

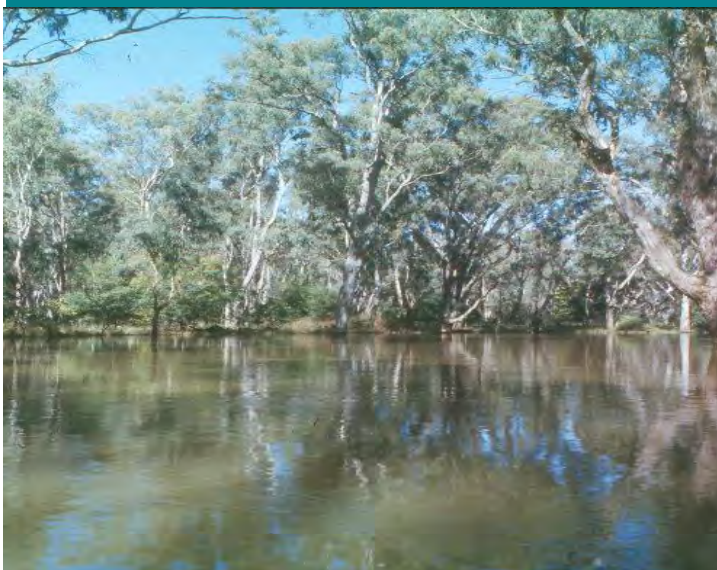
# Managing flows and Carp

J. Koehn, C. Todd, L. Thwaites, I. Stuart, B. Zampatti,  
Q. Ye, A. Conallin, L. Dodd and K. Stamation

February 2016

Arthur Rylah Institute for Environmental Research,  
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Department of Environment, Land, Water and Planning  
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**Front cover photo:** Flooded Ovens river (photo: John Koehn) and dead Carp at Lake Cargelligo (photo: Ivor Stuart).

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## Summary

Carp (*Cyprinus carpio*) are a worldwide, pervasive and very successful alien pest fish species that has invaded most of the Murray–Darling Basin (MDB) in less than 50 years. They are a highly visible fish, widespread and abundant, with biological attributes (e.g. high fecundity; highly mobile) that allow their populations to expand rapidly. Carp spawning and recruitment can be enhanced by flooding (especially onto floodplains), and as Carp are very abundant in MDB river systems, population responses can result in large increases in Carp numbers.

Water is managed in the MDB for a range of purposes, including consumption (e.g. irrigation, town water supplies, industry), recreation, and environmental benefit. Carp can readily respond to flow events; therefore, ‘all water’ (consumptive, environmental and even natural) flow events have the potential to contribute to increasing Carp populations. The primary objectives of environmental watering seek to achieve positive environmental outcomes for a range of native biota (including fish) and the ecological processes that support their populations. Therefore, there is a concern that some environmental watering events could potentially provide conditions conducive to Carp population increases that may be in conflict with the overall objective of positive environmental outcomes. The risk of adverse outcomes from Carp responses to flows are often considered and acknowledged in decision-making processes, but to date this has rarely been quantified.

One of the inherent challenges in managing flows for native biota is that there may also be unavoidable benefits to Carp or other unwanted species. Carp already occur in very high numbers in the MDB river systems; therefore, their population responses are likely to be large, being intrinsically linked to the existing high abundances. These high abundances mean that Carp populations in the MDB will be ongoing, with or without environmental water. In contrast, the abundances of many native fish species are often much lower than Carp, and hence they may not exhibit the same initial magnitude of population response. However, improvements in the long-term viability of many native fishes will rely on these smaller cumulative responses to flows. The spawning season of Carp overlaps considerably with that of many native fish species and can coincide with preferred times for watering of other biota (e.g. for optimal waterbird or vegetation outcomes). Becoming too risk-averse to any responses by Carp is, therefore, likely to diminish other desirable outcomes. So, although the ecological objectives for maximising benefits for native species (fish, vegetation and birds) through environmental flows must remain paramount, minimisation of the opportunities for Carp population expansion will be a secondary objective in most instances. Any potential increases in Carp populations require quantification so they can be balanced against other quantified environmental benefits (e.g. to native fish populations).

Our understanding of Carp biology indicates that we may intuitively expect some types of water management options in the MDB to increase Carp numbers. There are a range of different types of flow events in the MDB, from in-channel pulses to those that flood habitats such as wetlands and floodplains. Flow events that result in prolonged inundation of preferred Carp breeding and nursery habitats will significantly increase the risk of strong recruitment events and the subsequent increase in populations. Importantly, since the Millennium Drought there has also been an increased emphasis on the construction and use of infrastructure such as pumps and regulators to deliver water to maximise the floodplain area inundated per volume of water used. These initiatives pose risks for native fish as well as having the potential for increased production of Carp.

While there is concern about Carp population increases, adequate monitoring of flow events can be costly and does not always occur; therefore, we are often relying on implied (or at best anecdotal) information regarding ecological outcomes. In lieu of actual monitoring data, there is a need for methods or tools that can be utilised in the immediate future to explore the scale and magnitude of Carp population responses to flows, thus allowing quantification of risk. One such tool is modelling,

and in particular the modelling of populations. The development of a Carp population model allows the outcomes (population responses) from a range of flow management scenarios to be modelled and compared. It also allows managers of environmental flows to examine their planned events in the context of other flows in the system. The quantification of such potential outcomes provides valuable information for planners because it permits comparisons between different management decisions and allows forecasts of the expected outcomes to guide the setting of thresholds or targets. Outputs can also be used to inform decisions within risk management frameworks, either at a site or event level.

Up-to-date biological and ecological knowledge of Carp has been used to formulate conceptual models for key aspects of Carp life history, which have then been used to develop an age- and abundance-based stochastic population model. The model has been developed for the southern connected MDB (Murray, Murrumbidgee, Lachlan and Lower Darling river systems), with the option of adapting it for other areas, especially for the northern MDB. The model is supported by relevant population and reproductive data, expert opinion where necessary, and examples of regional Carp population dynamics. The model used an innovative assessment of the relative survival rates for each life stage within each identified habitat type for the southern connected MDB. A review of flow regimes and watering objectives, options and delivery mechanisms was undertaken to inform the flow scenarios to be modelled. Modelling that linked flows to habitat inundations (availability) was then undertaken for a range of habitat types and watering scenarios. Outcomes from this modelling could then be compared and assessed within a risk framework in order to guide management.

## Modelled Carp responses to flows

The most common managed environmental flow scenarios for the Murray River are likely to be:

- within-channel river pulses
- flows which may break out-of-channel/overbank in some regions
- water allocations to specific sites/wetlands (via channels or pumped)
- inundations using floodplain regulators.

Each of these scenarios can allow Carp access to different habitats, producing a different population response.

Our modelling demonstrates that while Carp are able to spawn in the river channel, larval survival and recruitment is much lower than under flooded conditions—floodplain habitats are much preferred over flowing main-river channel habitats. Hence, the risks of major Carp population increases are likely to be limited under within-bank flows, with Carp populations slowly declining in most instances. This is shown in Figure S1 (output 0), in which in-channel flows lead to a gradual decline in the Carp population.

Flows that provide some access to adjacent wetlands along the Murray River can progressively increase populations with increasing frequency of access (Figure S1, outputs 1–5). Indeed flows supplying irrigation water often allow access to these habitats every year and, therefore, may be supporting artificially high Carp populations in the main channel of the Murray River (Figure S1, output 1).

For many native fish, carefully designed in-channel hydrographs are likely to retain significant spawning and recruitment benefits for native fishes, with overbank flows potentially providing significant additional benefits to recruitment through increased productivity supporting early life stages. Such benefits need to be quantified so that balanced watering decisions can be made.



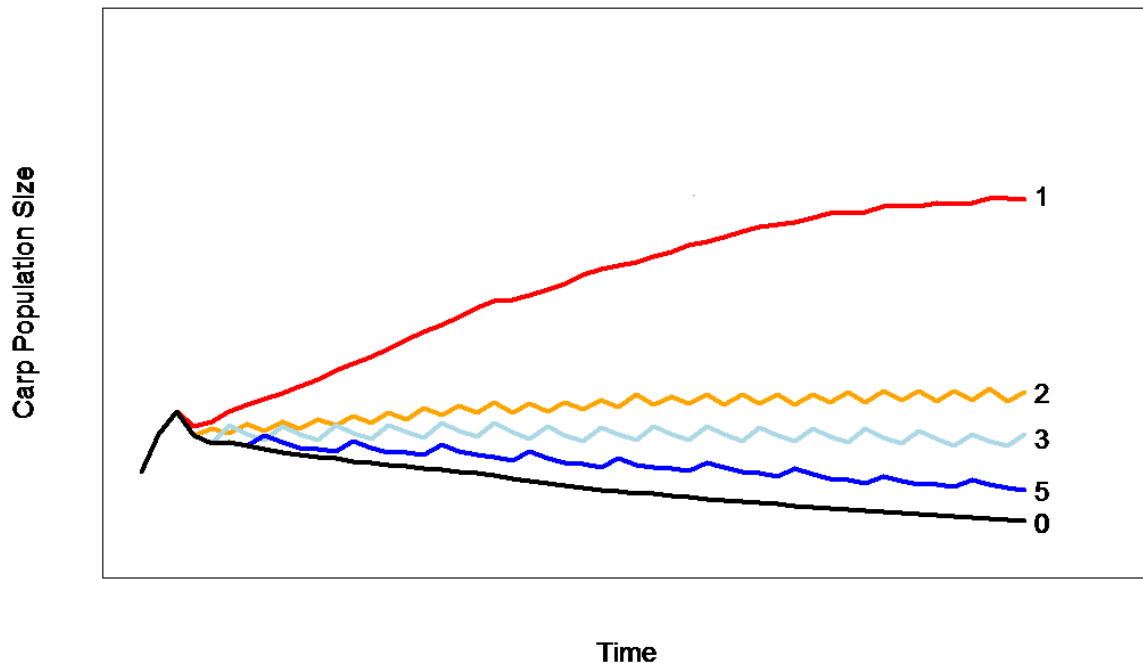


Figure S1. The likely relative changes in Carp populations over time with different flow sequences. Within-channel flows covering instream benches (0) and irrigation flows providing limited annual access to adjacent wetland habitats every fifth year (5), every third year (3), every second year (2) or every year (1).

The model indicates that the highest risk scenarios for Carp population increases all relate to floodplain inundation (natural and managed flooding, and inundations using regulators). Where major floods occurred during the simulation (see Figure S2), the chance of a large population increase was very high. Although natural large-scale flooding is a high-risk scenario, such events occur infrequently. Managers can exercise little control over these events, but they do need to be aware of the consequences of natural floods on Carp stocks and the potential interaction with future managed flow events. However, for other high-risk scenarios managers may have greater control options; therefore, this Carp model provides a valuable tool for exploring a variety of water management regimes. This may assist managers in making decisions with respect to various operating scenarios and in identifying which scenarios pose the highest risks of Carp population increases. This knowledge can then be considered in the context of the ecological objectives for native biota that management is targeting. It can also provide information on where active management of Carp may need to occur.

The model indicates that floodplain inundations can create a spike in Carp populations (shown in Figure S2) that can endure for some time after the flow event. These high-risk scenarios relate to both natural flooding and inundations using floodplain regulators but can also affect other ephemeral and regulated wetlands, wetlands adjoining weir pools, and terminal and off-channel lakes, where high population growth rates may also be maintained. There are two key components to be considered in developing management regimes: first, the sequencing of managed flows and floodplain inundations; and second, the return of Carp from the floodplain to the river metapopulation (the group of subpopulations between which movement of individuals can occur regularly e.g. from individual wetlands or river reaches). Given the relatively short time required for Carp to reach sexual maturity (2–3 years), increased abundance in Carp populations can be exacerbated by frequent sequential overbank flooding. For example, the use of floodplain regulators to deliver high-frequency managed flooding by otherwise within-channel river flows poses a

significant risk of maintaining a high Carp population as well as high emigration into the river channel. Therefore, this Carp model could be used to further explore the risk and to consider where, how and how frequently management interventions should occur for the best outcomes.

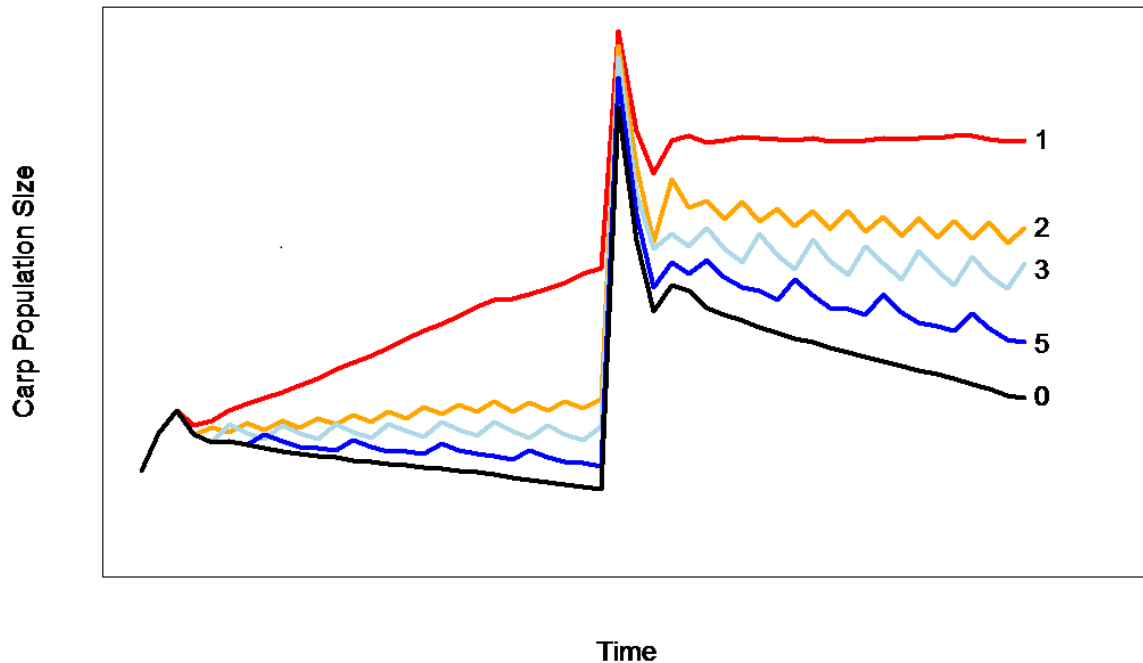


Figure S2. The likely relative changes in Carp populations over time, with different flow sequences providing a range of levels of access to adjacent wetland habitats and the inclusion of a flood or floodplain inundation

Within-channel flows covering in-stream benches only (0), and irrigation flows providing limited annual access to adjacent wetland habitats every fifth year (5), every third year (3), every second year (2) or every year (1).

The impact of changes in Carp populations on the river metapopulation can largely depend on the return of newly recruited Carp from off-channel habitats. Risk is increased if these population additions are cumulative, either from multiple sites or across consecutive years. In some cases this may be preventable by containing Carp on the floodplain, although this is likely to mean that there may also be limited return of fish of any species (particularly medium and larger bodied species). Thus, some benefits to the riverine native fish community and other aquatic biota may also be lost if all emigration from floodplains is reduced or prevented. Where the primary aim of flow restoration is to provide overbank flows, there is a need for a transparent recognition, by all stakeholders, that Carp may benefit and that their populations may increase. Any such increase should be placed within the context of existing Carp population levels and also of improvement in the condition of native biota and supporting ecosystem processes. Carp risk needs to be acknowledged and managed, but not at the expense of forgoing the benefits to the native biota (as per the original objectives). Key risks of increased Carp populations as a likely response to different components of flow regimes and water management are shown in Figure S3.

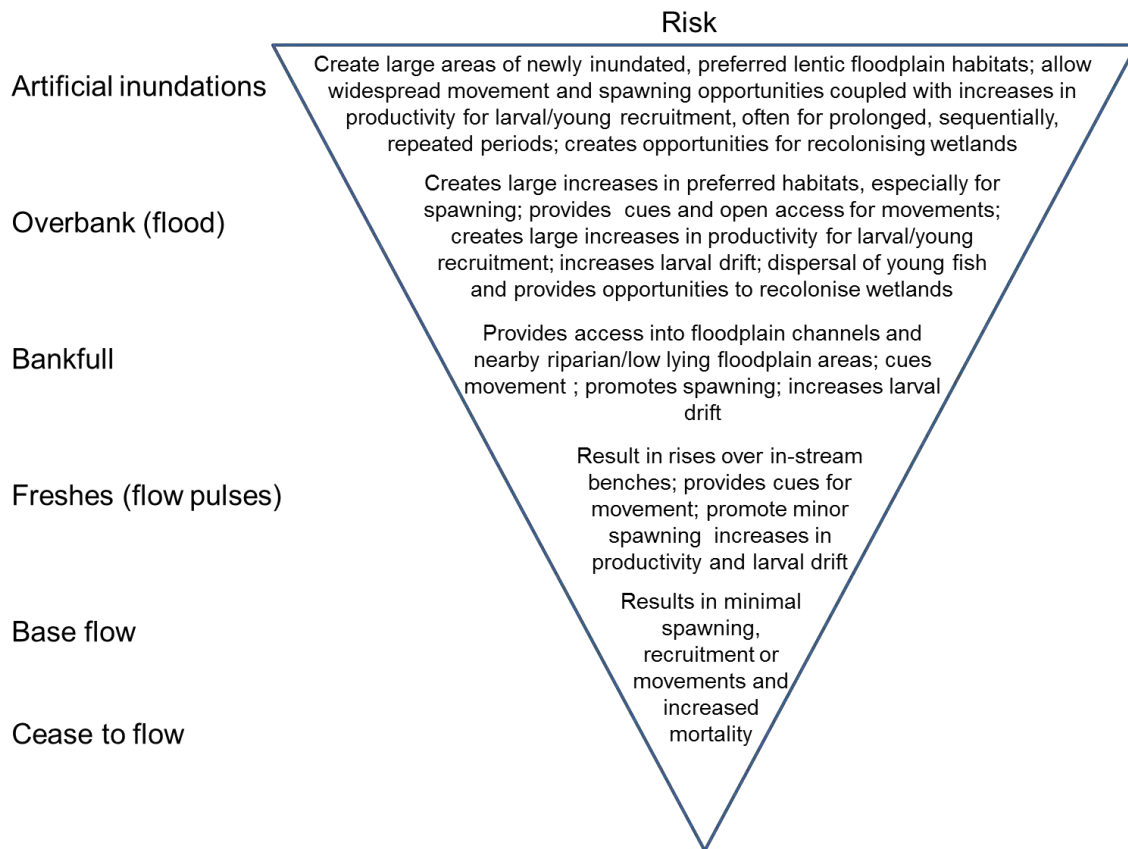


Figure S3. Summary of the key risks (without mitigating actions) for Carp population expansion in response to the various components of environmental water management

Managing the risk of an increase in Carp populations highlights the need for the development and implementation of adequate Carp management plans for all high-risk sites. Regional level plans and management should consider local attributes such as hydrology, flow volume, wetland inundation levels, height to fill thresholds, flow (and fish) connections, and how Carp life history and developmental stages (eggs, larvae, juveniles, etc.) are affected by them. While Carp management plans are required at a site scale, these could be assisted by an overarching MDB Carp management plan, better collaboration between water and Carp management and a clarification of agency responsibilities in relation to Carp. There is also a need to quantify the benefits of Carp management actions—this has largely been missing from Carp management to date, and clearly defined management goals (e.g. aquatic plant values) are a key to this evaluation.

The essence of changes to population abundance are encompassed in the following general population equation:  $N_{t+1} = \lambda N_t$ , where  $N$  is the population,  $\lambda$  the population growth rate and  $t$  is time; i.e. the population at a future time ( $t+1$ ) is a result of the population at time  $t$  multiplied by the population growth rate ( $\lambda$ ).  $\lambda$  can be derived mathematically and summarises the collective vital rates of fecundity and survival of all life stages of the species (i.e. eggs, larvae, juveniles, adults). Survival rates may be different for each life stage and the various habitats in which it occurs.  $\lambda$  then allows for the calculation of a theoretical doubling time for the population; i.e. when  $\lambda = 2$ , the population doubles annually.  $\lambda > 1.2$  could be considered a significant population growth rate. The following table indicates modelled estimates of Carp population growth rates for a range of flow–habitat types.

