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

Ecological water requirements of the Brunswick River

Looking after all our water needs

Environmental water report series
Report no. 7
June 2009

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Brunswick River

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Preface

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

The study program was funded by the Commonwealth and the Western Australian State Government as part of the National Action Plan for Salinity and Water Quality (NAP). The works program was put together by the Department of Water and the South West Catchments Council, which administers the NAP 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 2005 when funds were approved 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 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; this is 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 Brunswick River study uses PADFLOW and RESYM to determine the EWR and sustainable yield for two representative reaches of the river.

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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 two representative reaches of the Brunswick River which feeds into the Collie River in south-west Western Australia. The EWR for Brunswick River 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.

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 Brunswick River. 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 the Brunswick River from 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 for the two reaches, designed to achieve 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. Overall, the modelled annual EWR is approximately 68 per cent of the observed yearly flow for Reach 1 and 67 per cent for Reach 2. The modelled EWR also retains much of the variability present in the measured flow.

Chapter one
Introduction

This report presents the results of a study designed to determine the ecological water requirements (EWR) of the middle and lower reaches of the Brunswick River in the south-west of Western Australia (Figure 1).

The aim of the study was to identify the volume of water that could be abstracted from the river system while maintaining the current ecological values of the aquatic and near-channel (riparian) environment at a low level of risk. A more detailed description of the ecological water requirement is provided in Section 3.

The results of EWR studies allow the Department of Water to identify the ecological sustainable yield of the water resource, and place an appropriate water allocation limit, which takes into consideration the economic, social, cultural and ecological values of the system. The Department of Water is Western Australia's primary water resource management agency. This EWR study was undertaken with the aim of supporting water resource planning in the Collie River management area.

The Brunswick River EWR study is part of the South-West Environmental Water Provisions Project, which is being delivered by the department in partnership with the South-West Catchments Council. During this project, the EWRs of seven river systems in the south-west of WA will be determined. The seven waterways and their catchments, which include the Brunswick River, Capel River, Wilyabrup Brook, Cowaramup Brook, Margaret River, Chapman Brook and Lefroy Brook, were identified as priorities for research due to the high demand for water for irrigated agriculture, mining and water supply, and declining rainfall in south-west Western Australia.

This project was undertaken by the environmental water planning section of the Department of Water for the South-West Catchment Council with Wetland Research and Management acting as a principal sub-contractor. This report is based on the work reported in WRM 2008a.

Two representative reaches of the lower and middle Brunswick River were selected as study sites for this report. Reach 1 was situated on the lower reaches of the river, on gently undulating, sandplain terrain. Reach 2 was located in the middle sections of the catchment, near the transition zone between the Swan coastal plain and the Darling Scarp. More detailed descriptions of the two reaches are provided in Sections 2.3 and 4.2.

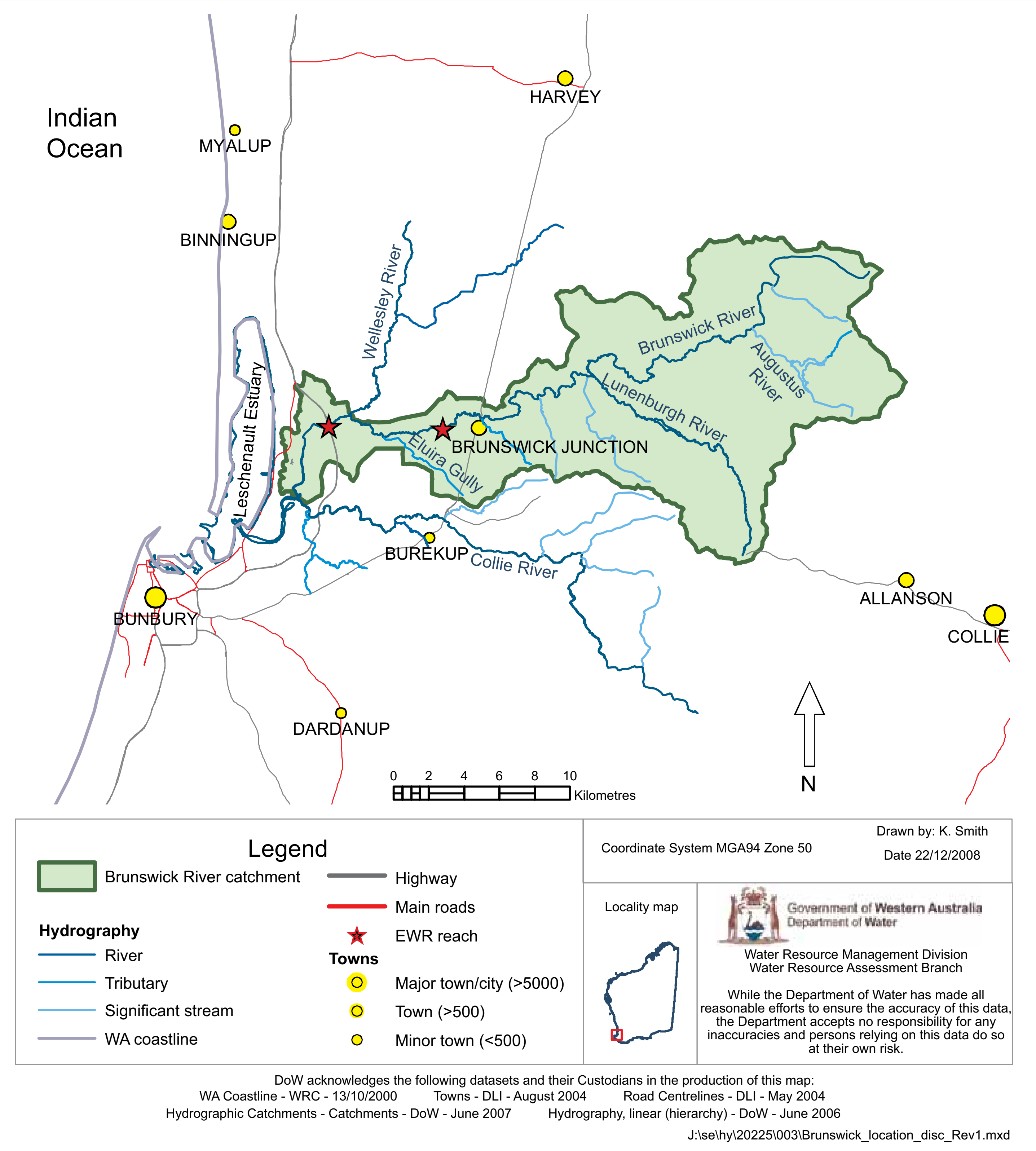
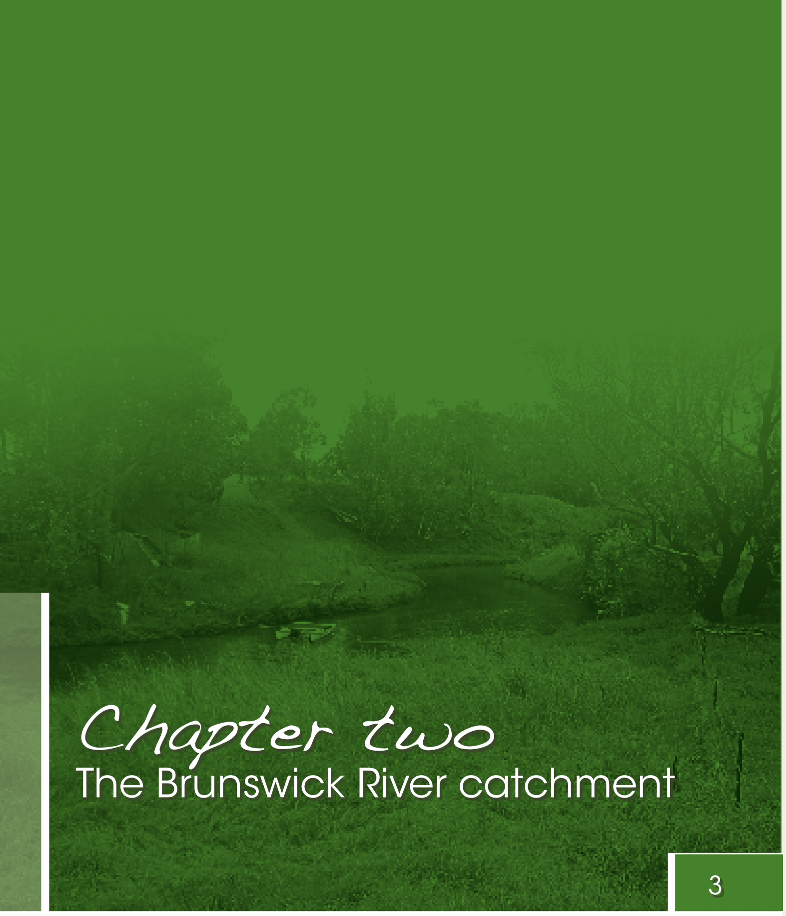


Figure 1
Location of the Brunswick River catchment and the EWR study reaches



Chapter two

The Brunswick River catchment

2.1 Location

The Brunswick River is located in the south-west of Western Australia (WA), approximately 140 km south of Perth and 30 km north-east of Bunbury. The river originates in jarrah *(Eucalyptus marginata)* forest on the Darling Scarp, east of the township of Brunswick Junction. It joins the lower Collie River at Point Latour, approximately 10 km from the Leschenault Estuary (McLaughlin and Jeevaraj 1994). The Brunswick River has several significant tributaries including the Ernest River, Augustus River, Lunenburgh River, Wellesley River and Eluira Gully (Figure 1).

The Brunswick River catchment has an area of 286 km^2 and includes the town of Brunswick Junction (Figure 1). The lower part of the Brunswick River catchment, which encompasses approximately one-third of the catchment's total area, is situated on the Swan coastal plain. The landscape of the coastal plain is gently undulating, in comparison to the more steeply incised valleys present along the Darling Scarp. The elevation of the catchment ranges from around 5 m AHD on the coastal plain in the west of the catchment, to 300 m AHD in the east along the Darling Scarp.

Approximately one-quarter of the upper Brunswick River catchment has been cleared of native vegetation (McLaughlin and Jeevaraj 1994). In the middle and lower parts of the catchment downstream of Brunswick Junction and on the Swan coastal plain, approximately three-quarters of the catchment and riparian zones have been cleared of native vegetation (Figure 2). Prior to European settlement, the riparian zone of the Brunswick River would have been relatively wide and densely vegetated, set within a floodplain containing both seasonally and permanently inundated swamps and marshes.

The removal of native vegetation has increased both the volume of surface runoff and the frequency of flows with sufficiently high energy to scour and erode the river channel. On the Swan coastal plain, the Brunswick River now flows within an incised channel, which contains mobile sandy gravel beds, as well as eroded and slumping banks. Unconsolidated sand moving downstream results in very turbid conditions during spells of high-energy flow (Rose 2004).
The lower section of the Brunswick River has also undergone substantial channel engineering, which has altered the course of the river.

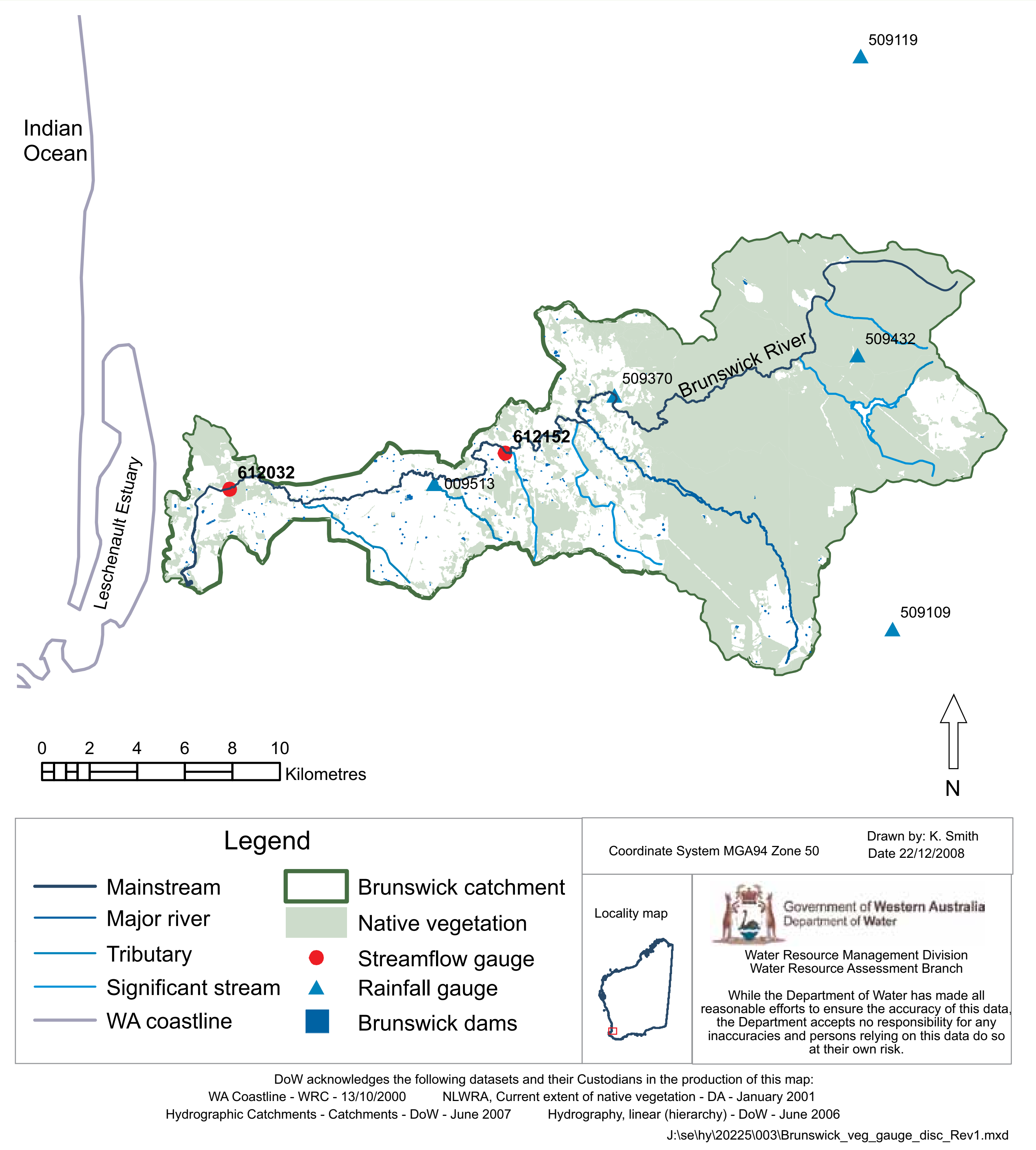


Figure 2

Map showing area of cleared and uncleared land in the Brunswick River catchment. The location of farm dams is also shown.

2.2 Climate

The Brunswick region is temperate with warm, dry summers and cool, wet winters. Maximum daytime temperatures can range from 17°C in winter to over 30°C for long periods in summer.

Average annual rainfall within the Brunswick catchment ranges between 900 and 1200 mm. Rainfall is slightly higher in the eastern portion of the catchment and decreases towards the coast (Crossley 2007). At Brunswick Junction, the average annual rainfall is 968 mm (calculated from 1909 to 2006) (Figure 4). Rainfall is highly seasonal, with approximately 80 per cent of annual rainfall occurring between May and September (Figure 6). Winter rainfall is associated with cold fronts that originate over the Southern Ocean and move across the south-west land division. Rain depressions from the decaying remnants of tropical cyclones may move in from the north-west in summer and bring occasional widespread heavy rain to the region.

Since 1975, there has been a decline in annual rainfall in the south-west region of WA, particularly in winter months. Before 1975, the long-term average annual rainfall was 1032 mm at Brunswick Junction, compared with an annual average of 867 mm between 1975 and 2006.

2.3 Hydrology

The Brunswick River generally flows year round in most years although it may cease to flow in the upper parts of the catchment during particularly long dry spells. Flow downstream of the confluence with the Augustus River is augmented slightly by summer releases from the Worsley Dam. The dam releases represent a small proportion of the annual flow and the Brunswick River is not subject to major regulating effects. For the most part, flow in the middle and lower part of the catchment is permanent, with summer flows maintained by groundwater discharges (Annan 2006).

Around 90 per cent of the total annual flow volume occurs between June and October (Figure 4). Peak flows tend to occur in August, when there is a mean total monthly flow of 15 GL (Figure 4). The lag between the peak rainfall month (June), and the peak flow month (August), suggests a large soil storage capacity in the catchment. Contributions from the local aquifer also tend to peak later in the season (Crossley 2007).

In Reach 2, which is located in the middle section of the catchment, annual flow has averaged 62 GL/ year from 1975 to 2003, ranging between 19 and 129 GL per year. Average annual flows at Reach 1,

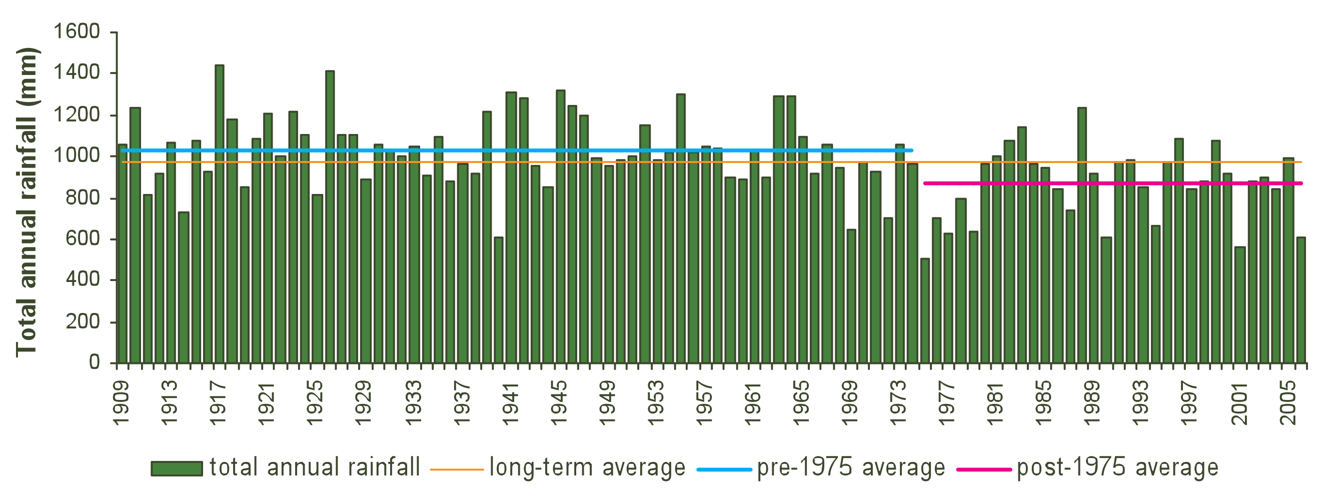


Figure 3

Total annual rainfall and long-term average for Brunswick Junction (009513) located in the lower portion of the catchment, were 111 GL/year over the same period, varying between 30 and 240 GL per year. The difference in total annual flow volumes between the two reaches indicates a significant gain in flow volume over an eight kilometre stretch of river, probably due to the confluence of the Brunswick and Wellesley Rivers upstream of Reach 1.

A relatively large proportion of rainfall that occurs in the catchment produces surface runoff. The runoff coefficient (which denotes the proportion of rainfall that becomes surface runoff, and which can vary between 0 and 1) for the period between 1975 and 2003 averaged around 0.3 (i.e. 30% of total rainfall became runoff and flowed into rivers). 'Bankfull' flows generally occur every two to three years, and correspond to flows between approximately 23 and 30 m^3/sec (Crossley 2007).

2.4 Hydrogeology

Seepage of groundwater can be important in maintaining winter baseflow, and for maintaining pools and flow during extended dry periods. Many aquatic plant and animal species rely on contributions from groundwater to maintain summer habitat.

The Brunswick River is strongly connected with its underlying superficial aquifers along most of its length (Annan 2006). The unconfined superficial aquifer occurs between 20 and 40 metres below the surface. It is comprised of weathered clay and sand in the east, and sand and limestone in the west. The aquifers are recharged by rainfall. Generally, water in the superficial aquifers flows west from the Darling Scarp towards the Swan coastal plain and contributes significantly to summer flows, and to water levels in swamps and wetlands (Annan 2006). The groundwater discharges are fresh to brackish west of the Wellesley River (Department of Water 2005).

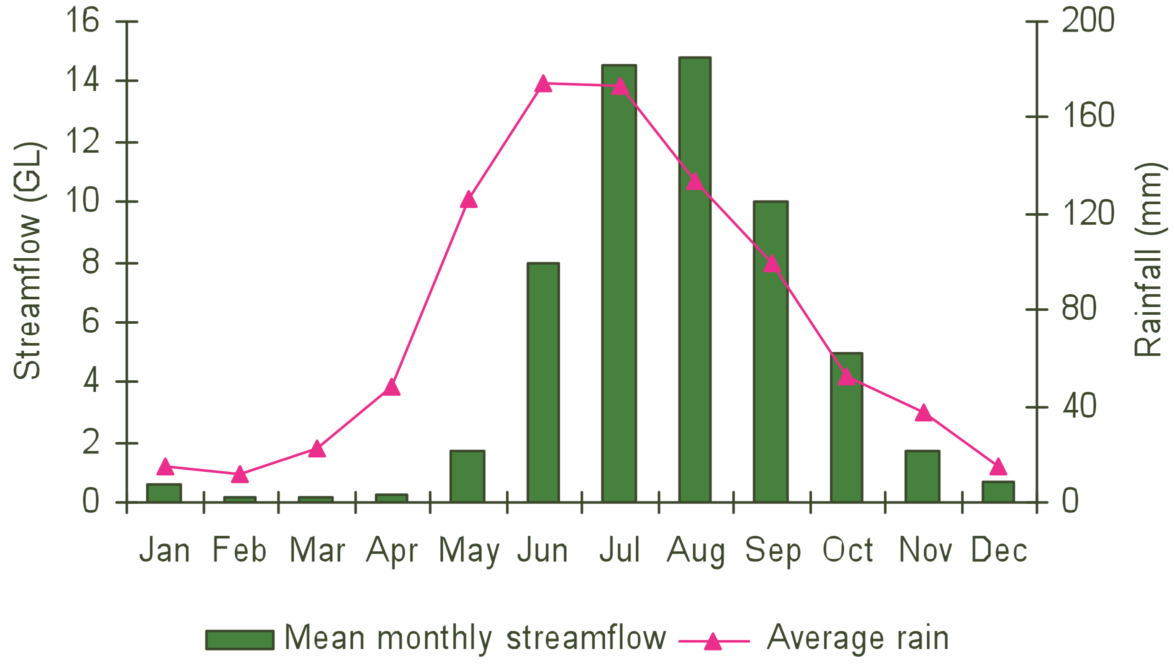


Figure 4

Mean monthly flow and rainfall at Olive Hill (612152)

2.5 Water resource development

Land use in the upper catchment is dominated by state forest, and by an alumina refinery run by Worsley Alumina. Historically used for dairy farming, the lower part of the catchment is now dominated by horticulture and grazing. A recent survey found eight licensed surface water users and ten unlicensed groundwater users extracting water from the Brunswick River system (Department of Water 2006).

The majority of land owners in the lower catchment receive water for stock and irrigation purposes from the Wellington Reservoir. Harvey Water is a private irrigators' cooperative (formerly known as South West Irrigation), and controls the distribution of irrigation water during the irrigation season from October to April. During the irrigation season, excess surface water runs off the properties and is discharged into the Brunswick River.

Recent mapping identified a total of 231 dams (Sinclair Knight Merz 2006) in the largely-cleared central and lower sections of the catchment (Figure 2). The farm dams have a total storage capacity of 539 ML, with individual dam storage capacities ranging between less than 0.1 ML to approximately 50 ML. There is approximately two ML of water stored in farm dams for every square kilometre of catchment (Boniecka 2006). The demand for irrigated agriculture is approximately 4.2 GL per year, of which four GL comes from scheme water captured from outside the Brunswick catchment, and 98 ML is supplied by farm dams (Table 1).

There are two storage dams within the Brunswick River catchment. The smaller of the two is the 20 ML capacity Beela Dam, which was constructed on the river in 1947 to supply the Brunswick Junction regional water supply scheme, which served Brunswick Junction and the nearby towns of Burekup and Roelands. The towns are now connected to the integrated water supply scheme and Beela Dam is no longer used for water supply.

The larger of the two dams is the Worsley Alumina refinery dam on the Augustus River, with a total storage capacity of 5.2 GL. Worsley Alumina is licensed to abstract 2.1 GL per year from the reservoir for its bauxite mining operations and is required by licence condition to ensure an output summer flow of approximately 35 ML/day from the reservoir to maintain downstream summer flows.

Modelling has shown that farm dams in the Brunswick catchment are not affecting the flow to any great extent at any time of the year (Sinclair Knight Merz 2007). The dams have a small aggregate storage capacity compared to annual runoff, and have reduced annual flow during late summer by around 10 per cent. The modelling showed that peak flows in winter are actually slightly higher with dams, possibly due to the increased runoff from the surface of the dams.

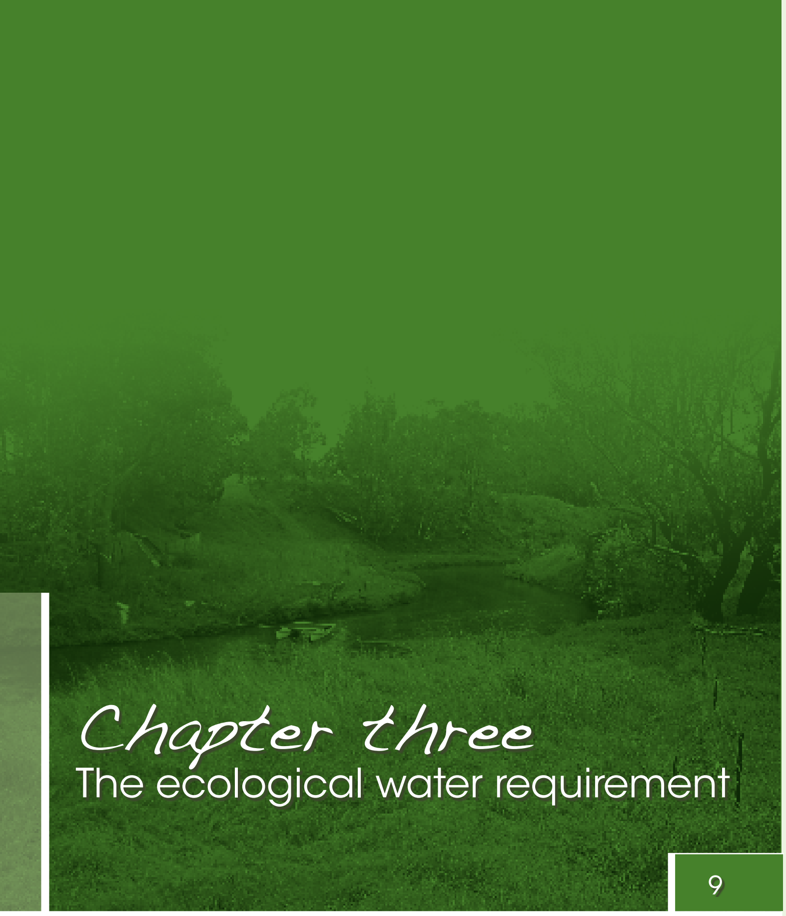
Table 1

Water use in the Brunswick catchment (ML/year)

Source: Department of Water (2006).

Use category	Self supply dams			Direct pumping	Scheme irrigation	Total
	On-stream	Off-steam				
		Diverted	Runoff			
Industrial	2,100					2,100
Recreation					10	10
Dairy		5.8	4.3		23	33
Vegetable				51		51
Orchard	6.0			1.9		7.9
Pasture	76			20	4,001	4,098
Vines	3.9					3.9
Domestic	8.6	9.4	7.6	9.2	2.2	37
Stock	12	6.8	33	37	50	138
Total	2,213	22	45	119	4,085	6,484

A view of the pool downstream of cross-section 4 in Reach 2



Chapter three

The ecological water requirement

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

The assessment of the EWR of a water body is closely related to the natural flows paradigm. According to the natural flows paradigm, the natural regime of flow is responsible for the evolution of the observed ecological state of a river (Poff 1997). The flow regime influences which species are present in rivers, and governs the processes that support a healthy, resilient aquatic ecosystem. The natural flows paradigm suggests that an 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 long-term trends in flow volume. Further information about how components of the flow regime influence ecological processes is given in Section 3.2.

3.1 Objective of this study

EWR studies can be carried out with various aims, such as:

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

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

The Brunswick River catchment has a long history of water resource development. Further, large areas of the catchment in the study reaches have been cleared of native vegetation. For these reasons, the aim of the Brunswick River EWR study is to determine an EWR that will maintain the ecological values of the Brunswick River in their present, post-development condition.

3.2 Components of the flow regime and their ecological functions

A river channel is a highly dynamic system, with a flow regime that varies seasonally and annually (Figure 5). Different components of the flow have particular ecological functions. For example, high flows scour pools and influence the distribution of sand bars and debris dams, which controls the nature, variability and spatial distribution of habitat. As a result, high flows have a direct influence on the structure of aquatic communities and food webs in rivers of the south-west of Western Australia (Pen 1999). Early season flows relieve summer stress (high temperatures and low oxygen), provide cues for breeding migrations of native fish, and provide habitat for microcrustaceans, aquatic insects, waterbirds, and larval stages of some terrestrial insects. Some of the key ecologically relevant elements of the flow regime in rivers of the south-west of Western Australia are detailed in the sections below, including periods of no flow, summer low flows, and high winter flows.

3.2.1 Periods of no flow

Many rivers in the south-west of Western Australia cease to flow in the dry period between December and April, especially during periods of below average rainfall, when regional groundwater tables fall below the base level of river channels. For example, the middle and upper reaches of the Brunswick River regularly cease to flow during summer during sequences of low rainfall years. However, in periods of above average rainfall, summer flows may be permanent.

As seasonal drying is part of the natural flow regime, endemic and other native fauna have adapted to periods when rivers recede to a series of disconnected pools. For example, many native fish can tolerate the high water temperatures and low oxygen levels that characterise pools in late summer. Exotic species, such as mosquito fish *(Gambusia holbrooki)* are less tolerant of such conditions. In order to survive, aquatic fauna move from ephemeral tributaries and upstream reaches to river pools or perennially-flowing lower reaches of the river. Permanent pools form critical habitat in ephemeral reaches of rivers (Pen 1999).

To maintain the adaptive resilience of native species to inter-annual variations in rainfall and long-term climate change, and to control populations of non-native species, the EWR flow regime must include periods of no flow in stretches of river that have historically experienced ephemeral flow conditions over summer.

3.2.2 Summer low flows

Summer low flows, including trickle flows, can maintain water levels and depth in the dry summer period and control water temperature. Summer low flows also maintain the circulation and water movement in pools, which prevents stratification and the depletion of oxygen by respiration processes in the bed of the stream, under the thermocline. In addition, summer low flows maintain habitat in shallow areas of the river, such as riffles and sandy runs, which are important habitat for aquatic invertebrates. The turbulent flow in these areas also oxygenates flow and improves the water quality of summer refuges such as pools (Pen 1999). Finally, low flows provide a longitudinal connection between downstream and upstream reaches and pools, and provide for continued downstream carbon movement.

