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Integrated Hydrological Operations Plan for the Billabong, Yanco and Colombo Creeks

Murray Local Land Services

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The Billabong Yanco Project

The Billabong Yanco Project was initiated by Murray Local Land Services (LLS) with funding from the Federal Government's National Landcare Program. The Billabong Yanco Project is guided by the Billabong Yanco Project Steering Committee which is made up of local stakeholders. The project aims to promote a resilient, productive Billabong Yanco system with healthy ecosystems and communities.

The Hydrological Operations Plan

The scope of this study was to develop a hydrological operations plan for the Billabong, Yanco and Colombo Creeks that integrates the economic, social and ecological needs and aspirations of key stakeholders in a balanced and equitable way. This project involved identifying and liaising with key Billabong Yanco System stakeholders to:

- review social, ecological and environmental studies;
- identify critical knowledge gaps that may influence the development of the plan and recommend a way forward;
- incorporate the needs and aspirations of stakeholders into the plan; and
- develop a prescriptive and pragmatic hydrological operations plan that integrates the needs and aspirations of key stakeholders in a balanced and equitable way.

The project is presented in two reports:

- a literature review and stakeholder consultation findings; and
- a hydrological operations plan (this report).

Hydrological Analysis and Management Opportunities

Managing Flow for Trout Cod in Upper Yanco Creek

The Yanco Creek and adjacent Murrumbigee River support an important self-sustaining population of the nationally endangered Trout Cod (Sharpe and Stuart 2014). The creek provides habitat conditions that were once widespread in the lowland Murray-Darling Basin but are now extremely rare: perennially fast flowing water, good water quality, good riparian vegetation, low macrophyte density and dense in-channel snag habitat.

Flow recommendations to promote Trout Cod abundance and breeding success were developed based on a flow-habitat model for Trout Cod developed by Sharpe et al (2013) and Sharpe and Stuart (2014), a review of physical habitat information and an analysis of hydrological data.

- Flows to support Trout cod should be managed in terms of a pre-breeding period, a breeding period and a non-breeding period.
- The non-breeding period extends from mid-summer to early spring.
- The objective in the non-breeding period is to facilitate Trout cod growth and survival. A minimum flow of 250 ML/d could be adopted as the target in the non-breeding period. At this flow a velocity of more

than 0.3 m/s is achieved, the water depth in runs is 0.8 m, pools are filled and low instream benches are inundated to 0.2 m. This flow provides connectivity between pools, access to pools, run and edge habitat and maintains suitable channel velocity. A higher baseflow than 250 ML/d would provide these outcomes with a higher degree of certainty.

- The breeding period is defined as being between September and December, when water temperatures exceed 15°C. In Yanco Creek water temperatures generally exceed this threshold from mid-September.
- The objective in the breeding period is to facilitate breeding by maintaining adequate inundation of nesting habitat.
- The flow required to inundate nesting habitat is uncertain. Inundation of high in-channel benches by a flow of 600 ML/d has been proposed as a target for breeding flow. Based on the requirement for inundated snags, a lower flow of 450 ML/d could be adopted as a target for breeding flows, but with a lower degree of certainty.
- Under the flow-habitat model, fluctuations below the breeding flow target contribute to breeding failure and should be avoided. Based on the best available fish ecology advice, flows should be maintained above the breeding flow target throughout the breeding period.
- Significant flow variability during spring is a characteristic of the natural habitat of Trout cod. However there is currently insufficient knowledge to determine what degree of flow variation is acceptable in managed watercourses.
- Flows should increase over the four weeks preceding the breeding season to promote conditioning and breeding behaviour. The pre-breeding increase in flow should take place between mid-August and mid-September.

The following investigations are required to refine environmental flow recommendations.

- The levels in the Yanco Creek and Colombo Creek channel where Trout cod nest, or potentially nest, should be investigated. The investigations should determine whether nests are associated with a particular depth or habitat feature such as snags, rocks or benches. This information will help identify the most sensitive flow thresholds for Trout cod breeding.
- A cross sectional survey and physical habitat survey is required of Yanco Creek and the unregulated section of Colombo Creek to map habitat so that flow can target specific habitat features.
- A hydraulic model is required for Yanco Creek and the unregulated section of Colombo Creek to relate discharge to habitat features, channel velocity and depth throughout the reach.
- The high stable flows spring and summer flows recommended in the Trout Cod flow-ecology model contrast strongly with the unregulated, variable flow regimes of the watercourses in which Trout Cod was historically abundant. The recommended Trout Cod breeding flow may be overly conservative. Investigations into Trout Cod breeding ecology and the significance of water level variation would refine the breeding flow recommendation and would better guide the management of hydrological risks to breeding.

In addition we note the following.

- The proposed new Yanco Weir and Regulator offers greater precision and responsiveness in flow delivery to Yanco Creek and may be better at managing breeding season flows for Trout Cod than the existing weir. However the potential benefits of the new weir and regulator must be considered against the requirement to build a fishway on the offtake channel, where currently there is none. Even under best practice design, the fishway will not be as transparent to fish movement as the current arrangements.

Enhancing Natural Flows with Regulated Flow Releases

High in-channel and overbank flows have been identified as an important ecological requirement of the Billabong Yanco System (Alluvium 2013). This study investigated the scope to increase the frequency of high in-channel and overbank flows by coordinating delivery of environmental water to the system with naturally occurring high flow events sourced from Upper Billabong Creek.

The target reaches for this flow enhancement strategy would be Mid-Billabong Creek, Lower Billabong Creek and Forest Creek/Wanganella. Flow from an environmental allocation would be delivered from the Murrumbidgee River through Upper Yanco Creek to Colombo Creek to meet with natural high flow sourced from Upper Billabong Creek. The intention would be to generate a higher flow that targets the environmental flow components of in-channel freshes, bankfull and overbank flows.

Upper Billabong Creek flow event travel times were analysed. The investigation found that the flow gauges on the creek do not give sufficient warning time to enable harmonisation of environmental flows delivered from headwater dams, via Yanco and Colombo creeks. While a minimum of 18 days notice is required to deliver environmental flows, the peaks of natural flow events in Billabong Creek typically travel from the most upstream gauge to the junction with Colombo Creek in 7 – 16 days.

600 ML/d was assumed to be the upper magnitude of flow that could be delivered to Billabong Creek via Colombo Creek as a managed environmental flow in winter and spring (June – November). The analysis found that most years provide opportunities to increase Colombo Creek flows up to 600 ML/d, although the duration and timing of these opportunities would be difficult to predict and even more difficult to synchronise with high inflows from the Billabong catchment.

Water balance modelling revealed that while there were numerous opportunities to enhance flows in Billabong Creek with environmental flows delivered from Yanco Creek, the opportunities to generate bankfull and overbank flows was limited. In general, the higher the magnitude of the environmental flow component and the further in distance from Colombo Creek, the fewer were the opportunities to enhance the flow to meet desired flow components.

Characteristics of Supplementary Water Events

Supplementary flows are important to many irrigators as an additional source of water for crop production. There is concern that operation of a proposed new Yanco Weir would decrease the frequency and duration of supplementary flows due to the greater range of flows that it is designed to control. The most important reaches of the system where this concern is relevant are the Mid-Yanco, Mid-Billabong and Lower Billabong, where the most irrigated crops are located.

Department of Primary Industries Water advised that surplus flows into effluents are typically managed to equalise opportunity (Andrew Brown, under approval of Danielle Baker, Director Water Analytics - DPI Water, pers. comm., 1 Sep 2017). Clause 69(3) of the Water Sharing Plan (New South Wales Government, 2017) also requires this more generally:

> "*(3) The taking of water under supplementary water access licences and supplementary water (Lowbidgee) access licences should, as far as possible, be managed to evenly share access opportunity between all supplementary water access licence holders and supplementary water (Lowbidgee) access licence holders permitted to access that event in accordance with the rules in this clause.*"

DPI Water expect that the proposed new Yanco Weir and Regulator would result in some degree of change in the pattern of availability of supplementary water. However, a principle of operation of the proposed regulator would be to make up that water at other times so that there would be no net loss in the share going to the Yanco system. Nevertheless, the regulator provides broad scope for hydrological change in the Billabong Yanco System and is a source of concern among stakeholders. Consultation will be important in the development of operating rules to assure stakeholders that these principles have been maintained and any plans to alter the timing of supplementary flows considers ecological, social and environmental risks and benefits .

A hydrological analysis was undertaken to characterise supplementary flows in the system under historical flow conditions. Eighty percent (80%) of the time that supplementary flows were announced in the Yanco Creek downstream of the Offtake, the discharge was less than 1,400 ML/d which is within the range of discharge that can be controlled at Yanco regulator. Thus, although supplementary flows tended to be associated with the high flow season, most of the time they were regulated flows. This suggests that the enhanced range of control offered by the proposed new weir and regulator at Yanco Offtake does not in itself pose a risk to access to supplementary water in the Yanco system. Of more importance is maintenance of the principle used to distribute supplementary flows, and this is essentially set out in Clause 69(3) of the Water Sharing Plan. To maintain these arrangements, this principle should be preserved in the new Water Sharing Plan, which is currently being reviewed.

Characteristics of Overbank Flows

Overbank flows are potentially important for watering floodplain wetlands. A hydrological analysis was undertaken to characterise the frequency and duration of overbank flows under historical flow conditions, under modelled scenarios of Current WSP (with Water Sharing Plan rules applying) and Future SDLA (with new Yanco Weir and regulator in operation). Modelled flow was investigated at four gauges: Yanco Creek at Yanco Bridge, Billabong Creek at Jerilderie, Billabong Creek at Conargo and Billabong Creek at Darlot.

Overall, the pattern of overbank flows was irregular in space and time. Overbank flows were more frequent in Mid-Yanco Creek reach than in Billabong Creek. Overbank flows will not be eliminated from the creek system under the proposed Future SDLA conditions. The frequency of overbank flow events would increase from the Current WSP scenario to the Future SDLA scenario at three of four analysed gauges, with a minor decrease at the other one (Yanco Creek at Yanco Bridge). The duration of overbank flows was similar between the scenarios for the four analysed gauges.

The rules in the model used in this analysis reflect priorities that prevailed at the time of its development. The model does not necessarily accurately depict the future flow regime. These results give an indication of the scope of water management rather than specific future conditions.

The peak and duration of some overbank flows can be reduced by the rapid rate of pumping that can occur when supplementary flows have been declared. It has been suggested by some community members that flow peaks could be protected by prohibiting pumping during the first few days of an overbank event. There is currently no legal framework in place to coordinate or enforce such a strategy. The proposal raises questions of equity among growers as those that depend on supplementary licences would suffer a greater imposition than those that can also access water under general licences.

Trend in End of System Flows

There is concern among stakeholders that that end of system flows have declined over time. This concern is based primarily on direct observation of the creek and from interpretation of the impacts of water policy on flow. Relevant policies include measures to increase delivery efficiency (such as CARM) and the sale of irrigation licences out of the region, both to other irrigators and to environmental water reserves. The issue of low end of system flows was investigated by examining the pattern of flows over time for the historical gauged and modelled flow series at Darlot, which is the most downstream gauge on Billabong Creek.

The main conclusions were that end of system flows were significantly reduced in all seasons during the Millennium Drought, but after the drought broke in 2010-2011, flows have since returned to a pattern similar to that which prevailed prior to the drought.

1 INTRODUCTION

1.1 THE BILLABONG YANCO PROJECT

The Billabong Yanco Project is an initiative of Murray Local Land Services (Murray LLS). The goal of the project is to collaborate with the local community in the Billabong Yanco region to identify and address issues relevant to local communities and environments. The project is being funded over four years by the NSW Government Catchment Action and the Australian Government's National Landcare Programme, and is being directed by a steering committee made up of various community stakeholder representatives. It focuses on the waterways in the project area and the environments, communities and production values these waterways support.

The project aims to promote 'a resilient, productive Billabong Yanco system, with healthy ecosystems and communities' by:

- improving the condition, diversity and connectivity of the ecological aspects of the system;
- increasing community cohesion and diversity; and
- improving the region's economic productivity and diversity.

The strategic plan for the Billabong Yanco Project explored opportunities to address these themes (Murray LLS, 2015) including the development of a project for the "integrated management of water flows in the Billabong Yanco Creek System".

1.2 SCOPE OF WORK

The scope of this project is to develop a hydrological operations plan for the Billabong, Yanco and Colombo Creeks that integrates the economic, social and ecological needs and aspirations of key stakeholders in a balanced and equitable way.

More specifically, this project involves identifying and liaising with key Billabong Yanco System stakeholders to:

- conduct an extensive literature review of social, ecological and environmental studies relevant to the development of the plan;
- undertake a gap analysis of the literature and identify critical knowledge gaps that may influence the development of the plan and provide recommendations on a way forward;
- identify and liaise with key stakeholders and incorporate their needs and aspirations into the plan; and
- develop a prescriptive and pragmatic hydrological operations plan that integrates the needs and aspirations of key stakeholders in a balanced and equitable way.

1.3 OVERVIEW

The Operations Plan focuses on key values, problems and opportunities for improvement, identified through a literature review and consultation with stakeholders that could potentially be addressed through hydrological management. Where required, hydrological investigations were completed to assess the key issues. This took the form of exploratory statistical description and analysis of modelled and gauged hydrological data to quantitatively characterise and attempt to explain each issue. The results of this analysis were used to generate recommendations for system operation that would lead to improved outcomes.

2 MANAGING FLOWS FOR TROUT COD

2.1 OBJECTIVES

Sharpe and Stuart (2014) developed a preliminary flow-habitat model for Trout cod in Upper Yanco Creek based on the hydrology of the creek and the life history of the fish. The model characterises the seasonal water requirements of Trout cod in relation to flow-dependent habitat features in the creek.

In this section we review and refine hydrological aspects of the model and make recommendations to manage the flow regime of Upper Yanco Creek to optimise Trout Cod outcomes.

2.2 THE FLOW-HABITAT MODEL

The flow-habitat model for Trout cod is drawn from Sharpe et al. (2013) and Sharpe and Stuart (2014), as well as the sources they cite (the citations are not repeated here).

Trout cod adults and juveniles are mostly 'sedentary' and occupy a very narrow home range of only tens of metres, up to a maximum of about 200 m, with strong site fidelity for a selected snag or snag complex or section of stream bank. Most movements from the home site are less than 10 m. Spawning occurs within the usual home range, or very close to it, and dispersal occurs when larvae drift with the current after leaving the nest.

Trout cod are associated with fast flowing water and high loadings of large and complex structural habitat including submerged rocks, undercut banks, submerged trees and branches (snags). Flow velocities of 0.3 to 0.6 m/s are considered a key habitat requirement for Trout cod.

Trout cod breed after a period of conditioning that involves gonad development, nest selection and courtship. Rising flows during this period increase access to food and nesting sites. Breeding takes place between September and December when water temperatures exceed 15 C. The breeding period is brief, occurring over about two weeks. The female typically spawns on hard surfaces such as snag complexes or hollow logs. The nest is guarded by the male. High, stable flows during breeding season are important to maintain inundation of nests and avoid abandonment by the male. Flow cues are not thought to be relevant to breeding, with spawning observed both during and outside of flood periods. Observations of spawning in the wild have only been made in flowing water.

After hatching, larvae, juveniles and adults require sufficient flow to provide food and protection from predators through the autumn and winter period.

Hydrological considerations in this model are:

- breeding condition and behaviour is stimulated by increasing flow in late winter (August/September);
- stable flows high enough to cover the preferred nesting sites between September and December maximise nesting site availability and breeding success;
- fluctuating water levels in spring that decline close to the level of the nests could result in abandonment by the male, which could pose a threat to the eggs; water levels falling below the level of the nests in spring threaten the nests with exposure, which would cause the death of eggs; and
- the survival of young and adults depends on sufficient flow in autumn and winter.

Hydrological risks to Trout cod in Yanco Creek identified from this model were that:

- Yanco Creek experiences 7-10 or 10-14 day cycles of oscillating flow with an amplitude of up to 1 m during the breeding season that potentially expose nests and reduce the availability of nesting habitat.

We sought to verify hydrological components of this model by investigating the following questions:

- what are the flow thresholds for baseflows, spawning flows and bankfull based on existing cross-sectional and hydraulic data?
- what is the seasonal temperature profile of Yanco Creek and can it inform environmental flow management?
- to what extent do water levels fluctuate under current conditions?
- are the amplitude and frequency of oscillations in Yanco Crrek much greater than would occur in an unregulated lowland river where Trout cod were found historically?
- do fluctuations result in exposure of nesting thresholds in the breeding season?
- does Yanco Creek discharge fall below the identified flow threshold in the non-breeding period?

2.3 FLOW THRESHOLDS

The flow-habitat model identifies in-channel hydraulic features that are important in the life cycle of Trout Cod. Sharpe and Stuart (2014) describe these features conceptually but did not specify the position of these features in the channel or the flows required to inundate and activate them. Here we review hydraulic and life history information to provide quantitative targets for Trout cod environmental flows.

Sharpe and Stuart (2014) found that the Trout cod population extends from the Murrumbidgee River through Upper Yanco Creek and into the upper section of Colombo Creek.

Alluvium (2013) established hydraulic relationships for one representative site in Upper Yanco Creek which provides the best available estimates of flow magnitude for the Trout cod process thresholds (Figure 1). They determined that a flow of 250 ML/d provided a water depth of 0.8 m over runs with a velocity of 0.3 m/s and inundates low instream benches to a depth of 0.2 m. The deepest refuge pool is inundated to maximum depth of 1.5 m. At 450 ML/d large instream wood is inundated and at 600 ML/d high instream benches are inundated to a depth of 0.2 m. Bankfull flows are achieved at 1,500 ML/d (Table 1).

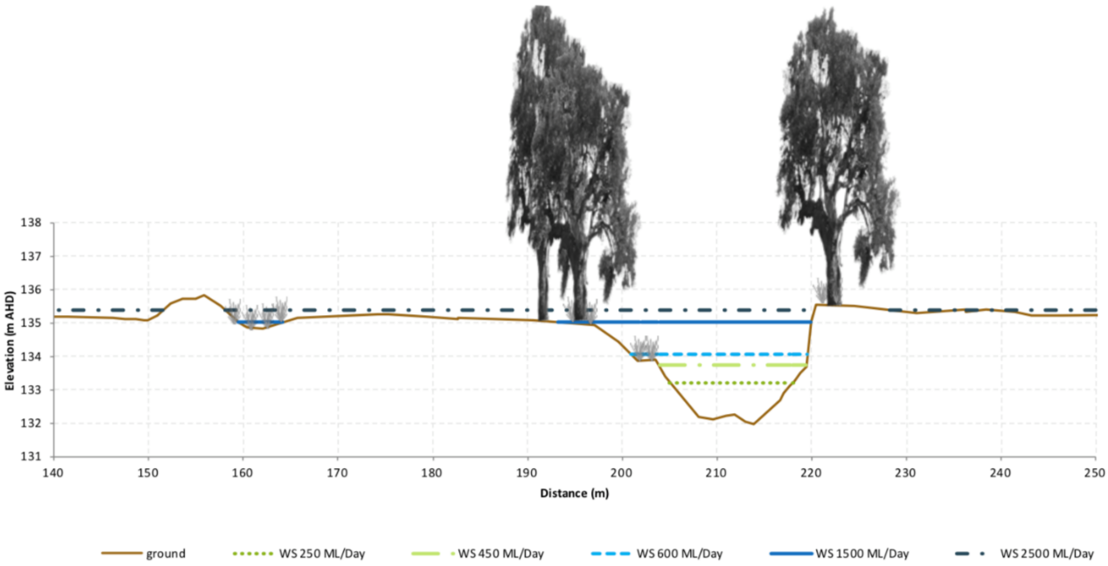


Figure 1. Cross section showing flow thresholds for ecologically significant features in Upper Yanco Creek (Alluvium 2013).

Table 1. Key hydraulic thresholds at a cross-section in Upper Yanco Creek (from Alluvium 2013).

Discharge (ML/d)	Level (m AHD)	Depth over runs (m)	Depth over low benches (m)	Depth over high benches (m)	Notes
250	133.1	0.8	0.2	exposed	Provides a velocity of 0.3 m/s with a depth of 1.5 m in the deepest refuge pool Inundates low benches, supports movement of large-bodied fish including Trout cod
450	133.8	1.5	0.9	exposed	Inundates large instream wood
600	134.0	1.7	1.1	0.2	Inundates high instream benches
1,500	135.0	2.7	2.1	1.2	Bankfull flow

The most downstream observation of Trout cod in Colombo Creek was at 'Site 11', which they described as located "about 3 km downstream of Morundah township". Alluvium (2013) did not determine hydraulic relationships for Colombo Creek due to the presence of weirs in the downstream section. Site 11 is in the upper free-flowing section and appears to be located close to the Morundah gauge, adjacent to the township. The cross-section and rating curve for Morundah gauge provides a hydraulic relationship for this part of Colombo Creek (Figure 2).

Historical flow data, cross-section elevation data, and the latest rating relationship for gauge 410014, were downloaded from DPI, Office of Water, Provisional River Data/Rivers and Streams/Real Time Data (http://realtimedata.water.nsw.gov.au/water.stm). There is an inconsistency in the site data, which gives the gauge zero elevation as 125.437 mAHD, and the cease to flow elevation as 125.036 mAHD, which suggests that negative values of stage should be recorded, but this is not the case. The lowest stage with zero discharge on the rating curve is 0.42 m stage, which corresponds to 125.867 mAHD, assuming the given gauge zero is correct. Here, the gauge zero is assumed to be correct. The cross-section indicates bankfull level is at 127.74 mAHD on the left bank, which corresponds with 1,250 ML/d (Figure 2). This contrasts with the value of 600 - 650 ML/d cited in Forest Creek Working Group (2000, p. 14), attributed to Jayawickrama, pers. comm., suggesting that this cross-section is not representative of the hydraulically limiting reach of Colombo Creek.

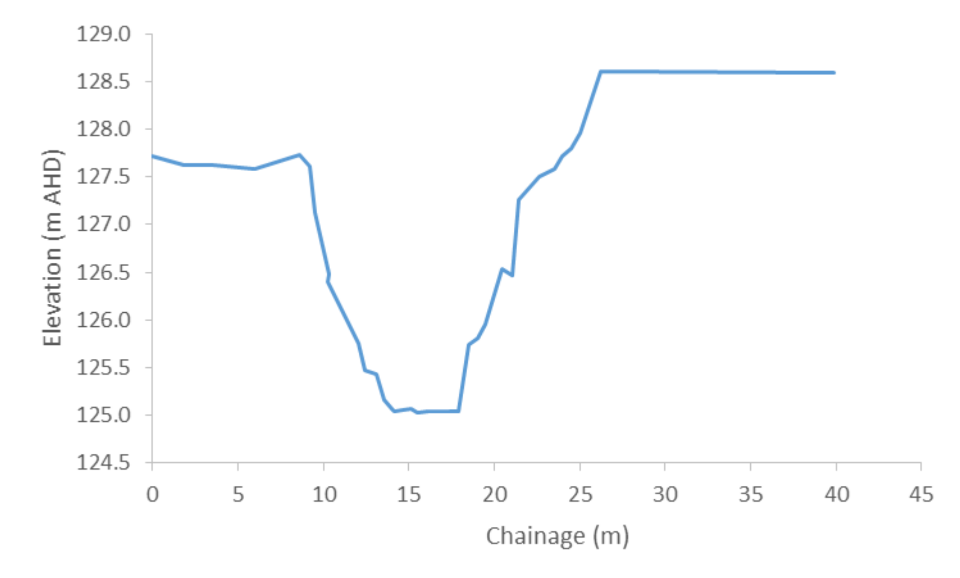


Figure 2. Cross-section at Colombo Creek at Morundah flow gauge (410014). Source: DPI, Office of Water, Provisional River Data/Rivers and Streams/Real Time Data (http://realtimedata.water.nsw.gov.au/water.stm).

There is a small bench on the right bank of the cross-section at 126.5 mAHD (Figure 2). Covering this bench with 0.2 m of water would require a discharge of 300 ML/d.

2.4 DISCHARGE TARGETS

Sharpe et al. (2013) proposed a generic hydrograph to support Trout cod populations in Upper Yanco Creek Reach (Figure 3). The key components were:

(a) a high winter baseflow to enable fish survival in deep water;

(b) late winter (i.e. August) flow ramp up onto benches to stimulate productivity, fish movement and gonad development;

(c) bank full flows during spring and early summer (September to December) to allow courtship, spawning, nesting and larval dispersal; and

(d) slow ramp down in January back to;

(e) winter refuge level.

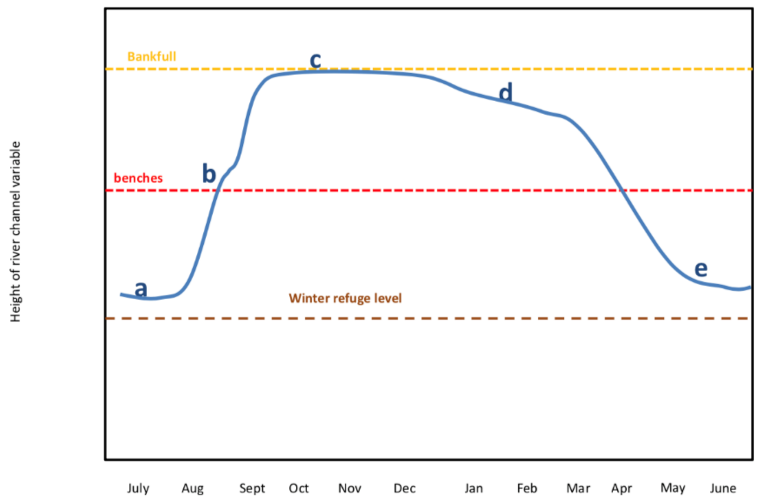


Figure 3. Generic large fish hydrograph (Sharpe et al. 2013)

Sharpe and Stuart (2014) recommended avoiding very low flow in winter due to the impacts on juvenile fish through poor water quality, low food availability, exposure to predation and increased angling pressure. This minimum flow corresponds to the year-round baseflow recommended by Alluvium (2013) of 250 ML/d in Upper Yanco Creek which inundates low benches, fills deep pools and wets the majority of the channel bed while maintaining a velocity of more than 0.3 m/s and supporting movement by large-bodied fish (Table 1).

Based only on the cross section at the Morundah gauging station it is not possible to identify a suitable baseflow threshold for Colombo Creek.

An uncertainty with the generic hydrograph is the discharge required for the spring high-flow event (component C in Figure 3). The objective of this flow is to support courtship, spawning, nesting and larval dispersal. The critical component is to maintain inundation of nesting sites, but field investigations are yet to confirm where these currently, or potentially, occur. Previous studies identify spawning sites as snag complexes, hard surfaces and hollow logs (Sharpe and Stuart 2014). Sharpe et al. (2013) initially recommended a bankfull discharge (1,500 ML/d), but this could be excessive, considering that Alluvium (2013) determined snags were inundated by flows of 450 ML/d. Alluvium (2013) proposed flows of 600 ML/d, which inundate high in-channel benches to a depth of 0.2 m, to support the movement and spawning of large-bodied fish such as Trout cod.

Clayton Sharpe (pers. comm. 30 Aug 2017) provided further advice that, assuming a flow of 600 ML/d would inundate spawning habitat, fluctuation in water levels between 600 ML/ and 1,500 ML/d would be undesirable due to the risks of triggering fish to nest at higher levels or stranding them in edge habitat. On this basis, a stable flow higher than 600 ML/d would present a lower risk as the target for spring flow in Upper Yanco Creek.

In Colombo Creek the limited cross section data indicates that a flow of 300 ML/d, which inundates a small in-channel bench at the Morundah gauge to 0.2 m, could be adopted as a provisional high spring flow target. However, this is a highly uncertain flow threshold that requires review upon field assessment and hydraulic modelling of this reach.

The delivery of breeding flows would involve an environmental allocation that is delivered to prevent discharge falling below a minimum threshold. The target would be mostly met by consumptive water deliveries with additional environmental water supplied to make up the difference. Water delivery to Yanco Creek is controlled by the operation of the Yanco Weir on the Murrumbidgee River which has limitations in responding to variation in Murrumbidgee flow and delivery demand. The proposed new Yanco Weir and Regulator would provide greater precision in flow delivery to Yanco Creek and may be more effective in controlling breeding season flows. However the potential benefits of the weir must be considered against the requirement to build a fishway on the offtake channel, where currently there is none. Even under best practice design, the fishway will not be as transparent to fish movement as the current arrangement.

2.5 SEASONAL TEMPERATURE PROFILE

While Trout cod breeding can occur from September to December, water temperature must exceed 15°C for spawning to occur (Stuart and Sharpe 2014). We reviewed water temperature data for Yanco Creek and related streams to clarify the times when flow management is most likely to result in breeding success.

Daily water temperature data were available from 1995 for Yanco Creek at Yanco Bridge. These temperature data were comparable to data available from other monitoring locations (Murrumbidgee River at Narrandera, and Billabong Creek at Darlot, Walbundrie and Upstream of Innes Bridge) for the same period; the data from all sites had a similar temporal pattern of water temperature (Figure 4). The water temperature records were of high quality except at Darlot, where some obviously erroneous values required editing.

