SINCLAIR KNIGHT MERZ
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GOULBURN BROKEN
CATCHMENT MANAGEMENT AUTHORITY

Broken and Boosey Creeks Environmental Flow Determination

FLOW RECOMMENDATIONS

- Final
- August 2007

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Sinclair Knight Merz
ABN 37 001 024 095
590 Orrong Road, Armadale 3143
PO Box 2500
Malvern VIC 3144 Australia
Tel: +61 3 9248 3100
Fax: +61 3 9248 3400
Web: www.skmconsulting.com

Executive summary

The current flow regime in Broken and Boosey Creeks is near permanent due to diversions from the Broken River at Casey's Weir. The Tungamah Pipeline Scheme will result in a substantial reduction in the diversion of water to the Broken Creek, especially in summer, and the flows in both Broken and Boosey Creeks will revert to a more natural, seasonally intermittent regime.

The Broken-Boosey Environmental Flows Technical Panel is of the opinion that reduced summer flows and the reinstatement of a more intermittent flow regime will result in a shift in the community composition of aquatic biota towards one more tolerant of dryer conditions, but that this is considered to represent an overall benefit to the ecology of the Broken and Boosey Creeks and result in the establishment of a more sustainable ecosystem. However, in order to compensate for the reduction in summer flows and restoration of a more natural summer flow regime the natural winter flow regime also needs to be restored. This requires the restoration of the natural frequency of cross-catchment transfers from the Broken River to the upper Broken Creek.

The current cross-catchment connection is artificially regulated via diversions at Casey's Weir. Prior to the construction of Casey's Weir there were at least two pathways where water from the Broken River would transfer to the Broken Creek under high flow conditions in the Broken River. The flow recommendations for Broken Creek require the reinstatement of the natural frequency of cross-catchment transfers. Analysis as part of this study indicates that cross-catchment transfers would occur on average once every two years for 1 to 2 days. The natural pathways for this transfer have been blocked; however it is possible to recreate the connection through regulated diversions at Casey's Weir up to 200 ML/d. For transfers greater than this volume infrastructure works (levee removal and culvert installation) would be required to reinstate the natural pathways.

For the Broken Creek it is recommended to restore a natural, seasonally intermittent flow regime with cease-to-flows in summer and low flows, freshes and high flows in response to local catchment runoff and cross-catchment transfers from the Broken River. Cross-catchment transfers from Broken River and local runoff generated in the upper parts of the catchment must be allowed to progress to downstream reaches.

- **Summary of flow recommendations for Broken Creek.**

Flow components	Reach 1			Reach 2			Reach 3		
	Vol (ML/d)	Freq.	Dur.	Vol (ML/d)	Freq.	Dur.	Vol (ML/d)	Freq.	Dur.
Summer (December-May)									
Cease-to-flow	Natural frequency and duration								
Low flow	No specific recommendation but allowed to occur as part of local catchment runoff								
Fresh	Up to 200 ML/d in response to local catchment runoff and transfers from Broken River	Allow to occur in response to local rainfall, not expected to occur via transfer from Broken River under natural conditions.		70-110	Propagation from upstream		30-70	Propagation from upstream	
Winter (June-November)									
Cease-to-flow	Natural frequency and duration								
Low flow	No specific recommendation but allowed to occur as part of local catchment runoff								
Fresh	Up to 200 ML/d in response to local catchment runoff and transfers from Broken River	Transfers from Broken River expected to occur once every 2 years in winter / spring for 1-2 days duration		70-110	Propagation from upstream		30-70	Propagation from upstream	
High / bankfull	1000 ML/d in response to local catchment runoff and transfers from Broken River	Expected to occur once every 10 to 20 years for 1-2 days duration. May require infrastructure works to allow volume to be delivered to Broken Creek.		15-350	Propagation from upstream		95-255	Propagation from upstream	
Overbank	No recommendation with regards to transfer from Broken River, but allowed to occur in response to local catchment rainfall								

The current study only determined flow recommendations for the upper Broken Creek. Detailed flow recommendations for the lower Broken Creek are yet to be determined, although emergency flow requirements are in place to manage poor water quality, flush accumulated *Azolla* from weir pools and manipulate fishway operation, particularly in summer. While not specifically examined in this study, it has been suggested that water could be delivered to the lower Broken Creek via diversions at Casey's Weir to meet these emergency flow requirements. It is likely that when water is needed to manage poor water quality or flush *Azolla* it would be required to be delivered immediately. As part of the current study losses, time lags and flow attenuation down the upper Broken Creek was examined and this provides insights into the ability to deliver flows to the lower Broken Creek.

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It is not possible to quantify losses in terms of the percentage of water diverted at Casey's Weir that reaches the lower Broken Creek. This is because there is limited information available to distinguish between operational and transmission losses. In addition, the antecedent conditions within the channel are likely to have a substantial influence on losses, for example it the channel is predominantly dry then losses will be significantly higher than if the channel was wet. However, it is possible to examine lag times and attenuation of peak flows, at least between Casey's Weir and Katamatite. Lag times for delivering water to the lower Broken Creek via the upper reaches is considerable and likely to be in the order of 1-3 weeks. In addition, there is significant attenuation of the flow peak as it moves downstream. The further downstream the flow needs to be delivered and /or the drier the channel lag times, peak flow attenuation and losses increase meaning the need to divert relatively large volumes of water over an extended period of time in order to deliver the required volume downstream. Furthermore, channel capacity in the Broken Creek upstream of Katamatite is relatively small so it may not be possible to deliver the required volumes to the lower Broken Creek without the risk of flooding in the upper reaches. Further investigations are needed to better understand the above issues and resolve uncertainty regarding the ability to route water to the lower Broken Creek.

For the Boosey Creek it is recommended to retain the current, essentially natural regime in Reach 4 and to restore the natural, seasonally intermittent regime in Reaches 5 and 6.

Flow components	Reach 4			Reach 5			Reach 6		
	Vol (ML/d)	Freq.	Dur.	Vol (ML/d)	Freq.	Dur.	Vol (ML/d)	Freq.	Dur.
Summer (December-May)									
Cease-to-flow	Natural frequency and duration								
Low flow	No specific recommendation but allowed to occur as part of local catchment runoff								
Fresh	50	2 or natural	6	50	2 or natural	6	100	2 or natural	7
Winter (June-November)									
Cease-to-flow	Natural frequency and duration								
Low flow	5 or natural if less								
Fresh	50	2 or natural	7	100	2 or natural	7	200	2 or natural	8
High	250	1 or natural	5	200	1 or natural	5	500	1 or natural	5
Bankfull	1500	1:2 or natural	2 or natural	1500	1:2 or natural	2 or natural	2500	1:2 or natural	2
Overbank	No recommendation but allowed to occur in response to local catchment rainfall at the natural frequency and duration								

In recommending an essentially natural regime we have specified the volume, frequency and duration of some flow components to ensure that natural elements of the flow regime are retained or reinstated. Although from a compliance perspective smaller or shorter duration events need to be protected and cannot be ‘extracted’ from the system. In other words, for events below the recommended duration or frequency the natural event needs to be preserved. This requires careful management of potential future impacts on the flow regime, for example associated with increased farm dam development or on-stream extractions.

The success of environmental flows often hinges on the mitigation of other limiting factors. Within the Broken-Boosey system a number of issues have been identified that may limit the achievement of ecological objectives even if flow recommendations are implemented. As such, it is recommended to:

- Assist vegetation recovery through fencing, grazing control and revegetation.
- Provide fish passage on all retained weirs.
- Investigate options for selective pool excavations in flowing reaches to restore refuge habitat because flow alone is unlikely to be sufficient to scour and transport significant quantities of sediment from pools, especially in Reach 1.
- Implement water management recommendations for Moodies Swamp.
- Retain Casey’s Weir to assist in the delivery of fresh flows up to 200 ML/d and investigate feasibility and infrastructure requirements to restore higher flows associated with the natural cross-connection between Broken River and Broken Creek.
- In conjunction with revision of environmental flow requirements for the lower Broken Creek undertake a more detailed analysis of losses between Casey’s Weir and lower Broken Creek to determine the suitability of delivering flows to the lower Broken Creek via Casey’s Weir.

Contents

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Project Steering Committee (PSC)	
Scott Morath	Goulburn Broken Catchment Management Authority
Rolf Weber	Department of Sustainability and Environment – Region
Paulo Lay	Department of Sustainability and Environment – River Health
Anne Graesser	Goulburn-Murray Water
Wayne Tennant	Goulburn Broken Catchment Management Authority
Project Advisory Committee (PAC)	
Scott Morath	Goulburn Broken Catchment Management Authority
Rolf Weber	Department of Sustainability and Environment – Region
Paulo Lay	Department of Sustainability and Environment – River Health
Anne Graesser	Goulburn-Murray Water
Bruce Wehner	Parks Victoria
Paula Tovey	Moira Shire Council
Bianca Wooley	Benalla Shire Council
Dougal Gilmour	Mid Goulburn Implementation Committee
Hank Sanders	Victorian Farmers Federation
Michael Lea-Whyte	Environment Victoria
Barry Flanner	Community Member
Geoffrey Mills	Community Member
Rod Squires	Community Member
Roland Atkinson	Community Member

Glossary of terms and abbreviations

AUSRIVAS	Australian River Grade and Assessment System.
Anastomosing	A channel that splits into several channels that rejoin repeatedly.
Biofilm	An organic matrix comprised of microscopic algae, bacteria and micro-organisms that grow on stable surfaces in water bodies (e.g. logs, rocks or large vascular plants).
Catchment	The area of land drained by a river and its tributaries.
Current flow series	Series of streamflows which represent the current level of development.
Compliance point	Gauging station at which flows are measured to ensure compliance with recommendations.
Debouching	Emerge into larger body or area.
Development	Converting land to a new use, which may include the construction of farm dams.
Dissolved oxygen (DO)	Concentration of oxygen in the water column. A measure of the amount of oxygen available to aquatic flora and fauna.
DSE	Department of Sustainability and Environment.
EFTP	Environmental Flows Technical Panel.
Environmental flow	Releases of water, periods of drying, or river flows allocated for the maintenance of aquatic and riparian ecosystem, measured in megalitres per day (ML/d).
Ephemeral stream	A waterway containing water only after intermittent or seasonal rain.
Floodplain	Temporarily inundated lateral river flats, usually of lowland rivers.
FSR	Flow Stressed Ranking.
GBCMA	Goulburn Broken Catchment Management Authority
Geomorphology	The study of the physical form of, and processes operating in, rivers. It aims to provide an understanding of the physical processes governing the current state of a river.
G-MW	Goulburn-Murray Water.
Groundwater	Water occurring below the ground surface.
Habitat	The place or environment in which a plant or animal usually lives; the subset of physical and chemical environmental variables that allow an organism to survive and persist.
Hydraulic modelling	The modelling of fluid flow in pipes and channels. Used in environmental flow studies to model flow in river channels.
Hydrology	The study of the surface and subsurface water. Sometimes used loosely to describe the water regime.
Instream	Of, or occurring within the wetted area of a running water body.
ISC	Index of Stream Condition. Presents an indication of the extent of change in respect of five key 'stream health' indices: hydrology, physical form, streamside zone, water quality and aquatic life.
Lentic	Pertaining to still bodies of water
Littoral	Edge or shore region where the water is shallow enough for continuous mixing.
Lowland waterway	A stream section at low altitude, that is sinuous and often with width to depth ratios greater than 20.

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Lotic	Pertaining to flowing water
LWD	Large Woody Debris. Branches and trees that have fallen in the river channel. Often referred to as snags.
Macroinvertebrates	Aquatic invertebrates whose body length usually exceeds 1 mm. Includes insects, crustacean, aquatic worms, and aquatic snails.
Macrophytes	The term is used to describe water plants other than microscopic algae; they may be floating or rooted.
Mean	Average. Equally far from two extremes.
Median	The middle value in an ordered sequence of values.
Megalitre (ML)	One million litres (an Olympic size swimming pool is about two megalitres).
Natural flow series	Series of streamflows which represent what streamflows would have historically been like without man-made diversions, demands and impoundments, not withstanding changes to land use over time.
Nutrients	Natural elements (usually phosphorus and nitrogen) that are essential for plant and animal growth.
Percentile exceedence flows	The flow which is exceeded for the defined percentage of time. E.g. the 80th percentile flow is exceeded 80% of the time and is therefore a low flow. Also commonly used: 20th and 50th percentile where 20th percentile exceedence flow is a relatively high flow and the 50th percentile exceedence flow may also be called the median flow.
pH	Level of acidity in a range from 0-14: low pH (values <7) refers to high acidity and high pH (values >7) refers to low acidity.
Pool	A stream section where there is no discernable flow and usually deep.
Reach	A length of stream that is reasonably uniform with respect to geomorphology, flow and ecology.
Recruitment	The addition of new members into a population through reproduction or immigration.
Regulated catchment/river	A river or creek where the flow of the river is controlled through the operation of large dams or weirs to meet water use demands downstream.
Riffle	A stream section with fast and turbulent flow over a pebble bed with protruding rocks. Characterised by a broken water surface.
Riparian	Vegetation found along the banks of streams and rivers.
Riparian zone	Any land which adjoins, directly influences, or is influenced by a body of water.
Run	A stream section with low to moderate laminar flow with unbroken water surface.
Water-dependent	Aquatic species or those dependent on river water for survival
SEPP	State Environment Protection Policy.
SIGNAL	Stream Invertebrate Grade Number Average Level.
SFMP	Stream Flow Management Plan.
Spawning	Production and deposition of eggs; related to fish reproduction.
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Snag	Branches and trees that have fallen in the river channel; also called Large Woody Debris (LWD).

Substrate	The base, or material, on the bed of the river.
Taxa	Any defined unit in the classification of living organisms (i.e. species, genus, family).
Threatened	A generic term used to describe taxa that are rare, vulnerable, endangered or insufficiently known and are subject to a threatening process.
Transect	Line drawn across a stream channel and perpendicular to the direction of flow for standardising measurements of width, depth velocity discharge etc.
Tributary	A river or creek that flows into a larger river.
Turbidity	The cloudy appearance of water due to suspended material (sediment).
Unregulated catchment/river	A river system where no major dams or weir structures have been built to assist in the supply, or extraction of water.
Upland	A stream section at high altitudes with a river channel often less than 10 times the channel depth.
Waterway	A longitudinal flow path in the landscape. It may be a well defined channel with defined bed and banks or a poorly defined depression line that only carries surface flow during rainfall or flood periods.
Weed	Any useless, troublesome or noxious plant, especially one that grows profusely.
VRHS	Victorian River Health Strategy.
VWQMN	Victorian Water Quality Monitoring Network.

1. Introduction

The Broken and Boosey Creek catchments lie in the Victorian Riverine Plains in northern Victoria. Flows in the Broken Creek and the mid and lower reaches of Boosey Creek have been regulated from as early as 1885 following the construction of the Casey's Weir and Major Creek Waterworks District stock and domestic supply system (State Rivers and Water Supply Commission 1964). Under the supply system water is diverted from the Broken River at Casey's Weir to the Broken Creek from where it is distributed via natural waterways (including shallow depressions) and a system of weirs and channels to stock and domestic users. This has resulted in the waterways of the district experiencing near perennial flows for the past 100 years. Under natural conditions most waterways in the catchment would have ceased to flow during dry periods, although permanent pools would have been retained in most years and some upper reaches of Boosey Creek may be spring fed.

The Casey's Weir and Major Creek Waterworks District stock and domestic supply system has recently been converted to a pipeline (hereon referred to as the Tungamah Pipeline Scheme) and this will result in a significant reduction in flow diversions from the Broken River to the Broken Creek and a consequent shift in the flow regime back towards a more intermittent natural regime. Previous studies have identified a number of benefits associated with the change in flow, including beneficial drying of riparian vegetation and wetlands during summer (Cottingham *et al.* 2001, ECC 2001, SKM 2005). However, a number of risks to instream fauna have also been identified as a result of a shift to a more natural regime, including loss of habitat and possible water quality impacts during cease-to-flow periods (Cottingham *et al.* 2001, SKM 2005, McMaster *et al.* 2006).

Environmental flows in the Broken Creek were considered as part of an environmental flow study for the Broken River in 2001 (Cottingham *et al.* 2001), however, specific flow recommendations were not made. A recent waterway management strategy for the Broken Creek recommended that a more detailed environmental flow study be undertaken (GHD/URS 2005). In particular, an environmental flow study will help to first, better understand the effects that the Tungamah Pipeline Scheme will have on ecological values in the region and second, to set flow recommendations to help protect environmental values that may be impacted by future changes in the flow regime.

This study is particularly focused on the Broken Creek and Boosey Creek upstream of Katamatite; the upper Broken Creek catchment. The flow requirements of the lower Broken Creek will be examined in a future study.

1.1 Project objectives

This project is aimed at developing environmental flow recommendations for Broken and Boosey Creeks upstream of Katamatite. Specific project objectives are to:

- develop daily current and natural flows, including an assessment of losses;
- determine frequency and magnitude of cross -catchment connections between Broken River and Broken Creek;
- select reaches for environmental flow assessments;
- identify water dependent environmental values and their condition within each reach;
- identify the flow regimes that will maintain / improve these values;
- recommend objectives for water dependent environmental values to achieve an ecologically healthy waterway;
- recommend environmental flows to support objectives; and
- identify complimentary works and further investigations.

Environmental flow recommendations are determined using the framework of the standardised statewide method for determining environmental water requirements in Victoria, referred to as the FLOWS method (NRE 2002). The method involves the collection of information through desktop studies, field assessment and consultation. The FLOWS method is an assessment of the environmental flow requirements to sustain and enhance ecological values and while operational issues are considered, it is important that operational issues do not compromise the flow assessment. As such, flow recommendations may be in conflict with operational requirements and these conflicts need to be considered and resolved as part of the implementation of flow recommendations.

1.2 This report

This report presents the final output of the study; the environmental flow recommendations for Broken and Boosey Creeks. The current report was preceded by a *Site Paper* (SKM 2006c) and *Issues Paper*(SKM 2006b). The *Site Paper* described the process used to divide the study area into representative reaches and the rationale for specific reach and site selections. The *Issues Paper* detailed the available information on the environmental values of the study area – water system management, hydrology, geomorphology, ecology and water quality. It also canvassed those catchment and stream flow issues that affect the condition of the environmental values which culminated in the determination of environmental objectives that contribute to achieving ecologically healthy waterways. The *Issues Paper* summarised all the supporting information required to determine the environmental flow requirements Broken Creek and Boosey Creek upstream of Katamatite.

Using hydrological and hydraulic data and information contained in the *Issues Paper*, the EFTP determined a series of flow recommendations. The outputs of this task are documented in this report, which provides the minimum flow recommendations and a comparison between the current flow regime and the flow recommendations for each flow component in each reach.

1.2.1 Report structure

Following this introduction, Section 2 provides a summary of the method used to develop flow recommendations for Broken Creek and Boosey Creek. Section 3 provides a summary of the assessment of cross-catchment transfers to inform the development of flow recommendations. The flow recommendations for Broken and Boosey Creeks are provided in Sections 4 and 5 respectively along with an overview of reach conditions and summary of reach objectives. Section 6 provides recommendations for complementary waterway works and further investigations required to support the environmental objectives and complement the environmental flow recommendations.

2. Method

The FLOWS method was used to determine environmental flow recommendations for Broken and Boosey Creeks. It provides a scientific framework for the assessment of flow requirements for waterways where there is some information available on the ecology, geomorphology and hydrology of the study area. The method has been specifically developed for determining environmental water requirements in Victoria and is based on the concept that key flow components of a natural flow regime influence various biological, geomorphological and physicochemical processes in waterways. Key flow components are likely to vary between river systems, but every stream system has some key flow components that are essential to maintain a healthy functioning aquatic ecosystem. The major steps in the application of the FLOWS method are shown in Figure 2.1.

A key component of the FLOWS method is the constitution of an Environmental Flows Technical Panel (EFTP). The EFTP consists of members that have expertise in a specific environmental discipline. Together, the EFTP identify specific environmental values and threats for the waterway and determine the key flow components and environmental flow recommendations that are required to support native instream and riparian biodiversity and natural stream and floodplain processes.

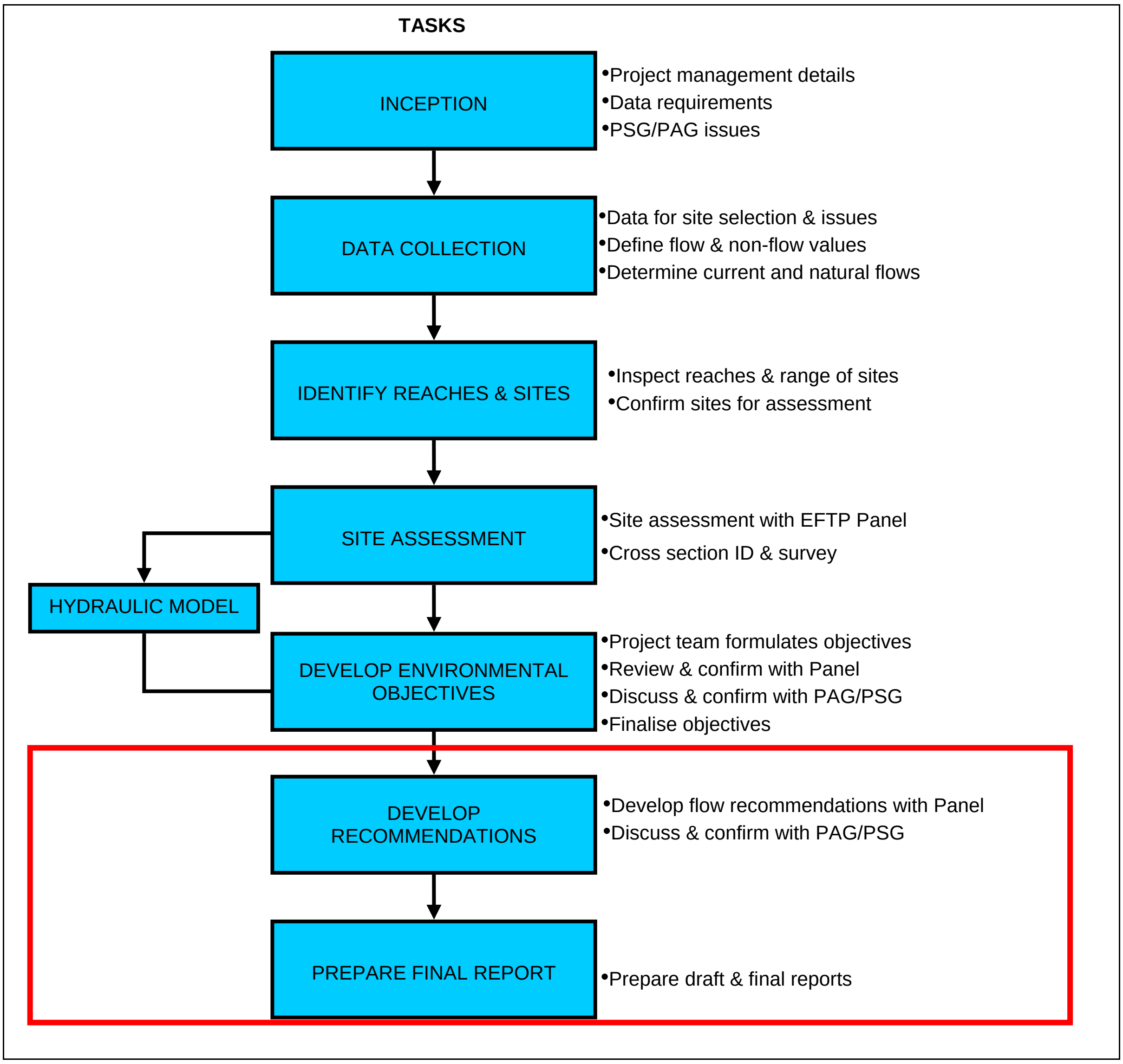
The EFTP consists of members that have expertise in an environmental discipline. Members of the EFTP for this project are (in alphabetical order, with fields of expertise):

- Dr Bruce Abernethy / Dr Axel Allgaier — Geomorphology
- Dr Nick Bond — Macroinvertebrates / drought ecology
- Dr David Crook — Fish ecology
- Dr Jane Roberts — Instream, riparian and wetland vegetation
- Dr Simon Treadwell — Water quality and ecological processes

The panel was supported by Simon Lang who provided expertise in hydrology and hydraulics. All panel members have considerable experience in the application of the FLOWS method and significant local knowledge, having been involved in a range of projects in the study area.

A project Steering and Advisory Committee were established for the project to provide a forum in which the creek's key stakeholders could provide technical input into the study. The Advisory Committee met on four occasions during the project. The first meeting was to provide an overview of the FLOWS process and to seek information on stakeholder views of the values and threats in the study area. The second meeting was undertaken whilst in the field and provided the Advisory Committee with an opportunity to observe and provide input to the FLOWS process undertaken at a field assessment site. The third meeting discussed the outcomes of the EFTP site assessment including an overview of key issues in each reach and discussion of preliminary environmental flow objectives. The forth meeting discussed and confirmed the draft environmental flow recommendations for each reach.

A brief description of the method applied to this project is provided below. The full method and rationale is provided in NRE (2002).



- **Figure 2.1 Outline of the steps involved in the FLOWS method (Tasks related to the current document are indicated by the red box).**

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2.1 Reach and site selection

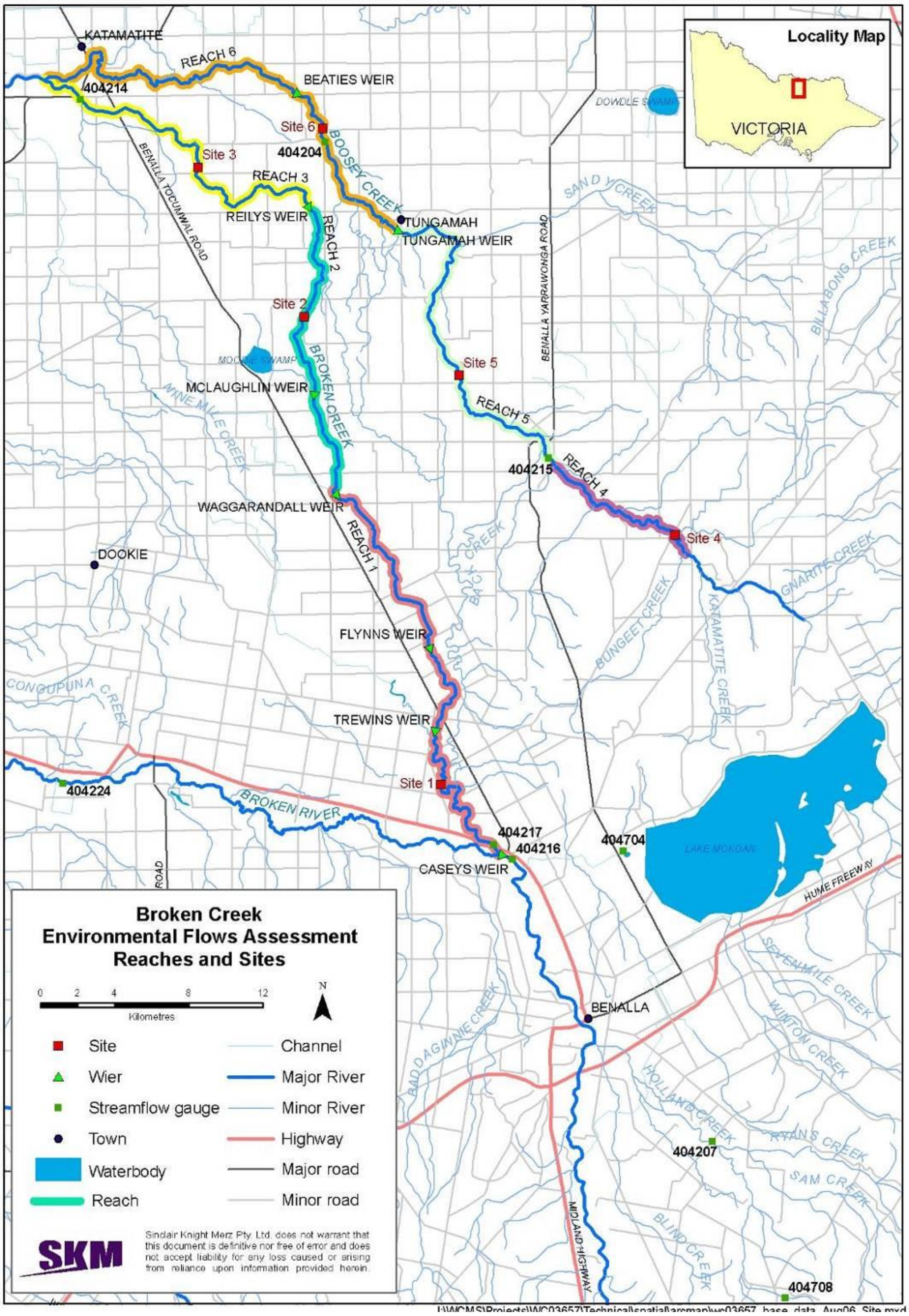
The first stage of this project was to collect and collate all available information relating to the study area so as to describe the operation of the system, hydrology, environmental values and ecological processes. The delineation of each of these characteristics was then used to separate the study area into five reaches (Figure 2.2) and (Table 2.1).

A catchment inspection was undertaken on 18 July 2006 to delineate reaches and select a site within each reach that was representative of the key features of the reach. These representative sites were then used in the detailed analysis to assist in quantifying environmental flow recommendations. The methods and outputs of this task are described in the *Site Paper* (SKM 2006c).

▪ **Table 2.1 Environmental flow reaches and EFTP assessment site locations**

Reach number	Reach Location	EFTP site location
1	Broken Creek: Casey's Weir to Waggarandall Weir	Broken Creek at Quinn Road
2	Broken Creek: Waggarandall Weir to Reilly's Weir	Broken Creek at Geary Road
3	Broken Creek Reilly's Weir to Katamatite (confluence with Boosey Creek)	Broken Creek at Mills Road
4	Boosey Creek: upstream of Rowan's Swamp	Boosey Creek at Bungeet Road
5	Boosey Creek: Rowan's Swamp to Tungamah	Boosey Creek at Boosey Creek Road
6	Boosey Creek: Tungamah to Katamatite (Confluence with Broken Creek)	Boosey Creek at Burramine Road Gauge

All sites, with the exception of Quinn Road in Reach 1, correspond with sites investigated by McMaster *et al.* (2006) as part of background monitoring for the Tungamah Pipeline Scheme. This allowed the use of data recorded during their monitoring study to provide a base for the current study. In particular, McMaster *et al.* (2006) undertook channel cross section surveys, vegetation surveys and fish surveys at each site during 2005 and 2006. Where appropriate, the channel cross-sections were used to extend the accuracy of survey work for the current study.