Table S1. Modelled estimates of Carp population growth rates for various flow–habitat types  
 Note,  $\lambda > 2$  rates are highlighted in bright orange and  $\lambda > 1.2$  rates are highlighted in pale orange.

Habitat–flow type	Theoretical population growth rate ( $\lambda$ )	Theoretical population doubling time (years)
Artificial floodplain inundation, e.g. Chowilla	2.60	0.73
River wetland e.g. Barmah–Millewa	2.43	0.78
Natural floodplain inundation	2.41	0.79
Wetland permanently connected, e.g. adjacent weir pool	1.78	1.20
Lakes (terminal), e.g. Alexandrina	1.74	1.25
Wetland perennial, e.g. Kow Swamp	1.52	1.66
Wetland ephemeral, e.g. Hattah Lakes	1.46	1.83
Lakes (off-stream), e.g. Lake Victoria	1.42	1.98
Main channel (Lower Murray)—cover benches	1.06	11.90
Main channel (Mid Upper Murray)—summer irrigation flow	1.02	35.0
Main channel (Mid Upper Murray)—cover benches	0.88	NA
Main channel (Lower Murray)—base flow	0.86	NA
Irrigation channels	0.80	NA
Channel (Mid Upper Murray)—base flow	0.77	NA

## Case studies

The generic modelling undertaken for this project has enabled some general management recommendations to be made. Our recommendations are also reinforced by case studies. Because there are a wide range of sites and scenarios that involve the management of flow and Carp, this complexity demands they be modelled on an individual basis. For example, there is a need to consider local hydrology, flow volume, wetland inundation levels, height-to-fill thresholds, flow connections, etc., as well as how Carp developmental stages are affected by these factors. Modelling of case studies, particularly relevant to priority areas and habitats in the MDB, has provided examples of the applicability of the model with site-scale detail and has illustrated model outputs. In order to simplify the key issues, the following steps were undertaken for each site:

1. developing a conceptual schematic diagram of the site
2. identifying the key habitats
3. determining the areas of each habitat

4. determining the likely flow regime and sequences
5. modelling the Carp population response.

We considered four case studies as representative examples of particular habitat types in the Murray River: the Lower Murray River downstream of Lock 1, the Edward–Wakool river system, the Chowilla floodplain, and the Barmah–Millewa floodplain. It is important to note that these case studies have only modelled Carp population responses and have not investigated the responses of other biota. As noted before, it is critical that Carp risk is acknowledged and managed where possible, but the primary objectives of environmental flows should be to maximise benefits to native biota.

### **Lower Murray River downstream of Lock 1**

The lower Murray case study includes the Lower Lakes (Albert and Alexandrina), the lower wetlands (which are mostly inundated on a long-term basis), and the Murray River to Lock 1. This case study considers five habitat types: river channel base flow, ephemeral wetland, permanently connected wetland, natural floodplain inundation, and terminal lakes. Modelling outputs show a system dominated by the dynamics of Carp in the Lower Lakes, with all scenarios indicating the rapid development of a large lakes population. This may have coincided with the large floods of the mid 1970s; however, it is more likely that the critical mass of breeding fish in the population is always present, with few limits on population growth. Also, the Carp population in the Lower Lakes produces large numbers of Carp available for dispersal to other parts of the river system, as exhibited by congregations of Carp at Lock 1. Removal by commercial harvesting may help reduce the population during drought or low flows.

#### ***Key modelled Carp outcome***

The Lower Lakes remains a significant source Carp population, regardless of flow; hence, any environmental flows provided will have little impact overall, except possibly in years of low flow. In times of drought or low flow, large-scale removal of Carp may be beneficial in significantly reducing Carp numbers in the Lower Lakes, particularly by reducing Carp available for dispersal.

### **Edward–Wakool river system**

The Edward–Wakool river system provides a good example of complicated water management. This system consists of a mosaic of rivers, wetlands and floodplains, with flows supplemented with water from a number of secondary sources, and the region crisscrossed with a number of ephemeral creeks. This case study considered three habitat types: in-channel cover of benches, summer irrigation flows, and natural floodplain inundation. Historical flow sequences that provided a broad spectrum of flow conditions (i.e. wetter and dryer periods) were used to examine the response of Carp populations.

Three scenarios were considered: (1) Wakool only; (2) Edward only and (3) Edward and Wakool combined. Scenario 3 had an increased carrying capacity because it modelled both rivers, assuming that Carp could move freely within the combined system. When the two rivers were treated as one system in which Carp from the Wakool could access the floodplain in the Werai Forest, Carp abundance doubled and the modelling indicated that the moderate flows that inundated the Werai Forest would maintain the Carp population in the Edward–Wakool system.

#### ***Key modelled Carp outcome***

Any flooding of the Werai Forest is likely to increase the population in the Edward–Wakool River System. Any use of the Edward River for water transfers is likely to contribute to a higher Carp population in this system.

*Note:* The Werai Forest, like many other sites, has many important values for native biota. Managers should consider the modelled Carp results against the objectives for native biota and potential

management options, as well as the need to deliver water through the Edward–Wakool river system for other purposes (e.g. consumptive deliveries).

### **Chowilla floodplain**

Chowilla is a large undeveloped River Red Gum (*Eucalyptus camaldulensis*) and Black Box (*Eucalyptus largiflorens*) floodplain in the lower Murray River where engineered artificial floodplain inundation using a regulator has been proposed. The Chowilla case study is a simplified study of two habitat types: within-channel flows (summer entitlement to South Australia) and floodplain inundation through natural or artificial means. Two flow scenarios were modelled: (1) 'observed' and (2) 'regulator-enabled' (applying the hypothetical operating regime of the Chowilla regulator). Artificial inundation or natural inundation of the Chowilla floodplain would similarly result in a large number of Carp being available for dispersal. The modelled flows from the operational strategy (Scenarios 1 and 2) show a doubling of the number of Carp available for export into the Murray River. If Carp access the Chowilla floodplain through the operation of the Chowilla regulator there would be significant recruitment and large numbers of Carp available for dispersal in 3 out of 5 years.

#### **Key modelled Carp outcome**

Artificially inundated floodplains provide a high-risk scenario that could significantly contribute to the greater Carp populations if fish were allowed to disperse from these habitats.

*Note:* Management of floodplains is extremely complex and challenging. These habitats often represent key Carp breeding sites, and it is difficult to manipulate flows to provide both positive outcomes for a range of native biota and minimal benefits to Carp. Water managers have high levels of control over regulator operations, and ultimately artificial floodplain inundation should be carefully considered, with frequent events minimised as much as possible. The Carp model can be used to explore a number of different management scenarios in further detail and to refine management over time.

### **Barmah–Millewa floodplain**

The Barmah–Millewa Forest is a large, complex floodplain wetland system in the Mid Murray River, and it includes Barmah and Moira lakes. It is used by Carp in the mid Upper Murray River as a preferred spawning site. The flow sequence determines the length of time water is on the floodplain, as well as the extent of the water on the floodplain: the larger the flow, the greater the extent; and the longer the flow, the higher the likelihood of breeding success by Carp. Historical flow data were used to model access to the floodplain. Three habitat types were modelled: summer irrigation flow, river wetland, and natural floodplain inundation. The Carp population in the Barmah–Millewa region maintains itself when only the summer irrigation flow is considered, although low abundances of Carp are available for dispersal. When Carp have access to either the Barmah–Moira lakes (river wetland) or the Barmah–Millewa floodplain, the average adult population size increases and the number of Carp available for dispersal significantly increases. The exploration of these scenarios indicates that interaction between the Barmah–Millewa floodplain and the Barmah–Moira lakes makes managing Carp in the region very difficult. While it may be possible to limit access to the Barmah–Moira lakes, it would be nearly impossible to limit access to the broader Barmah–Millewa floodplain. The outcomes from modelling this complex system indicate that the Barmah–Millewa floodplain and the Barmah–Moira lakes are capable of producing very large numbers of Carp for dispersal to other areas of the MDB. Annual high irrigation flows during conditions suitable for Carp spawning that provide access to the adjacent wetlands are likely to be artificially supporting higher Carp numbers.

#### **Key modelled Carp outcome**

When Carp have access to a natural floodplain or a river wetland, the population response can be large and can then provide large numbers of Carp for dispersal. Limiting access to the Barmah–Moira lakes could help contain Carp numbers in years without access due to natural flooding.

## Conclusion

Environmental water management is a relatively new science in which management actions and scientific endeavours are extending our knowledge base interactively. This study illustrates the utility of a population model for exploring potential changes in Carp populations arising from a range of flow scenarios, including environmental water management. Additional tools such as conceptual and population models (both for Carp and native fish) will greatly assist this management by allowing exploration of the relative outcomes of various options. While the development of this modelling has been a major step forward, there are several additional opportunities that could greatly progress water and Carp management in the future:

1. The development of a metapopulation model for Carp. While the current model can be utilised at any scale, the integration of a variety of habitats, areas and flows would provide outputs with greater amenity for flow managers. This would enable us to follow the fate of Carp that have been produced in one location, but migrated to other locations, and to explore the impact of large-scale emigration on management of the system.
2. Application of this model to the northern MDB, which has some key ecological differences from the southern MDB that need to be explored and incorporated. (Some work is expected to begin on this soon.)
3. Development of population models incorporating flows for a range of native fish species. (Work has just been initiated for eight species.)
4. Ultimately, a fish community model that can include interactions between species and watering options could be developed.

Current thinking indicates that planning for environmental flow and Carp management is best conducted over longer time frames (e.g. 10+ years) that can easily be accommodated with the use of modelling. Together with similar outputs from the newly initiated Native Fish Population Models Project, managers will soon be able to make comparisons of benefits and risks for a range of species so as to make more informed decisions regarding watering actions.

## Key messages

- Priority objectives for environmental water management in the MDB are to benefit native biota, and this focus must be maintained.
- Carp are a highly visible and abundant invasive fish species that can readily respond to flows, especially overbank flooding. The long potential spawning season for Carp overlaps with that of many native fishes and also with likely watering times for other biota; hence, careful management is needed.
- Natural flooding does promote Carp and native fish population growth, but water managers have little control over these flows.
- Carp are now a major component of MDB fish fauna, and their recruitment may be an inevitable by-product of some watering activities, including those for environmental objectives. The responses observed in Carp populations are influenced by existing high abundances. In general, however, in-channel environmental flows will have minimal impacts on Carp populations, but will have benefits to native fish populations. Furthermore, existing large reproductive Carp populations in the Lower Lakes of the Murray River mean that environmental flows into South Australia will have limited further impact on Carp numbers in the lower Murray River.
- Habitats and flows that result in high population growth rates pose the highest risk of increases in Carp populations, and these involve the inundation of floodplain, wetland or lake habitats.



- Artificial floodplain inundation using regulators is likely to pose a significant risk of increasing Carp populations. Such inundations may export Carp from floodplains and substantially increase the river metapopulation. Frequent, sequential inundations of the floodplain and the cumulative impacts from multiple large-scale sites constitute the greatest risk of increasing the Carp populations in the Murray River. Nevertheless, water managers have high levels of control over this type of management action and, hence, have the ability to manage such inundations carefully.
- Watering for non-fish outcomes could be considered during winter months (water temperatures <math><16^{\circ}\text{C}</math>) to minimise Carp recruitment. This may mean, however, that positive outcomes for native fish should not necessarily be expected. Winter watering events may not produce some of the desired outcomes for native biota, so the use of winter flows should be carefully considered in the context of ecological objectives.
- There is a need for Carp to be managed in conjunction with watering through the development and implementation of adequate Carp management plans for high-risk watering activities and sites (e.g. large wetland/floodplain areas), with actions based on pest management principles. These site plans would benefit from being set within the context of a coordinated, MDB-wide Carp management plan.
- In order to quantify the responses of Carp to flows and to manage populations, data from regular monitoring is needed. These data can also be incorporated into population models that can be used to forecast potential changes in Carp and native fish abundances over the appropriate temporal (decadal) timescales.
- There is a need to evaluate the benefits of flow management actions to native species so that these can be balanced against any impacts from any potential increases in Carp populations. A step towards this has occurred through the initiation of a project for developing native fish population models that will allow the benefits of environmental flows for fish to be explored.



## 1 Introduction

Alteration of flow regimes is one of the greatest threats to riverine fishes, and the Murray–Darling Basin (MDB) is among the world’s largest ecosystems impacted by flow regulation (Nilsson et al. 2005). As such, a key objective of the *Native Fish Strategy for the Murray–Darling Basin 2003–2013* was to redress the damaging impacts of flow regulation (MDBC 2004; Koehn and Lintermans 2012). Environmental flows and environmental water allocations (EWAs) are now widely recognised as rehabilitation techniques for restoring aspects of the natural flow regime in flow-altered systems, or for protecting critical flows in largely unaltered rivers (Arthington et al. 2010; Arthington 2012). Such flows provide a wide range of benefits to MDB fishes (see below, summary in Appendix 1, and Koehn et al. 2014a) and other native biota (especially waterbirds and riparian vegetation) (Kingsford and Auld 2005; Poff and Zimmerman 2010). Recent water reforms have resulted in major changes in flow management in the MDB, including a substantial increase in the availability of environmental water and a more ecologically sensitive management of regulated flows. The Basin Plan [Murray–Darling Basin Authority (MDBA 2010, 2011)] outlines environmental objectives and establishes the importance of environmental watering for the MDB.

The objectives of environmental flows under The Basin Plan are ‘to protect and restore environmental assets’ (MDBA 2010, 2011); many of the early objectives for EWAs were aimed at enhancing waterbirds populations or vegetation, but objectives for fish and other ecological assets are now commonly included (Koehn et al. 2014a, 2014c). During the recent ‘Millennium Drought’ (1997–2010) (van Dijk et al. 2013), in the MDB flows were often limited and used to maintain refuge habitats, but we now have the opportunity to move towards managing flows in the context of flow regimes over longer time frames and larger spatial scales. Since the early 2000s there has also been an increased emphasis on the construction and use of infrastructure such as pumps and regulators to apply water to floodplains (Pittock et al. 2012), especially along the Murray River. Under drought conditions, with limited water available for environmental purposes, the emphasis in EWAs was to maximise the floodplain area watered for the volume of water used. This resulted in the concept of the use of regulators to facilitate inundations by artificially impounding water on the floodplain. It is important to note, however, that impounded water on the floodplain is not the same as a natural flood; there are many differences and considerable risks for fish in particular (Mallen-Cooper et al. 2008, 2011; Koehn et al. 2014a). These include an increased likelihood of poor water quality or blackwater (King et al. 2012) and an increased production of the alien fish species Carp (*Cyprinus carpio*) (Bice and Zampatti 2011).

Although The Basin Plan has been a divisive social and political issue (Koehn 2015), the common goal of ‘a healthy fish community’ can help to reconnect disparate sectors of the community and to set the context for a positive public perception of the benefits of environmental flows. Indeed, the status of fish populations, especially of angling species, is the single measure by which the public is most likely to judge the successful management of rivers and water in the MDB (Koehn 2015). Carp, however, are viewed negatively by the Australian public and are considered a pest species (Koehn et al. 2000) with a high priority for control and management (Koehn and MacKenzie 2004). There is some concern that Carp populations may also benefit from both EWAs and the use of floodplain regulators (Mallen-Cooper et al. 2008, 2011; Koehn et al. 2014a). Although this is possible, there is a need to quantify any such changes and to interpret them in the context of a heavily modified and managed river system that is also subject to irrigation flows and natural flooding. Managing environmental flows requires maximising the benefits to native biota, while recognising the potential for some negative outcomes (real or perceived) in relation to Carp. Providing ecological benefits for native biota (including native fish) must remain the priority objective for environmental water management, and there is a risk that becoming too risk-averse in relation to any potential Carp impacts may compromise these established flow objectives (Koehn et al. 2014a).

This project provides: an up-to-date summary of the knowledge of Carp ecology (especially in relation to flows); a review of Carp management methods; development and use of a population model to predict potential Carp responses to a range of in-channel flows and wetland and floodplain inundation events; risk assessments for particular watering and management actions; and recommendations and management guidelines for managing flows and Carp. The Murray River is used as an example, but this project has applicability across the southern MDB. The specific objectives of the project are outlined below.

## 1.1 Project objectives

The priorities of this project are (i) to determine the response of Carp populations to flows and environmental watering (majority of project) as well as regulator-type water management interventions, and (ii) to provide a brief overview of Carp removal-type management options. The Murray River was used as an example, but outcomes are considered to be transferable across the southern MDB. As Carp will be subject to, and take advantage of, existing flow regimes (both modified and 'natural'), it is not possible or sensible to consider their populations only in relation to EWAs. It is possible that other aspects of flow regimes (such as irrigation releases, the provision of weir pools, and natural flood events) may have significant impact on Carp populations. Hence, this project has considered flows, and Carp more broadly, in relation to the whole flow regime.

The specific objectives of this project are to:

1. Provide an up-to-date review of the relevant Carp literature (from recent research publications and management plans), including: (a) Carp biology—especially recruitment, movements and population dynamics across differing spatial scales; (b) Carp management plans, risk assessments, likely watering locations, high profile wetlands, Carp 'hotspots', and floodplain regulator and pumping sites; and (c) a summary of recent and proposed watering plans.
2. Review the functionality and applicability of existing Carp population/management models, assess their limitations and usefulness in this process, and modify if necessary.
3. Develop a tool for quantifying any impacts of flows (including environmental watering) on Carp populations.
4. Model and undertake risk assessments of likely Carp population outcomes from various watering/management scenarios.
5. Develop practical recommendations or guidelines for the management of environmental water and the use of infrastructure to minimise the detrimental impacts of Carp.

## 2 Background

### 2.1 Murray–Darling Basin

The MDB covers 1.1M km<sup>2</sup> (14% of Australia’s land area) and extends over four States (South Australia, Victoria, New South Wales and Queensland) and a Territory (Australian Capital Territory). Ranging from 24° to 37° S in latitude and to more than 2000 m above sea level in altitude, the MDB experiences a wide range of climatic conditions, especially in rainfall and temperature. It contains the continent’s three longest rivers: the Darling (2740 km) (see Breckwoldt et al. 2004), the Murray (2530 km) (see Mackay and Eastburn 1990) and the Murrumbidgee (1690 km) (see Crabb 1997), each with their own characteristics. The Darling drains northern tributaries, with highly variable but predominantly summer rainfall; the Murrumbidgee drains southern New South Wales; and the Murray drains northern Victoria and contributes the bulk of the flow to the Lower Murray. Flows of the Murrumbidgee and Murray river systems are more consistent than those of the Darling River and are highly regulated by a series of dams in the upper reaches; interannual variability in flow, especially within the drier and temperate regions of the MDB, is extremely high (Walker et al. 1995), and these factors need to be considered when managing fish across this large area.

The concentration of agricultural development in the MDB has resulted in a large investment in storage dams and water infrastructure, most of which are located in the eastern MDB, capturing run-off from the western edge of the Great Dividing Range and providing water for irrigation and agriculture (Crabb 1997). This has placed significant ecological pressure on aquatic ecosystems, with high levels of flow regulation and subsequent changes to flow regimes. These changes include reduced natural flooding and major changes to flow seasonality (especially in the MidMurray River; Close 1990), high levels of water abstraction, and floodplain and riparian modification (MDBC 2004; Koehn 2015).

### 2.2 The Basin Plan

The Basin Plan identifies broad themes and establishes a range of objectives for environmental watering for the MDB (MDBA 2010, 2011). These objectives will be achieved through complementary strategies and plans developed at state and regional levels, and supplemented by the Basin-wide environmental watering strategy, which outlines additional outcomes and targets (Figure 1; MDBA 2014). The objectives encompass a range of native biota and ecological processes—the intended outcomes for native species must be balanced against unintended outcomes, such as increased Carp populations or blackwater (Figure 2).

