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Assessment of environmental water requirements for the proposed Basin Plan:

Lower Goulburn River (in-channel flows)

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Goulburn-Broken Region

Assessment of Lower Goulburn River (in-channel flows) environmental water requirements

1. Introduction

The Water Act 2007 (Cwlth) established the Murray–Darling Basin Authority (MDBA) and tasked it with the preparation of a Basin Plan to provide for the integrated management of the Basin's water resources. One of the key requirements of the Basin Plan is to establish environmentally sustainable limits on the quantities of surface water that may be taken for consumptive use, termed Sustainable Diversion Limits (SDLs). SDLs are the maximum long-term annual average volumes of water that can be taken from the Basin and they must represent an Environmentally Sustainable Level of Take (ESLT).

The method used to determine the ESLT is described in detail within *'The proposed "environmentally sustainable level of take" for surface water of the Murray-Darling Basin: Method and Outcomes,'* (MDBA 2011). A summary of the main steps undertaken to determine the ESLT is presented in Figure 1. The assessment of environmental water requirements including specification of site-specific flow indicators at a subset of hydrologic indicator sites (Step 3 of the overall ESLT method) is the focus of this document.

The work described herein is the MDBA's current understanding of the environmental water requirements of the in-channel environments of the Lower Goulburn River. It is not expected that the environmental water requirements assessments will remain static, rather it is intended that they will evolve over time in response to new knowledge or implementation of environmental watering actions. Within this context, feedback is sought on the material presented within this document whether that be as part of the formal draft Basin Plan consultation phase or during the environmental watering implementation phase within the framework of the Environmental Watering Plan.

1.1. Method to determine site-specific flow indicators

Assessment of environmental water requirements for different elements of the flow regime using the hydrologic indicator site approach is one of the key lines of evidence that has informed the proposed SDLs. Effort focussed on regions and parts of the flow regime with greatest sensitivity to the scale of reduction in diversions necessary to achieve environmental objectives, an ESLT and a healthy working Basin.

Within the overall framework of the ESLT method (Figure 1) the MDBA used an iterative process to assess environmental water requirements and develop site-specific flow indicators.

The hydrologic indicator site approach uses detailed eco-hydrological assessment of environmental water requirements for a subset of the key environmental assets and key ecosystem functions across the Basin. Effort focused on high flow (freshes, bankfull flows and overbank flows) requirements reflecting the prioritisation of effort on parts of the flow regime that are most sensitive to the determination of the ESLT and SDLs. The Lower Goulburn River is one of the key environmental assets where a detailed assessment of environmental water requirements was undertaken.

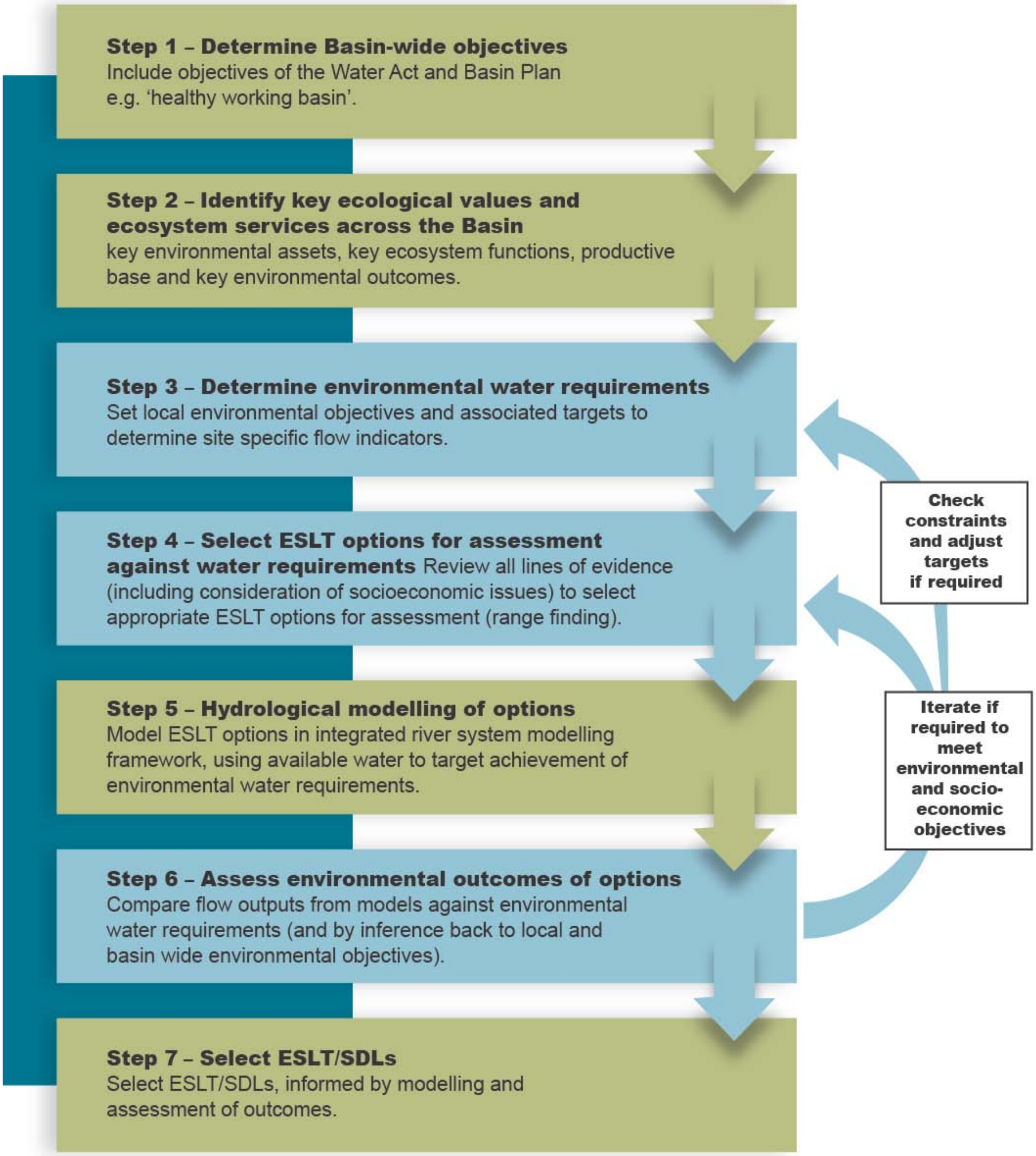

Figure 1 Outline of method used to determine an Environmentally Sustainable Level of Take (Source: MDBA 2011).

Detailed environmental water requirement assessments lead to the specification of site-specific flow indicators to achieve site-specific ecological targets. Flow indicators were expressed at a hydrologic indicator site or sites. Environmental water requirements specified at hydrologic indicator sites are intended to represent the broader environmental flow needs of river valleys or reaches and thus the needs of a broader suite of ecological assets and functions.

This report provides a description of the detailed eco-hydrological assessment of environmental water requirements for the in-channel environments of the Lower Goulburn River including information supporting the development of site-specific flow indicators for the site (with reference to flows gauged on the Goulburn River at Shepparton). More information on how the site-specific flow indicators for the site were used within the Basin-wide modelling process to inform the ESLT (i.e. Step 5 and 6 in Figure 1) can be found in the report *'Hydrologic modelling to inform the proposed Basin Plan: Methods and results'* (MDBA 2012).

A description of the detailed eco-hydrological assessments of environmental water requirements for other indicator sites, including overbank flow requirements of the Lower Goulburn River Floodplain, are described in other documents in the series *'Assessment of environmental water requirements for the proposed Basin Plan'*.

1.2. Scope and purpose for setting site-specific flow indicators

The MDBA's assessment of environmental water requirements and associated site-specific flow indicators at hydrologic indicator sites has been used to inform the development of SDLs. This enables the MDBA to estimate the amount of water that will be required by the environment over the long-term to achieve a healthy working Basin through the use of hydrological models. Accordingly, site-specific flow indicators are not intended to stipulate future use of environmental water. MDBA expects that the body of work undertaken to establish these site-specific flow indicators will provide valuable input to environmental watering but this watering will be a flexible and adaptive process guided by the framework of the Environmental Watering Plan and natural eco-hydrological cues. It will be up to the managers of environmental water, such as the Commonwealth Environmental Water Holder, State Government agencies, and local communities to decide how best to use the available environmental water during any one year to achieve environmental outcomes.

