JACOBS

Australian Platypus Conservancy

The Murray-Darling Freshwater Research Centre

Upper Broken Creek Flows Study

Issues and flow recommendations

September 2017

Upper Broken Creek Flows Study

Client Name:	Goulburn Broken CMA
Document Title:	Upper Broken Creek Flows Study – Issues Paper and flow recommendations
Document No.:	0001
Revision:	Final
Revision Date:	1 September 2017
Project/Proposal No:	IS177700
Project Manager:	Simon Treadwell
Prepared By:	MDFRC, Australian Platypus Conservancy, Jacobs
File Name:	C:\Users\Streadwell\Documents\My Documents\jobs\GBCMA\Broken CK FLOWS\draft final report\Upper Broken Creek Flows Study flow recs report_Final.docx

Jacobs Group (Australia) Pty Limited
ABN 37 001 024 095
Floor 11, 452 Flinders Street
Melbourne VIC 3000
PO Box 312, Flinders Lane
Melbourne VIC 8009 Australia

T +61 3 8668 3000
F +61 3 8668 3001
www.jacobs.com

Contents

Executive Summary

This Paper is the final deliverable in a series of reports that comprise the 2017 revision of the Upper Broken Creek environmental flow recommendations. It provides a review of the current condition of the water-dependent values associated with the Upper Broken Creek, presents environmental objectives that if achieved would sustain or enhance the environmental values of the creek and recommends a flow regime that if implemented would achieve the environmental objectives.

For the purposes of describing system characteristics and setting objectives and flow recommendations, the Upper Broken Creek has been delineated into 3 reaches and a number of sites in each reach have been examined by an Environmental Flows Technical Panel (EFTP).

Reach	Assessment sites
Reach 1, Casey's Weir to Waggarandall Weir	1a – Goorambat Bushland Reserve, Quinn Road (existing site) 1b – Trewins Weir Pool, Quinn Road (new Site)
Reach 2 Waggarandall Weir to Reillys Weir	2a – Geary Road (upstream of Pelluebla Road) (existing site) 2b - St James Road (new site)
Reach 3 Reillys Weir to Katamatite	3a – Carmody Road (existing site) 3b – Reillys Weir Pool (new site)

Flow in the upper Broken Creek is regulated via diversions to the creek from the Broken River at Casey's Weir. Prior to 2009, large volumes of flow were diverted to the creek to supply both irrigation and stock and domestic demands. Since 2009, stock and domestic demands have been met via an alternative source (pipeline from the East Goulburn Main) and there has been a consequent reduction in flow down Broken Creek with both peak flows and base flows being reduced. Reach 1 has experienced the greatest impact in terms of flow reduction. Despite the flow reduction, permanent flows into Reach 1 have been retained (in order to maintain supply for irrigation) and these have maintained permanent aquatic habitat. Although losses occur, the permanent flow into Reach 1 has also maintained near permanent low flows through Reach 2 (and to a lesser extent Reach 3, where losses are greater), at only slightly lower magnitudes than prior to the pipeline.

Despite the changes in flow, the aquatic values in the upper Broken Creek remain similar to those documented in 2007, prior to reductions in flow diversion to the creek, especially in Reach 1 where perennial flow has been retained. In this reach small and large-bodied native fish and platypus are present. However, suitable habitat for these species diminishes through Reach 2 and is generally absent in Reach 3 except for opportunistic species.

The nature of the creek in the future will be largely determined by whether sections of it are managed to be perennial or ephemeral. It is possible that Reaches 1 and 2 could be managed as perennial systems, while Reach 3 is left to develop into a series of wetlands. Given the low gradient of the system, rehabilitation of naturally occurring deep pools within any of the reaches is unrealistic through the delivery of regulated flows as boundary shear stresses high enough to mobilise consolidated bed and bank sediments cannot be feasibly produced. Furthermore, flows that are large enough to initiate scouring of pools in Reach 1 are likely to cause significant nuisance flooding of low-lying land in Reaches 2 and 3, where the channel capacity is much lower than in Reach 1. In the absence of scouring flows, weir pools in Reach 1 may act as surrogates for deep pool refuge habitat if maintained in a perennial state. However, this may require active sediment removal from weir pools, many of which have filled with sediment in recent years. Sediment removal by mechanical means should be considered as a potential complementary action to flow management, but due consideration must be given to the potential local and downstream disturbances (e.g. to vegetation and water quality) created through the use of such machinery.

Maintenance of perennial flow in the upper two reaches will likely maintain fish, platypus and macroinvertebrate populations. However, without naturally occurring high flow events and overbank floods, cues for fish movement will be limited and the abundances of large-bodied native fish are likely to remain low. In Reach 3, large-bodied fish and platypus are not likely to find suitable habitat conditions to support substantial resident populations, even under perennial or increased flow regimes. It is likely that this reach will only be periodically colonised by some individuals.

Changes in flow management can have conflicting effects for different flow-dependent assets. For instance, while extended drying may reduce unwanted stands of Cumbungi, this would have a negative effect on other water-dependent fauna. The most parsimonious approach for the system would seem to be to manage the upper parts of the system as perennial streams and the lower sections as an ephemeral series of wetlands. Maintaining perennial water in the upper reaches will ensure the maintenance of aquatic fauna, such as fish, but will also result in the retention of Cumbungi. While this is considered an issue by local landholders, Cumbungi is likely to have very little impact on flow patterns in the upper reaches and its removal would need to be considered carefully, particularly in view of the expense to other assets. For instance, given that flows are required for the maintenance of Moodies Swamp and that multi-year drying is required for killing off Cumbungi, it is not likely that this approach would be feasible. Reach 3 could either be managed as a perennial or ephemeral system. However, there are few assets within this reach that require perennial flow, and under natural conditions this section of the creek would have developed into a terminal wetland system.

The above issues were discussed with the Project Advisory Group and further considered by the Environmental Flows Technical Panel to develop a set of broad objectives for the creek. These were to maintain permanent habitat for fish and platypus in Reach 1 with a transition through Reaches 2 and 3 to a more seasonally intermittent system that provides opportunistic habitat for fish and platypus and maintains occasional / seasonal opportunities for dispersal during wet / higher flow years. Specific reach objectives were:

1) Manage Reach 1 to:
   - continue to provide permanent habitat for native fish, platypus, macroinvertebrates and other fauna
   - minimise accumulation of fine sediments and periodically engage distributary channels and floodplains
   - protect and enhance the diversity and extent of instream, littoral and riparian vegetation
   - maintain water quality (avoid periods of low dissolved oxygen) to protect fish and macroinvertebrates
   - explore opportunities for enhancing weir pools as deep water refuge habitat for fish and platypus
2) Manage Reach 2 to:
   - maintain opportunistic habitat for fish and platypus and provide for dispersal opportunities during wet years
   - minimise accumulation of fine sediments and periodically engage distributary channels and floodplains, and specifically maintain capacity to deliver environmental water to Moodies Swamp in a way that integrates flow delivery for the swamp with flow requirements for the creek.
   - protect and enhance the diversity and extent of instream, littoral and riparian vegetation
   - explore opportunities for enhancing weir pools (including those not required for current water supply operations) as deep water drought refuge habitat for fish and platypus
3) Manage Reach 3 to:
   - transition to a more seasonally intermittent waterway characterised by a well vegetated channel and riparian zone
   - allow for dispersal opportunities by fish and platypus during wet years
   - investigate whether existing weir pools / permanent pools should be actively managed as drought refuge habitat.

The history of drying and the associated current natural values in Reach 3 tend to mean there is little benefit in actively maintaining permanent flow in this reach. This reach may best be thought of as a series of terminal linear wetlands. It is likely that aquatic plants, invertebrates and amphibians capable of surviving dry periods, and native fish and platypus will opportunistically move into this reach when it is inundated. Actively delivering environmental flows to this reach to maintain permanent aquatic habitats and longitudinal connectivity should therefore be a lower priority, but nonetheless allowed to occur from time to time to provide occasional dispersal opportunities for biota.

Flow recommendations were developed to facilitate the achievement of the above objectives (Table E1). The specific flow recommendations are set for Reach 1 in order to maintain perennial flow for fish and platypus.

There are no specific flow magnitude recommendations for Reaches 2 and 3, as allowing flow from Reach 1 to progress downstream will support objectives for those two reaches. Recommendations are provided for dry, average and wet climate years. Figure E1Figure 11-1 provides a visualisation of the ideal flow regime in Reach 1 for each of these three scenarios.

An evaluation of how well the current regime meets the recommended regime indicates that irrigation operations are maintaining a permanent flow regime in the upper reaches of Broken Creek that generally supports present values. However, some elements of a preferred regime are missing. These include some higher winter flows, particularly in wet climate years, to assist platypus and fish dispersal and provide soil moisture for riparian vegetation.

While the current regime generally delivers a flow regime that allows instream values to persist, occasional higher flows in accordance with the recommendations (particularly coinciding with wet climate years) would provide additional benefit by improving the quality of benthic habitat, promoting dispersal by fish and platypus, and providing moisture and recruitment opportunities for riparian vegetation. These flows should be allowed to pass through all reaches, although a portion of the flow could be diverted to fill Moodies Swamp.

Complementary actions and further investigations aimed at maximising environmental outcomes have also been identified. These include, fencing of riparian zones, an investigation of weir pools to assess opportunities for selective pool excavation and removal of barriers to fish passage, and consultation with landholders regarding issues associated with inundation of low lying land in Reaches 2 and 3.

Table E1 Environmental flow recommendations for Reach 1 – Casey's Weir to Waggarandall Weir.

Stream		Broken Creek		**Reach 1**	Casey's Weir to Waggarandall Weir
Compliance point		Waggarandall Weir		**Gauge No.**	404239 (Waggarandall Weir)
Season	**Component**	**Volume***	**Frequency**	**Duration**	**Objective**
Summer / autumn (Dec-May)	Cease-to-flow	Not recommended			
	Low flow	5 ML/d (dry) 10 ML/d (avg) 10 ML/d (wet)	All season		M1.1, F1.1, P1.1
	Fresh	20 ML/d (avg) 50 ML/d (wet)	Once per year in average and wet climate years. Timed to coincide with filling Moodies Swamp. A proportion of the flow could be diverted to fill Moodies Swamp with the remainder passing to downstream reaches. Not required/expected in dry climate years.	Within the period Apr – Jun for as long as required to fill Moodies Swamp	W1.1, P1.2
	High flows	No specific recommendation but allowed to occur in response to local catchment runoff.			
Winter / spring (June-Nov)	Cease-to-flow	Not recommended			
	Low flow	10 ML/d (dry) 15 ML/d (avg) 20 ML/d (wet)	All season		M1.1, F1.1, P1.1
	Fresh	15 ML/d (dry) 20 ML/d (avg) 50 ML/d (wet)	Once per year in dry, average and wet climate years. A proportion of the flow could be diverted to fill Moodies Swamp, if a top up was required, with the remainder passing to downstream reaches.	2 weeks within the period Sep – Oct to coincide with topping up Moodies Swamp and growing period for vegetation. Duration could be longer if required to deliver water to Moodies Swamp	F1.2, P1.2, V1.2, V1.3, V1.4
	High flow / bankfull	Up to 200 ML/d	Only expected in very wet climate years once every 5 to 10 years in response to local catchment runoff. Local runoff could be augmented with transfers via Casey's Weir.	Determined by duration of local runoff. If augmentation from Casey's weir is provided, then 1-2 days.	G1.1, G1.2
	Overbank	No specific recommendation but allowed to occur in response to local catchment runoff.			

* Note that flows above 10-15 ML/d in Reach 2 are likely to cause localised nuisance flooding of low-lying land in some areas adjacent to the creek channel. Larger flows, up to 200 ML/d, cannot be realistically delivered through Reach 2 because of potential for more extensive inundation of private land.

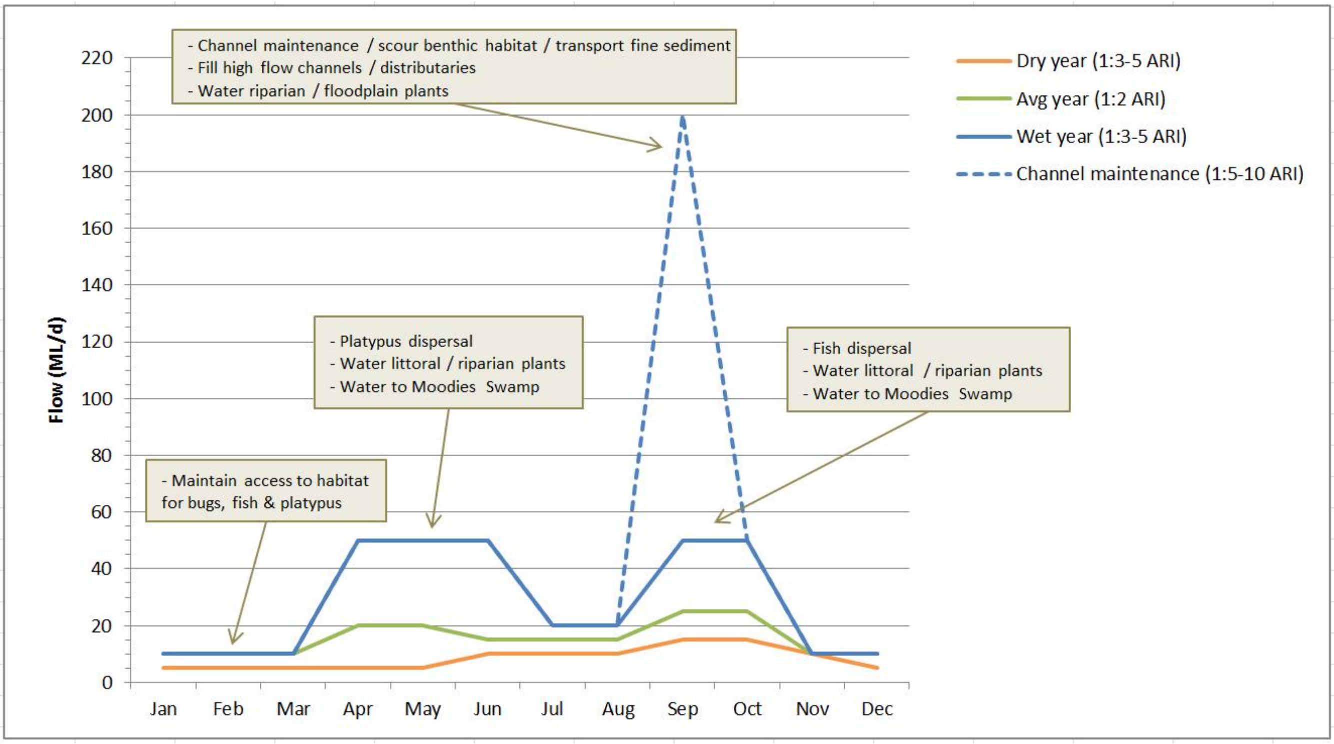


Figure E1 Visual representation of the ideal flow regime for Reach 1

1. Introduction

1.1 Broken Creek FLOWS assessment overview

The purpose of this project is to develop an updated set of environmental objectives and flow recommendations for the Upper Broken Creek (Casey's Weir to Katamatite and hereafter referred to as Broken Creek), using the revised FLOWS method (DEPI 2013).

Jacobs, formerly SKM, completed the previous flow study in 2007 during construction of the Tungamah Pipeline Scheme, which, once completed, was expected to lead to a more intermittent flow regime in Broken Creek (SKM 2007a). Since then it has become apparent that even with the Tungamah Pipeline Scheme in place, ongoing irrigation diversions along Broken Creek to supply irrigators between Casey's Weir and Waggarandall Weir mean that a more perennial flow regime is likely to persist. This permanent flow in the upper reaches means that some sections of Broken Creek can potentially support environmental values and objectives that were not considered in the 2007 study. It may also mean that some of the 2007 environmental flow objectives and recommendations are no longer valid.

In light of this, the existing flow recommendations for the Broken Creek need a comprehensive revision, especially for the upper reaches. In addition, the 2007 environmental flow recommendations provided little guidance on the acceptable degree of inter-annual flow variability associated with wet, dry and average climate conditions. The updated FLOWS method specifically addresses flow limits in different climatic conditions (DEPI 2013). Such recommendations are becoming critically important for river managers who have to plan environmental water use across multiple waterways and maximise the benefits of limited allocations during dry periods.

A 253 ML environmental entitlement is currently held in the Broken River system. To date this water has been used to provide a more natural wetting regime to Moodies Swamp, with water on route providing ecological benefits to the creek. In future, additional environmental water may become available in the Broken River system, which may provide greater opportunities to achieve environmental objectives.

The aim of the current project is to develop environmental flow recommendations for the Broken Creek system that:

- maximise environmental outcomes within the context of the ongoing need to provide regulated flows in summer-autumn to meet irrigation demands
- consider current and future environmental water availability, and the likely implications for environmental objectives that might be set for the Broken Creek system, and
- identify complementary actions that may enhance the benefits of environmental water delivery in this system.

1.2 Overview of the revised FLOWS method

The FLOWS method was initially developed in 2002 and has been improved by feedback from various groups that have applied it. DEPI (2013) formally incorporated many of those improvements in the FLOWS method Revision 2.

In this study, the FLOWS method is implemented in two stages.

Stage 1 involves project inception, data collation and review, identification of reaches and sites for detailed assessment and development of objectives for water-dependent environmental values.

Within Stage 1, consultation is undertaken with relevant stakeholders (including agencies, local community groups and individual land holders) to discuss the current condition of the creek, identify current flow-related issues and confirm water-dependent assets (fish, platypus, frogs etc.) that the community values and would like to see protected and enhanced through delivery of appropriate environmental flows. This stakeholder group is called the Project Advisory Group (PAG).

Stage 1 also documents the current condition of the system and the main flow-dependent values and environmental issues within the catchment. Selected members of the Environmental Flow Technical Panel (EFTP) tour the catchment and conduct a preliminary review of background information to divide the catchment into reaches and to select sites within each reach where detailed assessments will be undertaken. The EFTP use observations made during the detailed site assessments and a review of available literature to describe the main flow-related issues for the catchment and to develop a set of environmental objectives to manage water-dependent values in each reach. Qualified surveyors complete a feature survey of each FLOWS assessment site and the project hydrologist builds a hydraulic model to quantify the relationship between flow and inundation levels at each site. Two important outputs from Stage 1 are:

1) A *Site Paper*, which describes the reaches and sites selected for further assessment and the justification for that selection.
2) An *Issue Paper*, which outlines the expected flow requirements and ecological responses to particular flow components.

Stage 2 uses the results of detailed channel surveys and hydraulic models to derive flow recommendations that aim to meet the flow requirements of the water-dependent assets and values identified in Stage 1.

The main output from Stage 2 is a *Flow Recommendations Report*, which specifies the environmental flows that are required to meet the environmental flow objectives for each reach and describes any complementary management actions that may be required.

For the current project, the issues paper and flow recommendations paper have been merged (this report).

1.3 Environmental flows technical panel

The Environmental Flows Technical Panel (EFTP) for this project includes the following members:

- Dr Simon Treadwell (EFTP Chair)
- Dr Peter Sandercock (fluvial geomorphology & habitat stability)
- Dr Nick Bond (fish)
- Dr Daryl Nielsen (aquatic and riparian vegetation, food webs, ecosystem processes)
- Dr Gavin Rees (water quality)
- Dr Melody Serena (platypus)
- Ben Mason (hydrology and hydraulic modelling)
- Dr Michael Shackleton (macroinvertebrates)

1.4 Project advisory group

A Project Advisory Group (PAG) has been established to provide a forum in which Broken Creek's key stakeholders can provide technical input into the study by:

- helping to locate reference materials;
- providing local knowledge;
- providing technical support;
- providing local opinions about values and threats to the river and its users;
- ensuring that all important details are considered by the scientific panel developing the objectives and recommendations;
- providing an "on-ground" sanity check of the recommendations and data developed by the study;

- assisting with selection of reference sites and reaches; and
- assisting with development of flow objectives

1.5 Purpose and structure of this report

This *Issues and Flow Recommendations* report is the third and final output for the project. It provides a description of the water-dependent values and their condition and identifies possible outcomes for values based on a range of water management scenarios. Based on these potential outcomes, objectives for values and the broad flow components required to achieve objectives are identified. Finally, flow recommendations are provided for the creek that aim to achieve the objectives.

The main inputs to the report include observations from a site assessment completed by the EFTP on the 28th February / 1st March 2017, existing reports, and specific issues raised by members of the PAG and outcomes of discussion and deliberations by the EFTP, including a workshop to develop flow recommendations on 16th June 2017.

2. Overview of Broken Creek

2.1 General description

The Broken Creek catchment is located in the riverine plains of northern Victoria, north of Benalla (Figure 2-1). It has a total catchment area of ~3300 km^2 and is bordered to the south and west by the Broken and Goulburn River catchments, to the north by the Murray River catchment and to east by the Ovens River catchment. Broken Creek rises in the south east of the catchment and flows in a north westerly directly before discharging to the Murray River in the Barmah Forest, upstream of the Barmah township.

The catchment is mostly flat riverine plains within the Victorian Riverina bioregion. The flat nature of the catchment and its location within the riverine plains means that, under natural conditions, catchment runoff is low. It is thought that the current day Broken Creek may have once been the main channel for the Broken River, which now heads west from Casey's Weir (See Section 4.1). More recently, flows in the Broken Creek would have likely been intermittent, with flow occurring during winter and spring in response to local rainfall but with the creek drying to a series of pools during summer and autumn (SKM 2005).

There is an obvious natural connection between the Broken River and Broken Creek, but the connecting channel has been blocked by a levee and it is estimated that unregulated flows to the Broken Creek from the Broken River occur only about once every 20 to 30 years during large floods in the Broken River (SMEC 2005). However, under natural conditions (i.e. in the absence of the existing levee) this connection may have been more frequent, perhaps as often as once every 5 years (State Rivers and Water Supply Commission 1964), or even as frequent as 1 every two years, as suggested by (SKM 2006a).

Agricultural and water resource development over the past 100 years has significantly altered catchment and flow characteristics in the region. The catchment has been cleared for agriculture, with dryland grazing and cropping in the south and east and irrigation development in the central, north and west parts of the catchment. Historically, water was diverted from the Broken River at Casey's Weir to the Upper Broken Creek to provide water for the Casey's Weir and Major Creek Rural Waterworks District stock and domestic supply system and for small scale irrigation (State Rivers and Water Supply Commission 1964). To facilitate the movement of water through the flat landscape and to provide dam fills for the stock and domestic supply, many weirs have been constructed on the natural waterways in the region. Over six small weirs associated with the Casey's Weir and Major Creek Rural Waterworks District stock and domestic supply system are present on the upper Broken Creek.

In 2007 the Casey's Weir and Major Creek Rural Waterworks District stock and domestic supply system was piped (the Tungamah Pipeline Scheme). This was expected to result in a significant decrease in the volume of water diverted to the Broken Creek, which would lead to a more intermittent flow regime in Broken Creek (SKM 2007a). Since then it has become apparent that even with the Tungamah Pipeline Scheme in place, ongoing irrigation diversions through Broken Creek to supply existing irrigators between Casey's Weir and Waggarandall Weir mean that a more perennial flow regime has persisted. This permanent flow in the upper reaches means that some sections of Upper Broken Creek can potentially support environmental values and objectives that were not considered in the 2007 study.

2.2 Reach delineation and site selection

Natural flow regimes and environmental flow requirements vary along the length of waterways due to a number of factors including the location of tributaries, management of the system, channel morphology and structure, and location of important habitats and environmental values. For the purpose of developing environmental flow recommendations, environmental flow assessments need to be conducted in a number of river sections or reaches that represent the key features of the study area and can be identified by major tributary inflows, changes in landform, geology, channel or floodplain morphology, points of regulation (e.g. major weirs or offtakes), or changes in ecological processes or communities.

The 2007 FLOWS study (SKM 2007a) undertook a comprehensive review of the data available at the time and delineated three reaches and associated sites on the Broken Creek:

- Reach 1: Broken Creek from Casey's Weir and Waggarandall Weir (Goorambat Bushland Reserve, Quinn Road)
- Reach 2: Broken Creek from Waggarandall Weir to Reillys Weir (Geary Road)
- Reach 3: Broken Creek from Reillys Weir to the confluence with Boosey Creek (Downstream of Carmody Road).

Within each reach, sites were selected for detailed assessment based on:

- Being representative of the wider features of the reach;
- proximity to stream gauges;
- availability of information on environmental assets of the site;
- location of the main channel;
- site access; and
- availability of biological data.