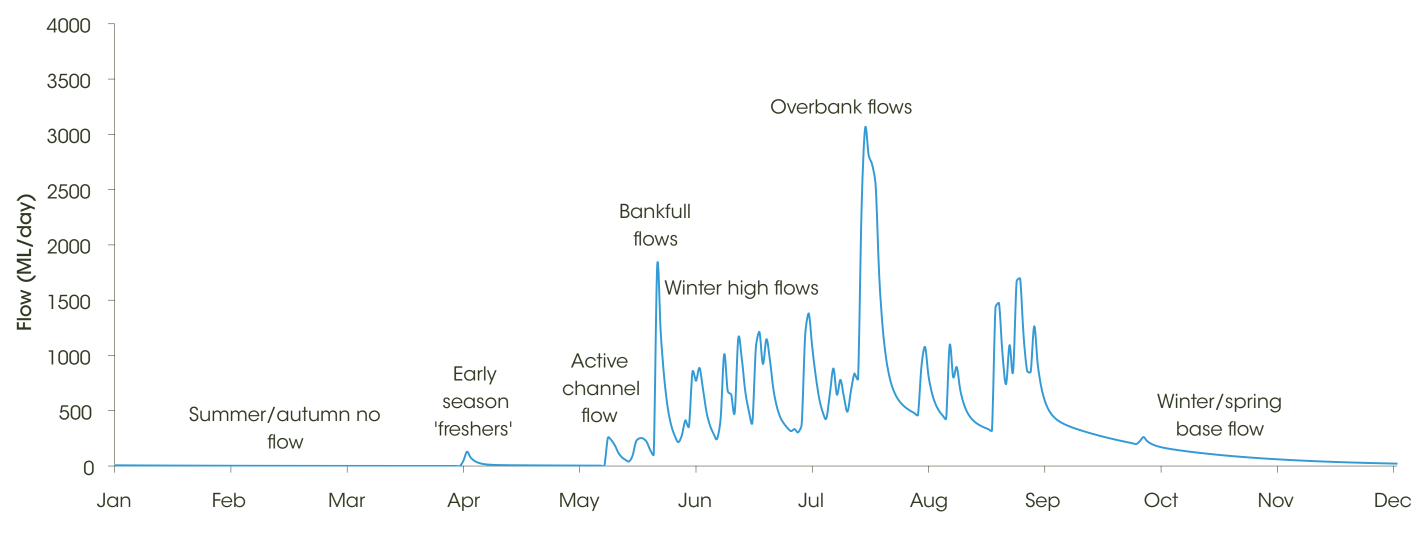


Figure 5

Representative hydrograph with different flow components labelled

3.2.3 Autumn and winter low flows

Autumn and winter low flows are those that occur in the early part of the flow season or during winter after prolonged periods of low rainfall and runoff. Flow during winter is variable between years, but is generally very reliable in the south-west of Western Australia and aquatic fauna have adapted to the winter rainfall and river flow, starting around May.

As pools dry out over summer, water quality deteriorates significantly as water temperature rise and oxygen levels decline. As pools shrink, the density of species such as fish increases, which leads to increased competition for space and resources and predation by birds and other predators (Pen 1999). The low flows that occur in autumn with the onset of winter rains are particularly important for aquatic fauna, as they relieve late summer stress in pool habitats.

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

3.2.4 Active channel flows

The morphology of a river changes in response to flow events that scour the channel, mobilise and deposit sediment and organic debris. In order to support a healthy and resilient ecosystem, it is important to maintain channel forming flows and the capacity for change.

Identifying and incorporating flows that maintain the low-flow channel is an important part of determining ecological water requirements. A well defined low flow channel is characteristic of many rivers in the south-west of Western Australia and can be seen as a `secondary' channel within the wider river channel. The low flow channel contains the pools that are important as deep water habitat, as summer refuges for aquatic fauna and for autochthonous (i.e. localised) algal production. The low flow channel contains the bulk of functional habitats in rivers, such as riffles and aquatic vegetation (Pen 1999). The flows that maintain the low flow channel tend also to inundate trailing vegetation, and provide cover and spawning habitat for fauna such as native fish.

The low flow channel is formed and maintained by moderately high winter flows that have sufficient energy and duration to scour banks and mobilise light sediments. The low-flow channel is also known as the active channel; because the flows that maintain an open channel occur in most years and because of the flows' frequency and energy, the low flow channel is actively eroding (Pen 1999). The depth of an active channel flow is not always obvious but it may be visibly defined in places by a line of scoured bare earth below which bankside vegetation is markedly less dense or completely absent.

It is generally accepted that flow events that reach the top of the active channel occur two or three times a year for south-west river systems (Water and Rivers Commission 2001). The duration of active channel flows tends to be longer than flood flows as it is maintained by groundwater discharges and seepage from the saturated soil profile.

3.2.5 Winter high flows

Winter high flows include the range of flows that are responsible for creating and maintaining the morphology of the river, including the main channel to the top of bank and the shape and extent of the floodplain. Winter high flows inundate the middle and higher sections of the river channel and are responsible for the creation of channel features such as low and high benches, or they may exceed `bankfull' and inundate habitat elements on the river floodplain.

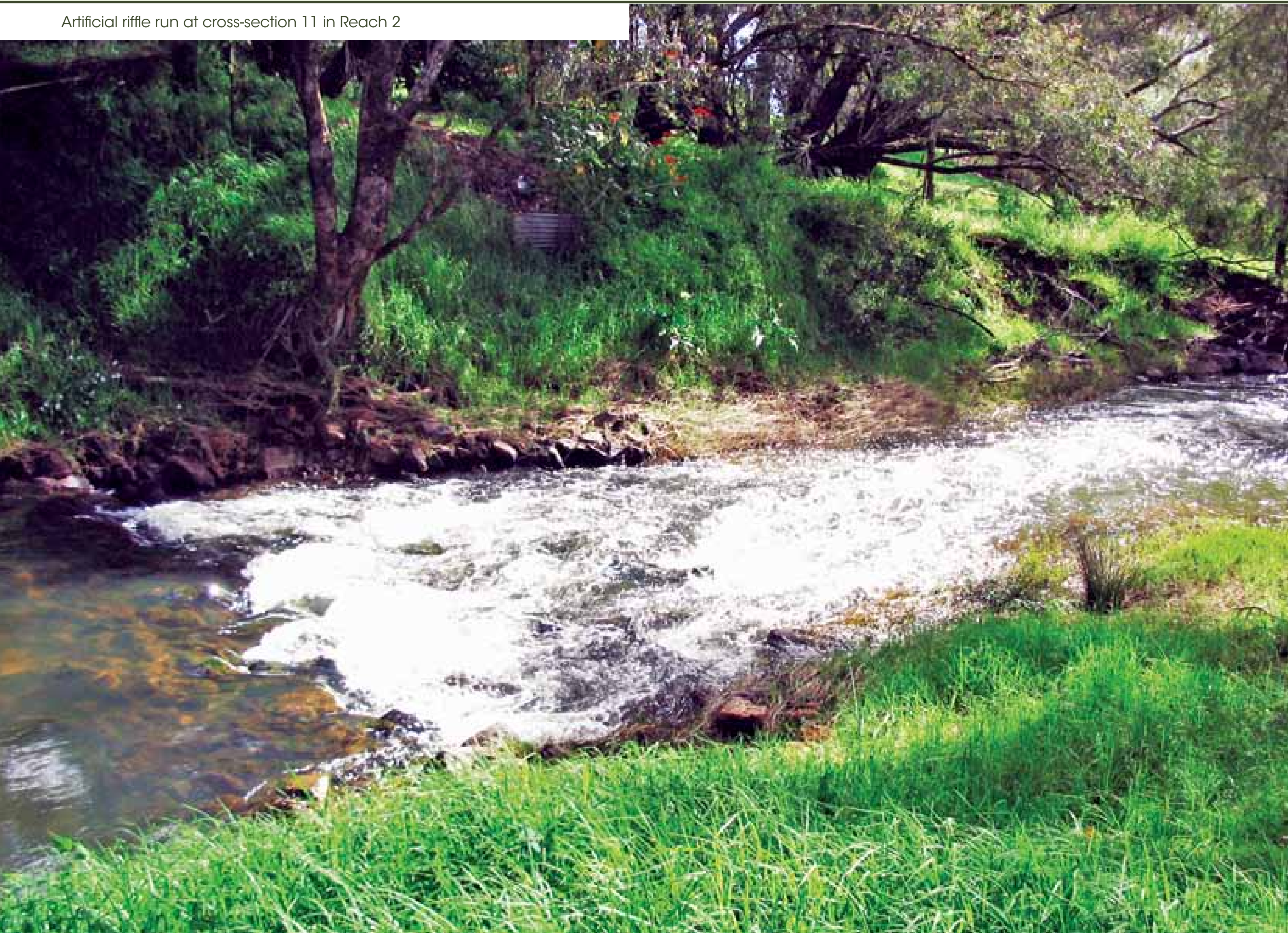
The extent and depth of a river channel is determined by flood flows that equal or exceed bankfull height (i.e. the highest vertical extent of the main river channel). The magnitude of a bankfull flow increases with distance downstream within a catchment, as more water is discharged into the main channel from tributaries. Flood flows (i.e. flows that reach or exceed bankfull height) in the south-west of Western Australia occur in mid-winter from runoff caused by heavy rain on saturated soils, and tend to occur at a frequency of about one flood event every one, two or three years. Flood flows are generally of short duration.

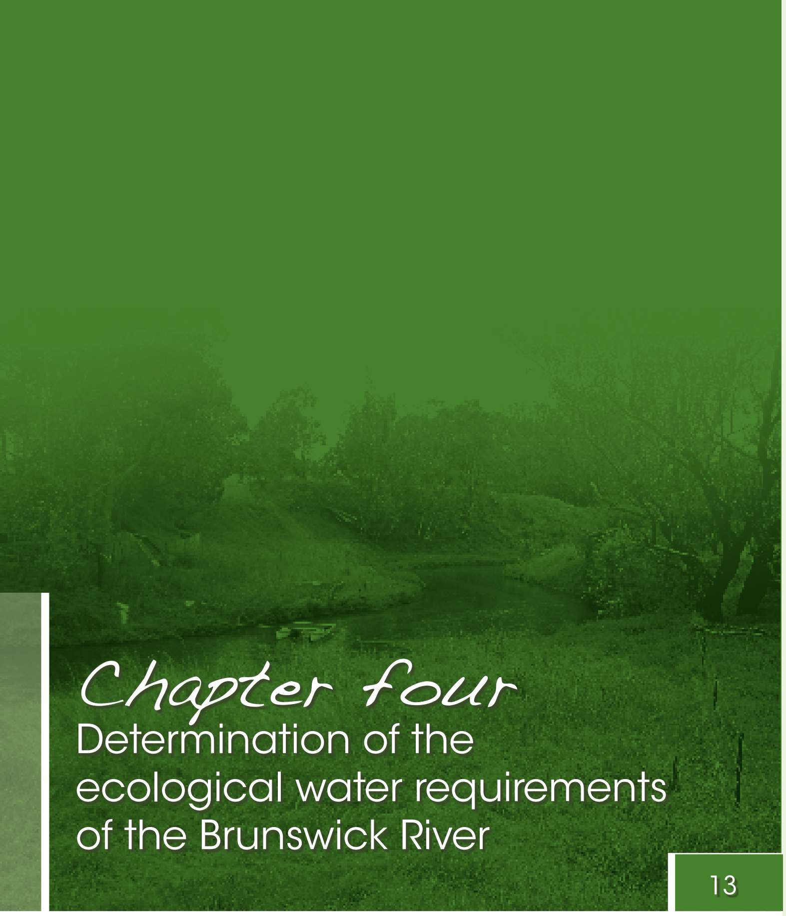
Winter high flows fulfil a variety of ecological functions. High energy flows scour the channel and prevent encroachment of riparian vegetation (vegetation growing along the banks of watercourses) into the river channel. They also scour deep pools of sediment and organic matter, which maintains pool depth and provides good quality refuge habitat for fish and other fauna as flow declines in summer (Pen 1999). The scouring of organic matter from pools also decreases biological oxygen demand during the following summer, and therefore helps to maintain oxygen levels within the tolerance range of native species.

Bankfull flows that inundate the floodplain also inundate and recharge shallow floodplain wetlands that are important feeding and nursery areas for frogs and native fish. Riparian and floodplain vegetation require occasional inundation to disperse seed, assist seed-set, and soak soil profiles to promote successful germination.

As a rule, bankfull and flood flows increase the width of the channel more than the depth. However, removing riparian vegetation often has the effect of increasing the depth of scouring during flood events, so that over time, a river with sparse riparian vegetation becomes increasingly incised. In many catchments, the clearing of vegetation for urban and rural development has made river systems sensitive to flooding, to the extent that 10-year or similar sized floods may cause catastrophic erosion (Lovett & Price 1999). Management practices such as de-snagging and creation of artificial channels increase flow velocity and lead to increased bank and bed erosion, resulting in increased severity of flooding downstream (Lovett & Price 1999).

Artificial riffle run at cross-section 11 in Reach 2





Chapter four

Determination of the ecological water requirements of the Brunswick River

4.1 Overall approach

The ecological water requirements (EWR) of the Brunswick River were determined using the proportional abstraction of daily flows method (PADFLOW). PADFLOW was developed by the department to better define the EWR of rivers with highly variable flow patterns. PADFLOW evolved out of experience with using the flow events method (FEM) to determine EWRs for rivers in the south-west of Western Australia (see, for example, WRM 2005a and 2005b).

The PADFLOW method develops a modelled EWR flow regime by progressively removing a proportion of daily flow from an existing flow record until the duration and frequency of flow spells of ecologically important flows is consistent with an EWR at a low level of risk to river ecology. PADFLOW and its supporting software were designed to be used within a collaborative workshop environment, with decisions guided by an expert panel. In the case of the Brunswick River, the panel included people with expertise in water resource management, channel hydraulics, hydrology, and aquatic ecology (Appendix 1). The expert panel determines whether a modelled EWR flow represents a low level of risk to ecological values by considering the duration and frequency of spells of particular magnitudes in the modelled EWR flow compared with the observed flow record.

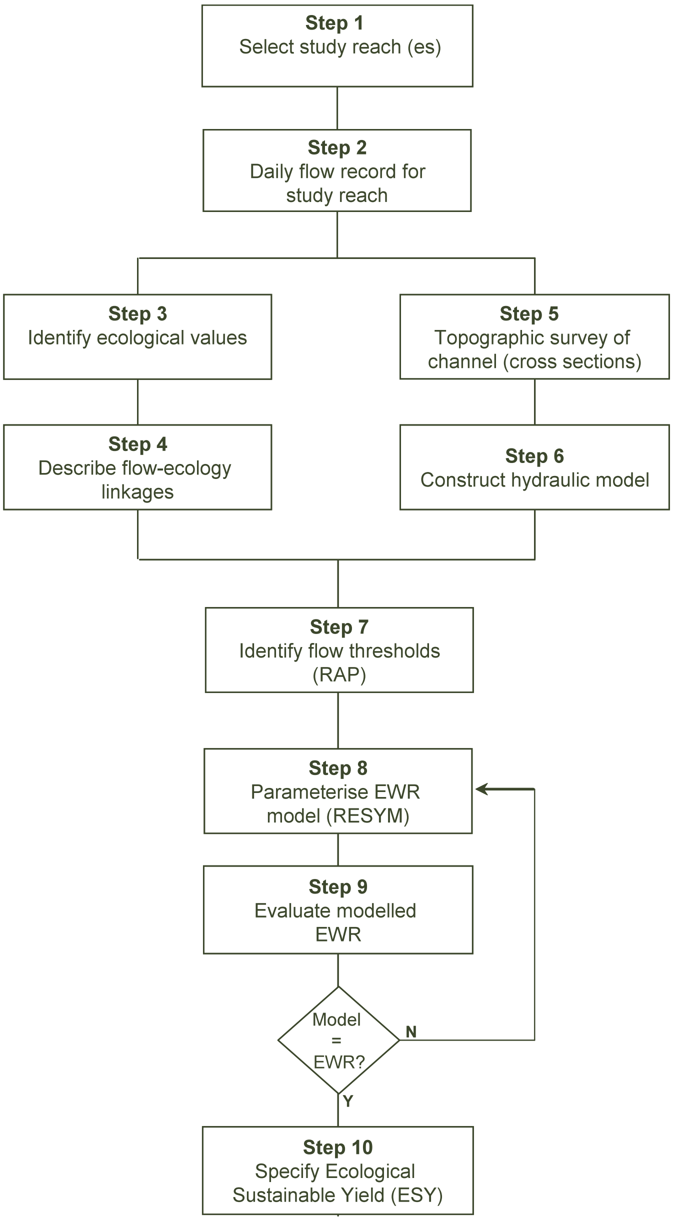


Figure 6

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

In this report, the term 'EWR flow' will be used to describe the modelled EWR flow regime developed as an estimate of the ecological water requirements of the Brunswick River. The term 'observed flow' refers to the gauged, historical flow record from the two study reaches (Reach 1 and Reach 2).

The flow chart in Figure 6 shows the key steps in determining the EWR flow of rivers using the PADFLOW approach. Steps 1 through 8 are identical to those associated with the flow events method. Steps 9 to 10 are associated specifically with the PADFLOW approach.

4.2 Selection of representative river reaches

EWR studies are based on detailed surveys of representative reaches of the river in question. The results from the individual reaches are used to estimate water requirements for the river system as a whole. The Brunswick River EWR study used data collected from two reaches, which were selected as being representative of the lower section (Reach 1) and middle section (Reach 2) of the river (Figure 1 and Figure 7).

Reach 1 is characteristic of a lowland, sandplain river. The reach covered the length of river from the confluence of the Brunswick River with the Wellesley River to the Australind Bypass bridge (Figure 7). The reach was characterised by extensive erosion with mobilised sand beds, channel evulsion at high flows, and top of bank erosion. The channel along this reach was fairly degraded, with sparse mature eucalypts and paperbark trees, and an understorey of introduced pasture grasses.

Reach 2 was located approximately eight kilometres upstream of Reach 1 and downstream of the Clifton Road Bridge, near the township of Brunswick Junction (Figure 7). The reach was representative of the river catchments on the upper parts of the Swan coastal plain, near the transition zone with the Darling Scarp. Vegetation consists of an open overstorey of native trees such as paperbarks, river gums and peppermints, with an understorey of introduced pasture grasses. This reach is characterised by large sections where the river banks are undercut and slumping. Restoration work that has been carried out over this stretch of the Brunswick River has included tree planting, installation of fencing to eliminate stock access to the river, and construction of meanders and artificial riffles.

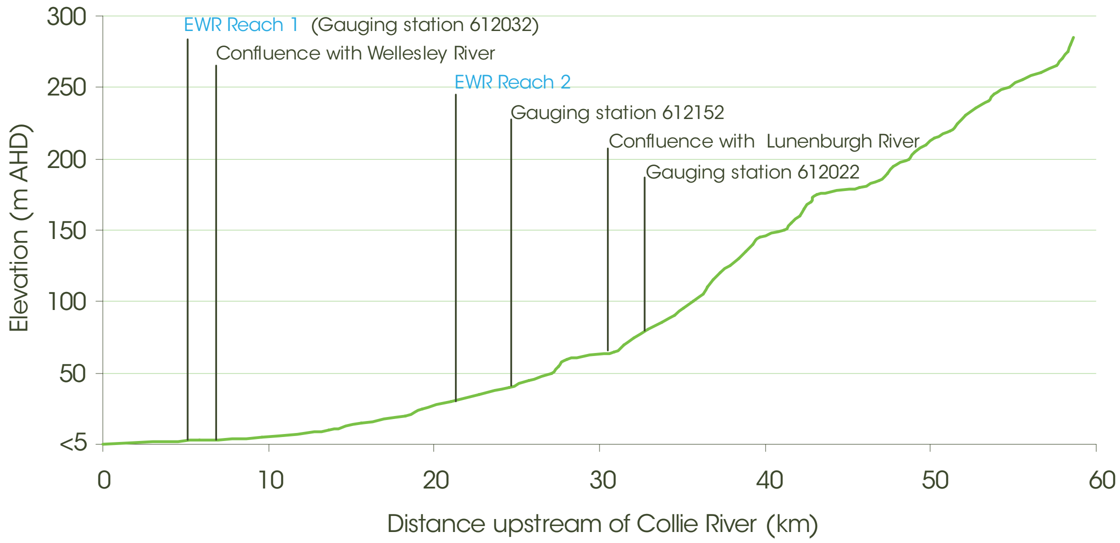


Figure 7

Elevation of the Brunswick River upstream from its confluence with the Collie River

4.3 Development of daily flow record

The PADFLOW method requires a detailed historical record of daily flow, stretching over many years. The downstream extent of Reach 1 coincides with the location of the Cross Farm gauging station (station number 612032) (Figure 2). Therefore, flow in the reach has been described using historical records from this station covering the period between January 1975 and December 2003.

Reach 2 was located approximately three kilometres downstream from the Olive Hill gauging station (612152) (Figure 2). The Olive Hill station has daily flow records from April 1961 to March 1983, which were used to construct the daily flow record for Reach 2. The Olive Hill gauging station has a catchment area of 225 km^2. Flow data from the Olive Hill gauging station was scaled to the smaller catchment upstream of Reach 2 using a catchment yield (ML/km^2) calculated from the Olive Hill gauging station. Gaps in the Olive Hill data series were filled using a linear correlation with recorded data from an upstream gauging station (Sandalwood – 612022), which provided daily data for the period January 1974 to December 2003 (Crossley 2007). For consistency with Reach 1, the daily flow record for Reach 2 was developed for the period January 1975 to December 2003.

4.4 Definition of the EWR objective

As described in Section 3.1, the objective for the Brunswick River EWR study was to develop a flow regime that would maintain the existing, modified ecological values and processes.

4.5 Ecological values and flow dependency

As the objective of this study is to define a flow regime for the Brunswick River that will maintain the existing ecological values, it follows that an important part of the study is to describe the existing condition of the river ecosystem, and define how the various components of the ecosystem depend on the flow regime.

The existing environmental attributes and ecological values of the Brunswick River were described in a literature review (WRM 2007) and during field sampling undertaken in autumn and late spring of 2007 (WRM 2008b). General information on the links between stream flow and geomorphological processes is provided in Sections 3.2.4 and 3.2.5. For detailed information pertaining to the life history characteristics of flora and fauna species, their degree of water dependence, and other general biological information refer to WRM 2007 and WRM 2008b. Summary information on the ecological values of the Brunswick River, and of the relationships between flow and ecological values and processes, is provided in the following sections.

4.5.1 Vegetation

The natural vegetation of the upper catchment is typically comprised of jarrah *(Eucalyptus marginata)* and marri *(Corymbia calophylla)* open woodland. Flooded gum *(E. rudis)* and swamp paperbark *(Melaleuca rhaphiophylla)* are common in the valley floors on the floodplain and in wet depressions along the river bank (Mattiske & Havel 1998) (Figure 8). The Darling Range ghost gum *(E. laeliae)* is also found on the Darling Scarp in the north. Low woodland comprised of rock sheoak *(Allocasuarina huegeliana)* and closed heath of species from the *Myrtaceae* and *Proteaceae* families occur on or near granite outcrops. Peppermint *(Agonis flexuosa)*, wandoo *(E. wandoo)* and blackbutt *(E. patens)* can also be found in lower elevations on the Darling Scarp. Around the study reaches, trees are found only in a narrow band comprised of a single row of isolated flooded gums and/or peppermints (Figure 8).

In the coastal areas of the Brunswick River catchment, vegetation comprises salt-marsh of bearded samphire *(Sarcocornia quinqueflora)*, shrubby glasswort *(Halosarcia indica)*, shorerush *(Juncus kraussii)*, saltwater sheoak *(Casuarina obesa)* and club rush *(Bolboschoenus caldwellii)*. Swamp paperbark and flooded gum are also present in this area (Mattiske & Havel 1998).

In the riparian zones of the lower Brunswick River, the native understorey has been almost completely replaced with introduced weed species and pasture (Figure 8). There are some areas containing remnant native understorey, comprising several sedge and rush species, including coastal saw sedge

Figure 8

Photos of the Brunswick River in Reaches 1 and 2 showing the condition of riparian vegetation

(Gahnia trifida), pale rush *(Juncus pallidus)*, twig rush *(Baumea juncea)* and common sword sedge *(Lepidosperma longitudinale)* or the coast sword sedge *(L. gladiatum)* and angle sword sedge *(L. tetraquetrum)*. The twig rush *(Baumea articulata)* and *B. riparia* can still be found in the more waterlogged areas of the river channel. Between the Clifton Road Bridge and Bunbury Bypass Bridge, the Brunswick River supports a narrow band of closed sedgeland comprising club rush *(Bolboschoenus caldwelli)*. Mat grass *(Hemarthria uncinata)* and small pennywort *(Centella cordifolia)* make up the native ground cover.

Relatively little is known of the magnitude and duration of flows that are important to maintain the health and vigour of the riparian vegetation of the Brunswick River. Environmental factors that influence plant vigour and are affected by river flow include: bank soil moisture content; the proximity of groundwater to the root zone; and the period and season of flooding that inundates the floodplain and riparian vegetation. Research has found that seed set, seedling establishment and recruitment for tree species such as flooded gum, swamp paperbark and modong *(Melaleuca preissiana)* are closely tied to flow events. For example, germination and survival of seedlings can be influenced by infrequent winter high flows, which pick up seeds and move them to open areas in full sunlight. Year-old tree seedlings often do not survive if they are inundated in their first winter after germination.

4.5.2 Aquatic invertebrates

A literature review found a number of studies on the aquatic invertebrates of the Brunswick River (WRM 2007). Papas et al. (1997) collected a total of 43 families of invertebrates in the upper parts of the catchment. They concluded that the structure and diversity of invertebrates in the upper sections of the river was representative of an undisturbed ecosystem. They found that the invertebrate community in the lower reaches was more typical of a river enriched with nutrients. Hale et al. (2000) also sampled invertebrates in the upstream reaches and tributaries of the Brunswick River and collected only 27 families of invertebrates.

WRM 2008b sampled macroinvertebrate populations in the Brunswick River in April and November of 2007 in Reaches 1 and 2 as part of this study. They collected 78 species of macroinvertebrate from 32 families (Appendix 2). Taxa collected included round worms (*Oligochaeta*), freshwater mussels (*Hydriidae*), freshwater limpets (*Ancylidae*), freshwater crayfish (*Decapoda*), water mites (*Unionicolidae* and *Oxidae*), waterboatman (*Hemiptera*), stoneflies (*Plecoptera*), mayflies (*Ephemeroptera*), dragonfly larvae (*Odonata*), midges, blackfly and cranefly (*Diptera*) and caddis fly larvae (*Trichoptera*). A list of macroinvertebrate taxa that have been collected from the Brunswick River is provided in Appendix 2.

There are five species of freshwater crayfish known to occur in the rivers of south-west Western Australia. Two of these, the smooth marron *(Cherax cainii)* and the gilgie *(C. quinquecarinatus)*, were found in the Brunswick River by Hale et al. (2000). The gilgie was the more abundant species (Hale et al. 2000). Morgan and Beatty (2006) also studied the gilgie and marron from the Brunswick and also found the gilgie to be more abundant and widespread than marron, which was collected upstream of the confluence with the Augustus River only (Morgan & Beatty 2006).

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

D: Photography by John J.S. Bunn

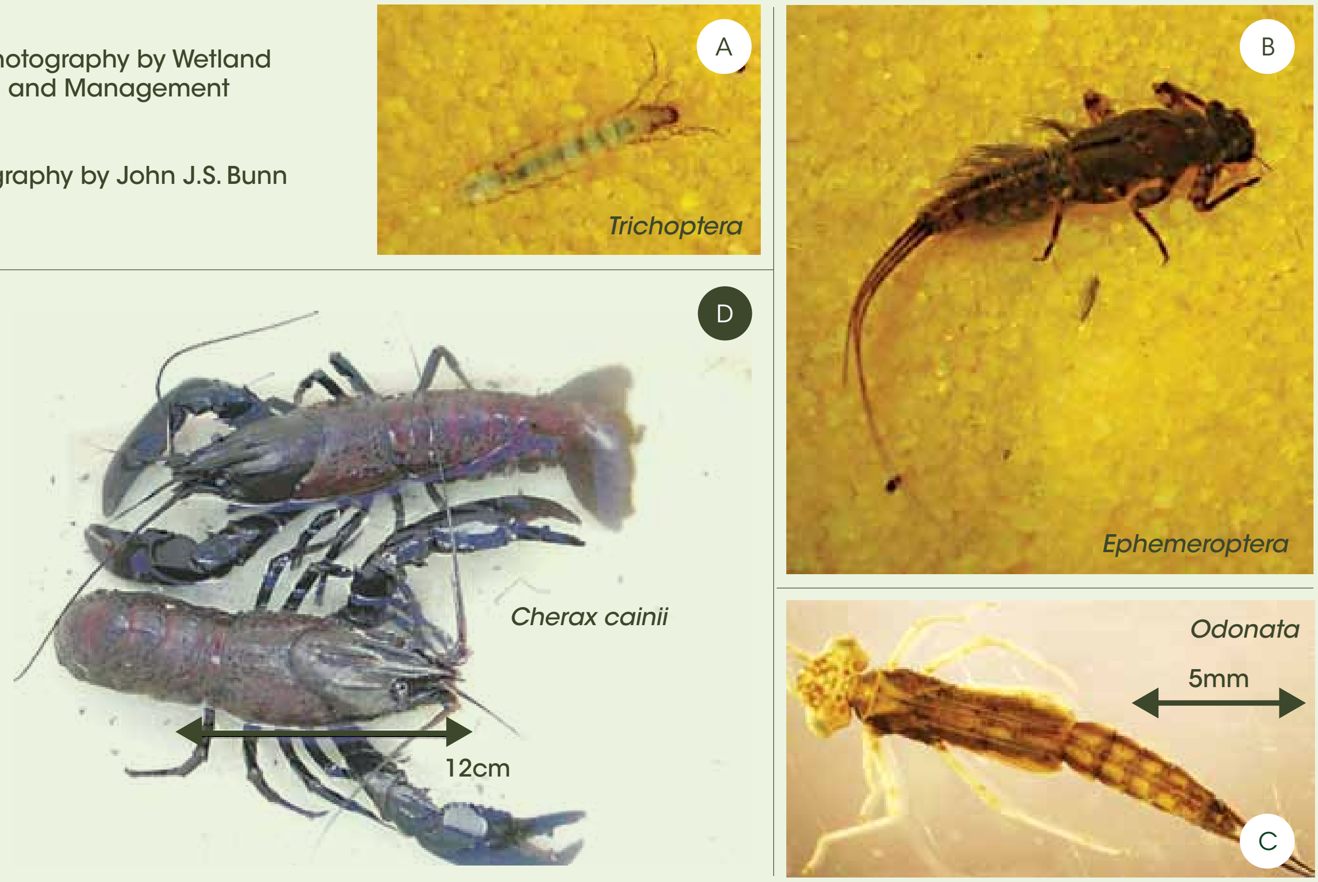


Figure 9

Macroinvertebrates of the Brunswick River

Freshwater mussels *(Westralunio carteri)* have been collected from the Brunswick River (WRM 2007). A decline in the mussel population has been reported, and populations are now fragmented in many areas of the south-west. Population declines have been linked with salinisation of rivers, and sedimentation of river beds and pools. Freshwater mussels are dependent on fish populations and migrations, as they are attached to fish for a stage of their life-cycle.

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

Most aquatic invertebrate species do not have physiological or life history strategies that allow them to survive seasonal drying. As adults, some insect species that are capable of flying are capable of moving to neighbouring waterbodies. Some invertebrates are capable of burrowing into moist sediments to avoid desiccation, including oligochaetes and gilgies. Gastropods, cladocerans, copepods and ostracods have some dessication-resistant stages in their life cycle (usually as an egg) and may undergo diapause during summer.

Invertebrate diversity is dependent on habitat complexity and diversity, since many species are essentially restricted to particular habitats (Brown & Brussock 1991; Humphries et al. 1996; Kay et al. 2001). Aquatic invertebrates occupy a wide range of habitat types including pools, riffles and sandy runs between pools, and dams of organic debris. Riffles and sandy runs tend to support a higher density and variety of invertebrates than other aquatic habitats. While the Brunswick River at Reach 1 does not have cobble or pebble riffle zones, it does have shallow sand runs which would have similar hydrological characteristics to riffles, such as high velocity flows and a diverse range of flows.

Some aquatic invertebrate species are associated with habitats such as snags, rocks, macrophyte beds and trailing riparian vegetation. Such invertebrates included oligochaetes, freshwater crayfish, larvae of many dragonfly and damselfly species, most species of chironomid and most caddisfly species. To maintain the distribution and abundance of these taxa, it is important to maintain sufficient flows to ensure snags, rocks, macrophytes and some overhanging riparian vegetation are inundated.