2. Location and extent

The Goulburn River is the major river in the Goulburn-Broken region and the largest Victorian tributary of the River Murray (Figure 2). It rises about 50 km south of Mansfield and flows in a north-westerly direction from the Great Dividing Range to the River Murray near Echuca. The Broken River, the secondary river in the region, forms about 25 km east of Mansfield and flows to the north through Benalla and then west to enter the Goulburn River near Shepparton. Broken Creek is a distributary of the Broken River, leaving the Broken River downstream of Benalla and joining the River Murray just upstream of Barmah. Spatial data used in Figure 2 are listed in Appendix A.

For the purposes of this report, the Lower Goulburn River extends from the Goulburn Weir near Nagambie to the River Murray junction. This corresponds to Reach 4 and 5 of the environmental flow studies which have been completed (Cottingham et al. 2003b; Cottingham et al. 2007; Victorian Department of Sustainability and Environment 2011) and management unit L1 of the Regional River Health Strategy (GBCMA 2005). The river channel below Lake Nagambie is relatively uniform, being deeply incised with clay bed and banks with the main variation in the channel being associated with the presence of benches and small point bars (Cottingham et al. 2003a). The Goulburn River channel downstream of Loch Garry is characterised by a regular and featureless parabolic cross-section with the major source of physical diversity provided by large wood (Cottingham et al. 2007).

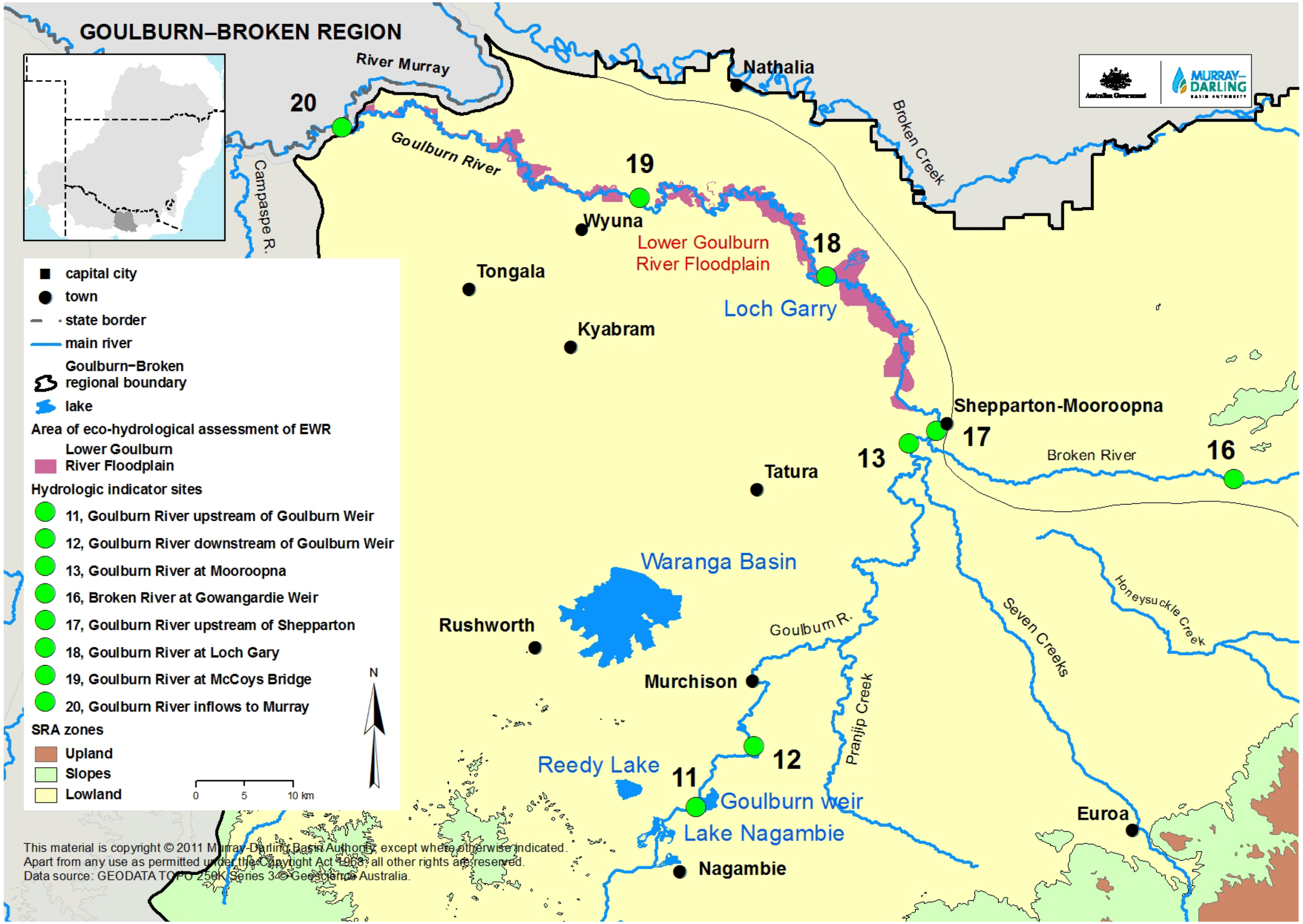

Figure 2 Location and extent of Lower Goulburn River key environmental asset. In-channel flow indicators are specified at Shepparton on the Goulburn River.

3. Ecological values

The 195 km stretch of the Goulburn River from Goulburn Weir to the confluence with the River Murray near Echuca is rated highly for its environmental assets and values (GBCMA 2005). Environmental values include Heritage River listing, presence of significant (e.g. EPBC Act listed) fauna and flora, presence of wetlands of national significance and rare wetland types, presence of self-sustaining native fish communities, native fish migration and riparian width and longitudinal connectivity.

The Goulburn River is listed as a Heritage River downstream from the Eildon Reservoir to the confluence with the Murray River in recognition of a number of different environmental and social values such as river red gum open forest/woodland, and yellow box and grey box woodland/open forest communities, significant habitat for vulnerable or threatened wildlife and native fish diversity and Murray cod habitat (GBCMA 2005)

At a local scale, a detailed assessment of the fish communities of the Lower Goulburn River from Goulburn Weir downstream to the River Murray junction has been undertaken for the period 2003-2009 (Koster et al. 2009). Based on data collected it was reported that the Lower Goulburn River has a diverse native fish population, which includes several species of recreational angling value and/or conservation significance.

At a regional scale, the ecosystem health of the Goulburn River was assessed as part of the Sustainable Rivers Audit (SRA) for the period 2004-2007. The SRA health assessment is comprised of three individual condition indices for fish, macro-invertebrates and hydrology which are combined to provide an overall indicator of river health (Davies et al. 2008). This assessment indicated that the condition of native fish populations within the Goulburn River is degraded with a fish condition indice of “extremely poor” at the valley scale with fish communities being most degraded in the upland zone and improving in the downstream slopes and lowland zones albeit still assessed as extremely poor and very poor condition (Davies et al. 2008). Across the survey area only 42% of individuals and 37% of fish biomass were native and only 56% of native species predicted under reference conditions were caught during sampling. The average biomass of native species in the Lowland Zone was substantially higher than in other zones and resulted from catches of Murray cod and Golden perch (Davies et al. 2008).

Several factors related to water management currently impact upon native fish populations in the Goulburn River. Among these is the impact of cold water releases from Lake Eildon (Cottingham et al. 2003a; Cottingham et al. 2007). Native flora and fauna in the upper reaches of the Goulburn River between Lake Eildon and Goulburn Weir are affected by cold water releases from Lake Eildon with subsequent strong temperature depression under the current flow management regime (Cottingham et al. 2003a; Cottingham et al. 2007). Species historically present included Murray cod, Trout cod and Macquarie perch - these species have not been recorded in the reach below Lake Eildon for more than 30 years (Cottingham et al. 2003a). In the downstream region between Goulburn Weir and the Murray River, habitat conditions become more favourable for native species and the impact of cold water releases is minimal (Cottingham et al. 2003a; Cottingham et al. 2007). Accordingly, the increase in fish diversity in the Lower Goulburn River described by Cottingham et al.

(2003a) and Davies et al. (2008) is one of the key reasons this report focuses on in-channel environments downstream of Goulburn Weir.