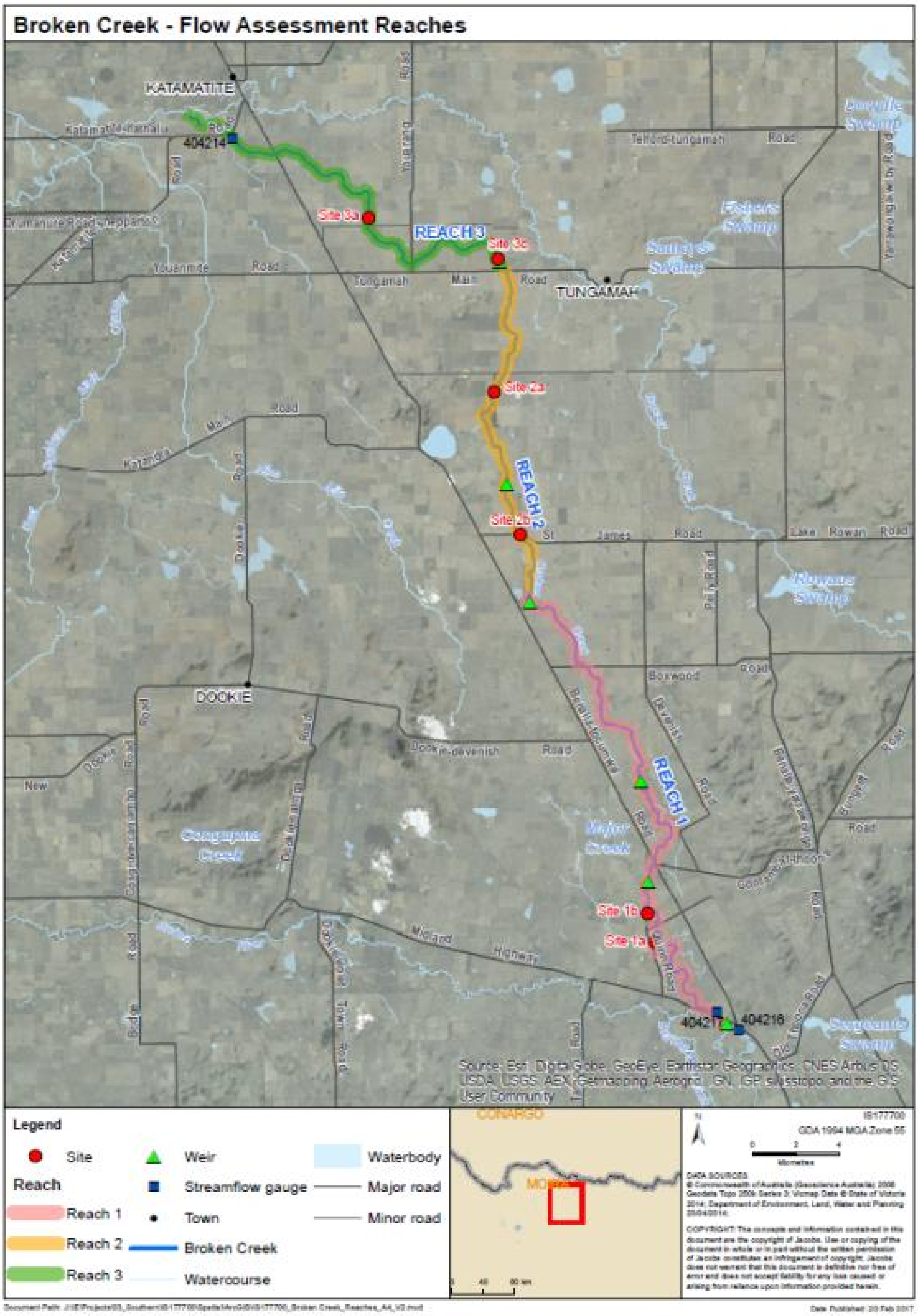
We have reviewed new information collected since the 2007 review and re-visited all reaches and sites assessed in the 2007 study. New information to inform the updates included (but was not limited to):

- Updated water quality information, including targeted water quality assessments undertaken by the Goulburn Broken CMA during the Millennium drought and Waterwatch data.
- Fish survey data collected as part of the Victorian Environmental Flow Monitoring Assessment Program (VEFMAP).
- Information gained through delivery of environmental water for Moodies Swamp.
- Outputs from various environmental flow-related research projects conducted by staff form the Murray-Darling Freshwater Research Centre.
- Assessment of platypus habitat and conservation opportunities along Broken Creek completed by the Australian Platypus Conservancy.
- Stream flow data and observations following changes in operations associated with the implementation of the Tungamah Pipeline Scheme.
- Observations from landholders and agency staff through Project Advisory Group consultation.

Based on the site inspections and review of new information, we recommended that the reach delineation and assessment sites from the 2007 study be retained, but that several new sites be included in the current assessment to: 1) consider the role of weir pools in providing permanent pool habitat, and 2) assess potential constraints in channel capacity (Table 2-1 and Figure 2-1). A more detailed description of each reach and site is provided in the Site Paper (Jacobs / MDFRC 2017).

Table 2-1 Reach and site locations.

Reach	Assessment sites
Reach 1, Casey's Weir to Waggarandall Weir	1a – Goorambat Bushland Reserve, Quinn Road (existing site) 1b – Trewins Weir Pool, Quinn Road (new Site)
Reach 2 Waggarandall Weir to Reillys Weir	2a – Geary Road (upstream of Pelluebla Road) (existing site) 2b - St James Road (new site)
Reach 3 Reillys Weir to Katamatite	3a – Carmody Road (existing site) 3b – Reillys Weir Pool (new site)



n **Figure 2-1 : Study area and reach and site locations**

3. Hydrology

3.1 Overview

There are three sources of flow in Broken Creek: regulated flow via diversions to the creek from the Broken River at Casey's Weir, unregulated flows from the Broken River during flood events and local catchment runoff. Regulated flows (for irrigation supply and environmental purposes) of up to 200 ML/d can be delivered via a regulator at Casey's Weir. Under current conditions, unregulated flows from Broken River start to enter the creek when Broken River flow exceeds ~50,000 ML/d at Casey's Weir (based on modelling of break out points and reference to times when floods flows in Broken River have been observed to enter Broken Creek – see SKM 2006a). These unregulated flows enter via overtopping of the regulator and inlet channel and via breakouts from the Broken River directly to Broken Creek at several points downstream of Casey's Weir. Catchment runoff is generated via rainfall in the Dookie Hills and Goorambat Hills with several small tributaries and catchment drains directing runoff to the Broken Creek.

There are three flow gauges along the creek to help characterise flow along the system and the relative contribution that different sources of water make to flow in the creek. These are located in the offtake channel at Casey's Weir (Gauge 404217), at Waggarandall Weir (Gauge 404239) and at Katamatite upstream of the confluence with Boosey Creek (Gauge 404214). These gauges can be used to assess the magnitude of flow entering the creek at Casey's Weir (i.e. inflow to Reach 1), the impact of diversions for irrigation by comparing flow at Casey's Weir with that at Waggarandall Weir (i.e. flows into Reach 2), and the impact of residual flows over Waggarandall Weir and catchment runoff by comparing flow at Waggarandall Weir with that at Katamatite (i.e. flow through Reach 3).

3.2 Current flow patterns

An analysis of the Broken Creek flow regime has been undertaken to show seasonal patterns in flow, changes in flow as a result of the commissioning of the Tungamah pipeline in 2009 (to replace the open channel Casey's Weir and Majors Creek Stock and Domestic supply system) and influences of irrigation, local catchment runoff and flood flows from the Broken River.

A plot of the daily flow from 1974 to 2017 is shown in Figure 3-1 and box plots of monthly variation in flow are shown in Figure 3-2. The plots show that prior to 2010 Broken Creek at Casey's Weir experienced a variable regime with annual peak flows typically in the range 60-100 ML/d and low flows of ~20 ML/d. As these flows travelled down the creek they were diverted at a number of locations to provide dam fills for the Casey's Weir Stock and Domestic system via a series of diversion weirs and open channels. In order to fill all dams, the dam fill period ran for ~9 months each year commencing in October. Flows consequently peaked through summer and diminished in a downstream direction. The stock and domestic supply system was piped in 2009 and flows were no longer diverted at Casey's Weir for stock and domestic supply, although diversions continued for irrigation purposes and for delivery of environmental flows to Moodies Swamp (see Section 3.3. for a discussion of current environmental flow deliveries). The change in operations can be clearly seen in the time series where post-2009 annual peak flows have fallen to ~40-60 ML/d and low flows are typically 5-10 ML/d.

The plots also show the changes in flow further downstream. Prior to the Tungamah pipeline, flows past Waggarandall and at Katamatite were significantly lower than the flows entering Broken Creek at Casey's Weir due to the majority of flows being diverted prior to Waggarandall and also at Reillys Weir. Since the pipeline was implemented, flows have declined at Waggarandall and Katamatite but not to the same degree as further upstream. Furthermore, the benefits of natural within catchment flows can clearly be seen in the hydrographs, with a shift towards higher flows in winter and spring, particularly at Katamatite. There are also significant travel time lags and attenuation of high flows as they travel downstream. SKM (2006a) estimated a travel time of around 4 days between Casey's Weir and Waggarandall Weir and another 3-4 days between Waggarandall Weir and Katamatite. In addition, the peaks of releases from Casey's Weir experience substantial attenuation before passing Katamatite.

The duration of flows of different magnitudes has also changed post pipeline. A spells analysis has been performed on the time series of flow at Casey's Weir to identify the changing flow regime over the last 40 years. Events over 100 ML/day, 50 ML/day, 25 ML/day, 10 ML/day, 5 ML/day and 2 ML/day are provided in Figure 3-3.

From the spells analysis the following observation are made;

- Prior to 2006, flows in excess of 100 ML/d were a regular occurrence in late summer/ early autumn of most years, often for an extended duration (several weeks). Since 2006 there have been no recorded flows over 100 ML/day.
- Prior to 2010, flows over 50 ML/d occurred for the majority of time from October to April. Since 2010 there have only been five short events over 50 ML/day.
- Under current conditions, flow rarely exceed 25 ML/d and is closer to 5-10 ML/d for the majority of time during the irrigation season.
- During the non-irrigation season flows are maintained at ~2-5 ML/d.

Under current conditions, flows diverted to Broken Creek for irrigation purposes are extracted by Waggarandall Weir (at the downstream end of Reach 1). Flows past Waggarandall Weir are in the order of 2 ML/d and are generally comprised of system/operational losses and rainfall rejections. System losses occur because, in order to supply irrigator demands, it is necessary to maintain a low base flow through the system even if no diversions are occurring (i.e. the system needs to remain 'charged').

Analysis of differences in flow patterns between dry, average and wet climate conditions has also been undertaken (Figure 3-4). Rainfall at Goorambat was used to define climate conditions – annual rainfall from 1890 to 2016 was ranked from the lowest to highest rainfall years. The lowest third of rainfall years were considered to represent dry climate conditions, whereas the middle third was considered to represent average climate conditions and the wettest third, wet climate conditions. Flow data (from 1970 onwards) for gauges along Broken Creek was then used to calculate the median monthly flow in each month for each climate type. The 90th percentile of wettest year flows was also determined.

At Casey's Weir, the flow during the irrigation season is highest in dry climate years and lowest in wet climate years – a function of irrigation demands being higher during dry periods. During the non-irrigation season there is no difference in median monthly flows because minimum passing flows are consistent regardless of annual climate type and there is little upstream catchment area providing additional runoff . However, a slightly higher flow is evident in the wettest months. Further downstream, the flow in wet climate years is higher than that in average and dry climate years, due to the influence of catchment runoff. As previously discussed, the flow regime also follows a more natural pattern with higher flows in winter/spring in association with catchment runoff. Peak flows during the wettest months occur at the most downstream site (Katamatite). During dry climate years flows can get very low through Reach 3 and may often cease. Even though permanent flows persist through Reach 1 and into Reach 2 (i.e. as spills over Waggarandall Weir), losses through Reach 2 and 3 in dry years are high and cease to flows are more likely to occur, especially through downstream reaches.

Flow is also influenced by unregulated cross-catchment inputs from the Broken River during extreme flood events. However, the frequency of these events is much reduced compared to the expected natural frequency because of river regulation and construction of levees and block banks between the Broken River and Broken Creek. Unregulated cross-catchment flows have only occurred twice in the past 45 years (1974 and 1993) but were predicted to occur around once in most years under natural conditions – although often only at small volumes. More detail on the nature of the cross-catchment connection is provided in Section 3.4.

In summary, since the stock and domestic system was piped there has been a significant reduction in both peak and base flow down Broken Creek. Reach 1 has experienced the greatest impact in terms of flow reduction. Despite the flow reduction, permanent flows into Reach 1 have been retained and these have maintained permanent aquatic habitat. Although losses occur, the permanent flow into Reach 1 has also maintained near permanent low flows through Reach 2 and Reach 3, but only at slightly lower magnitudes than prior to the pipeline. During wet climate years significant catchment runoff occurs and maintains a natural seasonal flow pattern through Reaches 2 and 3. However, during dry climate years cease-to-flows can occur, especially in Reach 3. Under current conditions, cross-catchment flows may contribute to channel scouring and widespread floodplain inundation around once every 20 years.

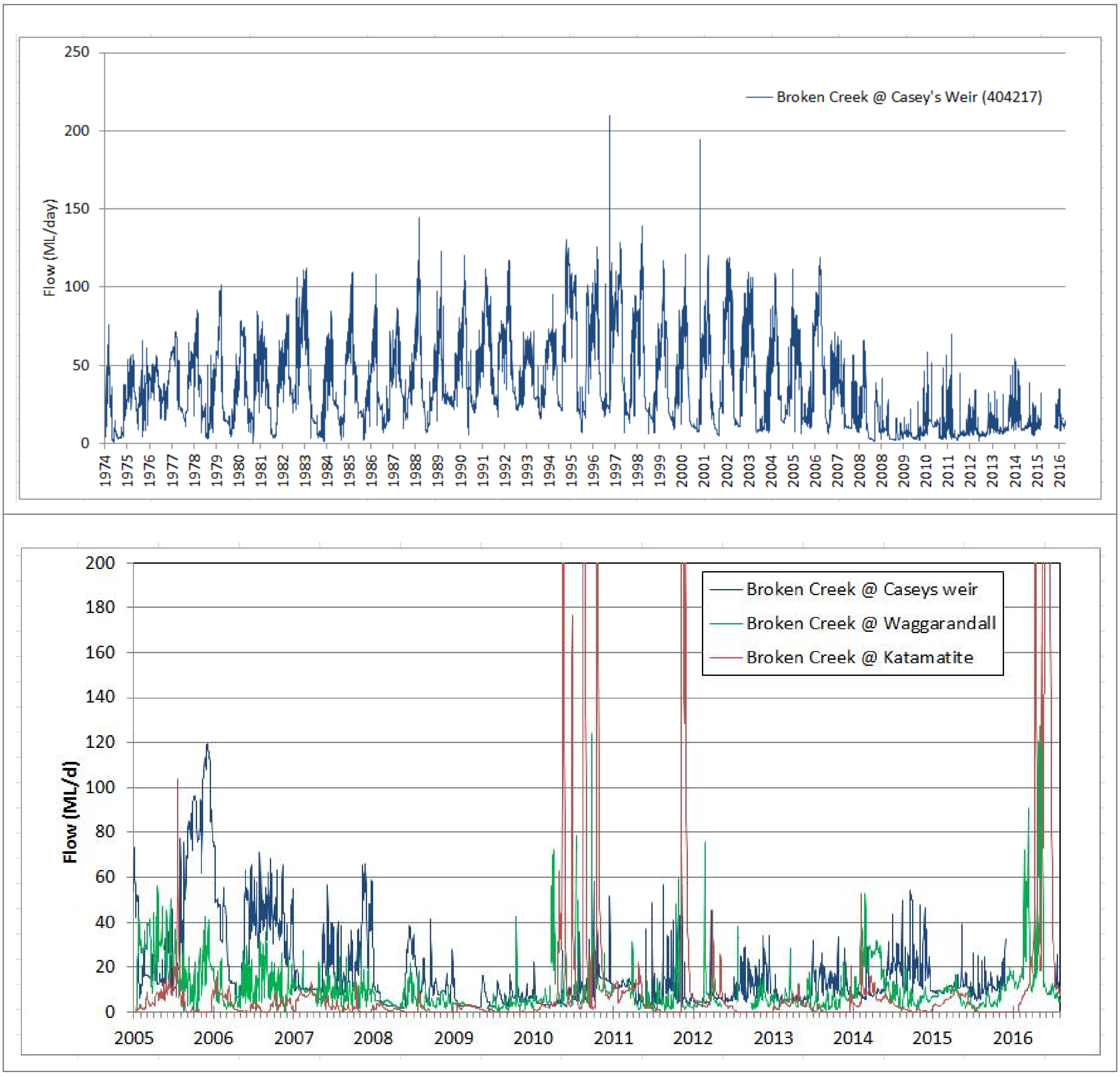


Figure 3-1: Time series flow to Broken Creek via Casey's Weir (404217) from 1975-2015 (upper panel) and compared with flow at Waggarandall Weir (Reach 2 – 404239) and Katamatite (Reach 3 - 404214) for the past 12 years (lower panel) showing changes since the commissioning of the Tungamah pipeline in 2009. Note truncation of y-axis to highlight low flows. High flows recorded at Katamatite are due to local catchment inputs.

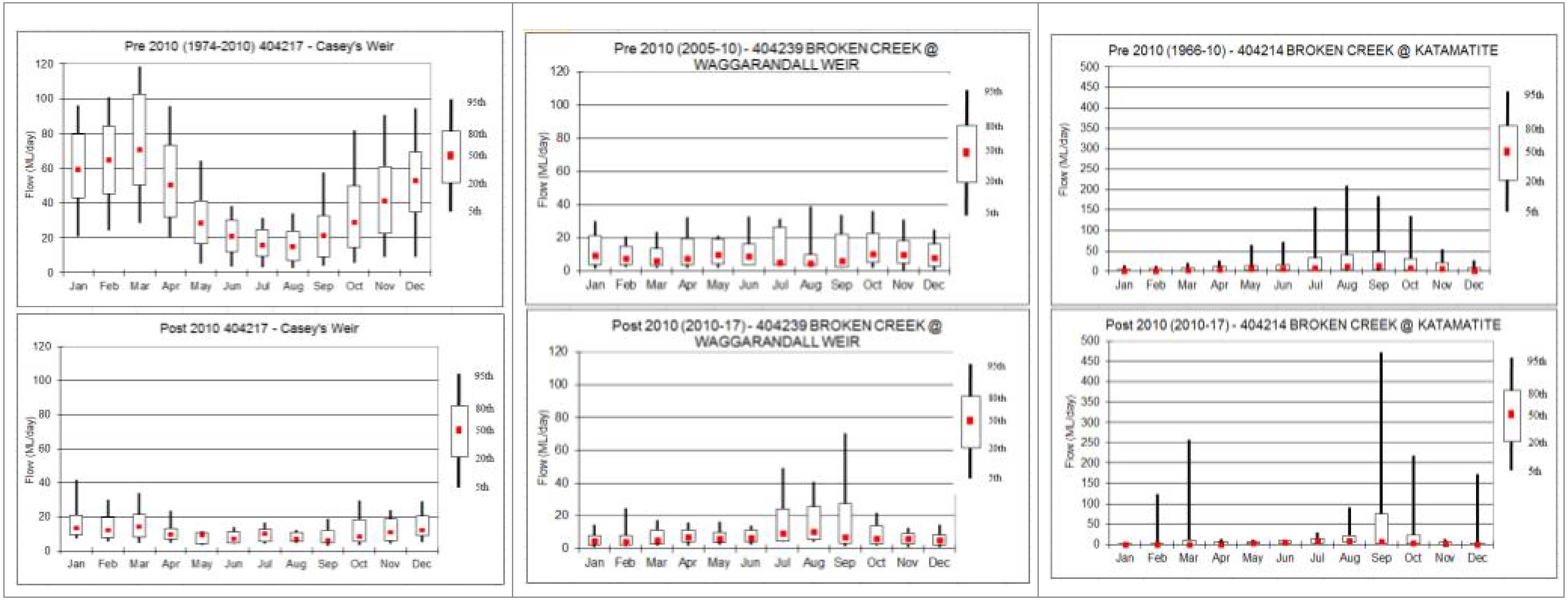


Figure 3-2: Variation in monthly flow pre and post Tungamah pipeline for Upper Broken Creek via Casey's Weir (Reach 1), Waggarandall Weir (Reach 2) and Katamatite (Reach 3).

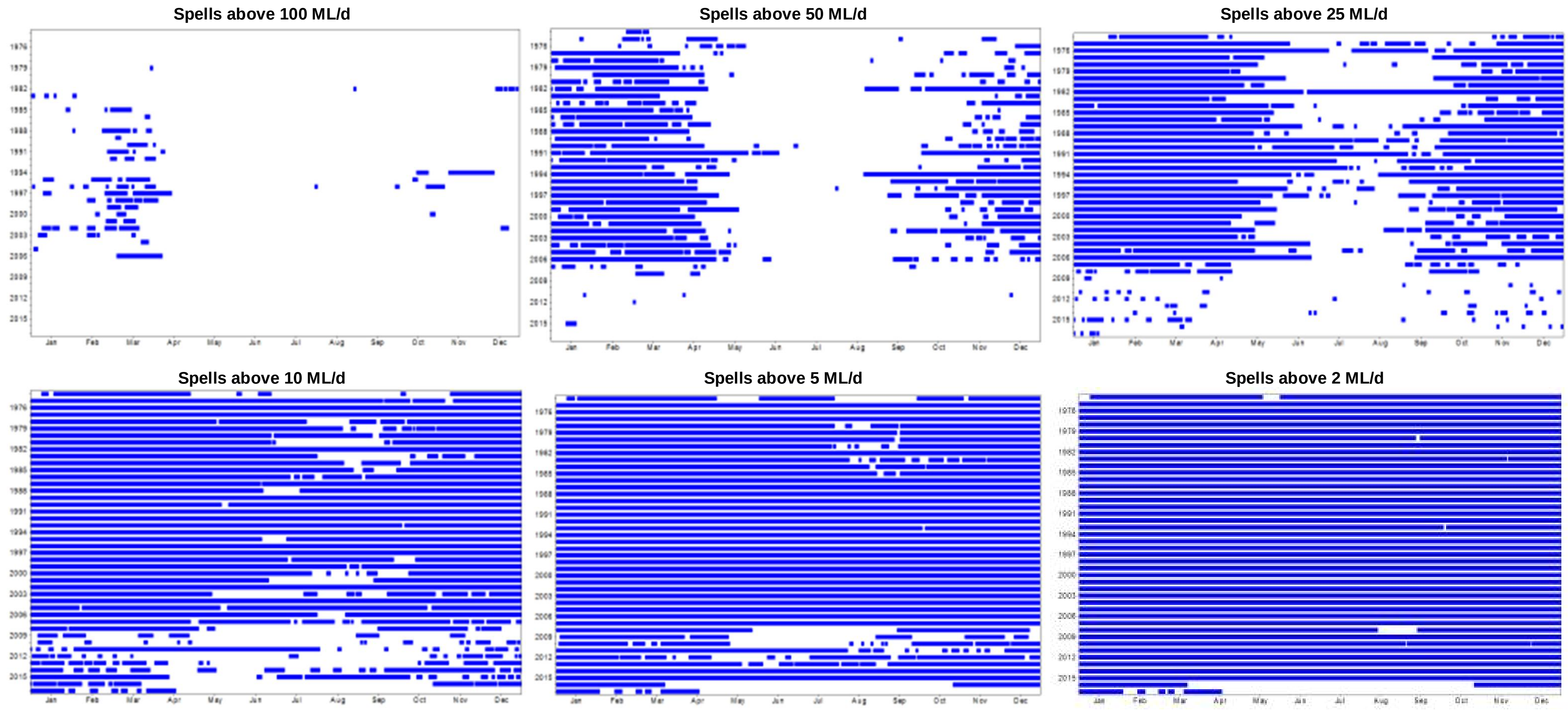


Figure 3-3: Duration of flow spells delivered to Broken Creek at Casey's Weir (note, data was missing for much of 2016).

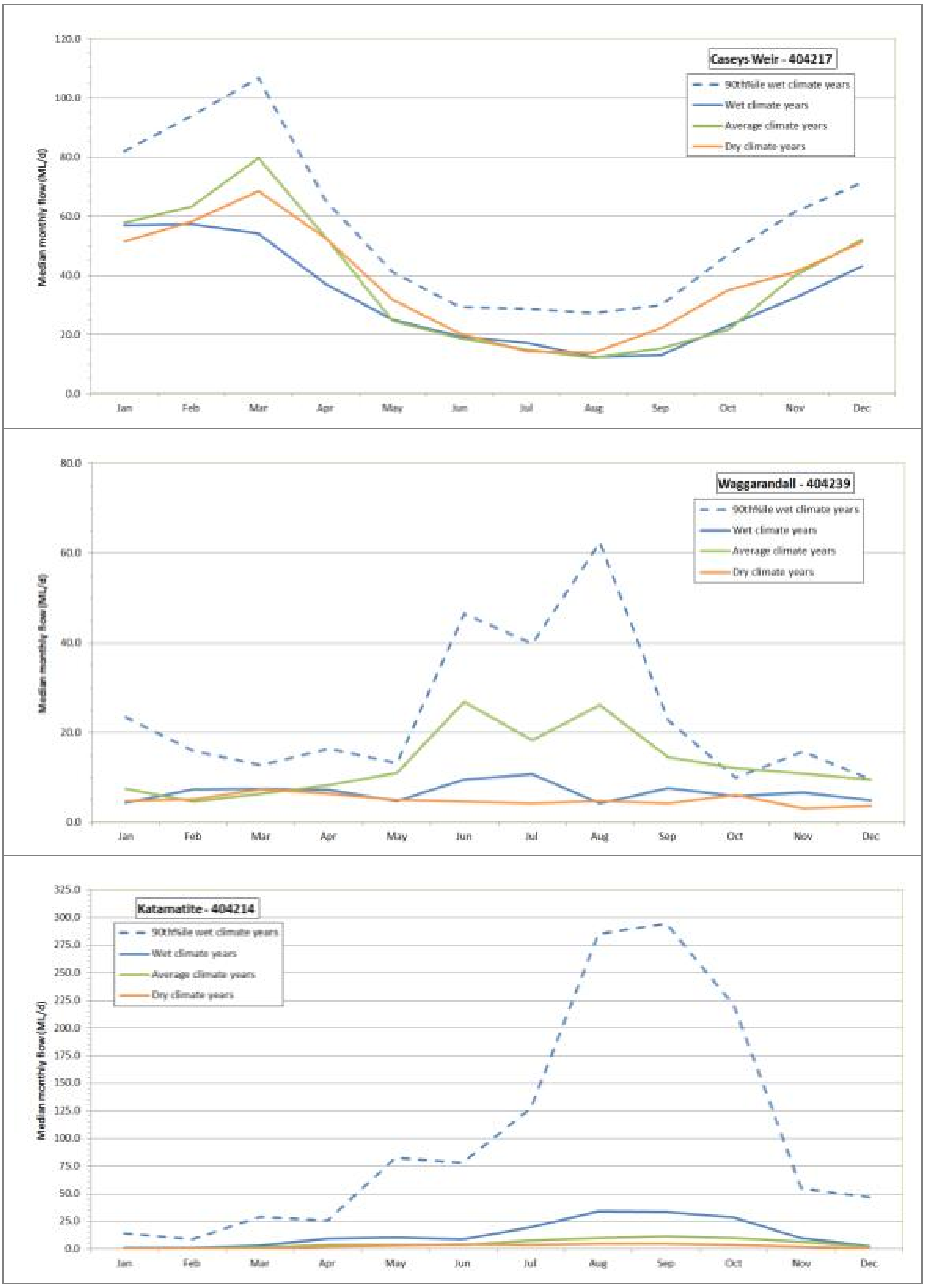


Figure 3-4 Wet, average and dry year flow patterns – average of monthly flow within each climate type for each reach (note difference in Y-axis scales).

