WAROONA MINERAL SANDS PROJECT

Ecological Water Requirements of Ferraro Brook - Intermediary Assessment

prepared for

ILUKA

by

— Wetland Research & Management —

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Final report
28/06/2005

Frontispiece: Upper Mayfield Drain, August 2004; view upstream (east) toward confluence of Ferraro Brook (right) and Wealand Brook (left), west of South West Highway (photo: L. Sadler).

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Acknowledgements

This project was commissioned by Iluka Resources Limited. Lisa Sadler and Shannon Jones supported the project and provided flow data and information on environmental management and operations of Iluka within the study area. The authors are grateful to John Mitchell, Neil Bruce, Gordon Chaffey and Peter and Lindy Ward who readily granted access to their pastoral properties and offered valuable information on existing and historic hydrology, ecology and water use within the area. Rob Donohue and Adrian Parker (both DoE) and Mark Rivers (Dept. of Agriculture) are thanked for assistance sourcing historic flow records. Finally, Lisa Sadler (Iluka) is thanked for constructive criticism of the final draft report.

Recommended Reference Format

WRM (2005). Waroona Mineral Sands Project: Ecological Water Requirements of Ferraro Brook – Intermediary Assessment. Unpublished report by Wetland Research and Management to Iluka Resources Limited. May 2005.

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SUMMARY

Assessments of Ecological Water Requirements (EWRs) were conducted for seasonal drainages potentially affected by a proposed water dam site for Iluka Resources' mineral sands mine development at Waroona. Possible reduced summer baseflows as a result of damming, coupled with groundwater abstraction during mining, have the potential to adversely affect the downstream riverine ecosystem. EWRs are based on the premise that the environment has a right to water and should be regarded as a legitimate user. The determination of EWRs for water resources around Western Australia is a fundamental part of the water allocation decision-making process as an input into determining the sustainable yield of those resources.

EWRs were scientifically determined determined using a 'holistic' methodology based on the Flow Events Method (FEM). The EWRs presented are the initial 'request' for the optimum water to the environment to maintain the existing ecological values of the system at a low level of risk. EWRs were formulated to both protect the existing ecological values (*i.e.* native fish and crayfish) and enhance degraded values (*i.e.* aquatic macroinvertebrates, remnant vegetation).

The assessment was conducted subsequent to baseline aquatic fauna surveys carried out in mid October 2004. Results of these field surveys were used to identify the important ecological components to be maintained by the flow regime. Detailed measurements of hydraulic geometry/channel morphology were then conducted in late November 2004 at the confluence of Ferraro Brook with Wealand Brook/Upper Mayfield Drain. Available rainfall data and stream flow records were used to determine the current and past hydrological state of the system. Flows to meet EWRs were modelled using RAP (**R**iver **A**nalysis **P**ackage) software incorporating the hydraulic model HEC-RAS (**H**ydrological **E**ngineering **C**entre, United States Army Corps of Engineers, **R**iver **A**nalysis **S**ystem).

Overall, the existing ecological condition of drainages was considered to be 'poor' with only one native and one introduced fish species, low to moderate diversity of aquatic invertebrates and riparian vegetation dominated by pasture species. Hydrology of the catchment is such that, while drain construction has mitigated natural flooding, land clearing has substantially increased overland flows, resulting in a net increase in discharge across the coastal plain compared to the historic condition. Drain and channel stability was 'poor' with extensive erosion, downcutting and bank slumping. In many reaches, the channel had eroded down to the underlying coffee-rock.

Key ecological components were determined to be; channel maintenance, remnant riparian trees, aquatic macroinvertebrates (including freshwater gilgies & koonacs), western minnows (*Galaxias occidentalis*) and long-necked tortoises (*Chelodina oblonga*).

The flow requirements to sustain these ecological values were assessed as:

- Sufficient winter-spring flows to ensure any snags, rocks, macrophytes and some overhanging riparian vegetation remains inundated. This ensures habitat diversity, and ultimately, macroinvertebrate diversity, is maintained;
- Sufficient winter flows to maintain upstream-downstream linkages and therefore transport of energy/carbon.
- An average depth of 5-10 cm is required over riffle zones to maintain winter-spring habitat for macroinvertebrates and provide for fish passage;
- Predictable winter-spring flooding must be maintained to encourage breeding and recruitment in the western minnows;
- Maintenance of natural seasonality, *i.e.* zero flow over summer and early autumn.

Flow Events Modelling (FEM), using the River Analysis Package (RAP) and the hydraulic model HEC-RAS (Hydrological Engineering Centre (US Army Corp of Engineers) River Analysis System) was then used to determine flow volume and frequency necessary to sustain these ecological water requirements. A summary of ecological flow recommendations determined for Ferraro Brook and Upper Mayfield Drain is presented in the table below.

Flow Component	Ecological attribute / Value	Season (duration)	Hydraulic metric	Ecological Flow Recommendation
Fish Passage Flow	Native fish diversity	Late Autumn - early Spring	Minimum depth over obstacles of 0.10 m; late May – November.	≥ 0.07 m^3/sec for duration of approx. 0.5 days in May, gradually increasing to 6 days in September, reducing again to 0.5 days in November.
Winter Low Flow	Invertebrates Native fish Vegetation Process	Winter - early Spring	Minimum stage height of 0.05 m & 100 % cover over gravel runs & riffles.	0.02 m^3/sec for duration of approx. 24 days/month during July, Aug. & Sept., with transition between summer & winter base flows during May/June & October/November.
Winter Medium Flow	Native fish Vegetation Process	Winter – early Spring	Flood lower benches	0.15 m^3/sec during winter with peak frequency of 2 days/month in July, Aug. & Sept., with peak duration of up to 7 days in July-Aug.
Active Channel Flow	Channel morphology	Winter	Active channel stage height on a 1:2 - 1:3 year frequency	0.45 m^3/sec for a duration of 1 day every 2 – 3 years.

Though winter flows are now greater than would have occurred historically, the seasonality of the flow regime has been maintained. Since the waterbodies are naturally seasonal, maintenance of summer surface flows in Ferraro Brook and Upper Mayfield Drain would not be required to maintain the existing riverine ecosystems. Any reduction in surface flows is likely to be compensated by overland paddock flows. Flows in Upper Mayfield Drain, below the confluence with Ferraro Brook, would also be maintained by flows from unregulated Wealand Brook. Over summer, channel pools are likely to be maintained by groundwater. Retention of winter flows for maintenance of pool morphology is recommended, in order that pools continue to provide a summer dry-season refuge for macroinvertebrate species and to a lesser extent, long-necked tortoises. Changes in flow regime posed by dam construction are not expected to affect the off-channel remnant wetlands and swamplands, which were considered more reliant on groundwater and sheetflow. However, excessive groundwater drawdown over summer may lead to localised reduction in water tables, increased summer water-stress in vegetation, loss of permanent channel pools and associated reductions in faunal diversity.

Recommendations

It is recommended that the system should be managed to maintain the existing ecological values (*i.e.* current macroinvertebrate diversity), with a priority to maintain the seasonality of the flow regime

The HAC-RAS model and resultant ratings curve for Ferraro Brook is preliminary, as it requires calibration against gauged flows. The accuracy of the models will be unknown until they are calibrated against a range of flows covering a range of stage heights. If dam construction were to proceed, recommended discharges to achieve stage heights should be field tested as part of an adaptive management programme for the system. A tiered approach to monitoring the effectiveness of the recommended environmental flows is presented.

1 INTRODUCTION

1.1 Background

As part of plans to establish a mineral sands mine near the township of Waroona, Iluka Resources Limited (Iluka) commissioned *Wetland Research and Management* (WRM) to assess the Ecological Water Requirements (EWRs) of seasonal Ferraro Brook potentially affected by a proposed water dam site for the mine. Initial mine development plans included the construction of a water dam on Ferraro Brook in the headwater region of Upper Mayfield Drain, immediately north-west of Waroona township. The dam would be used for storage of mine dewatering discharge and surface run-off. However, current plans are for the dam to be constructed adjacent to the brook (Iluka 2004b). Changes to the *Rights in Water and Irrigation Act 1914* now require that environmental considerations be taken into account in considering licence applications or applications for licence amendments. The approach adopted by the Department of Environment (DoE), the state agency responsible for licensing resources, is to consider the environmental requirements through the determination of EWRs, upon which the Environmental Water Provisions (EWPs) are based, with the residual water then being available for consumptive uses. In the event that a dam on Ferraro Brook may be required at some future stage, the EWR assessment was commissioned to determine the likely impact to downstream environments and to define a release strategy that would maintain the ecological values of the system.

Ferraro Brook is one of three brooks that cross the mine lease. The others are Wealand Brook to the north and Nanga Brook to the south. On the coastal plain, Wealand and Ferraro brooks join at the confluence with Upper Mayfield Drain. Flow in all three is seasonal, generally peaking during July-August. Groundwater maintains some small permanent pools within the channels over summer.

As well as dam construction, other mine activities with the potential to affect downstream flows include mine pit dewatering and modifications to surface run-off. Dewatering is anticipated (URS 2002) to cause localised[1] groundwater drawdown. This may reduce baseflows in Ferraro and Nanga brooks (URS 2002). The nature of hydraulic connectivity between surface and groundwaters in the area is currently under investigation by Iluka. Dewatering discharge will preferentially be used to meet operational water demands together with scheme water supplied through Harvey Water (Iluka 2004b).

Iluka plans to redirect all stormwater runoff from operational areas away from existing watercourses and into either the water dam or settling sumps. In a storm event, water will only be released from the water dam into Ferraro Brook. Runoff from undisturbed areas will be diverted into Ferraro and Nanga brooks. Surface and groundwater flow and quality will be monitored both upstream and downstream of all pit areas (Iluka 2004b).

Determining EWRs will identify the ecological values of surface waters potentially affected by the proposed development and enable the sustainable yield of the resource to be established.

[1] It is anticipated that the extent of water table drawdown will be restricted within the boundary of the mine lease and largely limited to within the pit areas (URS 2002).

1.2 Study Objectives

The aims of the current project were to:

1. Define the water dependent ecological values downstream of the possible dam site on Ferraro Brook;
2. Determine the EWRs of water dependent ecological values of Ferraro Brook;
3. Provide a preliminary assessment of the risk to flow-dependant ecosystems associated with change in flow regimes;
4. Make recommendations for future monitoring to assess the effectiveness of the calculated EWRs and to detect effects of changes of the current flow regime on downstream water dependent ecological values.

The current study addressed the water requirements of:

- Channel morphology;
- Riparian and aquatic vegetation;
- Aquatic faunas (invertebrates, fish & tortoises);
- Water quality;
- Ecological processes supporting aquatic food webs (carbon/energy linkages).

Maps of the study area, showing location of survey sites are given in Figures 1 and 2.

1.3 Statutory/Legislative Framework

The Western Australian approach to ensure that provision is made for the environment in the water allocation decision-making process is by using the concepts of Environmental Water Requirements and Environmental Water Provisions (WRC 2000). These concepts are consistent with the principles in the National Principles for the Provision of Water for Ecosystems (ARMCANZ/ANZECC 1996).

The need to recognise the ecological impacts of flow regulation and diversion has also occurred through a number of Commonwealth Government policies:

- Principles of Ecologically Sustainable Development (1992);
- Intergovernmental Agreement on the Environment (1992);
- COAG recommended fundamental water reforms, including the need to provide water for the environment as part of the introduction of comprehensive systems of water allocations;
- Draft National Water Quality Management Strategy (1994).

The Commonwealth and State agreements on water allocation issues reflect the emerging importance of EWRs in the overall management of river systems. Allocation of water to meet EWRs is based on the premise that the environment has a right to water, that is, the environment has to be regarded as a legitimate user.

In general terms, a water requirement is determined through scientific investigation and community consultation and can be ascribed to a defined value. A water provision is the amount of water allocated from a resource to meet (wholly or in part) the requirement.

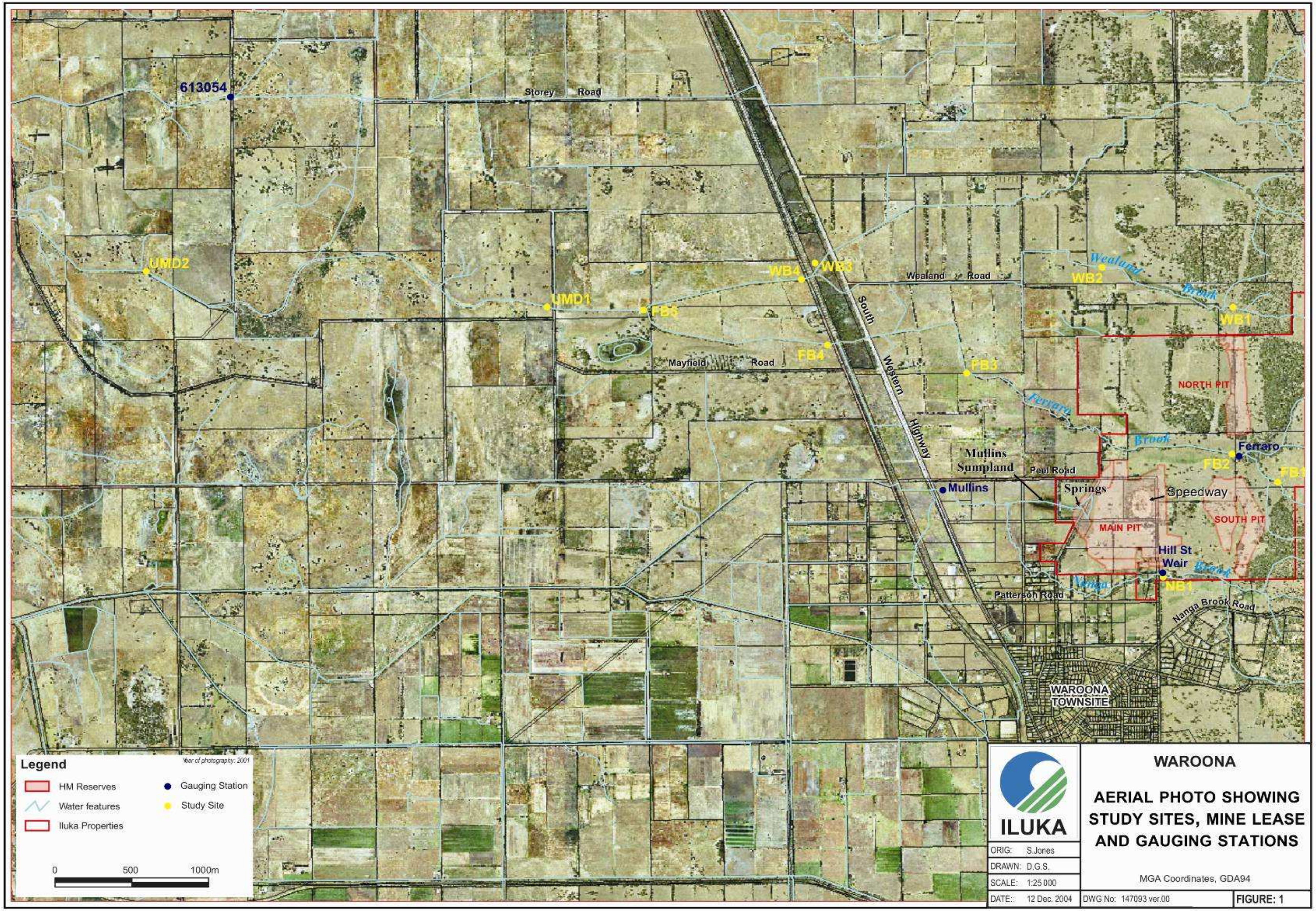

Figure 1. Aerial showing location of study sites, gauging stations and mine lease.

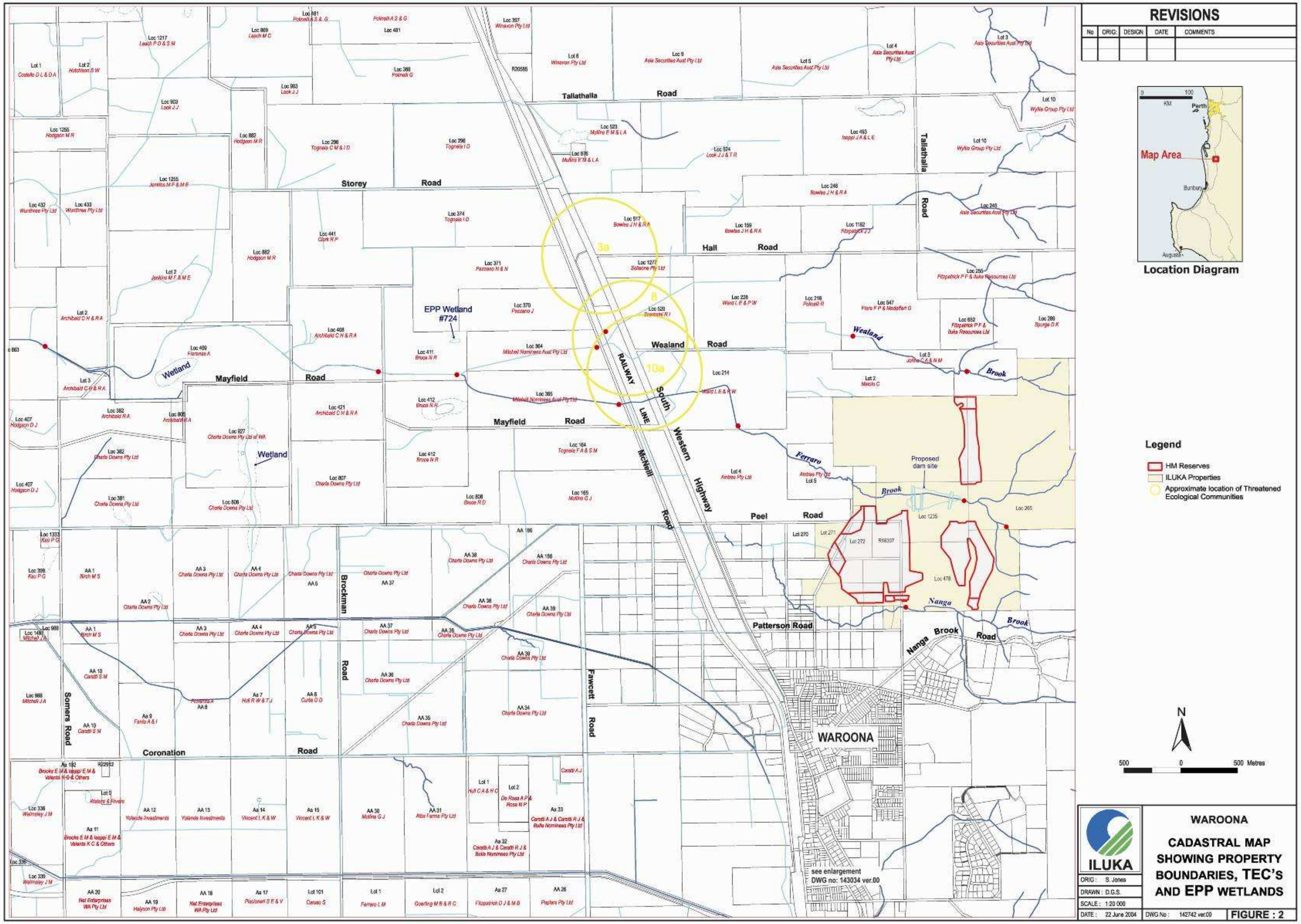

Figure 2. Cadastral map of study area, including potential dam site**.**

1.4 Ecological Water Requirements (EWRs)

EWRs are the water regimes required to sustain key ecological values (existing, historical or proposed for restoration) of water dependent ecosystems at a low level of risk. These requirements are a primary consideration in the establishment of EWPs during the water allocation decision-making process.