The ecological values of the Lower Goulburn River are reflected in the MDBA's assessment against the criteria used to identify key environmental assets within the Basin. The MDBA established five criteria to identify assets based on international agreements and broad alignment with the National Framework and Guidance for Describing the Ecological Character of Australian Ramsar Wetlands (Department of the Environment, Water, Heritage and the Arts 2008) and the draft criteria for identifying High Conservation Value Aquatic Ecosystems (SKM 2007).

Based on the ecological values identified for the Goulburn River, the system meets three of the five key environmental asset criteria (Table 1).

Table 1 Assessment of the Lower Goulburn River against MDBA key environmental assets criteria

Criterion	Ecological values that support the criterion
3. The water-dependent ecosystem provides vital habitat	Unlike other rivers across northern Victoria (e.g. Campaspe, Loddon), there was sufficient water to maintain continuous baseflow along the Lower Goulburn River during the Millennium Drought and thus sustain fish and macro-invertebrate populations during a time of ecological stress (Cottingham et al. 2010). The Lower Goulburn River supports breeding populations of a number of conservationally significant species including Murray cod and Trout cod (Koster et al. 2009). There is evidence that Murray cod spawn regularly in the Lower Goulburn River (Koster et al. 2009). In addition, spawning of the recreationally significant Golden perch in the Lower Goulburn River has also been observed (Koster pers. comm. 2011).
4. Water-dependent ecosystems that support Commonwealth, State or Territory listed threatened species or communities	The fish community of the Lower Goulburn River is significant in terms of its conservation value (Cottingham et al. 2003a; Koster et al. 2009). Seven native fish species have been recorded which have conservation status under state or federal legislation (Cottingham et al. 2003a; Davies et al. 2008; Koster et al. 2009): • Trout cod which are listed as endangered nationally under the Environmental Protection and Biodiversity Conservation (EPBC) Act 1999 and critically endangered under the Victorian Flora and Fauna Guarantee (FFG) Act 1988; • Macquarie perch which are listed as endangered nationally under the EPBC Act 1999 and endangered under the Victorian FFG Act 1988; • Murray cod which is listed as vulnerable nationally under the EPBC Act 1999 and endangered under the Victorian FFG Act 1988; • Silver perch which are listed as critically endangered under the Victorian FFG Act 1988; • Freshwater Catfish which are listed as vulnerable under the Victorian FFG Act 1988; • Unspecked hardyhead which are listed under the Victorian FFG Act 1988; and • Murray-Darling rainbow fish which are listed under the Victorian FFG Act 1988.
5. The water-dependent ecosystem supports, or with environmental watering is capable of supporting, significant biodiversity	The Lower Goulburn River has a diverse native fish population with a total of 16 native fish species recorded, which includes several species of recreational angling value and/or conservation significance (Cottingham et al. 2003a; Davies et al. 2008; Koster et al. 2009). Murray cod are the most abundant large-bodied native species in the Lower Goulburn River (Davies et al. 2008; Koster et al. 2009). Streams across the Goulburn catchment supports a rich and diverse macroinvertebrate fauna (Cottingham et al. 2007). The nature of the river changes downstream of Goulburn Weir, and as a consequence the macroinvertebrate community that one might expect to find there also changes (Cottingham et al. 2007).

4. Hydrology

The hydrology of the Lower Goulburn River Floodplain is driven by flows in the Goulburn River, via Goulburn Weir diversions as well as a number of effluent channels (CSIRO 2008). Compared to the adjacent River Murray, flows are much 'flashier', with large flows often persisting for only a few days or weeks, compared to weeks or months in adjacent reaches of the River Murray.

River regulation has resulted in significant alteration to the natural flow regime of the Goulburn River due to the operation of Lake Eildon and Goulburn Weir for irrigation supply (Davies et al. 2008). In order to describe the change in flows in the Lower Goulburn River due to the influence of this development, the MDBA analysed modelled flow data at McCoys Bridge for the period 1895 – 2009. Figure 3 illustrates how average monthly flows have changed between without-development and baseline flow regimes with the impact of development being to reduce average daily flows throughout the year, with a more pronounced effect during the high flow period from approximately June to November resulting in a less defined seasonal peak. These changes to the hydrology are representative of the Lower Goulburn River where diversions at Goulburn Weir mean that flows are significantly reduced compared to other reaches of the river however the seasonal pattern of flow is unchanged (Chee et al. 2009).

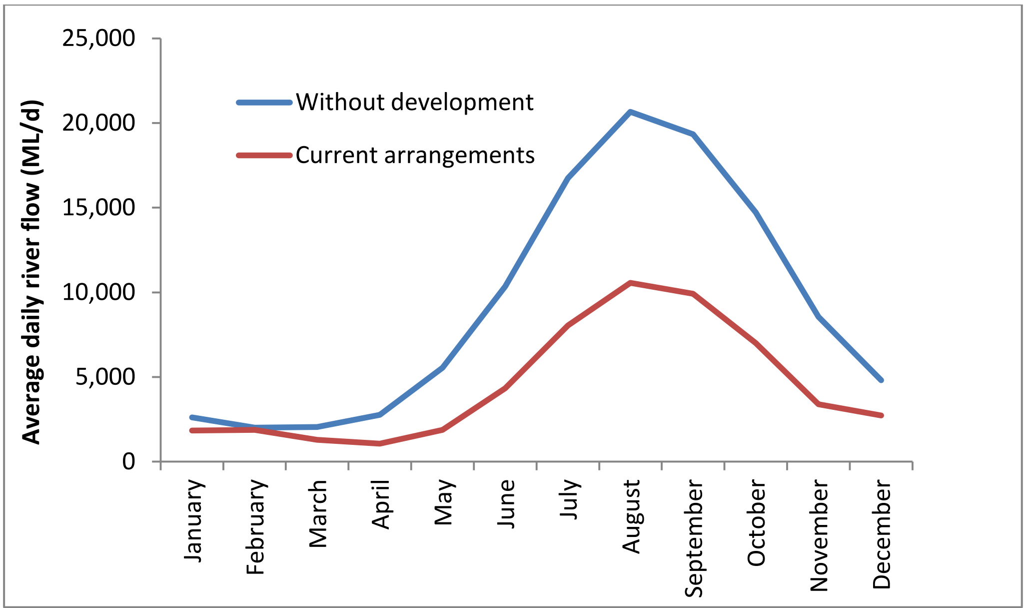

Figure 3 Modelled monthly flows for Goulburn River at McCoys Bridge under without-development and baseline (current arrangement) conditions for the period 1895-2009

Further analysis of modelled flow data for the period 1895 – 2009 was undertaken to describe changes to hydrology for in-stream events, specifically 'freshes'. Fresh events are flow pulses exceeding the underlying base flow and, depending on the river system, last anywhere between a few days and a few weeks. Fresh events are contained within the confines of the channel –they are not large enough to provide overbank flows.

For the analysis conducted, freshes were defined as flow events between baseflows (lower threshold) and bankfull flows (upper threshold). The lower (base flow) threshold is highly seasonal and for the purposes of MDBA fresh event analysis was defined using a hydrologic analysis based on high and low flow seasons (see MDBA 2012 for a description of the method used to define baseflows). The upper, bankfull threshold is based on Water Technology (2010), which identify that reaches of the Lower Goulburn River are characterised by flows of 20,000 ML/d generally confined to the river channel with limited floodplain inundation and anabranch flow adjacent to Loch Garry. Similarly, Cottingham et al. (2003b) and Cottingham et al. (2010) report that at 20,000 ML/d water starts leaving the main channel and flows into anabranches and wetlands such as the Wakiti Creek system

Table 2 presents the results of analysis of low season and high season freshes under without-development and baseline conditions for McCoys Bridge. In essence the tables present the characteristics of flows that exceed the baseflow and are less than the bankfull flow (this being the definition of a fresh). Flows that exceed the upper, bankfull threshold are not included in this assessment.

This analysis indicates that in-channel freshes within the Lower Goulburn River have been impacted to varying degrees by water resource development (Table 2). Both the 'number of events' and 'mean fresh volume' have declined, while the 'mean fresh duration' has been reduced for the high flow season (June to October) but is slightly increased compared to without-development conditions for the low flow season (December to April).