The data revealed that water temperatures suitable for Trout cod spawning were not achieved until mid-or late-September in most years (Figure 5). For example, the water warmed to 15°C early in September 2013, but late in September 2012 (Figure 4). This suggests that an environmental flow event to stimulate spawning could begin in mid-September with limited loss of spawning potential.

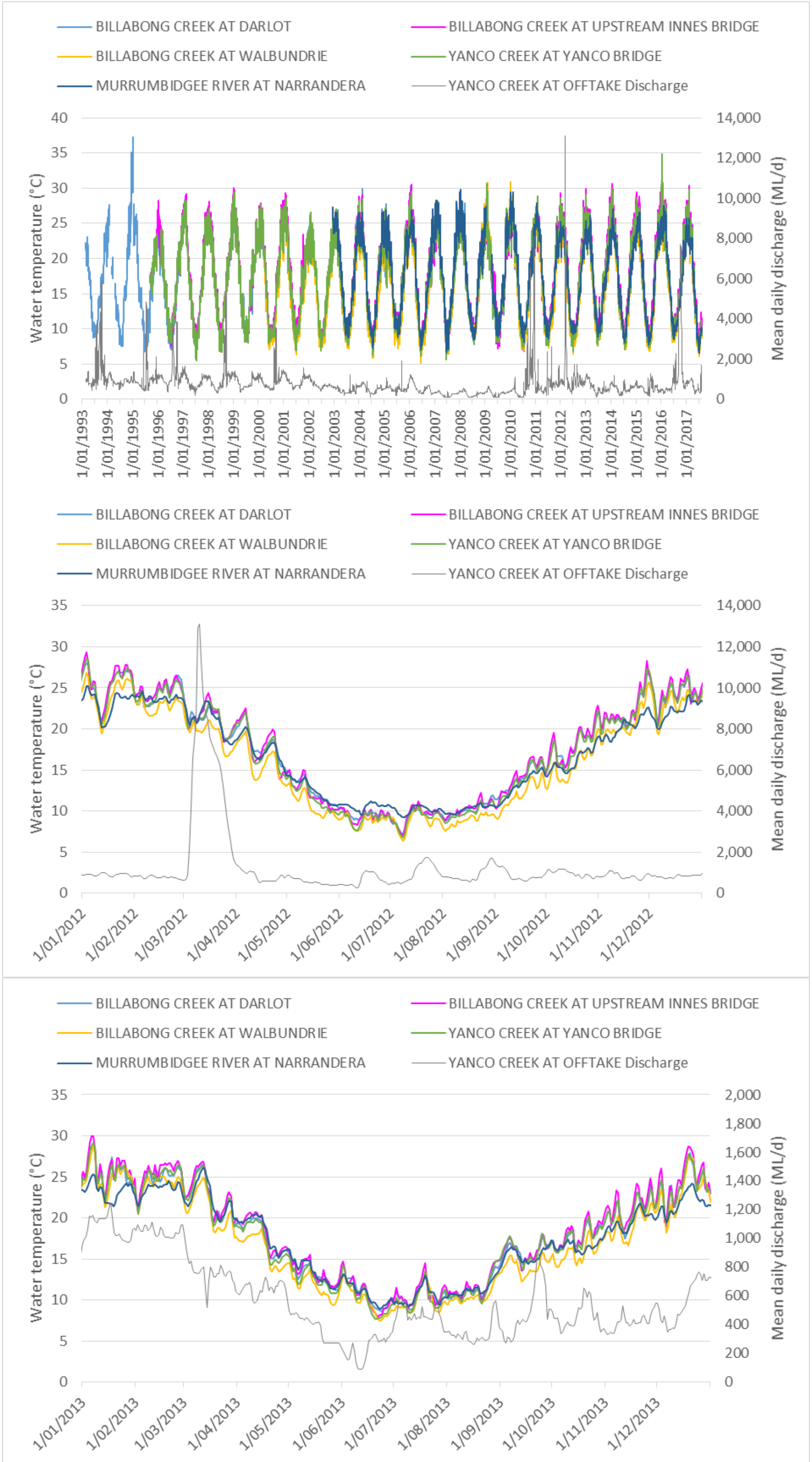


Figure 4. Daily time series of all available water temperature data from Yanco Creek system. Top plot shows all data, while two lower plots show detail for 2012 and 2013, compared with discharge at Yanco Creek Offtake.

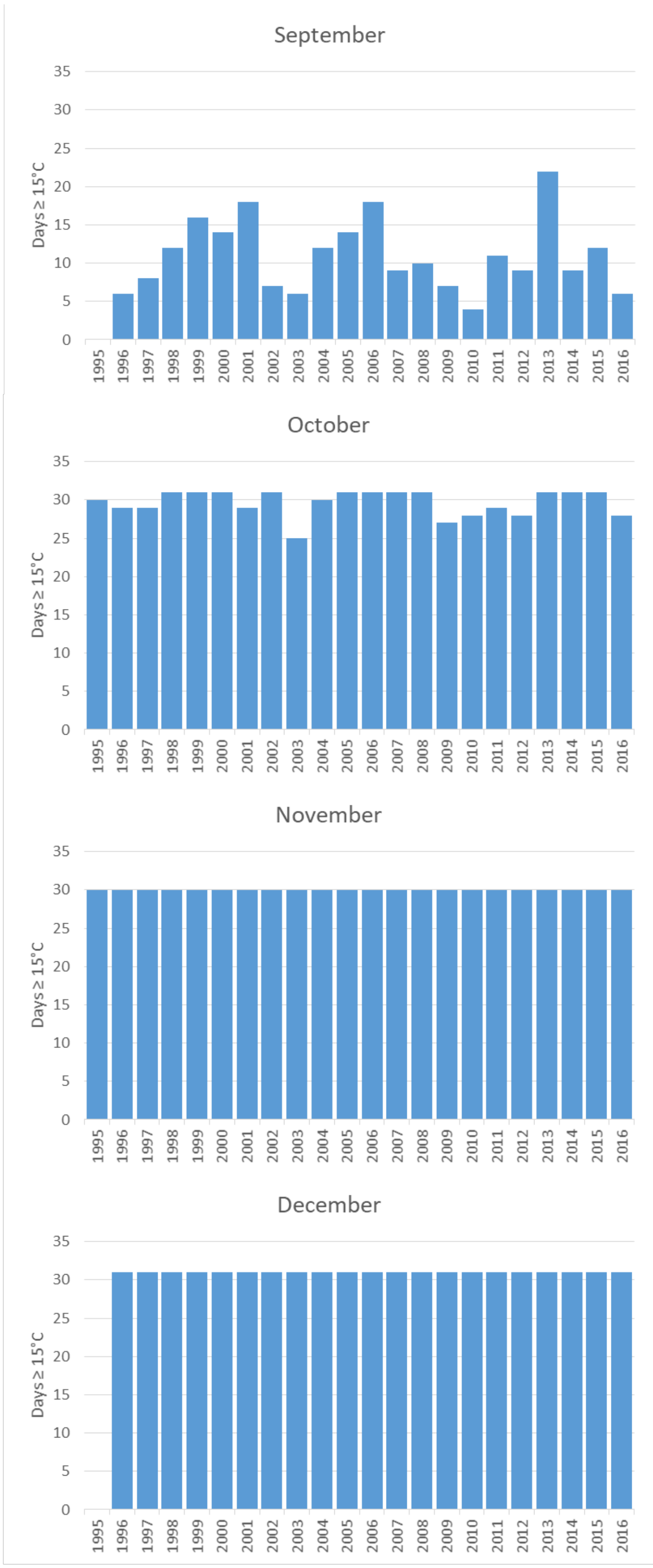


Figure 5. Annual time series of number of days for the months of the Trout cod breeding period when water temperature exceeded 15°C, in Yanco Creek at Yanco Bridge. Note: water temperature recording began 18/09/1995 with missing data in Dec 1995.

2.6 FLOW VARIABILITY

Flow variability was identified as a threat to the Trout cod population in Yanco Creek, based on the known breeding behaviour of Trout cod and interpretation of hydrological data (Sharpe and Stuart 2014). Of particular concern was large fluctuations in flow during the breeding season which have the potential to reduce the amount of nesting habitat and to expose established nests to the air, thereby destroying eggs.

Accurate characterisation of this threat is important for the development of management responses. In this section we review the hydrology of Yanco Creek to verify this threat. Sharpe and Stuart (2014), based on a visual interpretation of the hydrograph, determined:

- that there is 'wide variability in daily water levels' in spring and summer that 'are likely to have a negative effect upon aspects of the ecology of spawning and indeed recruitment success';
- that wide fluctuations in average daily discharge and water level in Yanco and Colombo Creeks 'are not part of the natural daily variation of lowland river systems';
- that 'the fluctuation in water level is extreme when considered in relation to the maximum water depth';
- that there is 'extraordinary variability and persistent oscillation in average daily discharge'; and
- that 'water levels persistently oscillated by more than half of the available stream depth over the course of 7-10 days throughout the known Trout cod breeding period'.

We endeavoured to validate these statements through quantitative analysis of available data. On the basis of the analysis and consideration of all available information, we developed flow recommendations to support Trout cod breeding.

2.6.1 SOURCE OF THE VARIABILITY

Sharpe and Stuart (2014) identified the delivery of water to meet irrigation needs as the source of cycles in flow of up to 1.0 m amplitude with a period of 7-10 days. However they also noted that the oscillation in water level was more pronounced in autumn and winter, i.e. outside the irrigation season. This suggests that factors other than irrigation delivery contribute to flow variation, specifically variation derived from runoff events in the catchment. Without daily records of operation of Yanco Weir and knowledge of its hydraulic characteristics it is difficult to attribute the cause of fluctuation in flow level in Yanco Creek as entirely due to weir operation, due to natural flow events, or a combination. The water level in the Murrumbidgee also fluctuates, and this changes the head level at Yanco Weir. In this way fluctuations caused by runoff events in the Murrumbidgee catchment can be transmitted to Yanco Creek.

2.6.2 CHARACTERISTICS OF TROUT COD BREEDING SEASON WATER LEVEL VARIATION

Sharpe and Stuart (2014) commented that the frequent and sometimes rapid water level variation over more than half the channel depth (1 m at the Yanco Offtake) in the Trout cod breeding season, as well as presenting a risk to breeding success in Upper Yanco Creek, was much greater than would be expected in a natural lowland river.

Trout cod evolved and persisted under the pattern of water level variation that occurred in the natural flow regimes of rivers within its natural range (Figure 6). Characterisation of the breeding season flow variability of rivers where Trout cod were formerly found or are currently found will provide information to assist understanding of this issue.

We characterised the breeding season water level variation in regulated Yanco Creek and then compared it with that of:

- the former unregulated regime and current regulated regime of the nearby Murrumbidgee River, represented by Narrandera gauge, where the last reported Trout cod in the lower Murrumbidgee was collected in 1969 and where a stocked population occurs (Lintermans, 2002, NSW Department of Primary Industries 2006, Koehn, et al., 2013), (Figure 6);
- the current regulated regime of the Murray River from below Yarrawonga Weir down to the Barmah Forest, represented by Tocumwal gauge, where the last remaining naturally occurring populations of Trout cod are found (NSW Department of Primary Industries 2006, Koehn et al. 2013, Figure 6); and
- the current unregulated regime of Seven Creeks in Victoria between Gooram Falls and Polly McQuinns Weir, represented by Downstream of Polly McQuinn Weir gauge, where a viable population occurs, the result of translocation of fish from the Goulburn River in 1921 and 1922 (NSW Department of Primary Industries 2006, Koehn et al. 2013, Figure 6).

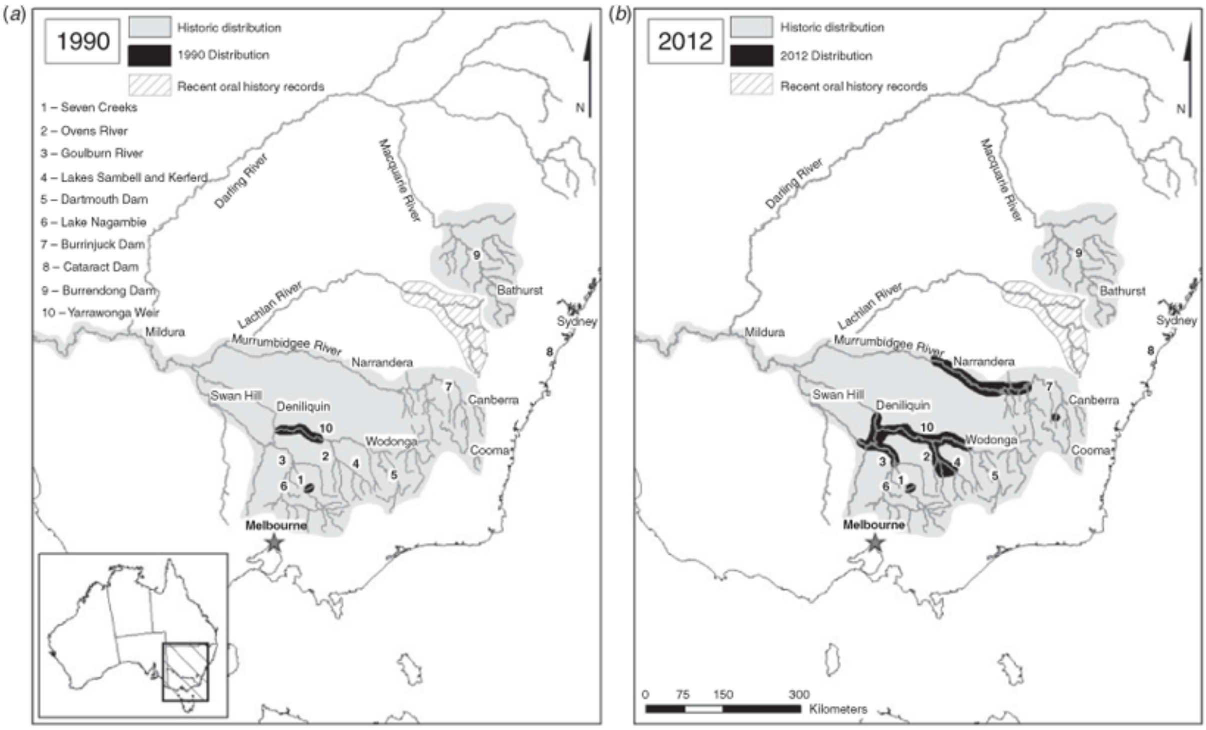


Figure 6. Historic and recent distribution of Trout cod in Australia. (a) 1990, (b) 2012. Source: Koehn et al. (2013).

Despite Trout cod occurring at the above sites on the River Murray and Seven Creeks, NSW Department of Primary Industries (2006) noted that "*Surveys conducted in the Murray River during 1995 and 1996 indicate that the level of recruitment is inadequate to sustain this population. Similarly, research has revealed that the population in Seven Creeks is insecure and will face extinction without management intervention*". The population of Trout cod in Seven Creeks has been actively managed through electrofishing and relocation upstream, and Koehn et al. (2013) considered the main threat to be fires washing ash into the stream, and competition from carp and predatory redfin. NSW Department of Primary Industries (2006) hypothesised that in the River Murray downstream of Yarrawonga, the movement patterns of Trout cod, including those associated with breeding, are suppressed by the regulated flow regime. However, using data from fish surveys, a population model predicted that this population was stable (Koehn et al. 2013). The investigation of Koehn et al. (2013) into the former and current distributions and ecology of Trout cod, the threats, and relative success of a recovery actions, made little mention of river hydrology or hydraulic habitat. The only reference to hydrology was in a table of threats, which included alteration of flow regimes, specifically "*Reduced flooding and altered seasonality in the Murray River; extraction from Seven Creeks*". Hydraulic habitat was referred to in the context of the importance of large wood, the reintroduction of which was considered a key recovery action, and hydraulic diversity offered by scour pools. Therefore, while evidence suggests that the current regimes of water level variation observed in the River Murray and Seven Creeks are tolerable by Trout cod, there is no basis to consider them ideal as a reference to guide flow management.

Data from breeding season months September to December were extracted from mean daily stage height time series data from the four gauges. The stage height range was related to water surface levels for selected discharges and ground levels at a cross-section from the site, although a cross-section was not available for Seven Creeks. The breeding season water level variation was characterised using two sets of indicators. The first set of indicators characterised variation in absolute stage height, by month, using minimum, 25th percentile, 75th percentile and maximum level. Half of the levels observed in each month fall between the 25th and 75th percentiles, known as the inter-quartile range. The second set of indicators characterised variation in the daily rate of rise and fall of stage height, by month, using maximum fall, maximum rise, 75th percentile fall and 75th percentile rise. The percentile calculations excluded days of zero rise and fall, which were a small proportion of the total days: 2.9% at Seven Creeks gauge, 1.8% at Yanco Creek gauge, 0.7% at Murrumbidgee River gauge unregulated period, 0.4% at Murrumbidgee River gauge regulated period, and 2.2% at River Murray gauge.

As expected, photographs and cross-sections (Figure 7, Figure 8, Figure 9 and Figure 10) illustrate the much greater size of the Murray and Murrumbidgee rivers. Although a cross-section was not available for Seven Creeks, the reach between Gooram Falls and Polly McQuinns Weir is known to have a very different morphological and hydraulic character than the three other sites. The stream is of variable width, relatively shallow, and high gradient. It is considered difficult to kayak, with numerous sections of continuous class III and IV rapids and four large waterfalls 15 m and higher. Koehn et al. (2013) described Seven Creeks as "*a small (5–7 m wide) stream with rock, gravel and sand substrates, and pools <2 m deep interspersed with rapids and cascades*". Unlike the other three gauges, which are located in channel sections (Yanco Offtake channel was artificially excavated), the gauge at Seven Creeks is located in the pool of a gauging weir (Figure 7). Thus, the relationship between discharge and stage height reflects the geometry of the weir, not the natural channel morphology. The weir appears to be narrower than the surrounding channel (Figure 7), so for low to medium flows, it likely amplifies the water level.

Stage height is measured from gauge zero, an arbitrary level determined when the gauge was established, which does not necessarily correspond with the lowest point on the bed of the creek. Also, zero discharge could correspond with a depth of ponded water at the gauge site. This means that absolute stage height does not necessarily indicate the depth of water available as habitat for fish at the site. The cease to flow stage heights for the latest rating tables were: River Murray at Tocumwal extrapolated from rating to be 0.25 m, Murrumbidgee River at Narrandera 0.64 m, Yanco Creek at DS Offtake 0.21 m, and Seven Creeks at DS Polly McQuinns Weir 0.363 m. At the Seven Creeks gauge, the stage is lower than 1.0 m for 98% of the time during September – December months, so in the absence of a large flood, the stage height would be expected to vary over a narrow range of about 0.6 m.

Long term average daily flows for the four sites also indicated the relative sizes of the streams. The values were calculated as: River Murray at Tocumwal regulated 12,915 ML/d (1975 – 2016), Murrumbidgee River at Narrandera unregulated 8,541 ML/d (1913 – 1928), Murrumbidgee River at Narrandera regulated 8,546 ML/d (1970 – 2016), Yanco Creek at DS Offtake regulated 859 ML/d (1970 – 2016), and Seven Creeks at DS Polly McQuinns Weir unregulated 109 ML/d (1966 – 2016). While channel morphology is a response to a number of controlling and modifying factors, in general, the lower the average flow, the smaller the channel (shallower and narrower). The relatively small size of Seven Creeks is also reflected in its catchment area of 153 km^2, compared to 29,010 km^2 for the River Murray at Tocumwal and 34,200 km^2 for the Murrumbidgee River at Narrandera.

It is not known if Trout cod breeding season hydraulic habitat requirements vary with river scale, i.e. a water level drop of 1 m over a few weeks was considered by Sharp and Stuart (2014) to present a risk in Yanco Creek but it is not known if, in a larger river, the same level of risk is associated with larger falls, and similarly, in a smaller river, associated with smaller falls. The same can be said of the daily rate of change in water level, which is typically faster in small flashy streams than large lowland rivers.

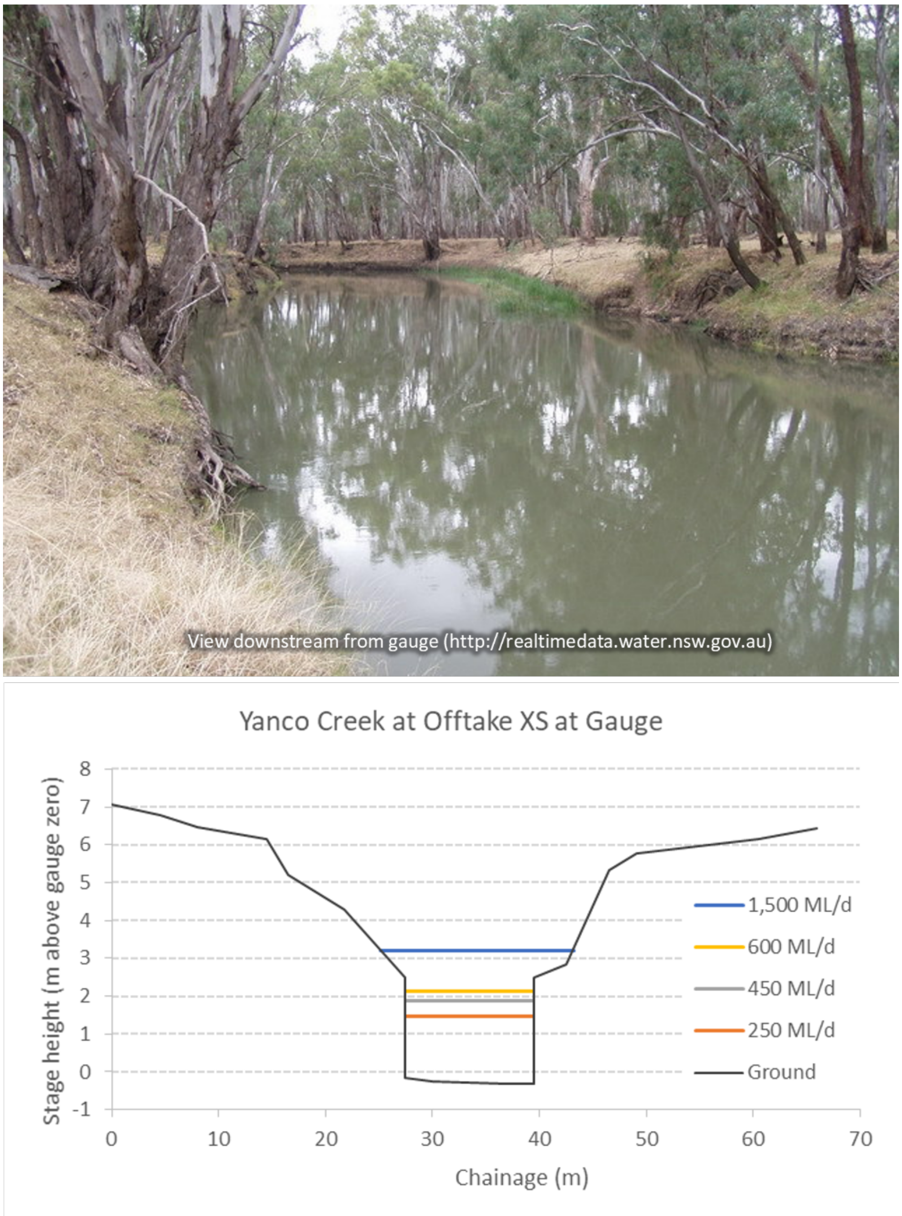
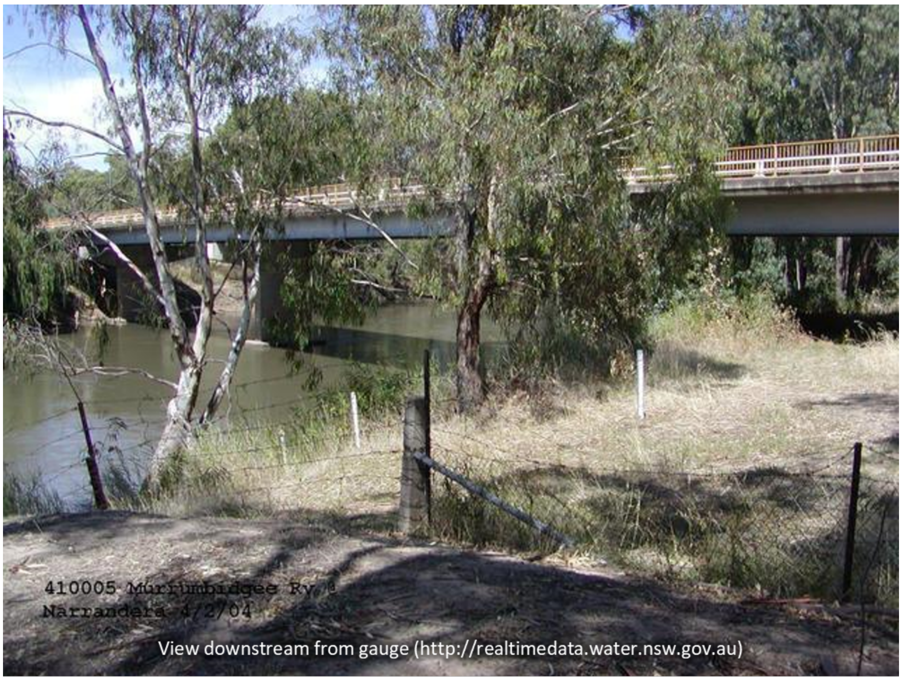


Figure 7. Photograph and cross-section of Yanco Creek at Offtake gauge. A flow of 1,500 ML/d is the channel capacity.

Figure 8. Photographs of Seven Creeks in the reach between Polly McQuinns Weir and Gooram Falls.



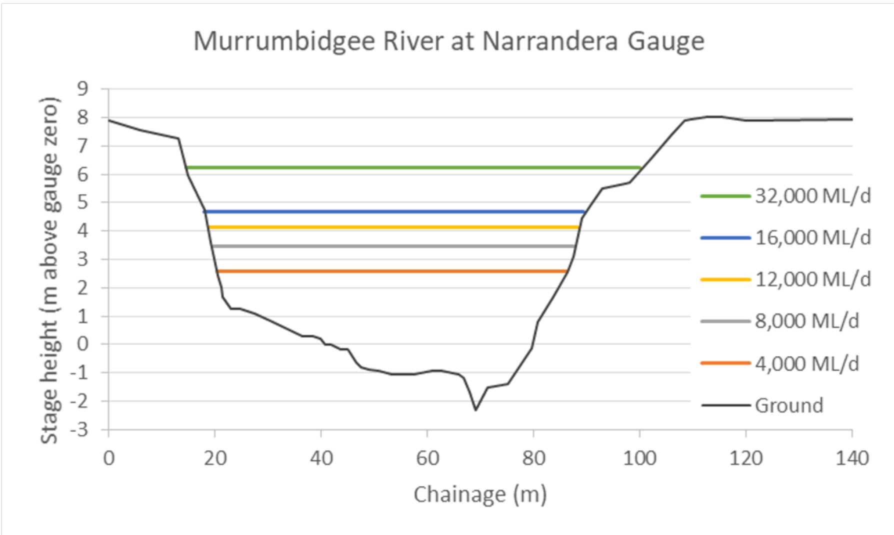


Figure 9. Photograph and cross-section of Murrumbidgee River at Narrandera gauge. A flow of 32,000 ML/d is the channel capacity constraint upstream at Gundagai given in the Water Sharing Plan.

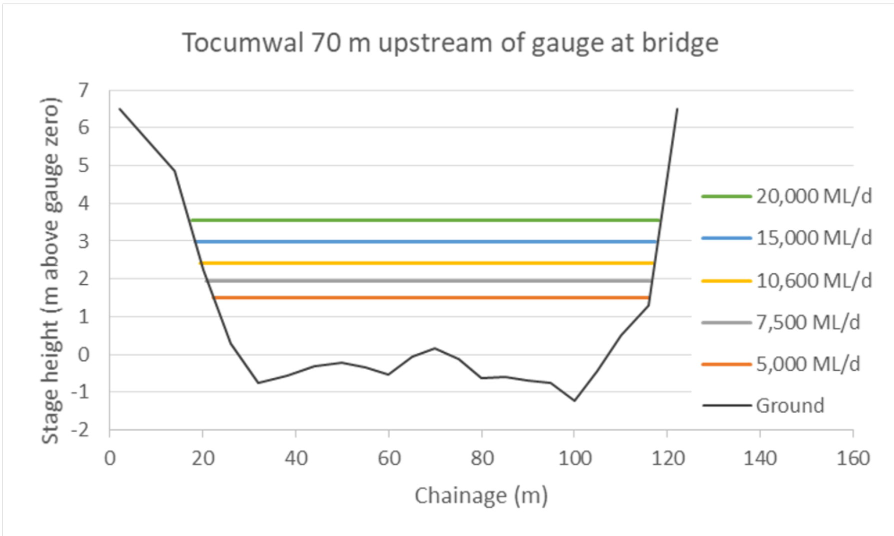


Figure 10. Photograph and cross-section of River Murray at Tocumwal gauge. A flow of 10,600 ML/d is the channel capacity constraint downstream at the Barmah Choke. Cross-section surveyed 23/08/1990, provided by Murray-Darling Basin Commission.

