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

Ecological water requirement for Lefroy Brook

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Report no. 6
January 2009

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Foreword

This study was carried out to determine the ecological water requirements (EWR) of Lefroy Brook. It is one of seven similar studies being done on rivers in the south west of Western Australia. The EWR study program also includes the Brunswick and Capel rivers, Wilyabrup Brook, Cowaramup Brook, Margaret River and Chapman Brook.

The study program was funded by the Commonwealth and state governments as part of National Action Plan for Salinity and Water Quality. The works program was put together by the Department of Water and the South West Catchments Council, which administers the National Action Plan funding. This program of work was designed to support the management of the rivers in the South West, which are under increasing pressure due to decreasing flows caused by climate change combined with increases in the abstraction and/or interception of water to meet demands for public water supply and irrigated agriculture. The primary objective of the program was to inform water resource planning decisions by providing estimates of the river systems ecologically sustainable yields.

The research program commenced in August of 2005 when funds were approved (as part of IP1) to carry out preliminary work needed to complete EWR studies. This work included, for example, flow modelling and reporting, reach-scale reconnaissance and site selection, biological surveys and river channel surveys and hydraulic modelling on a total of 12 reaches distributed between the seven rivers. The second round of funding (IP2) was approved in 2007 to complete the EWR studies including the specification of ecologically important flows to protect ecological values, and using this information to develop a modelled EWR flow regime based on the period from 1975 to 2003.

To better define the EWR and the resulting sustainable yields, the Department of Water developed a new approach to determining EWRs in rivers called the proportional abstraction of daily flows or PADFLOW. It is supported by software known as the river ecologically sustainable yield model or RESYM. The Lefroy Brook study represents the first use of PADFLOW and RESYM to determine a rivers EWRs and sustainable yields.

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Summary

The ecological water requirement (EWR) of a river is the water regime needed to maintain ecological values of water-dependent ecosystems at a low level of risk. This report describes the development of an EWR for Lefroy Brook, a tributary of the Warren River in south-west Western Australia. The EWR for Lefroy Brook was developed using a new approach called the proportional abstraction of daily flows method (PADFLOW), which evolved out of the department's experience with using the flow events method for EWR studies.

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

The EWR was developed with the aim of conserving the current ecological values of the cascades reach. Some elements of the pre-development flow regime were considered in specifying the EWR, especially characteristics of the summer flow regime. The EWR developed in this study used the flow records of Lefroy Brook for the period 1975 to 2003.

Flows to achieve a number of ecologically significant water depths, or flow thresholds, were identified using the hydraulic analysis module in the river analysis package (RAP). These thresholds support or achieve key ecological functions, such as depths required for pool water quality, fish migration, inundation of fish breeding habitat, and flows needed to scour the channel of sediment and maintain a diversity of habitat.

An expert panel used the flow thresholds to produce a modelled EWR flow regime that achieves each of a series of ecological objectives. The expert panel evaluated the EWR by comparing the frequency and duration of flow spells above each flow threshold for the EWR against the observed frequency and duration for the flow record between 1975 and 2003.

A three-year portion of the EWR is shown in Figure 1. The magnitude of the EWR is smaller than the observed daily flows except for very low summer flows. During low summer flows, the EWR and observed flows are equivalent. Overall, the modelled annual EWR is about 60% of the observed yearly flow. The modelled EWR also retains much of the variability present in the measured observed flow.

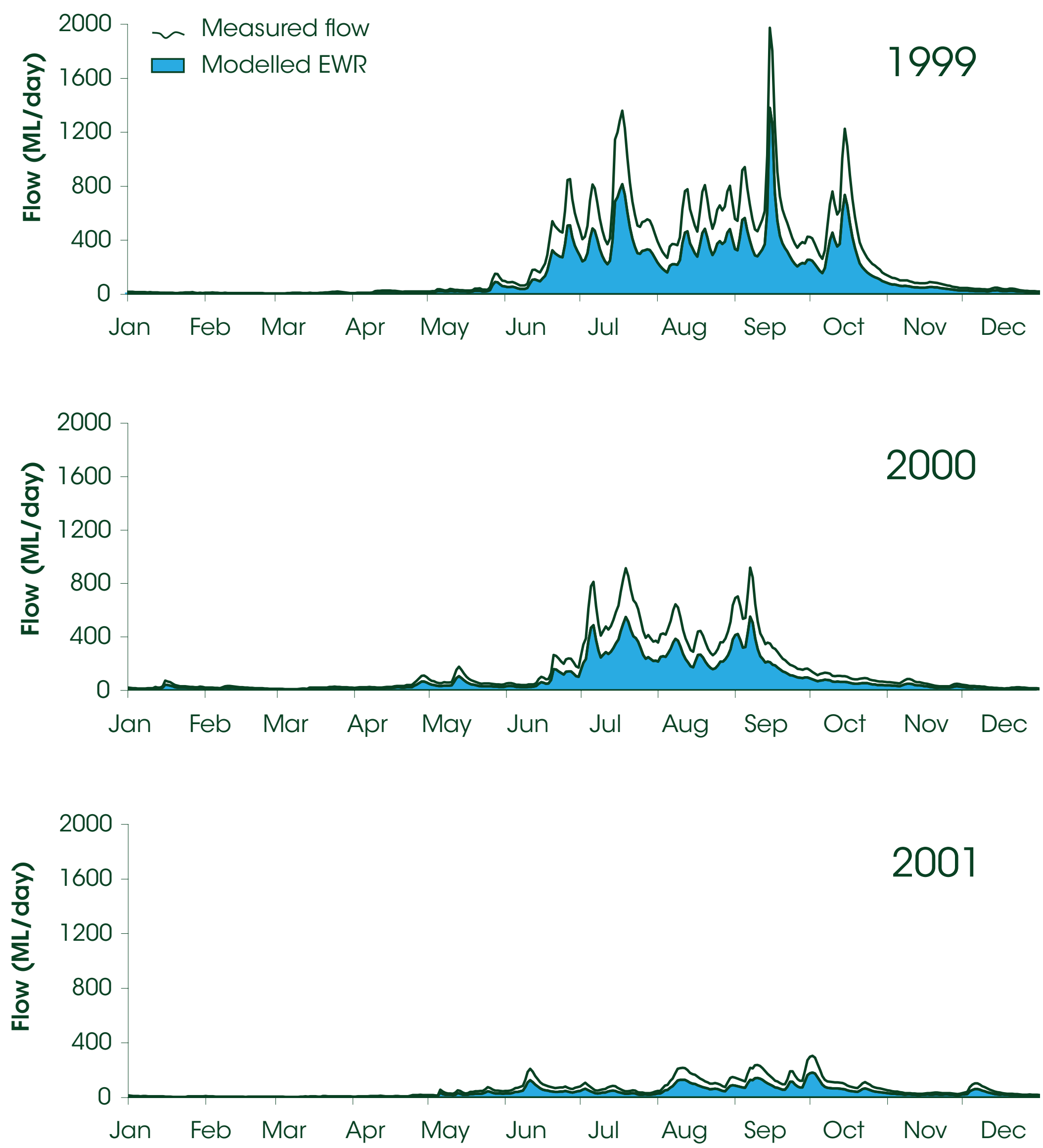
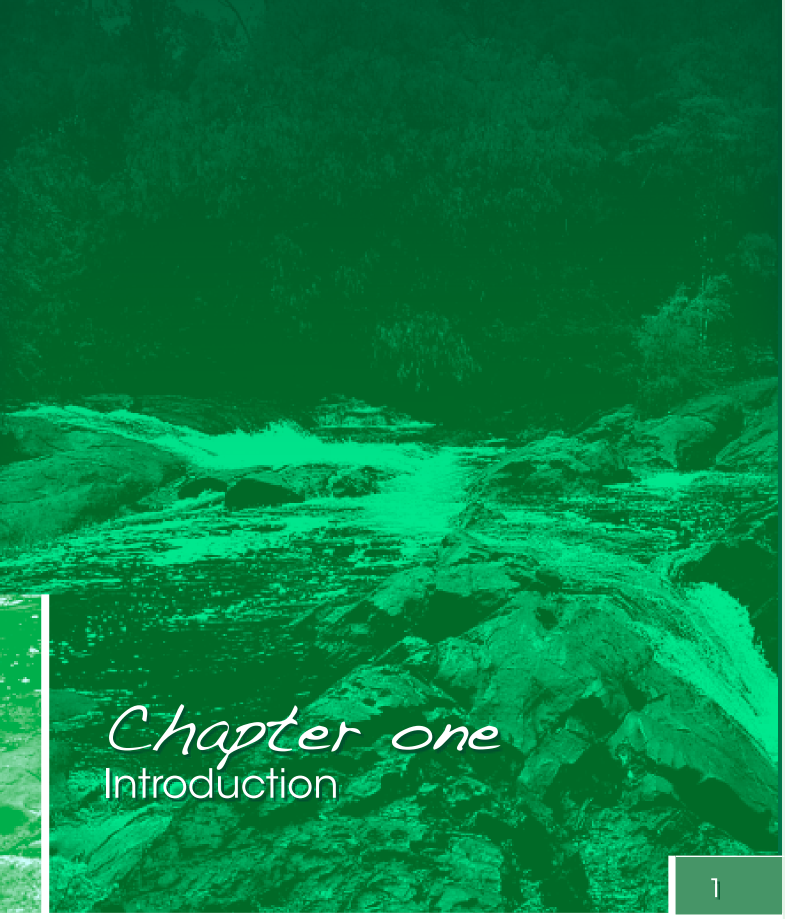


Figure 1

Observed flow and modelled EWR for Lefroy Brook – 1999, 2000 and 2001

Flow in 1999 was the second highest on record. A median flow was observed in 2000 and the flow in 2001 was the second lowest recorded in the period 1975 to 2003.

The proportion of water removed from the observed flow to produce the EWR is the volume of water that can be extracted while conserving current ecological values. The difference between the observed flow and EWR is considered to be an estimate of the ecologically sustainable yield (ESY) for Lefroy Brook. This study suggests that between 7 and 39 GL of water can be extracted from the cascades reach, depending on annual flow. This potential yield is additional to the current level of use in the developed areas of the catchment which may be harvested only with appropriate restrictions on when and how water can be abstracted.



Chapter one

Introduction

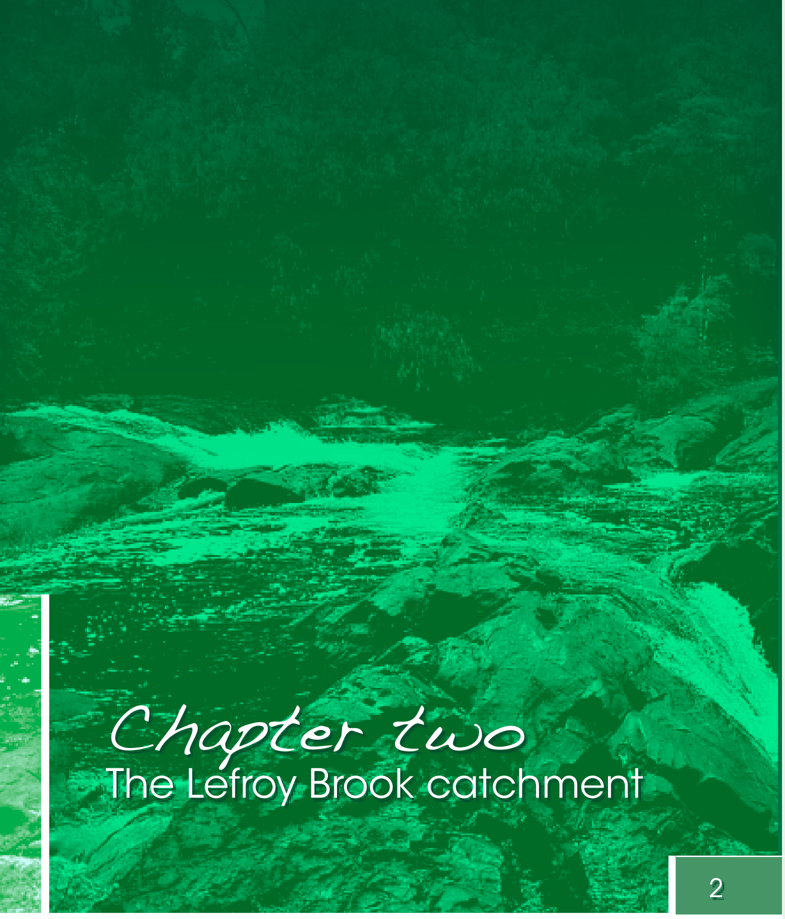
1

This report presents the results of a study designed to determine the ecological water requirements of Lefroy Brook in south west Western Australia. The Lefroy Brook study is part of a larger program called the South West Environmental Water Provisions Project, in which EWRs are being determined for the Brunswick River, Capel River, Wilyabrup Brook, Cowaramup Brook, Margaret River, Chapman Brook and Lefroy Brook. These seven waterways and associated catchments were identified as priorities for research due to the high demand for water for irrigated agricultural, mining and water supply, and declining rainfall in south-west Western Australia.

The Department of Water is Western Australia's primary water resource management agency. To support water resource planning in the south-west, the department carries out studies to determine the ecologically sustainable yield of surface waters in the region and place an appropriate water allocation limit taking into consideration economic, social, cultural and ecological values. This study was undertaken with the aim of supporting water resource planning in the Warren and Donnelly river management areas.

The ecological water requirement of a river is defined by the Department of Water as the water regime needed to maintain the ecological values of the river at a low level of risk. This study used a holistic approach to assessing the EWR of the cascades reach of Lefroy Brook. Holistic methods consider the riverine ecosystem and examine the water dependence of biodiversity, food-web interactions, ecological processes and individual species.

An ecological water requirement needs to be consistent with the natural flows paradigm which states that the natural regime of flow is responsible for the evolution of the observed ecological state of a river (Poff et al. 1997). It is the natural flow that has its biodiversity, food webs and processes that support a healthy and adaptive system. The natural flows paradigm suggests that an ecological water requirement must consider the total flow environment including the natural duration and frequency of ecologically important flow events, the annual and inter-annual flow regime, seasonal patterns of flow and the longer-term cyclical patterns in flow.



Chapter two
The Lefroy Brook catchment

2.1 Location

The Lefroy Brook catchment is located approximately 280 km south of Perth in south-west Western Australia. The town of Pemberton is located in the southern-central part of the catchment, near the confluence of East Brook and Lefroy Brook (Figure 2). The study site was located in the cascades reach of Lefroy Brook.

The catchment has an area of approximately 360 km^2 and drains the southward sloping part of the Darling Plateau known as the Ravensthorpe Ramp (De Silva 2004). The physiography has been described as dissected undulating land of low relief (Beard 1990). The Lefroy Brook joins the Warren River approximately 25 km upstream of the Warren River estuary.

2.2 Climate and hydrology

The region has a Mediterranean climate with cool, wet winters and hot, dry summers. Rainfall and flow in the region's rivers are highly seasonal and variable with cyclic periods of high rainfall (mid 1980s) and low rainfall (late 1970s). There is a period of three to four months in summer and early autumn during which there is little or no rainfall, and rivers recede to a series of disconnected pools or pools linked by very low flows (Brett 2007). Approximately 90% of rain falls between April and November (Figure 3).
For this report, the term 'summer flow' will be used to describe the period from December to April, and 'winter flow' for the period from May to November.

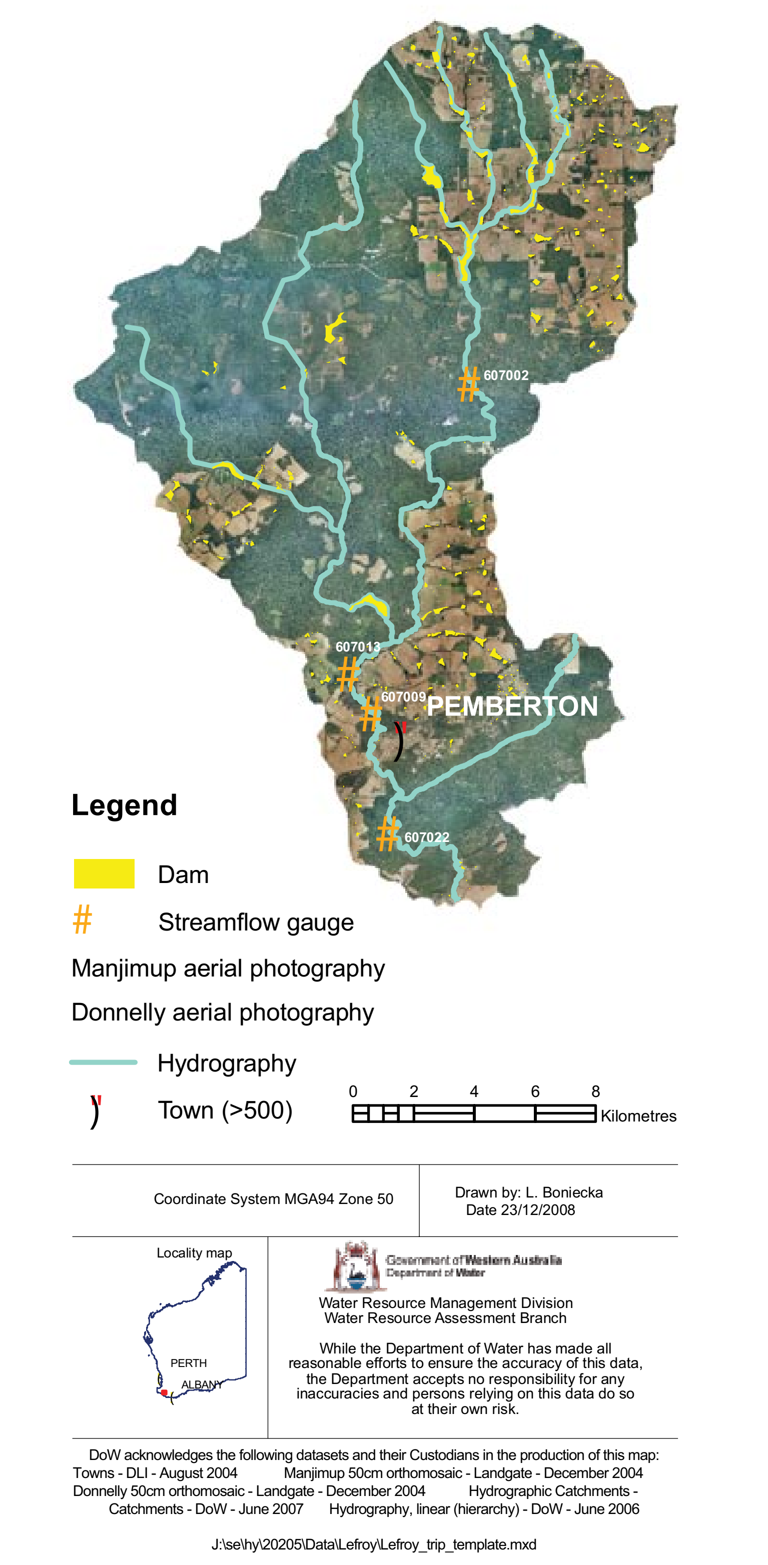


Figure 2
Map of Lefroy Brook catchment
The map shows Lefroy Brook and its major tributaries, together with farm dams and cleared areas supporting irrigated agriculture.

Streamflow in Lefroy Brook is highly seasonal, and has a similar seasonal pattern as rainfall, although there is a lag of about a month between the peak streamflow and peak rainfall (Figure 3). The lag is linked to soil storage, recharge of groundwater and the timing of peaks in groundwater level. The similarity between median and mean monthly streamflow (Figure 3) indicates that total annual flow is not dominated by infrequent large flow events.

The south west has experienced a long period of declining rainfall. In the Lefroy catchment, mean annual rainfall for the thirty years to 2004 was 1138 mm, down from the long term average to 2000 of 1218 mm (Table 1). The cascades reach of Lefroy Brook has a mean annual flow of 57.9 GL (1975 to 2004), which is down 16% from the 1952 to 2004 average. Over the same period, rainfall at Pemberton decreased by 7% (Table 1).