■ **Figure 2.2 Environmental flow reaches and assessment sites**

2.2 Field assessment

A field assessment of the representative sites was conducted by the EFTP on 17 and 18 August 2006. At each site, between six and nine cross sections were identified for subsequent surveying. These cross sections were selected as representative of the range of channel and habitat features of the site, such as pools, shallow runs, log jams or channel benches. Once selected, photographs were taken of each cross section and a sketch drawn to identify important geomorphic and habitat features. An evaluation of the key components of the flow regime at each of the sites was carried out to identify flows that would be geomorphologically or ecologically important for the creeks. The observations of the EFTP are documented in the *Issues Paper* (SKM 2006b) and were used to formulate objectives for each reach as described below.]

2.3 Hydrology

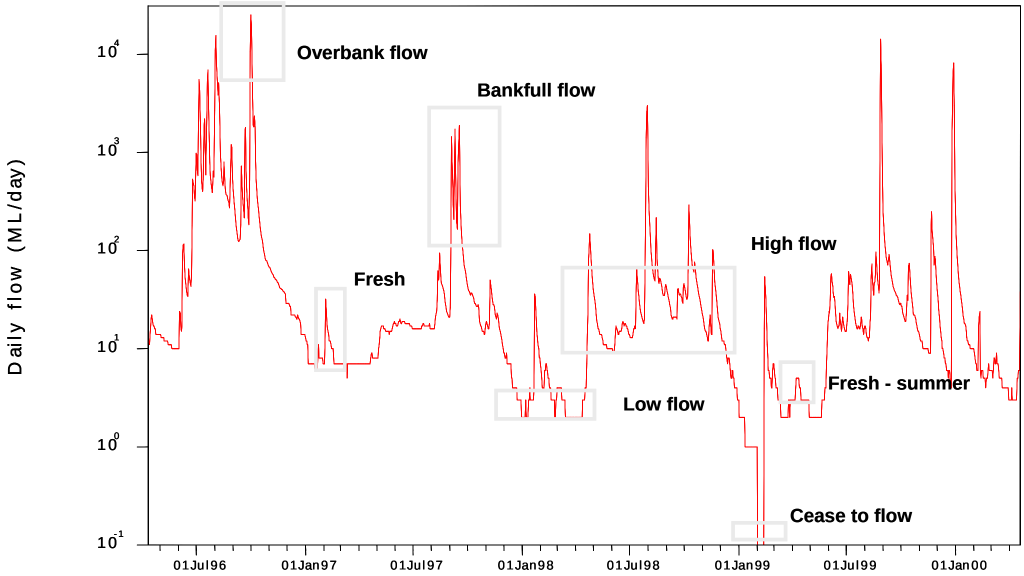
A detailed report has been prepared that describes the current and natural hydrology of Broken and Boosey Creeks, the nature of cross-catchment flows from the Broken River to the Broken Creek and the calculation of current and natural daily flows (SKM 2006a). The current flow series is the flow regime that refers to current use, including the effect of impoundments (e.g. farm dams) and diversions. The natural flow series is the flow regime that would exist if no diversion or impoundment of water occurred (ignoring the changes in flows that have occurred because of vegetation removal or landuse). The outcomes from the hydrology analysis were also incorporated in to discussions presented in the *Issues Paper* regarding current condition and flow objectives.

2.4 Environmental flow objectives and flow components

Environmental flow objectives set the direction and target for the environmental flow recommendations and are clear statements of what outcomes should be achieved in providing environmental flows. Environmental flow objectives were developed for those ecological assets that have a clear dependence on some aspect of the flow regime, such as:

- individual species and communities;
- habitats; and
- ecological (physical and biological) processes.

Flow components relevant to each objective were also identified. A flow component is a specific element of the flow regime (Figure 2.3) that fulfils a particular ecological or biophysical function (Table 2.2 and see Appendix A).



- **Figure 2.3 Typical daily flow series for a perennial stream. Note, in intermittent or ephemeral streams the cease-to-flow period is longer and there is often more variability in the frequency of higher flow events.**

- **Table 2.2: Environmental functions of different flow components. A more detailed description of each flow component can be found in Appendix A.**

Flow component	Function
Summer/autumn (December-May)	
Cease-to-flow	▪ Disturb lower channel features by exposing and drying sediment and bed material. ▪ Promote successional change in community composition through disturbance. ▪ Maintain a diversity of ecological processes through wetting and drying.
Low flow	▪ Disturb lower channel features by exposing and drying. ▪ Allow accumulation and drying of organic matter in the dry areas of the channel such as benches. ▪ Maintain permanent pools with an adequate depth of water to provide refuge habitat for aquatic biota.
Freshes	▪ Provide flow variability to maintain species diversity of emergent and marginal aquatic vegetation and to drive vegetation zonation patterns across the channel. ▪ Maintain emergent and marginal aquatic vegetation by wetting lower channel banks and benches. ▪ Improve water quality by flushing and turning over any stratified pools. ▪ Temporary increase in longitudinal connectivity between pools to allow fish movement.
Winter/spring (June – November)	
Low flow	▪ Sustained longitudinal connectivity for fish movement. ▪ Sustained inundation of riffles and lower benches to maintain habitat for emergent and marginal aquatic vegetation. ▪ Instigate die-back of terrestrial vegetation that has encroached down the bank during the summer low flow period. ▪ Increase habitat area for instream flora and fauna including access to large woody debris and overhanging banks.
Freshes / High flow	▪ Entrain terrestrial organic matter that has accumulated on benches. ▪ Provide sediment transport (sediment entrainment and deposition with no, or limited, net change in

Flow component	Function
Summer/autumn (December-May)	
	channel form). ▪ Provide flow variability to maintain species diversity of emergent and marginal aquatic vegetation and to drive zonation patterns on the banks. ▪ Provide cues for fish movement and spawning.
Bankfull	▪ Disturbance and resetting of aquatic and riparian vegetation communities. ▪ Transport sediment that has accumulated in pools. ▪ Transport organic matter that has accumulated in the upper channel. ▪ Removal of aquatic and riparian vegetation through scouring. ▪ Engage floodrunners and wetlands connected around bankfull.
Definition of terms: Cease-to-flow – no measurable flow in the river (although pools may retain water) Low Flow – flow that provides continuous flow through the channel within that reach Freshes – small and short duration peak flow event High Flow – large flow events with longer duration than freshes, these flows cover streambed and low in-channel benches Bankfull Flow – fill the channel and adjacent wetlands with little spill onto the actual floodplain	

Environmental flow objectives for Broken Creek and Boosey Creek are detailed in the *Issues Paper* (SKM 2006b) and have been endorsed by the project steering and advisory Committees.

2.5 Survey of selected reaches

Cross sections identified by the EFTP were surveyed and incorporated into a hydraulic model for each site. Cross section survey points focussed on the channel detail, with fewer points located within the riparian zone and floodplain. A total station was used to measure any significant changes in channel features across each cross section. Water level was recorded at all cross sections to assist in calibration of the hydraulic model. Invert levels (i.e. the lowest point) of flood runners were also surveyed to determine levels at which water commences to enter the flood runners. Cross sections were surveyed to AHD (Australian Height Datum).

2.6 Hydraulic modelling

2.6.1 Model set up

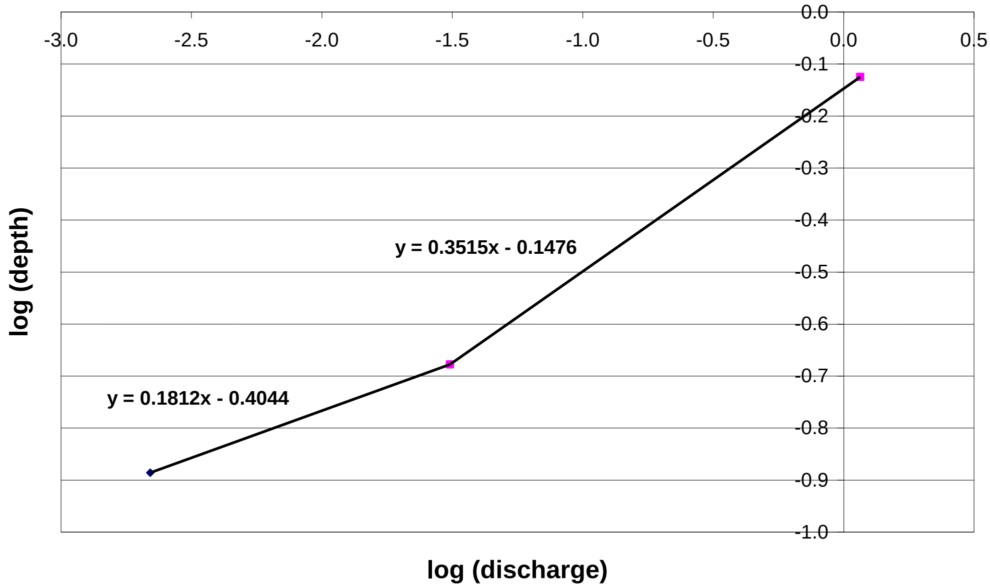
A one-dimensional hydraulic model of each site was prepared to develop a relationship between flow, water depth and velocity using the one dimensional steady state backwater analysis model HEC-RAS (v3.1.3). HEC-RAS calculates water surface profiles and other flow characteristics using a series of surveyed and interpolated cross sections and estimated roughness factors.

Roughness factors and other flow control features such as large woody debris (LWD) and in-stream vegetation were noted at each site. Sites 2, 3, 4 and 5 were also surveyed by Monash University as part of their study of the catchment (McMaster *et al.* 2006), and where appropriate this data was included in the HEC-RAS models used for the current project.

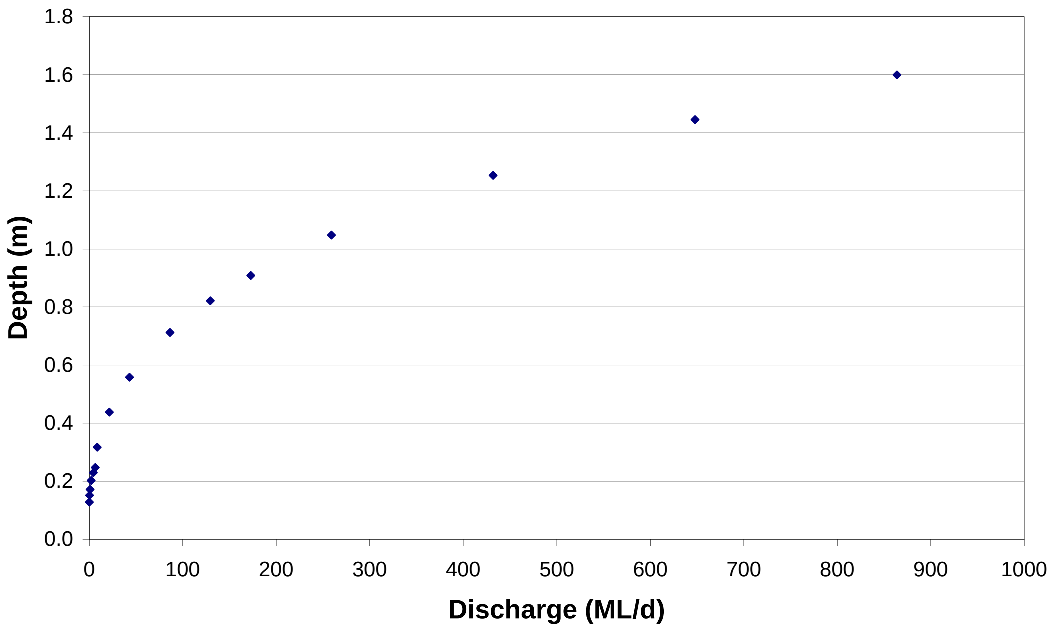
As part of the calibration process, the cross section and long section survey data was used to create interpolated cross sections, to represent features such as log weirs that occurred between the surveyed cross sections. These in-stream features often control water levels, and therefore their representation in the HEC-RAS models is critical. The cross sections, roughness, and in-stream controls were then adjusted so that, for the observed streamflows, modelled water levels matched the water levels surveyed by SKM and Monash University.

An important aspect of the calibration process was the assumed water level at the downstream end of each model (the downstream 'boundary condition'). For streamflows on the day of the SKM and Monash University surveys, the water level at the downstream end of each site was known. However, determining an appropriate boundary condition for a range of other flows was more difficult, because there were no surveyed water levels. Therefore, an alternative approach was needed.

Firstly, profiles at the most downstream cross-section for each HEC-RAS model were retrieved from model runs calibrated to water levels surveyed by SKM and Monash University, and from a model run which simulated an in-channel high flow (assuming a downstream boundary condition of normal depth with a slope of 1/1500 estimated from the 1:100,000 topographic maps). Secondly, these profiles were plotted on log-log axis (see Figure 2.4 as an example for Site 3). Through these points a trend line was fitted, which could be used to describe a rating curve for the most downstream cross-section (see Figure 2.5 as an example for Site 3).



- **Figure 2.4 Example log(depth) versus log(discharge) relationship for water levels surveyed by SKM (lowest depth), Monash University (middle depth) and simulated for a bankfull flow (highest depth) for Site 3.**



- **Figure 2.5 Example rating curve developed using the trend lines in Figure 2.4 for Site 3**

2.6.2 Model outputs

Significant effort has been made to ensure the hydraulic models are accurate, however it should be noted that the models have been calibrated to only one or two particular flows, as observed on the days of the SKM and Monash University surveys. The flows at each site on the days of survey were relatively small, and therefore there are potentially significant errors inherent in using the HEC-RAS models to estimate water levels at high flows. In other words, while the hydraulic models are relatively accurate at the flows observed on the days of survey, they may not be accurate for higher or lower flows. Each model has been created so as to minimise this error, but it is not possible to avoid it entirely without surveying the water levels at each site over a wide range of different flows. This level of effort would be time consuming (and potentially dangerous at high flows) and is outside the scope of this project.

A key output from the hydraulic model is a graphical representation of each transect. An example of a hydraulic output is provided in Figure 2.6. 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. Horizontal blue lines within the cross section represent the estimated water surface at various flows (which are detailed in the legend). The green hatching represents vegetation in the channel that prevents or restricts flow in that area.

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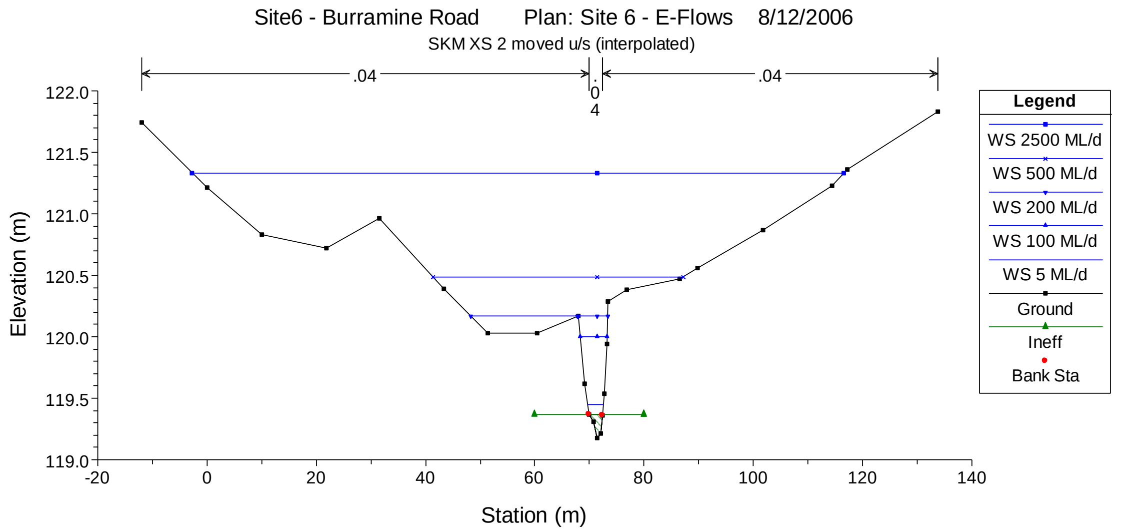
The outputs from the model include the flows (expressed in ML/d) required to cover the steam bed to a certain depth, or inundate channel features such as benches.



- **Figure 2.6 Example cross section output from the hydraulic model for Site 6.**

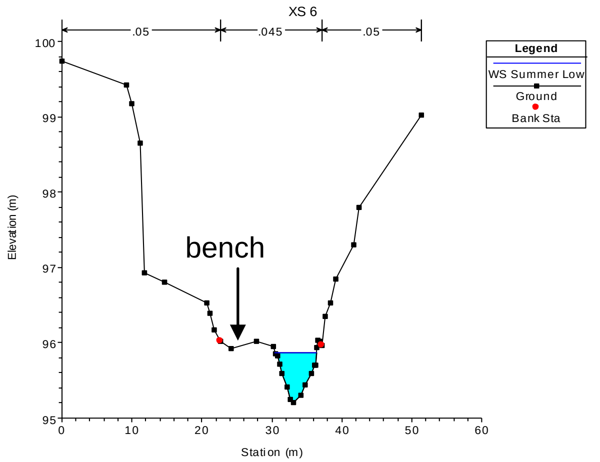
2.7 Development of environmental flow recommendations

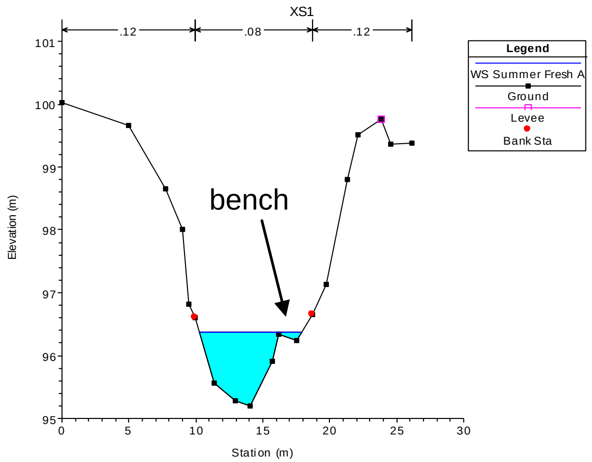
Environmental flow recommendations for Broken and Boosey Creeks were determined by the EFTP in a workshop conducted on 20 November 2006. The workshop was also attended by Scott Morath from GBCMA and Damian McMaster from Monash University.

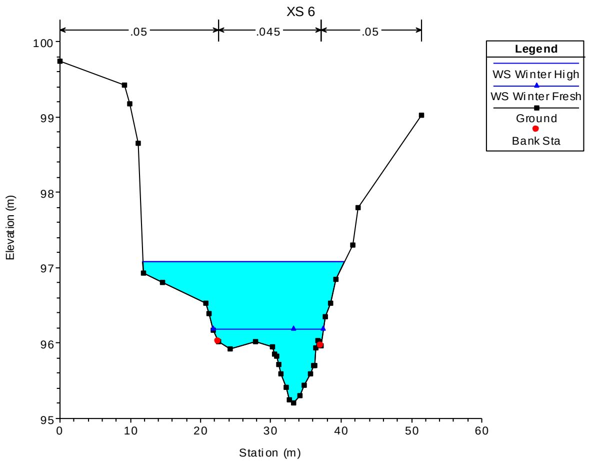
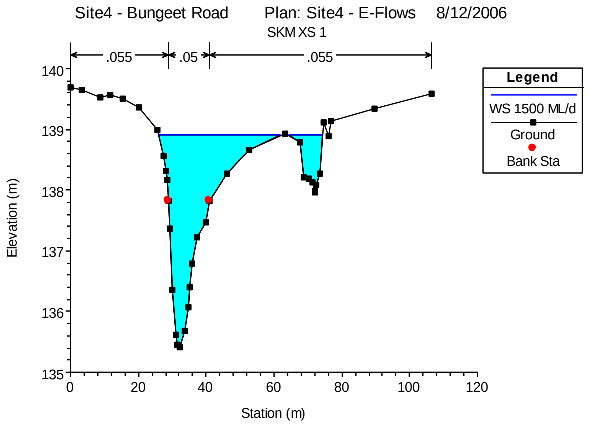
The EFTP worked through the process of determining flow recommendations on a reach by reach basis. For each reach the basic ecological condition was discussed and previously determined environmental flow objectives were summarised and reviewed. Photos and field notes taken during the field assessment were examined along with transects from the hydraulic model in order to identify key environmental features (i.e. benches, pools, backwaters etc). Operational issues were considered by the EFTP but flow recommendations were based on ecological requirements not operational requirements. As such, flow recommendations may be in conflict with operational requirements and these conflicts need to be considered and resolved as part of the implementation of flow recommendations.

Within each reach each flow component was considered in turn. If a particular flow component could be associated with an environmental flow objective for the reach, a flow recommendation was made. A range of criteria were used to determine suitable flows (Table 2.3). These criteria are reach specific depending on the species present and channel features. For each flow component the desired volume threshold, frequency of occurrence and duration was determined.

Table 2.3 Criteria used in determining environmental flow recommendations for each flow component.

Function	Criteria for determining recommendation
Low flow	
Minimum flow that provides a continuous flow throughout the channel (maintains permanent pools with an adequate depth of water to provide habitat for aquatic biota). Note, the cease-to-flow occurs when there is no discernable surface low flow. In seasonally intermittent streams, like the Broken and Boosey Creeks, pools retain permanent water except following a sequence of dry years if now winter flow occurs.	The EFTP used minimum depths for the following biota: **Macroinvertebrates** ▪ Depth of 100 mm at the deepest point of the shallowest cross section. **Fish** Dependent on size and therefore height of individual fish species. Depth needs to be sufficient such that each fish species remains wholly submerged (minimum for winter): ▪ Small bodied fish (e.g. pygmy perch, river blackfish) – 150 to 300 mm in pools; ▪ Large bodied fish (e.g. golden perch, Murray Cod) – 500 to 1000 mm in pools;
Minimum flow that provides a continuous flow throughout the channel, but allows the lower banks, benches and bars to dry.	 Morphological feature defined by individual cross sections. Example provided is for a summer low flow recommendation. Note, banks and benches are not inundated.
Minimum flow that provides a continuous flow throughout the channel for the inundation of habitat elements (aquatic vegetation).	Minimum inundation of channel (similar to that required for fish and macroinvertebrates)

Function	Criteria for determining recommendation
Freshes	
Disturbance to scour biofilms and flush fine sediments.	A velocity greater than 0.4 m/s was considered suitable to generate scouring flows (Biggs *et al.* 1999).
Access to habitat – increase riffle width and depth.	 The EFTP used an increase in habitat area (compared to low flows) and the inundation of in-channel benches and high flow channels as morphological features. Example provided is for a summer fresh recommendation. Note, that the bench is inundated.
Access to habitat – between pools.	**Fish** ▪ availability of fish passage in the shallowest cross section (see low flow – access to habitat above).
Maintenance of flood tolerant vegetation.	The EFTP used the inundation of in-channel low flow benches as morphological features (see HEC-RAS example output above).
High flows	
Provide spawning and movement opportunities for fish.	The EFTP used the inundation of in-channel high flow benches and deeper pools and runs compared to a fresh, as morphological features. The timing of these flows is linked to the biological requirements of individual fish species.

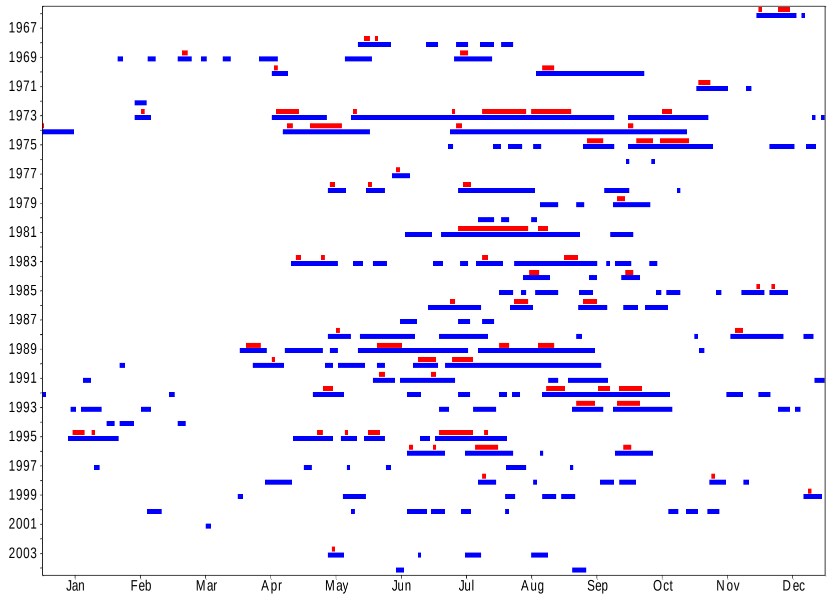
Function	Criteria for determining recommendation	
Bank wetting to promote flood tolerant vegetation and limit terrestrial vegetation.		The EFTP used the inundation of in-channel low flow and high flow benches as morphological features. In some reaches, a freshening flow fulfilled the objectives of a high flow. Example provided is for a winter fresh and high flow recommendation. The fresh inundates the low bench and the high flow inundates the higher bench located further up the bank.
Bankfull flow		
Disturbance and entrainment of organic material from the riparian zone. Maintain or rehabilitate current channel geometry. Maintain floodplain features (floodrunners, old channel courses etc.) by engagement.		Morphologically defined, with some interpretation required as cross sections may differ in capacity. Example provided is for a winter bankfull recommendation. Note water level is at the top of the bank for this cross section. The volume required for the engagement of floodrunners and old channel courses was determined by the invert or commence to flow level flow in these floodrunners/wetlands. The invert level is specific to each floodrunner and reach.

In addition, an 'or natural' proviso was added to the flow recommendations. This proviso allows for natural variability in the flow regime and is applicable to the cease-to-flow frequency and duration, low flow magnitude, and the frequency and duration of freshes, high flows and bankfull flows. The proviso requires that the recommendations need to be measured against the natural flow frequency and duration that would have occurred without any diversions, defined as 'natural' in this study.

The addition of the 'or natural' proviso to the low flow recommendation means that cease-to-flows can occur at the natural frequency and duration. The addition of the 'or natural' proviso to freshes, high and bankfull flows means that these flows will occur at their natural frequency and duration. If the natural flow at a compliance point in a reach is lower than the recommended flow, then the natural should be met rather than the minimum flow value. In this way, the flow variability, including cease-to-flow, is maintained in the natural state. In other words, for events below the recommended duration or frequency the natural event needs to be preserved

To assist with developing the flow recommendations a range of flow statistics were examined for the current and natural flow regimes and are presented in the following sections for each flows reach. Specifically, for each flow component spells analysis was undertaken using GetDat software to show the pattern over time of flows above or below certain flow volume thresholds (see Figure 2.7 for an example plot). While GetSpells software was used to summarise the frequency or number of events above or below a specified flow volume threshold per year, the duration in days of flow above or below the specified threshold volumes and the distribution of start month of flow events above or below specified threshold volumes (see Figure 2.8 for examples and a more detailed explanation of each GetSpells output).

Subsequent to the development of environmental flow recommendations for the Broken and Boosey Creeks some additional work was undertaken to assess the implications of the environmental flow recommendations for the wetting and drying regime of Moodies Swamp (SKM 2007). These implications are discussed in detail in the flow recommendations for Reach 2 (Section 4.3) where Moodies Swamp is located.



- **Figure 2.7 Example GetDat spells analysis. This plot shows the time series pattern in flows above specified volumes. In the example the pattern of flow spells above 1 ML/d is represented by the blue bars while flows above 10 ML/d are represented by the red bars. The periods where no coloured bar is show represents flows <1 ML/d.**

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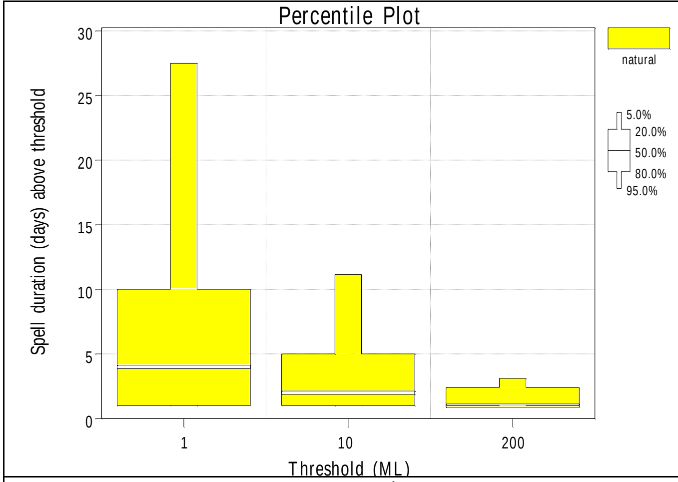
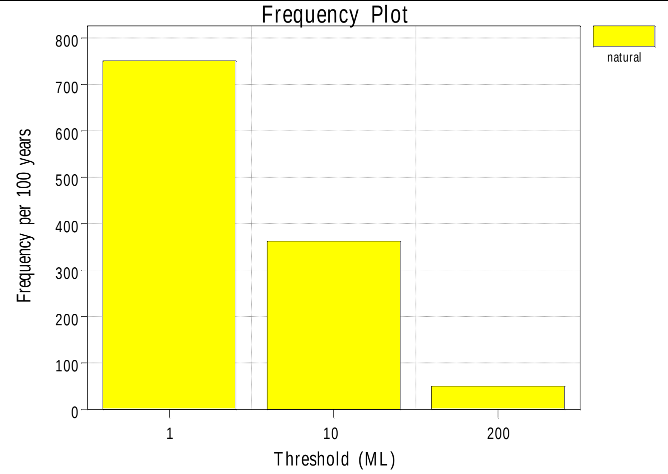
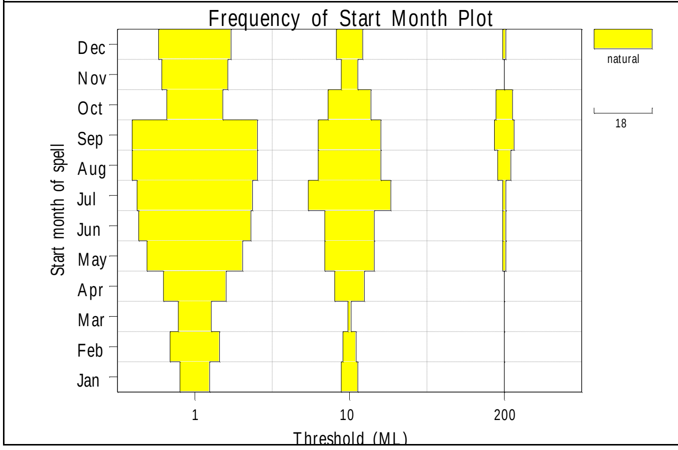
<table>
<tr>
<td>
</td>
<td>This plot shows statistics describing the duration of flow events or spells above specified threshold volumes. The plots are represented as box and whisker plots. In the example, flow events that are larger than 1 ML/d last for a median (50th%ile) duration of 4 days, 80% of events last less than 10 days, while 5% of flow events greater than 1 ML/d last longer than 27 days. As the flow threshold increases, in this example to 10 or 200 ML/d, the duration of the event decreases.</td>
</tr>
<tr>
<td>
</td>
<td>This plot shows the frequency or number of events per 100 years above the specified flow thresholds. In the example, over 700 flow events greater than 1 ML/d occur per 100 years (i.e. an average of 7-8 events per year). As the flow threshold increases the average number of events per year decreases. In the example a flow event greater than 200 ML/d occurs about 50 times per 100 years or on average once every two years.</td>
</tr>
<tr>
<td>
</td>
<td>This plot shows the distribution of start month for flows above specified thresholds. In this example, flow events above 1 ML/d can occur at any time of the year but the majority of events commence in late winter or early spring. The start time for larger flow events tends to be restricted to the winter-spring period.</td>
</tr>
</table>

- **Figure 2.8 Example GetSpells outputs and description of each plot.**

3. Cross-catchment flows from Broken River to Broken Creek

Under natural conditions, Broken Creek would have been an ephemeral waterway which flowed in response to local catchment runoff but which also carried occasional flood waters from the Broken River via a series of high flow channels linking the two waterways. The nature of this cross-connection has not been adequately described in previous studies. Under current conditions the frequency of naturally occurring cross-catchment flows is likely to have been reduced due to the construction the Midland Highway and accompanying levees, the construction of Casey's Weir, the regulation of diversions to Broken Creek and the regulation of flow in the Broken River due to the construction of Lake Nillahcootie and Lake Mokoan.

