR flow shows similar characteristics to the natural flow, although the EWR flow generally falls below 5.2 ML/day several days to one week before the natural flow. Importantly, the EWR and natural flows are very similar at the onset of winter, resulting in a minimal difference in the onset of sufficient flows for the Swan River goby's upstream migration.

In the crucial period between June and October, both the EWR flow and the natural flow have generally been above the threshold. The expert panel therefore concluded that the RESYM parameters in Table 5 met the objective to provide sufficient water for the Swan River goby's upstream migration in the lower reaches of Cowaramup Brook.

4.1.6 Inundation of medium-elevation benches

A winter flow 10.4 ML/day is required to inundate medium-elevation benches in Cowaramup Brook (Table 4). Inundation of medium-elevation benches washes organic carbon from the banks into the river and inundates trailing vegetation as habitat for a range of fauna. The panel considered it was important that this flow occurred at regular intervals, but neither the frequency nor duration needed to be identical to the natural frequency to maintain the flow's ecological function.

After the iterative modelling process (Figure 14), the expert panel agreed that retaining 70 per cent of natural flow in the 1.7 to 26.6 ML/day range for the EWR would maintain the flow's ecological functions (Table 5).

Flows above 10.4 ML/day in Cowaramup Brook have occurred naturally in all years between 1975 and 2003 and tend to rise above 10.4 ML/day between late May and late June (Figure 21). In most years, flows over the threshold last for between three and four months, with some years having one or two shorter spells lasting between one month and six weeks (e.g. 1976 and 2001). Flows above the threshold tend to be patchier towards the end of winter, during September and October (e.g. 1977 and 1990).

The pattern of flow greater than 10.4 ML/day in the EWR was similar to that of the natural flow – generally starting at the same time as, or within a few days of, the natural flow and falling below it a few days to a week prior. The intermittent short spells greater than 10.4 ML/day common in the May to June period and during spring are not always matched by the EWR flow. However, when flows naturally rise above 10.4 ML/day for more than a few days, flows in the EWR also moved above the threshold. In some years (e.g. 1978, 1987 and 1997), the duration of flows greater than 10.4 ML/day in the EWR was broken by short periods below the threshold lasting from a few days to a week, while the natural flow remained above the threshold over the same period. Nevertheless, in most years the EWR flow remains above the threshold for a similar frequency and duration to the natural flow.

The expert panel decided that the ecological impact of differences in frequency and duration between the modelled EWR flow series and the natural flow record was likely to be small.

4.1.7 Active channel flows

A discharge of 28.5 ML/day is required to achieve a depth of flow equal to the elevation of the active channel. Active channel flows are responsible for the morphology of the low-flow channel through mobilising sediment, scouring pools and limiting the encroachment of terrestrial vegetation. It is important that this flow occurs at regular intervals, but neither the frequency nor duration of flows in the EWR need to be identical to the natural flow record.

After the iterative modelling process (Figure 14), the expert panel agreed that retaining 90 per cent of natural flow in the 26.6 to 337.3 ML/day range for the EWR would provide for the maintenance of the low-flow channel (Table 5).

Plot 7 of Figure 21 compares the frequency and duration of flows above 28.5 ML/day in the EWR with that of the natural flow record. Flows sufficient to inundate the active channel were recorded in all years on record between 1975 and 2003, although the duration of these flows appeared to decline substantially in the three years after 2000.

The duration of flows greater than 28.5 ML/day varied considerably among years. Flows over the threshold were typically confined to the period between early June to early October. From 2001 to 2003, flows of this magnitude occurred between July and September as short sporadic spells of a few days to two weeks. In most years, there were four or five flow spells over the threshold, generally of around one to four weeks' duration. In 1992 active channel flows occurred throughout the winter period and in 1999 flows only fell below 28.5 ML/day for a week over the same period.

The pattern of flows greater than 28.5 ML/day in the natural flow were closely matched by the EWR flow for the majority of years on record. EWR flows over the threshold generally started and finished within a few days of the natural flow spells and ran for a similar duration. Where natural flows remained above the threshold for extended periods, such as in 1988 and 1992, EWR flow spells were sometimes discontinuous, with interspersed spells of a few days to a week occurring over the same period.

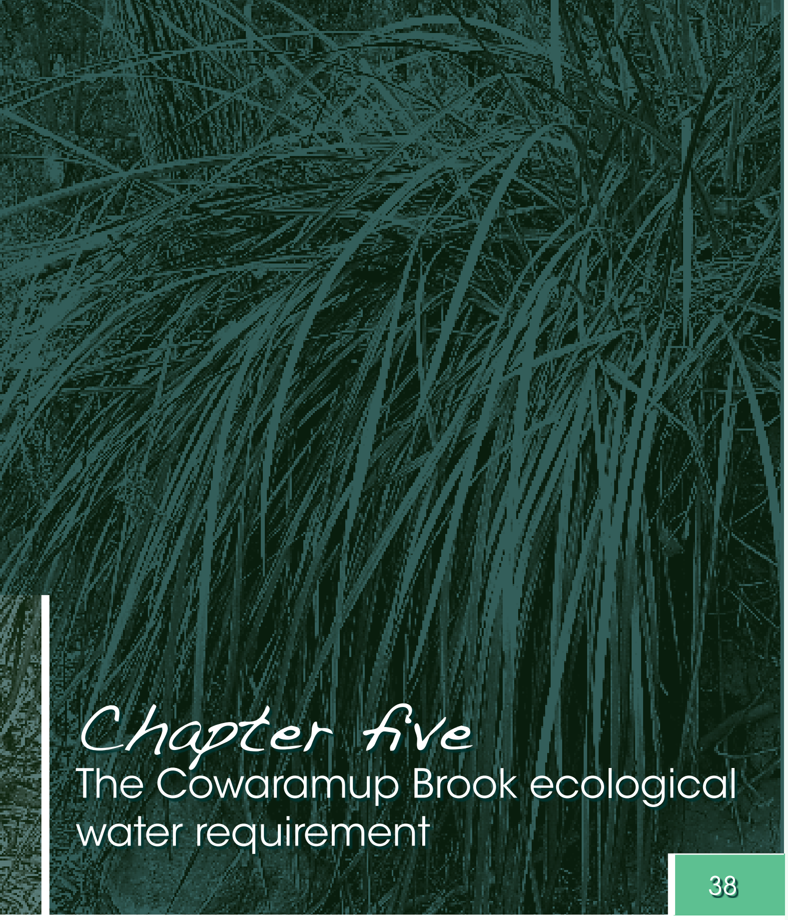
The expert panel concluded that the inter-annual frequency of active channel flows in the EWR had not changed and that the differences in the duration of flows would not affect their role in maintaining an open low-flow channel.