3.3 Current environmental flow deliveries

Environmental water is delivered past Waggarandall Weir to provide for filling of Moodies Swamp in accordance with seasonal watering proposals prepared by the GBCMA and delivered by GMW. Figure 3-5 shows environmental deliveries for Moodies Swamp in 2014/15 and 2015/16. Around 10 ML/d is passed down Broken Creek and diverted to the swamp via the Geary Regulator (downstream of Waggarandall Weir). In 2014/15, 887 ML of environmental water was delivered; in 2015/16, 500 ML of environmental water was delivered. Deliveries are timed to occur at the start or end of the irrigation season to avoid periods of high irrigation demand.

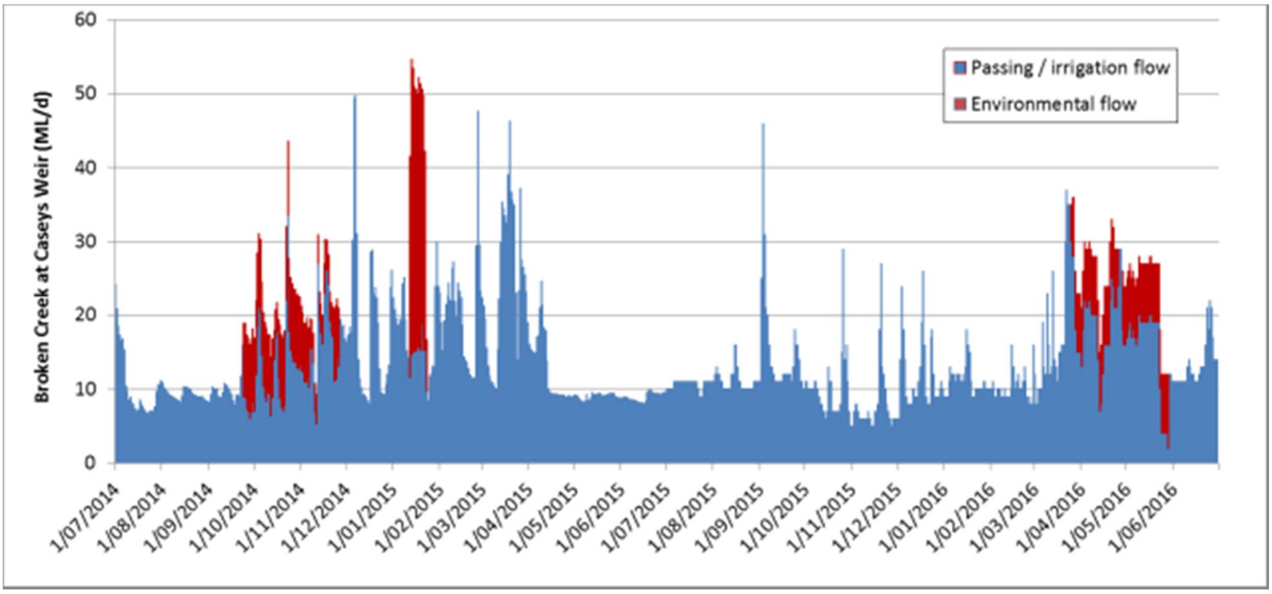


Figure 3-5 Environmental deliveries to Broken Creek in 2014/15 and 2015/16 (Data source: GMW). The blue shows the proportion of flow delivered to Broken Creek for irrigation and operational purposes, the red show additional flow delivered for environmental purposes (Moodies Swamp filling) on top of irrigation and operational flows.

3.4 Cross-catchment flows

Under natural conditions, Broken Creek would have been an ephemeral waterway that carried flood waters from the Broken River and some inflows from local catchment runoff. Two break-out points from the Broken River to the Broken Creek occur downstream of Casey's Weir (Figure 3-6).

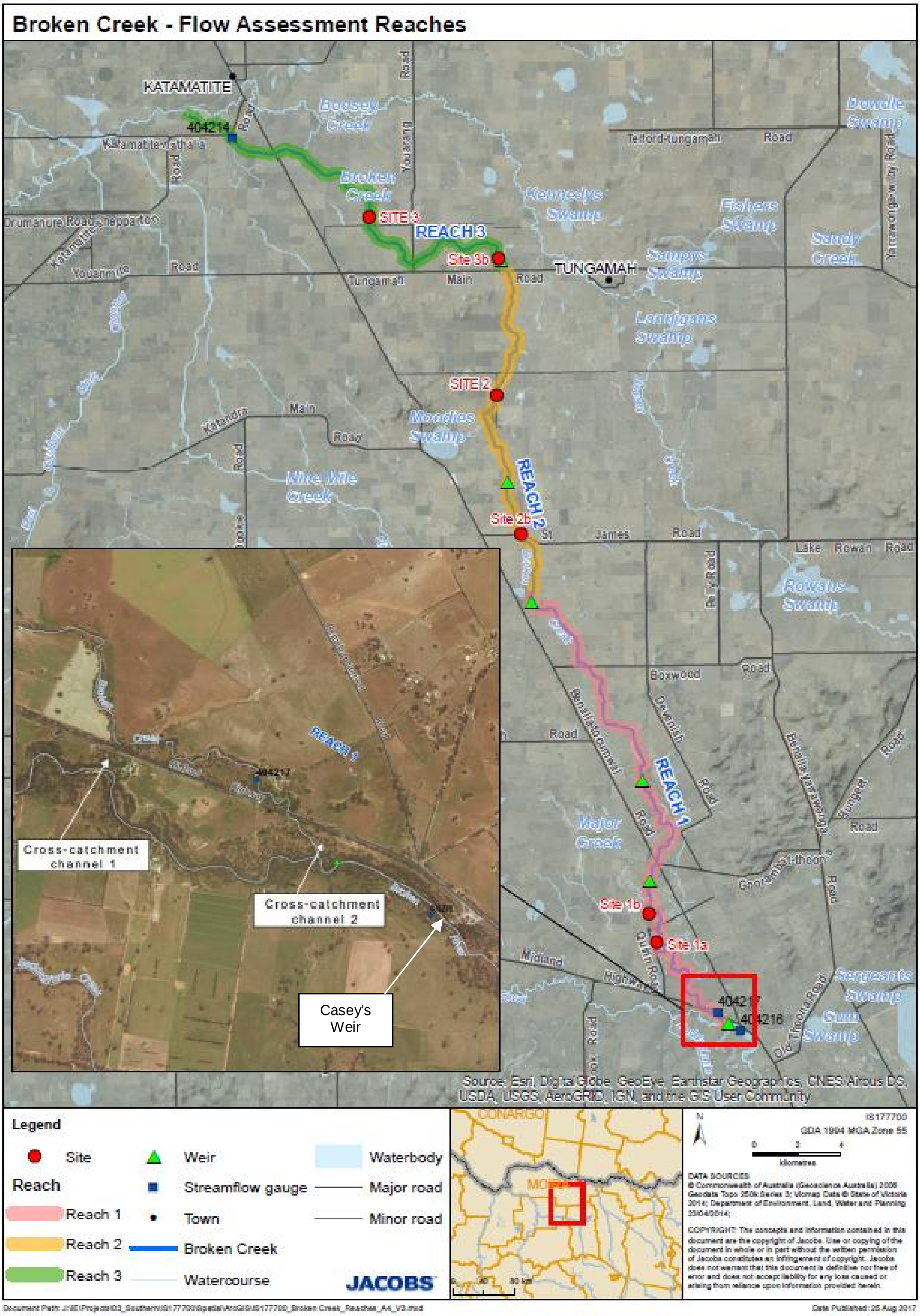


Figure 3-6 The location of cross-catchment (Broken River to Broken Creek) channels.

The threshold at which water flowed from the Broken River to Broken Creek under natural conditions (prior to river regulation and construction of levees and block banks) has been estimated to be around 15,000-20,000 ML/d at Casey's Weir (SKM 2006a). However, construction of the Casey's Weir regulator and block banks at the cross-catchment points identified in Figure 3-6 and the Midland Highway mean that flow in the Broken River must now exceed 50,000 ML/d to generate unregulated flows to Broken Creek (SKM 2006a). In recent times, only the 1974 and 1993 floods have flowed from the Broken River across the Midland Highway to Broken Creek (Figure 3-7). During these events, high flows travelled downstream and generated peaks at Katamatite of around ~5000 ML/d. At other times local catchment runoff has contributed to smaller peak flows up to ~2000 ML/d at Katamatite, except in 2012 (the flood of record), when flows peaked above 10,000 ML/d in the absence of flood flows from the Broken River (Figure 3-7) due to local rainfall across the Broken and adjacent Boosey Creek catchments (SES: Katamatite local flood guide). If the existing block bank was removed and the natural cross catchment threshold of 15,000-20,000 ML/d was restored, several more flood events in the Broken River would have flowed to Broken Creek, though none since 1996 (Figure 3-7).

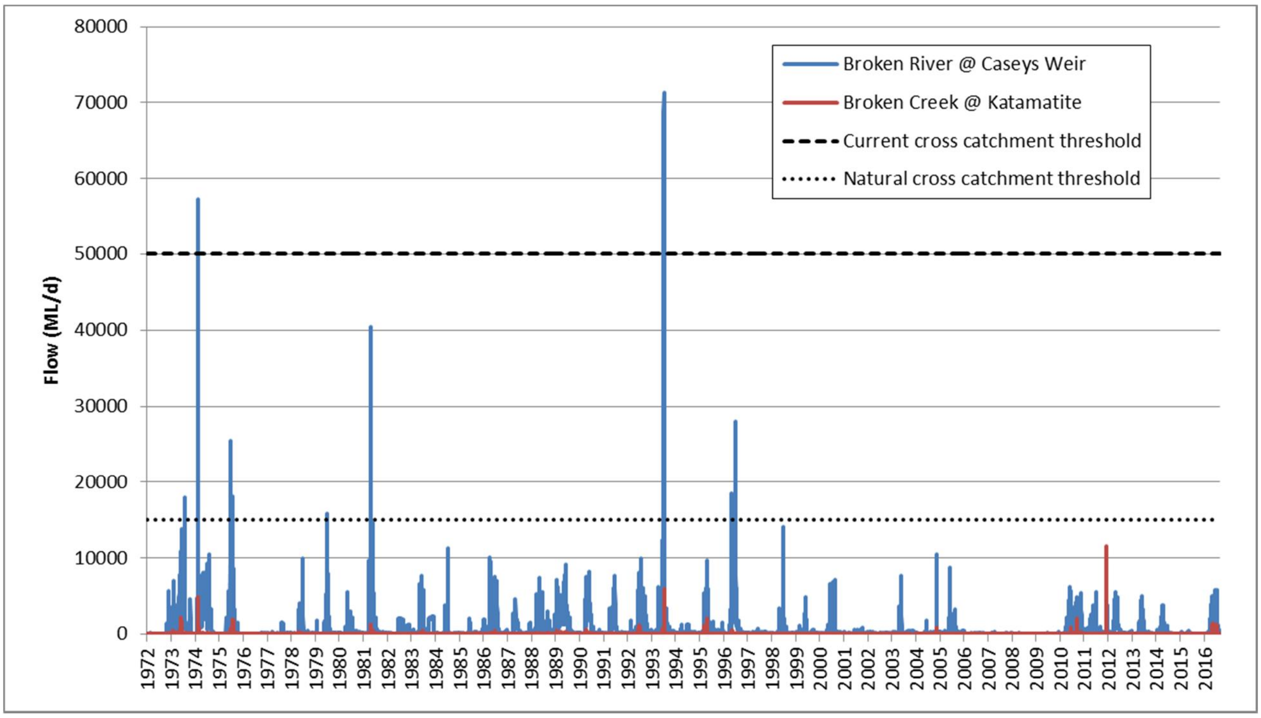


Figure 3-7 Comparison of flow in Broken River at Casey's Weir and Broken Creek at Katamatite (gauge 404214).

4. Geomorphology

4.1 Overview of condition and trajectory

The current geomorphological condition of Broken Creek should be considered in the context of the broader geological and historical changes that have shaped its evolution. Broken Creek occupies an ancestral course of the Broken River. The creek has its origins today in what is termed the Broken River Palaeovalley (Tickell 1989). This valley formed approximately 100 million years ago following the uplift of the central and eastern highlands. The palaeovalley has progressively backfilled with alluvial material and the Broken River has correspondingly changed its course in response to changing levels and landform influences (Tickell 1989).

The Broken Creek is therefore a descendant of the Broken River. Its present course exists as an effluent or floodplain distributary stream of the Broken River. Under natural conditions, Broken Creek would have been an ephemeral waterway that carried flood waters from the Broken River and also some inflows from local catchment runoff draining the Dookie and Goorambat Hills (SKM 1998). Flow would have extended across a number of distributary channels as influenced by differences in levels and variations in valley confinement and gradient across the plain. It is likely that the creek would have ceased to flow in most years, with water restricted to a series of pools or wetlands during summer and autumn. This is not dissimilar to early descriptions of numerous streams across south-eastern Australia as having a morphology consisting of chain of ponds and swampy meadows (Rutherfurd et al. 2000). If left to the natural course of its geomorphological development it is expected that the Broken Creek would have continued to fill with alluvial material and potentially revert to a swampy floodplain with a decreasingly distinct river channel. Such a trend is already evident from the upper to lower reaches of the study area (i.e. Reach 1 to Reach 3). A smaller ephemeral creek following the general course of Broken Creek may have persisted in the landscape maintained by runoff from the surrounding elevated hills.

Broken Creek has been highly modified following European settlement. The area was quickly opened up to pastoralists in the 1840-50's, following initial exploration in 1836 by Major Mitchell. Clearing of vegetation for pastures and crops quickly followed the introduction of the 1869 Land Act. Irrigated agriculture first commenced in the early 1890s when individual farmers began to irrigate their pastures using water diverted from Casey's Weir into the Broken Creek (Robinson and Mann 1996). More formal irrigation began in 1911 with the completion of the East Shepparton Channel and further development of the Murray Irrigation District in the late 1930s (Robinson and Mann 1996). Many small weirs have been constructed along the creek to facilitate the movement of water through the flat landscape and to provide dam fills for stock and domestic supply. The network of natural distributary channels and wetlands in the palaeovalley has also been disrupted through flood and drainage works.

Clearing of vegetation in the catchment and along the waterways would have resulted in increased erosion and sediment loads. The low gradient of Broken Creek means that it is geomorphologically disposed to sediment deposition. Sediment deposition along the creek has undoubtedly also been accelerated as a result of water resource development, especially due to the reduced frequency of higher magnitude flows as a result of the construction of a levee at the point of breakout from the Broken River. The construction of Casey's weir and associated diversion of flows into Broken Creek has resulted in the creek experiencing near perennial flows for the past 100 years. Continuous supply of irrigated water along the creek combined with irrigated drainage runoff increased the supply of fine sediments to the creek.

The natural disposition of the creek to deposition is further aggravated by the presence of weirs which function as efficient sediment traps. Vegetation encroachment has also been a response to the continued perennial flow regime, and this in turn is likely to have favoured further sediment deposition. With continued management of the creek as a conduit for irrigation water, it is expected that the creek will continue to fill with alluvial material impacting on the hydraulic capacity of the channel. Over the long-term this may influence its function as a conduit for irrigation water. Without physical intervention (i.e. channel dredging) it may be anticipated that the creek will continue to contract in dimensions, potentially forming a series of wetlands.

4.2 Reach condition summary

4.2.1 Reach 1: Broken Creek between Casey's Weir and Waggarandall Weir

The creek in this reach consists of a small sinuous channel with a moderate loading of large woody debris. Banks are comprised of cohesive silt/clay sediments. The overall morphology of the channel at Site 1 has not changed since 2006; however, there has been some encroachment of grasses and sedges at the channel margins (Figure 4-1).

Figure 4-1 : Repeat photos showing changes in channel condition at Site 1, Quinn Road, Goorambat, CS3 (looking upstream). Left panel August 2006 and right panel February 2017.

In some areas, vegetation has also established within the channel in association with accumulated debris and sediment. Analysis of repeat survey of VEFMAP cross-sections at this site and further downstream at Feldtman Road showed no notable geomorphic change in response to high flows experienced in 2010 (GBCMA 2014).

Analysis of an existing hydraulic model developed for this site indicates relatively low boundary shear stresses, <2 N/m^2 for flow of 200 ML/Day and up to 10 N/m^2 for high/bankfull flows of 1,000 ML/Day flows (Figure 4-2). Flows exceeding 600 ML/day may be effective in scouring softer unconsolidated clay (exceed threshold of 5 N/m^2) but they are unlikely to be effective in scouring cohesive consolidated bed and bank substrates (threshold 50 N/m^2) (Fredlund and Rahardjo 1993). Boundary shear stresses >100 N/m^2 are needed to remove in-channel vegetation (Hudson 1971, Reid 1989, Prosser and Slade 1994, Prosser et al. 1995).

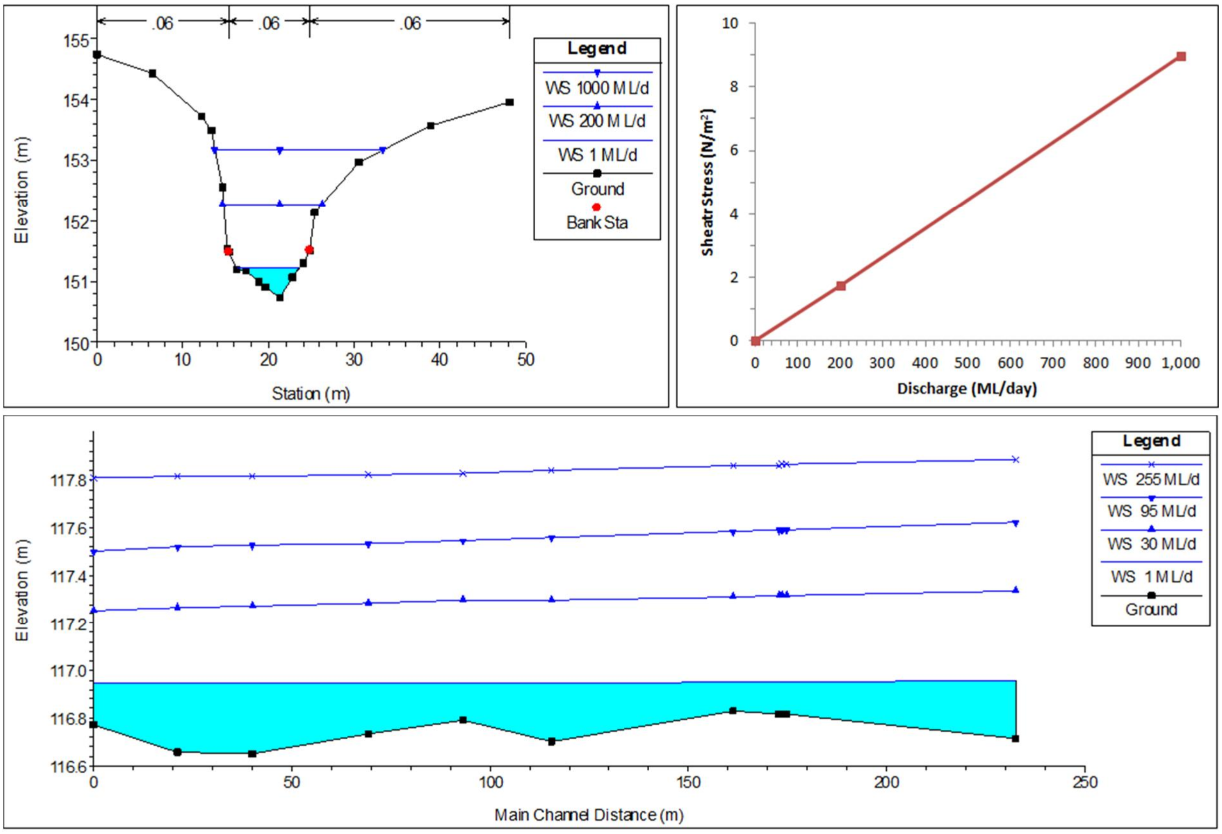


Figure 4-2 : Selected outputs from hydraulic model for Site 1, Quinn Road, Goorambat. Water levels and boundary shear stress for modelled flows at CS3 (above) and water surface profiles for modelled reach (below). Note the previous flows study recommended Summer and Winter Freshes up to 200 ML/Day and a high/bankfull flow of 1000 ML/Day fort his reach (SKM 2007b).

These results support the argument that the low gradient of the creek means that it is geomorphologically disposed to sediment deposition. The potential for sediment mobilisation and redistribution along the creek is considered to be very low for the range of boundary shear stresses calculated. The presence of a number of weirs along this reach further lowers the potential for sediment mobilisation and redistribution. While these weirs do locally raise water levels upstream and form artificial pools, they also trap and store sediment. Periodic scour and maintenance of pools along the creek in this reach is considered unrealistic as the boundary shear stresses generated by a regulated high flow release or even a breakout flow from the Broken River will not be high enough to exceed the thresholds required to mobilise sediments that have accumulated within the channel.

4.2.2 Reach 2: Broken Creek between Waggarandall Weir and Reillys Weir

The creek is less incised and smaller in hydraulic capacity through this reach. Comparison of photographs taken in 2006 and 2017 at Site 2 shows marked encroachment of vegetation across the channel (Figure 4-3).

Figure 4-3 : Repeat photos showing changes in channel condition at Site 2, Geary Road, Youarang, CS6 (looking downstream). Left panel August 2006 and right panel February 2017.

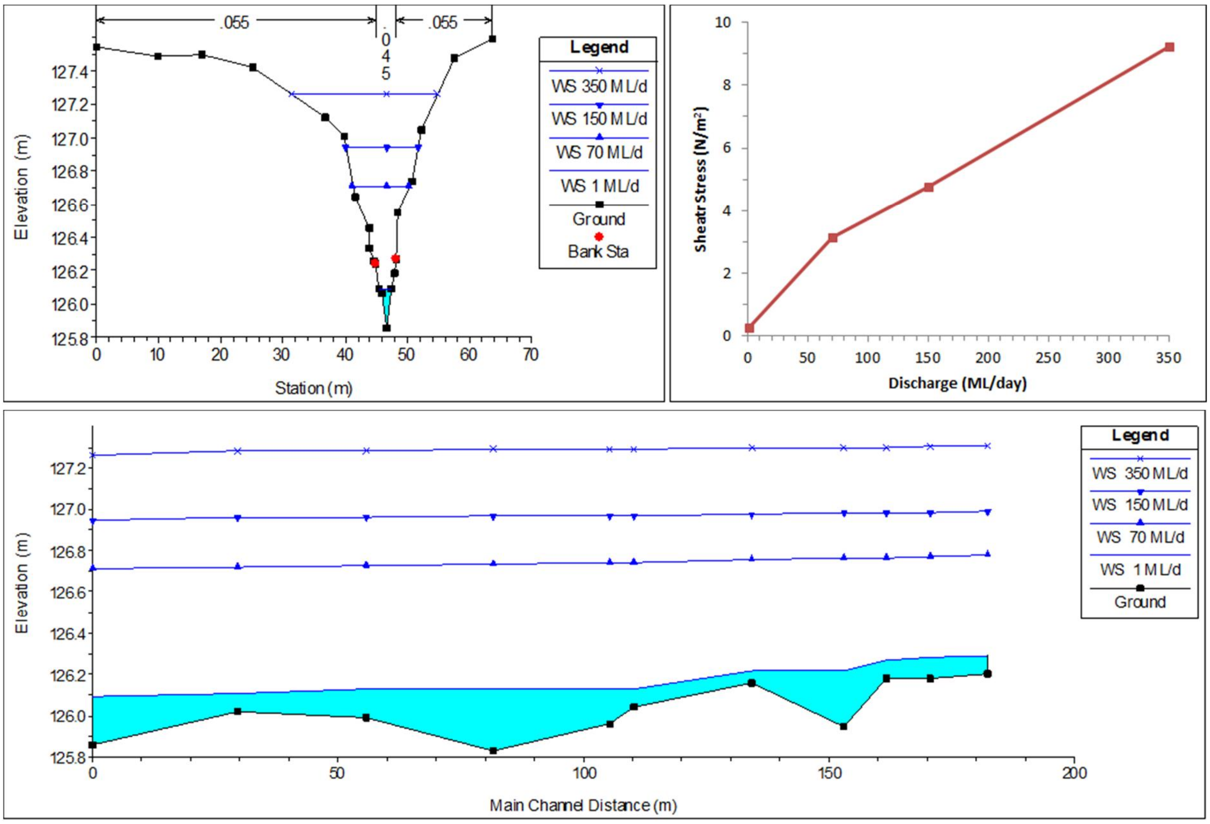


Figure 4-4 : Selected outputs from hydraulic model at Site 2, Geary Road, Youarang. Water levels and boundary shear stress for modelled flows at CS6 (above) and water surface profiles for modelled reach (below). Note the previous flows study recommended Summer and Winter Freshes of 70-110 ML/Day and a high/bankfull flow of 150-350 ML/Day (SKM 2007b).