As part of the current study we examined in more detail the cross-connection. In particular we surveyed a number of flow paths between the Broken River and Broken Creek and developed a hydraulic model of the connection in order to determine the natural frequency of cross-catchment flows. The details of this assessment are provided in (SKM 2006a) and are summarised below.

Two high flow paths between the Broken River and Broken Creek were identified (Figure 3.1). Channel 1 appears to represent the main breakout from Broken River to Broken Creek prior to the construction of Casey's Weir and the artificial diversion channel from the weir the natural Broken Creek channel. Channel 2 represents a secondary, although somewhat larger, channel. Under natural conditions both channels appear to have commenced to flow to Broken Creek for flows in Broken River less than bankfull. However, both channels have now been blocked at the Broken River and require flows of at least bankfull in order to become active. In addition, there is no culvert under the Midland Highway which would allow flow in Channel 2 to reach Broken Creek.

Surveys of the two channels were undertaken and linked with previously measured cross-section surveys of the Broken River and Broken Creek to build a MIKE 11 hydraulic model of the connection. In order to 'restore' the natural connection adjustments were made to relevant cross-sections to remove the impacts associated with channel blocks and levees.

Using the MIKE 11 model, a relationship was derived between flows in the Broken River and cross-catchment flows to the Broken Creek for a range of roughness coefficients (Manning's *n* values) For Broken River (Figure 3.2). Figure 3.2 shows how the Manning's *n* value influences the threshold at which cross-catchment flows occur and the volume of water transferred. Based on Manning's n used for previous studies and as recommended in the literature a value of 0.04 was chosen to best represent channel roughness (SKM 2006a).

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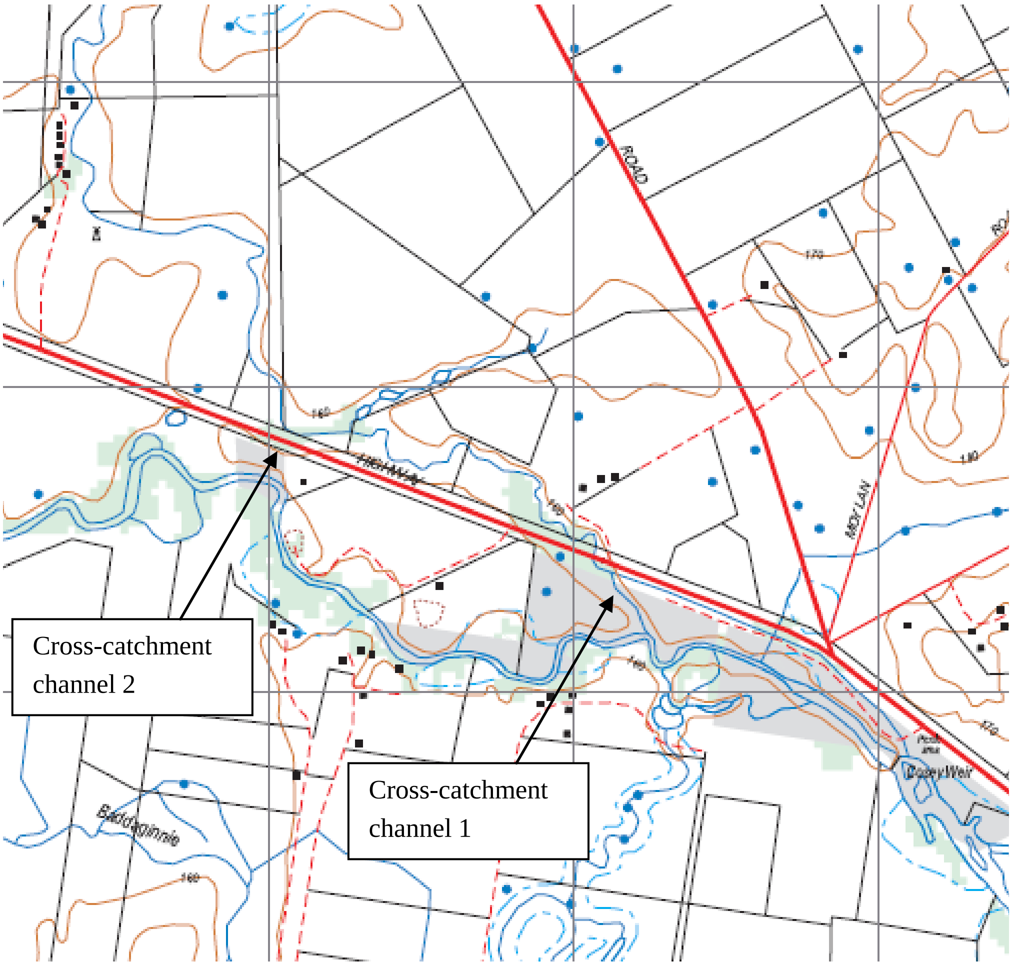
By applying the relationship in Figure 3.2 (assuming a Manning's *n* of 0.04) to a natural time-series of Broken River flows at Casey's Weir, a time-series of cross-catchment flows to the Broken Creek under natural conditions was derived (Figure 3.3).

Based on the above modelling the commence to flow threshold for flows to Broken Creek is estimated to be a flow of 14,500 ML/d in the Broken River. Flows of this magnitude are expected to occur around once every two years. The implications of the cross-catchment transfers is described in more detail in relationship to the delivery of environmental flow recommendations for Reach 1 of the Broken Creek in Section 4.2.



- **Figure 3.1 The location of cross-catchment (Broken River to Broken Creek) channels.**

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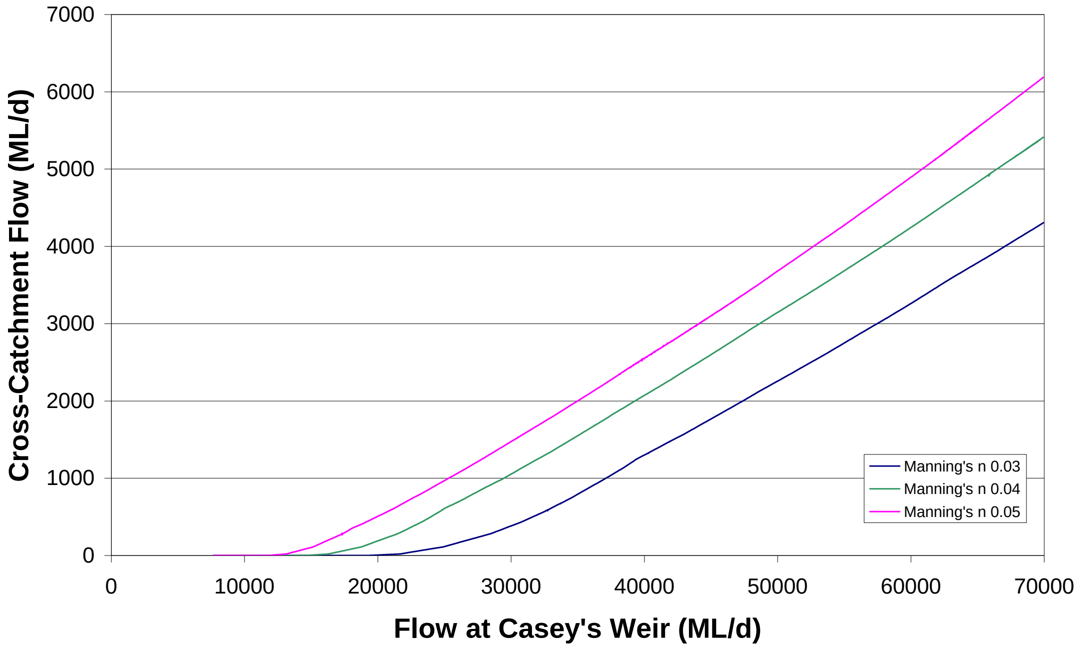
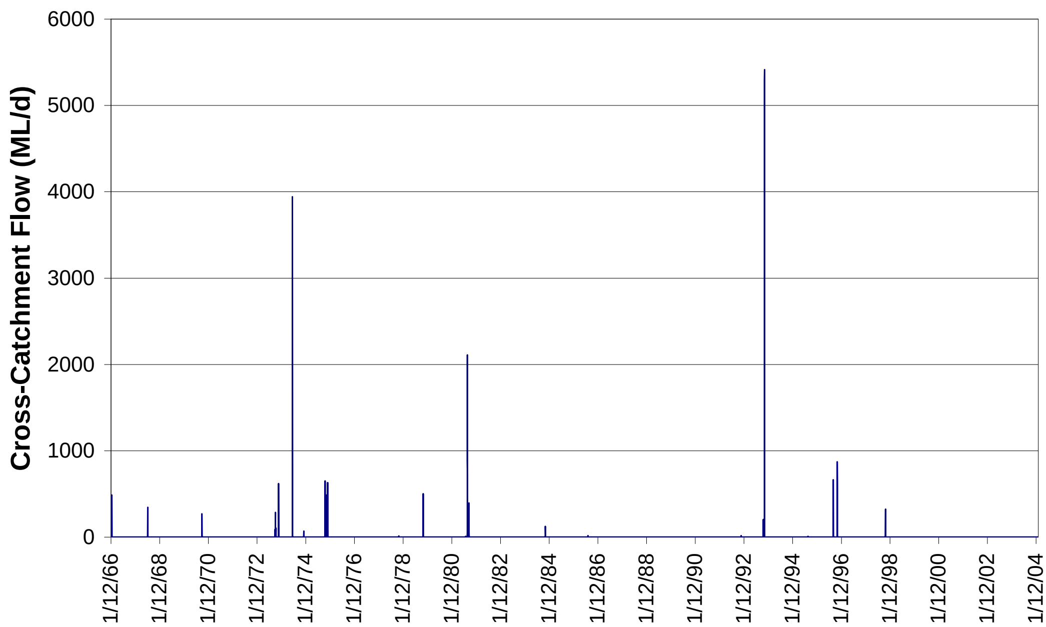


- **Figure 3.2 Cross-catchment flows from the Broken River to Broken Creek, assuming Manning's n of 0.03, 0.04 and 0.05.**



- **Figure 3.3 A time-series of cross-catchment flows to the Broken Creek from the Broken River under natural conditions, assuming a Manning's n of 0.04.**

4. Broken Creek flow recommendations

This section describes the environmental flow recommendations for Broken Creek. A summary of the current condition is provided along with the ecological objectives for each reach. Following this the flow recommendations for each reach are detailed.

4.1 Summary of current condition and ecological objectives

The current condition of Broken Creek is detailed in the *Issues Paper* (SKM 2006b) and summarised in Table 4.1.

■ **Table 4.1 Summary of current condition in Broken Creek**

Aspect	Current condition
Hydrology	■ Flows in the upper part of Broken Creek (Reaches 1 and 2) are elevated in spring and summer compared to natural for stock, domestic and irrigation uses. ■ Flows dependent on water release from Lake Nillahcootie and Lake Mokoan to Broken River and diversion at Casey's Weir to Broken Creek. ■ Winter flows are more similar to natural and are driven by local catchment runoff. ■ The frequency of natural transfers of flood flows from Broken River to Broken Creek has been reduced due to regulation in the Broken River and the construction of block banks across cross-connecting channels. ■ Median flow of ~50 ML/day in summer and ~20 ML/day in winter.
Geomorphology / channel habitat	■ The contemporary Broken Creek may have been an abandoned section of the Broken River. ■ The creek bed is generally muddy and shallow banks are exposed during low flows. ■ Original pool habitat may have been infilled over time due to high sediment load in water diverted to Broken Creek at Casey's Weir and reduction in frequency of higher flushing flows due to modifications to the natural connection between the Broken River and Broken Creek. ■ Weir pools and other, naturally shallow sections of the channel are shallow (maximum depth 0.5 m). ■ During low and cease-to-flow periods weir pools are likely to retain permanent habitat for aquatic biota and may act as a surrogate for deep pool refuge habitat.
Riparian and in-channel vegetation	■ Riparian vegetation is generally characterised as being discontinuous and fragmented to some degree. ■ There is some evidence of a shift in the vegetation community composition of the riparian zone towards species more tolerant of summer wetting as a result of regulated summer high flows.
Wetlands	■ Wetlands in the area are dominated by freshwater meadows and shallow freshwater marshes.
Fish	■ Six native fish species have been recorded in the Broken Creek study area – crimson-spotted rainbowfish, Murray cod, golden perch, gudgeon sp., Australian smelt and river blackfish. ■ Five exotic species have been recorded – carp, goldfish, redfin, mosquitofish, oriental weatherloach.
Macroinvertebrates	■ Based on EPA survey in 1999 and 2005 invertebrate assemblages in most reaches are below reference condition. ■ Invertebrate assemblage composed of fauna indicative of mild to moderate levels of pollution based on Signal index scores, although community composition is more likely to be driven by harsh physical characteristics associated with flow and water quality rather than pollution.
Water Quality	■ Routine water quality data indicates elevated turbidity and nutrient concentrations.

Ecological objectives are aimed at restoring an aquatic ecosystem with biota and processes indicative of an intermittent stream (Table 4.2 to Table 4.4). The current flow regime in Broken Creek is near permanent due to diversions from the Broken River at Casey's Weir. The Tungamah Pipeline Scheme will result in a substantial reduction the diversion of water to the Broken Creek. Summer diversions will still occur to supply irrigators between Casey's Weir and Waggarandall Weir. However, diversions will cease during winter and stream flows will return to a more natural, intermittent regime.

Under natural conditions Broken Creek would have been seasonally intermittent with prolonged cease-to-flows during summer and autumn and low flows during winter in response to local catchment runoff. Occasional higher flows would occur in response to cross catchment transfers from the Broken River.

The EFTP is of the opinion that reduced summer flows and the reinstatement of a more intermittent flow regime with prolonged cease-to-flows will result in a shift in the community composition of aquatic biota towards one more tolerant of dryer conditions, but that this is considered to represent an overall benefit to the ecology of the Broken Creek and result in the establishment of a more sustainable ecosystem. However, in order to compensate for the reduction in summer flows and restoration of a more natural summer flow regime the natural winter flow regime also needs to be restored.

Large winter flows are reliant on the cross-catchment transfer of a portion of high flows in the Broken River to the Broken Creek. The construction of levees and the Midland Highway between the Broken River and the Broken Creek downstream of Casey's Weir means that the natural frequency of cross-catchment transfers has been reduced (SKM 2006a). Reinstating the natural frequency of cross-catchment transfers is thus required. The volume of the cross-catchment transfer is related to the water level in the Broken River. As the Broken River flow increases above the commence to flow point for the Broken Creek the volume of water entering Broken Creek also increases. Thus, the following environmental flow recommendations for Broken Creek are consistent with the reduction in the summer diversions at Casey's Weir but the reinstatement of a more natural winter flow regime through reconnection of the natural cross-catchment transfers from Broken River.

Table 4.2 Reach 1 – Broken Creek at Quinn Road

Asset	Objective	No.	Function	Flow component	Timing
Geomorphology	■ Rehabilitate deep pool habitat ■ Facilitate sediment transport through reach	G1-1	■ Entrain and transport fine sediment that has accumulated in pools	Bankfull	Winter
Vegetation	■ Facilitate regeneration of River Red Gums away from channel margin and across an elevation gradient to higher ground, but consistent with distribution of mature trees. ■ Maintain biodiversity of in-channel vegetation (e.g. Water Ribbons *Triglochin* sp.). ■ Enhance species diversity and width of channel edge zone.	V1-1	■ Dry riparian zone and provide suitable conditions for flood tolerant rather than flood dependant riparian species	Cease-to-flow / low flow	All year
		V1-2	■ Variable water levels result in wet-dry zone at channel edge.	Fresh	All year
		V1-3	■ Growing opportunity for Water Ribbons.	High flow	Winter / Spring
		V1-4	■ Transport seed, prepare soil, reduce competition for River Red Gum seedlings. Irrigate juveniles and sapling away from river channel.	Bankfull	Winter/ spring
Fish	■ Restore a native fish community indicative of an ephemeral system	F1-1	■ Promote spawning by low flow specialist ■ Provide conditions that are unfavourable for exotic species	Cease-to-flow / low flow	Summer
		F1-2	■ Maintain aquatic habitats during periods of cease-to-flow – consistent with patterns from storm events.	Freshes	Summer
		F1-3	■ Provide opportunities for dispersal	High flow	Winter / Spring
Water quality	■ Maintain water quality, particularly in refuge pools	W1-1	■ Maintain aquatic habitats during periods of cease-to-flow – consistent with patterns from storm events.	Fresh	Summer / winter
		W1-2	■ Flush and replenish residual pools	High flows	Winter / Spring
Macroinvertebrates	■ Restore an ecologically healthy invertebrate community, characteristic of intermittent streams and including taxa relying on periodic drying to complete their life-cycle.	M1-1	■ Promote successional change in community composition through disturbance.	Cease-to-flow / low flow	Summer
		M1-2	■ Maintain aquatic habitats during periods of cease-to-flow – consistent with patterns from natural storm events.	Fresh	Summer
		M1-3	■ Movement of bed material to restore habitat diversity ■ Provide flow variability to generate a diversity of edge habitats	Fresh/High flow	Winter
		M1-4	■ Inundate accumulated organic matter in areas exposed during low flow/cease-to-flow	High flow	Winter

▪ Table 4.3 Reach 2 – Broken Creek at Geary Road

Asset	Objective	No.	Function	Flow component	Timing
Geomorphology	▪ Rehabilitate deep pool habitat ▪ Facilitate sediment transport through reach	G2-1	▪ Entrain and transport fine sediment that has accumulated in pools	Bankfull	Winter
Vegetation	▪ Reduce extent and abundance of Water Couch or ensure no further increase. ▪ Reduce likelihood of River Red Gums regenerating adjacent to channel. ▪ Enhance species diversity and width of channel edge zone.	V2-1	▪ Variable water levels result in wet-dry zone at channel edge	Cease-to-flow / low flow	Summer
		V2-2	▪ Variable water levels result in wet-dry zone at channel edge.	Fresh	Summer
		V2-3	▪ Inundate wetlands (e.g. Moodies Swamp) connected at bankfull flow	Bankfull flow	Winter
Fish	▪ Restore a native fish community indicative of an ephemeral system	F2-1	▪ Promote spawning by low flow specialist ▪ Provide conditions that are unfavourable for exotic species	Cease-to-flow / low flow	Summer
		F2-2	▪ Maintain aquatic habitats during periods of cease-to-flow – consistent with patterns from storm events.	Fresh	Summer
		F2-3	▪ Provide opportunities for dispersal	High flow	Winter / Spring
Water quality	▪ Maintain water quality	W2-1	▪ Maintain aquatic habitats during periods of cease-to-flow – consistent with patterns from storm events.	Fresh	Summer
		W2-2	▪ Flush and replenish residual pools	High flow	Winter / Spring
Macroinvertebrates	▪ Restore an ecologically healthy invertebrate community, characteristic of intermittent streams and including taxa relying on periodic drying to complete their life-cycle.	M2-1	▪ Promote successional change in community composition through disturbance.	Cease-to-flow / low flow	Summer
		M2-2	▪ Maintain aquatic habitats during periods of cease-to-flow – consistent with patterns from natural storm events.	Fresh	Summer
		M2-3	▪ Movement of bed material to restore habitat diversity ▪ Provide flow variability to generate a diversity of edge habitats	Fresh/High flow	Winter
		M2-4	▪ Inundate accumulated organic matter in areas exposed during low flow/cease-to-flow	High flow	Winter

Table 4.4 Reach 3 – Broken Creek at Mills Road.

Asset	Objective	No.	Function	Flow component	Timing
Geomorphology	▪ Rehabilitate deep pool habitat ▪ Facilitate sediment transport through reach	G3-1	▪ Entrain and transport fine sediment that has accumulated in pools	Bankfull	Winter
Vegetation	▪ Reduce extent and abundance of introduced sedges at the channel edge ▪ Increase diversity of channel-edge vegetation ▪ Minimise flow-related opportunities for River Red Gum regeneration	V3-1	▪ Variable water levels result in wet-dry zone at channel edge	Cease-to-flow / low flow	Summer
		V3-2	▪ Variable water levels result in development of wet-dry zone at channel edge	Fresh	Summer
Fish	▪ Restore a native fish community indicative of an ephemeral system	F3-1	▪ Promote spawning by low flow specialist ▪ Provide conditions that are unfavourable for exotic species	Cease-to-flow / low flow	Summer
		F3-2	▪ Maintain aquatic habitats during periods of cease-to-flow – consistent with patterns from storm events.	Fresh	Summer
		F3-3	▪ Provide opportunities for dispersal	High flow	Winter / Spring
Water quality	▪ Maintain water quality	W3-1	▪ Maintain aquatic habitats during periods of cease-to-flow – consistent with patterns from storm events.	Fresh	Summer
		W3-2	▪ Flush and replenish residual pools	High flow	Winter / Spring
Macroinvertebrates	▪ Restore an ecologically healthy invertebrate community, characteristic of intermittent streams and including taxa relying on periodic drying to complete their life-cycle.	M3-1	▪ Promote successional change in community composition through disturbance.	Cease-to-flow / low flow	Summer
		M3-2	▪ Maintain aquatic habitats during periods of cease-to-flow – consistent with patterns from natural storm events.	Fresh	Summer
		M3-3	▪ Movement of bed material to restore habitat diversity ▪ Provide flow variability to generate a diversity of edge habitats	Fresh/High flow	Winter
		M3-4	▪ Inundate accumulated organic matter in areas exposed during low flow/cease-to-flow	High low	Winter

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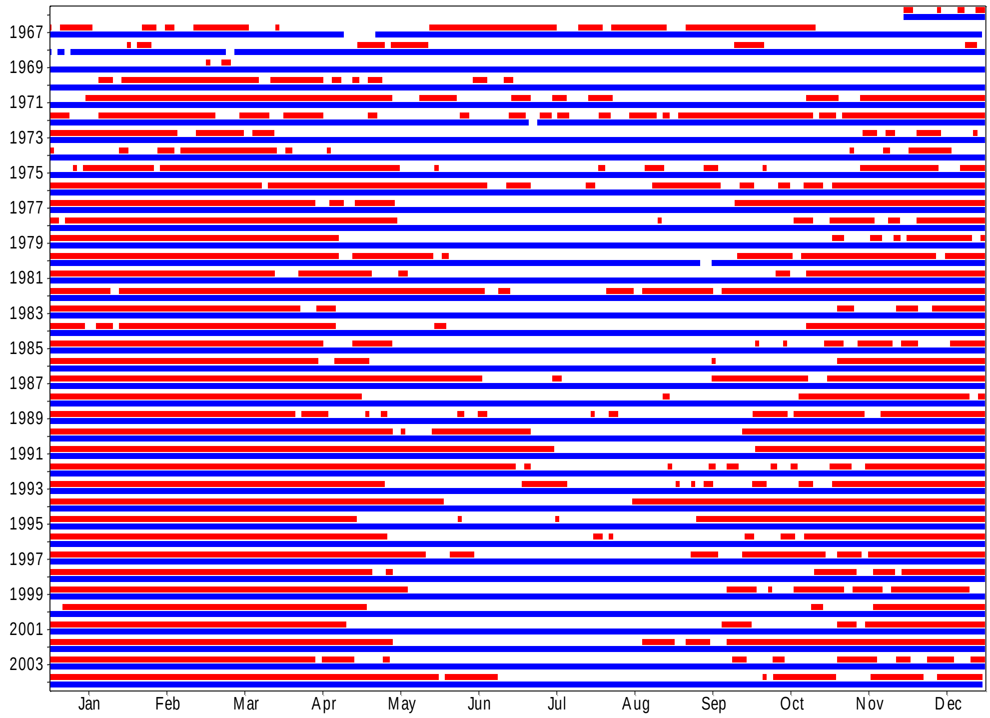
4.2 Reach 1: Casey's Weir to Waggarandall Weir

Under current conditions flow at Site 1 is near perennial with flows above 1 ML/d occurring almost continuously and flows above 30 ML/d occurring for long durations in most years, particularly during summer and autumn when diversions from the Broken River to the Broken Creek are at their greatest (Figure 4.1). It is recommended to restore a natural, seasonally intermittent flow regime to the Broken Creek with cease-to-flows in summer and low flows, freshes and high flows in response to local catchment runoff and cross-catchment transfers from the Broken River (Table 4.5).



- **Figure 4.1 Flow spells above 1 ML/d (blue bars) and 30 ML/d (red bars) under current conditions showing continuous flow.**

- **Table 4.5 Summary of flow recommendations for Reach 1: Broken Creek Casey's Weir to Waggarandall Weir.**

Stream		Broken Creek		**Reach**	Casey's Weir to Waggarandall Weir
Compliance point		Casey's Weir		**Gauge No.**	404216
Season	**Component**	**Volume**	**Frequency**	**Duration**	**Objective**
Summer	Cease-to-flow	yes	natural	natural	M1-1, F1-1, V1-1
	Low flow	No specific recommendation but allowed to occur as part of local catchment runoff.			M1-1, F1-1, V1-1
	Fresh	Up to 200 ML/d	Allow to occur in response to local rainfall, not expected to occur via transfer from Broken River under natural conditions.		M1-2, M1-3, F1-2, V1-2, W1-1
Winter	Cease-to-flow	yes	natural	natural	M1-1, F1-1, V1-1
	Low flow	No specific recommendation but allowed to occur as part of local catchment runoff and delivery of fresh			M1-1, F1-1, V1-1
	Fresh	Up to 200 ML/d in response to local catchment runoff and transfers from Broken River	Transfers from Broken River expected to occur once every two years in winter / spring for 1-2 days duration		M1-2, M1-3, F1-2, V1-2, W1-1
	High flow / Bankfull	1000 ML/d in response to local catchment runoff and transfers from Broken River	Based on natural frequency and duration of bankfull flow in Broken River. May require infrastructure works to allow volume to be delivered to Broken Creek. Event must be allowed to progress down whole system. Expected to occur once every ten to twenty years for 1-2 days duration		G1-1, M1-3, M1-3, W1-2, F1-3, V1-3, V1-4
	Overbank	No recommendation with regards to transfer from Broken River, but allowed to occur in response to local catchment runoff.			

4.2.1 Cease-to-flow and low flows

Cease-to-flows are required to reinstate the natural ephemeral flow regime, dry out water couch and reduce river red gum regeneration along channel margins. Pools will retain water during cease-to-flow periods and provide refuge for aquatic biota. Retained weir pools will also provide pool refuge during cease-to-flow periods. Cease-to-flows can occur at any time during the year. No specific low flow volume, duration or frequency has been recommended. However, low flows should be allowed to occur as part of local catchment runoff at any time during the year and as part of the delivery of fresh flows in winter. Low flows will connect pools that may have become isolated during cease-to-flows, freshen water quality and allow for localised movement of fish.