4.5.3 Fish

The south-west of Western Australia has relatively few species of native freshwater fish and a high degree of endemism compared with the rest of the continent (Pusey et al. 1989). Of the endemic species, the western minnow *(Galaxias occidentalis)*, pygmy perch *(Edelia vittata)* and nightfish *(Bostockia porosa)* are the most abundant and widespread.

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

Nightfish *Bostockia porosa*
Western pygmy perch
Western minnow

Figure 10
Native fish of the Brunswick River

There is anecdotal evidence that the distributions of both pouched lamprey *(Geotria australis)* and freshwater cobbler *(Tandanus bostocki)* are becoming increasingly restricted in the south-west due to habitat loss and flow regulation (WRM 2008a). Figure 10 illustrates some of the native freshwater fish species of the study area.

Five native species and one introduced species (the mosquitofish, *Gambusia holbrooki*) were recorded during surveys of the Brunswick River in 2007 for this study (WRM 2008b). Native fish included the nightfish, western minnow, Swan River goby *(Pseudogobius olorum)*, pygmy perch and pouched lamprey. Further information relating to life history characteristics, ecology and flow requirements can be found in WRM (2008b). None of the five native fish species sampled from the Brunswick River have physiological adaptations to withstand desiccation. These species rely on the presence of permanent water.

The introduced mosquitofish and redfin perch *(Perca fluviatilis)* were also recorded from the Brunswick River as part of field surveys for this study (WRM 2008b). Pusey et al. (1989) suggested that winter high spells reduce numbers of mosquitofish, which are poor swimmers, allowing for coexistence with small native species. Conversely, an absence of high winter flows favours mosquitofish, which results in a high incidence of fin nipping and damage to native species (Morgan et al. 1998; Storey 2000). Introduced species are poorly adapted to adverse water quality conditions encountered during periods of no flow in summer. For example, redfin perch cannot tolerate water temperatures greater than approximately 28°C (Morgan DL pers. comm.).

The breeding ecology of native species is strongly related to river flow. At least three native fish species (pygmy perch, western minnow and nightfish) undertake upstream migrations in winter and spring for breeding (Pen 1999). With the onset of winter flows in June or July, all three species move upstream from summer pools to small side tributaries to spawn on flooded vegetation and submerged reed beds (WRM 2008a). Their passage upstream may be obstructed by steep gradients, or natural obstructions such as rock bars and logs, and by infrastructure such as road culverts, weirs, and large and small dams.

Flows are required that maintain water depths that inundate trailing and aquatic riparian vegetation, a favoured spawning habitat for species such as pygmy perch and western minnow. Pygmy perch produce a number of clutches of eggs over the breeding period. The females spawn in the margins of rivers from about July to the end of the winter at intervals of six to eight weeks, often well after tributaries have stopped flowing (Pen 1999). The eggs, which take between 50 to 60 hours to hatch, are adhesive and are attached to benthic structures such as flooded vegetation. Flooded vegetation and shallow, flooded off-river areas also provide sheltered, low velocity nursery areas for growing juveniles (WRM 2008a). Flooding in winter and spring must be maintained to ensure breeding success and strong recruitment.

The duration and frequency of inundation of trailing and fringing vegetation can influence recruitment success. For example, if water levels fall too soon, or fluctuate greatly, fish eggs may be left above the water line and may dry out. Less successful recruitment may occur in those years in which reed beds and trailing vegetation are inundated for periods of less than five consecutive weeks. For fish with long life spans of three to five years, such as pygmy perch, high rates of recruitment need not occur every year to maintain healthy populations. Poor recruitment years occur naturally during periods of low rainfall. However, if conditions that are likely to result in poor recruitment occur in more than three years in a row, this may lead to a population age structure skewed towards older individuals.

There are many natural and artificial obstacles that could impede upstream migration of fish, such as logs, shallow riffles, rock bars, dams and weirs. Natural flow regimes include periods of high flows (also known as 'high spells') that submerge obstacles, allowing fish to move upstream. Such spells should last at least several hours to allow upstream migration of fish. Presumably, a series of winter high spells is required for fish to navigate upstream in a reach containing a series of barriers, such as a sequence of pools and riffles. An important consideration is the length of time that elapses between the onset of cues for breeding and migration (such as changes in water temperature and day length) and the submerging of barriers to upstream migration. If flows do not drown out barriers, migrating fish will congregate downstream until the critical flow is achieved.

During this time, predation on the waiting downstream congregation of fish may be intense, and may particularly affect gravid females that are ready to spawn.

Freshwater cobbler inhabit deeper areas of lakes and pools in slow moving rivers and spawn between November and January. This species was not collected by WRM (2008b); however, sampling techniques used are not ideal for collecting cobber in large numbers. Given that the species is known from similar systems in the Brunswick River area south of the Serpentine River (Morgan et al. 1998), for this study it is assumed cobbler occur also in the Brunswick River. Little is known of the breeding biology of cobbler; however, similar species in other parts of Australia 'nest' in the organic sediments of river pools. In WA, research has shown that adult cobbler undergo localised migrations (upstream and downstream) between pools within a 'home' range probably in search of food items. However, a peak in localised upstream migrations in spring and early summer suggests they may be a precursor to breeding (Beatty et al. 2008).

4.5.4 Reptiles

A number of species of reptile are likely to inhabit the riparian zone of the Brunswick River, and some can be regarded as reliant on aquatic and riparian food webs. A search of the literature found no published results of surveys of reptiles near the Brunswick River. However, based on the results of surveys nearby, some general comments can be made about the reptilian fauna of the study area. Many species of reptiles are expected to live in the riparian zone of the Brunswick River, including a variety of geckos, skinks and other lizards, as well as snakes, such as the tiger snake *(Notechis scutatus)* and dugite *(Pseudonaja affinis)* (Cogger 2000). The tiger snake is common in the region and is usually encountered along rivers, especially in the swampier reaches where it hunts for frogs. It readily takes to water in warm weather and is a strong swimmer. The western glossy swamp skink *(Egernia luctuosa)* inhabits dense ground cover on the margins of swamps, lakes and streams, while the western three-lined skink *(Acritoscincus trilineatum)* can be regarded as semi-aquatic as it tends to inhabit areas of damp soil (Cogger 2000).

The long-necked tortoise *(Chelodina oblonga)* is commonly encountered in south-west rivers, and is found across a range extending from Hill River in the north to the Fitzgerald River National Park east of Albany. Long-necked tortoises inhabit river pools,

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

Long-necked tortoise

Tiger snake

Figure 11
Reptiles of the Brunswick River

perennially-flowing streams and rivers, and areas of soft soil adjacent to river banks. The diet of the long-necked tortoise includes tadpoles, fish and aquatic invertebrates. In permanently flowing waters the long-necked tortoise has two breeding periods, in September–October and again in December–January, while in ephemeral river systems they tend to breed once a year in spring. Nests are constructed in sandy soil and eggs may take up to seven months to hatch. If local conditions deteriorate, tortoises can migrate long distances overland or aestivate in situ in burrows constructed in soft sediments. The survival of the long-necked tortoise depends on the presence of permanent water and on nearby areas of soft, damp soils in which to lay their eggs.

Many reptiles are associated with permanent and seasonal waterbodies, as these habitats provide a water source and a diverse array of prey species. However, the impact on reptile species caused by changes in the availability of fresh water in the south-west of Western Australia has not been studied, and there is little published information on reptile species' tolerance to changes in the availability of water in other geographic regions. In the absence of specific information, it is assumed that terrestrial reptiles are dependent on elements of the flow regime that maintain riparian vegetation and habitat, and ecological processes that protect aquatic biodiversity and biomass. It is also important for the survival of reptile species that permanent pools are maintained as a source of water and food during the dry summer months. Figure 11 shows some of the reptiles likely to be found in the Brunswick River area.

4.5.5 Amphibians

The south-west of Western Australia has at least 26 species of frog, of which about 20 spend a substantial part of their life cycle in moist environments adjacent to wetlands and streams. Most species require surface water during certain stages of their life cycle, for egg-laying and for the development of aquatic tadpoles into adult frogs (Table 2). Frogs tend to be unspecialised opportunistic feeders, eating mainly insects as adults, while tadpoles tend to graze on algae.

A: Photography by Rob Davis
B: Photography by DEC

Motorbike frog

Slender tree frog

Figure 12
Amphibians of the Brunswick River

Table 2

Habitat and breeding biology of frogs associated with the Brunswick River (WRM 2007). Information sourced from Tyler et al. (1994) and Cogger (2000).

Species	Habitat	Spawning	Tadpole ecology
Guenther's toadlet *(Pseudophryne guentheri)*	Constructs burrows beneath ground cover such as rocks timber and leaves	Period: autumn following rain. Site: eggs deposited on damp soil in tunnels	Habitat: early development in egg capsule Maturation: well developed tadpoles emerge when tunnels are flooded.
Glauert's froglet *(C. glauerti)*	Permanently moist areas at the edge of swamps and streams. In dry periods burrows into damp soil.	Period: following rain at any time of year except summer. Site: eggs laid in shallow puddles or moist litter alongside ponds and rivers.	Habitat: Swamps and still water at the edge of streams. Maturation: 90 days
Squelching froglet *(C. insignifera)*	Temporary and permanent swamps and permanent rivers on the coastal plain.	Period: winter. Site: Single eggs laid in shallow depressions.	Habitat: Swamps and slow flowing streams. Maturation: 150 days
Lea's frog *(Geocrinia leai)*	Habitat: Coastal and near coastal swamps and streams.	Period. Winter. Sites: Eggs laid in mass attached to aquatic vegetation above waterline.	Habitat: streams and swamps. Tadpoles emerge and drop into water. Maturation: >120 days
Slender tree frog *(Litoria adelaidensis)*	Dense vegetation in the margins of wetlands and slowly flowing streams.	Period: early spring. Site: Eggs in mass attached to aquatic vegetation often just below the water surface.	Habitat: Wetlands and slowly flowing water.
Motorbike frog *(L. moorei)*	Riparian areas of permanent wetlands and streams under rocks and logs. Also arboreal hiding beneath bark.	Period: Spring - summer. Site: Eggs laid in floating mass attached to vegetation	Habitat: Permanent wetlands and slowly flowing water. Maturation: 60 days

No specific studies of the Brunswick River frog fauna were found during an extensive literature review. A study of the nearby Kemerton region a short distance to the north of the Brunswick River and approximately three kilometres east of the Leschenault Inlet identified a number of frog species, including Glauert's froglet *(Crinia glauertii)*, the squelching froglet *(C. insignifera)*, Lea's frog *(Geocrinia leai)*, Gunther's toadlet *(Pseudophryne guentheri)*, the slender tree frog *(Litoria adelaidensis)*, and the motorbike frog *(Litoria moorei)* (Bamford & Watkins 1983). Some of the amphibians likely to be found in Brunswick River are shown in Figure 12.

All the identified frog species are closely associated with streams and swamps (Table 2). Spawning generally occurs in winter to spring, although the motorbike frog may continue to spawn in summer if water is present. Glauert's froglet inhabits marshy areas associated with swamps and damp areas beside pools on small streams, gutters and seeps in forested areas. The froglet lays eggs in shallow water, and tadpoles take about three months to mature in the shallow waters at the edges of rivers and swamps. The motorbike frog, Lea's frog and the slender tree frog lay eggs attached to emergent and submerged vegetation (Tyler et al. 1994). Guenther's toadlet lays eggs in tunnels and emerges when tunnels are inundated by winter floods.

4.5.6 Waterbirds

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

Riparian vegetation corridors are the most substantial areas of remnant vegetation remaining in some parts of the Brunswick River catchment. In the south-west of Western Australia, some species may depend on the habitat provided by riparian vegetation corridors for their survival (Pen 1999). The sections of the Brunswick River where the banks are still lined with paperbark and eucalypts provide important breeding habitat for a limited variety of waterbirds, including tree nesting ducks and herons. The paperbark swamps adjacent to the Brunswick River also provide roosting sites for Australian white ibis *(Threskiornis aethiopicus)* and straw-necked ibis *(Threskiornis aethiopicus)* (Bamford & Watkins 1983). Figure 13 shows some waterbirds observed in the surrounding areas of the Brunswick River, such as the wetland to the south of Reach 1.

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

Australian Shelduck

White faced Heron

Figure 13
Waterbirds of the Brunswick River

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

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

4.5.7 Mammals

No studies specifically detailing the mammal fauna of Brunswick River were located during a search of the literature; however, some comments can be made based on the results of other studies. Of the mammal species known to inhabit the region through which the Brunswick River flows, a number are reliant on the riparian vegetation zone either as habitat, or as a food source. Examples of such species include the brush-tailed phascogale *(Phascogale tapoatafa)*, quenda or southern brown bandicoot *(Isoodon obesulus)*, western ringtail possum *(Pseudocheirus occidentalis)* (Figure 14), and brushtail possum *(Trichosurus vulpecula)* (Taylor 2006). The two species of possums and the brush-tailed phascogale are reliant upon dense vegetation and the availability of hollow-bearing trees, which often occur near rivers and streams. Quenda occur only in areas with dense covering vegetation, such as the margins of wetlands, *Banksia* woodland and jarrah forest. The quokka *(Setonix brachyurus)* and the western grey kangaroo *(Macropus fuliginosus)* are also likely to inhabit the study area and frequent the riparian zone.

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

Figure 14
Mammals of the Brunswick River

The Brunswick River is within the known range of the water rat *(Hydromys chrysogaster)*. Water rats are found in rivers, swamps, lakes and drainage channels. They have broad, partially webbed hind feet, water-repellent fur, and a thick tail (Figure 14). 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 2007).

4.5.8 Carbon sources and ecosystem productivity

The diversity, biomass and productivity of ecosystems is controlled by the availability of a range of essential elements. 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 changes to 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, or as woody debris washed into the river from the riparian zone. This process requires the connection of downstream and upstream river reaches (Vannote et al. 1980). Carbon may also enter river systems as dissolved organic and inorganic carbon in groundwater and soil water. Direct inputs of carbon from in-stream production (phytoplankton and benthic algae) and processing of carbon through fungal, microbial and invertebrate pathways are also important in maintaining food webs.

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

4.6 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 geomorphological features of the aquatic system. The selection of these flow events and critical water levels was based on the advice of the expert panel, combined with published information.

The critical flows that maintain vegetation, aquatic invertebrates, native fish, reptiles, amphibians, waterbirds, mammals, carbon flows and channel morphology were determined using methods from previous, similar studies (WRM 2005a and 2005b). A series of critical flows were identified for each ecological component in different seasons. The key ecological objectives that were considered in the determination of the EWR for the Brunswick River, together with their associated flow criteria, are listed in Table 3. The objectives are listed in ascending order of the approximate volume of water required to fulfil the flow criteria.

Wetland Research and Management ecologist Andrew Storey instructing the surveyors

Table 3

Ecological objectives and flow criteria for the Brunswick River. Where applicable, different flow criteria have been noted for Reaches 1 and 2.

Ecological objective	Flow criteria	Flow component
Provide summer minimum flow to maintain water levels, water quality and dissolved oxygen levels in pools, and maintain upstream/downstream connectivity for carbon transfer	Flow rate of at least 0.01 m/s	Summer low flows
Inundate gravel runs and riffles as summer habitat for aquatic invertebrates	Riffles inundated to a depth of at least 5 cm over 50% of total riffle width	Summer low flows
Inundate gravel runs and riffles as winter habitat for aquatic invertebrates	Riffles inundated to a depth of at least 5 cm over 100% of total riffle width	Winter low flows
Allow upstream migration of small-bodied fish during spawning season	Water depth of at least 10 cm over obstacles	Winter and spring low flows
Allow upstream migration of large-bodied fish during spawning season	Water depth of at least 20 cm over obstacles	Winter and spring low flows
Inundate aquatic and trailing vegetation as habitat for invertebrates and vertebrates, and as spawning sites for fish and amphibians	Reach 1: Water depth of at least 20 cm Reach 2: Sufficient water levels to fill the depth of the active channel	Autumn, winter and spring low flows
Inundate low benches to flush organic matter into river and provide habitat	Sufficient water depth to commence inundation of low benches	Winter high flows
Inundate medium benches to flush organic matter into river, provide habitat and inundate vegetation	Reach 1: Sufficient water depth to commence inundation of medium benches Reach 2: N/A - No medium benches surveyed	Winter high flows
Maintain active channel morphology and scour pools	Sufficient water levels to fill the depth of the active channel	Winter high flows
Inundate high benches to flush organic matter into river and inundate riparian vegetation	Sufficient water depth to commence inundation of high benches	Winter high flows
Provide overbank flows to inundate floodplain, recharge floodplain wetlands, provide fauna habitat and aid seed dispersal and germination of riparian vegetation	Sufficient water levels to exceed top of bank	Winter high flows (flood event)

In one case (inundation of trailing vegetation as breeding habitat), the defining flow criteria were different for the two study reaches. The height of breeding habitat was not surveyed in the field, so alternative, surveyed heights were used in the analysis. In Reach 2, the active channel height was used to indicate the approximate height of trailing vegetation. For Reach 1, the active channel was unusually incised due to catchment clearing, making it inappropriate to use the active channel depth as an approximation of the height of trailing vegetation. The same flow criteria for upstream migration of small-bodied fish were used instead of the active channel height as an estimate of the depth of water required to inundate trailing vegetation in Reach 1.

The flow criteria listed in Table 3 were used to develop a set of flow-ecology 'rules' that describe the different components of the flow regime required to maintain the ecological values of the Brunswick River. These rules were used as defining criteria for hydraulic analysis in the river analysis package (RAP) software, a process which will be described in greater detail in Section 4.9.

4.7 Cross-section survey of the river channel

The sixth step of the PADFLOW method outlined in Figure 6 requires the collection of topographic data from a number of channel cross-sections. In the two study reaches of the Brunswick River, the cross-sections were located to characterise the shape and variability of the channel over each reach, and were positioned to include key hydraulic and ecological features such as depth-controlling features, backwaters, pools, riffles, large woody debris and channel constrictions. Figure 15 shows a schematic illustration of the process used to survey channel cross-sections and identify channel features. In November 2005, a total of 15 channel cross-sections were surveyed at Reach 1 (Figure 16), while 16 cross-sections were surveyed at Reach 2 (Figure 17).

Inserting a survey peg to locate a channel cross-section for subsequent channel surveys

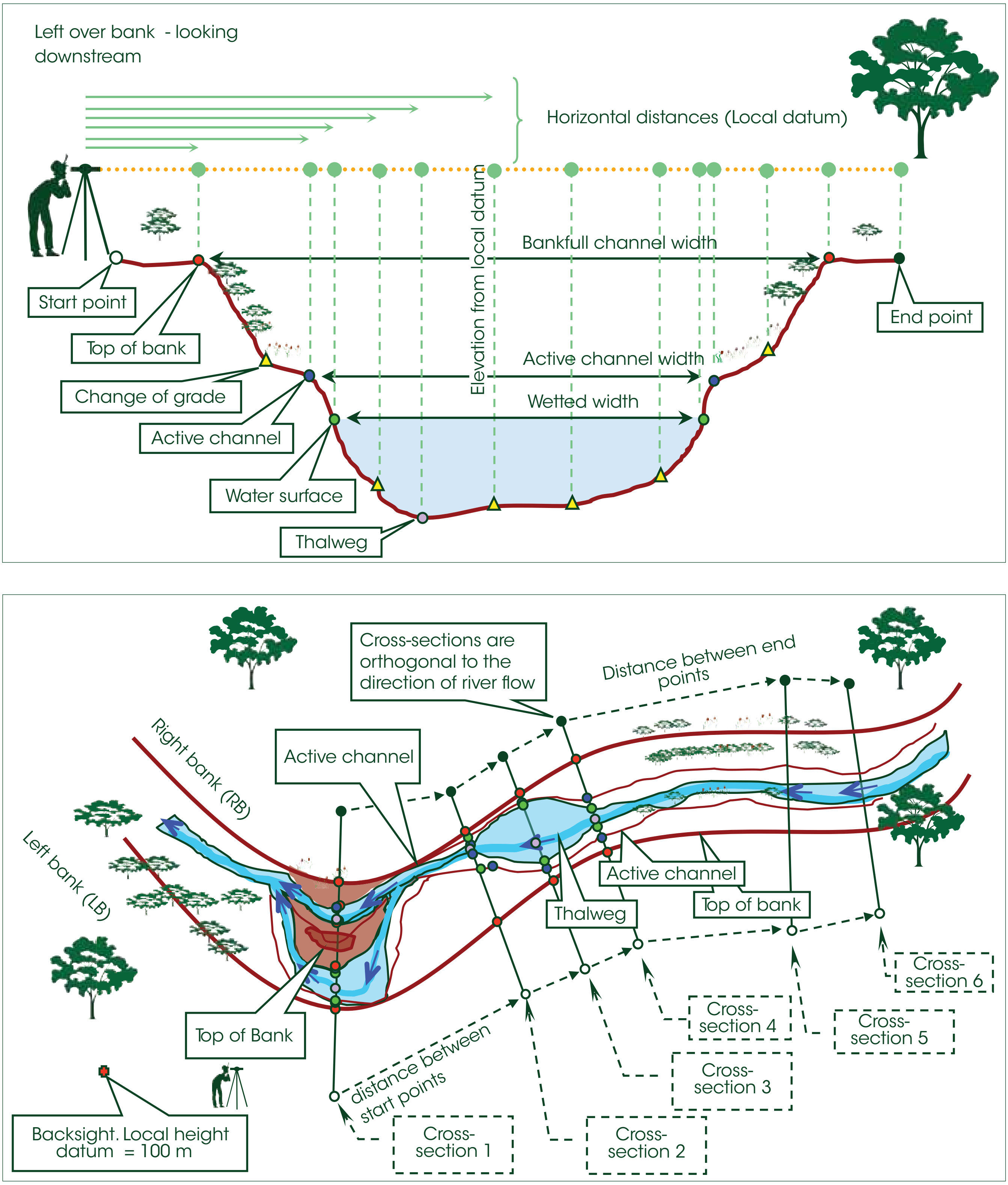
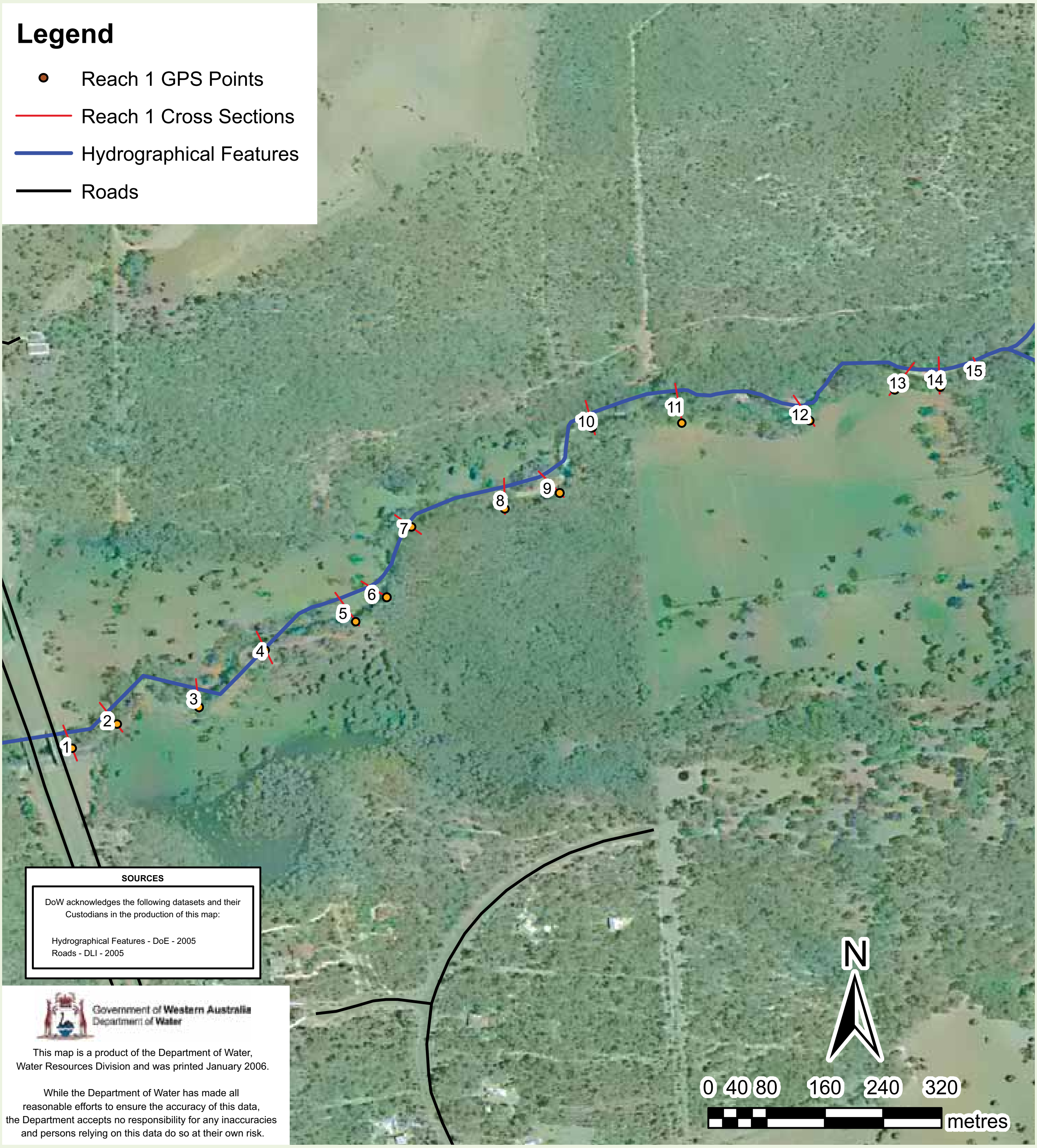


Figure 15

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



SOURCES

DoW acknowledges the following datasets and their Custodians in the production of this map:

Hydrographical Features - DoE - 2005
Roads - DLI - 2005

This map is a product of the Department of Water, Water Resources Division and was printed January 2006.

While the Department of Water has made all reasonable efforts to ensure the accuracy of this data, the Department accepts no responsibility for any inaccuracies and persons relying on this data do so at their own risk.

Figure 16

Location of 15 surveyed cross-sections in Reach 1 of the Brunswick River

Figure 17

Location of 16 surveyed cross-sections in Reach 2 of the Brunswick River

The cross-sectional profiles of the river channel are shown in Appendices 3 and 4. In Reach 1, two cross-sections (numbers 8 and 13) were located at the upstream end of shallow sandy runs and controlled water depth (Appendix 3). The remaining 13 cross-sections were situated across pools (Appendix 3). In Reach 2, thirteen of the cross-sections spanned pools, while three cross-sections (numbers 5, 11 and 15) were located at the furthest upstream extent of riffles, which are shallow features that control water depth (Appendix 4). Discharge data were measured during the cross-sectional surveying to assist in calibrating the hydraulic model to be developed for each reach. At the time of surveys the mean daily flow rate was 1.15 m^3/s and 1.85 m^3/s for Reaches 1 and 2 respectively.

The river channel in Reach 1 was characterised by its low gradient, extensive erosion, pools separated by sand and gravel runs, and a lack of in-stream vegetation, riffles or large woody debris.

These characteristics all suggest that the catchment upstream is generating more runoff at the present time than before European settlement, with the channel form changing to accommodate greater discharge and higher velocities. The sand and gravel runs present within the river channel would have an ecological function similar to the cobble or pebble riffle zones that are more characteristic of upland streams. The shallow runs would have higher velocity flows than surrounding areas, as well as a diversity of flows in summer relative to pools, but may not support such highly diverse invertebrate fauna compared with the more heterogeneous rocky riffle zones present in Reach 2.

Undercutting and slumping of banks is a notable feature of Reach 2. It also has a number of riffle and pool sequences, with some artificial riffles created in rocky areas. The pools within Reach 2 were generally deeper than one metre at the time of the field survey.

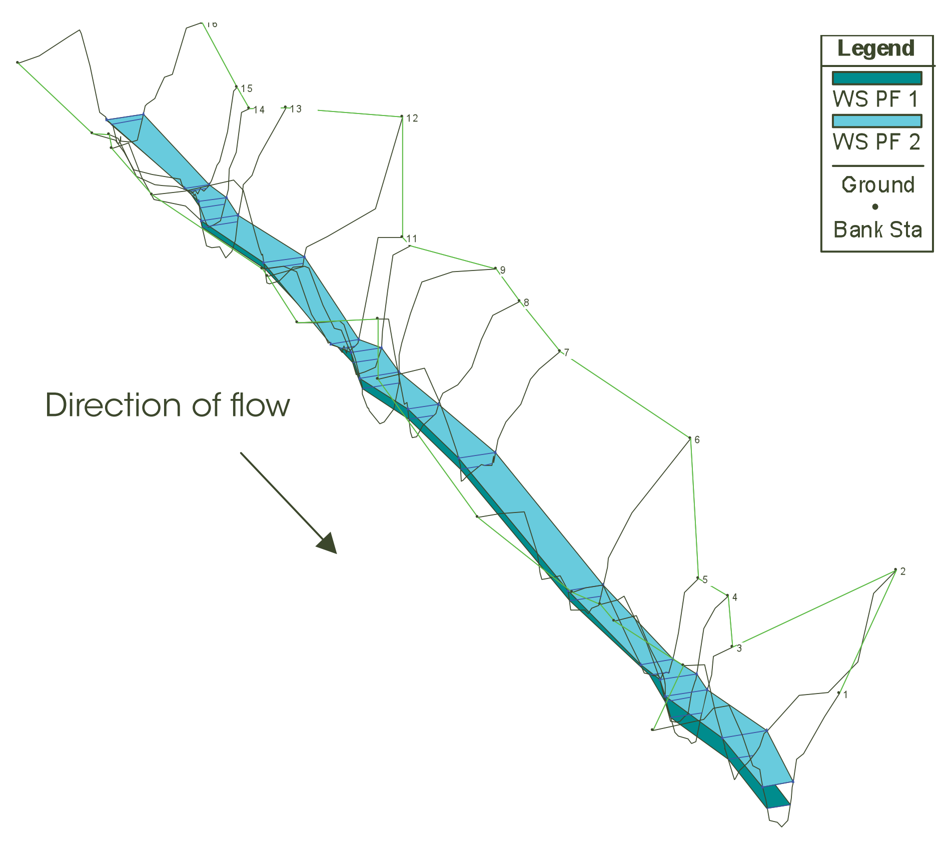


Figure 18

Structure of the HEC-RAS hydraulic model for Reach 2 in the Brunswick River. The blue trace shows the water level at the time of the channel surveys

4.8 Construction of hydraulic model

In the seventh step of the PADFLOW method (Figure 6), the cross-section data are used to construct a hydraulic model. The hydraulic model of both study reaches of the Brunswick River was created using the HEC-RAS (Hydrological Engineering Centre, United States Army Corps of Engineers, River Analysis System) modelling package. Observed relationships of discharge to stage height were used to calibrate the model. A diagram of the hydraulic model created for Reach 2 is shown in Figure 18.

Figure 19 shows the longitudinal profiles of the two study reaches. Reach 1 was characteristic of a lowland sandplain river, with very little change in gradient over the length of the reach. Thalweg depth (measured as the deepest part of the river channel in each cross-section) dropped by approximately one metre over the 1.4 km reach.