Table 2 Analysis of in-channel 'freshes' for low season and high season at McCoys Bridge modelled under without-development and baseline conditions for the period 1895-2009

Scenario	Baseflow (ML/day) (lower threshold)	Bankfull (ML/day) (upper threshold)	Number of events	Mean Fresh Duration (Days)	Mean Fresh Volume (ML)
High season: June – October					
Without-development	4816	20,000	489	8.84	78416
Baseline	4816	20,000	391	6.23	52863
Low season: December – April					
Without-development	1765	20,000	659	10.41	37967
Baseline	1765	20,000	405	10.95	31762

Note: * freshes are defined as a flow event that exceeds the baseflow and is less than the bankfull flow. This table shows the number of these events (freshes) that occurred in the model time period (114 years), as well as the mean duration and mean volume of these events.

The flow duration curve for Goulburn River at McCoys Bridge further illustrates that in-channel freshes in the Lower Goulburn River, as illustrated by the range within the green box, is one of the most significantly modified parts of the flow regime from without-development conditions (Figure 4). This is supported by Cottingham et al. (2003b) and Cottingham et al. (2010) who report that freshes are one of the components of the flow regime that has been affected by diversions. Further analysis of ecologically relevant in-channel flows is described below.

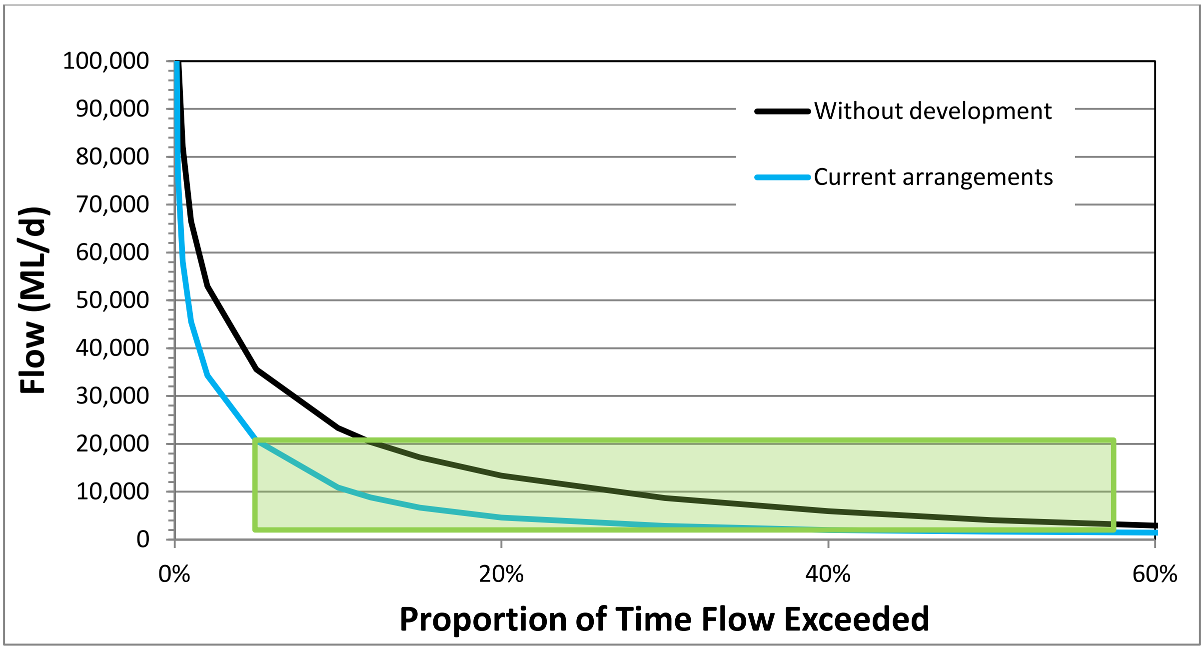

Figure 4 Flow duration curve for the Goulburn River at McCoys Bridge based on modelled data for the period 1895-2009 under without-development and baseline (current arrangement) conditions. The green box is used to highlight flows categorised as in-channel freshes using lower and upper thresholds adopted for analysis of modelled flow data.

5. Determining the site-specific flow indicators for the Lower Goulburn River (in-channel flows)

5.1. Setting site-specific ecological targets

The objective setting framework used to determine the ESLT is outlined in the report '*The proposed "environmentally sustainable level of take" for surface water of the Murray-Darling Basin: Method and Outcomes' (MDBA 2011).* In summary, the MDBA developed a set of Basin-wide environmental objectives and ecological targets, which were then applied at a finer scale to develop site-specific objectives for individual key environmental assets. Using these site-specific objectives, ecological targets that relate specifically to in-channel environments of the Lower Goulburn River were developed (Table 3). Information underpinning site-specific ecological targets is shown in Table 3.

Site-specific ecological targets formed the basis of an assessment of environmental water requirements and the subsequent determination of site-specific flow indicators for the Lower Goulburn River, as described below.

Table 3 Site-specific ecological targets for the Lower Goulburn River (in-channel flows).

Site-specific ecological targets	Justification of targets
• Provide a flow regime which supports recruitment opportunities for a range of native aquatic species (e.g. fish, frogs, turtles, invertebrates) • Provide a flow regime which supports key ecosystem functions, particularly those related to longitudinal connectivity and transport of sediment, nutrients and carbon	The lower sections of the Goulburn River downstream of Goulburn Weir contain vital habitat for native fish and supports diverse native fish populations due to limited impacts from thermal pollution, maintenance of natural seasonal flow patterns, connectivity between the Murray and upstream communities in the Goulburn and relatively intact in-stream habitat (Cottingham et al. 2003a; Davies et al. 2008; Koster et al. 2009). The importance of native fish populations within the Lower Goulburn River is highlighted by this area supporting breeding populations of the nationally vulnerable and endangered species such as Murray cod (*Maccullochella peelii peelii*) and Trout Cod (*Maccullochella macquariensis*) (Koster et al. 2009). Key ecosystem functions support fish, birds and invertebrates by: • maintaining connectivity within and between water-dependent ecosystems; • protecting and restoring carbon and nutrient dynamics; and • protecting refuges to support long-term survival and resilience of the populations dependent on them during drought and allow for their subsequent recolonisation.

5.2. Information used to determine site-specific flow indicators

In-channel flow pulses, or freshes, have important ecological functions including stimulating fish breeding and migration to fulfil requirements of life-history stages, increase wetted area including inundation of important in-channel habitat features such as benches, organic and inorganic sediment delivery to downstream reaches, mobilisation of fine particulate material that can smother submerged macrophytes and invertebrate habitat, dispersal of aquatic communities including drift and recolonisation of aquatic fauna and flora communities (Humphries et al. 1999; Cottingham et al. 2003b; Cottingham et al. 2010). Freshes serve to increase the diversity of flows, and hence habitat availability after a prolonged period of (stable) low flow or drought periods and can also assist in improving water quality through reducing stratification and increase dissolved oxygen concentrations (Cottingham et al. 2003b; Cottingham et al. 2010).

The development of site-specific indicators for in-channel environments of the Lower Goulburn River as described below has focussed on the in-channel fresh element of the flow regime to inundate key in-channel habitat and maintain native fish populations. The availability of suitable habitat within the main channel is critical to the viability of native fish populations in the Lower Goulburn River (Cottingham et al. 2007).

5.2.1. Inundation of key in-channel habitat

Bench inundation is considered important ecologically as it increases available habitat and supports biochemical processes such as carbon and nutrient cycling which contribute to increased rates of primary productivity and respiration, which, in turn, will result in increased invertebrate abundance and diversity (Cottingham et al. 2003b). Cottingham et al. (2003b) raised concerns that reduction in the frequency and/or duration of bench inundation will impact on the ecological condition and functioning of the Lower Goulburn River.

Hydraulic modelling for a typical stretch of the Lower Goulburn River (at Murchison) identified that discharge of 1,000 ML/d would commence to inundate in-channel features such as benches and increase the area of slackwater habitat for macrophytes, invertebrates and juvenile fish (Cottingham et al. 2003b; Cottingham et al. 2007). Analysis showed most benches, approximately 80% of bench area, are inundated by flows of 5000 ML/day (Cottingham et al. 2003b; Cottingham et al. 2007). Hydrological analysis undertaken by Cottingham et al. (2003b) indicated flow events that inundated low-lying benches in the Lower Goulburn River also occurred with a similar frequency under the regulated and unregulated flow regimes however their duration was greatly reduced under current conditions.