EWRs are determined on the basis of the best scientific information available. The determination of EWRs initially requires identification of key ecological values including ecological condition and health, biodiversity and rare/endangered species. In undisturbed environments, the usual aim in establishing EWRs is to protect the existing 'natural' ecological values at a low level of risk. The situation is less well defined for ecosystems that have been modified through regulation and/or as a result of land use changes. Where the environment has been disturbed, EWRs can be established to:

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

Some 'value judgements' need to be made when reaching a decision on which key ecological values are to be sustained. WRC (2000) guiding principles in the Environmental Water Provisions Policy for Western Australia, particularly Principles 1-4, provide important information about how these judgements should be made.

1.5 Environmental Water Provisions (EWPs)

Environmental Water Provisions (EWPs) are the water regimes that are determined before any allocation is made to consumptive use. They are defined by the Department of Environment as "the water regimes that are provided as a result of the water allocation decision-making process taking into account ecological, social and economic demands. They may meet in part or in full the ecological water requirements" (WRC 2000).

They define water regimes that protect both ecological and socio-cultural values of water resources and are set through the water allocation planning process. The degree to which ecological, social and economic goals are met will vary from case to case and may involve compromises between ecological, social and economic goals. DoE's guiding principles provide key information about the setting of EWPs.

The ***Desirable Future State*** of the river system (determined in consultation with the community) provides the context for the development of EWPs.

An integral part of developing EWPs is determining ***Social Water Requirements*** (SWRs). These are defined by WRC (2000) and by Kite *et al* (1998), and are elements of the existing or historic water regime that sustain socio-cultural values.

SWRs are not the primary consideration in the allocation decision making process but they may be established as part of the EWP depending on their impact on ecosystems and the significance of the social value sustained by the water regime. Social requirements may include water for domestic and stock use, recreational pursuits, landscape and aesthetic values and educational or scientific aspects. The desirable future state of the river system also provides a context for

SWRs. The determination of SWRs does not however, include uses of water for commercial or economic return.

2 FLOW EVENTS METHOD FOR DETERMINATION OF EWRS

In past years the 'Building Block Approach' has been the preferred method in Western Australia for determining EWRs for rivers and streams (Davies *et al*. 1998, Streamtec 1998, 2002, WEC & Streamtec 2000, Storey *et al*. 2001, WEC 2002, Storey & Davies 2002). However, following the development of the Flow Events Method (FEM) Stewardson 2001, Stewardson & Cottingham 2002) and with its successful application to eastern states rivers (Cottingham *et al*. 2003), the DoE is investigating the adoption of the FEM as an alternative method for determining EWRs in Western Australia.

The FEM was originally developed by the CRC for Catchment Hydrology (Stewardson 2001) to integrate the various *ad hoc* approaches being used for determining ecological water requirements throughout Australia. It was designed to provide a standardised, "transparent" analytical procedure, applicable to a broad range of river systems. While it advocates a consistent approach, the method still allows for the inclusion of expert opinion (Stewardson & Cottingham 2002). This approach offers an improvement on the less transparent 'Building Block' approach previously used in Western Australia. However, like the 'Building Block' approach, the FEM assumes that the various components of a flow regime, such as summer and winter baseflows, bankfull flows and flood flows (Figure 3), have different ecological functions (Poff *et al*. 1996, Richter *et al*. 1997) and that these need to be assessed independently (Cottingham *et al*. 2002, Stewardson & Cottingham 2002, Stewardson & Gippel 2003). Even periods of no flow may be important; *e.g*. in ephemeral and seasonal systems.

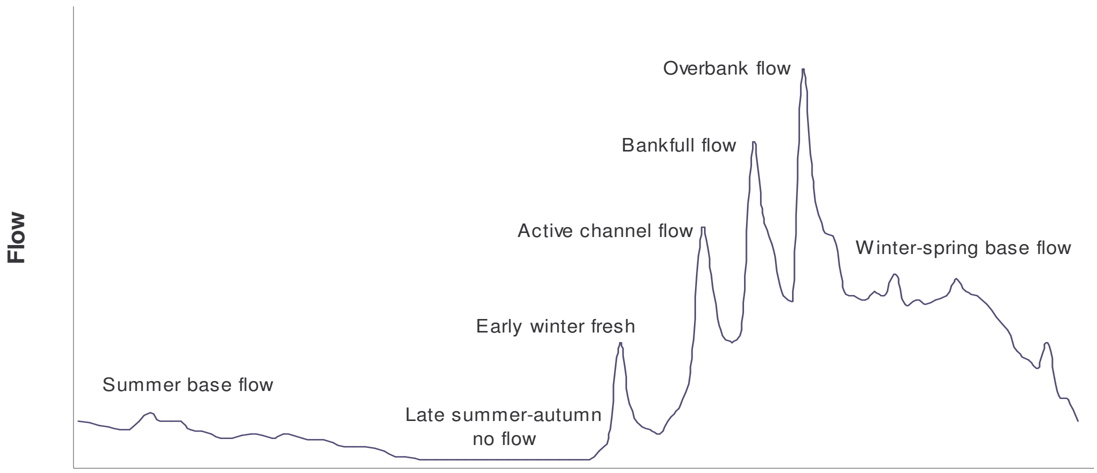

Figure 3. Time series showing typical components (events) of a natural flow regime relevant to river systems in south-west Australia (after Cottingham *et al*. 2003).

One of the main principals of the approach is that the altered river ecosystem (*e.g*. downstream from impoundments or abstraction) incorporates integral or 'key' ecological features of the original functional system; *i.e*. some of the natural flow variability should remain. FEM is a modification of the FLOWS method (SKM *et al*. 2002) developed in Victoria, but unlike the FLOWS method it has no *a priori* assumptions about the importance of hydrological events without first considering their significance to key ecological features of the system (Cottingham *et al*. 2003). FEM is an additive method and allows for as many or as few features to be evaluated as required.

All available data on existing and historic ecology, hydrology and channel morphology are used to identify those features likely to be affected by flow modifications. Environmental flow objectives specific to each reach are established, pursuant to determinations of acceptable level of risk posed by flow modifications. Hydraulic models (*e.g.* HEC-RAS) are then used to predict flows required to inundate features such as channel bed and benches to a certain depth in order to maintain key ecological features (*e.g.* water for fish passage; floodplain flows to inundate riparian vegetation and stimulate seed set) and meet environmental flow objectives. The frequency of flows and shape of the hydrograph for each important event is also modelled using the River Analysis Package (RAP) using the modelled water surface profiles from HEC-RAS.

In the instance of a system already regulated by impoundment/abstraction, the method compares the regulated flow regime to modelled unregulated flows for the same period to determine how far the hydrology has changes relative to pre-impoundment.

The current report details the use of FEM to determine EWRs for Ferraro Brook and represents one of only four applications of FEM in Western Australia. Its initial application to Ferraro Brook must be recognised as 'developmental' and allow for subsequent refinement. Figure 4 summarises the standard procedural steps in the application of FEM (and FLOWS) and indicates modifications made for the current study.

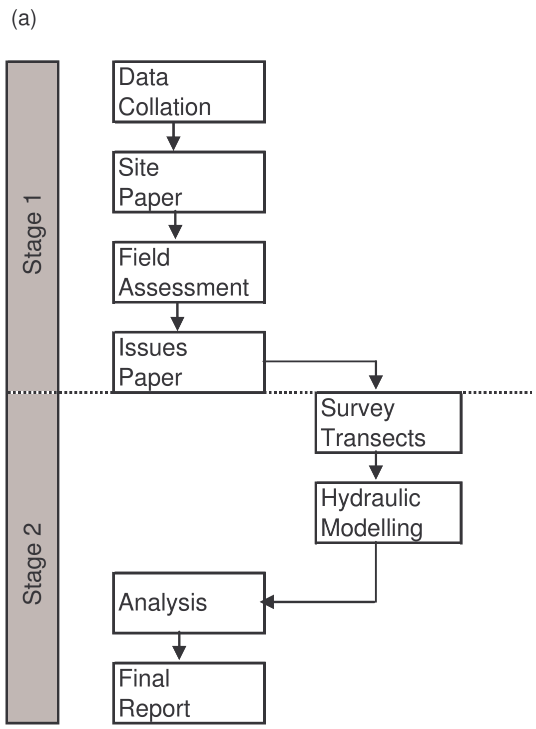

Figure 4. (a) Basic steps in the FEM (& FLOWS) method and (b) steps used in the current study (boxes in red emphasise modifications made for the current study).

Stage 1 data collation and field assessments as indicated in Figure 4, were conducted as part of the initial baseline surveys by WRM (2005) in October 2004. Assessment included a review of existing knowledge of aquatic ecosystems of the study area and rainfall and predicted climate change. Results of these field surveys were used to identify the important ecological components to be maintained by the flow regime. The current report deals primarily with Stage 2, *i.e.* survey transects (cross-sectional channel surveys), hydraulic modelling (HEC-RAS) and analysis (RAP).

3 HYDROLOGICAL STATE OF THE CATCHMENT

3.1 Available Data

The first stage in developing EWRs for a river system is to determine the past and current hydrological state of the catchment. This is critical, as typically the further a river system is removed from its historic hydrology, the more the environment, and therefore, its ecological value is impacted. However, there is often minimal data on which to establish current hydrology, and more often than not, even less data for establishing historical state.

In order to assess the current hydrological state of the system, long-term rainfall data for was sourced (WRM 2005) from the Bureau of Meteorology, Perth (Waroona townsite, station 009614). However there were no available long-term streamflow data for the Upper Mayfield Drain area. Short-term data were available for Iluka's gauging stations in the upper sub-catchment of Ferraro Brook and Nanga Brook, immediately to the south of the mine lease (refer Figure 2):

- Ferraro Brook Weir, possible dam site (period of record Jan. '95 – Dec. '02));
- Hill Street Weir, Nanga Brook (period of record Jan. '94 – Dec. '99);
- Mullins Sumpland, Nanga Brook (period of record Jan. '95 – Dec. '04).

The location of all gauging stations is indicated in Figure 2 and hydrographs of daily and average monthly discharge are given in Appendix 1. However, only one of these stations, Ferraro Brook Weir, was ultimately used for the current study. Existing annual flows in Wealand Brook and in downstream reaches of Ferraro Brook and Upper Mayfield Drain could not be adequately assessed due to the absence of gauging stations.

Medium-term data were available for DoE station 613054 on Mayfield Drain with a period of record of May 1982 – March 1999. However, this station is located 1.5 km north of the catchment for the current study area, at a pipe-head dam south of the intersection of Storey and Somers roads (Figure 2).

3.2 Rainfall

Long-term rainfall records for Waroona townsite (009614) showed the average annual rainfall for the period November 1935 - 2003 was 1,019 mm (refer WRM 2005). Maximum rainfall occurs between June - August (winter) with minimum rainfall occurring in January - February (summer). Average annual evaporation rates are around 1,700 – 1,800 mm.

Since 1975 there has been a significant reduction in mean annual rainfall in the southwest of Western Australia. The extent of the reduction between the 'Average Climatic Condition' period (pre-1975) and the 'Dry Period' (post-1975) varies regionally. The influence of this climate change on regional rainfall for Waroona was assessed as a precursor to modelling catchment hydrology (refer WRM 2005). There has been a significant ($p < 0.10$)[2] reduction in mean annual rainfall from pre-1975 years (mean = 1045 mm) compared with post-1975 years (mean = 978 mm) (Figure 5). This reduction in rainfall is most evident in winter months (May - August) with a tendency for slightly higher rainfall in summer (Figure 6). Though significant, mean annual rainfall has only reduced by 5%. This smaller than anticipated reduction probably reflected the shorter rainfall record (1936 – 2003), which did not include the higher rainfall period prior to the 1930s.

[2] t-test, df = 37,23, t-value = 1.522, p = 0.067.

As long-term rainfall and streamflow records were not available for the Ferraro Brook catchment, the influence of reduced rainfall on streamflow in the brook was inferred by comparison to south-west jarrah forest. Storey *et al.* (2001) estimated that mean annual rainfall for the Canning Dam area for the period 1975 - 1997 was 18% lower than the long term mean annual rainfall for 1912 - 1997. Similarly, WEC (2004) recorded a 20% reduction in rainfall for the Bickley Brook system and WEC (2002) calculated an 11% reduction in annual rainfall at Collie (Collie townsite, 1911 – 1997).

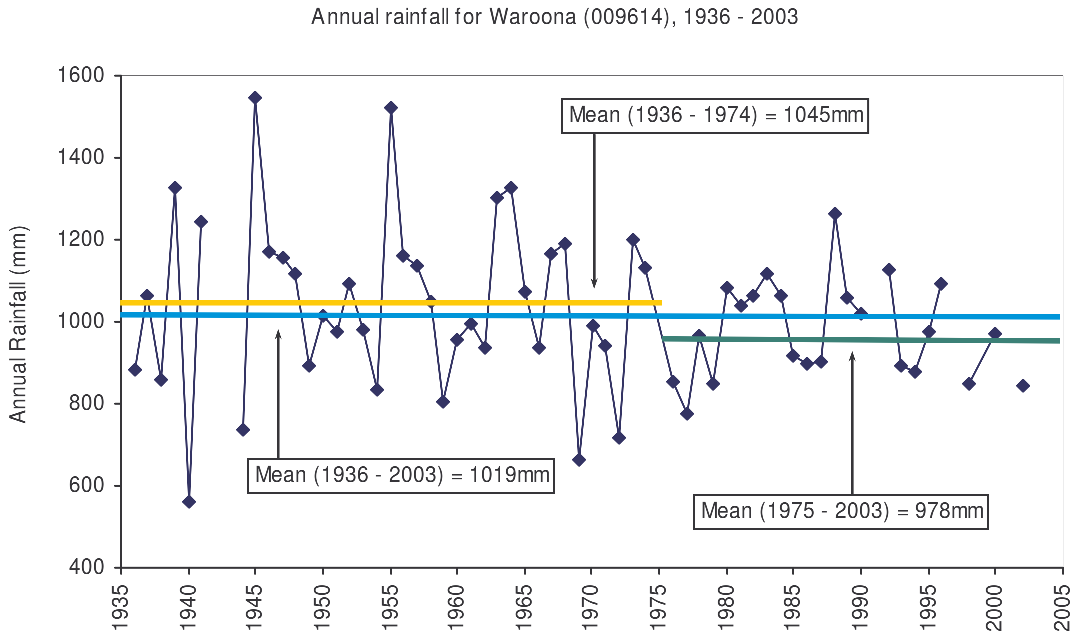

Figure 5. Average annual total rainfall for Waroona townsite for periods 1936 - 2003 (blue line), 1936 - 1974 (orange line) and 1975 - 2003 (green line).

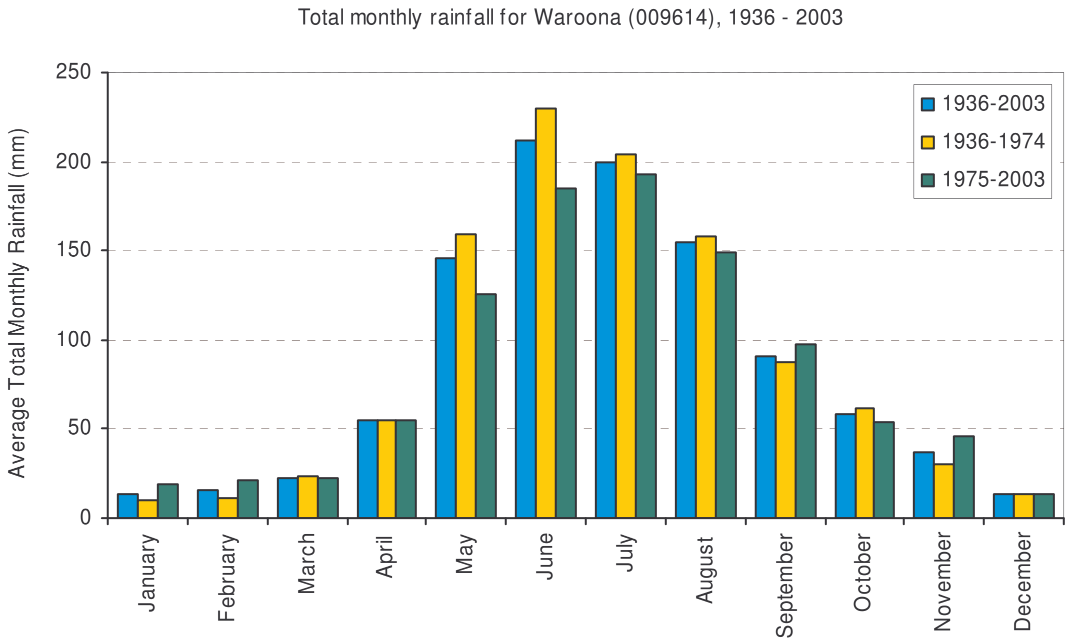

Figure 6. Average monthly rainfall for Waroona townsite for periods 1936 - 2003, 1936 - 1974, and 1975 - 2003.

A reduction in rainfall will influence catchment hydrology by reducing stream flows, particularly in the upper catchments. However, with increasing distance down the catchment these reduced flows are counter-acted by the effects of catchment clearing, which increases the proportion of precipitation resulting in run off. Clearing reduces interception and transpiration by vegetation. As a result, a greater proportion of rainfall runs off the land. In addition, the speed of run-off is increased. Together, these change the shape of the flood hydrograph from a relatively slow, flat response (*i.e.* taking a day for a flood peak to develop) to a very rapid response (*i.e.* a flood peaks in several hours following rainfall). Increased and more rapid runoff often results in channel widening and incision, whereby the bed of the river is degraded. The hydrology of Ferraro Brook is likely to have been altered by clearing, as evidenced from the unstable channel form, with excessive down-cutting/incision and eroding banks. The subsequent drainage network, directing flows into the Ferraro Brook will have extenuated/exacerbated this issue.

The historic change in rainfall and associated change in runoff has implications for calculating EWRs. The shape of the river channel is influenced by the action of bankfull discharge which is referred to as 'channel forming flows', and have been calculated to occur approximately one in every two to three years in south-western Australia. Reduced rainfall will mean that bankfull flows for the existing channel now occur at a lower frequency. Frequency of other flow scenarios also will be changed. These changes in catchment hydrology need to be assessed and considered when developing EWRs for a system.

3.3 Hydrology

As discussed above, relevant flow gauging data to assess the past and current hydrological state of the Ferraro Brook catchment was limited to one gauging station; Ferraro Brook, 1995 – 2005. This is only a very short data series on which to determine the hydrological state of the Ferraro Brook. In the absence of an extensive flow record, an option is to model daily flows. This, however, is a technically challenging exercise involving use of catchment run-off models, rainfall record and data on catchment condition and was beyond the scope of the current project. Therefore, the hydrological state of the catchment and subsequent Flow Event Modelling (FEM) in the River Analysis Package (RAP) was performed on this short flow record. The limited data means the record is not truly representative of the inter and intra variability experienced by this system over a longer period and it does not reflect changes due to clearing and the drier climatic period since 1975.

The complete flow record for the Ferraro Brook station (1995– 2005) formed the core data used in determining EWRs using the Flow Events Method (FEM) (refer Section 7). Summary analysis of these data is here presented to illustrate the general trends in flows in the Ferraro Brook.

A summary of the flow record for Ferraro Brook weir is summarised in Appendix 1. A plot of daily discharge data is given in Figure 7 and total annual discharge, mean and median monthly flows and frequency of flow occurrences are illustrated in Figure 8.

