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

Determining the environmental flow for

Wilyabrup Brook

Securing Western Australia's water future

Environmental water report series
Report no. 28
November 2015

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Disclaimer

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The report was prepared by Adam Green and Robert Donohue from the department's Environmental Water Planning section.

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Preface

The rivers of Western Australia's south-west region are under increasing pressure as below-average rainfall, and increased interception and abstraction to meet demands for water supply, irrigated agriculture, and reduced flows.

The *Whicher area surface water allocation plan* (Department of Water 2009) has been in place since its release in 2009. The evaluation of the plan in 2014 described key actions that needed to be progressively initiated over the next evaluation period, including:

- Identifying subareas where river ecology is at greatest risk from abstraction and review allocation limits and management arrangements.
- Using the results of ecological water requirement studies to set management criteria.

The results of this study will support water resource planning in the south-west and the evaluation of the risk to ecosystems with change in allocation limits and resource use, and declining flows due to climate change.

Summary

This report describes how the Department of Water determined environmental flows for two reaches of Wilyabrup Brook (Woodlands Reach and Juniper Reach) in south-west Western Australia. An environmental flow is the water regime needed to maintain a river's water-dependent ecological values at a low level of risk.

The Wilyabrup Brook environmental flow was developed using the Proportional Abstraction of Daily Flows (PADFLOW) method. PADFLOW was developed by the Department of Water for the highly variable streams of the South West region.

PADFLOW is supported by the River Ecologically Sustainable Yield Model (RESYM) decision support software. Using RESYM, we removed a proportion of flow from existing flow records for the Woodlands and Juniper reaches until the timing, duration and frequency of flow spells represented a low level of risk to river ecology.

Flow rates that achieve threshold water depths or velocities in important habitats (ecological–flow thresholds) were identified using the hydraulic analysis module in the River Analysis Package program. These threshold flows provide key ecological functions, such as:

- Summer flows required to maintain pool water quality.
- Water depths over barriers that allow for fish migration upstream.
- Inundation of breeding habitat.
- Flows needed to scour the channel of sediment and maintain a diversity of habitat.

We used the ecological flow thresholds in RESYM to produce environmental flow regimes for Woodlands Reach and Juniper Reach; each achieving a series of ecological objectives relevant to the reach.

Environmental flows were modelled using historical flow records (1974 to 2011) from two gauging stations in the Wilyabrup Brook catchment. Between 1974 and 2011, the environmental flow for Woodlands Reach averaged 68 per cent of annual flow and varied between 2.7 GL in 2006 and 37.4 GL in 1974. Over the same period, the environmental flow for Juniper Reach averaged 79 per cent of annual flow and varied between 2.2 GL in 2006) and 30.4 GL in 1974. In both reaches, the environmental flow retained much of the variability present in the historical flow.

The environmental flows that we determined in this study suggest that further development is possible in Wilyabrup Brook while still providing the water regimes needed to maintain the health, abundance and diversity of aquatic species.

1 Introduction

This report describes how the Department of Water developed environmental flows for two reaches of Wilyabrup Brook in the south-west of Western Australia – Juniper Reach in the middle of the catchment, and Woodlands Reach in the lower catchment. An environmental flow is the water regime that maintains the ecological values of water-dependent ecosystems at a low level of risk.

When developing an environmental flow we consider the flow requirements of endemic fish and aquatic invertebrates, amphibians and plants. We also consider the dependence of terrestrial species on the presence of water, especially during the dry season.

We developed the environmental flows with reference to a number of flow events that have known ecological functions. We considered changes to the timing, frequency and duration of these ecologically important flow events, their annual and seasonal pattern and inter-annual trends. We must retain these flow events and their functions in the environmental flow to maintain the structure of river ecosystems in Wilyabrup Brook.

1.1 The purpose of this study

The results of this and other environmental flow studies will support water resource planning in the Whicher resource management area. Refer to the *Whicher area surface water allocation plan* (Department of Water 2009).

The Wilyabrup Brook catchment and other catchments in the Whicher area have a long history of water resource development that mainly supports irrigated agriculture. As a result, large areas of the upper and middle catchment have been cleared of vegetation, including riparian vegetation.

This irrigation industry is reliant on water captured in on-stream farm dams. Water is used during the following dry season to irrigate crops such as grape vines. Wilyabrup Brook and its tributaries are priorities for research due to the high demand for water for irrigated agriculture and declining rainfall and runoff in the state's south-west.

The results of this study will help guide future water allocation decisions in the Wilyabrup Brook catchment. Allocation limits are needed in the Whicher area to guide licensing decisions, and to manage the impact that farm dams have on flow, reliability of supply to other users and water-dependent ecological values. The results of this study will also support the evaluation of the *Whicher area surface water allocation plan* (Department of Water 2009), the development of environmental flow targets and a monitoring and evaluation framework for the Whicher area.

2 Catchment description

Wilyabrup Brook is located in the Leeuwin-Naturaliste region of the south-west of Western Australia (WA), approximately 220 km south of Perth and 15 km north of Margaret River (Figure 1). The brook arises west of the Dunsborough fault near the town of Cowaramup, and flows north-west toward the coast and into the Wilyabrup Estuary. The mouth of the brook lies between the coastal towns of Yallingup and Gracetown. Wilyabrup Brook extends approximately 11.5 km inland, and has a total stream length of nearly 20 km. The total catchment area is approximately 90 km^2. Woodlands Brook is the main tributary in the Wilyabrup system, draining the north-east portion of the catchment (Figure 1).

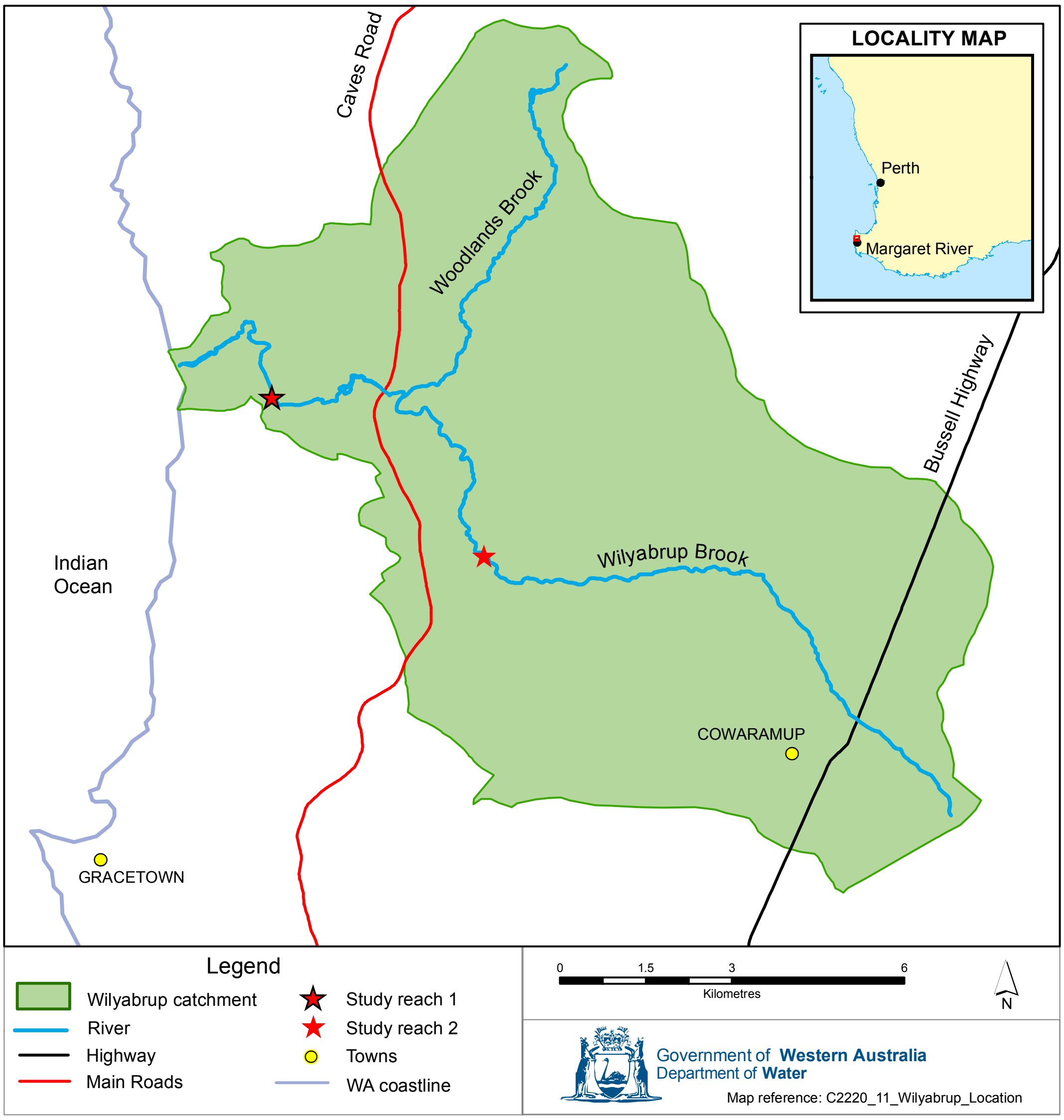


Figure 1 Location of Wilyabrup Brook and the environmental flow study reaches

Approximately 75 per cent of the Wilyabrup Brook catchment has been cleared of native vegetation (Figure 2). The upper section of the catchment is approximately 80 per cent cleared, whereas the lowest section of the catchment, downstream of the confluence of Woodlands Brook and Wilyabrup Brook, contains mostly intact native vegetation.

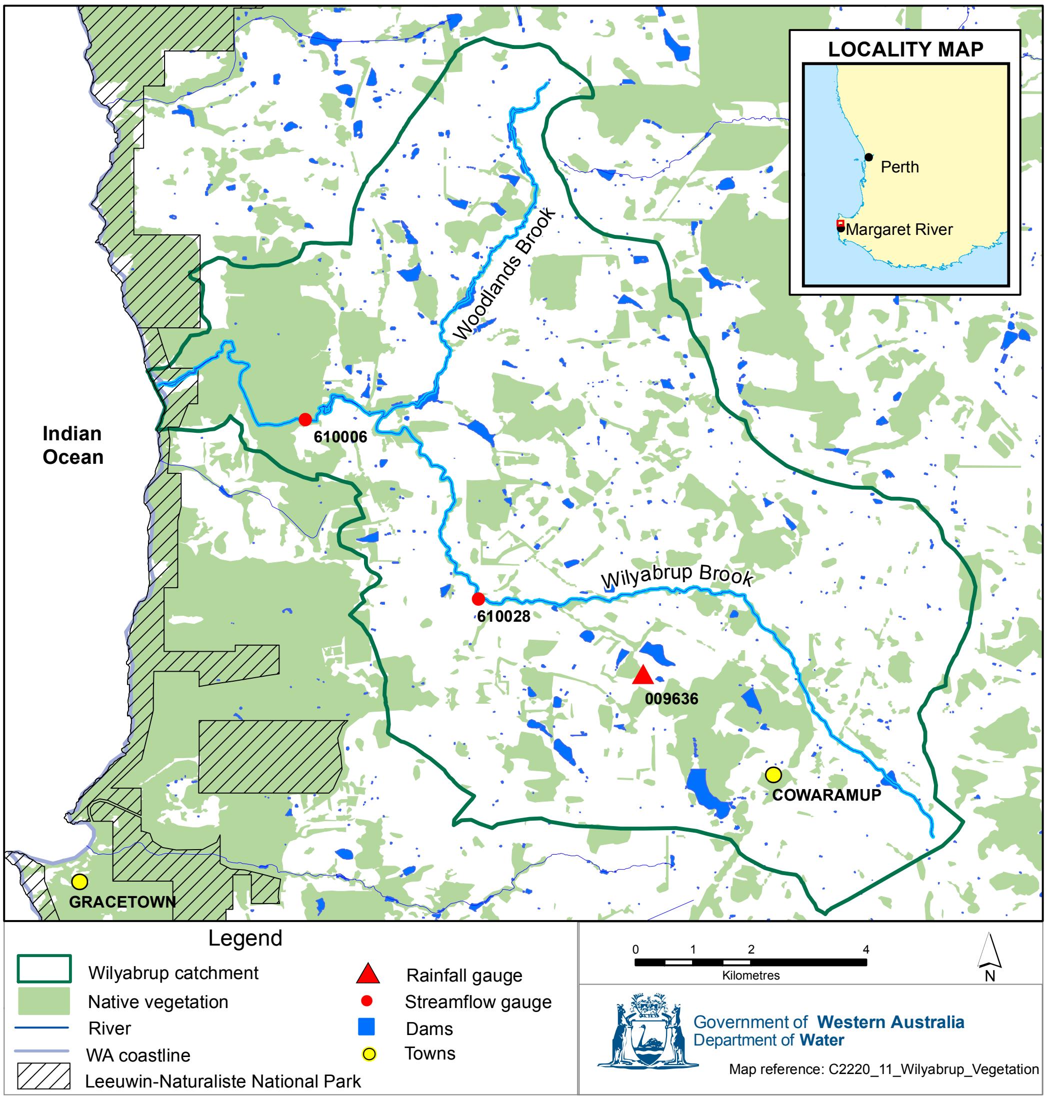


Figure 2 Areas of cleared and uncleared land in the Wilyabrup Brook catchment and the location of farm dams

This study focuses on two reaches of the Wilyabrup Brook (Figure 1) that are representative of its lower (Woodlands Reach) and middle (Juniper Reach) catchments. Further information on the study sites and how they were selected is provided in Section 4.2.

2.1 Climate

The Wilyabrup Brook catchment has a Mediterranean-type climate with hot, dry summers and mild, wet winters (Jury 2006). Rainfall increases along a gradient from north to south and from the coast in an inland direction, and is highly seasonal with approximately 78 per cent of annual rainfall occurring between May and September (Department of Water 2007).

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. In summer and autumn (December to May), monthly rainfall can be highly variable between years due to infrequent weather events such as summer thunderstorms.

Between 1975 and 2012 the average annual rainfall in the catchment was 1000 mm and ranged between 1237 mm in 1980 and 711 mm in 2006 (Figure 3). However, rainfall has declined over the last four decades and this is predicted to continue into the future (Department of Water 2007; CSIRO 2001) (Figure 3). The decline is particularly noticeable post 2000, with an annual average of 923 mm (2000–2011) compared to 1028 mm from 1975 to 1999 (Hall 2013).

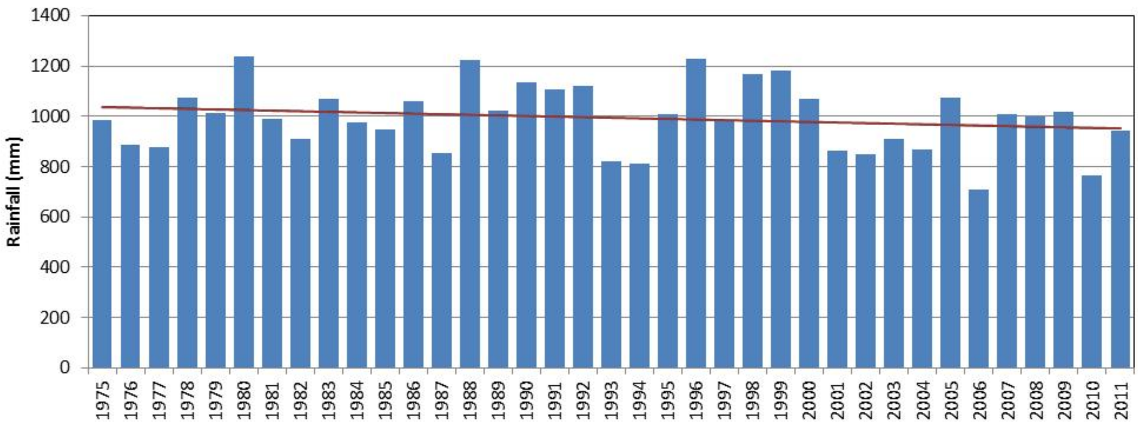


Figure 3 Annual rainfall series and trend for Wilyabrup Brook (from SILO data-drill: -33.80 latitude, 115.05 longitude, 1975–2012) (Source: Hall 2013)

2.2 Water resource development

Wilyabrup Brook flows through mostly agricultural land in its upper and middle catchment, with the downstream reaches flowing through the Leeuwin–Naturaliste National Park. Viticulture is the most prevalent agricultural use, occurring on approximately 40 per cent of the total catchment area (Jury 2006). Other common land uses include grazing and pasture, dairy farming and olive production. Most farming activities either use direct abstraction from the river, or on-stream and off-stream farm dams.

The Wilyabrup Brook catchment has 358 dams, of which 285 have a storage capacity less than 8 ML and are used primarily for stock and domestic purposes

(Table 1) (Hall 2013). There are 88 irrigation dams which comprise 92 per cent of the total dam volume in the catchment. They store between 1 ML and 330 ML of water and have a combined storage of 3.5 GL (Hall 2013). These dams are used to irrigate crops such as olives, wine grapes and nuts. The estimated total catchment demand for irrigated crops is about 1.3 GL/year (Bennett & Donohue 2009). Dam density along Wilyabrup Brook is significantly higher than other systems in the Cape to Cape region (Bennett & Donohue 2009).

Table 1 Dam usage types in the Wilyabrup Brook catchment

Dam usage	Number of dams	Volume (ML)
Aesthetic	13	23
Groundwater soak	3	3
Groundwater soak – off-stream	35	101
Irrigation – direct pump	5	276
Irrigation – on-stream	55	2539
Irrigation – spring rights	28	700
Stock and domestic	156	101
Stock and domestic – soak	63	40
TOTAL	358	3783

The dams are usually completely filled by catchment runoff by mid-May or 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, interception of catchment runoff by on-stream dams can reduce the magnitude of flows during summer and the 'shoulder' periods (between April and June, and November and January).

2.3 Hydrology

Flow in Wilyabrup Brook is gauged at two sites. In the lower reaches, Woodlands gauge (610006) has been recording flow since May 1973 and in the middle reaches, Juniper gauge (610028) has been recording from November 2004 (see Figure 2 for location). From 1974 to 2011, the average annual flow in Wilyabrup Brook (610006) was 22.6 GL and ranged between 4.4 GL in 2006 and 51 GL in 1974 (Table 5 and Appendix B).

Rainfall and runoff rates in the south-west vary seasonally with a high proportion of annual flow occurring between May and November. In Wilyabrup Brook, 98 per cent of annual flow occurs between June and October (Figure 4).

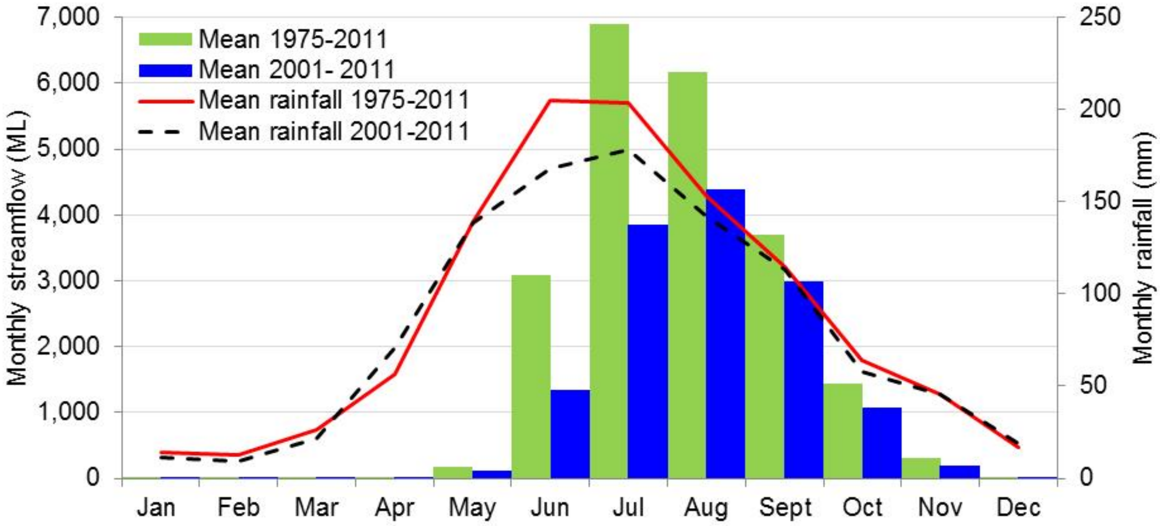


Figure 4 Comparison of mean monthly streamflow in Wilyabrup Brook (Woodlands gauging station 610006) and rainfall (meteorological station 009636) for 1975–2011 and 2001–2011

During the wet season (July to September) heavy winter rainfall results in frequent high flows. Peak flows generally occur between July and August (Figure 4).

Many streams in the south-west cease to flow for long periods in the dry season (summer/autumn). Between January and April, Wilyabrup Brook flows intermittently (Figure 5). Seepage and releases from the many farm dams in the catchment may mean that very low flows (trickles) persist between the storages and relatively small summer rain events may produce brief periods of runoff from saturated channel areas (Figure 5). This could explain why, at the bottom of the catchment (Woodlands gauge) (Figure 2), flows greater than 0.1 ML/day occur for around 11 per cent of the dry season (Department of Water 2007).

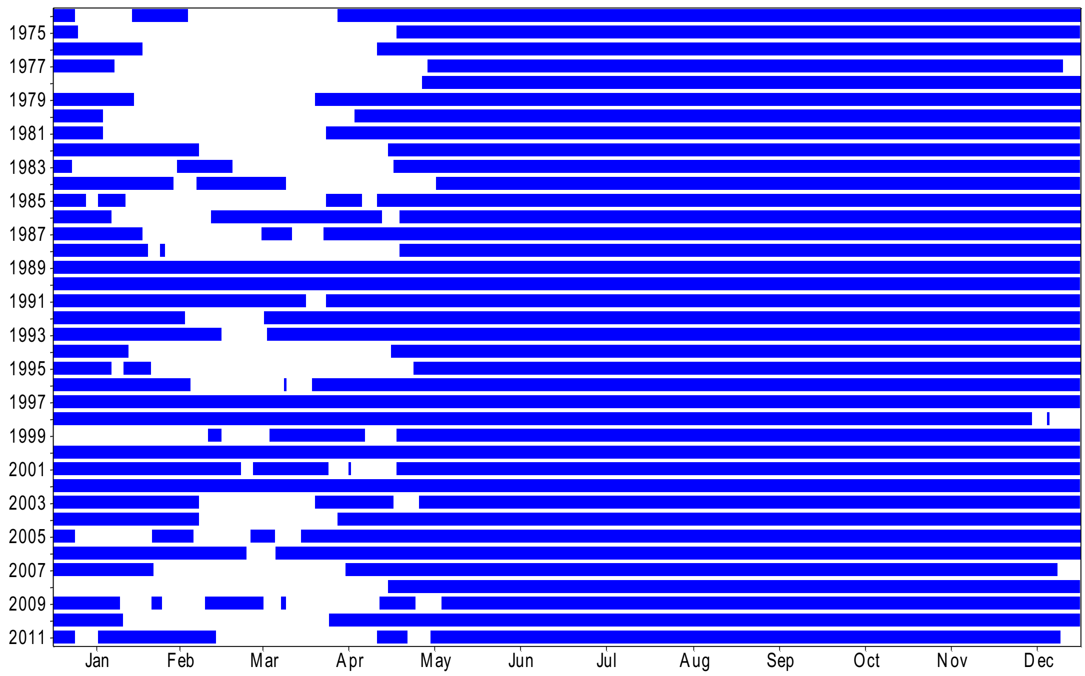


Figure 5 Flow above 0 ML/day in Wilyabrup Brook between 1975 and 2011 (Woodlands gauging station 610006)

The drying climate in the south-west has led to significant reductions in streamflow in rivers such as Wilyabrup Brook (Barron et al. 2012). This is particularly evident between 2000 and 2010, with the dry season getting longer and a reduction in the frequency and intensity of winter rainfall events (Figure 4 and Figure 6). As a result, wet season flows have declined since 2000 (Figure 4 and Figure 6).

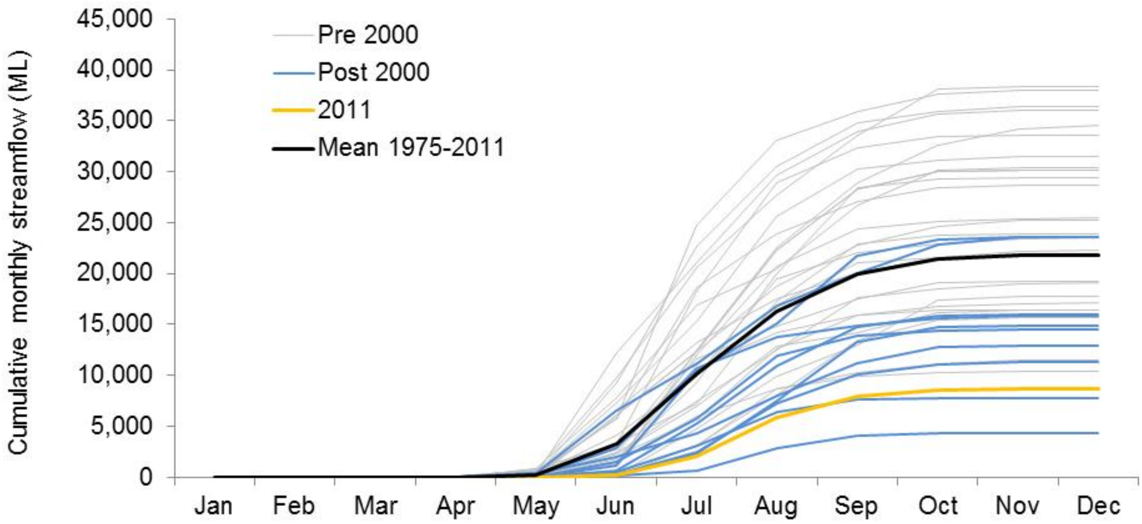


Figure 6 Cumulative monthly streamflow in Wilyabrup Brook (Woodlands gauging station 610006)

3 Ecological values and the flow regime

The water-dependent ecological values of a river develop as a result of long-term flow regimes, the presence and availability of habitat and the pattern of inundation of these habitats (Pen 1999; Poff et al.1997). It is important to understand the components of the flow regime that support a river's ecological values, so they can be maintained into the future.