Woody debris or snags are another important feature providing in-stream habitat within the Lower Goulburn River. Woody debris in the reach below Goulburn Weir has remained relatively intact (Cottingham et al. 2003a) which contrasts with the river between Lake Eildon and Goulburn Weir and in the river immediately upstream of the Murray River junction where extensive desnagging was undertaken in the past (Cottingham et al. 2003a). Field observations near Wyuna in the Lower Goulburn River indicate that the majority of snag material is above the water surface at flows of about 400ML/day, and almost all snags are submerged at flows of 4,000 ML/d (Cottingham et al. 2007).

Building upon previous hydrological assessment of freshes described within Cottingham et al. (2003b), Cottingham et al. (2007) defined freshes in ecological terms as a particular magnitude and duration required to meet specific ecosystem objectives outlined in their report. Ecological objectives were largely related to the habitat requirements of biota such as macro-invertebrates (e.g. disruption of biofilm, increased wetted area) and geomorphic processes such as the mobilisation of fine sediments. Short flow events of between 860 ML/d – 10,700 ML/d were defined to meet these ecosystem objectives for 'in-channel' processes in the Lower Goulburn River. For example, various macro-invertebrate and geomorphic in-channel objectives can be achieved by delivering freshes ranging from approximately 1,500 ML/d to 4,500 ML/d in summer.

Cottingham et al. (2010) provides further insight into the in-channel fresh water requirements of the Lower Goulburn River. This report considered potential ecosystem benefits from the delivery of environmental water as pulses along the Lower Goulburn River under three hypothetical scenarios. While this report was primarily focussed on short-term best use of environmental water for the current water year which considered antecedent conditions, information presented provides relevant flow-ecology knowledge regarding freshes. The recommended scenario was 2-3 freshes between 860 – 6,600 ML/d for a minimum duration of 14 days during the period December to April (Cottingham et al. 2010). Supporting information for the various parameters included:

- A fresh threshold of 860 – 6,600 ML/d was adopted based on the lower bounds recommended that correspond to achievement of specified ecological and geomorphic objectives. As it is desirable to test the ecosystem outcomes from freshes of different magnitudes, it was recommended that at least one fresh at the upper end of the 860 ML/d - 6,600 ML/d range be released (preferably late spring), as this will provide the strongest ecosystem signal;
- Examination of flow data indicated that freshes of 860 – 6,600 ML/d would occur between June and November each year under an unregulated flow regime, often with a duration of many weeks. They can also occur in the summer-autumn period, but with a much shorter duration (e.g. up to 4 days);

- At the time of report preparation, the Lower Goulburn River had experienced a large, overbank flow and therefore the short-term emphasis shifted from delivering freshes in winter-spring to their delivery in summer-autumn;
- Fresh(es) should be delivered to coincide with the timing window for Golden perch in order to maximise the chances of detecting an ecosystem response signal;
- The scientific panel considered that it would be better to deliver multiple freshes, rather than a single event. A single fresh is unlikely to affect the assemblage of plants on the river bank, however if there are multiple events then there may be a change in assemblage, as a second event would act as a selective filter on successful recruitment by drowning out young terrestrial species (intolerant of submergence) and causing a shift to amphibious species;
- If multiple freshes are delivered as managed releases (spring-autumn), then these should be at least 30 days apart to maximise the benefits expected from meeting ecosystem objectives for invertebrates (disrupting biofilms to refresh them as a food source) and preferably greater than 60 days apart in order to favour amphibious plant species over terrestrial species growing on low-lying benches; and
- Freshes of minimum 2 weeks duration are likely to increase the in-channel wetted area for aquatic macrophytes, inundate low-lying bench areas and allow invertebrate emergence and seed germination to take place. This may occur in either the non-growing (winter) or early growth (spring) season, and in turn remove some flood intolerant plants, as well as leaf litter and dead standing (plant) material.

5.2.2. Native fish

Native fish species are a well-recognised asset of the Lower Goulburn River, including a number of species listed as threatened or vulnerable under Federal or State legislation. It is clear that conditions within the Lower Goulburn River, including alterations to the natural flow regime, are negatively impacting on fish populations and limiting achievement of increases in the ecological condition of the fish assemblages (Cottingham et al. 2003b; Cottingham et al. 2007).

Investigations undertaken at various locations in the Murray Darling Basin indicate that flow patterns and variability are important for native fish and flows are linked to parts of the life cycle of native fish. For example:

- A number of fish species, such as Golden perch and Silver perch, require flow pulses or floods for spawning i.e. flood recruitment hypothesis (Humphries et al. 1999) Within channel rises in water level during spring and summer appear to play an important role as cues for fish migration and spawning (Mallen Cooper and Stuart 2003; Cottingham et al. 2007). Mallen Cooper and Stuart (2003) found that strong Golden Perch recruitment occurred in years where flow pulses of 1-2m in stage height within the main channel of the River Murray;
- Monitoring has shown that flows are an important factor in the larval survivorship and subsequent recruitment of Murray cod (Cheshire and Ye 2008; Cheshire and Ye 2010);
- A number of small-medium bodied native fish species breed opportunistically every year regardless of flow i.e. low flow recruitment hypothesis (Humphries et al. 1999). However, connectivity between the main river and adjacent wetlands, anabranches and still water habitats provided by increased flows improve recruitment of species such as Flathead

gudgeons and Australian smelt as larvae and juveniles require high concentrations of small prey to feed on and develop (Humphries et al. 1999).

There is still debate in the scientific literature as to the relative role of various types of flows to fish community dynamics, and an understanding of the nature of 'fish ecology'-'river flow' interactions is by no means clear (Humphries et al. 1999, Mallen-Cooper and Stuart 2003, Graham and Harris 2004, King et al. 2009). Silver perch (*Bidyanus bidyanus*), which have been recorded in the Goulburn system, require flow pulses or floods for spawning i.e. flood recruitment hypothesis (Humphries et al. 1999). Other factors such water temperature and day lengths, or the interaction of a range of environmental variables including flow, are suggested to also be important for native fish recruitment (King et al. 2009).

Despite the ongoing debate regarding the link between hydrology and fish ecology, available evidence supports that provision of flows that connect the river channel to the floodplain as well as in-channel flow variability as important to sustaining key ecological features such as native fish populations. The fish species present in the Goulburn River exhibit a variety of life history strategies and, as a result, a number of different ecological requirements need to be considered (Cottingham et al. 2003b). Flow indicators described for the Lower Goulburn River floodplain primarily based on the water requirements of flood dependent vegetation communities are expected to be sufficient to support life-cycle and habitat requirements of native fish associated with connectivity between the river and floodplain (MDBA 2012a).

A number of documents have been assessed to determine a range of in-channel flows required to support the life-cycle and habitat requirements of native fish including provision of cues for spawning and migration and access to food sources. However, it was found that no single existing plan or document sets out these requirements completely.

Flow threshold

Recent studies have provided information specific to the Lower Goulburn River on water requirements of key native fish species. Koster et al. (2009) report that Murray cod spawning in the Lower Goulburn River appears to occur irrespective of flow conditions with larvae collected every year from 2003-2009 during a range of flow conditions, including low flows. Similarly, Trout cod larvae were detected during periods of relatively low and stable flows supporting previous research that indicates Trout cod are able to spawn under a range of flow conditions. This finding is consistent with King et al. (2009) who also reported that spawning of Murray cod at Barmah-Millewa Forest was observed with positive change in flow and temperature, however the relationship was relatively weak and a range of factors appear to influence spawning of Murray cod.

While there is uncertainty regarding the effects of increased flow and temperature on triggering Murray cod spawning, there is evidence that flows are important for enhancing successful recruitment. Zampatti et al. (2008) suggest that Murray cod spawn annually regardless of flow and it is the environmental conditions present during the larval stage that is likely to influence successful recruitment of larvae to the adult population. Furthermore, it is suggested that flow, particularly small-scale hydraulics, maybe important for the survival of Murray cod larvae (Zampatti et al. 2008) and therefore diversity of flow and physical habitats within the Lower Goulburn River that would occur associated with inundation of low-lying benches and snags may facilitate the successful recruitment of Murray cod.