4.1.8 Bankfull and overbank flows

A flow of 282.5 ML/day is required to achieve a depth equal to or exceeding bankfull height. After the iterative modelling process (Figure 14), the expert panel agreed that retaining 90 per cent of natural flow in the 26.6 to 337.3 ML/day range for the EWR and 100 per cent of flows greater than 337.3 ML/day would preserve the regularity of bankfull and overbank flows, and subsequent floodplain inundation (Table 5).

Plot 8 of Figure 21 compares the frequency and duration of flows above 282.5 ML/day in the EWR with those of the natural flow record. As the plot shows, in Cowaramup Brook, flows of this magnitude are extremely rare: they have occurred only five times in the past 30 years and only once since 1988.

The duration of flows greater than 282.5 ML/day is very short, generally lasting less than three days. As such their ecological importance is probably minimal, but they may influence seed set and establishment of vegetation in the near-channel areas, as well as influence channel morphology. The panel felt that when they do occur naturally they should be incorporated into the EWR where possible. Plot 8 shows that the frequency of flows greater than 282.5 ML/day in the EWR matches closely the natural frequency of exceedance.



Chapter five
The Cowaramup Brook ecological water requirement

As the ecological water requirement (EWR) is generated as a percentage of daily flow, its volume varies with daily flow between years. Over all years on record (1975–2003), the EWR for Cowaramup Brook averaged around 80 per cent of annual flow, and varied between 73 and 85 per cent of annual flow, in accordance with the total annual discharge and the regime of flow events in any particular year. This EWR is relatively high compared with mean annual EWRs developed using the PADFLOW approach for other systems in Western Australia's south-west (e.g. Donohue et al. 2009a, 2009b), which tend to be around 60 to 70 per cent of total annual flow. This is most likely because the brook is small and there is relatively little capacity for abstraction without affecting the frequency and duration of flows above the ecological thresholds listed in Table 4.

To maintain Cowaramup Brook ecosystems, the EWR should include flows of similar magnitude at frequencies and durations that closely match those found in the natural flow regime (Poff et al. 1997). In larger, more permanent streams, it is possible to meet this objective during summer without risking fauna that depend on good quality summer habitat (see Donohue et al. 2009a). In very small, highly seasonal streams such as Cowaramup Brook, the quality of summer habitat may be naturally marginal, especially in periods of low rainfall. Any reduction in summer flows due to water abstraction therefore represents a risk to ecological values and processes.

For this study, the expert panel felt that with a stream as small and seasonal as Cowaramup Brook, it was important that key dry-season features of the natural flow regime were preserved exactly in the EWR flow. Further, given the infrequency of flood flows, the panel aimed to maintain these in the EWR. To achieve these two objectives, the River Ecological Sustainable Yield Model (RESYM) was set up so that if daily flow was less than 1.7 ML/day or higher than 337.3 ML/day, no water would be abstracted.

Importantly, the flow-duration curve in Figure 22 indicates that overall, the EWR flow retains the same permanency as the natural flow, with little change to the magnitude and duration of summer low flows. The EWR flow also retains infrequent short-duration flood flows. The EWR flow regime therefore has the same period of inundation of habitats (such as temporary pools and riffle areas) as the natural flow regime, and the same capacity for channel scouring and maintenance of channel morphology as would occur naturally.

These 'natural' characteristics of the EWR can be seen in all years of the historical record (Figure 23). For example, Plot 1 of Figure 23 is a daily time-series comparing the EWR against the natural flow regime for 1997. Note that the natural flow and the EWR are the same at the start of the winter flow season, and also as flows are receding from early-October until they cease to flow in late-November. The seasonal period of no-flow and the total duration of the annual flow period in the EWR is also the same as the natural flow regime (Figure 23, plots 1, 2 and 3). The timing and magnitude of flow peaks in the EWR are a good match for the natural flow (plots 1 and 3). Data on the natural flow and the modelled EWR for the period 1975 to 2003 for Cowaramup Brook are shown in Appendix 7. Notice that between December and April of every year, the monthly flow volumes in the natural flow tend to be reproduced exactly in the monthly EWR.

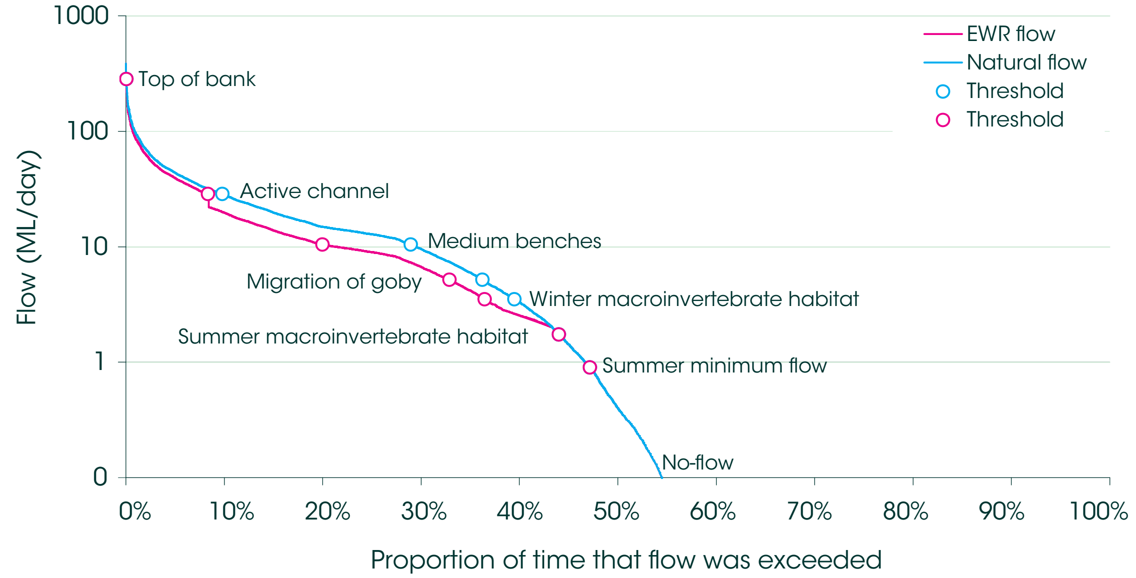


Figure 22

Flow duration curve for Cowaramup Brook, showing natural flow versus modelled EWR flow.

The blue line is the natural curve for the period 1975 to 2003 and the red curve is for the modelled EWR over the same period (based on the parameters in Table 5).