A summary of The Basin Plan objectives includes protecting and restoring:

- a subset of all water-dependent ecosystems
- ecological productivity
- ecological dispersal
- biodiversity (listed threatened species and support of their life cycles)
- representative populations and communities of native biota
- connectivity—longitudinal, lateral (between watercourses and floodplains/wetlands) and vertical (i.e. overcoming barriers to passage)
- diversity and dynamics of geomorphic structures, habitats, species and genes
- ecosystem function, e.g. recruitment, regeneration, dispersal, immigration and emigration

so that water-dependent ecosystems:

- support habitat diversity for biota at a range of scales
- are not adversely affected by water quality
- are resilient to climate change, climate variability and disturbances
- protect refugia and allow for subsequent recolonisation
- mitigate human-induced threats
- minimise habitat fragmentation.

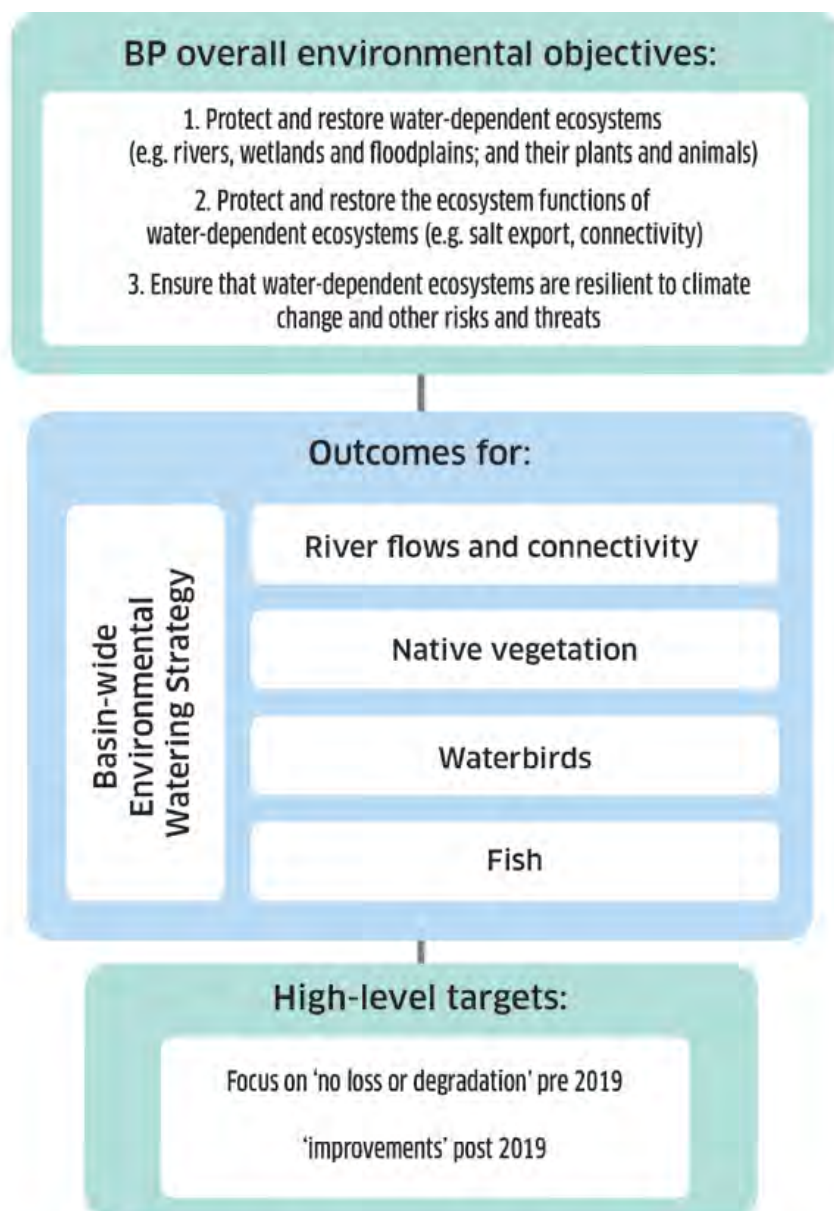


Figure 1. The environmental objectives, outcomes and targets for the Basin Watering Strategy (from MDBA 2014)

BP = Basin Plan.

<p><b>Environmental benefits</b></p> <p><b>To native biota</b></p> <p>Waterbirds (120 species)</p> <p>Native fishes (60 species)</p> <p>Native vegetation</p> <ul style="list-style-type: none"> <li>Riparian plants</li> <li>Wetland plants</li> <li>Floodplain plants</li> </ul> <p><b>To ecosystem processes</b></p> <p>Increased productivity</p> <p>Reproduction and recruitment</p> <p>Condition</p> <p>Connectivity</p>	<p><b>Potential risks</b></p> <p>Alien fish species</p> <ul style="list-style-type: none"> <li>Carp</li> <li>Gambusia, Weatherloach</li> </ul> <p>Blackwater/poor water quality</p>
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Figure 2. Ecological benefits and risks of environmental flow management

### 2.3 Fish and flows

Flows that naturally inundate floodplains or in-channel benches are fundamental to the processing and exchange of nutrients and organic matter between a river and its surrounds (Junk et al. 1989; Tockner et al. 2000). Such flooding is known to enhance fish recruitment, because it cues spawning and/or increases the availability and access to food for young fish, hence improving their growth and survival (Junk et al. 1989; Jardine et al. 2012). Some fish species actively move onto inundated floodplain habitats and use these food-rich areas to improve body condition and growth (Lyon et al. 2010; Tonkin et al. 2011).

Flow pulses, especially in spring and summer, stimulate adult and juvenile fish to move both upstream and/or downstream to spawn or exploit alternative habitats (Mallen-Cooper 1999; O'Connor et al. 2005; Mallen-Cooper and Brand 2007), and they promote spawning and recruitment (King et al. 2009; Zampatti and Leigh 2013). While flooding can provide many benefits to native fishes (see Section 2.3), there may also be occasions when it causes some negative outcomes. Flooding has been linked to increased recruitment and dispersal of alien fishes such as Carp, Oriental Weatherloach (*Misgurnus anguillicaudatus*) and Eastern Gambusia (*Gambusia holbrooki*) (Stuart and Jones 2006b; Beesley et al. 2012). Summer floods can create hypoxic blackwater events that can lead to fish kills (King et al. 2012; Leigh and Zampatti 2013) and may contribute to high sedimentation (Lyon and O'Connor 2008). Water managers need to consider these risks, and there is scope for EWAs to assist in risk mitigation (see Koehn et al. 2014a).

The five different levels of EWAs as determined by the Commonwealth Environmental Water Office (CEWO) are illustrated in Figure 3. Flows at these levels will each have different impacts on fish (see following sections), but the potential impacts on Carp for each are summarised in Table 1.

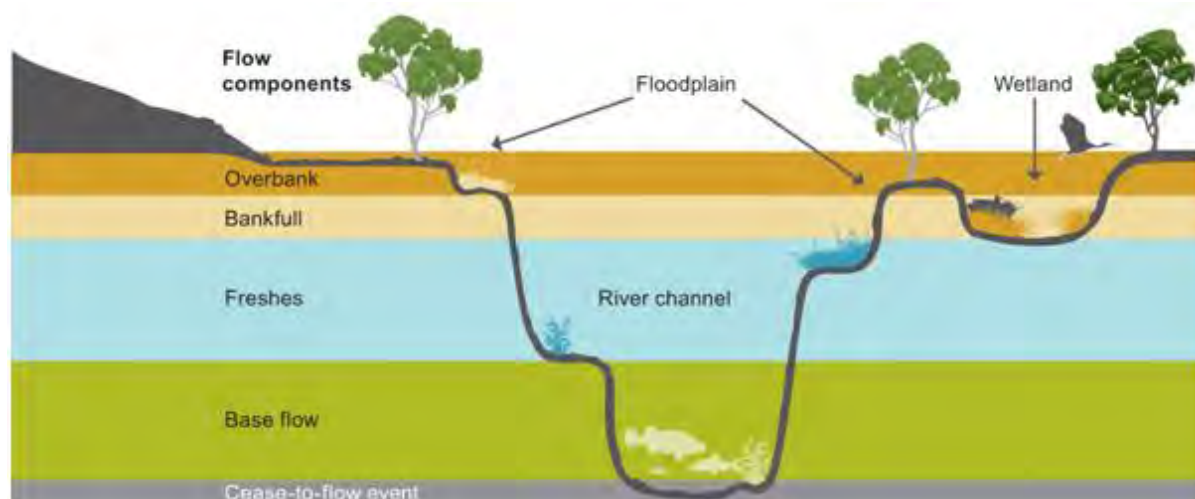


Figure 3. The five different environmental flow components (as determined by the Commonwealth Environmental Water Holder) (Gawne et al. 2013)

Table 1. The potential effects of the differing flows (see Figure 3) and water inundations on Carp

Flow type	Flow/habitat components	Impact on Carp
Overbank (flood)	Usually results from natural events; provides full access to floodplains and wetland habitats	Large increases in preferred Carp habitats, especially for spawning; open access for movements; large increases in productivity for larval/young recruitment; provides cues and allows widespread movement, spawning and recruitment; increases in larval drift; major dispersal of young fish; opportunities to recolonise wetlands; some adults can get trapped on the floodplain or in wetlands when waters subside.
Bankfull	This is irrigation flow for some reaches; increases flows into floodplain channels; inundates all benches and low wetlands	Provides access into floodplain channels and nearby riparian/low-lying floodplain areas; may provide movement cues; may be stable or variable in level; cues major upstream, downstream and lateral movements and formation of aggregations; promotes spawning; increases larval drift.
Freshes (flow pulses)	Variable flows; inundates in-stream benches	Rises over in-stream benches; provides cues for movement; may promote minor spawning; increases productivity.
Base flow	Stable water level within low-flow channel	Minimal spawning recruitment and movements.
Cease to flow	Stable water level	May result in refuge pools; increases chance of fish kills (Carp less affected than many species); minimal spawning recruitment and movement; increases mortality.
Artificial inundations		Provides access to large areas of inundated floodplain; creates largely lentic habitats; allows widespread movement and spawning opportunities, coupled with increases in productivity for larval/young recruitment, often for substantial periods.

## 2.4 Native fishes in the MDB

There is much concern over the health of rivers in the MDB, with 19 of the 23 river valleys rated in 'poor' to 'extremely poor' ecological condition (Davies et al. 2010, 2012). Native fish populations in the MDB have suffered serious declines and are estimated to be at ~10% of their pre-European settlement levels (MDBC 2004). Over half of the native wholly freshwater fish species (24 of 44) and four fish communities of the MDB are listed as threatened at either national or state level (Koehn and Lintermans 2012; Lintermans 2013). Given the relatively low number of endemic native fish



species in the MDB only 44 naturally occurring, Lintermans 2007), there is considerable concern for the future of native fishes in the MDB.

Fish in the MDB have a range of important ecological, conservation, cultural, recreational and economic values, and there is considerable public interest in them (Lintermans 2007; Koehn et al. 2014b). Aboriginal people have important cultural connections to MDB fishes (Rowland 2005; Ginns 2012) and recreational angling is an important pastime in Australia, with a participation rate of almost 20% nationwide (higher in rural areas) (Henry and Lyle 2003). Angling provides significant contributions to regional tourism, and an initial assessment of the economic contribution of recreational angling to the MDB suggested likely estimates of: AUD1.35B direct expenditure annually, AUD357M added expenditure, a AUD403M contribution to GDP, and a contribution of 10,950 jobs (Ernst and Young 2011).

The recognition of the importance of these values and the generally poor state of native fishes throughout the MDB led to the development and adoption of a *Native Fish Strategy for the Murray–Darling Basin 2003–2013* (NFS), which aims to restore populations to 60% of pre-European settlement levels after 50 years of implementation (MDBC 2004; Koehn and Lintermans 2012). While there are many threats to MDB fishes (Koehn et al. 2014b), improving altered flow regimes (and the use of EWAs) and the management of alien fish species are seen as key components of rehabilitation; these remain enduring objectives of the NFS (MDBC 2004; Koehn and Lintermans 2012). In particular, the main alien fish of concern is Carp, which makes up a large proportion of the biomass at many sites within the MDB (Koehn et al. 2000). Indeed, the provision of adequate flow regimes and the ‘control’ of Carp have been estimated at potentially contributing to ~75% of the recovery target (60% of pre-European levels) for native fish populations overall. This highlights the importance of projects such as this one in understanding how to manage Carp populations in relation to flows.

#### **2.4.1 Potential benefits of environmental flows to native fish**

Environmental flows can provide a wide range of benefits to native fishes of the MDB (see Koehn et al. 2014a; Appendix 1), including:

##### ***Spawning and recruitment***

- increased spawning of some species
- increased recruitment of some species

##### ***Growth and condition***

- increased body condition and growth

##### ***Habitat***

- habitat maintenance
- increased habitat area, e.g. flows into floodplain channels, expanded wetlands, prolonged inundation of floodplains
- increased habitat diversity
- provision of refuge areas during low flows

##### ***Movement and connectivity***

- within-channel movements for adult or juveniles of some species
- recolonisation opportunities
- movement of some species onto floodplains
- connectivity to the marine environment for the completion of diadromous species’ life history

- increased egg/larval dispersal

### **Ecosystem production**

- increased food production in wetland and floodplain habitats
- increased input of organic carbon and material from wetland and floodplain habitats for ecosystem productivity.

As the science of environmental flows is relatively new, the management and delivery of environmental water is currently developing at a rapid rate, and our knowledge is far from complete. Our understanding of fish–flow interactions is increasing, with increasing emphasis in recent research into aspects of fish biology in relation to flows for a variety of fish species, with many examples of new science (e.g. Beesley et al. 2011; see Appendix 1), reviews and syntheses (e.g. Koehn et al. 2014a) and management application (e.g. King et al. 2010) that can be used to guide and further develop the application of flows for fishes. Knowledge of these processes in relation to Carp can assist in their management.

## **2.5 Carp as an invasive species**

Alien fish species have received considerable attention internationally, with the integrity of aquatic ecosystems being challenged worldwide by species invasion (Moyle and Light 1996; Strayer 2010). Carp is one of the most pervasive invasive fish species (Zambrano et al. 2006; Weber and Brown 2009) and is now widely distributed around the world (Lever 1996). There are a number of common attributes that make invasive species successful (Ehrlich 1976; Morton 1978, 1997; Groves and Burton 1986; Ricciardi and Rasmussen 1998). An analysis of Carp shows that they have most of these attributes: wide environmental tolerances, rapid growth, high reproductive capacity, broad diet, gregariousness, mechanisms of dispersal, being associated with human activity, relatively high genetic variability (three different strains introduced into Australia: Prospect, Yanco and Boolarra; Shearer and Mulley 1978; Haynes et al. 2009), early sexual maturity, and short generation times (Koehn 2004; table 2). Thus, Carp have high invasive potential, and this has been manifested in their successful invasions, both in Australia (Koehn 2004) and elsewhere around the world (Zambrano et al. 2006).

Carp are native to Eastern Europe and central Asia, and they have been widely translocated to become successful invaders in parts of Europe; Asia; Africa; North, Central and South America; Oceania; and Australia (Lever 1996). They were first introduced to Australia on several occasions after the mid 1800s (Koehn et al. 2000), with different genetic strains having been recognised (Shearer and Mulley 1978; Haynes et al. 2009). Carp populations remained relatively contained until the introduction of the 'Boolara' strain into farm dams in Gippsland in Victoria in the 1960s, from where it spread rapidly throughout south-east Australia, particularly into the MDB (Koehn et al. 2000). Carp now occupy most of the MDB, with the exception of some northern reaches (where invasion is slowed by weirs) and at some altitudes above 700 m (Driver et al. 1997). Carp has become the most abundant large freshwater fish in south-east Australia (Koehn 2004), comprising more than 90% of the fish biomass in many areas, resulting in biomasses as high as 3144 kg/ha and densities of up to 1000 individuals/ha in the MDB (Harris and Gehrke 1997).

Carp are a highly mobile species, and within-catchment migrations and downstream larval drift have proven to be effective methods of population dispersal (Koehn and Nicol 1998, in press; Stuart et al. 2001). Human intervention is a major vehicle for invasion of Carp into new catchments, and transfer of Carp between catchments by anglers (either accidentally or deliberately) does occur, despite the illegality of keeping, transporting or releasing Carp in most states of Australia (Koehn et al. 2000; Lintermans 2004). The invasion of Carp in south-eastern Australia illustrates how quickly an alien fish species can spread and dominate fish communities. Their invasion history, dispersal mechanisms and



generalist ecological requirements indicate that expansion of Carp across most of the remainder of Australia is to be expected (Koehn 2004).

Table 2. Attributes of Carp as an invasive species (adapted from Koehn 2004)

Attribute	Details	References
Invasion history, wide distribution and abundance	Introduced and successfully established throughout Europe, Asia, Africa, North America, South America, Central America, Australia, New Zealand, Papua New Guinea and some islands of Oceania; likely further expansion	Lever (1996); Koehn (2004); Zambrano et al. (2006)
Wide environmental tolerances	Generally occur in most types of freshwater habitat and have high environmental tolerances: temperature ranges from 2 to 40.6°C, salinity up to about 14 ppt (0.4 seawater), pH from 5.0 to 10.5 and oxygen levels as low as 7% saturation	Horoszewicz (1973); Ott et al. 1980); Crivelli (1981); Hellawell (1986); Howes (1991)
High genetic variability	Multiple genetic strains in Australia	Shearer and Mulley (1978); Haynes et al. (2009)
Early sexual maturity	Males at 1 year, females at 2 years	Brumley (1996)
Short generation	2–4 years	
Rapid growth	Hatching of eggs is rapid (2 days at 25°C), and newly hatched Carp grow very rapidly	Balon (1975); Adamek (1998); Vilizzi and Walker (1999)
High reproductive capacity	They are highly fecund broadcast spawners, with egg counts as high as 2 million per female	Balon (1975); Banarescu and Coad (1991)
Broad diet	Omnivore/detritivore	Hume et al. (1983)
Gregariousness	A schooling species	Osborne et al. (2009); Bajer et al. (2011)
Natural mechanisms of dispersal	A mobile species, with fish moving between schools; dispersal can also occur with the downstream drift of larvae; rates of transfer can be affected by conditions such as flooding	Stuart et al. (2001); Koehn and Nicol (1998, in press)
Capacity for being commensal with human activity	Bred as an ornamental and aquaculture species; used as bait and sought by some anglers	Li and Moyle (1993); Lever (1996); Koehn et al. (2000)

High Carp abundances are a suggested potential contributor to the decline in native fish and a factor that may inhibit rehabilitation of native fish populations (MDBC 2004). However, the impacts of Carp on Australian fish are not well quantified (Koehn et al. 2000). Carp are, however, considered to be 'habitat modifiers' capable of affecting aquatic ecosystems (by altering bottom-up and top-down ecosystem processes; Weber and Brown 2014); when in high abundances, they are thought to detrimentally impact benthic habitats, water quality and the distribution and abundance of native

flora and fauna (Gehrke and Harris 1994; Miller and Crowl 2006; Matsuzaki et al. 2009; Howell et al. 2104; Weber and Brown 2014). In many locations Carp has either caused or been associated with large-scale and significant reductions in water quality and ecosystem health as a consequence of its habit of benthic feeding, during which it uproots plants and liberates sediments as well as nutrients (Parkos et al. 2003; Bajer et al. 2009; Weber and Brown 2009, 2011; Weber et al. 2010).

In Australia Carp have been shown to increase turbidity and nutrient availability (King et al. 1997), thus reducing photosynthetic production and visibility for visually feeding fish, destruction of aquatic vegetation (Roberts et al. 1995) and changes in the composition of zooplankton and macroinvertebrate communities (Robertson et al. 1997; Villizzi et al. 2014). Many of these impacts are due to the Carp's specialist feeding technique of sieving through the substrate, which allows them to take advantage of potentially underutilised resources, including detritus at the base level of the food chain. Detritus is likely to be abundant, especially given that true detritivorous fish are lacking in most Australian freshwater fish communities (Koehn 2004). With few effective predators, sequestered detrital carbon, rather than passing up through subsequent trophic levels of macroinvertebrates and smaller fish, may become 'locked' away from the trophic chain for the lifetime of the Carp (up to ~29+ years) (Koehn 2004).