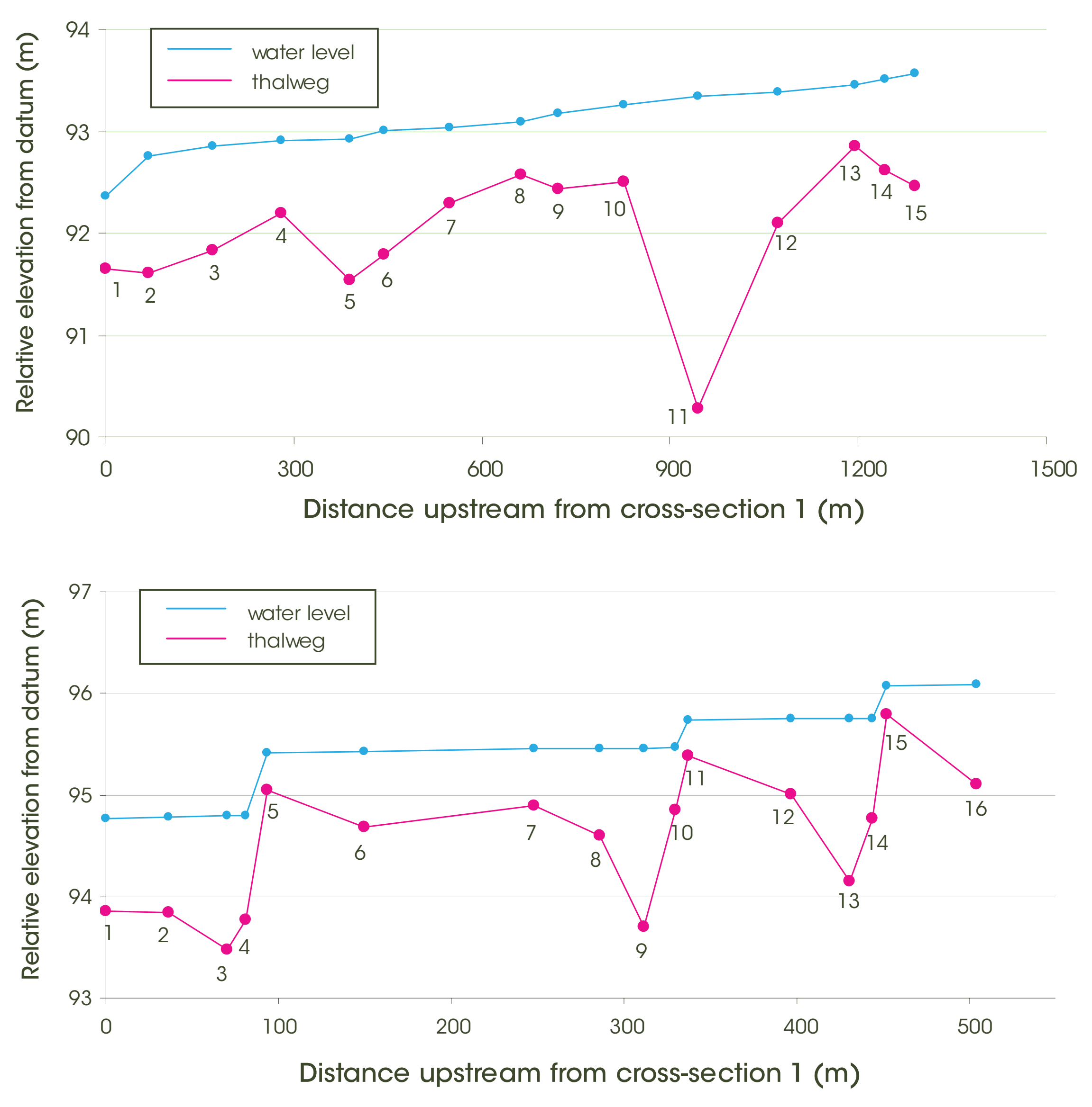


Figure 19

Longitudinal profiles of Reach 1 (upper plot) and Reach 2 (lower plot). The profiles show a series of shallow pools separated by sandy runs and riffles. The thalweg is the deepest continuous line along the river channel and represents the flow path during very low summer flows

The low gradient of Reach 1 may lead to a situation where controlling features (such as shallow sand bars and large logs) located downstream could influence water levels in the reach during medium- to high-magnitude flows.

Thalweg depth in Reach 2 fell by approximately 1.5 metres over the length of the reach. Water depth in Reach 2 was controlled by an artificial riffle at cross-section 5, and natural rock bars at cross-sections 11 and 15. These shallow, controlling features generate turbulence and high water velocity, even when flow volumes are relatively low. Water velocity is slower and less turbulent in the pools between riffles. These pools provide summer and winter habitat for a variety of aquatic fauna.

4.9 Identification of flow thresholds

The hydraulic model was loaded into the river analysis package (RAP) in order to determine the flow thresholds required to achieve each ecological objective detailed in Table 3. RAP uses the empirical relationships among channel geometry (and cross-sectional volume), water velocity and water levels to estimate the flow rate required to achieve a particular water depth over selected channel features. Depending on the flow-ecology rule applied, such features could include rock bars, benches, pools, riffles or the height of riparian vegetation. One of the key outputs of RAP is a 'rating curve', which graphically relates changes in discharge to changes in water depth or the wetted width of channel (refer to WRM 2008a). Appendices 5 to 10 show the critical flows required to inundate various features such as high benches and top of bank.

The ecologically critical threshold flow rates for Reach 1 and Reach 2 are summarised in Table 4. Some of the flow-ecology rules and corresponding flow events can fulfil multiple ecological objectives. More detailed descriptions of the derivation of the flow rates are provided in the following sections.

Sketching the river channel morphology at cross-section 2, Reach 1 just upstream of the Austalind Bypass Bridge

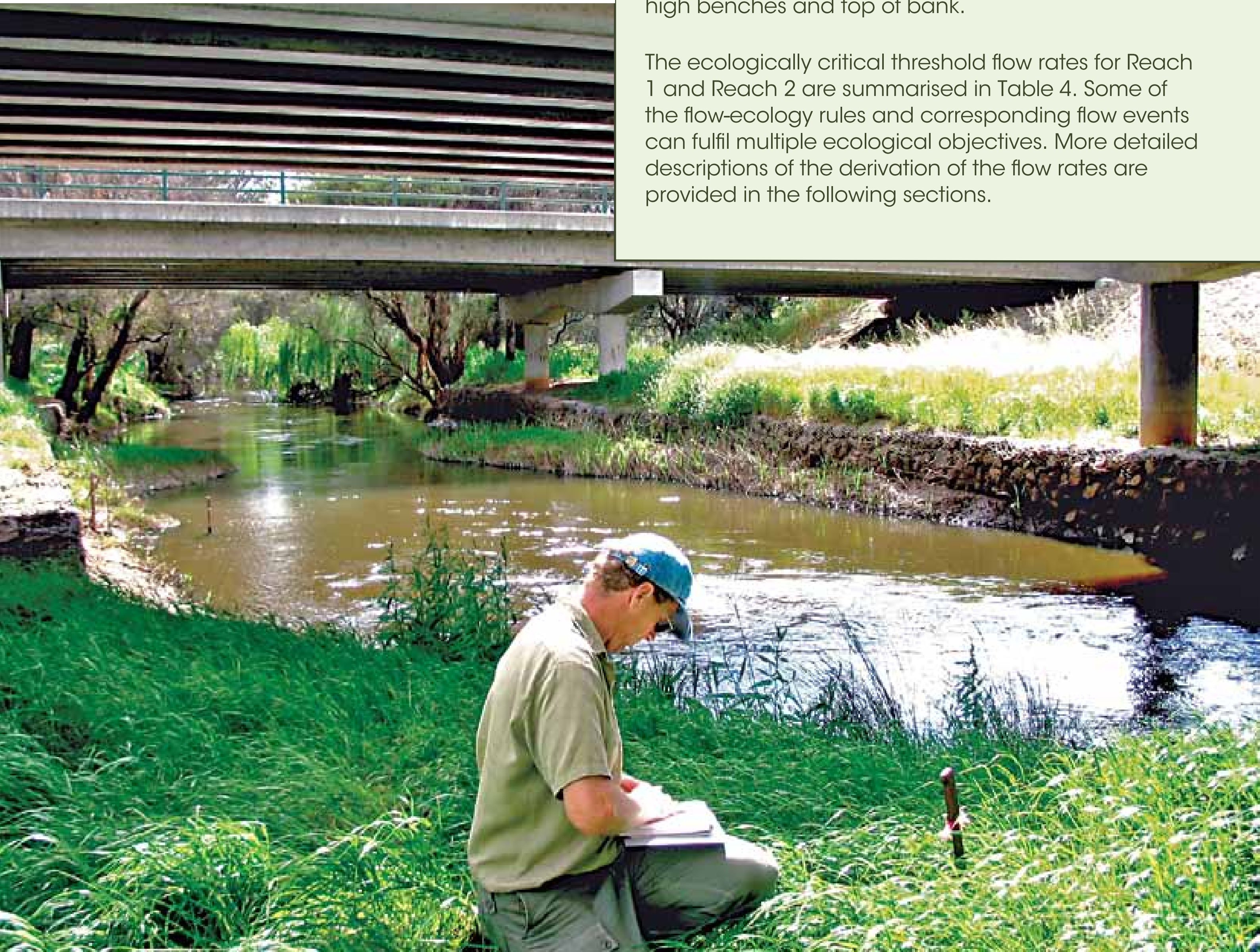


Table 4

Ecologically critical flow rates for Reach 1 and Reach 2 of the Brunswick River. The threshold flows detailed below are those that satisfy the flow objectives set out in Table 3

Flow-ecology rule	Threshold flow		Ecological functions
	Reach 1	Reach 2	
Minimum flow velocity of 0.01 m/s	0.02 m^3/s 1.7 ML/day	0.02 m^3/s 1.7 ML/day	Maintain water quality and dissolved oxygen levels in pools. Downstream carbon movement maintained by connectivity between pools.
Water depth of 5 cm over 50% of width of sandy runs	0.06 m^3/s 5.2 ML/day	0.17 m^3/s 14.7 ML/day	Provide summer habitat for macroinvertebrates.
Water depth of 5 cm over entire width of sandy runs	0.11 m^3/s 9.5 ML/day	1.4 m^3/s 119 ML/day	Provide winter habitat for macroinvertebrates.
Minimum thalweg depth of 10 cm at shallowest cross-section	0.11 m^3/s 9.5 ML/day	0.04 m^3/s 3.5 ML/day	Allow upstream spawning migration of small-bodied native fish.
Minimum thalweg depth of 20 cm at shallowest cross-section	0.25 m^3/s 21.6 ML/day	0.32 m^3/s 27.6 ML/day	Allow upstream spawning migration of large-bodied native fish. Inundate trailing vegetation.
Inundate low benches	0.36 m^3/s 31.1 ML/day	2.1 m^3/s 177 ML/day	Flush organic matter into river system. Inundate trailing vegetation, providing fish cover and spawning sites.
Inundate medium benches	4.1 m^3/s 352 ML/day	N/A - no medium benches	Flush organic matter into river system. Inundate trailing and emergent vegetation. Provide spawning habitat.
Inundate active channel	10.5 m^3/s 907 ML/day	2.0 m^3/s 171 ML/day	Scour and maintain low-flow channel. Inundate trailing vegetation. Prevent incursion of terrestrial vegetation. Flush organic matter into river system.
Inundate high benches	15.9 m^3/s 1374 ML/day	6.1 m^3/s 524 ML/day	Flush organic matter into river system. Inundate riparian vegetation. High energy flows to scour pools and maintain channel morphology.
Inundate floodplain	22.8 m^3/s 1974 ML/day	25.7 m^3/s 2217 ML/day	Inundate and recharge floodplain wetlands. Maintain floodplain wetland nursery areas for fish and tadpoles. Inundate channel and floodplain riparian vegetation. High energy flows to scour pools and maintain channel morphology.

4.9.1 Summer minimum flow

For both reaches, a flow rate of at least 0.02 m^3/s, equivalent to 1.7 ML/day, is required year-round to avoid stratification and maintain dissolved oxygen levels in pools, as well as maintaining connectivity between upstream and downstream reaches of the Brunswick River. Summer flows also maintain permanent pools that act as important summer refuge habitat for native fish and aquatic invertebrates, and as a source of water and food for a variety of riparian vertebrates.

The critical flow rate of 0.02 m^3/s was calculated as the average flow required to achieve a mid-pool water velocity of 0.01 m/s. All cross-sections containing pools were included in the hydraulic analysis for this objective. A water velocity of 0.01 m/s has been calculated as the minimum velocity required to prevent stratification and maintain dissolved oxygen at more than four mg/L (WRM 2008a).

4.9.2 Macroinvertebrate habitat

The water level criteria for macroinvertebrate habitat are a minimum of five centimetres depth over at least half of the total width of measured riffles or shallow runs in each reach during summer, and over the entire width of riffles during winter. Using the tools available in RAP, water levels in the hydraulic model of both reaches were manipulated to achieve at least five centimetres depth over the required widths of cross-sections containing either shallow runs or riffles.

In Reach 1, two cross-sections were located on sandy runs. The sandy runs at the two sites had an average width of four metres. The instantaneous flow rate required to inundate half of the average width of the shallow runs to a depth of five centimetres was 0.06 m^3/s, while a rate of 0.11 m^3/s was required to inundate the total width of shallow runs.

In Reach 2, three cross-sections were located on riffles, with a mean width of 7.7 metres. The flow rate required to inundate half of the average width of the riffle cross-sections to a depth of five centimetres was 0.17 m^3/s. For winter macroinvertebrate habitat, the flow rate required to inundate the entire width of riffle cross-sections was 1.4 m^3/s.

4.9.3 Upstream migration of native fish

The water level criteria for upstream migration of native fish were set at 10 centimetres minimum depth over barriers and shallow sections for small-bodied fish, and 20 centimetres depth for large-bodied native fish. The 10 centimetres minimum has been used in other EWR studies (WRM 2008a). This criterion is considered conservative for small species such as pygmy perch, western minnow, nightfish and small cobbler (<100 mm total length or TL). The key period for this flow is in the winter breeding period between June and November.

The minimum depth criterion of 20 centimetres for large-bodied fish has recently been confirmed for adult freshwater cobbler longer than 180 mm TL in the Blackwood River (Beatty et al. 2008). The 20 centimetres minimum flow, therefore, is required to allow movement of cobbler populations between pools within the river reach throughout the year. The key period for localised breeding migrations of cobbler is from November to January.

To determine the threshold flow for upstream migration of small fish, RAP was programmed to identify the flow that maintained a minimum depth of 10 centimetres over the shallowest cross-section in each reach. In Reach 1, the critical flow rate required to achieve a depth of 10 centimetres was 0.11 m^3/s. In Reach 2, the critical flow rate was 0.04 m^3/s.

Similarly, to determine the threshold flow for upstream migration of large-bodied fish, RAP was programmed to identify the flow that maintained a minimum depth of 20 centimetres over the shallowest cross-section in each reach. The critical flow rate calculated for Reach 1 was 0.25 m^3/s. In Reach 2, the threshold flow to allow upstream migration of large fish was 0.32 m^3/s.

4.9.4 Inundation of spawning habitat

As explained in Section 4.6, there were no field data on the elevation of preferred spawning habitat for native fish within each of the reaches. For Reach 1, the flow rate required to submerge the shallowest cross-section to a depth of 20 centimetres (i.e. the same flow required for upstream migration of large-bodied fish) was used as a proxy for spawning habitat. For Reach 2, the depth of the active channel was used to approximate the height of spawning habitat.

4.9.5 Inundation of low, medium and high benches

A number of ecological objectives are satisfied by inundating benches, including flooding of emergent macrophytes, inundation of trailing vegetation as cover and spawning habitat for fish, and provision of carbon inputs to the river system in the form of organic detritus and algal production.

The flow required to inundate the one low bench surveyed in Reach 1 (cross-section 10) was determined by identifying the increase in area of channel with a slope of less than 1:100. This defines channel features with a low gradient (i.e. benches) as opposed to steep banks. Using the rule of a slope (of 0.01) identified the flow at which there is a rapid increase in flooded area for a small increase in flow due to the low gradient bench being inundated. The flow required to inundate the single low bench at cross-section 10 in Reach 1 was 0.36 m^3/s (Appendix 5).

For medium and high benches in Reach 1, the flow required to inundate the benches was determined using the hydraulic model to calculate a flow rate that would fill the channel to an elevation where the benches became inundated at each cross-section. The average value from all cross-sections was then taken as the critical flow rate. The average flow rates required to inundate medium and high benches in Reach 1 were 4.1 and 15.9 m^3/s respectively (Appendices 6 and 7).

To determine the flow rate required to inundate low benches in Reach 2, a slightly different approach was used. The method used for Reach 1 picked up features too low in the channel to be benches, such as sand bars. To avoid these features, the criteria that the feature must be higher than 0.5 metres above the river thalweg was included in the analysis. Also, the low benches in Reach 2 were not so well defined as in Reach 1, so a slope of less than 1:10 (as opposed to 1:100 for Reach 1) was used to identify the increase in the wetted area of channel. The flow threshold needed to inundate the five low benches in Reach 2 was 2.1 m^3/s. (Appendix 5).

No medium benches were surveyed in Reach 2. High benches in Reach 2 were well defined and the slope rule of less than 1:100 (as used for low benches in Reach 1) was used to identify the flow required to commence inundation. The flow threshold needed to inundate the nine high benches in Reach 2 was of 6.1 m^3/s (Appendix 8).

4.9.6 Inundation of the active channel

The critical threshold to maintain an open, low-flow channel was defined as the flow required to fill the depth of the active channel. The elevation of the active channel was surveyed as the point on banks above which vegetation is stable and below which the bank is bare and without extensive vegetation. Using cross-sections taken at shallow sandy runs or riffles, the average depth from the deepest part of the river bed (thalweg) to the elevation of the active channel was used as the water level height needed to inundate to the active channel. Two shallow cross-sections were used in the calculation for Reach 1, and three shallow cross-sections were used in the hydraulic analysis for Reach 2.

For Reach 1, a flow rate of 10.5 m^3/s was sufficient to achieve the mean active channel height of 1.65 metres above the river bed. This flow is quite high for an active channel flow, which suggests that clearing in the catchment has increased flow velocity and magnitude, leading to accelerated erosion and incision of the river channel. In Reach 2, the flow required to inundate the channel to an average active channel height of 0.76 metres was 2.0 m^3/s.

There is a substantial, semi-permanent wetland system on the floodplain adjacent to Reach 1 that has significant value as habitat for waterbirds and other fauna such as invertebrates, fish, and reptiles. The wetland is groundwater fed but also receives water directly from the Brunswick River in winter through a low point on the river bank at cross-section 9. The flow required for water to flow into the side-channel and the wetland was calculated in RAP to be 10.4 m^3/s (Appendix 9), which is very similar to the flow required to maintain the active channel.

4.9.7 Bankfull and overbank flows

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

In Reach 1, seven cross-sections had a well-defined top of bank. The flow required for water levels to reach the height of the top of bank was calculated individually for each cross-section using RAP, and the average flow required to overtop the banks was taken as the ecologically critical flow rate for the reach. A flow of 22.8 m^3/s, equivalent to 1974 ML/day, was calculated as the average bankfull flow in Reach 1 (Appendix 10).

For Reach 2, only the right top of bank was included in hydraulic analysis because the left bank extended to riverside housing developments and was well above the surrounding floodplain level (and therefore unlikely to be inundated). Nine cross-sections contained a defined top of bank, and were included in hydraulic analysis. The average flow required to reach the top of bank across the nine cross-sections was 25.6 m^3/s, or 2217 ML/day (Appendix 11).

4.10 Parameterisation of the river ecological sustainable yield model

The historical flow record and the ecological flow thresholds were used to guide the construction of an ecological water requirement. Using the PADFLOW approach, the modelled EWR was developed using a water balance model called the river ecological sustainable yield model (or RESYM), which was developed specifically to be used with the PADFLOW approach. RESYM determines an EWR flow series by removing a proportion of the observed daily flow until the remaining water equals or exceeds each of the ecological flow thresholds identified in Section 4.9.

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 function(s) of the flows.

For each model run, the expert panel evaluated the frequency and duration of flows above the particular ecological flow threshold in the modelled EWR compared to 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 the following sections, 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.

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

The RESYM parameters used to generate the modelled EWR flow for Reach 1 and Reach 2 of the Brunswick River are shown in Table 5 and Table 6 respectively. The flow ranges shown in the tables were generated using observed data. It should be noted that flows of very large volume (i.e. flood flows that would exceed the banks) are very infrequent, whereas flows of lower volume are much more commonplace. As a result of the way that the RESYM parameters are derived, most of the ecologically critical flow thresholds are encompassed within the lowest three flow ranges listed for both Reach 1 and Reach 2. The highest flow ranges cover very infrequent events that occur at a frequency far less than once a year.

Table 5

Proportion of the observed daily flow volume that was retained to meet ecological water requirements within each flow class in Reach 1

Flow range (ML/day)	Ecological water requirements as percentage of daily flow
0 - 2.0	100%
2.1 - 49.9	70%
50.0 - 1046.9	60%
1047.0 - 1449.9	75%
1450.0 - 3053.9	85%
3054.0 - 4334.9	65%
4335.0 - 8179.9	60%
≥8180.0	100%

Table 6

Proportion of the observed daily flow volume that was retained to meet ecological water requirements within each flow class in Reach 2.

Flow range (ML/day)	Ecological water requirements as percentage of daily flow
0 - 2.4	100%
2.5 - 140.9	65%
141.0 - 922.9	70%
923.0 - 2525.9	60%
2526.0 - 3239.9	90%
≥3240.0	100%

4.11 Evaluation of key components of the modelled flow for Reach 1

The Gantt charts shown in Figure 20 compare the observed flow record for Reach 1 of the Brunswick River with the modelled EWR generated by RESYM. The modelled EWR uses a proportion of the observed daily flow within a defined series of flow ranges, as shown in Table 5. For Reach 1, there were nine unique flow thresholds, each of which was evaluated by comparing the observed flow with the modelled EWR flow. Each of the nine flow thresholds is represented as one 'Plot' on Figure 20. As shown in Table 4, two of the 'flow-ecology rules' (relating to winter habitat for macroinvertebrates and upstream migration of small-bodied fish) coincidentally had the same threshold flow in Reach 1. Further detail on the flow regimes associated with the nine unique threshold flows for Reach 1 is provided in the following sections.

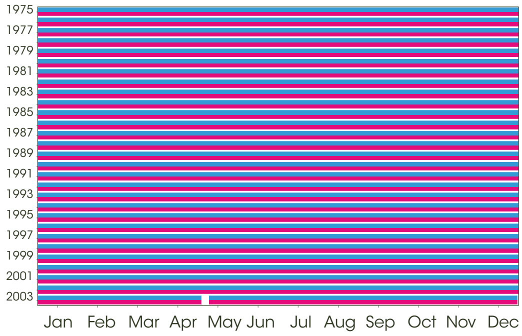
4.11.1 Summer minimum flow

A flow rate of at least 0.02 m^3/s or 1.7 ML/day is required in Reach 1 of the Brunswick River year-round to maintain flow permanency, reduce stresses on aquatic fauna and maintain water quality in pools. The critical period for this discharge is the driest part of the year between December and April. To provide for this objective, RESYM was set up to retain 100 per cent of the observed daily flow in the range between 0 and 2 ML/day (Table 5).

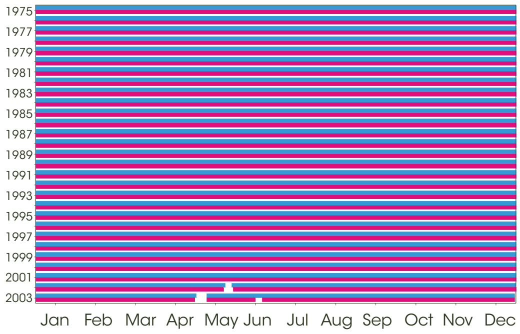
Plot 1 of Figure 20 compares the frequency and duration of flows above 1.7 ML/day in the RESYM-generated EWR flow with those for the observed flow record from 1975 to 2003. Flows of more than 1.7 ML/day occurred almost continuously throughout the entire flow record. There was a short period of approximately one week at the beginning of May in 2003 when observed flow fell below the threshold. As RESYM was set up to retain 100 per cent of daily flow below 2 ML/day, flows above 1.7 ML/day in the modelled EWR flow occurred with identical frequency and duration as for the observed flow.

Based on the information presented in Plot 1 of Figure 20, the expert panel concluded that summer low flows in the lower reaches of the Brunswick River would be maintained by the model parameters presented in Table 5.

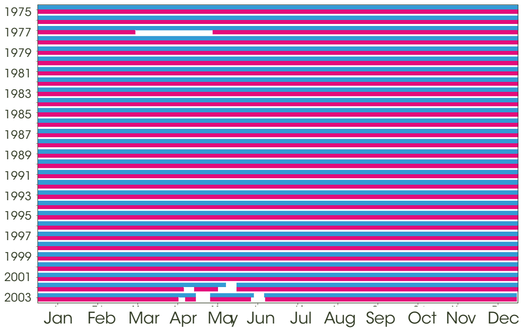
Plot 1: Summer minimum flow (0.02 m^3/s or 1.73 ML/day)



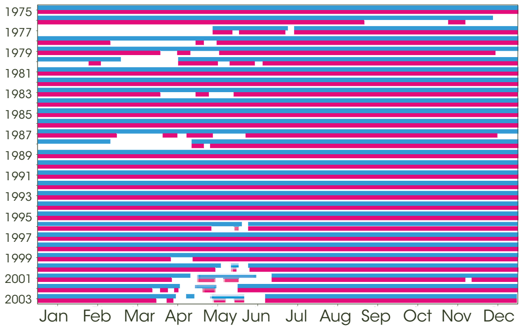
Plot 2: Summer macroinvertebrate habitat (0.06 m^3/s or 5.18 ML/day)



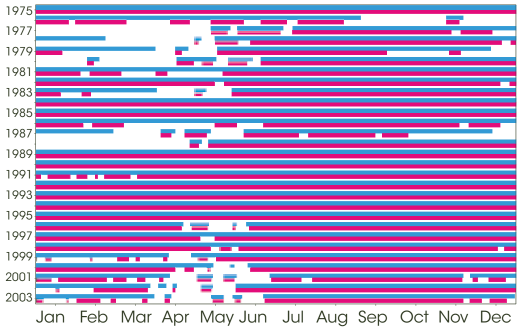
Plot 3: Upstream passage for small-bodied fish (0.11 m^3/s or 9.50 ML/day)



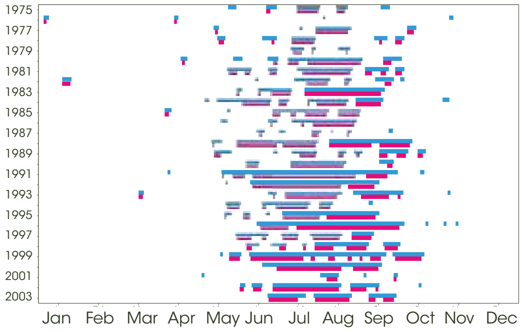
Plot 4: Upstream passage for large-bodied fish (0.25 m^3/s or 21.6 ML/day)



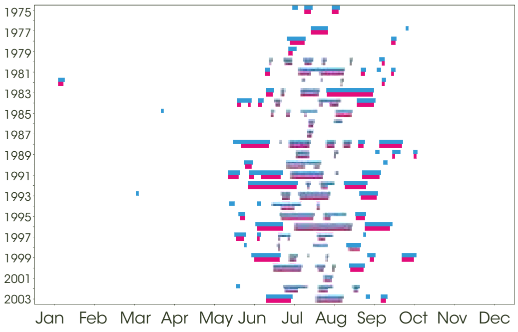
Plot 5: Inundation of low benches (0.36 m^3/s or 31.1 ML/day)



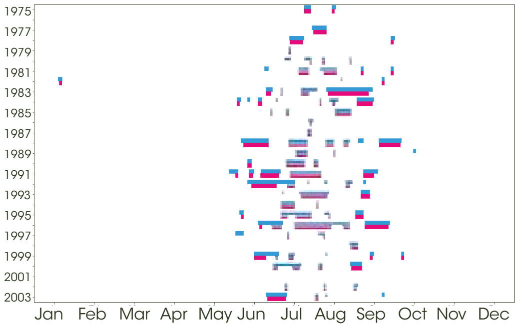
Plot 6: Inundation of medium benches (4.07 m^3/s or 352 ML/day)



Plot 7: Inundation of active channel (10.5 m^3/s or 907 ML/day)



Plot 8: Inundation of high benches (15.9 m^3/s or 1374 ML/day)



Plot 9: Inundation of floodplain (22.85 m^3/s or 1974 ML/day)

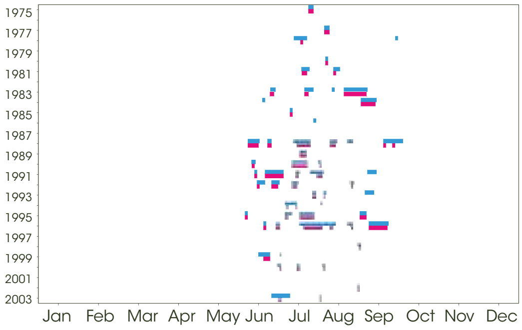


Figure 20

Flows above each of the ecological flow thresholds for the observed flow record (blue bars) compared with the modelled EWR flow (red bars) for Reach 1, generated by RESYM using the parameters in Table 5.

Based on the information presented in Plot 1 of Figure 20, the expert panel concluded that summer low flows in the lower reaches of the Brunswick River would be maintained by the model parameters presented in Table 5.

4.11.2 Summer macroinvertebrate habitat

To inundate sandy runs as habitat for invertebrates, an instantaneous flow rate of 0.06 m^3/s (or 5.2 ML/day) is required. Based on hydraulic analysis using RAP, this flow will inundate approximately 50 per cent of the width of shallow sandy runs to a depth of five centimetres. After the iterative process, as set out in Figure 6, it was agreed that the retention of 70 per cent of daily flow in the range between 2.1 and 49.9 ML/day met the objective to inundate sandy runs in summer (Table 5).

The frequency and duration of flows above 5.2 ML/day in the modelled EWR flow are compared with those for the observed flow record (1975–2003) in Plot 2 of Figure 20. Flows over 5.2 ML/day occurred almost continuously throughout the historical record from 1975 to 2003. In 2002 and 2003, there were short periods of approximately one week in May where flow fell below the threshold. Flows above 5.2 ML/day in the modelled EWR flow occurred with similar frequency and duration to those in the observed flow. There was a short period of several days in early June 2003 where the modelled flow fell below the threshold, while the observed flow remained above 5.2 ML/day.

Using the data presented in Plot 2 of Figure 20, the panel decided that flow frequency and duration above 5.2 ML/day in the modelled EWR series (based on the model parameters in Table 5) met the water requirements of invertebrate fauna in the dry months between December and May.

4.11.3 Winter macroinvertebrate habitat and upstream migration of small-bodied fish

A flow of 0.11 m^3/s or 9.5 ML/day is required to inundate the entire width of sandy runs in winter as invertebrate habitat. The same discharge is required to give sufficient water depth over obstacles (10 cm) to allow small-bodied fish to move upstream. To provide for these objectives, RESYM was set up to retain 70 per cent of the measured daily flow in the range 2.1 to 49.9 ML/day (Table 5).

Plot 3 of Figure 20 compares the frequency and duration of flows above 9.5 ML/day in the RESYM-generated EWR flow with those for the observed flow record. Flows over the threshold have occurred almost continuously throughout the period of past observations (1975 to 2003). There was one period in late May 2002 and two more in early May and mid-June 2003 when the observed flow dropped below the threshold. Each period lasted approximately one week. The modelled EWR flow was very similar to the observed flow, with similar short gaps in flow in 2002 and 2003. In 1977, there was an extended period of approximately two months when the modelled EWR flow would have fallen below the threshold, even though the observed flow remained above the threshold at all times.

Based on the close similarities between the observed flow and modelled EWR flows, the expert panel concluded that the RESYM parameters in Table 5 met the ecological objectives of maintaining winter macroinvertebrate habitat and providing sufficient water for migration of small-bodied fish in the lower reaches of the Brunswick River.

4.11.4 Upstream migration of large-bodied fish and inundation of spawning habitat

The only large-bodied freshwater fish in the Brunswick River, adult freshwater cobbler, requires a discharge of 0.25 m^3/s or 21.6 ML/day in Reach 1 to submerge obstacles to at least 20 centimetres and allow movement between river pools. The critical period for upstream migration for cobbler was deemed to be November to January, which coincided with the breeding period and an observed peak in localised upstream migration in the Blackwood River (Beatty et al. 2008). This flow also inundates emergent and fringing vegetation as spawning habitat for native fish. To provide for this objective, RESYM was set up to retain 70 per cent of daily flow in the range of 2.1 to 49.9 ML/day (Table 5).