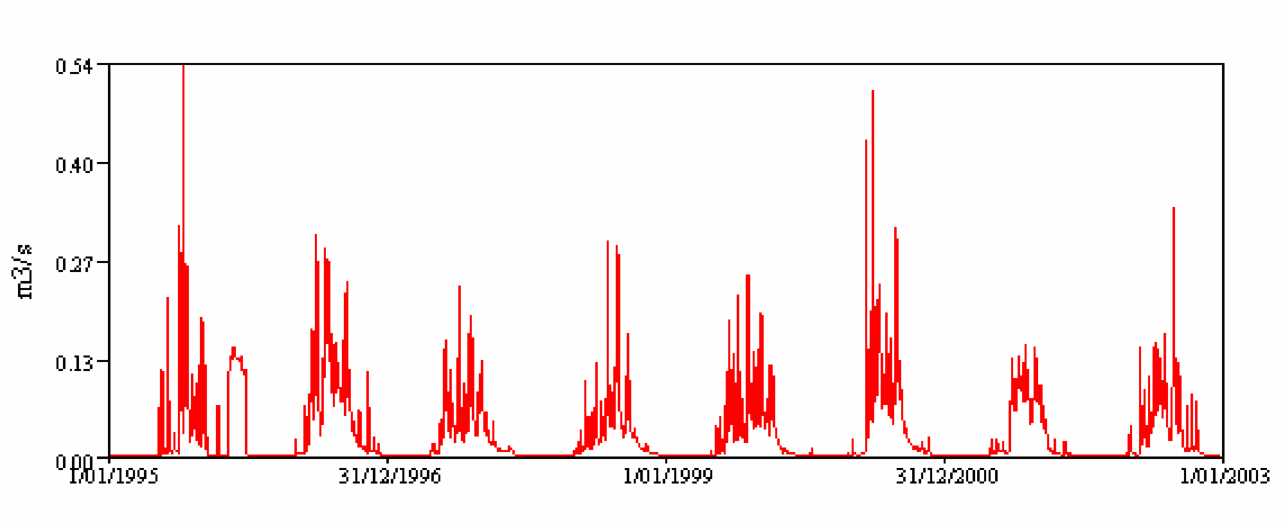

Figure 7. Total flow record for Ferraro Brook from 1995 – 2003, showing total daily discharge.

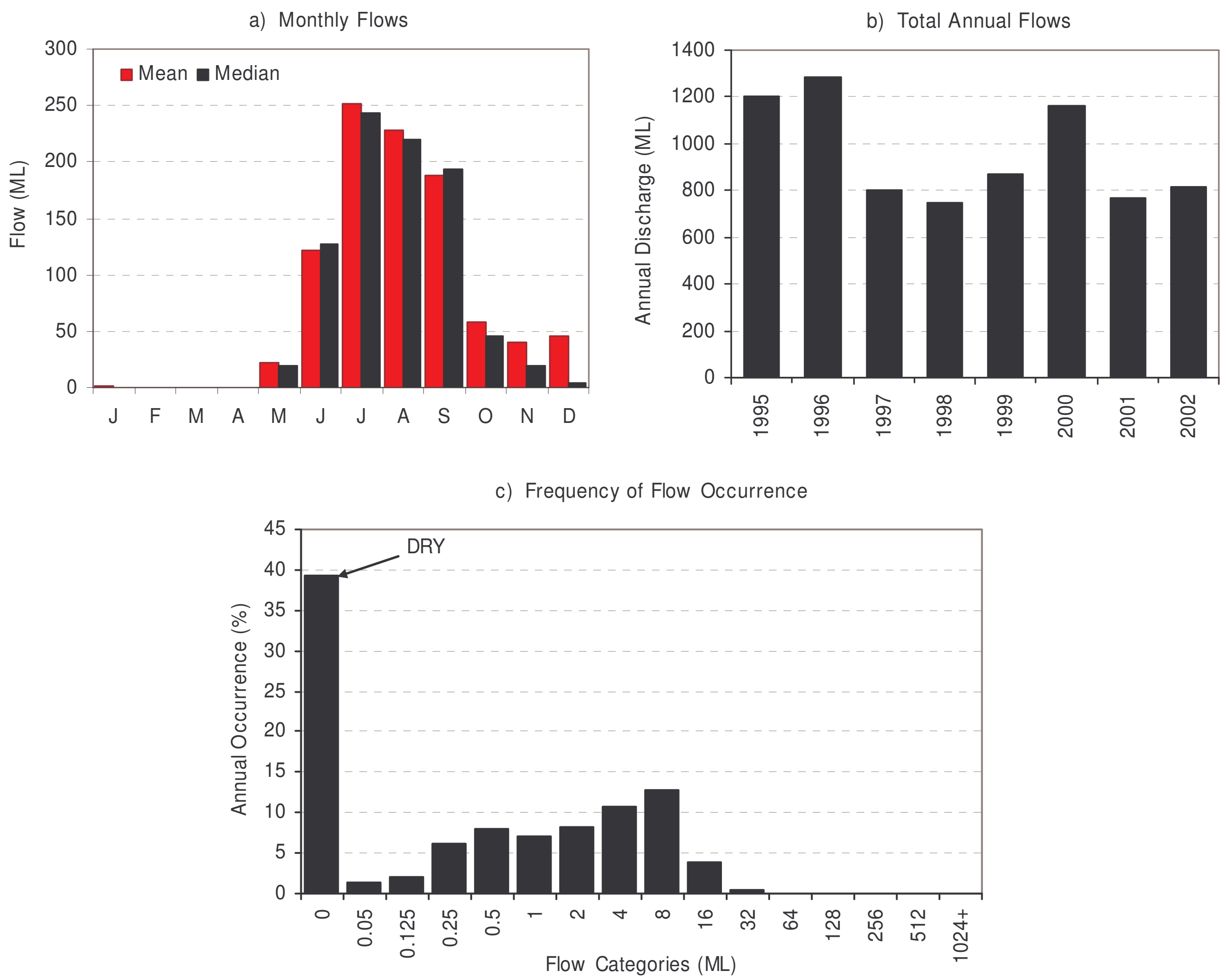

Figure 8. Flows recorded at Ferraro Brook (1995 – 2005); a) mean and median monthly flow; b) total annual discharge (ML); c) frequency of occurrence of annual flow events.

Plots of mean and median discharge clearly show the seasonality of flow in Ferraro Brook, with relatively high winter discharge and a predictable dry period in summer. Peak annual flows occur in July, August and September, with minimum flows through summer/autumn. Total annual discharge has shown considerable variation over the period of record and is correlated with rainfall. That is, high annual discharge was evident in 1995, 1996 and 2000 (Figure 8b), all of which were also high rainfall years (Appendix 1). The highest observed annual discharge occurred in 1996 (1,287.4 ML).

Summary of these data in flow duration curves, plotted for summer (1st November – 15th May) and winter (16th May – 31st Oct) flow seasons show greater frequency of high flows in winter (Figure 9).

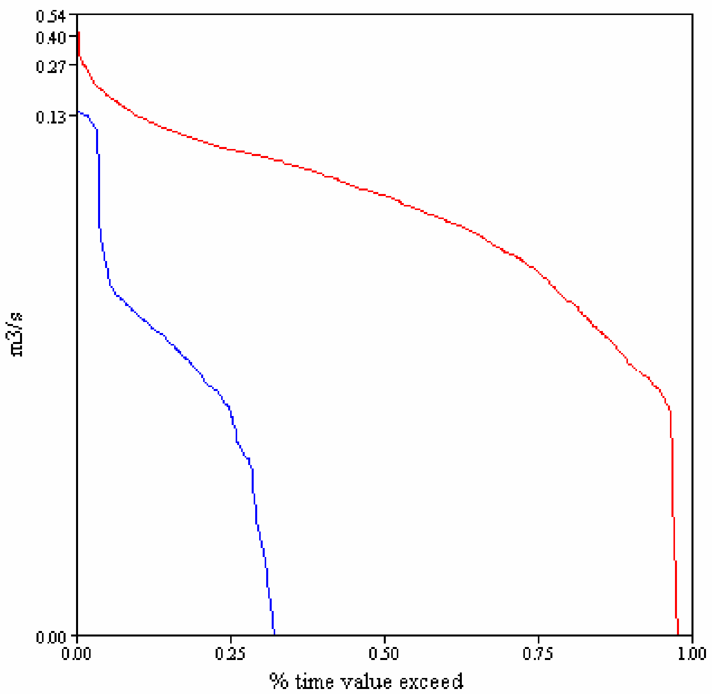

Figure 9. Flow duration curves for summer (blue) and winter (red) flow seasons for Ferraro Brook, showing duration of different flow magnitudes in each season.

3.3.1 Predictability & Seasonality of Stream Flow

Predictability and seasonality of flows influences the ecology and seasonal dynamics of stream communities and their overall species composition and are therefore considered of paramount importance to the ecology of a system. Predictability and seasonality therefore were assessed using the Time Series Analysis module in the River Analysis Package (RAP) using Colwell's Indices (Colwell 1974) which use daily streamflow records to describe temporal patterns in flow in terms of Predictability (P) Constancy (C) and Contingency (M). Predictability is the sum of Constancy and Contingency, where Predictability (P) is the likelihood of being able to predict a flow occurrence, and is maximised when the flow is constant throughout the year (*i.e.* high Constancy) or if the patterns of high or low flow occurrence is repeated every year of the total record. A Constancy (C) of 1 would occur when the flow is the same for all months/seasons, and a Contingency (M) of 1 would only occur if the pattern of flow is the same from year to year (*i.e.* high flows occur every winter). Patterns of discharge can thus be described not only in terms of the overall predictability but also the degree of seasonality.

Traditionally, Colwell's Index is applied to monthly flow categories however, RAP also allows analysis of pre-defined seasons. For the Ferraro Brook, Colwell's Indices were calculated for monthly flows and also flow seasons defined as summer (1st November - 15th May) and winter (the inverse of 'summer') as determined from high and low flow periods.

Analysis using both monthly and seasonal flow categories gave similar patterns in Predictability, however Constancy was higher for monthly as opposed to seasonal flows and the inverse was true for Contingency (Table 1). Flows had relatively high overall Predictability (*i.e.* likelihood of being able to predict a flow occurrence). In general terms, Contingency and Constancy were relatively low, with the latter particularly low for seasonal flows. This indicated that flows in the Ferraro Brook are reasonably predictable, most likely reflecting high winter and low summer flows regularly occurring each year, low Constancy, reflecting high inter-month differences in flows, and low Contingency, reflecting high inter-annual variation in flows (i.e. low flows in some years and high discharge in other years). Bearing in mind the short flow record, these analyses should be treated with some caution, hoever, the general overall patterns will likely hold for a longer time series.

Table 1. Predictability, Constancy and Contingency for monthly and seasonal (summer/winter) flows for Ferraro Brook.

Colwell's Indices	Monthly categories	Seasonal categories
Predictability	0.697	0.679
Constancy	0.396	0.183
Contingency	0.301	0.496

4 HYDRAULIC MODELLING

4.1 Introduction

A critical aspect of determining EWRs to protect key water-dependent environmental values and processes is the accurate surveying of the hydraulic geometry of the river channel. This is necessary to build hydraulic models which are then used to calculate the flows required to achieve specific water levels/discharges that drive important hydraulic and ecological processes. The first step in developing a hydraulic model is the accurate surveying of channel morphology using staff and dumpy to characterise the shape and variability on the channel. Replicate surveyed cross-sections (width and depth measurements) are then entered into the selected hydraulic model, which is then used to determine discharges required to achieve desired stage heights. Observed relationships of discharge to stage height are then used to calibrate the model.

4.2 Methods

4.2.1 Survey Reaches

The total amount of water required to sustain the identified key ecological values/processes was estimated based on *in situ* measurements of channel geomorphology (*sensu* Newbury & Gaboury 1993) taken on 25th November 2004 at Site FB5 (Figure 2). This site, at the confluence of Ferraro, Wealand and Upper Mayfield Drain and ~4 km below theproposed dam site, was chosen as most representative of brook conditions downstream of the mine area; sections east of South Western Highway were considered too down-cut. Within the site, cross-sectional surveys were conducted at three reaches:

Reach 1 – Ferraro Brook, immediately upstream of confluence with Wealand Brook; nine cross-section transects;

Reach 2 – Wealand Brook, immediately upstream of Ferraro Brook confluence; three cross-section transects;

Reach 3 – Upper Mayfield Drain, immediately below confluence of Ferraro and Wealand brooks; three cross-section transects.

Based on the principle, that if adequate flows to sustain ecological values are provided at the bottom end of a section of river and discharge is constant within the section, then values throughout the section concomitantly will be maintained. Therefore Reach 1, towards the downstream end of Ferraro Brook, was selected for the intensive survey of channel morphology for hydraulic modelling. Reaches 2 and 3 were surveyed to determine the relative contribution of flows in Ferraro Brook to Upper Mayfield Drain.

4.2.2 Cross-sectional Surveys

Replicate channel cross-sections were surveyed to characterise channel morphology of the reach. Temporary benchmarks were established along the reach for purposes of re-surveying, if necessary. The survey benchmarks, GPS location and number of cross-sections surveyed off each benchmark are summarised in Table 2.

Cross-sections were located to characterise the shape and variability of the channel over the reach and were positioned to include key hydraulic and ecological features such as controlling features, backwaters, pools, riffles, large woody debris and channel constrictions. These features, together with elevations of bankfull[3] and active channel (depth & width) were measured using a surveyors' dumpy and staff and a 100 m tape measure (Figure 10). Longitudinal distances between each cross-section were measured to determine change in elevation along each reach (*i.e.* slope).

Normally discharge is measured at the time of undertaking channel surveys to assist in calibrating the hydraulic model to be developed for the reach. A confined segment of stream of uniform shape is normally selected and replicate measurements of velocity taken across the channel using a flow meter. Velocity readings are then taken at 0.2, 0.6 and 0.8 of total depth at 10 cm increments across the channel width. Measurements are then used to calculate discharge (Q) as:

$$Q = \text{cross-sectional area} \times \text{average velocity}$$

However, Ferraro Brook was dry (except for several isolated pools) at the time the survey was conducted. Therefore, it was not possible to calibrate the model against a known discharge. The same applied to the cross-sections/models for lower Wealand Brook and Mayfield Drain.

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

Table 2. Locations of detailed cross-sectional survey sites on Ferraro Brook and additional sites on Wealand Brook and Upper Mayfield Drain. All locations are in WGS84. Locations indicate the left over-bank (LOB) end of each cross-section (*viz*. left of bank looking downstream).

Reach	Benchmark	Cross-section	Latitude	Longitude	Easting	Northing
Ferraro Brook	1	1	32˚48'48"	115˚53'24"	50 396114	636 8869
	1	2				
	1	3				
	1	4				
	1	5				
	2	6	32˚48'50"	115˚53'26"	50 3961 49	636 8799
	2	7				
	2	8				
	2	9				
Upper Mayfield Drain	3	10	32˚48'52"	115˚53'29"	50 395883	636 8790
	3	11				
	3	12				
Wealand Brook	4	13	32˚48'48"	115˚53'24"	50 396113	636 8898
	4	14				
	4	15				
	5	Foresight	32˚48'46"	115˚53'26"	50 3961148	636 8931

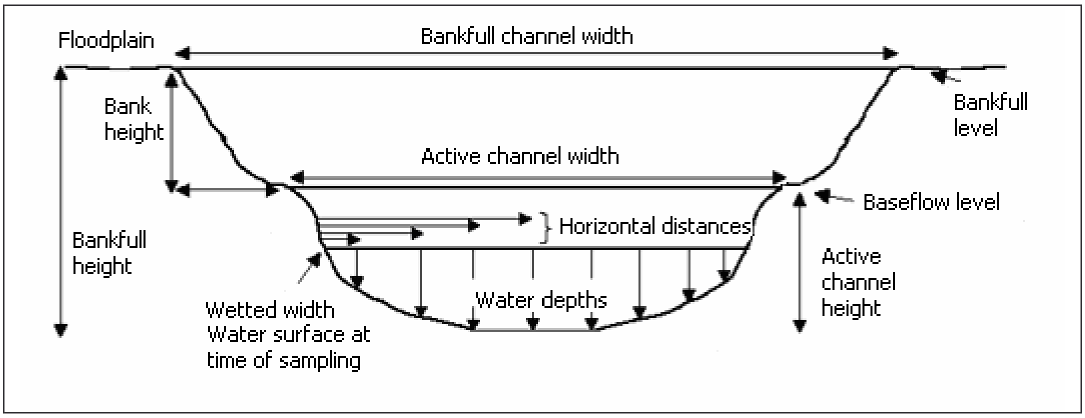

Figure 10. Example of channel cross-section measurements (after Parsons *et al.* 2002).

4.2.3 HEC-RAS Modelling

A hydraulic model was constructed for each reach using HEC-RAS (**H**ydrological **E**ngineering **C**entre, United States Army Corps of Engineers, **R**iver **A**nalysis **S**ystem), a one-dimensional, steady-state flow backwater analysis model.

To predict discharge, the hydraulic model relies heavily on subjective estimates of channel bed 'roughness' known as Manning's roughness coefficient or Manning's *n*. Bed roughness is determined by any factor that impedes water flow and includes bed substrates, organic debris (fallen logs *etc*), in-channel vegetation and channel meander/sinuosity. Manning's *n* may be calculated empirically using Manning's equation:

$$Q = \frac{AR^{2/3}S^{1/2}}{n}$$

Where, Q is discharge, A is cross-sectional area, S is slope, R is hydraulic radius (area divided by wetted perimeter) and *n* is Manning's *n*. If one or more variables are unknown, *n* may be estimated from Cowan's equation (Cowan 1956), which uses field observations of existing stream condition and from published tables of roughness coefficients for similar systems; *e.g.* the national Land and Water database of roughness values for Australian streams (http://www.rivers.gov.au/roughness/index.htm).

Ideally, discharge measurements for a range of discharge events of varying magnitude, related to water levels on selected cross-sections on the reach would be used in the HEC-RAS models to construct ratings curves (*i.e.* stage height vs. flow rate). This shows how stage height (depth) varies with discharge over time. Historic flow data would then be interrogated using the ratings curves from HEC-RAS in the RAP package in order to estimate recurrence intervals of each ecologically important flow event. Ideally, discharge at each site should be measured on a number of occasions (seasons & years) to cover a range of stage heights in order to produce the ratings curves and calibrate the HEC-RAS model to each reach. However, this was not possible given the time constraints of the current project. Therefore, the model was developed using a preliminary rating curve developed using a range of hypothetical discharges covering the range of known discharges, using log-scale discharge categories. Normal depth was used as the downstream boundary condition, with slope derived from changes in water surface level over the whole reach.

In addition to the main HEC-RAS model developed for Ferraro Brook, hydraulic models were developed for lower Wealand Brook and Upper Mayfield Drain. These models were based on only three cross-sections each and were solely to determine the likely relative contribution of each tributary (Wealand and Ferraro) to flows in Upper Mayfield Drain. HEC-RAS was used to model active channel flows in each reach and the discharge and channel characteristics compared.

4.3 Results

4.3.1 Reach Characteristics

The survey reaches were selected to be most representative of the system below the potential dam site. Reaches were characterised by trapezoidal drains with steep banks, sparse native riparian and in-stream vegetation, minimal woody debris and bed substrates dominated by sand, fine clays and silts (Plates 1 - 9). Riffle[4]-pool sequences were poorly defined, *i.e.* gravel runs with the occasional, shallow pool. Bank and bed substrates were not considered to be stable; there was evidence of extensive down-cutting, bank slumping and trampling by stock. Clearing has made the system prone to flooding. Bankfull flows occur most years and overbank flows at the confluence are common (G. Chaffey, pers. comm.). Levee banks have been constructed along Upper Mayfield Drain to control flood waters. Seasonal variation in habitat condition between late August and mid spring is illustrated in Plates 1 - 4.