To develop an environmental flow we need to consider the ecological values of the system. The existing environmental attributes and ecological values of Wilyabrup Brook have been described by Wetland Research and Management (2007a, 2008) and Jury (2006) and are summarised in Appendix A. 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.

In the following sections we discuss the relationship between the flow regime and the ecological values of Wilyabrup Brook, and how they should be considered in developing an environmental flow.

3.1 Vegetation

Environmental flows needed by riparian vegetation generally assume that there is water-dependent vegetation on the river banks and floodplain which requires periodic inundation to a shallow depth to disperse seed and saturate soils, promoting seed set (Pettit & Froend 2001; Wetland Research and Management 2007b). It is therefore important that the regularity of high flow events are preserved within the environmental flow regime, because these events inundate the top of river banks and commence the inundation of the floodplain.

Strong winter baseflows also have an important role in maintaining the morphology of the low-flow channel (active channel) by scouring and preventing the encroachment of riparian vegetation. These events need to occur at regular intervals throughout winter to maintain the variety of functional habitats found within the low flow channel, such as pools, riffles and aquatic vegetation.

3.2 Aquatic invertebrates

In the south-west of Western Australia, there are two main features that influence the community structure of aquatic fauna in rivers: seasonality; and predictability of flows (Wetland Research and Management 2007b). Variations in the seasonality of flow influence the structure of invertebrate communities and can lead to changes in life history patterns (Bunn et al. 1989).

Stream permanence has been found to be an overall determinant of the abundance and diversity of aquatic invertebrate fauna (e.g. Bunn 1986 and Bunn et al. 1989). Streams with intermittent flows have distinctive aquatic faunal communities compared with those of permanently flowing streams (Aquatic Research Laboratory

1989; Storey et al. 1990). Some macroinvertebrate species are found only in intermittent streams, while abundances of other species vary greatly between permanent and intermittent streams (Bunn et al.1989).

Spring and summer spawning is a common life-history characteristic of aquatic invertebrates in south-west Western Australia. Very few species breed during the wetter winter months, multiple times a year, or are capable of breeding year-round. Therefore some spring and summer flows, where present, should be maintained to enable breeding.

Invertebrate diversity depends on habitat complexity and diversity, because 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. In south-west rivers, inundation of these habitats begins in early autumn, providing stress relief following the dry season. These low-velocity flows are enough to oxygenate the riffle and sandy run habitats and are also important as flows decline leading into the dry season.

Some aquatic invertebrate species are associated with habitats such as snags, rocks, macrophyte beds and trailing riparian vegetation. They include oligochaetes, freshwater crayfish, larvae of many dragonfly and damselfly species, and most species of chironomid and caddisfly. To maintain the distribution and abundance of these taxa, it is important to maintain flows that will inundate snags, rocks, macrophytes and some overhanging riparian vegetation. This inundation is usually achieved during a high winter baseflow.

3.3 Fish

The breeding ecology of endemic fish species is strongly related to river flow. Components of fish biology most likely to be impacted by altered flow regimes are migration and reproduction, and access to spawning habitat (WRM 2007b).

Two endemic freshwater fish species found in Wilyabrup Brook (pygmy perch and western minnow) migrate upstream in winter and spring for breeding (Pen 1999). With the onset of winter flows in June or July, these species disperse from summer refuges to forage and move upstream to small side tributaries. Here they spawn on flooded vegetation and submerged reed beds (Wetland Research and Management 2008).

Fish also migrate to refuges such as permanent pools and flowing reaches in summer. Most spawning is likely to occur upstream of pool refuges and is over by August or September (Pen 1999) with fish requiring less water to move downstream between October and November.

There are many natural and artificial obstacles that can impede upstream migration of fish including logs, shallow riffles, rock bars, dams and weirs. Thus, the maintenance of winter flows that submerge these obstacles is necessary. Small-bodied fish such as the western minnow and western pygmy perch require a minimum depth of 0.1 m above obstacles to ensure migration, whereas large-bodied species such as the freshwater cobbler (not previously sampled in Wilyabrup Brook) require 0.2 m. Flows sufficient to drown out barriers 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 fish may be intense (Pen 1999).

The duration and frequency of inundation of trailing and fringing vegetation can influence recruitment success of endemic fish and should be maintained by the environmental flow. For example, if water levels fall too soon, or fluctuate greatly, fish eggs may be left above the waterline and may dry out. Flooded vegetation and shallow, flooded off-river areas also provide sheltered, low-velocity nursery areas for growing juveniles (Wetland Research and Management 2008). Less successful recruitment may occur in years when reed beds and trailing vegetation are inundated for less than five consecutive weeks. For fish with long life spans (three to five years) such as pygmy perch, high rates of recruitment do not need to occur every year in order to maintain healthy populations. Poor recruitment years occur naturally during periods of low rainfall.

Of the five endemic fish species sampled from Wilyabrup Brook (see Appendix A) none have physiological adaptations to withstand desiccation. These species rely on the presence of permanent water.

Environmental flows to maintain endemic fish species in Wilyabrup Brook should include:

- Flows that maintain refuge pools in summer to ensure the survival of native species.
- Predictable winter/spring flooding to ensure breeding success and strong recruitment in the western minnow. Sufficient water is required to inundate trailing riparian vegetation which is the preferred spawning habitat of the wester minnow in winter (Wetland Research and Management 2007b).
- Flows to provide for fish passage maintained at the current frequency and duration of fish passage events.

3.4 Frogs and reptiles

Most amphibians require surface water to lay eggs, and the water needs to be present for periods longer than six weeks for tadpoles to mature into adult frogs. Amphibians generally breed during the wet season in shallow waters at the edges of rivers and swamps and in small, flooded depressions. Frogs spawn on emergent and submergent vegetation (Tyler et al. 2000). Tadpoles require seasonal water in the form of backwaters, shallows, still pools or flooded vegetation on the floodplain (Wetland Research and Management 2007b). Therefore, environmental flows to meet the objectives for macroinvertebrate habitat and floodplain inundation would be sufficient to ensure the survival of frogs' eggs and tadpoles.

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 tolerance of species to changes in water availability has been poorly studied. In the absence of specific information, it is assumed that terrestrial reptiles are dependent on elements of the flow regime that maintain riparian vegetation and habitat, and 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.

3.5 Waterbirds

The ecology and habitat requirements of waterbirds must be considered at the landscape scale. Although many bushland birds use riverine habitats for nesting and as a source of water and food, these habitats are of only marginal value to most of the South West region's waterbirds (Pen 1999). However, the sections of Wilyabrup Brook where the banks are still lined with paperbarks, peppermints and eucalypts provide important breeding habitat for a limited variety of waterbirds, including tree-nesting ducks and herons. In addition, some species may depend on riparian vegetation corridors for their survival (Pen 1999).

No studies have specifically considered the water requirements of waterbirds in the south-west of Western Australia. However, some birds, such as heron, egrets and ducks, use the deeper, more permanent river pools as a summer refuge or as a hunting habitat. Heron, egrets and spoonbills feed almost entirely on aquatic fauna or other animals associated with waterways and wetlands. For diving birds such as cormorants and grebes, the high concentration of aquatic animals such as fish and invertebrates in permanent pools during the dry summer months, provides an important seasonal source of food.

In the absence of species-specific information on water-dependency, it is assumed that waterbirds associated with Wilyabrup Brook are dependent on the health of riparian vegetation, regular inundation of the floodplain and its wetlands, flows that maintain river pools and on the ecological process that maintain food webs and aquatic species diversity.

3.6 Mammals

Of the mammals known to occur along Wilyabrup Brook, water rats are the most closely associated with the river system. The two species of possums and the brush-tailed phascogale rely on dense vegetation and hollow-bearing trees, which often occur near rivers and streams.

Water rats are reliant on aquatic food webs, the presence of healthy riparian vegetation and the processes that maintain them. They are also known to suffer heat stress without access to water. As such, large permanent pools and flowing reaches with good riparian vegetation are essential habitat for water rats in intermittent streams.

To meet the environmental flow requirements of water rats in Wilyabrup Brook, flows to maintain depth in river pools either side of the dry season and to inundate riparian vegetation high on the river banks during winter should be maintained.

3.7 Carbon sources and ecosystem productivity

Aquatic ecosystems rely on energy from organic carbon from riparian zones (Water and Rivers Commission 2000). Flow-related processes that control the sources, fate and availability of carbon in food webs need to be considered in developing an environmental flow.

Many factors influence the production of carbon in rivers, including light penetration, nutrient levels and flows. Human activities such as clearing of riparian vegetation and flow regulation can substantially alter aquatic life through changes to the carbon cycle.

Some carbon enters rivers as fine particulate matter derived from upstream terrestrial vegetation. This process requires the connection of downstream and upstream river reaches (Vannote et al. 1980). 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 litter falling directly from overhanging vegetation. Carbon may also enter river systems as dissolved organic and inorganic carbon in groundwater and soil water. Direct inputs of carbon from in-stream production (phytoplankton and benthic algae) and processing of carbon through fungal, microbial and invertebrate pathways are also important in maintaining food webs.

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

Environmental flows to support carbon input and movement along Wilyabrup Brook should include:

- Winter flows to maintain upstream–downstream linkages and the transport of energy/carbon.
- Winter flows to maintain riparian vegetation as an energy source. For example, flows that inundate channel benches and wash leaf litter into the aquatic ecosystem.

- Flood flows to maintain carbon/energy linkages between the channel and it’s floodplain by inundating all channel benches to the top of bank.

4 Developing the environmental flow

4.1 Overview of approach

To determine a low-risk environmental flow for Wilyabrup Brook, the Department of Water used the Proportional Abstraction of Daily Flows (PADFLOW) method. PADFLOW was developed by the department to better define the flow regime of rivers with highly variable flow patterns, such as those in the south-west of Western Australia (Donohue et al. 2009a). It allows us to incorporate the timing, frequency and duration of ecologically important flow events we need to maintain within the environmental flow. The steps we followed are shown in Figure 7.

In PADFLOW, the environmental flow is developed from a gauged or modelled flow data time-series (historical flow record). Using the RESYM (River Ecologically Sustainable Yield Model) water balance model, proportions of daily flow are removed from different flow ranges (see Section 5). This is done in an iterative manner where a study team adjusts the proportions removed and assesses changes to the timing, frequency and duration of ecologically important flow events. We aim to maximise the abstraction of water from the existing flow regime without impacting on the current ecological values of the system. The remaining water left in the system is referred to as the environmental flow.

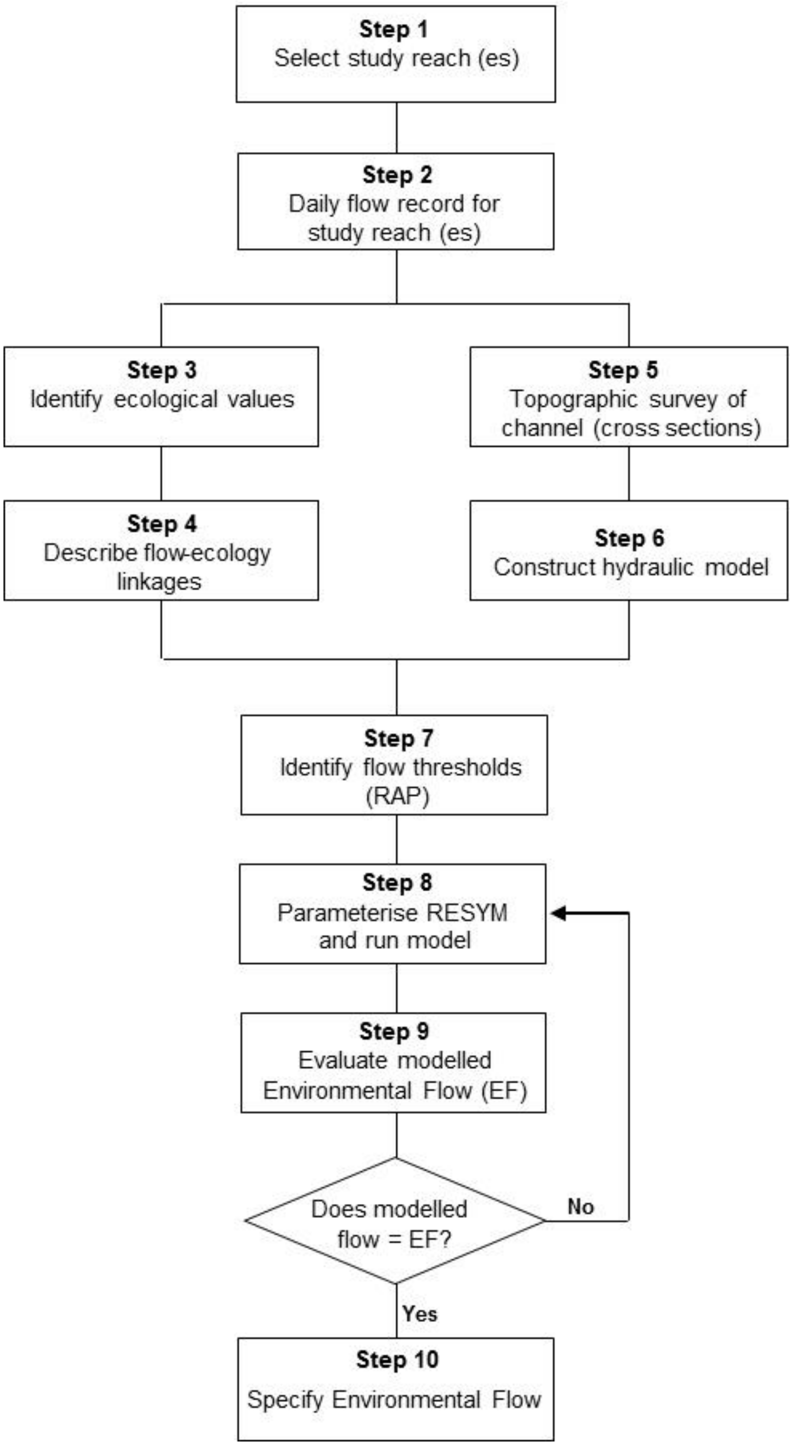


Figure 7 Flow chart showing steps in the Proportional Abstraction of Daily Flows (PADFLOW) method

4.2 Study reaches

We used data collected from two reaches representative of the lower (Woodlands Reach) and middle (Juniper Reach) sections of Wilyabrup Brook (Figure 1 and Figure 8). Two reaches were selected to capture the variability in habitat and channel form over the 20 km of stream length, with the lower reaches consisting of steep, cascading sections through national park, and the middle to upper reaches flowing through agricultural land.

When selecting the location for each study reach we considered accessibility, 'naturalness' of the channel morphology and proximity to a gauging station. The channel form is particularly important as it determines the magnitude of flows needed to inundate important habitats. Highly modified reaches, such as those cleared of vegetation, are not usually selected for environmental flow studies because it is difficult to identify critical hydraulic points and habitat types.

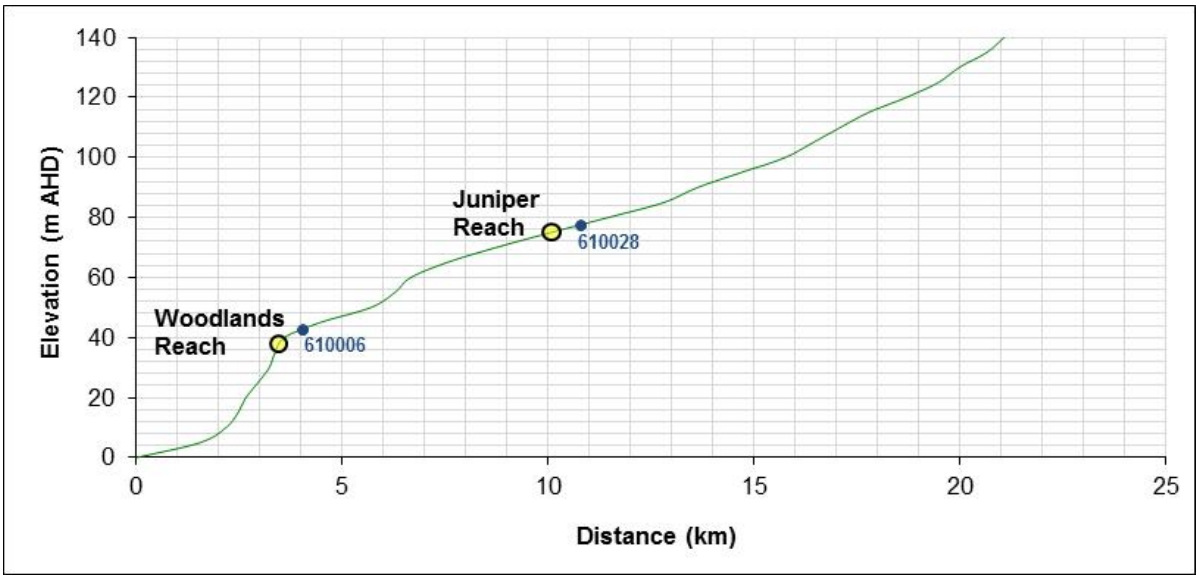


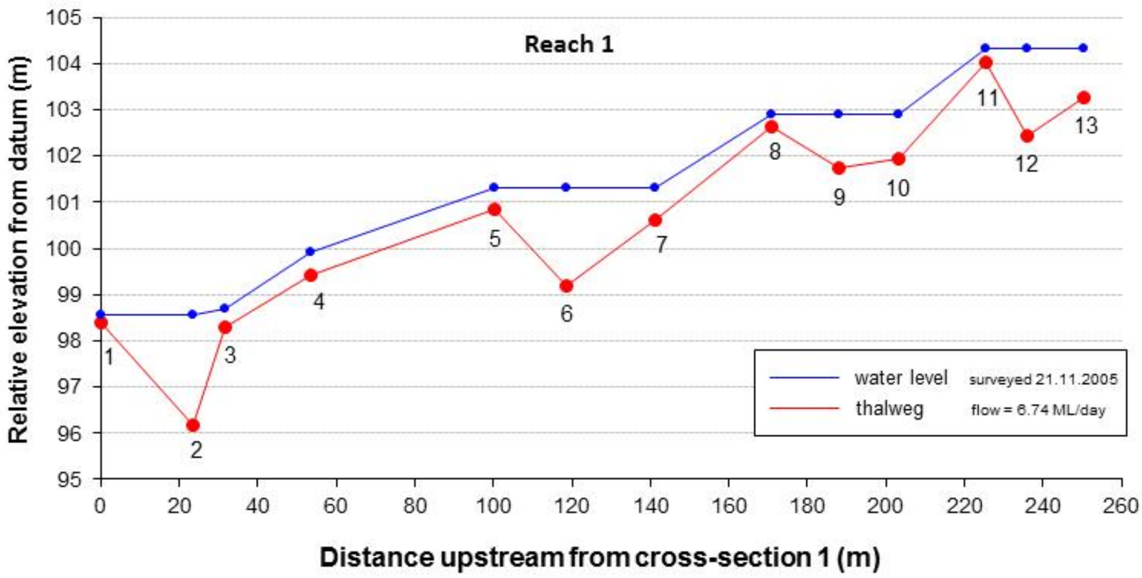
Figure 8 Elevation of Wilyabrup Brook from its point of discharge at Wilyabrup Estuary, to its headwaters near the town of Cowaramup

Woodlands Reach, located in the lower catchment between Caves Road and the river mouth (Figure 1), is a cascading reach that flows through the Leeuwin–Naturaliste National Park. It has a total length of 250 m and runs through relatively intact native vegetation. The reach is steep, dropping 6 m over its length, and consists of a series of four pools and three cascades flowing over large granite outcrops and boulders (Figure 9). Some of the pools are more than 2 m deep (Figure 11).

Figure 9 Woodlands Reach of Wilyabrup Brook with deep, slow flowing pool (left) and cascade flowing over granite outcrop (right). The flow rate is approximately 1.3 m^3/s

Juniper Reach is located in the middle of the catchment and flows through cleared agricultural land along a shallower, less rocky section of the brook within the gently undulating Margaret River Plateau (Figure 10). The reach is 350 m in length and has a lower gradient than Woodlands Reach, dropping less than 2 m over its length (Figure 11).

Figure 10 Juniper Reach of Wilyabrup Brook with deep, slow flowing pool (left) and riffle flowing over exposed laterite (right). The flow rate is approximately 0.5 m^3/s



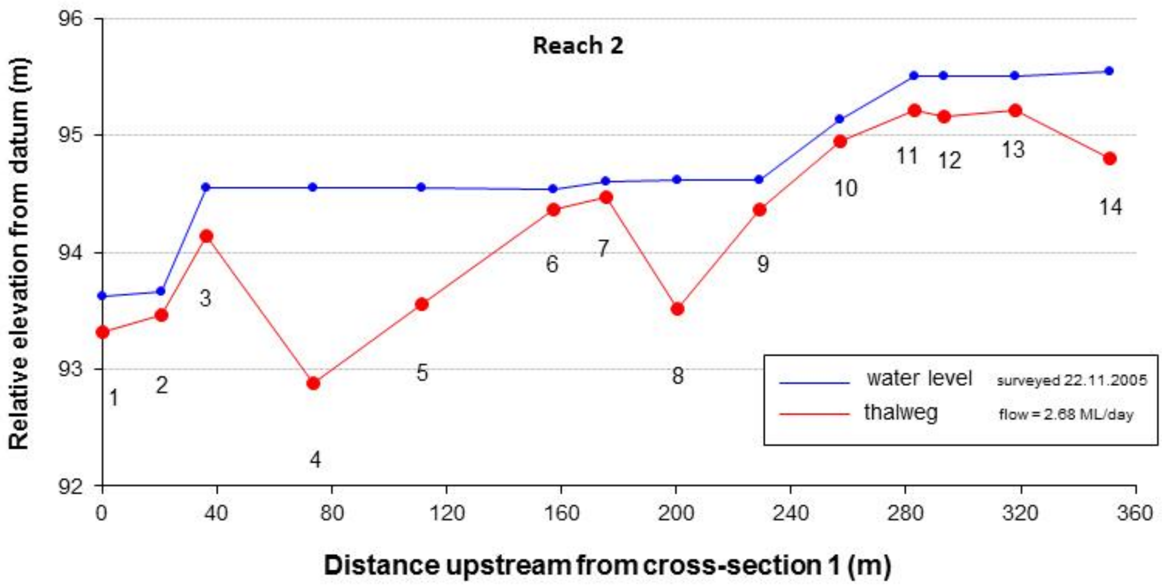


Figure 11 Longitudinal profiles of Woodlands Reach (upper plot) and Juniper Reach (lower plot) showing a series of pools separated by cascades or riffles

4.3 Flow data

RESYM requires a daily flow time-series covering a period that represents the variation in a river's flow regime.

Flow in the Woodlands Reach has been described using daily flow records (January 1974 to December 2011) from the Woodlands gauging station (610006), 500 m upstream (Figure 2).

Juniper gauging station (610028), located approximately 400 m upstream from Juniper Reach (Figure 2), has daily flow records from November 2004 to the present.

A daily flow record for Juniper Reach was constructed for the period January 1974 to 2011 based on the relationship between daily flow recorded at Woodlands and Juniper gauging stations for the period November 2004 to July 2012 (Figure 12). There is a good correlation between the two datasets (R^2 = 0.87) which is not surprising given they are both on the brook and have similar rainfall, soil and vegetation types.