5.1 The ecologically sustainable yield

The Cowaramup Brook EWR study was undertaken with the aim to support future water resource planning in the Whicher region of Western Australia's south-west. The decision of where and how to place limits on water allocation takes into account a number of economic and environmental factors, including the volume of water that can be abstracted in an ecologically sustainable manner.

The ecologically sustainable yield (ESY) of Cowaramup Brook is the volume of water that can be extracted while maintaining the current ecological values and condition of the river system, as well as the long-term evolutionary capacity of its biota. The difference between the modelled EWR flow and the natural flow is the volume of water that can be harvested from Cowaramup Brook without placing the natural environment at risk (Figure 27). This volume therefore represents the ESY of the brook. As the EWR study uses flow data that includes changes to the flow regime caused by existing on-stream dams, the sustainable yields in this study are additional to current use from the river system.

During the modelling process, the expert panel noted the difficulty of abstracting water from Cowaramup Brook without causing significant changes to the frequency and duration of flows above the ecologically critical thresholds (Table 4). For example, ecologically important 'high flows' found in the natural flow record would no longer exist in the modelled EWR flow record with any abstraction. It was only in the medium-flow ranges between 1.7 and 30 ML/day that water could be abstracted while also meeting ecological needs. Even within these ranges, only small volumes of daily flow could be abstracted (Plot 1 of Figure 23).

Based on the derived historical flow record, the average annual ESY for Cowaramup Brook between 1975 and 2003 was 670 ML and varied between a minimum of about 400 ML and a maximum of about 900 ML (Appendix 7). However, since 2000 annual yields have averaged only around 550 ML/year (Appendix 7).

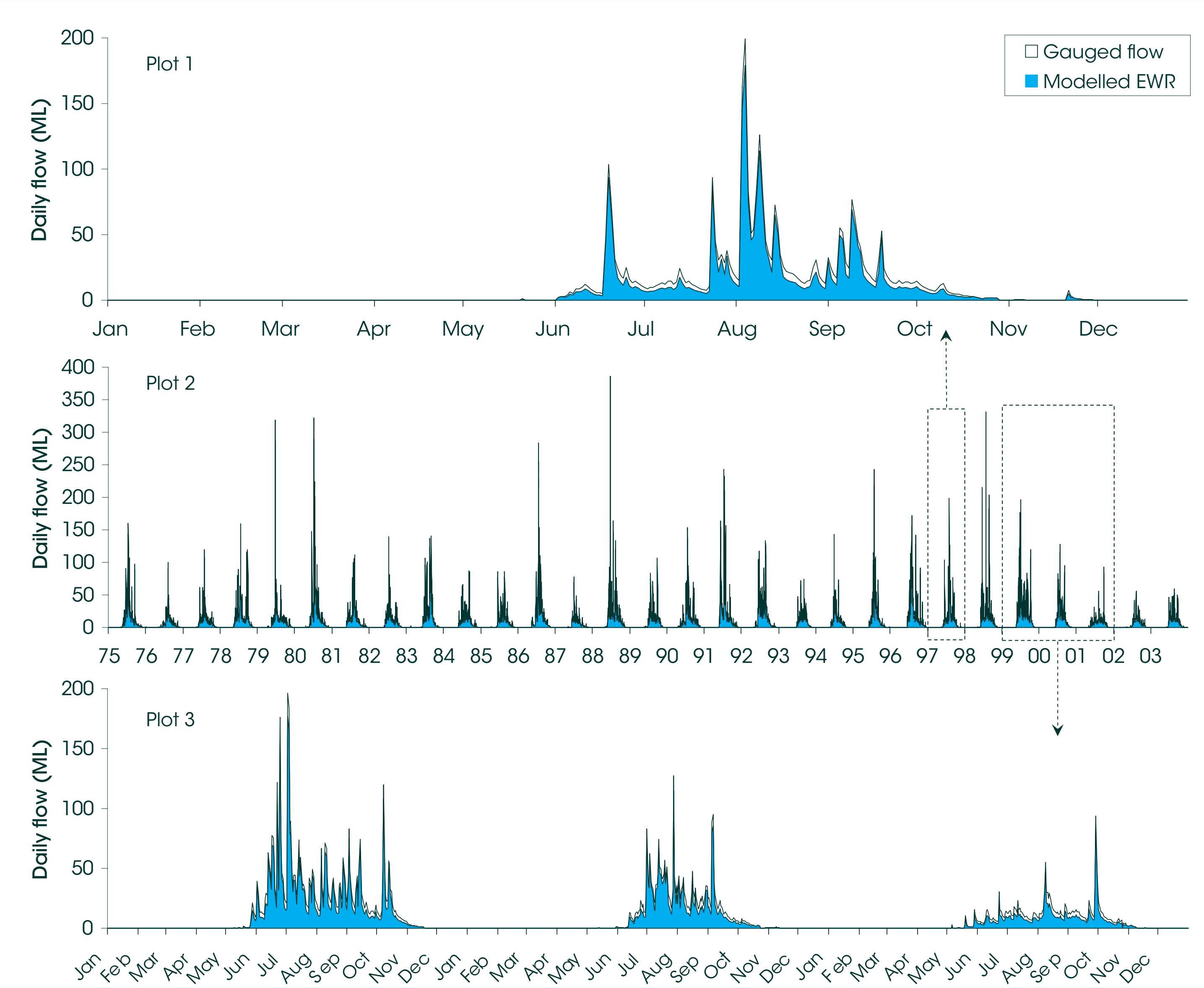


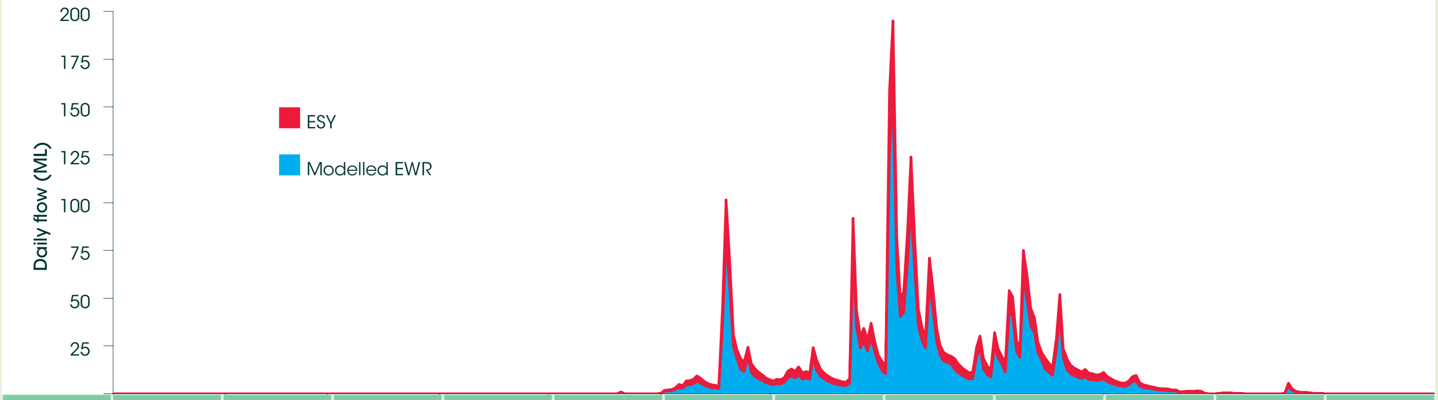
Figure 23

Time-series of the natural flow and modelled EWR flow for Cowaramup Brook.