Under the recommended environmental flow conditions, cease-to-flows (flows <1 ML/d) can occur for long periods throughout the year interspersed with low flows (1-10 ML/d) in most winters and springs (Figure 4.2). The median cease-to-flow duration is 12 days although 20% of cease-to-flow events can last for longer than 50 days. The median duration of flows greater than 1 ML/d is 4 days with 80% of events lasting 10 days or less (Figure 4.3). Low flows events occur relatively frequently, with an average 7 flow

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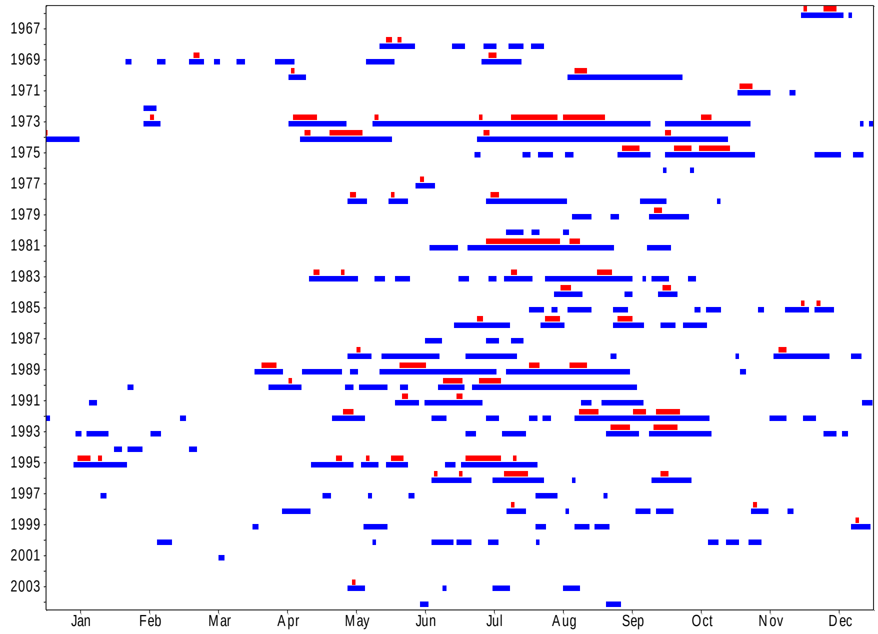
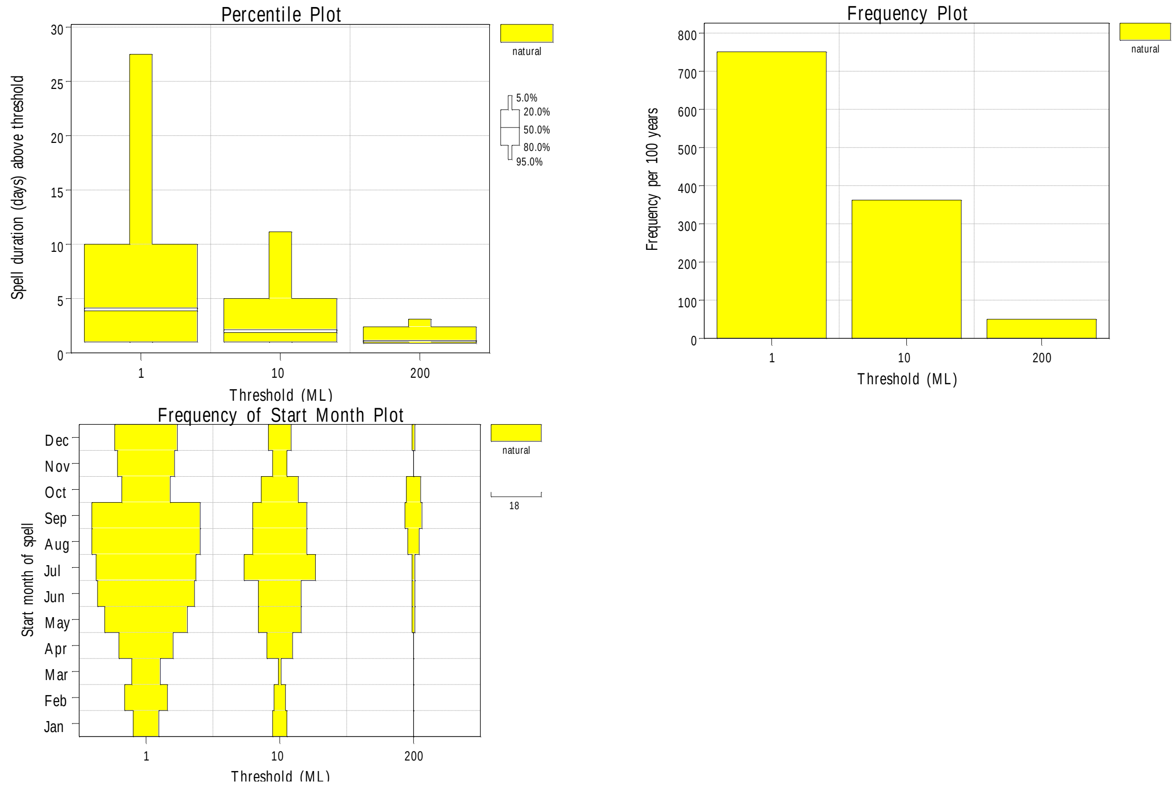
events above 1 ML/d occurring each year; most of which commence in winter and early spring (Figure 4.3).



- **Figure 4.2 Flow spells above 1 ML/d (blue bars) and 10 ML/d (red bars) under recommended natural conditions showing long periods of cease-to-flow (<1 ML/d).**



- **Figure 4.3 Spell durations (upper left), frequency (events per 100 years) (upper right) and distribution of start months (lower left) for flows above 1 ML/d, 10 ML/d and 200 ML/d thresholds under recommended natural conditions.**

4.2.2 Freshes

A fresh volume of up to 200 ML/d is recommended to inundate benches within the channel (e.g. bench in cross section 1 - Figure 4.4), transport some fine sediment that may have accumulated on benthic surfaces and provide wetting and drying regimes for littoral vegetation. Freshes can be met via local catchment runoff and via the restoration of the natural frequency of cross-catchment flows between the Broken River and Broken Creek. The ‘restoration’ of cross-catchment connections can be achieved artificially via diversions at Casey’s Weir (up to 200 ML/d can be delivered via diversions through Casey’s Weir) and triggered based on flows in the Broken River. Under natural conditions the cross connection would become active when the flow in Broken River reaches ~14,500 ML/d. Hence transfer to Broken Creek should commence when flow reaches ~14,500 ML/d in the Broken River at Caseys Weir according to the relationship specified in Figure 4.5. If flow in Broken River exceeds ~29,500 ML/d the high / bankfull flow recommendation can be instigated (see below).

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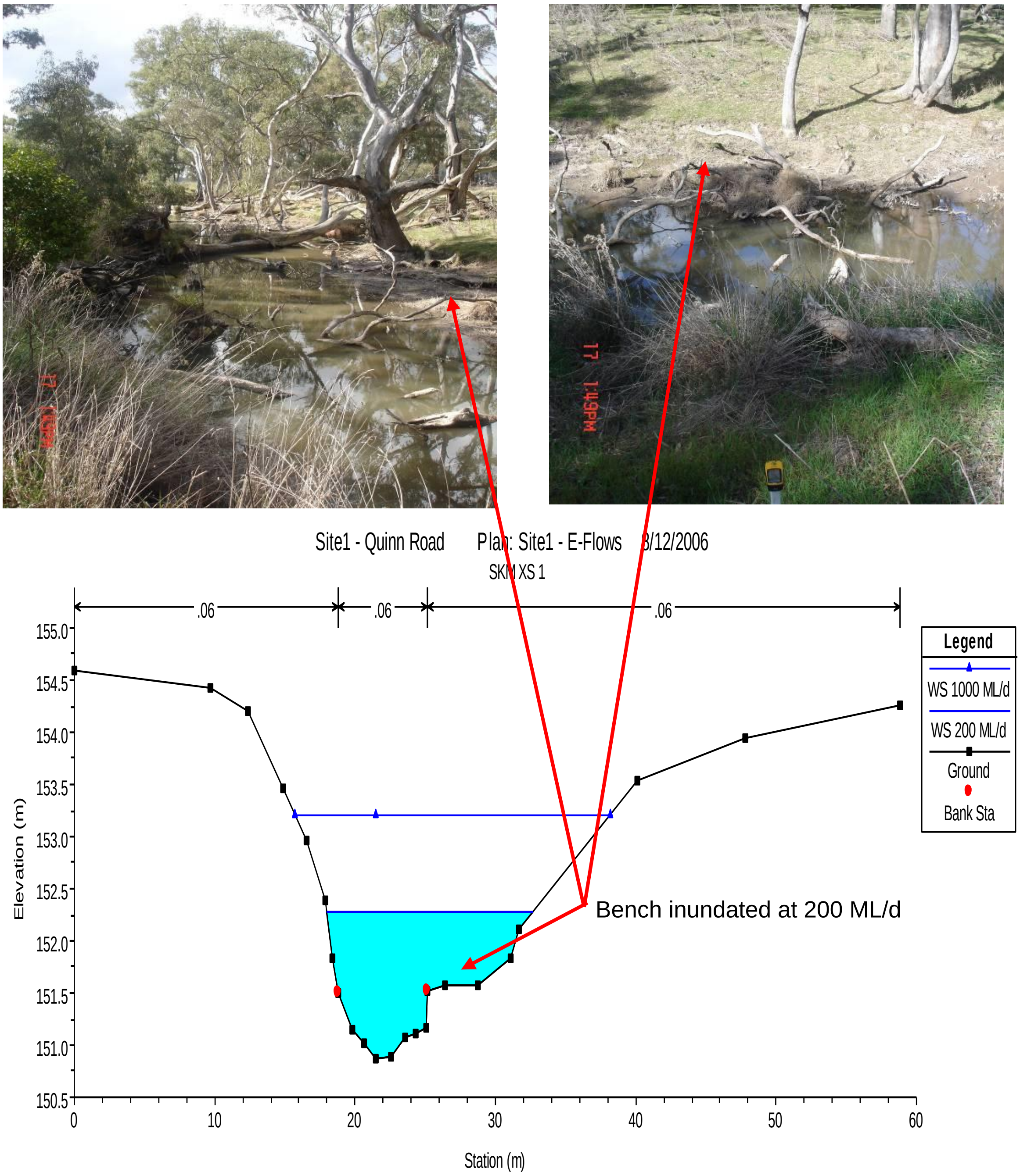
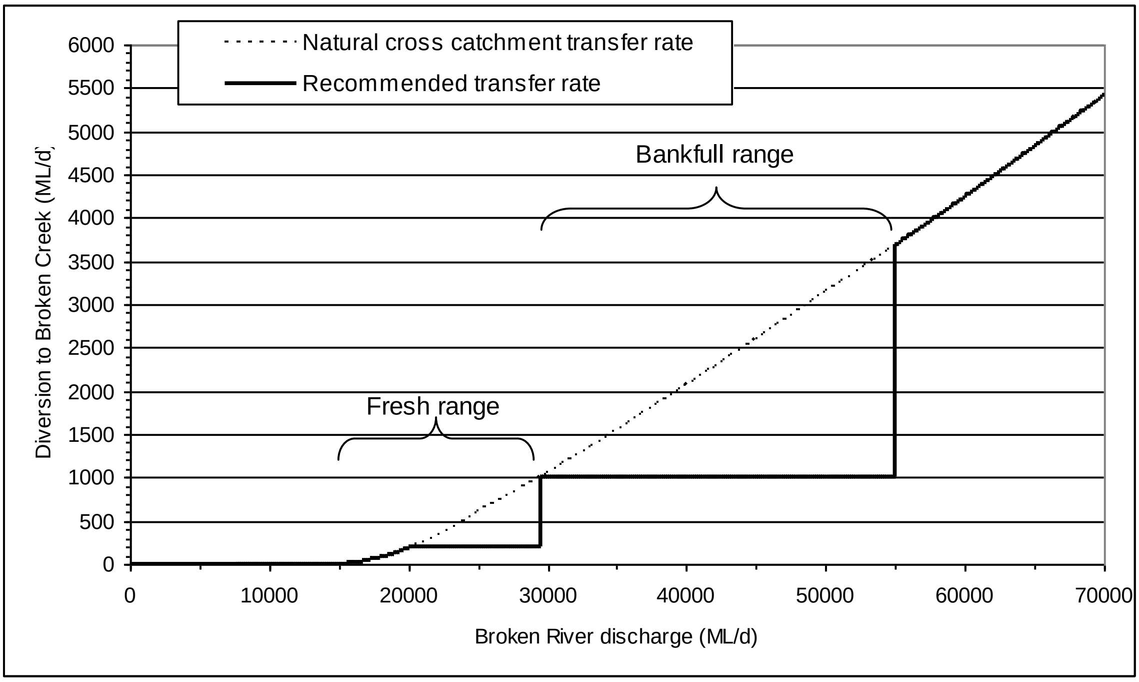
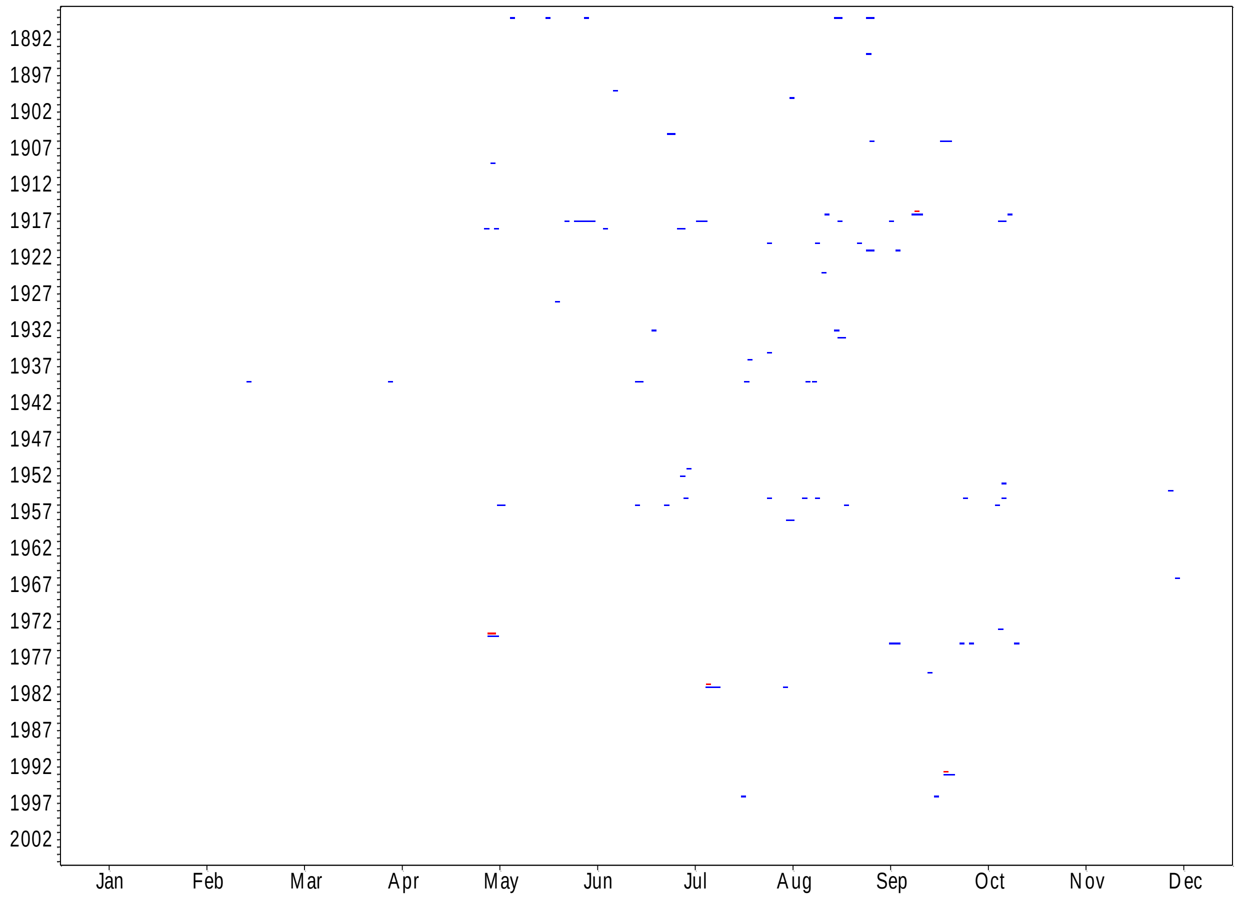


▪ **Figure 4.4 Stage height at Site 1 XS 1 showing bench inundated at 200 ML/d.**

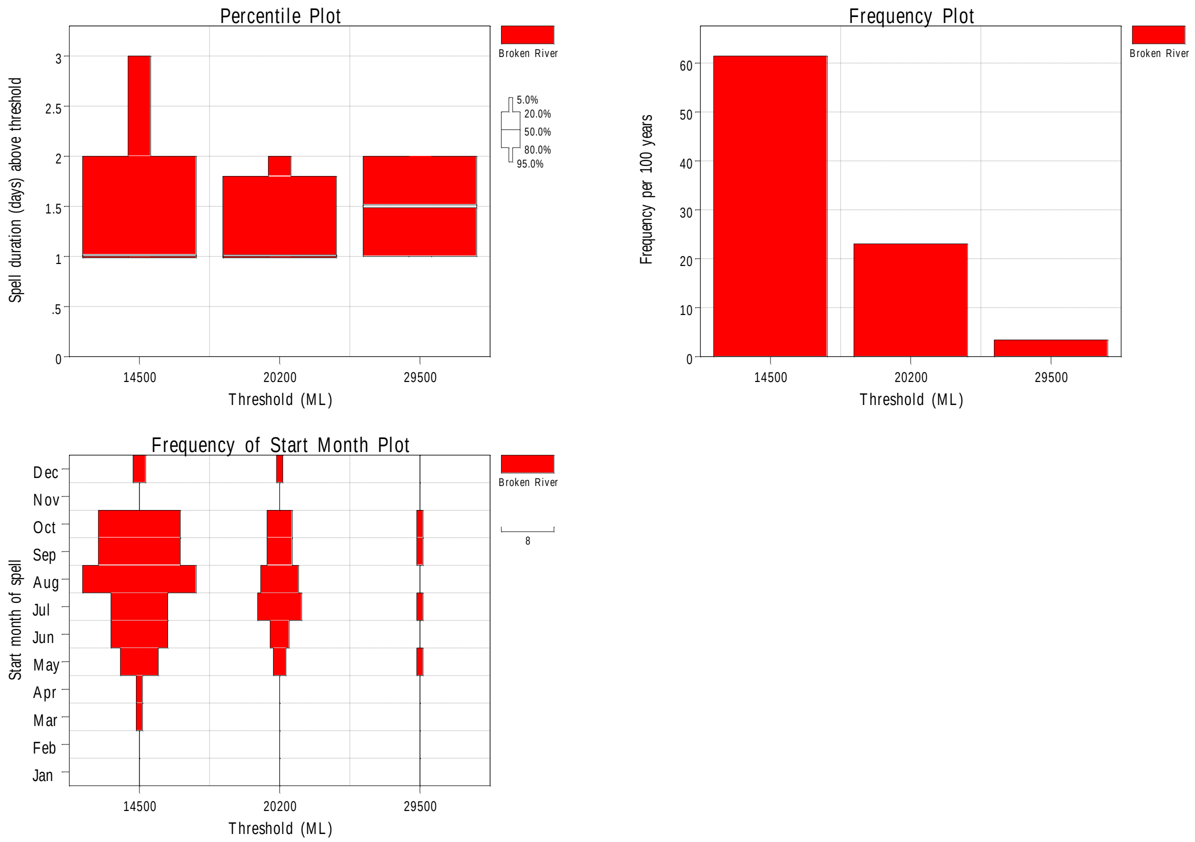


- **Figure 4.5 Rate of flow transfer to Broken Creek to meet fresh and bankfull flow recommendations for a given flow in Broken River**

The pattern of historical flows in the Broken River above 14,500 ML/d (the fresh trigger) and 29,500 ML/d (the bankfull trigger) is shown in Figure 4.6. Flow in Broken River above the fresh trigger of 14,500 ML/d is expected to occur on average once every second year and for a duration of 1-2 days (Figure 4.7). The maximum diversion rate for a fresh of 200 ML/d (equivalent to a flow in Broken River of around 20,200 ML/d) would only be expected to occur once every 4 to 5 years. In other words, transfers from Broken River to Broken Creek could be expected once every two years but the maximum transfer rate of 200 ML/d would only be expected once every four years. Flow in Broken River above the bankfull trigger of 29,500 ML/d is only expected once every twenty years for 1-2 days. Cross-catchment connections are expected to occur most frequently in late winter and early spring. With the potential decommissioning of Lake Mokoan winter and spring flows in Broken River will become less regulated so there may be a slight increase in the frequency of flows in the Broken River above the fresh trigger.



- **Figure 4.6 Flow spells in Broken River above 14,500 ML/d (blue bars) and 29,500 ML/d (red bars).**



- **Figure 4.7 Spell durations (upper left), frequency (events per 100 years) (upper right) and distribution of start months (lower left) for flows above 14,500 ML/d, 20,200 ML/d and 29,500 ML/d thresholds in Broken River.**

When restoration of the cross-catchment connection is coupled with local catchment runoff the frequency, peak volume and duration of fresh events in Reach 1 increases. Under these circumstances a fresh flow of 200 ML/d is expected to occur every second year for around 2-3 days in winter or spring (Figure 4.3). In other words, while the maximum transfer rate of 200 ML/d from Broken River to Broken Creek is expected once every four years the addition of local catchment runoff means that a 200 ML/d event can be expected every second year and for a longer duration than the duration of the cross catchment transfer.

4.2.3 High / bankfull flow

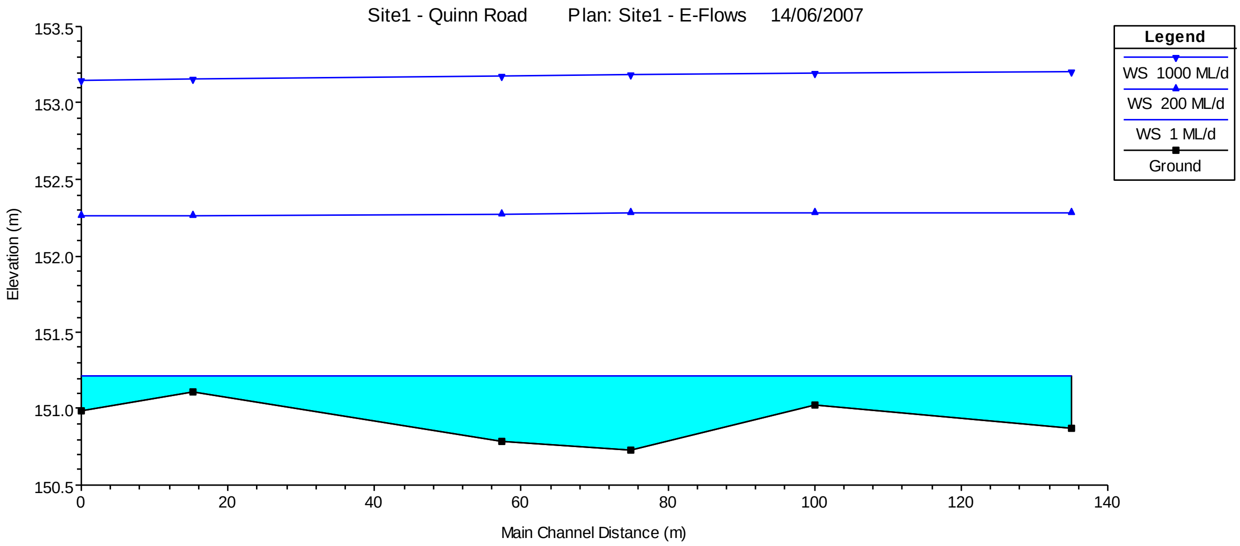
A high / bankfull flow of 1000 ML/d is recommended based on the frequency and duration of flows in the Broken River in excess of ~29,500 ML/d (Figure 4.5). Flows of this magnitude are relatively infrequent and only expected to occur once every 10-20 years for 1-2 days (Figure 4.7). However, they are important to assist with channel forming and sediment redistribution processes and to facilitate recruitment of flood tolerant floodplain and riparian vegetation. Fencing, stock removal and active revegetation is also required to assist recovery of riparian vegetation.

A bankfull flow of 1000 ML/d for Reach 1 will fill the entire channel (e.g. Figure 4.4). To allow flows of this magnitude to enter Broken Creek, infrastructure works may be required to reinstate the capacity of the natural cross-catchment connection channels.

Flows in Broken River in excess of ~55,000 ML/d are sufficient to overtop the Midland Highway and hence at this point it is not possible to control the rate of transfer to Broken Creek. While not specifically modelled in this study, 55,000 ML/d represents the 1974 flood peak, which was known to overtop the Midland Highway.

4.2.4 Long section

The water surface level for each flow threshold along a long section of Reach 1 is shown in Figure 4.8. A flow of 1 ML/d is sufficient to link shallow pools through the reach (e.g. at chainage 300 and 400) while flows of 200 and 1000 ML/d are sufficient to inundate benches and fill the channel respectively.



- **Figure 4.8 3D Long section showing water surface level for 1, 200 and 1000 ML/d flows at Site 1 (flow is from right to left).**

4.2.5 Losses and attenuation of flows to downstream reaches

As part of the current study losses, time lags and flow attenuation down the upper Broken Creek was examined in detail in SKM (2006a) and are summarised below.

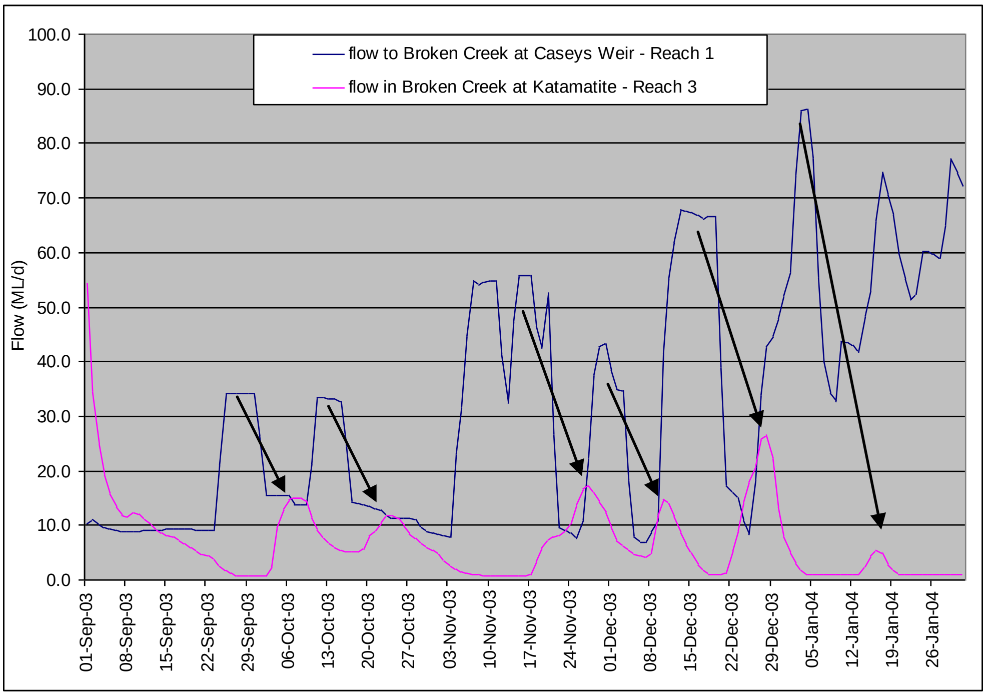
Losses

Losses occur as a result of extractions by consumptive users (operational) and by seepage, evaporation and retention along the channel (transmission losses). A previous study has examined losses in the upper Broken Creek (Casey's Weir to Waggarandall Weir) (SKM 2004) and further work on quantifying losses was undertaken as part of the current study and reported in detail in SKM (2006a). In summary, average annual losses between Casey's Weir and Waggarandall Weir were estimated at around 6310 ML/y, which is equivalent to around 37% of the water diverted to Broken Creek at Casey's Weir. Of this loss about 13% or 790 ML/y is from evaporation and seepage, the remainder being a combination of extractions to meet consumptive demand and retention along the channel. Unfortunately there is insufficient information available to specifically identify either operational losses or channel retention. In addition, these losses vary at different times of the year, for example, operation losses are likely to be greater during the irrigation season and when transfers are being made for stock and domestic supply, while channel retention losses are likely to be greatest when flows are low and the channel is predominantly dry (i.e. water is retained in pools as they fill). Further, the calculated losses described here only apply to the section of Broken Creek from Casey's Weir to Waggarandall Weir (equivalent to Reach 1). Cumulative losses as a portion of flow diverted at Casey's Weir increase with distance downstream and the greater the distance over which losses occur the greater the uncertainty in the loss estimates.

Once the Tungamah Pipeline Scheme is commissioned, any transmission or operational losses resulting from the transfer of stock and domestic water along Broken Creek will cease. Therefore, the volume of water lost to evaporation and seepage should return to more natural extents. However, if irrigators between Casey's Weir and Waggarandall Weir continue to be supplied from Broken Creek, and permanent flow in the Creek persists, transmission losses and operational losses resulting from supplying irrigators will also persist.

Lag time and attenuation

Significant lag times and attenuation of flow peaks occur between Casey's Weir and Katamatite (SKM 2006a). The travel time between Casey's Weir and Waggarandall Weir is approximately 4 days with a further 3 – 4 day travel time between Waggarandall Weir and Katamatite. In addition, the peak of releases from Casey's Weir experience substantial attenuation before passing Katamatite as a result of losses and extension of the time over which the flow event lasts. Therefore, if environmental flows are released down Broken Creek from the diversion at Casey's Weir, it will take approximately 8 days for those flows to reach Katamatite, and in that time there will be significant attenuation of the peak. This is demonstrated in Figure 4.9 for a series of flow peaks between Casey's Weir and Katamatite, which shows a 1-2 week lag time between peak flows at Casey's weir and peak flows at Katamatite and around a 50% reduction in the volume of the peak flow.



- **Figure 4.9 An example of the time-lag and attenuation between Casey's Weir (blue) and Katamatite (pink). Arrows track the individual flow peaks between the two locations.**

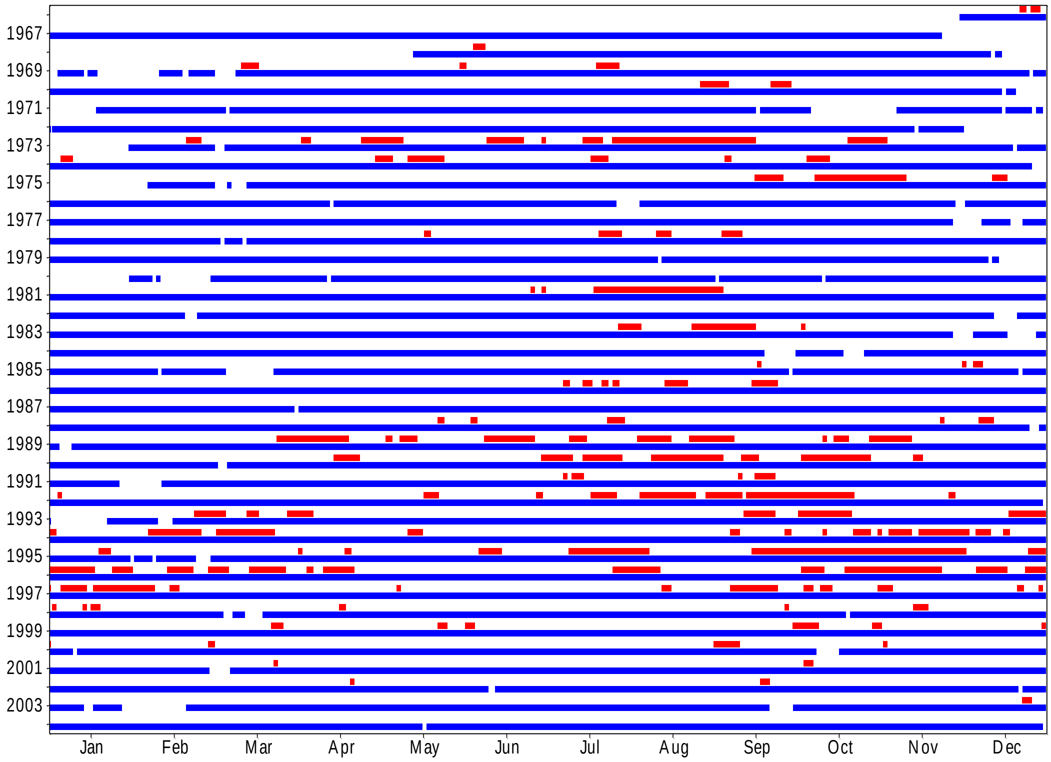
Routing water to lower Broken Creek and the Murray River via Casey's Weir

The current study only determined flow recommendations for the upper Broken Creek. Detailed flow recommendations for the lower Broken Creek are yet to be determined, although emergency flow requirements are in place to manage poor water quality, flush accumulated *Azolla* from weir pools and manipulate fishway operation, particularly in summer. While not specifically examined in this study, it has been suggested that water could be delivered to the lower Broken Creek via diversions at Casey's Weir to meet these emergency flow requirements. It is likely that when water is needed to manage poor water quality or flush *Azolla* it would be required to be delivered immediately. The above discussion on losses and attenuation provides insights into the ability to deliver flows to the lower Broken Creek.