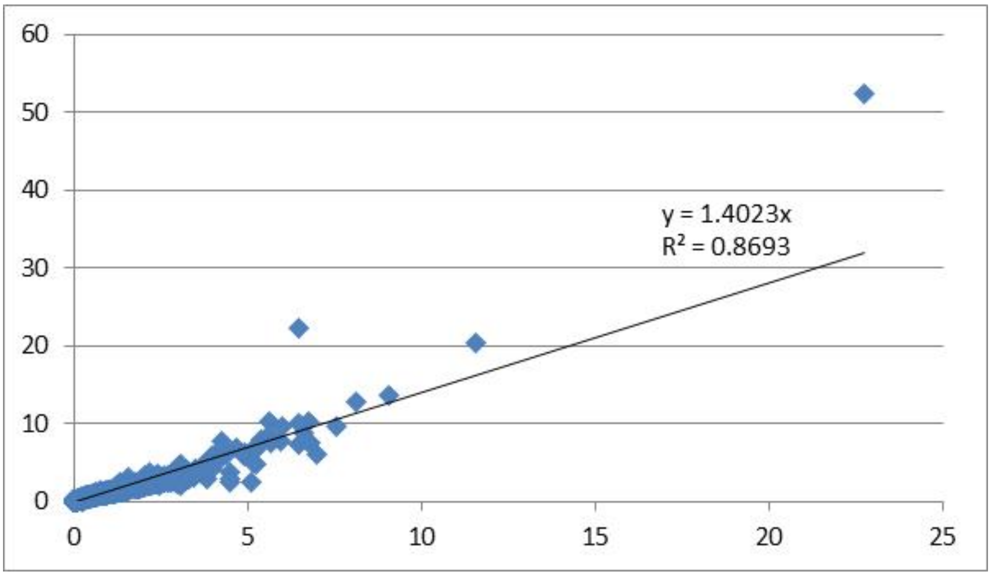


Figure 12 Plot showing the correlation between the Woodlands and Juniper gauging stations using data from November 2004 to July 2012

4.4 Hydraulic modelling

An essential component of environmental flow studies is determining the flow rates needed to achieve specific ecological functions such as the inundation of key habitats for aquatic fauna. To do this, we create hydraulic models of our study reaches. The models can predict the change in the depth of water in key habitats at different flow rates allowing us to determine the critical flow at which a particular habitat (such as a rocky riffle run) becomes inundated.

To construct hydraulic models we use a series of channel survey cross-sections and characterise the shape and variability of the channel profile (Step 5 in Figure 7). The cross-sections are located at key hydraulic and ecological features such as rock bars, backwaters, pools, riffles, channel benches, large woody debris and channel constrictions (Figure 13).

To model the channel geometry we surveyed 13 cross-sections at Woodlands Reach (Figure 14) and 14 cross-sections at Juniper Reach (Figure 15). Water levels were surveyed at each cross-section to assist with the model calibration.

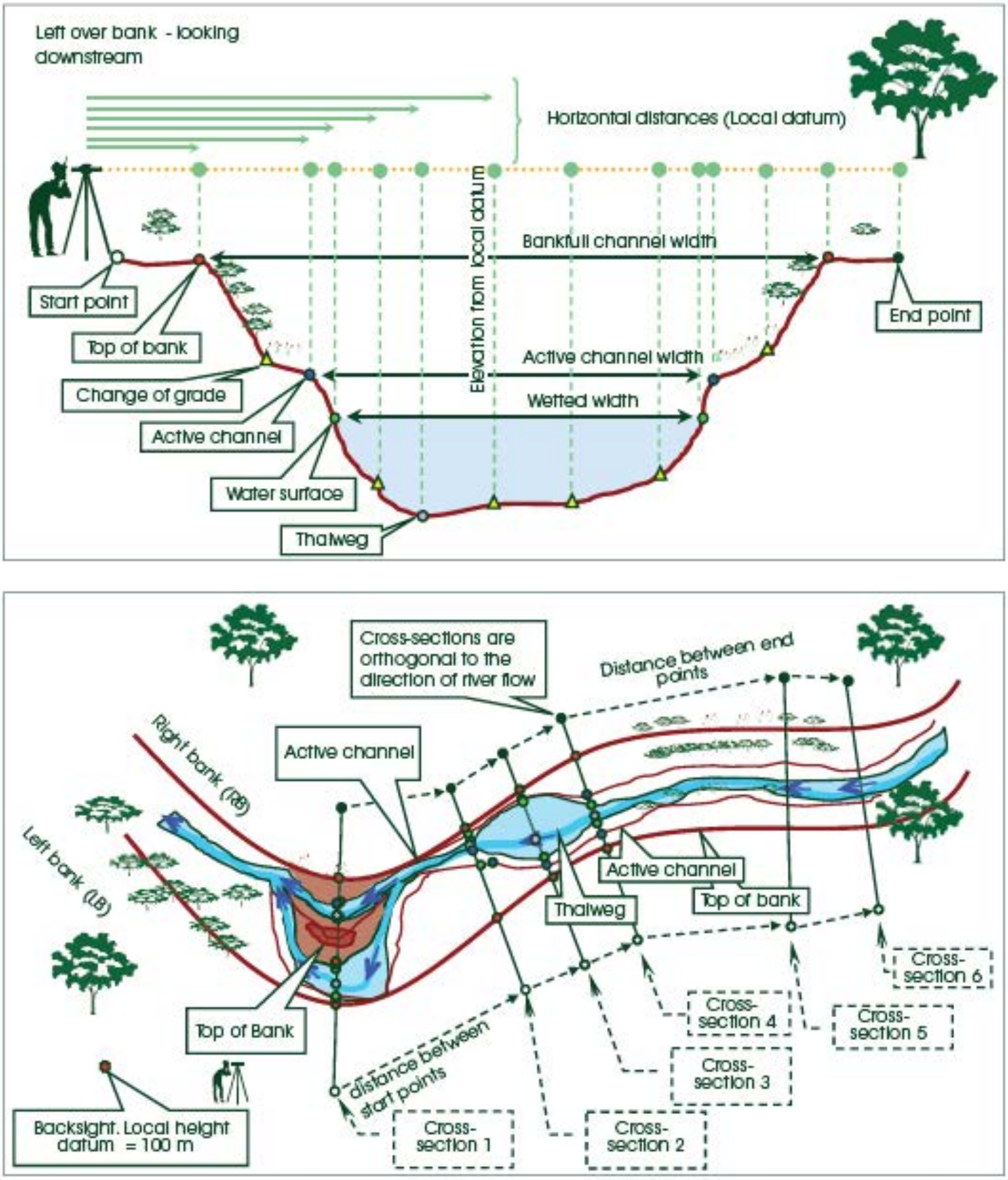


Figure 13 The upper graphic is a schematic showing point data collected on each cross section; the lower diagram shows the longitudinal layout of cross-sections along a river reach

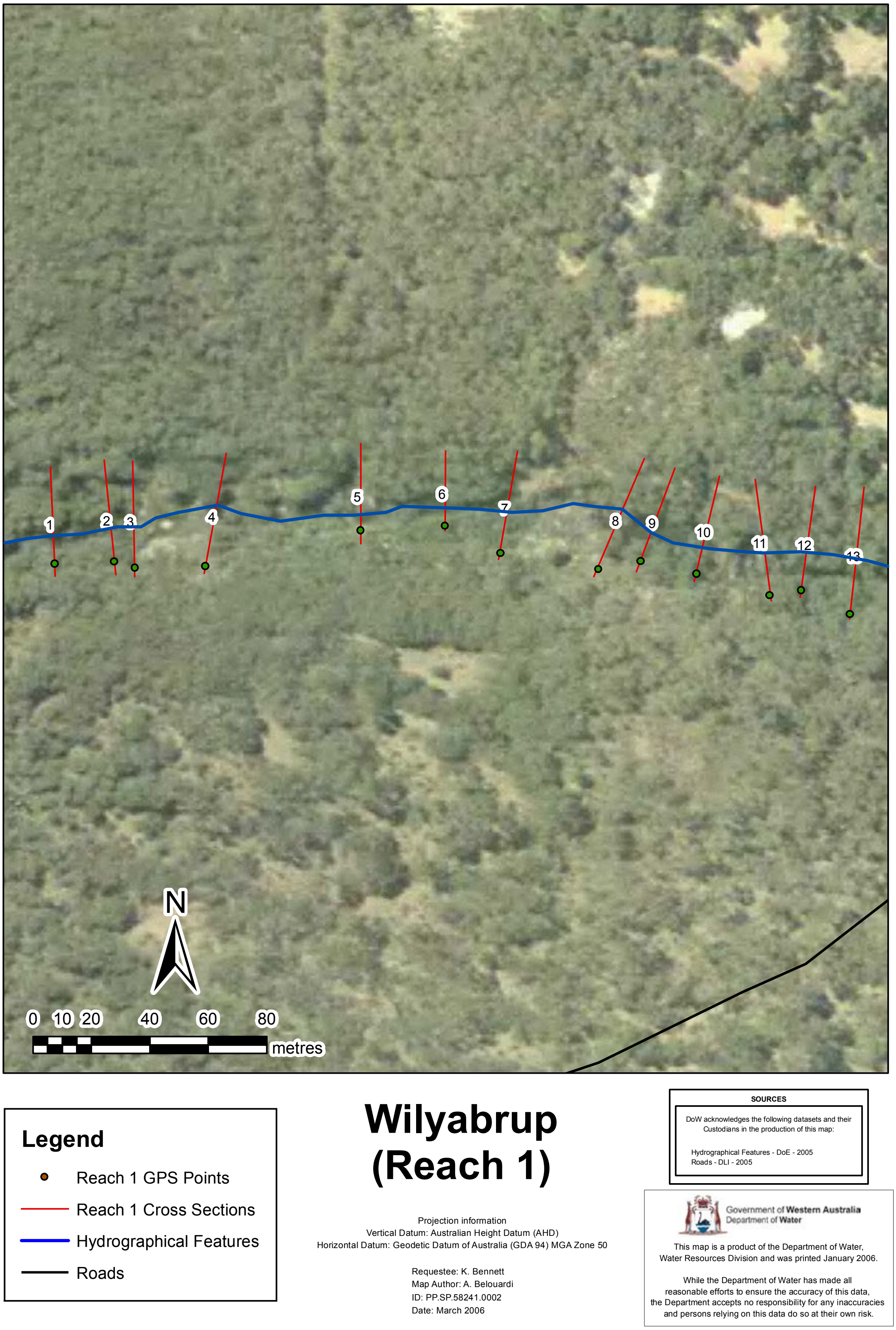


Figure 14 Location of cross-sections in Woodlands Reach

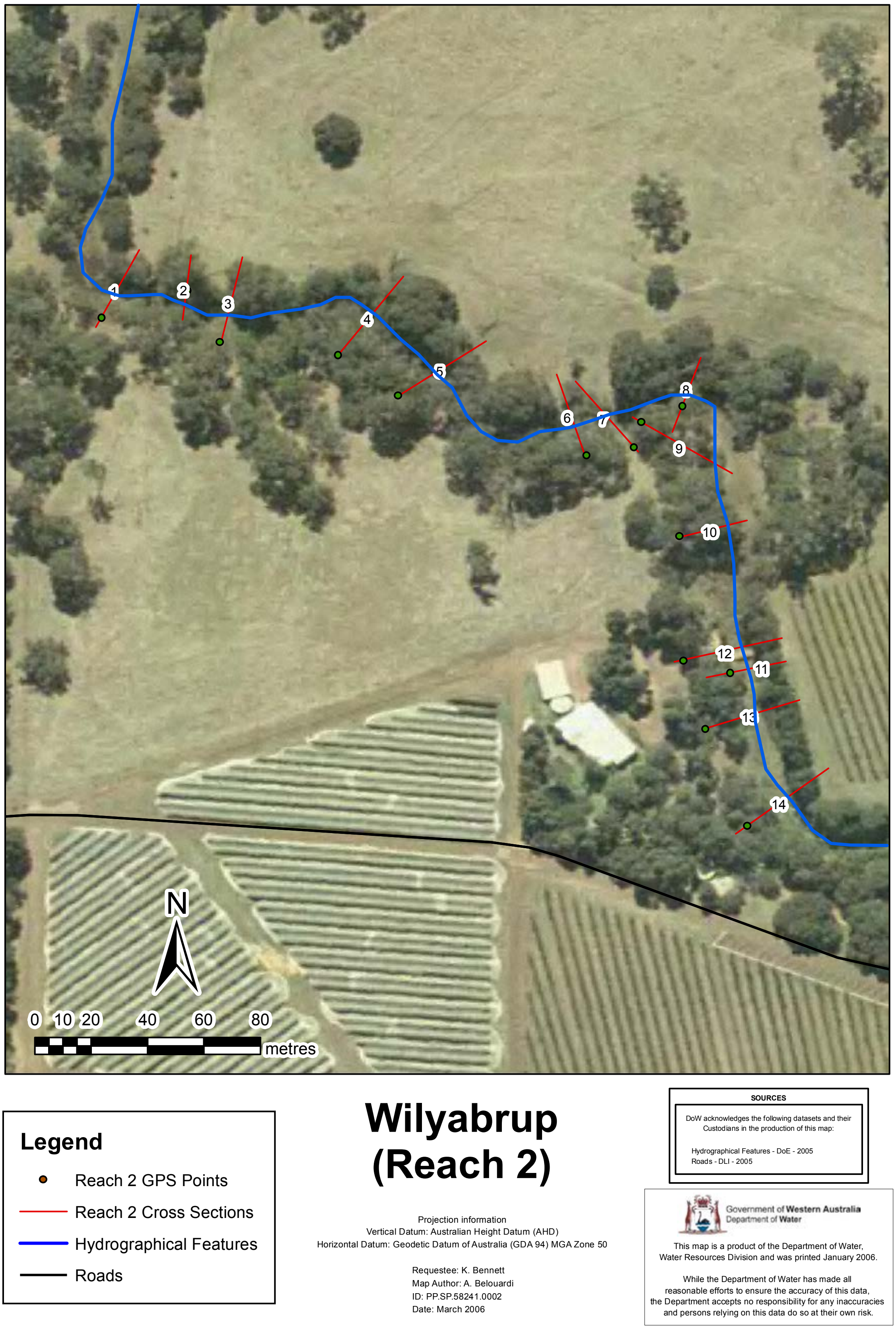


Figure 15 Location of cross-sections in Juniper Reach

The cross-sections were used to construct hydraulic models of the river channel in reaches 1 and 2 using the Hydrologic Engineering Center's River Analysis System (HEC-RAS). To calibrate the models, discharge measurements were taken during the 2006 flow season and related to surveyed water level heights at three cross-sections within each reach (downstream, mid-reach and upstream). A diagram of the hydraulic model created for Woodlands Reach is shown in Figure 16.

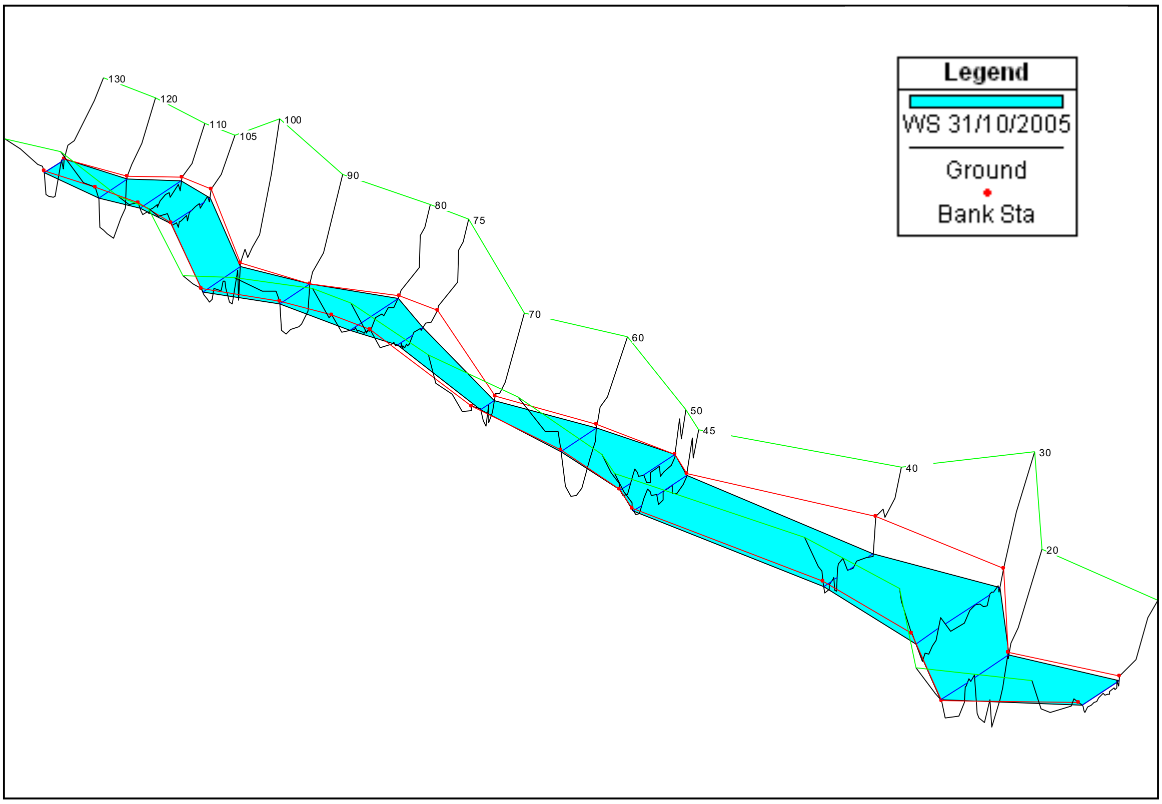


Figure 16 Structure of the HEC-RAS hydraulic model for Woodlands Reach; the blue trace shows the water level at the time of the channel surveys

At low flows, water level in Woodlands Reach is controlled by the cascade sections. Even at high flow, the steep and rocky cascades strongly influence the water level (Figure 11 and Figure 16). No riffle sections were noted within Woodlands Reach.

A number of shallow, controlling riffle features are present throughout Juniper Reach (Figure 11). These features generate turbulence and high velocity, even when flow volumes are relatively low. Water velocity is slower and less turbulent in the pools between riffles.

4.5 Ecological-flow thresholds

Using the ecological values assessment (Section 3 and Appendix A), the surveyed heights of ecological and hydraulic features on the channel (Section 4.4) and standard methods used in previous studies (e.g. Wetland Research and Management 2005a and 2005b; Donohue et al. 2009a) we developed flow-ecology rules for Wilyabrup Brook (Table 2). The flow-ecology rules are minimum flow or water level requirements, above which a specific ecological function is achieved. The flow rate required to achieve these flow-ecology rules is referred to as the 'ecologically critical flow rate' or 'ecological-flow threshold'.

Ecological-flow thresholds are the critical flows that maintain:

- aquatic habitat (for fish, invertebrates, frogs, water rats and turtles)
- migration pathways
- vegetation condition
- channel form
- carbon cycles
- water quality.

We used the River Analysis Package (RAP) program to determine the critical flow rates for each study reach (Table 2). RAP uses HEC-RAS (see Section 4.4) to model water depth at each cross-section with different rates of flow. We used the flow-ecology rules (see Table 2) in the RAP to identify the flow rate that achieves a particular water depth and associated ecological outcome at channel features such as rock bars, benches, pools and riffles.

The flow-ecology rules, the ecological-flow thresholds and the corresponding ecological functions for both study reaches are detailed in Table 2 and discussed in the following sections. It should be noted that each flow may fulfil multiple ecological objectives including some at flows below the threshold, as well as other ecological outcomes not specifically considered in this study.

Table 2 Ecologically critical flow rates for Woodlands and Juniper reaches of Wilyabrup Brook

Flow-ecology rule	Flow threshold		Ecological functions
	Woodlands Reach	***Juniper Reach***	
Water depth of 5 cm over 50% of width of riffles	N/A	5.18 ML/day	Provide spring/summer riffle habitat for macroinvertebrates
Minimum flow velocity of 0.01 m/s in pools	18.1 ML/day	7.78 ML/day	Maintain water quality and dissolved oxygen levels in pools Downstream carbon movement maintained through connectivity between pools
Minimum thalweg depth of 10 cm over all cross-sections	N/A	24.2 ML/day	Allow upstream spawning migration of small-bodied endemic fish
Water depth of 5 cm over entire width of riffles	N/A	31.1 ML/day	Provide winter riffle habitat for macroinvertebrates
Inundate benches	N/A	50.1 ML/day	Flush organic matter into river system Allow access to habitat on the benches
Inundate fringing vegetation to a depth of 10 cm	34.6 ML/day	66.5 ML/day	Provide cover and spawning sites for fish and frogs Provide habitat for invertebrates and vertebrates
Inundate active channel	228 ML/day	125 ML/day	Scour and maintain low-flow channel Prevent incursion of terrestrial vegetation Flush organic matter into river system
Inundate to top of bank	598 ML/day	367 ML/day	Inundate high riparian vegetation Inundate and recharge floodplain wetlands Maintain floodplain wetland nursery areas for fish and tadpoles High energy flows to scour pools and maintain channel morphology Flush organic matter into river system

Summer no-flow period

Intermittent streams in south-west Western Australia have distinctive faunal assemblages and any environmental flow should aim to maintain this fundamental flow characteristic. To maintain the natural no-flow period of Wilyabrup Brook we used an ecologically critical flow rate of 0 ML/day.

Macroinvertebrate habitat

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

The flow-ecology rule for inundation of macroinvertebrate habitat was not applied to Woodlands Reach due to its hydraulic nature. This stretch of Wilyabrup Brook is steep and comprised of rocky, cascading sections. Due to its slope there is little lateral inundation of rocky habitat and no riffle cross-sections were surveyed in the reach.

For Juniper Reach the flow rate required to inundate 50 per cent and 100 per cent of the riffle width to a depth of 5 cm was calculated for cross-sections 3, 6, 7, 9 and 10. The ecological-flow threshold was calculated as the average of these cross-sections (Table 2).

Migration of endemic freshwater fish

Freshwater fish move upstream and downstream while foraging, as part of spawning migrations and during dispersal from and retreat to summer refuges.

The minimum water depth criterion for upstream movements of small-bodied endemic fish was set at 10 cm over barriers and shallow sections. The 10 cm minimum is considered conservative for small species such as pygmy perch, western minnow and nightfish (<100 mm total length). No large-bodied native fish (e.g. cobbler) have been recorded in Wilyabrup Brook (Beatty et al. 2006).

The threshold flow for fish migration in Juniper Reach was the flow that maintained the minimum depth over the thalweg at each cross-section (Table 2).

The flow-ecology rule for fish passages was not applied to Woodlands Reach. This part of Wilyabrup Brook is comprised of rocky, cascading sections including drops that are impassable by fish under most flow conditions.

Pool water quality

In order to maintain pool water quality and fish diversity following dry periods in summer and autumn, a minimum average bulk water velocity of 0.01 m/s is recommended. This is the minimum velocity of flow required to avoid stratification and maintain mixing, thereby keeping dissolved oxygen levels above 2 mg/L (sensu Cottingham et al. 2003).

The threshold flow for pool water quality was calculated as the flow that maintains a 0.01 m/s bulk water velocity through all pool cross-sections (Table 2).

Inundation of fringing vegetation

During the cross-sectional survey of both study reaches, the heights of preferred spawning and protective habitats such as reed beds and fringing vegetation were measured. It was assumed that inundating this habitat to a depth of 10 cm will provide suitable cover and spawning sites for fish and habitat for other aquatic fauna such as invertebrates, water rats and frogs.

Using all cross-sections where the height of spawning habitat was measured, we calculated the average depth from the thalweg to 10 cm above the recorded height for each reach. The threshold flow was calculated as the flow that inundates all relevant cross-sections in a reach to this depth (Table 2).

Inundation of riverine benches

A number of ecological outcomes are achieved by inundating benches. The inundation of macrophytes, and trailing and near-channel vegetation provides habitat for foraging by fish, frogs and invertebrates. Flows that inundate benches also wash woody debris and leaf litter into the river, providing structure for habitat and organic carbon to fuel primary and secondary production and support species diversity and food webs.

No riverine benches were surveyed in Woodlands Reach.

Three benches were surveyed in Juniper Reach on cross-sections 6, 10 and 13. For each cross-section, we determined the flow that inundated the entire length of the bench. The three flow rates were averaged to give the threshold flow for bench inundation in Juniper Reach (Table 2).

Inundation of the active channel

Strong winter baseflows or 'active channel' flows influence the size, shape and condition of the channel through physical processes such as scouring (Arthington et al. 1993). They maintain the existing morphology of the low-flow channel by mobilising sediment, scouring, and limiting the encroachment of riparian vegetation. The scouring of river beds and undercutting of banks provides essential habitat for aquatic biota, particularly native fish.

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 above which vegetation is present and below which the bank is bare.

For Juniper Reach, the flow rate required to inundate each riffle cross-section to active channel height (cross-sections 3, 6, 7, 9, 10 and 11) was modelled. The ecological-flow threshold was calculated as an average of these flow rates.

Woodlands Reach is a cascading run and has no riffles (see Section 4.2); therefore all cross-sections were used in the analysis. The flow rate required to inundate each cross-section to the recorded active channel height was modelled and the average of these taken as the ecological-flow threshold (Table 2).

Bankfull and overbank flows

High-energy bankfull flows scour pools and maintain channel morphology, provide carbon to river ecosystems by washing accumulated detritus and leaf litter from benches into the channel, and inundate high riparian and floodplain vegetation.

For both study reaches, all surveyed cross-sections were included in the analysis. The flow rate required to inundate the channel to the lowest top of bank height (i.e. left or right bank) was modelled for each individual cross-section. The average of these flow rates was taken as ecological-flow threshold (Table 2).

5 Determining the environmental flow – RESYM

The environmental flow is determined from the historical gauged flow using the River Ecologically Sustainable Yield Model (RESYM) software.

The RESYM software allows the user to remove a proportion of daily flow relative to the magnitude of flow on any particular day. This is achieved by breaking up the entire range of daily flows in the historical flow record into flow ranges. Varying proportions of daily flow can then be removed from within each flow range. For example, to preserve low flows in summer and autumn, RESYM can be programmed to remove little or no flow in very low flow ranges and more flow in higher flow ranges.