Similar to Reach 1, hydraulic modelling indicates that even the high flow/bankfull flows of 150-350 ML/Day would generate relatively low boundary shear stresses in the range of 5-10 N/m^2 (Figure 4-4). These flows may scour softer unconsolidated sediments but are not sufficient to scour cohesive consolidated substrates or vegetated surfaces.

Continued deposition and accumulation of sediments is anticipated for this section of the creek. Perennial flows are enhancing the establishment of grasses and sedges along the channel, the foliage increasing the roughness of the channel and potential for sediment deposition. This is a positive feedback where sedimentation is enhanced by plant growth, and accumulated organic material and/or deposited sediments form areas for plant establishment. The creek today in this section of the reach has the appearance of a wetland as opposed to a defined waterway. The changes noted in the creek's form at this site, provides an insight into a future state in which other sections of the creek may be expected to transition to and highlight how this can take place over a relatively short period of time (i.e. decades).

4.2.3 Reach 3: Broken Creek between Reillys Weir and Katamatite

The gradient and hydraulic capacity of the creek is notably lower in this reach. The creek at Site 3 appears to have been dredged in the past to more effectively convey water through an otherwise shallow depression in the landscape (Figure 4-5). The morphology of the channel does not appear to have changed since 2006. Some encroachment of vegetation is noted at the margins of the channel.

Figure 4-5 : Repeat photos showing changes in channel condition at Site 3, Mills Road, CS1 (looking upstream). Left panel August 2006 and right panel February 2017.

Boundary shear stresses for the range of modelled flows are significantly lower than upstream reaches (Figure 4-6). High flow/bankfull flows of 95-225 ML/Day have boundary shear stresses that are below 3 N/m^2 at CS1 and comparison with other cross-sections shows that they generally do not exceed 5 N/m^2; the critical threshold for scour of unconsolidated soft clay substrates. Similarly to Sites 1 and 2, the hydraulic analysis of Site 3 supports the notion that the creek is geomorphologically disposed to deposition.

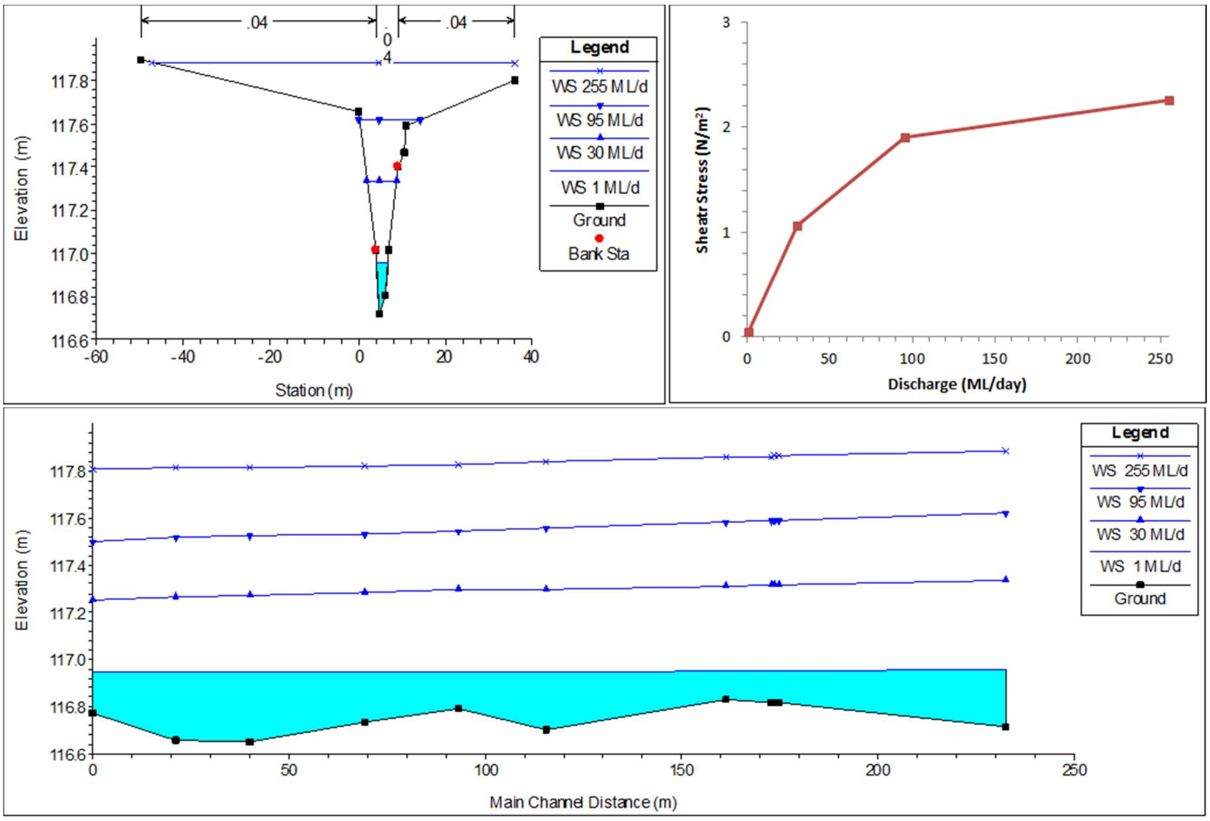


Figure 4-6 : Selected outputs from hydraulic model at Site 3, Mills Road. Water levels and boundary shear stress for modelled flows at CS1 (above) and water surface profiles for modelled reach (below). Note the previous flows study recommended Summer and Winter Freshes of 30-70 ML/Day and a high/bankfull flow of 95-255 ML/Day (SKM 2007b).

4.3 Review and update of geomorphology objectives

The 2007 flows study had two geomorphology objectives for each of the three reaches (SKM 2006b, 2007b). The first objective was to rehabilitate deep pool habitat and the second objective to facilitate sediment transport through the reach. The flow component identified to support this objective was bankfull flows, with the expected response being increased depth of flows and a more defined channel. It was also noted that some pools may require selective excavation.

Given the low gradients in the system it is unlikely that regulated environmental flows will generate sufficient shear stress to scour deep pool habitat and facilitate sediment transport. The system is in the process of transitioning to a new state that may not support deep pool habitat or the entrainment, transport and redistribution of sediment from pools.

It is expected that the creek will continue to accumulate sediments and the capacity of the channel will contract in its dimensions and form a series of wetlands. Indeed, the transition in the state of creek from a defined waterway to a wetland has been observed at a number of locations along its course over the past decade, especially in downstream reaches. The changes in flow regime have enhanced the conditions for plant establishment and growth, which in turn may increase the potential for organic matter to accumulate in the channel and/or sediment deposition, forming new areas for plant establishment. The final state of the creek is largely influenced by the degree to which it is managed as an ephemeral or perennial system and the vegetative response to drier or wetter conditions.

Overall objectives for geomorphology are largely driven by the objectives for other values. If it is desirable to maintain pool habitat for fish and platypus (see Section 6) then, where possible, objectives are to provide flows sufficient to mobilise sediments and maintain pools. This needs to recognise that flow alone is unlikely to be sufficient to achieve this outcome. While weir pools may provide surrogate deep pool habitat, they are also subject to infilling. Mechanical removal of sediments may be required in order to restore pool habitat. While high flows are unlikely to be strong enough to scour deep pools, they may be sufficient to scour fine sediment that has accumulated on the surfaces of submerged wood – hence helping to maintain the quality of benthic habitats for macroinvertebrates, which in turn, is beneficial to fish and platypus. An additional, and more easily achieved objective, is to maintain connections to wetlands that are distant to the creek, of particular importance being Moodies Swamp. This requires that larger flows are allowed to progress through the system, and while these flows may not contribute significantly to the transport of large quantities of sediment, they are still important to engaging floodplain wetlands, supporting floodplain vegetation communities and providing dispersal opportunities for a range of biota.

5. Vegetation

Data on the presence of instream vegetation were not collected as part of a formal monitoring program but consists of observations taken within each of the three reaches. Information is only provided on the more common species present.

5.1 Wetlands

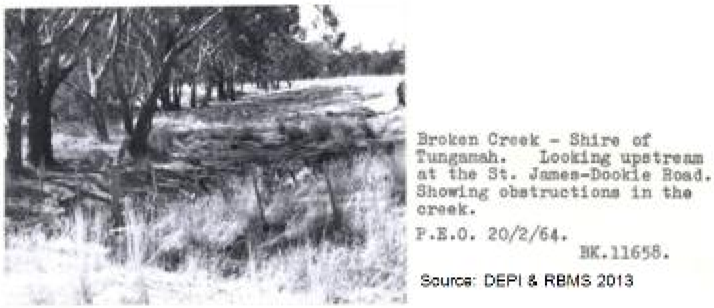
Only one wetland was visited - Moodies Swamp (Figure 5-1) - midway along Reach 2. Moodies Swamp is a 181.6 hectare seasonal, shallow freshwater marsh and listed as a nationally important wetland (Environment Australia 2001) and subject to an environmental watering plan (Goulburn Broken CMA 2012). Surveys of the vegetation in 2012 indicated that the dominant vegetation within the wetland is cane grass and aquatic herbs with a fringe of swampy woodlands (Goulburn Broken CMA 2012). Because Moodies Swamp has its own management watering plan we have not considered the environmental flow objectives of this site in the current document, although environmental flow recommendations for Broken Creek will be considered in the context of existing water regime recommendations for the swamp.

Figure 5-1 : Moodies Swamp, Broken Creek.

5.2 Riparian vegetation

The riparian zone appears to have undergone significant changes since 2007 (Table 5-1). In 2007, regeneration of River Red Gums (RRG) was evidenced by the occurrence of juveniles and saplings. There was no evidence of further recruitment of this species along the 3 reaches assessed during the March 2017 field survey. There was evidence that water couch was expanding and encroaching further into the river channel and significant beds of knotweed were also observed. The increased distribution of water couch and knotweed are likely to be indicative of more favourable growing conditions that result from low flows creating favourable habitat (soft damp sediments) for these species on in-channel benches.

Table 5-1: Observations of riparian vegetation in 2007 and 2017.

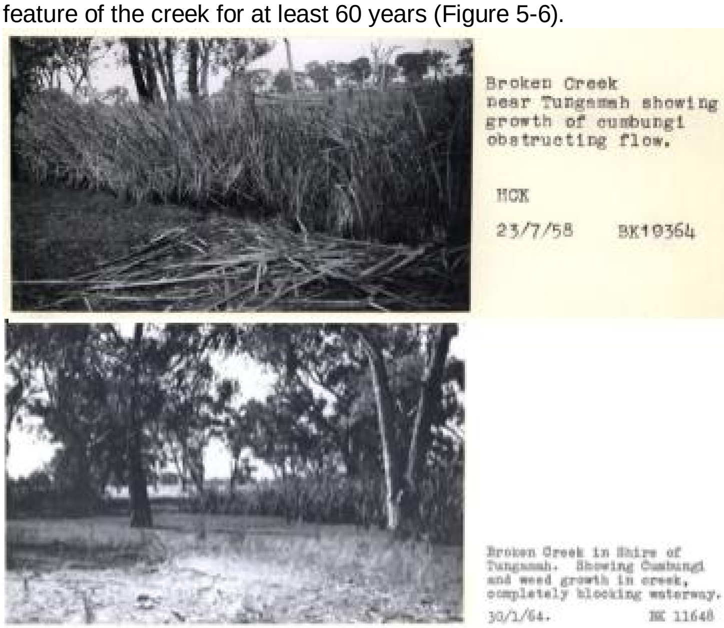
Species	Observations 2007	2017
River Red Gums (*Eucalyptus camaldulensis*)	Juvenile and sapling River Red Gum were conspicuous down Broken Creek; mostly close to the water line in Site 1; scattered across the bench/floodplain amongst the Water Couch turf at Site 2; and as a dense regeneration thicket at Site 3	The riparian zone along the three reaches is dominated by mature River Red Gums. In contrast to observations made in 2007 there was little evidence of any regeneration occurring. In the previous study it was noted that environmental conditions favouring the germination-establishment sequence for RRG only appeared to occur in a narrower area. This area now appears to be further reduced or non-existent. As a consequence the distribution of RRG will continue to become more contracted over time. This contraction may be due to grazing removing seedlings or most likely a lack of overbank flooding and loss of appropriate moisture regimes to promote germination and growth. Despite the lack of wide scale recruitment, there does appear to have been an increase in recruitment of RRG in recent years compared with historical photographs (Figure 5-2).   **Figure 5-2 Historical and current riparian zone at St James – Dookie**
Water couch (*Paspulum distichum*)	Dense mats noted at sites on the Broken Creek: on the bench / floodplain at Site 2, and also fringing the downstream side of the rock-ramp fishway at McLaughlin's Weir (Reach 2).	Water couch appears to be becoming more dominant along the margins of the creek particularly on benches, and was very common along the creek in all reaches (Figure 5-3).

Species	Observations 2007	2017
		 **Figure 5-3 Water couch in Reach 1** Water couch typically grows in moist to water-logged conditions (Roberts and Marston 2011). The expansion of water couch is likely to be indicative of low flowing perennial water regimes leading to expansion of damp benches within the river channel and favourable habitat for this species.
Knotweeds (*Persacaria* spp.)	No observations were specifically recorded for this species	Knotweed was observed in dense cover in sections along Reach 2 and 3 interspersed with tall spike rush and water couch (Figure 5-4). The expansion of knotweed is likely be due to similar causes as water couch with low flows creating favourable condition on benches for this species.  **Figure 5-4 Dense knotweed in Reach 2**

5.3 Instream

Observations of the instream vegetation suggest there has been an expansion and encroachment of species that prefer low flowing perianal water.

Table 5-2 : Observations of instream vegetation in 2007 and 2017.

Species	Observations 2007	2017
Cumbungi (*Typha domingesis*)	Observed to form extensive beds at various sites. A vigorous clump filled the channel upstream of Site 1; clumps were evident in the weirpool of Reillys Weir; upstream of Site 3, a clump was nearly blocking the channel, much had been dredged out, and seed was being washed downstream.	Cumbungi typically occurs in permanent or near permanent waterbodies or where high nutrient levels are present (Roberts and Marston 2011). There appears to be a continual expansion of Cumbungi within all 3 reaches (Figure 5-5). In general Cumbungi appears to extend across the entire section creating small slackwater regions where sediment can accumulate. This was particularly obvious up stream of Reillys Weir  **Figure 5-5. Cumbungi in Reach 1** Anecdotal observations from landholders suggest that Cumbungi (and other instream vegetation) is becoming an increasing problem with respect to blocking the channel, especially in sections of Reach 2 and 3, and, that the situation has worsened since flow regimes changed post the Tungamah pipeline. However, photos of Broken Creek from the 1950s and 60s show that dense stands of Cumbungi have been a feature of the creek for at least 60 years (Figure 5-6).  **Figure 5-6. Historical evidence of dense Cumbungi growth in Reach 3 from the 1950s and 60s (Source: DEPI and RBMS 2013).** It appears that historical control of Cumbungi has been achieved by

Species	Observations 2007	2017
		dredging and the use of herbicide. However, such active control may have ceased once the Tungamah pipeline was commissioned. If considered an ongoing management issue, control can be achieved by mechanical, chemical or burning to reduce the number of stems. Live and dead stems then need to be kept submerged to a sufficient depth (>45 cm) for at least one year (Apfelbaum 1985).
Tall Spike-rush (*Eleocharis sphacelata*)	Tall Spike-rush was noted at various places down Broken Creek: extensive beds through much of the weirpool at McLaughlin's Weir (all grazed to a few cm above water level, consistent with feeding activity of Purple Swamp Hen); within the channel at Site 2	Tall spike rush typically occurs in permanent or near permanent waterbodies. Spike rush was abundant in sections of Reach 2, completely dominating McLaughlins Weir and in some sections appearing to completely choke the creek channel.  **Figure 5-7. Tall spike rush dominating McLaughlins Weir** Control measures for spike rush are unknown but it is likely that measures used to control Cumbungi would be effective on this species.
Triglochin spp. (Water ribbons)	No observations recorded	Common in still to slow flowing water in wetlands and rivers (Cunningham et al. 2006) and may grow on wet mud or at depths of 2 meters (Sainty and Jacobs 1981). Water ribbons were recorded in all reaches (Figure 5-8). Although not common, its increased abundance would be indicative of reduced flows and more perennial water or restricted stock access.  **Figure 5-8 Triglochin in Reach 1**
Vallisneria australis (Ribbon weed)	No observations recorded	Anecdotal evidence suggests that ribbon weed was once widespread in many lowland rivers including the Broken River and Broken Creek in north-eastern Australia (T. Hillman pers. comm.). In most rivers it is now absent or only patchily distributed. Reasons for the decline in the distribution of ribbon weed are unknown but have been linked to a number of factors such as nutrient enrichment or disturbance by European carp (Roberts & Marston 2011). Ribbon weed is adapted to

Species	Observations 2007	2017
		growing and persisting in turbid rivers and wetlands (Roberts and Marston 2011) and was observed in Trewins Weir pool. Due to the loss of pools within the Broken Creek, weir pools may provide surrogate for habitat for plant species such as ribbon weed.

5.4 Review and update of objectives

Objectives for vegetation in the 2007 study were to:

- Facilitate River Red Gum regeneration away from channel margins, noting that it was desirable to avoid regeneration at the channel margin where excessive growth could impinge on the channel.
- Maintain and enhance the diversity of in-channel vegetation (e.g. Water Ribbons).
- Enhance native species diversity and width of the channel edge (littoral) zone.
- Reduce extent and abundance of water couch and introduced sedges.

Broken Creek currently supports diverse instream and littoral vegetation; however; there does appear to be limited River Red Gum recruitment. The objectives described above are still considered appropriate in that it is desirable to achieve recruitment of River Red Gum in the riparian zone and across the broader floodplain and maintain a diverse community of instream and littoral vegetation. However, there is also community concern regarding what is perceived to be excessive growth of vegetation in the creek channel, particularly in parts of Reach 2 and 3, and that this vegetation is slowing flow down, contributing to further channel contraction and causing flooding of low lying land adjacent to the creek. On this basis, the community is keen to understand whether the current vegetation condition is a function of flow changes resulting from the implementation of the Tungamah pipeline and whether flow manipulation could be used to manage excessive in-channel vegetation growth.

Anecdotal evidence suggests there have been recent (i.e. the 9 years since the implementation of the Tungamah Pipeline) changes to the vegetation communities along the Broken Creek, particularly with an increase in abundance of plants within the channel that prefer sustained perennial water (e.g. Cumbungi) and/or damp conditions (e.g. water couch). However, historical evidence indicates that growth of Cumbungi in the channel has been an ongoing feature of the waterway for many decades, particularly in Reaches 2 and 3. This suggests that the flow regime (or change in flow regime) in itself is not necessarily the primary factor influencing the condition of vegetation. Past activities, such as grazing and mechanical / chemical removal of in-channel vegetation, are likely to have been as or more influential on the condition of the channel than flow alone.

The current density of vegetation in the channel at various locations is not an ecological concern. Indeed, the existing vegetation communities (in terms of their diversity, abundance and spatial distributions) are an important ecological feature of the waterway, providing a diverse range of habitats, especially for fish, amphibians and birds. On this basis, the EFTP is of the opinion that the current vegetation condition is broadly consistent with overall objectives for the creek. Although, it is acknowledged that at some locations in-channel vegetation growth could be contributing to nuisance flooding and that site specific management may be required on a case by case basis. However, it is also clear that it will be difficult to manage in-channel vegetation with flow alone, without compromising other objectives. For example, vegetation can be removed by scouring during large flows, by prolonged drying that results in loss of viability of rhizomes, or by removal of above ground biomass (e.g. by mechanical removal, spraying or fire) followed by prolonged (up to three years) inundation (Apfelbaum 1985).

In Broken Creek, large managed flow events are unlikely to scour established vegetation successfully due to the limited channel capacity of the Broken Creek particularly in Reaches 2 and 3 (and see Section 4 for a discussion of stream geomorphology and inability for high flows to generate shear stresses sufficient to scour instream vegetation). In addition large natural flow events that have occurred in recent years (e.g. March 2012 when flow exceed 10,000 ML/d at Katamatite, and September 2016 when flow exceeded 160 ML/d at Waggarandall and 1500 ML/d at Katamatite) do not appear to have caused scouring and removal of mature stands of plants such as Cumbungi. This suggests that, from the perspective of managed flows, the only likely option for controlling species such as Cumbungi is biomass removal followed by prolonged drying or inundation.

It is likely that sufficient flows can be provided within Reaches 1 and 2 to maintain and support the current vegetation communities in their current condition. Within these reaches, Cumbungi does appear to be expanding in area but is unlikely to significantly influence flow patterns within the creek due to its capacity to bend and lay flat during periods of high flow. One option for vegetation control would be to implement an intermittent flow regime. This would lead to the consolidation of fine sediments, and prevent encroachment and establishment of riparian species, and would maximise the potential diversity of plants within the creek. However, this may be at odds with maintaining other waterway values such as maintaining suitable resident and refuge habitats for large-bodied fish and platypus.

It does appear unlikely that sufficient water can be provided for plant communities that require perennial flows in Reach 3. It is likely that this reach will become more intermittent. It is likely that the upper areas of this reach will become more wetland like and develop plant communities similar to those of other wetlands that occur within the region (such as Moodies Swamp). Below this, the creek is likely to become increasingly shallow and constrained and instream vegetation will be lost and replaced by more perennial species, such as knot weed and water couch. However, the creek will still carry seasonal flows from local catchment runoff and occasional overbank flows from the Broken River. Some of these flow events could be quite large and result in flooding.

6. Aquatic fauna

6.1 Macroinvertebrates

Data on the macroinvertebrate assemblages of the Broken Creek are sparse and no data exist from before flow diversions from the Broken River commenced. In 1999 and 2010 the Environment Protection Authority, Victoria, (EPA) conducted macroinvertebrate monitoring assessments of the Broken Creek as part of the Sustainable Rivers Audit (EPA 1999, Davies et al. 2012). While individual site assessment findings are available for the 1999 report, the 2010 data were aggregated into a basin-wide assessment for the Broken Valley and individual site assessments are not provided in Davies (2012). However, we were able to obtain individual site data directly from the EPA. In 2005/2006 the EPA conducted macroinvertebrate monitoring to assess any effects of the installation of the Tungamah pipeline. These data have not been published but are referred to in McMaster et al. (2006). Data from each of these monitoring assessments are available from the Atlas of Living Australia (http://www.ala.org.au/). McMaster et al. (2006) provides data on three Crustacean species present in the Broken Creek and an analysis of what effect changes in flow regime may have on these species. The sites included in all of these projects are distributed within each of the reaches chosen for the current FLOWS assessment, and are likely to be representative of the reaches as a whole.

The EPA monitoring programs are conducted using a standardised in-stream condition (ISC) protocol. This protocol combines relative abundances and measures of sensitivities to environmental stressors for macroinvertebrate taxa present at a site to indicate the level of degradation relative to reference condition. These are represented by two indicators, AusRivAS and SIGNAL scores. A summary of the AusRivAs and SIGNAL scores for the Broken Creek surveys is presented in Table 6-1. While AusRivAs and SIGNAL scores are the most widely used indicators of river health, they are not overly suitable for assessing intermittent streams, such as parts of Reach 3. This is largely due to the scarcity of “sensitive” taxa in these systems. Furthermore, while interpretations of SIGNAL scores are generally given as a scale of pollution impact (e.g. severe, moderate, mild, healthy), in low-land systems, such as the Broken Creek, low scores are likely to be driven more by environmental conditions (e.g. periods of no flow) than the presence of pollutants. This is reflected in the AusRivAs scores, which suggest that the macroinvertebrate assemblages at many sites in the Upper Broken Creek are equivalent to assemblages found under reference conditions for this type of system (i.e. AusRivAs Band A).

Table 6-1 : AusRivAs and SIGNAL scores for the Broken Creek, provided by the EPA Victoria, 2 May 2017.