2.6.2.1 YANCO CREEK DOWNSTREAM OF OFFTAKE

Stage height time series data were available for Yanco Creek at Downstream of Yanco Offtake from 1979 to 2016. The distributions of stage height in the months September to December were highly variable between years (Figure 11). In most years, the stage height did not consistently increase or decrease through the period September-December, although high flow years (with unregulated surplus flows) tended to have declining stage height over about 2.0 – 3.0 m through this period, with only 2010 showing a strong increase. In general, the lower was the absolute stage, the lower was the variability of stage. In 14 of the 38 years from 1979 to

2016 the September-December period was characterised by stage height being less than 2.124 m (600 ML/d) for most of the time, with the periods 2003 – 2009 and 2013 – 2015 having relatively low September-December stage height every year (Figure 11). Within any month of September to December, in most years the range of stage height was less than 1.0 m, with the exceptions being high flow years.

The distributions of daily rate of stage height change in Yanco Creek during the months September to December were highly variable between years (Figure 12). High flow years (with unregulated surplus flows) tended to have greater rates of change in stage, occasionally as much as 1.0 m per day, both rises and falls. In years of relatively low and mostly stable stage height rates of daily change were usually less than 0.4 m, but occasional high rates of change were observed in some otherwise stable years, e.g. 2011, 2005, 2003, and 2000.

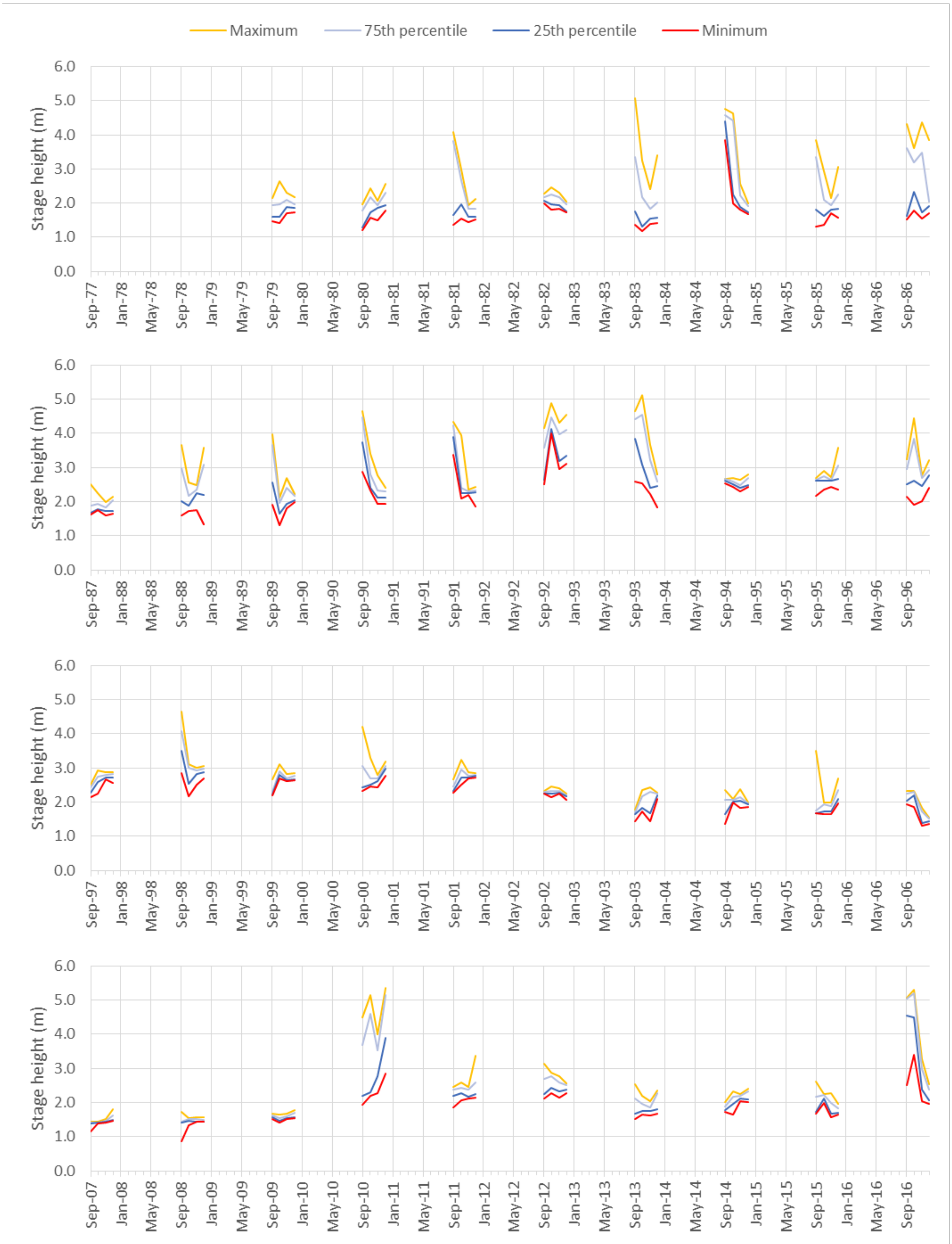


Figure 11. Historical variation in stage height at Yanco Creek Downstream of Yanco Offtake, 1979 – 2016.

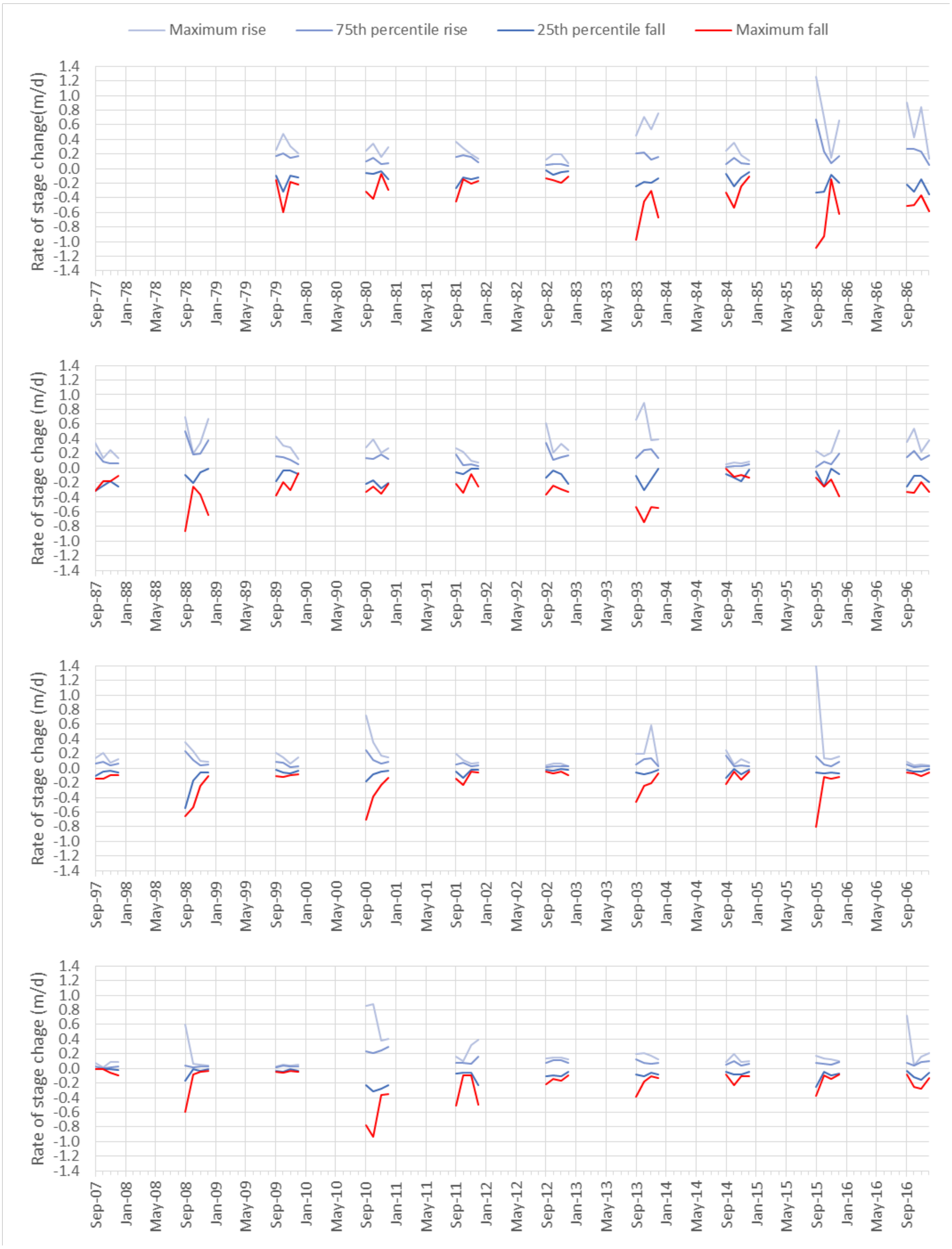


Figure 12. Historical variation in daily rate of rise and fall in stage height at Yanco Creek Downstream of Yanco Offtake, 1979 – 2016.

2.6.2.2 SEVEN CREEKS AT DOWNSTREAM OF POLLY MCQUINNS WEIR

Stage height time series data were available for Seven Creeks at Downstream of Polly McQuinns Weir from 1965 to 2016. The rating suddenly shifted downwards by about 0.4 m after 1972, suggesting the gauge was moved or altered. This analysis considered the 40 year period 1977 – 2016 was sufficiently long to characterise the stage height variation.

In most years, the stage height consistently decreased by 0.2 – 0.3 m through the period September-December, with some spikes in maximum stage, which reflects the natural hydrology of high flows in winter declining through spring (Figure 13). In general, the lower was the absolute stage, the lower was the variability of stage. Most of the time stage height varied over the narrow range of 0.4 to 1.0 m, but this represents the major proportion of the channel water depth (Figure 13). Within any month of September to December, in most years the range of stage height was less than 0.4 m, with the exceptions being high flow years.

The distributions of daily rate of stage height change in Seven Creeks during the months September to December were highly variable between years (Figure 14). High flow years tended to have greater rates of change in stage, occasionally as much as 0.4 m per day, both rises and falls, but daily rates of change were mostly less than 0.2 m.

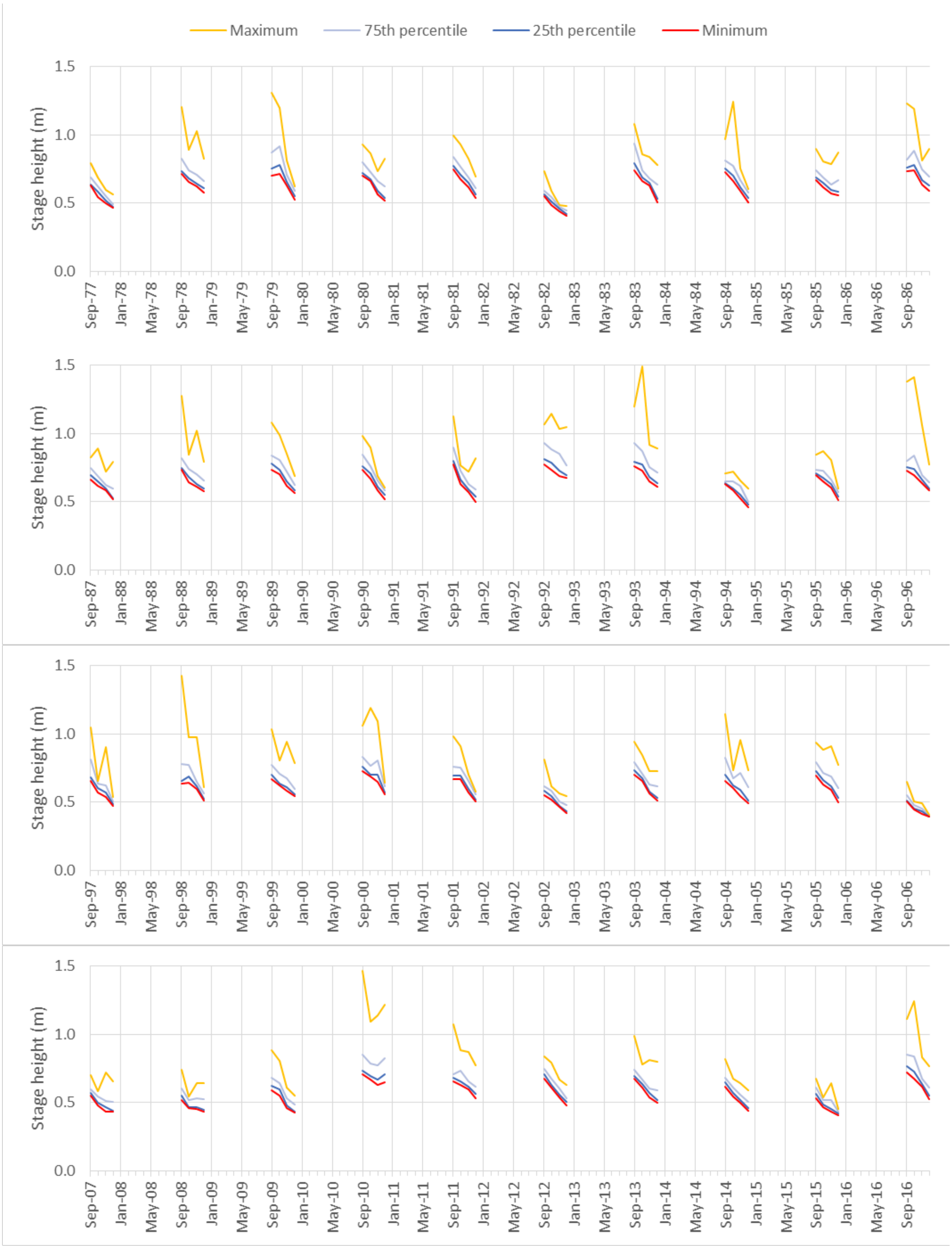


Figure 13. Historical variation in stage height at Seven Creeks Downstream of Polly McQuinns Weir, 1977 – 2016.

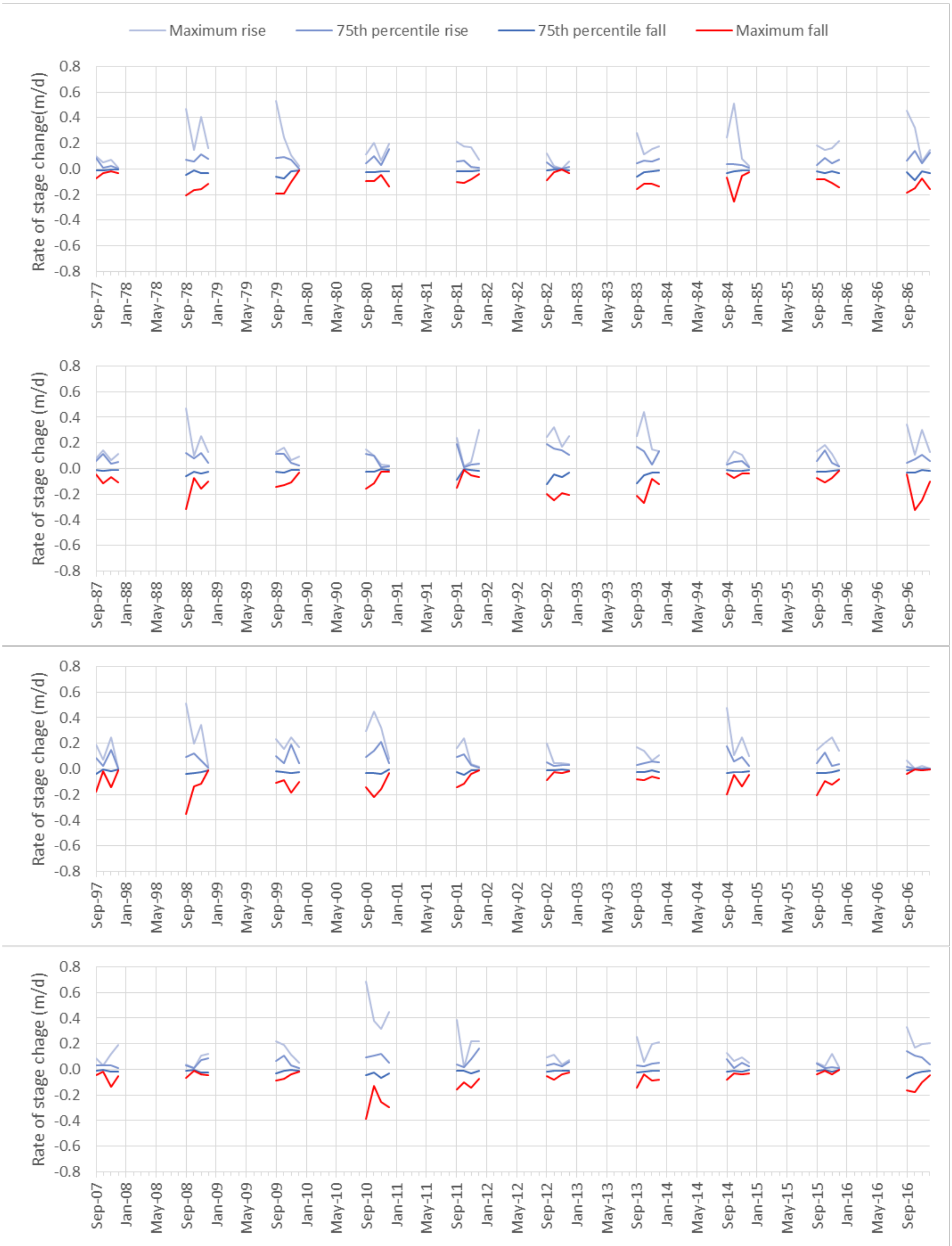


Figure 14. Historical variation in daily rate of rise and fall in stage height at Seven Creeks Downstream of Polly McQuinns Weir, 1977 – 2016.

2.6.2.3 RIVER MURRAY AT TOCUMWAL

Stage height time series data were available for River Murray at Tocumwal from 1975 to 2016. This analysis considered the 40 year period 1977 – 2016 was sufficiently long to characterise the stage height variation. The distributions of stage height in the months September to December were highly variable between years (Figure 15). Stage height could increase or decrease through the period September-December, or rise then fall or fall then rise. Over this period, stage height could vary by less than 0.5 m or by as much as 5.0 m. In general, the lower was the absolute stage in a month, the lower was the variability of stage. In years of low stage height variability, the discharge remained controlled below the constraint of Barmah Choke channel capacity (Figure 15). In high flow months when unregulated surplus flow occurred, the stage height could vary over 4.0 – 5.0 m, which represents a large proportion of the channel depth.

The distributions of daily rate of stage height change in the River Murry during the months September to December were highly variable between years (Figure 16). High flow years (with unregulated surplus flows) tended to have greater rates of change in stage, very occasionally as much as 1.0 m per day, both rises and falls. Most of the time the rates of daily change in stage height were less than 0.4 m.

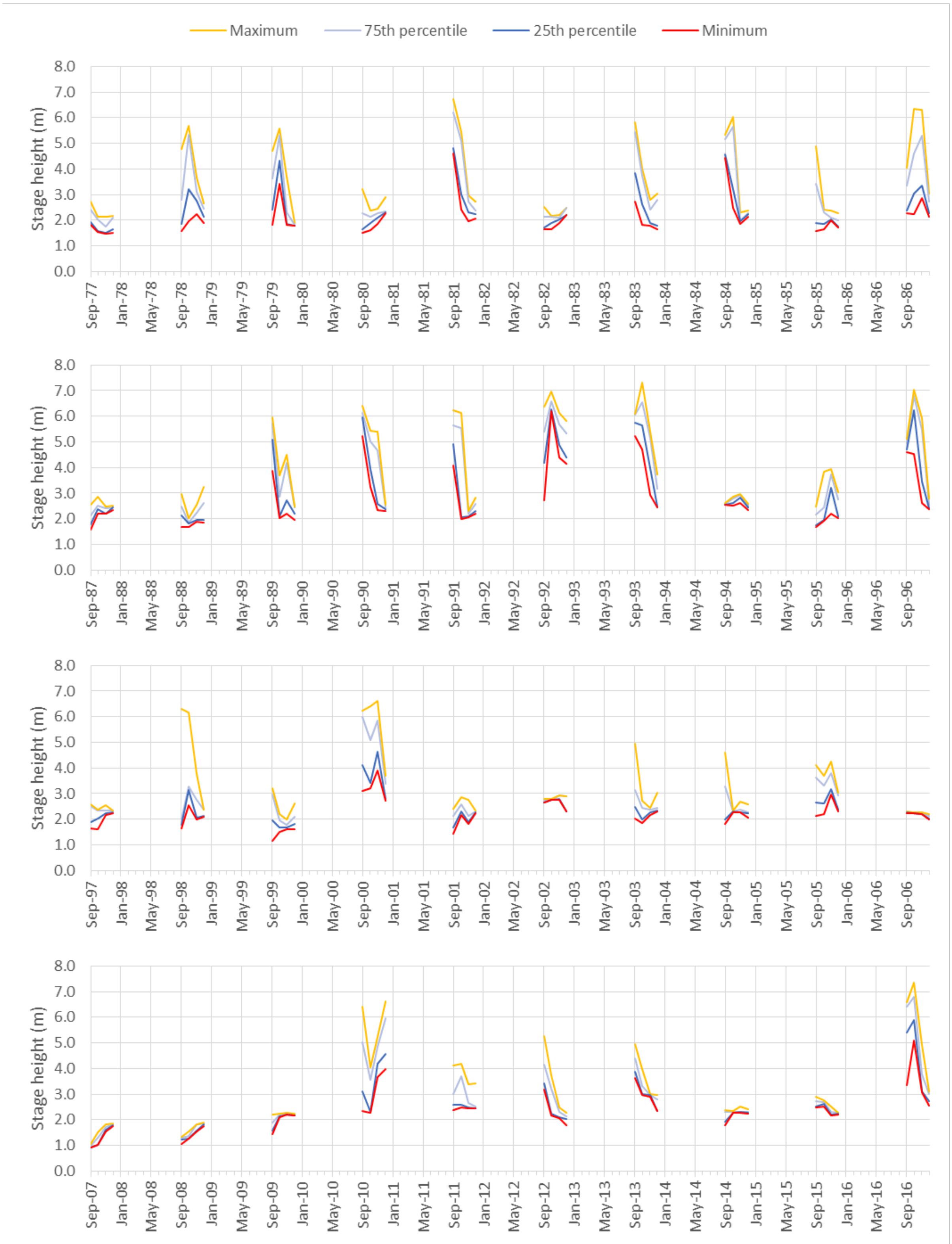


Figure 15. Historical variation in stage height at River Murray Tocumwal, 1977 – 2016.

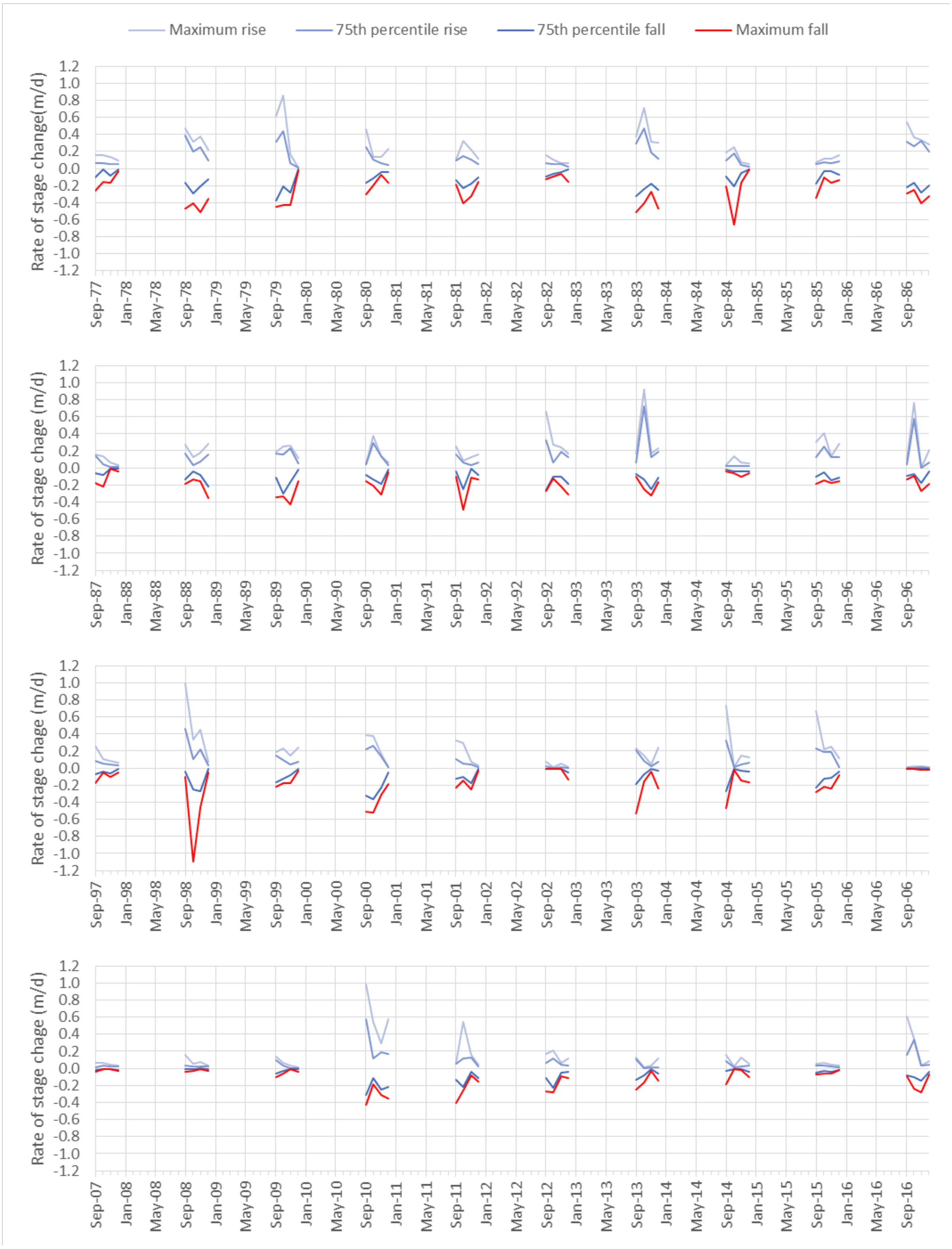


Figure 16. Historical variation in daily rate of rise and fall in stage height at River Murray Tocumwal, 1977 – 2016.

2.6.2.4 MURRUMBIDGEE RIVER AT NARRANDERA, UNREGULATED

Stage height time series data were available for Murrumbidgee at Tocumwal, prior to regulation by Burrinjuck Dam in 1928, from 1913 to 1928. The distributions of stage height in the months September to December were reasonably consistent between years (Figure 17). In most years, stage height decreased by 2.0 – 4.0 m through the period September-December or October-December, which reflects the natural hydrology of high flows in late-winter and early-spring declining through spring (Figure 17). Within any month of September to December, in most years the range of stage height was 1.0 – 3.0 m, which represents a large proportion of the channel depth.

The distributions of daily rate of stage height change in Murrumbidgee River under unregulated conditions during the months September to December were consistent between years (Figure 18Figure 16). Most of the time the rates of daily change in stage height were less than 0.5 m.

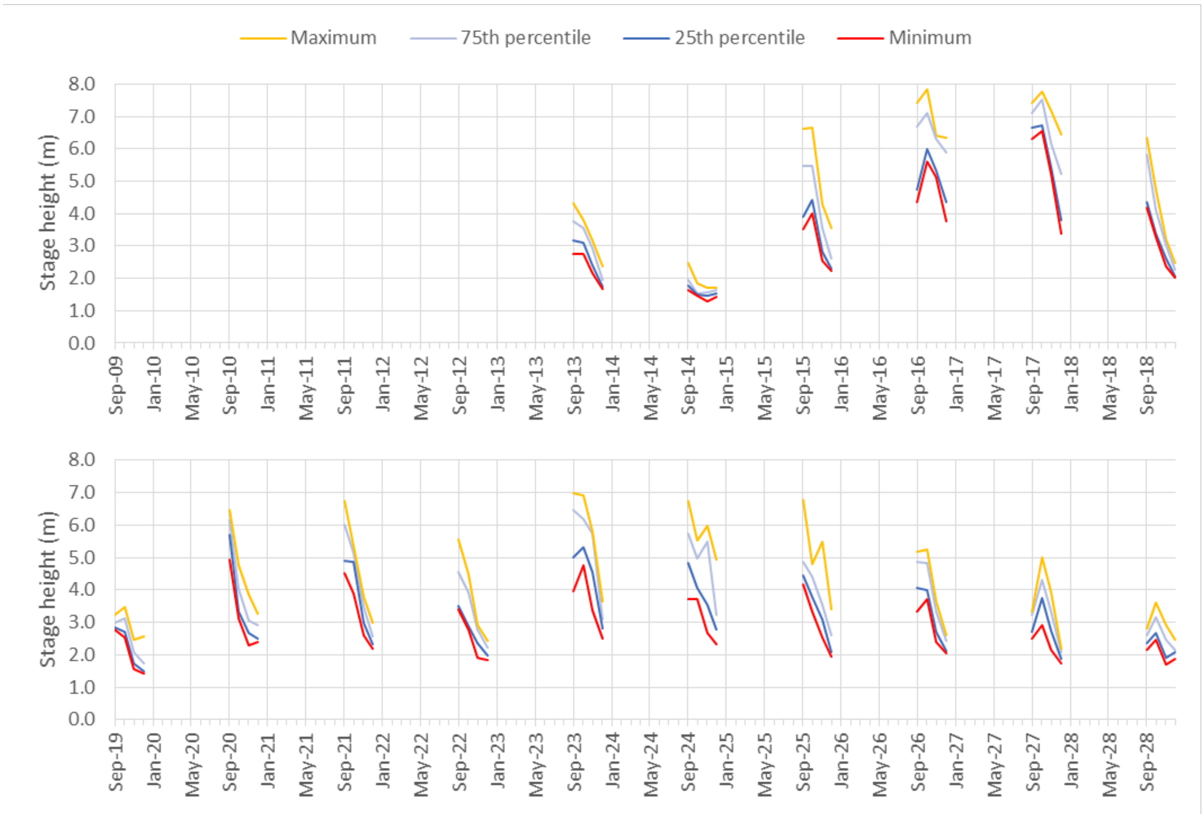


Figure 17. Historical variation in stage height at Murrumbidgee River Narrandera, unregulated, 1913 – 1928.