Plot 1 shows the daily record for 1997, whereas Plot 2 is for the period 1975 to 2003 and Plot 3 is for the period 1999 to 2001.

Figure 24 compares the ESY and the modelled EWR for Cowaramup Brook in 1997. The yield has been calculated at a daily time-step, and the ESY is shown for each day of the year. In that year, the annual ESY for Cowaramup Brook was 661 ML and the daily ESY ranged from 0 to 20 ML/day. The highest yields occurred between June and September. The ESY was 0 ML/day for all of the period between January and May, and in the month of December.

As was previously mentioned, the natural flow record incorporates water abstraction (from pumping and damming), as well as changes to pre-European flow patterns caused by clearing of native vegetation and other land uses. Therefore, the ESY given in Figure 24 is in addition to current levels of water abstraction, and is based on a flow regime that has been altered by human activities in the catchment.



Day of Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Ecologically sustainable yield (ML/day)												
1	0.0	0.0	0.0	0.0	0.0	0.0	2.9	5.2	3.3	4.4	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	2.7	4.6	7.2	3.6	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	3.0	16.2	5.9	3.1	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.9	2.9	19.9	5.0	2.8	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	1.3	3.3	8.3	5.5	2.4	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	1.9	3.7	5.1	5.2	2.2	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	1.6	4.0	5.4	8.5	2.2	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	2.6	3.6	8.7	7.3	2.6	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	2.7	4.3	12.6	7.7	3.5	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	3.0	4.3	8.1	6.2	3.8	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0	3.6	3.6	4.6	4.6	2.3	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	3.1	4.3	3.5	4.1	1.8	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0	2.5	7.4	9.2	8.2	1.6	0.0	0.0
14	0.0	0.0	0.0	0.0	0.0	2.1	5.4	7.2	6.6	1.5	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	1.8	4.0	5.7	5.7	1.4	0.0	0.0
16	0.0	0.0	0.0	0.0	0.0	1.7	4.3	3.5	4.9	1.2	0.0	0.0
17	0.0	0.0	0.0	0.0	0.0	1.5	3.7	7.8	4.2	1.1	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	4.8	3.3	6.6	8.9	1.0	0.0	0.0
19	0.0	0.0	0.0	0.0	0.0	10.4	2.9	6.2	5.3	0.9	0.0	0.0
20	0.0	0.0	0.0	0.0	0.0	6.9	2.7	6.0	7.2	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	3.2	2.5	5.6	5.5	0.0	2.2	0.0
22	0.0	0.0	0.0	0.0	0.0	7.2	2.3	4.8	4.6	0.0	1.0	0.0
23	0.0	0.0	0.0	0.0	0.0	5.6	3.1	4.2	4.1	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0	0.0	5.1	9.4	3.8	3.8	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.0	7.5	4.5	4.3	4.5	0.0	0.0	0.0
26	0.0	0.0	0.0	0.0	0.0	4.8	9.2	4.5	3.9	0.0	0.0	0.0
27	0.0	0.0	0.0	0.0	0.0	4.0	3.5	7.5	4.2	0.0	0.0	0.0
28	0.0	0.0	0.0	0.0	0.0	4.4	8.5	9.3	4.1	0.0	0.0	0.0
29	0.0		0.0	0.0	0.0	3.9	3.8	5.7	3.9	0.0	0.0	0.0
30	0.0		0.0	0.0	0.0	3.3	8.2	4.5	4.0	0.0	0.0	0.0
31	0.0		0.0		0.0		6.2	3.9		0.0		0.0
Total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	101.2	137.3	212.4	163.8	43.3	3.2	**0.0**

Figure 24

Daily ecologically sustainable yield for Cowaramup Brook, 1997

5.2 In Conclusion

The daily calculation of the ESY using PADFLOW allows for a level of precision in water planning that has not previously been available for the area. The results are particularly relevant to the construction of new dams, and whether new dams should be located on-channel or off-stream to take advantage of water available sustainably in periods of high flow.

This EWR study demonstrated that Cowaramup Brook (and probably other similar small-stream systems in the region) is a very low-yielding system and its ecological values are sensitive to any abstraction. Due to the low yields identified, water resource planners should be cautious in allocating water from the brook, particularly in periods of low rainfall and flow. Ecological values in small streams like Cowaramup Brook are likely to be further impacted by abstraction in the event of climate change and declining rainfall.

Appendix 1 Macroinvertebrates of Cowaramup Brook

Phylum	Subphylum	Class	Order	Family	Species
Platyhelminthes					
		Turbellaria			Turbellaria spp.
Mollusca					
		Gastropoda	Hygrophila	Planorbidae	*Ferrissia petterdi*
				Physidae	*Physa acuta*
Annelida					
		Oligochaeta			Oligochaeta spp.
		Hirudinea		Glossophonidae	Glossophonidae spp.
Arthropoda					
	Crustacea	Malacostraca	Amphipoda	Perthiidae	Perthia spp.
		Ostracoda			Ostracoda spp.
		Branchiopoda	Diplostraca		Cladocera spp.
		Maxillopoda	Cyclopoida		Cyclopoida spp.
	Chelicerata	Arachnida			Hydracarina spp.
	Uniramia	Insecta	Ephemeroptera	Caenidae	*Tasmanocoenis tillyardi*
				Baetidae	Cloeon sp.
					Baetidae spp.
				Leptophlebiidae	Leptophlebiidae spp.
			Odonata		Anisoptera spp.
				Hemicorduliidae	*Hemicordulia australiae*
				Libellulidae	*Orthetrum caledonicum*
					Libellulidae spp.
			Hemiptera	Corixidae	Sigara sp.
			Coleoptera	Dytiscidae	*Allodessus bistrigatus*
					Limbodessus inornatus
					Platynectes decempunctatus var polygrammus
					Rhantus suturalis
					Sternopriscus brownii
			Diptera	Chironomidae	Chironomidae spp.
					Chironomus aff. Alternans
					Cladopelma curtivalva
					Cryptochironomus griseidorsum
					Dicrotendipes sp.
					Harrisius sp.
					Polypedilum sp.