Reach	Site name	Year	Average AusRivAs Band	Average SIGNAL score
1	BROKEN CREEK AT BENALLA-TOCUMWAL ROAD	2006	A	5.3
	BROKEN CREEK AT COOPERS ROAD	2010	B	5.2
	BROKEN CREEK AT FELDTMAN ROAD	2005 2006 2007 2008 2011	B A B B A/B	5.1 5 5.8 5.2 5.3
	BROKEN CREEK AT GOORAMBAT	2005	B	5.4
	BROKEN CREEK AT MIDLAND HIGHWAY	2005 2006 2007 2008 2011	A A A A B	5.5 5.3 5.2 5.2 5.5
	BROKEN CREEK AT NOORAMUNGA	2008	A/B	5
2	BROKEN CREEK AT BOXWOOD ROAD	2007 2008 2011	B B B	5.1 5 5.25

	BROKEN CREEK AT GEARY ROAD	2005 2006 2007 2008 2010 2011	B B A A B B	5.1 5.4 5.3 5.5 4.8 5.4
	BROKEN CREEK AT LIDGERWOOD ROAD	2006 2008 2010	B A A/B	5.1 5.4 5.2
	BROKEN CREEK AT MANLEY ROAD, DEVENISH	2005	B	5.6
	BROKEN CREEK AT OLIVER ROAD	2006	B	5.2
	BROKEN CREEK AT PELLUEBLA ROAD	2006	B	5.45
	BROKEN CREEK AT WAGGARANDALL	2005	A	5.7
3	BROKEN CREEK AT MILLS ROAD	2005 2006 2007 2011	B A B B	5.5 5.4 5.6 5.7
	BROKEN CREEK AT SCHOOL ROAD	2006	A/B	5.25
	BROKEN CREEK AT TUNGAMAH ROAD	2006	A/B	5.2

A taxa list for selected sites is given in Appendix A. The macroinvertebrate community is largely dominated by tolerant, opportunistic taxa common in lowland waters. Many of these taxa are capable of “waiting out” adverse conditions, such as cease-to-flow situations, or can rapidly re-colonise an area after an adverse impact has passed. Of note are two taxa that require at least some flow: Hydropsychidae and Simuliidae. While Simuliidae have been recorded along the extent of the Upper Broken Creek, Hydropsychidae have been recorded from only two sites and their distribution is likely driven by local habitat availability (i.e. rocks for attaching silk structures). Three Decapoda taxa occur within the creek. Records of Parastacidae are most certainly of *Cherax destructor*, the common yabbie, and this species occurs at most sites throughout the system. This is further evidenced from Robinson and Mann (1996) and McMaster et al. (2006) who found this species throughout the Broken Creek. Freshwater shrimp (Atyidae) are also present at most sites. McMaster et al. (2006) recorded *Macrobrachium australiensis* (Freshwater prawn - here represented by the family Palaemonidae) in large numbers at each of five sites that fall within the reaches used for the current FLOWS assessment. However, the EPA data records this taxon at only one site within reach 1. The discrepancy between these results may be partly due to the targeted sampling regime of the McMaster study, but may also be due to temporal factors such as brief recruitment events. The sampling techniques employed in the EPA monitoring were not conducive to collecting freshwater mussels, and this taxon does not occur in the EPA data. However, Robinson and Mann (1996) document freshwater mussels occurring throughout the Broken, Boosey, and Nine Mile Creek system. Furthermore, shells of large freshwater mussels were sighted along the banks of the Upper Broken Creek during the site assessment stage of this FLOWS study suggesting they are still present. The presence of a healthy mussel population indicates relative flow stability over the long term. Mussels are adversely effected by increasing shear stress, especially when the timing of high shear stress corresponds with larval recruitment (Layzer and Madison 1995). While many mussel species are capable of burrowing into sediment to “wait out” dry periods (Haag et al. 2008), sudden decreases in water level have been documented to reduce population sizes, in some species, by up to 92% (Galbraith et al. 2014). Perennial flow regimes are likely to maintain healthy populations of freshwater mussels in this system. However, changes to a more ephemeral nature, as could occur in the Reach 3, may result in decreased abundances of mussels. Where rates of flow decrease can be manipulated, the ability for mussels to burrow into sediments should be considered. Furthermore, impacts on mussel populations need to be considered if mechanical removal of in-channel vegetation or sediment is considered as part of options to increase deep pool habitat for fish and platypus.

Given the low gradient of the channel, the local hydraulic environment is characterised by low water velocities and relatively small-scale diversity in local hydraulics, even moderate rises in water levels within the Broken Creek are unlikely to have any significant effect on the macroinvertebrate community assemblage. It is likely that habitat condition is a greater driver of macroinvertebrate composition than flow velocities and hydraulics in this system. There may be some localised responses from taxa requiring flow, specifically for feeding (e.g.

Hydropsychidae and Simuliidae), but this will largely be dependent on habitat availability, for instance suitable substrates on which to attach nets (rocks and logs). Scouring of biofilm from these substrates will increase habitat availability, but the velocities of water that would be needed to do this are considerable and not feasible in this system.

Some taxa, such as the freshwater prawn, require perennial inundation for survival and prefer flowing habitats (Richardson et al. 2004). The current perennial inundation of the channel has thus likely benefited these taxa, particularly in Reach 1, which has the largest area of inundated streambed. In the lower reaches, suitable conditions are still provided by the perennial inundation, but these reaches are likely to support smaller populations due to the small size of the channel. Importantly, populations in Reach 1 may act as source populations for re-colonising down-stream reaches (Reaches 2 and 3) after dry periods.

6.1.1 Macroinvertebrate community under various flow regimes

6.1.1.1 Current flow regime

Not accounting for outside impacts, such as changes in land use etc., shifts in macroinvertebrate community structure are not likely to occur if flow regimes remain as they currently are. The community currently consists of a mix of lowland taxa largely adapted to perennial inundation. There is a relatively diverse array of taxa including Hemiptera, Coleoptera, Odonata and Diptera. This includes taxa that are important as food sources for larger fauna (i.e. fish and platypus), such as decapods.

6.1.1.2 Lower than current regime, with periods of cease to flow

In this scenario we consider that lower flows will result in Reach 3 becoming a series of ephemerally connected wetlands. Under this scenario we would expect to see a decrease in the abundances of decapod species (i.e. freshwater prawns). Species, such as the freshwater yabbie are likely to persist in Reach 3 but become confined to wetland areas. Species that rely on flow for daily living, such as Hydropsychidae and Simuliidae, are likely to decrease if not disappear from the system. In particular, Hydropsychidae would likely disappear as suitable substrates for silk attachment, such as scoured woody debris surfaces, become unavailable. Abundances of freshwater mussels may decrease as cease to flow area increases and where cease to flow periods extend over multiple seasons mussels may disappear. More ephemeral areas are likely to become dominated by opportunistic species. These are generally species that undergo rapid life cycles or are good dispersers. Communities of ephemeral wetlands are commonly dominated by midges, hemipterans, and predatory beetles. It should be noted that changing a system from permanent to ephemeral would result in lower AusRivAs assessment scores and that this would not necessarily reflect a decrease in system health but the unsuitability of AusRivAs for assessing ephemeral systems. Should parts of the Broken Creek system be managed as ephemeral, other indicators of system health may be required.

6.1.1.3 Higher than current regime

Under higher flow conditions we would expect to see increases in the abundances of decapod species, such as the freshwater prawn, especially in Reach 3, should the flows reach that far downstream. Greater flows may result in greater abundance of flow-dependent species, such as Hydropsychidae and Simuliidae. However, this would largely depend on the creation of more habitat, for instance as stream height inundates more area or flows scour logs. Given the relatively weak flows possible in the system, such habitat creation is likely to be very limited. Abundance of freshwater mussels is likely to remain as current. However, variable flows that rapidly strand individuals or high shear stresses during the recruitment phase of mussels would result in decreases in abundance. Overall, under higher than current flow regimes the macroinvertebrate community is not likely to shift significantly. Most responses will be in the abundances of species rather than shifts in community composition.

6.2 Fish

Extensive surveys of fish populations have been undertaken in the Broken Creek over the last 10-15 years. As part of a monitoring program conducted in association with construction of the Tungammah pipeline, five sites were surveyed along Broken Creek (together with five sites in Boosey Creek) twice annually from 2005-2009

(McMaster et al. 2006, 2009, Reich et al. 2010). These sites spanned the three reaches being evaluated as part of the current study (two sites in Reach 1, and one site each in Reaches 2 and 3). In addition, from 2008-2015 two sites were surveyed annually within Reach 1 as part of the Victorian Environmental Flows Monitoring Program (VEFMAP)(Bloink and Stevenson 2015, McCasker et al. 2015). Finally, ad-hoc surveys have been undertaken in a number of weir pools (Monash University, unpublished data). These surveys provide a comprehensive picture of the distribution of individual species along the length of Broken Creek.

A total of 6 native and 5 exotic species have been observed across Upper Broken Creek (Table 6-2). Although fish assemblages are dominated by exotic species, notably carp and mosquitofish, several native species are also quite prevalent. Of these, Murray cod, golden perch and river blackfish are found predominantly in Reach 1, which has a larger channel capacity and more permanent flow. It is difficult to compare abundance estimates provided by the VEFMAP program with those of the earlier work of McMaster et al.; however, it appears from comparisons among the various reports that the numbers of Murray cod and golden perch have declined in Reach 1 in recent years. Historically both of these species have been heavily stocked into the Broken Creek (McMaster et al. 2006), and it has generally been assumed that most Murray cod and golden perch were either stocked fish, or emigrants from the Broken River, rather than being the result of local recruitment. This theory is reinforced by the absence of any evidence for local recruitment of either golden perch or Murray cod from analysis of size-structure and larval fish surveys (McMaster et al. 2006). Two other native species – Murray River rainbowfish and river blackfish are also restricted to Reach 1, while two other small-bodied native species - carp gudgeons (*Hypseleotris* spp.) and smelt – occur throughout the three reaches (Table 6-2).

Table 6-2 : Distribution of native and introduced fish across the three reaches. X indicates fish in low to moderate abundance. XX indicates higher abundances (McMaster et al. 2009, Bloink and Stevenson 2015, McCasker et al. 2015).

Scientific name	Common name	Native / exotic	Reach 1	Reach 2	Reach 3
Maccullochella peelii	Murray cod	N	X	-	-
Macquaria ambigua	golden perch	N	XX	X	X
Gadopsis marmoratus	river blackfish	N	X	-	-
Melanotaenia fluviatilis	Murray River rainbowfish	N	XX	-	-
Hypseleotris spp.	Carp gudgeon	N	X	X	X
Retropinna semoni	Australian smelt	N	X	X	X
Perca fluviatilis	redfin	E	X	X	X
Cyprinus carpio	carp	E	XX	XX	XX
Carassius auratus	goldfish	E	X	X	X
Gambusia holbrooki	Eastern mosquito fish	E	X	XX	X
Misgurnus anguillicaudatus	weatherloach	E	-	X	X

From the survey work of McMaster (McMaster et al. 2006, 2009), which included a number of sites in nearby Boosey Creek that experienced intermittent flow, it was concluded that perennial flows in Broken Creek played a fundamental role in sustaining populations of a number of species, especially Murray cod, golden perch, river blackfish and redfin.

At that time, there was a presumption of reduced irrigation demand, and hence also a reduction in flow volumes and flow permanence in Broken Creek, especially in Reach 1. This was predicted to lead to marked changes in the composition of the fish community (Bond et al. 2010). These predicted changes in hydrology were incorporated into the original flow recommendations for fish, which included specific reference to the restoration of a more natural intermittent regime (Sinclair Knight Merz 2007). The sustained presence of irrigation demand, changes the potential options available for managing native fish populations, especially in Reach 1 and 2 where perennial flows are likely to be sustained. In particular, the ongoing presence of a self-sustaining population of river blackfish at Flynn's Weir in Reach 1 (Bloink and Stevenson 2015) is a high priority value due to the loss of this species from many lowland rivers and creeks (Trueman 2007). Maintaining these populations will require efforts to provide relatively permanent flows in the creek. However, it is important to note that some of the species that are valued by local communities, such as golden perch and Murray cod, appear to persist only through stocking rather than through natural recruitment. Over the long-term these values may only be sustained by further stocking, coupled with management to maintain suitable habitats. For smaller bodied species, such as carp gudgeons, smelt and Murray River rainbowfish, maintaining suitable opportunities for spawning and recruitment will be important.

To this end, as well as being influenced by reach scale hydrology, meso and micro-habitat characteristics, water quality, longitudinal connectivity, and biotic interactions can all play a role in sustaining and restoring fish populations (Bond and Lake 2003). Each of these elements of the local environment remain important considerations for management of Broken Creek. As has been noted earlier, the Broken Creek channel has contracted considerably over the last century due to high sediment loads and stable baseflows. This has led to a decrease in the availability of deep pool habitats – both within the river channel and within weir pools, which have also more recently been filled with sediment and been colonised by emergent macrophytes.

From our field observations, even though fringing grasses have encroached on the channel, and cumbungi beds have expanded in some areas, the changes are unlikely to pose a significant threat to fish populations in Reaches 1 and 2. Conversely, the vegetation cover likely provides shelter from predators and sites for aquatic production by algae and macroinvertebrates that are an important source of food for fish. In Reach 3 the small-size of the channel reduces the likelihood of being able to provide suitable conditions for most species of native fish even if permanent flow is maintained, although there will likely be some individuals that colonise these reaches periodically.

Under more natural conditions high flow events, such as in-channel pulses and overbank floods, would likely have occurred more frequently, and potentially provided cues and opportunities for movement by drowning out small barriers. However, under current conditions many longitudinal barriers along upper Broken Creek exist in the form of small weirs and culverts that limit the opportunities for fish movement. The structures between Broken River and Broken Creek also restrict movement opportunities. While in-channel flow pulses will not increase connectivity with the Broken River, their role in promoting longitudinal connectivity within Broken Creek must be considered, provided barriers to fish movement are also addressed. Such events may also play a role in connecting in-channel benches, which are thought to be important sites for the transformation and transfer of terrestrial organic carbon to aquatic food-webs (Reid et al. 2008). Similarly, overbank flows can connect the Creek to low lying wetlands and billabongs, which can also be important sites of production and for rearing of native fish. The benefits of particular flow components for native species also need to be considered alongside the extent to which they will influence introduced species such as carp and gambusia, which also frequently occur in high densities in palustrine floodplain habitats (wetlands and marshes) connected to river channels (Bice and Zampatti 2011).

6.2.1 Fish community under various flow regimes

6.2.1.1 Current flow regime

As outlined above, the current flow regime, which consists of perennial flows in Reaches 1 and 2, are likely to continue to provide suitable habitat for large and smaller bodied native fishes in these two reaches, and in Reach 3, to maintain conditions that support opportunistic smaller bodied species such as carp gudgeons, and the invasive mosquito fish. This later species was observed to be abundant in these lower reaches at the time of the site visit. It is important to note that larger bodied native species such as Murray cod and golden perch are unlikely to recruit in this system, and opportunities for colonisation from the Broken River are limited. Stocking may therefore be required to sustain these populations in the future.

6.2.1.2 Lower than current regime, with periods of cease to flow

Loss of perennial flows would likely lead to the loss of larger bodied species in Reaches 1 and 2 (Bond et al. 2010). Short periods without flow would present a reduced risk where fish were able to access deep refuge pools. These historically may have been more common along the length of the creek, but have been lost from sediment deposition. Weir pools may also provide deeper habitats, but it is clear that these too are gradually being filled by sediment. Over time this will limit the ability of these habitats to act as a suitable refuge. Mechanical sediment removal could be a suitable approach to restoring the depth of weir pools, but would need to be done in such a way as to minimise short-term water quality impacts, damage to surrounding vegetation and impacts on mussel populations.

6.2.1.3 Higher than current regime

Greater flows being delivered into the Broken Creek would lead to greater water depths in Reaches 1 and 2, and more permanent flow in Reach 3. However, higher flows are unlikely to significantly alter the habitat characteristics in Reaches 1 and 2 in ways that would materially alter the suitability of conditions for different fish species. Higher flows would help with promoting dispersal, but existing barriers to movement need to addressed.

6.3 Platypus

Platypus live-trapping surveys have not been carried out to date along Broken Creek. However, some factual information about the species' recent distribution is available from sightings reports provided by reliable observers (including environmental consultants, natural resource managers and local landholders or anglers familiar with the animal's appearance in the wild). As summarised in Table 6-3, platypus have been observed at a variety of locations upstream of Katamatite since 2000. More than half of the sightings occurred at or very near to weir pools, including Casey's Weir (6 records), Trewins Weir (2 records), McLaughlins Weir (1 record), Waggarandall Weir (1 record) and Irvines Weir (1 record). Other sightings along the creek proper were mainly reported upstream of Waggarandall Weir in Reach 1, from Goorambat to as far downstream as South Boundary Road (6 of 8 records, 75%). The remaining two sightings respectively occurred near St James Road in 2010 (Reach 2) and at Youarang between School and Dickie Roads in 2010 (Reach 3). Although the table seems to imply that the frequency of regular platypus sightings has diminished since 2004, this is likely to primarily reflect the fact that records through 2004 were mainly obtained by actively seeking out and interviewing local landholders, whereas later reports were mainly supplied on an ad hoc basis by persons wanting to report a sighting. It's also worth noting that platypus have occasionally been seen downstream of Katamatite since 2000, with the most recent report to the Australian Platypus Conservancy involving a female captured at McPherson Road, c. 1 km upstream of the Dip Bridge, as bycatch in a 2010 fish survey.

Table 6-3 : Location of reliable platypus sightings along Broken Creek (upstream of Katamatite) since 2000. Records provided courtesy of Australian Platypus Conservancy and Atlas of Living Australia (latter marked by *).

Year(s)	Sightings frequency	Location	Reach
1995-2002	Regularly seen	Goorambat	1
1996-2002	Regularly seen	Between Flynn and Nooramunga Roads	1
2002	1 seen	Near Trewins Weir (Majors Creek offtake)	1
2002	Regularly seen	Casey's Weir	1
2003	Regularly seen	Casey's Weir	1
2003	Regularly seen	McLaughlins Weir	2
2003	Regularly seen	Waggarandall Weir	1
2004	Regularly seen	Near Feldman Road	1
2004	Regularly seen	Casey's Weir	1
2008	1 captured in fish survey	Near South Boundary Road	1
2008	1 seen	Casey's Weir	1
2008	1 seen	Between Devenish and St James	1
2009-2010	Regularly seen	Irvines Weir (during extreme drought)	3
2010	1 seen	Between School and Dickie Roads*	3
2010	1 female captured in fish survey	St James Road	2
2012	Seen on 2-3 occasions	Casey's Weir	1
2014	1 seen	Near Flynn Road	1
2015	1 seen	Casey's Weir	1
2017	Seen in last 12 months	Trewins Weir	1

An assessment of platypus habitat quality along Broken Creek at sites distributed from Casey's Weir to Gilmores Bridge in 2010 concluded that conditions from Casey's to Waggarandall Weirs (Reach 1) were generally good enough to support successful breeding (Serena and Williams 2010b). Assuming that maximum platypus density in this reach is currently similar to that recorded in moderately degraded peri-urban creeks near Melbourne (i.e. 1.2 to 2.1 animals/km: Serena 1994; Gardner and Serena 1995; Serena *et al*. 2014), platypus population size in Reach 1 is predicted to be in the order of 50-80 adults and subadults if flow remains reliably perennial.

In contrast to Reach 1, all of the non-weir sites inspected in Reaches 2 and 3 by Serena and Williams (2010b) were deemed to comprise suboptimal platypus habitat that was unlikely to support breeding females, though adult or subadult males and/or dispersing juveniles were considered likely to occur at a density < 0.5 animals/km (as extrapolated from Serena and Pettigrove 2005). The three weirs inspected in Reaches 2 and 3 were also deemed unlikely to support a breeding female, due to insufficient surface area (Reillys Weir, Gilmores Bridge gauging weir) or (probably) inadequate habitat quality (Irvines Weir). However, it was also noted that all three of these sites are expected to constitute reasonably good platypus foraging habitats as long as they hold enough water. In practice, their greatest value to local platypus management is likely to involve helping to sustain juveniles dispersing downstream to the Murray River (see below). In addition, Irvines Weir in particular appears to have functioned as a classic drought refuge for this species in 2010, when three platypuses were observed to be surviving in a remnant pool measuring about 30 cm deep x 15 m long when surface water had otherwise disappeared from adjoining parts of the creek (Serena and Williams 2010b).

Over the time frame considered in the current flows study, the primary management objective for platypus in Broken Creek will be to maintain a breeding population in Reach 1 that is reliably self-sustaining. Given that this population is expected to generate some surplus juveniles, a secondary management objective will be to assist successful dispersal of those juveniles that choose to move downstream, contributing to longer term re-establishment of a robust platypus population in the Murray River downstream of Tocumwal. With respect specifically to future flow-related management, these objectives are most likely to be achieved through the following actions:

- Avoid mandating cease-to-flow periods that may reduce platypus food resources in Reach 1, particularly in the form of benthic macroinvertebrates (Faragher et al. 1979; McLachlan-Troup et al. 2010; Marchant and Grant 2015).
- Maintain enough flow in Reach 1 to support platypus reproductive success, particularly in the critical pre-oestrus months of March-July (Serena et al. 2014; Serena and Grant in press).
- Reduce unconsolidated sediment in the channel, particularly in Reach 1. Significant negative relationships have been established between the prevalence of relatively fine inorganic particles and the distribution of platypus foraging activity (Serena et al. 2001; Grant 2004) and population density (Worley and Serena 2000). In addition, the platypus is known to forage preferentially at sites where water depth exceeds approximately 1 metre (Grant 2004).
- In the absence of a natural high flow event in late autumn/winter, schedule at least one high flow event in this period (ideally May) to expedite successful juvenile dispersal from Reach 1 in the downstream direction, particularly in years when reproductive success is predicted to be relatively high based on preceding patterns of seasonal flow (Serena et al. 2014; Serena and Grant in press). Apart from reducing energetic costs associated with platypus travel downstream, greater flow and water depth will reduce the likelihood that juveniles are subject to predation while dispersing (Serena and Williams 2010a).

7. Ecosystem Processes/ biogeochemical aspects

Of the biogeochemical aspects that may be considered important in any aquatic system, water quality has been recognized as key in developing flow objectives for the Upper Broken Creek.

A combination of targeted and opportunistic measurements of water quality have been made (McMaster et al. 2009). Of the three reaches that have been identified in the current study, the understanding of water quality in Reach 1, particularly the upper sections of this reach, is most well developed; primarily because Casey's Weir is the source water for the Upper Broken Creek and water quality at the uppermost sections of Reach 1 will reflect those of Casey's Weir. Downstream changes in water quality parameters occur as instream physical conditions and potential diffuse and point source inputs from the catchment change along the creek's length. Water quality measurements are available for mid and lower sections of the Broken Creek, but these data are not included in this reporting as the conditions in the lower sections of the creek are sufficiently different as to make it inappropriate to compare with the Upper Broken Creek. In general the water quality in Broken Creek is considered poor; with most measured parameters exceeding the ANZAC guidelines trigger values for south-east Australia (McMaster et al. 2009).

7.1 Suspended solids and nutrients

The two main trends recognised across reported water quality parameters are elevated nutrients and suspended solids (turbidity), leading to WQ that is considered poor to moderate (McMaster et al. 2009). In addition to quantitative data on turbidity, visual inspection of the creek has been carried out as part of earlier project site inspections and more recently with the site inspection by the EFTP (27-28th March 2017).

Reach 1 has the best water quality of all the reaches, and is described as moderate. This is not surprising given that Reach 1 water quality will be strongly driven by the source water. Site inspections along the length of the Upper Broken Creek show that turbidity generally increases downstream, a phenomenon common to river systems. However, visual observation indicated that instream turbidity is strongly modified by instream vegetation, leading to some sections where turbidity is visually decreased. This was most notable at MacLaughlins Weir, where extensive growth of *Eleocharis* sp. was likely to be contributing to increased deposition of suspended sediment.

Land holders along the upper sections of the creek report that pools that once existed on their properties are filling in with fine sediment, further reflecting a combination of the high and continued sediment loads carried within the channel. This is compounded by insufficient high flows that could lead to increased scouring.

Poor water quality was most notable at Reillys Weir. The weir pool appears to have a significantly decreased area of open water, as compared to observations from previous site visits (Figure 7-1). There was clear evidence of very soft bottom sediment. In addition, there were visible algal scums on the surface of the weir pool. Dissolved Oxygen (DO) measurements are not available for this weir pool; however, should there have been some deposition of organic material within the sediments, the open nature of the water body suggests that there may be some reduction in the DO of the water. This would be exacerbated in summer as water temperature increases are likely to be reasonably high.

Figure 7-1 Reillys Weir in 2007 (left panel) and 2017 (right panel) showing water level reduction and encroachment of vegetation.

The creek receives water from occasional point drainage as well as diffuse sources during rain events. It is likely that these events contribute additional sediment loads and nutrients to the creek.

Given the restricted capacity to introduce very high flows into the system, it is unlikely that much can be done with flow modifications that will mitigate the current trends in nutrients and sediment load. The current instream complexity that has occurred with the growth of macrophytes is moderating loads at some sites and these sites may provide some refuge for aquatic fauna. Activities such as dredging pools that have already filled need to be carefully considered in the overall management of the creek, as dredging will also distribute sediments downstream, leading to some additional, albeit short term smothering.

7.2 Salinity

Salinity generally increases with distance downstream and ranges from 134 to 596 µS/cm (see Figure 7-2) (GBCMA unpublished data). While these salinity levels are elevated over values that would typically occur in lowland rivers, they are not a major issue and not likely to influence the biological communities present in the Upper Broken Creek (Nielsen et al. 2003).

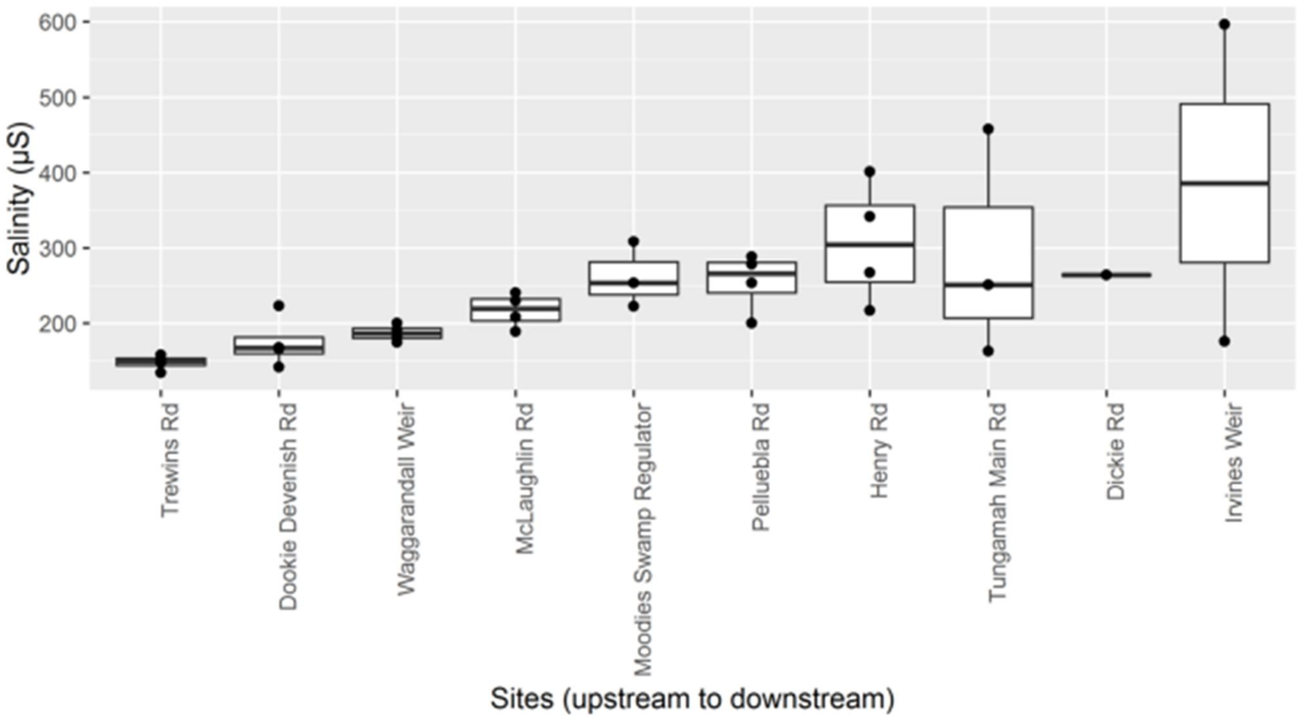


Figure 7-2 Box plots of salinity concentrations for each site (GBCMA unpublished data).