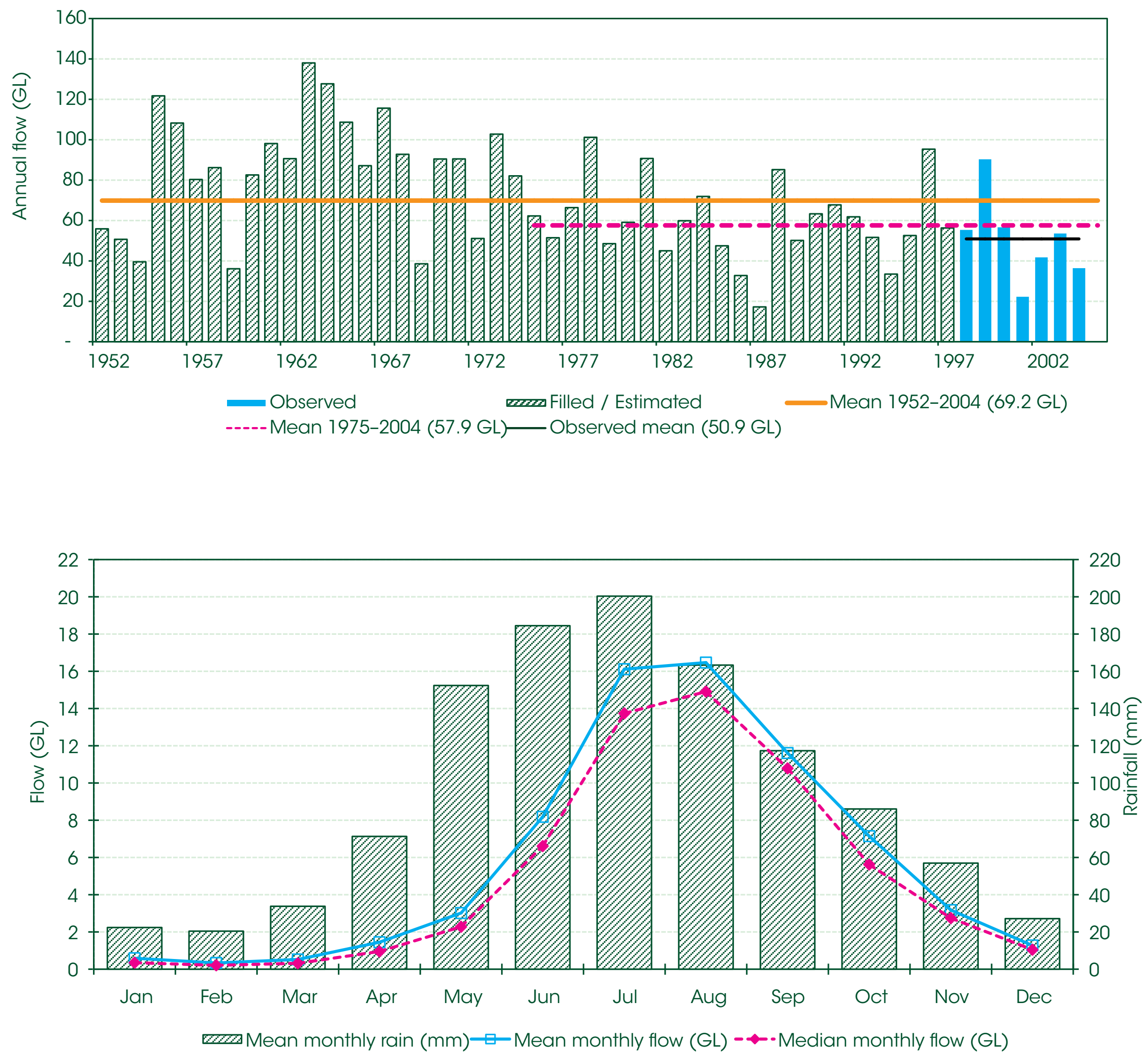


Figure 3

Variation in annual discharge and rainfall in the Lefroy Brook area

The upper plot shows modelled and observed annual flow in Lefroy Brook and variation in mean annual flow since 1995. The lower plot displays mean monthly rainfall at Pemberton and the seasonal pattern of flow in the period from 1975 to 2003.

Table 1
Annual rainfall and discharge in seven rivers of south-west Western Australia, 1975–2005

River	Catchment area km^2	Annual rainfall (1975–2005)		Annual flow (1975–2005)	
		Mean mm/year	Decline between 1975 and 2003 %	Mean GL/year	Decline between 1975 and 2003 %
Brunswick	286	911	9	55.1	13
Capel	635	735	11	44.8	
Chapman	184	1148	1	49.1	
Cowaramup	24	1055	12	3.4	
Lefroy	358	1138	7	57.9	16
Margaret	477	1046	8	86.2	
Wilyabrup	89	1065	7	23.9	

The relationship between rainfall and discharge in April, May and June (Figure 4) suggests that flow was lower in the decade of 1994–2003 than in the previous two decades, despite the fact that rainfall in May and June has varied little since 1975. The reduction in discharge coincides with the construction of Big Brook Dam in 1991 and the expansion of viticulture. An increase in the total storage capacity of on-stream dams within the catchment may explain the reduction in early winter flows, as the dams would be filling at this time of year.

Climate models predict that mean annual temperature in south-west Western Australia will increase by between 0.4 °C and 1.6 °C by 2030. Winter and spring rainfall is predicted to decrease by between 5% and 20%, while summer and autumn rainfall may either increase or decrease by 10%. Although the intensity of winter rainfall events is predicted to increase, the duration of rainfall events is expected to decrease. It is expected that this will correspond with an increase in evaporation and periods of very low rainfall (CSIRO 2001).

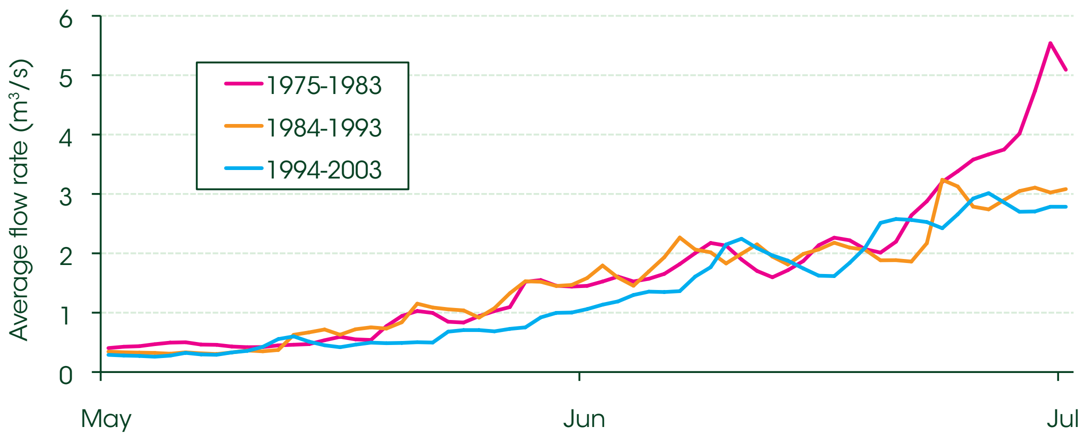


Figure 4
Hydrograph of early wet season flow rate in Lefroy Brook

Daily flow has been averaged for the periods indicated.

2.3 Hydrogeology

In the Lefroy Brook catchment, groundwater occurs mainly in the permeable zones of weathered rock, which are between 5 m and 30 m below ground level, and above bedrock. Groundwater flow within the weathered rock aquifer is either partly or completely confined by an impermeable clay layer and is characterised mainly by local flow systems. The aquifer recharges through direct rainfall infiltration and discharges to watercourses, wetlands and through evapotranspiration (De Silva 2004). The groundwater salinity is typically less than 1000 mg/L total dissolved solids (TDS) (De Silva 2004).

The Lefroy Brook catchment also contains several pocket areas of quartz veins and quartzite in the central and south-eastern areas. These areas form high-yielding fractured rock aquifers that can store significant amounts of water. These pockets of groundwater typically have salinity less than 500 mg/L TDS (De Silva 2004).

2.4 Water resource development

2.4.1 Water use

The major use of water in the Lefroy Brook catchment is for irrigated agriculture, which is characterised by self supply from farm dams. About 40% of the Lefroy catchment has been cleared for grazing, intensive livestock production, cropping, irrigated viticulture and horticulture (Brett 2007). Current licensed water entitlements amount to 15.3 GL per year, although it is thought that annual use is closer to 11 GL per year.

Recent mapping identified a total of 667 dams in the cleared areas of the upper and central areas of the Lefroy Brook catchment (Sinclair Knight Merz 2006). The dams have been constructed on-stream in cascading sequences. The farm dams vary in storage capacity from less than 0.1 ML to 380 ML and have a total storage capacity of 8870 ML. There are also three large water supply dams within the catchment with a combined storage of 2.5 GL.

During the last decade, there has been considerable investment in viticulture in the region, and this is expected to continue (Brett 2007). There are concerns that plantation forestry may be intercepting rainfall and reducing the amount of runoff from previously cleared areas (Beckwith Ecological Planning 2007).

2.4.2 Impact of farm dams on flows

The interception of runoff (and groundwater) by farm dams is known to diminish the magnitude and alter the seasonal pattern of river flow, especially in catchments with high levels of dam development (Sinclair Knight Merz 2007). In the Lefroy Brook, farm dams collect winter flows for irrigation over the drier period between October and May. Interception of flows by on-stream dams typically reduces the magnitude of summer flows and delays the start of winter flows downstream. These changes in flow regime have occurred over a period of around 30 years, which corresponds with the growth of irrigated agriculture in the catchment.

Modelling indicates that dams in the cleared parts of the catchment have reduced annual flows in the cascades reach by 15% and significantly reduce summer flows and flows in the early part of the flow season (May and June) (Sinclair Knight Merz 2007). Flows from about July to October have not been significantly affected, which suggests that the dams fill quickly and spill during the winter period (Sinclair Knight Merz 2007). As a result, interception by on-stream dams may be affecting ecosystems that are dependant on flows in the early part of the flow season. On-stream dams are a physical barrier to upstream movement of species especially fish during low flows. Some fish species may be able to negotiate dams during heavy winter rains and flood flows (Penn 1999).

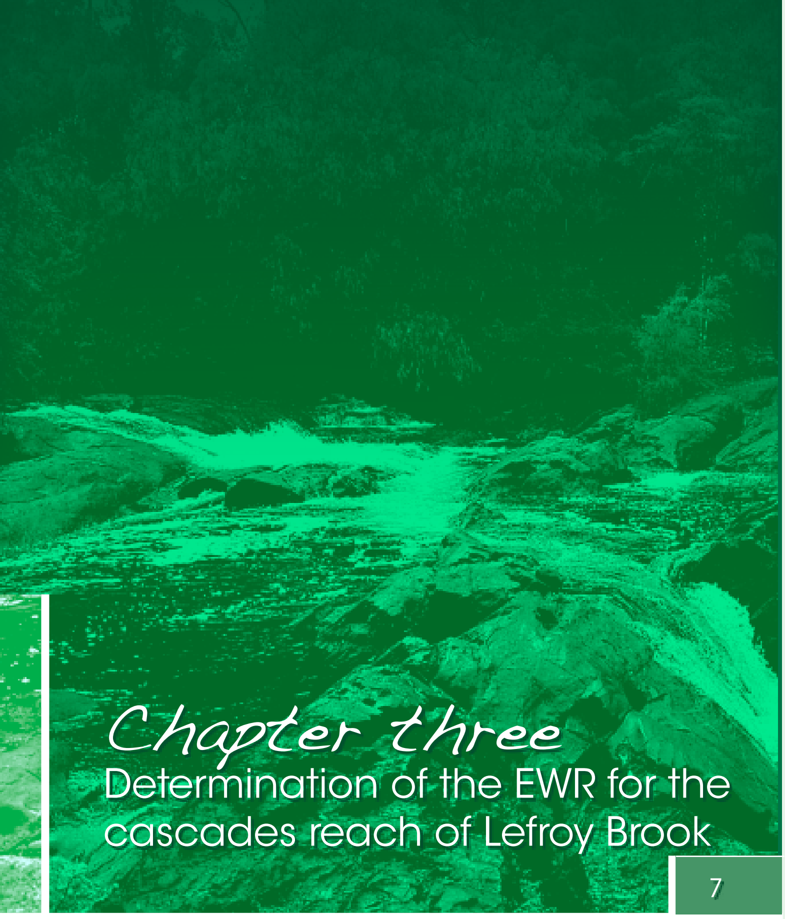
While the magnitude of summer flows has been reduced by dams, summer flow are more permanent, due to a combination of summer leakage from farm dams, summer releases from scour values and releases from Big Brook Dam. The changes in summer flow regime have provided a more permanent habitat for aquatic fauna and allowed a wider movement of fish within the reach. Some species of macroinvertebrates and non-native fish species may prefer more permanent flows.

Research has shown that the reduction in flows caused by on-stream farm dams varies with dam density (dams/km^2), dam storage (ML/km^2) and the volume of water taken from the dams (ML/km^2/year) (Sinclair Knight Merz 2001). There is approximately 25 ML of water stored for every square kilometre of the Lefroy Brook catchment (Boniecka 2006) and 45 ML/km^2 in the upper developed areas of the catchment. This value is amongst the highest levels of farm dam storage per catchment area in Australia, and is substantially greater than the sustainable diversion for the Lefroy Brook catchment, calculated as less than 20 ML/km^2 (Sinclair Knight Merz 2007).

2.5 Objective of the ecological water requirement study

The objective of this study was to determine the EWRs of the cascades reach of Lefroy Brook. This was done by developing a modelled EWR flow regime with a similar frequency and duration of flow spells observed since the construction of farm dams in the developed areas of the catchment and of Big Brook Dam in 1991. In some instances, the frequency and duration of flows of the pre-dam condition were also considered.

A further goal of the study was to identify a water yield that will protect the remaining ecological values in the cascades reach. The ESY determined during this study is based on post-dam flows, and specifies a potential yield that may be additional to the current level of water use (with appropriate restrictions).



Chapter three
Determination of the EWR for the cascades reach of Lefroy Brook

The proportional abstraction of daily flows (PADFLOW) method was used to model the EWRs for the cascades reach of Lefroy Brook. PADFLOW was developed by the Department of Water to support resource planning particularly for rivers with highly variable flow patterns. It evolved out of experience with using the flow events method to determine EWRs for rivers in the south west of Western Australia (see, for example, WRM 2005a and WRM 2005b).

The EWR study assumed that by achieving ecologically important flows ecological values will be protected at a low level of risk.

For example, high flows scour the channel and flood riparian vegetation, and thereby create a diversity of habitat in the river channel. Early season flows relieve summer stress (high temperatures and low oxygen), provide cues for breeding migrations of native fish, and provide habitat for larval stages of terrestrial insects, micro-crustaceans, fully aquatic insects, waterbirds, and in-stream and riparian vegetation (Figure 5).

The flow chart in Figure 5 shows the key steps in determining the EWR of a river using the PADFLOW method. Steps 1 through 8 are identical to those associated with the flow events method. Steps 9 to 11 are associated specifically with the PADFLOW approach. The steps are explained in the following sections.

> *"PADFLOW was developed by the Department of Water to support resource planning particularly for rivers with highly variable flow patterns"*

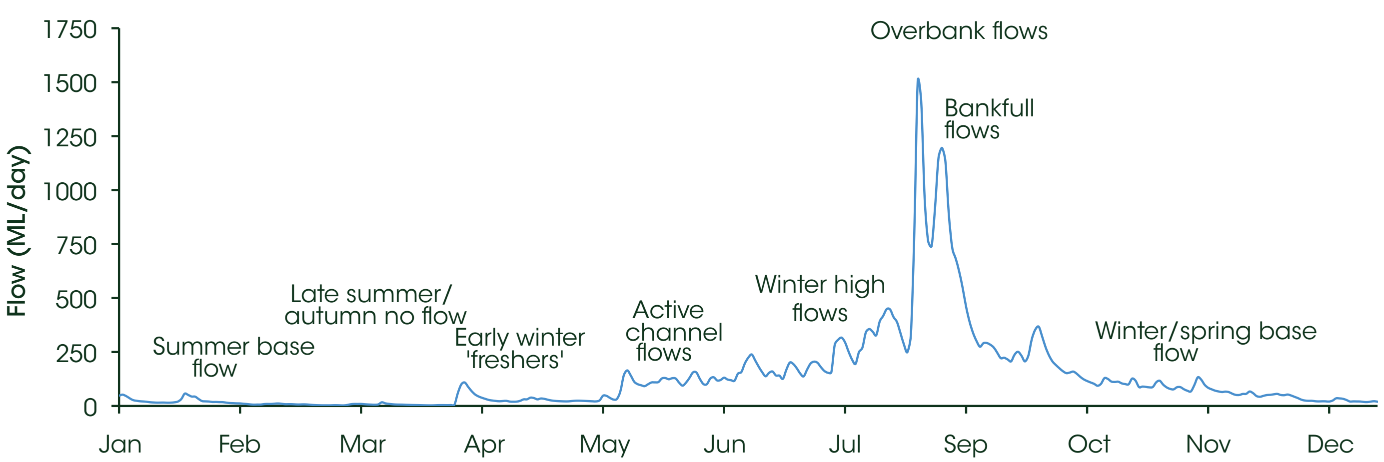


Figure 5
Representative hydrograph with different flow components labelled

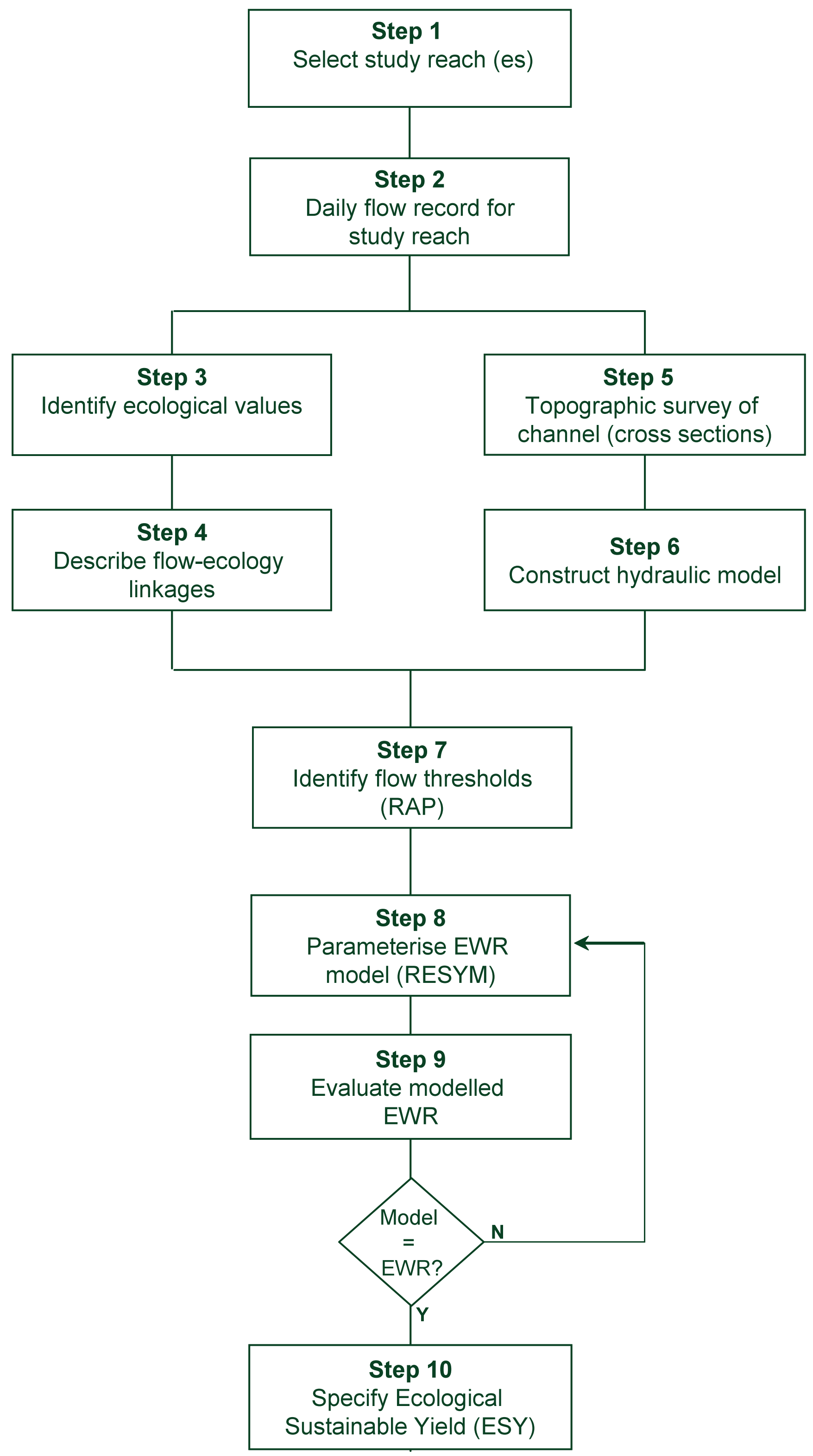


Figure 6
Diagrammatic representation of the proportional abstraction of daily flows method (PADFLOW method)

3.1 Selection of the study site

The ecology of a river is influenced by river hydrology at the basin scale however it is not feasible to assess the EWRs of rivers at broad scales because of limited resources. As a result, an EWR study is usually based on a relatively short, representative reach of river. Study sites are selected so that they allow inferences to be made about water requirements within the reach as a whole. Study reaches may cover many kilometres of river or only one or two kilometres, depending on factors such as slope, changes in grade, ecological condition, the presence of riparian vegetation, land use, confluence with tributaries and location of flow gauging sites.

Clearing and development for agriculture is concentrated in the middle and upper parts of the Lefroy Brook catchment. The cascades reach was selected as the representative reach for this study, as it is in good ecological condition and contains a gauging station with a good flow record. The expert panel visited the cascades reach in November 2005 to assess the ecological condition of the reach and to select a site for study and hydraulic modelling (step 6 in Figure 6).

3.2 Development of daily flow record

The PADFLOW method is a top down approach that works by progressively removing a proportion of flow from an existing daily flow record. For the Lefroy Brook study, the flow record from the Cascades gauging station was used (station number 607022). The station gauges 97% of the length of Lefroy Brook, and therefore includes contributions to flow from both the uncleared as well as cleared and developed parts of the catchment.