Source: WRM (2008a)

Appendix 1 Macroinvertebrates of Cowaramup Brook (contd.)

Phylum	Subphylum	Class	Order	Family	Species
Arthropoda					
	Uniramia	Insecta	Diptera	Chironomidae	*Stenochironomus* sp.
					Cladotanytarsus sp.
					Rheotanytarsus sp.
					Tanytarsus sp.
					Cricotopus annuliventris
					Paralimnophyes sp.
					Paramerina levidensis
				Ceratopogonidae	Dasyheleinae spp.
				Empididae	Empididae spp.
				Tipulidae	Tipulidae spp.
			Trichoptera	Hydroptilidae	Acritoptila/hellyethira spp.
				Leptoceridae	*Lectrides parilis*
					Leptoceridae spp.

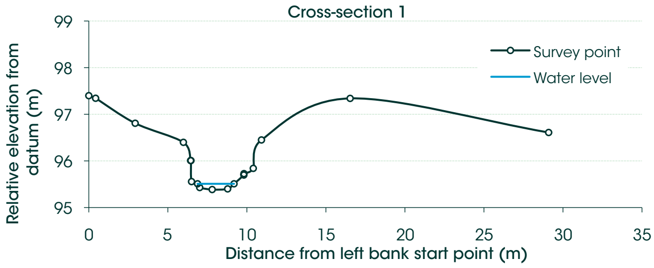
Source: WRM (2008a)

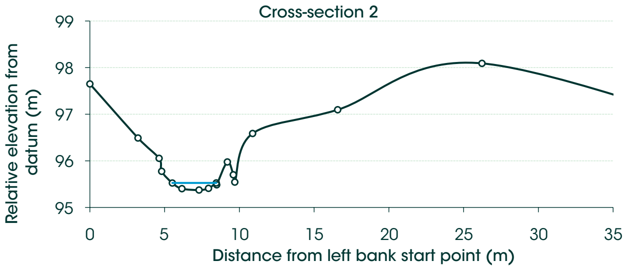
Appendix 2 Expert panel members

Dr Andrew Storey	Principal Ecologist - Wetland Research and Management
Mr Robert Donohue	Ecologist - Department of Water
Ms Katherine Bennett	Ecologist - Department of Water
Ms Jessica Lynas	Ecologist - Wetland Research and Management

Appendix 3 Channel cross-sections from Cowaramup Brook

Survey channel profiles for cross-sections 1 to 15. The blue line shows the water level at each cross-section at the time of survey.


Cross-section 1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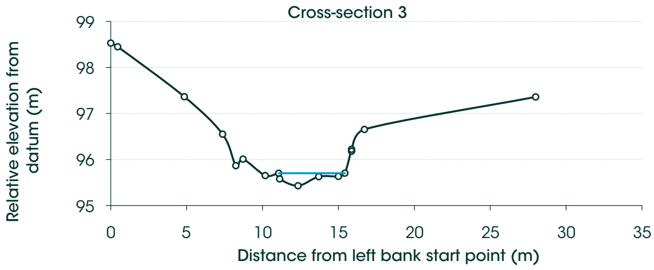
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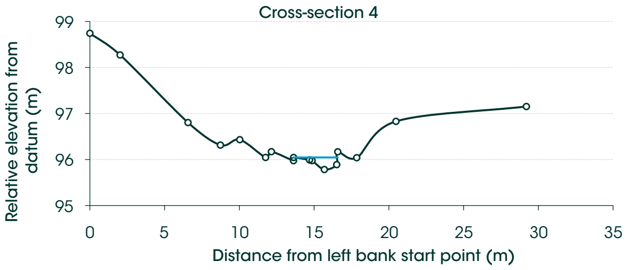
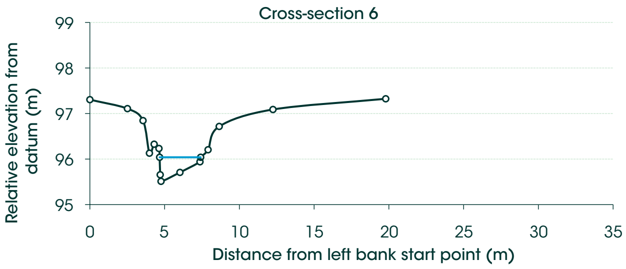

Cross-section 4


Cross-section 5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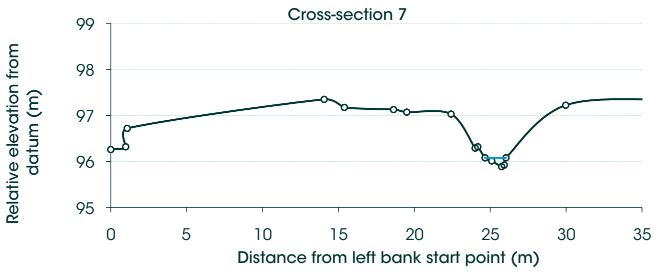

Cross-section 7


Cross-section 8

Appendix 3 Channel cross-sections from Cowaramup Brook (contd.)

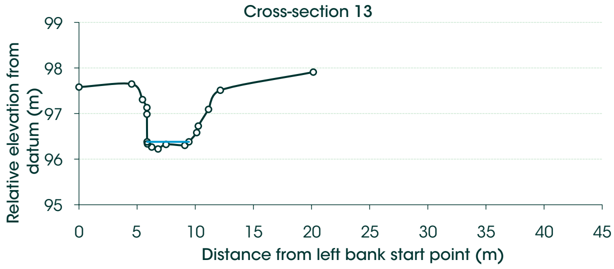
Survey channel profiles for cross-sections 1 to 15. The blue line shows the water level at each cross-section at the time of survey.