7.3 Hypoxic black water.

Black water is the term given to water rich in dissolved, coloured carbon and typically results when leaf litter is inundated, leaching dissolved organic carbon (DOC) into the water. A good proportion of the DOC is consumed by bacteria as a carbon source and, in doing so, bacteria also consume oxygen through respiration. If the leaching process occurs during warmer periods of the year, the rate of dissolved oxygen consumption in the water occurs at a much greater rate than the processes that combine to put oxygen into the water (diffusion and photosynthesis). The net result is that the DO can decrease to critically low levels, and at its extreme, the waters can become completely anoxic.

While speculative, there was some visual evidence that poor water quality may exist in such sections as Reillys Weir. Some monitoring throughout summer would be necessary to understand the nature of the oxygen dynamics in this pool, to determine its value as a suitable refuge for fauna.

8. Environmental Objectives

Determining appropriate management objectives must consider the desirability of particular ecological objectives against their cost and feasibility, and potential trade-offs with other social and economic goals. As noted earlier, a goal of the current review of the environmental flow targets for Broken Creek is to consider the range of potential environmental outcomes that can be achieved within the context of the ongoing need to provide regulated flows in summer-autumn to meet irrigation demands.

The requirement for permanent summer flows increases the potential to sustain many of the environmental values currently associated with the creek system, notably native fish and platypus. At the same time, there is a need to address concerns regarding the apparent encroachment of fringing vegetation and expansion of emergent aquatic macrophytes within both channel and weir pool environments, particularly through parts of Reaches 2 and 3.

Expansion of vegetation has almost certainly been facilitated by low magnitude perennial flows coupled with high sediment loads, which have increased the extent of shallow habitats suitable for plant growth. However, this encroachment is not a recent issue: historical evidence suggests that encroachment of vegetation on the channel has been a feature of the system for many decades, but changes in how vegetation encroachment is manged (i.e. cessation of mechanical or chemical control since the mid 2000s), may have made the issue appear more obvious.

In theory, controlling this expansion could be done by implementing a prolonged dry phase during summer to kill off the vegetation. However, this approach is not feasible in light of current irrigation demands, and would likely also pose a threat to the persistence of at least some native fish species and platypus. An alternative approach could be to utilise high flows to scour out vegetation. However, as noted earlier the low gradient of the channel means that such an approach is unlikely to be effective, as well as likely leading to undesirable inundation of private land. Thus, while vegetation expansion is clearly an issue for the local community, there are limited options to manage this concern through flow manipulation. Equally, the observed expansion is not necessarily compromising the flow-related objectives that are discussed below.

A range of possible environmental objectives for each reach for each asset type were identified and presented to the PAG for discussion and feedback. These objectives identified a range of possible ecological outcomes for the creek and the broad flow components required to achieve each objective. Because these objectives were considered independently for each asset type, they may differ and be contradictory among assets. For example, flows required to achieve an objective of scouring pools to remove sediment and create deep pool habitat for fish and platypus in Reach 1 are likely to be higher than the regulated flow that can be feasibly passed down Broken Creek from Casey's Weir, and as discussed above, may cause nuisance flooding in Reaches 2 and 3. Also, if it is considered desirable to maintain conditions for fish and platypus in Reach 2, then continuous low flows are likely to continue to promote further vegetation encroachment in the channel through Reach 3.

Subsequent to discussion with the PAG and further consideration by the EFTP, a refined set of objectives were confirmed with the overall objective being to maintain permanent habitat for fish and platypus in Reach 1 with a transition through Reaches 2 and 3 to a more seasonally intermittent system that provides opportunistic habitat for fish and platypus and maintains occasional / seasonal opportunities for dispersal during wet / higher flow years. Specific reach objectives are:

1) Manage Reach 1 to:
    - continue to provide permanent habitat for native fish, platypus, macroinvertebrates and other fauna
    - minimise accumulation of fine sediments and periodically engage distributary channels and floodplains
    - protect and enhance the diversity and extent of instream, littoral and riparian vegetation
    - maintain water quality (avoid periods of low dissolved oxygen) to protect fish and macroinvertebrates
    - explore opportunities for enhancing weir pools as deep water refuge habitat for fish and platypus
2) Manage Reach 2 to:

- maintain opportunistic habitat for fish and platypus and provide for dispersal opportunities during wet years
- minimise accumulation of fine sediments and periodically engage distributary channels and floodplains, and specifically maintain capacity to deliver environmental water to Moodies Swamp in a way that integrates flow delivery for the swamp with flow requirements for the creek.
- protect and enhance the diversity and extent of instream, littoral and riparian vegetation
- explore opportunities for enhancing weir pools (including those not required for current water supply operations) as deep water drought refuge habitat for fish and platypus

3) Manage Reach 3 to:
   - transition to a more seasonally intermittent waterway characterised by a well vegetated channel and riparian zone
   - allow for dispersal opportunities by fish and platypus during wet years
   - investigate whether existing weir pools / permanent pools should be actively managed as drought refuge habitat.

The history of drying and the associated current natural values in Reach 3 tend to mean there is little benefit in actively maintaining permanent flow in this reach. This reach may best be thought of as a series of terminal linear wetlands. It is likely that aquatic plants, invertebrates and amphibians capable of surviving dry periods, and native fish and platypus will opportunistically move into this reach when it is inundated. Actively delivering environmental flows to this reach to maintain permanent aquatic habitats and longitudinal connectivity should be a lower priority, but nonetheless allowed to occur from time to time to provide occasional dispersal opportunities for biota.

The final suite of objectives are summarised in Table 8-1 to Table 8-3.

Table 8-1 : Objectives for Reach 1. Broken Creek from Casey's Weir to Waggarandall Weir

Objective	Number	Function	Flow component	Timing	Expected response
Geomorphology					
Maintain channel form and where possible provide flows sufficient to mobilise sediments and maintain pools	G1.1	Minimise further sedimentation of pools	High flows	Winter/spring	Higher flows help to prevent excessive accumulation of sediment. However, flows alone are unlikely to be sufficient to significantly scour existing pools. Management of weir pools and selective excavation may be required to create deeper habitat pools.
Periodically engage distributary channels	G1.2	Engage channels to maintain drainage network	Bankfull / overbank flows		Overbank flows will spill into distributary channels helping to preserve the distributary drainage network and provide occasional inundation of off channel habitats.
Vegetation					
Promote the germination and recruitment of river red gums within the riparian zone.	V1.1	Provide soil moisture to promote germination Reduce grazing pressure on seedlings	Bankfull / overbank flows	Winter/spring	Germination and recruitment of river red gum requires overbank flows and exclusion of stock.
Maintain and promote in channel biodiversity (e.g. *Triglochin* spp)	V1.2	Scouring and maintenance of pools to provide habitat for *Triglochin* spp.	High flows	Winter/spring	*Triglochin* can survive periods of dry by persistence, is reliant on in channel pools. Flows need to be sufficient to mobilise sediment and maintain pools.
Minimise the spread of Cumbungi within the channel	V1.3	Scouring of pools	High flows	Winter/spring	Minimising the spread of Cumbungi is conditional on either prolonged drying or prolonged inundation at sufficient depth to prevent further growth.
Reduce the encroachment of riparian species (e.g. water couch) into the river channel	V1.4	Deep inundation of benches to limit growth of terrestrial species	High flows	Winter/spring	Deep inundation drowns species that prefer shallow / damp conditions.
Water Quality					
Maintain water quality	W1.1	Maintain pools during periods of low flow	Freshes	All year	Water quality should be maintained at levels that are not detrimental to aquatic biota (DO >6 mg/L)
Fish					
Maintain conditions for self-sustaining populations of small-bodied native fish Maintain conditions for survival of large-bodied native fish	F1.1	Maintain aquatic habitat for all native fish species	Low flow	All year	Sustained populations of river blackfish, smelt, Murray River rainbowfish, Carp Gudgeons and stocked native species (Murray cod and golden perch).
	F1.2	Provide migration cue and longitudinal passage for small and large-bodied native fish	High flow	Winter/Spring	Maintain population resilience to local fluctuations in abundance. Recolonization after drought conditions.
Platypus					
Maintain platypus population and support successful breeding and juvenile dispersal	P1.1	Maintain access to habitat and sufficient food resources	Low flows	All year	Low flows maintain access to habitat & provide conditions suitable for macroinvertebrates as a food source.
	P1.2	Provide opportunities for dispersal of juveniles	Freshes	Autumn	Increased flow promotes juvenile dispersal.
	P1.3	Avoid deliberate high flows in nesting season	Avoid high flow	Late spring/summer	Minimise unintended inundation of nests.
Macroinvertebrates					
Maintain self-sustaining populations of macroinvertebrates	M1.1	Maintain perennial nature of the reach. Maintain aquatic habitat including vegetation and wood.	Low flows	All year	Sustained populations of Decapoda species (shrimps).

Table 8-2 : Objectives for Reach 2. Broken Creek from Waggarandall Weir to Reillys Weir

Objective	Number	Function	Flow component	Timing	Expected response
Geomorphology					
Maintain channel form and where possible provide flows sufficient to mobilise sediments and maintain channel capacity for water delivery to Moodies Swamp	G2.1	Flush accumulated sediment	High flows	Winter/spring	Higher flows help to prevent excessive accumulation of sediment. However, flows alone are unlikely to be sufficient to significantly scour existing pools. Management of weir pools and selective excavation may be required to create deeper habitat pools.
Periodically engage distributary channels	G2.2	Engage channels to maintain drainage network	Bankfull / overbank flows		Overbank flows will spill into distributary channels helping to preserve the distributary drainage network and provide occasional inundation of off channel habitats (e.g. Moodies Swamp).
Vegetation					
Promote the germination and recruitment of river red gums within the riparian zone.	V2.1	Provide soil moisture to promote germination Reduce grazing pressure on seedlings	High flows	Winter/spring	Germination and recruitment of river red gum requires overbank flows and exclusion of stock.
Maintain and promote in channel biodiversity (e.g. *Triglochin* spp)	V2.2	Scouring and maintenance of pools to provide habitat for *Triglochin* spp.	High flows	Winter/spring	*Triglochin* can survive periods of dry by persistence is reliant on in channel pools. Flows need to be sufficient to mobilise sediment and maintain pools.
Minimise the spread of Cumbungi within the channel	V2.3	Scouring of pools	High flows	Winter/spring	Minimising the spread of Cumbungi is conditional on either prolonged drying or prolonged inundation at sufficient depth to prevent further growth.
Reduce the encroachment of riparian species (e.g. water couch) into the river channel	V2.4	Deep inundation of benches to limit growth of terrestrial species	High flows	Winter/spring	Deep inundation drowns species that prefer shallow / damp conditions.
Fish					
Maintain conditions for self-sustaining populations of small-bodied native fish Maintain conditions for survival / refuge habitat for large-bodied native fish - opportunistic	F1.1	Maintain refuge aquatic habitat for all native fish species	Low flow	All year	Sustained populations of small-bodied fish and opportunistic presence of larger bodied species – cease to flows may occur but permanent pool habitat expected to remain (e.g. McLaughlin's weir).
	F1.2	Provide migration cue and longitudinal passage for small and large-bodied native fish	High flows	Winter/Spring	Maintain population resilience to local fluctuations in abundance. Recolonisation after sustained drought conditions.
	F2.3	Inundate in-channel benches and low-lying fringing vegetation	High flows	Winter/Spring	Access to spawning habitat and food resources.
Platypus					
Maintain refuge / critical feeding habitat for platypus	P2.1	Maintain pools to serve as drought refuges and assist successful downstream dispersal of juveniles	High flows	Winter/spring	High flows provide connection that fills pools serving as drought refuges and providing foraging habitat for dispersing juveniles - cease to flows may occur but permanent pool habitat expected to remain.
Macroinvertebrates					
Maintain self-sustaining populations of macroinvertebrates	M2.1	Maintain refuge aquatic habitat including vegetation and large woody debris	Low flows	All year	Sustained populations of Decapoda species (shrimps) - cease to flows may occur but permanent pool habitat expected to remain.

Table 8-3 : Objectives for Reach 3. Broken Creek from Reillys Weir to the confluence with Boosey Creek

Objective	Number	Function	Flow component	Timing	Expected response
Geomorphology					
Transition towards a series of linear wetlands	G3.1	Sediment from upstream reaches will continue to accumulate in Reach 3	NA	NA	Accumulated sediment will result in further channel constriction. Even high flows are not competent to flush accumulated material through this reach. High flows will cause inundation of low lying areas.
Vegetation					
Promote the germination and recruitment of river red gums within the riparian zone.	V3.1	Provide soil moisture to promote germination Reduce grazing pressure on seedlings	Bankfull / overbank flows	Winter/spring	Germination and recruitment of river red gum requires overbank flows and exclusion of stock.
Promote the development of a vegetation community consistent with regional wetland EVCs	V3.2	Allow occasional inundation to a variety of depths to support wetland plant biota	Freshes/High flows	Autumn / winter / spring	Germination and recruitment of wetland plant species.
Fish					
Maintain conditions for opportunistic colonisation of small-bodied native fish	F3.1	Maintain opportunistic aquatic habitat for small-bodied native fish	Freshes/High flows	Autumn / winter / spring	Opportunistic presence of small-bodied native fish e.g. smelt, Murray River rainbowfish, Carp Gudgeons.
	F3.2	Provide migration cues and longitudinal passage for small and large-bodied native fish	High flow	Winter/Spring	Maintain population resilience to local fluctuations in abundance; Recolonization after sustained drought conditions.
Platypus					
Maintain opportunities for downstream dispersal by juveniles	P3.1	Longitudinal connection that provides opportunities for downstream dispersal of juveniles	Freshes/High flows	Autumn/early Winter	High flows provide connection that fills refuge pools and promotes successful downstream dispersal.
Macroinvertebrates					
Maintain self-sustaining populations of macroinvertebrates tolerant of cease to flow periods	M3.1	Allow occasional inundation to a variety of depths to support macroinvertebrate biota tolerant of cease to flow periods	Freshes/High flows	Winter/spring	Diverse macroinvertebrate community tolerant of cease to flow periods

9. Flow recommendations

Flow recommendations were developed with reference to reach objectives through a workshop with the EFTP on June 16, 2017. The flow recommendations are expressed in terms of a regime that specifies the timing (time of year), component / event (cease to flow, low flow, fresh, high flow, bank full or overbank flow), volume or magnitude, frequency (number of events per year or interval between events) and duration (days, months etc.). Collectively, the individual flow components comprise a regime that, if achieved, would have a high likelihood of achieving the specified environmental objectives.

Recommendations are further expressed in the context of climate conditions (dry, average or wet climate conditions – see Section 3 for discussion). This recognises that certain flow components are not required or expected in every year. For example, lower flows and fewer freshes are acceptable in dry climate years, and bankfull / overbank flows are only expected in some wet climate years.

9.1 Reach 1

Reach 1 recommendations (Table 9-1) are aimed at providing permanent low flows to maintain access to habitat by fish, platypus and macroinvertebrates and at providing freshes and high flows to flush pools and scour fine sediments (improve water quality and quality of habitat) and provide moisture on upper banks (improve conditions for riparian vegetation).

Table 9-1 Environmental flow recommendations for Reach 1 – Casey's Weir to Waggarandall Weir

Stream		Broken Creek		Reach 1	Casey's Weir to Waggarandall Weir
Compliance point		Waggarandall Weir		Gauge No.	404239 (Waggarandall Weir)
Season	**Component**	**Volume***	**Frequency**	**Duration**	**Objective**
Summer / autumn (Dec-May)	Cease-to-flow	Not recommended			
	Low flow	5 ML/d (dry) 10 ML/d (avg) 10 ML/d (wet)	All season		M1.1, F1.1, P1.1
	Fresh	20 ML/d (avg) 50 ML/d (wet)	Once per year in average and wet climate years. Timed to coincide with filling Moodies Swamp. A proportion of the flow could be diverted to fill Moodies Swamp with the remainder passing to downstream reaches. Not required/expected in dry climate years.	Within the period Apr – Jun for as long as required to fill Moodies Swamp	W1.1, P1.2
	High flows	No specific recommendation but allowed to occur in response to local catchment runoff.			
Winter / spring (June-Nov)	Cease-to-flow	Not recommended			
	Low flow	10 ML/d (dry) 15 ML/d (avg) 20 ML/d (wet)	All season		M1.1, F1.1, P1.1
	Fresh	15 ML/d (dry) 20 ML/d (avg) 50 ML/d (wet)	Once per year in dry, average and wet climate years. A proportion of the flow could be diverted to fill Moodies Swamp, if a top up was required, with the remainder passing to downstream reaches.	2 weeks within the period Sep – Oct to coincide with topping up Moodies Swamp and growing period for vegetation. Duration could be longer if required to deliver water to Moodies Swamp	F1.2, P1.2, V1.2, V1.3, V1.4
	High flow / bankfull	Up to 200 ML/d	Only expected in very wet climate years once every 5 to 10 years in response to local catchment runoff. Local runoff could be augmented with transfers via Casey's Weir.	Determined by duration of local runoff. If augmentation from Casey's weir is provided, then 1-2 days.	G1.1, G1.2
	Overbank	No specific recommendation but allowed to occur in response to local catchment runoff.			

* Note that flows above 10-15 ML/d in Reach 2 are likely to cause localised nuisance flooding of low-lying land in some areas adjacent to the creek channel. Larger flows, up to 200 ML/d, cannot be realistically delivered through Reach 2 because of potential for more extensive inundation of private land.

Where possible, flows should be delivered via releases from Casey's Weir but with the compliance point at Waggarandall Weir to ensure that flow recommendations are achieved along the entire reach (i.e. not diverted before Waggarandall Weir). Low flows, in particular, should be delivered via Casey's Weir; however, freshes and high flows could be achieved through a combination of local catchment runoff and releases from Casey's Weir. The following sections provide more detail and justification for each flow component.

9.1.1 Summer low flow

The summer low flow recommendation ranges from 5-10 ML/d depending on climate year. Hydraulic modelling shows a flow of 10 ML/d is required to inundate the base of the channel and provide sufficient depth through pools for fish and platypus (Figure 9-1). During dry periods a flow of 5 ML/d still provides continuous flow connection but large-bodied fish and platypus may need to spend the majority of time in weir pools, where the deepest pool habitat would be present. A flow of 5-10 ML/d is also sufficient to inundate benthic surfaces and large wood located in the bottom of the channel – habitat for macroinvertebrates.

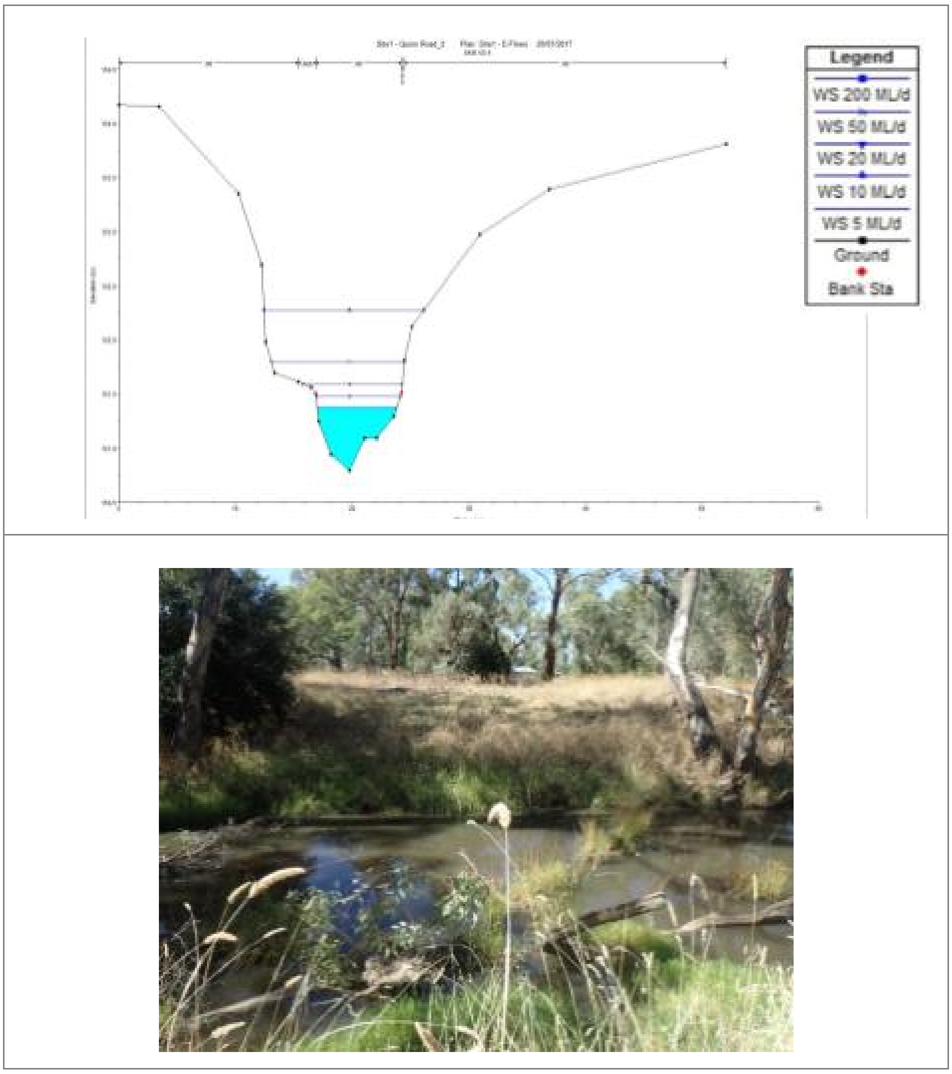


Figure 9-1 Cross Section 4 at Reach 1 Quinn Road showing 5-10 ML/d is sufficient to inundate bed of channel to a depth of 1-1.4 m.

Depending on irrigation demand and supply patterns, low flows may be achieved without the need for specific environmental flow augmentation. However, it is preferable that summer low flows be provided across the full length of the reach in order to maximise access to habitat for fish and platypus. This may require some additional releases in order to maintain flows as far downstream as Waggarandall Weir. Given that objectives for the reach are to maintain conditions for large-bodied native fish and platypus, cease to flows are not recommended.

9.1.2 Summer fresh

A fresh of at least 20 ML/d is recommended in average climate years, increasing to 50 ML/d in wet climate years. A fresh is not specifically recommended in dry climate years. The fresh volumes have been determined based on flows sufficient to provide passage for fish and platypus through shallow sections, drown out low level barriers and promote dispersal of juvenile fish and platypus and inundate low level benches within the channel to boost soil moisture for vegetation (Figure 9-2).

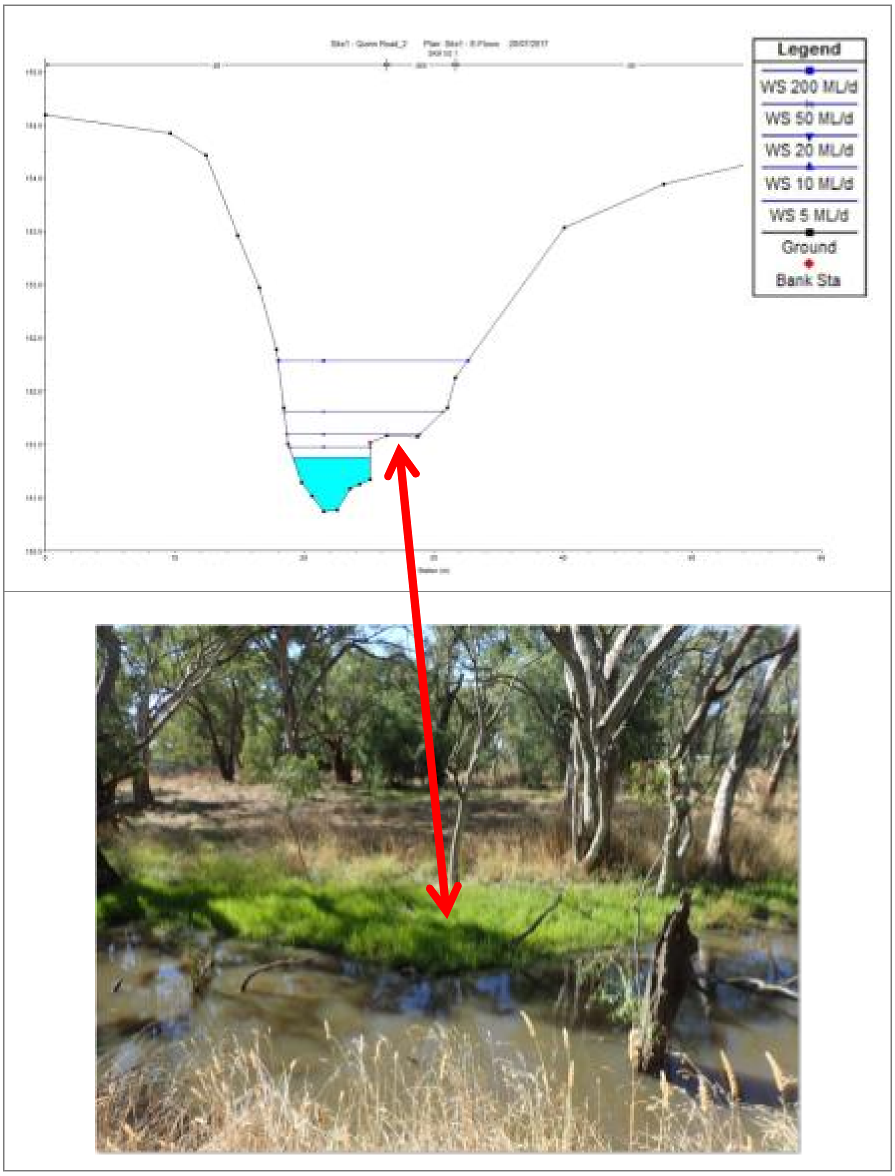


Figure 9-2 Cross Section 1 at Reach 1 Quinn Road showing a flow of 20-50 ML is sufficient to inundate the bench on the far bank (red arrow)

The fresh is recommended to occur in association with delivery of environmental water to Moodies Swamp in the period April-May (and hence can last as long as required to deliver flow to the swamp). A portion of the fresh can be diverted to Moodies Swamp with the remainder being allowed to pass further downstream.