Based on what information is available, and as describe above, it would appear that lag times for delivering water to the lower Broken Creek via the upper reaches is considerable and likely to be in the order of 1-3 weeks. In addition, there is significant attenuation of the flow peak as it moves downstream. The further downstream the flow needs to be delivered and /or the drier the channel lag times, peak flow attenuation and losses increase meaning the need to divert relatively large volumes of water over an extended period of time in order to deliver the required volume downstream. Furthermore, channel capacity in the Broken Creek upstream of Katamatite is relatively small (see Section 4.4) so it may not be possible to deliver the require volumes to the lower Broken Creek without the risk of flooding in the upper reaches. Further investigations are needed to better understand the above issues resolve uncertainty regarding the ability to route water to the lower Broken Creek.

4.3 Reach 2: Waggarandall Weir to Reilly's Weir - Geary Road

Under current conditions flow in Reach 2 is near perennial with flows above 1 ML/d occurring almost continuously and flows above 30 ML/d occurring in most years (Figure 4.10). Although compared to Reach 1, higher flows occur for shorter duration and predominantly in winter and spring because most flows diverted to Broken Creek at Casey's Weir have been extracted by Reach 2, so higher flows represent a more natural seasonality in this reach. For Reach 2 it is recommended to restore a natural, seasonally intermittent flow regime to the Broken Creek based on progression of upstream flows and with additional local catchment runoff (Table 4.6). For the purposes of assessing duration and frequency of various flow components the volumes for each component have been adjusted from those recommended for Reach 1 based on attenuation of flows from upstream.



- **Figure 4.10 Flow spells above 1 ML/d (blue bars) and 30 ML/d (red bars) in Reach 2 under current conditions showing near continuous flow.**

Table 4.6 Summary of flow recommendations for Reach 2: Broken Creek Waggarandall Weir to Reilly's Weir - Geary Road

Stream		Broken Creek		**Reach**	Waggarandall Weir to Reilly's Weir
Compliance point		Geary Road		**Gauge No.**	NA
Season	**Component**	**Volume**	**Frequency**	**Duration**	**Objective**
Summer	Cease-to-flow	yes	natural	natural	M2-1, F2-1, V2-1
	Low flow	No specific recommendation but allowed to occur as part of local catchment runoff			M2-1, F2-1, V2-1
	Fresh	70-110 ML/d - based on propagation of fresh flows from Reach 1 and the addition of catchment runoff			M2-2, M2-3, F2-2, V2-2, W2-1
Winter	Cease-to-flow	yes	Natural	natural	M2-1, F2-1
	Low flow	No specific recommendation but allowed to occur as part of local catchment runoff			M2-1, F2-1, V2-1
	Fresh	70-110ML/d - based on propagation of fresh flows from Reach 1 and the addition of catchment runoff			M2-3, W2-2
	High flow / Bankfull	150 - 350 ML/d	Based on natural frequency and duration of bankfull flow in Broken River. May require infrastructure works to allow volume to be delivered to Broken Creek. Event must be allows to progress down whole system.		G2-1, M2-3, M2-4, W2-2, F2-3, V2-3
	Overbank	No recommendation but allowed to occur in response to inflows from upstream and local catchment rainfall			

4.3.1 Cease-to-flow and low flow

As with Reach 1 cease-to-flows are required to reinstate the natural ephemeral flow regime, dry out water couch and reduce river red gum regeneration along channel margins. No specific low flow volume, duration or frequency has been recommended. However, low flows should be allowed to occur as part of local catchment runoff at any time during the year and as part of the delivery of fresh flows in winter. Low flows will connect pools that may have become isolated during cease-to-flows, freshen water quality and allow for localised movement of fish.

Under the recommended natural flow regime cease-to-flows can occur throughout the year, although mostly in summer (Figure 4.11), for a median duration of 14 days but with 20% of events lasting longer than 68 days. The median duration of flows greater than 1 ML/d is about double that of Reach 1 at 7 days with 80% of events lasting 20 days or less (Figure 4.12). As with Reach 1 low flow events occur relatively frequently, with an average 7 flow events above 1 ML/d occurring each year, relatively evenly distributed across the year (Figure 4.12).

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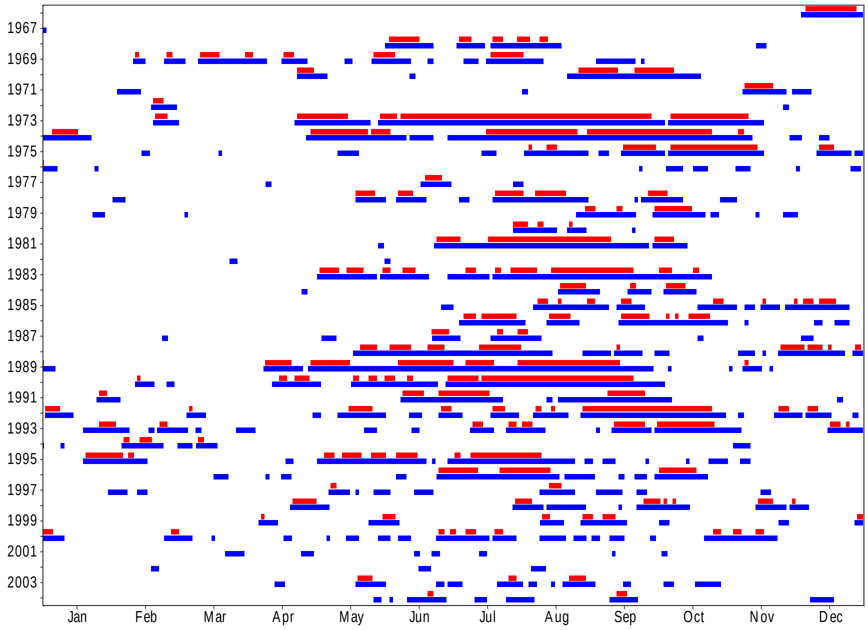
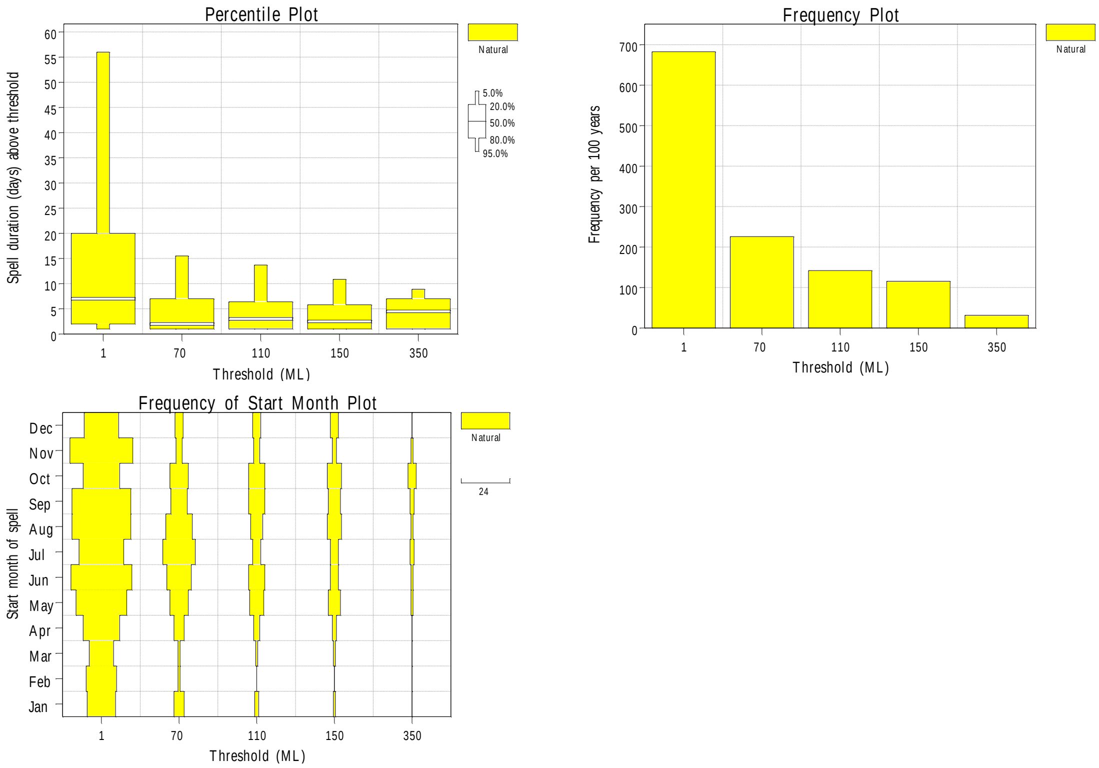


- **Figure 4.11 Flow spells above 1 ML/d (blue bars) and 10 ML/d (red bars) in Reach 2 under recommended natural conditions.**



- **Figure 4.12 Spell durations (upper left), frequency (events per 100 years) (upper right) and distribution of start months (lower left) for low flows above 1 ML/d, freshes (70-100 ML/d) and high flows (150-350 ML/d) under recommended natural conditions.**

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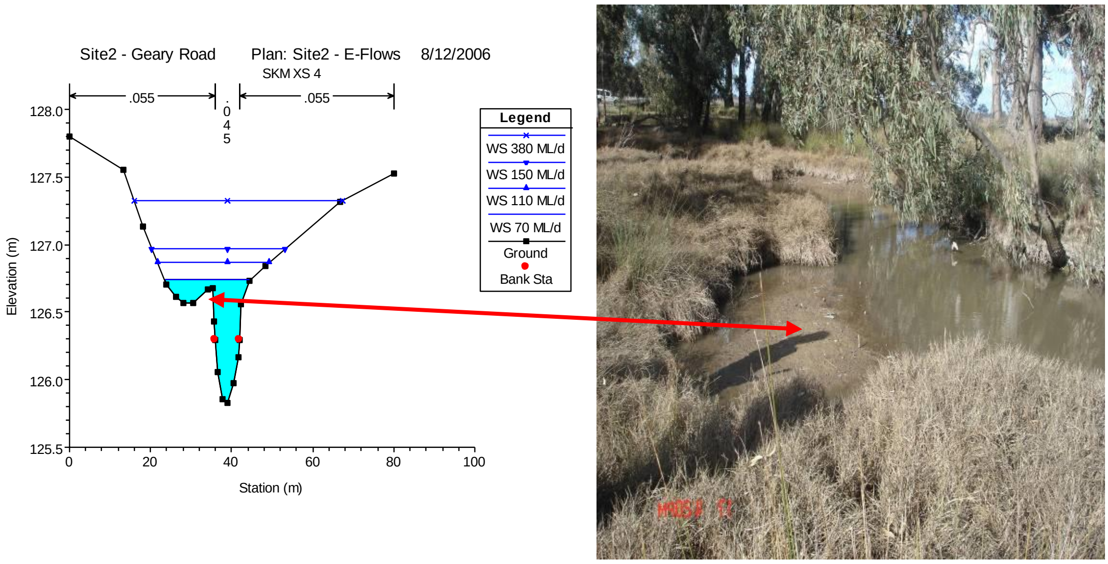
4.3.2 Freshes

Reach 1 freshes should be allowed to pass down the system. Attenuation will occur through downstream reaches so peak discharge in Reach 2 is less than 200ML/d depending on duration of the event. Based on the median duration of freshes in Reach 1 and attenuation, freshes in Reach 2 are estimated to range between 70 and 110 ML/d. A fresh of 70 ML/d is sufficient to inundate benches (e.g. Figure 4.13).



- **Figure 4.13 Reach 2 XS4 showing bench that would be inundated at fresh flows above 70 ML/d.**

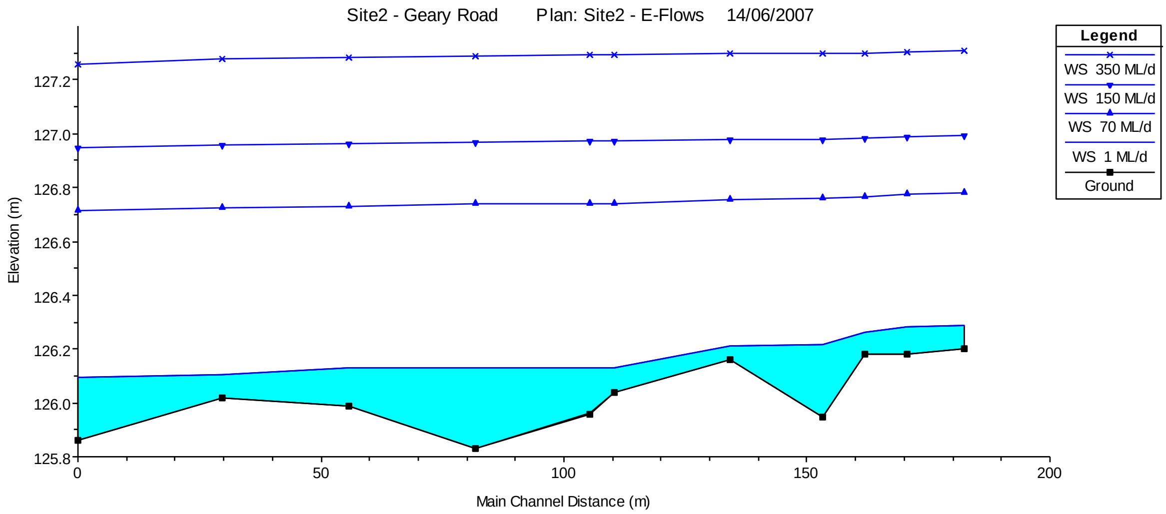
Freshes of 70-110 ML/d have a median duration of 2-3 days with 80% of events lasting less than 6 days (Figure 4.12). With increased catchment area associated with Reach 2, freshes occur up to twice per year compared to once every 2 years in Reach 1, mostly in winter and spring (Figure 4.12).

4.3.3 High flow / bankfull

Reach 1 high and bankfull flows should be allowed to progress downstream. Attenuation results in high flows being equivalent to around 150 ML/d and bankfull flows around 350 ML/d. Under the recommended natural regime high flows greater than 150 ML/d are predicted to occur for around 3 days once per year while flows greater than 350 ML/d are predicted to occur for around 5 days once every 4 to 5 years (Figure 4.12).

4.3.4 Long section

The water surface level for each flow threshold along a long section of Reach 2 is shown in Figure 4.14. A flow of 1 ML/d is sufficient to link shallow pools through the reach.



- **Figure 4.14 Long section showing water surface level for flows in Reach 2 (flow is from right to left).**

4.3.5 Flows to Moodies Swamp

Moodies Swamp is located on the Broken Creek floodplain in Reach 2. The wetland is considered to be of national significance because of its size and the presence of a number of flora and fauna species threatened at the state and national levels (DEH 2007). It receives water from the Broken Creek via the Geary and Moodie Channels and from local catchment runoff, but as a result of water resource development within the region, the natural hydrology of the wetland has altered over time.

Management plans for the wetland (SKM 2006d, DCE undated) recommended it be managed to:

- Maintain the wetland as a southern cane grass *Eragrostis infecunda* dominated freshwater marsh, and
- Provide breeding habitat for brolga *Grus rubicunda* and other significant wildlife.

The water regimes required to support cane grass and brolga breeding are relatively similar (Table 4.7) and require near annual inundation of two to six months in the winter/spring period to a depth <50 cm with an ideal range of 20-30 cm (SKM 2007). Artificial inundation in summer and early autumn should be avoided; however, if natural flood events occur during the summer/autumn period then the swamp should be allowed to fill.

Table 4.7 Comparison of water regime scenarios for Moodies Swamp (SKM 2007).

Management Objective	Timing of inflow	Frequency and duration
Cane Grass	Winter - spring	Frequency: near annual Duration: 180 day (range 90-270 day) Depth: <50 cm (range 20-50 cm)
Brolga	Autumn - spring	Frequency: not critical but near annual desirable for regional conservation objectives) Duration: 30-60 days at 20-30 cm deep plus a further 60-90 days 'wet' as swamp draws down

A hydraulic model linking flows in Broken Creek to Moodies Swamp has been used to determine the flows required in Broken Creek to inundate the swamp (SKM 2006d, 2007). Based on this modelling a range of works were identified on Broken Creek and the Geary Channel to enable the establishment of the recommended flooding regime. Specifically, it was recommended that a small weir (~70 cm high) be constructed in Broken Creek downstream of Geary Channel. The weir has the effect of raising the running level of Broken Creek to compensate for the previous lowering of the bed level in the vicinity of the Geary Channel offtake. Water can then be delivered to the swamp via a regulator on the Geary Channel. In addition to the weir, levee works are needed along sections of Geary Channel to increase channel capacity. Other works required are the installation of a 1.2 m wide regulator at the start of Geary Channel to replace the existing 40 cm wide regulator and for the first 400 m of the Geary Channel to be lowered to 128.4 mAHD; the same invert level as the regulator. The regulator is required at the inlet to the Geary Channel to prevent unseasonal high flows entering the swamp associated with rain rejection flows downstream of Waggarandall Weir that may occur during the irrigation season.

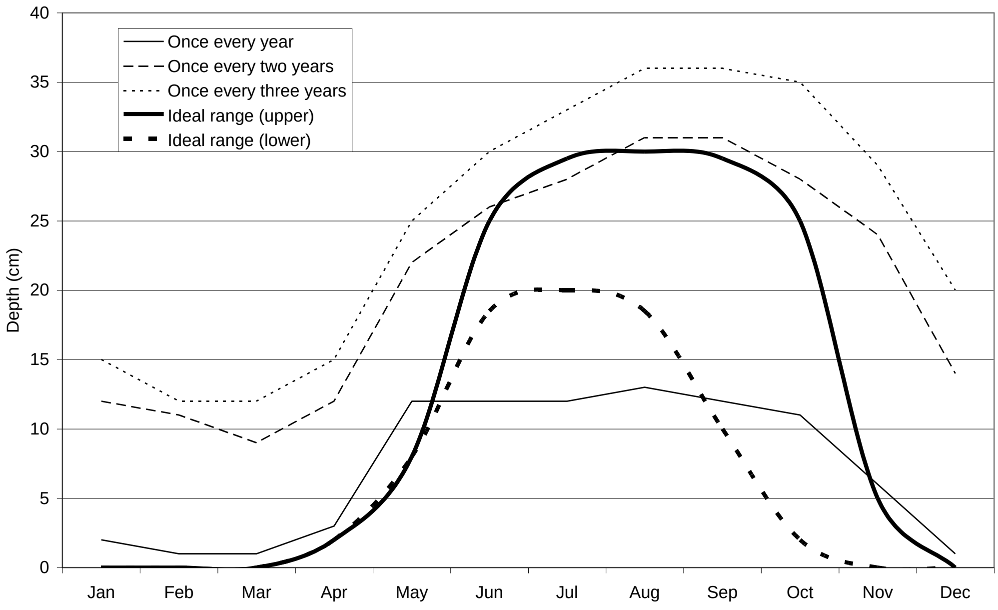
Under the proposed modifications, water should be allowed to enter the swamp to coincide with natural high flows in the Broken Creek and with runoff in the local Moodies Swamp catchment. Raising the running level of the creek through construction of the weir should enable a portion of naturally occurring high flow events to be delivered to the swamp via Geary Channel and limits the need to secure a specific environmental water allocation.

Preliminary modelling showed that with the weir in place and the existing operating rules for the Geary Channel regulator applied (i.e. regulator opened from May to November and closed at other times) all flow in Broken Creek from May to November up to 10 ML/d was directed into Moodies Swamp. Under these circumstances low flows in Broken Creek downstream of Moodies Swamp were reduced, or even eliminated. In order to protect low flows in Broken Creek operating rules for the Geary Channel were revised. The revised rules now require flows in Broken Creek during May to November to be higher than 10 ML/d before a portion of the creek flow can be directed to Moodies Swamp. During summer (December to April), flow in Broken Creek needs to be in excess of 50 ML/d before flow can enter Moodies Swamp. This new set of rules protects low flows in Broken Creek downstream of Moodies

Swamp and also prevents rain rejection flows downstream of Waggarandall Weir from entering the swamp during summer but still allows natural high flow events to enter the swamp.

Modelling has shown that under both the current and the recommended environmental flow regime (based on natural at Site 2) for Broken Creek, and with the recommended weir and revised operating rules in place, an annual to near annual inundation event occurs in the wetland. The inundation event can occur in any month of the year but most events commence in late autumn or winter in response to increased winter flows in Broken Creek. Under the current water regime there is a slightly higher frequency of events in the wetland at all depths compared with the recommended environmental flow regime.

Under current conditions the ideal inundation regime to support cane grass and brolga breeding occurs once every one to two years (Figure 4.15). Under the recommended environmental flow regime the ideal inundation regime for the swamp occurs once every two to three years conditions (Figure 4.16). Without the weir in place the ideal inundation regime will occur less than once every three years under both the current and environmental flow recommendation scenarios.



▪ **Figure 4.15 Plot showing typical depth and duration for the 1 in 1, 1 in 2 and 1 in 3 year event under the current flow scenario with the weir in place. The thick black lines show the upper and lower limits for the ideal inundation event that would provide suitable conditions for brolga breeding and cane grass subsistence.**

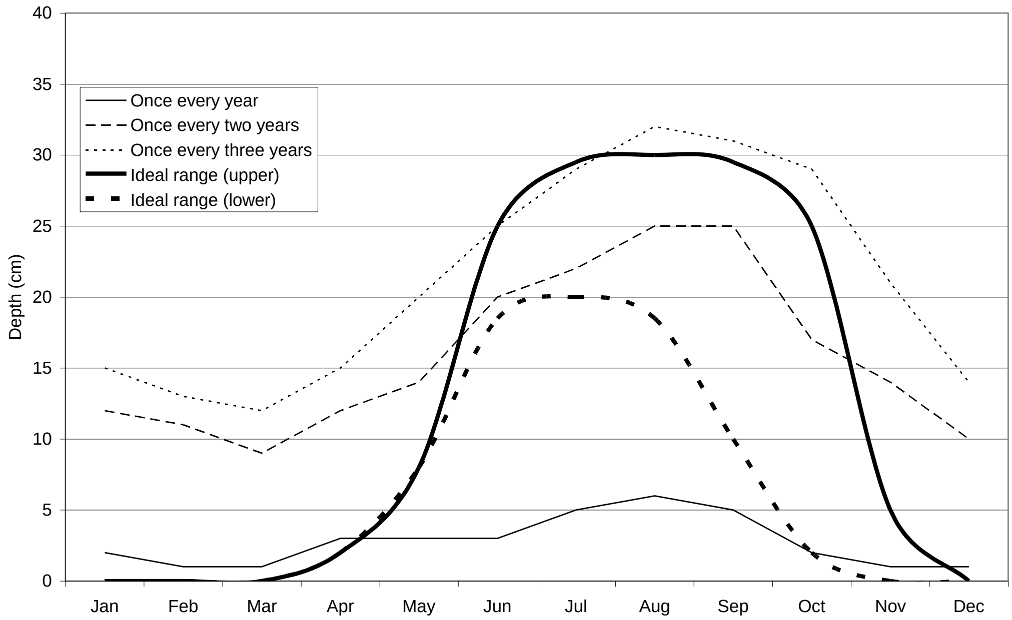


Figure 4.16 Plot showing typical depth and duration for the 1 in 1, 1 in 2 and 1 in 3 year event under the environmental flow recommendation scenario with the weir in place. The thick black lines show the upper and lower limits for the ideal inundation event that would provide suitable conditions for brolga breeding and cane grass subsistence.

Cane grass is relatively robust and drought tolerant once established and adaptable to a varied regime, and given that it is already persistent in Moodies Swamp under the historical regime, it is likely to persist under the recommended Broken Creek flow regime. With respect to brolga, suitable inundation events that fulfil breeding requirements will occur under the recommended regime, although not necessarily every year.

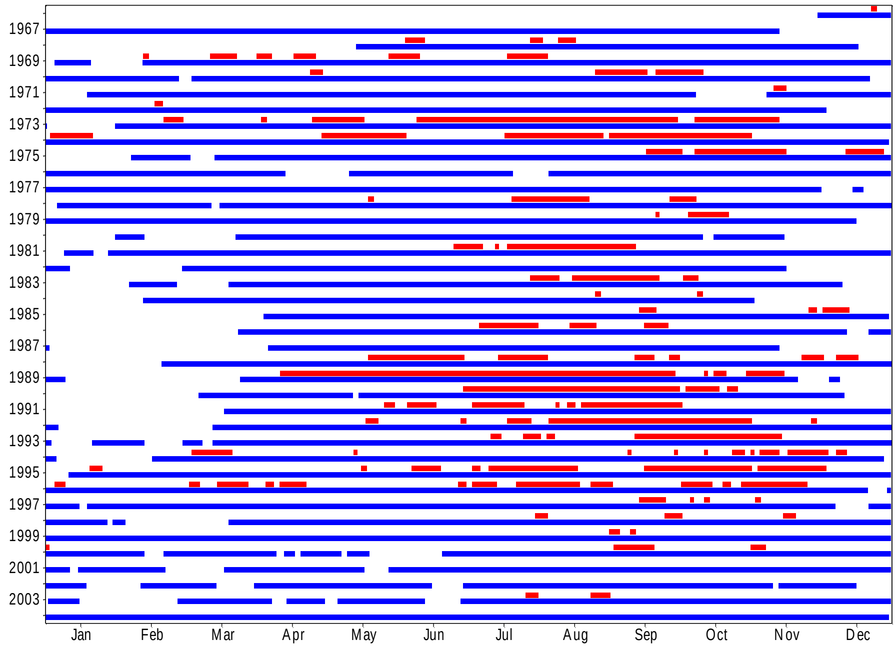
Under current conditions, inundation events, while modelled to occur every year, often did not because of ineffective application of existing operational rules for the Geary regulator, the impacts associated with previous dredging of the Broken Creek or interference in channel flows by landholders. So, the future regime, assuming it is successfully implemented (including construction of the weir in Broken Creek, modifications to Geary channel and delivery of the environmental flow recommendations to Broken Creek), provides a much more regular frequency of inundation compared to the historical regime.

In order to optimise the water regime and provide occasionally more frequent longer duration inundation events it may be necessary from time to time to artificially manipulate the water level in the wetland by making additional diversions to the swamp to 'top up' an existing event and prolong it's duration. For example to artificially extend the duration of an inundation event in order to ensure the success of a particular brolga breeding event or to provide optimal growth conditions for cane grass, for example following a sequence of dry years. Water would need to be supplied from the Broken River via diversion to Broken Creek at Casey's Weir and then into the wetland via the Geary regulator.

Volume shortfall calculations (SKM 2007) show that the maximum amount of water required to extend the duration of an inundation event is 200 ML per year, which equates to <15 ML/d and would be required very infrequently. Because the volumes of water required are very small they would best be sourced from unregulated flows in the Broken River. Diverting a small volume of unregulated Broken River flows to Broken Creek and then into Moodies Swamp would not impact on the reliability of supply to irrigators in the Broken system (because it is sourced from unregulated river flows) and would not measurably impact on downstream river health conditions in the Broken, Goulburn or Murray Rivers. However, such a volume could have a significant benefit for Moodies Swamp and would not detrimentally impact on the Broken Creek.

4.4 Reach 3: Reilly's Weir to Katamatite - Mills Road

Under current conditions flow in Reach 3 ceases for moderate periods of time in most summers (median duration cease-to-flow is 7 days) but is above 1 ML/d and often above 30 ML/d for most winter and spring periods (Figure 4.17). For Reach 3 it is recommended to retain the natural, seasonally intermittent flow regime based on progression of upstream flows and with additional local catchment runoff. For the purposes of the assessing duration and frequency of various flow components the volumes for each component have been adjusted from those recommended for upstream reaches based on attenuation of flows from upstream (Table 4.8).



- **Figure 4.17 Flow spells above 1 ML/d (blue bars) and 30 ML/d (red bars) in Reach 2 under current conditions showing near continuous flow.**

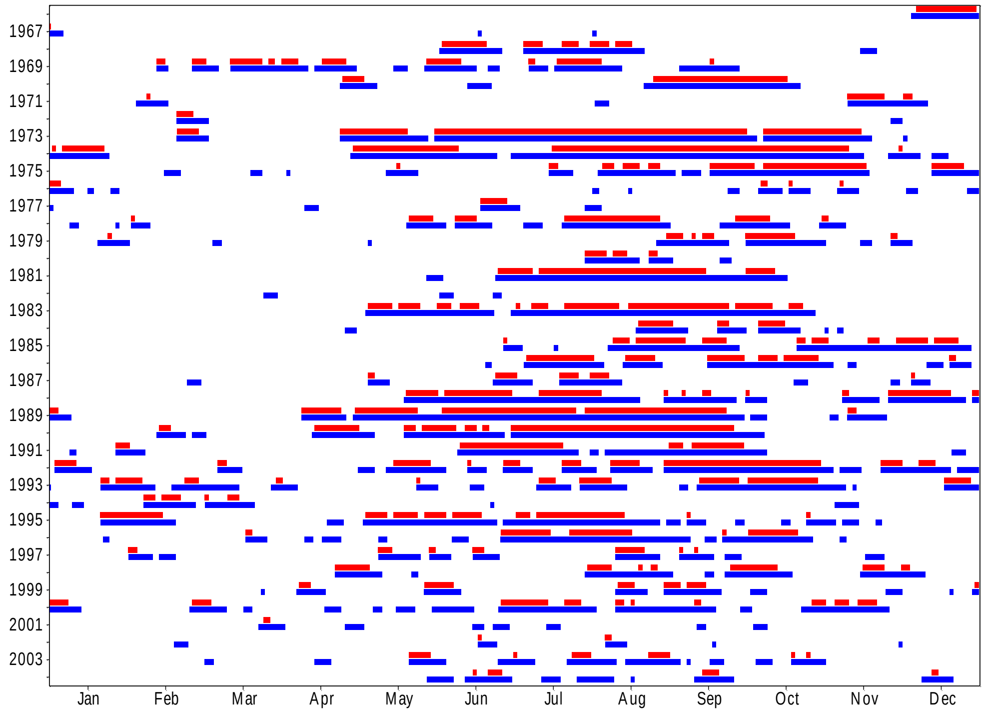
- **Table 4.8 Summary of flow recommendations for Reach 3: Broken Creek Creek Reilly's Weir to Katamatite - Mills Road**

Stream		Broken Creek		Reach	Reilly's Weir to Katamatite
Compliance point		Katamatite		Gauge No.	404214
Season	Component	Volume	Frequency	Duration	Objective
Summer	Cease-to-flow	yes	natural	natural	M3-1, F3-1, V3-1
	Low flow	No specific recommendation but allow to occur as part of local catchment runoff			M3-1, F3-1, V3-1, W3-1
	Fresh	30-70ML/d - based on propagation of fresh flows from upstream and the addition of catchment runoff			M3-2, F3-2, V3-2, W3-1
Winter	Cease-to-flow	yes	natural	natural	M3-1, F3-1, V3-1
	Low flow	No specific recommendation but allow to occur as part of local catchment runoff and delivery of freshes from upstream			M3-1, F3-1, V3-1, W3-1
	Fresh	30-70ML/d - based on propagation of fresh flows from upstream and the addition of catchment runoff			M3-2, , F3-2, V3-2, W3-1
	High flow / Bankfull	95-255ML/d - based on propagation of high flows from upstream and the addition of catchment runoff			G3-1, M3-4, M3-3, W3-2, F3-3,
	Overbank	No recommendation			

4.4.1 Cease-to-flow and low flow

As with upstream, cease-to-flows are required to reinstate the natural ephemeral flow regime. No specific low flow volume, duration or frequency has been recommended. However, low flows should be allowed to occur as part of local catchment runoff at any time during the year and as part of the delivery of fresh flows in winter.