Cross-section 9


Cross-section 10


Cross-section 11

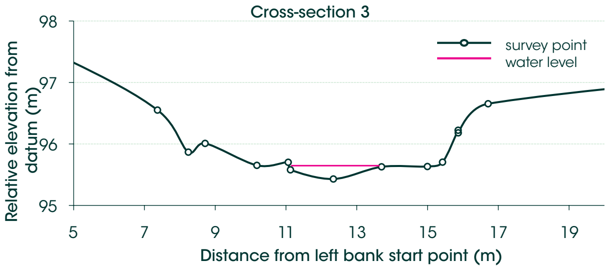

Cross-section 12

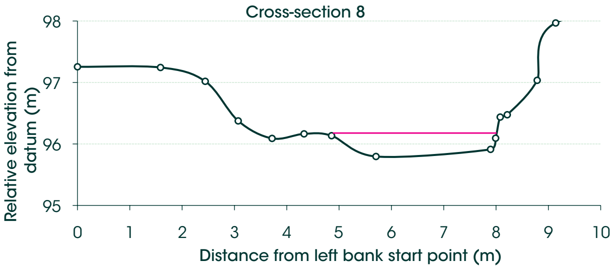

Cross-section 13


Cross-section 14

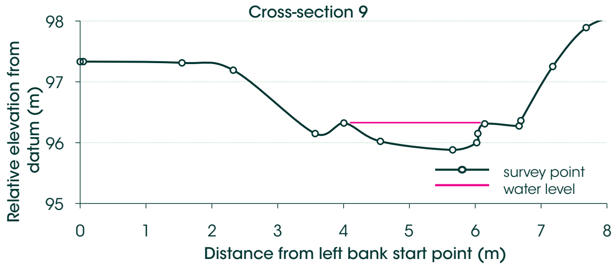

Cross-section 15

Appendix 4 Winter high flows required to inundate low-elevation benches in Cowaramup Brook

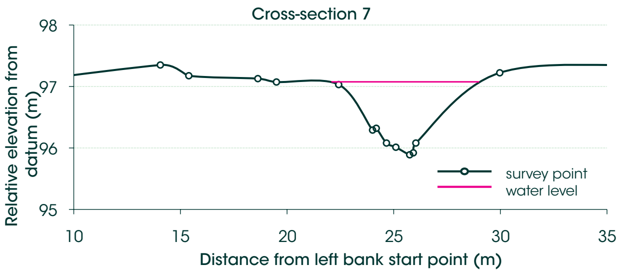


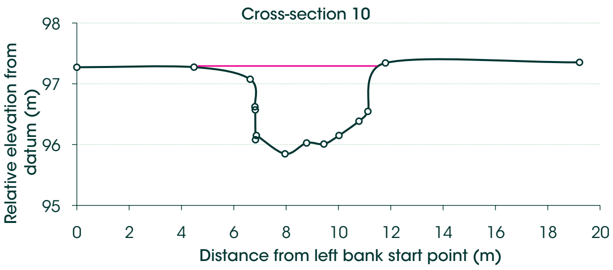


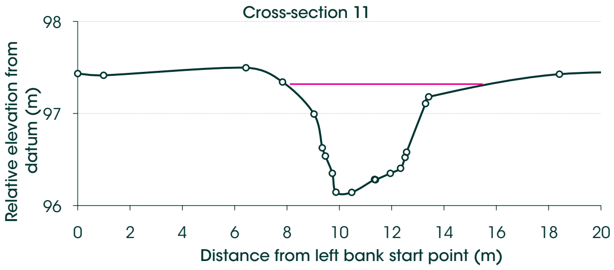
Appendix 5 Winter high flows required to inundate medium-elevation benches in Cowaramup Brook

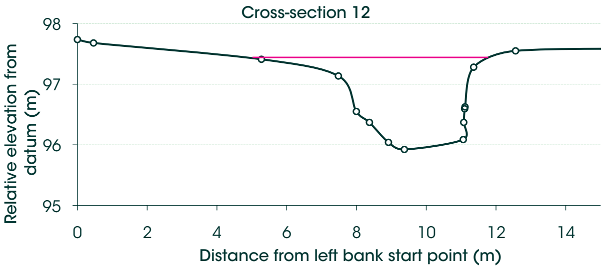


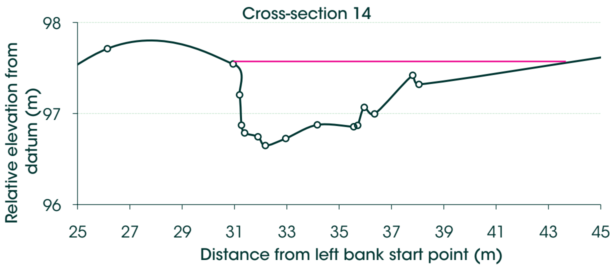
Appendix 6 Winter high flows required to achieve a bankfull flow in Cowaramup Brook


Cross-section 7


Cross-section 10


Cross-section 11


Cross-section 12


Cross-section 14

Appendix 7 Monthly flow, EWR and ESY for Cowaramup Brook (1975–2003)

All data in the table below are given in ML.