As with summer low flows, depending on irrigation demand and supply patterns, freshes may be achieved as part of the delivery of irrigation water. Across a 6-year period, dry, average and wet climate years are each expected to occur twice with one of the dry years being very dry and one of the wet years being very wet. Freshes are not specifically recommended in dry climate years, but should not be prevented from occurring if catchment runoff occurs.

9.1.3 Winter / spring low flow

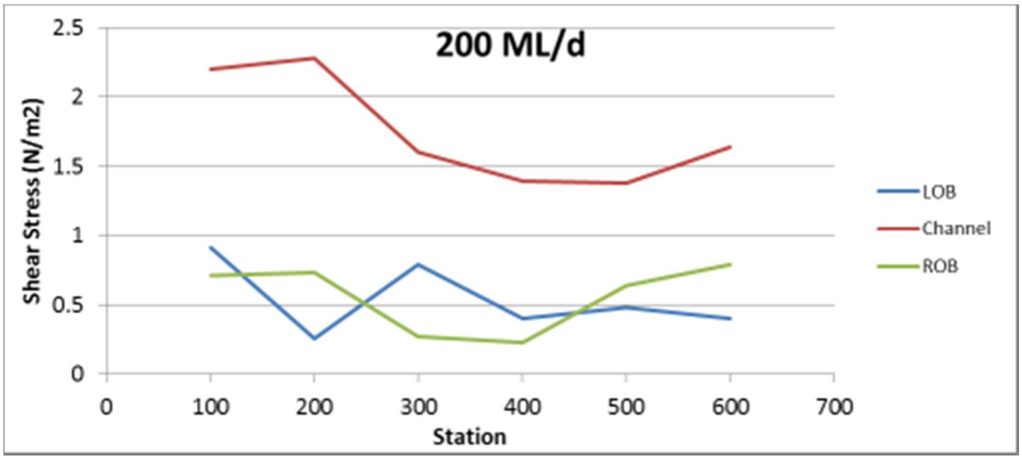
The winter low flow recommendation ranges from 10-20 ML/d depending on climate year. The winter low flow provides slightly deeper channel depths than summer low flows to maintain access to habitat by fish and platypus and to provide additional wetted benthic habitat for macroinvertebrate production. This is important because female platypuses have a high food demand through winter in the lead up to breeding and also in spring to support lactation. Hence maintaining high levels of macroinvertebrate production ensures there is sufficient food available for platypus.

9.1.4 Winter / spring fresh

The winter / spring fresh ranges from 15 ML/d in dry years to 20 ML/d in average years and 50 ML/d in wet years. The winter /spring fresh provides an increase in water depth to inundate stream benches and banks providing soil moisture for littoral vegetation (and drowning terrestrial vegetation that has encroached on the lower channel and low benches (e.g. water couch). The higher flows also provide opportunities for fish movement. The higher fresh volume in wet years reflects natural condition and is likely to be provided by catchment run-off, at least through the middle and lower parts of Reach 1 where tributary streams from the Goorambat Hills enter the Broken Creek. In dry climate years irrigation flows may provide some of the fresh requirement, given that in dry years irrigation deliveries may start earlier in the season. The winter / spring fresh should also be timed to occur in September / October to coincide with the peak growing season for vegetation and movement period for fish. It should also coincide with delivery of environmental water to Moodies Swamp (if a spring filling / top up is required as part of the Moodies Swamp seasonal watering plan) – a portion of the fresh could be diverted to Moodies Swamp with the remainder allowed to progress to downstream reaches. The duration of the winter / spring fresh should be 2 weeks (or as long as required to deliver water to Moodies Swamp) to allow sufficient time for soil moisture to develop and for fish movement to occur.

9.1.5 Winter high flow

A winter / spring high flow of up to 200 ML/d is recommended once every 5 to 10 years at Casey's Weir (translates to 70-110 ML/d at Waggarandall Weir due to attenuation and lag times – SKM 2006a). This event should occur only in very wet years and ideally should occur before October to reduce the risk that juvenile platypus are drowned in nesting burrows. This flow would inundate the riparian zone and some low lying parts of the floodplain, providing soil moisture and promoting recruitment events for River Red Gum away from the immediate channel margins. This event would also engage some distributary channels. In some parts of the reach, this event could also generate shear stresses that would help to scour fine silt and other accumulated materials. However, it is likely to be insufficient to create widespread scour of deeper pools. Specifically, a shear stress of 0.1 - 5 N/m^2 is required to scour silt through to sand and soft clay. A shear stress of 50 N/m^2 is required to scour stiff clay and 105 N/m^2 to scour aquatic vegetation. Hydraulic analysis of the channel in Reach 1 shows that 200 ML/d can achieve a shear stress through the middle of the channel of 1.5 to 2.5 N/m^2, sufficient to scour silt and some fine sand but not soft clay (Figure 9-3). Shear stresses on the channel margins are much lower (<1 N/m^2). These shear stresses are sufficient to scour silt off the surfaces of woody debris and hence maintain the quality of benthic habitat for macroinvertebrates, but they are insufficient to scour deep pools and instream vegetation.



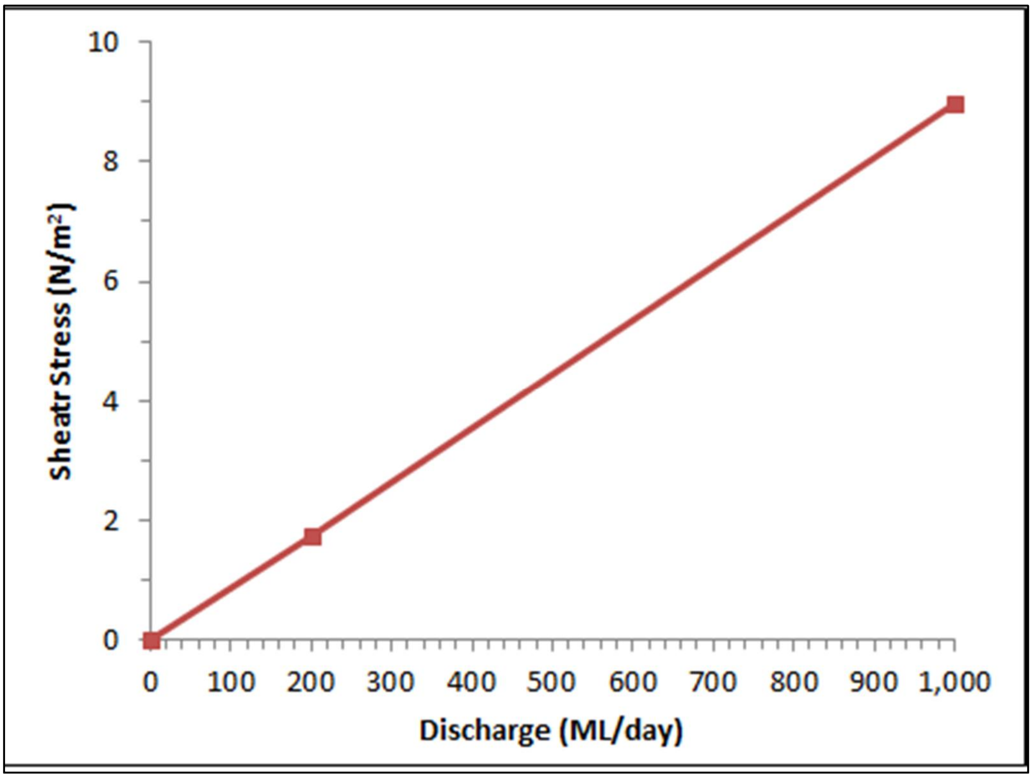


Figure 9-3 Shear stress along Reach 1 at a stream flow of 200 ML/d (upper panel) and relationship between flow and shear stress at cross section 3 (Station 300). LOB is left bank, ROB is right bank, channel is the middle channel or thalweg.

If larger flows could be directed down Broken Creek, for example, if the block bank at the Broken River was removed and unregulated flows were allowed to enter Broken Creek, shear stresses could increase. With the block bank removed, a flow of 15,000-20,000 ML/d would be needed in the Broken River to initiate unregulated flow into Broken Creek and a flow of 30,000-40,000 ML/d would be required in the Broken River to achieve a flow in Broken Creek of ~1000 ML/d. Hydraulic modelling shows that a flow of 1000 ML/d could generate shear stresses of up to ~ 10 N/m^2 at some cross sections. This shear stress could scour some soft clays, but is insufficient to scour stiff clays (50 N/m^2) and instream vegetation (105 N/m^2). On this basis, the ability for flow manipulation, including large scale works to remove existing block banks is unlikely to create conditions sufficient to generate widespread scour that would scour vegetation in the channel and restore deep pool habitat. Furthermore, even if high shear stress could be generated in upper reaches, the liberated sediment would be deposited in weir pools and within the channel further downstream. This would exacerbate the loss of deep pool habitat in weir pools and would also further reduce channel capacity in downstream reaches and increase the likelihood of inundation of low lying areas in Reaches 2 and 3. Despite this, moderate flows up to

200 ML/d (the maximum regulated flow) could achieve localised scour of soft silts that would help maintain the quality of benthic habitats, but not initiate wide scale pool scour.

9.2 Reach 2 and Reach 3

There are no specific flow recommendations for Reaches 2 and 3, but it is important that environmental flows in Reach 1 are allowed to pass downstream to Reaches and 2 and 3. In passing flows to downstream it is acknowledged there is significant flow attenuation and loss, and that under low flow conditions, sections of Reach 2 and 3 could cease to flow. Over time the system will adjust to a more intermittent / seasonal flow regime - although permanent aquatic habitat is expected to be retained through the two reaches in various pools (including weir pools) along the reach. This is consistent with objectives for these reaches (see Section 8).

Although specific flow magnitudes have not been identified for Reaches 2 and 3, it is important that high flows pass through all three reaches from time to time, providing connection between habitats and to the lower Broken Creek. If recommendations for freshes and high flows in Reach 1 are passed downstream it is expected that these flows will provide continuous connection, albeit at a reduced magnitude than that through Reach 1. Attenuation and lag times (from SKM 2006a) indicate that a flow of 200 ML/d at Casey's Weir corresponds to a flow of 70-110 ML/d through Reach 2 and 30-70 ML/d through Reach 3.

Inundation mapping based on a 2D hydraulic model shows that for some parts of the channel through Reaches 2 and 3 flows of these magnitudes exceed channel capacity and inundate low lying land adjacent to the channel. Figure 9-4 shows an example of the inundation mapping for 10, 50 and 100 ML/d through Reach 2. In this example, the inundation mapping shows that if the Geary Regulator (which enables flow to be directed to Moodies Swamp) is closed then localised inundation of low lying areas occurs with flows as low as 10 ML/d (steady state flow at Waggarandall Weir). However, if the Geary Regulator is open, then the majority of flow entering Reach 2 is directed towards Moodies Swamp. As flows increase the area of low lying land inundated also increases. If the Geary Regulator is open the area of inundation is decreased.

Detailed maps for a range of flows are provided in Appendix B. These maps show inundation through Reaches 2 and 3, including with and without the Geary Channel regulator being open. A detailed description of the inundation mapping approach is provided in Appendix C.

10 ML/d	50 ML/d	100 ML/d

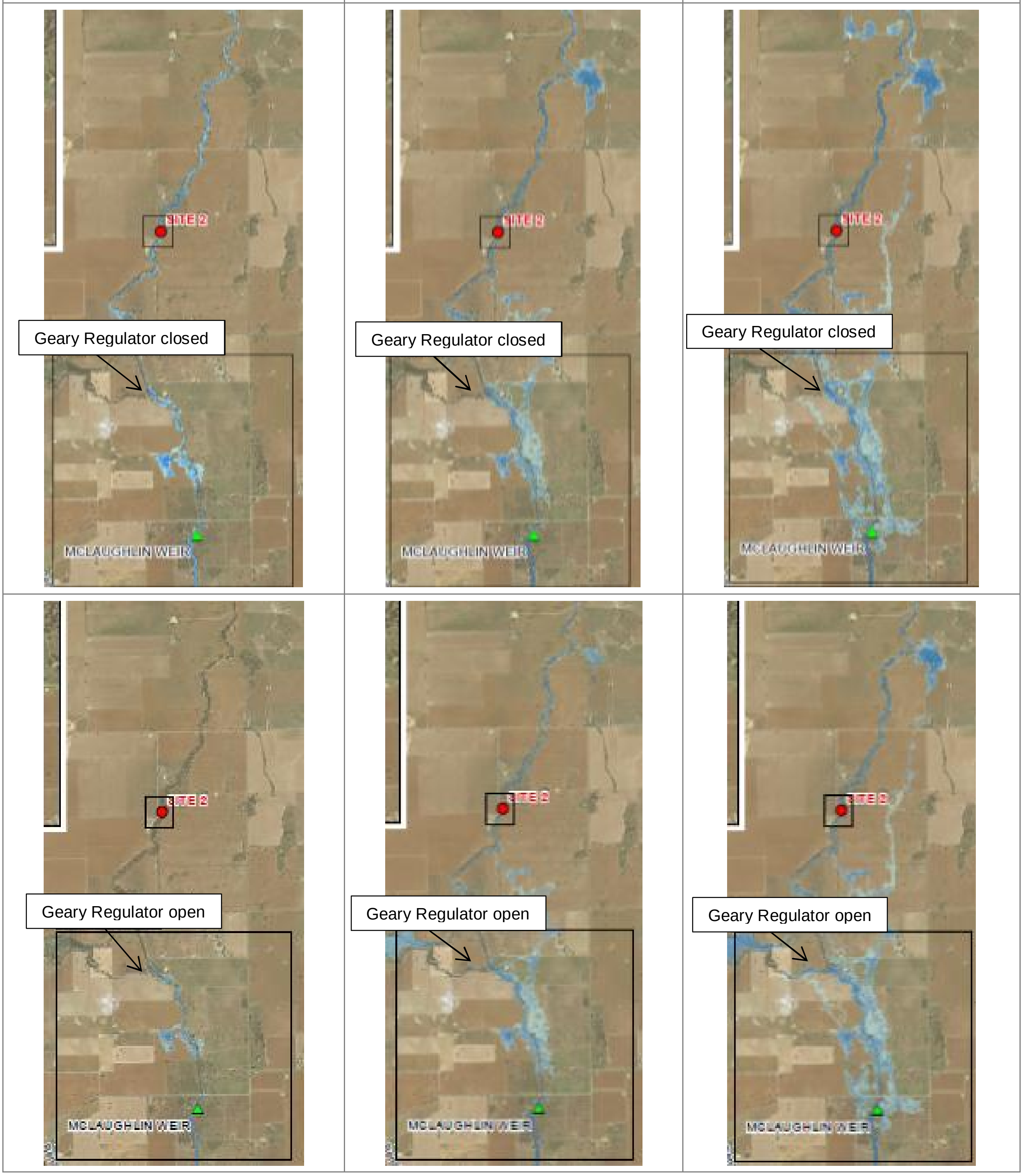


Figure 9-4 Inundation modelling for 10, 50 and 100 ML/d flows through Reach 2 showing increases in inundation of low lying areas within increased flow (upper panel - Geary Regulator closed, lower panel – Geary Regulator open) (See Appendix B for full maps and Appendix C for a description on the mapping method).

9.3 Achievement of recommended flow regime

An idealised representation of the recommended flow regime as compared with the current regime in Broken Creek at Casey's Weir (Reach 1), Waggarandall Weir (Reach 2) and Katamatite (Reach 3) is provided in Figure 9-5. This shows the relative differences in flow between dry, average and wet climate years and also seasonality of flow. Under current condition, the recommended summer flows are achieved at Casey's Weir as a result of irrigation deliveries. In most dry and average climate years, the summer low flows are also generally achieved at Waggarandall Weir, as a result of operational losses from irrigation delivery. During winter, low flow recommendation in dry and average climate years are also achieved but not in wet climate years. Note that the flow regime at Casey's weir is seasonally reversed (i.e. higher flows in summer than winter), but by Waggarandall Weir seasonality is partially restored (i.e. once irrigation water has been extracted from the creek). However, the winter low flow in wet climate years is lower than ideal.

Further downstream, through Reach 3, the current flow regime generally matches the preferred regime with cease-to-flows through summer in most years and higher winter flows in wet climate years, including occasional peak winter flows. These flows are predominantly achieved through catchment runoff rather than specific releases from upstream. This regime is consistent with objectives of allowing Reach 3 to transition to an intermittent flow regime with occasional opportunities for movement through the reach by fish and platypus.

In effect, irrigation operations are maintaining a permanent flow regime in the upper reaches of Broken Creek that generally supports present values, although some elements of a preferred regime are missing. These include some higher winter flows, particularly in wet climate years to support platypus and fish dispersal and for providing soil moisture for riparian vegetation. The need for the latter is most obvious based on an observed lack of recruitment of River Red Gum across the reach. While the current regime generally delivers a flow regime that allows instream values to persist, occasional higher flows in accordance with the recommendations (particularly when coinciding with wet climate years) would provide additional benefit by improving the quality of benthic habitat, providing dispersal opportunities for fish and platypus, and providing moisture and recruitment opportunities for riparian vegetation. These flows should be allowed to pass through all reaches, although a portion of the flow could be diverted to fill Moodies Swamp.

In passing higher flows to downstream reaches there is likely to be localised inundation of low lying areas adjacent to the channel. Inundation mapping identifies the general areas where localised inundation could occur. It is recommended that land holders be consulted in these areas prior to any large environmental flows being passed through Reaches 2 and 3.

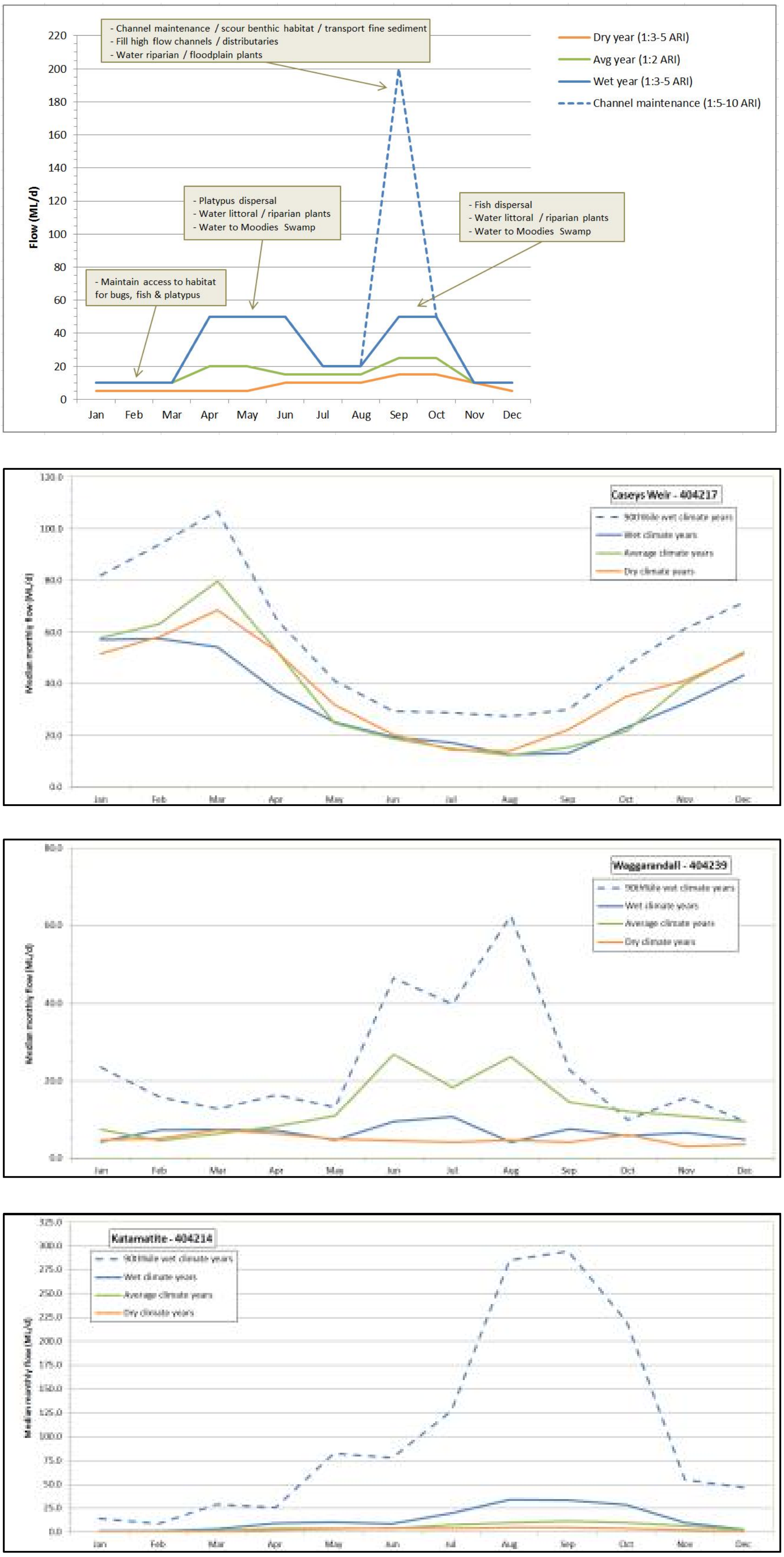


Figure 9-5 Idealised recommended flow regime in dry, average and wet climate years for Reach 1 (upper panel) compared with current flow at Casey's Weir, Waggarandall Weir and Katamatite.

10. Complementary activities and recommendations

The environmental flow recommendations have identified the preferred flow regime required to support environmental values and objectives within the upper Broken Creek. However, from the modelling of flow influences on channel form it is clear that flow alone is insufficient to create ideal habitat, especially for fish and platypus. Over time, pools have filled with sediment and reduced the quality of available habitat. High flows, even if the frequency and magnitude of unregulated flows from Broken River to Broken Creek was restored, do not create shear stresses high enough to scour significant volumes of sediment that has accumulated in pools. Moreover, even if flows were strong enough to scour large volumes of sediment from pools in upper reaches, this material would be deposited in weir pools and the channel in downstream reaches, further contributing to channel contraction and increasing the extent of inundation of low lying land.

It is also not feasible to use flows to scour vegetation growth in the channel. The shear stresses required to scour vegetation are even higher than those required to scour sediment. The current growth of vegetation in the channel does not pose a risk to environmental values or objectives, but there is a perception that in-channel vegetation is contributing to a narrowing of the channel and consequently is a factor in inundation of low lying areas. Under more natural conditions, dry periods would have helped in limiting vegetation encroachment. However, the implementation of long cease-to-flow periods is also not feasible or realistic given current objectives and, in Reach 1 at least, would pose a threat to survival of fish and platypus.

Land management practices and the continued presence of barriers to fish movement at existing weirs further limit the ability to maximise environmental outcomes for the creek, particularly in terms of improving the condition of riparian vegetation and supporting opportunities for dispersal by fish and platypus.

In order to address these issues a range of complementary works and further investigations are recommended:

- Assist riparian vegetation recovery through fencing, grazing control and revegetation.
- Undertake a detailed investigation of remaining weir pools along the creek to assess their suitability as refuge habitat for fish and platypus and make recommendations for 1) where selective excavation could be used to increase the availability of deep pool habitat and 2) where works are needed to improve opportunities for successful fish and platypus movement. The latter is very important if environmental flows aimed at facilitating fish and platypus dispersal are to be effective.
- Integrate the delivery of environmental water to Moodies Swamp with recommendations for Broken Creek.
- Work with landholders to identify areas where in-channel vegetation is contributing to nuisance flooding and develop site specific actions to address issues if considered necessary, particularly if any larger volume (>10 ML/d) flows are planned for delivery through Reach 2 and Reach 3.
- Consider stocking Reach 1 with Murray Cod and Golden Perch, following evaluation of weir pool habitat condition.
- Monitor the effectiveness of flow and other habitat works on stream condition and instream, riparian and floodplain assets, namely vegetation, fish and platypus responses.

At this stage it is not recommended to remove the block banks between the Broken River and Broken Creek. This is because their removal is unlikely to significantly increase the frequency of unregulated flows into the creek and, even if higher flows are achieved, these flows will not generate sufficient shear stress to scour deep pools, and they could also result in nuisance inundation of low lying land. Feasibility of pool habitat restoration through selective excavation should be explored through a detailed assessment of existing weir pools as described above.