### 2.5.1 Comparison of Carp and native fish species

Carp clearly differ from Australian native fishes in their behaviour, resource use and population dynamics, exhibiting a variety of ecological characteristics that give them a competitive advantage over many species, particularly in modified and degraded river systems (Koehn 2004). Reproductive advantages such as low spawning temperatures, and thus earlier spawning times, allow earlier access to resources than many native species have, and rapid hatching of eggs and larval growth enables them to escape predation pressure (Adamek 1998).

Compared with some native species, Carp prefer slow-flowing waters and have been observed to inhabit off-stream waters with slow or zero velocity (Koehn and Nicol 1998, 2014). Weir pool environments created in the Lower Murray favour lentic species such as Carp (Walker 2006), and Carp numbers have shown a positive correlation with the degree of river regulation (Gehrke 1997; Driver et al. 2005). Carp can also take advantage of spawning areas downstream of water storages that release hypolimnetic water at temperatures too cold to permit the spawning of native species (Koehn 2001).

There is the potential for competition by Carp (especially when in high abundances) for physical habitat space used by native species at both local (Crook et al. 2001; Koehn and Nicol 2014) and larger scales (Boys and Thoms 2006). Carp may be considered habitat generalists, and the degree of habitat overlap with native MDB fishes varies with species (Koehn and Nicol 2014). Habitats of juvenile Carp have been determined to be different from those of juvenile Murray Cod *Maccullochella peelii* (Jones and Stuart 2007) and a recent study by Koehn and Nicol (2014) showed Carp utilise slower waters, closer to the bank and with wood higher in the water column than Murray Cod and Trout Cod *Maccullochella macquariensis*; however, habitat use of Carp was similar to that of Golden Perch *Macquaria ambigua*.

Carp can be considered to recruit on floods, and although they can spawn under a range of flows, they may be considered flood spawners (at least in part), which makes them somewhat similar to Golden Perch and Silver Perch *Bidyanus bidyanus*, both large-bodied MDB native species (Humphries et al. 1999). Indeed, there is some evidence that the spawning and recruitment of Carp and Golden Perch is similar in the Lower Murray River (Bice et al. 2014). The attributes that make Carp such a successful invasive species (Table 2) also provide many advantages over MDB native fishes (Koehn 2004). In general, they are more fecund, spawn at lower temperatures (hence earlier in the season), can spawn multiple times, have earlier maturity and faster growth rates, and have less specific habitat requirements and a unique feeding process compared with native fishes. As Carp are long-

lived, these advantages are present for the population over long periods. Carp are also a species that is highly resistant and resilient to drought conditions (Crook et al. 2010).

Although Carp spawning may occur earlier than in many native fishes, the spawning season also overlaps with that of many fish species (see Appendix 3, Figure A3.9); hence, this may pose a potential conflict when managing flows that minimise opportunities for Carp recruitment while maximising benefits for native species. The ecological benefits for native species (including native fish), however, must remain the priority in order to meet the objectives of environmental watering and the Basin Plan and maximise the benefits to native species.

## 2.6 Carp response to flows and water management

Increased Carp spawning in relation to flows has been reported in a range of studies in both rivers and wetlands (Stuart and Jones 2006b; Bice and Zampatti 2011; Macdonald and Crook 2013; Bice et al. 2014; Thwaites and Fredberg 2014). However, there is little quantitative evidence regarding the consequences that these events have on adult Carp populations in the longer term. The regional examples of Carp population management presented in Section 4 give some indications of large increases in populations under some conditions, and there is anecdotal information and regional data that Carp numbers overall have increased substantially since the 2010–2011 natural flooding of the Murray River. Further examination of datasets, and monitoring that specifically quantifies Carp populations, is needed to further determine the impact of flow on populations. In lieu of more complete and instructive monitoring data, modelling of fish populations can be used to explore likely long-term population trajectories.

Natural flooding and managed artificial inundation of floodplains both expand the area and extent of potential habitat for Carp spawning and recruitment (Mallen-Cooper et al. 2011; Zampatti et al. 2011), heightening the risk that a Carp population will increase. King et al. (2003) found that Carp was the only species of fish to show a recruitment benefit from a floodplain inundation event on the Ovens River. It was recently noted that small watering events can prompt a similar recruitment response to that observed after prolonged watering (Beesley et al. 2011). Hydrology positively influences the recruitment strength of Carp populations through dispersal from nursery sources (Stuart and Jones 2006a, 2006b; Macdonald and Crook 2013). The absence of significant flows following such spawning events limits downstream dispersal and results in retention in closer nursery areas (Macdonald and Crook 2013).

Restoration measures, particularly artificial water level management in aquatic ecosystems, may result in a trade-off between achieving positive environmental outcomes and potential negative impacts, including providing a recruitment ‘hotspot’ for non-native species (Sheehy and Vik 2010; Bice and Zampatti 2011). Studies have shown that the isolation of a river reach and a managed rise in water level facilitates spawning and recruitment of a non-native fish species (Simenstad et al. 2006; Bice and Zampatti 2011) and should thus be carefully managed to minimise unwanted impacts in this regard. A case study of the Goolwa weir pool in the Lower Murray River shows that prior to levee construction, the abundance of Carp was similar in the Goolwa weir pool and Lake Alexandrina. Following water level management, the abundance of Carp in the Goolwa weir pool was ~1000 (by December) and ~250 (by April) times greater than its abundance in Lake Alexandrina as a result of recruitment of young-of-the-year fish (Bice and Zampatti 2011; see Section 4.1.11).

There has been little quantification of the response of Carp populations in Australia to natural flows, natural flooding, environmental flows and managed inundation events. When investigating the dynamics of Carp populations in the MDB using commercial catch data, Forsyth et al. (2013) found little evidence that Carp population growth rates increased following flood events once populations were established. It was noted, however, that there were some limitations to the dataset used; indeed, poor and inconsistent monitoring data has posed problems for this project. The extended period of floodplain inundation in the Mid and Lower Murray River that occurred due to natural

flooding over the summer of 2010–2011, however, is likely to have provided ideal conditions for the spawning and recruitment of Carp, resulting in elevated abundance in 2012 (Bice et al. 2014; Thwaites and Fredberg 2014).

Flow regulation has also been shown to influence the composition of lowland riverine fish communities, with Carp being predominant in regulated rivers (Gehrke et al. 1995; Gehrke and Harris 2001). The operation of floodplain regulators may greatly favour Carp by increasing the spawning area of shallow lentic water and increasing the frequency of inundation (Mallen-Cooper et al. 2008, 2011). Managed inundation will likely result in large numbers of young-of-the-year Carp on the Chowilla floodplain and recruitment into permanent creeks and the Murray River (Stuart et al. 2011). Water management regimes are also having a strong influence on the distribution and extent of Carp spawning and recruitment in the Lachlan River catchment. The diversion of water from the Lachlan River into Lake Brewster and Lake Cargelligo, in particular, appears to be enhancing Carp recruitment at these locations, which are subsequently seeding large lengths of the main river channel with juvenile Carp (Crook et al. 2013). In highly regulated rivers such as the Murray, Carp populations may have been enhanced by a range of management changes, including:

- the conversion of lotic to lentic habitats (e.g. weir pools)
- the provision of more stable water levels (that can provide summer refuges)
- the provision of irrigation flows that inundate in-channel benches and riparian or low-lying wetland habitats.

## 2.7 Carp management

### 2.7.1 Impact thresholds

Previous research has demonstrated a significant increase in turbidity at Carp densities of 50–75 kg/ha (Zambrano and Hinojosa 1999; Vilizzi et al. 2014), with noticeable shifts from a clear to a turbid water state at 200–300 kg/ha (Williams et al. 2002; Parkos et al. 2003; Haas et al. 2007; Matsuzaki et al. 2009). Declines in aquatic vegetation cover and detrimental effects on aquatic macrophytes have been observed at Carp densities ranging from 68 to 450 kg/ha (Hume et al. 1983; Fletcher et al. 1985; Osborne et al. 2005; Pinto et al. 2005; Bajer et al. 2009; Vilizzi et al. 2014) and a decline in native waterfowl use with Carp densities of ~100 kg/ha (Bajer et al. 2009). These impacts stem largely from the Carp's benthic feeding behaviour (Sibbing et al. 1986) and are most commonly reported in shallow off-stream habitats (Parkos et al. 2003) where Carp congregate (Smith and Walker 2004a; Stuart and Jones 2006a, 2006b).

Managing an invasive species below a predetermined density threshold, below which its impacts on environmental values are acceptable, is a key component of Integrated Pest Management (Braysher and Saunders 2003). Numerous studies have suggested threshold densities for Carp to be 100–174 kg/ha (Haas et al. 2007; Bajer et al. 2009; Matsuzaki et al. 2009), which are much lower than historic estimates of 450 kg/ha (Fletcher et al. 1985). Given that negative impacts are reported at even lower densities, these thresholds may need to be re-evaluated. Indeed, to achieve population reductions of 70–90% in order to minimise impacts, the threshold density required was modelled at 88 kg/ha in the Lachlan River catchment of the MDB (Brown and Gilligan 2014). To achieve such a threshold, a control program would need a reduction of 75–90% in the Carp population, which may be achievable through a range of control efforts (Brown and Gilligan 2014). This recent data indicates that the density at which Carp cause ecosystem impacts may be much lower than previously thought. There are many examples where MDB Carp populations have exceeded these threshold levels—Moira Lake: 190 kg/ha (Brown et al. 2003); a range of billabongs: 150–690 kg/ha (Hume et al. 1983); Bogan River: 690 kg/ha (Reid and Harris 1997); and the Campaspe irrigation channels: up to 619 kg/ha (Brown et al. 2003) (see also regional examples in Section 4).

### 2.7.2 Carp management in the MDB

Carp are a highly visible pest fish species that is perceived negatively by the public and thus should be managed carefully. There is the potential for large Carp recruitment events to be unfairly blamed on environmental flows, which may in turn erode public support for environmental watering. The life history traits of Carp (e.g. early maturity, high fecundity and fast growth rates) allow for rapid population growth under favourable conditions, hence providing considerable difficulties for management (Koehn 2004).

Carp are recognised as a serious vertebrate pest in Australia, and this has resulted in the development of a national approach to management and research (Carp Control Coordinating Group 2000a, 2000b) utilising an Integrated Pest Management approach (Koehn et al. 2000). While a coordinated national approach was advocated, this 'national' approach was largely unfunded and lacked Departmental accountabilities. As a consequence, pest management actions have largely been addressed through local management plans (Braysher and Barrett 2000; see examples in Section 4.3). A Carp management plan should do the following: (i) define the threats posed by Carp (e.g. detrimental impacts on wetland plants), (ii) set clear goals which address the real impacts (rather than simply killing as many as possible), (iii) identify and evaluate all management options and set priority actions, (iv) implement the management plan and control the damage done by Carp to an acceptable level, (v) monitor progress and evaluate it against the objectives. It is usually unrealistic that any established pest fish can be eradicated, that is, every last animal removed. Possible exceptions are where populations are isolated and in relatively low numbers, but no established widespread pest has ever been eradicated from Australia. Pest fish control should be integrated and use more than one applicable method and should also be undertaken in the context of the broader initiatives of native fish recovery (see below).

While much attention has been given to planning and investigating Carp management options, there has been less success on the ground. This may be due to a lack of funding for such actions, and Carp control actions in the Tasmanian lakes (Diggle et al. 2012) illustrate the high cost of control in a comparatively small, enclosed area. Many of the potential methods discussed above are not yet available, and removal remains one of the few active options. To date the Carp fishery has been limited and opportunistic, other removal has been ad hoc and conducted on a small scale (Jackson 2009; see Section 4.5 and Appendix 6 for additional details), and there has been no assessment of the impact of these removals on Carp populations. It has been suggested that large proportions of the population (e.g. 90%, Thresher 1997; 37% ongoing, Forsyth et al. 2013) need to be removed to ensure 'ongoing' benefits. All proposed methods for Carp management are discussed further in Section 4.5.

The impacts of Carp in Australia have not been well quantified; hence, there has been little consideration of economic repercussions. McLeod (2004) estimated that the economic impact of Carp was at least AUD4.0M per annum. His assessment included public sector control and research costs, attributed environmental costs (increased turbidity) and loss in recreational fisher returns, but not impacts on tourism. In an analysis of the effects of Carp in the Gippsland Lakes in Victoria, a rough estimate of the costs to the community was AUD175M over 5 years. This included losses to the native commercial fishery, recreational fishing, tourism and commerce (Gippsland Lakes and Catchment Action Group 1996). Investment in Carp management in Australia has also lacked the rigorous cost and benefit analysis needed to guide management decisions. Choquenot et al. (2004) highlighted the importance of bio-economic modelling in invasive pest management, using Carp management as an example; this kind of full cost–benefit analysis is yet to be conducted for Carp. Such an analysis will need to be balanced against benefits to native fishes so that management expenditure can be prioritised.

### 2.7.3 Management responsibilities in the MDB

There are a range of disparate agencies, many of which have unclear ‘responsibilities’ in relation to managing water and Carp within the MDB. This, combined with the multijurisdictional nature of the MDB, makes the task of coordinated management of flows in relation to Carp problematic—resulting in a disjointed approach. Some concerns over coordination and cooperation between agencies have already been encountered and addressed by the NFS for the MDB (Koehn and Lintermans 2012; Koehn et al. 2014b), with strategies and mechanisms developed to help overcome such issues. The Basin Plan has placed water management on a larger scale within the MDB so that the MDBA, the Commonwealth Environmental Water Holder (CEWH), Commonwealth and State Water holders, and Catchment authorities all have clearly defined responsibilities for delivery of environmental water, laid out in established watering strategies and plans.

While alien fish management has also been considered at a national scale, a program of action has not yet been adopted (Barrett et al. 2014). Indeed, concern has been expressed at the lack of recognition, commitment, consistency of approach, coordination between states and agencies and on-ground actions in relation to alien freshwater fish species (Barrett et al. 2014). Carp management may be considered variously by Environment/Natural Resource Management or Fisheries agencies, together with Water or Catchment authorities. There has generally been little interest from Biosecurity or other vertebrate pest organisations (e.g. Carp is not listed as a pest species in the state of New South Wales; <http://www.dpi.nsw.gov.au/agriculture/pests-weeds/vertebrate-pests/pest-animals-in-nsw>). So, although considerable knowledge is available, and there are defined approaches and a range of possible management techniques, there is a lack of coordination of Carp management, and it is often only considered at a site scale (see Section 4.3 for a review of Carp management plans)—there is no ultimate hierarchy of responsibility. The lack of future planning for Carp management relating to environmental watering is evident by the lack of tangible management options for managing risks caused by nay increase in Carp populaltions in current water planning documents (e.g. the Victorian Environmental Water Holder Seasonal Watering Plan 2014–15; [http://www.vewh.vic.gov.au/\\_\\_data/assets/pdf\\_file/0007/267604/VEWH-SWP-2014-15-web-Sec4-6.pdf](http://www.vewh.vic.gov.au/__data/assets/pdf_file/0007/267604/VEWH-SWP-2014-15-web-Sec4-6.pdf)).

There are, however, a range of principles that are useful for guiding water and Carp management in the MDB. Carp are part of the fish community of the MDB and must be managed as such. It will be some time before any of the proposed major control options are available, so coordinated pest management is required. Their biological attributes mean that Carp populations can respond quickly to out-of-channel inundations more rapidly than many native species. Hence, Carp proliferation can be an unwanted outcome from water management. Any increases in Carp must be considered in the context of increases from other actions (e.g. irrigation flows, natural flooding), and flow management actions can be managed to reduce risks and/or increase the outcomes in favour of native species. High-risk scenarios/locations should incorporate Integrated Pest (Carp) Management plans.



## 3 Environmental watering

### 3.1 Watering strategies

The CEWH (<http://www.environment.gov.au/water/cewo>) provides annual watering plans to help ensure that the supply of available Commonwealth environmental water will help achieve the overall environmental objectives under The Basin Plan. These watering options facilitate the scaling of actions across several potential inflow scenarios and integration across numerous specific sites within the MDB. They provide flexibility so that water use can best accompany natural inflows and aim to support ongoing environmental recovery following the extended drought period. Annual watering plans for 2013–2014, have been developed for 10 specific regions within the MDB, including the Mid Murray (i.e. Hume Dam to Euston) (CEWH 2013a) and the Lower Murray regions (i.e. Euston to Lower Lakes) (CEWH 2013b), with mechanisms for environmental water delivery and watering strategies for the Mid Murray (CEWH 2013a) and Lower Murray–Darling (CEWH 2013b). Environmental water is also held and delivered by a range of other agencies (e.g. Murray-Darling Basin Authority, State Environmental Water Holders) and there is considerable effort required to coordinate both plans and delivery to maximise environmental outcomes.

Hydrology in the Mid Murray region is influenced by inflows from the Upper Murray River and tributaries such as the Goulburn–Broken, Ovens, Kiewa, Campaspe and Murrumbidgee rivers). The Mid Murray is heavily regulated by the Hume Dam and the Yarrawonga, Torrumbarry and Euston weirs (Figure 4). Flows into the Lower Murray–Darling region are influenced by inflows generated within upstream sections of the MDB (i.e. the Upper Murray River and the Lower Darling River System). Inflows into the Darling River are primarily generated by rainfall events in the Northern MDB, whereas inflows in the Upper Murray River result from rainfall, storage operations and inflows from tributaries, including the Murrumbidgee, Ovens and Campaspe rivers. In the Lower Murray River, environmental water may be delivered via managed release from Murray River storages, including the Hume Reservoir, the Menindee Lakes system, Murray River tributaries and Lake Victoria (Figure 4).

### 3.2 Mechanisms for water delivery

At the site scale, environmental water can be actively delivered to in-channel locations, low-lying floodplains and wetlands by manipulating weir pool heights at locks and weirs to achieve desired water levels and flow. Manipulating these variables often aims to mimic the preregulation conditions that native species are adapted to (and in turn achieve the greatest ecological benefits for a given volume of water). Environmental water can be passively fed to pool-connected wetlands, regulated floodplain habitats (e.g. the Chowilla floodplain and the Barmah–Millewa forest) and irrigation systems by gravity and controlling regulators. Above-pool wetlands (e.g. the Hattah–Kulkyne lakes) and some irrigation systems require active delivery of environmental water via pumping against gravity; however, this can be expensive and cause injury or mortalities of entrained fish (Baumgartner and Boys 2012; Baumgartner et al. 2014).