By adjusting the proportion of flow removed from each range, water can be removed, while maintaining the capacity of the remaining flow regime to support water-dependant species and their habitats.

The remaining flow data series is evaluated with respect to its capacity to maintain current ecological values. This evaluation process is based around the timing, frequency and duration of flow events greater than or equal to the ecological-flow thresholds in Table 2.

There are two graphic outputs from RESYM that guide the development of the environmental flow:

- Time-series plots – these allow the comparison of historical and modelled daily flows at any scale over the entire period of record.
- Bar charts – these show changes in the timing, frequency and duration of flow events above the ecological-flow thresholds in the remaining flow regime.

For the two study reaches, daily flows recorded between 1974 and 2011 were placed into five flow ranges (Table 3 and Table 4). Proportions of daily flow were then removed from each flow range (Table 3 and Table 4). We assessed changes to the timing, frequency and duration of flows above the ecological-flow thresholds (flow spells) in Table 2, and the associated ecological risk from the reduced flow. The proportions of daily flow removed from each flow range were adjusted until the maximum amount of water had been removed from the historical flow regime, without compromising the ecological values in the system.

In evaluating the environmental flow we considered changes to the timing, frequency and duration of flow spells both within and across years. Whilst each ecological-flow threshold was evaluated individually, the final environmental flow reflects the evaluation of the timing, frequency and duration of flows above all the thresholds listed in Table 2.

The final RESYM parameters (the proportion of daily flow removed from each flow range) used to generate the environmental flow for Woodlands Reach and Juniper Reach are shown in Table 3 and Table 4 respectively. The flow ranges were generated using the historical flow records (1974–2011) described in Section 4.3. It should be noted that high magnitude flows (i.e. flood flows that would exceed the banks) are very infrequent, whereas lower magnitude flows are commonplace. As a result of the way that the RESYM parameters were derived, most of the ecological-flow thresholds are encompassed within the lower flow ranges listed for both study reaches. The highest flow ranges cover very infrequent events that occur less than once a year.

Table 3 Proportion of daily flow removed from each flow range to generate the environmental flow for Woodlands Reach

Flow range (ML/day)	Percentage removed (%)
0 to <1.65	0
≥1.65 to <196	40
≥196 to <1341	25
≥1341 to <2471	20
≥2471	0

Table 4 Proportion of daily flow removed from each flow range to generate the environmental flow for Juniper Reach

Flow range (ML/day)	Percentage removed (%)
0 to <1.43	0
≥1.43 to <8.33	20
≥8.33 to <48.8	30
≥48.8 to <1356	20
≥1356	0

5.1 Woodlands Reach

The environmental flow for Woodlands Reach is a proportion of the historical daily flow (1974–2011) within a defined series of flow ranges (Table 3). The following sections discuss how we assessed the timing, frequency and duration of flows above each ecological-flow threshold (Table 2) to define an environmental flow.

For graphical representation, the plots in the following sections only show the 1996–2011 flow period rather than the entire 1974–2011 historical flow as considered in the development of the environmental flow.

No-flow period

To maintain the timing and duration of no-flow periods and dry season trickles, no flow was removed from the historical record when flows were in the range of 0 ML to 1.65 ML per day. The environmental flow therefore keeps exactly the same dry period each year (Figure 17).

Over the 38-year record, the no-flow period for Woodlands Reach typically spans February, March and April. After April, flows in Woodlands Reach are usually continuous until December or January. In some years there was year-round flow, possibly due to seepage from farm dams and the study reach being at the bottom of the catchment.

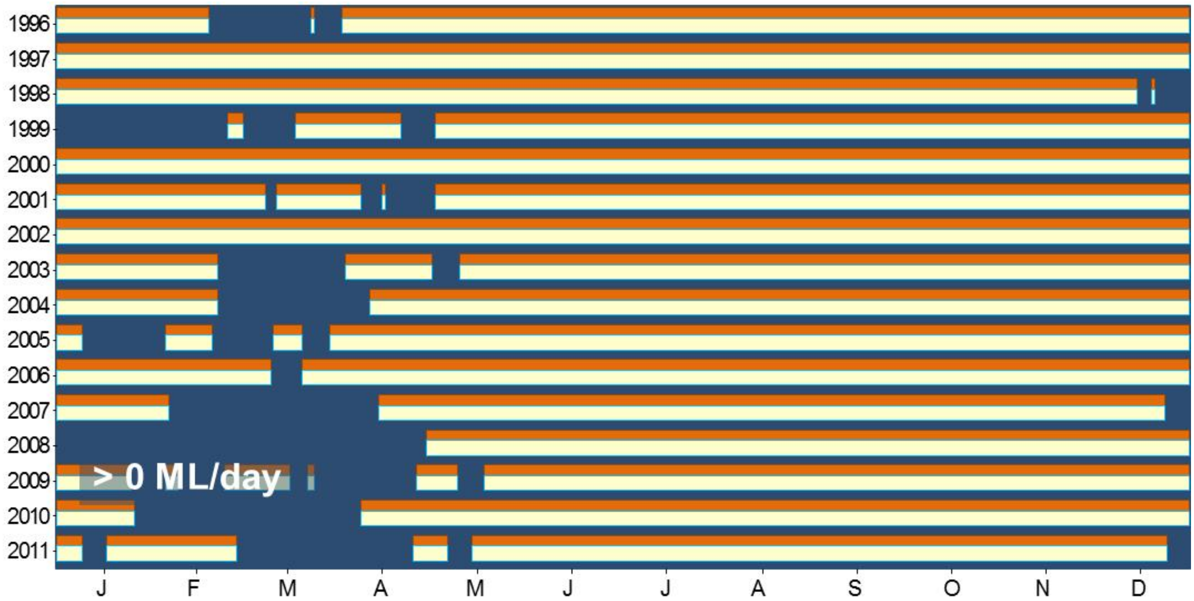


Figure 17 Timing, frequency and duration of flows above 0 ML/day in the environmental (yellow bars) and historical (orange bars) flows for Woodlands Reach

Pool water quality

A flow of 18.1 ML/day in Woodlands Reach will maintain pool water quality, reduce stresses on aquatic fauna and maintain downstream carbon movement by maintaining connectivity between pools (Table 2). To meet this objective, RESYM was set to retain 60 per cent of daily flow in the 1.65 ML to 196 ML per day range (Table 3).

Figure 18 compares flows above 18.1 ML/day in the environmental flow with those in the historical flow record from 1996 to 2011. Historical flows above 18.1 ML/day generally start between May and June and continue until October or November each year. No flows of this magnitude occurred between January and April over the period of record.

In the environmental flow, spells over the threshold generally started at the same time as in the historical flow and ran for a similar period (Figure 18).

The critical period for pool water quality in south-west streams is at the end of summer and start of autumn when water temperatures are at their highest and oxygen level in the pools may be low. Combined with falling water levels and crowding, poor water quality stresses aquatic fauna as the dry season progresses. Flows above 18.1 ML/day do not occur during this period in Woodlands Reach. This is a relatively high flow rate needed to maintain water quality compared to pools in other rivers in the south-west (see Green et al. 2011 and Donohue et al. 2009), which is related to the large pools in the reach and the flow volumes needed for mixing and circulation to occur at depth. We still aimed to preserve the frequency and duration of flows above 18.1 ML/day when they occur in the historical flow, so the timing of stress relief is maintained in the environment flow.

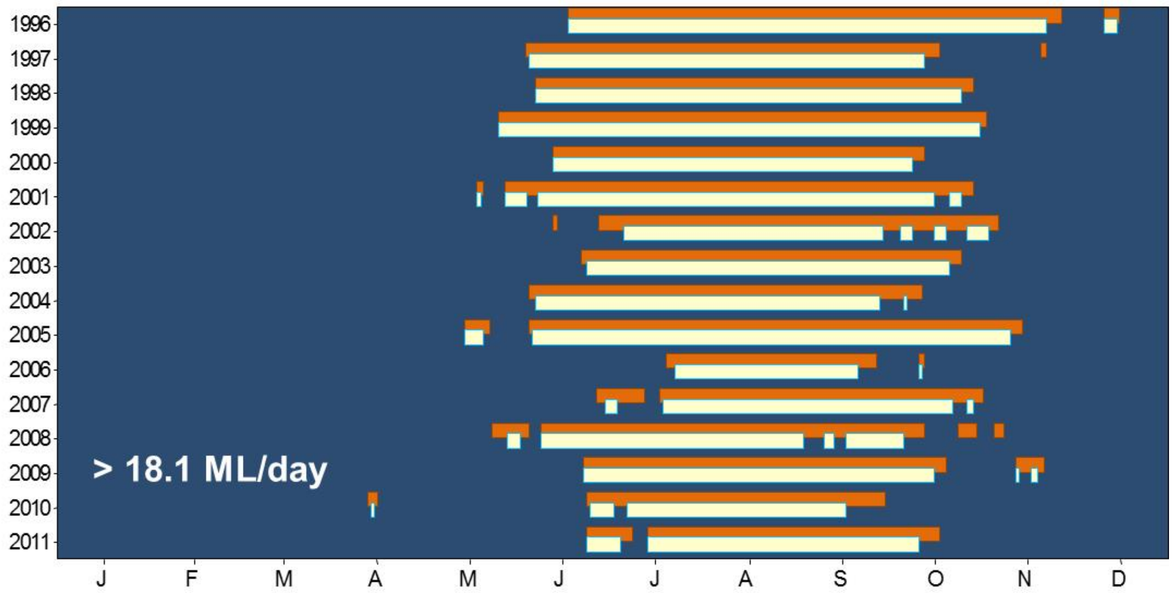


Figure 18 Timing, frequency and duration of flows above 18.1 ML/day in the environmental (yellow bars) and historical (orange bars) flows for Woodlands Reach

Inundation of fringing vegetation

A flow of at 34.6 ML/day in Woodlands Reach will inundate in-stream vegetation used by endemic fish as spawning sites, and as habitat and protective cover for other aquatic species (e.g. invertebrates, frogs and water rats) (Table 2). To meet this objective, RESYM was set to retain 60 per cent of daily flow in the 1.65 ML to 196 ML per day range (Table 3).

Figure 19 compares flows above 34.6 ML/day in the environmental flow with those in the historical flow record from 1996 to 2011. Historical flows sufficient to inundate fringing vegetation regularly occurred between June and October as one continuous spell. Shorter spells of this magnitude, generally less than one week in duration, were common in the ‘shoulder’ periods between May and June, and October and November.

Flows of greater than 34.6 ML/day in the environmental flow generally started within a few days of those in the historical flow and fell below the threshold a few days to a week earlier. In some years, environmental flow fell below the threshold while those in the historical flow remained above the threshold, however this was only for short periods of less than a week (Figure 19).

Fringing vegetation was inundated for sufficient periods to allow eggs to hatch and larvae to mature in all years on record. Years such as 2006 and 2010 may have been of concern if there were a number of similar years occurring back-to-back. The restricted availability of nursery and spawning areas in these years would increase competition and predation rates on fry, which can then impact upon recruitment rates. However, these were the two lowest annual flows of the 38 years on record and surrounding years had flows sufficient to inundate spawning habitat for two to three months at a time.

With this in mind, and noting the similarity between environmental and historical flow during the key winter spawning period, we concluded that endemic fish will have ample opportunity for successive spawning within their lifetime under the environmental flow.

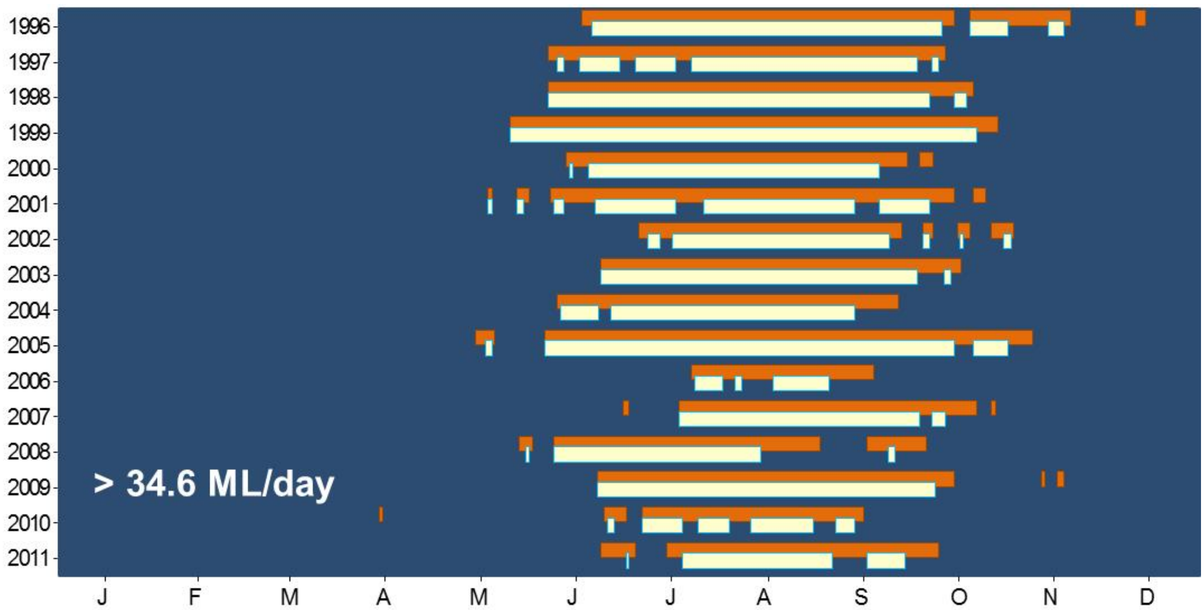


Figure 19 Timing, frequency and duration of flows above 34.6 ML/day in the environmental (yellow bars) and historical (orange bars) flows for Woodlands Reach

Inundation of the active channel

A flow of 228 ML/day in Woodlands Reach is required to achieve a depth of flow equal to the elevation of the active channel (Table 2). It is important that this flow occurs at regular intervals, but neither the frequency nor duration of the flow in the environmental flow need be identical to the historical flow.

To maintain the low-flow channel, RESYM was set to retain 75 per cent of daily flow in the 196 ML to 1341 ML per day range (Table 3).

Figure 20 compares flows above 228 ML/day in the environmental flow with those in the historical flow record from 1996 to 2011. This is a relatively large flow compared to active channel flows in other south-west streams probably due to the high gradient, cascading nature of the reach and the large volume of pools. Historical flows sufficient to inundate the active channel occurred in all years on record but only as short spells of a few days to a week post 2000. The frequency and duration of these flows was highly variable across years and, with the exception of 1996, occurred only between June and October.

Environmental flows sufficient to inundate the active channel occurred in all years on record except 2011 (a year of very low magnitude winter flows) and showed a similar frequency of occurrence to the historical flow (Figure 20). The sometimes shorter duration of active channel flows in the environmental flow was not considered an issue as they were still occurring with enough frequency to perform the flows function of scouring the channel, maintaining channel form and preventing vegetation encroachment. It was concluded that there would be relatively little ecological impact from the differences in frequency and duration between the environmental flow and the historical flow.

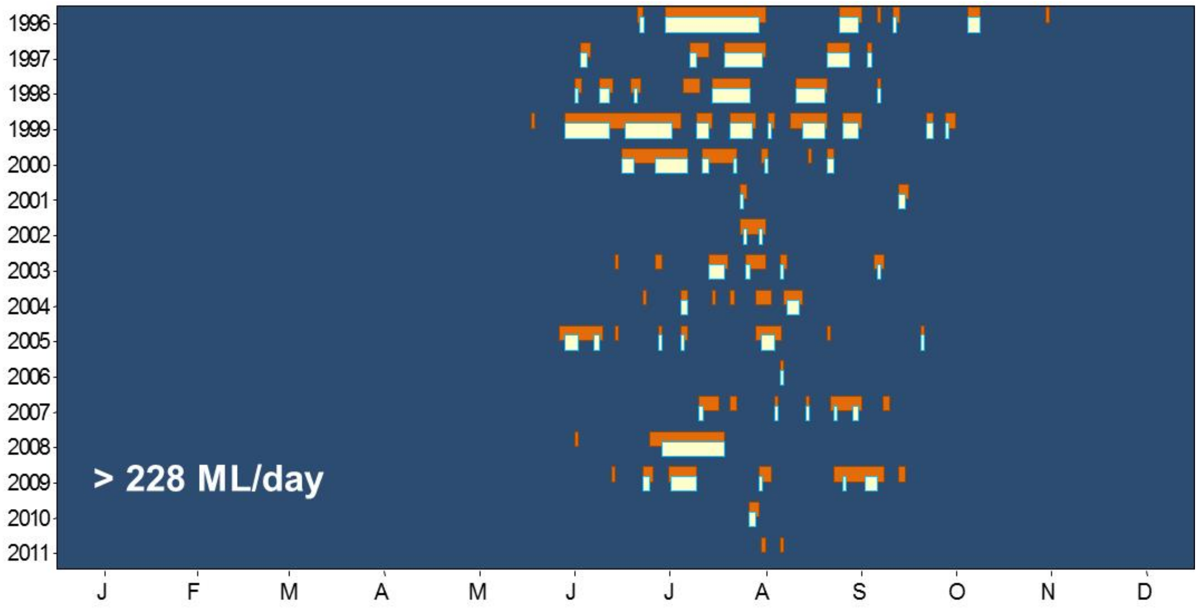


Figure 20 Timing, frequency and duration of flows above 228 ML/day in the environmental (yellow bars) and historical (orange bars) flows for Woodlands Reach

Bankfull and overbank flows

A flow of 598 ML/day is required to achieve a depth equal to or exceeding bankfull height in Woodlands Reach (Table 2). To preserve the regularity of bankfull and overbank flows and subsequent floodplain inundation, RESYM was set to retain 75 per cent of flow in the 196 ML to 1341 ML per day range (Table 3).

Figure 21 compares flows above 598 ML/day in the environmental flow with those in the historical flow record from 1996 to 2011. The plot shows a significant drop in the frequency of bankfull flows post 2000 with only three events occurring between 2001 and 2011 (two in 2005 and one in 2009). In the 27 years on record prior to this, 1985 was the only year where flows did not reach bankfull height. Flows of this magnitude typically occur between June and September as short spells of less than one week.

Environmental flows above 598 ML/day are a close match to those in the historical flow. Although sometimes shorter in duration, the frequency and timing of bankfull events is very similar throughout the record (Figure 21).

Bankfull and overbank events are irregular and of short duration, so it is important that the environmental flow mimics the current frequency. Throughout the 38 year record, environmental flows sufficient to overtop the banks are present for the vast majority of events captured in the historical flow. Although the duration of these events is slightly shorter in the environmental flow, they still occur with enough frequency to perform the flow's ecological functions (see Section 3.1).

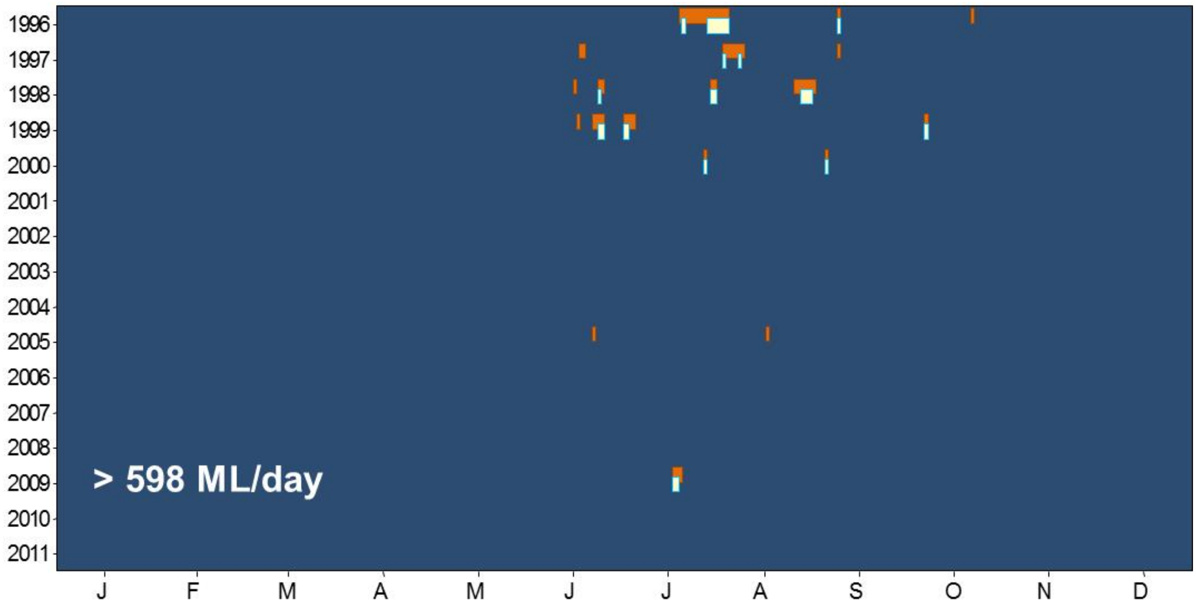


Figure 21 Timing, frequency and duration of flows above 598 ML/day in the environmental (yellow bars) and historical (orange bars) flows for Woodlands Reach

Flood events

The highest ecologically critical height measured during the Woodlands Reach cross-sectional survey was top of bank height (Section 4.5). As mentioned in the previous section, a flow of 598 ML/day was required to reach this height on the channel. During the 38 year period on record, flows in Woodlands Reach of Wilyabrup Brook were as high as 2748 ML/day and were greater than the bankfull threshold for an average of five days per year (175 days in total over the period of record). High-energy flows such as these scour the floodplain and begin the inundation necessary to maintain wetland areas adjacent to river systems.

Given the large range of flows greater than the highest ecological threshold for Woodlands Reach, a threshold of 1200 ML/day was introduced to provide for irregular, large flood events and to ensure the environmental flow was preserving these higher range flows.

To meet this objective, RESYM was set to retain 75 per cent of flow in the 196 ML to 1341 ML per day range, 80 per cent of flow in the 1341 ML to 2471 ML per day range and 100 per cent of flow greater than 2471 ML/day (Table 3).

The timing, frequency and duration of flows greater than 1200 ML/day in the environmental flow is compared with those in the historical flow record from 1996 to 2011 in Figure 22. Historical flows exceeded 1200 ML/day in 14 of the 38 years and only once post 1999 (in 2009). Flows of this magnitude were quite rare, only occurring between June and August and lasting for up to a few days.

The overall timing, frequency and duration of flows greater than 1200 ML/day is very similar between the environmental and historical flows with only two years (1982 and 1996) having events that were not captured in the environmental flow (Figure 22).

Flood events in Woodlands Reach are extremely rare and when they do occur, typically only last for one or two days. The ecological importance of these flows is likely to be related to seed set and establishment of vegetation in upper- and outer-floodplain areas, and they most likely influence channel and floodplain morphology. With these events still occurring with similar frequency across years, the ecological function of these flows would not be compromised.

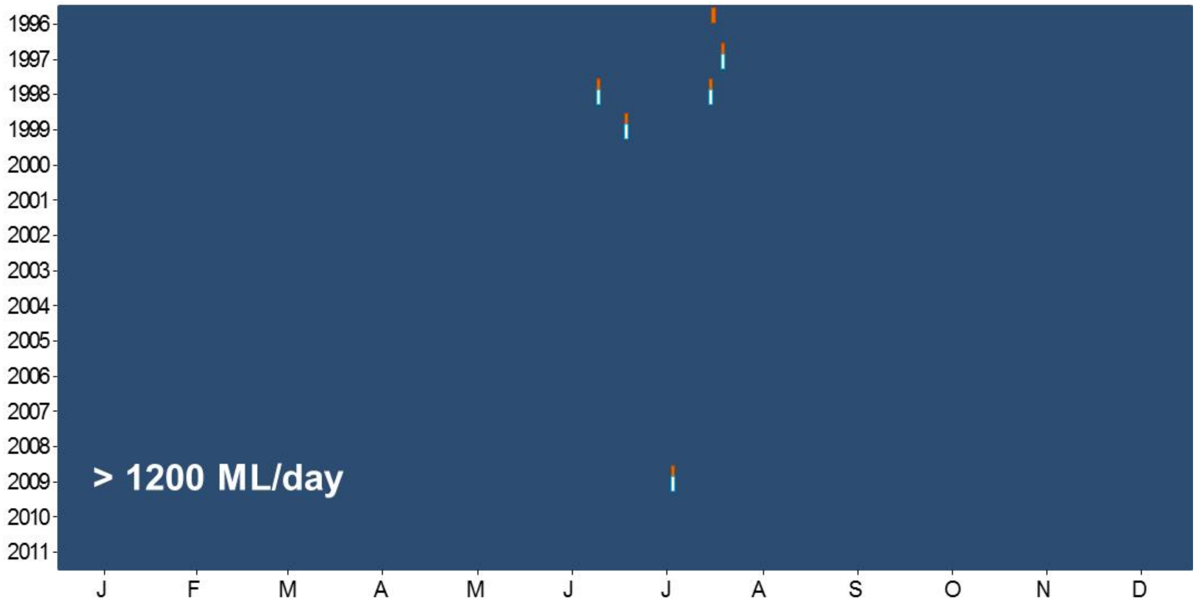


Figure 22 Timing, frequency and duration of flows above 1200 ML/day in the environmental (yellow bars) and historical (orange bars) flows for Woodlands Reach

5.2 Juniper Reach

The environmental flow for Juniper Reach is a proportion of the historical daily flow (1974–2011) within a defined series of flow ranges (Table 4). The following sections discuss how we assessed the timing, frequency and duration of flows above each ecological-flow threshold (Table 2) and defined an environmental flow.