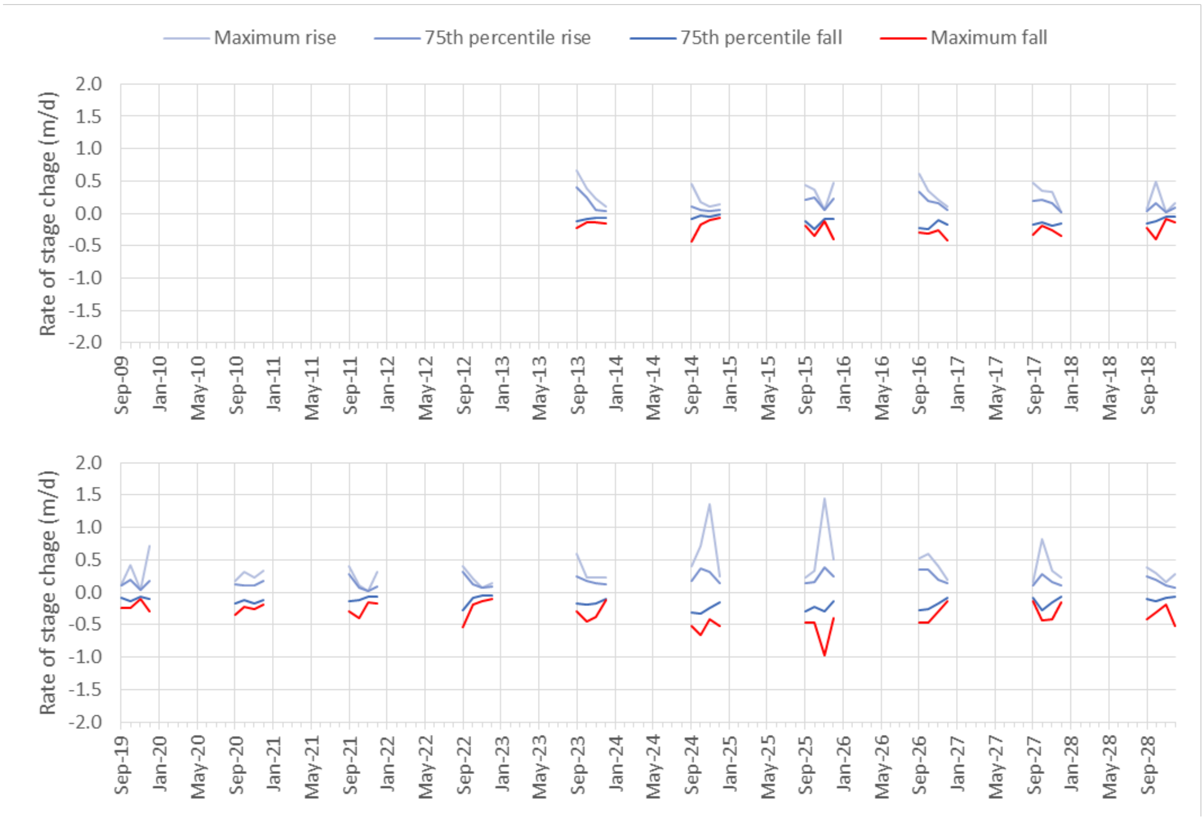


Figure 18. Historical variation in daily rate of rise and fall in stage height at Murrumbidgee River Narrandera, unregulated, 1913 – 1928.

2.6.2.5 MURRUMBIDGEE RIVER AT NARRANDERA, REGULATED

Stage height time series data were available for Murrumbidgee River at Narrandera, following regulation by Blowering Dam from 1970, from 1973 to 2016. This analysis considered the 40 year period 1977 – 2016 was sufficiently long to characterise the stage height variation. Unlike the unregulated regime, the distributions of stage height in the months September to December were highly variable between years (Figure 19). Stage height could increase or decrease through the period September-December, or rise then fall or fall then rise. Over this period, stage height could vary by less than 1.0 m or by as much as 5.0 m. In general, the lower was the absolute stage in a month, the lower was the variability of stage. In stable years, with a monthly range in stage height of 1.0 – 2.0 m, the discharge remained controlled below about 10,000 – 12,000 ML/d, which relates to channel capacity constraints in the Lowbidgee area downstream (Figure 19). In high flow months, when unregulated surplus flow occurred, the stage height could vary over 2.0 – 4.0 m, which represents a large proportion of the channel depth.

The distributions of daily rate of stage height change in the Murrumbidgee River under regulated conditions during the months September to December were, unlike under unregulated conditions, highly variable between years (Figure 20). High flow years (with unregulated surplus flows) tended to have greater rates of change in stage, very occasionally as high as 1.0 m per day fall, and up to 1.5 m per day rise. Most of the time the rates of daily change in stage height were less than 0.5 m.

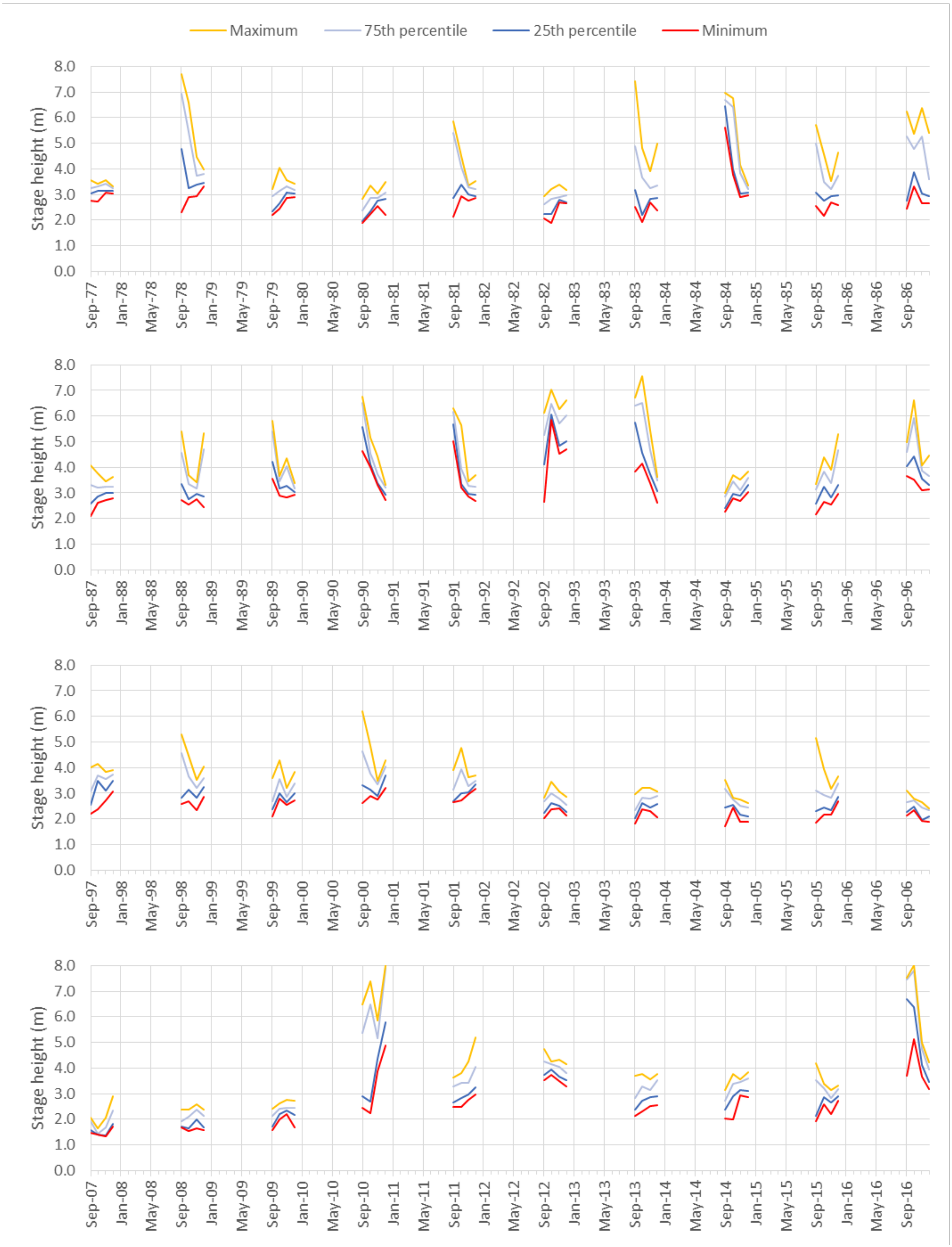


Figure 19. Historical variation in stage height at Murrumbidgee River Narrandera, regulated, 1977 – 2016.

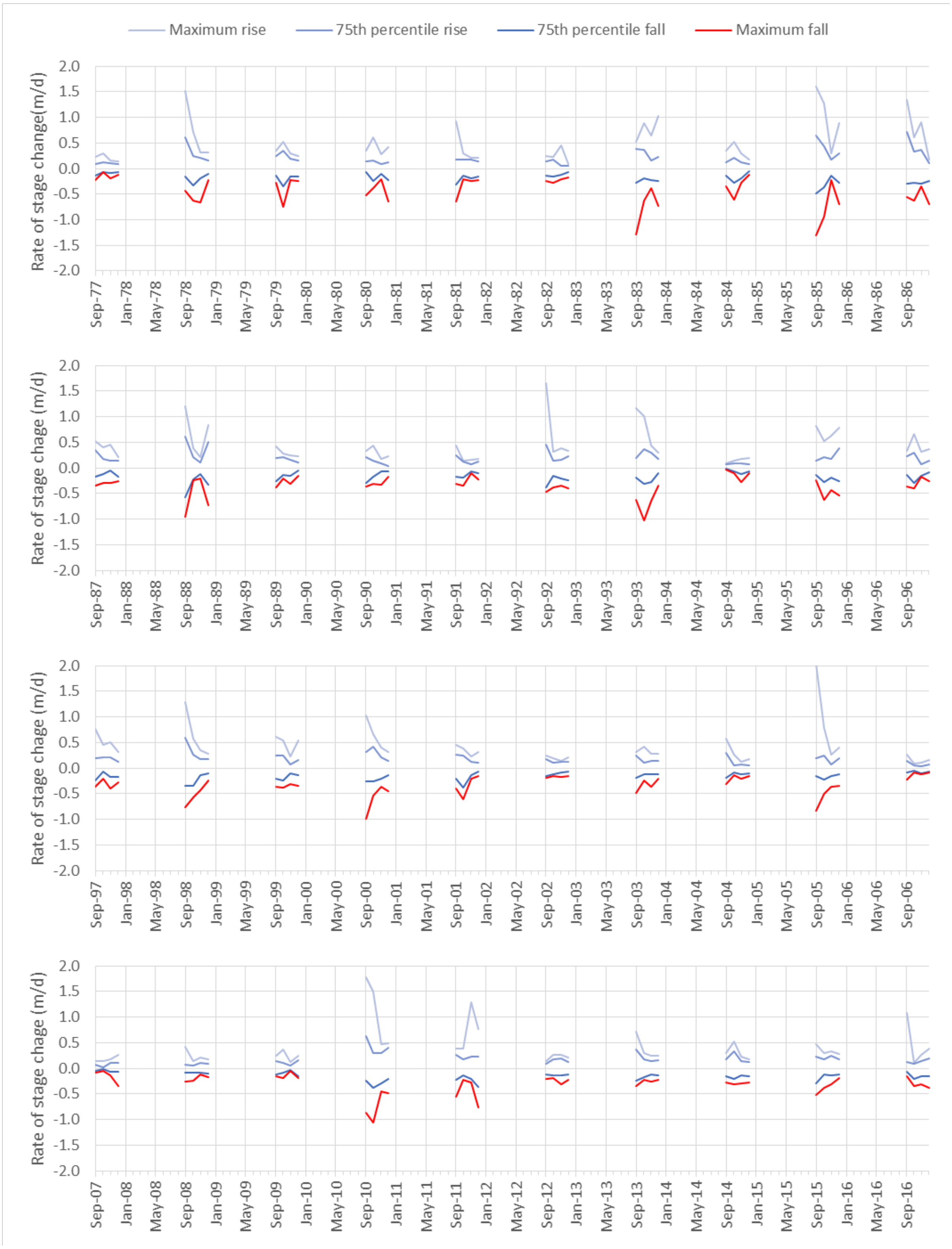


Figure 20. Historical variation in daily rate of rise and fall in stage height at Murrumbidgee River Narrandera, regulated, 1977 – 2016.

2.6.2.6 DISCUSSION OF OBSERVED TROUT COD BREEDING SEASON WATER LEVEL VARIATION

The main outcomes of comparing September-December breeding season stage height regimes at four sites positively associated with Trout cod was the marked difference between the natural and regulated regimes, and the remarkable similarity between the regulated regimes. Compared over the same period of record, the regime of Yanco Creek at the Offtake, although a much smaller stream, was similar to those of the Murrumbidgee River at Narrandera and the River Murray at Tocumwal, characterised by either highly variable or relatively stable stage height within the breeding season, and a high level of variation in the breeding season stage height regimes between years. Highly variable stage height occurred in years with unregulated surplus flows, while years with more stable stage height regimes were associated with flows being controlled by upstream structures most of the time.

At Yanco Creek at the Offtake, the typical range of monthly stage height variation in the more stable years was 0.2 – 1.0 m, although this was closer to 1.0 m in recent years since 2011. A variation of 1.0 m in typical regulated flows for September-December represents a little less than half the flowing channel depth, but pools would offer greater depths. Daily falls in stage height were mostly less than 0.4 m, while drops of up to around 1.0 m per day were observed very occasionally, and not in recent years.

At Murrumbidgee River at Narrandera under regulated conditions, the typical range of monthly stage height variation in the more stable years was 1.0 – 2.0 m, although this was towards the high end of the range in recent years since 2011. A variation of 2.0 m in typical regulated flows for September-December represents a little more than half the flowing channel depth, but pools would offer greater depths. Daily falls in stage height were mostly less than 0.5 m, while drops of up to around 1.0 m per day were observed very occasionally, and not in recent years.

At River Murray at Tocumwal, the typical range of monthly stage height variation in the more stable years was 0.2 – 1.5 m. A variation of 1.5 m in typical regulated flows for September-December represents somewhat more than half the flowing channel depth, but pools would offer greater depths. Daily falls in stage height were mostly less than 0.4 m, while drops of up to around 1.0 m per day were observed very occasionally, and not in recent years.

Modelled unregulated regimes were examined at Seven Creeks and Murrumbidgee River at Narrandera. Although these streams contrast in scale and morphology, they shared some common characteristics in Trout cod breeding season water level regimes. These sites typically had substantial declines in water levels through the September-December period, as natural high flow season water levels receded. The declines were equivalent to almost the entire range of flowing water level in the case of Seven Creeks, and 2.0 – 4.0 m in the case of the Murrumbidgee River, which represents significantly more than half of the expected channel depth at that time of year. Within months, water level varied by about 0.3 – 0.4 m in Seven Creeks and about 1.0 – 3.0 m in Murrumbidgee River (greater than range under stable regulated conditions). In both cases, the variations cover a high proportion of the flowing channel depth. In Seven Creeks, daily falls in stage height were mostly less than 0.2 m, while drops of up to around 0.4 m per day were observed very occasionally, and not in recent years. In Murrumbidgee River, daily falls in stage height were mostly less than 0.5 m, while drops of up to around 1.0 m per day were observed very occasionally.

Overall, the regulated water level regimes were less variable than the unregulated regimes. However, regulated regimes were more variable from year to year, ranging from stable to highly variable. Given that all observed cases could have highly variable flows in the breeding season, the hypothesis that consistently stable water level regimes are positively associated with the occurrence of sustainable Trout cod populations was not supported by this analysis. Although the Trout cod habitat model identifies the role of stable spring flows in breeding success, this should be considered in relation to other habitat factors. Koehn et al. (2013) concluded that "*Key recovery actions include stocking of hatchery-produced fish to establish new populations, regulations on angling (including closures), education (particularly identification from the closely related Murray cod, M. peelii) and habitat rehabilitation (especially re-instatement of structural woody habitats). In particular, the establishment of new populations using hatchery stocking has been a successful action*."

2.7 INTERMITTENCY AT KEY THRESHOLDS

Fluctuations in flow and water level have been identified as threats to Trout cod breeding, specifically fluctuations of up to 1 m (half the channel depth) on a 7 to 10 day or 10 to 14 day cycle. These fluctuations were previously identified from a visual interpretation of the hydrograph (Sharpe and Stuart 2014). Here we quantify intermittency for the three key thresholds of 250 ML/d, 450 ML/d and 600 ML/d by reviewing flow data for the six years following the end of the Millennium Drought in 2011. Data were reviewed for each year for the period from 15 September to 31 December, which is the period within the breeding season where water levels in Yanco Creek are likely to exceed 15 °C. For each threshold the percentage of days below and the duration of events over were determined (Table 2).

Table 2. Analysis of flows at the Yanco Creek offtake for time spent below key habitat thresholds during the Trout cod breeding season (15 September to 31 December) in the years 2011 to 2016

Year	450 ML/d threshold		600 ML/d threshold	
	Percent of days under	Duration of events over (days)	Percent of days under	Duration of events over (days)
2011	0%	108	2%	31, 76
2012	0%	108	1%	4, 103
2013	50%	11, 3, 9, 1, 2, 2, 6, 1, 19	77%	8, 2, 2, 13
2014	14%	6,87	47%	3, 6, 1, 8, 2, 12, 4, 3, 1, 17
2015	51%	44, 3, 2, 4	71%	17, 6, 8,
2016	0%	108	11%	66, 8, 7, 15

The 450 ML/d threshold was identified by Alluvium (2013) as inundating large woody debris and providing a depth of 1.5 m over runs. In three of the six years since the end of the Millennium Drought water levels did not fall below the 450 ML/d threshold during the breeding season. Four of the five years included sustained periods above the threshold with the shortest event being 44 days in 2015. The year 2013 was the most intermittent, with the water level fluctuating above the 450 ML/d threshold on nine occasions with each event being 19 days or shorter.

A flow of 600 ML/d is thought to provide 200 mm depth over high channel benches (Alluvium 2013) and may be a suitable target to optimise Trout cod breeding. Flow fell below this threshold in all six years. The years 2011, 2012 and 2016 provided sustained periods of more than 66 days duration above the threshold but the years 2013, 2014 and 2015 did not provide any events longer than 17 days.

The duration of events below potential nesting thresholds is highly variable and is not consistent with a regular cycle of fluctuations.

We undertook a more detailed characterisation of the magnitude and frequency of these fluctuations in water level through statistical analysis of the daily stage height time series data from Yanco Creek at the Offtake for the months September to December, for the years 2011 to 2016.

The procedure was to first identify all significant points of change in direction of stage height by comparing the stage height of each day with the stage height of the three previous and following days. A peak occurred if the stage height on the day was greater than these surrounding days, and similarly, a nadir occurred if the stage height on the day was lower than these surrounding days. If this produced more than one peak between two nadirs, only the highest one was retained. The magnitude of the fall was then calculated as the difference in stage between the nadir and the previous peak. The interval between the previous nadir was also calculated. In addition, the discharge on the day of the nadir was noted.

A total of 61 significant falls in discharge occurred in the September-December period over the years 2011 to 2016 (Table 3). Of these, only 4 exceeded 1.0 m, with an additional one being close to 1.0 m (0.956 m). Of these 5 events, only 2 involved a fall to a discharge lower than 600 ML/d, one in 2015 and one in 2016. The magnitude of the fall in stage height is less important than the nadir reached, if the nadir is below the level of critical spawning habitat. Of the 61 falls, 32 fell to a level lower than the suggested critical discharge for Trout cod spawning of 600 ML/d (Table 3). There was a pattern to this phenomenon, with a distinction to be made between variable years and stable years. Twenty six of the critical falls in stage occured in 2013, 2014 and 2015. The year 2012 had no critical falls in stage (Table 3).

The median interval between the occurrence of the nadirs was 9 days. The inter-quartile range of 7 days suggests high dispersion in the intervals between nadirs. This indicates that the fluctuations do not occur on a regular cycle.

Table 3. Events of water level decline during the Trout cod breeding season (15 September to 31 December) at Yanco Creek at the Offtake in the years 2011 to 2016, showing the magnitude of the fall (*H*), the discharge when the water level reached its nadir (Q_{min}) and the time interval since the previous water level nadir (*t*). An asterisk on *H* is associated with Q_{min} falling below 600 ML/d. Events sorted from largest to smallest.

#	2011			2012			2013		
	H (m)	Q_{min} (ML/d)	*t* (days)	*H* (m)	Q_{min} (ML/d)	*t* (days)	*H* (m)	Q_{min} (ML/d)	*t* (days)
1	1.223	622	10	1.069	657	12	0.879*	340	7
2	0.692*	448	2	0.557	713	16	0.697*	437	23
3	0.646	628	3	0.491	700	17	0.572*	332	19
4	0.426*	564	14	0.329	701	15	0.366*	351	11
5	0.380	661	21	0.319	616	8	0.259*	388	12
6	0.317	609	10	0.314	697	6	0.229*	272	4
7	0.306	615	3	0.296	725	3	0.107*	410	9
8	0.266	611	11	0.182	998	9	0.083	706	21
9	0.164	723	10	0.165	595	6	0.058*	392	6
10	0.139*	592	6	0.100	823	6			
11	0.103	620	3	0.046	745	5			
12	0.064	747	7	0.030	876	7			
13	0.016	679	5						
#	**2014**			**2015**			**2016**		
	H (m)	Q_{min} (ML/d)	*t* (days)	*H* (m)	Q_{min} (ML/d)	*t* (days)	*H* (m)	Q_{min} (ML/d)	*t* (days)
1	0.402*	493	7	0.956*	350	9	2.369	1234	62
2	0.357*	338	16	0.734*	579	3	1.008*	555	15
3	0.226*	541	7	0.430*	444	12	0.613*	511	12
4	0.214*	551	15	0.359*	301	7	0.28*	518	12
5	0.187*	534	12	0.285*	348	13	0.126	867	2
6	0.155*	385	11	0.234*	340	10			
7	0.147*	584	6	0.169*	337	8			
8	0.145*	572	16	0.159*	337	6			
9	0.098	729	15	0.157	588	6			
10	0.062*	402	5	0.147	596	7			
11				0.132	603	21			
12				0.086*	360	9			

2.8 CONCLUSIONS AND RECOMMENDATIONS

This analysis provides guidance on how water should be managed in Yanco Creek to support Trout cod.

- Flows to support Trout cod should be managed in terms of a pre-breeding period, a breeding period and a non-breeding period.
- The breeding period is defined as being between September and December, when water temperatures exceed 15°C. In Yanco Creek water temperatures are sufficiently warm from about mid-September.
- The objective in the non-breeding period is to facilitate Trout cod growth and survival. A minimum flow of 250 ML/d could be adopted as the target in the non-breeding period. At this flow a velocity of more than 0.3 m/s is achieved, the water depth in runs is 0.8 m, pools are filled and low instream benches are inundated to 0.2 m. This flow provides connectivity between pools, access to pools, run and edge habitat and maintains suitable channel velocity. A higher baseflow than 250 ML/d would provide these outcomes with a higher degree of certainty.
- The objective in the breeding period is to facilitate breeding by maintaining adequate inundation of nesting habitat.
- The flow required to inundate nesting habitat is uncertain. Inundation of high in-channel benches by a flow of 600 ML/d has been proposed as a target for breeding flow. Based on the requirement for inundated snags, a lower flow of 450 ML/d could be adopted as a target for breeding flows, but with a lower degree of certainty.
- Under the flow-habitat model, fluctuations below the breeding flow target contribute to breeding failure and should be avoided. Significant flow variability during spring is a characteristic of the natural habitat of Trout cod. However there is currently insufficient knowledge to determine an acceptable limit for flow variation in managed watercourses. Therefore it is recommended that flow in Yanco Creek is maintained above the adopted breeding flow target throughout the breeding season.
- Flows should increase over the four weeks preceding the breeding season to promote conditioning and breeding behaviour. The pre-breeding increase in flow should take place between mid-August and mid-September.

We have reviewed previous hydrological analysis by Sharpe and Stuart (2014) and note the following:

- The proposition that breeding habitat is affected by regular oscillations in flow of up to one metre every 7-10 or 10-14 days was not supported by hydrological analysis. Water levels rarely fluctuate by one metre and when events occur they rarely involve a fall below 600 ML/d. Smaller water level fluctuations involving a fall below 600 ML/d are more common, with 32 events identified in the years 2011 to 2016. These events are clustered with most (26 events) occurring in 2013, 2014 and 2015 and few or no events occurring in 2011, 2012 and 2016. The events are highly dispersed and do not follow a regular cycle.
- The proposition that water level variability in Yanco Creek during the breeding season is greater than would occur in a natural lowland watercourse is not supported by hydrological analysis. In low flow years (i.e. those without large flood inflows) water level variability in Yanco Creek is a smaller proportion of channel depth than would occur under the unregulated flow regime of the Murrumbidgee at Narrandera. While Seven Creeks is not a lowland watercourse, it is unregulated and supports a Trout cod population. The water level variability in Seven Creeks is also higher than in the regulated Yanco Creek during the breeding season as a proportion of channel depth.
- The proposition that high water level variability in Yanco Creek can be attributed to irrigation water supply was not supported by hydrological analysis. Water level variability during the breeding season in Yanco Creek is highest in high flow years due to the contribution of unregulated catchment inflows. Water level variability is lowest in low flow years when storages, weirs and regulators exercise the

greatest control. The same pattern was observed under the regulated flow regimes of the Murrumbidgee at Narrandera and the Murray at Tocumwal.

Knowledge Gaps

- The levels in the Yanco Creek and Colombo Creek channel where Trout cod nest, or potentially nest, should be investigated. The investigations should determine whether nests are associated with a particular depth or habitat feature such as snags, rocks or benches. This information will help identify the most sensitive flow thresholds for Trout cod breeding.
- A cross sectional survey and physical habitat survey is required of Yanco Creek and the unregulated section of Colombo Creek to map habitat so that flow can target specific habitat features.
- A hydraulic model is required for Yanco Creek and the unregulated section of Colombo Creek. A hydraulic model is required to relate discharge to habitat features, channel velocity and depth throughout the reach.
- The high stable flows in spring and summer recommended in the Trout cod flow-ecology model contrast strongly with the unregulated flow regimes of the watercourses in which Trout cod was historically abundant. There is a risk that the recommended Trout cod breeding flow is overly conservative. Investigations into Trout cod breeding ecology and the significance of water level variation would be beneficial.
- Ecological investigations are required to refine the flow requirements for Trout cod during the breeding season. Information is required to identify the most sensitive times for flow management within the breeding season and the duration and separation interval of breeding flow events.

In addition we note the following.

- Care should be taken in identifying the presence of Trout cod with flow regulation. While it is true that Trout cod habitat has been created in Yanco Creek by regulated water, the key factor is the supply of water to a suitable watercourse, rather than river regulation itself. The critical habitat components provided by Yanco Creek are high velocities, hydrodynamic complexity, high snag density and perennial aquatic habitat. These components have become exceedingly rare in the former distribution of Trout cod. In contrast the provision of high stable flows in spring and summer in regulated watercourses has become widespread.
- Flow regimes in Yanco Creek should be planned with regard to the natural flow regimes of former Trout cod habitat. These flow regimes featured a high degree of variability comprising peaks from runoff events and a gradual decline in baseflow from spring to summer. Understanding the responses and tolerance of Trout cod to flow variability is important to targeting environmental flows effectively and optimising breeding outcomes.
- The proposed new Yanco Weir and Regulator offers greater precision and responsiveness in flow delivery to Yanco Creek and may be better at managing breeding season flows for Trout cod than the current arrangements. However the potential benefits of the weir must be considered against the requirement to build a fishway on the offtake channel, where currently there is none. Even under best practice design, the fishway will not be as transparent to fish movement as the current arrangement.