In contrast, there are strong links between flow and spawning of Golden perch. Mallen-Cooper and Stuart (2003) presented evidence from the middle reaches of the River Murray that rises in flow contained within the river channel during spring may lead to Golden perch fish recruitment. The authors hypothesised that Golden perch had spawned and recruited (i) predominantly during within-channel flows, or (ii) during both within-channel flows and floods. Similarly, King et al. (2009) in a review of existing knowledge of the requirements for successful breeding of native fish in the River Murray reported that for the Barmah-Millewa forest there was a strong relationship between Golden perch spawning strength and occurrence with water temperatures and increased flow. Inferences that can be made from a single study are generally only limited to the population or area where the study was conducted however this is consistent with previous studies and literature which also suggest that Golden perch spawning and recruitment is linked with an increase in flows, particularly within channel flows (King et al. 2009). Zampatti et al. (2011) present data to support that strong Golden perch recruitment is not reliant on flood flows i.e. overbank and that even relatively small in-channel flow events may support significant recruitment and Cheshire and Ye (2010) also report that a within channel flow pulse is sufficient to induce breeding and promote larval survivorship for both Golden and Silver perch.

Koster et al. (2009) revealed a lack of Golden perch spawning in the Goulburn River between 2003 and 2009 – a period characterised by relatively low and stable flows. Monitoring in November 2010 detected Golden perch eggs in significant numbers indicating that spawning had occurred within the Lower Goulburn River (Koster pers. comm. 2011). This spawning event was preceded by a large overbank event. In the case of the Lower Goulburn River work undertaken by Koster et al. (2009) and subsequent surveying suggests that Golden perch spawning may be reliant on bankfull or overbank flows which are addressed by flow indicators specified for the Lower Goulburn River Floodplain (MDBA 2012a).

Acoustic-tracking studies of Golden perch movements have shown that some individuals leave the Lower Goulburn River and enter the River Murray following the arrival of freshes along the Lower Goulburn River (e.g. approximately 3,500 ML/d, Koster et al. 2009). This is consistent with previous studies that have demonstrated a link between Golden perch movements and increased flows. It is possible that this movement out of the Goulburn River is pre-spawning migration to breeding sites in the River Murray.

As with Golden perch, Koster et al. (2009) revealed a lack of spawning and recruitment by Silver perch in the Goulburn River during the period 2003-2009. This result contrasts with the regular collection of Silver perch eggs and/or larvae over the last six years in the River Murray. The lack of evidence of spawning by Silver perch in the Goulburn River may be due to unfavourable environmental conditions (e.g. low flows). The result may also be related to low abundances of adult Silver perch in the Goulburn River.

Timing

Fish generally spawn during the warmer months (spring/summer) when conditions are ideal for maximum growth and there is maximum production of food for larvae and juveniles. While King et al. (2009) reported that most fish species appear to be flexible in their spawning period, their review of previous studies suggests the probable spawning period for Murray cod is October to December, Trout cod is October to December, Silver perch is November to February and Golden perch is October to March. This is consistent with larvae surveying in Koster et al. (2009) that collected

Murray cod larvae around mid November to mid December, Trout cod from mid November to early December and Golden perch in November. A range of small to medium bodied native fish species including Carp gudgeon, Flat-headed gudgeon, Bony herring, Unspecked hardyhead, Murray-Darling rainbowfish and Australian Smelt are also likely to spawn during the spring/summer period however many of these species are more flexible in their spawning timing compared to the large bodied native fish species (King et al. 2009).

Frequency

In-channel freshes are categorised as events that typically would occur in most years and it is assumed that restoring this element of the flow regime has an important ecological role in the maintenance of native fish populations. Some fish species are short-lived, for example, Australian smelt live 1-2 years (Zampatti et al. 2008) therefore it is important that regular breeding opportunities are provided to maintain sustainable populations. Cheshire and Ye (2010) report that protracted low flow conditions pose a significant risk to spawning success and larval survivorship of Murray cod, Golden perch and Silver perch and restoration of flow variability through in-channel freshes is therefore important for a range of native fish species.

5.2.3. Other Biota

The understanding of flow-ecology relationships for faunal groups other than native fish populations generally has more uncertainty owing to the reduced number of studies undertaken for these species. The MDBA is confident that the site-specific flow indicators determined for native fish species will also have valuable beneficial effects on the life-cycle and habitat requirements of amphibians, and water-dependent reptiles and invertebrates. Key ecosystem functions associated with river connectivity and sediment and nutrient transport will also be enhanced.

5.3. Proposed flow indicators

The site-specific flow indicators for in-channels flows in the Lower Goulburn River as set out in Table 4 represent an amalgam of best available information from existing literature described in Section 5.2, checked against an analysis of modelled without-development and baseline flow data. Site-specific flow indicators are expressed on the Goulburn River at Shepparton. This location corresponds to the site of flow indicators specified for the Lower Goulburn River floodplain and is considered representative of the broader Lower Goulburn River as it is downstream of all major tributaries and therefore will ensure longitudinal connectivity.

The site-specific flow indicators associated with the ecological targets for the Lower Goulburn River should be read in their entirety to understand the environmental water requirements as multiple flow indicators will contribute to achieving each ecological target. This approach has been used because it is not possible to define a single flow threshold for each ecological target.

Flow indicators as specified for fresh element of the flow regime attempt to strike a balance between desirable flow threshold, duration and timing with desirable frequency and represent a variable flow regime that is consistent with the “without-development” hydrology of the site. Modelled flow data for the period 1895-2009 was analysed to assess the combination of magnitude (1,000 ML/day to 6600 ML/day) and duration (4-14 days) that occurred frequently under without-development conditions during the ecologically relevant spring/summer period. This was compared with the relative proportion of years that the key flow events occur under baseline conditions to understand the extent to which these flows have been reduced by water resource development.

Generally, the flow indicator metric with the greatest level of uncertainty across the Basin is the definition of the desirable frequency of specified flow events, expressed as the proportion of years an event is required. This uncertainty is due to a number of reasons. Firstly, it is likely that there are thresholds for many plants and animals beyond which their survival or ability to reproduce is lost, but the precise details of those thresholds are mostly unknown or where there is information our knowledge is evolving. Secondly, in-channel flows even under pre-development conditions are extremely variable which subsequently makes specification of a single frequency metric deceptively certain. For many species and ecological communities the relationship between water provisions and environmental outcomes may not be threshold based, rather there could be a linear relationship between flow and the extent of environmental outcomes or the condition of a particular ecological species/community.

Recognising the degree of confidence in specifying a desirable frequency, 'low–uncertainty' and 'high–uncertainty' frequency of flow events have been specified (Table 4). For the low uncertainty frequency, there is a high likelihood that the environmental objectives and targets will be achieved. The lower boundary of the desired range is referred to here as the high uncertainty frequency which is effectively the best estimate of the threshold, based on current scientific understanding, which, if not met, may lead to the loss of health or resilience of ecological communities, or the inability of species to reproduce frequently enough to sustain populations. The high uncertainty frequencies attempt to define critical ecological thresholds.

For in-channel flows in the Lower Goulburn River the MDBA has relied on general ecological principles and hydrological analysis to inform the high and low uncertainty frequencies in the absence of more specific information on desired frequency.

As advocated by Poff *et al* (2010) the degree to which the hydrology of a system is altered from natural, indicates a decline in the integrity of the aquatic ecosystem. In working rivers such as many of those in the Basin it is not possible nor desirable to reinstate "natural" flows, however in general scientific methods use the degree of change, from natural flows, as a measure of assessment.

As part of the Sustainable Rivers Audit (SRA), Davies et al. (2008) identified 5 categories to assess river condition and ecosystem health. In the SRA, reference condition is a reconstruction of the hydrology of the system without significant human intervention (e.g. dams, irrigation development) and is equivalent to the concept of 'without-development' as applied in the modelling framework used by the MDBA. The classes identified in the SRA are in Table 5.

It is likely that the level to which flow alteration is important will be different for different fish species, different life stages of fish species and for other biota and ecosystem functions. However there is a reasonably limited science base to draw on to set informed high and low uncertainty frequencies. As such, as a first step to including flow indicators for in-stream needs, the MDBA has drawn on the SRA classification and is proposing that 60% protection of key aspects of the in-stream flows as a reasonable start to identify in-stream needs. For major floodplain assets such as those described in environmental water requirement reports, a larger information base is available to identify site specific flow indicators.