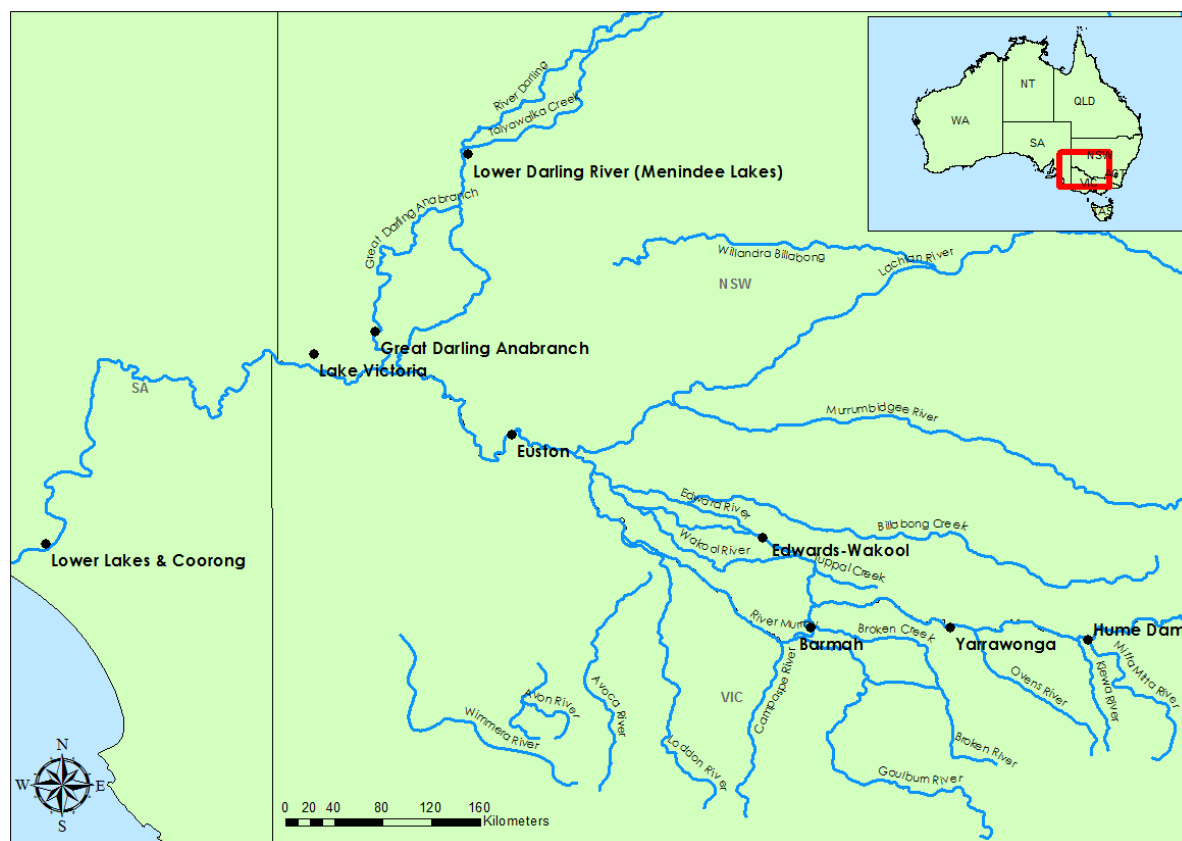


Figure 4. Map of key water infrastructure storage and watering sites in the southern connected MDB

## 4 Carp management

### 4.1 Regional examples of Carp population growth and control

There is a general lack of compiled, quantitative data on the status of Carp populations throughout the MDB, particularly in relation to population growth. This proved to hinder some parameterisation of the Carp model in this project, especially when attempting to set carrying capacities. It should be noted that Carp (and fish) abundance is measured and reported in a number of ways—these are summarised in Table 3. The absolute abundance (number of individuals) or biomass of Carp is rarely known, except if a lake dries out and the large adults are counted. In most instances, Carp abundances are estimated from two metrics: (i) proportional abundance and (ii) Catch-per-unit-effort (CPUE). Unfortunately, CPUE as a basic statistic is rarely reported, because most data are variable and statistically transformed for analysis purposes. For researchers and managers, the density of Carp (expressed as kg/ha) is often a more useful metric because it can be easily associated with the area of a floodplain lake. The impact threshold (e.g. 100 kg/ha) can be estimated from electrofishing sampling, but determining or estimating absolute population numbers from electrofishing can be difficult due to variability in detection (or capture) rates (Lyon et al. 2014). Biomass and density estimates may be assisted by having known length–weight relationships that can be applied to abundances. An examination of regional examples of Carp population increases



(provided below; see Figure 4 for locations) and their management has provided some indications of how readily populations can expand, and what densities can be achieved across a range of habitats within particular time frames.

Table 3. Metrics used for measuring Carp populations

Metric	Definition
Absolute abundance	The total number of Carp in a population: rarely known and difficult to collect, but can be estimated from relative abundance.
Proportional abundance	The number of Carp as a percentage of the total number of fish in a given community or area.
CPUE	CPUE is an indirect measure of the abundance of Carp whereby changes in CPUE can be used to infer changes in true abundance: easy to collect and can be used to estimate absolute abundance; CPUE is often referred to as relative abundance.
Biomass	The mass of living (or recently living) Carp in a given area at a given time (usually reported in kilogram or tonne).
Density	For Carp, this is usually estimated in kg/ha. A Carp density of >100 kg/ha will likely be associated with environmental impact.

#### 4.1.1 Lake Crescent and Lake Sorrell (Tasmania)

In 1995 Carp were detected in Lake Crescent and Lake Sorrell, and over the ensuing 20 years a wide range of control measures were deployed (at a cost of ~AUD\$15M). Large-scale rotenone poisoning, draining the lakes, and physical removal were the three major eradication options, but only removal was deemed viable. To undertake this challenging task, several staff were employed to plan and implement physical control in the two lakes. The integrated control methods included: containment screens, littoral barrier netting, radio-tagged 'Judas' fish (sterilised males), boat electrofishing, and increased public awareness (Diggle et al. 2012; Taylor et al. 2012). In addition, population modelling and validation with mark–recapture work was carried out. The program has successfully eradicated Carp (~7800 individuals) from Lake Crescent, but in Lake Sorrell there were major Carp breeding events associated with a rise in water levels in December 2009, and ~37,000 individuals were removed. Despite extensive sampling effort, by 2013 only 15 Carp had been collected prior to the October spawning season. Hence, managers are now targeting containment in the much larger Lake Sorrell, with the longer-term objective of possible eradication.

#### 4.1.2 Lake Cargelligo (NSW)

The Lake Cargelligo system is a fully regulated off-stream series of three lakes in the middle reaches of the Lachlan River catchment, with a storage capacity of ~36,000 ML, a surface area of 1500 ha, and a maximum depth of 3.7 m. Lake Cargelligo is usually operated at near-full capacity, supplied by water releases from Wyangala Dam or by unregulated tributary flow. As the lake can be isolated from the Lachlan River, there is some potential, if Carp were removed, for the lake to be maintained Carp-free.

As part of a Carp control demonstration project, Lake Cargelligo was fished by a commercial fisher (K&C Fisheries Global Pty Ltd) in 2009 (Gilligan et al. 2010). Carp were removed from the closed lake population in several efforts by seine nets, gillnets and fyke nets, with a yield of 3–8 kg/ha. However, when the lake dried in December 2009, many thousands of Carp were left stranded on the lake bed, and the remaining absolute abundance was estimated at 120–140 tonnes (= 80–93 kg/ha when the

lake is full (Keith Bell, K&C Fisheries, pers. comm.) (Figure 5). Commercial and recreational fishing, even in closed systems, can rarely achieve any significant impact on Carp abundance and is best applied when lakes are drying. Lake Cargelligo refilled after the drought broke in late 2010 and Carp reinvaded. Carp control in Lake Cargelligo is now being undertaken with tagged Judas Carp and targeted removal (Martin Asmus, NSW DPI, pers. comm.).



Figure 5. Adult Carp left stranded on the bed of Lake Cargelligo at the height of the Millennium Drought in December 2009

This was one of many examples of whole Carp populations being killed as small and medium impoundments dried (photo: Ivor Stuart).

#### 4.1.3 Lachlan River (NSW)

The Lachlan Catchment Management Authority trialed two Williams' Carp cages (Stuart et al. 2006) in vertical-slot fishways on the lower middle reaches of the Lachlan system in 2009. This was the first trial of automated Carp cages at unmanned remote sites. The two stainless steel Carp cages (Figure 6) including design, fabrication, certification, installation, automation and power supply, were reasonably expensive at \$63,000 each, excluding monitoring and operating costs (Gilligan et al. 2010). Few Carp were collected in the cages, probably due to a combination of drought and flood conditions, few Carp migrating, poaching, and limited commissioning and monitoring of the cages. There were also issues with debris management because the cages were located in the weir pool rather than inside the fishway. The two cages were relocated to the Murray CMA in late 2013.

In November 2013 a third cage was installed at Booligal Weir fishway and this fully automated solar powered system was performing well. By the end of December 2014, a reasonable number of Carp (419 Carp or 626 kg over 322 sample days) had been collected with no bycatch of native fish (Martin Asmus, NSW DPI, pers. comm.). From CPUE electrofishing sampling in the river nearby, it appears that the local Carp biomass is reasonably low; hence, the cage probably effectively removed the low to moderate number of migrating Carp. The technical advancement of a remote solar-powered cage function was, however, significant.



Figure 6. The Booligal Weir Williams' Carp separation cage in 2014

This fully automated and solar-powered cage is proving highly reliable at removing the small numbers of Carp that have migrated since installation in November 2013 (photo: Martin Asmus, NSW DPI).

#### 4.1.4 Moira Lake (NSW)

Moira Lake is a large (1500-ha), significant wetland in southern NSW, adjacent to the Murray River and Barmah wetlands. The lake is shallow and fringed by marshlands with an abundance of reeds and rushes and is inhabited by large numbers of Carp, which breed during flooding in spring and summer (Stuart and Jones 2006b). In late summer and autumn as the flood water recedes, water is drained back to the Murray through the Moira channel regulator, and Carp aggregate above this structure. Commercial fisher, Mr Keith Bell (K&C Fisheries Global Pty Ltd) harvests the Carp with nets and traps under an agreement with Forests NSW, who manage Moira Lake. The first year of the trial (2001) resulted in 76 tonne of Carp (or 77 kg/ha) being removed, and this has been followed by 40 tonne in 2004 and 32 tonne in 2010. In winter 2014, 40 tonne were removed (Keith Bell, K&C Fisheries Global, pers. comm.), and each year up to 40 tonne of Carp become stranded and die. The ad hoc nature of the Carp harvest reflects the limited site-access conditions. Access to Moira Lake while it is drying can be hampered by weather conditions; hence, Carp removal is restricted to only a few weeks a year (in late autumn and winter). The size classes of harvested Carp include both adults and juveniles. Few native fish have been observed in the lake when the water recedes, except for small-bodied fish such as Australian Smelt (*Retropinna semoni*), which pass through the Carp nets.

#### 4.1.5 Hattah Lakes (Victoria)

Hattah Lakes is a major wetland complex (13,000 ha) within the 48,000 ha Hattah–Kulkyne National Park in the semi-arid Mallee landscape. Hattah Lakes encompasses 20 freshwater lakes that connect to the Murray River via Chalka Creek and a series of other flood runners. Since 2005, periods of water pumping from the Murray River have been undertaken to help reverse the ecological decline



of the floodplain wetlands that occurred due to reduced overbank flooding. Carp are a significant risk to the Hattah Lakes: in the deeper permanent lakes they form self-sustaining populations from which reinvasion of the shallow floodplain lakes can occur, and eggs and larvae can be introduced during water-pumping events. The relative abundance of Carp in the Hattah Lakes is high (~52% of the large-bodied fish community, with a CPUE of ~90 Carp/ha in Chalka Creek; Henderson et al. 2012). To help prevent reinvasion of Little Lake Hattah, which dried in autumn 2013, Carp screens were installed on the regulating structure (Figure 7). These screens appear to be effective in blocking large Carp invasion, with aggregations below the screens in spring 2013 (Peter Kelly, Mallee CMA, pers. comm.).



Figure 7. The Little Lake Hattah regulator, where Carp screens for subadult and adult fish were installed in 2013

These screens block reinvasion of the dry wetland during a water-pumping event (photo: Ivor Stuart).

#### 4.1.6 Lake Bonney (South Australia)

Lake Bonney is a large (7 km long by 3.5 km wide) floodplain lake adjacent to the Lower Murray River near Barmera, South Australia. In mid 2007, the lake was disconnected from the Murray River main channel as part of a water savings initiative, but by mid 2008 native fish kills in the lake following the receding water levels and increased salinity prompted environmental water delivery. Environmental water (10, 26 and 25 GL) was delivered to Lake Bonney in 2008, 2009 and 2010, respectively. During the 2008 and 2009 EWAs, large Carp aggregations formed at the inflow plumes for ~2 months. A total of 35 and 52 tonnes of Carp were manually harvested by commercial fishers and the general public in 2008–2009 and 2009–2010, respectively (Thwaites and Smith 2010; Thwaites 2011). Despite these efforts, ~121 tonnes of Carp (~77 kg/ha) were still present in Lake Bonney (Thwaites and Smith 2010). A Williams' Carp separation cage was trialled in 2010 to more efficiently manage the Carp population (Figure 8); however, during 2010 there were no observable aggregations, which resulted in low harvest quantities (Thwaites 2011). Approximately 2.3 tonnes of Carp (529 individuals) were harvested from 28 September – 25 October 2010 by the Williams' Carp separation cage. The reduction in the magnitude of Carp movement during 2010 was most likely the result of the timing of the allocation (4–5 months earlier than previous years and during low water temperatures, 10°C) and the temporal improvement in the lake's water quality.



Figure 8. Photograph of the Wetland Carp Harvesting System at Lake Bonney, incorporating the Williams' Carp separation cage, gantry, hoist, Carp pivot screens and Carp deflector screens (Thwaites 2011)

Completing the infrastructure are sluice gates (out of view, river [left] side of culverts), walkway mesh, handrails and security fencing (photo: Ben Smith).

#### 4.1.7 Brenda Park (South Australia)

Brenda Park is a large (~2.4 km long by 0.5 km wide) terminal wetland on the lower Murray River south of Morgan, and it has historically supported large populations of Carp. In November 2009, a 2-year large-scale trial was commenced in the wetland to quantify Carp impacts in a series of experimental fenced exclusion plots (Vilizzi et al. 2013, 2014) (Figure 9). Within 12 months of commencement, water transparency, aquatic macrophyte cover, and benthic invertebrate richness and diversity outside the enclosures had all decreased as a result of the direct and indirect effects of Carp feeding. Zooplankton levels fluctuated throughout the period, depending upon the presence of Carp young-of-the-year. No direct effect of Carp on smaller native fish was detected. A major finding of the study was that Carp have a significant effect on water transparency and aquatic macrophyte cover at a mean density of 68 kg/ha, which broadly concurs with recent work from North America and Mexico, but this is a much lower biomass than previously thought (i.e. 450 kg/ha) (Vilizzi et al. 2014).



Figure 9. Fully fenced experimental Carp exclusion plot used in Brenda Park wetland (Vilizzi et al. 2013) (photo: Anthony Conallin)

#### 4.1.8 Lock 1 (South Australia)

The Carp biomass below Lock 1, on the lower Murray River, is among the highest in the MDB, and many thousands of adult Carp can usually be observed below the weir (Figure 10). In 2009 a vertical-slot fishway was completed, and a Williams' Carp separation cage was trialled from November 2007 to February 2008 (Conallin et al. 2008). The trial involved South Australian water weir keepers, scientists and a commercial fisher harvesting from the cage only. Seventy tonnes of Carp were removed from the cage, with negligible native fish bycatch. Since then, on-site SA Water staff and commercial fishers have continued to operate the Carp separation cage, with up to 5.4 tonne of Carp per day being removed and up to 130 tonne removed each spring to summer. A total of 545 tonne have been removed to May 2014 (Barry Cabot, SA Water, pers. comm.), and an annual catch of ~125–130 tonne appears reasonable without major flooding or drought impacts (Table 4). Most of the Carp catch occurs in spring and early summer (September to December; Table 5) each year. In spring (early October) 2014, the Carp harvest began with catches in the order of 1.7–1.9 tonnes per 24 h (Barry Cabot, SA Water, pers. comm.). These Carp go to the South Australian crayfish industry for bait or to Charlie Carp to be converted into garden fertiliser (Gary Warwick, SA commercial fisher, pers. comm.).

Table 4. Total annual catches of Carp at Lock 1 since November 2007

Note that the catches from 2011/12 to 2013/14 are 'representative' years without major breaks in sampling due to flood or drought. Data courtesy Barry Cabot (SA Water).

Year	Carp catch (kg)	Note
2007/08	23,434	First year of cage testing; cage installed in mid-November 2007
2008/09	53,512	Low tailwater due to drought
2009/10	18,898	Drought caused limited access to fishway until January 2010
2010/11	73,516	Cage removed 1 December due to flood
2011/12	125,093	
2012/13	121,234	
2013/14	130,012	
<b>Total catch</b>	<b>545,699</b>	





Figure 10. Carp aggregating below Lock 1 on the Murray River, South Australia  
Between 2009 and 2014, a Williams' Carp separation cage removed up to 130 tonne of Carp annually that migrated through the fishway (photo: Ivor Stuart).

Table 5. Monthly catches of Carp at Lock 1 for 2013/14, demonstrating that most of the catch occurs in spring and early summer (September to December)

Data courtesy Barry Cabot (SA Water).

Month/year	Carp catch (kg)
Jul 2013	0
Aug 2013	380
Sep 2013	37,419
Oct 2013	31,848
Nov 2013	8,230
Dec 2013	37,775
Jan 2014	8,110
Feb 2014	4,410
Mar 2014	1,840
Apr 2014	0
May 2014	0
Jun 2014	0
<b>2013 Total</b>	<b>130,012</b>

#### 4.1.9 Goolwa channel (South Australia)

In August 2009 a temporary earthen structure was constructed across the Goolwa Channel and Lake Alexandrina (Figure 11). The purpose of the earthen structure was to impound and raise water levels in the Goolwa weir pool to limit exposure of acid sulphate soils and also to provide a freshwater refuge for aquatic fauna at the height of the Millennium Drought. Following water level management, enhanced spawning and recruitment of Carp within the Goolwa weir pool (the 'impounded area' that was subjected to water level management) led to dramatic population increases (Bice and Zampatti 2011). These abundances within the Goolwa weir pool were dominated by young-of-the-year Carp (>99% of total individuals). The timing of elevated water levels provided ideal conditions for Carp spawning and recruitment, coinciding with the peak spawning period. It was recommended that greater consideration of the ecological risks and benefits of managed water level inundations is required for future engineering interventions.



Figure 11. Earthen levee constructed across the Goolwa Channel separating the 'Goolwa weir pool' from the rest of Lake Alexandrina (photo: Chris Bice, SARDI)

#### 4.1.10 Banrock Station Wetlands (South Australia)

Banrock Station Wetlands, located on the Lower Murray River near Barmera, South Australia, is a floodplain-wetland complex that is listed as a 'wetland of international importance' under the Ramsar Convention. This site was described as a Carp recruitment 'hot spot' in previous monitoring surveys (Smith 2006). During early 2007 this normally 'flow-through system' was dried as part of a government initiative to conserve water. Banrock Station was later granted an EWA refilling event that was delivered in June 2008 through the northern inlet of the wetland complex. The wetland was maintained as a flow-through system through the outlet from July to December 2008. During this time, the movements and spawning of Carp were investigated (Conallin et al. 2012). The overwhelming majority of Carp entered the wetland via the downstream outlet (outlet  $n = 4709$ , inlet  $n = 4$ ). Movements commenced in early August in response to increasing water temperatures, peaked in mid-September before spawning, then declined and were close to zero by December. Movements into the wetland were regarded as spawning movements because 99% of captured Carp were in 'prime' spawning condition. Carp were absent from the wetland from June to early August during the beginning of the EWA, which may offer some support for filling wetlands during cooler months.



#### 4.1.11 Lower Lakes (Albert and Alexandrina, South Australia)

Lake Alexandrina and Lake Albert form 'the Lower Lakes' and are two connected large freshwater lakes situated in south-eastern South Australia. The lakes operate at a level of ~0.75 m above sea level and cover an area of ~840 km<sup>2</sup>. They receive freshwater inflows from the Murray River (northern end of Lake Alexandrina), the Eastern Mount Lofty Ranges tributaries, groundwater discharge, local run-off, and rainfall on the lake surfaces (DEWNR 2014). The lakes are isolated from the Murray Mouth and the Coorong by a system of barrages that are operated to maintain lake levels (MDBC 2006). Lake Alexandrina has a surface area of 662.3 km<sup>2</sup>, a mean depth of 2.8 m and a volume of 1629.4 GL [at +0.75 m Australian Height Datum (AHD)]. Lake Albert lies to the south-east of Lake Alexandrina and is the smaller of the two lakes with a surface area of 177.1 km<sup>2</sup>, a mean depth of 1.7 m and a volume of 282.2 GL (at +0.75 m AHD). It is a terminal lake that exchanges water with Lake Alexandrina via the Narrung Narrows (DEWNR 2014). The lakes open-water zone (<0 m AHD) is sparsely vegetated (Gehrig et al. 2011).