3 ENHANCING NATURAL FLOWS WITH REGULATED FLOW RELEASES

3.1 BACKGROUND

High in-channel or overbank flows contribute to important ecological outcomes (Alluvium, 2013). The frequency of high in-channel and overbank flows in Mid- and Lower Billabong Creek/Forest Creek part of the Yanco system could potentially be increased by coordinating delivery of environmental water to the system via Yanco Creek Offtake with naturally occurring high flow events sourced from Upper Billabong Creek.

The target reaches for this flow enhancement strategy would be Mid-Billabong Creek, Lower Billabong Creek and Forest Creek/Wanganella. Flow from an environmental allocation would be delivered from the Murrumbidgee River, through the Offtake to Upper Yanco Creek, past Tarabah Weir to Colombo Creek to meet with natural high flow sourced from Upper Billabong Creek. The intention would be to generate a higher flow that targets the environmental flow components including in-channel freshes, bankfull and overbank flows.

Sinclair Knight Merz (2011) reported the travel time from headwater dams to Yanco Offtake was 7.5 days. Travel time from the Offtake to Tarabah Weir was 2.5 days, from Tarabah Weir down Colombo Creek to Innes Bridge, 3.4 km downstream of Billabong Creek junction, was 8 days. Thus, the time required to deliver environmental water from headwater dams to the junction of Colombo and Billabong creeks would be about 18 days. Practical implementation of a Billabong Creek flow enhancement strategy would require accurate forecast of an impending flow peak in Billabong Creek at its junction with Colombo Creek at least 18 days in advance, so that environmental releases could be harmonised with Billabong Creek runoff. Flows in Billabong Creek at its junction with Colombo Creek could be forecast using real time data from a suitable upstream gauge and knowledge of travel time from the gauge to the junction. The forecast could be extended by one or two days using a rainfall-runoff model that predicted flows in the headwaters on the basis of rainfall data from the main catchment source area. The Bureau of Meteorology has a number of rainfall stations in the upper catchment, including at Holbrook (Croft Street). Lacking adequate flow forecasts to harmonise environmental flows sourced from dams and sent to Billabong Creek via Yanco and Colombo creeks, environmental releases could still be made in spring to provide a high baseflow that would then be complemented and further increased by the prevailing runoff in Billabong Creek. The upper limit on baseflow for this strategy is the 600 – 650 ML/d bankfull capacity of Colombo Creek at Morundah (Forest Creek Working Group, 2000, p. 14).

Alluvium (2013) identified environmental flow components for the Billabong/Forest Creek part of the Yanco system that could be the target of the flow enhancement strategy (Table 4). Each of these thresholds would be associated with various ecological benefits, with some being more important than others. Although Alluvium (2013) recommended quite narrow timing windows for these components, worthwhile benefits would likely be achieved between June and January (inclusive) in Mid- and Lower Billabong Creek reaches and between September and February (inclusive) for Forest Creek.

Table 4. Target winter-spring-summer environmental flow components of a strategy to enhance flows in Billabong/Forest Creek system. Source of reach definition and environmental flow components is Alluvium (2013).

Reach	Season	Type	Threshold (ML/d)
Mid-Billabong Creek (Reach 4a, Colombo Creek to Jerilderie)	June-January	Fresh	700
		Bankfull	2,500
Mid-Billabong Creek (Reach 4b, Jerilderie to Yanco Creek)	June-January	Overbank	1,600
Lower Billabong Creek (Reach 5, Yanco Creek to Edward River)	June-January	Fresh	700
		Fresh	1,200
		Bankfull	1,500
		Overbank	3,000
Forest Creek (Reach 6, Regulator to Wanganella Swamp)	September-February	Fresh	800
		Overbank	1,500

Hydrological analysis was undertaken to investigate the potential to implement a Billabong Creek flow enhancement strategy. A number of issues were examined:

- Travel time of flow events in Upper Billabong Creek, to determine if there would be sufficient warning time to implement delivery of environmental flows via Yanco and Colombo creeks to harmonise with flow peaks sourced from Upper Billabong Creek.
- The frequency and duration of flow exceeding 600 ML/d during winter and spring in Colombo Creek under the current flow regime. If this is a common occurrence then there is no need to consider implementing an environmental flow.
- Characterisation of typical winter and spring flows in Billabong Creek to determine if they have potential for beneficial enhancement. To create an overbank flow of 3,000 ML/d, events would need to be at least 2,400 ML/d to add to the 600 ML/d from Colombo Creek. If lower than 2,400 ML/d they may still provide useful lower magnitude freshes.

3.2 UPPER BILLABONG CREEK FLOW EVENT TRAVEL TIME

There are five flow gauges in Upper Billabong Creek, plus the gauge at Innes Bridge which is just downstream of the junction of Billabong Creek and Colombo Creek. The distances of these gauges from the junction were measured from a topographic layer using GIS (Table 5). Historical mean daily flow data were downloaded from DPI, Office of Water, Provisional River Data/Rivers and Streams/Real Time Data (http://realtimedata.water.nsw.gov.au/water.stm). The period of time that could be analysed for all gauges (1/09/2001 to 20/08/2017) was set by the earliest record from the gauge Billabong Ck @ DS Ten Mile and Mountain Cks and ending at the date of data download.

The methodology used to investigate travel time of flow peaks down Upper Billabong Creek was to select all peaks at the most upstream gauge at DS Ten Mile and Mountain Cks that exceeded 2,500 ML/d, and then trace the peaks downstream at the other gauges, noting the date and peak magnitude (Table 6). The threshold of 2,500 ML/d was chosen because it would result in sampling a sufficient number of flow peaks for the analysis and also because it would include all of the events that would have a peak magnitude worth enhancing at the end of Billabong Creek. Two peaks just above 2,500 ML/d (2/06/2013 and 13/08/2013) were eliminated from the sample because the equivalent peaks could not be found at the downstream gauges. This resulted in 18 events sampled from the gauge records. Most of these event peaks were not widely spaced from each other in time, being associated with multi-peaked events, or with multiple events in particularly rainy seasons. In a few cases the timing of the equivalent peak at a downstream gauge preceded the timing at the upstream gauge. This would have been due to significant rainfall associated with the event occurring downstream (west) prior to falling in the headwaters. The hydrographs changed shape significantly on their passage downstream, sometimes acquiring additional peaks. This created some uncertainty in selection of equivalent peaks, but it would not have impacted the main conclusions from the analysis.

The flow peak magnitude changed little between DS Ten Mile and Mountain Cks and Walbundrie gauges, a distance of 215 km (Table 5, Figure 21) along a very sinuous creek course. The mean travel time of the peak over this distance was 2 days and the maximum was 3 days (Figure 21), which could suggest rapid downstream progression of flood waves. It is more likely that the hydrograph at Walbundrie is a response to local rainfall occurring coincidentally with that in the catchment upstream of DS Ten Mile and Mountain Cks as well as the flood wave originating in the headwaters.

Between Walbundrie and Cocketgedong, a distance of 146.9 km, the event hydrographs underwent major transformation. The peak magnitude diminished dramatically and the time to reach Cocketgedong from DS Ten Mile and Mountain Cks increased to a mean of 8 days and a maximum of 15 days (Figure 21). Flow events that peaked at >10,000 ML/d at DS Ten Mile and Mountain Cks reduced to less than 1,500 ML/d at Cocketgedong gauge (Table 5). Downstream reduction in peak magnitude and temporal lag is associated with attenuation due to flow resistance. Assuming no loss of flow from the channel, a lower peak magnitude would also be associated with increased event duration. This was not the case with the data from Upper Billabong Creek, where the main explanation for reduced flow peak magnitude is loss of flow from the main channel. Some of the flow would be stored on the floodplain and the remainder transferred downstream via secondary flow paths. This result is consistent with the geomorphic description of the creek system by (Hetherington, 2000). Downstream of Bulgandry, where the creek enters the Riverine Plain, the channel depth decreases markedly, particularly downstream of Walbundrie, and there are more floodouts. The creek at Rand has a capacity 60 percent of that at Walbundrie (Hetherington, 2000). This reach has a significant anabranching section, and also connects with Nowranie Creek, which flows to Billabong Creek at Innes Bridge, downstream of the gauge. Thus, flow events sourced from Upper Billabong Creek recorded at the gauge DS of Innes Bridge are relatively small (Figure 21) because they do not include the flow that escaped the main channel.

The main conclusion from analysis of Upper Billabong Creek flow event travel times is that the flow gauges on the creek do not give sufficient warning time to enable harmonisation of environmental flows delivered from headwater dams, via Yanco and Colombo creeks. While a minimum of 18 days notice is required to deliver environmental flows, the peaks of natural flow events in Billabong Creek typically travel from the most upstream gauge to the junction with Colombo Creek in 7 – 16 days. The flow measured at Cocketgedong gauge does not include all of the flow sourced from the headwaters of Billabong Creek catchment, with a significant proportion flowing to the downstream reaches via secondary ungauged channels.

Table 5. Flow gauges on Upper Billabong Creek

Gauge number	Gauge name	Data availability	Distance from Colombo Creek junction
410012	Billabong Ck @ Cocketgedong	1/11/1912 to present	6.1 km upstream
410091	Billabong Ck @ Walbundrie	1/06/1965 to present	153.0 km upstream
410182	Billabong Ck @ Hillview	4/06/2001 to present	256.5 km upstream
410183	Billabong Ck @ Parkside	5/06/2001 to present	314.8 km upstream
410186	Billabong Ck @ DS Ten Mile and Mountain Cks	30/08/2001 to present	368.3 km upstream
410170	Billabong @ US Innes Bridge	1/01/1995 to present	3.4 km downstream

Table 6. Flow event peaks traced through Upper Billabong Creek from 1/09/2001 to 20/08/2017.

Billabong Ck @ DS Ten Mile and Mountain Cks (410186)			Billabong Ck @ Parkside (410183)			Billabong Ck @ Hillview (410182)			Billabong Ck @ Walbundrie (410091)			Billabong Ck @ Cocketgedong (410012)			Billabong @ US Innes Bridge (410170)		
Peak (ML/d)	Date	Time (d)	Peak (ML/d)	Date	Time (d)	Peak (ML/d)	Date	Time (d)	Peak (ML/d)	Date	Time (d)	Peak (ML/d)	Date	Time (d)	Peak (ML/d)	Date	Time (d)
2935	16/08/2003	0	7342	16/08/2003	0	3184	15/08/2003	-1	3445	16/08/2003	0	743	22/08/2003	6	959	24/08/2003	8
3671	25/08/2003	0	13720	26/08/2003	1	5428	26/08/2003	1	3681	27/08/2003	2	1159	2/09/2003	8	1395	4/09/2003	10
4906	11/09/2005	0	6881	12/09/2005	1	6623	12/09/2005	1	5180	13/09/2005	2	1325	20/09/2005	9	1445	22/09/2005	11
5579	29/09/2005	0	7700	30/09/2005	1	7044	30/09/2005	1	6025	1/10/2005	2	1573	9/10/2005	10	1606	11/10/2005	12
8237	8/03/2010	0	4512	9/03/2010	1	4159	10/03/2010	2	5401	10/03/2010	2	131	23/03/2010	15	580	19/03/2010	11
7292	5/09/2010	0	5322	6/09/2010	1	4802	7/09/2010	2	5593	7/09/2010	2	742	14/09/2010	9	2015	21/09/2010	16
28066	16/10/2010	0	38416	16/10/2010	0	37660	17/10/2010	1	42831	17/10/2010	1	1288	26/10/2010	10	3596	31/10/2010	15
2954	1/11/2010	0	3008	2/11/2010	1	3308	2/11/2010	1	3435	2/11/2010	1	950	10/11/2010	9	1080	23/11/2010	22
11264	9/12/2010	0	11009	10/12/2010	1	12496	10/12/2010	1	9075	10/12/2010	1	909	10/12/2010	1	3804	20/12/2010	11
17754	6/02/2011	0	18536	7/02/2011	1	18501	7/02/2011	1	20248	7/02/2011	1	1441	19/02/2011	13	4216	21/02/2011	15
11105	18/02/2011	0	8132	21/02/2011	3	8475	19/02/2011	1	10046	21/02/2011	3	1440	26/02/2011	8	3893	28/02/2011	10
8908	14/03/2011	0	7801	15/03/2011	1	7602	15/03/2011	1	6568	15/03/2011	1	1475	14/03/2011	0	4034	15/03/2011	1
6483	18/08/2011	0	7358	19/08/2011	1	6794	19/08/2011	1	7970	20/08/2011	2	1326	28/08/2011	10	2570	30/08/2011	12
7509	30/09/2011	0	6222	1/10/2011	1	7104	1/10/2011	1	8231	1/10/2011	1	1296	11/10/2011	11	2140	12/10/2011	12
21561	4/03/2012	0	30565	5/03/2012	1	32633	5/03/2012	1	29583	5/03/2012	1	1483	12/03/2012	8	4227	14/03/2012	10
2790	24/08/2013	0	2041	26/08/2013	2	2130	26/08/2013	2	2096	26/08/2013	2	911	1/09/2013	8	1400	2/09/2013	9
3061	18/09/2013	0	2697	19/09/2013	1	2857	19/09/2013	1	2509	19/09/2013	1	927	26/09/2013	8	1209	27/09/2013	9
10583	3/09/2016	0	10802	4/09/2016	1	10324	4/09/2016	1	11074	5/09/2016	2	1570	11/09/2016	8	3708	14/09/2016	11

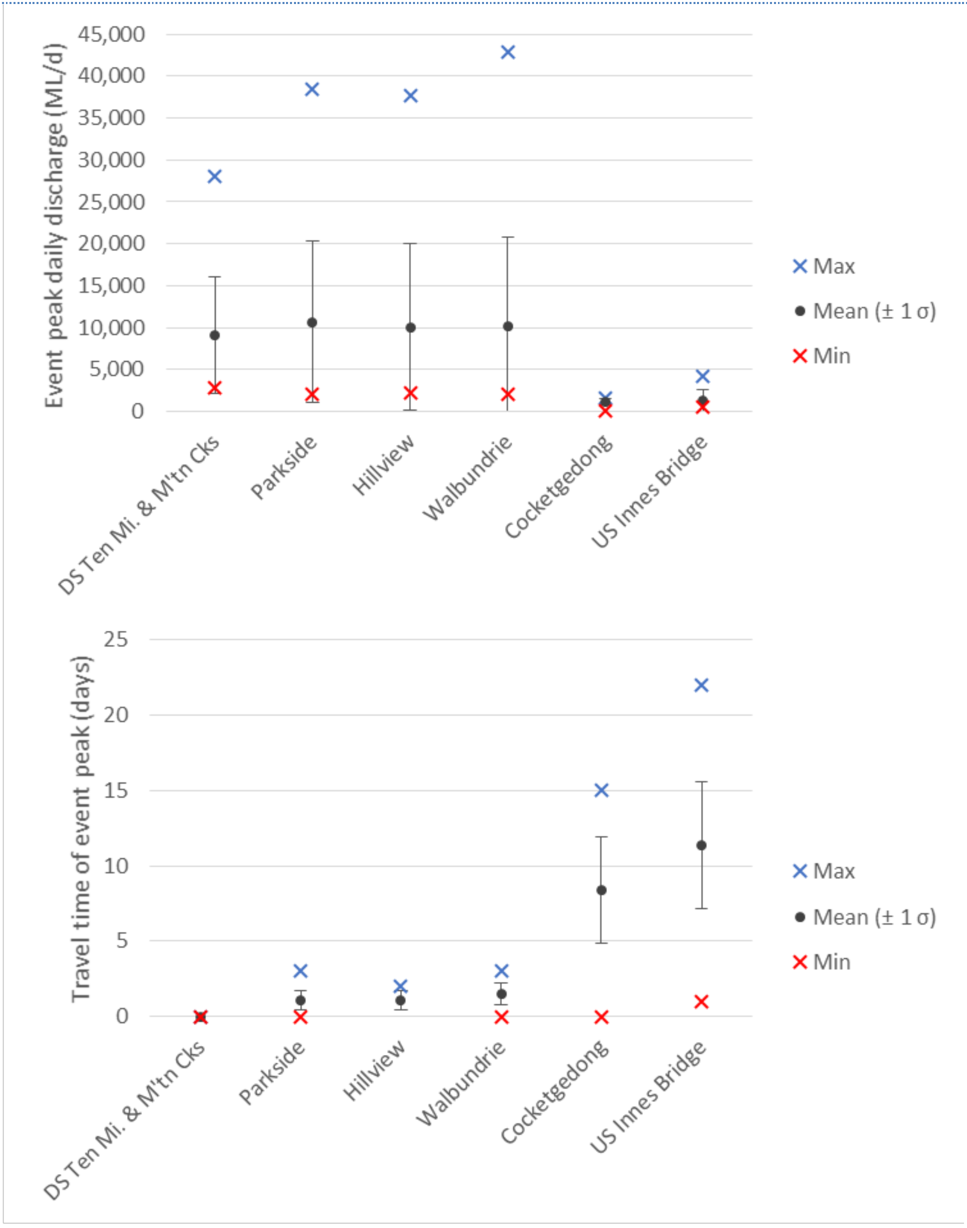


Figure 21. Descriptive statistics of flow event peak magnitude and downstream travel time for 18 events on Upper Billabong Creek from 1/09/2001 to 20/08/2017. Travel time is from most upstream gauge.

3.3 CHARACTERISTICS OF FLOW EXCEEDING 600 ML/D IN COLOMBO CREEK

The capacity of Colombo Creek was reported to be 600 – 650 ML/d by Forest Creek Working Group (2000). Alluvium (2013) did not provide a cross-section from this reach of the system that might have indicated the bankfull level, nor did they recommend a bankfull flow component for this reach. On this basis, 600 ML/d was assumed to be the upper magnitude of flow that could be delivered to Billabong Creek as a managed environmental flow in winter and spring (June – November). Of interest is the current frequency and duration of flows >600 ML/d at the gauges in Colombo Creek upstream of Billabong Creek junction, namely Colombo Ck @ Morundah (410014) and Colombo @ Coonong Weir (41000210). The gauge Billabong @ US Innes Bridge (410170), located 3.4 km downstream of Billabong/Colombo creek junction, was also included because a significant proportion of the event flow from Billabong Creek enters downstream of this point.

The methodology used to investigate this issue was spells analysis. Events were regarded as independent if the peaks were separated by more than 7 days. The three gauges had records of varying length, with Morundah gauge being the longest.

The limited available data suggests that the frequency and duration of spells >600 ML/d could decrease slightly between Morundah and Coonong Weir (Figure 22). At Morundah, 49 percent of years had a spell of flow >600 ML/d, although the 9 year period 2001 – 2009 had no spells (Figure 22). Mean spell duration was 17.5 days, but duration was highly variable, ranging up to 106 days. At Coonong Weir, 4 of the 7 years of record experienced a spell >600 ML/d. At the gauge US Innes Bridge on Billabong Creek, the data suggest that spells >600 ML/d were more common than at Morundah gauge on Colombo Creek, with 71 percent of years experiencing a spell. Mean spell duration was 32 days, but duration was highly variable, ranging up to 159 days (Figure 22). The spells of flow >600 ML/d at this location were more frequent and longer in duration than in Colombo Creek due to contributions from Billabong Creek, and further downstream, additional Billabong Creek flow would enter from secondary channels.

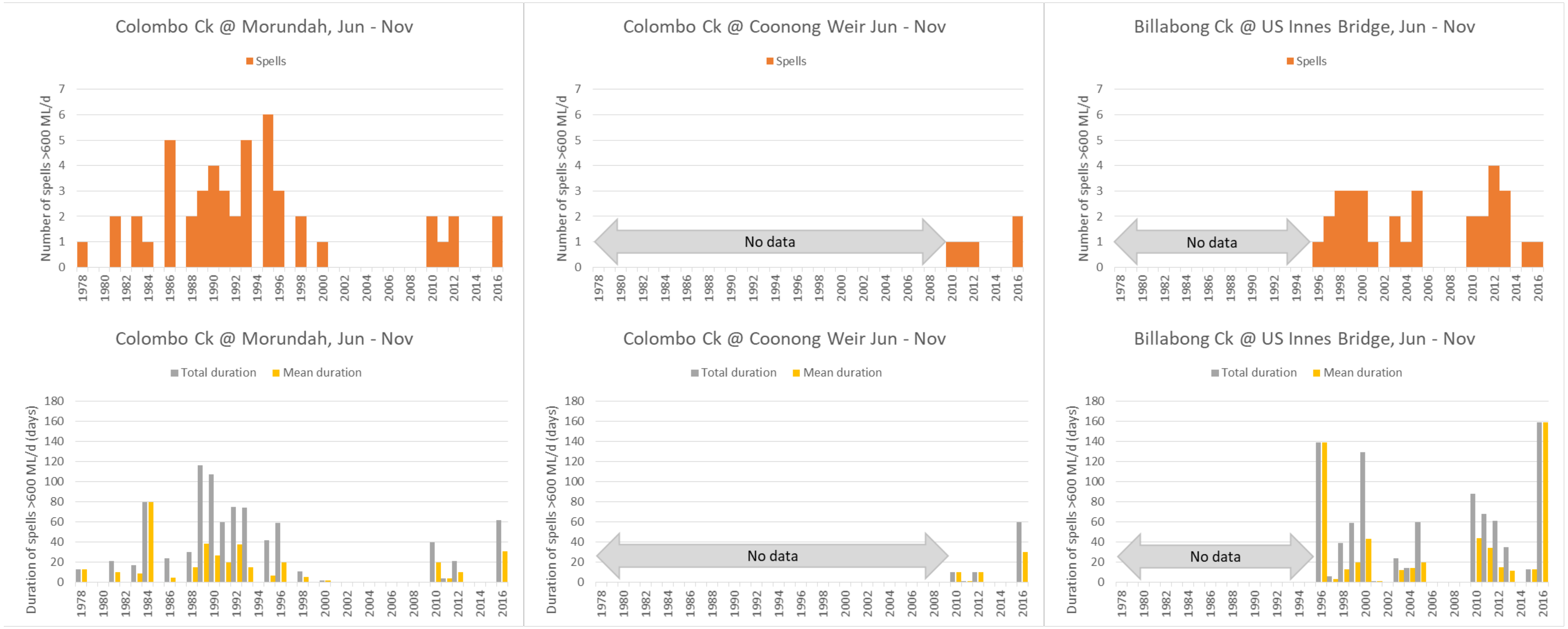


Figure 22. Characteristics of spells >600 ML/d in winter-spring at two gauges on Colombo Creek and also at US Innes Bridge gauge on Billabong Creek, just downstream of the junction of Colombo and Billabong creeks.

3.4 CHARACTERISTICS OF WINTER AND SPRING FLOW IN BILLABONG CREEK AND FOREST CREEK

Opportunities to enhance flows in Mid- and Lower Billabong Creek and Forest Creek, and the volume of environmental flow required to be delivered at Yanco Offtake, depend on:

1. The required timing and magnitude of the Billabong Creek/Forest Creek environmental flow components (Table 4)
2. The flow in Colombo Creek at the time, as limited by the channel capacity of 600 ML/d
3. The travel time of flow from source to environmental flow target reach
4. The flow in the environmental flow target reach at the time, as determined by the combined flows of Colombo Creek and the natural inflows from the Upper Billabong Creek system plus other secondary inflows

This issue was investigated by modelling the theoretical availability of all such opportunities that would have arisen in the historical flow record using a simple water balance of gauged flow data. The length of the modelled time series was limited by the period of available flow record. Forest Creek Offtake would be the ideal target gauge for the Forest Creek system (termed Reach 6 by Alluvium 2013), but this gauge did not begin recording until September 2014, so the downstream gauge at Warriston Weir, which began recording in September 1980, was used. The model had no ability to identify opportunities for boosting flows that would be the most practical for environmental flow delivery, nor could it identify the most promising opportunities in terms of ecosystem benefit.

The practicalities of environmental flow delivery depend on numerous factors, including difficulty in: (i) significantly varying the environmental flows from day to day in order to remain within downstream channel capacity constraints, and (ii) remaining at or above the downstream environmental flow threshold given a situation of varying downstream natural inflows to the system.

Environmental flows are likely to have diminishing ecosystem benefits the longer is their duration beyond a certain optimum value, and benefits are also likely to diminish the further the environmental flows are from the central part of the active season. Here, no upper or lower limits were placed on the duration of an environmental flow event created by flow enhancement, and each day of the active season was considered equal in terms of potential ecosystem benefit. Given these assumptions, the results described all potential flow enhancement opportunities, and not all of these would necessarily be practical or worthwhile. Perhaps only a minority of these opportunities would have good potential for implementation.

The water balance did not account for evaporative and seepage losses that might occur during transit. Travel times were directly from, or interpolated from, Sinclair Knight Merz (2012, p. 42 - 43).

The water balance model was described by the following equations and conditions:

$$QE_{BbIB,d} = Q_{BbIB,d} + QE_{CoMo,d}$$

$$EF_{ColMo,d-tt} = QE_{CoMo,d} - Q_{CoMo,d}$$

$$QE_{TG,d} = Q_{TG,d} + EF_{CoMo,d-tt}$$

$$EF_{ColMo,d-tt} = 0$$

if: $QE_{CoMo,d} \geq 600\ \text{ML/d}$; $Q_{TG,d} \geq EFT_{TG,d}$; $QE_{TG,d} < EFT_{TG,d}$; d out of season

where,

Q = Ambient flow in river, as daily rate in ML/d

QE = Ambient flow in river enhanced with environmental flow, as daily rate in ML/d

EF = Environmental flow delivered, as daily rate in ML/d

EFT = Environmental flow target, as daily rate in ML/d

d = subscript denoting day at target environmental flow gauge

$CoMo$ = Subscript denoting gauge at Colombo Creek, Morundah

TG = Subscript denoting target gauge for environmental flows, i.e. Billabong Creek, Innes Bridge; Billabong Creek, Jerilderie; or Forest Creek, Hartwood Weir

tt = Subscript denoting travel time from Colombo Creek, Morundah to target gauge, i.e. Reach 4a: Innes Bridge, Billabong Creek – 7 days; Reach 4b: Jerilderie, Billabong Creek – 9 days; Reach 5: Conargo, Billabong Creek – 15 days; Reach 6: Warriston Weir, Forest Creek – 19 days

The flow thresholds to enhance were identified from the environmental flow recommendations of Alluvium 2013.

The results of the modelling revealed that while there were numerous opportunities to enhance flows in Billabong Creek with environmental flows delivered from Yanco Creek for freshes, the opportunities to generate bankfull and overbank events was limited (Figure 23, Figure 24, Figure 25, Figure 26 and Figure 27). In general, the higher the magnitude of the environmental flow component, and the further in distance from Colombo Creek, the fewer were the opportunities to enhance the flow to meet flow components. Conditions were such that the overbank flow component for Forest Creek (1,500 ML/d) could not be generated through flow enhancement on any day in the historical record.

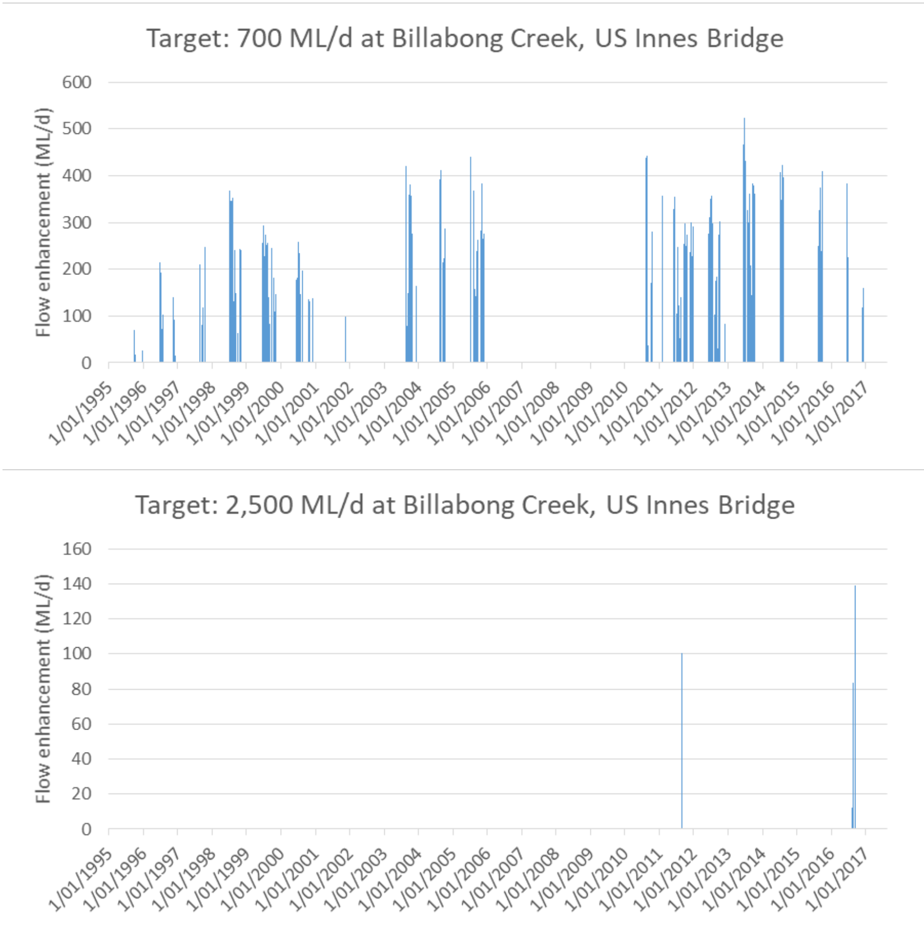


Figure 23. Time series of daily volume of environmental flow delivered from Yanco Creek Offtake that could be used to enhance flow in Billabong Creek at US Innis Bridge to meet 700 ML/d fresh (top), and 2,500 ML/d bankfull (bottom) flow components, in June to January inclusive.