As the station was only commissioned in July 1997, the discharge record was too short to be used to assess the river's ecological water requirements. To develop a longer flow record, daily from the Cascades gauging station (station number 607103) was correlated with those from the Rainbow Trail gauging station, which is located higher in the catchment, in order to extend the cascades reach flow record back to 1975.

3.3 Definition of the EWR objective

There are a number of possible objectives for an EWR study. Some of these are to:

- maintain the existing natural condition of a river system
- maintaining ecological values that have evolved over a long history of water resource development
- restore lost ecological values
- a combination of these objectives.

Given the interception and storage of water by Big Brook Dam and the changes to flow caused by farm dams, the objective for the Lefroy Brook EWR study was to develop a flow regime that would maintain post-dam ecological values.

3.4 Ecological values

EWR studies require information on the species that are or should be present in the study reach. This can be quite simple, such as developing a species list based on a literature review combined with site-specific surveys, but it may involve more complex tasks like identifying food-webs and ecological interactions. For this study, existing ecological values of the cascades reach were identified from a review of information on the flora and fauna of the rivers of south-west Western Australia, as well as a site specific study involving seasonal sampling. The results of these studies were reported in WRM and Department of Water (2007) and WRM (2008).

The fish of Lefroy Brook were studied before the construction of Big Brook Dam by Pen et al. in 1991 and after dam construction by Morgan and Gill in 1996. The macroinvertebrate fauna of Lefroy Brook were studied by the Department of Environment and Conservation in 2005 (DEC 2005). Further information on ecological values of Lefroy Brook and the other river systems can be found in WRM and Department of Water (2007) and WRM (2008), as well as the cited literature.

These studies noted that some species were in the process of adapting to flow regime change, especially for that induced by the construction of Big Brook Dam. There has been no recent work describing how fish have been affected by Big Brook Dam, the rapid growth of irrigated agriculture or the presence of farm dams.

3.4.1 Vegetation

The riparian vegetation of Lefroy Brook in the cascades reach is in relatively healthy condition (Figure 7). Vegetation in the region is characterised by tall karri (*Eucalyptus diversicolor*) forests on deeper loam soils of the valley sides and floors and jarrah (*E. marginata*) and marri (*Corymbia calophylla*) forests on the lateritic ridges. Tea-tree shrubs and trees from the *Myrtaceae* family and sedges from the *Cyperaceae* family are common in wetlands and in riparian areas.

Surveys carried out in April and November 2007 (WRM 2008) found that the overstorey in the cascades reach was comprised of juniper myrtle (*Taxandria juniperus*) and peppermint (*Agonis flexuosa*), with an understorey of reeds and rushes and introduced blackberry (*Rubus fruticosus*). Juniper myrtle were typically found on lower benches, channel banks, higher benches and levees, while mature peppermints were largely restricted to the higher levees. The perennial herb *Persicaria decipiens* was found on lower benches and the understorey of channel banks, while higher benches were dominated by sedges from the *Lepidosperma* genus.

Figure 7

Cascades reach of Lefroy Brook with healthy riparian vegetation

The photograph shows a pool in the foreground, the start of a sandy run in the background and large woody debris in the channel.

3.4.2 Freshwater macroinvertebrates

Lefroy Brook supports a diverse community of macroinvertebrates typical of south-west rivers. A list of macroinvertebrates collected from Lefroy Brook in April and November of 2007 is shown in Appendix 1. Collected macroinvertebrates included larvae of mayfly (*Ephemeroptera*), dragonflies and damselflies (*Odonata*), mosquitoes (*Culicidae*), non-biting midges (*Chironomidae*), biting midges (*Ceratopogonidae*), black fly (*Simulidae*), soldier fly (*Stratiomyidae*), crane fly (*Tipulidae*), and caddis fly (*Trichoptera*). The list also includes round worms (*Nematoda*), segmented worms (*Oligochaeta*), aquatic snails (*Gastropoda*), water fleas (*Cladocera*), seed shrimp (*Ostracoda*), copepods (*Copepoda*), side swimmers (*Amphipoda*), freshwater shrimp (*Palaeomonidae*), freshwater crayfish (*Parastacidae*), diving beetles (*Coleoptera*), and true aquatic bugs (*Hemiptera*). Figure 8 shows an assortment of macroinvertebrate species.

There have been no published studies of the ecology of freshwater crayfish of Lefroy Brook. The smooth marron (*Cherax cainii*) and the gilgie (*Cherax quinquecarinatus*), species native to rivers of the south west of Western Australia, have been collected from the brook (WRM 2008).

Most species of invertebrate breed in winter and mature to emerge in spring, particularly univoltine species that complete only one lifecycle per year. However, ephemeral and perennial streams have different taxa. In permanently flowing streams summer flows are important for species with long life cycles (longer than six months) and for species to survive over summer. Given the relative permanency of flows in Lefroy Brook downstream of cascades reach, spring and summer flows should be maintained to provide habitat for these species.

A, B, C: Photography by Wetland Research and Management (WRM).

D: Photography by John J.S. Bunn

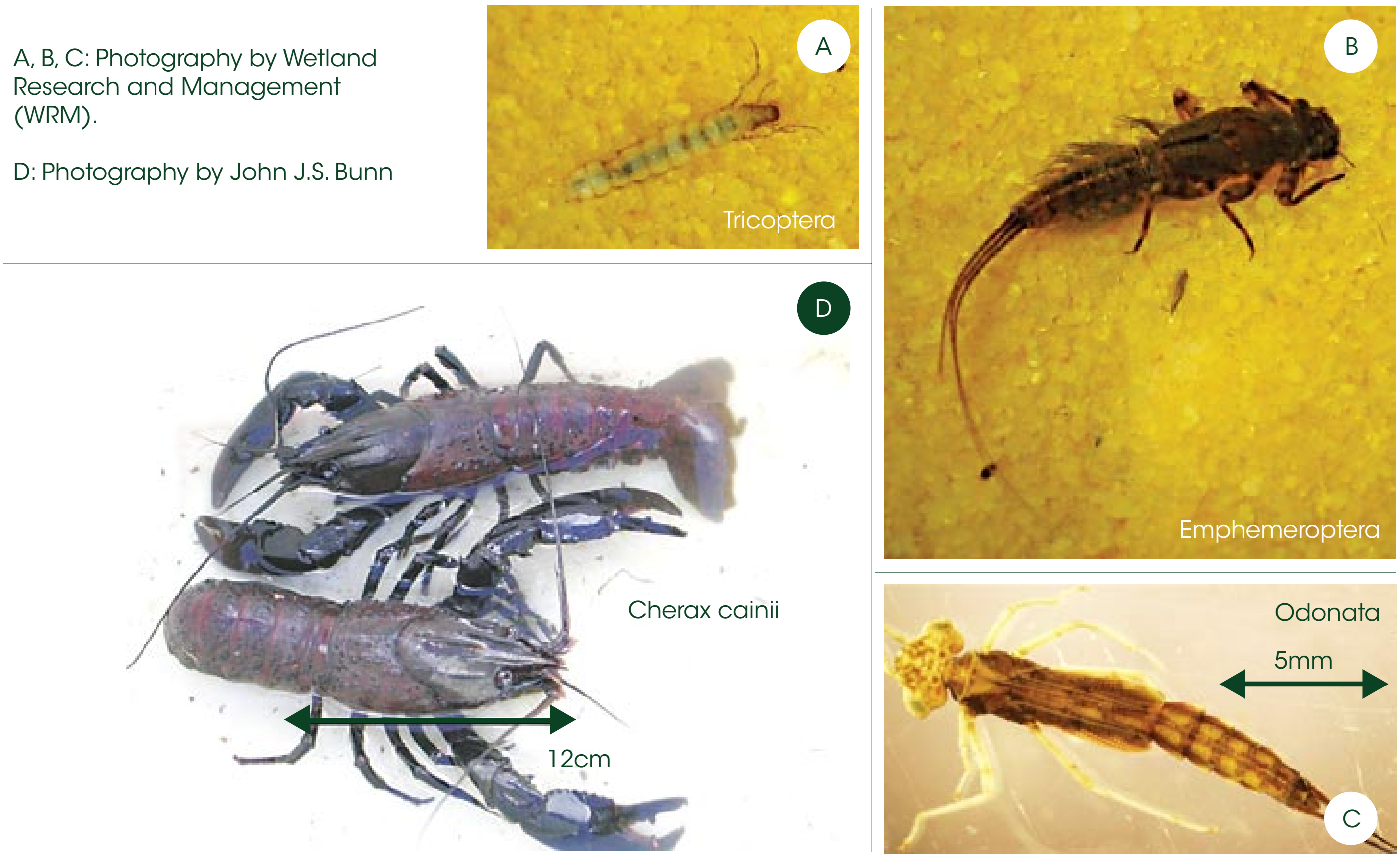


Figure 8
Some macroinvertebrates of Lefroy Brook

Few species have adaptations that allow them to survive seasonal drying, with most flying to neighbouring water bodies as pools dry out. Oligochaetes and gilgies burrow into moist sediments to avoid desiccation. Other invertebrates, such as the gastropods and micro-crustaceans, have resistant stages in their life cycle (usually the egg stage) or undergo diapause during summer.

Macroinvertebrate diversity is dependent on habitat complexity and diversity, since many species are restricted to particular habitats (Humphries et al. 1996; Kay et al. 2001). Oligochaetes, freshwater crayfish, dragonflies, damselflies, mayflies, chironomids and caddisflies are associated with complex habitats such as snags, rocks, riffles, sandy runs, macrophyte beds and trailing vegetation of Lefroy Brook.

Rocky riffles are well oxygenated, contain many interstitial pockets between rocks and pebbles, have high habitat heterogeneity, and concordantly exhibit high biodiversity. Rocky riffles are not present in the cascades reach of Lefroy Brook. Instead, pools are separated by relatively transient sandy runs formed by large woody debris across the channel, which would have similar hydrological characteristics to riffles.

Gilgies prefer areas of high flow and oxygen and react to low water levels by retreating into burrows constructed under debris on the stream bed or in river banks. Smooth marron, which are common in the cascades reach, prefer the deeper and broader water of pools. Marron may dig shallow excavations, but do not retreat to burrows over summer, and prefer to shelter under logs or stones in deep areas. Permanent flows or pools are therefore required for the smooth marron and gilgies of Lefroy Brook.

A, B: Photography by Dave Morgan
C: Photography by Glenn Shiell

Western pigmy perch

Nightfish *Bostokia porsa*

Western minnow

Figure 9
Native fish of Lefroy Brook

3.4.3 Native fish

South-west Western Australia has few native freshwater fish and has a high degree of endemism compared with the rest of Australia. Of the native species in the south-west, the western minnow (*Galaxias occidentalis*), western pygmy perch (*Edelia vittata*) and nightfish (*Bostockia porosa*) are the most abundant and widespread. There is anecdotal evidence that the distributions of pouched lamprey (*Geotria australis*) and freshwater cobbler (*Tandanus bostocki*) are becoming increasingly restricted in distribution due to habitat loss, salinity and flow regulation. Figure 9 illustrates some of the native freshwater fish species of the study area.

The native fish of Lefroy Brook were surveyed in the early 1990s in a study of the upstream migration of pouched lamprey and the distribution and abundance of the various other species (Pen et al. 1991). The native species collected by Pen et al. (1991) were, in order of abundance, western pygmy perch, mud minnow (*Galaxiella munda*), nightfish, pouched lamprey, and western minnow. Only pygmy perch and pouched lamprey were collected in the cascades reach of Lefroy Brook in April and November of 2007 (WRM 2008). Sampling results suggest the possibility of a decline in the diversity of native fish in Lefroy Brook since the construction of Big Brook Dam.

The mud minnow and pouched lamprey are at risk and have conservation significance. The range of the mud minnow has been considerably reduced and it is now largely restricted to the extreme south-west corner of Western Australia (Morgan and Beatty 2005). The abundance and distribution of the mud minnow above the Big Brook Dam has also declined since the last study in 1991 (Morgan and Gill 1996) and none were collected in 2007 sampling below the dam (WRM 2008). Threats to mud minnows include habitat alteration, introduction of exotic species and alteration to habitat from flow regulation and water abstraction (Morgan et al. 1998). The western pygmy perch and nightfish have also become relatively uncommon in Lefroy Brook.

The pouched lamprey is the only surviving member of the genus in Australia and one of only four species found in the southern hemisphere (Potter 1996; Allen et al. 2002).

Habitat alteration, construction of dams, extraction of groundwater and agricultural practices are also believed to have led to the loss of pouched lamprey from many areas (Pen et al. 1991). Competition from and predation by exotic fish species such as rainbow trout (*Oncorhynchus mykiss*) and redfin perch (*Perca fluviatilis*) may also be a factor in the decrease of fish diversity. Flow regulation and summer flows of low variability favours exotic species over natives (Pen et al. 1991). The 1991 study did not collect any introduced *Gambusia* or redfin perch in the brook, while Morgan et al. (1998) found both species to be abundant and widely distributed, particularly in the dam.

None of the native species found in Lefroy Brook are adapted to withstand desiccation. This suggests that permanent water within or downstream of the cascades reach is required to conserve existing fish populations. Information relating to life history characteristics, ecology, and flow requirements can be found in WRM (2008).

The components of the flow-related breeding ecology of native species are upstream migration, inundation of spawning habitat and regular winter and spring flooding. Pygmy perch lay adhesive eggs that sink and attach to bottom structures such as flooded vegetation. The females spawn in the lateral flooded margins of rivers from July to the end of the winter at intervals of six to eight weeks, often well after tributaries have stopped flowing (WRM 2008). Western minnow and nightfish prefer to spawn in small tributaries on flooded vegetation and submerged reed beds (WRM 2008). The use of flooded margins of the main channel by pygmy perch may be a behavioural adaptation that decreases the risk of spawning failure by minimising egg predation, competition for breeding habitat, and the chance of egg desiccation. The prime period for breeding success of pygmy perch is probably during the breeding migrations of western minnow and nightfish into tributaries.

Sufficient water is therefore required to inundate trailing riparian vegetation, a favoured spawning habitat for species such as pygmy perch and to inundate small tributaries to allow access to breeding habitat for species such as the western minnow and nightfish.

Flooded vegetation, shallow side channel and backwater areas associated with sandy runs also provide sheltered, low velocity nursery areas for larvae and growing juveniles (WRM and Department of Water 2007). The duration and frequency of inundation is also important. If water levels fall too soon, or fluctuate greatly, eggs may be left above the water line and dry out.

Within rivers there are many natural and artificial obstacles to upstream migration of fish, such as logs, shallow riffles and rock bars. Natural flow regimes include flows that provide enough water for fish to navigate natural and man-made obstacles. It is generally accepted that migrating fish negotiate barriers within hours of inundation. Therefore, a series of short spells of several hours or an extended spell are required for fish to navigate upstream in a reach containing a series of barriers.

To summarise, the ecological water requirement for the cascades reach includes the following components:

- sufficient water to maintain freshwater pools in summer
- winter and spring flows that inundate breeding habitats
- winter flows that allow upstream migration.

3.4.4 Amphibians and reptiles

There have been no studies of the amphibians or reptiles of Lefroy Brook. Museum records (2003–07) suggest that Lefroy Brook may support a diversity of frog species, including the slender tree frog (*Litoria adelaidensis*), motorbike frog (*Litoria moorei*), Tschudi's froglet (*Crinia georgiana*), Glauert's froglet (*Crinia glauerti*), small western froglet (*Crinia subinsignifera*), Lea's frog (*Geogrinia leai*) and the moaning frog (*Heleioporus eyrie*). The motorbike frog can be abundant in the reeds, grasses and vegetation of riparian zones. This species is found in areas with permanent water, where it hides beneath bark, rocks or logs. Eggs are laid in spring to mid-summer, with the spawn clump being attached to submerged vegetation (Tyler et al. 2000).

Frogs play an important role in ecosystems and require for water at some stage of their life cycle. Frogs spend much of their lives in moist environments, such as marshes, swamps and riparian zones. Many species require surface water during parts of their life cycle, including the egg laying and tadpole stages.

Terrestrial reptiles that are largely restricted to the margins of waterways and are likely to be found in the cascades reach include the tiger snake (*Notechis scutatus*), marbled gecko (*Christinus marmoratus*), bardick (*Echiopsis curta*), red-legged skink (*Ctenotus labillardieri*) and the four-toed earless skink (*Hemiergis peronii*). The bardick is listed on the IUCN Red List as a 'vulnerable' species.

The long-necked tortoise (*Chelodina oblonga*) is a high order predator with a diet that includes tadpoles, fish, and aquatic invertebrates. They are dependent on aquatic food-webs and the flow regimes that maintain them. In permanent waters *C. oblonga* has two breeding periods (September–October and December–January), while in ephemeral waters they tend to breed once in spring. *C. oblonga* nests in sandy soils and eggs may take up to seven months to hatch. If local conditions deteriorate, they can migrate long distances overland or aestivate in situ in burrows.

The impact on reptile ecology caused by changes in the availability of water in south-west Western Australia has not been studied. Little has been published on the specific water requirements of amphibians and reptiles. A number of species of reptile are likely to inhabit the riparian zone of Lefroy Brook, and are regarded as dependent on aquatic and riparian food webs. Figure 10 illustrates some of the species of amphibian and reptile found likely to be found in the Lefroy Brook area.

3.4.5 Waterbirds

There have been no studies of waterbirds carried out in the Lefroy Brook area. Birds that have been observed in the area include the black swan (*Cygnus atratus*), Australian shelduck (*Tadorna tadornoides*), Australian wood duck (*Chenonetta jubata*), Pacific black duck (*Anas superciliosa*), white-faced heron (*Egretta novaehollandiae*), Australian white ibis (*Threskiornis molucca*), straw-neck ibis (*Threskiornis spinicollis*), and the hooded plover (*Thinornis rubricollis*). Other waterbirds observed within the area include the musk duck (*Biziura lobata*), white-necked heron (*Ardea pacifica*), yellow-billed spoonbill (*Platalea flavipes*) and the blue-billed duck (*Oxyura australis*) (WRM and Department of Water 2007). The hooded plover is on the Department of Environment and Conservation (DEC) Threatened Species List as a priority 4 species.

Waterfowl are completely dependent on the presence of surface water, with wetlands and swamps forming prime habitat. The ecology and habitat requirements of water birds should be also considered at the landscape scale. Many birds, including heron and spoonbills, feed predominantly on aquatic fauna or animals associated with waterways. In the absence of more detailed information, waterfowl of the cascades reach are considered dependent on flows that provide habitat and food.

A: Photography by Rob Davis
B: Photography by DEC
C: Photography by Andrew Storey
D: Photography by Bert and Bab Wells/DEC

Figure 10
Reptiles and amphibians of Lefroy Brook

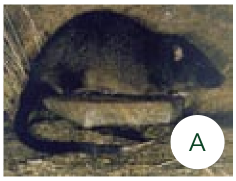
3.4.6 Mammals

An extensive literature search did not identify specific studies relating to mammals of the Lefroy Brook area. Department of Environment and Conservation records contain information on threatened species within the Lefroy Brook area, including the western ringtail possum (*Pseudocheirus occidentalis*) (Figure 11) and the quokka (*Setonix brachyurus*). Lefroy Brook flows through the known range of a number of mammals that inhabit riparian areas, including the water rat (*Hydromys chrysogaster*), brushtail possum (*Trichosurus vulpecula*), western grey kangaroo (*Macropus fuliginosus*), and the southern brown bandicoot or quenda (*Isoodon obesulus*).

Water rats (*Hydromys chrysogaster*) are found in rivers, swamps, lakes and drainage channels. They have broad, partially-webbed hind-feet, water-repellent fur, and a thick tail (Figure 11). Water rats are water-dependent and are known to suffer heat stress without access to water. They construct nesting burrows in banks that are stabilised by riparian vegetation, and forage along the shoreline for food such as crayfish, mussels, fish, plants, water beetles, water bugs, dragonfly nymphs and smaller mammals and birds. Water rats are reliant on aquatic food webs, the presence of healthy riparian vegetation and the processes that maintain them. They restrict their movements to shallower waters less than two metres deep. The range of water rats has declined in south-west Western Australia due to salinisation and clearing of riparian vegetation (WRM and Department of Water 2007).

The quenda is also found in dense vegetation associated with rivers, swamps and lakes, particularly Banksia woodland and jarrah forest. Current threats include fragmentation and loss of habitat. Other species identified above are found in higher densities in vegetation adjacent to rivers and wetlands.

Water rat



A: Photography by Bert and Bab Wells/DEC
B: Photography by DEC

Western ring tailed possum

Figure 11
Water rat and western ring-tailed possum

3.4.7 Carbon sources and processing

Carbon is the principal building block of all living tissue. The quantity and type of carbon can determine the biomass, biodiversity and complexity of river life. Flow-related processes that control the sources, fate and availability of carbon in food webs need to be considered in developing ecological water requirements. 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 change in the carbon cycle.

Aquatic ecosystems are reliant on energy inputs, in the form of organic carbon, from catchments and riparian zones (WRC 2000). Some carbon enters the lower river reaches in the form of fine particulate organic matter derived from upstream terrestrial vegetation. This process requires the connection of downstream and upstream river reaches (Vannote et al. 1980). Also important for maintaining aquatic food webs are energy inputs from in-stream production and processing through fungal, microbial and invertebrate pathways involving phytoplankton and benthic algae (Thorp and Delong 1994). Localised movement of carbon (for example, in the form of leaf litter and organic material) from the floodplain and channel benches into the watercourse is also an important process for providing energy to aquatic food webs. The cascades reach has healthy riparian vegetation and is considered to be an important source of carbon for aquatic life.