[4]Riffle = rock, gravel or sandbars lying just below the water surface that result in increased water turbulence.

Plate 1. Confluence of Ferraro, Wealand and Upper Mayfield Drain in August 2004. View upstream (east). Wealand Brook entering from left. Down-cut drainage channels (photo: L. Sadler).

Plate 2. Confluence of Ferraro, Wealand and Upper Mayfield Drain in August 2004; view upstream along Ferraro Brook (photo: L. Sadler).

Plate 3. Confluence in November 2004. View upstream along Wealand Brook with Ferraro Brook entering from right. Channel encroachment by pasture grasses. Clump of native macrophyte visible in foreground.

Plate 4. Confluence in November 2004 of Ferraro, Wealand and Upper Mayfield Drain; view upstream along Wealand Brook. Bank slumping and trampling by cattle.

Plate 5. Ferraro Brook reach, benchmark #1, cross-section #1. Bed rock in the stream channel affecting low flows.

Plate 6. Ferraro Brook reach, benchmark #2, cross-section #8. View upstream. Cattle fence across small channel pool at boundary between properties.

Plate 7. Ferraro Brook reach, benchmark #1, cross-section #1. Channel downcut Bank slumping and trampling by cattle.

Plate 8. Ferraro Brook Brook reach, benchmark #1, cross-section #3; downcut banks, exposed tree (*Eucalyptus rudis*) roots.

Plate 9. Upper Mayfield Drain, in August 2004. View from farm bridge downstream of the confluence, near benchmark #3, cross-section #12 (photo: L. Sadler).

4.3.2 HEC-RAS Models

A hydraulic model was constructed for the lower Ferraro Brook using HEC-RAS. The key outputs from the model are:

- Graphical presentation of each cross-section transect along the reach;
- Longitudinal elevation of the whole reach;
- Summary table of hydraulic properties for the reach;
- A ratings curve for the reach.

Examples of cross-sections from the reach are shown in Figure 11. In these, the black line, 'Ground' in the legend represents the ground surface, reflecting the channel shape at each cross-section. Small black squares on the ground line show the exact points where survey measurements were taken to represent the shape of the channel. The x-axis shows distance (m) across the channel from left floodplain to right floodplain, and the y-axis shows the elevation, in m above an arbitrary datum, with the elevation of each successive cross-section surveyed to the same datum. Horizontal blue lines within the cross-section represent water surface for the various flows detailed in the legend (Active Channel flow ~ 1 m^3/sec), and the red symbols, 'Bank station' in the legend indicate a user-selected stage height on each cross-section, which, for the Ferraro Brook was Active Channel height. Assumed Manning's *n* for active channel and left and right floodplain are indicated across the top of each cross-section.

The longitudinal one-dimensional and three-dimensional profiles (Figure 12 & 13) show the overall slope and longitudinal shape of the reach. On the plots, the black line, 'Ground' in the legend represents the thalweg, being the deepest, central point of the channel. The small black squares on the ground line show the exact points where each cross-section was located. The blue line indicates water level for the modelled flow, and the left overbank (LOB) top of bank level is indicated. The water level for the flow profile is in-filled with blue shading.

HEC-RAS models output a range of hydraulic parameters which describe the hydraulic properties of each cross-section on each reach for each flow profile. The model has a choice of 254 different parameters, a selection of the more commonly used parameters are presented in Table 3 for the reach. The final main output of interest from HEC-RAS is the ratings curve for the reach, which shows the relationship between discharge and stage height (water depth). Under ideal conditions, this would be derived by repeated gauging of discharge at the selected reach for a range of flow scenarios over time, with water depth recorded on each occasion. These observed readings would then used to calibrate the HEC-RAS model and produce a rating curve.

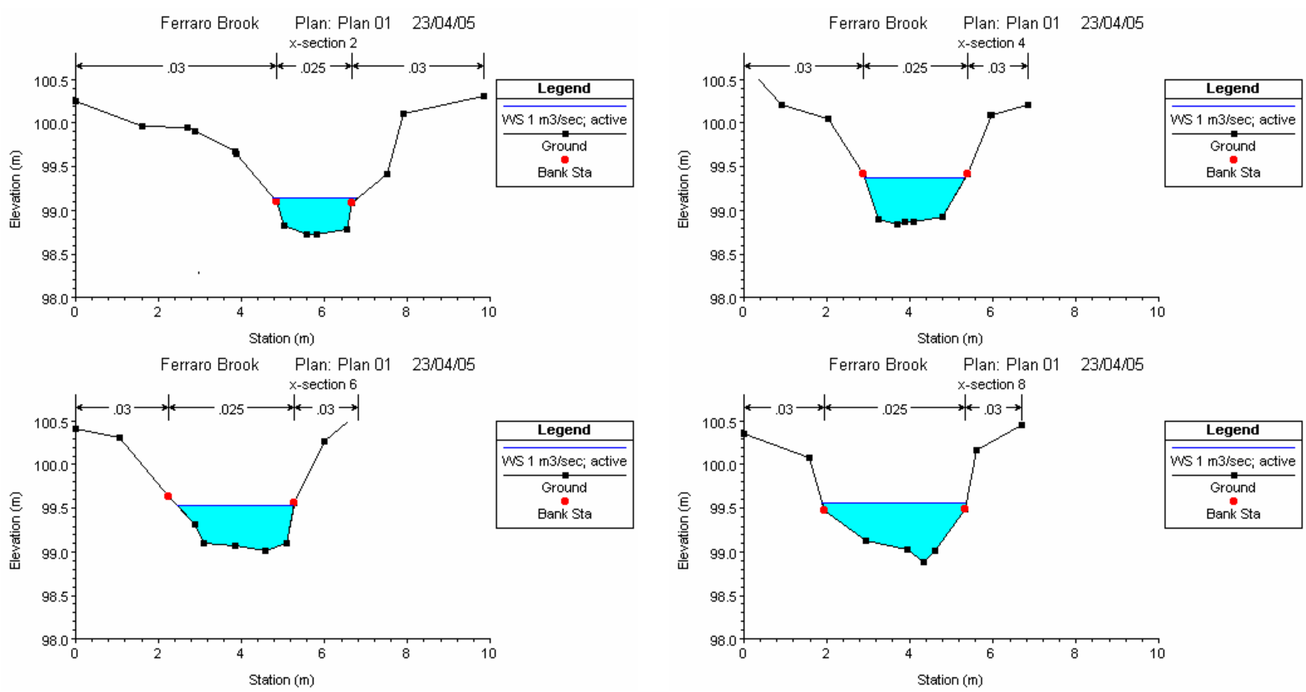

Figure 11. Examples of transect cross-sections, showing cross-section #2, #4, #6 and #8 from the reach. Plots show water level for one flow profile (flow required to reach Active Channel height), left overbank (LOB) top of bank level, with water level for the lower flow profile in-filled. Red symbols indicate Active Channel height on each cross-section. Manning's *n* for active channel and over-bank floodplain on left and right bank are across the top of each plot.

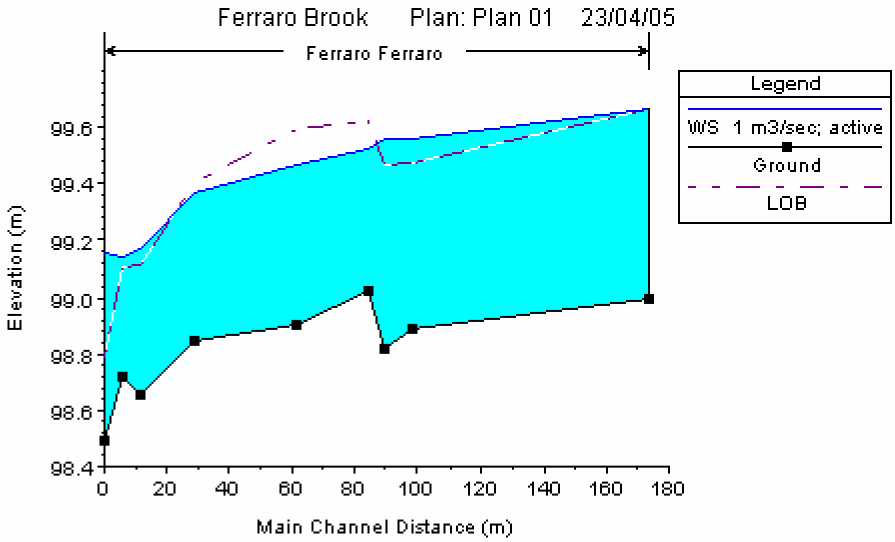

Figure 12. Longitudinal profile of Ferraro Brook survey reach showing location of cross-sections, water level for Active Channel flows, left overbank (LOB) top of bank level, with water level for the flow profile in-filled in blue.

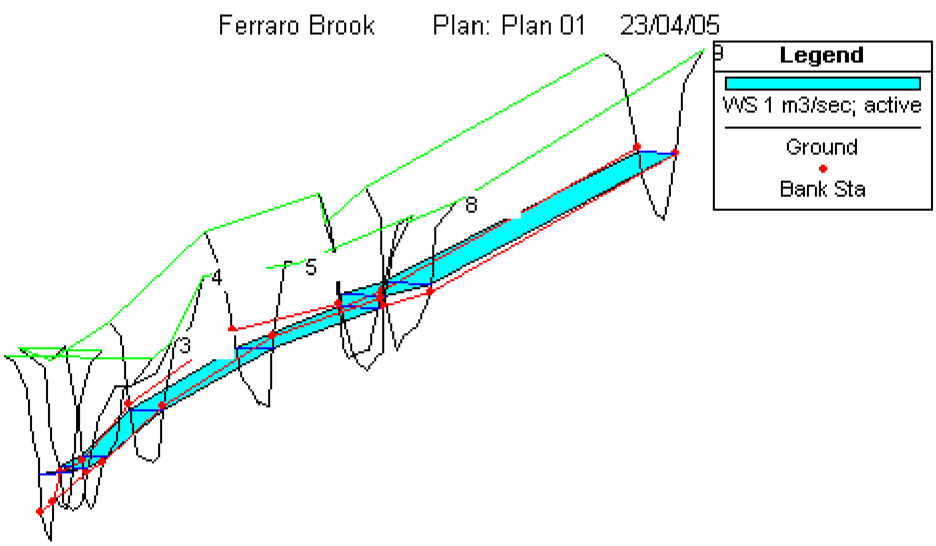

Figure 13. Three-dimensional profile of Ferraro Brook survey reach showing location of cross-sections, water level for Active Channel flows, left overbank (LOB) top of bank level, with water level for the flow profile in-filled in blue.

Table 3. Hydraulic parameters output by HEC-RAS.

HEC-RAS Plan: Plan 01 River: Ferraro Reach: Ferraro Profile: 1 m3/sec; active												
Reach	River Station	Profile	Q Total	Min Ch El	WS Elev	Crit WS	EG Elev	EG Slope	Vel Chnl	Flow Area	Top Width	Froude # Chnl
			(m3/s)	(m)	(m)	(m)	(m)	(m/m)	(m/s)	(m2)	(m)	
Ferraro	9	1 m^3/sec	1	99	99.6624		99.7	0.001809	0.87	1.15	2.77	0.43
Ferraro	8	1 m^3/sec	1	98.89	99.557		99.58	0.00127	0.74	1.36	3.48	0.37
Ferraro	7	1 m^3/sec	1	98.82	99.5578		99.57	0.000541	0.57	1.76	3.31	0.24
Ferraro	6	1 m^3/sec	1	99.02	99.5196		99.57	0.002581	0.96	1.04	2.81	0.5
Ferraro	5	1 m^3/sec	1	98.9	99.4632		99.51	0.002405	0.95	1.06	2.68	0.48
Ferraro	4	1 m^3/sec	1	98.85	99.363		99.42	0.002986	1.05	0.95	2.45	0.54
Ferraro	3	1 m^3/sec	1	98.66	99.1701	99.15	99.32	0.009854	1.74	0.58	1.85	0.93
Ferraro	2	1 m^3/sec	1	98.72	99.1411	99.1	99.27	0.00813	1.58	0.64	1.99	0.85
Ferraro	1	1 m^3/sec	1	98.49	99.1545	99.05	99.22	0.00332	1.27	0.97	2.66	0.56

Codes:

Q Total = total flow in cross-section.
Min Ch El = minimum channel elevation.
WS Elev = calculated water surface from energy equation.
Crit WS = critical water surface elevation; water surface corresponding to the minimum energy on the energy versus depth curve.
EG Elev = energy grade line for given WSEL.
EG Slope = slope of the energy grade line.
Vel Chnl = average velocity of flow in main channel.
Flow Area = total area of cross-section active flow.
Top Width = top width of the wetted cross-section.
Froude # Chnl = Froude number for the main channel.

In addition to the main HEC-RAS model developed for Ferraro Brook, hydraulic models were developed for lower Wealand Brook and Upper Mayfield Drain. Comparison of channel characteristic indicated that Ferraro and Wealand brooks were comparable in size, with similar wetted cross-sectional area and wetted perimeter for active channel flows, and likely contributed similar flows to Upper Mayfield Drain when both were experiencing active channel flows (Table 4). The River Analysis Package (RAP) was used to estimate discharge required to achieve active channel flows for Wealand Brook and Upper Mayfield Drain (Table 4), as determined from ratings curves for each reach (Figure 14). The same analysis was peformed for Ferraro Brook, but is reported in more detail in Section 7.

Table 4. Hydraulic parameters output by HEC-RAS for Ferraro Brook, Wealand Brook and Mayfield Drain for an active channel flow in each system, giving approximate discharge (m^3/sec), wetted cross-sectional area (m^2), wetted width of channel (m) and wetted perimeter (m).

Reach	Discharge	Wetted Cross-sectional Area	Channel Width	Wetted Perimeter
	(m^3/s)	(m^2)	(m)	(m)
Ferraro Brook	0.45	1.06	2.67	2.79
Wealand Brook	0.75	0.95	2.69	3.02
Upper Mayfield Drain	1.40	1.98	3.51	3.80

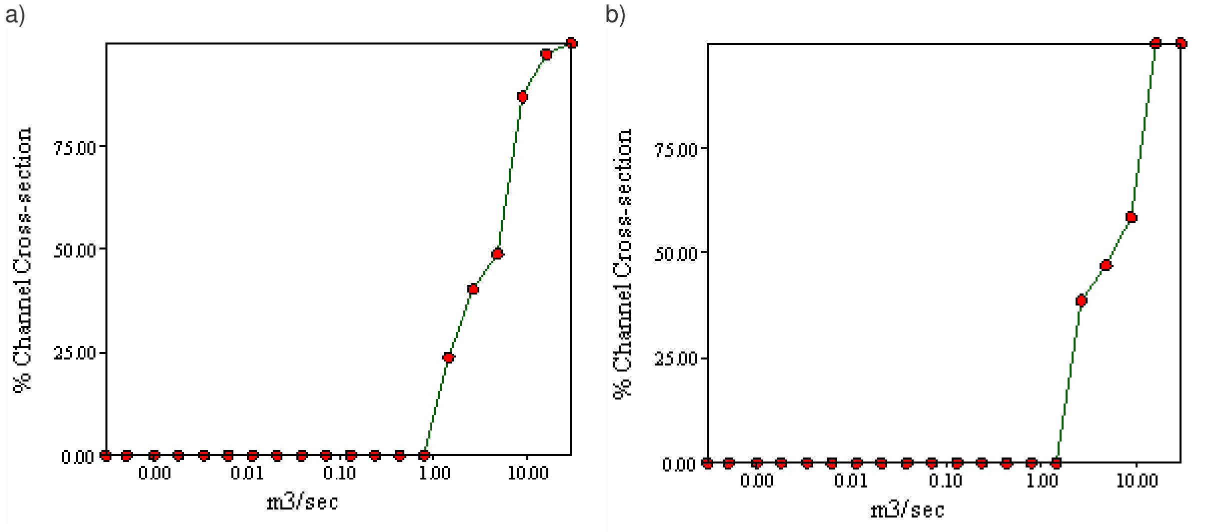

Figure 14. Reach level rating curve for discharge to attain active channel stage height for a) Wealand Brook and b) Upper Mayfield Drain, with threshold flows of 0.75 m^3/sec and 1.4 m^3/sec required to reach active channel flow respectively.

5 FLOW REQUIREMENTS OF KEY VALUES AND PROCESSES

5.1 Channel Morphology

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

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

Channel survey is therefore important to calculate the flows required to promote the desirable aspects of channel maintenance, but avoid high flows that have a detrimental effect on processes and fauna. Surveys indicated the channel is currently unstable and eroding, most likely from greater and faster runoff as a result of catchment clearing, with active channel flows events now occurring every year with most likely a number of events each year. Consequently, there is a large volume of mobile sediments in some reaches and this has the potential to infill pools. Therefore, adequate scouring flows need to be retained in winter to maintain pools, but a reduction in active flow events to 1:3 years may help ameliorate bed and bank erosion. Nor are frequent overbank flows desirable where levee banks have been constructed to control flood waters.

5.2 Riparian Vegetation

WRM (2005) considered the stream landscapes within the study area to be extremely degraded due to historic clearing of catchment vegetation, drain construction and unrestricted livestock access. Pasture species dominated the riparian understorey vegetation with few other native species present. There were only remnant pockets of mature overstorey, mostly *Eucalyptus rudis* and *Melaleuca* spp with sparse in-stream vegetation, mostly isolated clumps of sedge and rush at the level of the active channel and some *Potomageton* and *Lemna* sp in pools. Though the regional ecological value of most of the remnant riparian vegetation was considered to be low, local landcare groups have begun streamlining and revegetation to improve the ecological condition of the drains west of South Western Highway of the drains.

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

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

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

Vegetation of the riparian zone can either intercept groundwater or directly extract channel water. Determination of the extent to which riparian vegetation is reliant on groundwater was beyond the scope of the current study. In seasonal and ephemeral systems, deep-rooted tree and perennial vegetation are typically phreatophytic[5], but may (particularly the younger recruits) also use soil moisture and brook/drain flood waters during the wet season (Groom *et al.* 2000, 2001), However, it is expected that existing high overland/sheet flows and higher than historic groundwater tables and groundwater recharge in the Waroona study area would adequately compensate any reduction in flows. Flows from the unregulated Wealand Brook would also supplement flow in Upper Mayfield Drain, below the confluence with Ferraro Brook. Flows approximating channel forming (active) flows would inundate benches and existing riparian

[5] Phreatophytic = groundwater dependent

vegetation within the drainage channels. Active channel and winter medium flows would also assist in seed dispersal downstream.

In the unlikely event that reductions in rainfall, coupled with dam construction should lead to reduced overland as well as overbank flows, then provision of supplemental water may be required to assist local landcare schemes re-establish riparian vegetation.

5.3 Aquatic Fauna

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

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

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

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

The other major influence on aquatic fauna is the degree of temporal concordance of the flow regime, *i.e.* the degree to which a flow regime is not only seasonal but also predictable year-to-year (McMahon 1989, Bunn & Davies 1990, Bunn 1995). The high temporal concordance of south-western streams contrasts with streams elsewhere in Australia. Stable flows are a distinctive feature of lowland rivers during the dry season. Species that are susceptible to high and variable flows can synchronise life cycles so that the sensitive stages (*e.g.* the larvae of crustaceans or pupating stages of some insects) occur only during the dry season. As a consequence, unusually high discharge events during the dry season may be detrimental to the persistence of these species. It is important, therefore, that dry season flows below proposed impoundments remain benign without dramatic changes in flow rate. Any freshwater releases/discharges from the mine area should match the normal seasonal timing for the system, and the shape of the hydrograph of flood events (*i.e.* rates of rise and fall and duration of peak flows) should also conform to the range normally experienced by the system. Excessively high discharge events, particularly outside the normal seasonal range will have deleterious effects on fauna and flora, as will too rapid a rise or fall in the flood hydrograph. Though winter flows in the study area are now greater than would have occurred historically, the seasonality of the flow regime is currently maintained.