Table 4 Site-specific ecological targets and associated flow indicators for in-channel flows: Lower Goulburn River

Site-Specific Ecological Targets	Site-Specific Flow Indicators					Without-development and baseline event frequencies	
	Flow required (measured at Shepparton; ML/d)	Duration	Timing	Frequency - proportion of years event required		Proportion of years event occurred under modelled without-development conditions (%)	Proportion of years event occurred under modelled baseline conditions (%)
				Low uncertainty (%)	High uncertainty (%)		
Provide a flow regime which supports recruitment opportunities for a range of native aquatic species (e.g. fish, frogs, turtles, invertebrates) Provide a flow regime which supports key ecosystem functions, particularly those related to longitudinal connectivity and transport of sediment, nutrients and carbon	5,000	14 days (continuous)	October to November	66	49	82	28
	2,500	8 day total duration comprised of 2 events each a minimum of 4 days with at least 30 days separating the events	December to April	48	36	60	10

Note: Multiplication of the flow rate by the duration and frequency (proportion of years event required) does not translate into the additional volume of water the site needs to be environmentally sustainable. This is because part of the required flow is already provided under baseline conditions. Additional environmental water required is the amount over and above the baseline flows.

Table 5 SRA ecosystem health classes

Condition of ecosystem health	Difference from reference condition	Metric
Good	Near Reference Condition	Greater than 80% of reference
Moderate	Moderate Difference	Greater than 60% of reference
Poor	Large Difference	Greater than 40% of reference
Very Poor	Vary large Difference	Greater than 20% of reference
Extremely Poor	Extreme Difference	Less than 20% of reference

Based on these principles the high and low uncertainty frequencies for the in-stream flows specified here are defined based on an analysis of modelled without-development flow with the high and low uncertainty frequencies set at 60% and 80% of the frequency that the specified events occurs under without-development conditions.

From an ecological perspective, the optimal inter-annual timing for delivery of fresh events would be to occur following a bankfull or overbank flow as per Cottingham et al. (2010). One of the potential benefits of sequencing in-channel and overbank events would to be maximise potential recruitment success of Golden perch and Silver perch that are known to spawn in response to high flows. The environmental water requirements specified for the Lower Goulburn River floodplain recommend a bankfull/overbank flow of 25,000 ML/d occur in 70-80% of years and larger overbank events of 40,000 ML/d occur at a lower frequency of 40-60% of years (MDBA 2012a). Therefore, given the overlap in frequencies sought for in-channel fresh events and overbank flows it is realistic and logical to sequence in-channel and overbank events to maximise native fish recruitment outcomes. This information also provides ecological relevance to the desired frequencies of in-channel fresh events that have been developed based on hydrological analysis of modelled without-development flow data. This does not however infer that fresh events should only be delivered in conjunction with bankfull/overbank events and in the absence of a high flow event, spring and summer fresh event(s) have an important ecological role in inundating key habitat and providing flow variability.

It is also worth noting that the in-channel fresh water requirements specified for the Lower Goulburn River in Table 4 have been developed as flow indicators for input/assessment of modelling scenarios to inform estimates of the volume of water required to reinstate this flow component. Consistent with the scope and purpose for setting site-specific flow indicators as described in Section 1.2, on-ground delivery of in-channel fresh water requirements are expected to enhance flow variability and take into account more specific environmental flow recommendations, operational delivery issues, antecedent conditions and previous monitoring as part of an adaptive management approach to environmental water delivery.

6. Flow Delivery Constraints

Basin wide environmental objectives have been developed within the context of being deliverable in a working river system that contains public and private storages and developed floodplains. To understand and assess the implications of key constraints on the ability to achieve flow indicators specified for in-channel flows in the lower sections of the Goulburn River, MDBA has drawn upon a combination of existing information (e.g. Water Sharing Plans, operating rules of water agencies, flood warning levels) and practical knowledge of river operators supported by testing using hydrological modelling.

Given the relatively low thresholds of the site specific flow indicators, the achievement of these indicators and associated of site-specific ecological targets are considered deliverable as mostly regulated flows (Table 6).

Table 6 Site-specific flow indicators for in-channel flows in the lower section of the Goulburn River and the effect of system constraints

Site-specific ecological targets	Site-specific flow indicators
Provide a flow regime which supports recruitment opportunities for a range of native aquatic species (e.g. fish, frogs, turtles, invertebrates) Provide a flow regime which supports key ecosystem functions, particularly those related to longitudinal connectivity and transport of sediment, nutrients and carbon.	5,000 ML/d for 14 consecutive days between October & November for 49% of years Two events annually of 2,500 ML/d for 4 consecutive days between December & April for 36% of years

Key

(blue)	Achievable under current operating conditions Flow indicators highlighted in blue are considered deliverable as mostly regulated flows under current operating conditions.
(yellow)	Achievable under some conditions (constraints limit delivery at some times) Flow indicators highlighted in yellow are considered achievable when delivered in combination with tributary inflows and/or unregulated flow events. They may not be achievable in every year or in some circumstances, and the duration of flows may be limited to the duration of tributary inflows.
(brown)	Difficult to influence achievement under most conditions (constraints limit delivery at most times) Flow indicators highlighted in brown require large flows that cannot be regulated by dams and it is not expected that these flows can currently be influenced by river operators due to the river operating constraints outlined above.

7. Summary and conclusion

The Lower Goulburn River is a key environmental asset within the Basin and is an important site for the determination of the environmental water requirements of the Basin. MDBA has undertaken a detailed eco-hydrological assessment of in-channel flows for the Lower Goulburn River. Specified flow indicators are indicative of a long-term flow regime required to enable the achievement of site-specific ecological targets for in-channel environments along the Lower Goulburn River and for the broader river valley and reach. Along with other site-specific flow indicators developed across the Basin at other hydrologic indicator sites, these environmental flow requirements were integrated within hydrological models to inform the ESLT. This process including consideration of a range of constraints such as those outlined in Section 6 is described in further detail within the companion report on the modelling process '*Hydrologic modelling to inform the proposed Basin Plan: Methods and results*' (MDBA 2012).

The flow indicators in this report are used to assess potential Basin Plan scenarios. MDBA (2012) summarises how the proposed draft Basin Plan released in November 2011 performs against flow indicators for in-channel flows in the Lower Goulburn River.

References

Cadwallader, PL & Lawrence, B 1990, Fish. In *The Murray* (Eds. N Mackay and D Eastburn) p. 317-363. Murray Darling Basin Commission, Canberra.

Chee, YE, Webb, JA, Stewardson, M & Cottingham, P 2009, *Victorian environmental flows monitoring and assessment program: monitoring and evaluation of environmental flow releases in the Goulburn River*, report for Goulburn Broken Catchment Management Authority and the Victorian Department of Sustainability and Environment, eWater Cooperative Research Centre, Canberra.

Cheshire, KJ & Ye, Q 2008, *Larval fish assemblage structure below Locks 5 and 6, in the River Murray, South Australia from 2005 to 2007: with reference to the water manipulation trials.* SARDI Publication Number F2007/000705-1. SARDI Research Report Series No.175. South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Cheshire, KJ & Ye, Q 2010, Chapter 5. The influence of hydrology and water quality in structuring the inter-annual and spatial dynamics of larval fish assemblages in the Lower River Murray, South Australia. In *Influences of salinity, water quality and hydrology on early life stages of fishes in the Lower River Murray, South Australia*. (Eds Q Ye, KJ Cheshire and DG McNeil) pp. 128-159. SARDI Publication Number F2009/000470-5. SARDI Research Report Series No.446. South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Cottingham, P, Stewardson, M, Crook, D, Hillman, T, Roberts, J & Rutherfurd, I 2003a, *Flow-related environmental issues associated with the Goulburn River below Lake Eildon*, report to Victorian Department of Sustainability and Environment and Murray–Darling Basin Commission, Cooperative Research Centre for Freshwater Ecology, Canberra.

Cottingham, P, Stewardson, M, Crook, D, Hillman, T, Roberts, J & Rutherfurd, I 2003b, *Environmental flow recommendations for the Goulburn River below Lake Eildon*, technical report 01/2003, Cooperative Research Centre for Freshwater Ecology, Canberra.

Cottingham, P, Stewardson, M, Crook, D, Hillman, T, Oliver, R, Roberts, J & Rutherfurd, I 2007, *Evaluation of summer inter-valley water transfers from the Goulburn River*, report to Goulburn-Broken Catchment Management Authority, Shepparton, Victoria.