3.5 Flow–ecology linkages

The fifth stage of the PADFLOW method (Figure 6) is to describe the 'flow–ecology linkages' – in other words, the flow events and critical water levels that are thought to maintain the known ecological values and features of the stream. The selection of these flow events and critical water levels was based on advice of the expert panel combined with published information.

Ecologically critical flow events that maintain native fish, crayfish, macroinvertebrates, water rats, tortoises, carbon flows, water quality, vegetation and channel morphology were determined using methods based previous studies (see WRM 2005a; WRM 2005b). A series of critical flows were identified for each ecological component in different seasons. Flow-ecology 'rules' consistent with each flow–ecology link were then developed for analysis in the RAP software (which will be described in section 3.8). The flow–ecology links considered for determining the EWR for Lefroy Brook are listed in Table 2.

Table 2
Flow-ecology linkages and flow objectives for Lefroy Brook

Ecological component	Rule number	Flow objective	Flow component
Fish	1a	Trailing vegetation inundated by 10 cm to provide spawning habitat.	Winter low flows
	1b	Dissolved oxygen levels maintained by a water velocity of at least 0.01 m/s.	Summer low flows
	1c	Water depth of at least 10 cm throughout the reach to allow upstream fish migration.	Winter low flows
	1d	Pools maintained at a depth of 80 cm to provide refuge for fish and crayfish and habitat for tortoises and frogs.	Summer low flows
Other vertebrates	2a	Pools maintained at a depth of 80 cm to provide refuge for water rats. Rushes and reed beds are inundated to provide habitat for fauna.	Summer low flows
Macroinvertebrates	3a	Riffles inundated to a depth of at least 5 cm over 100% of width to provide habitat*.	Winter low flows
	3b	Riffles inundated to a depth of at least 5 cm over 50% of width to provide habitat.	Summer low flows
Carbon sources	4a	Lower benches inundated to flush detritus and leaf litter into the channel*.	Winter high flows
	4b	Higher benches inundated to flush detritus and leaf litter into the channel.	Winter high flows
	4c	Downstream carbon movement maintained by connectivity between pools.	Summer low flows
Vegetation	5a	Riparian vegetation on lower banks and benches inundated to prevent incursion of terrestrial vegetation.	Winter high flows
	5b	Riparian vegetation on higher banks and benches inundated to prevent incursion of terrestrial vegetation.	Winter high flows
Channel morphology	6a	Water level to reach top of bank or high bench height to maintain channel structure and scour pools.	Winter high flows (flood event)

* Flows of intermediate magnitude between rules 3a and 4a will flood small side tributaries and allow upstream migration of native fish for spawning and reproduction.

3.5.1 Dissolved oxygen

All species of native fish found in Lefroy Brook require permanent water to survive. The deeper areas of the brook, especially the pools, provide refuge during the low flow periods between December and April. To maintain sufficient dissolved oxygen levels in water, a flow velocity of 0.01 m/s is required in pools for as long as possible throughout summer. Models predict that a flow of this velocity is needed to prevent the thermal stratification of water in pools. Currently, it is unlikely that pool fauna of the lower reaches of Lefroy Brook experience serious oxygen stress given the generally constant summer flow, although oxygen stress may occur during exceptionally long, dry summers (WRM 2008).

As permanent summer flows are part of the existing flow regime, the panel decided to incorporate this as an objective into the EWR. Constant summer flows may help relieve summer heat stress for rainbow trout in Lefroy Brook. Consideration of the water needs of non-native species is not normally part of EWR development. In this case, protection of the trout fishery is a socio-economic objective that is included in the assessment, as Lefroy Brook is one of south-west Western Australia's premier trout fishing rivers.

3.5.2 Fish migration

In Lefroy Brook, native fish migrate upstream and into small tributaries to spawn during the winter months. Winter flows are needed for these fish to move upstream over riffles, snags and other barriers. Native species such as the western minnow, pygmy perch and nightfish have been known to negotiate waters as shallow as 1 cm when trying to move upstream under duress. Generally, a minimum water depth of 20 cm is given as the requirement for upstream migration of large-bodied fish such as the freshwater cobbler (Storey et al. 2001; Streamtec 2002). As cobbler have not recently been collected in Lefroy Brook (WRM 2008), for this study a minimum depth of 10 cm is considered adequate for native fish to negotiate barriers and move upstream to breed (WRM 2008).

3.5.3 Spawning sites for native fish

The flow–ecology links in Table 2 were used as a guide to model flow rates that would inundate aquatic vegetation in the cascades reach (rule 1a), and flows that would link the main channel with side tributaries (flow range between rules 3a and 4a). Together, such events would provide important spawning habitat for native fish.

The panel recognised that for long-lived fish species (that is, about five years), high rates of recruitment need not occur every year to maintain healthy populations. Native fish in south-west rivers are adapted to a highly variable climate and flow regime. The panel took the position that any year when reed beds and trailing vegetation were not continuously inundated for more than five weeks would be a poor recruitment year. Poor recruitment years occur naturally during periods of low rainfall. Poor recruitment years may also occur due to excessive abstraction of water. The panel considered that poor recruitment winters should not occur for more than three consecutive years, if such an event were the result of excessive abstraction. No limit was set for the number of consecutive naturally occurring poor recruitment years. Consecutive years of low rainfall were interpreted as an adaptive pressure and a risk to recruitment, rather than an event likely to precipitate collapse or extinction of native fish populations.

3.5.4 Macroinvertebrate habitat

Macroinvertebrates occupy a wide range of habitat types including pools, riffles and sandy runs between pools, and accumulations of organic debris. For this study it was assumed that shallow sandy runs have the same water requirement for macroinvertebrates as rocky riffles and must be inundated to a depth of at least 5 cm across at least 50% of the run width in summer, and across the entire run width in winter (WRM 2005a; WRM 2005b). To protect macroinvertebrate diversity, sandy runs should be inundated in summer and winter at a frequency and duration that is similar to that found in the natural flow regime.

3.5.5 Productivity and carbon

Organic matter is a primary source of energy for river ecosystems. A significant amount of organic carbon enters south-west rivers through litter fall washed into the river channel when vegetated benches (and floodplains) are inundated. Benches should be regularly inundated to maintain this source of carbon.

3.5.6 Channel morphology

High energy flows scour river channels and mobilise and distribute sediments. These high flows are responsible for channel morphology and complexity, and distribution of habitat. The cross-section of the cascades reach is U-shaped in profile, with a series of low and high benches, but without a defined floodplain or even top of bank in places (Appendix 2). These benches support vegetation and accumulate organic debris. High flows that inundate high benches or reach the top of the river bank are required to scour the channel and maintain features such as benches and pools, as well as flooding and scouring terrestrial vegetation that may have germinated on the benches and in the channel during dry periods (WRM and Department of Water 2007).

Active channel flows are needed to scour and maintain the low flow channel. They are included as part of this objective, and are considered to be of similar magnitude to the flows required to inundate trailing vegetation.

3.6 Cross-section survey of the river channel

The sixth step of the PADFLOW method (Figure 6) involves collecting point data of a number of channel cross-sections. The cross-sections were taken at points on the channel that have features that, for example, control water depth (rock bars), or where particular habitat types or effects of channel features need to be captured by the hydraulic modelling (such as river pools and riffles). Figure 12 shows a schematic illustration of the process used to survey channel cross-sections and identify channel features.

The cross-sections are used to develop a hydraulic model of the river channel, which is used to relate flow rates to water depths (step 7 of the PADFLOW method illustrated in Figure 6). Hydraulic models are used to predict the depth of water at different locations in the study reach from upstream flow (section 3.7).

The cascades reach of Lefroy Brook is located in a well-vegetated part of the catchment, downstream of Pemberton and just upstream from the Cascades gauging station (Figure 2). A section of the river of approximately 460 m was surveyed in November 2005, when the mean daily flow rate was 0.8 m3/s. A total of 15 channel cross-sections were surveyed at points characterised by key hydraulic features, including high points in the channel bed and pools (Figure 13). Cross-sectional profiles of the river channel are shown in Appendix 2.

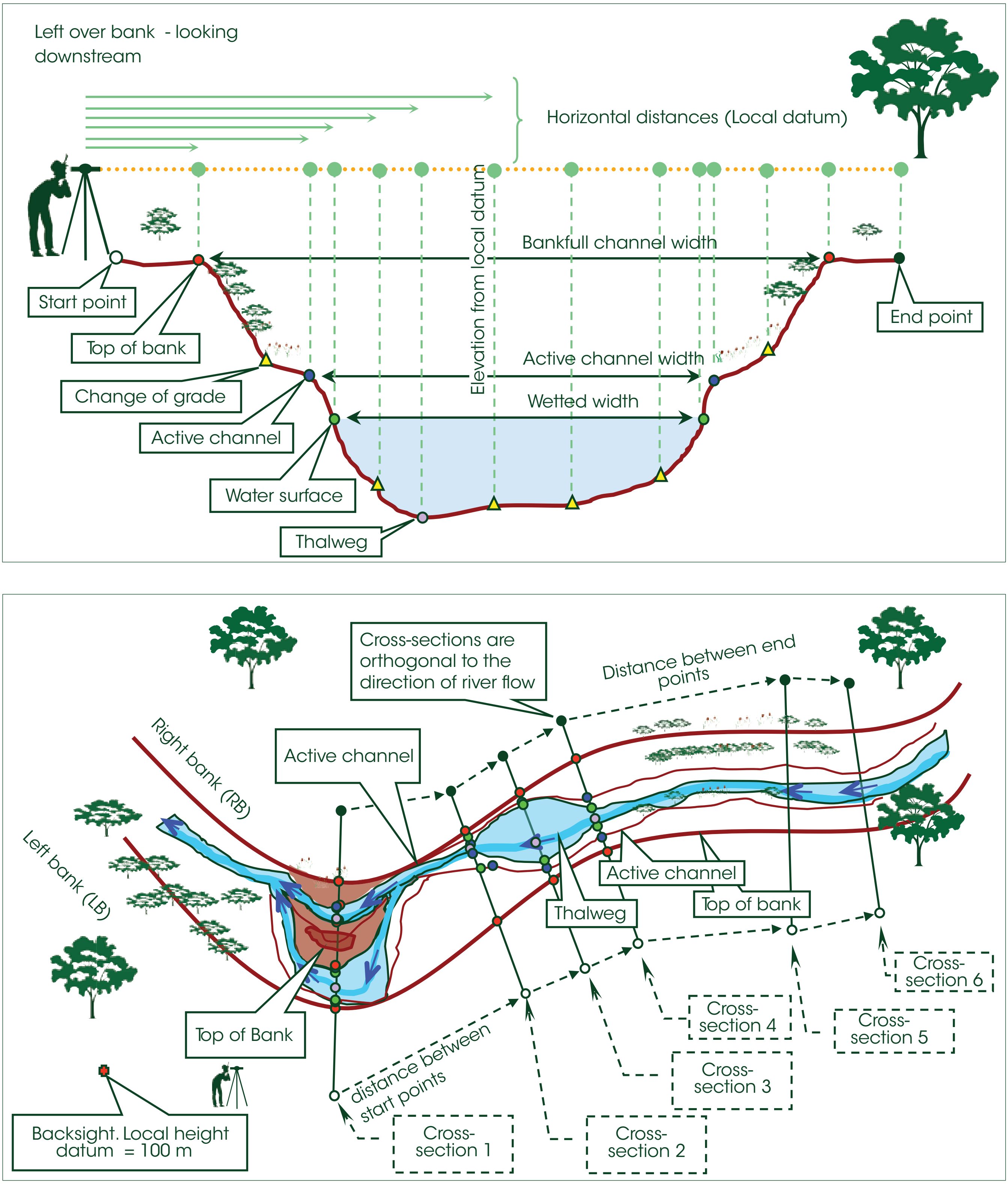


Figure 12

Representative river reach showing features and survey points

The upper diagram illustrates how point data are collected for surveyed cross-sections. The lower diagram shows the layout of cross-sections along a hypothetical river reach. A total of 15 cross-sections were surveyed for Lefroy Brook.

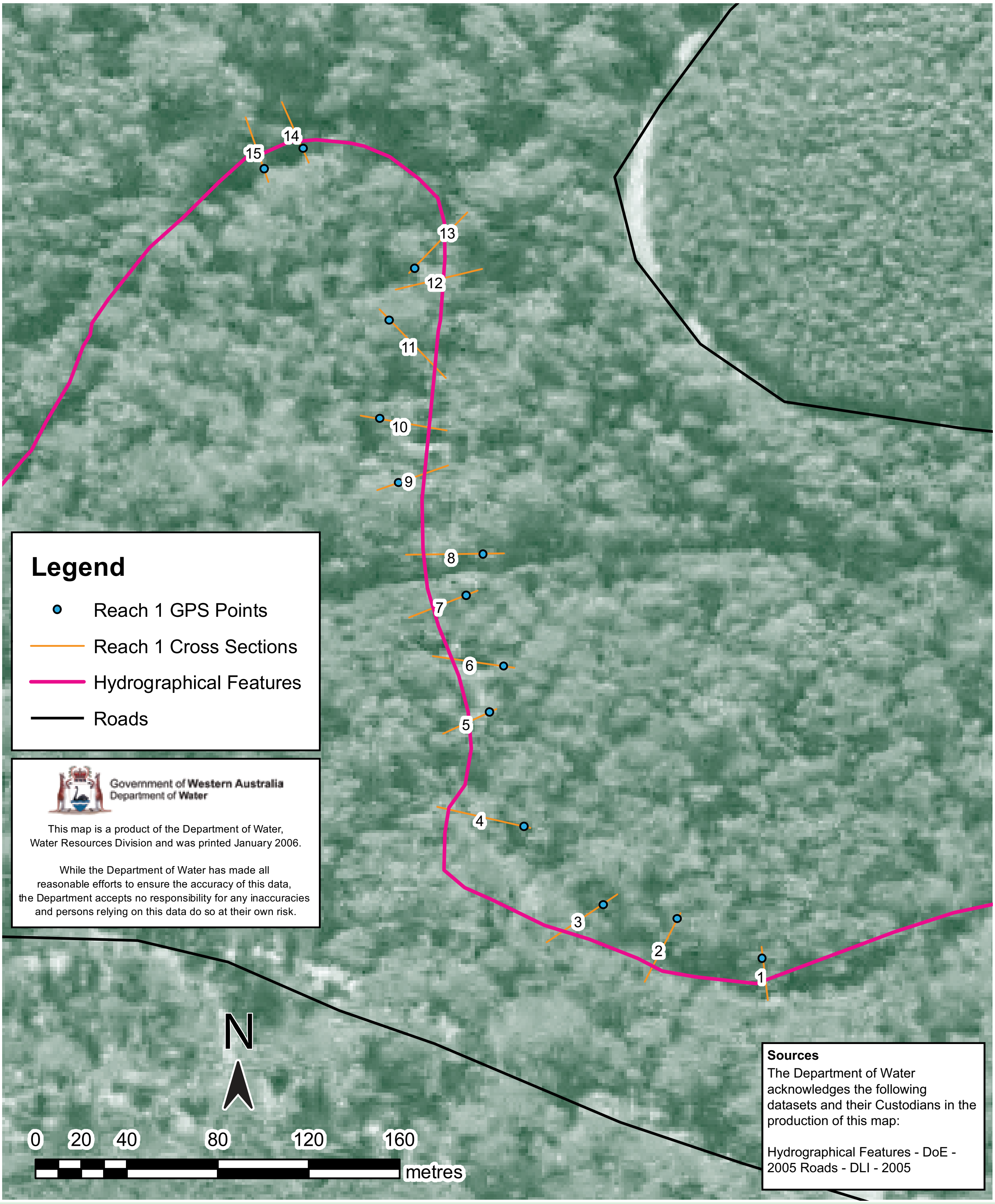


Figure 13

Location of the 15 surveyed cross-sections in the cascades reach

3.7 Construction of hydraulic model

In the seventh step of the PADFLOW method (as illustrated in Figure 6), the cross-section data are used to construct a hydraulic model. The hydraulic model of the cascades reach of Lefroy Brook was created using the HEC-RAS modelling package (Figure 14). The river channel in the cascades reach is characterised by a series of shallow pools separated by shallow sandy runs. In Figure 14, the blue trace shows the water level at the time of the channel surveys. The surveyed cross-sections (numbered 1 to 15) are identified by the red arrows. The other cross-sections were interpolated between the surveyed cross-sections by the HEC-RAS model. Cross-section 8 was located at a railway bridge located in the middle of the EWR reach. Several pylons were within the river channel, but the bridge itself was more than 10 m above the river and well above the level of floods.

Figure 15 shows a longitudinal profile of the cascades reach from cross-section 1 (furthest downstream) to cross-section 15 (furthest upstream). The river fell by approximately 0.5 m over the length of the reach. Water depth is controlled by shallow features at cross-sections 6, 9 and 12. Water flow is rapid and more turbulent within the sandy runs downstream of those three cross-sections. The longitudinal profile shows a series of shallow pools separated by sandy runs, with large woody debris across the channel controlling water levels. The thalweg is the deepest continuous line along the river channel and represents the flow path during very low flows.