The Lower Lakes support a large biomass of Carp, which are commercially harvested by the Lakes and Coorong Fishery, predominantly as bycatch of the native fishery, but also as a targeted species. On average, 518 tonne of Carp are removed annually from the Lower Lakes by commercial fishing (Figure 12a). Commercial catches of Carp in this fishery peaked in the early to mid 1990s (999 tonne harvested in 1991/1992) and were high towards the end of the drought between 2005/06 and 2008/09. Catch rates (CPUE) followed a similar trend to total catch, except for the most recent years (2011/12 to 2013/14), when catch rates were high, but total catches were low (Figure 12b). Qualitative analysis of CPUE data against annual flow (at Lock 1) and the Lake Alexandrina water level were used to assess the influence of freshwater flow on Carp abundance (Figure 12b). When factoring in a time lag of 2 years to allow for recruitment into the fishery, CPUE generally showed a positive relationship with flow, with the exception of the drought years (2002–2009), when the opposite trend was evident (Figure 12b). This anomaly may be explained by a contraction of available habitat due to a reduction in water level (Figure 13), resulting in concentration of fish and an increase in CPUE. High CPUE in the early 1990s was likely driven by enhanced recruitment in response to high flow years in the late 1980s. Due to effort shifts in the multispecies, multigear fishery across the Lower Lakes, the Coorong and marine coastal regions (Ferguson et al. 2013), and the lack of targeted catch-and-effort data (due to confidentiality in catch reporting), some caution needs to be taken with interpretation of data.

A population estimate of 180,000 adult Carp >500 mm total length (TL) (750 tonne) (with an upper maximum (95% CI) of 415,154 individuals) was made using tag recaptures for Lake Albert (Thwaites et al. 2010). The number of Carp <500 mm TL present in the lake was unknown. Given the relative sizes of Lakes Albert and Alexandrina and assuming an even distribution of habitats and Carp, this would give an overall estimate of 846,000 adult Carp (upper maximum estimate of 1.95M adult Carp) for the Lower Lakes.

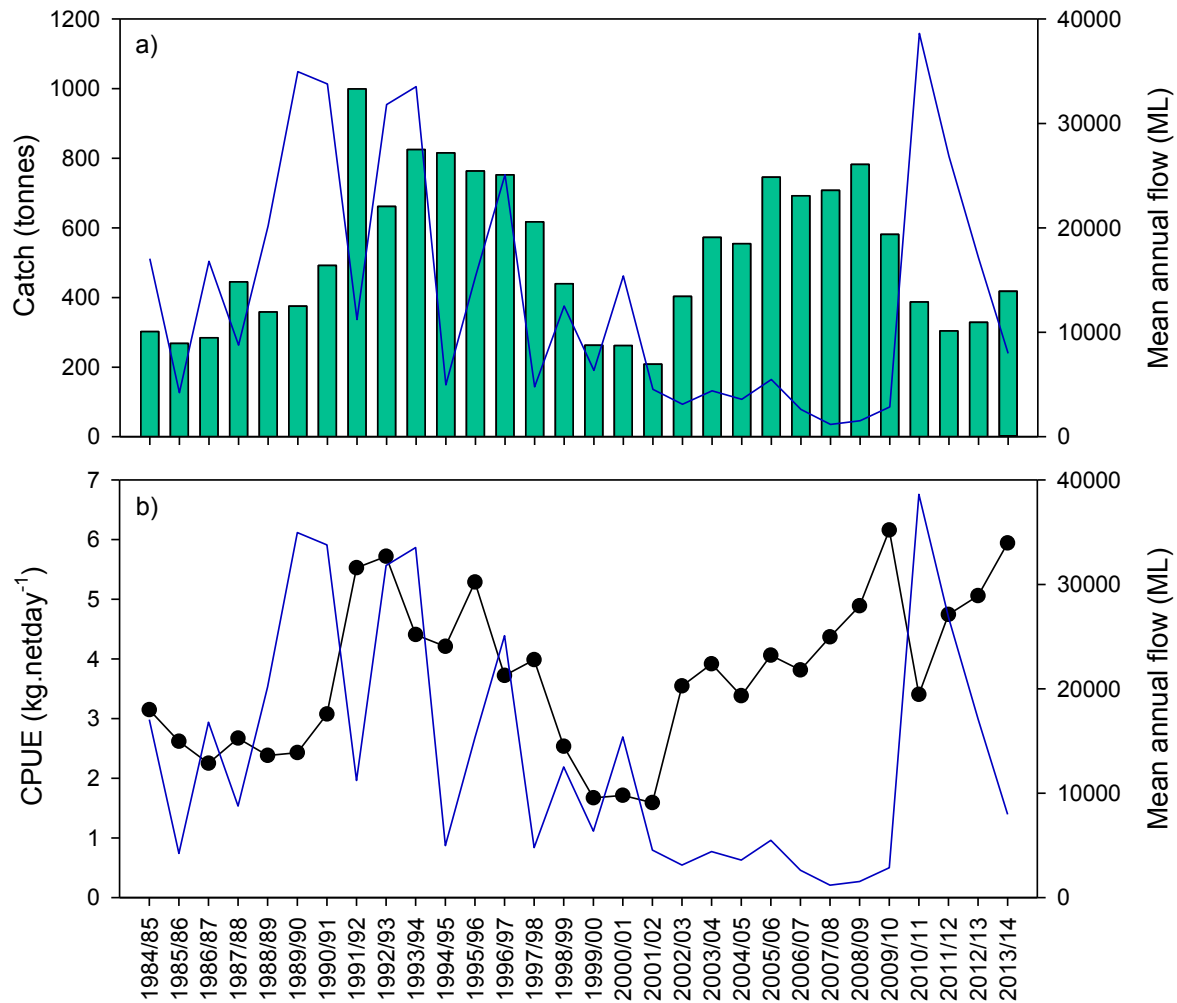


Figure 12. Carp (a) total annual catch and (b) targeted and non-targeted (pooled) catch-per-unit effort (CPUE) in Lakes Alexandrina and Albert (pooled) plotted against river flow (blue line) at Lock 1 (Blanchetown) from 1984/85 to 2013/14  
All catch presented is of that taken using large-mesh gill nets.

Analysis of available Lower Lakes autumn fyke-netting data (2008–2014) (data from Bice et al. 2008; Wedderburn and Barnes 2009; Wedderburn and Hillyard 2010; Wedderburn and Barnes 2011, 2012, 2013, 2014) revealed that Carp recruitment (measured using 0+, <150 mm Carp CPUE) was high during 2010 and 2011, and moderate in 2012 (Figure 14). The greatest recruitment event (0+ Carp in 2011, which were spawned during 2010) was associated with drought-breaking floods and refilling of wetlands. Conversely, the high but variable recruitment (CPUE  $\pm$  S.E: 10.7  $\pm$  8.7) observed in 2010 corresponded to spawning in 2009 during the drought. Recruitment in this low-flow year, however, was primarily influenced by a large spawning event within the Goolwa Channel that was associated with artificial water level manipulation (Bice and Zampatti 2011; see Goolwa Channel – Section 4.9), where a number of sampling sites were situated.

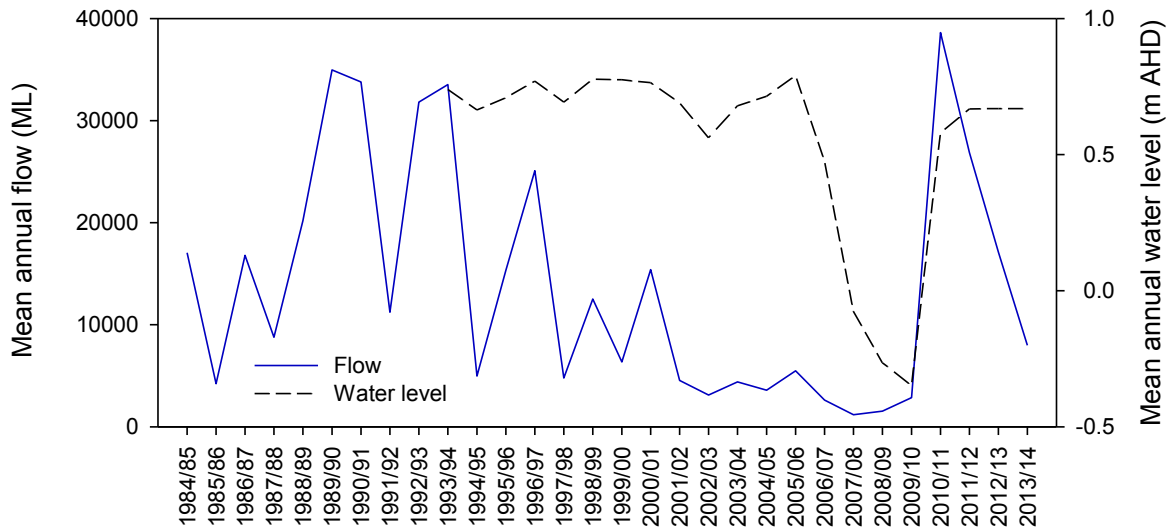


Figure 13. Annual river flow (at Lock 1) (ML) and water level in Lake Alexandrina (m AHD, measured upstream of Tauwiterie) from 1984/85 to 2013/14  
Note that no data is available between 1984/85 and 1992/93.

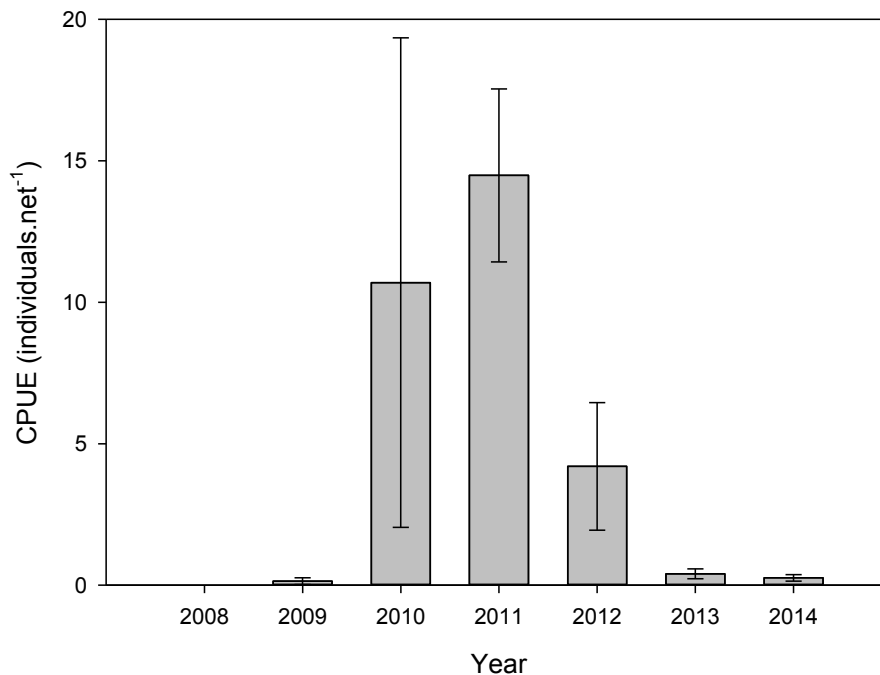


Figure 14. Mean autumn CPUE  $\pm$  S.E. of 0+ Carp in the Lower Lakes from 2008 to 2014  
0+ Carp were defined as individuals <150 mm TL, based on the modal progression of Carp size classes (SARDI unpubl. data). CPUE of 0+ Carp was 0 individuals/net in 2008.

#### 4.1.12 Lower Murray River wetlands (South Australia)

In 2012 Thwaites and Fredburg (2014) assessed the response of Carp populations to the rewetting of 12 lower Murray River wetlands (three above and nine below Lock 1, Blanchetown) following natural flooding after the Millennium Drought. Of all wetland fish species, Carp displayed the greatest positive response to the flood, with significant increases in relative abundance from 2005/06 levels within seven (Yatco Lagoon, Sweenys Lagoon, Noonawirra, Devon Downs North, Lake Carlet, Rock Gully and Murrundi) of the 12 wetlands sampled (pre-drought baseline surveys) (Smith 2006). The

increase in available spawning habitat (i.e. inundated submerged, terrestrial and aquatic vegetation; Nicol et al. 2013) associated with extended floodplain inundation during the latter half of the known Carp spawning period provided ideal conditions for Carp to proliferate. Bice et al. (2014) also reported an increased abundance of Carp in the main channel of the lower Murray River. While increased Carp abundance was a by-product of flooding, the overall importance of flooding to native fish communities cannot be overlooked (Cheshire et al. 2012; Zampatti and Leigh 2013a, 2013b). The response of Carp to floodplain/wetland inundation will require careful management in order to minimise benefits for Carp while maximising benefits for native species (e.g. Carp screens vs native fish passage).

In 2012–13, ~786 GL of CEWH was delivered to the Lower Murray River, in conjunction with other environmental flows. Environmental watering created a flow pulse of ~19,000 ML/day in December in the Lower Murray River. The spawning and recruitment of Carp in two wetlands (Kroehns and Overland Corner) of the Lower Murray River was investigated to assess the response to environmental water delivery (Ye et al. 2015). Macroscopic and microscopic analysis of reproductive development, size frequencies of juvenile Carp and daily ageing of young-of-the-year showed no evidence to suggest that Carp spawning and recruitment was enhanced during the period of water delivery. Ageing of small juvenile Carp indicated that most of the Carp spawned in 2012 were derived from spawning events that occurred during unregulated high flows from late August to November, while less than 5% were derived from spawning that occurred in early December. The response of Carp to environmental water delivery in this example contrasts with the responses shown elsewhere (Lake Bonney, Goolwa Channel and Banrock Station Wetlands), when water was delivered during the species' peak spawning period. This demonstrates that environmental flow delivery may not necessarily lead to enhanced Carp recruitment if delivered at an appropriate time. The results should also be considered in the context of unregulated flows (which may have potentially influenced spawning and recruitment prior to environmental water delivery) and also of the potential benefits to native biota.

#### **4.1.13 Constructed urban wetlands and Torrens Lake (South Australia)**

A program to attempt to eradicate Carp from constructed, managed aquifer recharge wetlands in Urban Adelaide (SARDI, unpubl. data) using rotenone yielded the following population/density data:

- Munno Para Wetland (~5 years old)—total of 12,000 Carp (average weight 510 g, average length 300 mm TL) removed from a 5 ha wetland, which equates to ~1225 kg/ha
- Stebonheath Wetland (~5 years old)—total of 9000 Carp (average weight 376 g, average length 264 mm TL) removed from a 3.4 ha wetland, which equates to ~998 kg/ha.

These results highlight the rapid expansion of Carp populations and provide examples of Carp occurring in high densities.

Torrens Lake is a 4 km stretch of the Torrens River (surface area ~17 ha) in Adelaide's Central Business District, fed by urban stormwater run-off and environmental flows from upstream storages. A Carp population estimate and removal trial was conducted using recaptures of tagged fish. A Peterson population estimate for Carp within the lake was ~1286 (3857 kg; 223 kg/ha) with  $\pm 95\%$  confidence intervals of 2480 Carp (7443 kg; 429 kg/ha) and 729 Carp (2187 kg; 126 kg/ha), respectively. Subtracting the targeted removal harvest of 178 Carp (534 kg) from this population estimate leaves an estimated total population of ~1108 (3323 kg; 191 kg/ha). This indicates that the targeted harvesting event removed ~14% of the estimated population (7% of the upper 95% and 24% of the lower 95% CI).

## 4.2 Key Carp populations

In the main channel of most rivers, suitable spawning habitat, such as submerged vegetation in lentic environments, is scarce. Hence, off-channel water bodies are major point sources for Carp, producing up to 98% of recruits (Stuart and Jones 2001, 2002; Crook and Gillanders 2006). It has been suggested that Carp exhibit source–sink population structure on a broad scale (Pulliam 1996; Driver et al. 2005): the most significant source populations are represented by unregulated lowland rivers, but the sink populations are represented by slope zones of catchments. Early studies at finer scales in the mid-reaches of the Murray River, south-eastern Australia, suggest that Carp’s reproductive activity and recruitment is not widespread, but is restricted to certain floodplain/wetland systems or ‘hotspots’ (Gilligan and Schiller 2003; Crook and Gillanders 2006; Stuart and Jones 2006b).

Gilligan (unpubl. data) analysed electrofishing survey data from 152 sites in the MDB across three seasons from 2005/06 to 2007/08. The CPUE of young-of-the-year Carp [ $<150$  mm fork length (FL)] was used to identify Carp recruitment ‘hotspots’ within the MDB. Although adult Carp populations were widespread and abundant across the MDB, populations were supported by a limited number of areas (hotspots) where juveniles were present (Gilligan, unpubl. data). Across the MDB, twelve Carp recruitment hotspots were identified: Mid Darling, Lower Macquarie, Wimmera, Lower Gwydir, Koondrook–Perricoota–Gunbower, Lower Border Rivers, Lower Castlereagh, Great Cumbung Swamp, Upper Wakool, Barmah–Millewa Forest, Lower Murray River (between Lake Victoria and Chowilla) and Lake Brewster (Figure 15).

The results from this study suggest that Carp reproduction is localised and restricted to a relatively small number of hotspots within the MDB. However, while efforts were made to try and identify the Carp spawning hotspots in the MDB, considerably fewer sites were sampled than anticipated (152/303 sites) due to the drought impeding full completion of the project. Furthermore, it is important to note that sites within the Lower Murray River in South Australia (including the Lower Lakes) support high abundances of Carp and are likely to also contain recruitment hotspots. Indeed, some 70% of wetland area in the Lower Murray is perennially inundated and permanently connected, and this is recognised as important Carp spawning habitat (Vilizzi 1998; Smith and Walker 2004b).

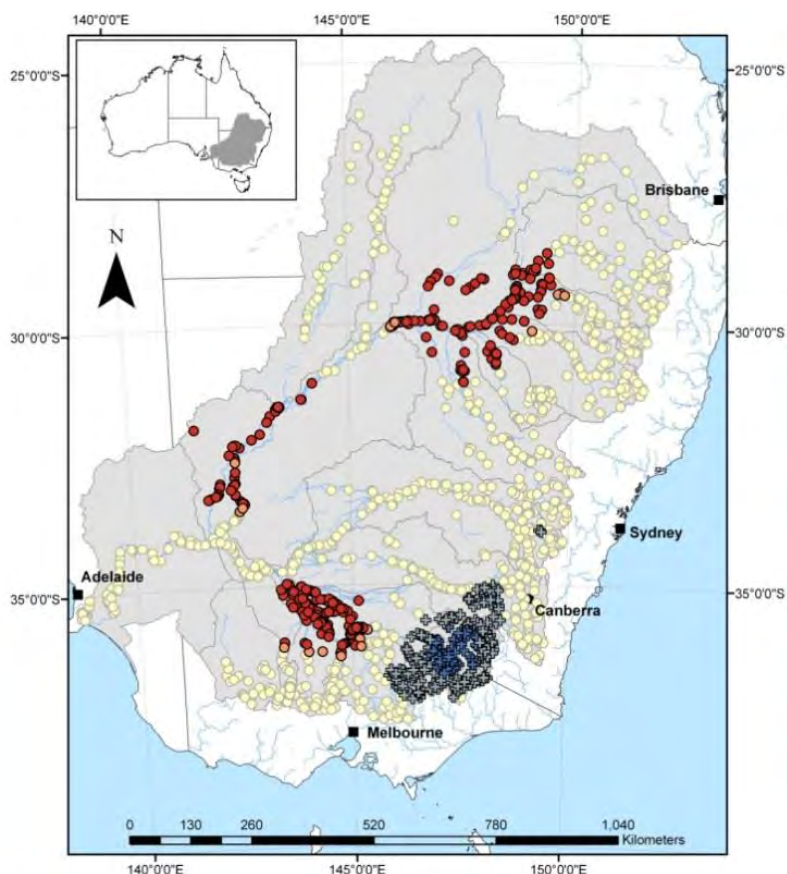


Figure 15. Distribution of young-of-the-year Carp *Cyprinus carpio* abundance within the MDB (Gilligan, unpubl. data)

Red points represent statistically significant hotspots; blue/grey crosses represent statistically significant coldspots and yellow points represent non-significant sites. Orange points represent sites that have higher-than-average young-of-the-year abundance at the local valley scale but which are not significant at the MDB scale.