Cottingham, P, Crook, D, Hillman, T, Oliver, R, Roberts, J & Stewardson, M 2010, *Objectives for flow freshes in the lower Goulburn River 2010/11*, report to the Goulburn-Broken CMA and Goulburn Murray Water.

CSIRO 2008, *Water availability in the Goulburn–Broken*, a report to the Australian Government from the CSIRO Murray–Darling Basin Sustainable Yields Project, CSIRO, Australia.

Davies, PE, Harris, JH, Hillman, TJ & Walker, KF 2008, *Sustainable Rivers Audit Report 1: a report on the ecological health of rivers in the Murray–Darling Basin, 2004–2007*, Report prepared by the Independent Sustainable Rivers Audit Group for the Murray–Darling Basin Ministerial Council, Murray–Darling Basin Commission, Canberra.

Department of the Environment, Water, Heritage and the Arts 2008, National framework and guidance for describing the ecological character of Australian Ramsar wetlands, module 2 of the national guidelines for Ramsar wetlands — implementing the Ramsar Convention in Australia, viewed 5 January 2010, <www.environment.gov.au/water/publications/environmental/wetlands/module-2-framework.html>

GBCMA 2005, *Regional River Health Strategy 2005-2015,* Goulburn Broken Catchment Management Authority, Shepparton.

Gehrke, PC, Brown, P, Schiller, CB, Moffatt, DB & Bruce, AM 1995, 'River regulation and fish communities in the Murray–Darling River system, Australia'. *Regulated Rivers: Research and Management* 11, 363-375.

Graham, R & Harris, JH 2004, *Floodplain inundation and fish dynamics in the Murray-Darling Basin. Current concepts and future research: a scoping study*. CRC for Freshwater Ecology, Canberra.

Humphries, P, King, AJ and Koehn, JD 1999, 'Fish, flows and flood plains: links between freshwater fishes and their environment in the Murray-Darling River system, Australia'. *Environmental Biology of Fishes* 56, 129-151.

Humphries, P, Brown, P, Douglas, J, Pickworth, A, Strongman, R, Hall, K & Serafini, L 2008, 'Flow-related patterns in abundance and composition of the fish fauna of a degraded Australian lowland river'. *Freshwater Biology* 53, 789-813.

King, AJ, Humphries, P & Lake, PS 2003, 'Fish recruitment on floodplains: the roles of patterns of flooding and life history characteristics'. *Canadian Journal of Fisheries and Aquatic Sciences* 60, 773-786.

King, AJ, Ramsey, D, Baumgartner, L, Humphries, P, Jones, M, Koehn, J, Lyon, J, Mallen-Cooper, M, Meredith, S, Vilizzi, L, Ye, Q & Zampatti, B 2009, *Environmental requirements for managing successful fish recruitment in the Murray River Valley – Review of existing knowledge*, Arthur Rylah Institute for Environmental Research Technical Report Series No. 197, Department of Sustainability and Environment, Heidelberg.

Koster, W, Crook, D & Dawson, D 2009, *Lower Goulburn Fish Communities Project – 2009 Annual Report*. Arthur Rylah Institute for Environmental Research, Department of Sustainability and Environment, Heidelberg.

Mallen-Cooper, M 1993, Habitat changes and declines of freshwater fish in Australia: what is the evidence and do we need more*?* In *Sustainable Fisheries through Sustaining Fish Habitat* (Ed. DA Hancock) pp. 49-56. Proceedings of the Australian Society for Fish Biology Workshop, August 1992. Bureau of Rural Resources, Canberra.

Mallen-Cooper, M & Stuart, IG 2003, 'Age, growth and non-flood recruitment of two potamodromous fishes in a large semi-arid/temperate river system'. *River research and applications* 19: 697-719.

MDBA (Murray-Darling Basin Authority) 2012*, Hydrologic modelling to inform the proposed Basin Plan: Methods and results.* Murray-Darling Basin Authority, Canberra.

MDBA (Murray-Darling Basin Authority) 2012a*, Assessment of environmental water requirements for the proposed Basin Plan: Lower Goulburn River Floodplain.* Murray-Darling Basin Authority, Canberra.

Poff, NL, Richter, BD, Arthington, AH, Bunn, SE, Naiman, RJ, Kendy, E, Acreman, M, Apse, C, Bledsoe, BP, Freeman, MC, Henriksen, J, Jacobson, RB, Kennen, JG, Merritt, DM, O'Keefe, JH, Olden, JD, Rogers, K, Tharme, RE & Warner, A 2010, 'The Ecological Limits of Hydrologic Alteration (ELOHA): A new framework for developing regional environmental flow standards.' *Freshwater Biology* 55:147-170.

Rowland, SJ 1989, 'Aspects of the history and fishery of the Murray cod, *Maccullochella peeli* (Mitchell) (Percichthyidae)'. *Proceedings of the Linnean Society of New South Wales* 111, 201-213.

Schiller, C & Harris, JH 2001, Native and alien fish. In *Rivers as Ecological Systems – the Murray-Darling Basin* (Ed. W Young) pp. 229-258. Murray-Darling Basin Commission, Canberra.

SKM (Sinclair Knight Merz) 2007, *High Conservation Value Aquatic Ecosystems project - identifying, categorising and managing HCVAE*, Final report, Department of the Environment and Water Resources, 16 March 2007,
<www.environment.gov.au/water/publications/environmental/ecosystems/hcvae.html>

Victorian Department of Sustainability and Environment 2011, *Overbank flow recommendations for the lower Goulburn River*, Victorian Department of Sustainability and Environment, Melbourne.

Walker, KF & Thoms, MC 1993, 'Environmental effects of flow regulation on the lower River Murray, Australia'. *Regulated Rivers: Research and Management* 8, 103-119.

Water Technology 2010, *Goulburn River environmental flows hydraulics study,* report for the Goulburn–Broken Catchment Management Authority, Melbourne.

Zampatti, BP, Leigh, SJ & Nicol, JM 2008, *Chowilla Icon Site – Fish Assemblage Condition Monitoring 2005-2008*. SARDI Publication Number F2008/000907-1. SARDI Research Report Series No. 319. South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Appendix A

Data used in producing hydrologic indicator site maps

Data	Dataset name	Source[a]
Basin Plan regions	Draft Basin Plan Areas 25 May 2010	Murray–Darling Basin Authority (2010)
Dam walls/barrages	GEODATA TOPO 250K Series 3 Topographic Data	Geoscience Australia 2006
Gauges	100120 Master AWRC Gauges	
Icon sites	Living Murray Indicative Icon Site Boundaries	Murray–Darling Basin Commission (2007)
Irrigation areas	Combined Irrigation Areas of Australia Dataset	Bureau of Rural Sciences (2008)
Lakes	GEODATA TOPO 250K Series 3 Topographic Data	Geoscience Australia (2006)
Maximum wetland extents	Wetlands GIS of the Murray–Darling Basin Series 2.0 (Kingsford)	Murray–Darling Basin Commission (1993)
National parks/nature reserves	Digital Cadastral Database	New South Wales Department of Lands (2007)
National parks/nature reserves	Collaborative Australian Protected Areas Database — CAPAD 2004	Department of the Environment, Water, Heritage and the Arts (2004)
Nationally important wetlands	Directory of Important Wetlands in Australia Spatial Database	Department of the Environment, Water, Heritage and the Arts (2001)
Ocean and landmass	GEODATA TOPO 250K Series 3 Topographic Data	Geoscience Australia (2006)
Ramsar sites	Ramsar wetlands in Australia	Department of the Environment, Water, Heritage and the Arts (2009)
Rivers	Surface Hydrology (AUSHYDRO version 1-6)	Geoscience Australia (2010)
Roads	GEODATA TOPO 250K Series 3 Topographic Data	Geoscience Australia (2006)
SRA Zones	Sustainable Rivers Audit Zones	MDBA 2008
State border	GEODATA TOPO 250K Series 3 Topographic Data	Geoscience Australia (2006)
State forests	Digital Cadastral Database	New South Wales Department of Lands (2007)
Towns	GEODATA TOPO 250K Series 3 Topographic Data	Geoscience Australia (2006)
Weirs	Murray–Darling Basin Weir Information System	Murray–Darling Basin Commission (2001)
Weirs 2	River Murray Water Main Structures	Murray–Darling Basin Authority (2008)

[a] Agency listed is custodian of relevant dataset; year reflects currency of the data layer.