5.3.1 Aquatic Macroinvertebrates

Consistent with other surveys of disturbed watercourses on the coastal plain, WRM (2005) found aquatic macroinvertebrate diversity to be low-moderate. Fauna was dominated by cosmopolitan species with no species considered rare or restricted in distribution. However, of note was the presence of two freshwater crayfish, both regional endemics: gilgies (*Cherax quinquecarinatus*) and koonacs (*Cherax plebejus*). To further understand the relationships between aquatic macroinvertebrates and their environment and how changes to the hydrological regime may impact on these relationships, a review of the life history characteristics of all species recorded from this study was undertaken. Some species have been extensively studied, while there is little information on others. A range of sources were referenced for information on macroinvertebrates life histories, including but not limited to; Shipway (1951), Watson (1962), Williams (1980), Hynes and Bunn (1984), Bunn *et al.* (1986), Bunn (1988), Boulton (1989), Storey and Edward (1989), Storey *et al.* (1990, 1991), Bunn and Davies (1992), Trayler *et al.* (1996), Cartwright (1997), Davis and Christidis (1997), Maguire *et al.* (1999), Edward et al. (2000), St Clair (2000), McKie and Cranston (2001), Gooderham and Tsyrlin (2002), Lawrence and Jones (2002), and the authors' own experience. Taxonomic keys to species were also consulted for relevant information on habitat preferences and distribution. The authors are currently compiling a general database on Western Australian macroinvertebrate species to include flow requirements (seasonal versus permanent), habitat preferences, diet, habit, length of life cycle and breeding season. Development of the database is on-going.

Spring/summer spawning is a common life history characteristic of many aquatic macroinvertebrates, and those recorded from the current study area are no exception. Very few species found in the system breed during the wetter winter months, and few are likely capable of breeding year-round. Therefore, some spring flows should be maintained to provide breeding habitat.

Since the waterbodies in the Waroona study area are naturally seasonal, maintenance of summer surface flows in Ferraro Brook and Upper Mayfield Drain would not be required to maintain the existing riverine ecosystems. Many of the macroinvertebrates currently occurring in the system have life history traits which would allow them to survive periods of seasonal drying. Some species are capable of burrowing into moist sediments to avoid desiccation, including the freshwater crayfish. Although gilgies are capable of burrowing to avoid summer drying, soils must be moist to ensure their gills remain hydrated. They have no resistant stage in their life cycle.

Others groups are thought to have some resistant stage to their life cycle (usually the egg stage) and may undergo diapause during summer. Many species (particularly those with winged, terrestrial adult stages) are known to inhabit both seasonal and permanent waters. However in order to maintain existing levels of biodiversity it is important that some pools persist over summer for species susceptible to summer drying. It is expected that groundwaters and high water tables will continue to maintain permanent pools, with EWRs for freshwater crayfish being met by these and flow recommendations for other key components, *i.e.* macroinvertebrates, active channel flows and fish passage flows (see below).

Macroinvertebrate diversity is also 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.* 1999). A vast number of aquatic invertebrates for example, are associated with complex habitats such as snags, rocks, macrophyte and trailing riparian vegetation, which have largely been removed from Ferrrao Brook and Upper Mayfield Drain. If streamlining projects were to improve these features, sufficient flows would also need to be provided to keep them inundated, thereby ensuring a diversity of in-stream habitats was maintained.

Riffle zones are also regarded as highly productive habitat for macroinvertebrates (Brown & Brussock 1991). Fauna that inhabit riffles depend on the constant flow of water for delivery of food and oxygen. For a seasonal system, it is important to maintain coverage of riffles in spring to maintain biodiversity. It is acknowledged that water levels naturally will be lower in spring and therefore it is unrealistic to inundate the whole width of the riffle during low flow spring months. Therefore, the dual objectives of maintaining an average depth of 5 cm with a 100% coverage of the riffle were considered adequate to maintain a low-flow winter channel over riffle zones and were regarded as the minimum necessary to support benthic invertebrate communities (Storey *et al.* 2001, Storey and Davies 2002, Streamtec 2002).

5.3.2 Fish Fauna

Only one native fish, the western minnow (*Galaxias occidentalis*), and one introduced fish the mosquitofish (*Gambusia holbrooki*) was recorded from the study area (WRM 2005). To understand how changes in flow regime may affect individual species of fish, it is necessary to understand the life history strategies and breeding times. Some species have been extensively studied, while there is little information on other species. A range of sources were referenced for information on species, and these included; Merrick & Schmida (1984), EPA (1987), Pusey *et al.* (1989), ARL (1990b), Pusey and Edward (1990), Pen and Potter (1991a,b,c), Pen *et al.* (1993), Sarti (1994), Watts *et al.* (1995), Pusey and Bradshaw (1996), Morgan *et al.* (1998), Allen *et al.* (2000), Morgan and Gill (2000), Morgan *et al.* (in press), WRC (2002b) and ACWA (2004). Although there is likely to be some variation in breeding season and development in different river systems, the overall flow requirements will remain the same. For a detailed summary of reproduction and life history srategies of each species refer WRM (2005).

Given the seasonal nature of the system, small pool sizes and lack of in-stream habitats, Ferraro Brook /Upper Mayfield Drain do not afford ideal habitat for native fish. It is highly unlikely that western minnows breed in the system on a regular basis, but rather use it opportunistically. Predictable winter/spring flooding coupled with a diversity of in-stream and trailing vegetation habitsts would be required to encourage breeding in western minnows. Inundated trailing riparian vegetation is known to be a favoured spawning habitat in other south-west systems. If water levels fall too soon, or fluctuate greatly, any eggs may be left dry and desiccate.

Retention of medium flows from late autumn to early spring will provide passage for minnows that opportunistically use the drainages and allow fish to seasonally recolonise.

The mode of delivery of winter flows to provide for fish passage is also a critical issue. It is generally acknowledged that flows should be delivered in pulses to provide sufficient depth to maximise the ability of accumulated fish to traverse natural and man-made obstacles. Generally, fish will wait below a barrier until a spate allows them to negotiate upstream. The duration of the higher flows required for fish to negotiate an obstacle is open to conjecture. It is likely that for any individual obstacle, the majority of fish that have accumulated downstream would negotiate the feature within hours of it being passable. In the lower Ferraro brook and Upper Mayfield Drain, there were few natural obstacles such as fallen logs, shallow riffles and small, short water falls. Therefore, elevating flows for an average depth of 10 cm with a 100% coverage of riffles over a period of several hours would probably allow fish to negotiate any individual obstacle.

WEC (2002) suggested that increased flows do not need to be continuous, but should be maintained, as pulses to simulate spates, for at least ten days during each of the months of August and September. Streamtec (2002) recommended fish passage flows for the Samson Brook in August, September and October, with 15 flood events in September alone. This aspect of EWRs for fish requires further development. Ideally, the number of passage flow events should be based on the natural frequency of events, which will be related to the frequency of south-westerly frontal systems from early winter through to spring. The 15 events in September recommended for the Samson Brook seems excessive, with natural events likely occurring at a lower frequency in any one month. Also, native fish start to migrate upstream as soon as winter flows commence (*i.e.* late May - early June; A.W. Storey, pers. obs.), therefore, passage flows need to start earlier in the winter (*i.e.* May) and continue through winter. Late winter/spring flows may be lower as fish are able to move downstream over obstacles in considerably less water than required to move upstream.

5.4 Long-necked Tortoises

Long-necked tortoise (*Chelodina oblonga*) are known to occur in the system (G. Chaffey, pers. comm.). This species commonly requires summer refugia in the form of permanent pools, although this is not critical as long-neck tortoise can aestivate. The juveniles likely use shallow-inundated floodplain areas for growth where they remain away from the faster flows and where the waters are very productive, supporting abundant macroinvertebrate and macrophytes populations which provide food and cover. In perennial systems long-neck tortoise nest in spring (Sept. – Oct.) and again in summer (Dec. – Jan.), but in seasonal systems they nest in spring only (they either aestivate in summer or relocate to other water bodies). Loss of permanent pools may result in a decline in population size as they will nest in spring only. Conversely, permanent flows may lead to a build-up in numbers through increased recruitment, with flow-on effects to prey items (tadpoles, fish and invertebrates).

Maintenance of winter low and medium flows for invertebrates and fish were considered the minimum necessary to support tortoises.

5.5 Water Quality

In certain situations, provisions for EWRs may be specifically designed as flushing flows to remove poor quality water that arises over summer due to lack of riparian shading, high temperatures, low dissolved oxygen, accumulating leachates, waste materials and increased microbial activity – all of which can prove lethal to aquatic fauna trapped in small pools. Such flows are not warranted for Waroona study area since the drainages are naturally dry during the summer 'risk period'. Winter flows approximating channel forming (active) flows would be sufficient to provide the minimum average velocity of 0.01 m/sec in pools that is generally recommended to avoid stratification, maintain mixing and thereby maintain dissolved oxygen levels > 2mg/L (*sensu* Cottingham *et al*. 2003) and water quality.

5.6 Energy Flows

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

Existing models of ecological processes differ in the interaction between a river and the catchment. The River Continuum Concept (RCC) (Vannote *et al.* 1982) emphasises an upstream-downstream linkage in energy flow, where material derived from forested regions supports downstream ecosystems. Reservoirs inhibit this upstream-downstream linkage in carbon flow. In these circumstances, the input from the riparian zone and tributaries below reservoirs are important to maintain the connectivity between forested and lower reaches.

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

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

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

In the current study area, the historic condition would have been the predominance of the RCC in the upland reaches on and at the base of the Scarp, switching to RPM across the coastal plain. Loss of vegetation from the upper catchment means that sources of allochthonous material are reduced and any dam would further reduce downstream movement. Similarly carbon inputs from the floodplain have been reduced.

Storey *et al.* (2001), Storey and Davies (2002) and Streamtec (2002) considered that baseflows recommended for macroinvertebrates combined with fish passage and active channel flows are typically adequate to maintain upstream-downstream energy linkages (winter through to spring). Naturally higher winter flows and overland runoff will maintain floodplain linkages.

6 ISSUES, PRESSURES AND ECOLOGICAL FLOW OBJECTIVES

Based on the hydrological state of the catchment, current catchment land uses and observed ecological values, a range of management issues and pressures likely to affect the ecological values of the system were identified. Broad key issues are summarised in Table 5.

Based on the above catchment management issues and pressures and existing ecological values, the ecological flow objectives for key features of Ferraro Brook were considered to be:

Channel morphology

- Maintain some winter high flows (active channel flows) to flush channel of accumulated sediments and organic detritus.
- Maintain frequency of active channel flows at 1:2 to 1:3 years, to help control erosion.

Riparian Vegetation

- Maintain some winter medium and high flows inundate lower benches and existing riparian vegetation within the drainage channel and to assist with seed dispersal.
- It was considered that inundation of the floodplain for seed set and germination would be met by existing, higher than historic water tables and overland runoff during winter (July-August).
- Maintain flow periodicity; *i.e.* dy over summer, to prevent proliferation of weed species within the channel.

Aquatic invertebrates

- Maintain flow periodicity; *i.e.* dy over summer.
- Maintain winter low flow (baseflow) of 5 cm (0.05 m) stage height over riffles from winter through to early spring.
- Permanent pools to support current biodiversity would be mainted by higher than historic water tables.

Freshwater crayfish

- It was considered that the EWRs for freshwater crayfish would be met by the winter-spring low flow proposed for aquatic macroinvertebrates and flows for fish passage (see below).

Freshwater fishes

- Maintain a flow of 10 cm (0.1 m) stage height to allow passage of western minnows from late autumn winter through to early spring.
- Occasional, higher natural flood events will provide additional fish passage flows for negotiating larger obstacles.

Energy flows

- Maintain winter medium flows for upstream-downstream transport of energy/carbon.
- Flows to maintain riparian vegetation as an energy source for the RPM (River productivity Model). These are likely to be met be existing overland flows. Overbank flows not desirable where levee banks have been constructed.

The key ecological features and the flow components to be assessed for each ecological value have been summarised in Table 6 as flow objectives, with the various ecological values grouped under common flow objectives. These were analysed using hydraulic models and the Flow Events Method (FEM).

Table 5. Issues and pressures affecting hydrology, flow regime and ecology of Ferraro Brook and Upper Mayfield Drain.

Driving Force	Issue	Time of Year	Hydrological/WQ Effects	Potential Ecological Effects
Catchment clearing	Increased ground-water levels in upper reaches.	Winter	Increased contribution of runoff to flows in upper reaches.	Changes in assemblage structure of native fish, bugs, flora. Decline in vegetation vigour; shift towards species more tolerant of inundation.
	Increased ground-water levels in lower reaches.	Winter	Increased contribution of groundwater & runoff to flows in lower reaches.	Changes in assemblage structure of native fish, bugs, flora. Decline in vegetation vigour; shift towards species more tolerant of inundation.
		Summer	Catchment seeps & springs become more reliable; greater flow permanence in lower reaches.	Changes in assemblage structure of native fish, bugs, flora. More reliable refugia for bugs & fish; better recruitment/survival of species intolerant of seasonal drying. Water quality problems in permanent pools over summer due to nutrient input & lack of riparian shading.
	Faster & greater run-off causing channel erosion in upper & lower reaches.	Winter	Bed & bank erosion. Channel incision. Mobile sand slugs. Increased turbidity/suspended sediment.	Pool infilling from mobile sand/silt with associated loss of habitat. Erosion of banks and associated riparian vegetation. Channel incision resulting in riparian vegetation being 'suspended' on drying floodplain. Isolation/reduced connectivity of channel overbank flows with floodplain which provides seasonally inundated habitat for fish & frogs.
	Reduction in amount of large woody debris in channel.	All year	Increased water velocities. Bed & bank erosion.	Erosion of banks & associated riparian vegetation Loss of in-stream habitat diversity & associated loss of faunal diversity. Reduced carbon/energy source with associated loss of in-stream productivity.
Channel straightening / Drain construction	Faster & greater run-off causing channel erosion in lower reaches.	Winter	Increased water velocities. Bed & bank erosion. Channel incision. Mobile sand slugs. Increased turbidity/suspended sediment.	Erosion of banks and associated riparian vegetation. Channel incision resulting in riparian vegetation being 'suspended' on drying floodplain. Isolation/reduced connectivity of channel overbank flows with floodplain which provides seasonally inundated habitat for fish & frogs. Loss of in-stream habitat diversity & associated loss of faunal diversity.

Driving Force	Issue	Time of Year	Hydrological/WQ Effects	Potential Ecological Effects
				Reduction in seasonal swamp habitats & associated loss of faunal diversity.
Impoundment & abstraction from Ferraro Brook	Reduced peak flows.	Winter.	Channel forming flows occur with reduced frequency.	Loss of channel forming flows resulting in infilling of pools with sediment; loss of channel morphology. Riparian encroachment into channel; overall reduction in habitat diversity.
Impoundment & abstraction from Ferraro Brook	Reduced frequency of intermediate flow events.	Winter to early Spring.	Reduced frequency of fish passage events.	Loss of fish access to habitat.
Releases from dam	Insufficient flow to maintain coverage of stream channel.	Early Spring.	Insufficient flows so that riffle zones (biodiversity 'hot spots') dry out	Invertebrate fauna that breed in spring will be lost from the system if the channel is allowed to dry too early in the season.
Releases from dam/discharge areas	Releases do not conform to system expectations in terms of shape and size of hydrograph.	All year.	Unseasonal releases, with faster than normal increase/decrease in stage height.	Fauna washed from system or left stranded & desiccated due to too rapid increase or drawdown.
Releases from dam/discharge area	Releases do not conform to system expectations in terms of size of peak flows.	All year.	Excessive releases/dichargeswill result in scouring & erosion.	Elevated turbidity, soluble solids & sedimentataion; excessive velocities; bank and bed erosion; loss of habitats.

Table 6. Ecological values and objectives determined for Ferraro Brook.

Flow component	Ecological attribute / Value	Ecological objective	Season (duration)	Time series (pulse/spells)	Hydraulic metric	Consequence of not meeting objective
Fish Passage Flow	Fish diversity	Passage for small bodied fish moving upstream from late autumn through into early spring across natural obstacles (*i.e.* rock bars, shallow riffles and LWD).	Late Autumn through into early Spring	Events (size and frequency) / duration	Minimum depth over obstacles of 0.10 m for small species (*i.e.* western minnow) late May to November.	Loss of migratory species from parts of the system if passage restricted. Reduced connectivity.
Winter Low Flow (Base flow)	Process	Seasonal inundation of benches for allochthonous litter transfer. Predictions of Riverine Productivity Model; seasonal inundation & recession 'collects' detrital material in main channel which supports food webs.	Winter	Medium wet season events	Inundate riffles & gravel runs in winter	Detrital material important in food webs. Loss of this material may limit abundance and/or presence of some species.
	Fish	Stage height to ensure any marginal fringing vegetation & reeds/rushes are 'trailing' & thereby providing fish cover and spawning sites.	Winter	Flow duration	Duration of baseflow sufficient to inundate trailing vegetation – based on elevation on cross-sections	Insufficient flows will leave trailing vegetation above water and not accessible. Insufficient continuous duration may expose and dehydrate any eggs spawned onto vegetation.
	Invertebrates	Gravel runs & riffles maintained in summer as biodiversity 'hotspots'.	Winter	Flow duration	Minimum stage height to maintain current area of gravel runs & riffles to a depth of 0.05 m.	Reduced biodiversity as obligate gravel run/rapid dwelling species will be lost from the system.
	Vegetation	Inundate any emergent macrophytes and aquatic plants	Winter	Flow duration	Inundate riffles & gravel runs in winter	Loss of biodiversity
Winter Medium Flows	Process	As for Winter Low Flows				
	Native Fish	As for Winter Low Flows				
	Vegetation	Riparian vegetation - main channel bank & emergent vegetation. Seasonal inundation of emergent and main channel bank vegetation.	Winter	Flow duration	Inundate lower banks and benches in winter.	Change from historic water regime = change in plant community (terrestrialisation) with associated change in structure. Enhanced opportunity for terrestrial weeds (*e.g.* grasses). Riparian vegetation supplier of LWD as aquatic habitat & of material to support detrital food webs. Regulator of nuisance algal growth, through shading.

Flow component	Ecological attribute / Value	Ecological objective	Season (duration)	Time series (pulse/spells)	Hydraulic metric	Consequence of not meeting objective
Active Channel Flows	Channel morphology	Maintain pools & channel form. The proposed dam has the potential to reduce the magnitude of large flow events which are important for channel maintenance as pools provide refugia for fauna in summer & require regular scouring to prevent excessive build up & infilling.	Winter	Event magnitude / frequency	Channel forming flows – flows to active channel stage height on a 1:2 - 1:3 year frequency.	Loss of pool depth = reduced carrying capacity for fish, loss of summer refugia for fish. Greater encroachment by riparian vegetation. Higher BOD with associated risk of low DO in summer. Loss of benthic fauna due to smothering by fine sediment build up, smothering of snags in pools = reduced habitat. Loss of species requiring permanent water in preference to those with strategies to survive seasonal flows.
		Prevent incursion of riparian vegetation into channel. There is a dynamic relationship between flow, sediment deposition & vegetation encroachment on the channel.	Winter	Event magnitude / frequency	Channel forming flows – flows to active channel stage height on a 1:2 - 1:3 year frequency.	Area of active channel will decrease. Peripheral velocities will be reduced resulting in more sediment deposited & weed incursion.
Summer Zero Flow	Seasonal flows	Maintain a period of drying in summer	Summer	Base flow	Zero flows.	Channel incursion by pasture grasses. Establishment and domination by exotics species such as carp, yabbies, mosquitofish *etc*. Change from historic water regime = change in plant community (towards mesic species). Water quality problems associated with nutrient loading & lack of riparian shading.