Under the recommended flow regime cease-to-flows can occur throughout the year, although mostly in summer (Figure 4.18), for a median duration of 12 days but with 20% of events lasting longer than about 60 days. The low flow pattern is similar to upstream, although the median duration of flows greater than 1 ML/d is slightly longer, at 9 days with 80% of events lasting 25 days or less, indicating that attenuation and runoff from increased catchment area results in extending the duration of low flows.

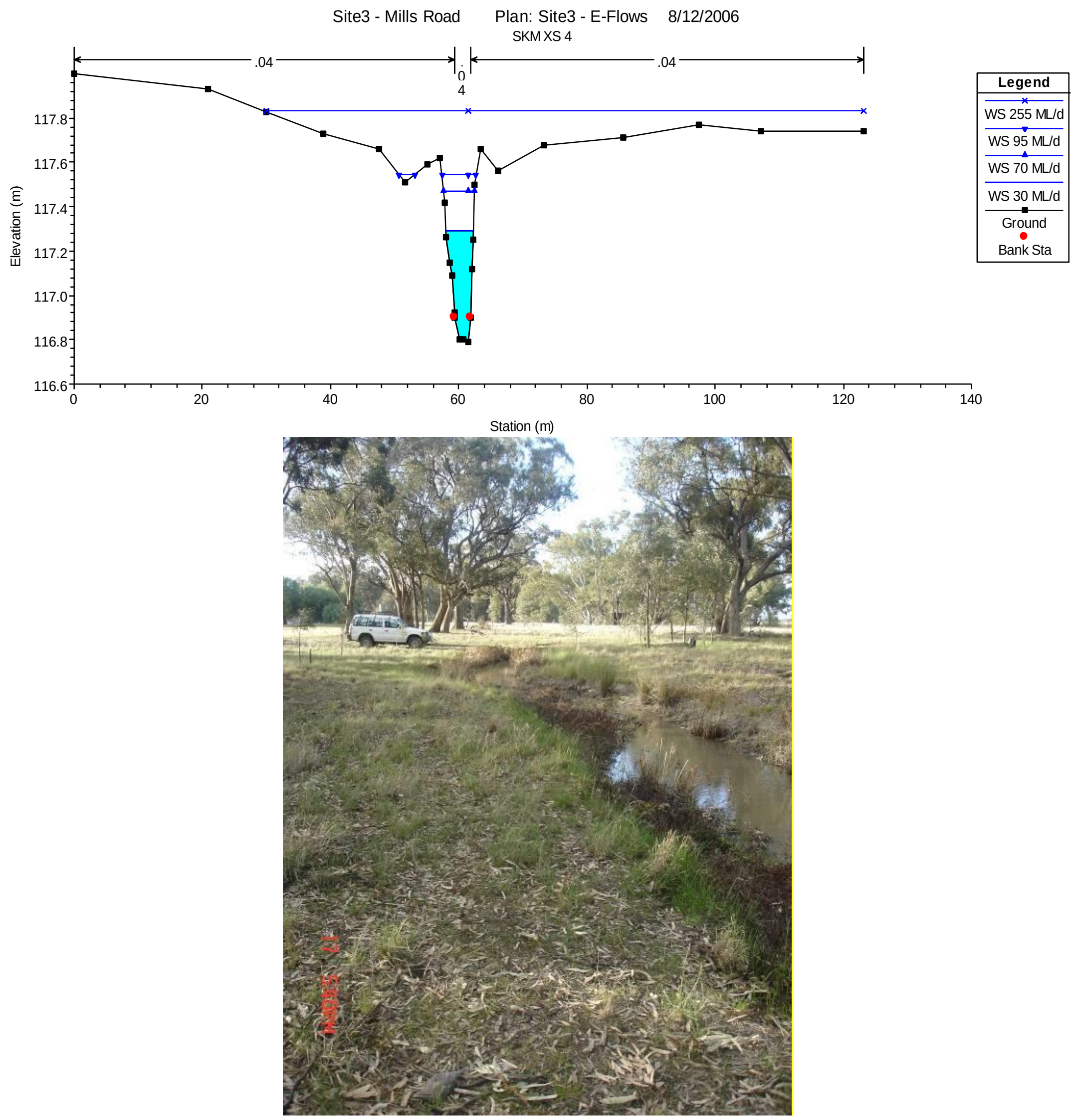


▪ **Figure 4.18 Flow spells above 1 ML/d (blue bars) and 10 ML/d (red bars) in Reach 3 under recommended natural conditions.**

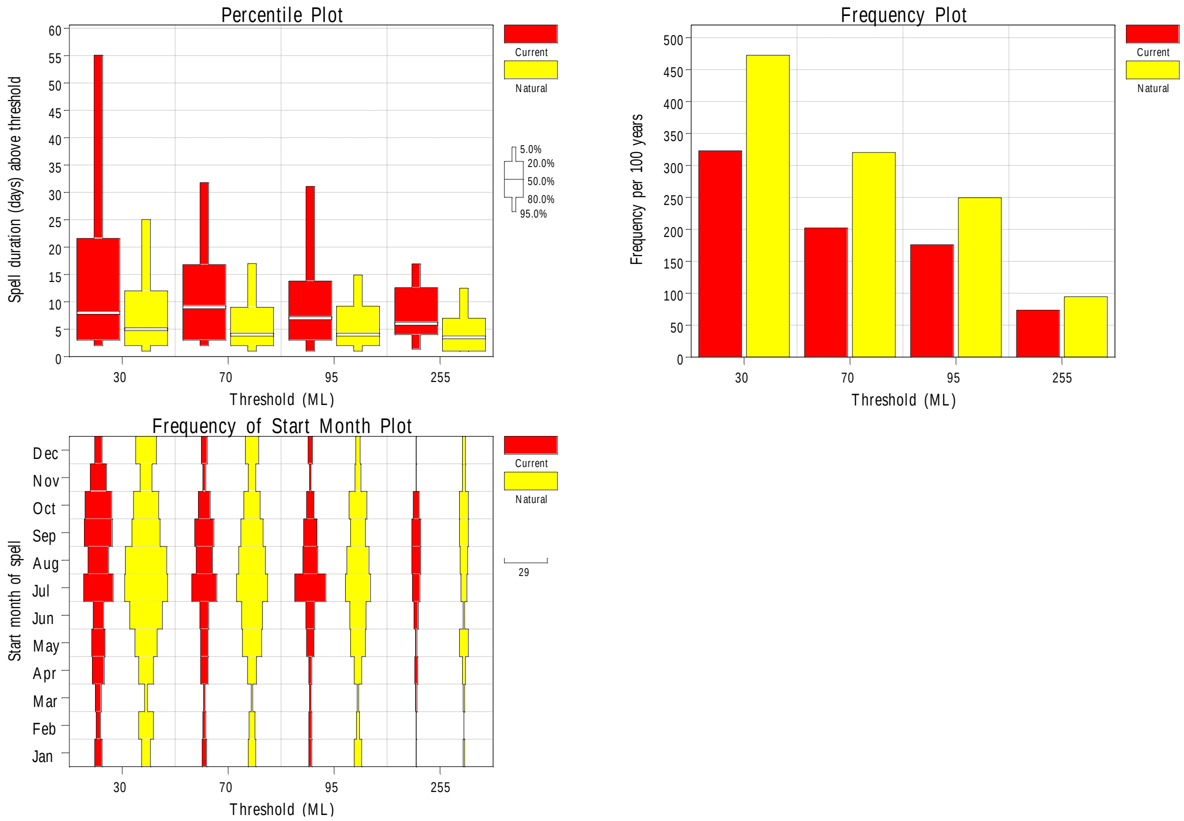
4.4.2 Freshes and high flows

Freshes and high flows should be allowed to pass down the system. Attenuation will occur through downstream reaches so peak discharge in Reach 3 is less than upstream reaches depending on duration of the event. Freshes in Reach 3 are estimated to range between 30 and 70 ML/d and high flows to range between 95 and 255 ML/d. The channel is relatively uniform through Reach 3, perhaps as a result of past dredging, and there are few channel features to inundate during freshes. However higher flows will result in the inundation of channel margins and potentially wide sections of the floodplain (e.g. Figure 4.19).

Although low flows are of longer duration under current conditions in Reach 3 than recommended, there is little difference in the pattern of fresh and high flows between current and recommended. This is because all diversions to Broken Creek have been removed from the system by Reach 3 so the regime is essentially similar to natural. Under recommended flows the median duration for freshes (30-70 ML/d) and high flows (95-255 ML/d) is 5 days or less (Figure 4.20); which is slightly shorter than under current conditions. On average freshes could be expected to occur two to three times per year, mostly in winter or spring, but high flows would be less frequent, although both components would occur more frequently than current (Figure 4.20).



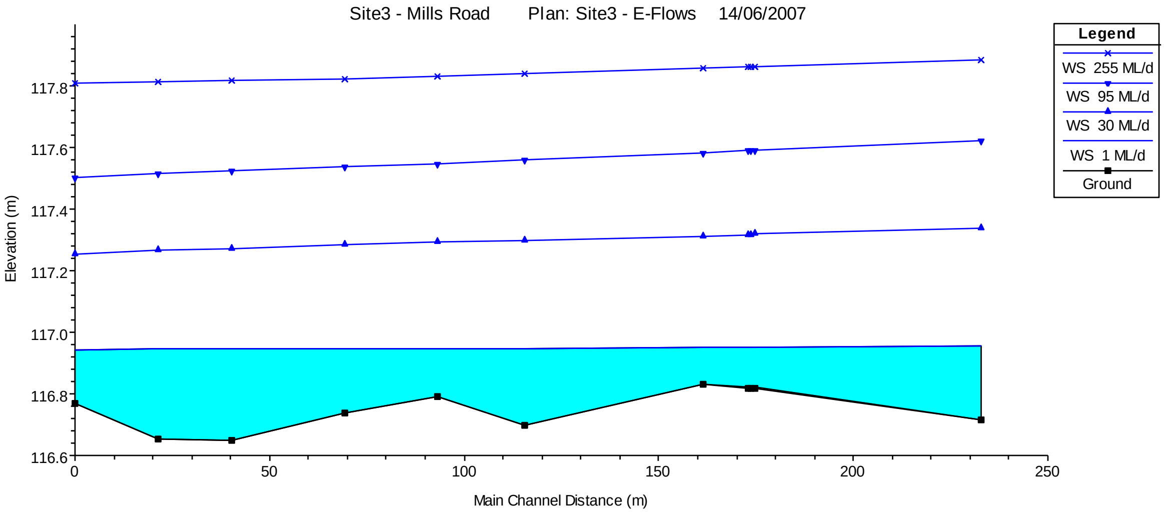
- **Figure 4.19 Reach 3 XS4 showing channel margins inundated during fresh flows and floodplain inundated during high and bankfull flows.**



- **Figure 4.20 Spell durations (upper left), frequency (events per 100 years) (upper right) and distribution of start months (lower left) for freshes (30-70 ML/d) and high flows (95-255 ML/d) under current and recommended natural conditions in Reach 3.**

4.4.3 Long section

The water surface level for each flow threshold along a long section of Reach 3 is shown in Figure 4.21. A flow of 1 ML/d is sufficient to link shallow pools through the reach. The high / bankfull flow volume of 255 ML/d represents a channel depth of about 1 m, but could result in significant shallow flooding of the floodplain (see Figure 4.19 which shows floodplain width inundation greater than 100 m.



▪ **Figure 4.21 Long section showing water surface level for flows in Reach 3 (flow is from right to left).**

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5. Boosey Creek flow recommendations

This section describes the environmental flow recommendations for Boosey Creek. A summary of the current condition is provided along with the ecological objectives for each reach. Following this the flow recommendations for each reach are detailed.

5.1 Summary of current condition and ecological objectives

The current condition of Boosey Creek is detailed in the *Issues Paper* (SKM 2006b) and summarised in Table 5.1.

- **Table 5.1 Current condition: Boosey Creek**

Aspect	Current condition
Hydrology	▪ Flows in the upper reaches (Reach 4) exhibit a natural seasonal intermittency with prolonged cease-to-flow periods during summer and autumn. ▪ Flows in the mid and lower reaches (Reaches 5 and 6) are elevated in spring, summer and autumn for stock and domestic uses via diversion from Broken Creek at Flynn's Weir via Back Creek (Reach 5) and via the Boosey Broken link Channel at Reilly's Weir (Reach 6). ▪ Median Summer flow of ~5ML/day in summer and ~10ML/day in winter. ▪ Hydrology in upper reaches is influenced by farm dams.
Geomorphology	▪ Morphology is varied with sections of steep, incised channel (Reach 4 and Reach 5) and other areas containing broad inset floodplain elements (Reach 6).
Riparian and in-channel vegetation	▪ Riparian vegetation is generally characterised as being discontinuous and fragmented to some degree, although it is of overall better quality than along the Broken Creek.
Wetlands	▪ Wetlands in the area are dominated by freshwater meadows and shallow freshwater marshes.
Fish	▪ Seven native fish species have been recorded in the Boosey Creek study area – southern pygmy perch, mountain galaxias, flathead gudgeon, Australian smelt, gudgeon sp., Murray cod, golden perch. ▪ Five exotic species have been recorded – carp, goldfish, redfin, mosquitofish, oriental weatherloach.
Macroinvertebrates	▪ Based on EPA survey from 1999 and 2005 invertebrate assemblages in most reaches are below reference condition. ▪ Invertebrate assemblage composed of fauna indicative of mild to moderate levels of pollution.
Water Quality	▪ No routinely collected data is available for Boosey Creek.

Ecological objectives for Boosey Creek are aimed at maintaining an aquatic ecosystem with biota and processes indicative of an intermittent stream in Reaches 4 and 5 where the current flow regime retains a large portion of its seasonal intermittency (Table 5.2 and Table 5.3) and of restoring biota and processes indicative of an intermittent stream in Reach 6 where the current flow regime is perennial due to transfers from Broken Creek (Table 5.4). Following pipelining of the Casey's Weir and Major Creek Waterworks

District stock and domestic supply scheme the diversion of water to the Boosey Creek via Back Creek and along the St James – Tungamah Rd will cease and the flow regime in Reach 5 will revert to natural (Reach 4 is already essentially natural). The flow regime in Reach 6 may still be influenced by flows transferred from the Broken Creek via the Broken Boosey Link Channel from Reilly's Weir. The future of this link is unclear at this stage.

▪ Table 5.2 Reach 4 – Boosey Creek at Bungeet Ck Road.

Asset	Objective	No.	Function	Flow component	Timing
Geomorphology	▪ Maintain deep pool habitat ▪ Facilitate sediment transport through reach	G4-1	▪ Entrain and transport fine sediment that has accumulated in pools	Bankfull	Winter
Vegetation	▪ Maintain current riparian and in-channel vegetation by maintaining intermittent flow regime with marked seasonal variability	V4-1	▪ Prevents establishment of in-channel or nuisance terrestrial vegetation	Cease-to-flow	Summer-Autumn
		V4-2	▪ Provides disturbance that prevents persistence of terrestrial and ephemeral plants	Bankfull	Winter
Fish	▪ Maintain a native fish community indicative of an ephemeral system	F4-1	▪ Promote spawning by low flow specialists ▪ Provide conditions that are unfavourable for exotic species	Cease-to-flow / low flow	Summer
		F4-2	▪ Maintain aquatic habitats during periods of cease-to-flow – consistent with patterns from storm events.	Fresh	Summer
		F4-3	▪ Provide opportunities for dispersal	High flow	Winter / Spring
Water quality	▪ Maintain water quality	W4-1	▪ Maintain aquatic habitats during periods of cease-to-flow – consistent with patterns from storm events.	Fresh	Summer
		W4-2	▪ Flush and replenish residual pools	High flow	Winter / Spring
Macroinvertebrates	▪ Maintain an ecologically healthy invertebrate community, characteristic of intermittent streams and including taxa relying on periodic drying to complete their life-cycle.	M4-1	▪ Promote successional change in community composition through disturbance.	Cease-to-flow	Summer
		M4-2	▪ Maintain aquatic habitats during periods of cease-to-flow – consistent with patterns from natural storm events.	Fresh	Summer
		M4-3	▪ Movement of bed material to maintain habitat diversity ▪ Provide flow variability to generate a diversity of edge habitats	Fresh/High flow	Winter
		M4-4	▪ Inundate accumulated organic matter in areas exposed during low flow/cease-to-flow	High flow	Winter

Table 5.3 Reach 5 – Boosey Creek at Boosey Creek Road.

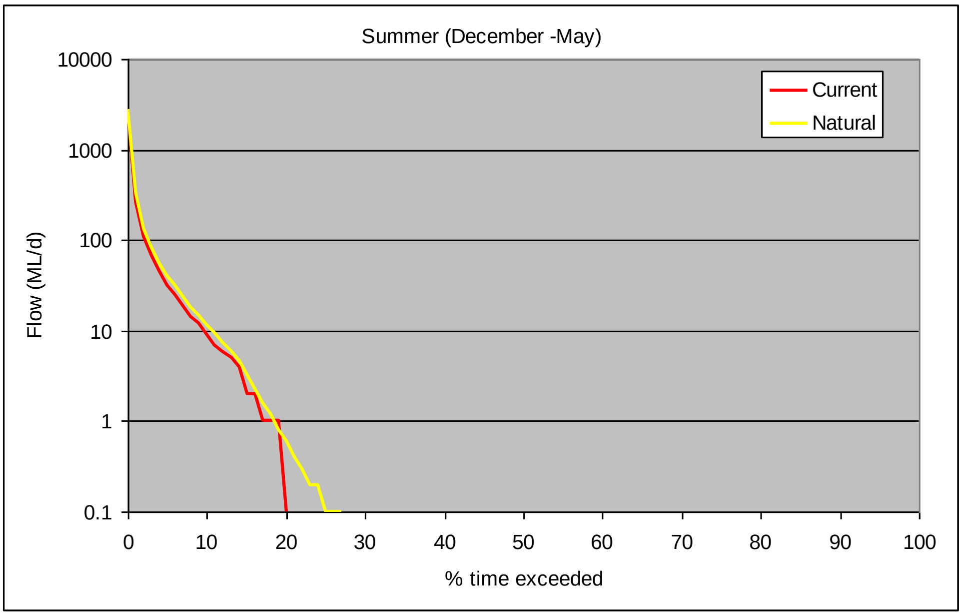
Asset	Objective	No.	Function	Flow component	Timing
Geomorphology	▪ Maintain deep pool habitat ▪ Facilitate sediment transport through reach	G5-1	▪ Entrain and transport fine sediment that has accumulated in pools	Bankfull	Winter
Vegetation	▪ Maintain current in-channel and channel-edge vegetation ▪ Maintain current condition of River Red Gum wetland.	V5-1	▪ Variable water levels result in development of wet-dry zone at channel edge	Cease-to-flow / Low flow	Summer
		V5-2	▪ Variable water levels result in wet-dry zone at channel edge	Fresh	Summer
		V5-3	▪ Inundate wetlands connected at bankfull	Bankfull	Winter
Fish	▪ Maintain a native fish community indicative of an ephemeral system	F5-1	▪ Promote spawning by low flow specialists ▪ Provide conditions that are unfavourable for exotic species	Cease-to-flow	Summer
		F5-2	▪ Maintain aquatic habitats during periods of cease-to-flow – consistent with patterns from storm events.	Fresh	Summer
		F5-3	▪ Provide opportunities for dispersal	High flow	Winter / Spring
Water quality	▪ Maintain water quality	W5-1	▪ Maintain aquatic habitats during periods of cease-to-flow – consistent with patterns from storm events.	Fresh	Summer
		W5-2	▪ Flush and replenish residual pools	High flow	Winter / Spring
Macroinvertebrates	▪ Maintain an ecologically healthy invertebrate community, characteristic of intermittent streams and including taxa relying on periodic drying to complete their life-cycle.	M5-1	• Promote successional change in community composition through disturbance.	Cease-to-flow	Summer
		M5-2	• Maintain aquatic habitats during periods of cease-to-flow – consistent with patterns from natural storm events.	Fresh	Summer
		M5-3	• Movement of bed material to maintain habitat diversity • Provide flow variability to generate a diversity of edge habitats	Fresh / High flow	Winter
		M5-4	• Inundate accumulated organic matter in areas exposed during low flow/cease-to-flow	High flow	Winter

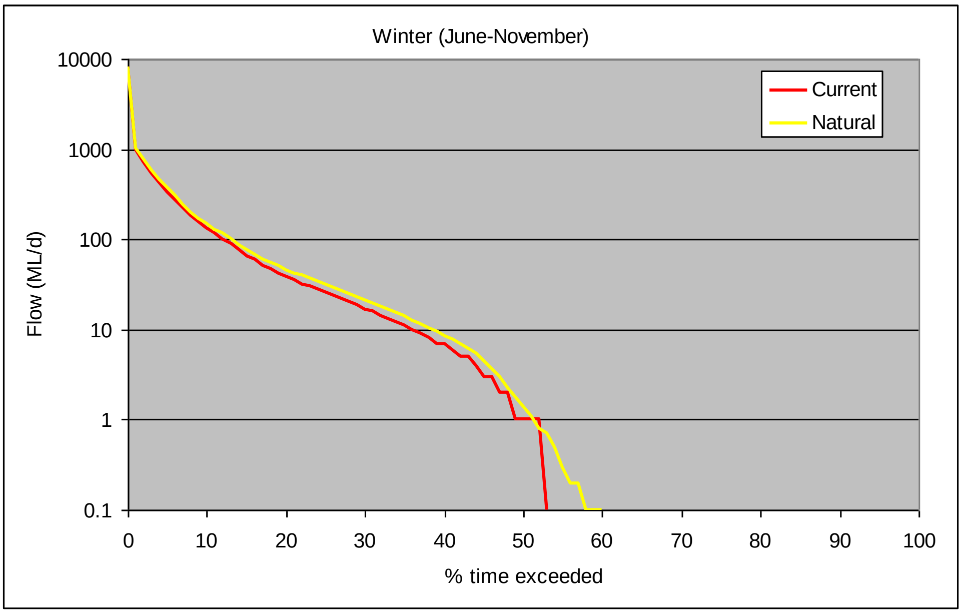
Table 5.4 Reach 6 – Boosey Creek at Burramine Road.

Asset	Objective	No.	Function	Flow component	Timing
Geomorphology	■ Maintain deep pool habitat ■ Facilitate sediment transport through reach	G6-1	■ Entrain and transport fine sediment that has accumulated in pools	Bankfull	Winter
Vegetation	■ Maintain riparian vegetation ■ Maintain diversity of channel edge vegetation.	V6-1	■ Variable water levels result in development of wet-dry zone at channel edge	Low flow	Summer
		V6-2	■ Variable water levels result in wet-dry zone at channel edge	Fresh	Summer
		V6-3	■ Inundate benches within the channel	High flow	Winter
Fish	■ Restore a native fish community indicative of an ephemeral system	F6-1	■ Promote spawning by low flow specialists ■ Provide conditions that are unfavourable for exotic species	Cease-to-flow / Low flow	Summer
		F6-2	■ Maintain aquatic habitats during periods of cease-to-flow – consistent with patterns from storm events.	Fresh	Summer
		F6-3	■ Provide opportunities for dispersal	High flow	Winter / Spring
Water quality	■ Maintain water quality	W6-1	■ Maintain aquatic habitats during periods of cease-to-flow – consistent with patterns from storm events.	Fresh	Summer
		W6-2	■ Flush and replenish residual pools	High flow	Winter / Spring
Macroinvertebrates	■ Restore an ecologically healthy invertebrate community, characteristic of intermittent streams and including taxa relying on periodic drying to complete their life-cycle.	M6-1	■ Promote successional change in community composition through disturbance.	Cease-to-flow	Summer
		M6-2	■ Maintain aquatic habitats during periods of cease-to-flow – consistent with patterns from natural storm events.	Fresh	Summer
		M6-3	■ Movement of bed material to restore habitat diversity ■ Provide flow variability to generate a diversity of edge habitats	Fresh / High flow	Winter
		M6-4	■ Inundate accumulated organic matter in areas exposed during low flow/cease-to-flow	High flow	Winter

5.2 Reach 4: Bungeet Creek to Rowan's Swamp – Bungeet Ck Road

Reach 4 is upstream of any influence of the Casey's Weir and Major Creek Waterworks District stock and domestic supply scheme, hence there is very little difference between current and natural flows (Figure 5.1). The differences that do occur are due to impacts associated with farm dams capturing a portion of the catchment runoff and some minor on-stream extractions (SKM 2006b).





- **Figure 5.1 Flow exceedence curves for current and natural flows in Reach 4 in summer (upper panel) and winter (lower panel).**

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The environmental flow recommendations for Reach 4 are to retain the current, essentially natural, seasonally intermittent regime (Table 5.5). In recommending a natural regime we have still considered HEC RAS modelling of channel features to confirm flow volumes required for freshes and high / bankfull flows. We have also specified frequency and duration of fresh and high / bankfull flow events to ensure that the important elements of the natural regime are retained. This requires careful management of potential future impacts on the flow regime, for example associated with increased farm dam development or on-stream extractions.

- **Table 5.5 Summary of flow recommendations for Reach 4: Boosey Creek Bungeet Creek to Rowan's swamp – Bungeet Ck Road**

Stream		Boosey Creek		**Reach**	Bungeet Creek to Rowan's swamp
Compliance point		Bungeet Ck Road		**Gauge No.**	NA
Season	**Component**	**Volume**	**Frequency**	**Duration**	**Objective**
Summer	Cease-to-flow	yes	natural	natural	M4-1, F4-1, V4-1
	Low flow	No specific recommendation but allow to occur as part of local catchment runoff			M4-1, F4-1, V4-1
	Fresh	50 ML/d	2 per season or natural if less than 2 events	6	M1-3, F4-2, W4-1, W4-2
Winter	Cease-to-flow	yes	natural	natural	M4-1, F4-1, V4-1
	Low flow	5 or natural			M4-1, F4-1, V4-1
	Fresh	50 ML/d	2 per season or natural	7	M1-3, F4-2, W4-1, W4-2
	High Flow	250 ML/d	1 per year or natural	5	M4-4, M4-3, M4-2, F4-3
	Bankfull	1500 ML/d	Once every 2 years or natural	2	G4-1, V4-2
	Overbank	No recommendation			

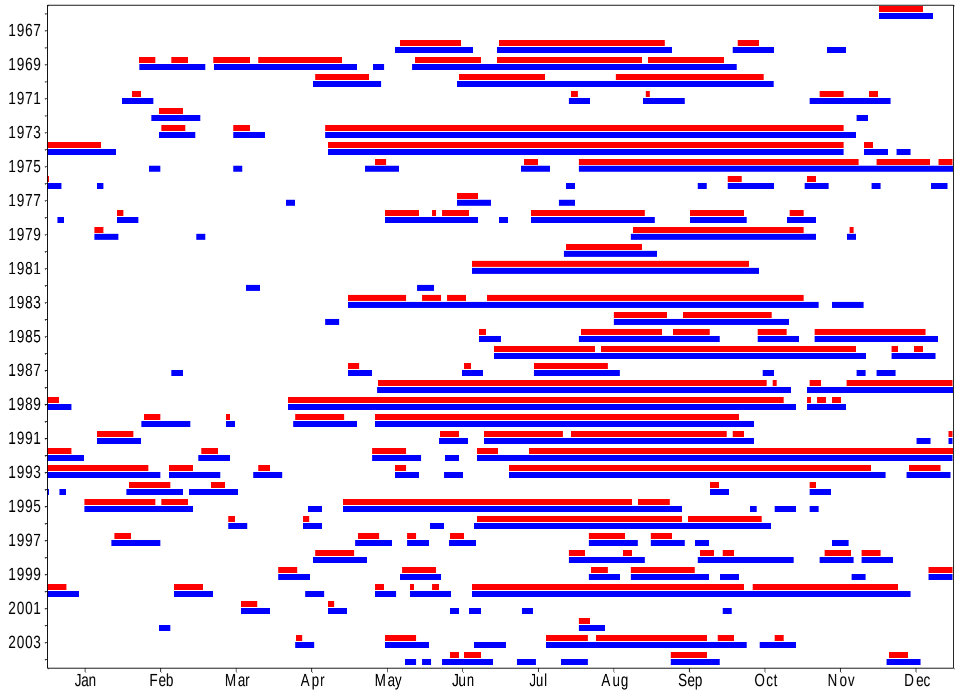
5.2.1 Cease-to-flow / low flow

Cease-to-flows and low flows are required to retain the current, natural seasonally intermittent flow regime. No specific low flow volume, duration or frequency has been set for summer although in most years low flows persist through winter and a minimum flow of 5 ML/d or natural if lower has been specified to keep pools full and connected leading into summer when flows will naturally cease. However, cease-to-flow periods should still be allowed to occur during winter at the natural frequency and duration

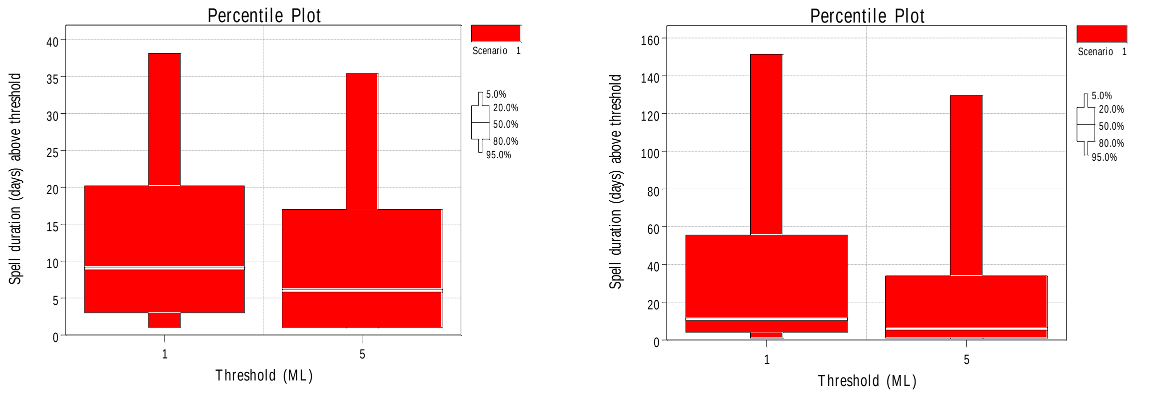
Under the current and recommended regime cease-to-flows (<1 ML/d) can occur at anytime during the year (Figure 5.2), although the majority of cease-to-flow events occur in summer. The median duration summer cease-to-flow is around 40 days with 20% of events lasting longer than 114 days. The median duration winter cease-to-flow is around 15 days with 20% of events lasting longer than 50 days. On average 3 cease-to-flow events occur in each summer and winter.