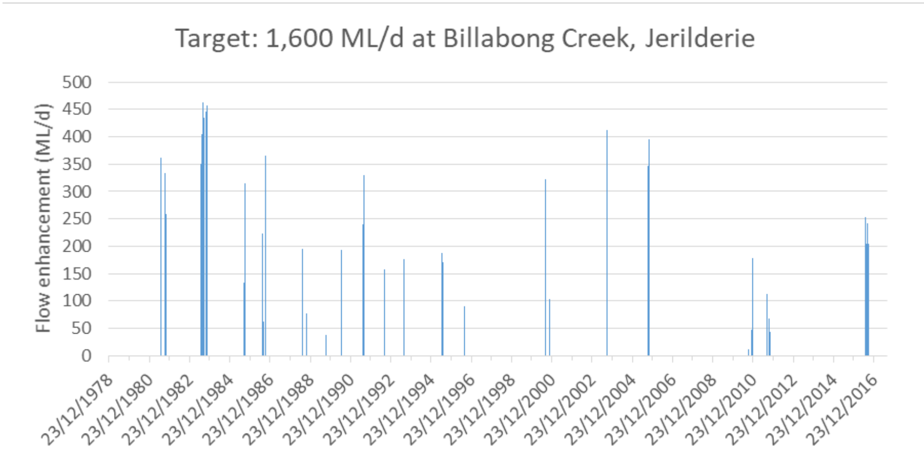


Figure 24. Time series of daily volume of environmental flow delivered from Yanco Creek Offtake that could be used to enhance flow in Billabong Creek at Jerilderie to meet 1,600 ML/d overbank flow component, in June to January inclusive.

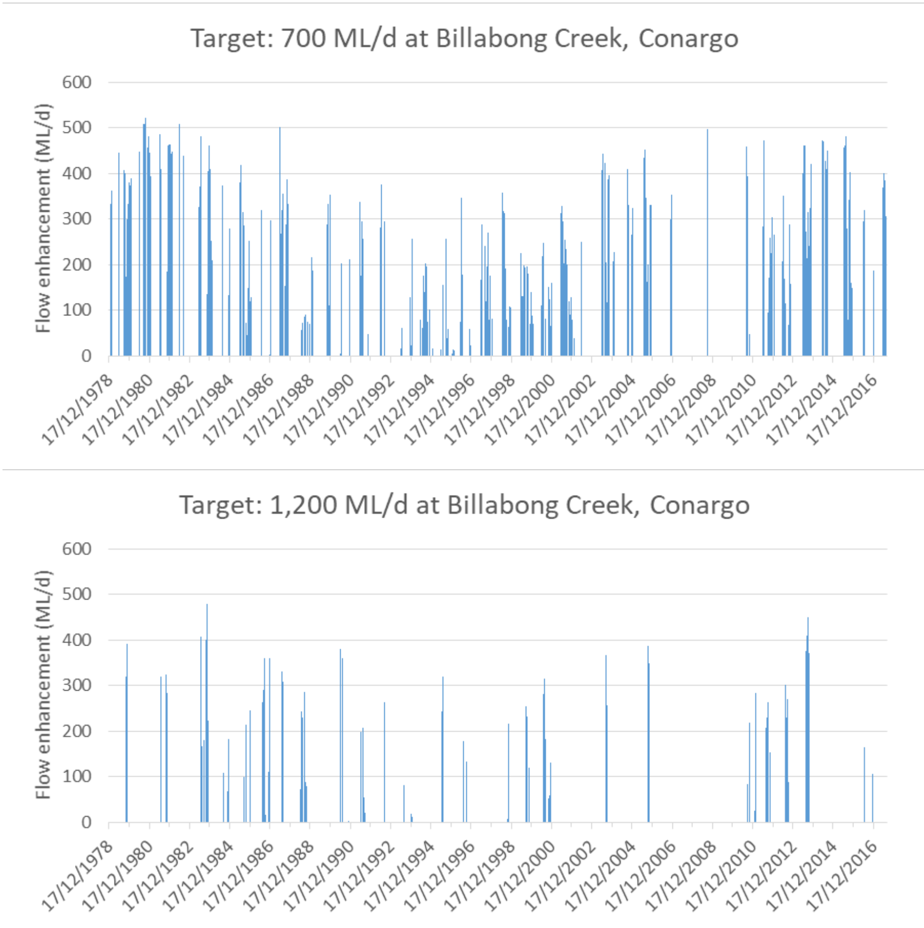
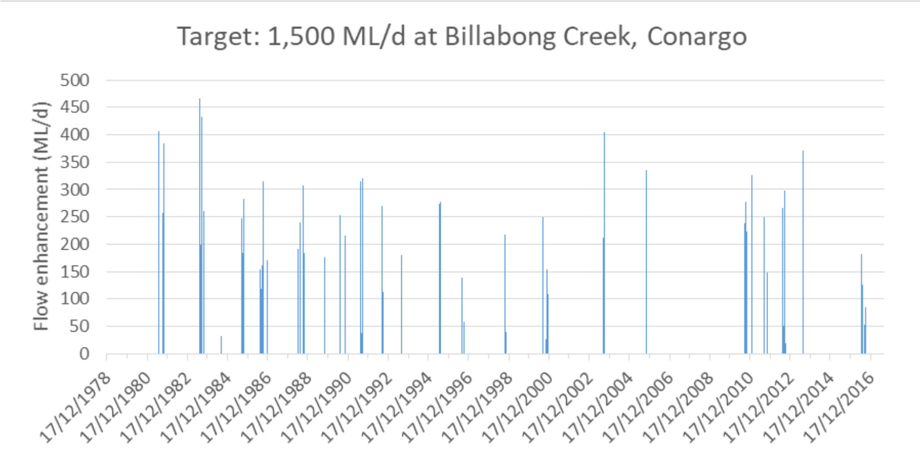


Figure 25. Time series of daily volume of environmental flow delivered from Yanco Creek Offtake that could be used to enhance flow in Billabong Creek at Conargo to meet 700 ML/d fresh (top), and 1,200 ML/d fresh (bottom) flow components, in June to January inclusive.



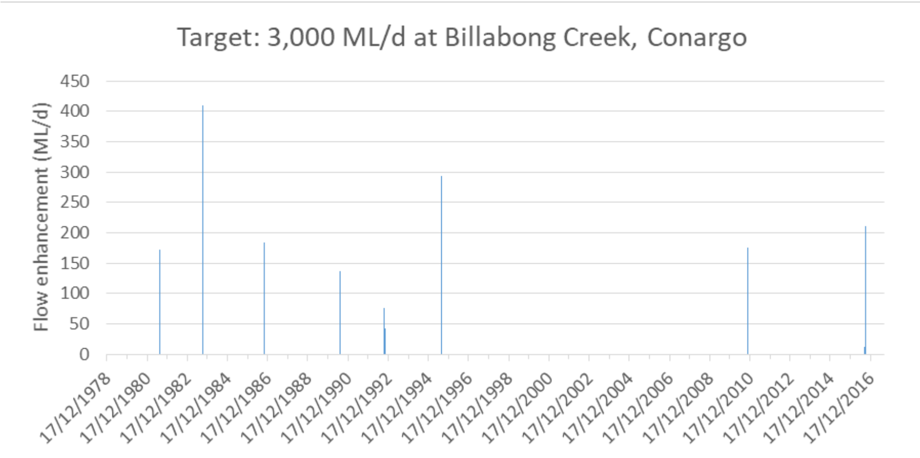


Figure 26. Time series of daily volume of environmental flow delivered from Yanco Creek Offtake that could be used to enhance flow in Billabong Creek at Conargo to meet 1,500 ML/d bankfull (top), and 3,000 ML/d overbank (bottom) flow components, in June to January inclusive.

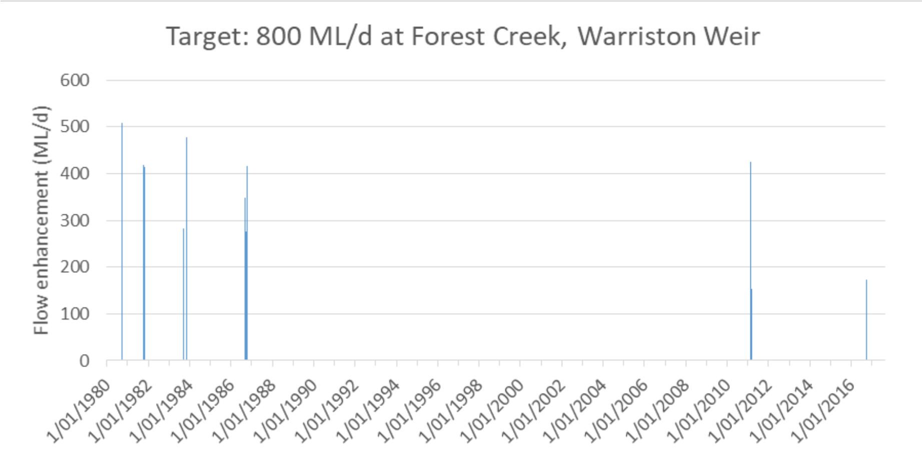


Figure 27. Time series of daily volume of environmental flow delivered from Yanco Creek Offtake that could be used to enhance flow in Forest Creek at Warriston Weir to meet 800 ML/d fresh flow component, in September to February inclusive.

3.5 CONCLUSIONS

In summary, this investigation found the following.

- Flow gauges on Upper Billabong Creek do not give sufficient warning time to enable harmonisation of environmental flows delivered from headwater dams via Yanco and Billabong Creeks.
- Even so, in most years, Colombo Creek has some spare capacity to support the delivery of environmental flows during winter and spring (June to November), up to a channel capacity limit of 600 ML/d. The duration and timing of these opportunities is difficult to predict.
- These opportunities are poorly suited to generating bankfull or overbank flows. In general, the higher the magnitude of the environmental flow component and the further in distance from Colombo Creek, the fewer were the opportunities to enhance the flow to meet environmental flow components.

4 CHARACTERISTICS OF SUPPLEMENTARY WATER EVENTS

4.1 BACKGROUND

Supplementary flows, also known as surplus flows and off-allocation water, are important to many irrigators as an additional source of water that can potentially benefit crop production. There is concern that the frequency and duration of supplementary flows could decrease when the proposed new Yanco Weir and regulator becomes operational due to the greater range of flows that it is designed to control. The most important reaches of the system where this concern is relevant are the Mid-Yanco, Mid-Billabong and Lower Billabong, where the most irrigated crops are located.

Department of Primary Industries Water provided information (Andrew Brown, under approval of Danielle Baker, Director Water Analytics - DPI Water, pers. comm., 1 Sep 2017) regarding the matter of how supplementary flows might be affected by the proposed new Yanco Weir and regulator. It was noted that in other valleys with similar regulated effluents, DPI Water have a very long history of sharing surplus flows into effluents to equalise access opportunity. Clause 69(3) of the Water Sharing Plan (New South Wales Government, 2017) also requires this more generally:

> "*(3) The taking of water under supplementary water access licences and supplementary water (Lowbidgee) access licences should, as far as possible, be managed to evenly share access opportunity between all supplementary water access licence holders and supplementary water (Lowbidgee) access licence holders permitted to access that event in accordance with the rules in this clause.*"

DPI Water expects that the proposed new Yanco Weir and regulator would result in some degree of change in the pattern of availability of supplementary water. For example, when Murrumbidgee River flow events with available surplus water are targeted to benefit the Mid-Murrumbidgee wetlands, the total volume entering Yanco Creek could be less than it would be under the current arrangement. However, a principle of operation of the proposed regulator would be to make up that water at other times so that there would be no net loss in the share going to the Yanco system. These principles, and the framework to monitor and report on them, have not yet been developed.

A hydrological analysis was undertaken to characterise the frequency, duration, timing and magnitude of supplementary flows in the system under historical flow conditions. Daily time series data of announced supplementary flow for the period from 2004/05 to 2016/17 was provided by Andrew Brown (DPI, Water, pers. comm., 1 Sep 2017). The data also included volume ordered and used. These data are not reported here, but it is noted that water was not necessarily ordered and used when supplementary flows were announced.

The main objective of this analysis was to characterise: (i) the duration and frequency of opportunities (spells of time) to access supplementary water, and (ii) the timing and magnitude of flows when supplementary flows were announced.

4.2 DURATION AND FREQUENCY OF SUPPLEMENTARY WATER OPPORTUNITIES

The time series of supplementary flows were considered according to water year beginning 1 July. The spells of supplementary water for each reach of the Yanco system were plotted as time series, as well as annual spell frequency and duration (Figure 28, Figure 29, Figure 30, Figure 31, Figure 32 and Figure 33).

Overall, the duration and frequency characteristics of supplementary flow opportunities were similar across the entire Yanco system, and the characteristics mirrored those of supplementary flow availability in the

Murrumbidgee River downstream of Narrandera. Years 2004/05 amd 2005/06 had a small number of short spells of supplementary water, and years 2006/07, 2007/08 and 2008/09 had no supplementary water available. Year 2009/10 also had limited supplementary water availability but wetter conditions from 2010/11 to 20017/17 provided more opportunities for supplementary water access.

4.3 TIMING AND MAGNITUDE OF SUPPLEMENTARY WATER OPPORTUNITIES

The distributions of timing and magnitude of supplementary water for each reach of the Yanco system were plotted as frequency histograms. For timing, frequency was expressed as mean number of days per year within fortnightly classes, for the period 2004/05 to 2016/17 (Figure 34, Figure 35, Figure 36, Figure 37 and Figure 38). For discharge magnitude, frequency was expressed as mean number of days per year within discharge classes scaled according to the characteristic discharge range for each reach, for the period 2004/05 to 2016/17 (Figure 34, Figure 35, Figure 36, Figure 37 and Figure 38).

Overall, the distributions of timing of supplementary flow opportunities were similar across the entire Yanco system (although lagged due to travel time), and the distributions corresponded to that of supplementary flow availability in the Murrumbidgee River downstream of Narranderra. The majority of supplementary flow opportunities were available in the period June to November, which corresponds with the natural high flow season.

The magnitude of flows at the times when supplementary flows were announced were mostly within channel capacity for all reaches. Seventy-five percent (75%) of the time that supplementary flows were announced in the Murrumbidgee River downstream of Narranderra, the discharge was less than 15,000 ML/d (Figure 34), which is within the range of Murrumbidgee River discharge that can be controlled at Yanco Weir and regulator (Alluvium, 2013). Similarly, eighty percent (80%) of the time that supplementary flows were announced in the Yanco Creek downstream of the Offtake, the discharge was less than 1,400 ML/d (Figure 34), which is within the range of discharge that can be controlled at Yanco regulator (Alluvium, 2013). Thus, although supplementary flows tended to be associated with the high flow season, most of the time they were regulated flows. This suggests that the enhanced range of control offered by the proposed new weir and regulator at Yanco Offtake does not in itself pose a risk to access to supplementary water in the Yanco system. Of more importance is maintenance of the principle used to distribute supplementary flows, and this is essentially set out in Clause 69(3) of the Water Sharing Plan.

Further down the Yanco system, supplementary water availability was largely associated with sub-bankfull flows. In mid-Yanco Creek the bankfull level corresponds with 800 ML/d (Alluvium, 2013). In the Morundah to Yanco Bridge reach, 78% of the time when supplementary flows were announced the creek flow was less than this (Figure 35). In the Yanco Bridge to Wiraki reach, it was 81% of the time and in the Wiraki to Puckawidgee reach it was 84% of the time (Figure 35). In Colombo Creek the bankfull level corresponds with 600 ML/d. In the Morundah to Coonong Weir reach, 85% of the time when supplementary flows were announced the creek flow was less than this (Figure 36). In the Coonong Weir to Billabong junction reach, it was 89% of the time (Figure 36). In mid-Billabong Creek, the bankfull level corresponds with 2,500 ML/d from Colombo Creek junction to Jerilderie and is less than 1,600 ML/d further downstream (Alluvium, 2013). In the Colombo Creek junction to Jerilderie reach, 99% of the time when supplementary flows were announced the creek flow was less than bankfull (Figure 37). In the Jerilderie to Algudgerie reach, it was 77% of the time (Figure 37). In Lower Billabong Creek, the bankfull level corresponds with 1,500 ML/d (Alluvium, 2013). In the Puckawidgee to Wanganella reach, 71% of the time when supplementary flows were announced the creek flow was less than bankfull (Figure 38, Figure 37). In the Wanganella to Darlot reach, it was 72% of the time, and in the reach downstream of Darlot it was 74% of the time (Figure 38).

4.4 CONCLUSIONS

In summary, this investigation found the following.

- Supplementary flows are important to many irrigators as a source of water for crop production. There is concern that operation of a proposed new Yanco Weir would decrease the frequency, duration or timing of supplementary flows due to the greater range of flows that it is designed to control.
- The share of supplementary water between the Murrumbidgee and the Yanco Billabong system is guided by DPI Water policy and Clause 69(3) of the Water Sharing Plan which prescribe that access to access to supplementary water is shared between licence holders as equitably as possible.
- The proposed new Yanco Weir and Regulator would provide scope to control higher discharges than the current weir and offtake channel.
- However, eighty percent of the time when supplementary flows are announced, flow downstream of the Yanco Offtake was less than 1,400 ML/d, which is within the range of discharge that can be controlled at Yanco regulator. This suggests even under the current arrangements, policy, rather than infrastructure constraints, is the primary control in determining the share of supplementary flows between the Yanco Billabong system and the Murrumbidgee.
- Nevertheless, the regulator provides broad scope for hydrological change in the Billabong Yanco System and is a source of concern among stakeholders. Consultation will be important in the development of operating rules to assure stakeholders that these principles have been maintained and any plans to alter the timing of supplementary flows considers ecological, social and environmental risks and benefits.
- To maintain the current arrangements, the existing policy settings should be preserved in the forthcoming revision of the Water Sharing Plan and operational guidelines of any new offtake regulator. Policy settings should reflect the timing of existing supplementary flows, particularly the importance of spring flows to summer crops.

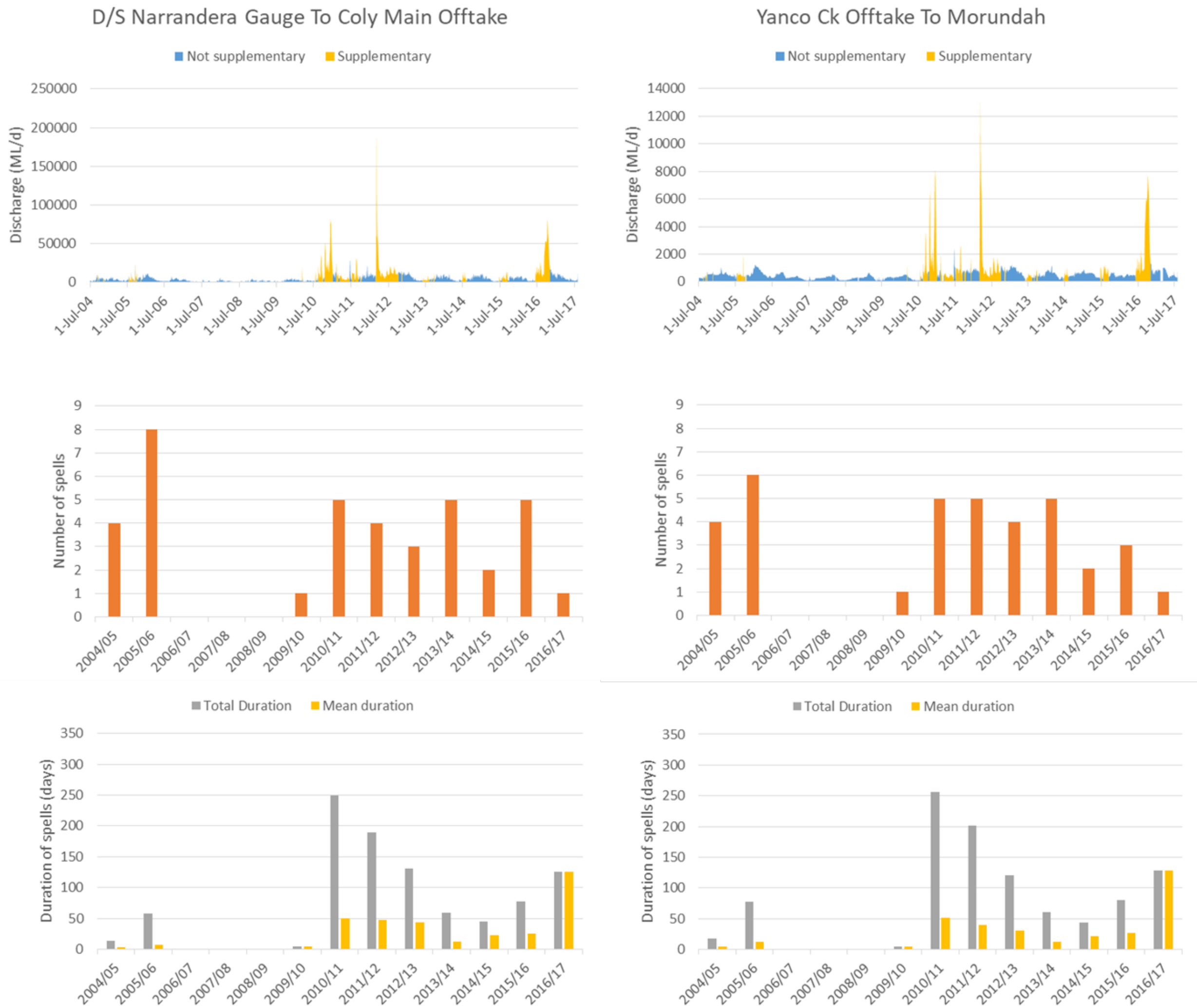


Figure 28. Frequency and duration of spells of announced supplementary flow at Murrumbidgee River DS Narranderra, and Upper Yanco Creek, for gauged historical flows 2004/05 – 2016/17.

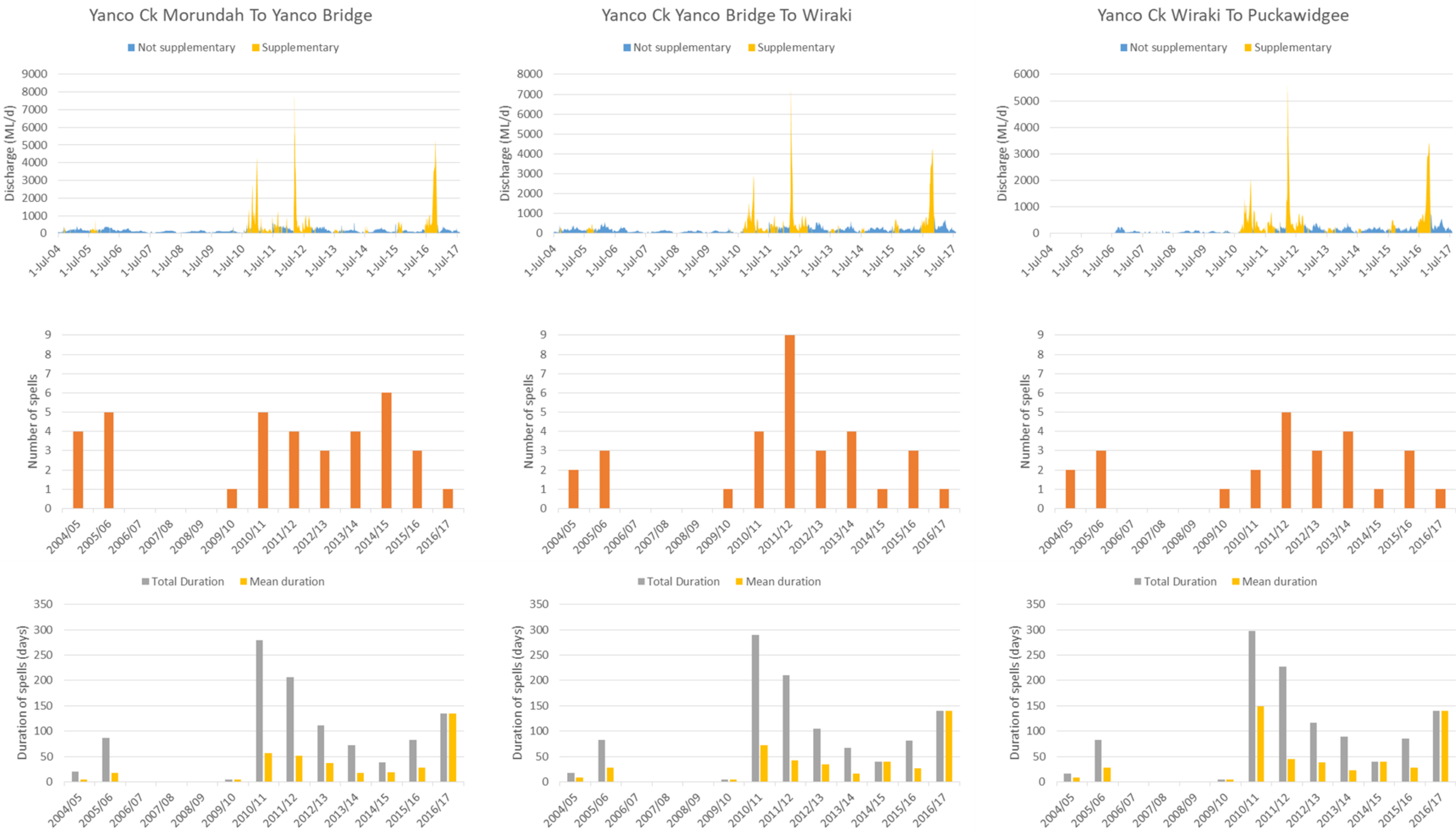


Figure 29. Frequency and duration of spells of announced supplementary flow at Mid-Yanco Creek, for gauged historical flows 2004/05 – 2016/17.

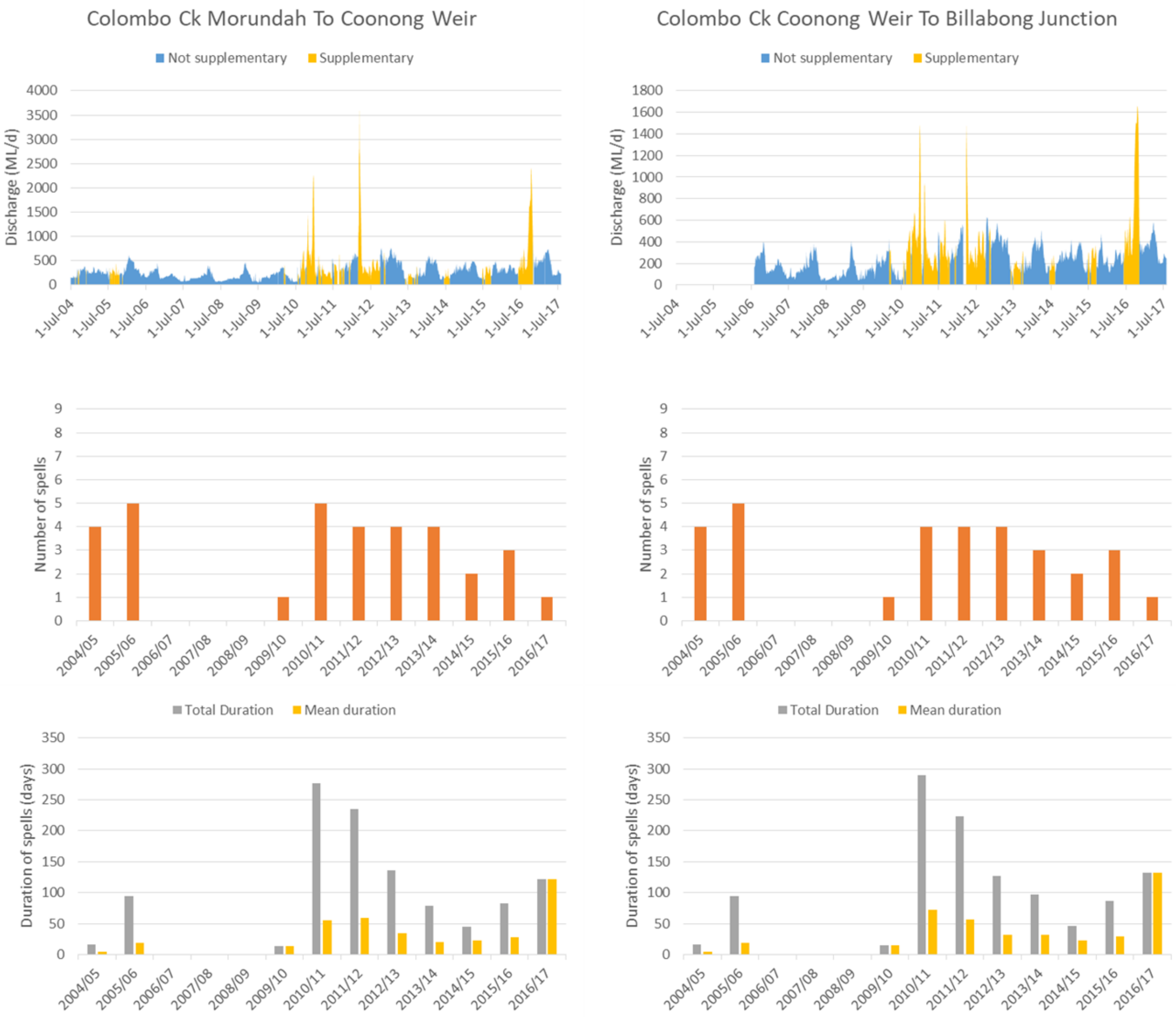


Figure 30. Frequency and duration of spells of announced supplementary flow at Colombo Creek, for gauged historical flows 2004/05 – 2016/17.