It is also not recommended to use the upper Broken Creek as a conduit for delivering water to the lower Broken Creek. This is because the capacity of the channel diminishes significantly in a downstream direction, resulting in substantial losses of water. Transfers to the lower Broken Creek are therefore very inefficient. Furthermore, the low channel capacity means the transfer of large volumes of water would create nuisance inundation of low lying land.

11. Conclusions

Broken Creek exists as a distributary system and if left to its natural trajectory would have filled with alluvial material, likely becoming an ephemeral waterway with decreasing flow permanence as one moves downstream. It is possible that the system would have reverted to a series of wetlands connected by a less distinct main channel. The development of the system for stock and domestic use slowed this trajectory and since the cessation of S&D flows in the creek this trajectory continues.

The nature of the creek in the future will be largely determined by whether sections of it are managed to be perennial or ephemeral. It is possible that Reaches 1 and 2 could be managed as perennial systems, while Reach 3 is left to develop into a series of wetlands. Given the low gradient of the system, rehabilitation of deep pools within any of the reaches using flow alone is unrealistic, as boundary shear stresses strong enough to mobilise consolidated bed and bank sediments cannot be feasibly produced. In the absence of scouring flows, weir pools may act as surrogates for deep pool refuge habitat if maintained in a perennial state. However this may require active sediment removal from weir pools, many of which have filled with sediment in recent years. Sediment removal by mechanical means should be considered as a potential for complementary action to flow management, but due consideration must be given to the potential local and downstream disturbances (e.g. to vegetation and water quality) created through the use of such machinery.

Maintenance of perennial flow in the upper two reaches will likely maintain fish, platypus and macroinvertebrate populations. However, without naturally occurring high flow events and overbank floods, cues for fish movement will be limited and the abundances of large-bodied native fish are likely to remain low. In Reach 3, large-bodied fish and platypus are not likely to find suitable habitat conditions even under perennial or increased flow regimes. It is likely that this reach will only be periodically colonised by some individuals. Similarly, maintenance of current flows or increases in flow is not likely to significantly affect macroinvertebrate communities. However, allowing Reach 3 to develop into a series of wetlands would result in the disappearance of macroinvertebrate species requiring perennial flows, a decrease in decapod and mussel species, and an increase in opportunistic species.

The stability of the channel over the past decade, despite occasional large floods (e.g. 2010/11 and 2016), reveals the low shear stresses this system experiences. This has produced ideal conditions for the vegetation community to become dominated by plants that prefer perennial water and/or damp conditions. Encroachment by water couch and Cumbungi is evident, with Cumbungi being a concern to local landholders. The encroachment of these plants can be prevented through flow management; however, this would involve instituting cease-to-flow events with a prolonged drying phase to kill off rhizomes, or extended periods of deeper inundation. Such management is unlikely to be feasible in the upper reaches, but may be implemented in sections of Reach 3 subject to sufficient control of streamflows at key locations upstream (i.e. to generate long durations of drying). Under this management scenario the vegetation communities in the upper sections of Reach 3 are likely to become more like other wetlands in the area, while instream vegetation in the lower sections is likely to disappear and be replaced by more terrestrial species such as knot weed and water couch.

Changes in flow management can have conflicting effects for different flow-dependent assets. For instance, while extended drying may reduce unwanted stands of Cumbungi, this would have a negative effect on other water-dependent fauna. The most parsimonious approach for the system would seem to be to manage the upper reaches as perennial streams and the lower reach as a series of ephemeral / seasonal wetlands. Maintaining perennial water in the upper reaches will ensure the maintenance of aquatic fauna, such as fish, but will also result in the perseverance of Cumbungi. While this is considered an issue by some local landholders, Cumbungi is likely to have very little impact on flow patterns in the upper reaches and its removal would need to be considered in view of the expense to other assets. For instance, given that flows are required for the maintenance of Moodies Swamp and that multi-year drying is required to kill off Cumbungi, it is not likely that this approach would be feasible. Reach 3 could either be managed as a perennial or ephemeral system. However, there are few assets within this reach that require perennial flow and under natural conditions this section of the creek would have developed into a terminal wetland system.

The above issues were discussed with the PAG and further considered by the EFTP, to develop a set of objectives for the creek. These are to maintain permanent habitat for fish and platypus in Reach 1 with a transition through Reach 2 and 3 to a more seasonally intermittent system that provides opportunistic habitat for fish and platypus and maintains occasional / seasonal opportunities for dispersal during wet / higher flow years. Specific reach objectives were:

1) Manage Reach 1 to:
   - continue to provide permanent habitat for native fish, platypus, macroinvertebrates and other fauna
   - minimise accumulation of fine sediments and periodically engage distributary channels and floodplains
   - protect and enhance the diversity and extent of instream, littoral and riparian vegetation
   - maintain water quality (avoid periods of low dissolved oxygen) to protect fish and macroinvertebrates
   - explore opportunities for enhancing weir pools as deep water refuge habitat for fish and platypus
2) Manage Reach 2 to:
   - maintain opportunistic habitat for fish and platypus and provide for dispersal opportunities during wet years
   - minimise accumulation of fine sediments and periodically engage distributary channels and floodplains, and specifically maintain capacity to deliver environmental water to Moodies Swamp in a way that integrates flow delivery for the swamp with flow requirements for the creek.
   - protect and enhance the diversity and extent of instream, littoral and riparian vegetation
   - explore opportunities for enhancing weir pools (including those not required for current water supply operations) as deep water drought refuge habitat for fish and platypus
3) Manage Reach 3 to:
   - transition to a more seasonally intermittent waterway characterised by a well vegetated channel and riparian zone
   - allow for dispersal opportunities by fish and platypus during wet years
   - investigate whether existing weir pools / permanent pools should be actively managed as drought refuge habitat.

The history of drying and the associated current natural values in Reach 3 tend to mean there is little benefit in actively maintaining permanent flow in this reach. This reach may best be thought of as a series of terminal linear wetlands. It is likely that aquatic plants, invertebrates and amphibians capable of surviving dry periods, and native fish and platypus will opportunistically move into this reach when it is inundated. Actively delivering environmental flows to this reach to maintain permanent aquatic habitats and longitudinal connectivity should therefore be a lower priority, but nonetheless allowed to occur from time to time to provide occasional dispersal opportunities for biota.

Flow recommendations were developed to facilitate the achievement of the above objectives (Table 11-1). The specific flow recommendations are set for Reach 1 in order to maintain perennial flow for fish and platypus. There are no specific flow magnitude recommendations for Reaches 2 and 3, as downstream flow from Reach 1 will support objectives for those two reaches. Recommendations are provided for dry, average and wet climate years. Figure 11-1 provides a visualisation of the ideal flow regime in Reach 1 for each climate year type.

An evaluation of how well the current regime meets the recommended regime indicates that irrigation operations are maintaining a permanent flow regime in the upper reaches of Broken Creek that generally supports present values, although some elements of a preferred regime are missing. These include some higher winter flows, particularly in wet climate years, to promote successful platypus and fish dispersal and provide soil moisture for riparian vegetation.

While the current regime generally delivers a flow regime that allows instream values to persist, occasional higher flows in accordance with the recommendations (particularly in wet climate years) would provide additional benefit by improving the quality of benthic habitat, providing dispersal opportunities for fish and platypus, and providing moisture and recruitment opportunities for riparian vegetation. These flows should be allowed to pass through all reaches, although a portion of the flow could be diverted to fill Moodies Swamp.

Complementary actions and investigation aimed at maximising environmental outcomes have also been identified. These include, fencing of riparian zones, an investigation of weir pools to assess opportunities for selective pool excavation and removal of barriers to fish passage, and consultation with landholders regarding issues associated with inundation of low lying land in Reaches 2 and 3.

Table 11-1 Environmental flow recommendations for Reach 1 – Casey's Weir to Waggarandall Weir

Stream		Broken Creek		**Reach 1**	Casey's Weir to Waggarandall Weir
Compliance point		Waggarandall Weir		**Gauge No.**	404239 (Waggarandall Weir)
Season	**Component**	**Volume***	**Frequency**	**Duration**	**Objective**
Summer / autumn (Dec-May)	Cease-to-flow	Not recommended			
	Low flow	5 ML/d (dry) 10 ML/d (avg) 10 ML/d (wet)	All season		M1.1, F1.1, P1.1
	Fresh	20 ML/d (avg) 50 ML/d (wet)	Once per year in average and wet climate years. Timed to coincide with filling Moodies Swamp. A proportion of the flow could be diverted to fill Moodies Swamp with the remainder passing to downstream reaches. Not required/expected in dry climate years.	Within the period Apr – Jun for as long as required to fill Moodies Swamp	W1.1, P1.2
	High flows	No specific recommendation but allowed to occur in response to local catchment runoff.			
Winter / spring (June-Nov)	Cease-to-flow	Not recommended			
	Low flow	10 ML/d (dry) 15 ML/d (avg) 20 ML/d (wet)	All season		M1.1, F1.1, P1.1
	Fresh	15 ML/d (dry) 20 ML/d (avg) 50 ML/d (wet)	Once per year in dry, average and wet climate years. A proportion of the flow could be diverted to fill Moodies Swamp, if a top up was required, with the remainder passing to downstream reaches.	2 weeks within the period Sep – Oct to coincide with topping up Moodies Swamp and growing period for vegetation. Duration could be longer if required to deliver water to Moodies Swamp	F1.2, P1.2, V1.2, V1.3, V1.4
	High flow / bankfull	Up to 200 ML/d	Only expected in very wet climate years once every 5 to 10 years in response to local catchment runoff. Local runoff could be augmented with transfers via Casey's Weir.	Determined by duration of local runoff. If augmentation from Casey's weir is provided, then 1-2 days.	G1.1, G1.2
	Overbank	No specific recommendation but allowed to occur in response to local catchment runoff.			

* Note that flows above 10-15 ML/d in Reach 2 are likely to cause localised nuisance flooding of low-lying land in some areas adjacent to the creek channel. Larger flows, up to 200 ML/d, cannot be realistically delivered through Reach 2 because of potential for more extensive inundation of private land.

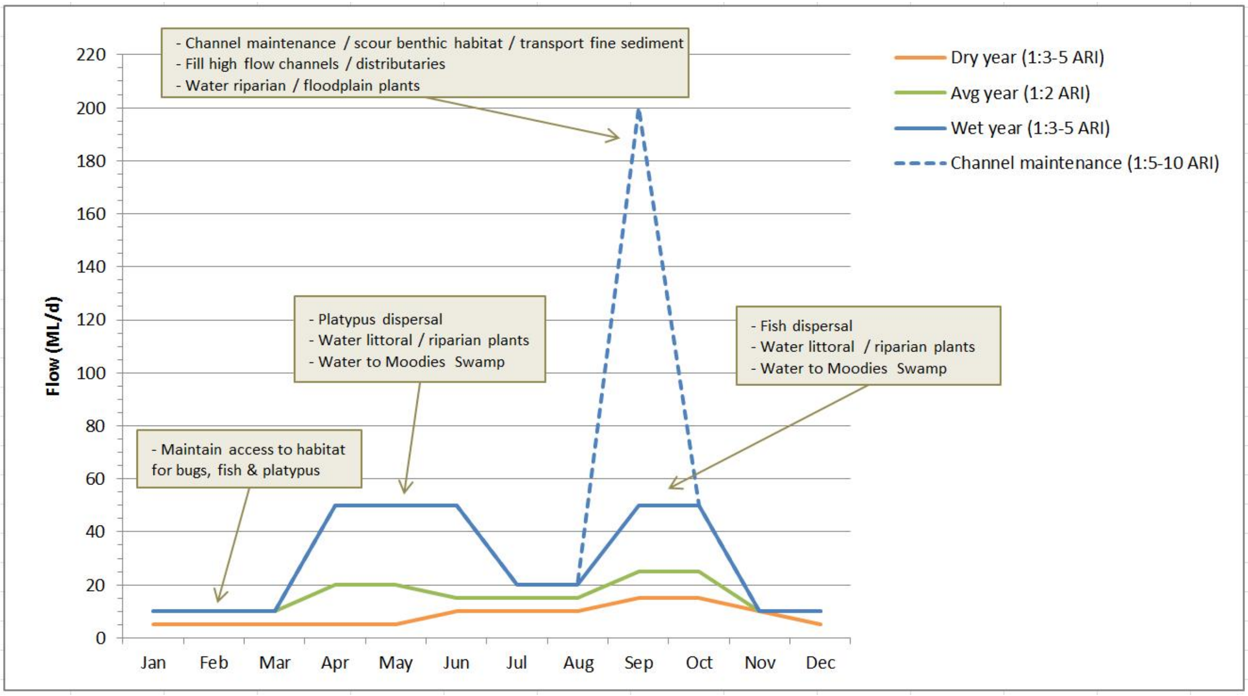


Figure 11-1 Visual representation of the ideal flow regime for Reach 1

12. References

Apfelbaum, S. I. 1985. Cattail (Typha spp.) management. Natural Areas Journal 5:9-17.

Bice, C. M. and B. P. Zampatti. 2011. Engineered water level management facilitates recruitment of non-native common carp, Cyprinus carpio, in a regulated lowland river. Ecological Engineering 37:1901-1904.

Bloink, C. and K. Stevenson. 2015. 2015 VEFMAP fish monitoring of the Goulburn River, Broken River and Broken Creek. Report by Ecology Australia prepared for Goulburn Broken Catchment Management Authority, Melbourne.

Bond, N. R. and P. S. Lake. 2003. Local habitat restoration in streams: constraints on the effectiveness of restoration for stream biota. Ecological Management and Restoration 4:193-198.

Bond, N. R., D. McMaster, P. Reich, J. R. Thomson, and P. S. Lake. 2010. Modelling the impacts of flow regulation on fish distributions in naturally intermittent lowland streams: an approach for predicting restoration responses. Freshwater Biology 55:1997-2010.

Cunningham, G. M., W. E. Mulham, P. L. Milthorpe, and J. H. Leigh. 2006. Plants of Western New South Wales. Inkata, Sydney.

Davies, P., M. Stewardson, T. Hillman, J. Roberts, and M. Thoms. 2012. Sustainable Rivers Audit 2: The ecological health of rivers in the Murray–Darling Basin at the end of the Millennium Drought (2008–2010). Murray–Darling Basin Authority, Canberra.

DEPI. 2013. FLOWS - a method for determining environmental water requirements in Victoria. Edition 2. Department of Environment and Primary Industries, Melbourne.

DEPI and RBMS. 2013. Historical Waterways Photographs. Compiled by the Department of Environment and Primary Industries and the River Basin Management Society. http://rbms.com.au/media/historical-photos/.

Environment Australia. 2001. A Directory of Important Wetlands in Australia, Third Edition. Environment Australia, Canberra.

EPA. 1999. The health of streams in the Goulburn and Broken catchments. Victoria.

Faragher, R.A., Grant, T.R., and Carrick, F.N. (1979). Food of the platypus (*Ornithorhynchus anatinus*) with notes on the food of brown trout (*Salmo trutta*) in the Shoalhaven River, N.S.W. Australian Journal of Ecology 4:171-9.

Fredlund, D. G. and H. Rahardjo. 1993. Soil Mechanics of Unsaturated Soils. John Wiley & Sons, Inc., New York.

Galbraith, H. S., C. J. Blakeslee, and W. A. Lellis. 2014. Behavioral responses of freshwater mussels to experimental dewatering. Freshwater Science 34:42-52.

Gardner, J.L., and Serena, M. 1995. Spatial organisation and movement patterns of adult male platpus, *Ornithorhynchus anatinus* (Monotremata: Ornithorhynchidae). Australian Journal of Zoology 43:91-103.

GBCMA. 2014. Assessment of channel change and achievement of geomorphological objectives in the Goulburn and Broken catchments: 2008-2010. Report prepared by Goulburn Broken Catchment Management Authority.

Goulburn Broken CMA. 2012. Moodies Swamp Environmental Water Management Plan. Goulburn Broken Catchment Management Authority, Shepparton, Victoria.

Grant, T. (2004). Depth and substrate selection by platypuses, *Ornithorhynchus anatinus*, in the lower Hastings River, New South Wales. Proceedings of the Linnean Society of New South Wales 125:235-241.

Hudson, N., editor. 1971. Soil Conservation. Cornell University Press, Ithaca.

Layzer, J. B. and L. M. Madison. 1995. Microhabitat use by freshwater mussels and recommendations for determining their instream flow needs. Regulated Rivers: Research & Management 10:329-345.

Marchant, R., and Grant, T. R. (2015). The productivity of the macroinvertebrate prey of the platypus in the upper Shoalhaven River, New South Wales. Marine and Freshwater Research 66:1128-1137.

McCasker, N., R. K. Kopf, and P. Humphries. 2015. Analysis of fish assemblage data from the Goulburn-Broken Catchment (2008-2014). Institute for Land, Water and Society, Charles Sturt University. Prepared for the Goulburn Broken Catchment Management Authority.

McLachlan-Troup, T. A., Dickman, C. R. & Grant, T. R. (2010) Diet and dietary selectivity of the platypus in relation to season, sex and macroinvertebrate assemblages. Journal of Zoology 280:237-246.

McMaster, D., N. R. Bond, P. Reich, and P. S. Lake. 2006. Research on the ecological impacts of flow regime reversal and weir removal in the Broken-Boosey Creek system: Interim report on benchmarking data from 2005-2006. Unpublished report prepared by Monash University for the Goulburn Broken Catchment Management Authority.

McMaster, D., N. R. Bond, P. Reich, and P. S. Lake. 2009. Research on the ecological responses to flow alterations in the Broken-Boosey Creek system. Unpublished report prepared by Monash University for the Goulburn Broken Catchment Management Authority.

Nielsen, D., M. Brock, G. Rees, and D. S. Baldwin. 2003. Effects of increasing salinity on freshwater ecosystems in Australia. Australian Journal of Botany 51:655-665.

Prosser, I. P., W. E. Dietrich, and J. Stevenson. 1995. Flow resistance and sediment transport by concentrated overland flow in a grassland valley. Geomorphology 13:71-86.

Prosser, I. P. and C. J. Slade. 1994. Gully formation and the role of valley-floor vegetation, southeastern Australia. Geology 22:1127-1130.

Reich, P., D. McMaster, N. R. Bond, and L. Metzeling. 2010. Examining the ecological consequences of restoring flow intermittency to artificially perennial lowland streams: Patterns and predictions from the Broken—Boosey creek system in northern Victoria, Australia. River Research and Applications 26:529-545.

Reid, D. J., G. P. Quinn, P. S. Lake, and P. Reich. 2008. Terrestrial detritus supports the food webs in lowland intermittent streams of south-eastern Australia: a stable isotope study. Freshwater Biology 53:2036-2050.

Reid, L. M., editor. 1989. Erosion of Grassed Hillslopes. University of Washington, Washington.

Richardson, A., J. Growns, and R. Cook. 2004. Distribution and life history of caridean shrimps in regulated lowland rivers in southern Australia. Marine and Freshwater Research 55:295-308.

Roberts, J. and F. Marston. 2011. Water regime for wetland and floodplain plants: a source book for the Murray-Darling Basin. National Water Commission.

Robinson, D. and S. Mann. 1996. Natural values of the public lands along the Broken, Boosey and Nine Mile Creeks of Northeastern Victoria. Report prepared by the Goulburn Valley Environment Group for Goulburn-Murray Water and the National Parks Service.

Rutherfurd, I., K. Jerie, and N. Marsh. 2000. A rehabilitation manual for Australian Streams. CRC for Catchment Hydrology & LWRRDC, Canberra.

Sainty, G. R. and S. W. Jacobs. 1981. Waterplants of New South Wales. New South Wales: Water Resources Commission 550p.-illus., col. illus., maps, keys.. En Icones, Maps, Chromosome numbers. Geog 7.

Serena, M. 1994. Use of time and space by platypus (*Ornithorhynchus anatinus*: Monotremata) along a Victorian stream. Journal of Zoology 232:117-131.

Serena, M. and Grant, T.R. In press. Effect of flow on platypus (*Ornithorhynchus anatinus*) reproduction and related population processes in the upper Shoalhaven River. Australian Journal of Zoology.

Serena, M., and Pettigrove, V. 2005. Relationships of sediment toxicants and water quality to the distribution of platypus populations in urban streams. Journal of the North American Benthological Society 24:679-689.

Serena, M., and Williams, G. 2010a. Factors contributing to platypus mortality in Victoria. The Victorian Naturalist 127:178-183.

Serena, M., and Williams, G. A. 2010b. Platypus population assessment and recommended management actions along Broken Creek. Unpublished report prepared by Australian Platypus Conservancy for Goulburn Broken CMA.

Serena, M., Williams, G. A., Weeks, A. R., and Griffiths, J. 2014. Variation in platypus (*Ornithorhynchus anatinus*) life-history attributes and population trajectories in urban streams. Australian Journal of Zoology 62:223-234.

Serena, M., Worley, M., Swinnerton, M. and Williams, G. A. 2001. Effect of food availability and habitat on the distribution of platypus (*Ornithorhynchus anatinus*) foraging activity. Australian Journal of Zoology 49:263-277.

SKM. 1998. Broken Creek Management Strategy. Report prepared by SKM for Goulburn Broken Catchment Management Authority.

SKM. 2005. Casey's Weir and Major Creek Rural Waterworks Authority - Focused environmental assessment of pipeline proposal. Updated version March 2005., Report prepared by Sinclair Knight Merz for Goulburn-Murray Water.

SKM. 2006a. Broken and Boosey Creeks environmental flow determination: Current and natural flows. Report by Sinclair Knight Merz for Goulburn Broken Catchment Management Authority.

SKM. 2006b. Broken and Boosey Creeks Environmental Flow Determination: Issues Paper. Report prepared by SKM for Goulburn Broken Creek Catchment Management Authority.

SKM. 2007a. Broken and Boosey Creeks environmental flow determination: Flow recommendations. Report by Sinclair Knight Merz for Goulburn Broken Catchment Management Authority.

SKM. 2007b. Broken and Boosey Creeks environmental flow determination: Flow recommendations., Report by Sinclair Knight Herz for Goulburn Catchment Management Authority.

SMEC. 2005. Nathalia flood study. Report prepared by SMEC for the Moira Shire Council and Goulburn Broken Catchment Management Authority.

State Rivers and Water Supply Commission. 1964. Broken Creek Water Supply Systems. Investigations Division, State Rivers and Water Supply Commission, Victoria.

Tickell, S. J. 1989. Dookie 1:100 000 Map Geological Report. Geological Survey Report No. 87.

Trueman, W. T. 2007. Some Recollections of Native Fish Inthe Murray-Darling System with Special Reference to the Trout Cod. Native Fish Australia.

Worley, M., and Serena, M. 2000. Ecology and conservation of the platypus in the Wimmera River catchment: IV. Results of habitat studies, summer 1999. Unpublished report prepared by Australian Platypus Conservancy for Rio Tinto Project Platypus.

Appendix A. Macroinvertebrate taxa data

Taxa present at sites on the Broken Creek (upstream – downstream). Data obtained from the Atlas of Living Australia (http://www.ala.org.au/) accessed 27 April 2017.

		SITES and YEARS SAMPLED										
TAXA	SIGNAL2 grade	Trewin Rd 2006	Noormunga Rd 2008	Cooper rd 2010	Harcourt Rd 2005	South Boundry rd 2008/2010	Oliver rd 2006	Yundool rd 2005	Geary rd 2010	Pelleubla rd 2006	Dikie rd 2006	School rd 2006
Aeshnidae	4	*										*
Ancylidae	4	*	*		*	*	*	*	*	*	*	*
Atyidae	3	*	*	*	*	*	*	*			*	*
Baetidae	5	*	*	*	*	*	*	*	*	*	*	*
Belostomatidae	1		*			*						
Caenidae	4	*	*	*		*	*	*			*	*
Ceratopogonidae	4		*	*		*					*	*
Chironomidae	3	*	*	*	*	*	*	*	*	*	*	*
Coenagrionidae	2	*	*	*	*	*		*	*	*	*	*
Corduliidae	5		*			*						*
Corixidae	2	*	*	*	*	*	*	*	*	*	*	*
Culicidae	1					*			*			
Dugesiidae	2		*									
Dytiscidae	2	*	*		*	*	*		*	*	*	*
Ecnomidae	4			*		*	*					*
Elmidae	7				*							
Empididae	5						*					
Erpobdellidae	1		*									
Glossiphoniidae	1		*			*				*	*	*
Gordiidae	5	*										
Gyrinidae	4	*		*	*			*	*			*
Haliplidae	2					*						
Hebridae	3					*						
Hydraenidae	3		*	*		*	*	*	*	*		
Hydridae	2											*
Hydrometridae	3				*							*
Hydrophilidae	2	*	*	*	*	*	*	*	*	*	*	*
Hydropsychidae	6			*			*					
Hydroptilidae	4	*				*					*	*
Janiridae	3			*			*			*		
Leptoceridae	6	*	*	*	*	*	*	*	*	*	*	*
Leptophlebiidae	8											*
Lestidae	1		*			*			*			
Lymnaeidae	1		*									
Mesoveliidae	2											*
Notonectidae	1	*	*	*	*	*		*	*	*	*	*
Palaemonidae	4		*									
Parastacidae	4	*		*	*	*	*	*			*	
Perthiidae	4					*						
Physidae	1	*	*	*		*			*	*	*	*
Planorbidae	2		*	*		*			*		*	*
Pyralidae	3					*						
Saldidae	1			*								
Sciomyzidae	2								*			
Scirtidae	6		*	*		*					*	*
Simuliidae	5	*		*		*	*	*	*		*	
Stratiomyidae	2	*	*						*			
Tipulidae	5	*		*								
Veliidae	3	*	*	*	*	*	*	*	*	*	*	*

Appendix B. Inundation mapping

Appendix C. Inundation mapping method report