The frequency and duration of flows above 21.6 ML/day in the RESYM-generated EWR flow are compared with those for the observed flow record (1975–2003) in Plot 4 of Figure 20. Flows above the threshold have occurred continuously for 20 of the years on record between 1975 and 2003. Since 1999, there have been one to three flow periods below the threshold every year, lasting up to two weeks at a time. These 'below threshold' periods of flow have generally occurred in April, May and early June, towards the end of the dry part of the year. Lengthier periods of flow below 21.6 ML/day occurred in 1977, 1980 and 1988, with the longest period of low flow of around four and a half months occurring in 1977.

The modelled EWR flow shows similar characteristics to the measured flow, with the exception of a number of extended periods of over one month where the modelled flow fell below the threshold while the observed flow remained higher than 21.6 ML/day. This situation occurred in the latter part of 1976, in the autumn of 1978, 1983 and 1987, and over the summers of 1979–80 and 1987–88. Since 1989, the modelled EWR flow has been very similar to the observed flow. Modelled and observed flows tend to commence at the same time, but the modelled EWR flow often tapers out before the observed flow, usually in mid-autumn.

Over the crucial period between June and October, the modelled EWR flow and the measured flow have been very similar, and have almost always been above the threshold of 21.6 ML/day. Using this information, the expert panel concluded that the RESYM parameters in Table 5 met the objective to provide sufficient water for migration of large-bodied fish and inundation of spawning habitat in the lower reaches of the Brunswick River.

4.11.5 Inundation of low benches

A flow of 0.36 m^3/s or 31.1 ML/day is required to inundate low benches. Inundation of low benches flushes carbon into the river system, inundates fringing vegetation and provides access to small tributaries for periods that may be adequate for successful spawning. This objective is a winter-critical objective, with the chief period of interest between May and October. To provide for this objective, RESYM was set up to retain 70 per cent of the measured daily flow in the range 2.1 to 49.9 ML/day (Table 5).

Plot 5 of Figure 20 compares the frequency and duration of flows above 31.1 ML/day in the RESYM-generated EWR flow with those for the observed flow record. Flows above the threshold have occurred continuously throughout 15 of the years between 1975 and 2003. In all except three of the years on record, there have been no flow periods below 31.1 ML/day for more than about one week between the start of July and the end of November. Between 1996 and 2003, flows above the threshold have often been intermittent throughout April, May and June.

Modelled EWR flows have generally been similar to the observed flows over 31.1 ML/day. However, there have been a number of extended periods (i.e. more than one month), when the modelled EWR flow would have fallen below the measured discharge. This has tended to occur in late spring, summer and early autumn. Examples of such events occurred in 1978, 1979, 1981, 1983, 1986, 1987, 1999 and 2002.

Inundation of low benches fulfils the ecological functions of flooding emergent macrophytes, flushing organic carbon into the river system and providing spawning habitat and cover for fish. As the modelled EWR and the observed flow were generally very similar during the critical months of May to October, the expert panel concluded that the RESYM parameters in Table 5 met the objective of providing sufficient water to inundate low benches in the lower reaches of the Brunswick River.

4.11.6 Inundation of medium benches

Inundation of medium benches within Reach 1 requires a discharge of 4.1 m^3/s or 352 ML/day. To provide for this objective, RESYM was set up to retain 60 per cent of the daily flow volume within the flow range between 50 and 1046.9 ML/day (Table 5).

The frequency and duration of flows above 352 ML/day in the RESYM-generated EWR flow are compared with those for the observed flow record (1975–2003) in Plot 6 of Figure 20. Flows over the threshold have occurred in all years on record, typically between May and October, with a total annual duration ranging between two weeks (e.g. 1976) and around four months (e.g. 1991 and 1999).

The modelled EWR flow closely mimics the observed flow over the threshold, although it is common for the duration of the modelled flow to commence just after and finish just before the observed discharge over 352 ML/day. For a small number of events, the modelled EWR flow over 352 ML/day was intermittent throughout a long period of observed flow over the threshold (for example, during the winter of 1999).

As the ecological purposes of inundating medium benches are to wash organic carbon from the banks into the river and inundate trailing and riparian vegetation as fish habitat, it is important that this flow occurs at regular intervals; but neither the frequency nor duration of these flows need be identical to the natural frequency to maintain the flow's ecological function. The expert panel decided that the ecological impact of differences in frequency and duration between the modelled EWR series and the observed flow record would likely be small.

4.11.7 Inundation of the active channel

A discharge of 10.5 m^3/s or 907 ML/day is required to maintain active channel morphology. This flow is required to inundate the average depth of the bed to active channel height along the entire reach, with the active channel height defined as the level on the banks above which vegetation is stable and below which the bank is eroding and without extensive riparian vegetation. To provide for this objective, RESYM was set up to retain 60 per cent of the daily flow volume between 50 and 1046.9 ML/day (Table 5).

Plot 7 of Figure 20 compares the frequency and duration of flows above 907 ML/day in the RESYM-generated EWR flow with those for the observed flow record. Flows sufficient to inundate the active channel were recorded in all except one of the years on record between 1975 and 2003. Flows over the threshold were most common between June and September, although some short periods were recorded in January, March, April, May and October. There was a great deal of inter-annual variation in the total duration of flows over the threshold. In some years, flows over 907 ML/day occurred almost throughout the entire winter (e.g. in 1988, 1991 and 1996), while in other years there were short periods (i.e. around one week) over the threshold interspersed with periods of one to four weeks below the threshold (e.g. in 1982, 1986, 1989, 1997 and 1998).

Flows of greater than 907 ML/day were slightly less frequent and almost always of shorter duration in the modelled EWR flow than in the measured flow. Events for which there was no modelled EWR flow tended to be the shorter observed events of one week or less. For the longer duration events (the longest of which lasted approximately six weeks in 1996), modelled EWR flow was over the threshold for almost the entire duration of the observed flow.

The ecological purpose of active channel flows is to maintain the shape of the channel by mobilising sediment, scouring pools and preventing riparian vegetation from encroaching into the channel. It is important that this flow occurs at regular intervals, but neither the frequency nor duration of these flows need be identical to the natural frequency to maintain the flow's ecological function. The expert panel concluded that there would be relatively little ecological impact from the differences in frequency and duration between the modelled EWR series and the observed flow record.

4.11.8 Inundation of high benches

Inundation of high benches and associated vegetation in Reach 1 requires a discharge of 15.9 m^3/s or 1374 ML/day. To provide for this objective, RESYM was set up to retain 75 per cent of the daily flow volume in the range between 1047 and 1449.9 ML/day (Table 5).

The frequency and duration of flows above 1374 ML/day in the RESYM-generated EWR flow are compared with those for the observed flow record (1975–2003) in Plot 8 of Figure 20. Flows over the threshold have occurred in all but two of the years on record, typically between June and September. There is high variability in the duration of these flows both within and between years. The longest lasted for approximately six weeks in 1996, but a more 'typical' duration seems to be about two to three weeks.

As with active channel flows, in the modelled EWR, flows over the threshold were slightly less frequent than in the measured flow record. However, on many occasions the duration of the modelled and observed events was equivalent. Events for which there was no modelled EWR flow were generally those of one week or less.

As the ecological purpose of inundating high benches is to wash organic carbon from the banks into the river, it is important that this flow occurs at regular intervals, but neither the frequency nor duration of the flows need be identical to the natural frequency to maintain the flow's ecological function. The expert panel felt that the physical impact of differences in frequency and duration between the modelled EWR and the observed flow record would probably be small.

4.11.9 Bankfull and overbank flows

A discharge of 22.8 m^3/s or 1974 ML/day is required to commence inundation of the floodplain and associated riparian vegetation. To provide for this objective, RESYM has been set up to retain 85 per cent of the daily flow volume in the range between 1450 and 3053.9 ML/day, 65 per cent of the daily flow volume between 3054 and 4334.9 ML/day, 60 per cent of the daily flow volume between 4335 and 8179.9 ML/day, and 100 per cent of the daily flow volume over 8180 ML/day (Table 5).

Plot 9 of Figure 20 compares the frequency and duration of flows above 1974 ML/day in the RESYM-generated EWR flow with those for the observed flow record. Flows above the threshold have occurred at least once in all but five of the 28 years on record. These flows have occurred between about the beginning of June and the beginning of October. Flows over the threshold have ranged in duration between one day and approximately one month, but have typically occurred as short spells over a few days, separated by intervals of one to three weeks. From 1998 to 2003, the average annual duration of flows over the threshold appears to be lower than between 1987 and 1996.

The modelled EWR flow is very similar to the observed flow record. Modelled EWR flows have often been of slightly shorter duration (around 20 to 30 per cent shorter) than the observed flow. Of the 48 events over the threshold between 1975 and 2003, there have been nine occasions when the observed flow reached the threshold of 1974 ML/day, but the modelled EWR flow remained below the threshold for the entire recorded spell.

Overbank flows are required to inundate and recharge wetlands located on the floodplain of the Brunswick River, and to aid in the seed dispersal and germination of riparian plant species such as *Eucalyptus rudis* and paperbark (*Melaleuca spp.*). These events are irregular and of short duration, so it is important that the modelled EWR mimics the frequency of natural events. Given that the modelled EWR would have provided sufficient flow to overtop banks for over 80 per cent of observed events over the threshold, the expert panel concluded that the RESYM parameters in Table 5 met the objective to provide sufficient water to inundate the floodplain in the lower reaches of the Brunswick River.

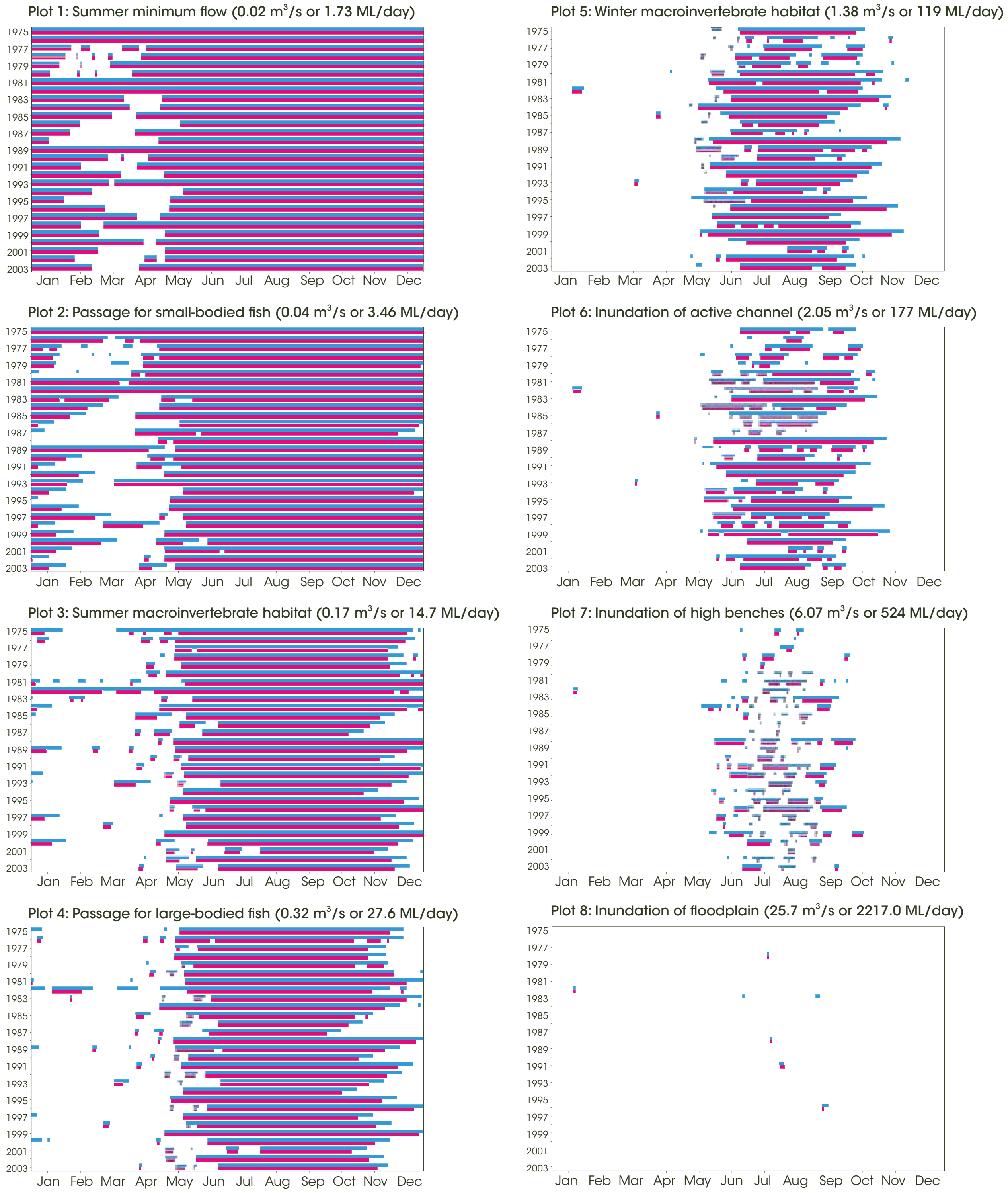
4.12 Evaluation of key components of the modelled flow for Reach 2

The Gantt charts shown in Figure 21 compare the observed flow record for Reach 2 of the Brunswick River with the modelled EWR generated by RESYM. The modelled EWR uses a proportion of the observed daily flow within a defined series of flow ranges, as shown in Table 6. For Reach 2, there were nine unique flow thresholds, each of which was evaluated by comparing the observed flow with the modelled EWR flow (refer Table 4). However, two of the flow thresholds were very similar (those relating to inundation of low benches and the active channel) and therefore evaluated together, giving a total of eight different modelled flow thresholds. Each of the eight flow thresholds is represented as one `Plot' on Figure 21. Further detail on the flow regimes associated with the eight threshold flows for Reach 2 is provided in the following sections. Note that the flow events are listed in order of increasing magnitude, and that this order is not the same as that derived for Reach 1.

4.12.1 Summer minimum flow

A flow rate of at least 0.02 m^3/s or 1.7 ML/day is required in Reach 2 of the Brunswick River to maintain flow permanency, reduce stresses on aquatic fauna and maintain water quality in pools. To provide for this objective, RESYM was set up to retain 100 per cent of the observed daily flow in the range between 0 and 2.4 ML/day (Table 6).

Plot 1 of Figure 21 compares the frequency and duration of flows above 1.7 ML/day in the RESYM-generated EWR flow with those for the observed flow record from 1975 to 2003. Flows of more than 1.7 ML/day occurred almost continuously from late May to mid-January throughout the entire flow record. Observed flows of less than 1.7 ML/day have occurred in all but three of the years on record. There tended to be one continuous period of flow below the threshold every year at some point between late January and late May, lasting anywhere from at least one month, and sometimes up to three and a half months. As RESYM was set up to retain 100 per cent of daily flow below 2 ML/day, flows above 1.7 ML/day in the modelled EWR flow occurred with identical frequency and duration as for the observed flow.



Plot 1: Summer minimum flow (0.02 m^3/s or 1.73 ML/day)

Plot 2: Passage for small-bodied fish (0.04 m^3/s or 3.46 ML/day)

Plot 3: Summer macroinvertebrate habitat (0.17 m^3/s or 14.7 ML/day)

Plot 4: Passage for large-bodied fish (0.32 m^3/s or 27.6 ML/day)

Plot 5: Winter macroinvertebrate habitat (1.38 m^3/s or 119 ML/day)

Plot 6: Inundation of active channel (2.05 m^3/s or 177 ML/day)

Plot 7: Inundation of high benches (6.07 m^3/s or 524 ML/day)

Plot 8: Inundation of floodplain (25.7 m^3/s or 2217.0 ML/day)

Figure 21

Flows above each of the ecological flow thresholds for the observed flow record (blue bars) compared with the modelled EWR flow (red bars) for Reach 2, generated by RESYM using the parameters in Table 6.

The observed discharge data shows that flow in the upper reaches of the Brunswick River is perennial, with a period of very low or zero flow in late summer to autumn. The required flow has rarely been achieved year-round in the 'natural' flow regime, so neither will it be in the modelled EWR. The expert panel concluded that the existing summer low flows in the upper reaches of the Brunswick River would be maintained by the model parameters presented in Table 6.

4.12.2 Upstream migration of small-bodied fish

To allow upstream migration of small native fish, an instantaneous flow rate of 0.04 m^3/s or 3.5 ML/day is required. Based on the results of hydraulic modelling, this flow will achieve a depth of 10 centimetres over the shallowest section, which was a bar at cross-section 8. The critical period for this flow is from around June to November, when small-bodied fish migrate upstream to spawn. To provide for this objective, RESYM was set up to retain 65 per cent of the observed daily flow in the range between 2.5 and 140.9 ML/day (Table 6).

The frequency and duration of flows above 3.5 ML/day in the RESYM-generated EWR flow are compared with those for the observed flow record (1975–2003) in Plot 2 of Figure 21. Flows above 3.5 ML/day in the modelled EWR flow occurred with similar frequency and duration to those in the observed flow. Between June and December, historical flows have generally been above 3.5 ML/day. Flow periods below 3.5 ML/day have occurred in all but three of the years on record. Extended low periods of flow below the threshold (i.e. two to four months duration) have occurred almost every year at some point between the end of November and the middle of May.

The modelled EWR flow tended to commence at the same time as the observed flow, but generally finished about two weeks before the observed flow fell below the threshold. This is likely due to a rainfall-induced rapid increase in discharge at the start of winter, and a more gradual decline in discharge in late spring and early summer. It is important to note that the modelled EWR and observed flow commence at the same time, as fish follow environmental cues at the beginning of the migration season to commence spawning.

Due to the similarities between the observed and modelled EWR discharges, the panel decided that flow frequency and duration above 3.5 ML/day in the modelled EWR series (based on the model parameters in Table 6) met the water requirements for upstream migration of small-bodied native fish in Reach 2.

4.12.3 Summer macroinvertebrate habitat

A flow of 0.17 m^3/s or 14.7 ML/day is required to inundate half the measured width of sandy runs and provide macroinvertebrate habitat in summer. To provide for this objective, RESYM was set up to retain 65 per cent of the measured daily flow in the range 2.5 to 140.9 ML/day (Table 6).

Plot 3 of Figure 21 compares the frequency and duration of flows above 14.7 ML/day in the RESYM-generated EWR flow with those for the observed flow record. Flows of this magnitude have occurred naturally from late autumn or early winter through late spring to mid-summer. In some years, there have been intermittent, short periods of flow over the threshold, at intervals throughout summer and early autumn.

Historically, flows above 14.7 ML/day have not occurred during the driest parts of the year in Reach 2, so it is likely that invertebrates in this part of the river are adapted to this seasonal lack of habitat in the middle reaches of the Brunswick River in late summer. Due to the similarities in the frequency and duration of flows above 14.7 ML/day in the observed and EWR flow, the panel decided that the modelled EWR series (based on the model parameters in Table 6) met the summer water requirements of invertebrate fauna in Reach 2.

4.12.4 Upstream migration of large-bodied fish

A discharge of 0.32 m^3/s or 27.6 ML/day is required to submerge obstacles to at least 20 centimetres and allow large adult freshwater cobbler to move upstream. To provide for this objective, RESYM was set up to retain 65 per cent of daily flow in the range of 2.5 to 140.9 ML/day (Table 6).

The frequency and duration of flows above 27.6 ML/day in the modelled EWR flow are compared with those for the observed flow record (1975–2003) in Plot 4 of Figure 21. The pattern of flow was very similar to that observed for the previous objective of small-bodied fish, with continuous flows over the threshold from late autumn or early winter to mid-spring or early summer. There have been relatively few periods of flow over the threshold during summer and autumn. The critical period for upstream migration for large-bodied fish was deemed to be June to October; during these months, the observed flow has generally been above the required flow of 27.6 ML/day.

The modelled EWR flow has typically commenced at the same time as the observed flow, but tends to taper out and finish one to two weeks earlier. There have been a small number of breaks in the modelled EWR flow during the winter months, at the same time as the observed flow remained above the threshold. Over the crucial period between June and October, the modelled EWR flow and the measured flow have been similar, and have almost always been above the threshold of 27.6 ML/day. Using this information, the expert panel concluded that the RESYM parameters in Table 6 met the objective to provide sufficient water for migration of large-bodied fish in the upper reaches of the Brunswick River.

4.12.5 Winter macroinvertebrate habitat

A flow of 1.4 m^3/s or 119 ML/day is required to inundate 100 per cent of the measured width of riffles in Reach 2. This objective is a winter-critical objective, with the chief period of interest between May and October. To provide for this objective, RESYM was set up to retain 65 per cent of the measured daily flow in the range 2.4 to 140.9 ML/day (Table 6).

Plot 5 of Figure 21 compares the frequency and duration of flows above 119 ML/day in the RESYM-generated EWR flow with those for the observed flow record. Flows above the threshold have occurred in all years on record (1975–2003). Flows over the threshold have occurred mainly between May and November, although there have been short periods of flow above the threshold outside of these times. Flows over the threshold tend to be continuous throughout the winter period, although there have been occasional periods of flow below the threshold in mid-winter.

Modelled EWR flows have generally occurred with a similar frequency and duration to the observed flows over 119 ML/day. However, there have been a number of short periods of one to two weeks in winter when the modelled EWR flow would have fallen below the threshold discharge. Modelled EWR flows and observed flows have tended to commence at the same time, although EWR flows over the threshold have generally tapered off around two weeks before the observed flow fell below the threshold.

As the modelled EWR flow and the observed flow were generally similar during the critical months of May to October, the expert panel concluded that the RESYM parameters in Table 6 met the objective of providing sufficient water to inundate invertebrate habitat in the middle reaches of the Brunswick River during winter.

4.12.6 Inundation of the active channel and low benches

A discharge of 2.1 m^3/s or 177 ML/day is required to fill the active channel and maintain the morphology of the low-flow channel. The same flow also inundates the low benches found in Reach 2. The active channel height is defined as the level on the banks above which vegetation is stable, and below which the bank is eroding and without extensive riparian vegetation. Inundation of low benches flushes organic carbon into the river and provides access to small tributaries by native fish for periods that allow successful spawning. To provide for this objective, RESYM was set up to retain 70 per cent of the daily flow volume between 141 and 922.9 ML/day (Table 6).

Plot 6 of Figure 21 compares the frequency and duration of flows above 177 ML/day in the RESYM-generated EWR flow with those for the observed flow record. Flows sufficient to inundate the active channel and flood low benches were recorded in all years on record (1975 and 2003). Flows over the threshold were most common between May and October. There was notable interannual variation in the total duration of flows over the threshold. In some years, flow over 177 ML/day occurred almost continuously for four or five months, while in other years there were intermittent periods of flow, of two to three weeks duration, interspersed with periods of flow below the threshold.

Flows of greater than 177 ML/day were slightly less frequent and almost always of shorter duration in the EWR flow than in the observed flow. Events for which there was no modelled EWR flow tended to be the shorter observed events of one week or less. For the longer duration events, the modelled EWR flow tended to taper out one or two weeks before the observed flow.

The ecological purpose of this flow is to maintain the shape of the low flow channel by preventing riparian vegetation from encroaching into the channel, and to wash organic matter that has accumulated on low benches into the river. It is important that this flow occurs at regular intervals, but neither the frequency nor duration of flows above 177 ML/day need be identical to the natural frequency to maintain the flow's ecological function. The expert panel concluded that there would be relatively little ecological impact from the differences in frequency and duration between the modelled EWR flow and the observed flow record.

4.12.7 Inundation of high benches

Inundation of high benches and associated vegetation in Reach 2 requires a discharge of 6.1 m^3/s or 524 ML/day. To provide for this objective, RESYM was set up to retain 70 per cent of the daily flow volume in the range between 141 and 922.9 ML/day (Table 6) .

The frequency and duration of flows above 524 ML/day in the RESYM-generated EWR flow are compared with those for the observed flow record (1975–2003) in Plot 7 of Figure 21. Flows over the threshold have occurred in all years on record, even if only for short periods of less than one week. Flows over the threshold have typically occurred between May and October. There has been great variability in the duration of flows exceeding the threshold both within and between years. The longest period of time where flows exceeded 524 ML/day was approximately six weeks in 1996 and 1991, but a more 'typical' duration is between two and three weeks.

Flows over the threshold were less frequent in the modelled EWR flow than in the measured flow record. However, on many occasions the duration of the modelled and observed events was similar. Modelled EWR flow events over the threshold occurred in all years except for 1976, during which the observed flow over the threshold lasted just a few days.

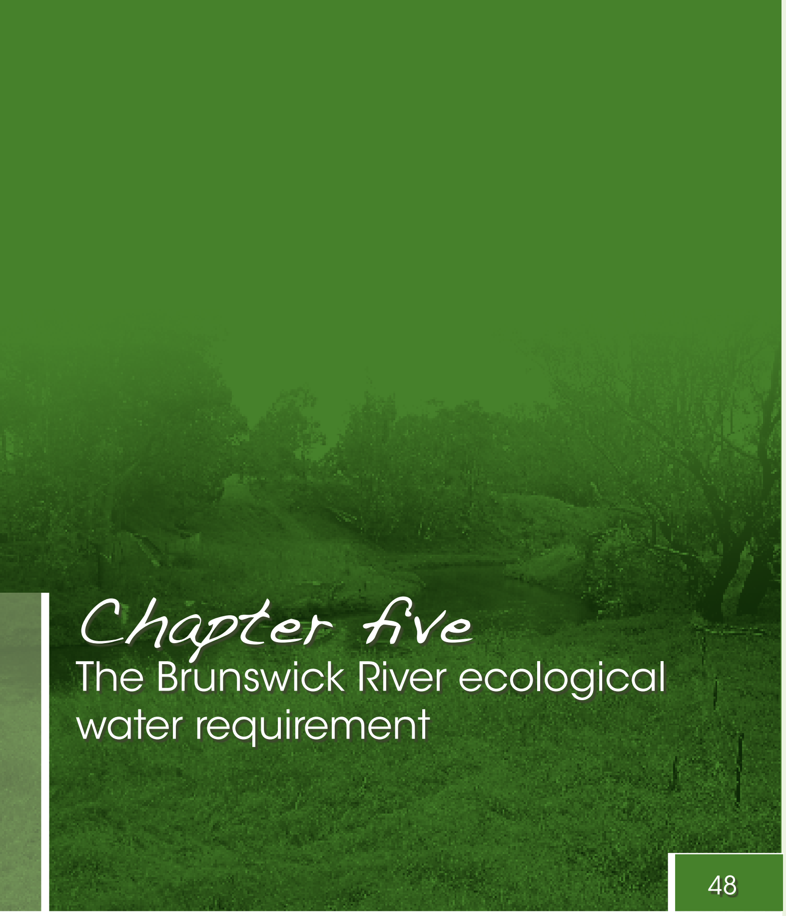
As the ecological purpose of inundating high benches is to wash organic carbon from the banks into the river, it is important that this flow occurs at regular intervals; but neither the frequency nor duration of spells need be identical to the natural frequency to maintain the flow's ecological function. The expert panel therefore felt that the physical impact of differences in frequency and duration between the modelled EWR series and the observed flow record would probably be small.

4.12.8 Bankfull and overbank flows

A discharge of 25.7 m^3/s or 2217 ML/day is required to commence inundation of the floodplain and associated riparian vegetation. To provide for this objective, RESYM has been set up to retain 60 per cent of the daily flow volume in the range between 923 and 2525.9 ML/day, 90 per cent of the daily flow volume between 2526 and 3239 ML/day, and 100 per cent of the daily flow volume over 3240 ML/day (Table 6).

Plot 8 of Figure 21 compares the frequency and duration of flows above 2217 ML/day in the RESYM-generated EWR flow with those for the observed flow record. Flows of this magnitude have occurred just seven times in the 28 years on record, giving an average return interval of once every four years. Periods of flow above the threshold have been short (i.e. one week or less). The modelled EWR flow shows similar characteristics to the observed flow. Modelled EWR flows over the threshold occurred for five of the seven observed events.

Overbank flows are required to inundate and recharge wetlands located on the floodplain of the Brunswick River, and to aid in the seed dispersal and germination of riparian plant species such as *Eucalyptus rudis* and paperbark (*Melaleuca spp.*). These events are irregular and of short duration, so it is important than the modelled EWR mimics the frequency of natural events. Given that the modelled EWR would have to provided sufficient flow to overtop banks for over 70 per cent of observed events over the threshold, the expert panel concluded that the RESYM parameters in Table 6 met the objective to provide sufficient water to inundate the floodplain in the upper reaches of the Brunswick River.



Chapter five

The Brunswick River ecological water requirement

After consideration of the frequency and duration of ecologically functional flows in both the observed and modelled flow, the expert panel concluded that the modelled EWR flow regime described in the preceding sections would maintain the ecological values of the lower reaches of the Brunswick River system at a low level of risk.

The complete modelled EWR flow for Reach 1 of the Brunswick River for the period 1975–2003 (based on the extraction parameters in Table 5) is shown in Figure 22. An example of the interannual differences in the observed and EWR flow is shown in Figure 23, which shows the detail of the modelled EWR flow and observed flow in Reach 1 for the years 1987, 1988 and 1989. As is clearly shown in the figures, the modelled EWR flow acquires a varying proportion of the observed flow, according to the magnitude of any particular event. The difference between the modelled EWR flow and the measured flow is the volume of water that could be harvested sustainably, without placing the natural environment at risk.

Figure 24 (Reach 1) and Figure 25 (Reach 2) compare the flow duration of the observed flows against the modelled EWR flow regime. The curves show the percentage of time that flows of particular volumes have been exceeded, with reference points on the flow duration curve to indicate the flow rate required to satisfy key flow-ecology linkages.

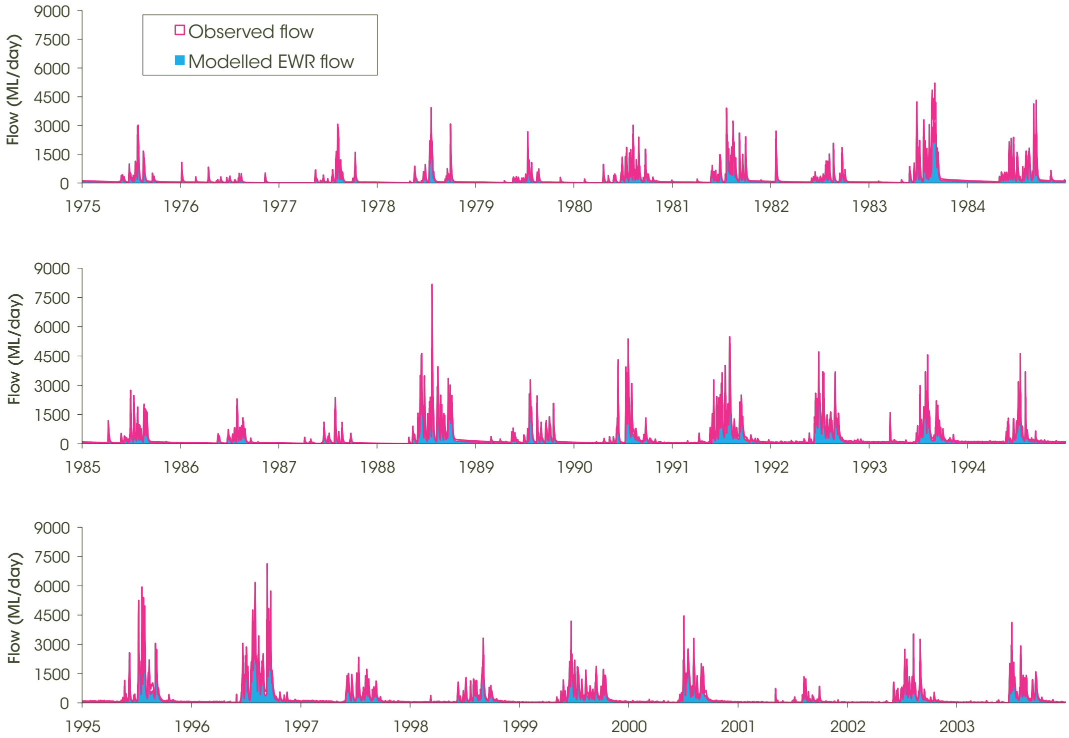


Figure 22

Time series of the observed flow and modelled EWR flow for Reach 1 of the Brunswick River, 1975–2003

The difference between the blue line (observed flow record) on Figure 24 and Figure 25 and the red line (modelled EWR flow) represents the volume of water that is additional to the calculated ecological water requirements of the lower and middle reaches of the Brunswick River system.