Low flows occur in both summer and winter (Figure 5.2), although the duration of winter low flows is substantially longer than those in summer. The winter low flow recommendation of 5

ML/d has a median duration of 6 days, although in most years the winter low events lasts for substantially longer than this (Figure 5.3).



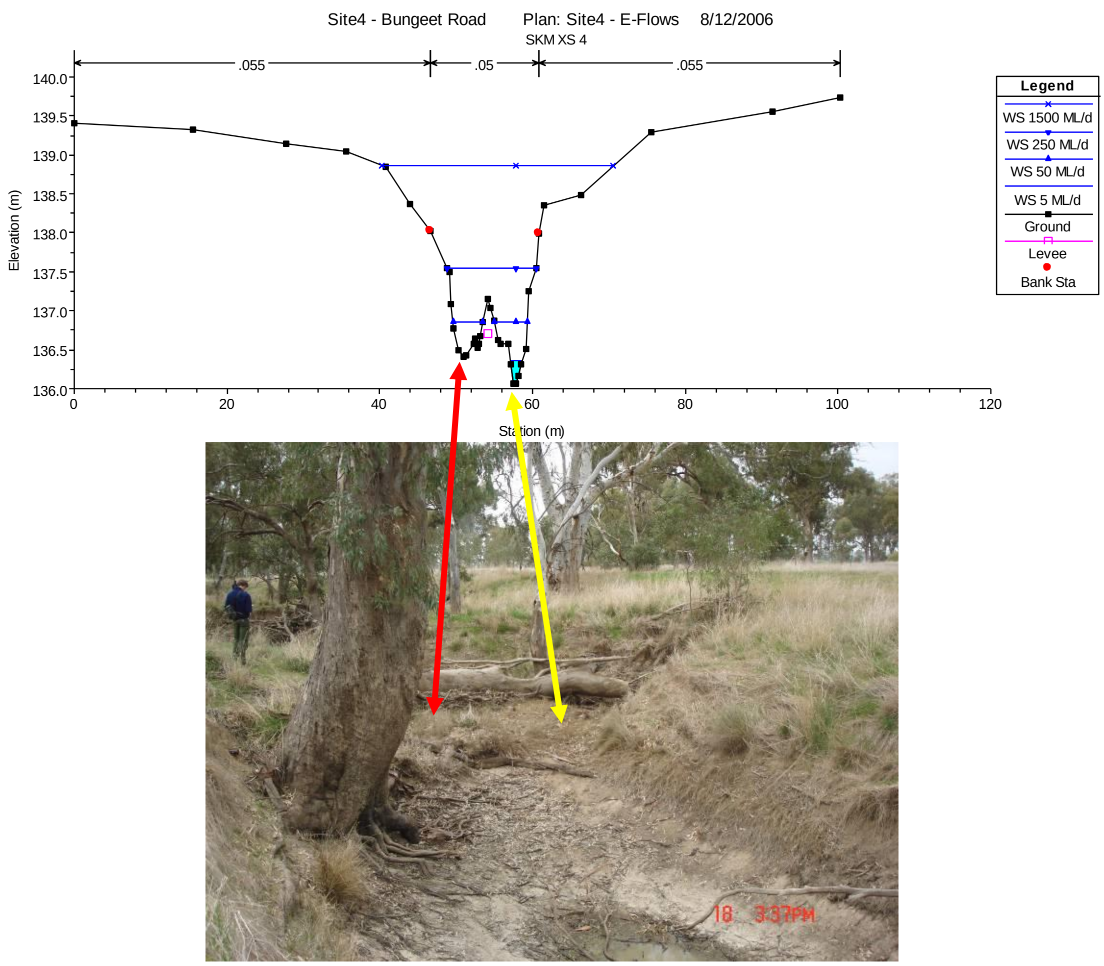
- **Figure 5.2 Flow spells above 1 ML/d (blue bars) and 5 ML/d (red bars) in Reach 4 under recommended current flow conditions.**



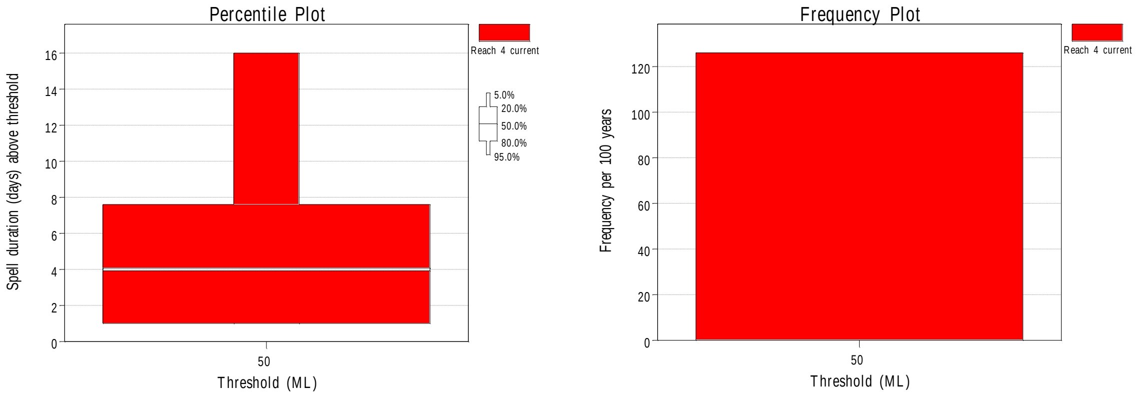
- **Figure 5.3 Low flow spell durations in summer (left) and winter (right) for Reach 4 under the current (recommended) regime.**

5.2.2 Freshes

Freshes are required to provide variability during low flows, connect pools, inundate low benches and backwaters, and freshen water quality (Figure 5.4). The recommended fresh volume in both summer and winter is 50 ML/d for 6 days in summer and 7 days in winter. Two events per season are recommended, or natural if less than two events naturally occur. The recommended summer duration of 6 days is longer than the natural median duration of 4 days (Figure 5.5), but it is estimated that 6 days of higher flows are required to ensure that pools fill throughout the reach, especially if starting volumes are very low. From a compliance perspective a summer fresh would not be counted unless it reached the recommended duration. This means that other, smaller or shorter duration freshes need to be protected and cannot be ‘extracted’ from the system. In other words, for events below the recommended duration or frequency the natural event needs to be preserved.

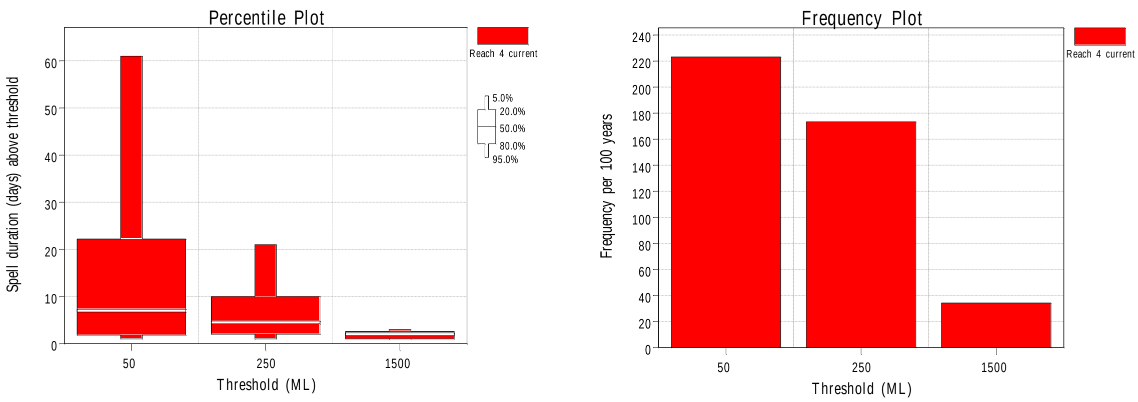


- **Figure 5.4 Reach 4 XS 4 showing vegetated bar/backwater inundated at fresh flows (red arrow) and channel connecting pools at low flows (yellow arrow).**



- **Figure 5.5 Duration (left) and frequency per 100 years (right) of summer freshes (50 ML/d) under recommended natural flow conditions.**

The recommended winter fresh of 50 ML/d for a duration of 7 days matches the median duration under current conditions and occurs on average twice per season (Figure 5.6). For events below the recommended duration or frequency the natural event needs to be preserved.



- **Figure 5.6 Duration (left) and frequency per 100 years (right) of winter fresh, high and bankfull flows under recommended natural flow conditions.**

5.2.3 High and bankfull flows

High flows fill the majority of the channel (Figure 5.4), inundate higher benches, scour sediment and around LWD, assist in fish movements and dispersal and disturbs vegetation on banks. The winter high flow recommendation is 250 ML/d once per year for 5 days. For events below the recommended duration or frequency the natural event needs to be preserved. Under current conditions the median duration high flow is 5 days and one to two events occur each year (Figure 5.6).

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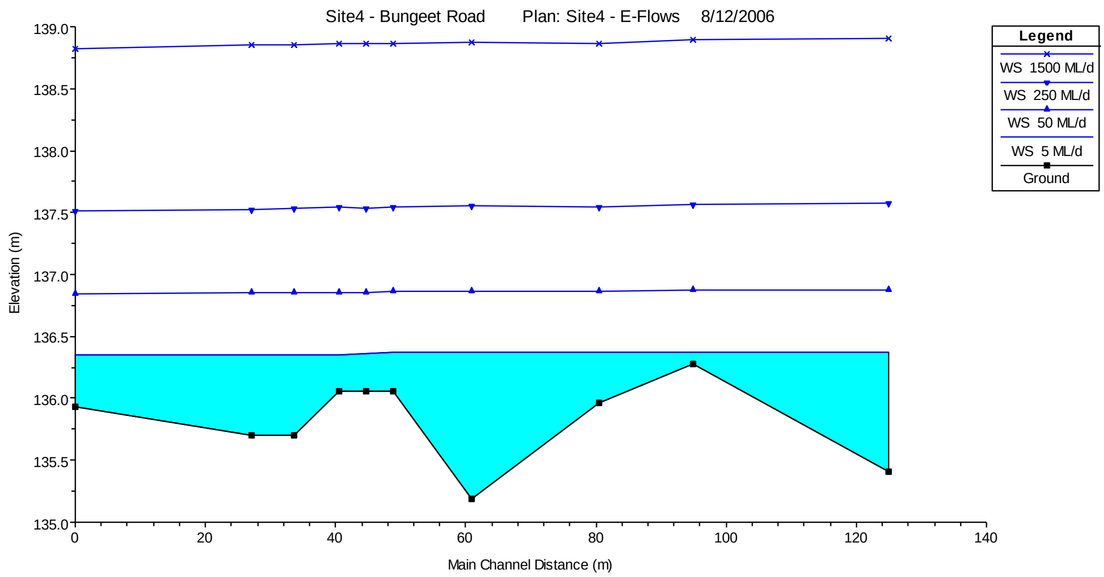
Bankfull flows form a similar function to high flows, although the entire channel is full and channel forming processes are more likely to occur. The recommended bankfull flow is 1500 ML/d once every second year for 2days. This matches the current bankfull flow frequency and duration (Figure 5.6).

Long section

The water surface level for each flow threshold along a long section of Reach 4 is shown in Figure 5.7. Water surface levels indicate that recommended low flows are sufficient to fill pools and provide a depth over shallow runs of around 10 cm. Freshes and higher flows provide a depth over the shallowest section of around 1 m.



▪ **Figure 5.7 Long section showing water surface level for all flow thresholds in Reach 4.**

5.3 Reach 5: Rowan's swamp to Tungamah – Boosey Ck Road

The current flows in Reach 5 are influenced by diversions from Broken River, which enter Boosey Creek via Back Creek in the upper part of the reach. Under the current regime flows are elevated in summer compared to natural, although the winter flow regime is similar to natural. There is no current time series flow prepared for Reach 5 because of the lack of gauge information and unknowns relating to the nature of diversions from Broken Creek. A natural time series flow has been prepared based on catchment rainfall runoff and a short gauge record at Lake Rowan, upstream of the influence of Back Creek diversions. The Lake Rowan gauge (404215) could be reactivated in order to assist with assign environmental flow compliance.

Following pipelining of the Casey's Weir and Major Creeks Waterworks District flows in Reach 5 will revert to natural. The environmental flow recommendations for Reach 5 support this outcome to reinstate an essentially natural, seasonally intermittent regime (Table 5.6). As with Reach 4, in recommending a natural regime we have still considered HEC RAS modelling of channel features to confirm flow volumes required for freshes and high / bankfull flows. We have also specified frequency and duration of fresh and high / bankfull flow events to ensure that the important elements of the natural regime are retained. This requires careful management of potential future impacts on the flow regime, for example associated with increased farm dam development or on-stream extractions.

- **Table 5.6 Summary of flow recommendations for Reach 5: Boosey Creek Rowan's swamp to Tungamah – Boosey Ck Road**

Stream		Boosey Creek		**Reach**	Rowan's swamp to Tungamah
Compliance point		Boosey Ck Road		**Gauge No.**	404215
Season	**Component**	**Volume**	**Frequency**	**Duration**	**Objective**
Summer	Cease-to-flow	yes	natural	natural	M5-1, F5-1, V5-1
	Low flow	No specific recommendation but allow to occur as part of delivery of fresh			M5-1, F5-1, V5-1
	Fresh	50 ML/d	2 per season or natural if less than 2 events	6	M5-2, F5-2, W5-1, V5-2
Winter	Cease-to-flow	yes	natural	natural	M5-1, F5-1, V5-1
	Low flow	5 or natural			M5-1, F5-1, V5-1
	Fresh	100 ML/d	2 per season or natural	7	M5-2, F5-2, W5-1, V5-2
	High Flow	300 ML/d	1 per year or natural	5	M5-3, M5-4, W5-2, F5-3
	Bankfull	1500 ML/d	Once every 2 years or natural	2	G5-1, V5-1
	Overbank	No recommendation			

5.3.1 Cease-to-flow / low flow

Cease-to-flows and low flows are required to retain the current, natural seasonally intermittent flow regime. No specific low flow volume, duration or frequency has been set for summer although in most years low flows persist through winter and a minimum flow of 5 ML/d or natural if lower has been specified to keep pools full and connected leading into summer when flows will naturally cease. However, cease-to-flow periods should still be allowed to occur during winter at the natural frequency and duration

Under the recommended regime cease-to-flows (<1 ML/d) can occur at anytime during the year (Figure 5.8), although the majority of cease-to-flow events occur in summer. As with Reach 4, the median duration summer cease-to-flow is around 40 days with 20% of events lasting longer than 114 days. The median duration winter cease-to-flow is around 15 days with 20% of events lasting longer than 50 days. On average 3 cease-to-flow events occur in each summer and winter. There

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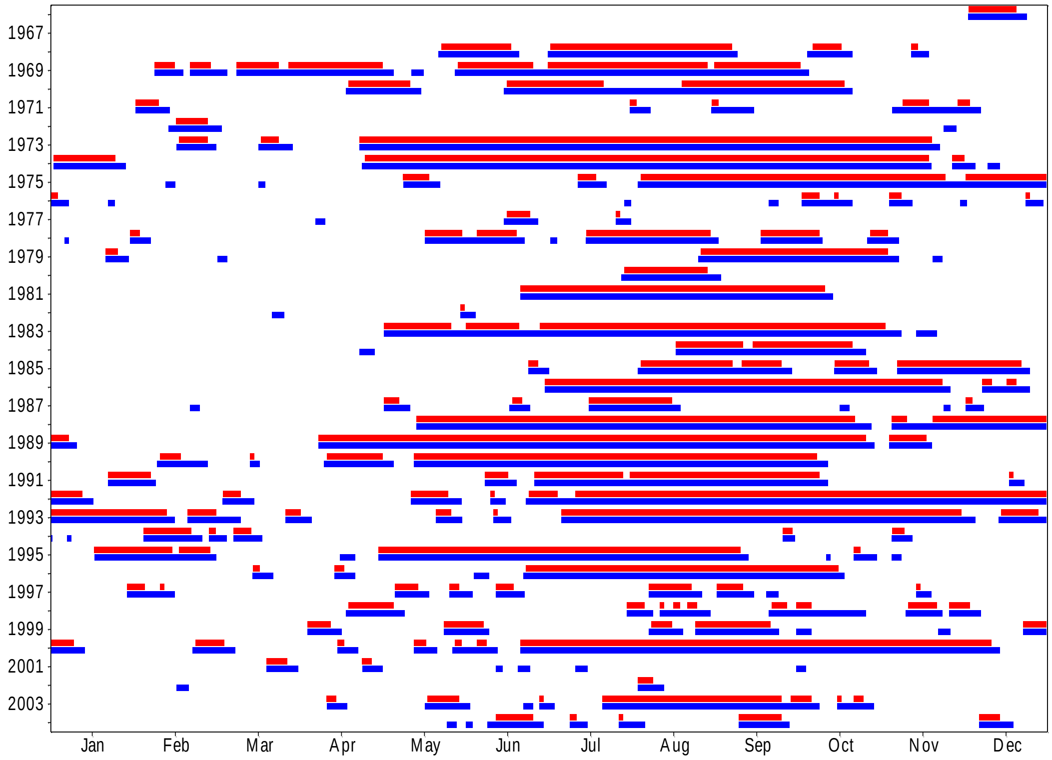
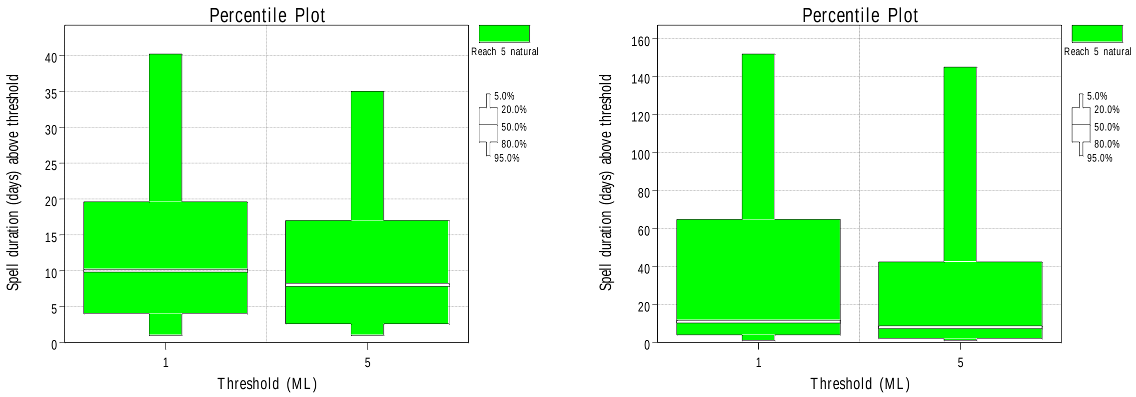
is little difference in the cease-to-flow patterns between Reach 4 and Reach 5 because the greatest contribution to flows in the reach come from the upstream catchment and there are few tributary inflows in Reach 5.

As with Reach 4, low flows occur in both summer and winter (Figure 5.8) although the duration of winter low flows is substantially longer than those in summer. The winter low flow recommendation of 5 ML/d has a median duration of 6 days, although in most years the winter low events lasts for substantially longer than this (Figure 5.9).



- **Figure 5.8 Flow spells above 1 ML/d (blue bars) and 5 ML/d (red bars) in Reach 5 under recommended natural flow conditions.**



- **Figure 5.9 Low flow spell durations in summer (left) and winter (right) for Reach 5 under the recommended natural regime.**

5.3.2 Freshes

Freshes are required to provide variability during low flows, connect pools, inundate low benches and backwaters, and freshen water quality (Figure 5.10). The recommended fresh volume in summer is 50 ML/d for 6 days and in winter is 100 ML/d for 7 days. Two events per season are recommended, or natural if less than two events naturally occur. The recommended summer duration of 6 days is equivalent to the natural median duration (Figure 5.11). From a compliance perspective a summer fresh would not be counted unless it reached the recommended duration. This means that other, smaller or shorter duration freshes need to be protected and cannot be 'extracted' from the system. In other words, for events below the recommended duration or frequency the natural event needs to be preserved.

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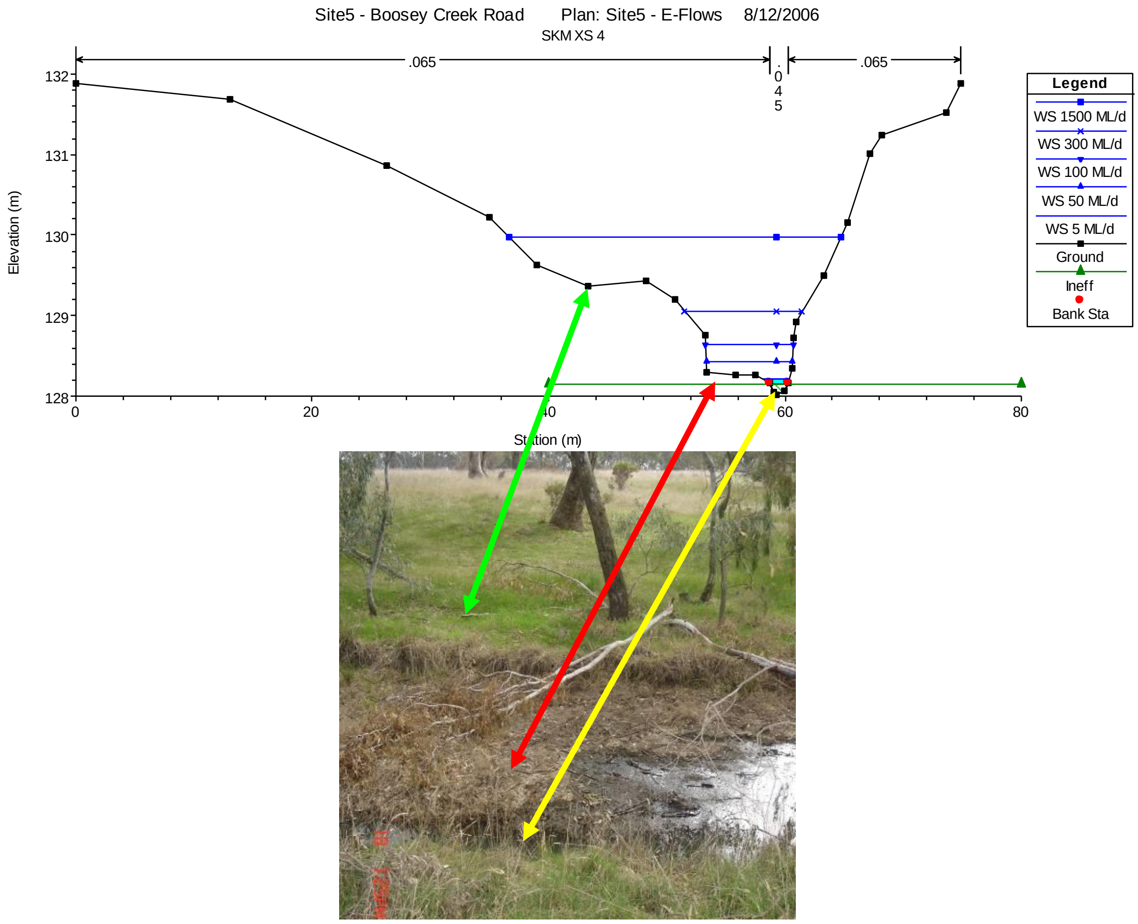
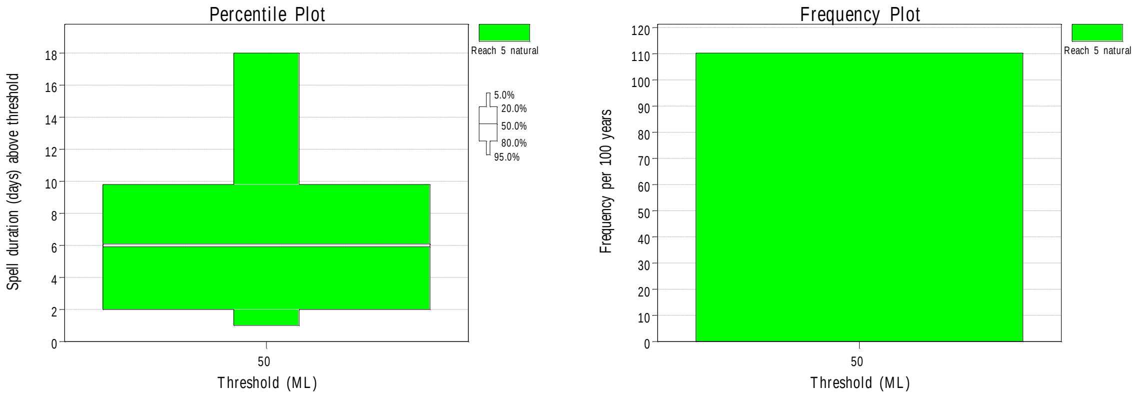
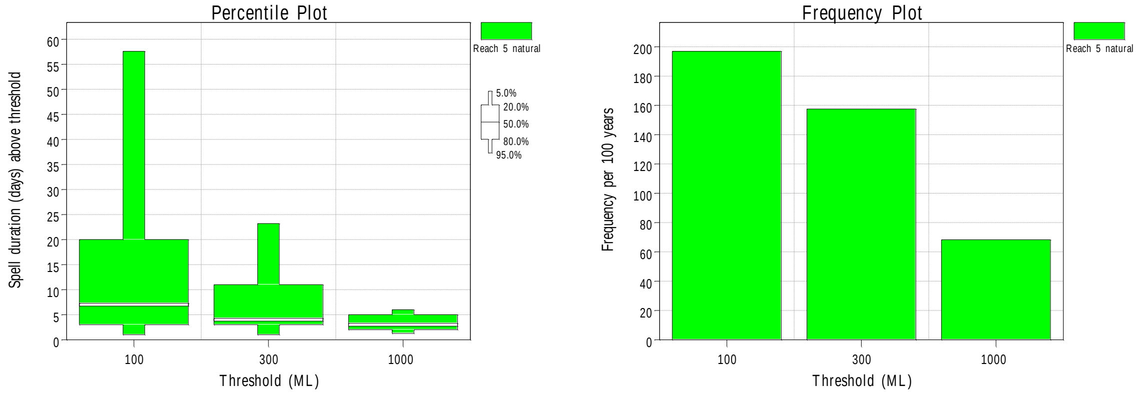


■ **Figure 5.10 Reach 5 XS 4 showing low flow channel (yellow arrow), pool backwater inundated at fresh flows (red arrow) and bench/inset floodplain inundated at bankfull flow (green arrow).**



■ **Figure 5.11 Duration (left panel) and frequency per 100 years (right panel) of summer freshes (50 ML/d) under recommended natural flow conditions.**

The recommended winter fresh of 100 ML/d for a duration of 7 days matches the median duration under natural conditions and occurs on average twice per season (Figure 5.12). For events below the recommended duration or frequency the natural event needs to be preserved.



- **Figure 5.12 Duration (left panel) and frequency per 100 years (right panel) of winter fresh, high and bankfull flows under recommended natural flow conditions.**

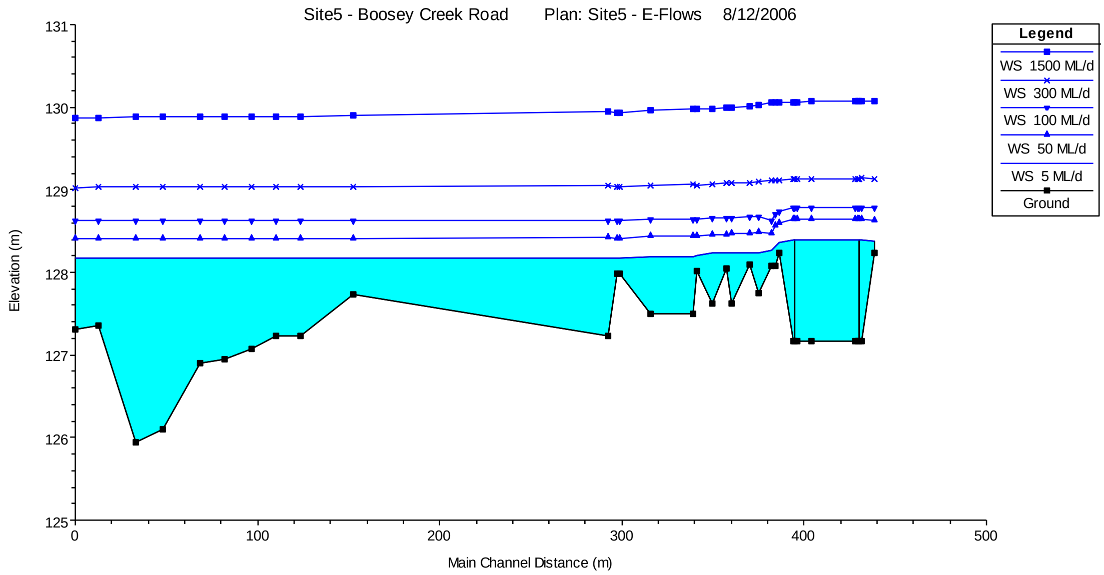
5.3.3 High and bankfull flows

The winter high flow recommendation is 300 ML/d once per year for 5 days, this is similar to the natural event (Figure 5.12). For high flow events below the recommended duration or frequency the natural event needs to be preserved.

Bankfull flows form a similar function to high flows, although the entire channel is full and channel forming processes are more likely to occur (Figure 5.10). The recommended bankfull flow is 1500 ML/d once every second year for 2 days. This matches the natural bankfull flow frequency and duration (Figure 5.12).