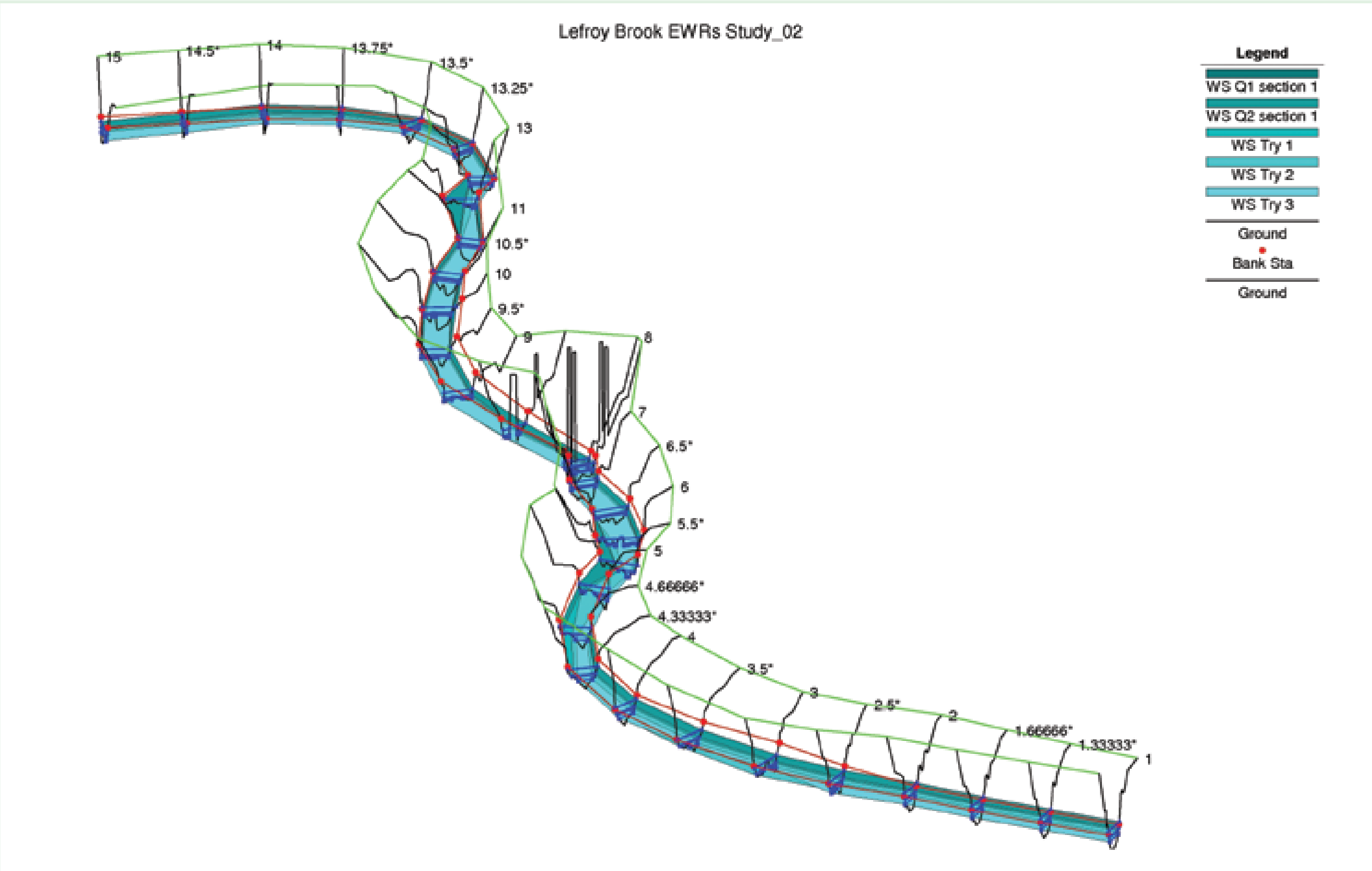


Figure 14
Structure of Lefroy Brook HEC-RAS hydraulic model

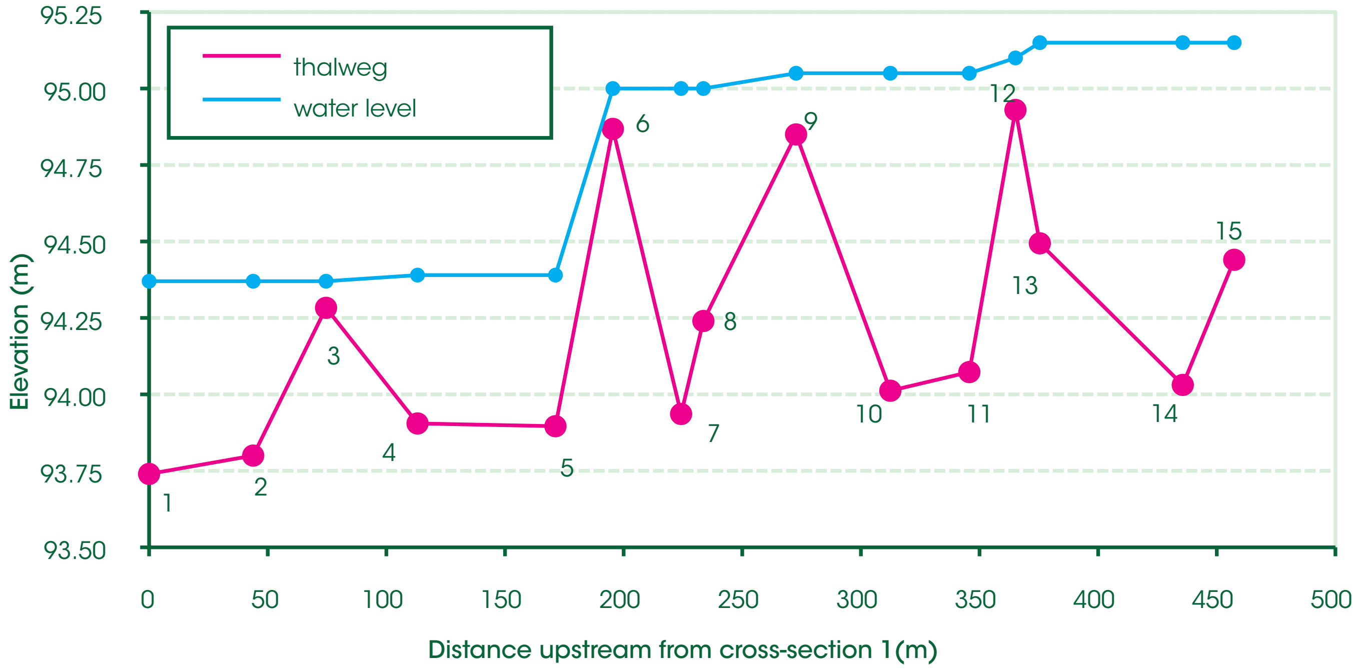


Figure 15
Longitudinal profile of the cascades reach of Lefroy Brook

Water depth for approximately 200 m upstream of cross-section 6 was controlled by a large tree trunk lying on the bed of the river. Large tree trunks control water depth in many areas of the cascades reach and tend to be associated with sand bars and a build-up of organic debris. Rock bars and stony riffles were not identified in the selected reach. Cross-sections 9 and 12 were located at the upstream end of sandy runs, where water was slightly deeper. All other cross-sections were placed across slow-flowing areas, such as pools. Deeper pools accumulate organic matter, which provides cover and food for invertebrate detritivores and grazers. At each cross-section, the height of fringing vegetation that may be used by fish as spawning habitat was noted. Benches were noted at the time of survey and are apparent in the cross-section profiles.

3.8 Identification of flow thresholds

The hydraulic model was loaded into the river analysis package in order to determine the flow thresholds required to achieve each ecological objective detailed in Table 2 and in Section 3.5. RAP is used to determine the flow rate needed to satisfy each objective by achieving a certain water depth over channel features, such as rock bars (fish migration), benches (carbon sources), key habitat (pools) and over bank flows (riparian vegetation). The ecologically critical threshold flow rates are summarised in Table 3.

Table 3
Ecologically critical flow rates in Lefroy Brook
The threshold flows detailed below are those that satisfy the flow objectives set out in Table 2.

Flow–ecology rule	Threshold flow		Ecological functions
	m3/s	ML/day	
Minimum pool depth of 80 cm.	0.01	0.86	Provide pool habitat for macroinvertebrates, native fish, tortoise, frogs and water rats. Downstream flow of carbon maintained by connectivity between pools.
Minimum flow velocity of 0.01 m/s.	0.07	6.05	Maintain oxygen levels in pools by preventing thermal stratification.
Depth of 5 cm over 50% of the width of sandy runs.	0.19	16.4	Provide summer habitat for macroinvertebrates.
Minimum thalweg depth at cross-sections 6, 9 and 12 of 10 cm.	0.12	10.4	Allow upstream spawning migration of native fish.
Depth of 5 cm over 100% of the width of sandy runs.	0.67*	57.9	Provide winter habitat for macroinvertebrates.
Inundate to active channel depth. Inundate trailing vegetation to a depth of 10 cm.	1.40*	121	Active channel flow to scour and maintain low flow channel. Inundate trailing vegetation which is a preferred spawning site of native fish.
Inundate low benches.	3.80*	319	Provide carbon to river ecosystems by washing accumulated detritus and leaf litter from low benches into channel. Flood low riparian vegetation. Scour and maintain channel morphology.
Inundate high benches.	12.4	1080	Provide carbon to river ecosystems by washing accumulated detritus and leaf litter from high benches into channel. Flood high riparian vegetation. High energy flows to scour pools and maintain channel morphology

* Flows between 0.67 m^3/s and 3.8 m^3/s will also connect the main channel with small side tributaries and allow migration of the western minnow and nightfish to spawning habitat.

3.8.1 Summer minimum flow

A flow rate of at least 0.01 m^3/s, equivalent to 0.86 ML/day, is required between December and April to maintain a minimum depth of 80 cm in pools and to maintain connectivity between sandy runs and pools. This flow also maintains availability of habitat for native fish and macroinvertebrates, as well as food for water rats and waterbirds.

3.8.2 Dissolved oxygen

A flow rate of 0.07 m^3/s is required to prevent thermal stratification of pools and maintain dissolved oxygen levels. The threshold flow was determined in RAP by applying a binary rule that stipulated a flow velocity of at least 0.01 m/s applied to all cross-sections. The critical part of the reach was the deep pool at cross-section 7, where flow velocity was slowest.

3.8.3 Habitat for macroinvertebrates

In summer, a flow rate of 0.19 m3/s is required to inundate 50% of the total width of shallow sandy runs to a depth of 5 cm. Shallow sandy runs were found at cross-sections 6, 9 and 12. The lateral width of the sandy runs was 9.2 m at cross-section 6, 11.3 m at cross-section 9, and 4.0 m at cross-section 12. The flow rate required to inundate 50% of the width of each cross-section was calculated using RAP, and the mean value was taken as the summer flow threshold for macroinvertebrate habitat.

In winter, a flow rate of 0.67 m3/s is required to inundate 100% of the total width of shallow sandy runs to a depth of 5 cm. The same three cross-sections were used as for summer habitat for macroinvertebrates. The flow rate required to inundate 100% of the width of the three cross-sections was calculated in RAP, and the mean value used as the winter flow threshold for macroinvertebrate habitat.

3.8.4 Fish migration

A flow rate of 0.12 m^3/s is required to facilitate small-bodied fish migration. This was determined in RAP by applying the rule of a minimum thalweg depth of 10 cm throughout the reach. The discharge required to inundate cross-section 6 was used as the threshold flow, as this was the shallowest section of the reach (Figure 15).

3.8.5 Spawning habitat

The flow rate of 1.40 m^3/s to inundate sedges as spawning habitat was determined using the water level function in RAP. The location of fringing sedges was recorded during surveys at cross-sections 1, 3, 4, 5, 9, 10 and 13. The flow rate required to inundate trailing vegetation to a depth of 10 cm ranged between 0.75 m^3/s at cross-section 5 and 3.15 m^3/s at cross-section 13 (Figure 16).

In Figure 16 the blue line denotes the modelled water depth, while the red line represents the water depth at the time of survey. For cross-section 5, the required water depth was reached at a flow rate of 0.75 m3/s, while for cross-section 13, a flow rate of 3.15 m3/s was required.

The range in flow rates required to inundate trailing vegetation may be due to the trailing vegetation growing at different water levels, as a result of different rooting substrate or vegetation types, an error in recording the location of fringing vegetation, or error in the model. Therefore, the median discharge of 1.40 m^3/s was taken as the value for the whole reach, rather than choosing the highest value of 3.15 m^3/s to inundate cross-section 13.

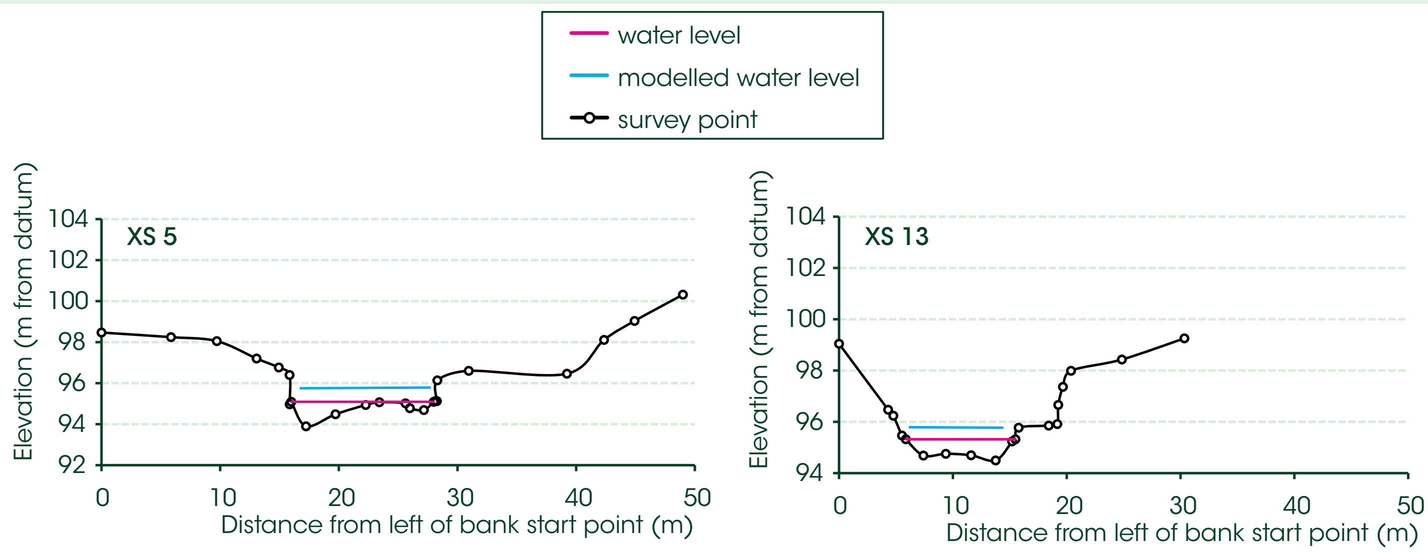


Figure 16
Modelled water level required for spawning habitat at cross-sections 5 and 13 in the cascades reach

3.8.6 Bench inundation

The flow rate of 3.80 m^3/s to inundate lower benches was determined using the water level function in RAP. The only surveyed lower bench was at cross-section 13 and the water level was adjusted to inundate the bench to a minimum depth of 5 cm (Figure 17).

A flow of 12.4 m^3/s to inundate higher benches and maintain channel morphology was determined using the water level function in RAP. A high bench stretches between cross-sections 5 and 6 and there is another slightly lower one at cross-section 7 (Figure 17). The flow rate of 12.4 m^3/s inundated the bench at cross-section 7 and cross-section 5. Because the bench at cross-section 5 is connected to the bench at cross-section 6, it was assumed that cross-section 6 would also be inundated at this flow rate.

In Figure 17 the blue line shows the predicted water depth at a flow rate of 12.4 m^3/s, which breached a high levee at cross-section 5 and inundated low benches at cross-sections 6 and 7. A flow rate of 3.80 m^3/s resulted in a water depth that inundated the low bench at cross-section 13 to a depth of 5 cm. The red line shows the depth of water at the time of survey.

Figure 17
Modelled water levels required to inundate benches in the cascades reach

3.9 Parameterisation of the ecologically sustainable yield model

The historical flow record and the ecological flow thresholds are used to guide the construction of an ecological water requirement. With the PADFLOW approach, the modelled EWR is developed using a water balance model called the river ecologically sustainable yield model (or RESYM), which was developed specifically to be used with PADFLOW. RESYM develops a modelled EWR flow regime by removing a proportion of the observed daily flow until the remaining water equals or exceeds each of the ecological flow objectives identified in step 8 of the method (see Figure 6).

RESYM software is designed to be used in a workshop environment during which the expert panel parameterises and evaluates the resulting modelled EWR. The proportion of the observed daily flow retained for the EWR depends on the magnitude of the measured flow and the ecological functions of the flow event.

3.10 Evaluation of the RESYM-generated EWR

For each model run, the expert panel evaluated the frequency and duration of spells above the particular ecological flow threshold in the modelled EWR compared with the frequency and duration of the spells in the observed data record. Gantt Charts showing the frequency and duration of flows above each threshold for both the observed and modelled EWR flow are part of the graphical output of RESYM.

The final parameters used in RESYM to generate the modelled EWR were developed iteratively by an expert panel which evaluated the flows produced by each model against the ecological thresholds. Using the Gantt Charts shown in Figure 18, the expert panel considered the length of the flow period or spell that the EWR exceeded each ecological threshold. If the panel considered that the frequency and duration of flow above each threshold differed significantly from that in the measured flow it was concluded that the modelled output was not consistent with an EWR at a low level of risk (steps 9 and 10 in Figure 6).

The model parameters were then adjusted accordingly, the model re-run, the results evaluated again, and so on until the panel considered that the model parameters produced a modelled EWR flow that was consistent with a low level of risk.

The expert panel evaluated each run of the RESYM model by evaluating the change (from the observed flow series) in frequency and duration of spells above each threshold developed using the RAP. The RESYM parameters used to generate the accepted EWR flow for the cascades reach are shown in Table 4.

While the panel evaluated each threshold individually, it must be emphasised that the EWR is the sum of all thresholds. In evaluating the charts in Figure 18, the panel considered the frequency and duration of spells greater than the thresholds both within and between years for all the ecological flow thresholds.

Table 4
Proportion of the observed daily flow volume retained to meet the EWR of Lefroy Brook

Flow range ML/day	EWR as a % of daily flow volume
0–0.9	100
1–9.9	50
10–34.9	70
35–1599	60
1600–2199	70
≥2200	100

Figure 18

Comparison of the frequency and duration of spells above each of the ecological flow thresholds for the observed flow record and the modelled EWR

3.10.1 Summer flows

A flow rate of at least 0.01 m^3/s or 0.86 ML/day is required in Lefroy Brook between December and April to maintain a flow connection between the sandy runs and pools. To provide for this objective, RESYM was set up to retain 100% of the observed daily flow in the range between 0 and 0.9 ML/day (Table 4). A higher summer flow of 0.07 m^3/s or 6.05 ML/day was included in the modelling to maintain oxygen levels in pools. To provide for this objective, RESYM was set up to retain 50% of the observed daily flow in the range from 1 to 9.9 ML/day (Table 4).

The frequency and duration of spells above 0.86 ML/day and 6.05 ML/day in the RESYM-generated EWR flow are compared with those in the observed flow record in Charts 1 and 2 of Figure 18. Chart 1 shows that spells over 0.86 ML/day occurred naturally in all months in most years. Spells above 0.86 ML/day in the modelled EWR flow occurred in the same frequency and for the same duration as for the observed flow.

Chart 2 shows that spells above 6.05 ML/day have occurred in all years on record (1975–2003). Before 1995, the duration of these spells ranged from being continuous (1982), to occurring in one to four broken spells lasting only a few days to a couple of months. After 1995, the duration of spells over 6.05 ML/day tended to be longer, with few events shorter than three weeks in duration. The duration of spells over 6.05 ML/day was shorter in the modelled EWR than that which occurred naturally. However, by maintaining some connectivity in summer, the EWR allows for some cycling of carbon throughout the in-stream ecosystem and some movement of water within pools throughout the summer months.

Based on Charts 1 and 2, the expert panel concluded that the distribution and quality of summer habitat in the lower reaches of Lefroy Brook would be maintained by the summer low flows produced by RESYM using the parameters in Table 4.

3.10.2 Fish migration

A flow rate of at least 0.12 m^3/s or 10.4 ML/day is required to allow small-bodied native fish to move upstream of the high point in the cascades reach (cross-section 6). To provide for this objective, RESYM was set up to retain 70% of the measured daily flow in the range of 10 to 35 ML/day (Table 4).

The duration and frequency of spells above 10.4 ML/day in the modelled EWR flow is compared to that in the measured flow in Chart 3 of Figure 18. Chart 3 shows that before 1995, spells above 10.4 ML/day occurred naturally in summer, lasting between one and five weeks, except for 1982 when it was exceeded for the entire summer. In all years, winter flows were above 10.4 ML/day. After 1995, summer spells over 10.4 ML/day tended be of longer duration and more frequent.

The frequency and duration of spells above 10.4 ML/day in the modelled EWR closely matched the winter pattern in the observed flow record. Summer spells before 1995 in the EWR flow are less frequent and of shorter duration compared with the observed record. After 1995, the frequency and duration of summer spells greater than 10.4 ML/day occurred at a similar frequency and duration in both the observed flow and the EWR.

The critical period for breeding migration is from about May to August. In this period the duration of spells above 10.4 ML/day for the measured flow and the modelled EWR series were nearly identical. The panel concluded that the RESYM parameters in Table 4 met the winter objective associated with small-bodied fish passage in Lefroy Brook.

3.10.3 Summer habitat for macroinvertebrates

To inundate summer habitat for macroinvertebrates and other fauna adapted to this habitat, a flow rate of 0.19 m^3/s or 16.4 ML/day is required. Based on RAP analysis, this flow will inundate approximately 50% of the width of sandy runs to a minimum depth of 5 cm. To provide for this objective, RESYM was set up to retain 70% of the observed daily flow in the range between 10 and 35 ML/day (Table 4).

The duration and frequency of spells over 16.4 ML/day in the RESYM-generated EWR are compared with the observed flow record in Chart 4 of Figure 18. Spells above 16.4 ML/day occurred naturally between December and May. Before 1995, spells over the threshold either did not occur (as in 1984), or spells were discontinuous with low spells lasting from a few days up to six weeks. In the pre-1995 EWR, spells above 16.4 ML/day occur less frequently and for shorter periods than in the observed flow record (Chart 4 of Figure 18).

Following the construction of Big Brook Dam in 1995, spells over 16.4 ML/day in the observed flow record were more frequent and longer compared to pre-1995. After 1995, spells above 16.4 ML/day occurred in a regime similar to the observed flow record, but were less frequent and shorter in duration.

The panel was of the opinion that spell frequency and duration in the EWR met the water requirements of invertebrates in the dry months between December and May, and agreed that the RESYM parameters in Table 4 met the ecological objective for 50% coverage of sandy run habitat in summer.

3.10.4 Winter macroinvertebrates

A flow of above 0.67 m^3/s or 57.9 ML/day is needed to inundate the entire width of sandy runs in winter. To achieve this flow in the EWR, RESYM was set up to retain 60% of the daily flow volume within the flow range between 35 and 1600 ML/day (Table 4).

The frequency and duration of spells over 57.9 ML/day in the modelled EWR flow is compared to that in the observed flow record in Chart 5 of Figure 18. Chart 5 shows that spells above 57.9 ML/day occur naturally in the cascades reach between the months of May and November. Outside of this period they occur irregularly or not at all, depending on the annual pattern of rainfall.

In the modelled EWR flow, the duration of winter spells over 57.9 ML/day closely matched that in the observed flow record. However, there were some differences in the duration of spells at the start and end of the winter period (Chart 5). It is the winter months when the availability of sandy run habitat for macroinvertebrates is important, so these animals are unlikely to be affected by changes in the duration of spells at the start and end of winter.

As the differences in the duration of spells between the modelled EWR and observed flow were limited to the shoulder periods of winter, the panel concluded that the RESYM parameters in Table 4 met the ecological objective of providing winter habitat for macroinvertebrates.

3.10.5 Spawning habitat for native fish

To inundate in-stream vegetation used by native fish as spawning sites, the RAP modelling predicted that a flow rate of at least 1.4 m^3/s or 121 ML/day is needed. To generate the modelled EWR series that meets this flow objective, RESYM was set up to retain 60% of the daily flow, when the observed flow was between 35 and 1600 ML/day (Table 4).

The occurrence of spells over 121 ML/day in the modelled EWR flow is compared with the measured flow record in Chart 6 of Figure 18. Spells above 121 ML/day occurred naturally in the cascades reach in every year of the record from about May to December, although in 1977 and 1978 spells above the threshold commenced in early March. The results indicate that habitat would be available for native fish to spawn in the cascades reach for between seven and nine months of the year. The duration of spells above 121 ML/day in the modelled EWR are marginally shorter than in the observed flow record.

The panel considered that spawning sites should be continuously inundated for a period of at least six weeks to allow eggs to hatch and larvae to mature. Spells of at least six weeks' duration occurred in the EWR in all years on record. From the EWR series in Chart 6, it is apparent that native fish will have ample opportunity for successful spawning within their lifetime. The panel concluded that the modelled EWR flow generated by the parameters in Table 4 achieved the ecological objective relating to inundation of breeding habitat.