Year	Data	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1975	Flow	0.0	0.0	0.0	0.0	74.2	793.8	1838.9	747.0	473.8	146.8	50.2	2.4	4127
	EWR	0.0	0.0	0.0	0.0	55.4	652.9	1618.7	572.5	370.1	102.8	45.9	2.4	3421
	ESY	0.0	0.0	0.0	0.0	18.8	140.9	220.2	174.6	103.7	44.0	4.3	0.0	707
1976	Flow	3.4	0.0	0.0	0.0	17.9	93.8	369.6	817.5	287.3	141.7	70.0	5.5	1807
	EWR	3.4	0.0	0.0	0.0	16.6	73.7	274.6	653.8	201.1	106.4	55.2	5.5	1390
	ESY	0.0	0.0	0.0	0.0	1.3	20.0	95.0	163.7	86.2	35.4	14.8	0.0	416
1977	Flow	0.0	0.0	0.0	0.0	14.2	368.1	687.8	832.4	253.6	313.6	51.0	1.9	2523
	EWR	0.0	0.0	0.0	0.0	14.2	272.1	529.8	652.5	177.5	219.5	44.3	1.9	1912
	ESY	0.0	0.0	0.0	0.0	0.0	96.1	158.0	179.9	76.1	94.1	6.7	0.0	611
1978	Flow	0.0	0.0	0.0	0.0	147.7	1004.3	1305.2	541.7	971.3	450.4	61.1	3.4	4485
	EWR	0.0	0.0	0.0	0.0	106.5	829.2	1122.7	398.1	802.2	350.3	50.2	3.4	3663
	ESY	0.0	0.0	0.0	0.0	41.3	175.0	182.5	143.6	169.1	100.1	10.9	0.0	822
1979	Flow	0.2	0.0	0.0	12.7	94.0	914.0	931.6	642.2	404.6	256.0	122.5	8.5	3386
	EWR	0.2	0.0	0.0	12.7	68.1	739.7	762.2	502.7	283.2	181.3	92.5	8.5	2651
	ESY	0.0	0.0	0.0	0.0	25.9	174.4	169.4	139.6	121.4	74.7	29.9	0.0	735
1980	Flow	0.1	0.0	0.0	8.8	39.5	825.4	2713.5	1181.0	451.4	270.2	65.0	10.6	5565
	EWR	0.1	0.0	0.0	8.8	33.6	688.3	2415.5	993.7	315.9	189.1	57.0	10.6	4713
	ESY	0.0	0.0	0.0	0.0	6.0	137.1	298.0	187.3	135.4	81.1	7.9	0.0	853
1981	Flow	0.6	0.0	0.0	1.0	63.7	575.0	861.6	1354.8	409.7	144.4	91.7	18.1	3520
	EWR	0.6	0.0	0.0	1.0	45.1	417.4	714.6	1154.3	286.8	106.2	74.3	16.1	2816
	ESY	0.0	0.0	0.0	0.0	18.7	157.6	147.0	200.5	122.9	38.2	17.4	2.0	704
1982	Flow	3.4	0.1	0.0	0.0	3.3	380.3	1312.8	484.9	419.6	262.3	30.2	1.2	2898
	EWR	3.4	0.1	0.0	0.0	3.3	274.3	1112.1	339.4	309.1	184.3	30.2	1.2	2257
	ESY	0.0	0.0	0.0	0.0	0.0	106.1	200.7	145.5	110.4	77.9	0.0	0.0	641
1983	Flow	0.0	3.2	0.0	0.0	2.9	280.8	1071.4	1547.9	1196.6	153.1	27.8	1.0	4285
	EWR	0.0	3.2	0.0	0.0	2.9	217.7	884.8	1332.5	1025.0	113.4	25.9	1.0	3606
	ESY	0.0	0.0	0.0	0.0	0.0	63.1	186.6	215.4	171.7	39.7	2.0	0.0	678
1984	Flow	0.8	0.5	0.3	0.0	24.8	364.6	740.7	728.4	756.2	146.0	96.1	3.1	2861
	EWR	0.8	0.5	0.3	0.0	19.0	274.6	589.1	559.1	603.8	109.1	74.8	3.1	2234
	ESY	0.0	0.0	0.0	0.0	5.8	90.0	151.6	169.3	152.4	36.8	21.3	0.0	627
1985	Flow	0.0	0.0	0.0	4.2	0.4	316.5	550.9	990.9	492.2	157.0	54.6	1.1	2568
	EWR	0.0	0.0	0.0	4.2	0.4	245.3	403.0	819.3	360.1	114.3	47.0	1.1	1995
	ESY	0.0	0.0	0.0	0.0	0.0	71.2	147.9	171.6	132.2	42.7	7.7	0.0	573
1986	Flow	0.2	0.0	0.1	0.0	134.2	375.0	2172.1	1506.1	490.5	200.1	31.3	0.3	4910
	EWR	0.2	0.0	0.1	0.0	94.3	314.5	1901.3	1320.6	343.3	141.7	30.4	0.3	4147
	ESY	0.0	0.0	0.0	0.0	39.9	60.5	270.8	185.5	147.1	58.5	0.9	0.0	763
1987	Flow	0.0	0.0	0.0	0.1	3.4	245.0	658.7	420.1	212.8	71.3	24.9	0.8	1637
	EWR	0.0	0.0	0.0	0.1	3.4	172.2	527.3	294.1	149.8	60.1	20.7	0.8	1228
	ESY	0.0	0.0	0.0	0.0	0.0	72.8	131.4	126.0	63.1	11.3	4.2	0.0	409
1988	Flow	0.2	0.0	0.0	0.0	54.3	1725.7	1260.2	1233.4	604.8	293.2	69.0	0.9	5242
	EWR	0.2	0.0	0.0	0.0	46.2	1521.8	1063.2	1059.6	444.0	205.2	51.4	0.9	4393
	ESY	0.0	0.0	0.0	0.0	8.1	203.9	197.0	173.8	160.9	87.9	17.5	0.0	849
1989	Flow	0.5	0.3	0.4	0.3	1.9	42.3	671.4	756.2	458.7	663.6	69.8	0.6	2666
	EWR	0.5	0.3	0.4	0.3	1.9	36.5	516.9	582.1	328.7	529.0	55.0	0.6	2052
	ESY	0.0	0.0	0.0	0.0	0.0	5.8	154.5	174.1	130.0	134.6	14.8	0.0	614

Appendix 7 Monthly flow, EWR and ESY for Cowaramup Brook (1975–2003) (contd.)

All data in the table below are given in ML.