7 FLOW EVENTS MODELLING FOR FERRARO/UPPER MAYFIELD DRAIN

7.1 FEM Approach

Flow Events Modelling (FEM) was used to estimate the frequency of ecologically significant flow events under the observed, unregulated hydrological regime for Ferraro Brook. The term 'event' refers to a particular suite of hydrologic or hydraulic conditions identified as significant for maintaining the ecological values of the study reach. FEM typically comprises two steps: 1) the derivation of 'rating curves' to relate each flow event to flow magnitude and 2) the analysis of the flow record at each reach (Cottingham *et al.* 2003). Rating curves describe the relationship between ecologically significant flow events (*e.g.* fish passage flows) and flow rate. The flow events are defined in terms of specific criteria that can be described in a spreadsheet (*e.g.* minimum depth in the reach of 0.1 m). The rating curves are derived using the relationship between flow rate and stage height. This was established using the hydraulic model HEC-RAS (Section 4) and the cross-section survey data from each reach. As discussed in Section 4, actual flows over the range of stage heights could not be surveyed for the current project, therefore, rating curves were derived by running steady-state flow simulations for a range of flow rates covering the range of flows likely for the system (*i.e.* 0.001 – 10 m^3/sec). The FEM was then used to determine the frequency and magnitude of ecologically significant flow events, whereby the flow record was transformed into records of events using the rating curves. The event record was then analysed for aspects such as flow duration; *i.e.* the percentage of time that an event of a particular magnitude is exceeded or not exceeded, depending upon how the criteria is defined. The analyses can look at the whole flow record, or restrict the analysis to specific seasons (*e.g.* fish passage in winter).

Original development of the FEM was for application to the Gouldburn River in eastern Australia (Cottingham *et al.* 2003). The Goulbourn is a regulated river and FEM compared regulated flow to modelled natural flow in order to compare differences between the natural and modified regimes (i.e. differences in frequency and duration of bench inundation). This is an aspect to which FEM is particularly suited. For the current study, FEM was used to describe the current frequency of events (observed flow record under regulation by the FWL) against the modelled frequency of events (modelled flow record for no flow regulation).

7.2 Flow Data

FEM depends upon a relatively long, complete record of mean daily flows for the reach to be modelled. As discussed in Section 4, the only flow data Ferraro Brook were daily flows for eight years at Iluka's upper catchment gauging station (1995 – 2002). As this station was located approximately 4 km upstream of the survey reach, mean annual flows at the reach will be greater than at the weir due to increased catchment area and input of surface water into *via* the drainage network across the coastal plain. It was assumed that if flows measured at the survey reach were adequate to meet the desired ecological objectives for the survey reach, then the same objectives would be satisfied for all reaches below the proposed dam. However, because of transmission gains (and possibly transmission losses in summer) between the gauging station and the survey reach, the total flow calculated for the survey reach may not need to be released in full from the proposed dam. By timing releases to coincide with natural events, the size of the releases may be optimised.

As discussed in Section 4, the absence of flow data was resolved by developing a preliminary ratings curve based on a range of hypothetical discharges covering the range of known discharges (1995 – 2002), using log-scale discharge categories.

7.3 Ecological Flow Recommendations

Flow events deemed ecologically important, following consideration of the identified ecological values and current scientific knowledge of the water requirements of these values are summarised together with flow recommendations in Table 7 at the end of Section 7. In general terms, the values, processes and features to be maintained and therefore modelled by FEM included:

- Winter baseflow for inundation of riffles and gravel runs, inundation of emergent macrophytes and provision of trailing vegetation for fish habitat, flow connectivity for energy transfer;
- Fish passage flows to allow movement of native fish up stream to reach spawning habitats from late autumn to early spring;
- Channel forming (active channel) flows in winter for maintaining channel shape;
- Winter medium flow events for inundation of lower benches for energy transfer and seed dispersal of riparian vegetation;
- Maintain period of summer zero flow to prevent the proliferation of weed species and water quality issues associated with nutrient loading, low flows, low velocities, low riparian shading, and increased summer temperatures.

Flows normally estimated, but **not required** for this system due to it being seasonally flowing/a drain with high conveyance capacity, include:

- Summer base flow to maintain perennial flows, inundation of riffles for macroinvertebrate habitat and maintain dissolved oxygen levels above critical thresholds;
- Floodplain flow events for channel maintenance, flushing sand from pools, riparian vegetation inundation, inundation of high benches.

Details of modelled output are discussed below.

7.3.1 Fish Passage

Based on fish surveys, fish passage flows are required with a minimum threshold depth of 10 cm over perceived obstacles for the Ferraro Brook to allow upstream movement of the small bodied western minnow. Hydraulic analysis was performed to determine flows that achieved the above threshold, calculated as a minimum threshold depth for the reach.

Hydraulic analysis produced a reach-level rating curve for Ferraro Brook (Figure 15) which indicated a discharge threshold of 0.07 m^3/sec, below which fish passage was not possible along the reach, and above which passage was possible, with the percentage of cross-section width[6] available for passage increasing to an asymptote of maximum passage at approximately 10 m^3/sec (Figure 15). This maximum percentage channel cross-section for fish passage is an extreme value as it reflects overbank flooding, and therefore also includes the floodplain. These flows are unlikely for a trapezoidal drain designed to convey flood flows. The effective area for fish passage is the channel below bank full, which is approximately 17% of the cross-section width. The critical flow is the minimum flow at which fish passage is possible, which is 0.07 m^3/sec. Cross-section #2 on the Ferraro Brook reach was the critical threshold point limiting fish passage. Once the threshold depth of 0.1 m was achieved at cross-section #2, fish passage was possible throughout the reach.

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[6] Cross-section width used to calculate cross-section area (A) and hence discharge (Q) via the equations: A = width x depth x height; Q = A x average velocity (refer Sction 4).

Analysis of seasonality of fish passage showed greater passage in winter than summer (Figures 16 & 17) with peak fish passage in September (Figure 18), and with passage commencing in May. Analysis of the whole flow period indicated a mean of 10.6 fish passage events each winter, with a mean duration of 6.3 days for each event. The mean total number of days per winter for fish passage was 62 days (Figure 19).

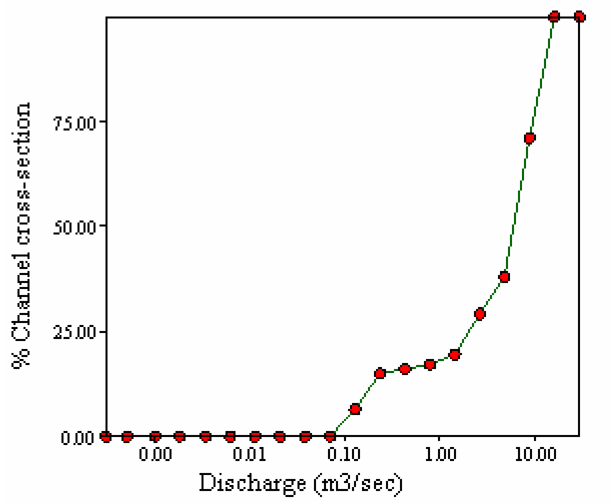

Figure 15. Reach level rating curve for fish passage on Ferraro Brook, showing change in percent channel width (y-axis) with increasing discharge (m^3/sec) (x-axis). The fish passage criteria of 10 cm minimum threshold depth is achieved with a discharge of 0.07 m^3/sec, with cross-section #2 being the critical cross-section.

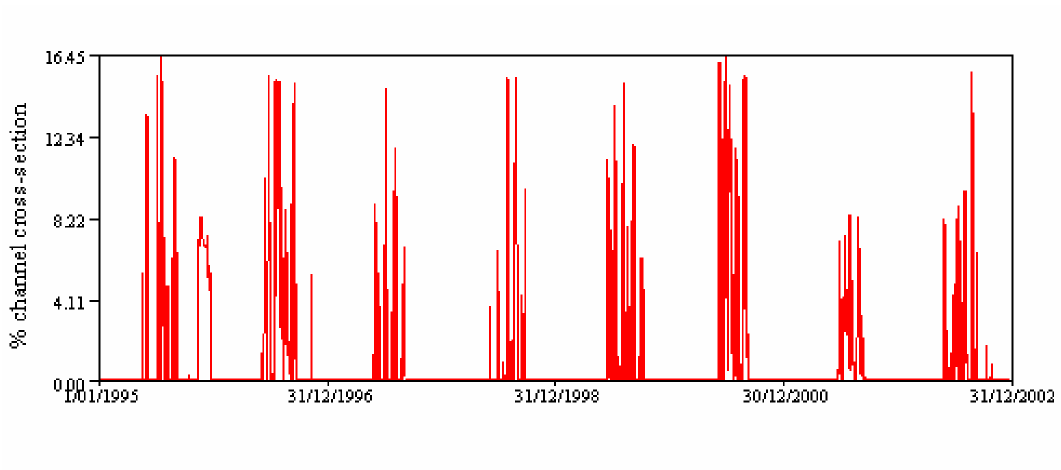

Figure 16. Changes in percent of total cross-section width inundated by > 10 cm minimum depth, for the Ferraro reach and thereby allowing fish passage. Fish passage was constricted by cross-section #2, and the threshold criteria of 0.1 m minimum depth was achieved with a discharge of 0.07 m^3/sec.

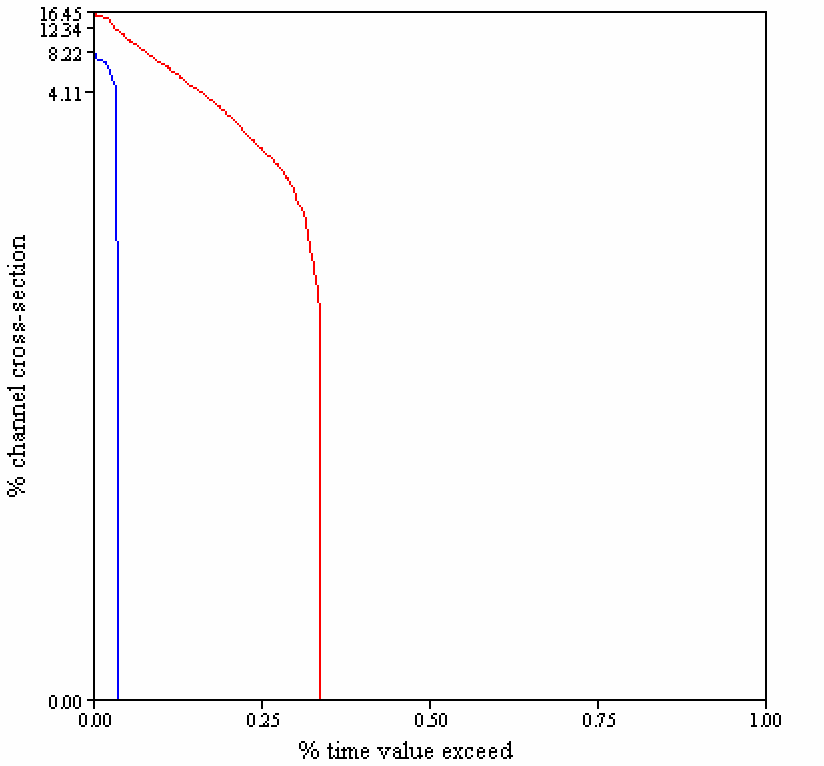

Figure 17. Flow duration curves for fish passage for summer (blue) and winter (red).

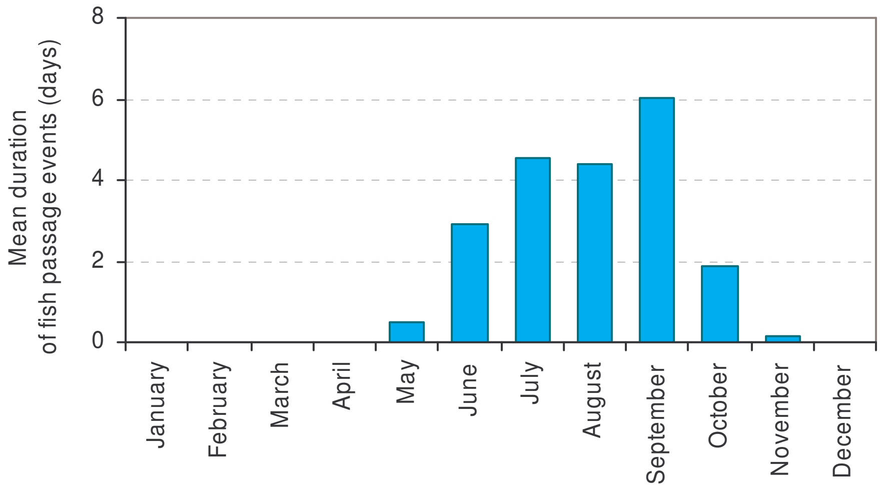

Figure 18. Mean duration of fish passage each month for the whole flow record (1995 - 2002).

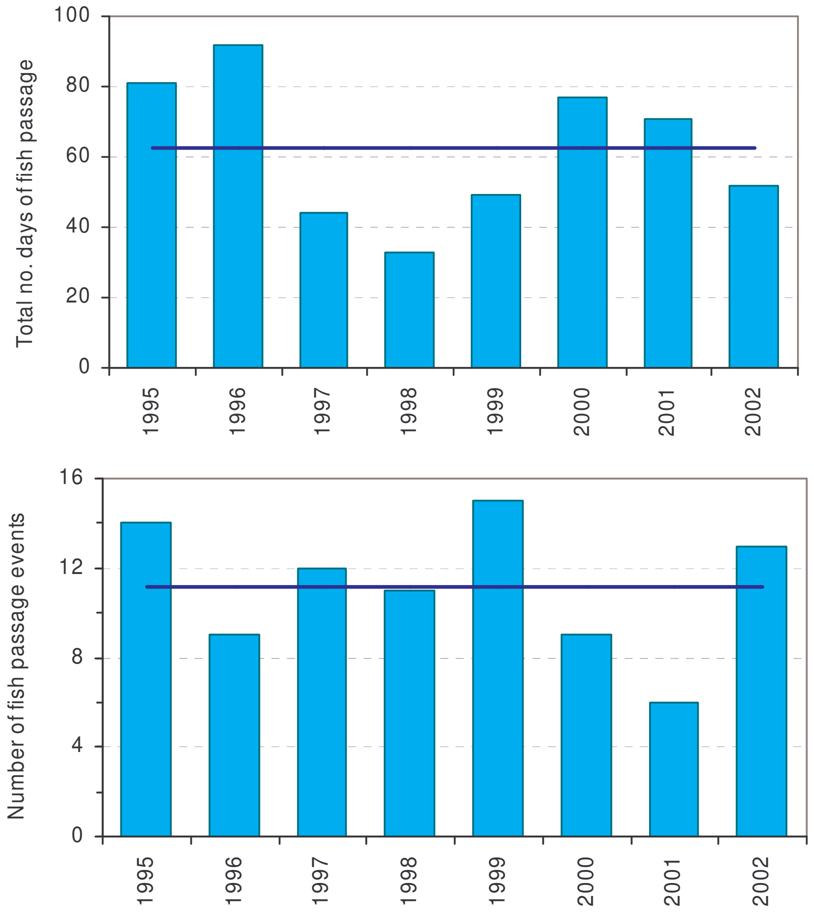

Figure 19. Total duration (days) of fish passage each year (top) and number of fish passage events per year (bottom) for the whole flow record (1995 to 2002). Dark blue lines indicate the mean for each flow type.

Required minimum duration of fish passage flows is unknown for south west native species, but depends on many factors, including the distance to travel. Required duration of fish passage may be estimated based on distance over which migration is required versus estimated swimming speed. The distance from the confluence of Ferraro Brook with Wealand Brook/Upper Mayfield Drain to the base of the Scarp where the proposed mine is to be located is conservatively 4 km (allowing for meanders *etc*). This is the effective distance over which fish may want to migrate to reach the higher gradient stream on the Scarp. The general rule of thumb for maximum swimming speed of fish is 10 x body length (Brad Pusey, Griffith University, pers. com.). Therefore, the upper (**maximum**) swimming speed would be 50 cm/sec for a conservative fish size of 5 cm (generally equivalent to sub-adults for most south west native species). Using what is estimated to be a conservative average migration speed of $1/20^{th}$ of this speed (*i.e.* 2.5 cm/sec) and assuming continuous swimming (which is unlikely), it would take a fish 2.8 days to cover this distance of Ferraro Brook. If an even more conservative migration speed of 1 cm/sec were to be applied, it would take an individual 6.9 days to cover this distance. Even allowing for increased water velocities along parts of the reach, fish could cover the distance in the calculated average flow duration for a single fish passage event. Given there are numerous passage events each winter, fish should easily be able to migrate the length of Ferraro Brook.

7.3.2 Winter Low Flows

The objectives for a winter base flow are to maintain total inundation of riffles and gravel runs as biodiversity 'hotspots' for macroinvertebrates, maintain inundation of low-lying emergent macrophytes, provide trailing vegetation for fish habitat and provide flow connectivity for energy transfer (downstream movement of carbon).

Based on channel morphology (broad, flat bed with relatively uniform substrate), and the low-lying position of emergent macrophytes on the cross-section, it was considered that the above objectives collectively would be provided for by the 'Rule of Thumb' for riffle inundation, *i.e.* a minimum average depth of 5 cm (0.05 m) with 100 % coverage of riffle cross-section.

Hydraulic analysis was used to calculate discharge required to achieve a mean depth of 0.05 m with 100% coverage of the riffles (riffles were located on cross-sections 2, 4, 5, 6, & 9). The mean width of the riffle zones, as taken from channel cross-sections, was 1.36 m. Discharge required to achieve 0.05 m average depth with > 1.36 m of channel cross-section inundated was then taken from the rating curve as 0.02 m^3/sec (Figure 20). Application of this rating curve to the short flow record for Ferraro Brook indicated that winter low-flows occurred for the majority of each winter (Figure 21), however, there were short periods when flows in winter were insufficient to maintain channel cross-section coverage (Figure 22). On average, winter low flows occurred for 123 days each winter, with upper and lower ranges of 137 and 103 days respectively. Summary of flow duration by months showed greatest duration of inundation in the winter months of July, August and September (24.5 days per month), with reduced extent of inundation in shoulder periods (late autumn/early winter; May (2.5 days) & June (15.3 days), and late spring; October (11 days), November (2. days)), as flows commence/recede (Figure 22).

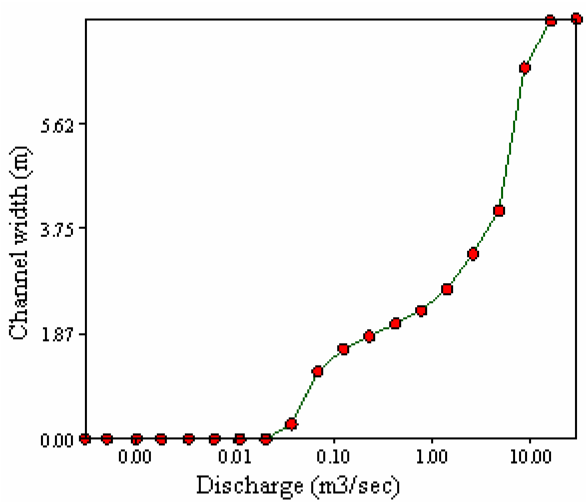

Figure 20. Rating curve for inundation of riffles (cross-sections 2, 4, 5, 6, & 9) to 0.05 cm average depth with 100% cross-section coverage (= 1.36 m of cross-section total width) on Ferraro Brook. Change in channel width meeting these objectives (y-axis) with increasing discharge (m^3/sec) (x-axis) is shown. The threshold criteria of 0.05 m average depth with 100% coverage of riffles (1.36 m width) was achieved with a discharge of 0.02 m^3/sec.