The flow-duration curves compare the gauged 'natural' flow with the modelled EWR flow across the full range of flow. They show for example, that the lowest volume flows (i.e. less than 10 ML/day) have been achieved around 80 to 90 per cent of the time in both the observed and modelled EWR flow. Similarly, very high volume flows (over 1500 ML/day in Reach 1 and over 1000 ML/day in Reach 2) occur infrequently (less than five per cent of the time period on record).

The plots also show how the ecological flow thresholds are distributed across the observed flow range. Notice the threshold flows are not evenly distributed across flow ranges. The thresholds in Reach 1 form two distinct clusters, one in low flow ranges below about 30 ML/day and another in the high flow ranges above 350 ML/day (Figure 24). This distribution of thresholds probably reflects the highly incised morphology of the river channel. The even distribution of the flow thresholds in Reach 2 is more typical of a natural shaped river channel (Figure 25).

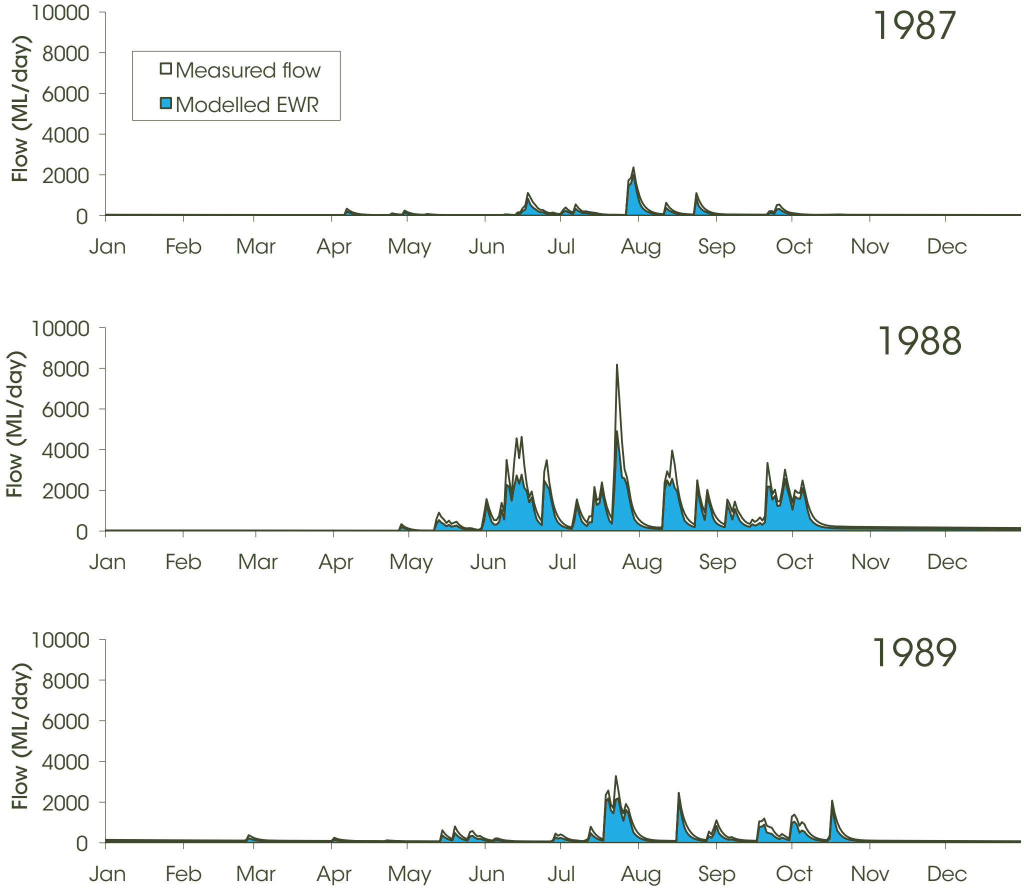


Figure 23

Observed flow and modelled EWR flow for Reach 1 of the Brunswick River: 1987, 1988 and 1989. Flow in 1987 was the lowest on record while 1988 had the highest flow on record. A medium to low flow year was observed in 1989.

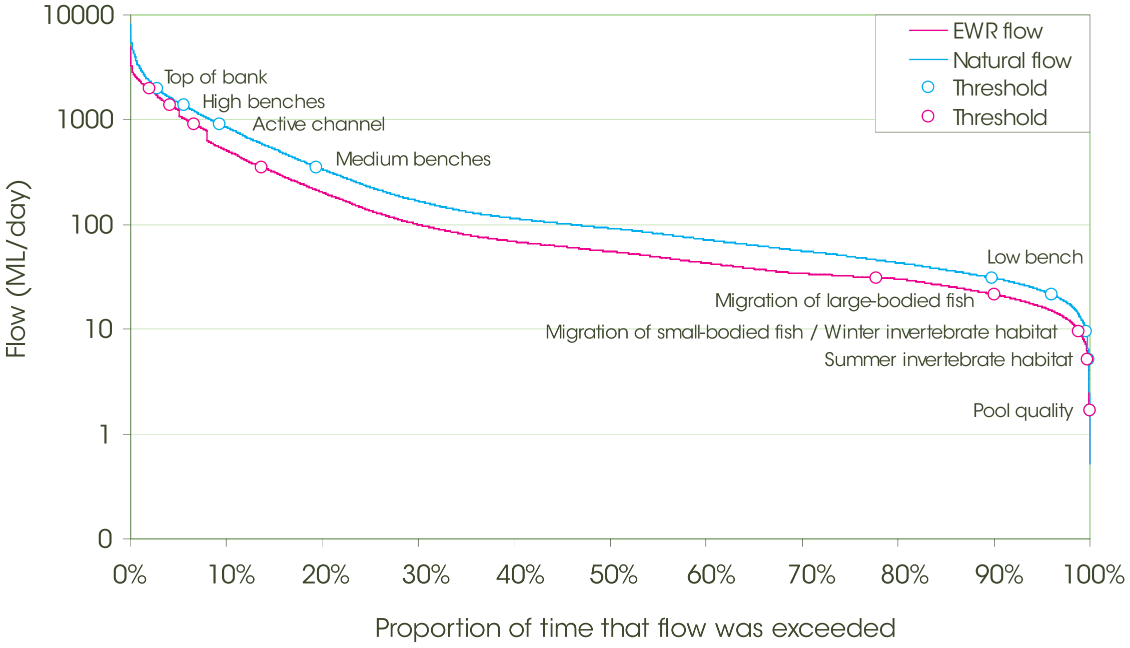


Figure 24

Flow duration curve for Reach 1 of the Brunswick River, showing observed flow versus modelled EWR flow. The blue line is the observed curve for the period 1975–2003 and the red curve is for the EWR flow over the same period (based on the parameters in Table 5).

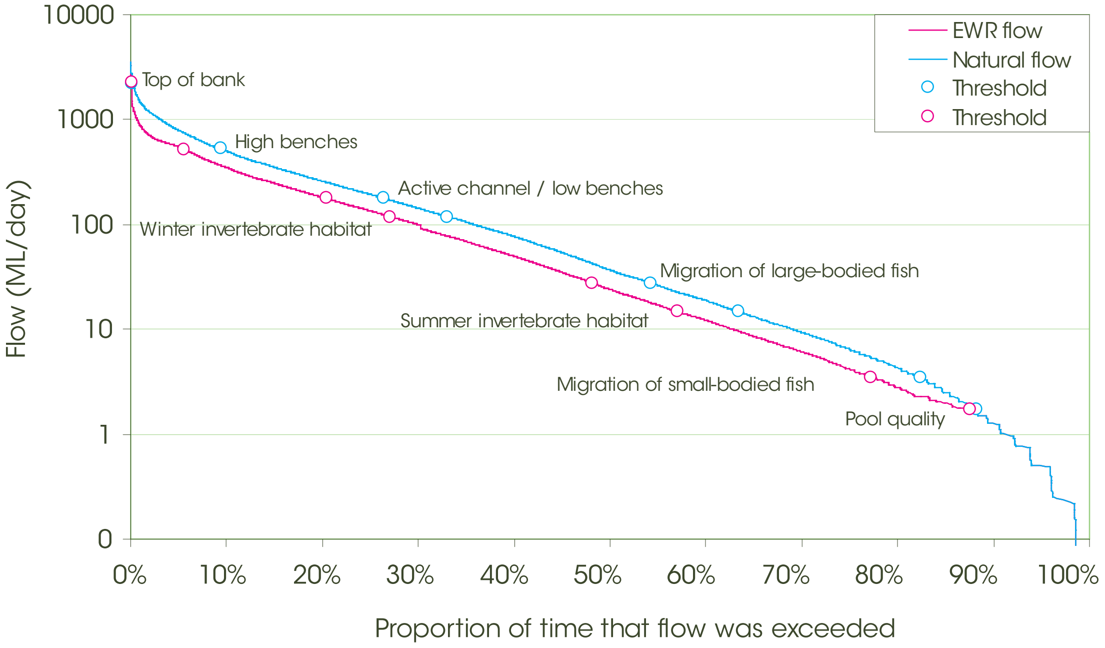


Figure 25

Flow duration curve for Reach 2 of the Brunswick River, showing observed flow versus modelled EWR flow. The blue line is the observed curve for the period 1975–2003 and the red curve is for the EWR flow over the same period (based on the parameters in Table 6).

5.1 Advantages and limitations of using RESYM and the PADFLOW method

There are a number of advantages and limitations of the PADFLOW method (including the application of RESYM) that must be mentioned. PADFLOW differs markedly from other methods that have previously been used to determine EWRs in Western Australia. Most notably, PADFLOW results in an EWR that varies substantially from year to year, whereas other methods such as the 'flow events method' tended to produce a static 'base' volume of water for each month of the year, with additional water allocated to flow events of unusually high magnitude that have a natural recurrence interval of more than one year.

The PADFLOW method produces an EWR that is more 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). Because RESYM generates an EWR as a proportion of the observed flow record, the final EWR series retains the variability present in the natural daily flow, including variation in annual volume (Figure 22) and seasonal patterns (Figure 23), while at the same time incorporating long-term trends in flow.

Two other key features of PADFLOW and the resultant EWR are the inclusion of periods of zero or very low flow, and the ability to incorporate trends in rainfall and streamflow into the EWR. One of the aims of producing any EWR in south-west rivers is to maintain the river's natural pattern of flows. Research on invertebrate communities in south-west rivers has shown that perennial and seasonally flowing rivers have different and characteristic invertebrate communities. In non-permanent streams or rivers, it is important to incorporate periods of no-flow into the EWR to maintain these characteristic fauna. It is also important that the duration of these no-flow periods does not change substantially in the EWR flow to avoid causing stress to aquatic fauna in river pools, particularly fish species. Few native fish in the south-west of Western Australia have evolved physiological adaptations to survive desiccation.

To date, long-term trends in rainfall and streamflow due to climate change have not been considered in EWR studies conducted in Western Australia. While the change in rainfall and flows in the south-west may be anthropogenic, a drying climate is an evolutionary pressure for water-dependent species. In order to survive, water-dependent species will need to adapt to increasing periods of no flow or very little flow over the summer. The harsh environmental conditions of highly variable climate is partly responsible for the low diversity of invertebrates and fish and high levels of endemic species currently found in the south-west of Western Australia. It is important to incorporate long-term variability in flows into the EWR flow, thereby minimising the risk that native species will become accustomed to an EWR flow that is based on average conditions, including periods of high rainfall and streamflow, not current or future trends.

There are also some important limitations to the use of PADFLOW that must be considered. Figure 24 and Figure 25 show how the process of extracting a proportion of the daily volume of water flowing through the Brunswick River has decreased the duration of flows above each key ecological threshold across the entire range of flows. This is an unavoidable consequence of removing water from any river system. PADFLOW, like most other methods of calculating a river system's EWR, emphasises the volume of water needed to fulfil key ecological functions more than it does the length of time required for flows above a particular flow threshold to achieve ecological objectives. As a consequence, PADFLOW cannot evaluate how decreasing the duration of flow events across the entire range of flows might influence channel morphology or broad-scale ecological and geomorphological processes.

Despite these problems, the modelled EWR flow regime developed using the PADFLOW method has produced a flow regime for the Brunswick River that conserves many of the ecologically-important features of the natural flow regime. Importantly, the flow-duration curves indicate that there has been no change to flow permanency, and little change to the magnitude and duration of summer low flows, or to the frequency and duration of very high magnitude flows (Figure 24 and Figure 25).

5.2 The ecologically sustainable yield for the Brunswick River

The Brunswick River EWR study was carried out to support water resource planning in the lower Collie River basin. The decision of where to place limits on water allocation considers a number of economic and environment factors including the yield of water that is ecologically sustainable. The EWR that was defined for Reach 1 and Reach 2 of the Brunswick River has been used to define the ecologically sustainable yield (ESY) of the river.

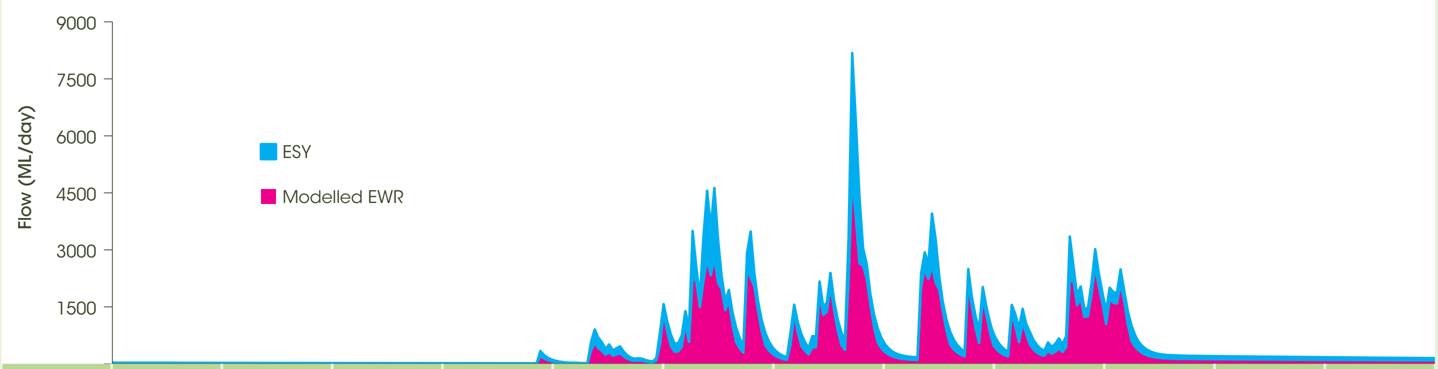
The ESY of the Brunswick River is the volume of water that could be extracted for use from the river while maintaining the current ecological values, the condition of the river system and the evolutionary capacity of its biota. The ESY is equivalent to the difference between the total discharge of the river and the modelled EWR flow for any given time period (see Figure 22 and Figure 23 for a graphic representation).

As an example of the detailed level at which ESY can be calculated, Figure 26 (Reach 1) and Figure 27 (Reach 2) compare the observed flow and the modelled EWR for 1988 for both study reaches of the Brunswick River. The yield has been calculated at a daily time step, and the ESY is shown for each day of 1988. In that year, the annual ESY for Reach 1 was 64 GL. The daily ESY ranged from less than five ML/day to over 3000 ML/day. In Reach 2, the daily ESY ranged from 0 ML/day to 800 ML/day, with a total annual ESY for the entire reach of 43 GL. The highest yields occurred between June and September, and the lowest in the late summer period.

It must be noted that the observed flow record incorporates water extraction (from pumping and damming), as well as changes to pre-European flow patterns caused by clearing of native vegetation and other land uses. Therefore, the ESY figures given in Figure 26 and Figure 27 would be in addition to current levels of water extraction, and are based on a flow regime that has been altered by human activities in the catchment.

As with flows, the annual total ESY of a river depends on rainfall, and is inherently variable from one year to the next. The PADFLOW approach quantified the ESY for the Brunswick River for the 28-year period between 1975 and 2003, as shown in Appendix 12 (Reach 1) and Appendix 13 (Reach 2). Based on the results of this study, the annual ESY for Reach 1 of the Brunswick River varied between about 10 and 70 GL/year depending on the annual flow (Appendix 12). The ESY in Reach 2 varied between about five and 45 GL/year over the same period (Appendix 13). It should be recognised that the yields in Reach 1 and Reach 2 are not independent of each other. Any abstraction from Reach 2 affects the yield available for allocation in Reach 1. For water resource proposals, these data are useful to inform the decision-making process and to model the reliability of the sustainable level of supply.

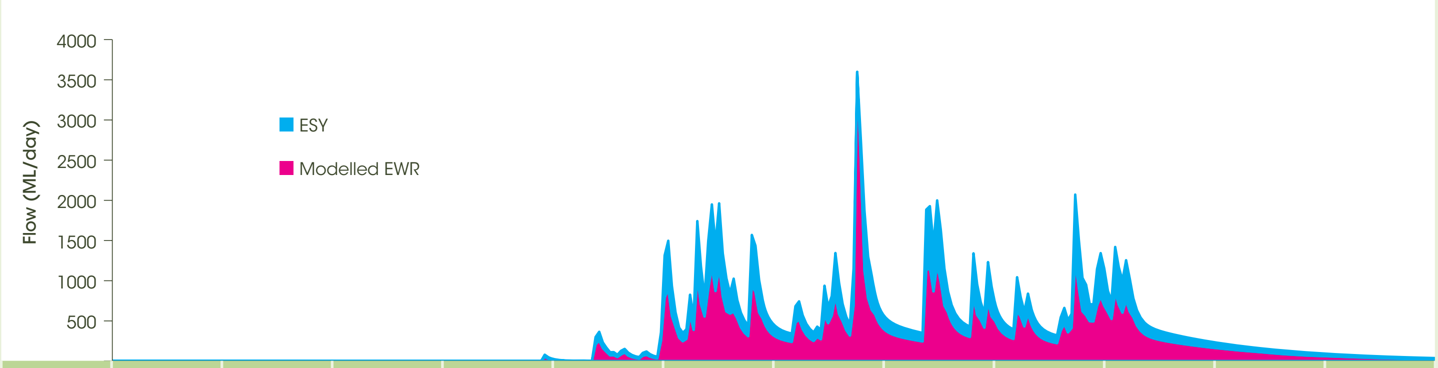
Observing the hydraulics and channel flow prior to marking out a cross-section



Day of Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Ecologically sustainable yield (ML/day)												
1	9	7	6	5	48	236	176	210	242	348	81	69
2	9	7	6	5	35	280	133	164	189	301	80	69
3	8	7	6	5	26	309	104	133	153	283	80	69
4	8	7	6	5	15	214	84	111	128	280	79	68
5	8	7	6	5	12	215	71	97	233	373	79	68
6	8	7	6	5	9	298	334	86	326	289	79	68
7	8	7	6	5	8	347	234	79	379	346	78	67
8	8	7	6	5	7	383	274	75	362	405	78	67
9	8	7	6	5	6	1224	312	71	262	304	78	67
10	8	7	6	5	6	384	226	69	334	235	77	66
11	8	7	6	5	6	263	168	357	252	188	77	66
12	8	7	6	5	232	1180	292	440	196	156	76	66
13	8	7	6	5	362	1823	287	394	158	134	76	65
14	8	7	6	5	275	1254	325	1385	141	119	76	65
15	8	7	6	5	228	1851	227	1151	226	109	75	65
16	8	7	6	5	158	1150	241	344	178	102	75	64
17	8	7	6	5	205	346	359	243	212	97	74	64
18	8	7	6	5	142	250	250	291	268	93	74	64
19	8	7	6	5	164	292	293	340	207	91	74	63
20	8	7	6	5	184	338	335	255	294	89	73	63
21	8	7	6	5	128	379	244	197	1173	87	73	63
22	8	7	6	5	90	270	1158	157	386	86	73	62
23	8	7	6	5	65	195	3272	130	272	85	72	62
24	8	7	6	5	54	437	2553	374	306	85	72	62
25	8	7	6	5	59	1219	1758	264	218	84	72	62
26	8	6	6	5	55	361	456	314	221	83	71	61
27	8	6	6	5	41	250	395	366	321	83	71	61
28	7	6	6	136	31	292	276	303	453	82	70	61
29	7	6	6	95	24	332	327	226	357	82	70	60
30	7		5	67	62	239	377	271	281	82	70	60
31	7		5		332		278	320		81		60
Total	**246**	**198**	**182**	**435**	**3066**	**16612**	**15820**	**9218**	**8726**	**5263**	**2253**	**1998**

Figure 26

Daily ecologically sustainable yield for Reach 1 of the Brunswick River, 1988



Day of Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Ecologically sustainable yield (ML/day)												
1	1	0	0	0	10	526	137	160	175	262	67	31
2	1	0	0	0	7	599	125	148	151	225	65	30
3	1	0	0	0	5	374	117	140	136	568	63	29
4	1	0	0	0	3	182	111	133	126	467	61	28
5	0	0	0	0	3	125	106	128	118	402	59	28
6	0	0	0	0	2	106	102	123	417	502	57	27
7	0	0	0	0	2	118	205	119	238	411	56	26
8	0	0	0	0	2	248	223	115	185	234	54	25
9	0	0	0	0	2	166	171	112	252	190	52	24
10	0	0	0	0	1	697	139	108	193	162	51	24
11	0	0	0	0	1	471	120	105	157	145	49	23
12	0	0	0	0	1	238	107	754	135	133	48	22
13	0	0	0	0	90	597	129	771	121	125	46	22
14	0	0	0	0	109	780	116	578	112	119	45	21
15	0	0	0	0	69	581	375	800	105	114	44	20
16	0	0	0	0	50	785	202	653	100	110	49	20
17	0	0	0	0	38	536	243	461	96	106	48	19
18	0	0	0	0	39	412	538	260	163	103	46	19
19	0	0	0	0	27	253	390	209	199	99	45	18
20	0	0	0	0	45	410	213	178	153	96	44	17
21	0	0	0	0	46	228	165	158	176	93	42	17
22	0	0	0	0	36	180	136	145	829	90	41	16
23	0	0	0	0	27	151	460	136	603	88	40	16
24	0	0	0	0	21	133	0	129	414	85	39	15
25	0	0	0	0	17	628	275	536	380	83	37	15
26	0	0	0	0	36	574	748	383	212	80	36	15
27	0	0	0	0	42	404	521	219	211	78	35	14
28	0	0	0	0	30	227	426	179	458	75	34	14
29	0	0	0	28	23	182	247	493	537	73	33	13
30	0		0	17	19	154	204	370	460	71	32	13
31	0		0		107		177	213		69		13
Total	4	0	0	45	909	11064	7228	9015	7610	5458	1418	636

Figure 27

Daily ecologically sustainable yield for Reach 2 of the Brunswick River, 1988

5.3 Implications for water resource planning

The results of this study are relevant to future water resource planning and management in the Brunswick River catchment. The daily calculation of the ESY using PADFLOW allows for a level of precision in water planning that has not previously been available for the area. The results are particularly important to the construction of new dams, and whether new dams should be located on-channel or off-stream.

Self-supply irrigators in the south-west intercept and store water for the summer irrigation season in small dams constructed on the river channel. The on-channel dams harvest water in the early part of the winter period. In summer, the dams intercept a large proportion of the summer low flows. However, even in highly developed catchments, the dams fill quickly in winter and begin to spill by around July (Sinclair Knight Merz 2007). This means that the sustainable total volume of on-stream dam development would be roughly equivalent to the total volume of the daily ESY in the early part of winter. Effectively, most of the discharge from the middle to late part of the flow season cannot be stored in on-stream dams, as they would already be full.

There have been proposals to require dams to be constructed off-stream and filled from daily pumping. The daily ESY generated using the PADFLOW method would be equivalent to the volume of water that could be sustainably pumped from the river and stored in off-stream storages. This means that the sustainable volume for off-stream dams would be far greater than the volume of water that could be sustainably intercepted and stored in on-channel dams, principally because flows in the middle and later part of winter could be pumped and stored off-stream without placing ecological values at risk. Given the increase in yield, there may be an economic incentive to construct future dams off-stream rather than on-channel.

The results of this study and those of the EWR study for Lefroy Brook (Donohue et al. 2009) indicate that relatively large volumes of water may be available during winter high flows with low additional risk to flow-dependent ecological values and processes, even in catchments with high levels of on-stream water storage. However, the allocation of water from winter high flows to consumers would need to be accompanied by appropriate restrictions on licence holders to maintain abstractions within the sustainable yields reported in Section 5.2 and also to protect downstream users. Restrictions could include limits on the daily volume of water pumped from the river, limits on when pumping may commence (i.e. after existing on-stream dams begin to spill), and a requirement for off-stream storage.

For development scenarios involving large water supply dams, the annual ESY is an important consideration. Where the management of the dams includes requirements for environmental releases, the daily sustainable yields may help define the daily volume to be released and the regime of releases needed to meet ecological objectives. The proportions of daily flow shown in Table 5 and Table 6 could be used as the basis for rules controlling environmental releases of water as a proportion of total inflow to the reservoir.

5.4 Future studies and monitoring

To confirm the accuracy of the calculated flows, it is recommended that monitoring of each study reach is conducted to confirm the relationship between flow, water depth and the ecological objectives.

Monitoring is needed to test the accuracy of the HEC-RAS hydraulic model and allow re-calibration if needed. If the HEC-RAS model does not predict the flow-depth relationship accurately, the ecological flow thresholds are incorrect and need to be changed as all subsequent EWR and ESY calculations will be affected. The monitoring would test the threshold flows listed in Table 4. Water depth must be measured for a range of discharges, particularly flows within the low flow channel but also high flows where possible to ensure that the values reported in this study are accurate.

Appendix 1 Expert panel members

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

Appendix 2 Macroinvertebrates of the Brunswick River

Phylum/Class	Order/Suborder	Family	Species
Nematoda			*Nematoda spp.*
Mollusca			
	Gastropoda	Ancylidae	*Ferrissia petterdi*
		Lymnaeidae	*Pseudosuccinea collumella*
		Physidae	*Physa acuta*
Annelida			
	Oligochaeta		*Oligochaeta spp.*
	Polychaeta		*Polychaeta spp.*
Crustacea			
	Decapoda	Palaemonidae	*Palaemonetes australis*
	Ostracoda		*Ostracoda spp.*
	Copepoda		*Calanoida spp.*
			Cyclopoida spp.
	Amphipoda	Perthidae	*Perthia spp.*
Insecta			
	Ephemeroptera	Caenidae	*Tasmanocoenis tillyardi*
		Baetidae	*Baetidae spp. (imm./damaged)*
		Leptophlebiidae	*Atalophlebia sp.AV17*
			Leptophlebiidae spp. (imm./damaged)
	Odonata		
	- Zygoptera		*Zygoptera spp. (imm.)*
	- Anisoptera	Gomphidae	*Zephyrogomphus lateralis (imm.)*
	Hemiptera	Veliidae	*Microvelia sp. (F)*
		Corixidae	*Micronecta sp.*
			Sigara sp. (F)
	Coleoptera	Dytiscidae	*Allodessus bistrigatus*
			Hyphydrus elegans
			Limbodessus inornatus
			Megaporus howitti
			Necterosoma darwini
			Onychohydrus scutellaris
			Rhantus suturalis
			Sternopriscus brownii (F)
		Gyrinidae	*Aulonogyrus/Macrogyrus sp. (L)*
			Aulonogyrus strigosus
			Macrogyrus (Triblogyrus) sp.
		Hydrophilidae	*Helochares sp. (L)*
			Limnoxenus zealandicus
			Paracymus pygmaeus
		Hydrochidae	*Hydrochus sp.*
		Hydraenidae	*Octhebius sp.*
	Diptera	Chironomidae	*Chironomidae spp. (P)*

Source: WRM (2008b).

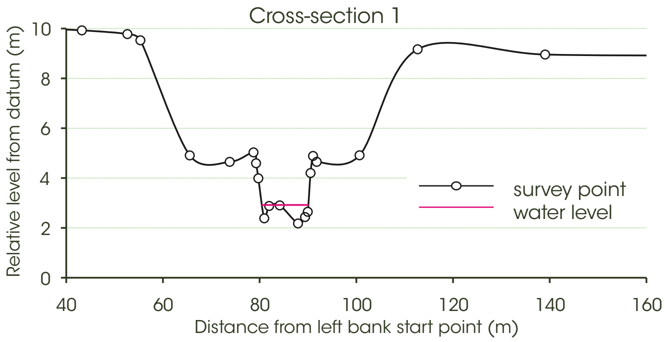
Appendix 2 Macroinvertebrates of the Brunswick River

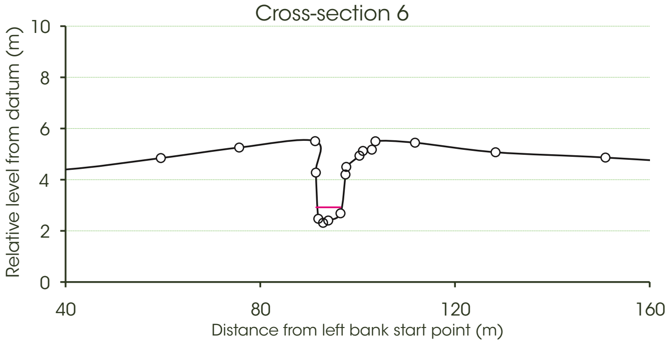
Phylum/Class	Order/Suborder	Family	Species
Insecta			
	Diptera	Chironomidae	
		- Chironominae	*Chironomus aff. alternans*
			Cladopelma curtivala
			Cryptochironomus griseidorsum
			Dicrotendipes sp.
			Parachironomus sp.
			Polypedilum leei
			Polypedilum nubifer
			Polypedilum watsoni
			Polypedilum sp.
			Stenochironomus sp. (V40)
			Cladotanytarsus sp.
			Tanytarsus sp.
		- Orthocladiinae	*Corynoneura sp.*
			Cricotopus amuliventris
			Nanocladius sp.
			Parakiefferiella sp. (nr. variegatus)
			Paralimnophyes sp.
			Thienemanniella sp.
			unknown genus (VSC11)
		- Tanypodinae	*Paramerina levidensis*
			Procladius villosimanus
		Ceratopogonidae	*Ceratopogoniinae spp.*
			Forcypomiinae spp.
		Culicidae	*Anopheles sp.*
		Empididae	*Empididae spp.*
		Psychodidae	*Psychodidae spp.*
		Simuliidae	*Simulium ornatipes*
			Simulidae spp. (P)
		Stratiomyidae	*Stratiomyidae spp.*
		Tipulidae	*Tipulidae spp.*
	Trichoptera		*Trichoptera spp. (imm.)*
		Ecnomidae	*Ecnomus sp.*
		Hydropsychidae	*Cheumatopsyche sp.AV2*
			Hydropyschidae spp. (imm.)
		Hydroptilidae	*Acritoptila/Hellyethira spp.*
			Hydroptilidae sp.A
		Leptoceridae	*Oecetis sp.*
			Notalina sp. AV16
			Triplectides australis
			Leptoceridae spp. (imm)
	Lepidoptera	Pyralidae	*Nymphulinae spp.*

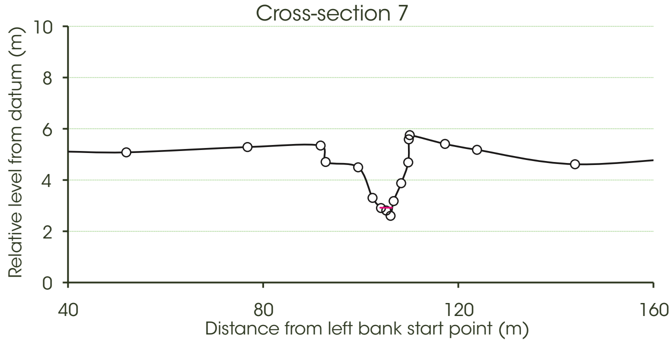
Source: WRM (2008b).