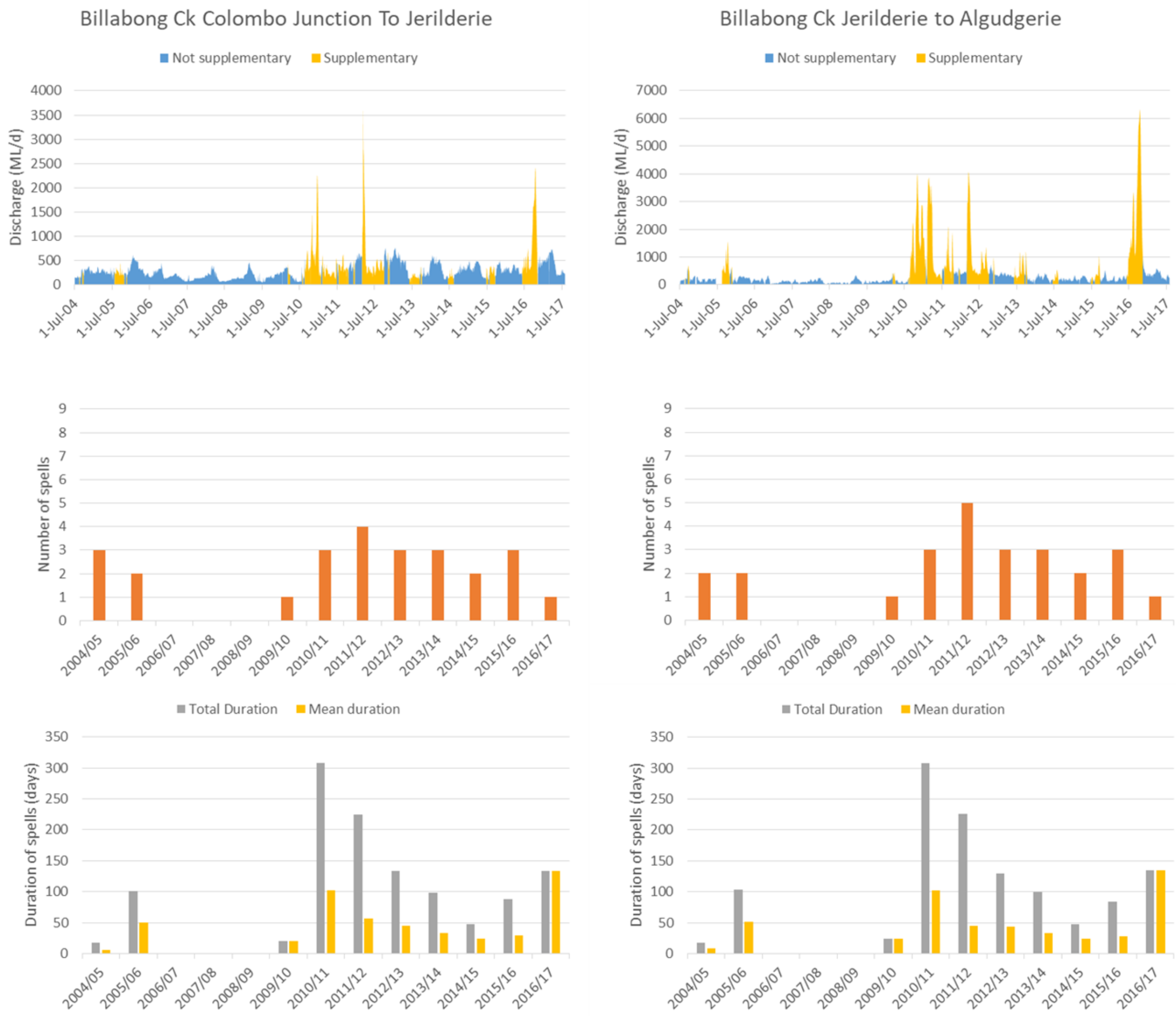


Figure 31. Frequency and duration of spells of announced supplementary flow at Mid-Billabong Creek, for gauged historical flows 2004/05 – 2016/17.

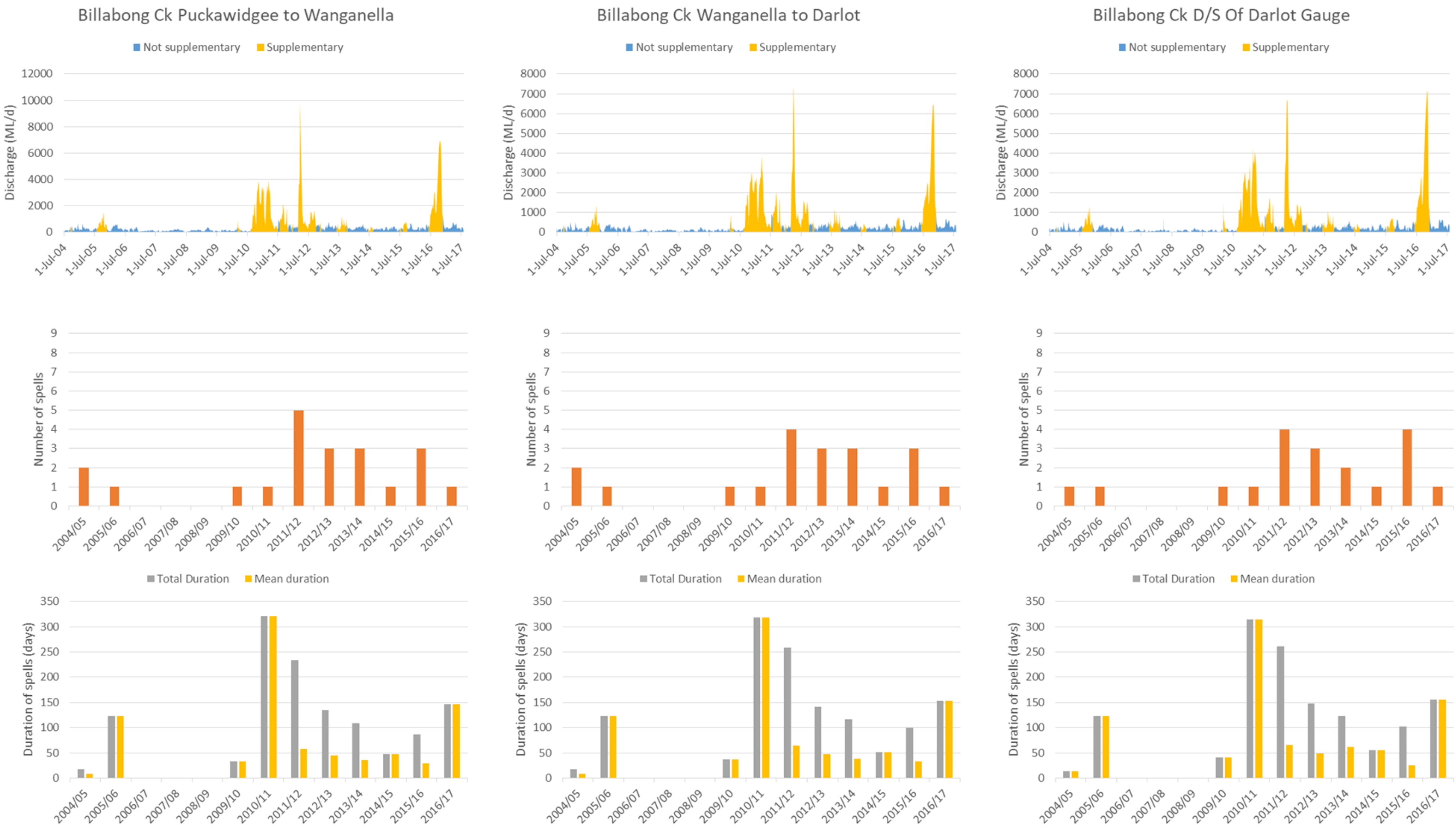


Figure 32. Frequency and duration of spells of announced supplementary flow at Lower Billabong Creek, for gauged historical flows 2004/05 – 2016/17.

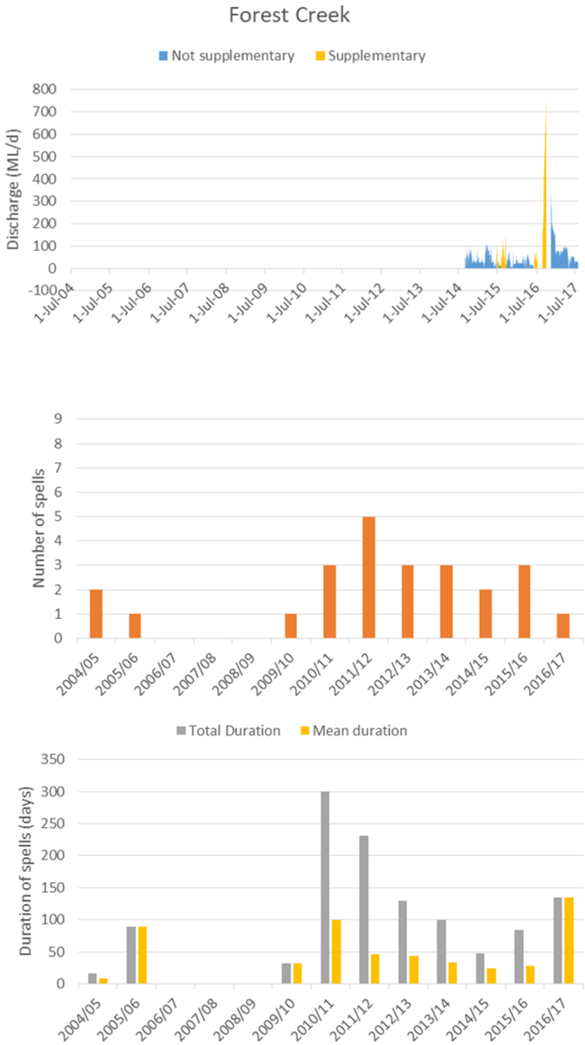


Figure 33. Frequency and duration of spells of announced supplementary flow at Forest Creek, for gauged historical flows 2004/05 – 2016/17.

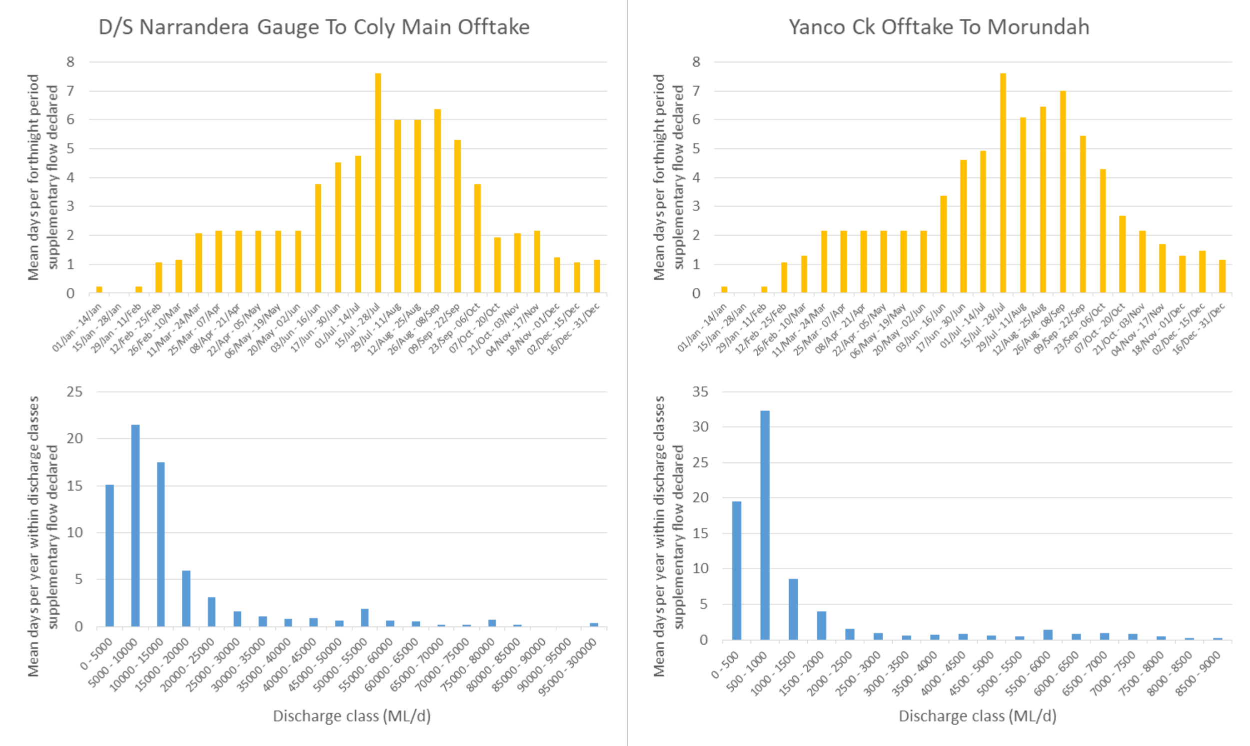


Figure 34. Distributions of timing and magnitude of spells of announced supplementary flow at Murrumbidgee River DS Narranderra, and Upper Yanco Creek, for gauged historical flows 2004/05 – 2016/17.

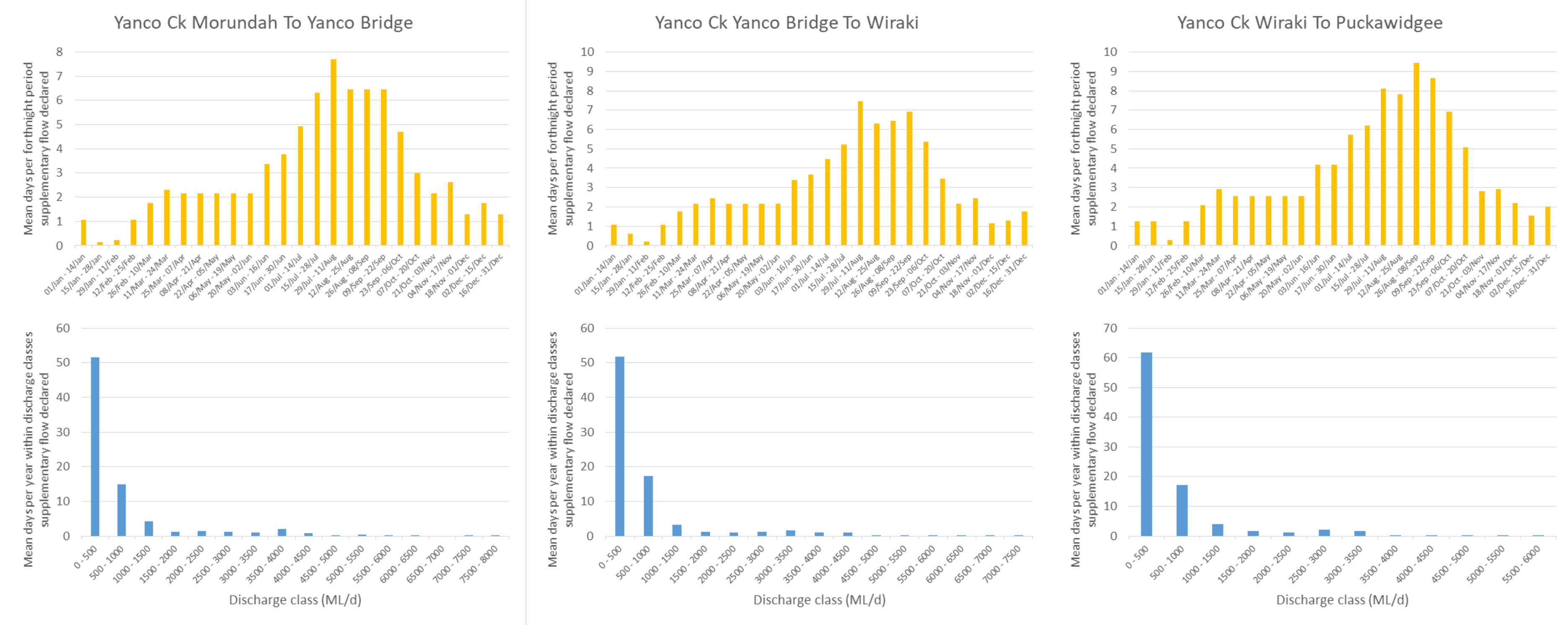


Figure 35. Distributions of timing and magnitude of spells of announced supplementary flow at Mid-Yanco Creek, for gauged historical flows 2004/05 – 2016/17.

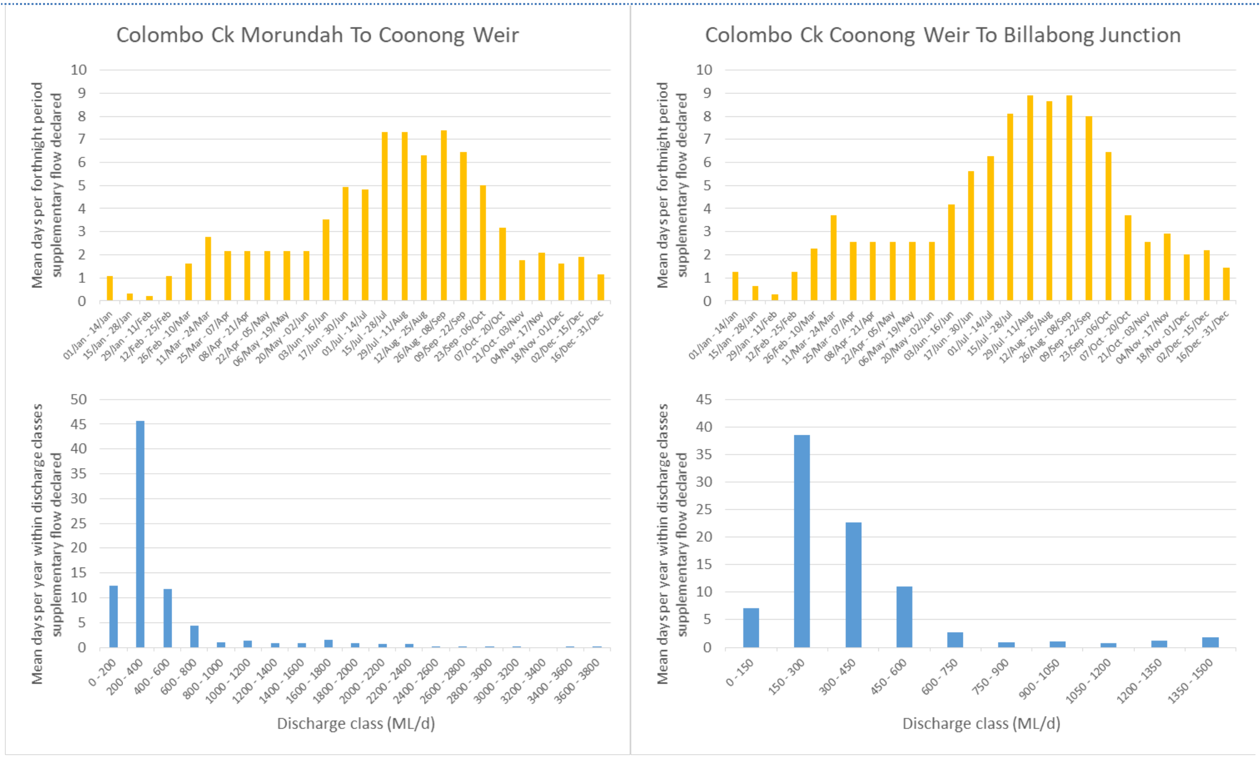


Figure 36. Distributions of timing and magnitude of spells of announced supplementary flow at Colombo Creek, for gauged historical flows 2004/05 – 2016/17.

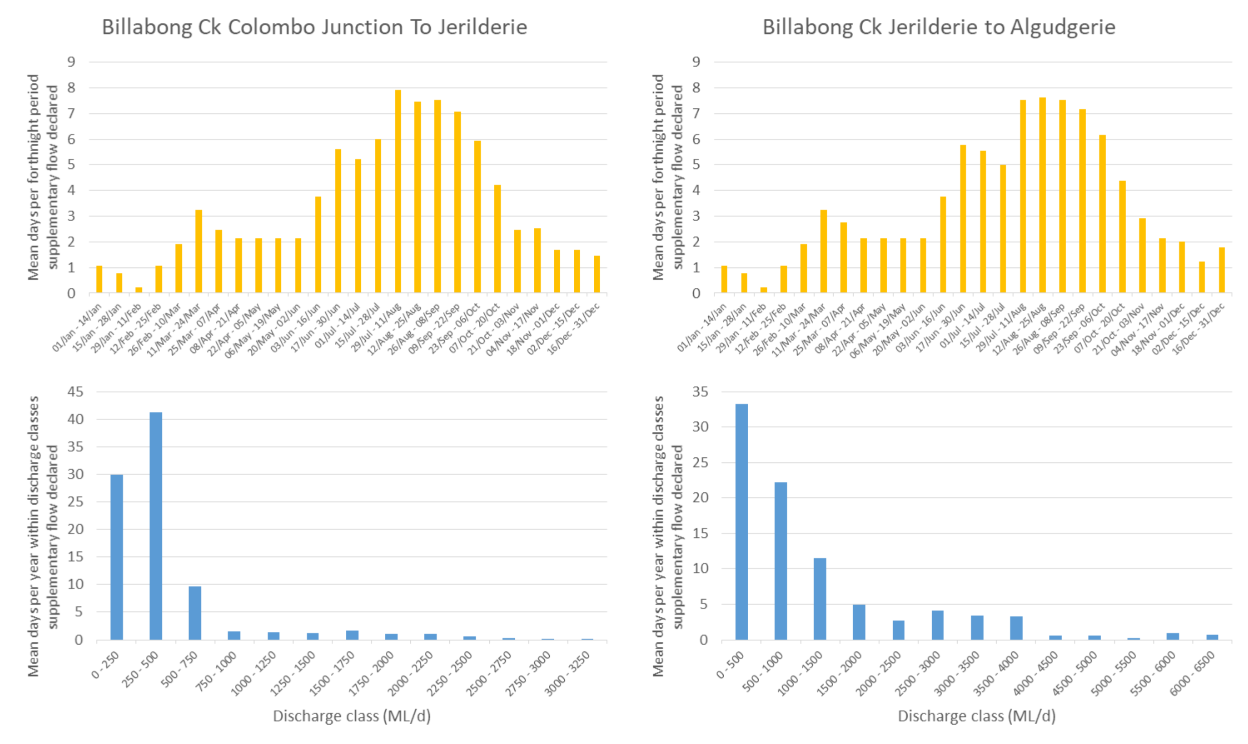


Figure 37. Distributions of timing and magnitude of spells of announced supplementary flow at Mid-Billabong Creek, for gauged historical flows 2004/05 – 2016/17.

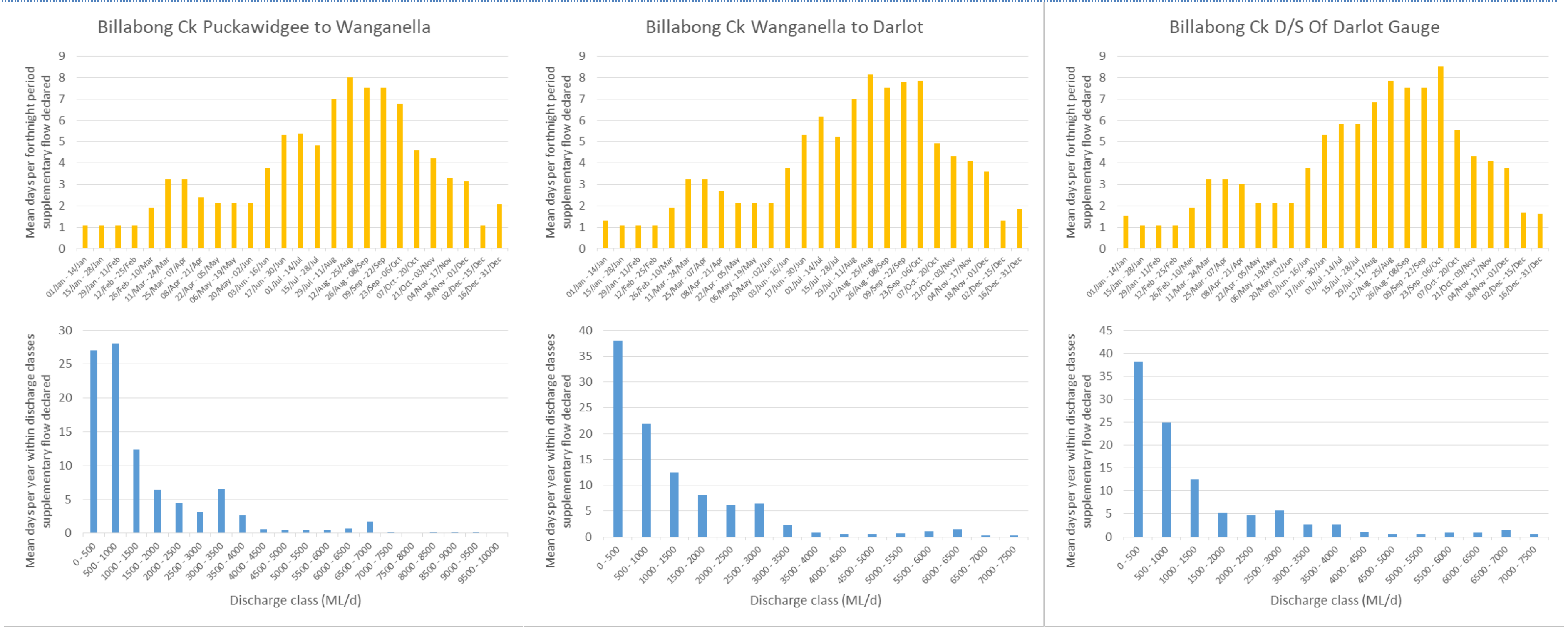


Figure 38. Distributions of timing and magnitude of spells of announced supplementary flow at Lower Billabong Creek, for gauged historical flows 2004/05 – 2016/17.

5 CHARACTERISTICS OF OVERBANK FLOWS

5.1 ANALYSIS

Overbank flows, or flows that are above channel capacity, are potentially important for watering floodplain wetlands. The frequency and duration of overbank flows could decrease when the proposed new Yanco Weir regulator becomes operational due to the greater range of flows that it is designed to control.

A hydrological analysis was undertaken to characterise the frequency and duration of overbank flows in the system under historical flow conditions, and also under modelled scenarios of Current WSP (with Water Sharing Plan rules applying) and Future SDLA (with new Yanco Weir and regulator in operation). The historical and the Current WSP series were similar, with the main differences being the longer length of the modelled series (1895 – 2015), and the modelled series representing application of recent flow management conditions throughout the entire record, while water demands and flow management policies would have varied through time in the historical records. The calibration of the Current WSP scenario was done some time ago, with the main objective being to correctly simulate the general flow pattern rather than focusing on precise simulation of particular flow events (Andrew Brown, DPI, Water, pers. comm., 16 March 2017). The Future SDLA series (1895 – 2009) is a post-Basin Plan benchmark scenario that was created recently to support a number of Murrumbidgee proposals, and it includes the environmental flows recommended by Alluvium (2013) (Andrew Brown, DPI, Water, pers. comm., 16 March 2017). The rules in the model reflect priorities that prevailed at the time of its development and the model does not necessarily accurately depict the future flow regime.

No attempt was made to determine the importance of overbank flows to specific wetlands. This would require a separate investigation of commence to flow thresholds and other aspects of floodplain hydraulics.