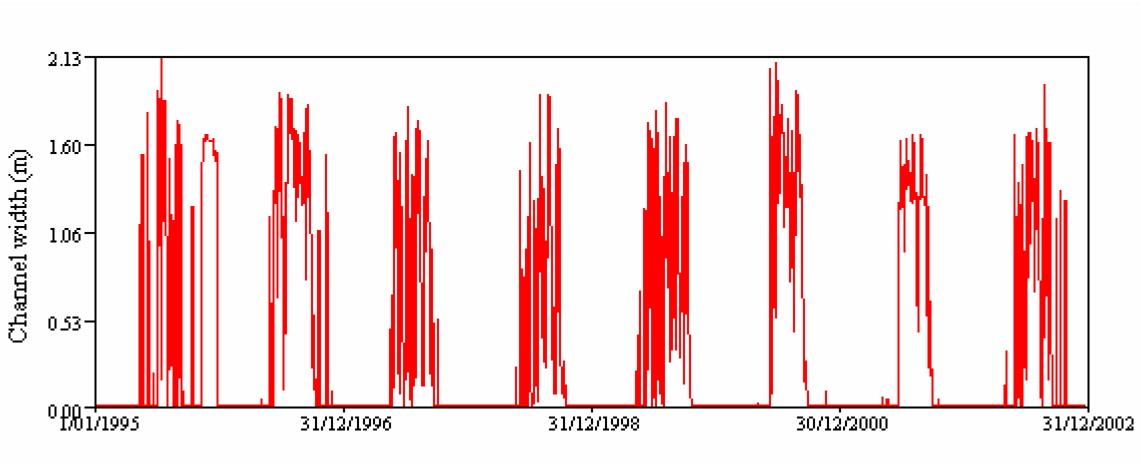

Figure 21. Changes in channel cross-section width inundated by > 5 cm (0.05 m) average depth. A threshold of 100% coverage of riffle habitat equates to 1.36 m cross-section width. Riffles were located on cross-sections 2, 4, 5, 6, & 9, and the threshold criteria of 0.05 m average depth with 100% coverage of riffles was achieved with a discharge of 0.02 m^3/sec.

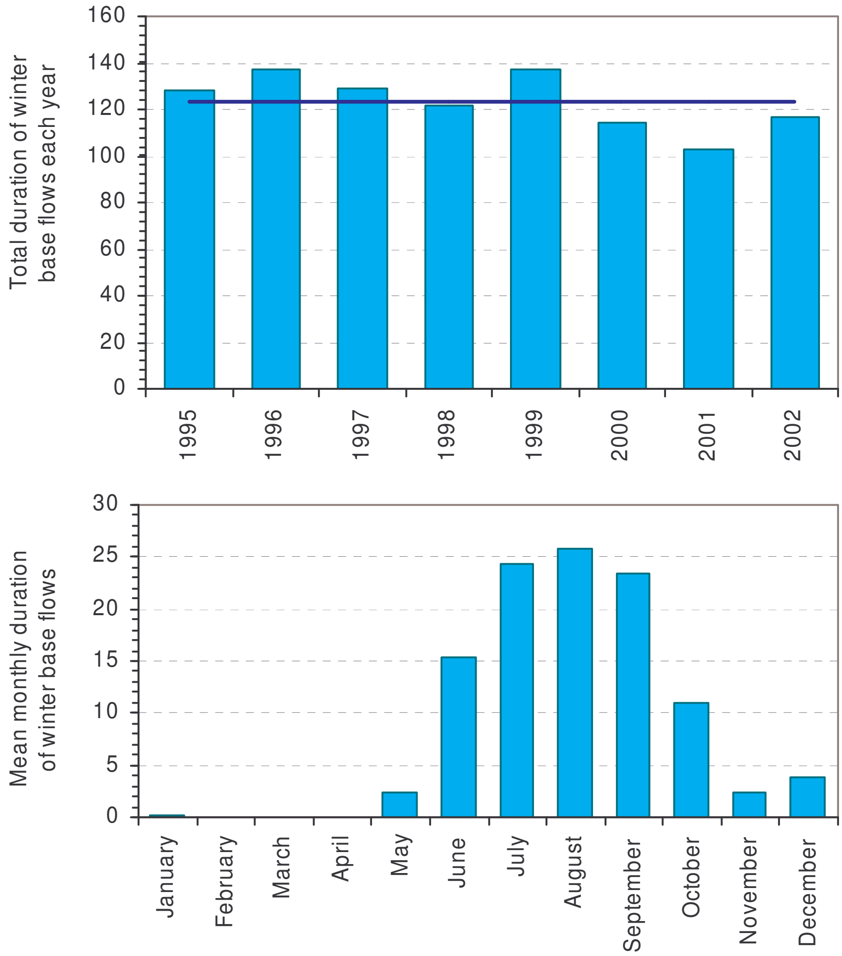

Figure 22. Duration of winter base flows for available flow record, showing total duration each year (top) and mean monthly duration across years for riffle inundation for a threshold criteria of 0.05 m average depth with 100% coverage of riffles, achieved with a discharge of 0.02 m^3/sec. Dark blue line indicates mean duration across years.

The flow duration curves for inundation of riffles in winter versus summer indicated greater inundation of riffles in winter, compared with summer, as would be expected (Figure 23). The threshold flow was not met at all times in winter, but periods of flow below that required were generally short, with average duration of below-threshold flows in May, June, July, August, September, October and November of 6.1, 2.7, 1.5, 1.0, 1.5, 2.5 and 6.5 days respectively (*i.e.* the longest period in August when flows did not meet the winter low flow threshold was 1.0 day). However, it should be noted that Ferraro Brook did not 'dry' in these low flow periods, rather base flow dropped below the threshold of 0.02 m^3/sec. Time series analysis of periods of zero flow days per month, averaged across years indicated no zero flow days in winter months (June, July, August), with only occasional zero flow days in shoulder periods (May, September and October) (Figuer 24).

Analysis indicated a threshold discharge of 0.02 m^3/sec was required in winter months to maintain 100% inundation of riffles, with this flow occurring 82% of the time in winter (July, August and September), and 26% of the time in shoulder periods. It is recommended that this threshold flow of 0.02 m^3/sec is maintained as a minimum base flow throughout winter to maintain ecological values dependent on a winter base flow. The transition from summer to winter base flows should occur in the shoulder months of May/June, with a recession back to summer base flow/zero flow in October/November. The frequency and duration of winter base flows should be as described above.

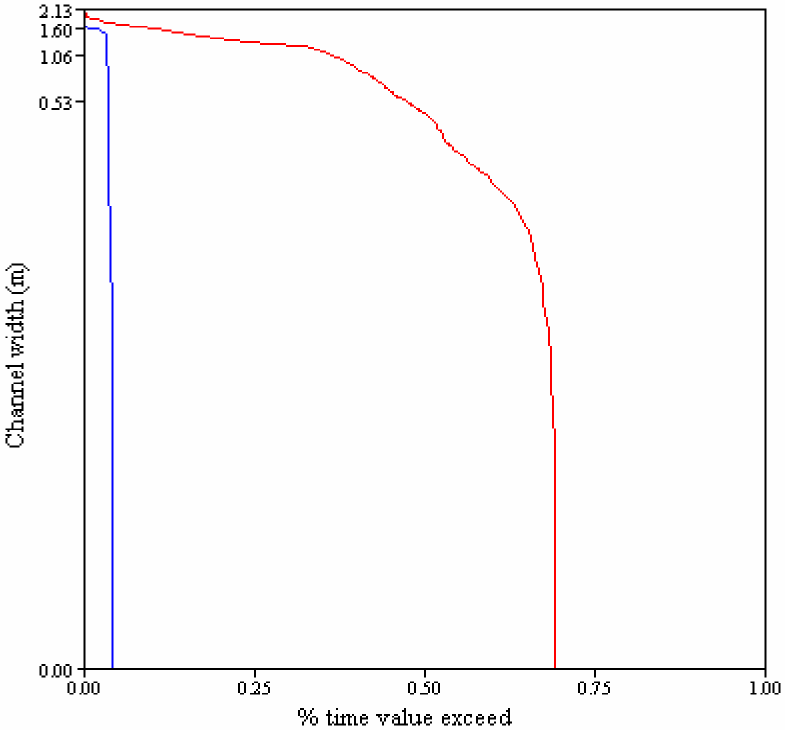

Figure 23. Flow duration curves for changes in percent of cross-section inundated by 5 cm average depth with 100% of riffle habitat inundated (cross-sections 2, 4, 5, 6, & 9) for summer and winter flows for duration of flow record.

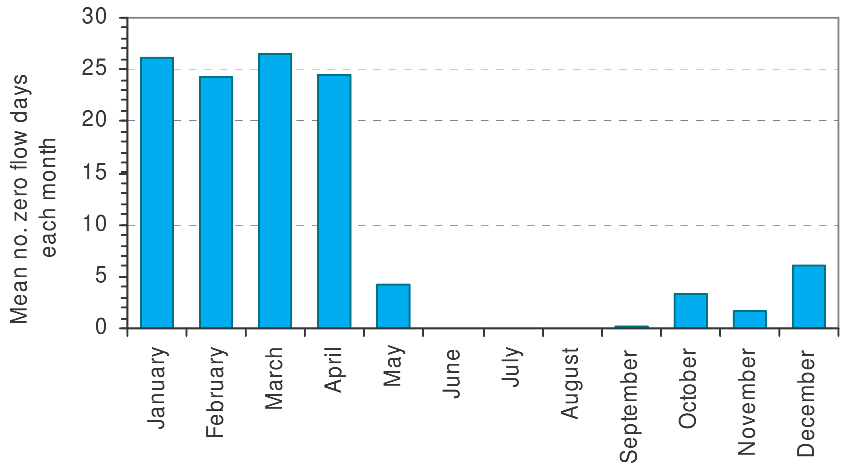

Figure 24. Mean number of zero flow days each month for the available flow record (1995 – 2002).

7.3.3 Winter Medium Flows

The objective of medium flow events in winter is the inundation of lower banks and benches for flooding of emergent macrophytes, provision of trailing vegetation as cover and spawning habitat for fish, provide inputs of autochthonous (algal production) and allochthonous energy (leaf litter/detritus) from benches, which support components of in-stream foodwebs, and fish passage over larger obstacles. These flows will have a lower frequency and shorter duration than fish passage flows, and a higher frequency and longer duration than larger events, such as active channel/channel forming flows.

Hydraulic analysis of channel morphology and time series analyses of flow data, combined with observed stage height for benches in the channel, surveyed onto channel cross-sections, were used to calculate magnitude and recurrence interval of medium winter flows for Ferraro Brook.

Using the channel cross-sections, the average depth to achieve flows sufficient to inundate lower benches and other values to be supported by medium winter flows was 0.3 m. Using this stage height, the reach-level rating curve produced by hydraulic analysis calculated a discharge of 0.15 m^3/sec as necessary to achieve the desired stage heights (Figure 25). The flow duration hydrograph for winter medium flows indicates they occurred regularly each year, throughout most of the winter months (Figure 26). Time series analysis indicated there were 46 events greater the 0.15 m^3/sec in the flow record (1995 – 2002), with a mean duration of each event of 1.9 days and a maximum duration of 11 days in July 1996 and 10 days in July 2000. On average, there were 6 events above 0.15 m^3/sec each winter, with a mean discharge of 0.222 m^3/sec, and with an average of 13 days each winter when flows exceeded the winter medium flow threshold.

Analysis of the frequency and duration of winter medium flow events indicated they predominantly occurred in winter and early spring (except for a small number of events in November), with peak frequency of events in July, August and September, with peak duration in July and August (Figure 27).

It is therefore recommended that winter medium flow events of > 0.15 m^3/sec are maintained with a frequency, duration and periodicity as described above.

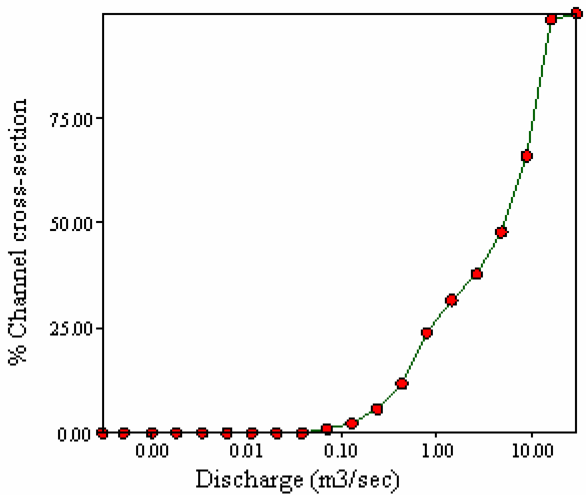

Figure 25. Reach level rating curve for discharge to attain winter medium flow stage height, with threshold flow of 0.15 m^3/sec required for a reach mean stage height of 0.3 m.

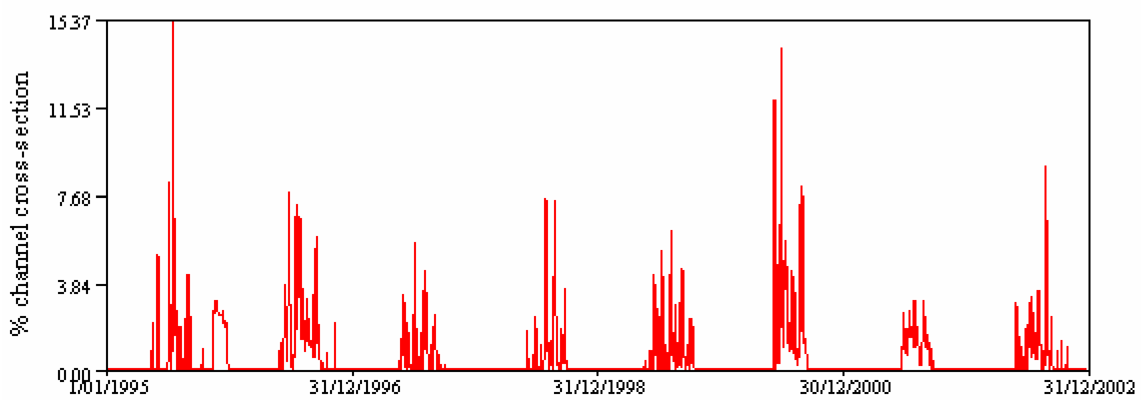

Figure 26. Flow hydrograph showing frequency and magnitude of events when winter medium flows occurred (> 0.15 m^3/sec) during available flow record (1995 – 2002).

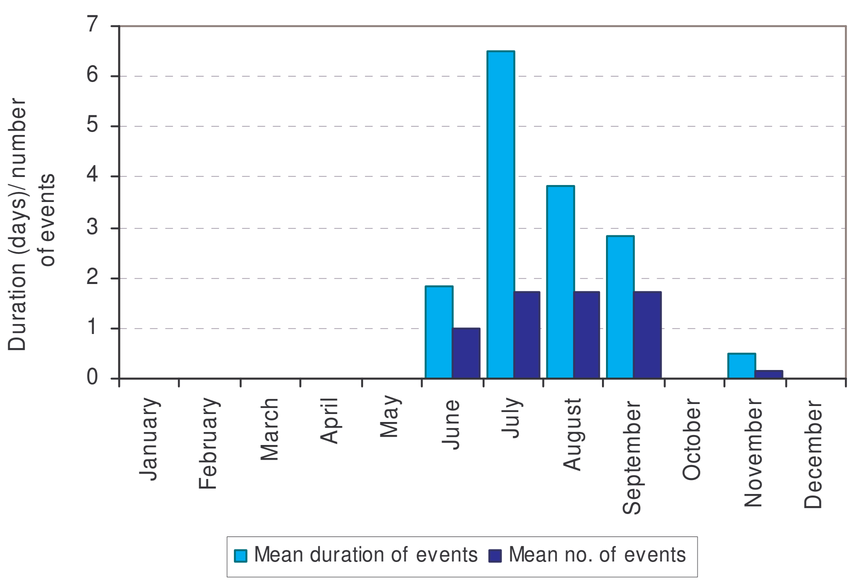

Figure 27. Mean duration (days) and number of events when winter medium flows occurred (> 0.15 m^3/sec) during the available flow record (1995 – 2002).

7.3.4 Active Channel Flows

Active channel flow events typically occur on a 1:2 to 1:3 year frequency in unregulated, unmodified south-west river systems. On this basis, there should be approximately three active channel flow events for the flow record available for Ferraro Brook (1995 – 2002). However, Ferraro Brook is now modified to act as a drain to convey excess surface run-off and groundwater. Therefore, the recurrence interval of active channel flows may be modified from that expected for a 'natural creek line'. In addition, the stage height at which current active channel flows occur, as determine from cross-sectional surveys (*i.e.* the level on the banks above which vegetation is stable and below which the bank is eroding/bare, and without extensive riparian vegetative growth) also may be different (*i.e.* at a lower or higher elevation) from that expected for an unregulated flow regime. Hydraulic analysis of channel morphology and time series analyses of flow data, combined with observed stage height for current active channel as taken from channel cross-sections, were used to calculate magnitude and recurrence interval of active channel flows for Ferraro Brook.

Using the channel cross-sections, the average depth of the active channel, taken from the deepest part of the channel (thalweg depth) was 0.545 m. Using this stage height, the reach-level rating curve produced by hydraulic analysis calculated a discharge of 0.45 m^3/sec as necessary to achieve active channel flows (Figure 28). Examples of an active channel flow in selected cross-sections are presented in Figure 29.

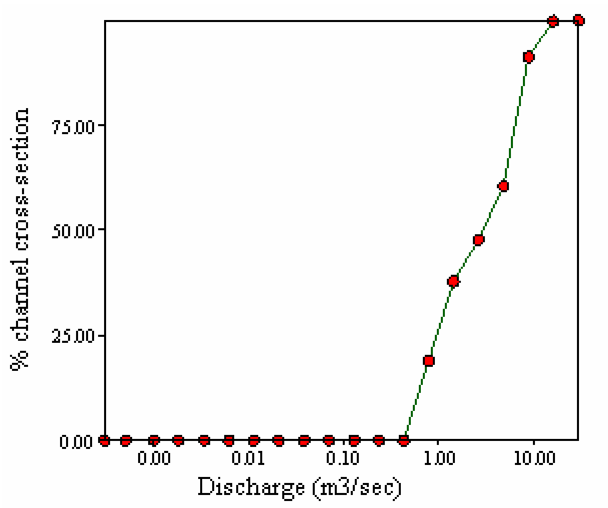

Figure 28. Reach level rating curve for discharge to attain active channel stage height, with threshold flow of 0.45 m^3/sec required to reach active channel flow (mean stage ht of 0.545 m).