Appendix 3 Channel cross-sections from Reach 1 of the Brunswick River

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



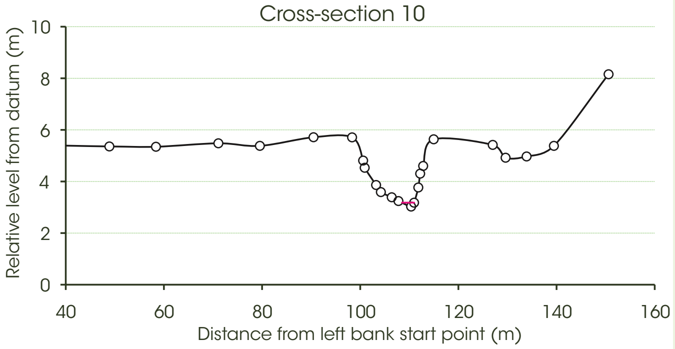




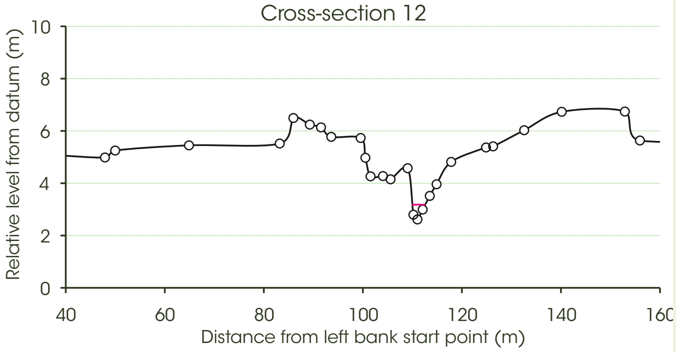
Appendix 3 Channel cross-sections from Reach 1 of the Brunswick River

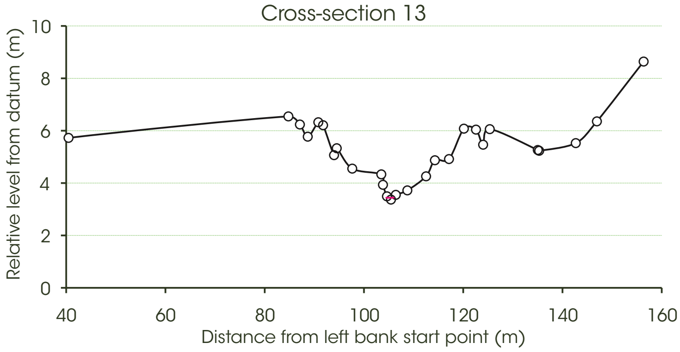
Survey channel profiles for cross-sections 1 to 15. The red line shows the water level at each cross-section at the time of survey.

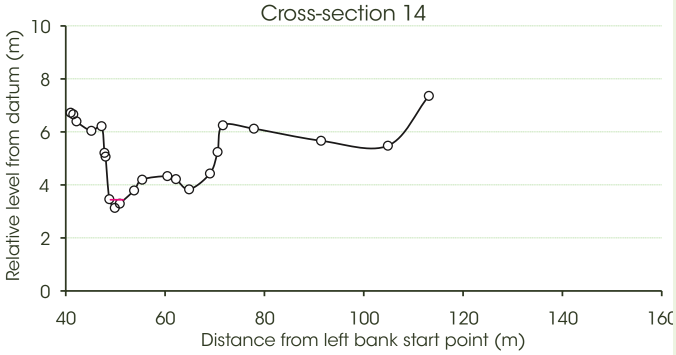

Cross-section 9

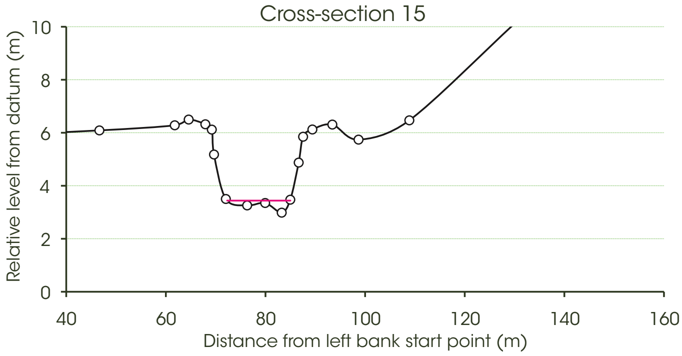

Cross-section 10


Cross-section 11


Cross-section 12

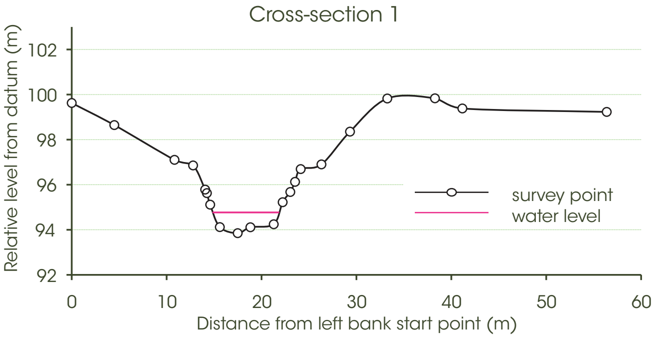

Cross-section 13


Cross-section 14

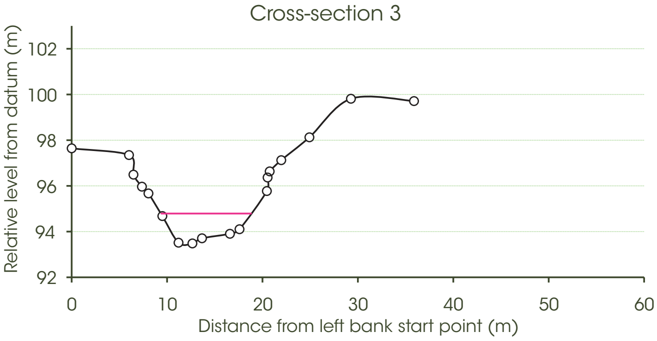

Cross-section 15

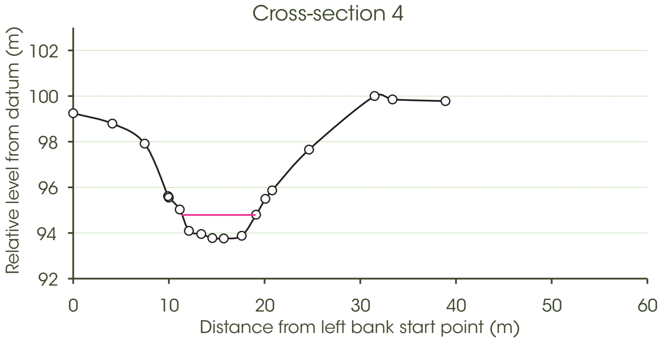
Appendix 4 Channel cross-sections from Reach 2 of the Brunswick River

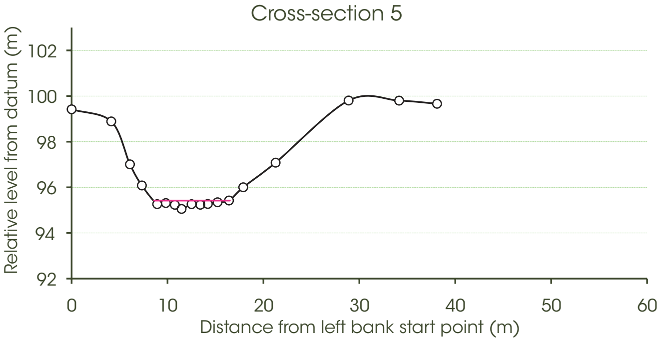
Survey channel profiles for cross-sections 1 to 16. The red line shows the water level at each cross-section at the time of survey.


Cross-section 1

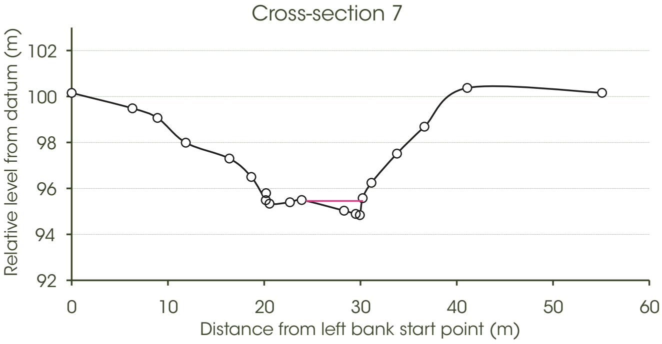

Cross-section 2

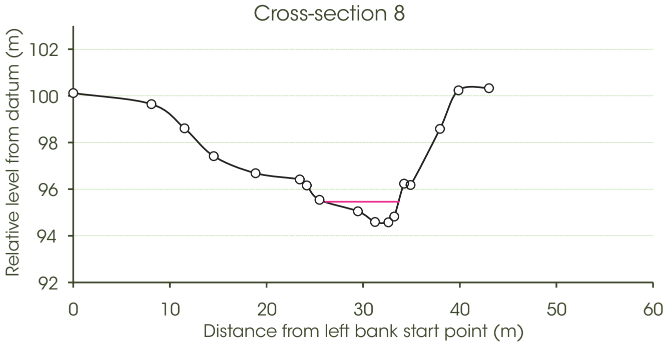

Cross-section 3


Cross-section 4


Cross-section 5


Cross-section 6


Cross-section 7

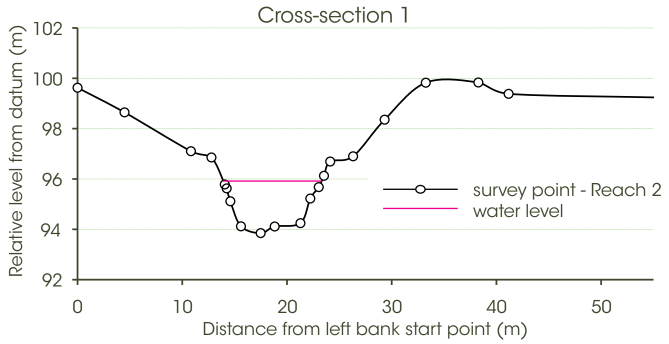

Cross-section 8

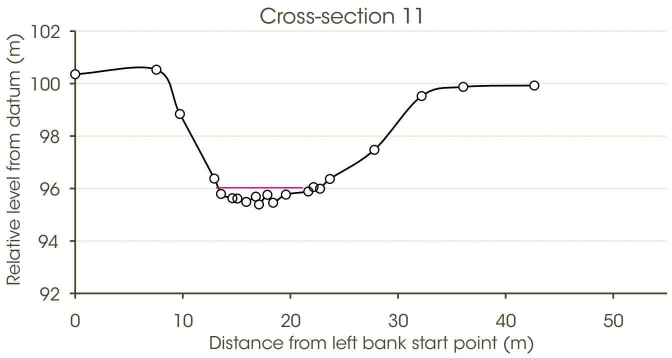
Appendix 4 Channel cross-sections from Reach 2 of the Brunswick River

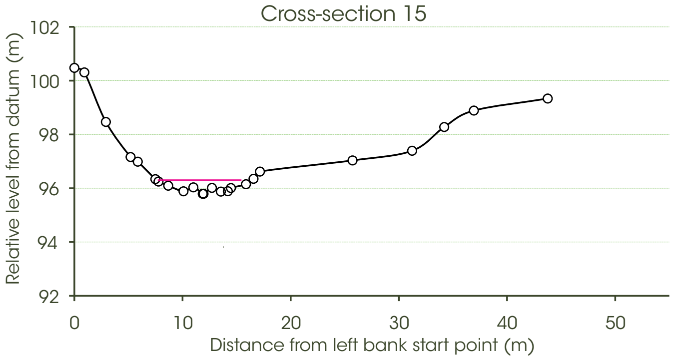
Survey channel profiles for cross-sections 1 to 16. The red line shows the water level at each cross-section at the time of survey.

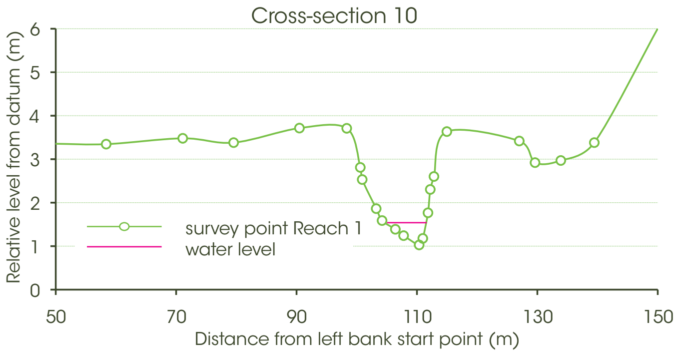
Appendix 5 Winter high flows required to inundate low benches in Reaches 1 and 2 of the Brunswick River

The plot at the bottom right in green is for Reach 1 and the remaining plots represent Reach 2.

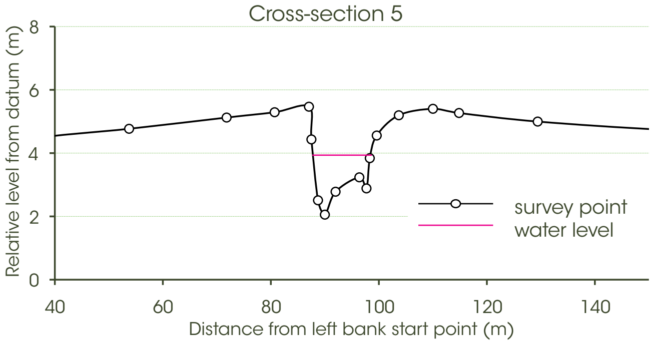


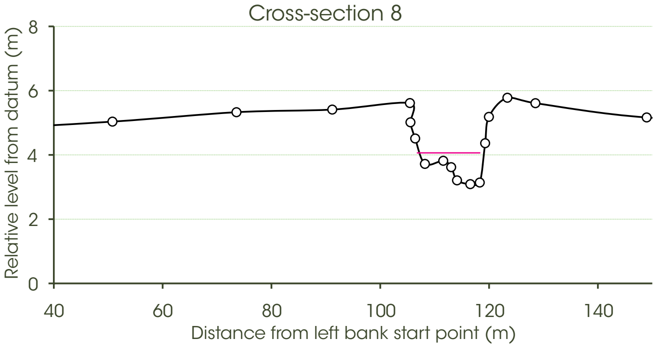


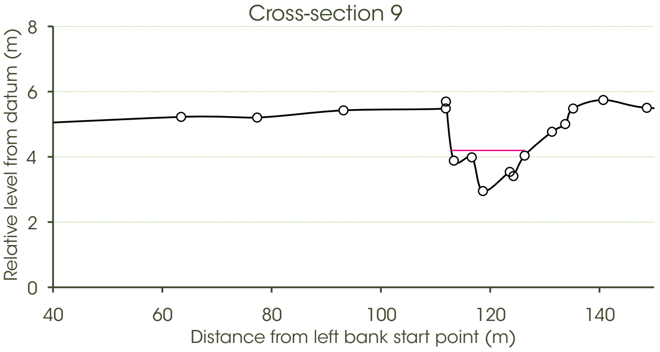


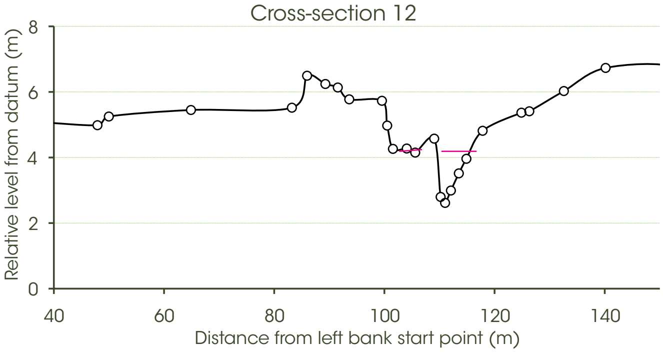


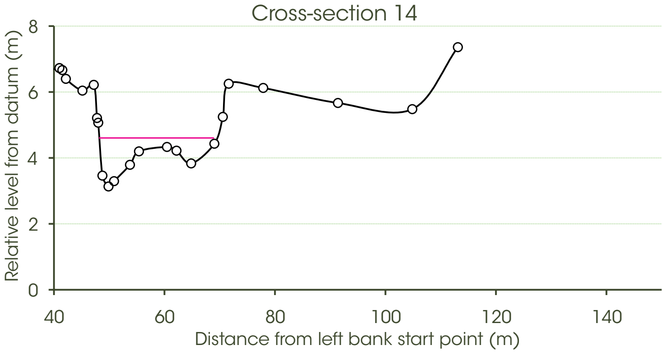
Appendix 6 Winter high flows required to inundate medium benches in Reach 1 of the Brunswick River



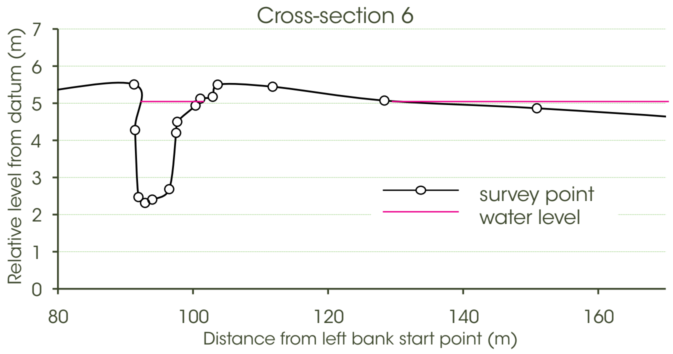




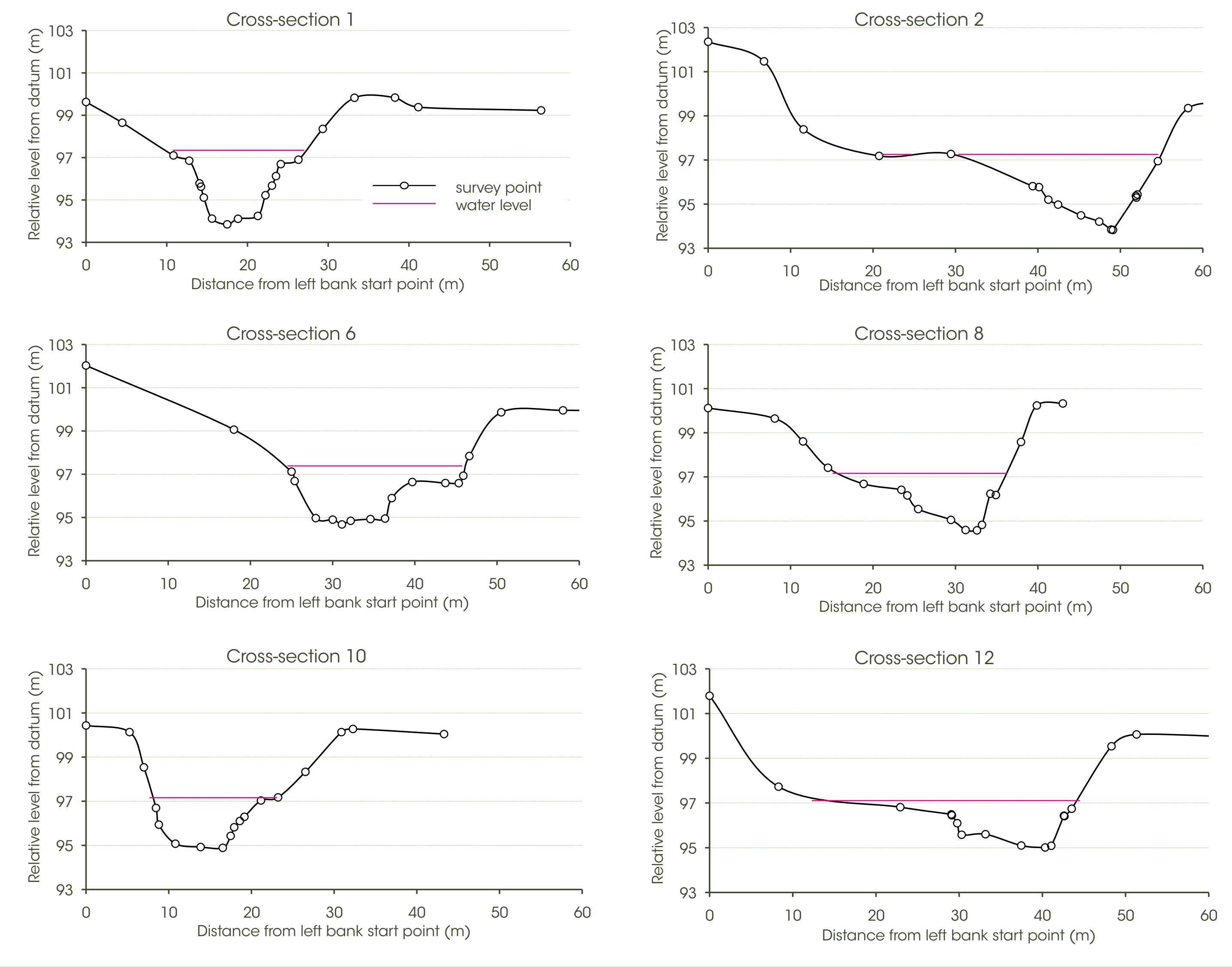




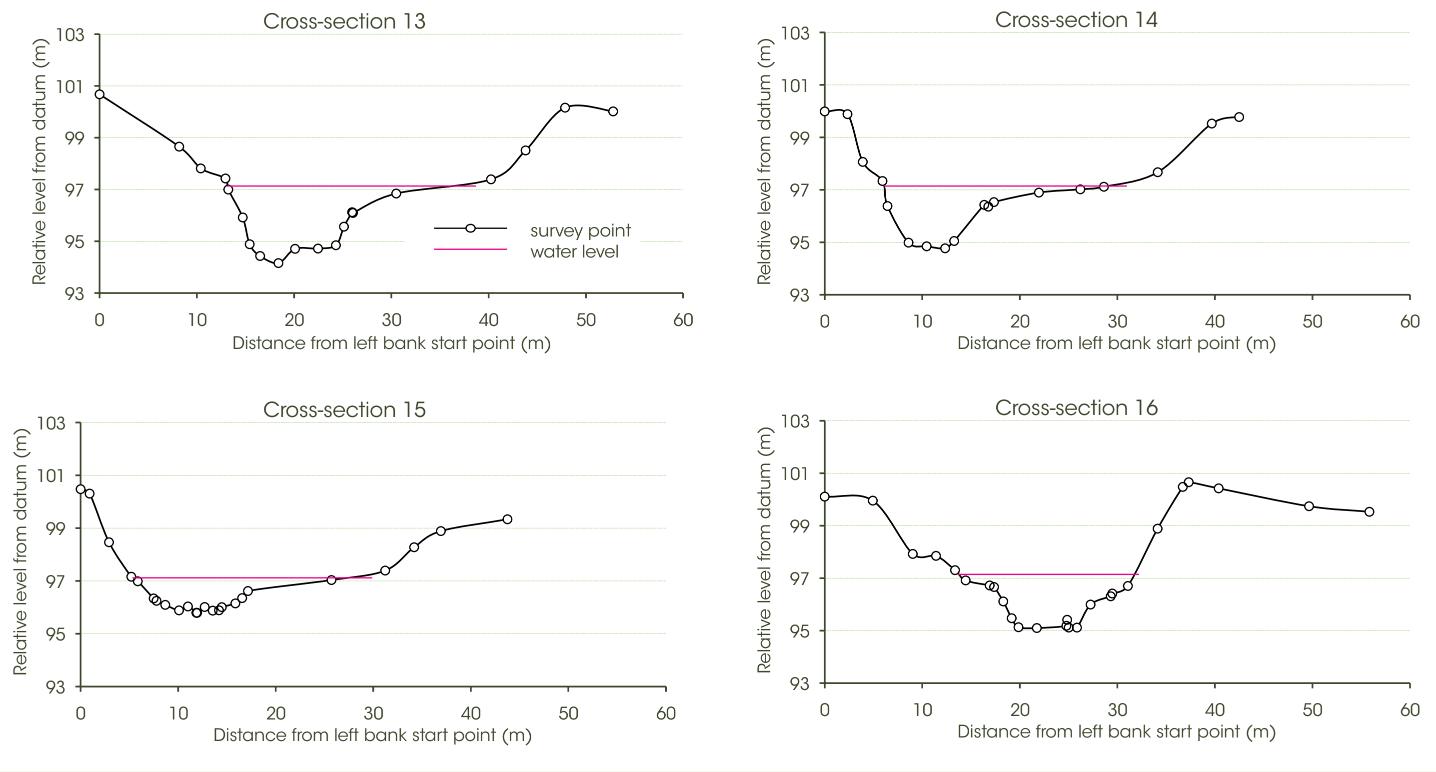
Appendix 7 Winter high flows required to inundate high benches in Reach 1 of the Brunswick River



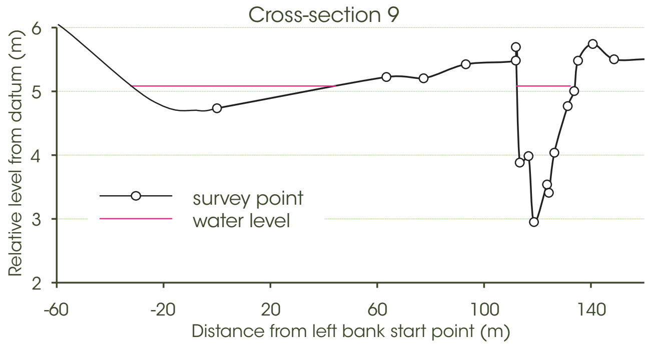
Appendix 8 Winter high flows required to inundate high benches in Reach 2 of the Brunswick River



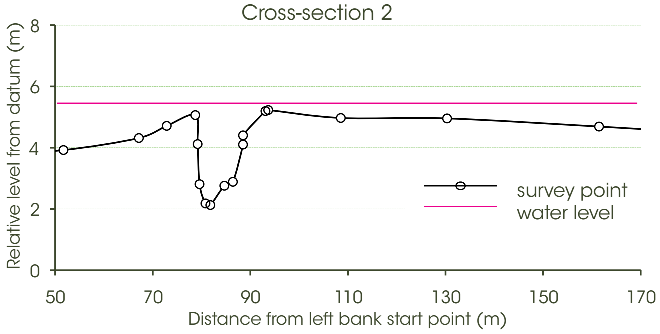
Appendix 8 Winter high flows required to inundate high benches in Reach 2 of the Brunswick River

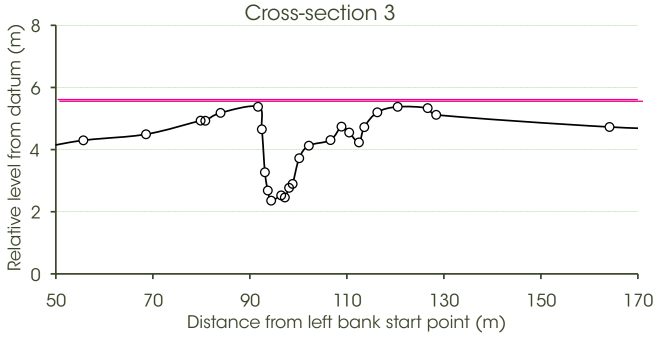


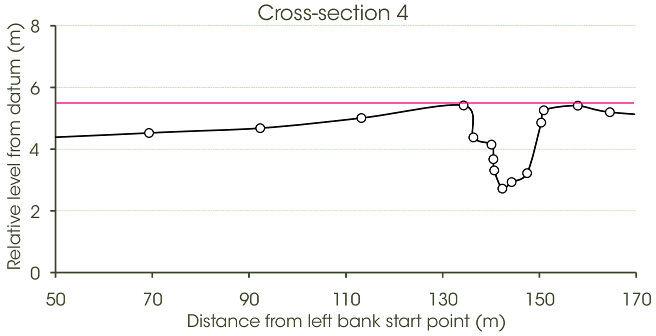
Appendix 9 Winter high flows required to inundate the wetland on the left over bank of the Brunswick River via a side channel

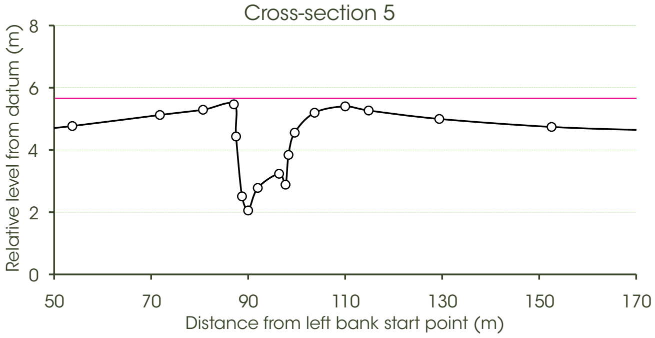


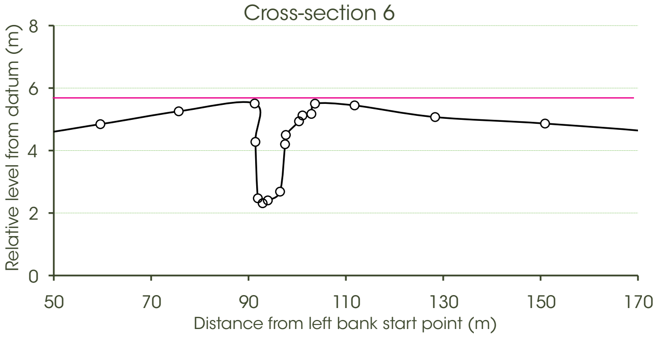
Appendix 10 Winter high flows required to achieve a bankfull flow in Reach 1 of the Brunswick River

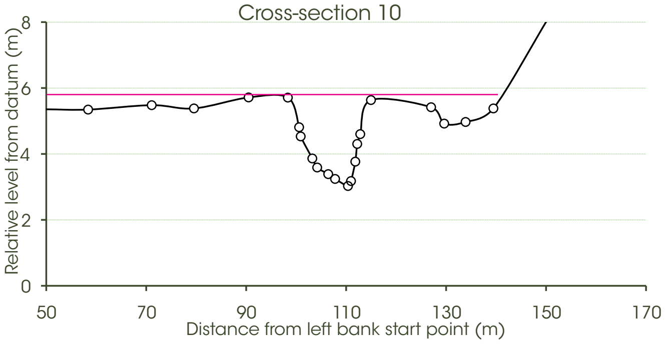


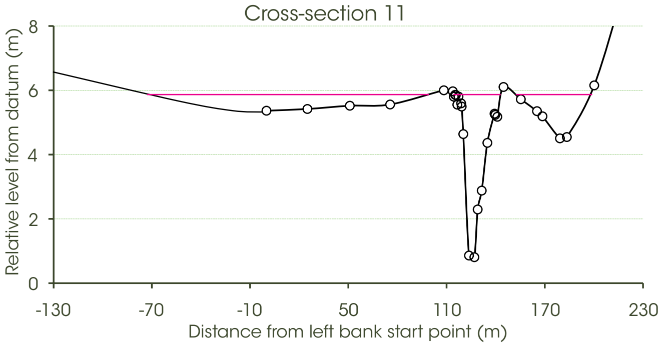




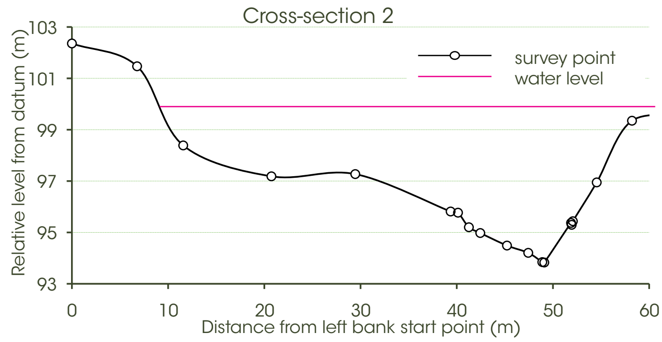


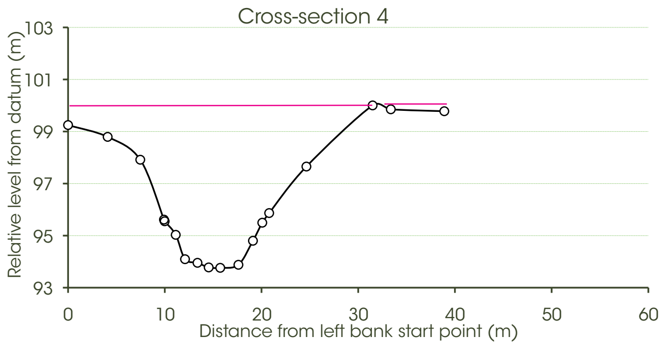






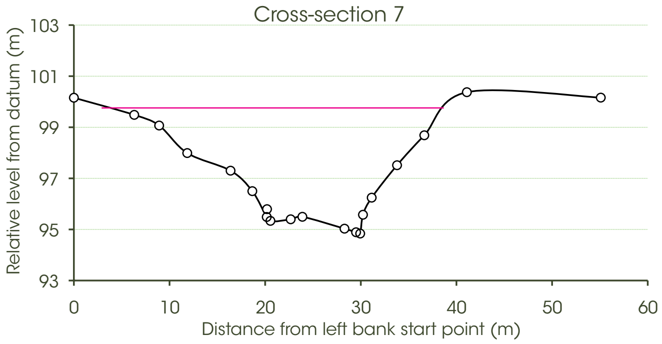
Appendix 11 Winter high flows required to achieve a bankfull flow in Reach 2 of the Brunswick River


Cross-section 2


Cross-section 4

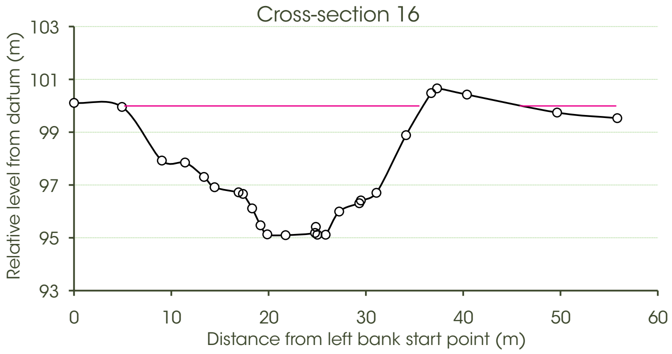

Cross-section 5


Cross-section 6


Cross-section 7


Cross-section 8

Appendix 11 Winter high flows required to achieve a bankfull flow in Reach 2 of the Brunswick River



Appendix 12 Monthly flow, EWR and ESY for Reach 1 of the Brunswick River (1975–2003)

All data in the table below are given in GL.