### 4.3 Carp management plans and site risk assessments

Although a strategic framework was set for managing Carp at the national level (Carp Control Coordinating Group 2000a, 2000b; Koehn et al. 2000), management arrangements and responsibilities have changed significantly since those documents were drafted, and most management is now conducted at a local scale. This project has undertaken a review of existing Carp management plans and risk assessments (Figure 16, Appendix 5) and identified key areas still in need of plans. In summary, there are few Carp management plans that would be considered adequate. Indeed, such plans are missing from many key areas identified for environmental water management (especially where there are no fish objectives). This point is further illustrated by the lack of strategy and limited options for managing Carp risks contained in watering frameworks (e.g. Victorian Environmental Water Holder 2014; <http://www.environment.gov.au/water/cewo>; <http://www.mdba.gov.au/sites/default/files/Basin-Plan/Basin-Plan-Nov2012.pdf>).

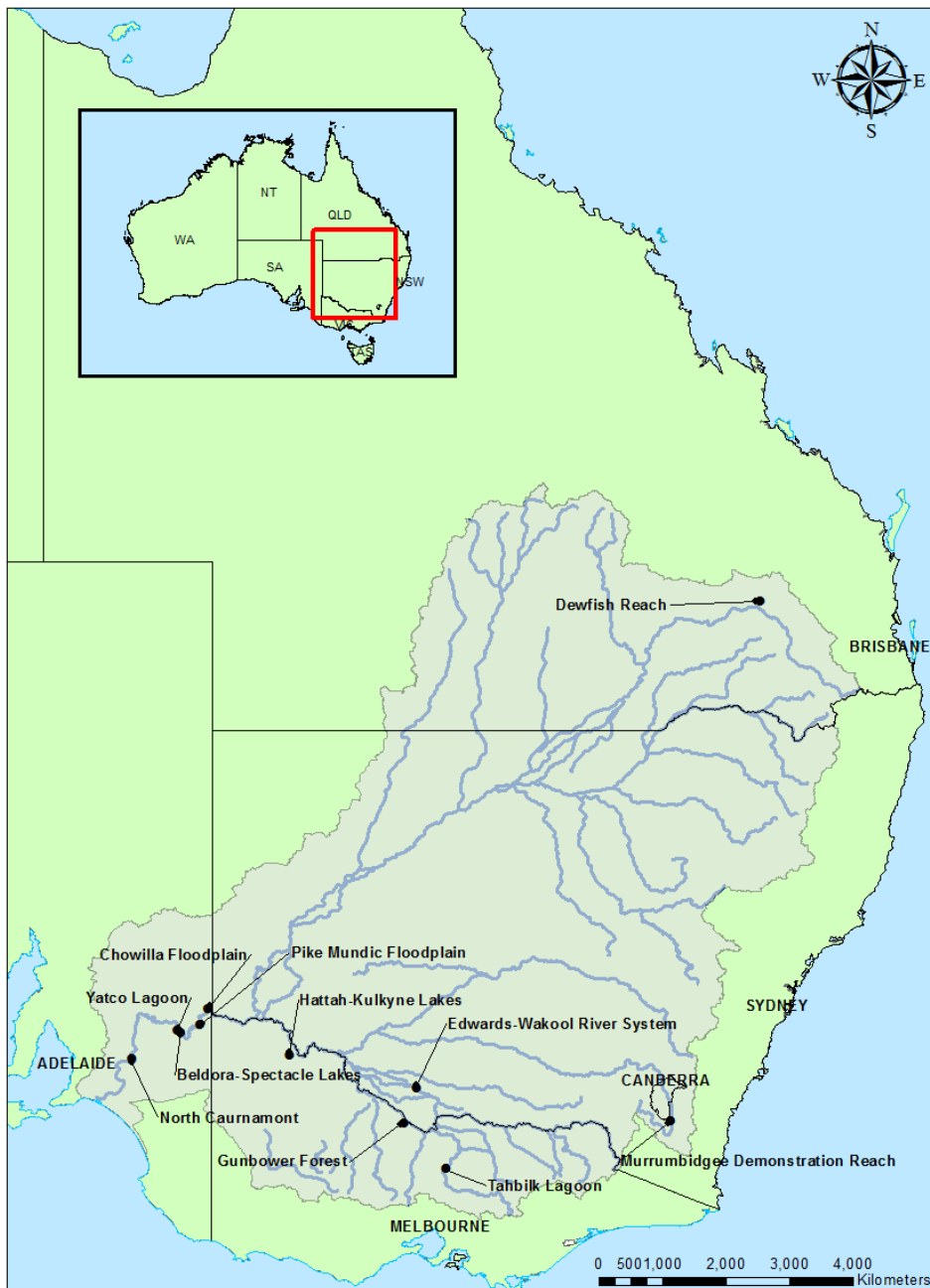


Figure 16. Sites where Carp management plans have been reviewed

The development of Carp management plans requires a systematic and strategic approach (Braysher et al. 2008) that relies on an understanding of the ecology and biology of Carp and of non-target species (Smith et al. 2009) as well as site-specific issues, including hydrology, morphology and resource availability. Careful consideration of the benefits and potential impacts associated with proposed interventions (i.e. Carp screens, separation cages) and management/operational strategies (i.e. flow delivery, draining) is required. Ultimately, a Carp management plan should promote an informed, integrated and adaptive approach that seeks to disadvantage/control Carp while minimising impacts on non-target native species, particularly since total Carp eradication is unlikely and the potential for negative impacts is high (Braysher et al. 2008). Existing Carp management plans vary in the degree to which they consider these issues, with some presenting an informed, integrated and adaptive approach (i.e. Stuart et al. 2011, Stuart and Mallen-Cooper 2011;



Appendix 5) and others briefly considering Carp management as one component of a more generalised site management plan (see Appendix 5). Furthermore, there are few risk assessments where pest management planning is included as a component. Indeed, all high-risk locations (see Section 8) need Carp plans that are integrated into water management planning.

#### 4.4 Proforma Carp management plan

Given the variation in approaches to Carp management plans and the major gaps in site-specific plans at high priority sites (e.g. the MDB-wide Carp management plan, Barmah–Millewa, Koondrook–Perricoota, Lower Lakes, Darling River), this project has included a proforma structure that may be used to facilitate the development of Carp management plans (Appendix 4). The following components form the basis of such plans:

- background material
- identifying ecological assets
- development of Carp population conceptual models
- hydrodynamic/inundation modelling
- Carp population dynamics modelling
- risk assessment
- Carp management workshop
- report on likely Carp response to proposed watering scenarios
- identification of appropriate Carp management measures.

#### 4.5 Review of Carp management methods

Considerable resources have been invested in developing and evaluating novel strategies to manage Carp. In Australia, there is a national management strategy (Carp Control Coordinating Group 2000a) and several texts outlining the species' ecology and management options (Roberts and Tilzey 1997; Koehn et al. 2000). Common management methods rely on a strong understanding of Carp ecology and aim to target or exploit intrinsic behaviours (i.e. migrations, spawning). The utility of each method is dependent on several factors, including season (i.e. spawning vs winter), scale (i.e. individual wetlands, river reach, whole of system), hydrology (i.e. base flow vs flood) and resource availability (Table 6). Specific options for Carp management include operational and intervention techniques or a combination of both. To date, these largely rely on commercial fishing, steel mesh Carp exclusion screens in wetland flow control structures to restrict access to spawning sites (French et al. 1999; Hillyard et al. 2010), electrical barriers for restricting movements (Verrill and Berry 1995), barrier netting and liming to sabotage spawning (Inland Fisheries Service 2008), tracking Judas Carp to locate and harvest aggregations (Inland Fisheries Service 2008), jumping traps (William's Carp separation cages; Stuart et al. 2006; Thwaites 2011), push traps (Thwaites et al. 2010), pheromone traps (Sorensen and Stacey 2004), chemical pesticides (Sanger and Koehn 1997; Clearwater et al. 2008) and water level manipulations to reduce access to littoral spawning sites and expose eggs to desiccation (Shields 1957; Yamamoto et al. 2006). The strategic delivery of water to disadvantage Carp by providing a non-preferred inundation regime or mosaics of fast- and slow-flowing habitats has been proposed, but is yet to be fully evaluated (Stuart et al. 2011).

Genetic control measures ('daughterless' Carp; Thresher 2008) and biological technologies [Koi Herpes Virus (KHV); McColl et al. 2007] are also in development. The proposed future release (possibly by 2017) of the KHV has been suggested to have the potential to result in significant mortality rates (70–90%; McColl et al. 2007; Brown and Gilligan 2014), especially when combined



with daughterless Carp and conventional methods (e.g. Carp cages, summer drying, reducing summer floodplain inundation). Although KHV may promise large-scale population impacts (Brown and Gilligan 2014), it is still not available for deployment; hence, control measures to date have largely been limited to small-scale exclusions and harvest (e.g. Jackson 2009; Hillyard et al. 2010).

Although single methods can be extremely effective at reducing Carp numbers, Carp management relies on an integrated approach to using pest management principles that focus on clear objectives aimed at reducing impacts, not just at removing Carp (Koehn et al. 2000; Brown and Walker 2004). Indeed, Carp were successfully eradicated from Tasmania's Lake Crescent using a combination of techniques, including tracking, spawning sabotage, netting and electrofishing (Inland Fisheries Service 2008). Brown and Gilligan (2014) evaluated potential Carp control strategies using a metapopulation model and found Carp removal methods could reduce biomass by ~50% in the study area (Lachlan River catchment), but that this was not sufficient to reduce densities below the thresholds associated with ecological damage.

Little consideration has been given to prevention of recruitment from water management or natural flooding in rivers. There are, however, some valuable lessons in the Tasmanian experience with regard to denying Carp access to spawning habitats (drawdowns, barrier netting, etc.; Diggle et al. 2012); while impractical to implement in rivers in the MDB, they do illustrate the value of managing spawning areas. Flows and Carp spawning ecology are intimately linked, and water delivery onto or retention on floodplains should be considered within a Carp management plan.

Predation does not appear to be a limiting factor for Carp in southern Australia, where there are few large fish predators (Cadwallader and Backhouse 1983; Allen et al. 2002)—most predatory native species have already suffered massive declines (Cadwallader and Lawrence 1990). Serious predation by birds is also unlikely (Barker and Vestjens 1989). The rapid expansion of Carp within these regions may have been assisted by this lack of predatory pressure. Habitat separation of young Carp from predators such as Murray Cod and Golden Perch, together with limited gape size, mean that predatory impacts on populations are likely to be minor (Doyle 2012). However, even in the presence of predators, a highly fecund species such as Carp may simply overwhelm predators with large numbers of juveniles, and as the growth rate of juveniles is rapid, they can quickly reach a size that precludes their consumption by most predators. At present, mechanical options such as screens, wetland drying or removal (Figure 17) remain the main management options. Additional details of the methods listed in Table 6 are provided in Appendix 6.

In order to effectively manage Carp, there is also the need for a properly designed and implemented monitoring strategy. The lack of available consistent and appropriate data has been identified as an impediment by this and other studies (e.g. Forsyth et al. 2013).

Table 6. Carp management options, potential effect on Carp population, and applicability to flow bands (components)

Cease to flow—1; Base flow—2; Freshes—3; Bankfull—4; Overbank—5. \*= not yet available for use.

Management option	Comments	Flow band				
		1	2	3	4	5
Exclusion screens (French et al. 1999; Hillyard et al. 2010)	<p>By restricting access of adult Carp to wetland spawning grounds, this can be an effective 'localised' control method.</p> <p>Without active screen management (i.e. opening/closing) or periodic wetland drying there is potential to 'compress' larger Carp into wetlands.</p> <p>Flow control structures are required, which can be expensive to install and manage.</p> <p>Will impact large-bodied native fish by restricting wetland access.</p> <p>Do not prevent access by juveniles, which can then grow to adult size in wetlands.</p>	✓	✓	✓	✓	
Williams' Carp separation cages (Stuart et al. 2006)	<p>Can remove large tonnages of Carp during annual spawning migrations.</p> <p>Most cost-effective in river fishways.</p> <p>Requires expensive infrastructure to mechanically lift and empty captured fish.</p> <p>Can impact native fish if trapped fishways become blocked by Carp during migration periods.</p> <p>Requires coordinated removal from traps and provisions for disposal.</p> <p>Only deployable in engineered fishways (e.g. vertical slot), not 'natural' fishways such as rock ramps.</p>	✓	✓	✓	✓	
Pushing traps (Thwaites et al. 2010)	<p>Field trials have shown this method to work in combination with separation cages (jumping traps).</p> <p>When fitted as an 'exit gate' in exclusion screens, push traps may have control application by allowing large Carp to exit a wetland.</p>	✓	✓	✓	✓	

Management option	Comments	Flow band				
		1	2	3	4	5
Targeted harvesting: electrofishing/netting	<p>Unlikely to catch all Carp, but will aid in reducing numbers on a 'localised' scale.</p> <p>Can remove large tonnages of Carp during annual spawning migrations with large nets.</p> <p>Depending on the level of effort required to achieve a satisfactory reduction in the biomass of Carp, this may be an expensive option.</p> <p>There may be some native species bycatch.</p> <p>Can be labour-intensive (e.g. electrofishing) and difficult at some sites (e.g. remote, snaggy).</p> <p>Removal by anglers has limited impact on populations, but may increase public awareness of the problem.</p>	✓	✓	✓		
Wetland draining/drying	<p>Draining and drying can be extremely effective in eradicating Carp.</p> <p>Not species-specific, so will impact native fish species present.</p> <p>If the wetland cannot be fully drained then there is the possibility of destroying any fish remaining in residual pools with rotenone (see chemical piscicides below).</p> <p>High possibility of invasive species re-establishing during refilling.</p> <p>Impractical during environmental water delivery.</p>	✓	✓	✓		
Water level manipulations (Shields 1957; Yamamoto et al. 2006)	<p>Used to prevent access to spawning sites (fringing wetlands or vegetation).</p> <p>Used to expose and desiccate eggs deposited on fringing vegetation.</p> <p>Can be effective for Carp, which spawn on submerged vegetation.</p> <p>Requires flow and water level control structures.</p> <p>Timing of manipulations is critical because there is potential to impact native species spawning.</p>	✓	✓	✓		

Management option	Comments	Flow band				
		1	2	3	4	5
Wetland disconnection	<p>Disconnect the wetland at the inlet and utilise fish-smart (e.g. screened) irrigation off-take techniques to pump water from the river into the wetland.</p> <p>Will restrict large- and small-bodied fish (native and invasive) from entering the wetland.</p> <p>Depending on the mesh utilised and the time when pumping occurs, there may still be some potential to introduce Carp eggs and larvae.</p> <p>Potential issues with the mesh basket fouling with entrained debris/fish—will require regular cleaning.</p> <p>Potentially high impact because complete disconnection will exclude native species from accessing the wetland.</p>	✓	✓	✓		
Tracking and targeting schools associated with Judas Carp (Inland Fisheries Service 2008)	<p>Shown to very effective in Lake Crescent (Tasmania); however, is likely to be less effective in the MDB.</p> <p>Requires scientific expertise and equipment.</p> <p>Can identify exploitable behaviours.</p> <p>Conducted in conjunction with targeted removal.</p>	✓	✓	✓	✓	
Chemical piscicides such as rotenone (Sanger and Koehn 1997; Clearwater et al. 2008)	<p>Can be effective at locally eradicating Carp; however, not species-specific and will destroy native fish species.</p> <p>May provide localised control in relatively small, isolated waters.</p> <p>Will require large quantities of chemical and potentially several applications; thus can be expensive.</p> <p>Wetland will need to be isolated and residual chemical treated to avoid downstream mortalities.</p> <p>Requires specialised training and permits.</p> <p>May be difficult acquiring permits due to presence of native species.</p>	✓	✓	✓		

Management option	Comments	Flow band				
		1	2	3	4	5
Barrier netting (Inland Fisheries Service 2008)	<p>Fine-mesh netting is deployed to restrict access of fish to preferred spawning habitat, i.e. fringing vegetation.</p> <p>Has been effective in Tasmania at reducing spawning success of Carp.</p> <p>The volume of fine-mesh netting required to net-off all fringing habitat is expensive.</p> <p>Labour intensive to install, remove and maintain.</p> <p>May provide localised management.</p>	✓	✓	✓		
Commercial fishing	<p>Can remove large tonnages of Carp (e.g. an average of ~500 tonne per year from Lower Lakes Fishery).</p> <p>Likely to be size-selective.</p> <p>Unlikely to catch all Carp, but will aid in reducing numbers on a 'localised' scale.</p> <p>There may be some native species bycatch.</p> <p>Difficult to undertake in most river situations.</p>	✓	✓	✓	✓	✓
*Electrical barriers (Verrill and Berry 1995)	<p>Used to restrict movements (usually upstream) of fish by establishing an electrical field between two electrodes. Fish are shocked—they either turn around or are briefly paralysed and flow downstream before recovery.</p> <p>Unsuitable due to cost and potential risks to the general public and native species.</p>	✓	✓	✓		
Habitat rehabilitation	<p>Used to advantage native fishes and to disadvantage Carp</p> <p>Strategic water delivery.</p> <p>Needs to be evaluated.</p>	✓	✓	✓		
Pheromone lure traps (Sorensen and Stacey 2004)	<p>Can be expensive and requires scientific expertise.</p> <p>Limited success in field trails.</p>	✓	✓	✓		

Management option	Comments	Flow band				
		1	2	3	4	5
*Daughterless Carp (Thresher 2008)	<p>Alters the genes of Carp so they only produce male offspring, thus skewing sex ratios.</p> <p>The altered gene becomes part of the genetic make-up of offspring.</p> <p>Long-term commitment to breed and release enough genetically altered Carp for the gene to permeate through populations.</p> <p>Could provide large-scale control, but is expensive.</p> <p>Deployment in the wild still many years away.</p>	✓	✓	✓	✓	✓
*Cyprinid herpes virus (CHV-3; McColl et al. 2007)	<p>Highly contagious water-borne virus.</p> <p>Viral particles in water active for up to 3 days.</p> <p>Infected fish die within 3 days of exposure.</p> <p>Most infectious between 22 and 27°C; virtually no occurrence of disease above 30°C or below 15°C.</p> <p>Some Carp can survive and become carriers.</p> <p>Carp–goldfish hybrids less susceptible.</p> <p>To date, no evidence to suggest natives will be infected.</p> <p>Could provide large-scale control.</p> <p>Deployment in the wild still many years away.</p>	✓	✓	✓	✓	✓
Predation by native biota	<p>May impact eggs, larvae or more likely, juvenile Carp.</p> <p>Predatory fish species are mainly Murray Cod and Golden Perch: their habitats do not always overlap with those of juvenile Carp, and impacts of predation may not be great (Doyle 2012).</p> <p>Predation may also occur by birds such as Australian Pelicans (<i>Pelecanus conspicillatus</i>) and cormorants, but the level of predation is unknown.</p> <p>Adult Carp may be taken by larger birds and Murray Cod, but this is expected to be limited due to the Carp's large size.</p> <p>Stocking with predatory fish species will take many years before adult populations capable of predation are established.</p>	✓	✓	✓	✓	✓



Figure 17. Removal is the most common on-ground management action currently undertaken for Carp (photo: Ivor Stuart)

## 5 Ecological concepts and models

It was considered important to examine and discuss a range of ecological concepts to ensure that development of the Carp population model was based on sound scientific principles and that all project participants had a clear understanding of those concepts. A review of the ecological knowledge about Carp is provided in Appendix 2 and includes:

- life stages; life history
- population dynamics (including carrying capacity and variability)
- spatial scales
- regional differences, sites to landscape scale, and connectivity
- movements, aggregations and dispersal
- seasonality (temporal scales)
- habitat types
- ecosystem functioning and processes
- refugia
- flow regimes (components, cues/thresholds).

Conceptual models were then developed based on this knowledge (see Appendix 3). The establishment of agreed conceptual models for the various components of Carp ecology was seen as essential for guiding the structure and development of the population model, for identifying any assumptions made within the population model determining the scenarios to be modelled, and for interpretation of results for management.



## 6 Carp population model

### 6.1 Carp populations and modelling

This section describes the development of a Carp population model to explore the consequence of various flow patterns and access to floodplains and wetlands. It also demonstrates how the models may be used to inform the management of EWAs. The Carp model can assess the possible consequences to populations (abundances, biomasses, structures) caused by the impacts of watering management actions and can be applied over a range of spatial and temporal scales (i.e. sites to river reaches or basins, and years to decades).