For graphical representation, the plots in the following sections only show the 1996–2011 flow period rather than the entire 1974–2011 historical flow as considered in the development of the environmental flow.

No-flow period

To maintain the timing and duration of periods of no-flow and dry season trickles, no flow was removed from the historical record when flows were in the range of 0 ML to 1.43 ML per day. The environmental flow therefore keeps exactly the same dry period each year (Figure 23).

Over the 38-year record, the no-flow period for Juniper Reach typically spans January to early May. After May, flows are usually continuous until December. Some years had flows through summer and early autumn but this was extremely rare post 2000 (Figure 23).

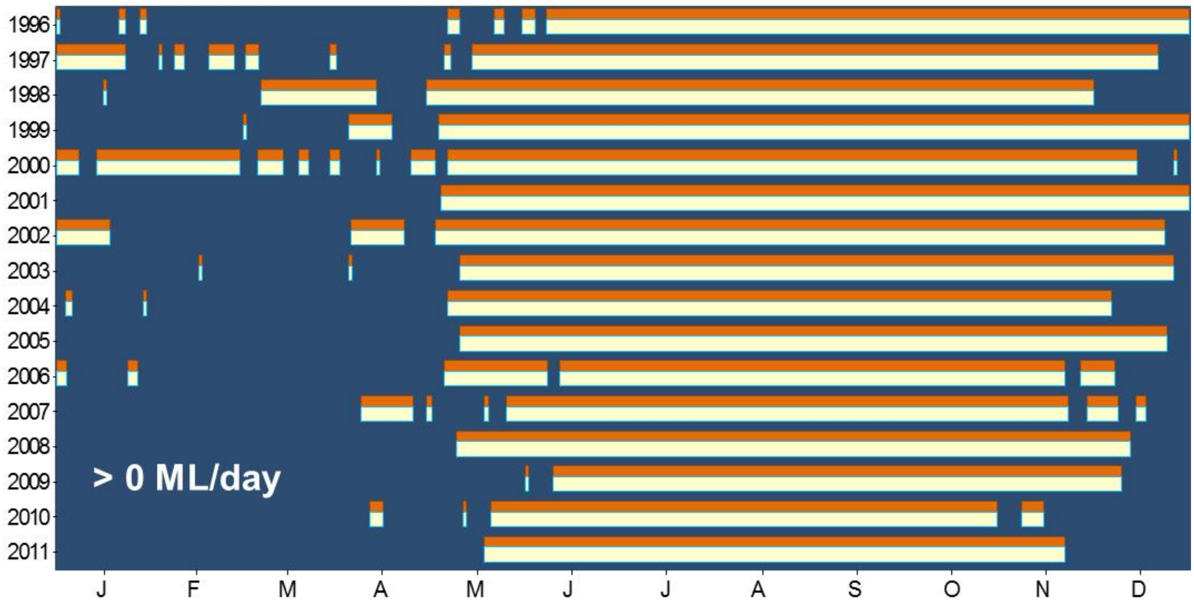


Figure 23 Timing, frequency and duration of flows above 0 ML/day in the environmental (yellow bars) and historical (orange bars) flows for Juniper Reach

Spring/summer macroinvertebrate habitat

A flow of 5.18 ML/day in Juniper Reach will inundate half the width of riffles to a depth of at least 5 cm (Table 2). To meet this objective, RESYM was set to retain 80 per cent of daily flow in the 1.43 ML to 8.33 ML per day range for the environmental flow (Table 4).

This is typically a spring/summer objective but as shown in Figure 24, historical flows above 5.18 ML/day rarely occur in Juniper Reach during summer. These flows commence between May and June and remain above the threshold until October or November. They are rarely present during the summer months with notable exceptions in 1976, 1983 and 1996. Macroinvertebrates are known to retreat and survive in more permanent refuges such as permanent reaches and river pools when preferred riffle habitat is not available (Chester & Robson 2011; Robson et al. 2011). It is likely that macroinvertebrates in this part of the river are adapted to this seasonal lack of habitat over summer.

The timing, frequency and duration of environmental flows above 5.18 ML/day over the period of record are a close match to those in the historical flow record (Figure 24). Importantly, the flows during spring are maintained in the environmental flow and the rarer summer and autumn events are also captured.

The absence of summer riffle habitat flows in the historical record shows that the flow criterion is not always met naturally within Juniper Reach. It was still important to preserve these flows where they did occur, particularly in the ‘shoulder’ periods and the rare occasion that they were present during summer.

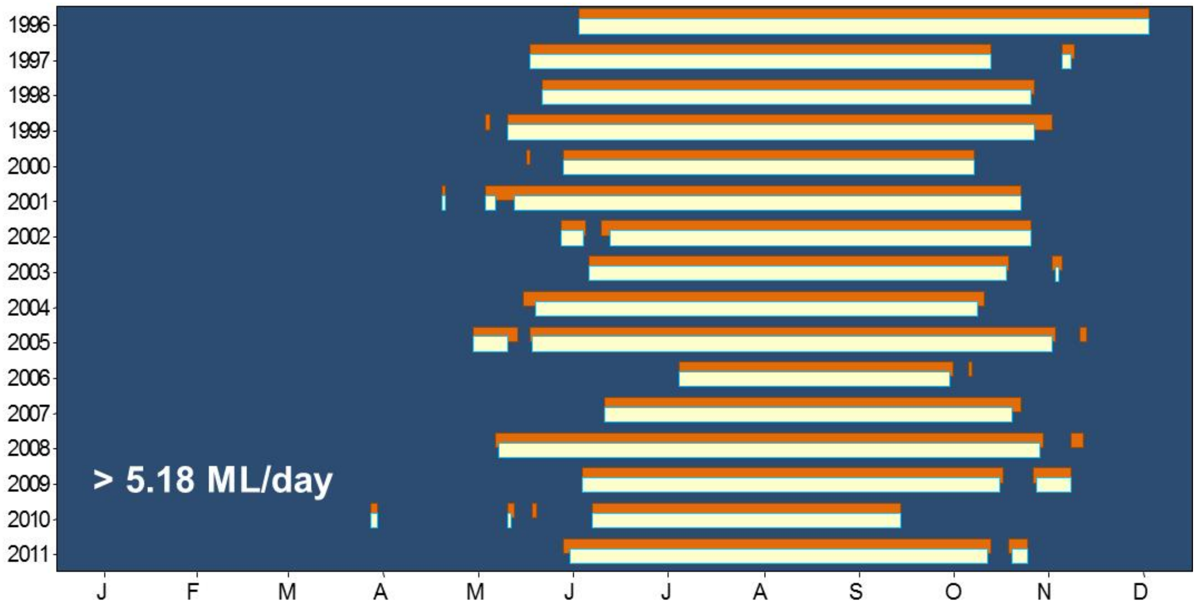


Figure 24 Timing, frequency and duration of flows above 5.18 ML/day in the environmental (yellow bars) and historical (orange bars) flows for Juniper Reach

Pool water quality

A flow of 7.78 ML/day in Juniper Reach will maintain pool water quality, reduce stresses on aquatic fauna and maintain downstream carbon movement by connectivity between pools (Table 2). To provide for this objective, RESYM was set to retain 80 per cent of daily flow in the 1.43 ML to 8.33 ML per day range (Table 4).

Figure 25 compares flows above 7.78 ML/day in the environmental flow with those in the historical flow record from 1996 to 2011. Historical flows of more than 7.78 ML/day generally occurred as one continuous spell from approximately June to early November. Some shorter spells of one or two weeks' duration were present later in the year and in some years, as early as May. There were only a few minor events between January and April over the 38 years on record.

Environmental flows above 7.78 ML/day closely resemble those in the historical flow record. In some years, environmental flows fell below the threshold slightly earlier in spring. In years where flows rose back above 7.78 ML/day for short periods late in the year (November–December), this was also captured in the environmental flow (Figure 25).

As for Woodlands Reach, flows over the threshold for pool water quality are absent during the critical period at the end of summer and start of autumn. This is due to the intermittent nature of flow in Wilyabrup Brook and the large volume of the pools. Where these flows do occur in the historical flow, they are closely matched by the environmental flow.

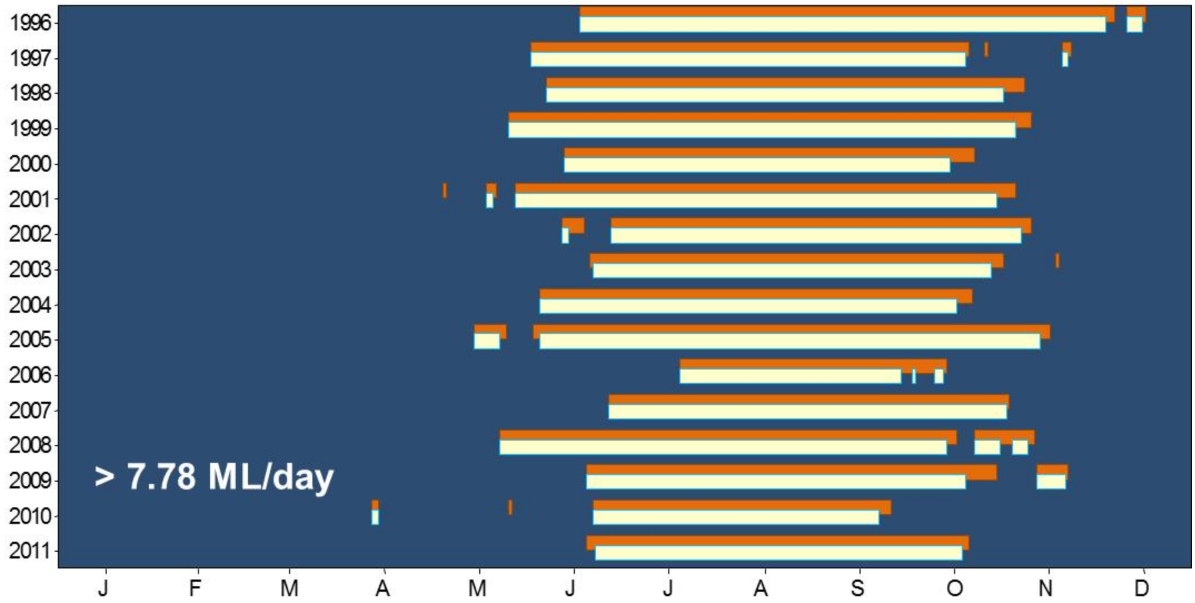


Figure 25 Timing, frequency and duration of flows above 7.78 ML/day in the environmental (yellow bars) and historical (orange bars) flows for Juniper Reach

Upstream migration of small-bodied endemic fish

A flow of 24.2 ML/day is required to allow upstream migration of small-bodied endemic fish (Table 2) in Juniper Reach (no large-bodied fish have been recorded in Wilyabrup Brook). Based on the results of hydraulic modelling, this flow will achieve a depth of greater than 10 cm over the thalweg at each cross-section (see Section 4.5). To meet this objective, RESYM was set to retain 70 per cent of daily flow in the 8.33 ML to 48.8 ML per day range (Table 4).

Flows above 24.2 ML/day in the environmental flow are compared with those in the historical flow record from 1996 to 2011 in Figure 26. Historical flows over the threshold occur consistently between June and October while none are present between January and April for the entire period of record. The duration of spells above the threshold is quite variable from year to year, ranging from two to five months over the wet season. These flows commence between May and July and fall below the threshold as early as September and as late as November. Short periods of flow above the threshold are common in the shoulder periods of May–June and September–October.

The critical period for this flow is from mid-May to August–September, when small-bodied fish migrate upstream to spawn. Most spawning is over by August or September, with fish needing less water to move downstream between October and November.

Environmental flows above 24.2 ML/day occur with a similar frequency and duration to those found in the historical flow record (Figure 26). Flows that allow for fish passage in the environmental flow generally begin within a few days of those in the historical flow and fall below the threshold up to a week earlier in spring (Figure 26).

It is important to note that fish passage flows in both the environmental flow and historical flow reach the 24.2 ML/day threshold at a similar time, as fish respond to environmental and flow cues at the start of the migration season to move upstream into spawning habitat.

In most years, between June and mid-October, environmental flows closely replicate those in the historical flow. One exception was the lowest flow year on record – 2006 – where environmental flows fell below the fish passage threshold several times during the two-month spell in the historical flow (Figure 26). This would not be ideal if these years were occurring back-to-back, however there were still significant periods above the threshold in 2006 that would have allowed fish to move between pools.

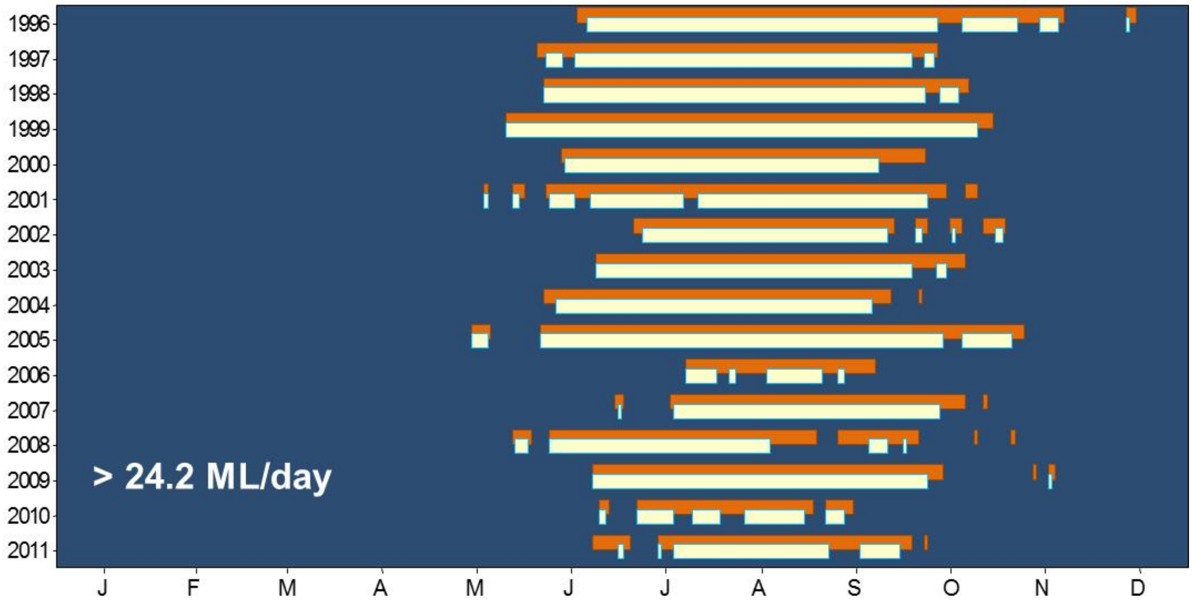


Figure 26 Timing, frequency and duration of flows above 24.2 ML/day in the environmental (yellow bars) and historical (orange bars) flows for Juniper Reach.

Winter macroinvertebrate habitat

A flow of 31.1 ML/day is required in Juniper Reach to inundate the entire width of riffles for winter macroinvertebrate habitat (Table 2). This objective is winter-critical, with the main period of interest being May to October. To meet this objective, RESYM was set to retain 70 per cent of daily flow in the 8.33 ML to 48.8 ML per day range (Table 4).

Figure 27 compares flows above 31.1 ML/day in the environmental flow with those in the historical flow record from 1996 to 2011. Historical flows of this magnitude generally start between late May and June and run through to September or October before falling below the threshold. It is not uncommon for shorter spells of up to a week to occur as late as November.

In most years flows above 31.1 ML/day in the environmental flow commence at the same time as those in the historical flow and remain above the threshold for a similar period. In years post 2005, the environmental flow fell below the threshold during winter for slightly longer periods than the historical flow (Figure 27). Analysis of the hydrograph (time-series plot) for the environmental flow in RESYM showed that during these periods, the environmental flow did not drop far below the 31.1 ML/day threshold, meaning the majority of the width of riffles would still be still inundated to 5 cm. This also applies to the spring months where the environmental flow fell below 31.1 ML/day a few days to a week earlier than the historical flow. Large sections of the riffles would still have been inundated during these periods.

Based on the similarity between the historical and environmental flows over 31.1 ML/day, especially between the critical months of May to October, it was concluded that the environmental flow met the objective of maintaining winter macroinvertebrate habitat in Wilyabrup Brook's middle reaches.

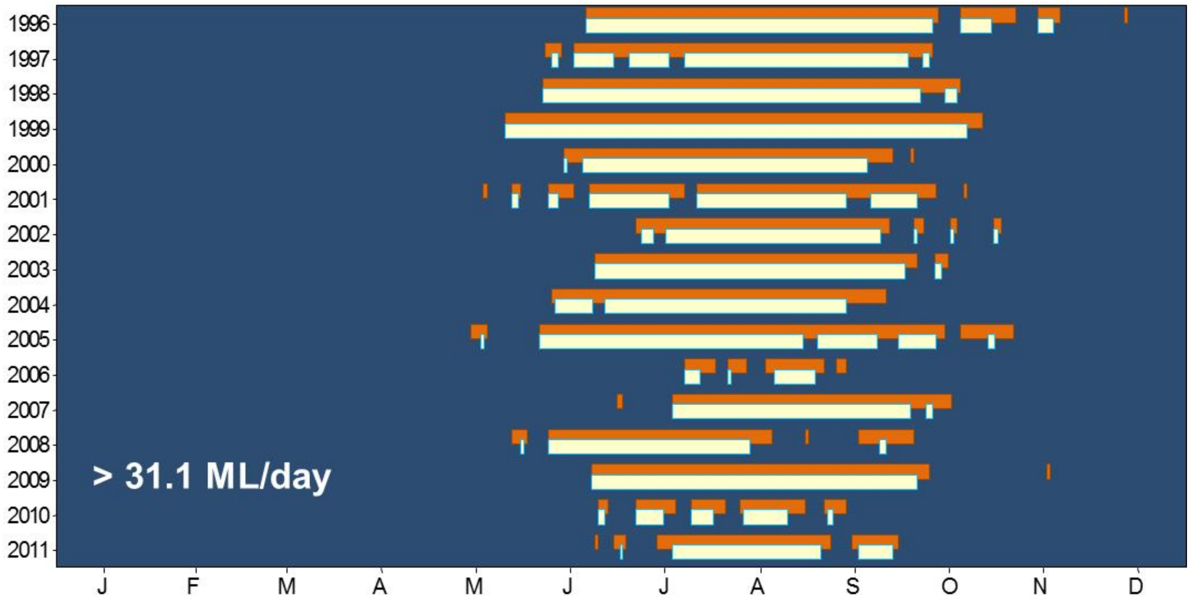


Figure 27 Timing, frequency and duration of flows above 31.1 ML/day in the environmental (yellow bars) and historical (orange bars) flows for Juniper Reach

Inundation of riverine benches

A flow of 50.1 ML/day is required to inundate riverine benches in Juniper Reach (Table 2). This objective is winter-critical, with the main period of interest being May to October. To maintain the ecological functions of the flow, RESYM was set to retain 80 per cent of flow in the 48.8 ML to 1356 ML per day range (Table 4).

Figure 28 compares flows above 50.1 ML/day in the environmental flow with those in the historical flow record from 1996 to 2011. Historical flows sufficient to inundate benches were recorded for all years on record, although 2006 only had two short spells of under a week each. Flows typically ran from June through to September or October and remained above the threshold in most years. Shorter, interspersed spells of flow above the threshold were seen as late as October and November in some years.

Environmental flows over 50.1 ML/day were a close match to those in the historical flow record, beginning at the same time in most years and typically spanning two to three months. Environmental flows sometimes fell below the threshold for short periods during winter while those in the historical flow remained above. Importantly, during the critical months of between May and October, flows above 50.1 ML/day in both the environmental flow and historical flow were a close match (Figure 28).

It was concluded that the slight differences in frequency and duration between the environmental flow and the historical flow would not impact the flow's function to flush carbon into the river system, inundate fringing vegetation and provide access to bench habitat and small tributaries for spawning.

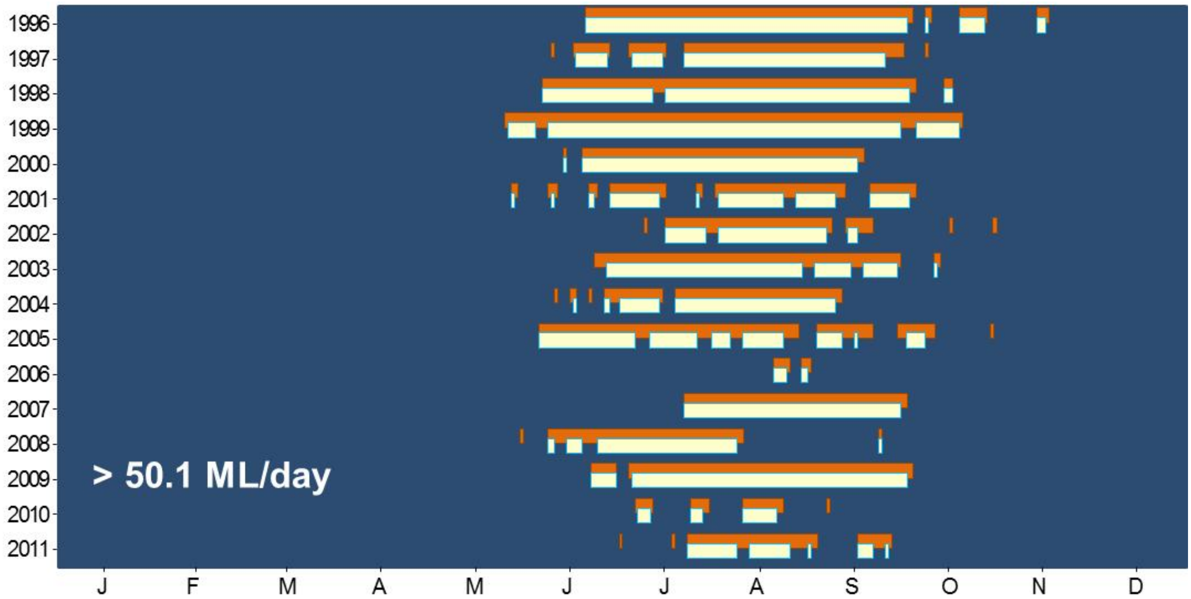


Figure 28 Timing, frequency and duration of flows above 50.1 ML/day in the environmental (yellow bars) and historical (orange bars) flows for Juniper Reach

Inundation of fringing vegetation

A flow of 66.5 ML/day in Juniper Reach will inundate in-stream vegetation used by endemic fish as spawning sites and as habitat and protective cover by other aquatic species (e.g. invertebrates, frogs and water rats) (Table 2). To meet this objective, RESYM was set to retain 80 per cent of daily flow in the 48.8 ML to 1356 ML per day range for the environmental flow (Table 4).

Flows above 66.5 ML/day in the environmental flow are compared with those in the historical flow record from 1996 to 2011 in Figure 29. Historical flows sufficient to inundate spawning habitat occurred in all years on record, usually between June and October and lasting one to three months. There was a notable decline in flows greater than 66.5 ML/day post 2000.

Environmental flows over the threshold were also present in all years and were a close match to those in the historical flow. In some years, the environmental flow fell below the threshold while the historical flow remained above. This was only for short periods of less than a week (e.g.1976, 1988, 1996 and 2007) (Figure 29).

In 2006 and 2010, there were only short spells of flow sufficient to inundate fringing vegetation in the historical record. Whilst these events were of shorter duration in the environmental flow, their timing and frequency was the same (Figure 29). This was not considered a significant risk to recruitment as these were the two lowest flow years on record and in surrounding years, fringing vegetation was inundated for sufficient periods for spawning.

Due to the close similarity of flows above 66.5 ML/day in the historical and environmental flow, particularly during the winter spawning period, we concluded that the environmental flow met the objective of providing sufficient winter spawning habitat in Wilyabrup Brook's middle reaches.