Year	Data	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1975	Flow	3.7	2.8	2.7	2.3	4.0	7.3	24.3	14.5	4.8	2.5	2.0	1.8	72.6
	EWR	2.2	1.7	1.6	1.4	2.4	4.4	18.1	10.1	2.9	1.5	1.2	1.1	48.5
	ESY	1.5	1.1	1.1	0.9	1.6	2.9	6.1	4.4	1.9	1.0	0.8	0.7	24.1
1976	Flow	4.8	2.0	1.6	4.2	2.6	2.5	3.1	4.8	0.9	0.8	2.7	0.7	30.5
	EWR	3.1	1.3	1.0	2.6	1.6	1.6	1.9	2.9	0.6	0.5	1.7	0.5	19.2
	ESY	1.8	0.7	0.5	1.6	1.0	1.0	1.2	1.9	0.3	0.2	1.0	0.2	11.3
1977	Flow	0.6	0.4	0.4	0.4	4.1	3.1	5.9	29.8	1.9	8.4	1.5	1.4	57.9
	EWR	0.4	0.3	0.3	0.2	2.5	1.9	3.8	21.6	1.1	5.6	1.0	1.0	39.7
	ESY	0.2	0.1	0.1	0.1	1.6	1.2	2.2	8.2	0.7	2.8	0.6	0.4	18.2
1978	Flow	1.2	0.9	0.9	0.7	5.8	6.9	30.8	3.0	9.4	8.8	1.9	1.7	72.0
	EWR	0.8	0.6	0.6	0.5	3.5	4.2	23.7	1.8	5.8	6.4	1.1	1.0	50.1
	ESY	0.4	0.3	0.3	0.2	2.3	2.7	7.1	1.2	3.6	2.5	0.7	0.6	21.8
1979	Flow	1.4	1.1	1.1	1.2	2.7	4.7	17.3	6.7	1.5	1.2	1.9	1.0	41.8
	EWR	1.0	0.8	0.7	0.8	1.7	2.8	12.0	4.0	1.0	0.9	1.2	0.7	27.6
	ESY	0.4	0.3	0.3	0.4	1.0	1.9	5.3	2.7	0.5	0.4	0.7	0.3	14.2
1980	Flow	0.8	1.3	0.6	4.4	3.3	8.6	21.9	27.2	13.4	5.1	2.5	2.2	91.4
	EWR	0.6	0.8	0.4	2.7	2.0	5.6	15.8	19.8	8.7	3.1	1.5	1.3	62.3
	ESY	0.2	0.5	0.2	1.7	1.3	3.0	6.1	7.4	4.7	2.0	1.0	0.9	29.1
1981	Flow	1.9	1.4	1.3	1.7	5.4	14.4	26.7	35.6	19.2	8.7	3.4	2.9	122.6
	EWR	1.1	0.9	0.9	1.1	3.3	9.8	19.7	26.0	14.0	5.8	2.1	1.7	86.5
	ESY	0.8	0.5	0.4	0.6	2.1	4.7	6.9	9.6	5.2	2.9	1.4	1.2	36.1
1982	Flow	12.0	2.4	2.2	1.8	1.6	6.7	11.1	16.0	10.9	4.4	1.9	1.6	72.7
	EWR	8.8	1.5	1.3	1.1	1.0	4.0	6.8	11.1	7.6	2.7	1.1	1.0	47.9
	ESY	3.3	1.0	0.9	0.7	0.6	2.7	4.2	5.0	3.3	1.8	0.7	0.6	24.8
1983	Flow	1.4	1.3	1.1	0.9	1.6	22.6	32.6	61.1	45.5	5.9	4.9	4.3	183.1
	EWR	1.0	0.9	0.7	0.6	1.0	14.9	24.8	41.1	31.8	3.5	2.9	2.6	125.8
	ESY	0.4	0.4	0.3	0.3	0.6	7.8	7.8	20.0	13.7	2.3	1.9	1.7	57.3
1984	Flow	3.7	3.0	2.7	2.8	10.9	26.8	14.9	27.1	34.9	4.4	5.8	3.5	140.5
	EWR	2.2	1.8	1.6	1.7	6.6	20.3	10.1	19.7	25.8	2.6	3.5	2.1	97.9
	ESY	1.5	1.2	1.1	1.1	4.4	6.5	4.8	7.4	9.1	1.7	2.3	1.4	42.5
1985	Flow	2.9	2.2	2.1	6.2	3.6	9.9	25.7	26.8	5.4	2.8	2.5	2.1	92.3
	EWR	1.7	1.3	1.3	3.9	2.2	6.6	18.5	19.3	3.2	1.7	1.5	1.3	62.6
	ESY	1.1	0.9	0.8	2.3	1.5	3.3	7.1	7.5	2.2	1.1	1.0	0.8	29.7
1986	Flow	1.8	1.4	1.3	1.1	4.2	4.0	15.1	22.0	3.7	2.1	1.6	1.4	59.7
	EWR	1.1	0.9	0.9	0.8	2.6	2.5	10.6	13.9	2.2	1.2	1.0	1.0	38.7
	ESY	0.7	0.5	0.4	0.3	1.6	1.5	4.6	8.0	1.5	0.8	0.6	0.4	21.1
1987	Flow	1.2	0.9	0.9	2.2	1.4	6.5	11.8	9.7	3.8	1.5	1.1	1.0	41.9
	EWR	0.8	0.7	0.6	1.4	0.9	4.1	9.0	6.2	2.3	1.0	0.8	0.7	28.4
	ESY	0.4	0.3	0.3	0.8	0.5	2.4	2.8	3.5	1.4	0.5	0.3	0.3	13.5
1988	Flow	0.8	0.7	0.6	1.2	7.7	57.3	52.8	37.5	36.4	20.6	5.6	5.0	226.2
	EWR	0.6	0.5	0.4	0.8	4.7	40.7	37.0	28.3	27.6	15.3	3.4	3.0	162.2
	ESY	0.2	0.2	0.2	0.4	3.1	16.6	15.8	9.2	8.7	5.3	2.3	2.0	64.0

Appendix 12 Monthly flow, EWR and ESY for Reach 1 of the Brunswick River (1975–2003)

All data in the table below are given in GL.

Year	Data	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1989	Flow	4.3	3.8	3.6	3.3	8.0	3.9	28.7	13.2	13.4	17.4	3.1	2.7	105.5
	EWR	2.6	2.3	2.2	2.0	4.8	2.3	21.9	9.1	8.7	11.8	1.9	1.6	71.2
	ESY	1.7	1.5	1.5	1.3	3.2	1.6	6.8	4.1	4.7	5.7	1.2	1.1	34.3
1990	Flow	2.3	1.8	1.9	2.5	3.7	20.0	48.4	24.8	10.3	4.8	2.3	1.8	124.6
	EWR	1.4	1.1	1.1	1.5	2.3	13.3	34.9	17.0	6.6	2.9	1.4	1.1	84.6
	ESY	0.9	0.7	0.8	0.9	1.5	6.7	13.5	7.8	3.8	1.9	0.9	0.7	40.1
1991	Flow	1.4	1.4	1.5	4.2	8.4	37.7	54.4	45.4	28.7	7.5	4.7	3.2	198.5
	EWR	0.9	0.9	1.0	2.5	5.8	29.0	41.1	29.2	21.2	4.5	2.8	1.9	140.8
	ESY	0.5	0.5	0.5	1.7	2.6	8.7	13.3	16.2	7.5	3.0	1.9	1.3	57.7
1992	Flow	2.6	2.6	2.8	2.8	4.7	39.4	46.2	36.5	19.1	4.5	4.2	3.7	169.1
	EWR	1.6	1.6	1.7	1.7	2.8	29.7	34.6	26.2	13.0	2.7	2.5	2.2	120.2
	ESY	1.1	1.0	1.1	1.1	1.9	9.7	11.5	10.4	6.1	1.8	1.7	1.5	48.9
1993	Flow	3.0	2.7	6.7	3.6	3.0	5.3	36.9	31.5	26.5	8.4	5.3	3.7	136.6
	EWR	1.8	1.6	4.4	2.2	1.8	3.2	27.9	22.9	18.8	5.0	3.2	2.2	95.1
	ESY	1.2	1.1	2.3	1.5	1.2	2.1	9.0	8.6	7.7	3.4	2.1	1.5	41.5
1994	Flow	3.5	3.2	3.4	3.3	6.3	13.7	40.9	16.3	6.3	4.3	3.4	3.0	107.8
	EWR	2.1	1.9	2.0	2.0	4.0	9.0	30.1	10.7	3.8	2.6	2.0	1.8	72.0
	ESY	1.4	1.3	1.4	1.3	2.3	4.8	10.9	5.6	2.5	1.7	1.4	1.2	35.8
1995	Flow	3.0	2.6	3.1	2.4	6.1	14.8	66.4	28.2	23.1	4.3	2.6	2.0	158.6
	EWR	1.8	1.6	1.9	1.4	3.8	10.7	47.1	19.3	17.2	2.6	1.6	1.2	110.1
	ESY	1.2	1.1	1.2	0.9	2.3	4.0	19.3	9.0	5.9	1.7	1.0	0.8	48.5
1996	Flow	1.8	1.6	1.9	1.5	1.6	20.9	63.1	63.2	66.2	9.5	5.4	3.7	240.4
	EWR	1.1	1.0	1.2	1.0	1.0	16.1	45.3	47.7	46.2	5.7	3.2	2.2	171.6
	ESY	0.7	0.6	0.8	0.6	0.6	4.8	17.8	15.5	20.0	3.8	2.2	1.5	68.8
1997	Flow	3.5	2.9	3.0	2.2	2.2	21.8	19.8	20.4	12.3	2.5	2.0	1.9	94.5
	EWR	2.1	1.8	1.8	1.3	1.4	14.9	13.8	14.0	7.7	1.5	1.2	1.2	62.7
	ESY	1.4	1.2	1.2	0.8	0.8	6.9	6.0	6.4	4.6	1.0	0.8	0.8	31.8
1998	Flow	1.6	1.5	2.3	1.9	1.6	8.6	12.1	23.0	22.6	6.2	2.6	1.7	85.7
	EWR	1.0	0.9	1.4	1.1	1.0	5.5	7.8	15.7	15.6	3.7	1.6	1.1	56.6
	ESY	0.6	0.6	0.9	0.7	0.6	3.1	4.3	7.3	7.0	2.5	1.0	0.6	29.2
1999	Flow	1.3	1.1	1.2	0.9	6.8	33.2	29.0	17.5	18.4	20.4	3.6	2.5	135.9
	EWR	0.9	0.8	0.8	0.6	4.3	25.2	21.3	11.3	12.5	14.0	2.1	1.5	95.4
	ESY	0.4	0.3	0.4	0.3	2.5	8.0	7.6	6.2	5.9	6.3	1.4	1.0	40.5
2000	Flow	2.0	1.8	2.2	1.8	1.0	4.2	46.2	29.9	19.9	3.6	2.7	1.9	117.2
	EWR	1.2	1.1	1.3	1.1	0.7	2.5	35.5	21.0	13.8	2.1	1.6	1.2	83.2
	ESY	0.8	0.7	0.9	0.6	0.3	1.6	10.7	8.9	6.1	1.4	1.1	0.7	33.9
2001	Flow	1.5	1.4	1.5	0.8	2.9	0.8	2.6	13.0	6.1	3.2	1.5	1.4	36.7
	EWR	1.0	0.9	0.9	0.6	1.8	0.5	1.6	8.4	3.7	1.9	1.0	0.9	23.2
	ESY	0.5	0.5	0.5	0.3	1.1	0.3	1.0	4.6	2.5	1.3	0.6	0.5	13.5
2002	Flow	1.2	1.1	1.2	0.7	0.8	10.7	31.2	25.4	18.5	5.3	2.5	1.6	100.3
	EWR	0.8	0.8	0.9	0.5	0.5	6.6	22.2	16.9	12.8	3.2	1.5	1.0	67.6
	ESY	0.4	0.4	0.4	0.2	0.3	4.1	9.1	8.5	5.7	2.1	1.0	0.6	32.8
2003	Flow	1.2	1.3	1.2	0.9	1.0	8.4	33.6	29.0	18.3	4.9	2.4	1.5	103.7
	EWR	0.8	0.8	0.8	0.6	0.6	6.6	24.7	20.7	12.5	2.9	1.5	1.0	73.5
	ESY	0.4	0.4	0.4	0.3	0.3	1.8	8.9	8.4	5.8	1.9	1.0	0.6	30.2

Appendix 13 Monthly flow, EWR and ESY for Reach 2 of the Brunswick River (1975–2003)

All data in the table below are given in GL.

Year	Data	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1975	Flow	0.7	0.3	0.4	0.6	1.4	4.5	15.3	13.3	7.1	4.2	1.9	0.8	50.5
	EWR	0.5	0.2	0.3	0.4	0.9	3.1	10.2	9.1	4.9	2.9	1.2	0.5	34.1
	ESY	0.2	0.1	0.1	0.2	0.5	1.4	5.1	4.2	2.1	1.4	0.7	0.3	16.3
1976	Flow	0.7	0.2	0.1	0.7	1.6	2.5	4.1	8.2	3.1	2.3	1.9	0.7	26.1
	EWR	0.5	0.1	0.1	0.4	1.1	1.7	2.8	5.7	2.0	1.5	1.2	0.4	17.6
	ESY	0.3	0.1	0.0	0.2	0.6	0.8	1.3	2.5	1.1	0.8	0.6	0.2	8.6
1977	Flow	0.2	0.0	0.0	0.1	0.8	2.2	4.9	16.5	2.7	5.3	1.1	0.4	34.2
	EWR	0.1	0.0	0.0	0.1	0.5	1.5	3.3	10.9	1.8	3.6	0.7	0.3	22.8
	ESY	0.1	0.0	0.0	0.0	0.3	0.7	1.5	5.6	0.9	1.7	0.4	0.1	11.4
1978	Flow	0.2	0.0	0.0	0.1	1.8	6.1	20.0	5.0	6.4	9.8	1.1	0.5	51.2
	EWR	0.1	0.0	0.0	0.1	1.2	4.2	13.6	3.4	4.4	6.3	0.7	0.3	34.6
	ESY	0.1	0.0	0.0	0.0	0.6	1.9	6.3	1.6	2.0	3.5	0.4	0.2	16.6
1979	Flow	0.2	0.0	0.1	0.3	0.6	2.6	11.4	4.7	3.0	2.7	1.6	0.4	27.6
	EWR	0.1	0.0	0.0	0.2	0.4	1.7	7.5	3.2	2.0	1.8	1.1	0.3	18.3
	ESY	0.1	0.0	0.0	0.1	0.2	0.9	3.9	1.5	1.0	0.9	0.6	0.2	9.3
1980	Flow	0.1	0.0	0.0	0.7	1.8	7.1	11.3	17.7	9.3	6.6	2.5	0.9	58.1
	EWR	0.0	0.0	0.0	0.5	1.2	4.9	7.9	12.0	6.5	4.6	1.6	0.6	39.9
	ESY	0.0	0.0	0.0	0.2	0.6	2.2	3.4	5.8	2.8	2.0	0.9	0.3	18.2
1981	Flow	0.6	0.3	0.3	0.4	1.7	10.3	19.4	27.2	12.7	7.8	3.0	1.5	85.0
	EWR	0.4	0.2	0.2	0.3	1.2	7.2	12.2	17.6	8.6	5.3	2.0	1.0	56.1
	ESY	0.2	0.1	0.1	0.1	0.5	3.1	7.2	9.5	4.0	2.5	1.0	0.5	28.9
1982	Flow	11.0	1.5	0.7	0.7	1.1	5.3	14.6	11.8	8.0	5.6	1.4	0.7	62.4
	EWR	9.5	1.0	0.5	0.5	0.7	3.7	10.0	8.2	5.6	3.8	0.9	0.5	44.7
	ESY	1.5	0.5	0.3	0.2	0.4	1.7	4.6	3.6	2.4	1.8	0.5	0.3	17.7
1983	Flow	0.3	0.5	0.2	0.0	0.4	13.5	20.0	29.2	34.6	8.9	3.4	1.4	112.4
	EWR	0.2	0.3	0.1	0.0	0.3	8.6	13.0	18.5	22.5	6.2	2.3	0.9	72.8
	ESY	0.1	0.2	0.1	0.0	0.1	4.9	7.0	10.8	12.2	2.7	1.1	0.5	39.5
1984	Flow	0.5	0.2	0.1	0.1	8.1	15.0	9.4	10.4	14.4	3.8	2.3	0.8	65.2
	EWR	0.4	0.1	0.1	0.1	5.5	10.0	6.6	7.3	9.6	2.5	1.5	0.5	44.2
	ESY	0.2	0.1	0.0	0.0	2.6	5.0	2.8	3.1	4.9	1.2	0.8	0.3	21.0
1985	Flow	0.3	0.1	0.1	1.9	1.2	7.6	13.7	14.4	5.7	2.1	0.9	0.3	48.4
	EWR	0.2	0.1	0.1	1.3	0.8	5.0	9.2	10.1	3.9	1.4	0.6	0.2	32.8
	ESY	0.1	0.0	0.0	0.6	0.4	2.6	4.6	4.3	1.8	0.7	0.3	0.1	15.5
1986	Flow	0.1	0.0	0.0	0.0	1.1	1.5	9.4	12.1	4.0	1.7	0.6	0.3	30.9
	EWR	0.1	0.0	0.0	0.0	0.7	1.0	6.5	8.4	2.7	1.1	0.4	0.2	21.3
	ESY	0.0	0.0	0.0	0.0	0.4	0.5	2.9	3.6	1.3	0.6	0.2	0.1	9.6
1987	Flow	0.1	0.0	0.0	0.6	0.6	2.8	9.7	5.6	2.1	0.9	0.3	0.1	22.9
	EWR	0.1	0.0	0.0	0.4	0.4	1.9	6.5	3.8	1.4	0.6	0.2	0.1	15.5
	ESY	0.0	0.0	0.0	0.2	0.2	0.9	3.2	1.8	0.7	0.3	0.1	0.0	7.5
1988	Flow	0.1	0.0	0.0	0.1	2.8	29.9	26.6	25.2	22.0	16.2	4.4	1.8	129.2
	EWR	0.1	0.0	0.0	0.1	1.9	18.8	19.4	16.2	14.3	10.8	3.0	1.2	85.9
	ESY	0.0	0.0	0.0	0.0	0.9	11.1	7.2	9.0	7.6	5.5	1.4	0.6	43.4

Appendix 13 Monthly flow, EWR and ESY for Reach 2 of the Brunswick River (1975–2003)

All data in the table below are given in GL.

Year	Data	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1989	Flow	0.7	0.4	0.4	0.3	2.2	3.4	15.5	8.9	7.7	6.9	1.8	0.8	49.1
	EWR	0.5	0.2	0.3	0.2	1.5	2.2	10.3	6.1	5.4	4.7	1.2	0.5	33.1
	ESY	0.2	0.1	0.2	0.1	0.7	1.2	5.2	2.8	2.4	2.1	0.6	0.3	16.0
1990	Flow	0.3	0.1	0.1	0.3	1.0	7.7	19.4	13.2	5.4	2.3	0.9	0.3	50.9
	EWR	0.2	0.1	0.1	0.2	0.6	5.1	12.4	9.0	3.7	1.5	0.6	0.2	33.6
	ESY	0.1	0.0	0.0	0.1	0.3	2.6	7.1	4.2	1.7	0.8	0.3	0.1	17.3
1991	Flow	0.1	0.0	0.0	0.5	1.9	17.8	21.8	32.5	22.2	7.1	2.7	1.1	107.7
	EWR	0.1	0.0	0.0	0.3	1.3	11.9	14.4	24.1	14.5	4.9	1.7	0.7	74.0
	ESY	0.0	0.0	0.0	0.2	0.6	6.0	7.4	8.4	7.7	2.1	0.9	0.4	33.8
1992	Flow	0.4	0.2	0.1	0.0	1.6	16.2	20.7	24.8	16.6	4.9	1.9	0.8	88.1
	EWR	0.3	0.1	0.1	0.0	1.0	10.5	13.9	15.8	11.1	3.3	1.3	0.5	57.9
	ESY	0.1	0.1	0.0	0.0	0.5	5.7	6.8	9.0	5.5	1.5	0.7	0.3	30.2
1993	Flow	0.3	0.1	1.7	0.6	0.5	0.7	11.2	13.2	10.9	3.2	1.2	0.5	44.0
	EWR	0.2	0.1	1.2	0.4	0.3	0.5	7.7	9.0	7.6	2.1	0.8	0.3	30.1
	ESY	0.1	0.0	0.5	0.2	0.2	0.2	3.5	4.2	3.3	1.1	0.4	0.2	13.9
1994	Flow	0.2	0.1	0.0	0.0	2.1	9.9	17.9	9.6	4.0	1.4	0.5	0.2	46.0
	EWR	0.1	0.1	0.0	0.0	1.5	6.9	12.1	6.6	2.7	0.9	0.3	0.1	31.4
	ESY	0.1	0.0	0.0	0.0	0.7	3.0	5.8	3.0	1.3	0.5	0.2	0.1	14.6
1995	Flow	0.1	0.0	0.0	0.0	3.9	12.4	25.8	22.5	15.1	4.4	1.7	0.7	86.8
	EWR	0.1	0.0	0.0	0.0	2.7	8.3	16.5	14.9	10.1	3.0	1.1	0.4	57.1
	ESY	0.0	0.0	0.0	0.0	1.2	4.2	9.3	7.6	5.1	1.4	0.6	0.2	29.7
1996	Flow	0.3	0.1	0.0	0.0	0.7	11.8	23.0	31.9	35.5	11.2	4.2	1.7	120.5
	EWR	0.2	0.1	0.0	0.0	0.4	7.6	15.2	20.2	24.4	7.8	2.9	1.1	79.9
	ESY	0.1	0.0	0.0	0.0	0.2	4.3	7.8	11.7	11.1	3.3	1.4	0.6	40.6
1997	Flow	0.7	0.2	0.1	0.0	0.8	13.8	11.1	13.0	7.2	2.3	0.9	0.4	50.5
	EWR	0.4	0.2	0.1	0.0	0.5	9.4	7.6	9.0	5.0	1.5	0.6	0.2	34.5
	ESY	0.2	0.1	0.0	0.0	0.3	4.3	3.6	4.0	2.2	0.8	0.3	0.1	16.0
1998	Flow	0.1	0.0	0.8	0.2	0.4	7.5	8.3	14.0	11.7	4.4	1.4	0.6	49.6
	EWR	0.1	0.0	0.5	0.1	0.3	5.1	5.7	9.8	7.9	3.0	0.9	0.4	33.9
	ESY	0.0	0.0	0.3	0.1	0.1	2.4	2.7	4.2	3.9	1.4	0.5	0.2	15.8
1999	Flow	0.2	0.1	0.0	0.0	4.4	18.7	16.9	16.5	17.9	19.1	4.9	2.0	100.7
	EWR	0.1	0.1	0.0	0.0	3.0	12.5	11.3	11.2	11.7	12.5	3.4	1.3	67.0
	ESY	0.1	0.0	0.0	0.0	1.4	6.2	5.6	5.3	6.2	6.6	1.5	0.7	33.7
2000	Flow	0.8	0.3	0.1	0.2	0.3	1.9	27.4	17.4	13.5	3.7	1.4	0.6	67.6
	EWR	0.5	0.2	0.1	0.2	0.2	1.3	17.4	11.6	9.0	2.5	0.9	0.4	44.1
	ESY	0.3	0.1	0.0	0.1	0.1	0.6	10.0	5.8	4.5	1.2	0.5	0.2	23.5
2001	Flow	0.2	0.1	0.0	0.0	1.0	0.3	0.8	8.5	4.7	2.3	0.7	0.3	18.9
	EWR	0.1	0.1	0.0	0.0	0.7	0.2	0.5	5.8	3.2	1.5	0.5	0.2	12.8
	ESY	0.1	0.0	0.0	0.0	0.4	0.1	0.3	2.7	1.5	0.8	0.2	0.1	6.2
2002	Flow	0.1	0.0	0.0	0.1	1.3	7.1	16.9	13.1	10.6	3.2	1.2	0.5	54.1
	EWR	0.1	0.0	0.0	0.1	0.8	4.9	11.6	9.1	7.1	2.1	0.8	0.3	36.9
	ESY	0.0	0.0	0.0	0.0	0.4	2.2	5.3	4.1	3.5	1.1	0.4	0.2	17.2
2003	Flow	0.2	0.1	0.0	0.3	1.1	4.2	18.6	13.1	9.1	3.4	1.3	0.5	52.0
	EWR	0.1	0.1	0.0	0.2	0.7	2.8	12.4	8.9	6.3	2.2	0.8	0.3	34.9
	ESY	0.1	0.0	0.0	0.1	0.4	1.4	6.3	4.2	2.9	1.1	0.5	0.2	17.0

Shortened forms

DEC	Department of Environment and Conservation
EWR	Ecological water requirement
HEC-RAS	Hydrological Engineering Centre, United States Army Corps of Engineers, River Analysis System
PADFLOW	Proportional abstraction of daily flows
RAP	River analysis package
RESYM	River ecological sustainable yield model

Glossary

Abstraction	The permanent or temporary withdrawal of water from any source of supply, so that it is no longer part of the resources of the locality.
Aquifer	A geological formation or group of formations capable of receiving, storing and transmitting significant quantities of water. Usually described by whether they consist of sedimentary deposits (sand and gravel) or fractured rock.
Bankfull height	The highest vertical extent of the main river channel.
Baseflow	The component of streamflow supplied by groundwater discharge.
Benthic organisms (benthos)	Sedementary organisms (plants and animals) that dwell on or in the sediment at the bottom of a water body.
Brackish water	Water of moderate salinity (technically having a salinity of between 1500 and 5000 mg/L of dissolved salts).
Confluence	A running together or flowing together, e.g. where a tributary joins a river.
Detritus	Organic material, including animal waste products and the remains of animals, plants and micro-organisms, together with the associated microbial community (bacteria and fungi).
Ecological water requirement	The water regime needed to maintain the ecological values (including assets, functions and processes) of water-dependent ecosystems at a low level of risk.
Emergent macrophyte	Species of aquatic plants that grow with roots in the sediment and have stems, flowers and most of the mature leaves protruding above the water surface.
Ephemeral	Only exists for a short period.
Exotic species	An animal or plant that has been introduced to a region (as opposed to native or indigenous species).
Extraction	The taking of water, defined as removing water from or reducing the flow of a waterway or overland flow.
Fresh water	Water whose salinity is less than 1000 mg/L.
Geomorphology	The study of the origin, characteristics and development of landforms.
Hydrogeology	The hydrological and geological science concerned with the occurrence, distribution, quality and movement of groundwater, especially relating to the distribution of aquifers, groundwater flow and groundwater quality.
Hydrograph	A graph showing the height of a water surface above an established datum plane for level, flow, velocity or other property of water with respect to time.
Hydrology	The study of water, its properties, movement, distribution and utilisation above, on and below the surface of the earth.
Inundation	The movement of surface water onto an area where it sits on the ground surface for extended periods.

Licence	A formal permit that entitles the holder to 'take' water from a watercourse, wetland or underground source.
Macroinvertebrates	Invertebrates are animals without backbones. Macroinvertebrates are big enough to be seen with the unaided human eye, though they can be very small. Aquatic invertebrates are termed macroinvertebrates if they are retained on a 0.25 mm mesh net. The main groups are worms, snails, crustaceans (e.g. prawns) and insects.
Macrophytes (aquatic)	Rooted aquatic plants, e.g. eelgrass.
On-stream storage	Storages (e.g. farm dams) that are built on or within a defined waterway or watercourse.
Perennial vegetation	Permanent vegetation that does not have a period of dormancy. Includes trees, shrubs and many species of grasses.
Phytoplankton	Microscopic (up to 1–2 mm in diameter) free-floating or weakly mobile aquatic plants, e.g. diatoms, dinoflagellates, chlorophytes, blue-green algae.
Remnant vegetation	The parts of the natural vegetation still existing after major change to the environment.
Riffles	Swift-flowing areas, where the water is rippled or broken and cascades over rocks. Logs are known as riffle zones.
Riparian vegetation	Vegetation growing along banks of watercourses, including the brackish upstream reaches of estuaries.
Riparian zone	The zone along or surrounding a waterway where the vegetation and natural ecosystems benefit from and are influenced by the passage and storage of water.
Runoff	Water that flows over the surface from a catchment area, including streams. This water results from the rate of precipitation being greater than the rate of infiltration.
Stratification	Formation of layers in a body of water.
Superficial aquifer	The aquifer nearest the surface on the coastal plain, formed in sediments of Quaternary or late Tertiary age.
Sustainable yield	The sustainable yield is the level of water extraction from a particular system that, if exceeded, would compromise key environmental assets or ecosystem functions and the productive base of the resource.
Taxa	Any grouping within the classification of organisms such as species, genus, order.
Thalweg	The line joining the lowest points of successive cross-sections of a channel. Usually associated with the path of highest velocity.
Tributary	A stream, creek or small river which flows into a larger stream, river or lake.
Turbid	Opaque or muddy with particles of extraneous matter.
Water balance	The relationship between input, storage and output within a hydrological system.
Water regime	A description of the variation of flow rate or water level over time.

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