3.10.6 Inundation of low and high benches

A flow rate of 3.8 m^3/s or 319 ML/day is needed to inundate low benches, while a daily flow of 1080 ML will inundate high benches. A second function of flow within this range is to inundate secondary channels and tributaries, allowing native fish to move into these habitats to spawn. To provide regular flooding of low and high benches and to maintain channel morphology, RESYM was set up to retain 60% of the observed daily flow in the range between 35 and 1600 ML/day (Table 4).

The duration of spells above 319 and 1080 ML/day in the modelled EWR flow is compared with the observed flow record in Charts 7 and 8 of Figure 18. Chart 7 shows that spells over 319 ML/day occur naturally between late May and November, and have varied between years in both number and duration. For some winters there are five to six spells over the threshold, lasting from a few days to several weeks. In other years, spells over 319 ML/day lasted for months, or even for most of the winter period, as in 1998.

Variability of high spell frequency and duration is even greater for spells above 1080 ML/day (Chart 8). Flows of this magnitude did not occur naturally every year, but at irregular intervals of between two and three years. Flows over the threshold have been restricted to the period between July and October. Notably, spells of this magnitude have not occurred since 1998.

Spells greater than 319 and 1080 ML/day were less frequent and of shorter duration in the EWR than in the measured flow (Charts 7 and 8). As the purpose of this flow is to wash organic carbon from the banks to the river, it is important that this flow occurs at regular intervals, but neither the frequency nor duration of spells need be identical to the natural frequency to achieve the flow objective. The expert panel reasoned that the physical impact of differences in frequency and duration between the EWR and the observed flow record would probably be small. Charts 7 and 8 also suggest that the period of connection with tributaries in the modelled EWR is adequate to allow upstream migration of native fish into tributaries.

3.11 The modelled ecological water requirement

The parameters in Table 4 produced a daily EWR containing spells that achieved the desired ecological thresholds, also listed in Table 4. The modelled EWR flow is shown for the period 1975 to 2003 in Figure 19. Figure 20 shows the detail of the modelled EWR for the years 1999, 2000 and 2001.

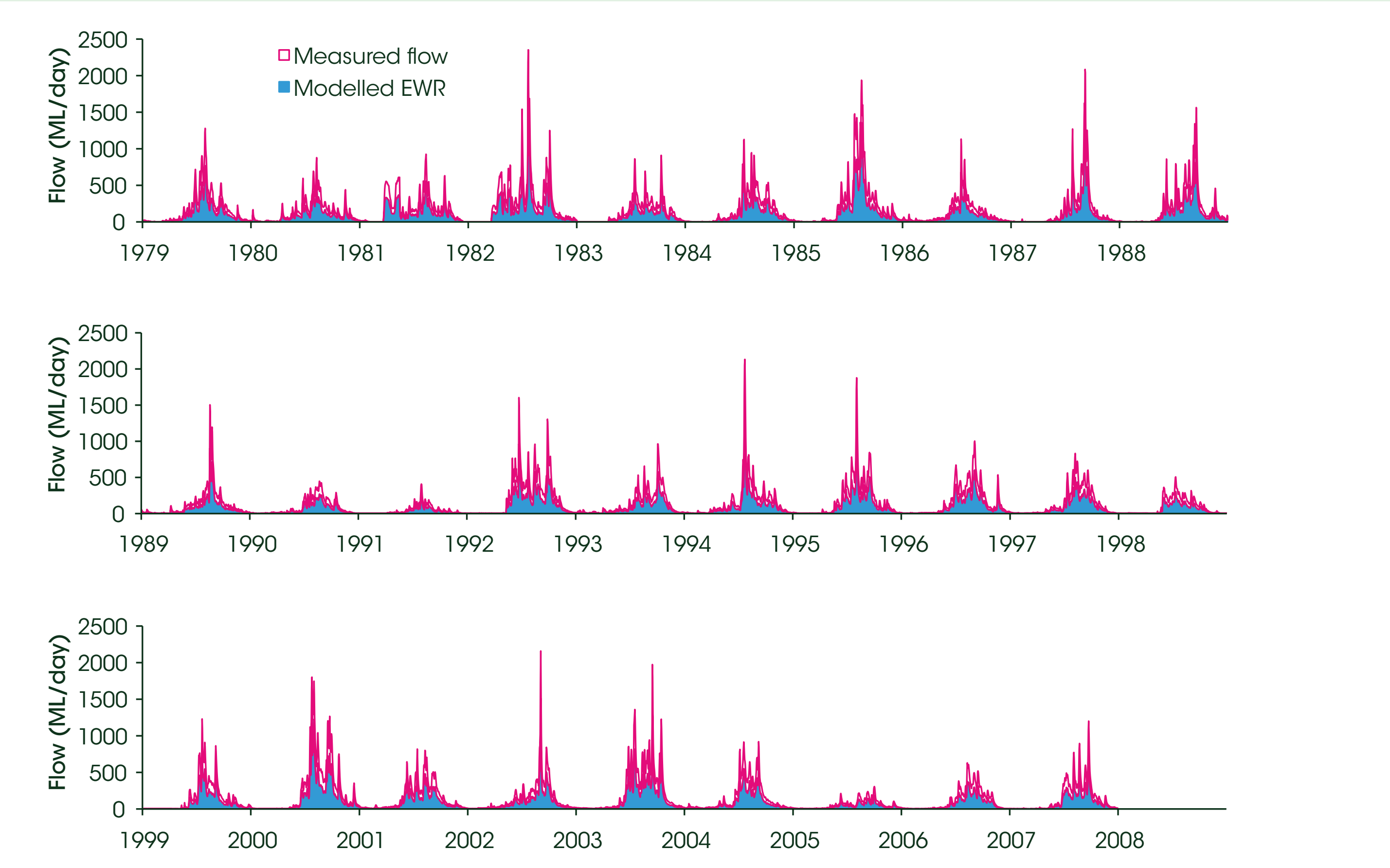


Figure 19
Times series of the measured and modelled EWR, 1975–2003

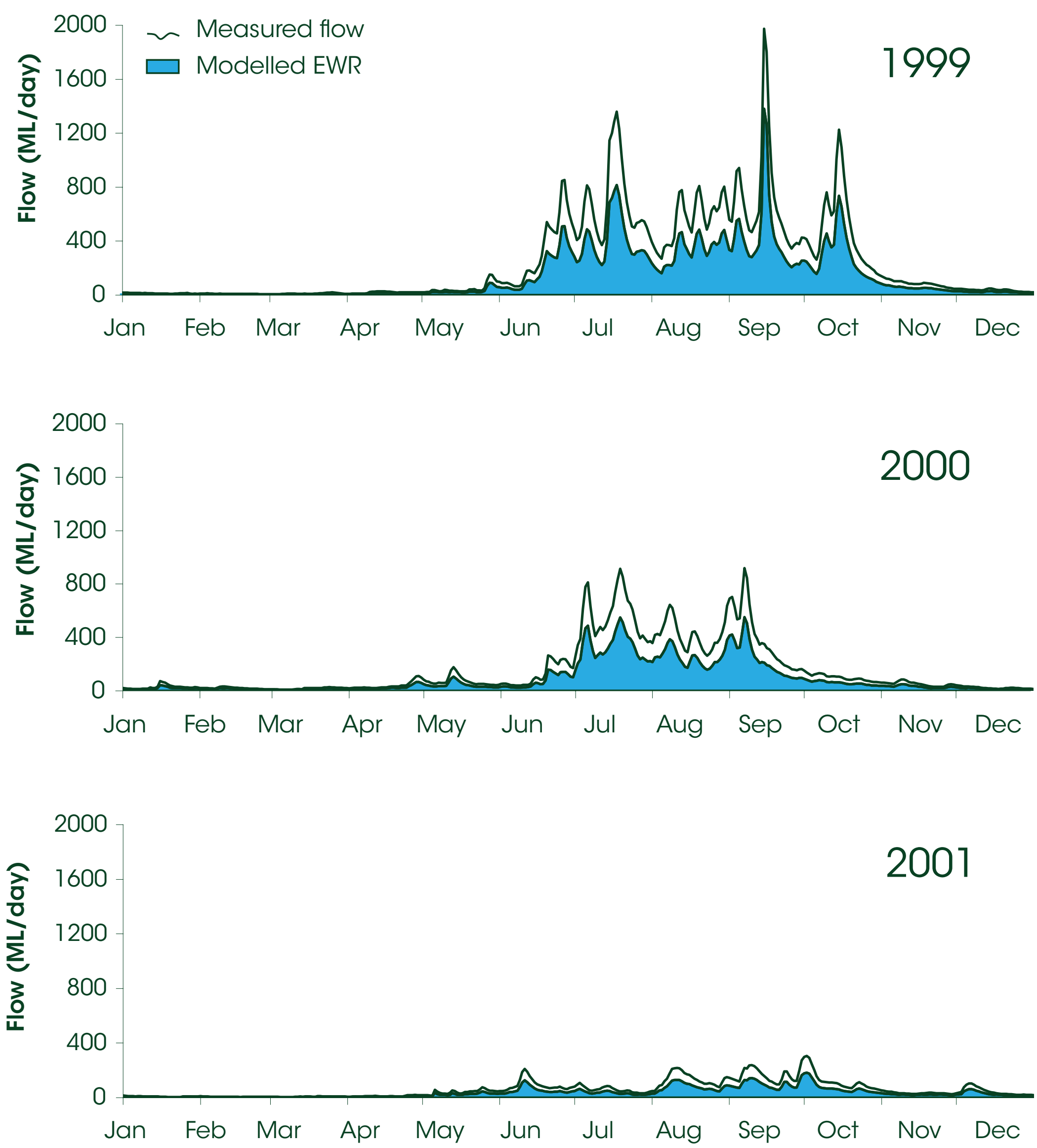


Figure 20

Observed flow and modelled EWR for Lefroy Brook – 1999, 2000 and 2001

Flow in 1999 was the second highest on record. A median flow was observed in 2000 and the flow in 2001 was the second lowest recorded in the period 1975 to 2003.

the observed flow record, the final EWR series retains the variability present in the natural daily flow including variation in annual volume, seasonal patterns, and the same cyclic and long-term trends (Figure 19 and Figure 20). The approach generates an EWR that is consistent with the natural flows paradigm and the need to reproduce natural patterns of flow to maintain the ecological character of a river system (Poff et al. 1997). The variation in the proportion of measured flow retained in different flow ranges can be seen, for example, between May and August of 2001 (Figure 20).

Figure 21 compares the flow duration of the natural flows against the modelled EWR. The blue line is the observed curve for the period 1975–2003 and the red curve is for the modelled ecological water requirement over the same period (based on the parameters in Table 4). The curves show the percentage of time that flows of particular volumes have been exceeded. The lowest volume flows (that is, less than 10 ML/day) have been achieved for at least 90% of the time in both the observed and modelled and EWR flow. Similarly, very high volume flows (over 1000 ML/day) occur infrequently (less than 2% of the time period on record).

The figure shows how the modelled EWR preserves flows across the full range of the observed flows. Importantly, there has been no change to flow permanency, or to the occurrence of exceptionally high flows. The difference between the blue line on Figure 21 (observed flow record) and the red line (modelled EWR flow) represents the volume of water that is additional to the calculated ecological water requirements of the cascades reach of Lefroy Brook.

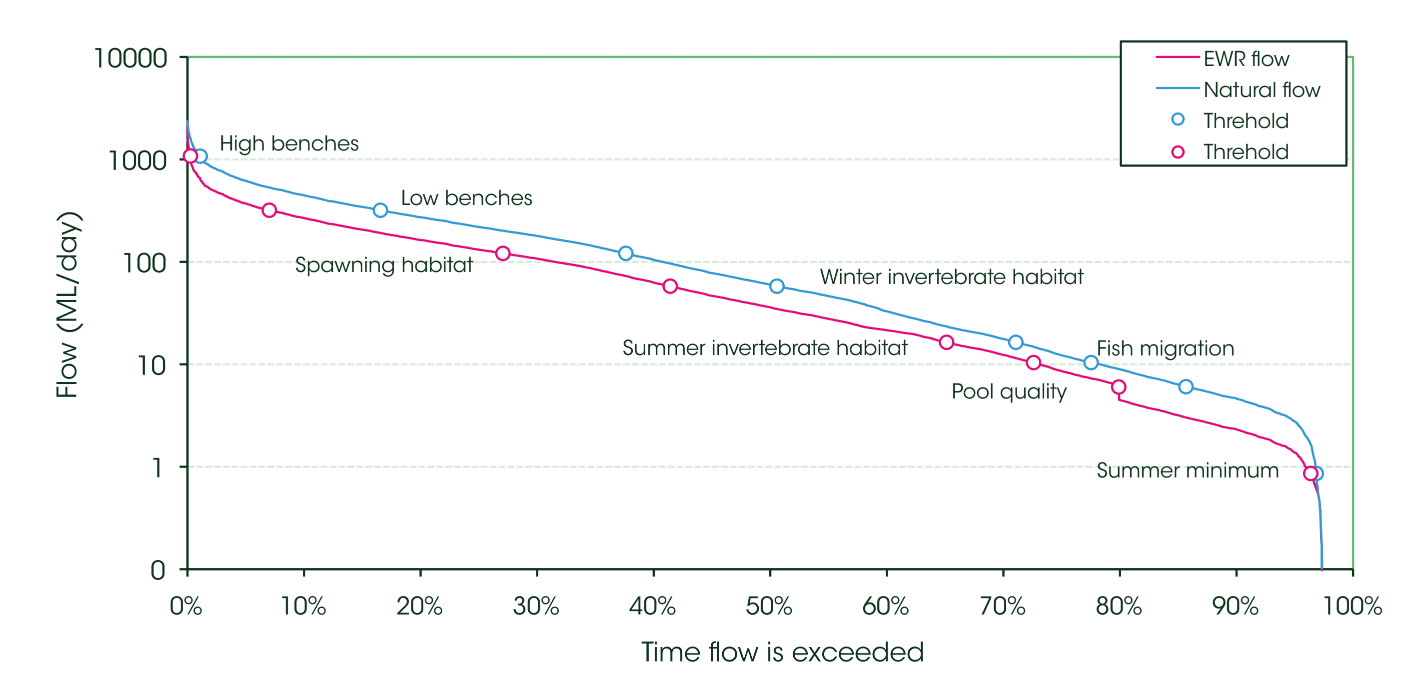
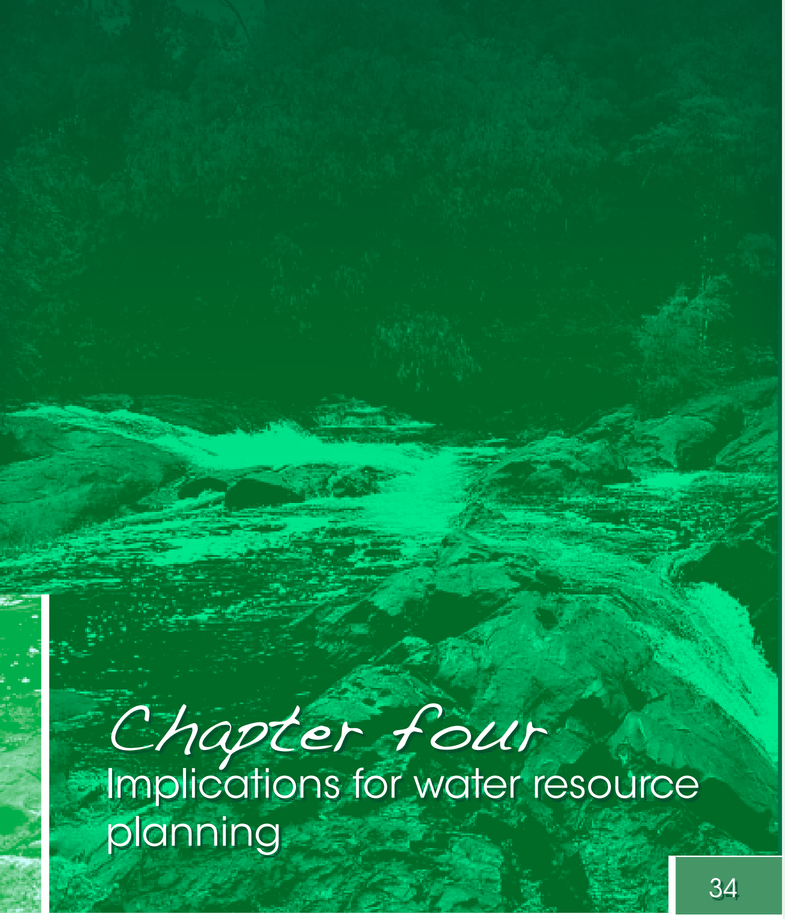


Figure 21
Daily flow duration curve for Lefroy Brook, observed flow vs. modelled EWR flow



Chapter four
Implications for water resource planning

Figure 22 shows an example daily flow and ecological water requirement for the year 2000. The difference between the observed daily flow and the modelled ecological water requirement is the amount of water that can be abstracted from the system without placing ecological values at high risk. This means that the volume of water between the observed flow and modelled ecological water requirement is an estimate of the ESY of the cascades reach of Lefroy Brook. As RESYM generates the ecological water requirement at a daily time-step, the ESY can be calculated at any time step from daily to annual and long-term average. It can also be used to determine the reliability of supply of an allocation. The ESY of a river is not a constant, but a variable controlled by annual rainfall and flow (Figure 19 and Figure 20).

4.1 Sustainability

Allocation decisions are made in consideration of the environmental, economic and social costs and benefits. An ecologically sustainable allocation or yield is the volume of water that can be abstracted while conserving ecological values. The sustainability concept may also include the volume of water that can be allocated to new users without affecting supply to existing users. Environmental sustainability and securing the supply of existing users are often complementary. In situations where use delivers significant economic benefits, a decision may be made to exploit a source to a level which does not fully meet the ecological water requirement. This level of use is considered sustainable, because it meets resource objectives and actions taken to manage environmental impacts of high use[1].

The Lefroy Brook ecological water requirement study was carried out to support surface water resource planning and management in the Warren–Donnelly Basin. This study determined an ecological water requirement for Lefroy Brook and used this to define the ecologically sustainable yield.

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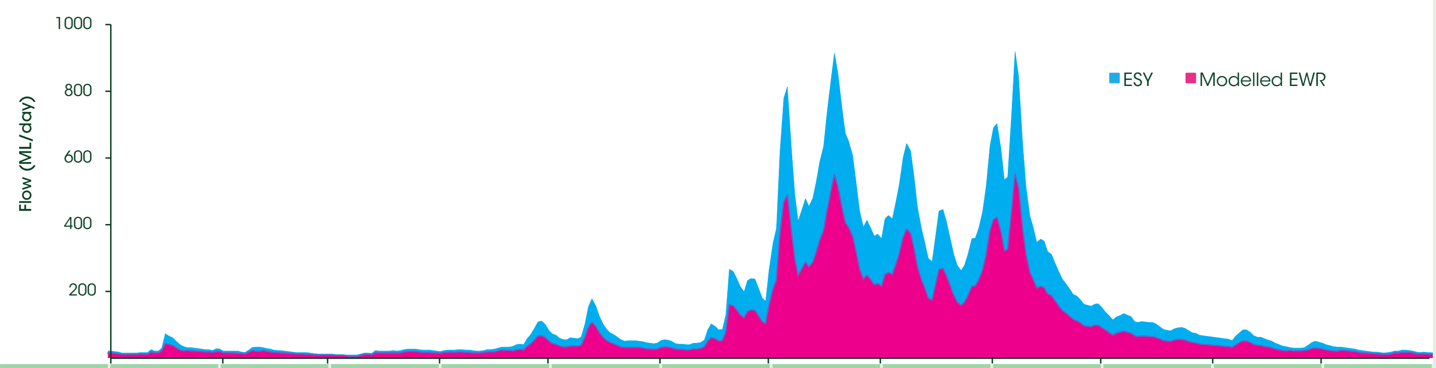
[1] The combination of high use and impact management can lead to good economic and environmental outcomes. To manage environmental impacts in high use catchments, licences to take water may include conditions such as environmental releases (from large dams), low flow by-pass structures for on-stream farm dams and limiting pumping into off-channel storages to the winter flow period.

4.2 Ecologically sustainable yield for Lefroy Brook

The annual ESY for Lefroy Brook is between 7 and 39 GL, based on the results of the modelled ecological water requirement for the period between 1975 and 2003. The average ESY is 23 GL per year (Table 5). The ecological water requirement was modelled using the measured flows between 1975 and 2003, which includes the impact of abstraction for irrigation on the measured flow rates. This means that the sustainable yield based on the modelled ecological water requirement is a volume that is additional to the current level of water use. For this discussion, 'use' is defined as the volume of water intercepted by and stored in dams.

The current licensed allocation in Lefroy Brook catchment is about 15 GL per year. About 9 GL of water is stored in farm dams. These figures are for an area that has been cleared for agricultural development, which comprises about 37% of the catchment (Figure 2). As discussed in section 2.3, if the cleared areas of the catchment are fully developed, the ESY calculated from the ecological water requirement results refers to a potential, additional volume of water that can be extracted from the cascades reach and from the remaining undeveloped areas upstream.