The methodology used to investigate this issue was spells analysis of daily flow series at key gauge sites using overbank levels given in Alluvium (2013) to set the flow thresholds. Water would begin to overtop the banks just above bankfull, but more widespread flows would require a minimum flow similar to what Alluvium (2013) defined as the overbank flow component. The statistics reported were total days per year of unregulated flow, mean duration of spells in each year, and frequency of spells in each year. The gauges, and corresponding thresholds, selected for analysis were:

- Mid-Yanco reach: Yanco Creek at Morundah (410015) and Yanco Creek at Yanco Bridge (410169) – overbank threshold 1,000 ML/d
- Mid-Billabong reach: Billabong Creek at Jerilderie (410016) – overbank threshold 3,000 ML/d upstream of Jerilderie and 1,600 ML/d downstream of Jerilderie
- Lower Billabong reach: Billabong Creek at Conargo/Puckawidgee (410017) and Billabong Creek at Darlot (410134) – overbank threshold 3,000 ML/d

The modelled flow series for Jerilderie were excluded from the analysis because of an apparent error in the data. The flows in these series were considerably lower than in the gauged flow record. No flow events exceeded 3,000 ML/d (overbank) in the 119 year long Current WSP series and there were only 24 such events in the Future SDLA series, all occurring before 1996. This compares with 61 events spread throughout the historical gauged series, even though this record was shorter. For this reach, for the modelled Current scenario from 1910 to 2009, Alluvium (2013, p. 73) reported 44 events exceeding 3,000 ML/d within the September to January period, so they must have used a different modelled data series than the one supplied for this project.

The results of overbank flow spells analysis were summarised as long-term frequency (percent of years with at least one spell) and mean annual duration (Table 7), and also plotted as time series (Figure 39, Figure 40, Figure 41, Figure 42 and Figure 43). The calculation of mean annual duration included only years with an overbank spell. Caution is required when comparing the results for historical series with those of the modelled scenarios, as the historical series were shorter.

Overall, the pattern of overbank flows was irregular in space and time. Overbank flows were more frequent in Mid-Yanco Creek reach than in Billabong Creek. The results describe broad patterns only, with the actual frequency and duration of overbank flows varying within reaches, according to local variations in flow event magnitudes and overbank thresholds. Overbank flows will not be eliminated from the creek system under the proposed Future SDLA conditions. The frequency of overbank flow events would increase from the Current WSP scenario to the Future SDLA scenario at three of four analysed gauges, with a small decrease at the other one. The duration of overbank flows was similar between these scenarios for the four analysed gauges (Table 7).

The SDLA modelling should be interpreted with caution. The modelling provides a general indication of the scope and effect of proposed river operations and does not represent the optimal or the only possible operational arrangement.

The peak and duration of some overbank flow events can be reduced by the rapid rate of pumping that can occur when supplementary flows have been declared. It has been suggested by some community members that flow peaks could be protected by prohibiting pumping during the first few days of an overbank event. There is currently no legal framework in place to coordinate or enforce such a strategy and it would have to be adopted on a voluntary basis. The proposal raises questions of equity among growers as those that depend on supplementary licences would suffer a greater imposition than those that can also access water under general licences.

Table 7. Summary of frequency and duration of spells of overbank flow events at Mid-Yanco, Mid-Billabong and Lower Billabong reaches, for gauged historical flows and Current and Future modelled flow scenarios.

Reach/Gauge	Threshold	Frequency (% of years)			Annual duration mean ±1σ (days)		
		Historical	Current WSP	Future SDLA	Historical	Current WSP	Future SDLA
Mid-Yanco							
Yanco Creek at Morundah	1,000 ML/d	65%	56%	69%	56 ±52	49 ±49	42 ±44
Yanco Creek at Yanco Bridge	1,000 ML/d	33%	76%	70%	27 ±23	58 ±59	43 ±46
Mid-Billabong							
Billabong Creek at Jerilderie (US)	3,000 ML/d	37%	-	-	40 ±42	-	-
Billabong Creek at Jerilderie (DS)	1,600 ML/d	55%	-	-	62 ±48	-	-
Lower Billabong							
Billabong Creek at Conargo/Puckawidgee	3,000 ML/d	42%	14%	27%	51 ±46	32 ±45	42 ±45
Billabong Creek at Darlot	3,000 ML/d	41%	14%	22%	47 ±36	31 ±47	34 ±46

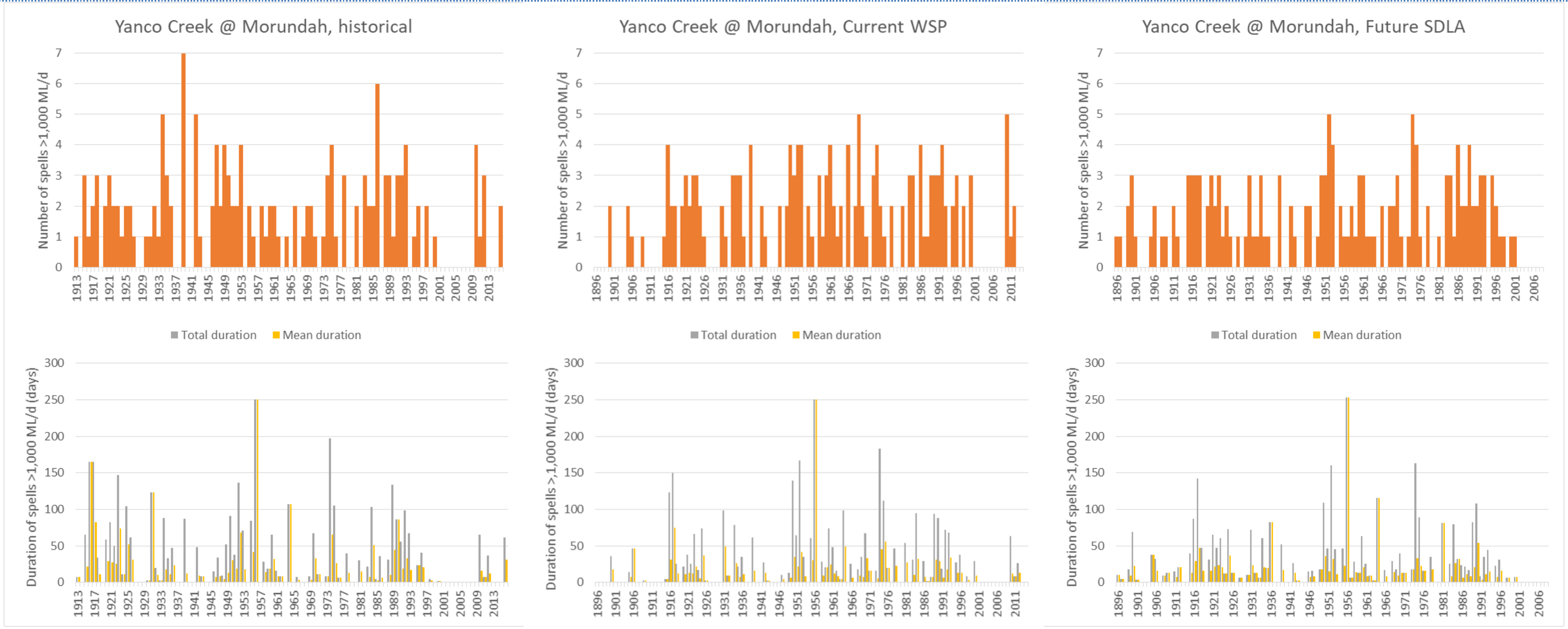


Figure 39. Frequency and duration of spells of overbank flow events at Mid-Yanco Creek, Morundah for gauged historical flows and Current and Future modelled flow scenarios.

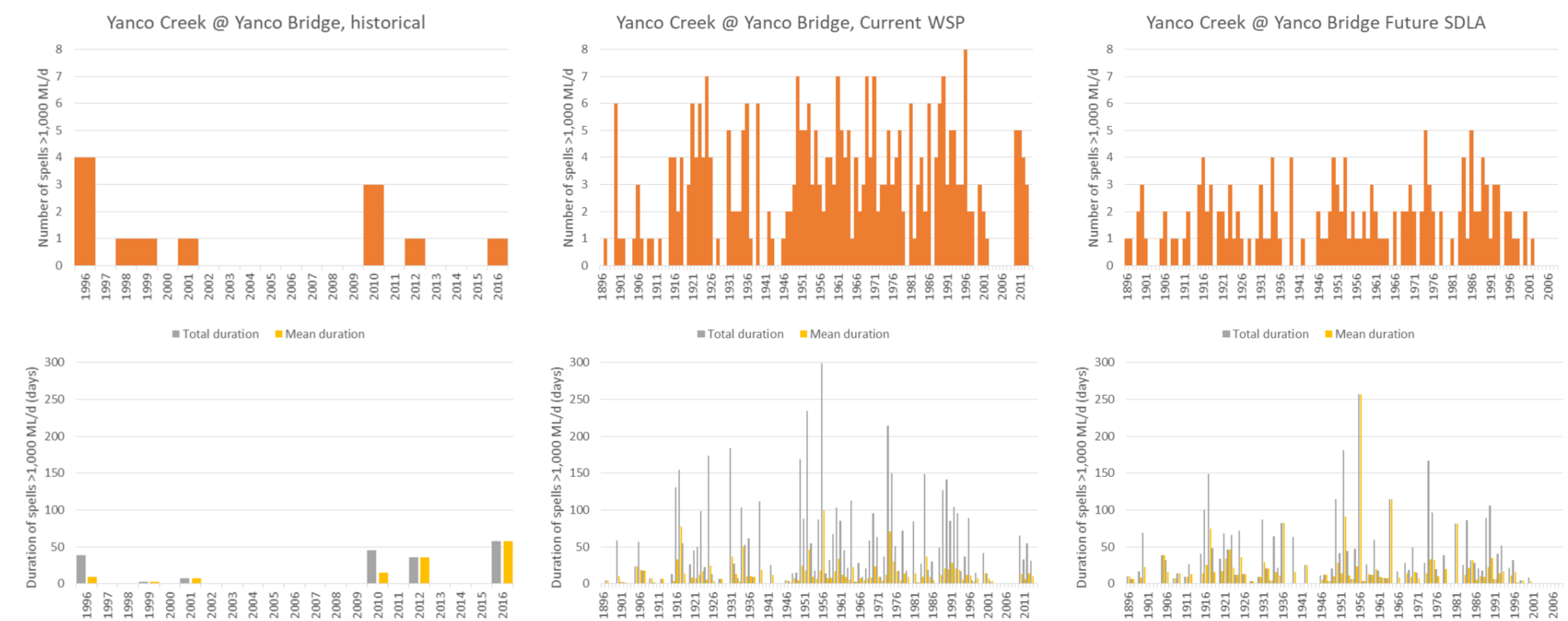


Figure 40. Frequency and duration of spells of overbank flow events at Mid-Yanco Creek, Yanco Bridge for gauged historical flows and Current and Future modelled flow scenarios.

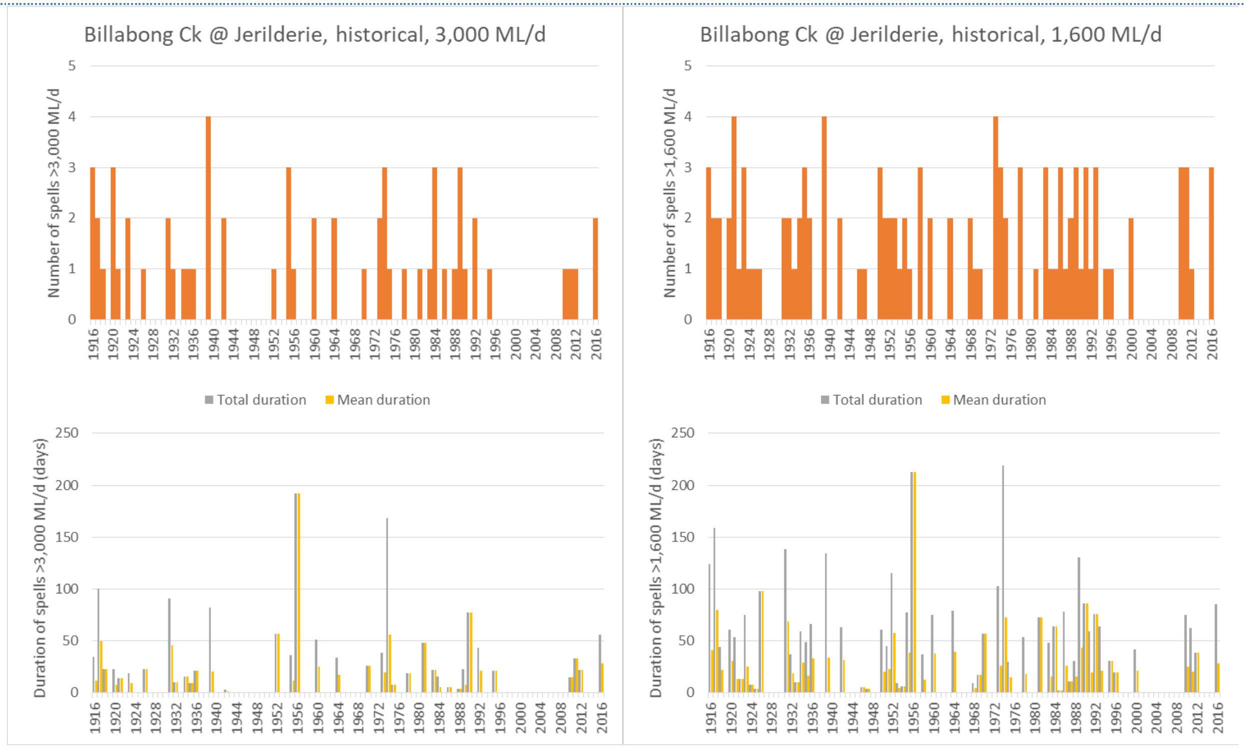


Figure 41. Frequency and duration of spells of overbank flow events at Mid-Billabong Creek, Jerilderie, for two flow thresholds, for gauged historical flows.

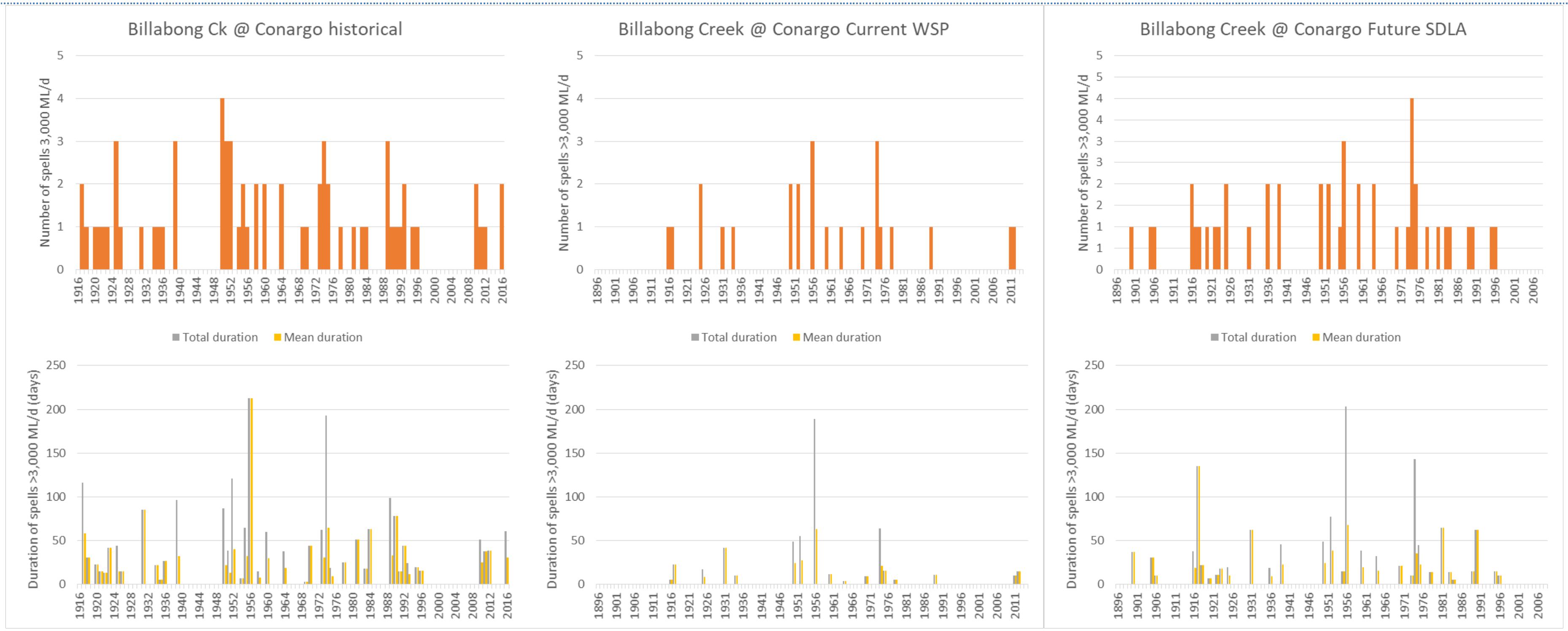


Figure 42. Frequency and duration of spells of overbank flow events at Lower Billabong Creek, Conargo/Puckawidgee for gauged historical flows and Current and Future modelled flow scenarios.

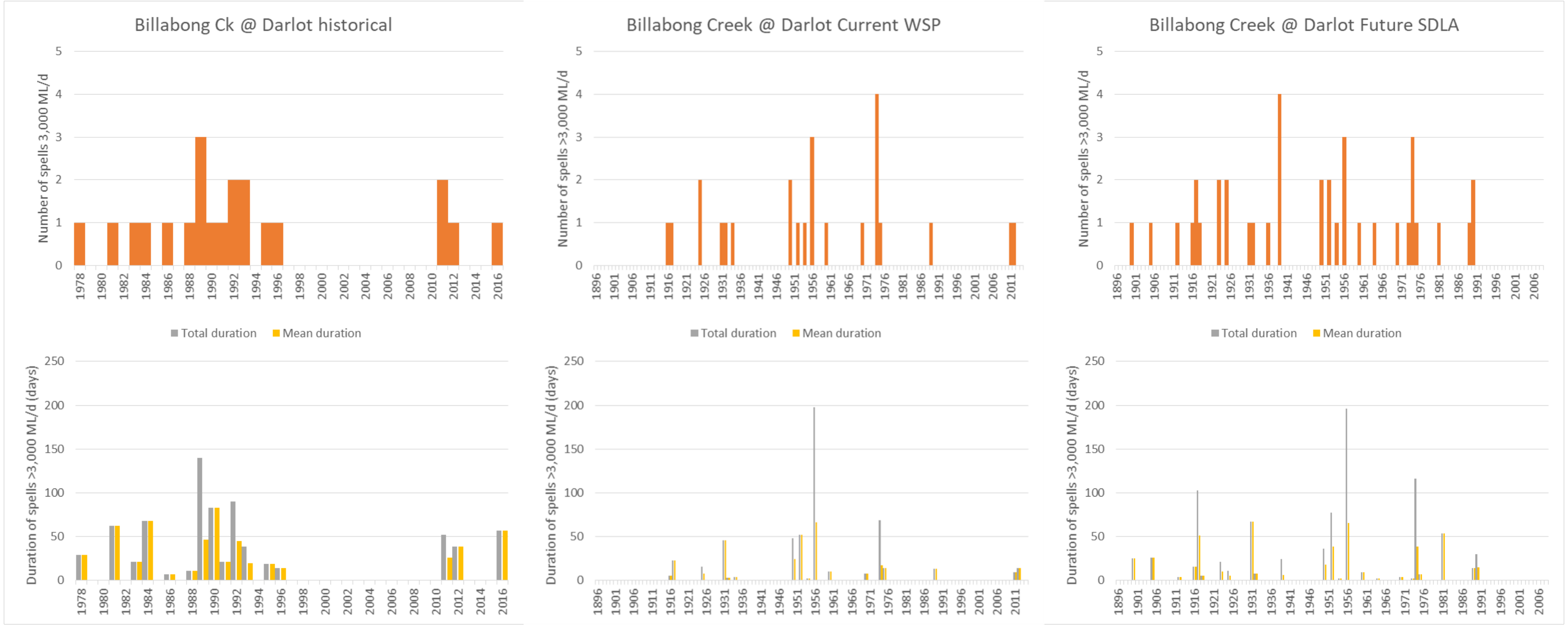


Figure 43. Frequency and duration of spells of overbank flow events at Lower Billabong Creek, Darlot for gauged historical flows and Current and Future modelled flow scenarios.

5.2 CONCLUSIONS

In summary, this investigation found the following.

- Overbank flows are important in contributing to the water requirements of floodplain wetlands.
- A hydrological analysis was undertaken to characterise the frequency and duration of overbank flows under historical flow conditions, under modelled scenarios of the Current WSP (Water Sharing Plan rules applying) and Future SDLA (with new Yanco Weir and regulator in operation).
- Overall the pattern of overbank flows was irregular in space and time. Overbank flows were more frequent in Mid-Yanco Creek than in Billabong Creek.
- Overbank flows will not be eliminated from the creek system under the proposed Future SDLA conditions. The frequency of overbank flow events would increase from the current WSP scenario to the Future SDLA scenario at three of the four analysed gauges with a small decrease at the other one. The duration of overbank flows was similar between the scenarios for the four analysed gauges.
- The model scenarios analysed in this investigation reflect the rules that prevailed at the time of its development. The model does not necessarily accurately depict the future flow regime. These results give an indication of the scope of water management rather than specific future conditions.
- The peak and duration of some overbank flows can be reduced by the rapid rate of pumping that can occur when supplementary flows have been declared. It has been suggested by some community members that flow peaks could be protected by prohibiting pumping during the first few days of an overbank event. There is currently no legal framework in place to coordinate or enforce such a strategy.

6 TREND IN END-OF-SYSTEM FLOWS

6.1 BACKGROUND

There is concern among stakeholders that end of system flows have declined over time. This concern is based primarily on direct observation of the creek and from interpretation of the impacts of water policy on flow. Relevant policies include measures to increase delivery efficiency (such as CARM) and the sale of irrigation licences out of the region, either to growers elsewhere or for environmental water reserves. The issue of low end of system flows was investigated by examining the pattern of flows over time for the historical gauged and modelled flow series at Darlot.

6.2 ANALYSIS

Trend in time series can be detected using a range of statistical techniques, depending on whether the expected trend is gradual or stepped. A step change is when the variable significantly increases or decreases at a point in time, called a change point. Daily discharge time series are usually highly variable and not open to trend analysis. It is more common to test for trend in seasonal or annual flow volumes. Trend in river discharge time series can be due to natural climatic variation, changed catchment land use affecting runoff rates, regulation and diversion of the flow, or often, a number of factors overlapping to varying degrees through time. Trend testing involves first establishing a hypothesis about the expected trend, ideally based on knowledge of how the drivers of trend have operated in the catchment or river. Lacking this knowledge, a hypothesis could be established on the basis of visual examination of the time series. In this case, if a significant trend or change point is found, this might help exploration of potential causes of hydrological changes.

Trend analysis was undertaken using TREND trend/change detection software (Chiew & Siriwardena, 2005). TREND has 12 statistical tests, based on the WMO/UNESCO Expert Workshop on Trend/Change Detection and on the CRC for Catchment Hydrology publication Hydrological Recipes (Grayson, Argent, Nathan, McMahon, & Mein, 1996). Here, the non-parametric Mann-Kendall test for trend and CUSUM test for step change were preferred to the parametric tests in order to avoid the requirement of normality in the distribution of the data. Statistical significance was tested using a two-sided tail test at $\alpha \leq 0.05$.

Visual examination of the time series of historical gauged daily flows at Darlot revealed variable flows until about 1997, followed by a decline until 2010, then a return to the previous pattern (Figure 44). The reasons for this are not clear, but the Millennium Drought, which in the River Murray began in 1997 and ended in 2009 (Chiew & Prosser, Water and Climate, 2011; Gippel, 2014), would be a candidate explanation.

Variation in the historical gauged flow series would reflect climate variability and the response of water demand and water management to that variability, plus flow management priorities and rules changing over time. The modelled Current WSP flow series and the Future SDLA series have constant flow management priorities and rules, so the variation would be due to climate variability and the response of water demand and water management to that variability.

Averaging the historical daily data annually and by season confirmed the general pattern apparent in the daily data (Figure 45), with all seasons showing a statistically significant declining trend in discharge with statistically significant change points ranging from 1996 to 2000 depending on the season (Table 8). The modelled Current WSP and Future SDLA series showed a similar pattern, but more subtle than that of the gauged data (Figure

45), such that decreasing trends were weaker or not significant in some seasons, and change points were weak or not significant (Table 8).

The greater variability of flows in the historical gauged series could be due to changing management and demand over time. The less severe reduction in flows in the late 2000s in the modelled data could be due to inclusion of Water Sharing Plan rules that came into effect in 2016, and environmental flow rules being included in the Future SDLA scenario. The removal of years and seasons with very high flows in the modelled series is difficult to explain for the Current WSP scenario. For the Future SDLA scenario it could be due to the capacity of the proposed new Yanco Weir and regulator to control a greater range of flows.

Data from the period beginning 2010 – 2011 suggested increasing flows in all seasons in the historical gauged and Current WSP series (the Future SDLA series ended in 2009), which corresponds with the end of the Millennium Drought. However, trend analysis of the annual series from 1997 to 2016 (gauged) and 1997 to 2015 (Current WSP) failed to detect significant trend or change point. This result reflects the high variability of the data and short period of post-drought record.

Annual flow data from the post drought period from 2010 onwards were compared with pre-1997 data before the onset of the drought. The medians were compared using the rank sum test and the means were compared using Student's t test. For both the gauged historical and the modelled Current WSP series, the post drought period was not significantly different to the pre-drought period.

The main conclusions to be drawn from this analysis are that end of system flows were significantly reduced in all seasons during the Millennium Drought, but after the drought broke in 2010-2011, flows have since returned to a pattern similar to that which prevailed prior to the drought.

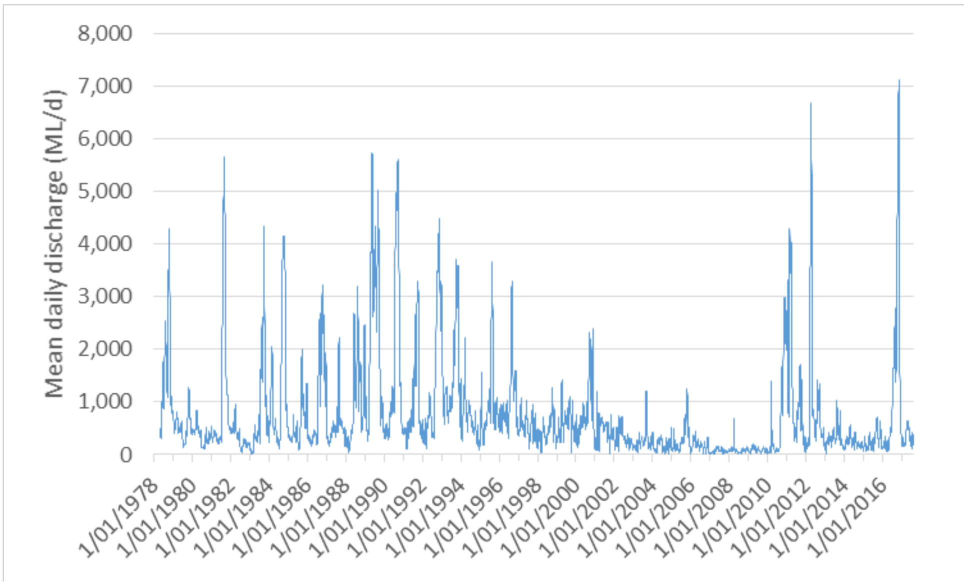


Figure 44. Historical gauged daily flow series from Billabong Creek @ Darlot gauge (410134), from 1978 to present.

Figure 45. Historical gauged (1978 – 2016), modelled Current WSP (1978 – 2015, except spring) and modelled Future SDLA (1978 – 2009, except spring) annual and seasonal flow series for Billabong Creek @ Darlot gauge (410134).

Table 8. Results of trend analysis for annual and seasonal flow series from Billabong Creek @ Darlot.

Series	Period	Mann-Kendall		CUSUM	
		Trend	Sign. (α)	Change point	Sign. (α)
Historical gauged 1979-2016	Annual	Decreasing	0.01	1996	0.01
	Summer	Decreasing	0.01	1997	0.01
	Autumn	Decreasing	0.05	2001	0.01
	Winter	Decreasing	0.05	2000	0.05
	Spring	Decreasing	0.01	2000	0.05
Modelled Current WSP 1979-2015	Annual	Decreasing	0.05	None	-
	Summer	Decreasing	0.01	None	-
	Autumn	None	-	None	-
	Winter	Decreasing	0.05	None	-
	Spring	Decreasing	0.05	None	-
Modelled Future SDLA 1979-2009	Annual	Decreasing	0.01	1996	0.01
	Summer	None	-	None	-
	Autumn	Decreasing	0.01	2000	0.05
	Winter	Decreasing	0.01	2000	0.05
	Spring	Decreasing	0.05	None	-

6.3 CONCLUSIONS

In summary, this investigation found the following.

- There is concern among stakeholders that end of system flows have declined over time.
- End of system flows were significantly reduced in all seasons during the Millenium Drought.
- After the drought broke in 2010-2011, flows have returned to a similar pattern to that which prevailed prior to the drought.

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