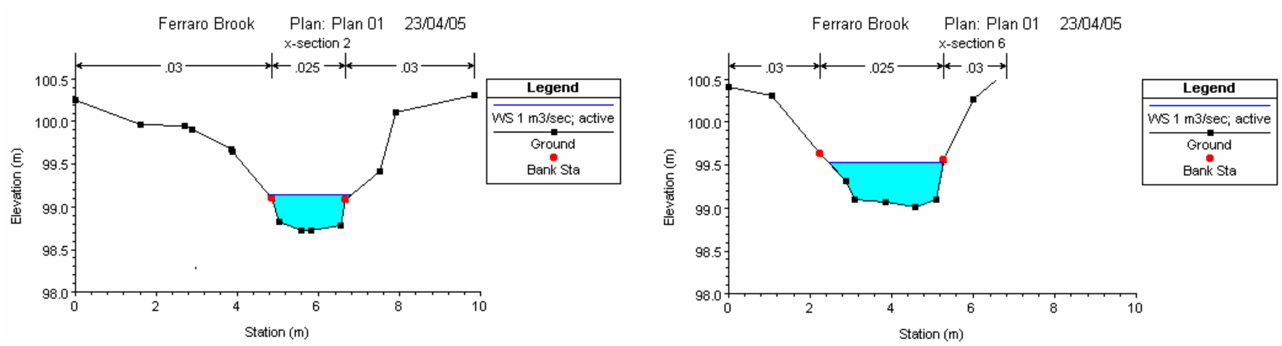

Figure 29. Examples of channel cross-sections from Ferraro Brook indicating active channel stage height (for a discharge of 0.45 m^3/sec.

The time series hydrograph for active channel flows indicated three occurrences of active channel flows in the flow record (one in 1995 and two in 2000) (Figure 30), with a mean duration of active channel flow events of one day, with a total of three days of active channel flows since 1995.

As discussed above, active channel flows are anticipated to occur every 2 – 3 years for south-west rivers. Analyses for Ferraro Brook indicated that discharge to meet current active channel stage height (depth as measured from channel cross-sections) occurred at approximately this frequency, however, the flow record is very short to undertake this analysis with confidence. It is therefore recommended that active channel flows of 0.45 m^3/sec are maintained with a frequency of 1:2 to 1:3 years, with each event lasting approximately 1 day. Flows of greater frequency, magnitude or duration may cause excessive erosion of this drainage channel.

Figure 30. Flow hydrograph showing frequency and magnitude of events when active channel flows occurred (> 0.45 m^3/sec) during available flow record (1995 – 2002).

7.3.5 Winter High Flows

In many EWR studies bankfull or floodplain inundation flows are often recommended to inundate and recharge wetlands on the floodplain, allow access by fauna to wetlands, provide nursery areas for fish and tortoise, disperse riparian seed, assist seed set, and promote successful germination. The floodplain adjacent to Ferraro Brook survey reach (and much of Ferraro Brook as it passes across the Swan Coastal Plain) is highly modified, consisting of agricultural land, isolated wetlands/sumps, with minimal intact riparian vegetation. Most values on the coastal plain are now supported by surface flooding in winter and elevated groundwater levels in summer, with little dependence on overbank flows. Because of the trapezoidal shape of the channel (designed for flood conveyance), overbank flows in Ferraro Brook would require large events. Historically, this system has run at bankfull following winter flood events, reflecting the greater runoff and effects of flow diversions into the 'drainage system'. Such high flows likely destabilise the channel causing bank and bed erosion and loss of instream vegetation. Given the nature of the sandy soils on the coastal plain, combined with the shape of the channel, such erosion could be excessive in certain situations, particularly if the frequency and duration of bankfull flows became excessive. Therefore, it is recommended that specific flows to attain bank full stage height are not provided, although, they will likely occur 'naturally' due to the drainage network serving this system.

7.3.6 Summer Zero Flows

Ferraro Brook is characterised by high seasonality, with long periods of zero flow in summer months. This period of zero flow is important in maintaining the current structure of riparian vegetation assemblages, macrophyte communities, invertebrate and fish communities, preventing the establishment of and domination by exotics species such as mosquitofish, carp (*Crassius auratus*) and yabbies (*Cherax destructor*), all of which are known to be present in the neighbouring Drakesbrook/Waroon Drain system (WRM 2003). Increased flow duration, with a reduction in duration of periods of zero flow will likely allow the proliferation of weed species. Summer flows would also likely suffer from algal blooms and episodic anoxia due to the potential high nutrient loads off surrounding arable land combined with low water velocities, low riparian shading and increased summer temperatures. Increased dry season flows will likely indicate groundwater discharge, reflecting increased groundwater levels.

Time series analyses showed that zero flows occur in Ferraro Brook on an average 126.9 days per year. The longest single period of zero flow was 137 days (Dec. 1997 to May 1998), with the average period of zero flow being 115.9 days. The main period of zero flow is normally during January to April inclusive, with occasional periods in May and November/December (Figure 24). It is recommended that the mean duration of zero flow days should be maintained during the summer/autumn months to prevent the channel becoming a refuge for weed species and avoid water quality issues in warmer summer months.

Table 7. Summary of ecological flow recommendations determined for Ferraro Brook using the Flow Events Method and River Analysis Package.

Flow Component	Ecological attribute / Value	Season (duration)	Hydraulic metric	Ecological Flow Recommendation
Fish Passage Flow	Native fish diversity	Late Autumn - early Spring	Minimum depth over obstacles of 0.10 m; late May – November.	≥ 0.07 m^3/sec for duration of approx. 0.5 days in May, gradually increasing to 6 days in September, reducing again to 0.5 days in November.
Winter Low Flow	Invertebrates Native fish Vegetation Process	Winter - early Spring	Minimum stage height of 0.05 m & 100 % cover over gravel runs & riffles.	0.02 m^3/sec for duration of approx. 24 days/month during July, Aug. & Sept., with transition between summer & winter base flows during May/June & October/November.
Winter Medium Flow	Native fish Vegetation Process	Winter – early Spring	Flood lower benches	0.15 m^3/sec during winter with peak frequency of 2 days/month in July, Aug. & Sept., with peak duration of up to 7 days in July-Aug.
Active Channel Flow	Channel morphology	Winter	Active channel stage height on a 1:2 - 1:3 year frequency	0.45 m^3/sec for a duration of 1 day every 2 – 3 years.
Winter High Flow	Vegetation Native fish Process	Winter	Overbank and floodplain inundation	None
Summer Zero Flow	Seasonal flows	Summer	Zero flows	Zero flow Jan. to April inclusive.

8 CONCLUSIONS AND MANAGEMENT CONSIDERATIONS

8.1 System Condition & Flow Modelling

The aquatic ecosystems within the current study area have been greatly modified by land clearing, rising water tables and increased runoff. Currently the channel appears unstable (excessive, unnatural erosion) and has a low diversity of habitats and ecological values. Therefore, the system should be managed to prevent further degradation, maintain existing ecological values (*i.e.* current native crayfish and remnant overstorey vegetation) with a priority to maintain the seasonal flow regime. Permanent summer pools are currently maintained by groundwater and not surface flow. While these small, shallow pools support minimum ecological values, they do provide summer refuge for freshwater crayfish, tortoises and many invertebrate species. Excessive groundwater drawdown may make them vulnerable to drying with an associated reduction in faunal diversity.

HEC-RAS models for Ferraro, Wealand and Upper Mayfield Drain are only preliminary in that they have not been calibrated against known flows because the channel was dry when surveyed. The models were developed using assumed channel roughness and measured channel slope as the downstream boundary condition. The accuracy of the models will be unknown until they are calibrated against a range of flows covering a range of stage heights. This would involve repeated surveying to gain stage height to discharge relationships, likely over a winter/spring period.

The gradient of the Upper Mayfield Drain system is generally very low as it crosses the coastal plain. Because of this low gradient, it is possible that features downstream of the survey reach may influence flows in the survey reaches. For example, a flow constriction one kilometre or more downstream, such as a bridge or culvert, or even an accumulation of woody debris may impede flows to such an extent that flows back-up and 'flood' the survey reaches. There is anecdotal evidence that this regularly occurs at the South Western Highway culvert on Ferraro Brook (P.W. Ward, Aintree Pty Ltd, pers. comm.). This 'damming' will result in greater water depths in the survey reaches than predicted by the models for a known discharge. It is most likely to occur in high flows (*i.e.* above active channel flows), since gradients are probably sufficient to allow the system to flow unimpeded for discharges below active channel. The only way to definitively define the longitudinal distance of backwater effects in these drains would be to undertake extensive longitudinal surveys over several kilometres, which was beyond the scope of the current project.

8.2 Implementing Preliminary EWRs

The ideal scenario for implementing EWRs from a dam operation perspective would be to have specific releases for each day of the year to meet the recommended EWRs and then these flows are released on a daily basis through the year, from one year to the next. Although this will incorporate seasonality in the system, such an operating strategy does not allow for the natural, inherent variability in ecological systems, or inherent year to year climate variability. For example, natural active channel flows statistically occur every 2 - 3 years in south-west Australian rivers, however, in a drought situation they may have a much longer recurrence interval. Therefore, there is no justification as to why they should be released on a 1:2 or 1:3 year frequency in a regulated system if an adjacent free-flowing system (*e.g.* Wealand Brook) is in drought. Also, some EWR objectives, in some years may be partially or totally met by natural rainfall events and therefore total volumes to meet the desired objectives may or may not need to be released from the dam. These issues must be considered when implementing EWRs in a regulated system.

For a river that is fully impounded, with no local catchment runoff or groundwater contribution to flows below the dam (an unlikely scenario), then the total environmental flow would need to be released from the dam. However, in the current situations there is local catchment runoff and a groundwater contribution and therefore only part of the environmental flow would need to come from the dam. The proportion that needs to be released will depend upon the extent of local contributions, which will vary seasonally. When implementing environmental flows, dam releases may be minimised by augmenting/piggybacking on natural events. This will require flow monitoring in Ferraro Brook to determine stage height relative to desired flow objective, with additional flows to meet the objective then released from the dam. Infrastructure (*i.e.* valve size) must accomodate dam releases that meet the higher flow objectives. In such a situation, releases would have to be timed to augment natural events.

Typically, releases from dams are deep (hypolimnetic), cold water releases. This can cause problems, particularly if the deeper water is low in oxygen levels due to stratification. Anoxic releases will be detrimental to fauna in the receiving environment and should be avoided. Another consideration is the release of cold water. This is not such a problem in winter when ambient temperatures are low, but will be detrimental to fauna in summer. Cold water releases disrupt growth and development of aquatic fauna and may delay development to an extent whereby recruitment fails. Ideally, there should be a multiport offtake from the dam and a regularly updated vertical temperature profile of the dam used to match the off-take level to the temperature of the receiving environment.

An inherent requirement for any environmental release strategy is that releases mimic the natural rates of rise and fall of equivalent events in an unregulated system. This is especially critical for larger events such as active channel or medium winter floods. Too rapid an increase in flow may wash away fauna or cause excessive erosion, while too rapid a drawdown may strand fauna, leave eggs exposed to dessicate and cause bank slumping, whereby saturated banks can not dry sufficiently as levels fall and collapse under their own weight. Instantaneous (*i.e.* hourly) discharge data are required to calculate rates of rise and fall and such data were not available for Ferraro Brook.

8.3 Monitoring and Revision

A critical aspect of implementing environmental flows is monitoring in an adaptive context. A tiered approach to monitoring is recommended, whereby Tier 1 monitoring would be used to assess whether the recommended releases achieve the desired stage heights (*i.e.* flow to inundate riffles in winter), Tier 2 monitoring would test whether specific ecological objectives were met (*e.g.* fish passage; pool aggradation) and Tier 3 monitoring would assess overall effects of the environmental flows on the ecological condition of the system (*e.g.* changes in in-stream and floodplain vegetation; loss of aquatic fauna species). An adaptive context would require revision of flows in response to results of monitoring. For example, if flows are insufficient to cover riffles in winter, then they need to be increased, conversely, if they are too large, then they should be reduced. The monitoring tiers effectively reflect monitoring priorities with Tier 1 monitoring taking highest priority.

8.3.1 Tier 1 Monitoring: Meeting Flow Objectives

Flow objectives to test are:

- Is winter-early spring base flow adequate to inundate riffles to 5 cm average depth with average of 100% lateral coverage;

- Is the recommended fish passage flow adequate to give a minimum depth threshold for the reach of 10 cm;
- Is the recommended active channel flow adequate to provide a stage height equivalent to active channel stage height;
- Is the recommended winter medium flow sufficient to inundate lower banks and benches for energy transfer.

Monitoring will require measurement of discharge at the proposed dam release point and at the survey reach on Ferraro Brook under the varying releases. Stage height (depth) must be measured for each discharge to assess whether the objectives were met. Monitoring will need to consider time taken for flow releases from the dam to reach the confluence with Upper Mayfield Drain and releases will need to be modified if flow objectives are not met. Monitoring will also help determine the contribution of catchment runoff to both surface flow and groundwater recharge.

8.3.2 Tier 2 Monitoring: Meeting Ecological Objectives

Ecological objectives to test are:

- Are fish able to migrate up through the study reach when the required flows are delivered;
- Has the revised flow regime resulted in bank or bed erosion or accumulation of sediment in pools due to excessive or inadequate flows, respectively.

Assessing these objectives will require the design of specific short-term programmes to measure attributes such as fish passage through the reach and bed/bank erosion/aggradation.

8.3.3 Tier 3 Monitoring: Monitoring Ecosystem Health

Ecosystem health objectives to test are:

- Has there been any change in macroinvertebrate community composition, species diversity and occurrence of rare/restricted distribution species following implementation of the revised flow regime;
- Has there been a change in the composition of native and introduced fish or in the that may be indicative of increasing/decreasing population health;
- Has there been a change in the distribution of aquatic and riparian plants in and adjacent to the channel in response to the revised flow regime.

Assessing these objectives will require the design of on-going, low frequency monitoring programmes to sample aquatic faunal assemblages (to species level) and distribution of aquatic and riparian vegetation. Designs must be standardised for on-going monitoring purposes, using accepted methodologies, with frequency of application determined by anticipated rate of change in the attribute being monitored. Frequency initially may be quite high (*i.e.* annual for fish and macroinvertebrates) and then reduced/stopped once there is confidence in there being no oberved effect.

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APPENDIX 1. SUMMARY OF FLOW DATA FOR FERRARO BROOK

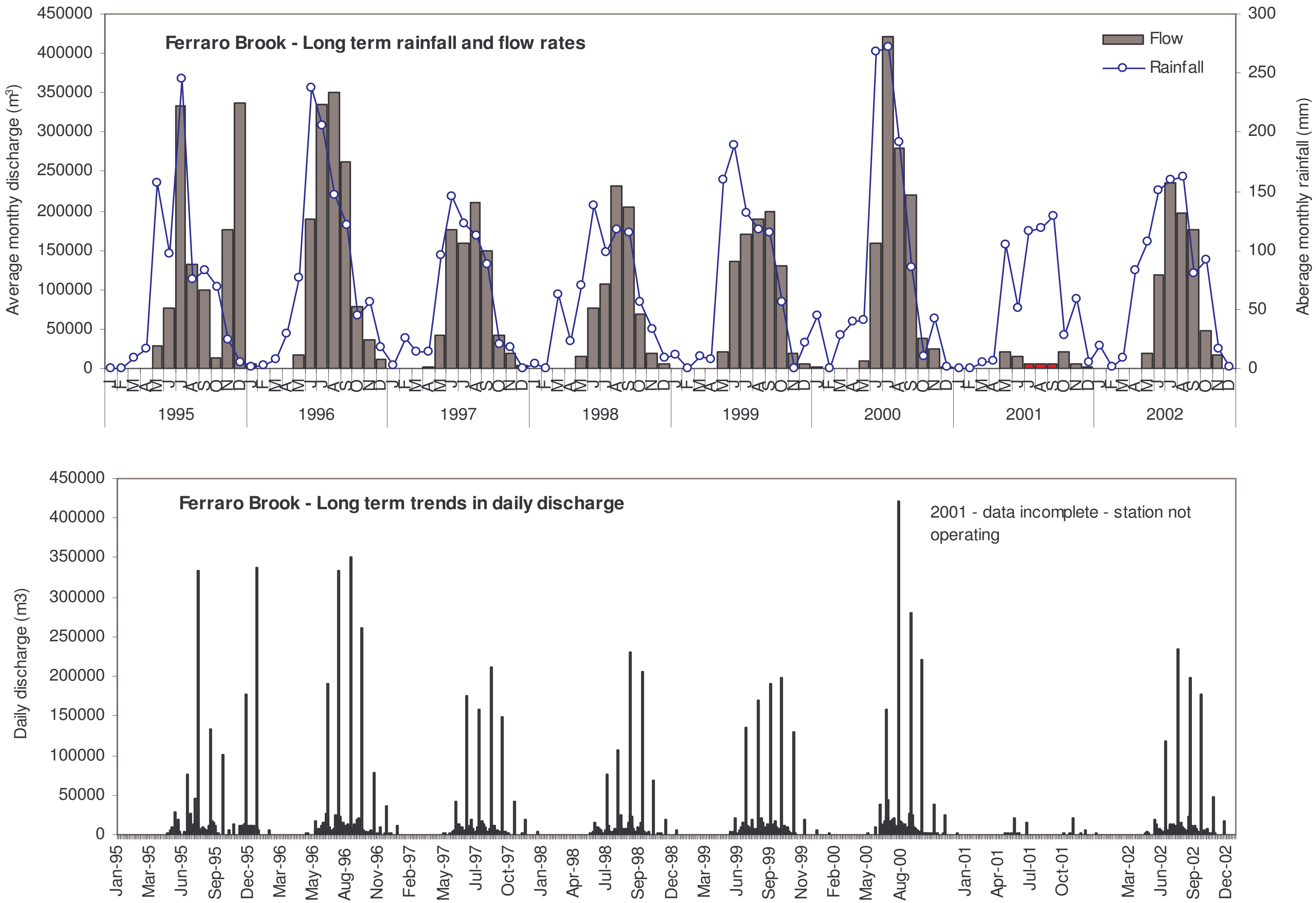

Figure A1. Hydrographs for Iluka surface water gauging station on Ferraro Brook.

Table A1. Mean, median and percentile flows recorded at Iluka surface water gauging station on Ferraro Brook.

Ferraro Brook (Iluka gauging station)

Month	No.	Mean (ML)	Median (ML)	pctl10	pctl20	pctl30	pctl40	pctl50	pctl60	pctl70	pctl80	pctl90
Jan	8	1.11	0	0	0	0	0	0	0	0	2.55	6.36
Feb	8	0	0	0	0	0	0	0	0	0	0	0
Mar	8	0	0	0	0	0	0	0	0	0	0	0
Apr	8	0.35	0	0	0	0	0	0	0	0.06	0.69	2.09
May	8	21.65	19.90	9.16	15.66	16.91	18.88	19.90	20.92	21.82	28.40	41.41
Jun	8	121.83	126.84	42.93	75.89	76.77	118.14	126.84	135.55	159.04	176.02	190.31
Jul	8	251.41	243.08	107.61	158.53	169.65	234.76	243.08	251.41	332.79	334.35	422.18
Aug	8	227.56	219.14	132.85	189.83	197.95	210.71	219.14	227.57	230.78	279.75	351.09
Sep	8	188.04	193.31	105.20	148.57	176.52	188.04	193.31	198.57	205.25	220.69	261.47
Oct	8	58.14	45.02	12.71	29.29	39.07	41.48	45.02	48.56	77.71	85.83	130.46
Nov	8	40.04	19.94	6.10	17.75	18.53	19.33	19.94	20.54	23.96	37.03	177.07
Dec	8	45.89	3.92	0	1.79	1.94	2.88	3.92	4.96	5.59	12.20	337.78

Mean Annual Discharge = 956.03 ML   No. observations = 8   Period of record = Jan. '95 – Dec. '02

Median Annual Discharge = 840.98 ML