Day of Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Ecologically sustainable yield (ML/day)												
1	6	6	4	6	33	21	106	144	277	60	25	18
2	6	6	4	7	29	22	138	167	281	55	25	16
3	5	6	3	7	27	21	156	171	252	50	23	15
4	5	6	3	7	24	20	246	167	214	46	23	14
5	4	6	3	7	22	17	312	187	217	49	22	13
6	4	5	3	7	22	17	326	208	293	51	21	10
7	5	5	4	8	24	16	253	241	368	53	26	9
8	5	7	4	7	24	16	198	258	339	52	31	9
9	5	9	4	7	23	16	164	249	259	50	34	9
10	5	13	4	7	25	18	179	218	206	44	34	8
11	5	13	4	6	41	18	191	182	171	43	31	7
12	8	10	4	6	61	18	182	156	156	44	27	7
13	6	9	4	7	71	22	192	139	139	43	25	6
14	6	8	7	8	62	34	211	120	143	43	25	6
15	9	7	6	8	50	41	235	116	140	43	23	6
16	29	7	6	8	41	38	254	146	128	41	21	5
17	26	7	6	9	34	34	295	176	124	37	20	5
18	24	6	6	10	30	35	334	179	114	34	18	5
19	20	6	7	10	28	52	366	164	105	33	16	5
20	16	6	6	10	25	107	342	143	95	33	15	5
21	14	5	7	14	22	104	302	124	90	35	13	6
22	9	5	8	16	20	96	270	111	83	36	9	6
23	9	5	8	16	21	86	260	105	77	37	9	7
24	9	5	8	16	21	80	243	111	74	36	9	7
25	8	5	8	23	21	93	211	124	70	33	9	7
26	8	4	8	28	20	95	177	144	65	30	9	6
27	8	4	7	36	19	95	157	144	64	30	16	5
28	7	4	7	44	18	84	166	156	62	27	19	5
29	7	4	7	44	18	72	156	176	65	27	20	5
30	8		7	40	17	68	146	205	65	26	19	5
31	8		6		18		149	255		26		5
Total	**295**	**187**	**172**	**428**	**911**	**1454**	**6917**	**5186**	**4736**	**1246**	**616**	**242**

Figure 22
Daily ecologically sustainable yield for Lefroy Brook for the year 2000

Modelling suggests that dam development has affected low summer flow and flow in the early part of the flow season as irrigation dams fill. As the dams fill quickly high winter flows have not been as severely affected. Existing interception of water by on-stream dams may be causing unacceptable impacts on the river environment at low flow and in the early part of the flow season. The dams are having less impact on winter high flows which suggest that limited additional water maybe available for allocation at higher flows with appropriate restrictions.

4.3 Implications for management of farm dams in south-west Western Australia

One of the benefits of using RESYM to model the ecological water requirement of a river is that yields can be generated for any period and adjusted to a particular use scenario. Situations involving any form of pumping or diversion to off-stream storage require the ESY to be specified at a daily time-step. The sustainable allocation is the maximum aggregate volume of water that can be diverted each day by all users without placing ecological values at high risk.

To better define a sustainable level of dam development and storage, an ESY should be defined for the period during which water is harvested. In the Lefroy Brook catchment, this period is from about May to the end of June. Based on the results of this study, the ESY for an industry using on-stream dams (for the uncleared areas of Lefroy Brook) in the May – June period is around 3 GL on average, and varies between about 1 and 10 GL depending on inter-annual variation in rainfall and runoff (Table 5).

When defining a sustainable allocation limit for the catchment, it must be emphasised that the ecological consequences of interception of river flow by dams in low flow years are more severe than in high flow years. On-stream dams in the Lefroy Brook have a fixed capacity, with minimal capability to control the volume stored. In low flow years, dams store the same volume of water as in high flow years, but intercept a larger proportion of total flow. The amount of water available to fill downstream dams decreases, the period before the dams begin to spill extends further into the winter flow season, and the risk to downstream ecology and downstream water users is heightened. This trend may become more apparent in years to come, based on the current predictions for a drying climate in the south-west of Western Australia.

The easiest way to manage a sustainable allocation in self-supply irrigation is if storages are located off-stream and filled by pumped diversions from draw points (Sinclair Knight Merz 2007). Off-stream construction may also allow addition water to be sustainably abstracted during high flow periods.

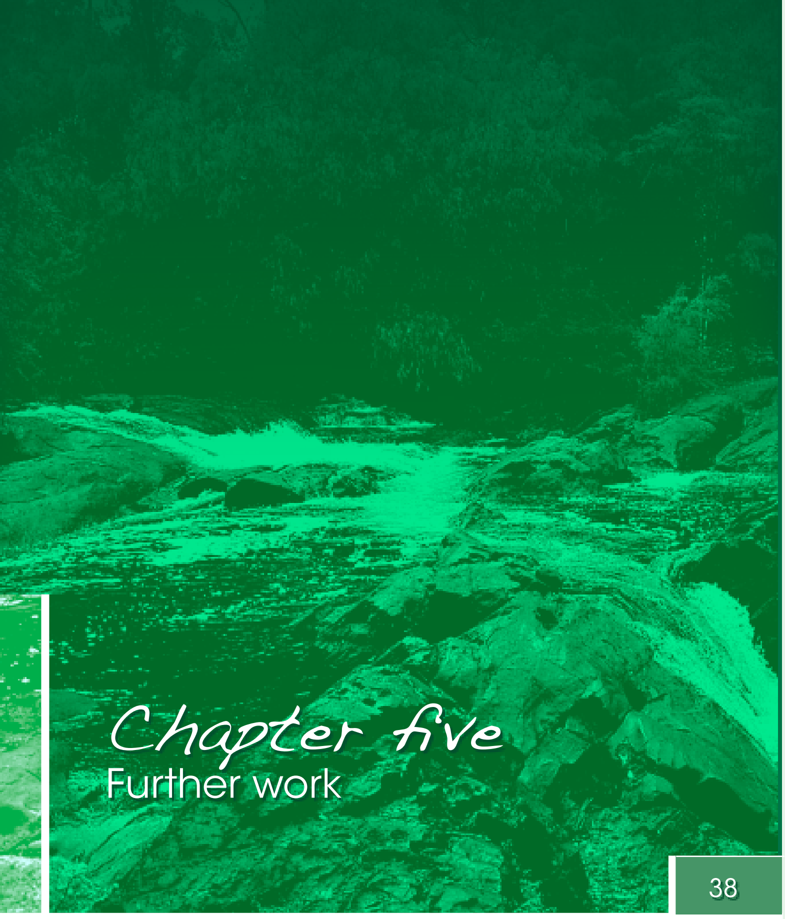
There are significant financial costs associated with locating storages off-stream. The results of this study suggest that there may be an increase in the sustainable allocation limit, and therefore an economic benefit (and incentive) to placing storages for irrigation off-stream.

It is neither practical nor financially viable to replace all existing on-stream dams with off-stream storages or to construct all new dams off-stream. An approach to water resource management is needed that accommodates both on-stream dams and off-stream storages within catchments. This may involve managing on-stream dams to within a sustainable level based on the ESY for the period that on-stream dams intercept flows (see for example Table 5) and a second tier of abstractions involving pumped diversions to off-stream storages during high winter flows. The pumping to off-stream storage should be restricted to within the sustainable yield and commence only after the on-stream dams have filled.

Table 5
Ecologically sustainable yield for the cascades reach of Lefroy Brook, 1975 to 2005

Year	Monthly ESY GL												May and June GL	Annual total GL
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec		
1975	0.1	0.0	0.1	0.3	1.1	3.3	7.2	6.0	3.3	2.0	1.0	0.3	4.4	24.8
1976	0.4	0.1	0.1	0.8	1.2	2.5	3.7	5.6	2.2	1.7	1.8	0.6	3.7	20.5
1977	0.1	0.0	1.5	4.0	4.1	1.8	2.7	5.9	2.0	3.1	1.1	0.1	5.9	26.5
1978	0.0	0.0	0.9	4.8	5.1	4.1	9.4	3.7	5.3	4.1	0.8	0.6	9.2	38.8
1979	0.0	0.0	0.0	0.2	0.6	1.6	4.6	3.7	2.8	3.9	1.5	0.4	2.2	19.4
1980	0.1	0.0	0.0	0.4	0.5	1.3	5.6	6.7	3.6	3.7	1.2	0.5	1.8	23.6
1981	0.1	0.0	0.1	0.3	0.7	3.8	8.5	12.9	4.3	2.6	1.5	0.7	4.5	35.5
1982	0.4	0.2	0.2	0.4	0.7	2.6	6.0	3.5	2.0	1.2	0.6	0.2	3.3	17.8
1983	0.1	0.1	0.0	0.0	0.2	1.1	4.5	5.1	9.8	1.5	0.7	0.2	1.3	23.3
1984	0.1	0.0	0.1	0.1	1.2	3.4	4.1	6.8	8.8	1.5	2.1	0.8	4.6	28.8
1985	0.3	0.1	0.1	0.4	0.5	1.5	2.4	7.6	3.5	1.4	0.9	0.3	2.0	18.8
1986	0.1	0.1	0.1	0.2	0.4	0.5	2.7	4.1	2.5	1.8	0.5	0.1	0.9	12.9
1987	0.1	0.1	0.1	0.1	0.2	0.6	1.7	2.2	0.9	0.5	0.3	0.1	0.8	6.8
1988	0.1	0.1	0.1	0.1	1.7	8.0	5.8	6.0	5.4	5.3	1.5	0.3	9.7	34.1
1989	0.3	0.1	0.1	0.4	0.6	0.8	2.7	3.9	3.2	6.2	1.3	0.2	1.4	19.9
1990	0.1	0.1	0.2	0.7	1.0	1.8	6.8	6.2	3.1	2.6	1.6	0.3	2.8	24.5
1991	0.1	0.1	0.1	0.2	0.7	3.1	5.5	7.6	6.0	1.6	1.3	0.3	3.8	26.5
1992	0.1	0.1	0.1	0.1	0.7	2.1	4.8	5.8	6.5	1.9	1.9	0.6	2.8	24.6
1993	0.1	0.1	0.1	0.1	0.8	0.8	3.6	6.3	5.0	2.5	0.8	0.1	1.6	20.6
1994	0.1	0.1	0.1	0.1	0.6	2.8	3.8	2.5	2.1	1.1	0.2	0.1	3.4	13.4
1995	0.1	0.1	0.1	0.1	0.2	1.7	7.2	4.7	3.9	1.4	1.2	0.4	1.9	21.0
1996	0.1	0.1	0.1	0.1	0.3	2.1	8.8	9.1	8.9	5.2	1.4	1.4	2.4	37.5
1997	0.2	0.2	0.2	0.3	1.0	4.1	4.2	5.5	4.3	1.4	0.8	0.3	5.1	22.3
1998	0.1	0.1	0.3	0.4	0.9	1.9	2.3	4.1	7.8	2.9	0.7	0.3	2.8	21.6
1999	0.1	0.1	0.1	0.2	0.6	3.8	8.5	6.8	8.0	6.0	1.1	0.4	4.4	35.6
2000	0.3	0.2	0.2	0.4	0.9	1.5	6.9	5.2	4.7	1.3	0.6	0.2	2.4	22.4
2001	0.1	0.1	0.1	0.1	0.5	1.1	0.7	1.6	2.0	1.5	0.4	0.5	1.6	8.8
2002	0.1	0.1	0.1	0.1	0.2	0.9	2.8	4.7	4.4	2.3	1.0	0.1	1.1	16.6
2003	0.1	0.1	0.1	0.1	0.3	1.1	4.3	5.7	6.0	2.3	1.1	0.2	1.4	21.4
2004	0.3	0.2	0.2	0.3	0.8	3.5	3.6	4.0	2.4	1.2	1.0	0.4	4.3	17.8
2005	0.0	0.0	0.0	0.0	0.4	3.9	5.0	5.8	5.4	4.9	1.8	0.5	4.3	27.7
Max	**0.4**	**0.2**	**1.5**	**4.8**	**5.1**	**8.0**	**9.4**	**12.9**	**9.8**	**6.2**	**2.1**	**1.4**	**3.3**	**38.8**
Min	**0.0**	**0.0**	**0.0**	**0.0**	**0.2**	**0.5**	**0.7**	**1.6**	**0.9**	**0.5**	**0.2**	**0.1**	**0.8**	**6.8**
Mean	**0.1**	**0.1**	**0.2**	**0.5**	**0.9**	**2.4**	**4.9**	**5.5**	**4.5**	**2.6**	**1.1**	**0.4**	**9.7**	**23.0**

* Note: The ESY was calculated as the difference between the modelled EWR and the measured daily flow. The mean, minimum and maximum ESY for May and June (i.e. the approximate period during which dams are filled) were calculated by adding the monthly ESY for May and June together for each year in the flow record.



Chapter five
Further work

The modelled EWR flow regime developed as a result of this study is based largely on knowledge about the water requirements of a few water-dependent species. There remain many gaps in our knowledge of the relations between changes to flow regime and the diversity and abundance of water-dependent plants and animals. Research in this area will assist in refining ecological water requirements to provide better information for water resource planning and management.

The review of literature for this study identified that the cascades reach of Lefroy Brook has significant ecological values associated with a system that has adapted to a history of flow regulation and water abstraction. Past fish studies suggest some ecological adaptation to changes in flow as a result of Big Brook Dam. Research is required to investigate fish adaptation and flow change associated with Big Brook Dam and farm dams.

5.1 Resource management

This study focused on the cascades reach of Lefroy Brook. To support water resource planning and management, work is required on the impact of farm dams on flows in the river reaches immediately downstream of the developed areas of the catchment.

It is also important that future ecological water requirement studies focus on undeveloped rivers. The rivers and sites should be selected so that the results of the studies would assist with the specification of sustainable yields of high flows in the developed areas of the upper and middle Lefroy Brook catchment, and developed parts of other catchments in the region.

The results of this study suggest that additional water may be available in developed areas of catchments if irrigation storage were located off-stream and pumped abstractions limited to flows ranges that are not being impacted by on-stream dams. A cost-benefit economic analysis may identify a significant financial incentive for locating farm dams off-stream.

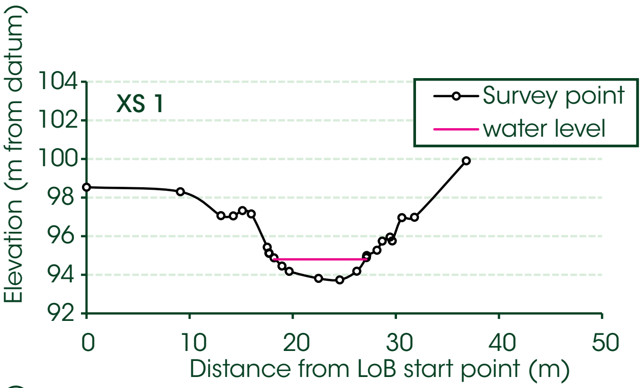
A regulatory framework that accounts for on-stream and off-stream dams should be developed. This would include sustainable limits for different types of storage and rules governing maximum aggregate storage for on-stream dams and maximum daily pump rates for diversions to off-stream storage.

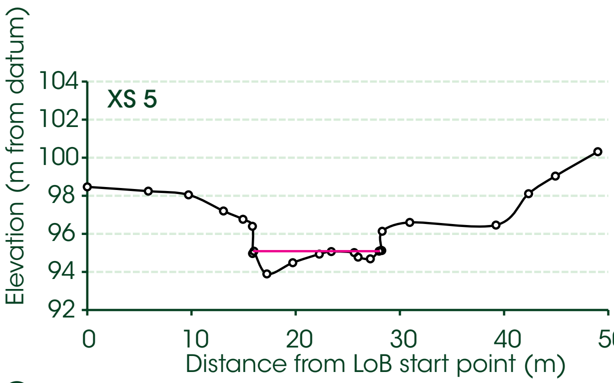
Appendix A — Macroinvertebrates of Lefroy Brook

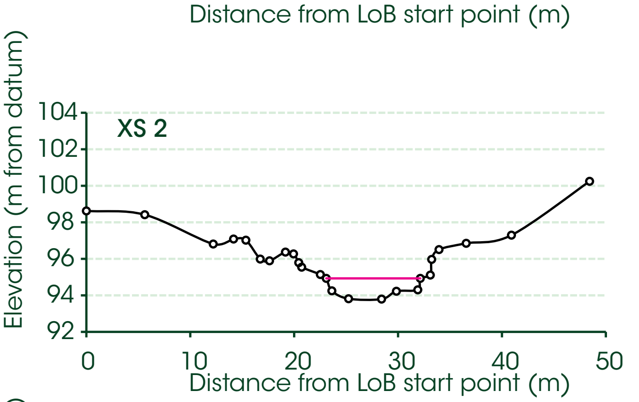
Macroinvertebrates of Lefroy Brook	
Nematoda spp.	*Rietha sp. (V5)*
Ferrissia petterdi	*Stenochironomus sp.*
Glyptophysa sp.	*Cladotanytarsus sp.*
Oligochaeta spp.	*Rheotanytarsus sp.*
Cherax cainii	*Stempellina sp.*
Cherax quinquecarinatus	*Tanytarsus sp.*
Palaemonetes australis	*unknown genus (V15)*
Cladocera spp.	*Botryocladius bibulmun*
Cyclopoida spp.	*Cricotopus amuliventris*
Perthia sp.	*Parakiefferiella sp.*
Janiridae spp.	*Thienemanniella sp.*
Ostracoda spp.	*Procladius paludicola*
Hydracarina spp.	*Paramerina levidensis*
Tasmanocoenis tillyardi	*Ceratopogoniinae spp.*
Baetidae spp.	*Dasyheleinae spp.*
Allodessus bistrigatus	*Forcypomiinae spp.*
Sternopriscus sp. (larvae)	*Ceratopogonidae spp.*
Sternopriscus marginatus	*Empididae spp.*
Octhebius sp.	*Tipulidae spp.*
Zygoptera spp.	*Anopheles sp.*
Austroaeschna anacantha	*Simulium ornatipes*
Austrosynthemis cyanitincta	*Simulidae spp.*
Microvelia sp.	*Stratiomyidae spp.*
Diptera spp. (pupae)	*Daternomina sp.*
Chironomidae spp. (pupae)	*Cheumatopsyche sp. (AV2)*
Dicrotendipes sp.	*Oecetis sp.*
Paracladopelma sp.	*Lectrides parilis*
Polypedilum sp.	*Triplectides australis*
Polypedilum watsoni	*Leptoceridae spp. (immature)*
Riethia sp. (V4)	

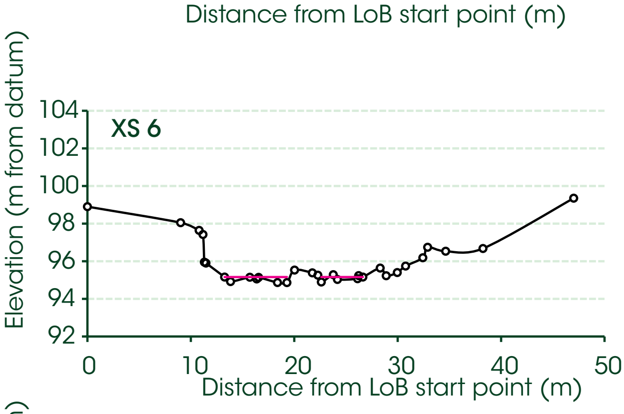
Appendix B — Channel cross-sections from Lefroy Brook

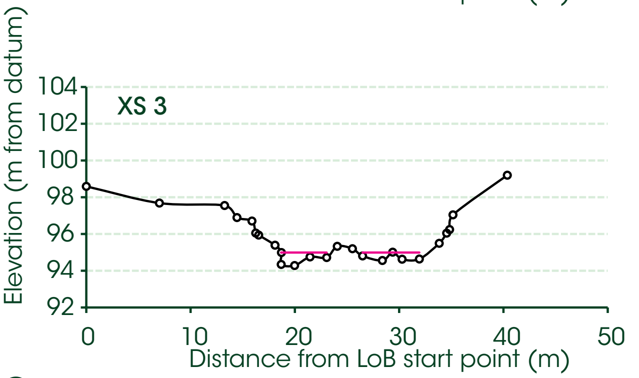
This appendix contains the survey channel profiles for the 15 cross-sections. The red line shows the water level at each cross-section at the time of survey. Cross-section 8 was taken below a railway bridge and the section shows the surveyed bridge pylons.