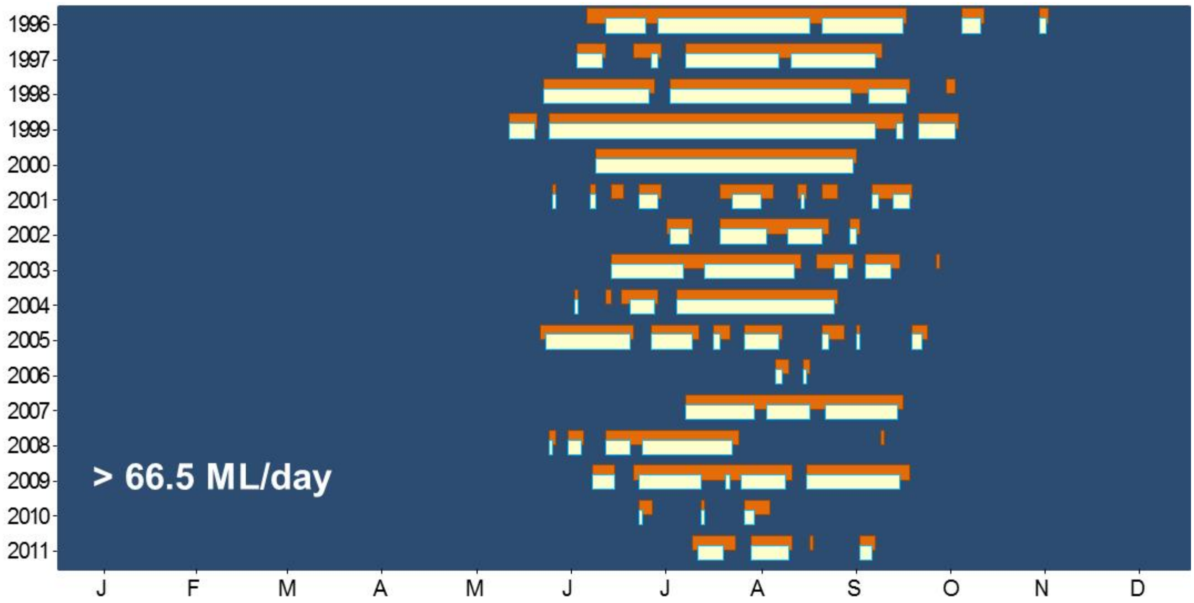


Figure 29 Timing, frequency and duration of flows above 66.5 ML/day in the environmental (yellow bars) and historical (orange bars) flows for Juniper Reach

Inundation of the active channel

A flow of 125 ML/day is required to achieve a depth of flow equal to the elevation of the active channel in Juniper Reach (Table 2). It is important that this flow occurs at regular intervals, but neither the frequency nor duration in the environmental flow need be identical to the historical flow. To maintain the low-flow channel, RESYM was set to retain 80 per cent of flow in the 48.8 ML to 1356 ML per day range (Table 4).

Figure 30 compares flows above 125 ML/day in the environmental flow with those in the historical flow record from 1996 to 2011. Historical flows above the threshold have occurred in all years on record but vary significantly in their frequency and duration. Only two years on record had active channel flows outside of the period June–October. Spells above the threshold ranged from a few days to two months during the winter flow period. There was a significant decline in active channel flows post 2000, with 2006 only having one spell of a few days' duration.

In general, environmental flows above 125 ML/day closely mimic those in the historical flow. The environmental flow spells are of similar frequency but often slightly shorter duration. This is particularly noticeable post 2000, where environmental flows above 125 ML/day occur over the same period as those in the historical flow but for shorter durations (Figure 30). In years where flows remained above the threshold for one to two months in the historical flow, the environmental flow often fell below the threshold during the same period. This was generally only for a few days at a time and would not influence the scouring capacity of the flow.

As there was no change to the timing and inter-annual frequency of active channel flows in the environmental flow, we concluded that the differences in duration would not affect the flow's function of scouring pools and maintaining an open low-flow channel.

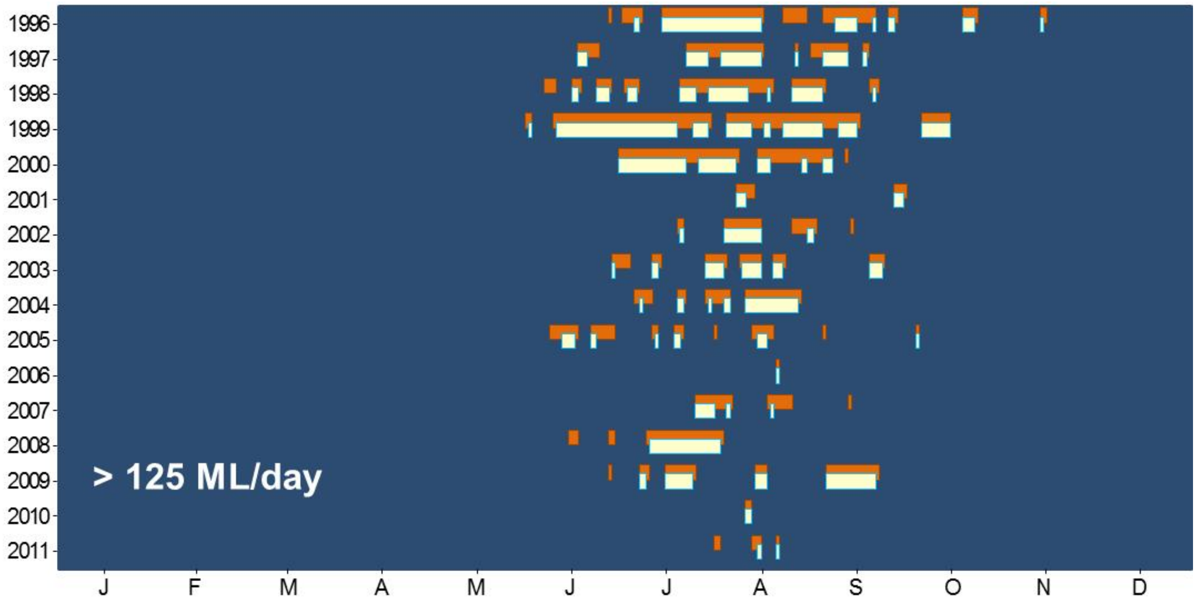


Figure 30 Timing, frequency and duration of flows above 125 ML/day in the environmental (yellow bars) and historical (orange bars) flows for Juniper Reach

Bankfull and overbank flows

A flow of 367 ML/day is required to achieve a depth equal to or exceeding bankfull height in Juniper Reach (Table 2). To preserve the regularity of bankfull and overbank flows, and subsequent floodplain inundation, RESYM was set to retain 80 per cent of flow in the 48.8 ML to 1356 ML per day range and 100 per cent of flow greater than 1356 ML/day for the environmental flow (Table 4).

Figure 31 compares flows above 367 ML/day in the environmental flow with those in the historical flow record from 1996 to 2011. Historical flows over 367 ML/day occurred in all but three years on record (2004, 2006 and 2007). These flows were most common during July and August and ranged in duration from one day to just under a month. Short spells of flow less than one week in duration were present in June and occurred as late as September or October in some years. There were very limited bankfull events post 2000, and where they did occur, only lasted for a few days.

Where bankfull flows were present in the historical flow they were generally captured in the environmental flow. Spells in the environmental flow were sometimes shorter in duration and occasionally fell below the threshold for short periods when those in the historical flow were longer than one week. Spells less than a few days' duration were not always met by the environmental flow, however the timing, frequency and duration of bankfull events within and across years remains relatively unchanged (Figure 31).

Bankfull and overbank events are irregular and of short duration, so it is important that the environmental flow mimics the frequency of recorded events. It was concluded that that the frequency of bankfull events in the environmental flow would provide sufficient water to scour pools, maintain channel morphology, provide carbon to river ecosystems and inundate floodplain areas in Wilyabrup Brook's middle reaches.

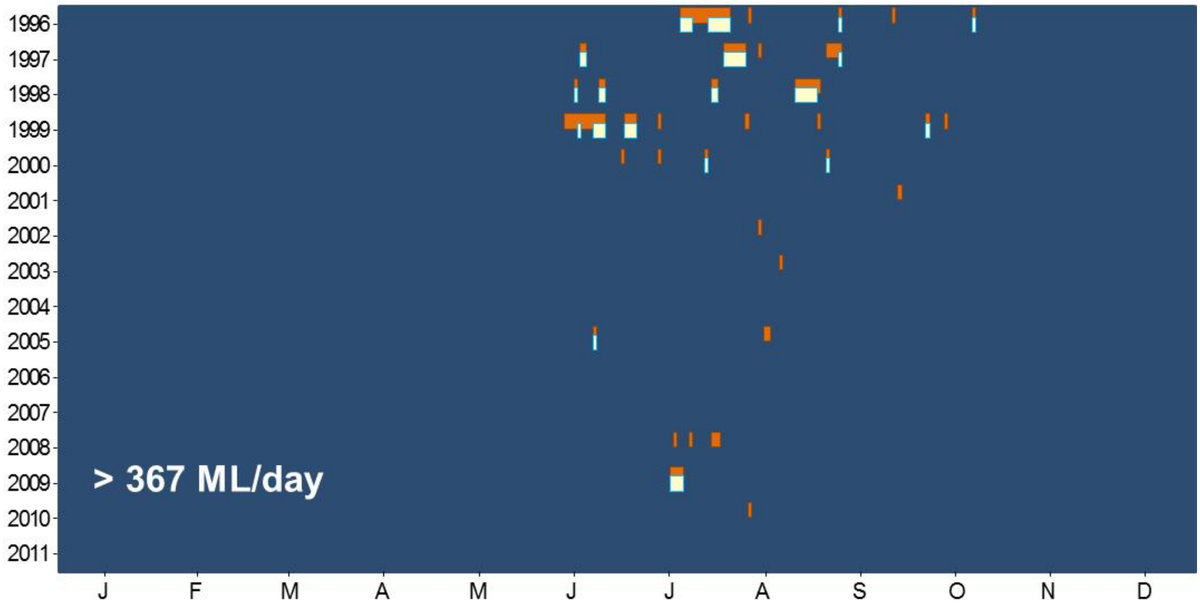


Figure 31 Timing, frequency and duration of flows above 367 ML/day in the environmental (yellow bars) and historical (orange bars) flows for Juniper Reach

Flood events

The greatest ecologically critical flow-depth measured during the Juniper Reach channel survey was top of bank height. As mentioned in the previous section, a flow of 367 ML/day is required to reach this height (Table 2). During the 38 year record, flows in Juniper Reach were as high as 2285 ML/day and were greater than the bankfull threshold for an average seven days per year (261 days over the 38 years).

High-energy flows such as these scour the floodplain and begin the inundation necessary to maintain wetland areas adjacent to river systems.

Given the large range of flows greater than the highest ecological threshold, 900 ML/day was introduced as a threshold for Juniper Reach to provide for irregular, large flood events and to ensure that the environmental flow preserves high-range flows.

To meet this objective RESYM was set to retain 80 per cent of flow in the 48.8 ML to 1356 ML per day range and 100 per cent of flow greater than 1356 ML/day for the environmental flow (Table 4).

Flows greater than 900 ML/day in the environmental flows are compared with those in the historical flow record from 1996 to 2011 in Figure 32. Historical flows exceeded 900 ML/day in 14 years with spells lasting from one to five days. Only 30 days over the whole record had flows of this magnitude. These flows always occurred between late June and early August.

Environmental flows greater than 900 ML/day were present for 12 of the 14 years in the historical flow. These events ranged from one to two days in duration (Figure 32).

Flood events of this magnitude in Juniper Reach are rare and when they do occur, generally only last for one or two days. The ecological importance of these flows is probably related to seed set and establishment of vegetation in outer-floodplain areas, and they most likely influence channel and floodplain morphology. As the frequency of flood events is closely replicated by the environmental flow, we were confident that the flow's ecological function had not been compromised.

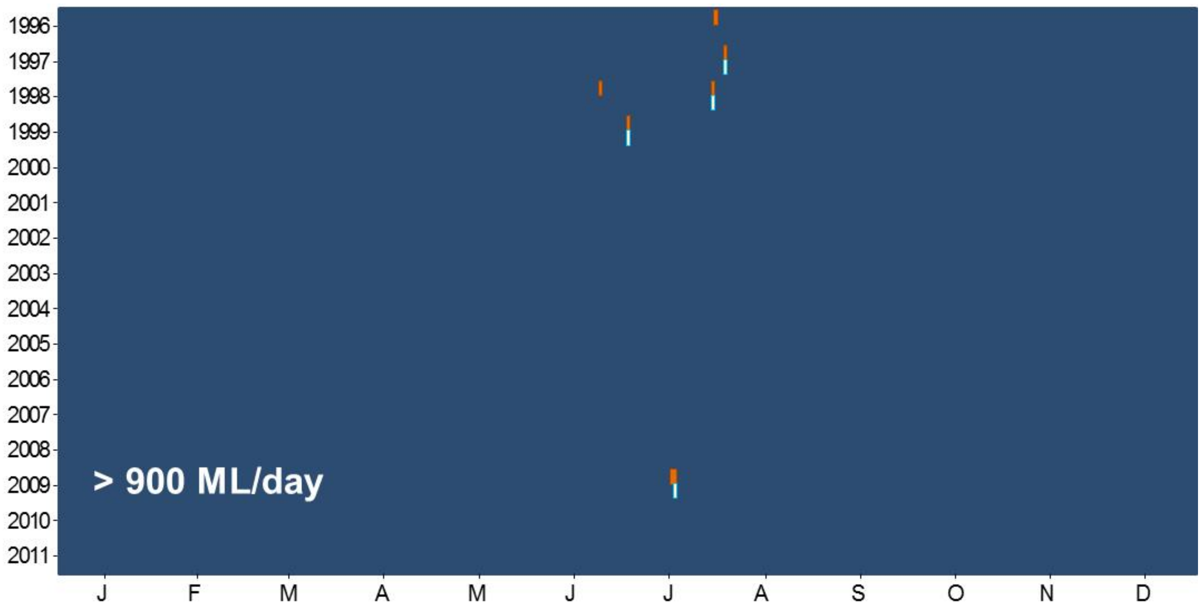


Figure 32 Timing, frequency and duration of flows above 900 ML/day in the environmental (yellow bars) and historical (orange bars) flows for Juniper Reach

6 The Wilyabrup Brook environmental flow

The annual pattern of summer drought and winter flood is a key feature of Wilyabrup Brook and other rivers in the south-west of Western Australia (Kennard et al. 2010). This sequence of a wet season followed by a dry season during which flow may cease, is a fundamental pattern in south-west streams. It has been shown to have a strong influence on the morphology of aquatic species, their life-history strategies, and variations in their abundance and diversity.

In developing an environmental flow we aimed to maintain this key flow characteristic for Wilyabrup Brook in the Woodlands and Juniper reaches.

Flow–duration curves comparing the proportion of time that a daily flow was exceeded between the historical flow data and the environmental flow for Woodlands and Juniper reaches are shown in Figure 33 and Figure 34. The curves show that over the 38 years on record (1974–2011), the environmental flow for both study reaches retains the same permanency as in the historical flow, with little change to the magnitude and duration of summer low flows at either site.

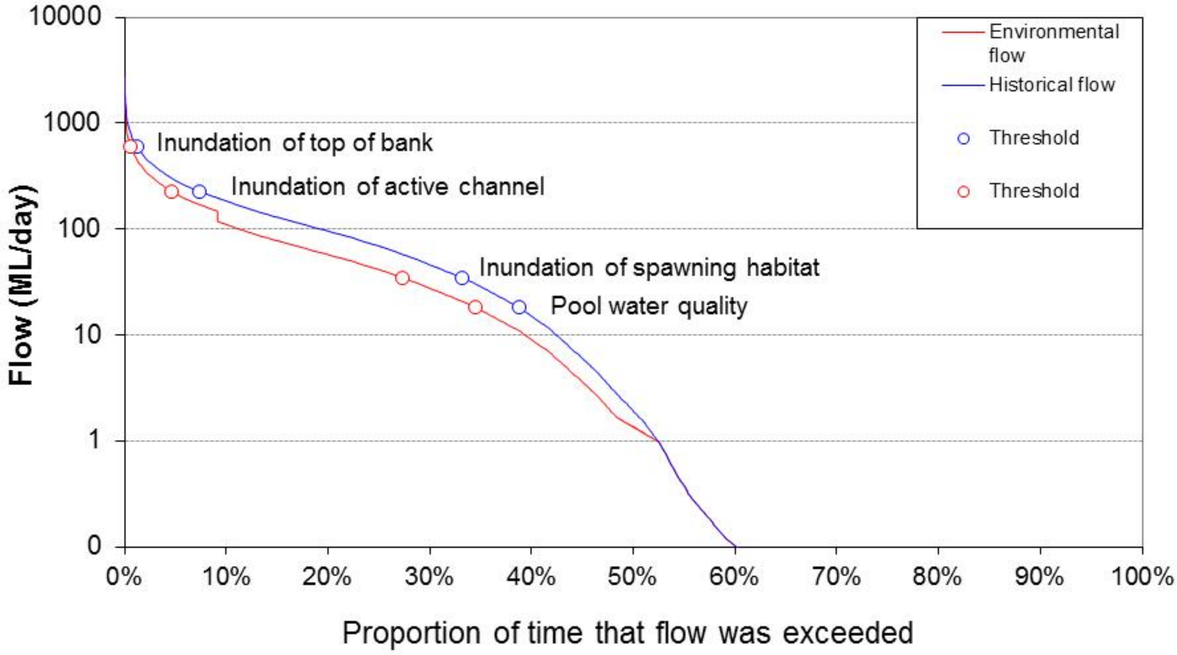


Figure 33 Woodlands Reach flow duration curves - historical flow record (blue curve) and the environmental flow (red curve) for the period 1974 to 2011

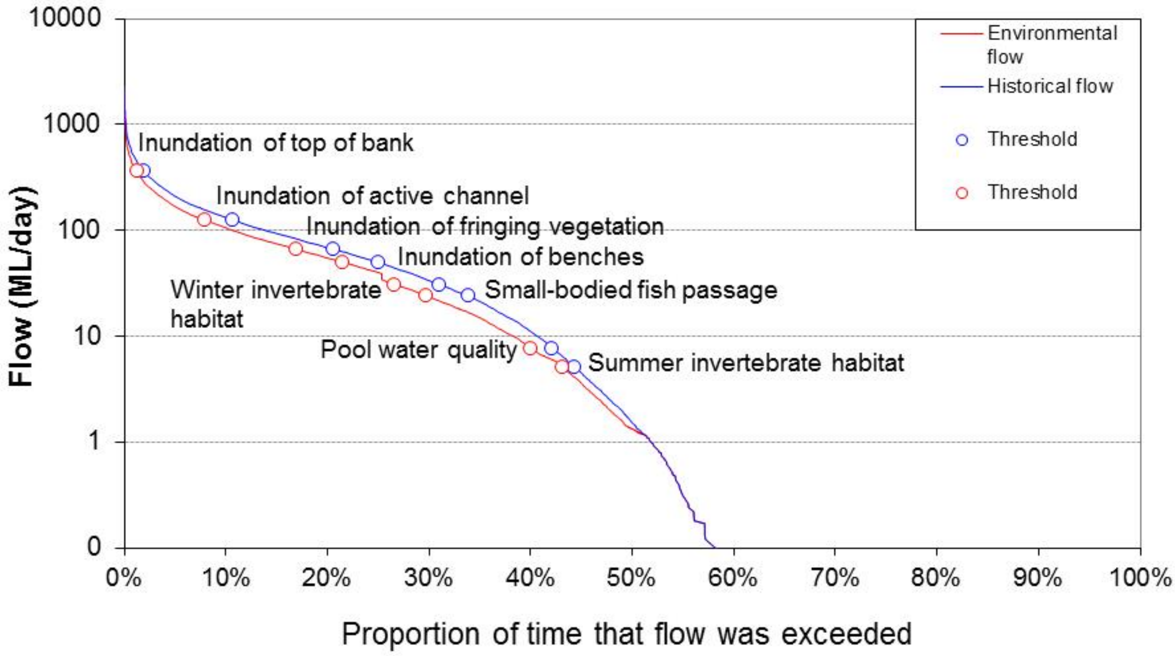


Figure 34 Juniper Reach flow duration curves - historical flow record (blue curve) and the environmental flow (red curve) for the period 1974 to 2011

If flows in Wilyabrup Brook were to decline to the level of the environmental flow, the environmental pressures on aquatic fauna due to the seasonal intermittency of flow would be the same. Dry season stresses due to declining flows, and high water temperatures from lack of water circulation in pools and other refugia, would also be the same.

The timing and duration of early season trickle and low flows is unchanged, as is the recession of flow leading into the cease to flow (Figure 35). Species are therefore receiving the same environmental cues to disperse and move upstream, and have the same opportunity to retreat downstream to permanent refuges prior to the dry season.

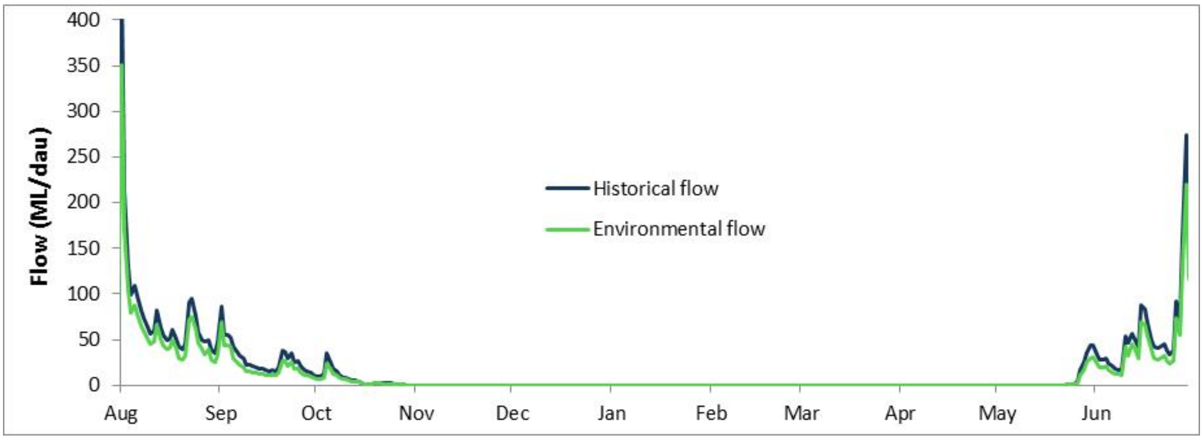


*Figure 35 Similarity between environmental and historical flow during the critical low flow periods either side of the wet season. *Data from Juniper Reach August 1994 to July 1995*

The environmental flow also retains the infrequent short-duration flood flows seen in the historical flow record. It therefore has the same period of inundation of habitats as the historical flow regime, and the same capacity for channel scouring and maintenance of channel morphology.

Figure 36 shows the historical flow and environmental flows in detail, using Woodlands Reach as an example. Plot 1 is a median flow year (1979), plot 2 shows the entire period of record (1974–2011) and plot 3 shows consecutive high, median and low flow years (1999–2001). The plots show that distribution and volume of flow peaks and troughs in the environmental flow closely follow those in the historical flow. For example, the environmental flow in wet years such as 1999 is much larger than in 2001, one of the drier years on record (Figure 36).

The seasonal pattern of flow in the environmental flow for Woodlands Reach is a close match to that in the historical flow, including the duration of the winter flow period and the summer no-flow period (plot 3 Figure 36). The magnitude of individual flow events is smaller in the environmental flow but the overall frequency of high-flow events between years, their timing, and seasonal pattern, is a good match with the historical flow (plots 1 and 3, Figure 36).

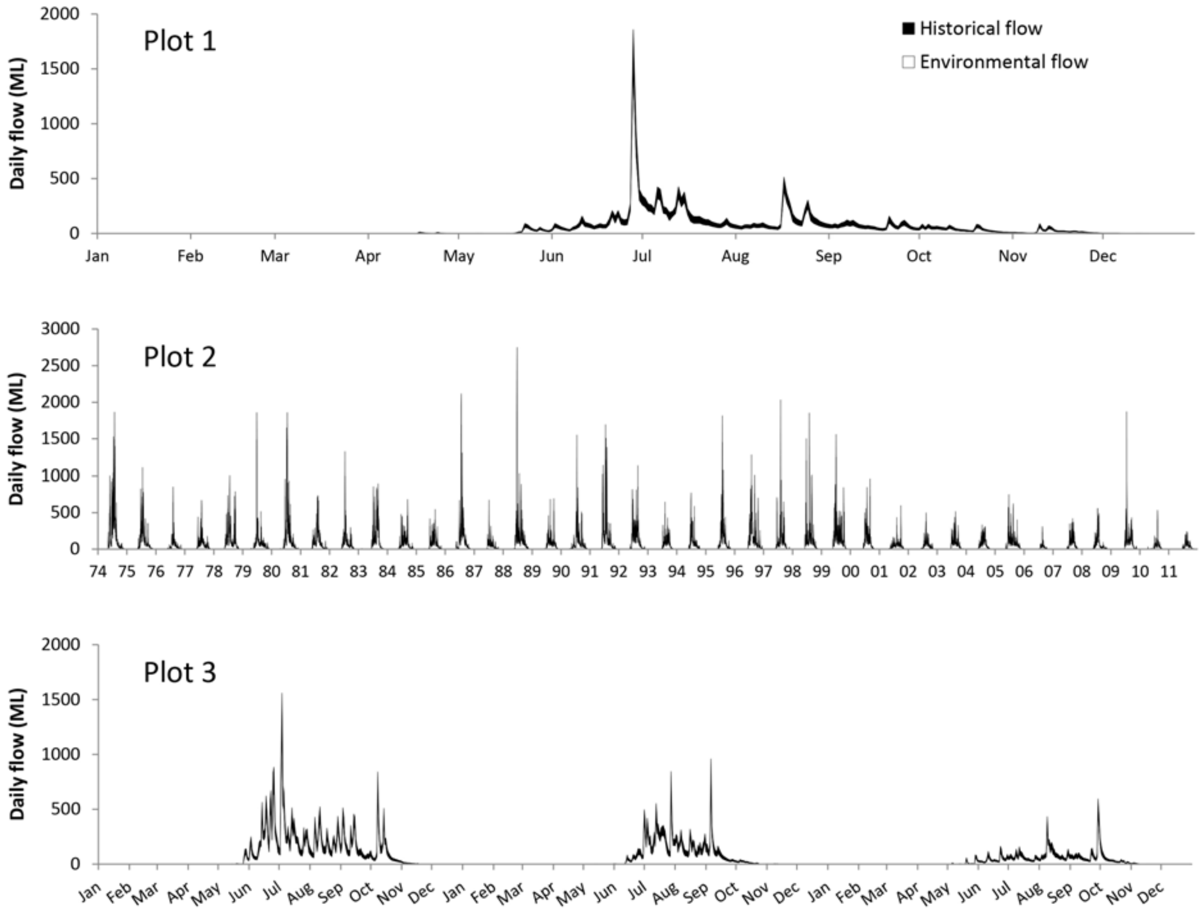


Figure 36 Time-series of the historical flow and modelled environmental flow for Woodlands Reach

Appendices B and C show monthly and annual data on the historical and environmental flows for the period 1974–2011 for Woodlands and Juniper reaches respectively. Between December and April of every year (the dry season), the monthly flow volumes in the historical flow tend to be reproduced exactly in the monthly environmental flow.