Long section

The water surface level for each flow threshold along a long section of Reach 4 is shown in Figure 5.13. Water surface levels indicate that recommended low flows are sufficient to fill pools and provide a depth over shallow runs of around 10 cm. Freshes and higher flows provide a depth over the shallowest section of around 1 m.



▪ **Figure 5.13 Long section showing water surface level for all flow thresholds in Reach 5.**

5.4 Reach 6: Tungamah to Katamatite – Burramine Road

The current flows in Reach 6 are influenced by diversions to and extractions from Reach 5 and by transfers from Broken River via the Broken-Boosey link channel at Reilly's Weir. Current flows are derived from gauge data downstream of the point where the Broken-Boosey channel enters Boosey Creek (gauge 404204). Under the current regime low flows are elevated in summer compared to natural, although the winter flow regime is similar to natural.

Following pipelining of the Casey's Weir and Major Creeks Waterworks District flows in Reach 6 will revert to natural, although the Broken-Boosey link channel may continue to operate and divert a portion of Broken Creek flows to Boosey Creek from time to time to minimise some flooding impacts in Broken Creek between Reilly's Weir and Katamatite (Reach 3). The environmental flow recommendations for Reach 6 support the return to an essentially natural, seasonally intermittent regime (Table 5.7). As with upstream reaches, in recommending a natural regime we have still considered HEC RAS modelling of channel features to confirm flow volumes required for freshes and high / bankfull flows. We have also specified frequency and duration of fresh and high / bankfull flow events to ensure that the important elements of the natural regime are retained. This requires careful management of potential future impacts on the flow regime, for example associated with increased farm dam development or on-stream extractions.

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- **Table 5.7 Summary of flow recommendations for Reach 6: Tungamah to Katamatite – Burramine Road**

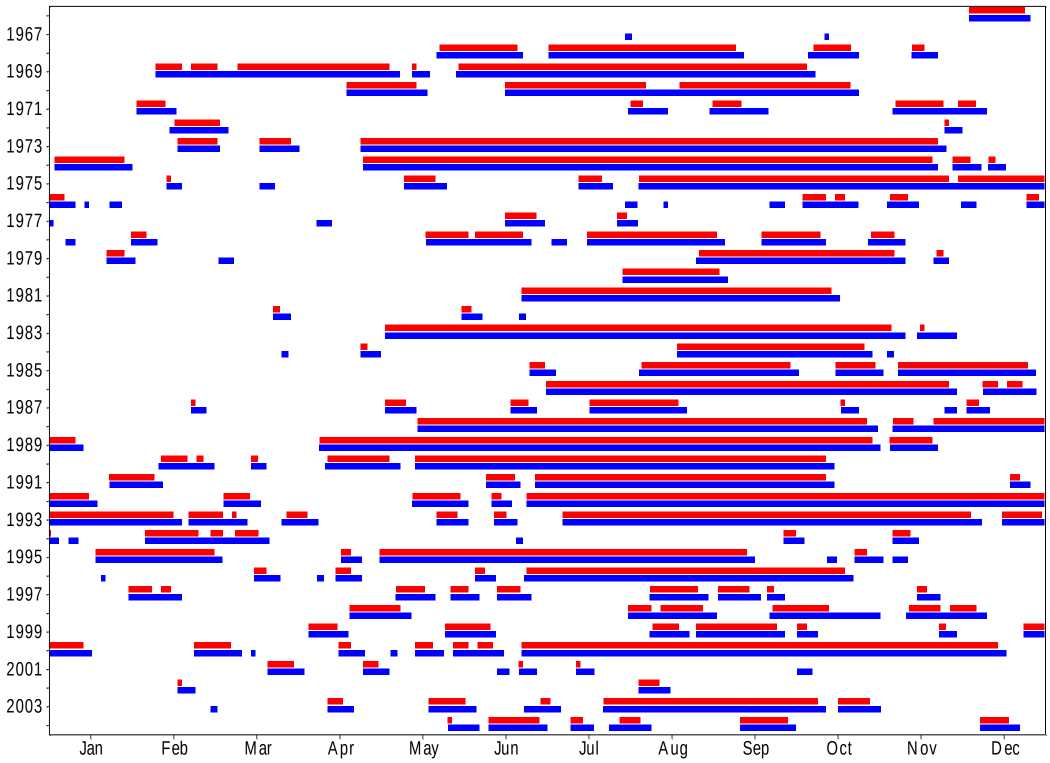
Stream		Boosey Creek		**Reach**	Tungamah to Katamatite
Compliance point		Burramine Road		**Gauge No.**	404204
Season	**Component**	**Volume**	**Frequency**	**Duration**	**Objective**
Summer	Cease-to-flow	yes	natural	natural	M6-1, F6-1, V6-1
	Low flow	No specific recommendation but allow to occur as part of delivery of fresh			V6-1, F6-1, M6-1
	Fresh	100 ML/d	1 per season or natural	7	M6-2, F6-2, W6-1, V6-2
Winter	Cease-to-flow	yes	natural	natural	V6-1, F6-1, M6-1
	Low flow	5 or natural			V6-1, F6-1, M6-1
	Fresh	200 ML/d	2 per season or natural	8	M6-2, F6-2, W6-1, V6-2
	High Flow	500 ML/d	1 per year or natural	5	M6-3, M6-4, W6-2, F6-3, V6-3
	Bankfull	2500 ML/d	Once every 2 years or natural	2	G6-1, V5-1
	Overbank	No recommendation			

5.4.1 Cease-to-flow / low flow

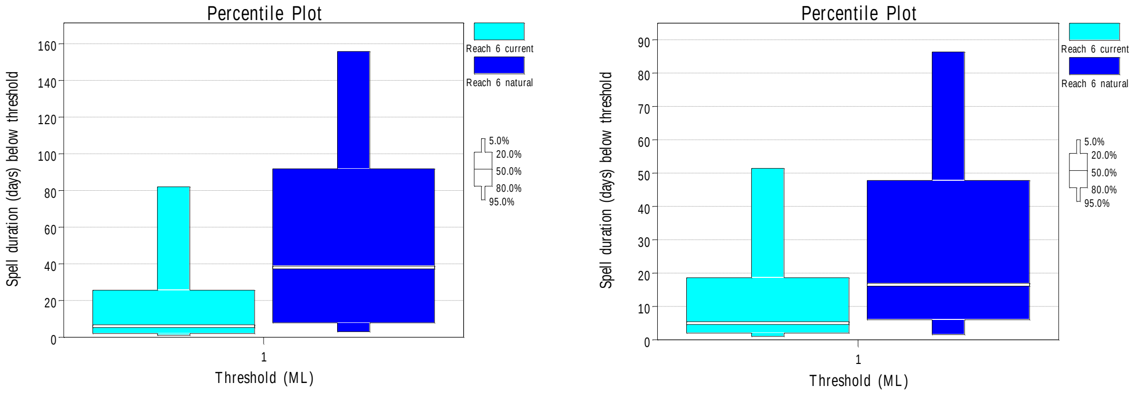
Cease-to-flows and low flows are required to reinstate the natural seasonally intermittent flow regime. No specific low flow volume, duration or frequency has been set for summer although in most years low flows persist through winter and a minimum flow of 5 ML/d or natural if lower has been specified to keep pools full and connected leading into summer when flows will naturally cease. However, cease-to-flow periods should still be allowed to occur during winter at the natural frequency and duration

Under the recommended regime, cease-to-flows (<1 ML/d) can occur at anytime during the year (Figure 5.14), although the majority of cease-to-flow events occur in summer. Under current conditions in summer the median cease-to-flow duration is 6 days; under natural (recommended) condition the median cease-to-flow duration is 38 days (Figure 5.15). In winter the median cease-to-flow duration is half that of summer under natural conditions.

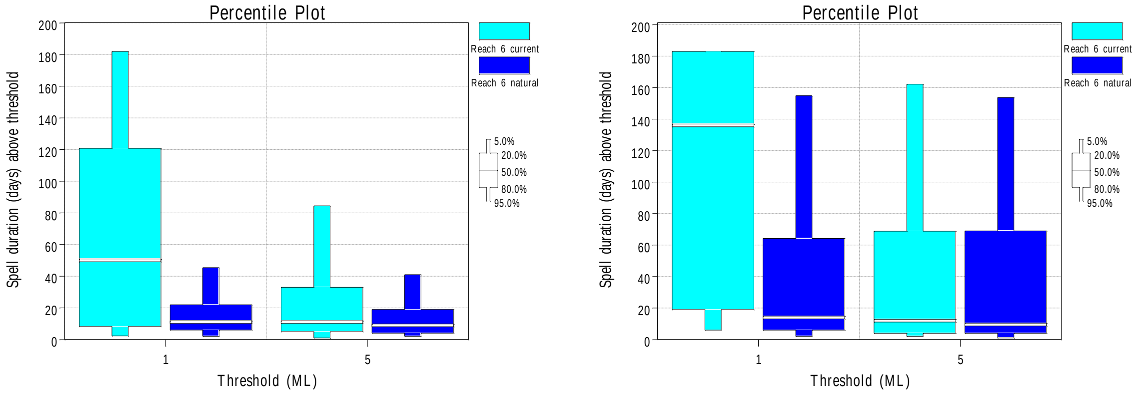
Low flows occur in both summer and winter although the duration of winter low flows is substantially longer than those in summer. Low flows of around 1 ML/d under current conditions occur for longer durations than natural, however, there is little difference between current and natural in the duration of flows greater than 5 ML/d, especially in winter (Figure 5.16).



- **Figure 5.14 Flow spells above 1 ML/d (blue bars) and 5 ML/d (red bars) in Reach 6 under recommended natural flow conditions.**



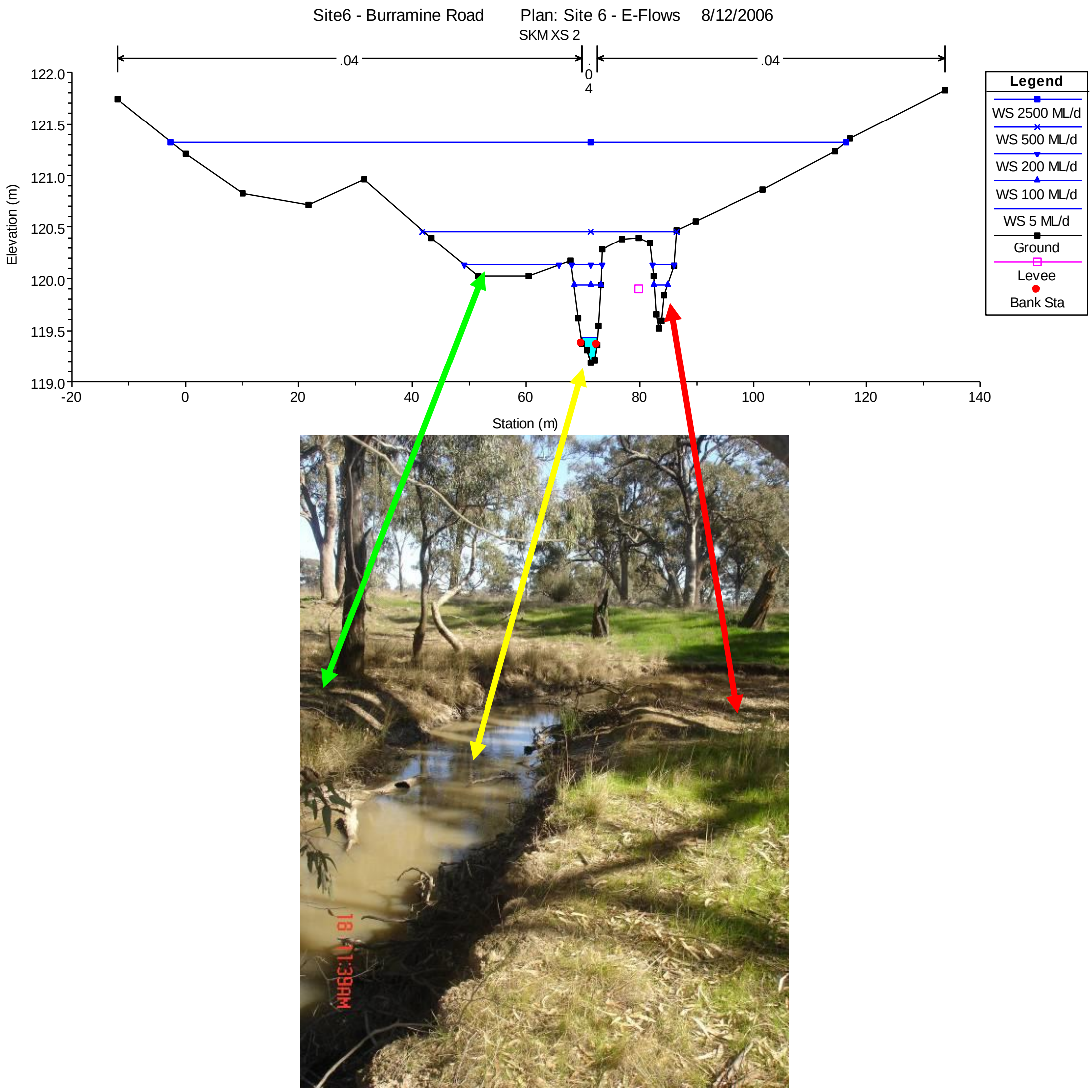
- **Figure 5.15 Cease-to-flow spells (<1 ML/d) under current and recommended natural conditions for summer (left) and winter (right) in Reach 6.**



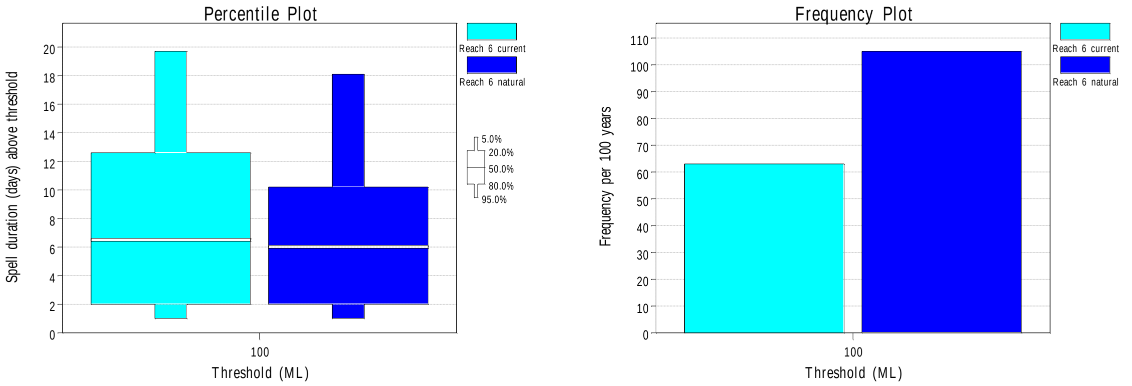
- **Figure 5.16 Low flow spell durations in summer (left) and winter (right) for Reach 6 under the current and recommended natural regime.**

5.4.2 Freshes

Freshes are required to provide variability during low flows, connect pools, inundate low benches and backwaters, and freshen water quality. The creek channel in Reach 6 is associated with an inset floodplain, which contains a number of high flow channels; these channels would be engaged during fresh and high flows (Figure 5.17). The recommended fresh volume in summer is 100 ML/d for 7 days and in winter is 200 ML/d for 8 days. One to two events per season are recommended, or natural if less than two events naturally occur. The recommended summer duration of 7 days, this is similar to the current and natural median durations (Figure 5.18). From a compliance perspective a summer fresh would not be counted unless it reached the recommended duration. This means that other, smaller or shorter duration freshes need to be protected and cannot be ‘extracted’ from the system. In other words, for events below the recommended duration or frequency the natural event needs to be preserved.

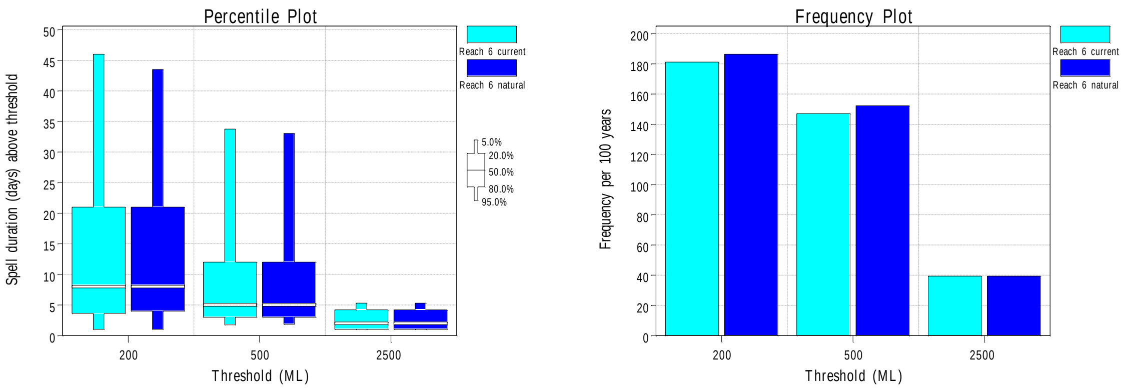


- **Figure 5.17 Reach 6 XS 2 showing low flow channel (yellow arrow), high flow channel inundated at fresh flows (red arrow) and bench/inset floodplain inundated at high flows flow (green arrow). The broader floodplain is inundated at Bankfull flows**



▪ **Figure 5.18 Duration (left) and frequency per 100 years (right) of summer freshes (100 ML/d) under current and recommended natural flow conditions.**

The recommended winter fresh of 200 ML/d for a duration of 8 days matches the median duration under current and natural conditions and occurs on average almost twice per season (Figure 5.19). For events below the recommended duration or frequency the natural event needs to be preserved.

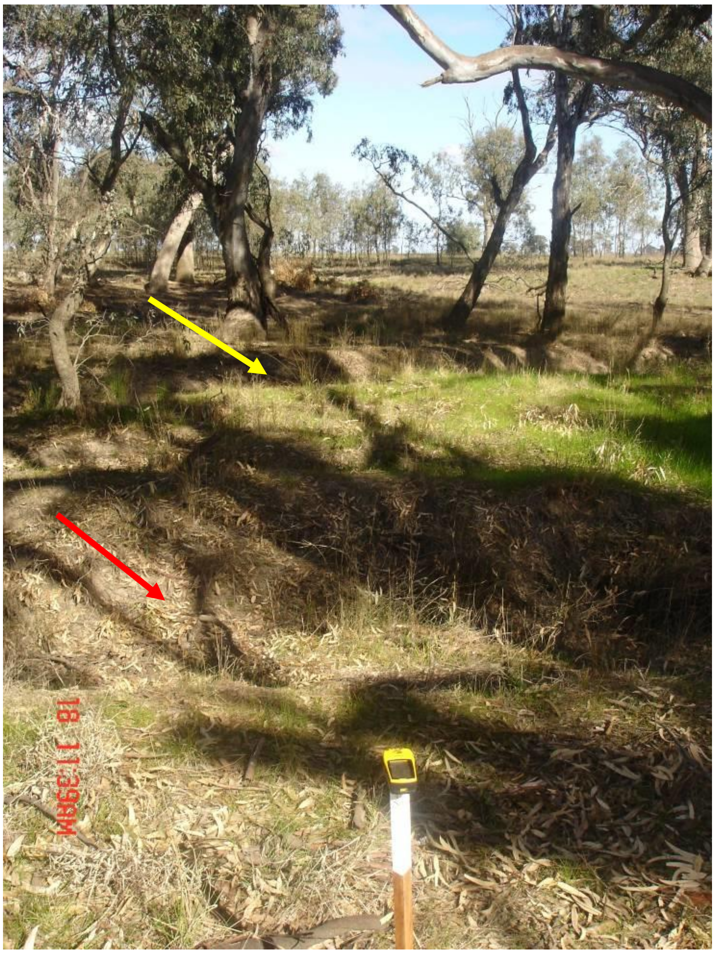


▪ **Figure 5.19 Duration (left panel) and frequency per 100 years (right panel) of winter fresh, high and bankfull flows under current and recommended natural flow conditions.**

5.4.3 High and bankfull flows

High flows fill the majority of the channel inundate higher benches, scour sediment and around LWD, assist in fish movements and dispersal and disturbs vegetation on banks. The winter high flow recommendation is 500 ML/d once per year for 5 days, this is identical to the current and natural event (Figure 5.19). For high flow events below the recommended duration or frequency the natural event needs to be preserved.

Bankfull flows form a similar function to high flows, although in Reach 6 Bankfull flows also inundate the inset floodplain associated with the creek (see Figure 5.17 and Figure 5.20). The recommended bankfull flow is 2500 ML/d once every second year for 2 days. This matches the current and natural bankfull flow frequency and duration (Figure 5.19).



- **Figure 5.20 Transverse photo of XS 2 showing main low flow channel (yellow arrow), high flow channel (red arrow) and broader inset floodplain that is inundated at Bankfull flows.**

Long section

The water surface level for each flow threshold along a long section of Reach 4 is shown in Figure 5.21. Water surface levels indicate that recommended low flows are sufficient to fill pools and provide a depth over shallow runs of greater than 10 cm. Freshes and higher flows provide a depth over the shallowest section of around 1 m and bankfull flows provide a depth of around 2 m.

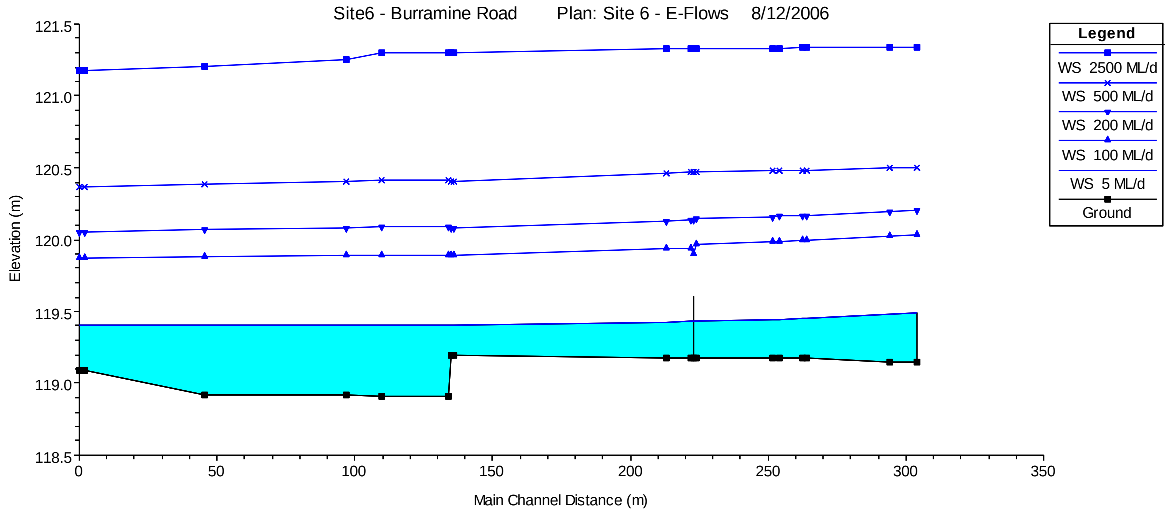


Figure 5.21 Long section showing water surface level for all flow thresholds in Reach 6 (flow is from right to left).

6. Complementary works / investigations

The success of environmental flows often hinges on the mitigation of other limiting factors. Within the Broken-Boosey system a number of issues have been identified that may limit the achievement of ecological objectives even if flow recommendations are implemented. As such, it is recommended to:

- Assist vegetation recovery through fencing, grazing control and revegetation.
- Provide fish passage on all retained weirs.
- Investigate options for selective pool excavations in flowing reaches to restore refuge habitat because flow alone is unlikely to be sufficient to scour and transport significant quantities of sediment from pools, especially in Reach 1.
- Implement water management recommendations for Moodies Swamp.
- Retain Casey’s Weir to assist in the delivery of fresh flows up to 200 ML/d and investigate feasibility and infrastructure requirements to restore higher flows associated with the natural cross-connection between Broken River and Broken Creek.
- In conjunction with revision of environmental flow requirements for the lower Broken Creek undertake a more detailed analysis of losses between Casey’s Weir and lower Broken Creek to determine the suitability of delivering flows to the lower Broken Creek via Casey’s Weir.

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Appendix A Flow component description

A.1 Summer/autumn

Cease-to-flow

Cease-to-flow is the period of no discernable flow in a waterway, or in practice when there is no measurable flow at a stream gauge, representative of the relevant reach. This may lead to total or partial drying of the stream channel, depending on the evaporation rate, groundwater exchange, depth of pools and the duration of cease-to-flow. Under natural conditions Broken Creek would have been an ephemeral waterway that conveyed occasional flood waters from the Broken River and with some inflow from the local catchment. Boosey Creek was also an ephemeral waterway (and remains so in the upper and mid reaches). Boosey Creek has a larger catchment with more reliable surface runoff and hence a more predictable flow during winter and spring. Even so records from 1966-1976 indicate that ceases to flow events occurred ~67% of the time (SKM 2006a).

Cessation of flow is a common natural occurrence in Australian streams and there are a range of ecological functions provided by this flow component (Poff and Ward 1989, Boulton *et al.* 2000). During these periods, the river may contract to a series of isolated pools that are important refugia for recolonisers upon the return of flow. The biota in these pools is likely to be subject to intensified predation and physicochemical stresses (e.g. low dissolved oxygen concentrations). However, aquatic biota are relatively mobile and usually have the ability to recolonise these habitats following the restoration of flow, as long as there are effective habitat refuges (Jowett and Duncan 1990). In addition, some biota exhibit specific life history adaptations to cope with cease-to-flow, such as the development of eggs, resting stages, seeds or subterranean tubers tolerant of desiccation. A cease-to-flow can often confer a competitive advantage to native biota over introduced species that may not be adapted to the harsh conditions. Drying of habitats and organic matter facilitates the decomposition and processing of organic matter and following rewetting this then provides a fresh pool of nutrient and carbon inputs for the system (Baldwin and Mitchell 2000).

Overall there is a significant ecological benefit associated with cease-to-flows. However, there are risks in the removal or extension of the duration of this component or addition of the component in a system in which it did not naturally occur. The cease-to-flow period is a period of stress for the ecosystem and extension of the duration of this period can have deleterious effects on the ecosystem, such as increases in water temperature and even loss of habitat through reduction in residual pool volume as pools dry out. Conversely, the reinstatement of a cease-to-flow period in a stream that has otherwise become perennial (e.g. Broken Creek) can result in a number of benefits, such as a reduction in the prevalence of exotic species, particularly fish, that are not adapted to prolonged cease-to-flow periods.

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Low flow

The summer/autumn low flow refers to the channel base flow and may be that component of stream flow retained after water has been diverted. The objective of this flow is to maintain permanent pool and riffle habitats and expose areas of the streambed (including parts of riffles) and large woody debris (LWD). Exposure of the streambed allows the accumulation of terrestrial organic matter and acts as a disturbance to reset successional processes for macroinvertebrate, biofilm and vegetation communities.

The low flow also serves to provide sufficient water levels to inundate shallow runs and riffles for macroinvertebrates and provide adequate depth in pool refuges for fish. Maintaining connectivity between pools also helps to slow the deterioration of water quality that occurs in pools during low flow periods.

Freshes

Summer/autumn freshes refer to the short duration increases in flow in the channel due to localised rainfall events. This variation in water levels is important for maintaining species diversity in the emergent and marginal aquatic vegetation communities and is the principal driver of zonation at the channel margins. This is because different species have varying degrees of tolerance to the timing and duration of inundation. Another function of the freshes is to wet low-lying channel zones such as riffles and benches, thereby helping relieve drought-stress on emergent and marginal vegetation that has become exposed during the low flow or cease-to-flow periods. Fish and other aquatic fauna are more able to move between pool habitats during freshes because of the increased depth across shallow areas. The brief increases in flow also helps to improve water quality by flushing and mixing pools that have begun to stagnate and become stratified, in particular during prolonged periods of low and/or cease-to-flow.

A.2 Winter/spring

Low flow

Low flows during winter and spring provide conditions of sustained water levels and provide an overall increase in available habitat for aquatic biota compared to the summer period as LWD, branch-piles and banks become inundated and available for colonisation. The winter low flow also facilitates fish movement and invertebrate drift and inundates the lower parts of the banks. Prolonged inundation of the lower banks drowns encroaching terrestrial vegetation while maintaining habitat for emergent and marginal vegetation during the spring growth season. An increase in habitat availability may compensates for a decrease in primary production in winter (low light and low temperatures) which in turn leads to a decrease in competition for limited resources and relieves summer low flow stress. Habitat diversity will also increase as higher flows create a greater diversity of flow velocity habitats.

Freshes

Freshes are short duration increases in flow that occur during the high flow period between June and November in response to short duration rain events. Similar to the summer/autumn freshes, the winter/spring freshes provides flow variability important for maintaining diverse aquatic vegetation along the edges of waterways. Freshes entrain organic matter that has accumulated in the terrestrial channel sections, and to a lesser degree transport sediment. Entrainment and deposition of sediment is unlikely to result in a net change in channel form during these flow events.

High flow

Winter high flows are seasonal increases in flow that fill the channel to a deeper extent than winter freshes. They effectively wet and connect most habitats within the main channel and provide lateral connectivity between the main channel, high-flow channel (floodrunners) and benches. Maintaining occasional inundation of these habitats provides significant carbon returns to the stream after a period of significant production (e.g. plants, algae and macroinvertebrates) and provides connectivity for fish to move between habitats.

Bankfull

Bankfull flow essentially refers to a flood flow that fills a large proportion of the river channel and floodrunners without escape onto the floodplain. A bankfull flow acts as a significant disturbance to the geomorphology and ecology of the river. These large flows can reform the channel by scouring banks and transporting sediment. Ecological succession will be reset in both aquatic and riparian communities as plants and animals are swept downstream or drowned. Organic matter that has accumulated in the higher levels of the channel will be entrained and transported downstream. Included in the organic material will be LWD that becomes dislodged and then redeposited in the lower parts of the channel. Bankfull flows are also important for providing water to wetlands adjacent to the channel (e.g. Moodies Swamp on the Broken Creek and Rowans Swamp on Boosey Creek).

In the Broken Creek bankfull flows are likely to be generated via cross catchment transfers of high flows in the Broken River, although heavy rainfall within the catchment may be sufficient to generate bankfull flows if the duration of rainfall is long enough. In the Boosey Creek bankfull flows will be generated by widespread rainfall in the upper catchment or transfers of flood flows from the Broken Creek via Back Creek.

Overbank

Overbank flows are flood flows that overtop the banks and spill onto the floodplain. In Broken Creek and Boosey Creek no overbank flows have been recommended, as the high and bankfull flows are considered to fulfil the environmental flow objectives. Overbank flows may still occur in the system in response to widespread rainfall and flood transfers from Broken River. While not specifically recommended, overbank flows should nonetheless be allowed to occur to provide floodplain inundation and connectivity with wetland depression in the broader landscape.