Year	Data	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1990	Flow	0.3	0.1	0.2	16.1	106.1	345.1	1388.1	911.1	617.4	311.3	107.5	4.4	3808
	EWR	0.3	0.1	0.2	16.1	83.8	248.6	1200.9	737.7	483.8	217.9	81.4	4.4	3075
	ESY	0.0	0.0	0.0	0.0	22.3	96.5	187.2	173.5	133.6	93.4	26.0	0.0	732
1991	Flow	0.3	0.3	0.1	0.0	16.8	1329.8	2003.6	1043.9	634.8	183.8	90.8	2.8	5307
	EWR	0.3	0.3	0.1	0.0	12.5	1156.0	1742.4	851.0	491.2	132.3	72.4	2.8	4461
	ESY	0.0	0.0	0.0	0.0	4.3	173.8	261.2	192.9	143.6	51.5	18.5	0.0	846
1992	Flow	0.3	0.0	0.8	0.6	68.7	1013.6	1134.8	1491.7	662.2	164.2	59.2	5.4	4601
	EWR	0.3	0.0	0.8	0.6	50.0	881.8	965.3	1310.0	510.1	121.7	52.2	5.4	3898
	ESY	0.0	0.0	0.0	0.0	18.7	131.8	169.5	181.7	152.1	42.5	7.1	0.0	703
1993	Flow	0.3	0.0	0.0	0.1	0.5	13.1	473.6	712.0	784.7	306.8	28.2	0.3	2319
	EWR	0.3	0.0	0.0	0.1	0.5	11.0	348.6	536.9	608.8	222.2	27.3	0.3	1756
	ESY	0.0	0.0	0.0	0.0	0.0	2.2	125.1	175.1	175.8	84.6	1.0	0.0	564
1994	Flow	0.0	0.0	0.0	0.0	8.7	514.4	1061.6	540.9	274.9	98.6	2.7	0.2	2502
	EWR	0.0	0.0	0.0	0.0	8.7	405.7	896.2	407.3	192.4	75.4	2.7	0.2	1988
	ESY	0.0	0.0	0.0	0.0	0.0	108.8	165.5	133.6	82.5	23.1	0.0	0.0	513
1995	Flow	0.0	0.0	0.0	0.0	0.3	238.0	1551.4	1225.5	551.5	147.0	41.4	2.8	3758
	EWR	0.0	0.0	0.0	0.0	0.3	167.6	1342.2	1042.7	415.9	106.8	36.2	2.8	3114
	ESY	0.0	0.0	0.0	0.0	0.0	70.4	209.1	182.8	135.6	40.1	5.2	0.0	643
1996	Flow	0.2	0.0	0.0	0.0	1.1	188.9	1670.9	1383.9	912.1	565.9	260.5	63.5	5047
	EWR	0.2	0.0	0.0	0.0	1.1	132.4	1454.3	1177.8	732.0	450.8	191.9	51.0	4191
	ESY	0.0	0.0	0.0	0.0	0.0	56.5	216.6	206.1	180.1	115.1	68.6	12.5	855
1997	Flow	0.4	0.3	0.3	0.1	1.9	510.4	598.3	1433.9	824.5	161.7	19.9	0.5	3552
	EWR	0.4	0.3	0.3	0.1	1.9	409.1	461.0	1221.6	660.6	118.4	16.7	0.5	2891
	ESY	0.0	0.0	0.0	0.0	0.0	101.2	137.3	212.4	163.8	43.3	3.2	0.0	661
1998	Flow	0.0	0.0	0.4	0.4	4.0	881.1	977.7	1386.2	827.0	277.6	27.7	0.0	4382
	EWR	0.0	0.0	0.4	0.4	4.0	738.9	821.4	1167.3	657.8	194.3	27.7	0.0	3612
	ESY	0.0	0.0	0.0	0.0	0.0	142.2	156.3	218.9	169.2	83.3	0.0	0.0	770
1999	Flow	0.0	0.0	0.0	0.2	86.8	1336.0	1546.0	1032.0	838.8	686.0	37.1	0.4	5563
	EWR	0.0	0.0	0.0	0.2	63.2	1146.0	1344.2	854.5	677.1	550.2	32.8	0.4	4669
	ESY	0.0	0.0	0.0	0.0	23.6	190.0	201.7	177.5	161.7	135.8	4.2	0.0	895
2000	Flow	0.5	0.5	0.5	0.2	4.4	260.4	1343.3	844.2	617.8	95.2	8.1	0.4	3175
	EWR	0.5	0.5	0.5	0.2	4.4	184.5	1176.8	652.2	477.2	72.2	8.1	0.4	2577
	ESY	0.0	0.0	0.0	0.0	0.0	75.9	166.5	192.1	140.7	23.1	0.0	0.0	598
2001	Flow	0.0	0.0	0.0	0.0	67.6	279.1	378.6	550.1	509.7	253.9	18.4	1.0	2059
	EWR	0.0	0.0	0.0	0.0	51.7	195.3	265.0	402.9	391.8	179.4	18.4	1.0	1506
	ESY	0.0	0.0	0.0	0.0	15.9	83.7	113.6	147.2	117.9	74.6	0.0	0.0	553
2002	Flow	0.3	0.0	0.0	0.3	6.3	39.5	357.5	716.4	431.8	176.9	51.6	0.4	1781
	EWR	0.3	0.0	0.0	0.3	6.3	36.2	259.4	547.7	308.9	123.8	39.0	0.4	1322
	ESY	0.0	0.0	0.0	0.0	0.0	3.3	98.2	168.6	122.8	53.1	12.6	0.0	459
2003	Flow	0.1	0.0	0.0	0.1	3.4	125.9	656.5	814.2	558.1	201.7	15.2	0.4	2376
	EWR	0.1	0.0	0.0	0.1	3.4	100.3	476.7	634.4	417.1	144.1	15.2	0.4	1792
	ESY	0.0	0.0	0.0	0.0	0.0	25.6	179.7	179.9	141.0	57.6	0.0	0.0	584

Shortened forms

ARL	Aquatic Research Laboratory
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CCG	Cape to Cape Catchments Group
DEC	Department of Environment and Conservation
DoW	Department of Water
ESY	ecologically sustainable yield
EWR	ecological water requirement
HEC-RAS	Hydrological Engineering Center, United States Army Corps of Engineers, River Analysis System
PADFLOW	Proportional Abstraction of Daily Flows (approach)
RAP	River Analysis Package
RESYM	River Ecologically Sustainable Yield Model
WRC	Water and Rivers Commission
WRM	Wetland Research and Management

Glossary

Abstraction	The permanent or temporary withdrawal of water from any source of supply, so that it is no longer part of the resources of the locality.
Aquifer	A geological formation or group of formations capable of receiving, storing and transmitting significant quantities of water. Usually described by whether they consist of sedimentary deposits (sand and gravel) or fractured rock.
Bankfull	Refers to a discharge of a river that completely fills its channel and the elevation of the water surface coincides with the bank margins. Any further rise in water level would cause water to move into the floodplain.
Biodiversity	Biological diversity or the variety of organisms, including species themselves, genetic diversity and the assemblages they form (communities and ecosystems). Sometimes includes the variety of ecological processes within those communities and ecosystems.
Biomass	The total mass of living matter in a given unit area.
Biota	All the plant and animal life of a particular region.
Catchment	Area of land from which rainfall runoff contributes to a single watercourse, wetland or aquifer.
Climate change	A change of climate attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.
Diapause	A physiological state of dormancy with very specific triggering and release conditions.
Ecologically sustainable yield	The level of water extraction from a particular system that, if exceeded, would compromise key environmental assets or ecosystem functions.
Ecological water requirement	Water regime needed to maintain the ecological values (including assets, functions and processes) of water-dependent ecosystems at a low level of risk.
Ecosystem	A community or assemblage of communities of organisms, interacting with one another, and the specific environment in which they live and with which they also interact, e.g. a lake. Includes all the biological, chemical and physical resources and the interrelationships and dependencies that occur between those resources.
Environment	Living things, their physical, biological and social surroundings, and the interactions between them.
Extraction	Taking of water, defined as removing water from or reducing the flow of a waterway or from overland flow.
Flow	Streamflow in terms of m^3/yr, m^3/d or ML/yr. Also known as discharge.
Gravid	Bearing eggs or embryos; pregnant.
Groundwater	Water that occupies the pores and crevices of rock or soil beneath the land surface.
Piscivorous	Fish eating.
Riparian	Of or relating to the bank of a river or stream.
Surface water	Water flowing or held in streams, rivers and other wetlands on the surface of the landscape.
Thalweg	The line joining the lowest points of successive cross-sections of a channel. Usually associated with the path of highest velocity.
Water-dependent ecosystems	Those parts of the environment that are sustained by the permanent or temporary presence of water.
Water regime	A description of the variation of flow rate or water level over time. It may also include a description of water quality.

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