Over the period of record, the annual volume of the environmental flow for Woodlands Reach averaged 68 per cent of the annual flow, and varied between 62 per cent and 73 per cent. In Juniper Reach, the environmental flow averaged 79 per cent of annual flow, varying between 74 per cent and 82 per cent. The average annual environmental flow for both study reaches is similar to that of other nearby rivers where the PADFLOW approach has been used, at approximately 70–80 per cent of total annual flow (e.g. Donohue et al. 2010 and Green et al. 2011).

Annual environmental flow volumes between 1974 and 2011 ranged from 2.7 GL to 37.4 GL in Woodlands Reach (Table 5 and Appendix B), and 2.2 GL to 30.4 GL in Juniper Reach (Table 6 and Appendix C).

Table 5 Summary of annual flow volumes from the historical flow record and modelled environmental flow (1974–2011) for Woodlands Reach

	Historical flow	**Environmental flow**	**Environmental flow as a percentage (%) of historical flow**
Average	22.6 GL	15.6 GL	68%
Minimum	4.4 GL	2.7 GL	62%
Maximum	51.0 GL	37.4 GL	73%
Median	22.0 GL	15.0 GL	68%

Table 6 Summary of annual flow volumes from the historical flow record and modelled environmental flow (1974–2011) for Juniper Reach

	Historical flow	**Environmental flow**	**Environmental flow as a percentage (%) of historical flow**
Average	16.5 GL	13.2 GL	79%
Minimum	2.9 GL	2.2 GL	74%
Maximum	37.9 GL	30.4 GL	82%
Median	15.2 GL	12.0 GL	79%

6.1 Conclusion

The environmental flows developed for the Woodlands and Juniper reaches of Wilyabrup Brook are flow regimes below which there would be a risk to the health of in-stream ecology. The environmental flows will maintain the abundance and diversity of aquatic species and their habitats by maintaining the components of the flow regime that are responsible for the current ecological state of Wilyabrup Brook. These components are essential to the system’s resilience to pressures such as climate change.

The annual environmental flows in this study closely matched the historical annual volume and seasonal pattern of flow (measured at the gauging stations) that will maintain water-dependent species and their habitats. The results of the study will be used to evaluate the risk to ecosystems associated with additional levels of surface water use in the Wilyabrup Brook catchment. To confirm the volume of water that may be available for licensing we assess the reliability of supply to water users, environmental risk and the impact of future climate change.

Care should be taken when using environmental flows to guide annual water allocation decisions as most surface water in the south-west is harvested in fixed, on-stream farm dams which predominantly intercept early winter flows and low flows late in the flow season. The environmental flows in this study however, can be used as a baseline flow regime by which to monitor flows, and assess the ecological risk resulting from future water allocation in the Wilyabrup Brook catchment. This will be done as part of the implementation and evaluation of the *Whicher area surface water allocation plan* (Department of Water 2009).

6.2 Future studies and monitoring

A monitoring program will be developed for the *Whicher area surface water allocation plan*, including Wilyabrup Brook, to determine if the plan's objectives (see Department of Water 2009) are being met, drive adaptive management and be responsive to climate trends. The monitoring program will:

- assess the accuracy of the modelled ecological-flow thresholds in Woodlands and Juniper reaches by monitoring the relationship between flow and water depth
- assess if the recommended flows achieve the desired water levels predicted by the HEC-RAS hydraulic model
- assess if the magnitude, timing, frequency and duration of flows remaining after capture and use from farm dams are consistent with those in the recommended environmental flow (see Section 5)
- assess if ecological objectives are being met by undertaking periodic monitoring of stream ecology focusing on the diversity and abundance of macroinvertebrates and fish
- support the annual evaluation of flows, water use and allocation limits in the Wilyabrup Brook catchment.

Appendices

Appendix A — Ecological values of Wilyabrup Brook

Vegetation

Foreshore condition assessments undertaken by Jury (2006) along the length of Wilyabrup Brook showed that Woodlands Reach, located near the mouth of the brook (Figure 1), was in 'near pristine' condition. Overstorey species included marri (*Corymbia calophylla*), jarrah (*Eucalyptus marginata*) and peppermint (*Agonis flexuosa*), as well as heartleaf poison (*Gastrolobium bilobum*) (Figure A1). A number of different species of rushes and sedges were present along the riverbank, including *Lepidosperma* spp. and *Baumea* spp. (Jury 2006). A number of environmental weeds were reported for this stretch of the river, including arum lily (*Zantedeschia aethiopica*) and exotic *Acacia* species.

Figure A1 Riparian vegetation of Woodlands Reach

The condition assessment for Juniper Reach, located in the middle of the Wilyabrup Brook catchment (Figure 1), noted that the section of the river was prone to erosion and degraded in parts. The majority of the channel flows through agricultural land, and has been subject to removal and degradation of native vegetation (Figure A2). Erosion is evident where there is stock access to the channel, and there are few native understory species (Jury 2006). Remnant native overstorey species include marri, blackbutt (*Eucalyptus pilularis*) and peppermint, with patches of tea tree. A number of serious weeds were present within the reach, including blackberry (*Rubus* sp.), arum lily and bridal creeper (*Asparagus asparagoides*).

Figure A2 Riparian vegetation of Juniper Reach

Aquatic Invertebrates

A targeted sampling program for macroinvertebrates was undertaken for this study in autumn and spring of 2007 (Wetland Research and Management 2008). A total of 94 macroinvertebrate taxa were found. Arthropod taxa (i.e. crustaceans, arachnids and insects) comprised 87 of the macroinvertebrate taxa found. Of all the seven freshwater systems that were surveyed by Wetland Research and Management (2008), Wilyabrup Brook recorded the highest number of taxa. Over three quarters of the individual macroinvertebrate specimens collected were insects. A list of macroinvertebrate taxa that have collected from the Wilyabrup Brook is provided in Table A1.

Table A1 Macroinvertebrates of Wilyabrup Brook

Phylum	Subphylum	Class	Order	Family	Species
CNIDARIA					
		HYDROZOA		**Hydriidae**	Hydra spp.
MOLLUSCA					
		GASTROPODA	**Hygrophila**	**Planorbidae**	*Ferrissia petterdi*
				Lymnaeidae	*Pseudosuccinea columella*
				Planorbidae	Glyptophysa sp.
				Physidae	*Physa acuta*
ANNELIDA					
		OLIGOCHAETA			Oligochaeta spp.
		HIRUDINEA		**Glossophonidae**	Richardsonidae spp.
ARTHROPODA					
	CRUSTACEA	**MALACOSTRACA**	**Amphipoda**	**Perthiidae**	Perthia spp.
		OSTRACODA			Ostracoda spp.
		BRANCHIOPODA	**Diplostraca**		Cladocera spp.
		MAXILLOPODA	**Calanoida**		Calanoida spp.
			Cyclopoida		Cyclopoida spp.
	CHELICERATA	**ARACHNIDA**	**Acariformes**		Oribatida spp.
					Hydracarina spp.
	UNIRAMIA	**INSECTA**	**Ephemeroptera**	**Caenidae**	*Tasmanocoenis tillyardi*
					Caenidae sp.
				Baetidae	Cloeon sp.
					Baetidae spp.
				Leptophlebiidae	Leptophlebiidae spp.
			Odonata	**Aeshnidae**	Aeshnidae spp.
				Hemicorduliidae	*Hemicordulia australiae*
				Libellulidae	*Orthetrum caledonicum*
					Diplacodes haematodes
			Orthoptera	**Tettigoniidae**	Anisoptera spp.
			Hemiptera	**Veliidae**	Microvelia sp.
					Microvelia peramoena
					Veliidae spp.
				Hebridae	*Hebrus axillaris*
				Corixidae	Micronecta sp.
					Sigara truncatipala
ARTHROPODA	**UNIRAMIA**	**INSECTA**	**Hemiptera**	**Corixidae**	
					Corixidae sp.
				Notonectidae	Anisops sp.

Phylum	Subphylum	Class	Order	Family	Species
			Coleoptera	**Carabidae**	Carabidae spp.
				Dytiscidae	*Allodessus bistrigatus*
					Limbodessus inornatus
					Megaporus howitti
					Necterosoma penicillatus
					Paroster sp.
					Platynectes decempunctatus var polygrammus
					Platynectes sp.
					Rhantus suturalis
					Sternopriscus brownii
					Sternopriscus minimus
					Sternopriscus multimaculatus
					Sternopriscus sp.
					Copelatus sp.
				Gyrinidae	Macrogyrus (Triblogyrus) sp.
				Haliplidae	*Haliplus gibbus*
					Haliplus sp.
				Hydrophilidae	*Berosus approximans*
					Limnoxenus zealandicus
					Paracymus pygmaeus
				Hydraenidae	Octhebius sp.
			Diptera	**Chironomidae**	Chironomidae spp.
					Chironomus aff. alternans
					Cladopelma curtivalva
					Cryptochironomus griseidorsum
					Parachironomus sp.
					Polypedilum sp.
					Stenochironomus sp.
					Cladotanytarsus sp.
					Rheotanytarsus sp.
ARTHROPODA	**UNIRAMIA**	**INSECTA**	**Diptera**	**Chironomidae**	
					Tanytarsus sp.
					Botryocladius freemani
					Corynoneura sp.
					Cricotopus annuliventris

Phylum	Subphylum	Class	Order	Family	Species
					nr. Gymnometriocnemus
					Parakiefferiella sp.
					Parakiefferiella sp. (nr. variegatus)
					Thienemanniella sp.
					Apsectrotanypus maculosus
					Paramerina levidensis
					Pentaneura sp.
					Procladius paludicola
				Ceratopogonidae	Ceratopogoninae spp.
					Dasyheleinae spp.
					Forcypomiinae spp.
					Ceratopogonidae spp.
				Culicidae	Anopheles sp.
					Culex sp.
					Culicidae spp.
				Empididae	Empididae spp.
				Simuliidae	*Simulium ornatipes*
					Simulidae spp.
				Tipulidae	Tipulidae spp.
			Trichoptera		Trichoptera spp.
				Ecnomidae	Ecnomus sp.
					Daternomina sp.
					Ecnomidae spp.
				Hydroptilidae	Acritoptila/Hellyethira spp.
				Leptoceridae	*Notalina spira*
					Leptoceridae spp.

There are five species of freshwater crayfish known to occur in the rivers of south-west Western Australia. Both smooth marron (*Cherax cainii*) and gilgie (*C. quinquecarinatus*) have been found within Wilyabrup Brook (Beatty et al. 2006). Gilgies are the more common of the two species within the brook, whereas marron require larger, deeper pools as refugia during summer (Beatty et al. 2006).

In streams, aquatic invertebrate communities are influenced strongly by: seasonality, habitat diversity, and permanence of flows. These are points are discussed briefly below.

Fish

Five endemic fish species were recorded during surveys of the Wilyabrup Brook (Beatty et al. 2006). Only two of the five species recorded were true freshwater species, the western pygmy perch (*Nannoperca vittata*) and the western minnow

(*Galaxias occidentalis*). The Swan River goby (*Pseudogobius olorum*), western hardyhead (*Leptoatherina wallacei*) and the big-headed goby (*Afurgobius suppositus*) are estuarine species. While the other two estuarine species were found only near the mouth of Wilyabrup Brook, the Swan River goby penetrated further upstream. Landholders reported that mud minnows (*Galaxias munda*) had been sighted in the brook, although no specimens were collected by Beatty et al. (2006). No nightfish were captured in the brook, even though they are found in nearby freshwater systems. Nightfish (*Bostockia porosa*) and the introduced mosquitofish (*Gambusia holbrooki*) were not captured in the brook, even though they are found in nearby freshwater systems (Wetland Research and Management 2007a).

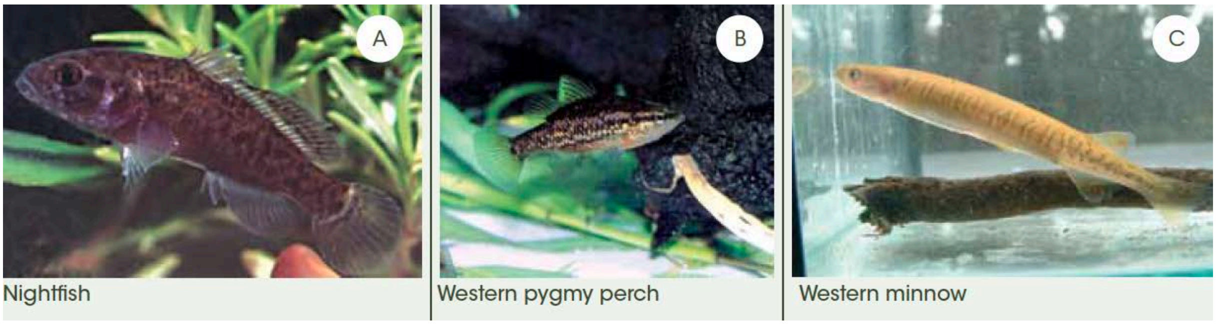


Figure A3 Endemic fish of Wilyabrup Brook. Source: (A, B) Photography by Dave Morgan. (C) Photography by Glenn Shiell.

Frogs and reptiles

The breeding requirements and tadpole ecology of species known to occur (Western Australian Museum database, Department of Parks and Wildlife or other records) in or at the nearby Cowaramup Brook (5 km to the south of Wilyabrup Brook) are listed in Table A2. Most require surface water for egg laying and over six weeks for tadpoles to mature into adult frogs. Most species breed during the wet season in the shallow waters at the edges of rivers and swamps and in small flooded depressions. Frogs spawn on emergent and submergent vegetation (Tyler et al. 2000). Tadpoles graze on aquatic algae. Adult frogs tend to be unspecialised opportunistic feeders, eating anything they can overcome and swallow whole, mainly insects.

Table A2 Habitat and breeding biology of frogs likely to occur in the Wilyabrup Brook area. Information 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	<u>Period:</u> July to October <u>Site:</u> Large and separate laid in shallow seep water or wet ground that will soon be flooded	<u>Habitat:</u> Tadpoles show lotic adaptions <u>Maturation:</u> 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

A literature review found no published surveys of reptiles for the Wilyabrup Brook (Wetland Research and Management 2007a). However, in areas of good riparian condition, similar species may be found as those which inhabit the riparian zone of the nearby Margaret River (Wetland Research and Management 2007a). Such species include the tiger snake (*Notechis scutatus*), the western glossy swamp skink (*Egernia luctuosa*) the western three-lined skink (*Acritoscincus trilineatum*) and the long-necked tortoise (*Chelodina oblonga*) (Figure A4). The first three reptile species are reliant upon riparian vegetation for survival and tend to be limited to areas of damp soil. Long-necked tortoises inhabit river pools, perennially-flowing streams and rivers, and areas of soft soil adjacent to river banks.

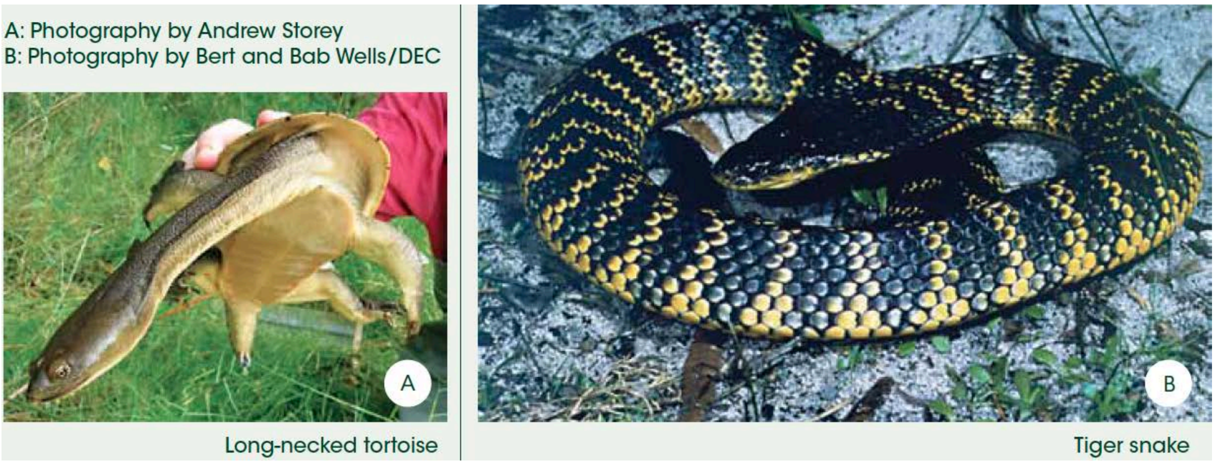


Figure A4 Reptiles of Wilyabrup Brook

Waterbirds

There have been no specific studies on the waterbird fauna of Wilyabrup Brook (Wetland Research and Management 2007a). Waterbird species that have been observed frequently in the region include the black swan (*Cygnus atratus*), Australian shelduck (*Tadorna tadornoides*), Australian wood duck (*Chenonetta jubata*), Pacific black duck (*Anas superciliosa*), Australian pelican (*Pelecanus conspicillatus*), white-faced heron (*Egretta novaehollandiae*), Australian white ibis (*Threskiornis molucca*), straw neck ibis (*Threskiornis spinicollis*), red-capped plover (*Charadrius ruficapillus*), hooded plover (*Thinornis rubricollis*) and the sacred kingfisher (*Tordirhamphus sanctus*) (Figure 10). The Department of Parks and Wildlife lists the hooded plover as a Priority 4 species.

Other waterbirds that have been observed less frequently, or are thought occur within the region are the musk duck (*Biziura lobata*), mallard duck (*Anas platyhychos*), pink-eared duck (*Malalcorhynchus membranaceus*), white-necked heron (*Ardea pacifica*), nankeen night heron (*Nycticoraz calendonicus*), glossy ibis (*Plegadis falcinellus*), royal spoonbill (*Platalea regia*), yellow-billed spoonbill (*Platalea flavipes*) and the blue-billed duck (*Oxyura australis*) (WRM 2007a). Examples of some of the waterbird species likely to inhabit Wilyabrup Brook are shown in Figure A5.

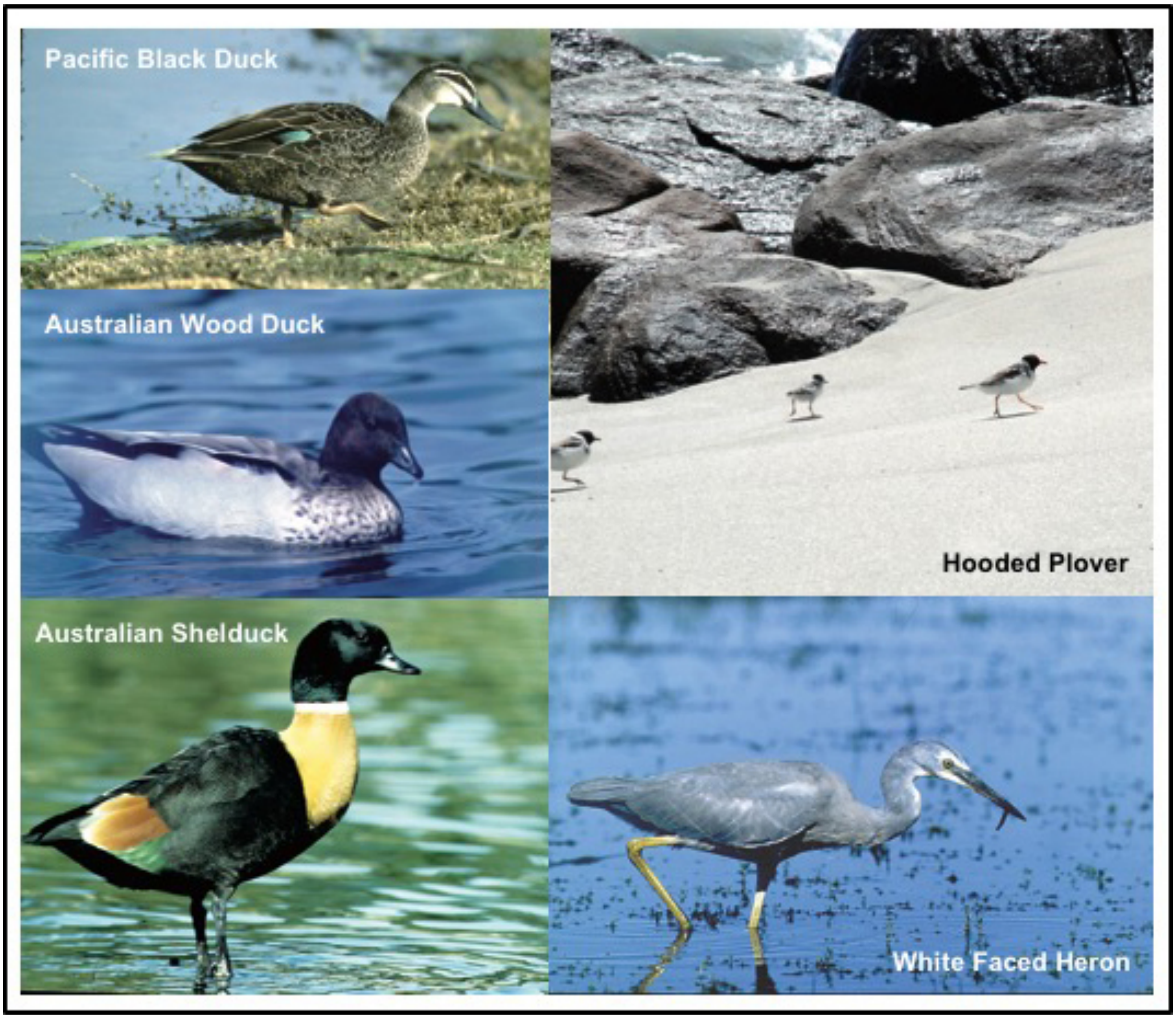


Figure A5 Waterbirds of Wilyabrup Brook. Source: Department of Parks and Wildlife

Mammals

Native mammal species that have been positively identified from the study area include the brushtail possum (*Trichosurus vulpecular*), the western ringtail possum (*Pseudocheirus occidentalis*), the brush-tailed phascogale (*Phascogale tapoatafa*), chuditch (*Dasyurus geoffroii*), the water rat (*Hydromys chrysogaster*) and the pygmy possum (*Cercartetus concinnus*) (Figure A6). Of these, water rats are the most closely associated with the river system.

The range of water rats has declined in south-west Western Australia due to salinisation and clearing of riparian vegetation (Wetland Research and Management 2007a). The two species of possums and the brush-tailed phascogale are reliant upon dense vegetation and the availability of hollow-bearing trees, which often occur near rivers and streams.

Other species that occur in the region and have habitat preferences that make them likely to preferentially utilise the riparian zone include the quenda or southern brown bandicoot (*Isoodon obesulus*) and the quokka (*Setonix brachyurus*).