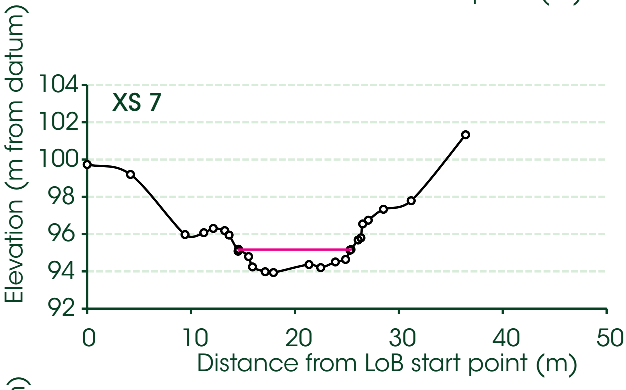


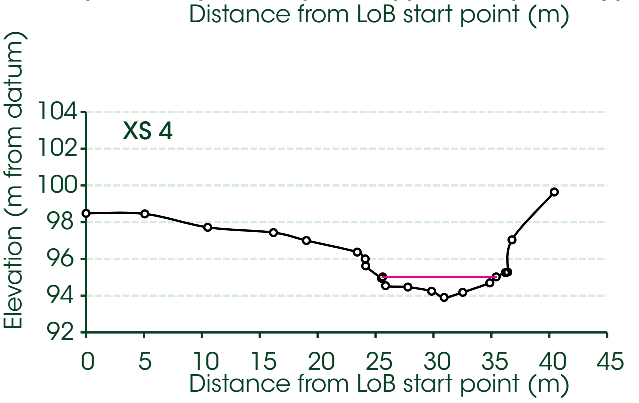


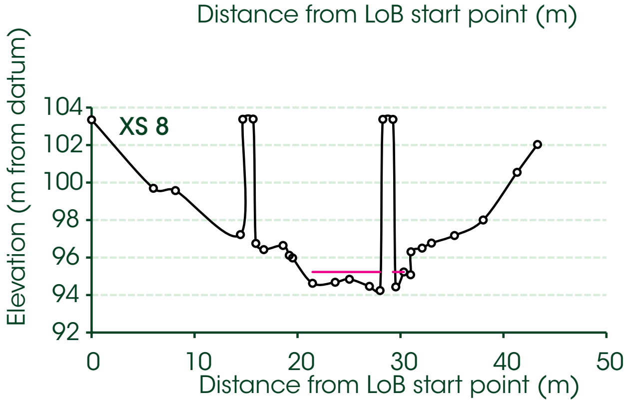




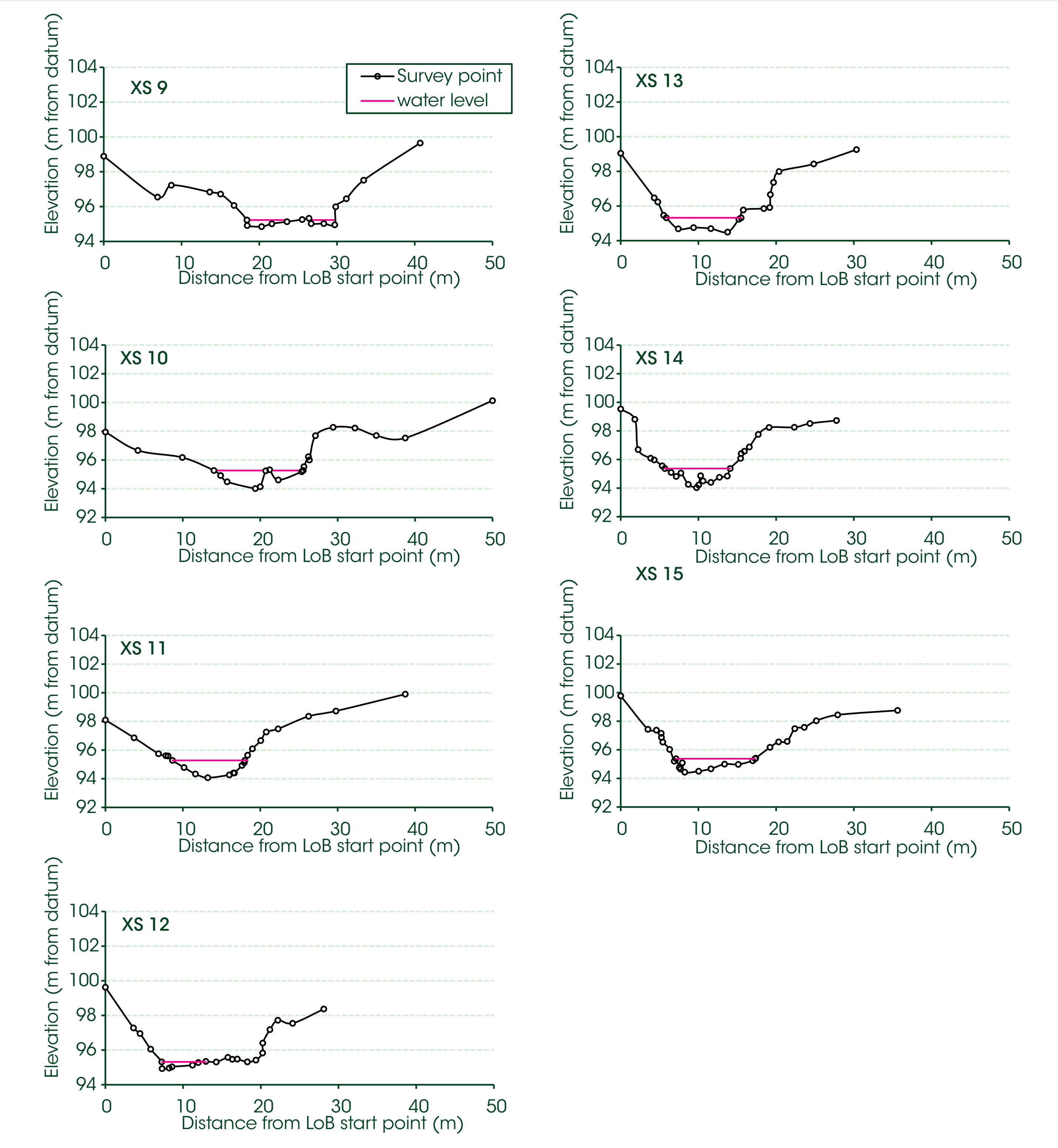








Appendix B — Channel cross-sections from Lefroy Brook (continued)



Appendix C — Monthly flow, EWR and ESY for the cascades reach of Lefroy Brook (1975—2005)

All data in the table below are in GL.

Year	Data	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1975	Flow	0.4	0.1	0.4	1.0	2.7	8.1	18.1	14.9	8.3	5.0	2.5	0.8	**62**
	EWR	0.3	0.0	0.2	0.6	1.6	4.9	10.9	8.9	5.0	3.0	1.5	0.5	**38**
	ESY	0.1	0.0	0.1	0.3	1.1	3.3	7.2	6.0	3.3	2.0	1.0	0.3	**25**
1976	Flow	1.1	0.3	0.3	2.0	3.0	6.2	9.1	13.9	5.4	4.2	4.4	1.5	**51**
	EWR	0.7	0.2	0.2	1.2	1.8	3.7	5.5	8.3	3.3	2.5	2.7	0.9	**31**
	ESY	0.4	0.1	0.1	0.8	1.2	2.5	3.7	5.5	2.2	1.7	1.8	0.6	**21**
1977	Flow	0.4	0.0	3.8	10.0	10.3	4.5	6.7	14.8	5.0	7.6	2.7	0.4	**66**
	EWR	0.3	0.0	2.3	6.0	6.2	2.7	4.0	8.9	3.0	4.6	1.6	0.2	**40**
	ESY	0.1	0.0	1.5	4.0	4.1	1.8	2.7	5.9	2.0	3.1	1.1	0.1	**27**
1978	Flow	0.0	0.0	2.2	12.1	12.7	10.4	27.5	9.3	13.2	10.3	2.1	1.5	**101**
	EWR	0.0	0.0	1.3	7.2	7.6	6.2	18.2	5.6	7.9	6.2	1.3	0.9	**62**
	ESY	0.0	0.0	0.9	4.8	5.1	4.1	9.3	3.7	5.3	4.1	0.8	0.6	**39**
1979	Flow	0.0	0.0	0.0	0.5	1.6	4.0	11.6	9.3	7.0	9.7	3.7	1.0	**49**
	EWR	0.0	0.0	0.0	0.3	1.0	2.4	7.0	5.6	4.2	5.8	2.2	0.7	**29**
	ESY	0.0	0.0	0.0	0.2	0.6	1.6	4.6	3.7	2.8	3.9	1.5	0.4	**19**
1980	Flow	0.2	0.1	0.1	1.0	1.4	3.2	13.9	16.7	9.1	9.3	3.0	1.2	**59**
	EWR	0.1	0.0	0.0	0.6	0.8	1.9	8.4	10.0	5.5	5.6	1.8	0.8	**36**
	ESY	0.1	0.0	0.0	0.4	0.5	1.3	5.6	6.7	3.6	3.7	1.2	0.5	**24**
1981	Flow	0.3	0.1	0.2	0.8	1.9	9.5	21.2	34.1	10.8	6.4	3.7	1.9	**91**
	EWR	0.2	0.0	0.1	0.5	1.2	5.7	12.7	21.2	6.5	3.8	2.2	1.2	**55**
	ESY	0.1	0.0	0.1	0.3	0.7	3.8	8.5	12.9	4.3	2.6	1.5	0.7	**35**
1982	Flow	1.2	0.6	0.5	1.0	1.8	6.6	14.9	8.7	4.9	3.0	1.4	0.5	**45**
	EWR	0.8	0.4	0.3	0.6	1.1	4.0	8.9	5.2	2.9	1.8	0.9	0.4	**27**
	ESY	0.4	0.2	0.1	0.4	0.7	2.6	6.0	3.5	1.9	1.2	0.6	0.2	**18**
1983	Flow	0.1	0.1	0.0	0.1	0.7	2.7	11.2	12.9	26.0	3.8	1.8	0.5	**60**
	EWR	0.1	0.1	0.0	0.0	0.5	1.6	6.7	7.7	16.2	2.3	1.1	0.3	**37**
	ESY	0.1	0.0	0.0	0.0	0.2	1.1	4.5	5.1	9.8	1.5	0.7	0.2	**23**
1984	Flow	0.1	0.1	0.1	0.2	3.1	8.4	10.3	17.0	21.9	3.8	5.1	1.9	**72**
	EWR	0.1	0.0	0.1	0.1	1.9	5.0	6.2	10.2	13.1	2.3	3.1	1.1	**43**
	ESY	0.1	0.0	0.1	0.1	1.2	3.4	4.1	6.8	8.8	1.5	2.1	0.7	**29**
1985	Flow	0.8	0.2	0.2	1.0	1.4	3.6	6.0	18.9	8.8	3.6	2.1	0.9	**48**
	EWR	0.6	0.1	0.1	0.6	0.9	2.2	3.6	11.3	5.3	2.1	1.3	0.6	**29**
	ESY	0.3	0.1	0.1	0.4	0.5	1.5	2.4	7.5	3.5	1.4	0.8	0.3	**19**
1986	Flow	0.2	0.1	0.4	0.5	1.1	1.3	6.7	10.2	6.2	4.4	1.2	0.4	**33**
	EWR	0.1	0.1	0.2	0.3	0.7	0.8	4.0	6.1	3.7	2.6	0.7	0.3	**20**
	ESY	0.1	0.1	0.1	0.1	0.4	0.5	2.7	4.1	2.5	1.8	0.5	0.1	**13**
1987	Flow	0.1	0.1	0.1	0.3	0.6	1.6	4.3	5.4	2.2	1.2	0.8	0.3	**17**
	EWR	0.1	0.1	0.1	0.2	0.4	1.0	2.6	3.2	1.3	0.8	0.5	0.2	**10**
	ESY	0.1	0.1	0.1	0.1	0.2	0.6	1.7	2.2	0.9	0.5	0.3	0.1	**7**
1988	Flow	0.1	0.1	0.1	0.1	4.2	20.0	14.4	14.9	13.4	13.2	3.7	0.8	**85**
	EWR	0.1	0.1	0.1	0.1	2.5	12.0	8.6	8.9	8.0	7.9	2.2	0.5	**51**
	ESY	0.1	0.1	0.1	0.1	1.7	8.0	5.8	6.0	5.4	5.3	1.5	0.3	**34**

Appendix C — Monthly flow, EWR and ESY for the cascades reach of Lefroy Brook (1975—2005) (continued)

All data in the table below are in GL.

Year	Data	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1989	Flow	0.8	0.3	0.4	1.1	1.6	2.0	6.8	9.6	8.0	15.5	3.3	0.7	**50**
	EWR	0.5	0.2	0.3	0.7	1.0	1.2	4.1	5.8	4.8	9.3	2.0	0.5	**30**
	ESY	0.3	0.1	0.1	0.4	0.6	0.8	2.7	3.9	3.2	6.2	1.3	0.2	**20**
1990	Flow	0.3	0.4	0.4	1.8	2.4	4.4	19.0	15.6	7.6	6.6	3.9	0.9	**63**
	EWR	0.2	0.2	0.3	1.1	1.4	2.7	12.2	9.4	4.6	3.9	2.3	0.6	**39**
	ESY	0.1	0.1	0.2	0.7	1.0	1.8	6.8	6.2	3.0	2.6	1.6	0.3	**24**
1991	Flow	0.3	0.2	0.2	0.5	1.9	7.7	13.7	20.3	14.9	4.1	3.3	0.9	**68**
	EWR	0.2	0.1	0.1	0.3	1.1	4.6	8.2	12.7	8.9	2.5	2.0	0.6	**41**
	ESY	0.1	0.1	0.1	0.2	0.7	3.1	5.5	7.6	6.0	1.6	1.3	0.3	**27**
1992	Flow	0.2	0.2	0.3	0.3	1.7	5.3	12.0	14.6	16.2	4.9	4.6	1.6	**62**
	EWR	0.1	0.1	0.2	0.2	1.1	3.2	7.2	8.7	9.7	2.9	2.8	1.0	**37**
	ESY	0.1	0.1	0.1	0.1	0.7	2.1	4.8	5.8	6.5	1.9	1.9	0.6	**25**
1993	Flow	0.3	0.2	0.3	0.4	2.0	2.1	9.1	15.9	12.6	6.3	2.0	0.4	**52**
	EWR	0.2	0.1	0.2	0.3	1.2	1.3	5.4	9.5	7.6	3.8	1.2	0.3	**31**
	ESY	0.1	0.1	0.1	0.1	0.8	0.8	3.6	6.3	5.0	2.5	0.8	0.1	**21**
1994	Flow	0.2	0.2	0.2	0.2	1.4	7.0	9.5	6.2	5.1	2.7	0.5	0.2	**33**
	EWR	0.1	0.1	0.1	0.1	0.9	4.2	5.7	3.7	3.1	1.6	0.4	0.1	**20**
	ESY	0.1	0.1	0.1	0.1	0.6	2.8	3.8	2.5	2.1	1.1	0.2	0.1	**13**
1995	Flow	0.2	0.2	0.1	0.1	0.6	4.4	18.1	11.8	9.7	3.5	3.0	1.1	**53**
	EWR	0.1	0.1	0.1	0.1	0.4	2.6	10.9	7.1	5.8	2.1	1.8	0.7	**32**
	ESY	0.1	0.1	0.1	0.1	0.2	1.7	7.2	4.7	3.9	1.4	1.2	0.4	**21**
1996	Flow	0.3	0.2	0.2	0.2	0.7	5.1	23.2	23.2	22.3	12.9	3.6	3.5	**95**
	EWR	0.2	0.1	0.1	0.1	0.4	3.1	14.4	14.1	13.4	7.8	2.2	2.1	**58**
	ESY	0.1	0.1	0.1	0.1	0.3	2.1	8.8	9.1	8.9	5.2	1.4	1.4	**37**
1997	Flow	0.7	0.5	0.6	0.8	2.6	10.3	10.4	13.6	10.7	3.5	1.9	0.8	**56**
	EWR	0.5	0.3	0.4	0.5	1.6	6.2	6.2	8.2	6.4	2.1	1.1	0.5	**34**
	ESY	0.2	0.2	0.2	0.3	1.0	4.1	4.2	5.4	4.3	1.4	0.7	0.3	**22**
1998	Flow	0.2	0.3	0.9	1.0	2.1	4.7	5.7	10.3	20.4	7.2	1.6	0.9	**55**
	EWR	0.1	0.2	0.6	0.7	1.3	2.8	3.4	6.2	12.6	4.3	1.0	0.6	**34**
	ESY	0.1	0.1	0.3	0.4	0.9	1.9	2.3	4.1	7.8	2.9	0.7	0.3	**22**
1999	Flow	0.4	0.3	0.4	0.6	1.5	9.4	21.2	17.1	20.9	14.9	2.6	1.2	**90**
	EWR	0.3	0.2	0.2	0.4	0.9	5.6	12.7	10.3	12.9	8.9	1.6	0.7	**55**
	ESY	0.1	0.1	0.1	0.2	0.6	3.7	8.5	6.8	8.0	5.9	1.1	0.4	**36**
2000	Flow	0.9	0.6	0.6	1.2	2.3	3.6	17.3	13.0	11.8	3.1	1.6	0.7	**57**
	EWR	0.6	0.4	0.4	0.8	1.4	2.2	10.4	7.8	7.1	1.9	1.0	0.5	**34**
	ESY	0.3	0.2	0.2	0.4	0.9	1.5	6.9	5.2	4.7	1.2	0.6	0.2	**22**
2001	Flow	0.3	0.2	0.2	0.4	1.3	2.8	1.8	4.1	4.9	3.8	1.0	1.4	**22**
	EWR	0.2	0.1	0.1	0.2	0.8	1.7	1.1	2.5	3.0	2.3	0.7	0.9	**13**
	ESY	0.1	0.1	0.1	0.1	0.5	1.1	0.7	1.6	2.0	1.5	0.4	0.5	**9**
2002	Flow	0.3	0.1	0.2	0.3	0.6	2.4	6.9	11.7	10.9	5.6	2.5	0.3	**42**
	EWR	0.2	0.1	0.1	0.2	0.4	1.4	4.1	7.0	6.6	3.4	1.5	0.2	**25**
	ESY	0.1	0.1	0.1	0.1	0.2	0.9	2.8	4.7	4.4	2.2	1.0	0.1	**17**
2003	Flow	0.1	0.1	0.1	0.3	0.8	2.8	10.8	14.3	14.9	5.9	2.7	0.8	**54**
	EWR	0.1	0.1	0.1	0.2	0.5	1.7	6.5	8.6	8.9	3.5	1.6	0.5	**32**
	ESY	0.1	0.1	0.1	0.1	0.3	1.1	4.3	5.7	5.9	2.3	1.1	0.2	**21**

Shortened forms

DEC	Department of Environment and Conservation
EWR	ecological water requirement
ESY	ecologically sustainable yield
IUCN	International Union for the Conservation of Nature
TDS	total dissolved solids
WRM	Wetland Research and Management

Glossary

Aestivate	Become inactive during drought, including slowing down bodily functions.
Diapause	A period of suspended development.
Inter-annual	Between years.
Thalweg	The deepest continuous line along the river channel. Represents the flow path during very low flows.
Endemism	The ecological state of being unique to a place. Describes species that are native to a particular geographic area or continent.
Univoltine	Species in which one generation reaches maturity each year.

Photography taken by Simon Brett

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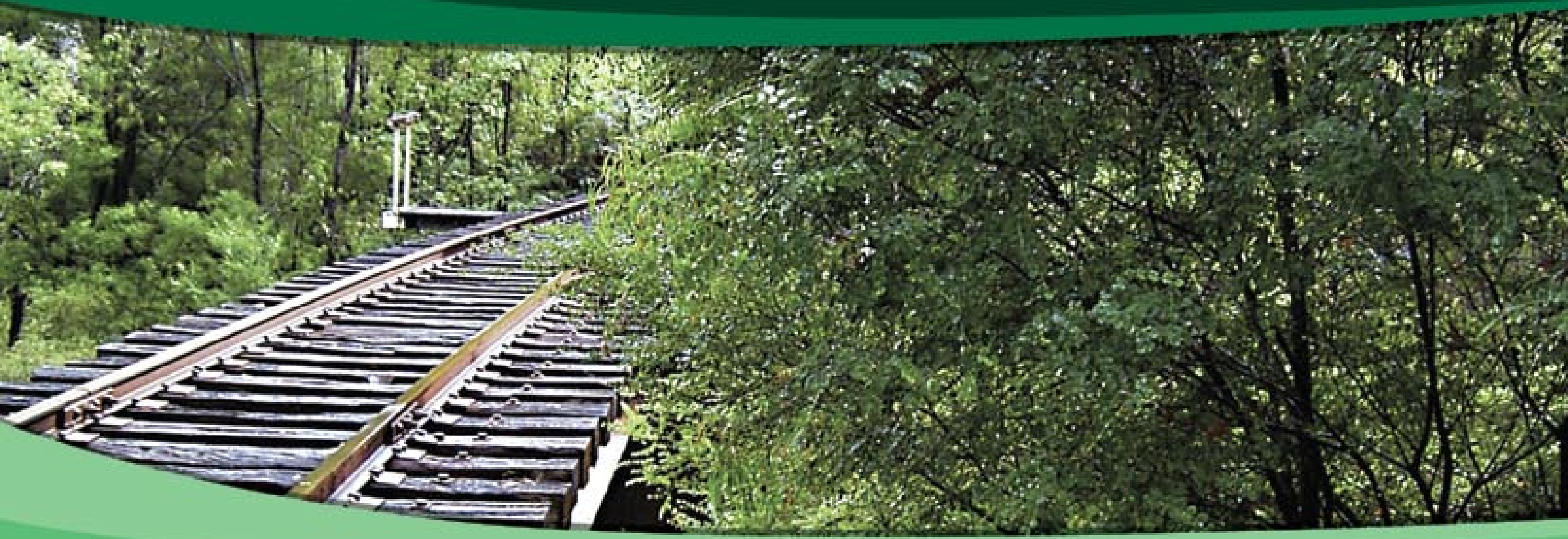

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