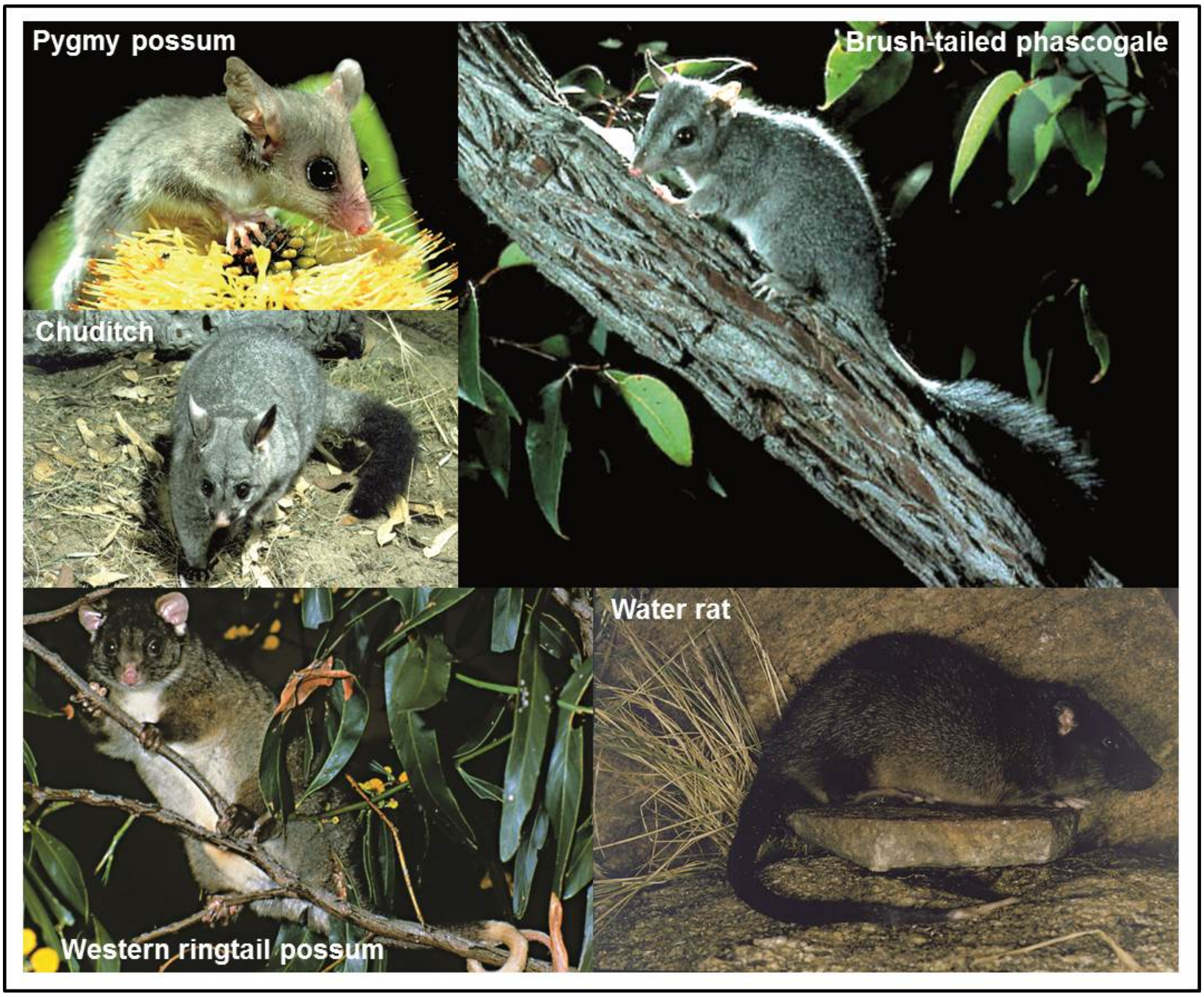


Figure A6 Mammals of Wilyabrup Brook. Source: Department of Parks and Wildlife

Appendix B — Monthly historical flow and environmental flow (EF) for Woodlands Reach (1974–2011)

Year	Data	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1974	Flow	0.000	0.000	0.000	0.001	3.546	7.311	15.734	8.588	1.529	0.860	0.318	0.016	37.9
	EF	0.000	0.000	0.000	0.001	2.806	5.836	12.865	6.870	1.180	0.614	0.229	0.014	30.4
1975	Flow	0.000	0.000	0.000	0.000	0.309	3.943	9.556	3.924	2.396	0.998	0.209	0.010	21.3
	EF	0.000	0.000	0.000	0.000	0.232	3.130	7.645	3.139	1.899	0.704	0.156	0.009	16.9
1976	Flow	0.014	0.000	0.000	0.000	0.067	0.377	1.806	4.159	1.235	0.589	0.286	0.023	8.6
	EF	0.012	0.000	0.000	0.000	0.053	0.272	1.404	3.327	0.921	0.421	0.207	0.021	6.6
1977	Flow	0.000	0.000	0.000	0.000	0.057	1.707	3.432	4.348	1.049	1.393	0.214	0.008	12.2
	EF	0.000	0.000	0.000	0.000	0.046	1.327	2.733	3.473	0.754	1.064	0.156	0.008	9.6
1978	Flow	0.000	0.000	0.000	0.000	0.606	5.178	6.795	2.639	4.680	2.477	0.252	0.014	22.6
	EF	0.000	0.000	0.000	0.000	0.457	4.142	5.436	2.093	3.719	1.937	0.183	0.014	18.0
1979	Flow	0.000	0.000	0.000	0.051	0.394	4.501	4.910	3.190	1.898	1.069	0.500	0.036	16.5
	EF	0.000	0.000	0.000	0.040	0.295	3.855	3.928	2.543	1.485	0.789	0.369	0.031	13.3
1980	Flow	0.001	0.000	0.000	0.035	0.154	4.144	14.055	6.186	2.156	1.213	0.267	0.046	28.3
	EF	0.001	0.000	0.000	0.028	0.117	3.290	11.521	4.949	1.691	0.907	0.196	0.039	22.7
1981	Flow	0.003	0.000	0.000	0.004	0.192	2.875	4.337	7.079	1.932	0.619	0.403	0.079	17.5
	EF	0.003	0.000	0.000	0.004	0.144	2.287	3.452	5.663	1.513	0.445	0.300	0.060	13.9
1982	Flow	0.014	0.000	0.000	0.000	0.013	1.785	6.815	2.372	1.986	1.194	0.127	0.005	14.3
	EF	0.014	0.000	0.000	0.000	0.013	1.391	5.452	1.879	1.534	0.894	0.097	0.005	11.3
1983	Flow	0.000	0.013	0.000	0.000	0.011	1.353	5.535	7.937	6.269	0.638	0.115	0.003	21.9
	EF	0.000	0.010	0.000	0.000	0.011	1.071	4.428	6.349	5.015	0.450	0.090	0.003	17.4
1984	Flow	0.004	0.002	0.001	0.000	0.097	1.672	3.756	3.758	3.851	0.597	0.412	0.013	14.2
	EF	0.003	0.002	0.001	0.000	0.070	1.289	2.988	3.006	3.056	0.426	0.300	0.012	11.2
1985	Flow	0.000	0.000	0.000	0.017	0.001	1.524	2.753	5.120	2.410	0.653	0.225	0.005	12.7
	EF	0.000	0.000	0.000	0.014	0.001	1.203	2.181	4.096	1.899	0.457	0.168	0.005	10.0
1986	Flow	0.001	0.000	0.000	0.000	0.603	1.811	11.144	7.966	2.500	0.826	0.131	0.001	25.0
	EF	0.001	0.000	0.000	0.000	0.457	1.418	9.520	6.373	1.987	0.584	0.100	0.001	20.4
1987	Flow	0.000	0.000	0.000	0.000	0.014	1.167	3.240	2.024	0.898	0.292	0.107	0.004	7.7
	EF	0.000	0.000	0.000	0.000	0.012	0.921	2.568	1.567	0.649	0.213	0.081	0.004	6.0
1988	Flow	0.001	0.000	0.000	0.000	0.187	8.954	6.555	6.350	3.149	1.339	0.288	0.004	26.8
	EF	0.001	0.000	0.000	0.000	0.144	7.850	5.244	5.080	2.519	1.009	0.206	0.004	22.1
1989	Flow	0.002	0.001	0.001	0.001	0.008	0.157	3.366	3.872	2.239	3.270	0.297	0.003	13.2
	EF	0.002	0.001	0.001	0.001	0.007	0.119	2.671	3.098	1.766	2.583	0.215	0.003	10.5
1990	Flow	0.001	0.000	0.001	0.062	0.438	1.568	7.133	4.744	3.028	1.330	0.464	0.019	18.8
	EF	0.001	0.000	0.001	0.049	0.322	1.195	5.689	3.795	2.379	0.985	0.343	0.016	14.8
1991	Flow	0.002	0.002	0.000	0.000	0.062	6.805	9.996	5.849	3.204	0.766	0.372	0.013	27.1
	EF	0.002	0.002	0.000	0.000	0.045	5.433	7.997	4.679	2.554	0.553	0.267	0.012	21.5
1992	Flow	0.000	0.000	0.003	0.002	0.275	5.150	5.938	7.687	3.430	0.682	0.241	0.024	23.4
	EF	0.000	0.000	0.003	0.002	0.202	4.114	4.750	6.150	2.739	0.478	0.179	0.020	18.6
1993	Flow	0.001	0.000	0.000	0.000	0.002	0.049	2.267	3.664	4.044	1.468	0.120	0.001	11.6
	EF	0.001	0.000	0.000	0.000	0.002	0.036	1.777	2.931	3.235	1.124	0.093	0.001	9.2
1994	Flow	0.000	0.000	0.000	0.000	0.033	2.243	5.764	2.555	1.219	0.416	0.012	0.000	12.2
	EF	0.000	0.000	0.000	0.000	0.027	1.752	4.611	2.031	0.920	0.297	0.010	0.000	9.6
1995	Flow	0.000	0.000	0.000	0.000	0.001	1.007	7.922	6.420	2.738	0.632	0.175	0.011	18.9
	EF	0.000	0.000	0.000	0.000	0.001	0.751	6.318	5.136	2.163	0.454	0.127	0.010	15.0
1996	Flow	0.000	0.000	0.000	0.000	0.004	0.899	8.403	7.446	4.726	2.764	1.167	0.263	25.7
	EF	0.000	0.000	0.000	0.000	0.004	0.712	6.722	5.957	3.781	2.165	0.863	0.190	20.4

Year	Data	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1997	Flow	0.002	0.001	0.000	0.000	0.007	2.472	2.906	7.427	4.206	0.681	0.081	0.002	17.8
	EF	0.002	0.001	0.000	0.000	0.006	1.936	2.283	6.244	3.364	0.499	0.061	0.002	14.4
1998	Flow	0.000	0.000	0.002	0.001	0.016	4.506	4.675	7.353	4.459	1.272	0.117	0.000	22.4
	EF	0.000	0.000	0.002	0.001	0.015	3.601	4.016	5.883	3.567	0.957	0.088	0.000	18.1
1999	Flow	0.000	0.000	0.000	0.001	0.401	6.837	8.030	5.355	4.331	3.411	0.159	0.002	28.5
	EF	0.000	0.000	0.000	0.001	0.318	5.461	6.424	4.284	3.465	2.687	0.117	0.002	22.8
2000	Flow	0.002	0.002	0.001	0.001	0.016	1.129	7.004	4.396	3.124	0.397	0.034	0.001	16.1
	EF	0.002	0.002	0.001	0.001	0.015	0.880	5.603	3.517	2.462	0.281	0.028	0.001	12.8
2001	Flow	0.000	0.000	0.000	0.000	0.283	1.225	1.708	2.705	2.389	1.199	0.078	0.004	9.6
	EF	0.000	0.000	0.000	0.000	0.217	0.919	1.313	2.145	1.874	0.898	0.061	0.004	7.4
2002	Flow	0.001	0.000	0.000	0.001	0.025	0.157	1.634	3.606	2.067	0.714	0.238	0.001	8.4
	EF	0.001	0.000	0.000	0.001	0.024	0.119	1.259	2.885	1.614	0.510	0.176	0.001	6.6
2003	Flow	0.000	0.000	0.000	0.000	0.013	0.517	3.391	4.230	2.796	0.857	0.065	0.002	11.9
	EF	0.000	0.000	0.000	0.000	0.012	0.401	2.713	3.384	2.223	0.624	0.052	0.002	9.4
2004	Flow	0.000	0.000	0.000	0.000	0.032	1.079	3.173	4.557	1.534	0.351	0.057	0.003	10.8
	EF	0.000	0.000	0.000	0.000	0.026	0.808	2.522	3.646	1.168	0.252	0.048	0.003	8.5
2005	Flow	0.000	0.000	0.000	0.000	0.263	3.529	2.892	3.343	1.688	1.683	0.419	0.047	13.9
	EF	0.000	0.000	0.000	0.000	0.189	2.816	2.296	2.670	1.294	1.274	0.300	0.038	10.9
2006	Flow	0.004	0.000	0.000	0.000	0.084	0.033	0.330	1.378	0.854	0.211	0.026	0.005	2.9
	EF	0.004	0.000	0.000	0.000	0.068	0.029	0.237	1.027	0.610	0.156	0.024	0.005	2.2
2007	Flow	0.000	0.000	0.000	0.038	0.004	0.119	1.738	3.318	2.850	1.013	0.091	0.008	9.2
	EF	0.000	0.000	0.000	0.031	0.004	0.091	1.340	2.650	2.280	0.727	0.071	0.008	7.2
2008	Flow	0.000	0.000	0.000	0.000	0.239	1.885	5.308	2.190	0.839	0.506	0.218	0.014	11.2
	EF	0.000	0.000	0.000	0.000	0.177	1.463	4.246	1.686	0.595	0.358	0.162	0.013	8.7
2009	Flow	0.000	0.000	0.000	0.000	0.000	0.743	7.876	2.976	3.954	0.839	0.243	0.010	16.6
	EF	0.000	0.000	0.000	0.000	0.000	0.592	6.746	2.381	3.163	0.625	0.180	0.010	13.7
2010	Flow	0.000	0.000	0.000	0.032	0.035	0.278	1.292	1.981	0.649	0.050	0.012	0.000	4.3
	EF	0.000	0.000	0.000	0.022	0.028	0.202	0.979	1.525	0.468	0.042	0.010	0.000	3.3
2011	Flow	0.000	0.000	0.000	0.000	0.005	0.257	1.295	2.639	1.421	0.458	0.073	0.000	6.1
	EF	0.000	0.000	0.000	0.000	0.005	0.189	0.985	2.093	1.076	0.327	0.059	0.000	4.7

Appendix C — Monthly historical flow and environmental flow (EF) for Juniper Reach (1974–2011)

Year	Data	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1974	Flow	0.000	0.000	0.000	0.001	3.546	7.311	15.734	8.588	1.529	0.860	0.318	0.016	37.9
	EF	0.000	0.000	0.000	0.001	2.806	5.836	12.865	6.870	1.180	0.614	0.229	0.014	30.4
1975	Flow	0.000	0.000	0.000	0.000	0.309	3.943	9.556	3.924	2.396	0.998	0.209	0.010	21.3
	EF	0.000	0.000	0.000	0.000	0.232	3.130	7.645	3.139	1.899	0.704	0.156	0.009	16.9
1976	Flow	0.014	0.000	0.000	0.000	0.067	0.377	1.806	4.159	1.235	0.589	0.286	0.023	8.6
	EF	0.012	0.000	0.000	0.000	0.053	0.272	1.404	3.327	0.921	0.421	0.207	0.021	6.6
1977	Flow	0.000	0.000	0.000	0.000	0.057	1.707	3.432	4.348	1.049	1.393	0.214	0.008	12.2
	EF	0.000	0.000	0.000	0.000	0.046	1.327	2.733	3.473	0.754	1.064	0.156	0.008	9.6
1978	Flow	0.000	0.000	0.000	0.000	0.606	5.178	6.795	2.639	4.680	2.477	0.252	0.014	22.6
	EF	0.000	0.000	0.000	0.000	0.457	4.142	5.436	2.093	3.719	1.937	0.183	0.014	18.0
1979	Flow	0.000	0.000	0.000	0.051	0.394	4.501	4.910	3.190	1.898	1.069	0.500	0.036	16.5
	EF	0.000	0.000	0.000	0.040	0.295	3.855	3.928	2.543	1.485	0.789	0.369	0.031	13.3
1980	Flow	0.001	0.000	0.000	0.035	0.154	4.144	14.055	6.186	2.156	1.213	0.267	0.046	28.3
	EF	0.001	0.000	0.000	0.028	0.117	3.290	11.521	4.949	1.691	0.907	0.196	0.039	22.7
1981	Flow	0.003	0.000	0.000	0.004	0.192	2.875	4.337	7.079	1.932	0.619	0.403	0.079	17.5
	EF	0.003	0.000	0.000	0.004	0.144	2.287	3.452	5.663	1.513	0.445	0.300	0.060	13.9
1982	Flow	0.014	0.000	0.000	0.000	0.013	1.785	6.815	2.372	1.986	1.194	0.127	0.005	14.3
	EF	0.014	0.000	0.000	0.000	0.013	1.391	5.452	1.879	1.534	0.894	0.097	0.005	11.3
1983	Flow	0.000	0.013	0.000	0.000	0.011	1.353	5.535	7.937	6.269	0.638	0.115	0.003	21.9
	EF	0.000	0.010	0.000	0.000	0.011	1.071	4.428	6.349	5.015	0.450	0.090	0.003	17.4
1984	Flow	0.004	0.002	0.001	0.000	0.097	1.672	3.756	3.758	3.851	0.597	0.412	0.013	14.2
	EF	0.003	0.002	0.001	0.000	0.070	1.289	2.988	3.006	3.056	0.426	0.300	0.012	11.2
1985	Flow	0.000	0.000	0.000	0.017	0.001	1.524	2.753	5.120	2.410	0.653	0.225	0.005	12.7
	EF	0.000	0.000	0.000	0.014	0.001	1.203	2.181	4.096	1.899	0.457	0.168	0.005	10.0
1986	Flow	0.001	0.000	0.000	0.000	0.603	1.811	11.144	7.966	2.500	0.826	0.131	0.001	25.0
	EF	0.001	0.000	0.000	0.000	0.457	1.418	9.520	6.373	1.987	0.584	0.100	0.001	20.4
1987	Flow	0.000	0.000	0.000	0.000	0.014	1.167	3.240	2.024	0.898	0.292	0.107	0.004	7.7
	EF	0.000	0.000	0.000	0.000	0.012	0.921	2.568	1.567	0.649	0.213	0.081	0.004	6.0
1988	Flow	0.001	0.000	0.000	0.000	0.187	8.954	6.555	6.350	3.149	1.339	0.288	0.004	26.8
	EF	0.001	0.000	0.000	0.000	0.144	7.850	5.244	5.080	2.519	1.009	0.206	0.004	22.1
1989	Flow	0.002	0.001	0.001	0.001	0.008	0.157	3.366	3.872	2.239	3.270	0.297	0.003	13.2
	EF	0.002	0.001	0.001	0.001	0.007	0.119	2.671	3.098	1.766	2.583	0.215	0.003	10.5
1990	Flow	0.001	0.000	0.001	0.062	0.438	1.568	7.133	4.744	3.028	1.330	0.464	0.019	18.8
	EF	0.001	0.000	0.001	0.049	0.322	1.195	5.689	3.795	2.379	0.985	0.343	0.016	14.8
1991	Flow	0.002	0.002	0.000	0.000	0.062	6.805	9.996	5.849	3.204	0.766	0.372	0.013	27.1
	EF	0.002	0.002	0.000	0.000	0.045	5.433	7.997	4.679	2.554	0.553	0.267	0.012	21.5
1992	Flow	0.000	0.000	0.003	0.002	0.275	5.150	5.938	7.687	3.430	0.682	0.241	0.024	23.4
	EF	0.000	0.000	0.003	0.002	0.202	4.114	4.750	6.150	2.739	0.478	0.179	0.020	18.6
1993	Flow	0.001	0.000	0.000	0.000	0.002	0.049	2.267	3.664	4.044	1.468	0.120	0.001	11.6
	EF	0.001	0.000	0.000	0.000	0.002	0.036	1.777	2.931	3.235	1.124	0.093	0.001	9.2
1994	Flow	0.000	0.000	0.000	0.000	0.033	2.243	5.764	2.555	1.219	0.416	0.012	0.000	12.2
	EF	0.000	0.000	0.000	0.000	0.027	1.752	4.611	2.031	0.920	0.297	0.010	0.000	9.6
1995	Flow	0.000	0.000	0.000	0.000	0.001	1.007	7.922	6.420	2.738	0.632	0.175	0.011	18.9
	EF	0.000	0.000	0.000	0.000	0.001	0.751	6.318	5.136	2.163	0.454	0.127	0.010	15.0

Year	Data	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1996	Flow	0.000	0.000	0.000	0.000	0.004	0.899	8.403	7.446	4.726	2.764	1.167	0.263	25.7
	EF	0.000	0.000	0.000	0.000	0.004	0.712	6.722	5.957	3.781	2.165	0.863	0.190	20.4
1997	Flow	0.002	0.001	0.000	0.000	0.007	2.472	2.906	7.427	4.206	0.681	0.081	0.002	17.8
	EF	0.002	0.001	0.000	0.000	0.006	1.936	2.283	6.244	3.364	0.499	0.061	0.002	14.4
1998	Flow	0.000	0.000	0.002	0.001	0.016	4.506	4.675	7.353	4.459	1.272	0.117	0.000	22.4
	EF	0.000	0.000	0.002	0.001	0.015	3.601	4.016	5.883	3.567	0.957	0.088	0.000	18.1
1999	Flow	0.000	0.000	0.000	0.001	0.401	6.837	8.030	5.355	4.331	3.411	0.159	0.002	28.5
	EF	0.000	0.000	0.000	0.001	0.318	5.461	6.424	4.284	3.465	2.687	0.117	0.002	22.8
2000	Flow	0.002	0.002	0.001	0.001	0.016	1.129	7.004	4.396	3.124	0.397	0.034	0.001	16.1
	EF	0.002	0.002	0.001	0.001	0.015	0.880	5.603	3.517	2.462	0.281	0.028	0.001	12.8
2001	Flow	0.000	0.000	0.000	0.000	0.283	1.225	1.708	2.705	2.389	1.199	0.078	0.004	9.6
	EF	0.000	0.000	0.000	0.000	0.217	0.919	1.313	2.145	1.874	0.898	0.061	0.004	7.4
2002	Flow	0.001	0.000	0.000	0.001	0.025	0.157	1.634	3.606	2.067	0.714	0.238	0.001	8.4
	EF	0.001	0.000	0.000	0.001	0.024	0.119	1.259	2.885	1.614	0.510	0.176	0.001	6.6
2003	Flow	0.000	0.000	0.000	0.000	0.013	0.517	3.391	4.230	2.796	0.857	0.065	0.002	11.9
	EF	0.000	0.000	0.000	0.000	0.012	0.401	2.713	3.384	2.223	0.624	0.052	0.002	9.4
2004	Flow	0.000	0.000	0.000	0.000	0.032	1.079	3.173	4.557	1.534	0.351	0.057	0.003	10.8
	EF	0.000	0.000	0.000	0.000	0.026	0.808	2.522	3.646	1.168	0.252	0.048	0.003	8.5
2005	Flow	0.000	0.000	0.000	0.000	0.263	3.529	2.892	3.343	1.688	1.683	0.419	0.047	13.9
	EF	0.000	0.000	0.000	0.000	0.189	2.816	2.296	2.670	1.294	1.274	0.300	0.038	10.9
2006	Flow	0.004	0.000	0.000	0.000	0.084	0.033	0.330	1.378	0.854	0.211	0.026	0.005	2.9
	EF	0.004	0.000	0.000	0.000	0.068	0.029	0.237	1.027	0.610	0.156	0.024	0.005	2.2
2007	Flow	0.000	0.000	0.000	0.038	0.004	0.119	1.738	3.318	2.850	1.013	0.091	0.008	9.2
	EF	0.000	0.000	0.000	0.031	0.004	0.091	1.340	2.650	2.280	0.727	0.071	0.008	7.2
2008	Flow	0.000	0.000	0.000	0.000	0.239	1.885	5.308	2.190	0.839	0.506	0.218	0.014	11.2
	EF	0.000	0.000	0.000	0.000	0.177	1.463	4.246	1.686	0.595	0.358	0.162	0.013	8.7
2009	Flow	0.000	0.000	0.000	0.000	0.000	0.743	7.876	2.976	3.954	0.839	0.243	0.010	16.6
	EF	0.000	0.000	0.000	0.000	0.000	0.592	6.746	2.381	3.163	0.625	0.180	0.010	13.7
2010	Flow	0.000	0.000	0.000	0.032	0.035	0.278	1.292	1.981	0.649	0.050	0.012	0.000	4.3
	EF	0.000	0.000	0.000	0.022	0.028	0.202	0.979	1.525	0.468	0.042	0.010	0.000	3.3
2011	Flow	0.000	0.000	0.000	0.000	0.005	0.257	1.295	2.639	1.421	0.458	0.073	0.000	6.1
	EF	0.000	0.000	0.000	0.000	0.005	0.189	0.985	2.093	1.076	0.327	0.059	0.000	4.7

Shortened forms

CSIRO	Commonwealth Scientific and Industrial Research Organisation
DPaW	Department of Parks and Wildlife
EWR	ecological water requirement
HEC-RAS	Hydrological Engineering Center, United States Army Corps of Engineers, River Analysis System
PADFLOW	Proportional Abstraction of Daily Flows (method)
RAP	River Analysis Package
RESYM	River Ecologically Sustainable Yield Model

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.
Carbon cycle	The circulation of carbon through the ecosystem.
Catchment	Area of land from which rainfall runoff contributes to a single watercourse, wetland or aquifer.
Chironomid	A family of nematoceran flies.
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.
Desiccation	The state of extreme dryness or the process of extreme drying.
Historical flow	Refers to the post-development flow record (1974–2011) for Woodlands and Juniper reaches of Wilyabrup Brook.
Environmental flow	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.
Flow	Streamflow in terms of m^3/yr, m^3/d or ML/yr. Also known as discharge.
Food web	Describes the eating relationships between species within an ecosystem.
Groundwater	Water that occupies the pores and crevices of rock or soil beneath the

	land surface.
Natural flows paradigm	A belief amongst ecologists that the natural regime of flow is responsible for the evolution of the observed ecological state of a river.
Oligochaete	Any worm of the subclass Oligochaeta (class Clitellata, phylum Annelida). Common all over the world and living in the sea, fresh water and moist soil.
Piscivorous	Fish-eating.
Riffle	A shallow area of a stream where water flows rapidly over a rocky or gravelly stream bed causing rippling of the water's surface or small waves.
Surface water	Water flowing or held in streams, rivers and other wetlands on the surface of the landscape.
Terrestrial	Lives on the land.
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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