A simplified description of a system or process is a model. Models are useful for examining complex processes and interactions. Population models are often specifically developed to represent a single species and its dynamic interactions with its environment, and have the potential to describe how humans impact their environment. Population models are used in a variety of applications, including setting harvest limits, epidemiology and disease control, and threatened species modelling (Todd et al. 2011). Population models are useful in setting up a rigorous logical framework that removes subjective opinion from the process and helps us to understand the consequence of our assumptions, to explore key knowledge gaps and to ascertain the impact of management decisions. Decisions can be made with full awareness of the uncertainties involved, making it possible to claim... “if this is the state of the world and we take these actions, then these are the consequences” (Todd et al. 2004).

In recent years a number of models have been developed for Australian native freshwater fish. A population viability analysis of Trout Cod by Todd et al. (2004) examined some key uncertainties and provided useful strategies for reintroduction, which were later successfully implemented in the Ovens River (Lyon et al. 2012). Todd et al. (2005) examined the threatening process of cold-water releases on Murray Cod and developed a case study for the Mitta Mitta River, explaining the decline of Murray Cod in that system. Koehn and Todd (2012) extended this work to include numerous threatening processes confronting the Murray Cod: thermal pollution, fishing, illegal fishing, catch-and-release mortality, fish kills, larval loss, habitat changes, and stocking. In addition, a more general study was undertaken to determine whether population models could be developed for the breadth of both native and alien fish species found in the MDB (Todd et al. 2011). This work highlighted the utility of developing models to explore the consequence of EWAs on the MDB’s fish fauna.

Not only does the creation of a model provide a useful tool for management, but the modelling process itself can also generate considerable benefits. These include: the review and collation of up-to-date knowledge, including recent and unpublished work; and the involvement of management staff and stakeholders, especially in a collaborative workshop situation. These collaborations engender understanding, ownership and trust in the model and the development process and also ensure that the correct management context is considered and that the priority questions are addressed.

### 6.2 Review of Carp population models

Although various types of models have been developed for Carp in recent years (Lorenzen 1996; Brown and Walker 2004; Weber et al. 2011; Colvin et al. 2012; Forsyth et al. 2013; Brown and Gilligan 2014), for a species that is as highly invasive and internationally widespread as Carp (Koehn et al. 2000) it is surprising that there have not been more population models developed to explore management options. We found only a limited number of publications specifically relating to population modelling and Carp, and none of these specifically examined recruitment or in particular

the drivers of recruitment strength relating to the four key early life-history stages: egg, larvae, fingerling and young-of-the-year survival.

There are three modelling publications that specifically relate to the management of Carp in Australia: (1) Carpsim (Brown and Walker 2004); (2) a Bayesian wetland watering model (Gawne et al. 2012); and (3) a review (Forsyth et al. 2013).

1. Brown and Walker 2004: CarpSim is a biomass model underpinned by a 30 age class model. The model uses fisheries-type constructs that are theoretical in nature, such as natural mortality and fishing mortality, and both of these forms of mortality are constant in the model. The dynamics of the model are driven by recruitment to age 1. Recruitment strength is driven by two types of environmental drivers (the Southern Oscillation Index and Murray River flows), but is not related to available habitat or productivity of habitats. Years are classified as good or bad, so that a time series of good and bad years are generated for recruitment. CarpSim is no longer maintained by the Victorian Department of Primary Industries and when downloaded could not be installed or run. It is likely that CarpSim would require a large amount of reprogramming to be flexible enough to be applied to the various flow scenarios being considered in this project.
2. Gawne et al. (2012): a Bayesian wetland watering model developed in Netica, designed to assist in making management decisions. This is a static model (i.e. it doesn't vary through time), and it does not allow feedback loops, such as density-dependent type mechanisms—a likely driver of recruitment strength. The inputs are useful and may help structure particular management scenarios that can be explored using a more dynamic model over time.
3. Forsyth et al. (2013): this paper was a theoretical exercise examining a suite of unstructured population models to see which best explained the observed outbreak in Carp numbers in the MDB. The conclusion was that the main ecological driver for Carp dynamics was overbank flooding. It requires extensive CPUE time series data for undertaking any analysis and was based on individual models.

### 6.3 Model structure and development

After reviewing the available models, it was decided that the best model construct for the purpose of this study required a mechanistic understanding of the dynamics of Carp early life history, because recruitment strength drives Carp dynamics. This exploration of early life history also required an examination of the habitats utilised by Carp in this phase of their development and the likely productivity associated with habitats.

We used the life history and available data for Carp to guide the construction of a stochastic, age-based population model with an explicit description of egg, larval, fingerling and young-of-the-year survival. A stochastic age-based model allows the availability of various habitat types to drive the dynamics, and flows determine the availability of habitat.

We defined 14 flow–habitat types (see also Appendix 8 for further descriptions):

- H1 Main Channel (Mid Upper Murray)—base flow;
- H2 Main Channel (Mid Upper Murray)—cover benches;
- H3 Main Chanel (Mid Upper Murray)—summer irrigation flow;
- H4 Main Channel (Lower Murray)—base flow;
- H5 Main Channel (Lower Murray)—cover benches, summer entitlement;
- H6 River wetland, e.g. Barmah–Millewa;
- H7 Wetland perennial, e.g. Kow swamp;

- H8 Wetland ephemeral, e.g. Hattah Lakes;
- H9 Wetland permanently connected, e.g. adjacent weir pool;
- H10 Natural floodplain inundation;
- H11 Artificial floodplain inundation, e.g. Chowilla;
- H12 Lakes (off-stream), e.g. Lake Victoria;
- H13 Lakes (terminal), e.g. Alexandrina; and
- H14 Irrigation channels.

This construct allowed for a variety of scenarios to be considered, such as mechanistic-type scenarios in which access to certain habitats occurs at different frequencies or at specific flow time series. Such examination can help comprehension of the scale of Carp dynamics under natural or modified modelled flow scenarios to determine the likely impact on Carp dynamics, and consequently can be used to inform specific flow management. The life history of Carp is well known (see Section 2 and Appendix 2). In general Carp are: long-lived, up to 34 years old; fast growing, attaining a maximum size of ~80 cm; exhibit variable fecundity with size; and are sexually mature by the age of 3.

The model development process is illustrated in Figure 18, and details of the supporting structure, information and data are given in Appendix 7.

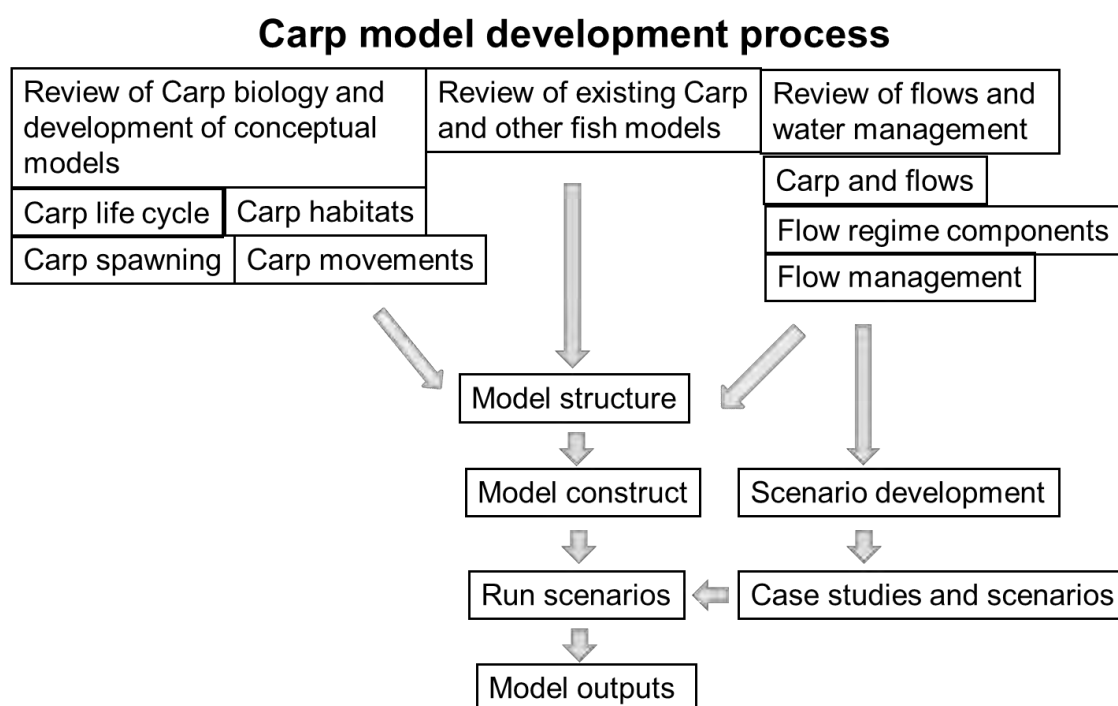


Figure 18. Conceptual diagram for the development of Carp population modelling in relation to flows

## 6.4 Guiding principles

The model development workshop determined the need to establish some general principles for the model development and use. These included:

- Any risks posed by Carp must be considered in the context of the benefits to native species. The benefits to native fish need to be considered in a similar way to the disbenefits of Carp, and the approaches and outputs need to be somewhat compatible.
- There needs to be clear identification of when and where Carp are an issue.
- All aspects of the flow regime need to be considered.
- Risks of Carp as a consequence of water management options need to be considered as a related (but separate) issue.
- The model must be compatible for use in conjunction with pest management principles, where eradication is not the objective, but where multifaceted management actions to minimise impacts are needed.
- There is a need to consider landscape scales and longer time frames when dealing with this long-lived species (not just the immediate watering)—preferably greater than a decade.
- Investment in Carp ‘control’ options and their use is an important component of Carp–water management that needs to be considered beyond this project.
- The ecological concepts, the population model, the scenario testing and the experimental learning must all add to the published science (evidence-based management) and adaptive management.
- There are likely to be regional differences for the Carp model. A further model may be needed—this is especially likely for the northern MDB.
- A regional inundation model will be used, but a metapopulation model would be preferred (see Table 7). This is particularly important, given the high rates of movement and larval drift.
- There are recognised knowledge gaps for mortality and movement of early life stages.
- Survival is dependent on habitat, flow, pool quality, drought, etc. Expert assessment will have to be used for this.
- Mortality is highest between larval and young-of-the-year stages (prior to the change to benthic feeding).
- There are other complexities in relation to flows (e.g. rain rejection flows, flows from tributaries, works/repairs) that are not necessarily connected/synchronised.
- There are always female Carp that can spawn at most times of the year if they can match the temperature window.
- The model needs to be applicable to local case studies, i.e. it can be independent of spatial scale.

## 6.5 Spatial scale and differentiation

Spatial scale is determined by the length of the river system of interest and the interacting habitat types specified for that system. While it is possible to scale the model up for potentially MDB-wide representation, detail about the response of the system to specific habitat components may be lost. Focusing on too fine a scale will require numerous assumptions about the behaviour of Carp at that scale, so some care is required in defining the scale of any scenario considered. MDB-wide scale impacts can be explored and, while not part of this project, building of a metapopulation model would facilitate an overall Basin-wide view, while still maintaining detail around particular regional areas. Some clear regional differences have already been incorporated into this modelling project—especially a separation of the mid and lower river and the Lower Lakes due to management and

ecological differences. Also, differences in the southern and northern MDB may be evident and need exploring. The various habitat types across the breadth of the MDB would allow those regional differences to remain embedded in a single population model, and connecting a series of single population models into a metapopulation model would allow the model to be scaled up, thus providing insight into the complexity of managing water and its impact on Carp dynamics. Key attributes of the regional approach of this project and the potential for further development of a metapopulation model are given in Table 7.

Table 7. Key attributes of metapopulation and regional models for Carp

Metapopulation model	Regional model
Whole of system approach (integrated)	Run specific case studies at smaller scales
More detailed	Less detailed—use examples
Greater resolutions—case studies and management	Flows—different areas for specific zone populations
Greater confidence for individual wetland and flow scenarios	Movements—areas of habitat available, unavailable or not blocked
Allows greater sensitivity for management	Even distribution of movements
Requires very detailed analysis of movements, e.g. likelihood and direction. Need model for Lower Lakes	Can weight the preferred habitat areas, e.g. highly productive wetlands
Shows greater level of detail for individual ‘unit’ types	
Discreet populations—need model for lower reach weir pools. Need models for each population? Specify the percentage of population moving	
Spawning—individual quality of habitat per type	

## 6.6 Assumptions and uncertainties

There are a number of uncertainties that must be recognised when building any population model. Density dependence is an important unknown, and there is little or no information available for Carp. We know that high densities can be attained, but it is not clear whether these densities can be maintained. The density-dependence mechanism adopted in the model is to constrain adults in the river channel, acknowledging that there must be an upper limit to the density of Carp that a river can maintain. Generally speaking, we have applied the rule of one Carp per linear metre of river as the maximum density in any river modelling, although this is likely to be an underestimate. A top-down approach to density dependence was applied to adult Carp, similar to that used by Todd et al. (2004); in other words, there is some advantage in being older, where older fish get first option on available resources. Other key uncertainties are the estimates of the early life history parameters; without further studies these remain unknown, and we are reliant on the expert elicitation process to provide plausible estimates. Dispersal is not well characterised in the model, other than acknowledging that it occurs in a multitude of ways, and there are likely to be more juveniles than adults dispersing. It has, however, been considered and incorporated into the Barmah–Millewa case study because it is known that adults migrate to and from this favoured spawning site. The key flow thresholds were characterised by time spent at these levels. The period used for successful hatching and larval development to become fingerlings was determined to be at least 25 days with flows greater than a particular threshold. Altering this to a longer period would change the outcomes of some scenarios modelled.

## 6.7 Model scenarios and outputs

There is a very large range of flow and habitat scenarios that could be modelled for this project. To investigate them comprehensively would be both confusing and beyond the scope of this project. Hence, we have only included some of the key areas and outputs that have been highlighted by the modelling process and its development. The key illustrations of floodplain inundation and flow sequencing are given in the examples below. Further, more detailed, site-specific examples are given in the case studies (Section 7). Outputs have been largely limited to adult female population size and the probability of both large and small Carp populations (in the form of risk curves). Because of the array of conditions that are peculiar to any particular site, it is best that individual case studies are modelled to inform site-based management.

### 6.7.1 Flow sequences

Using a hypothetical early life history set of parameters that describe a base flow, and an irrigation flow that inundates a theoretical river wetland, it may be possible to minimise Carp numbers by manipulating the irrigation flows so that wetlands are not inundated every year (Figure 19a). There is a reasonable chance that access to the wetlands every year (70% of the population being >100,000 female adults at least once in the simulation: Figure 19b) or every second year (25% >100,000: Figure 19b) will produce an extremely high Carp population at least once in the 50-year time frame. Whereas no access or access every fifth year produces consistently lower likelihoods of population explosion (Figure 19b). The likelihood of the population being small is much higher when there is no or limited access to the river wetland compared with more frequent access to the wetland (Figure 19c).

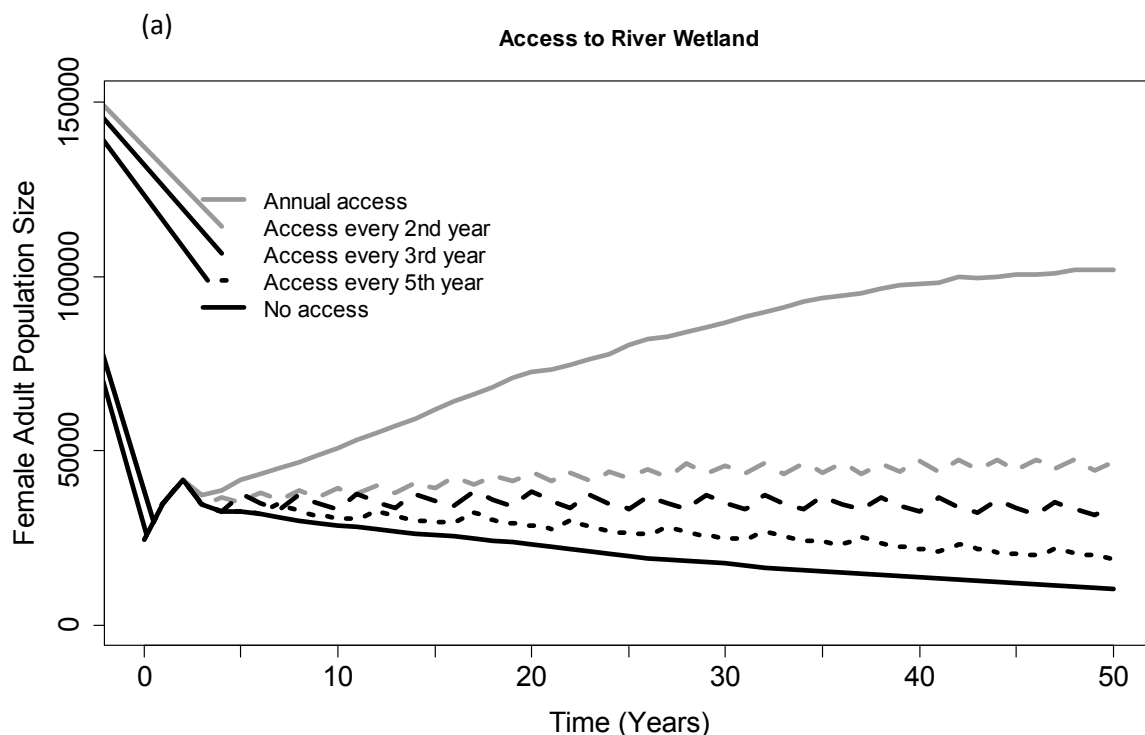
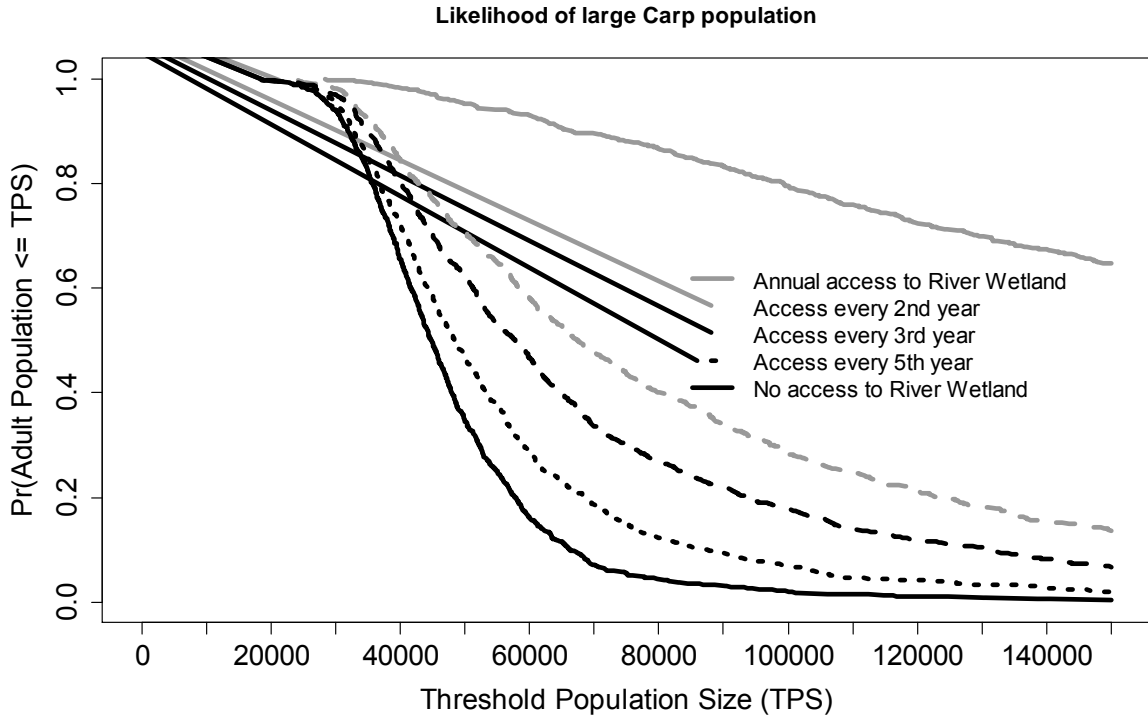
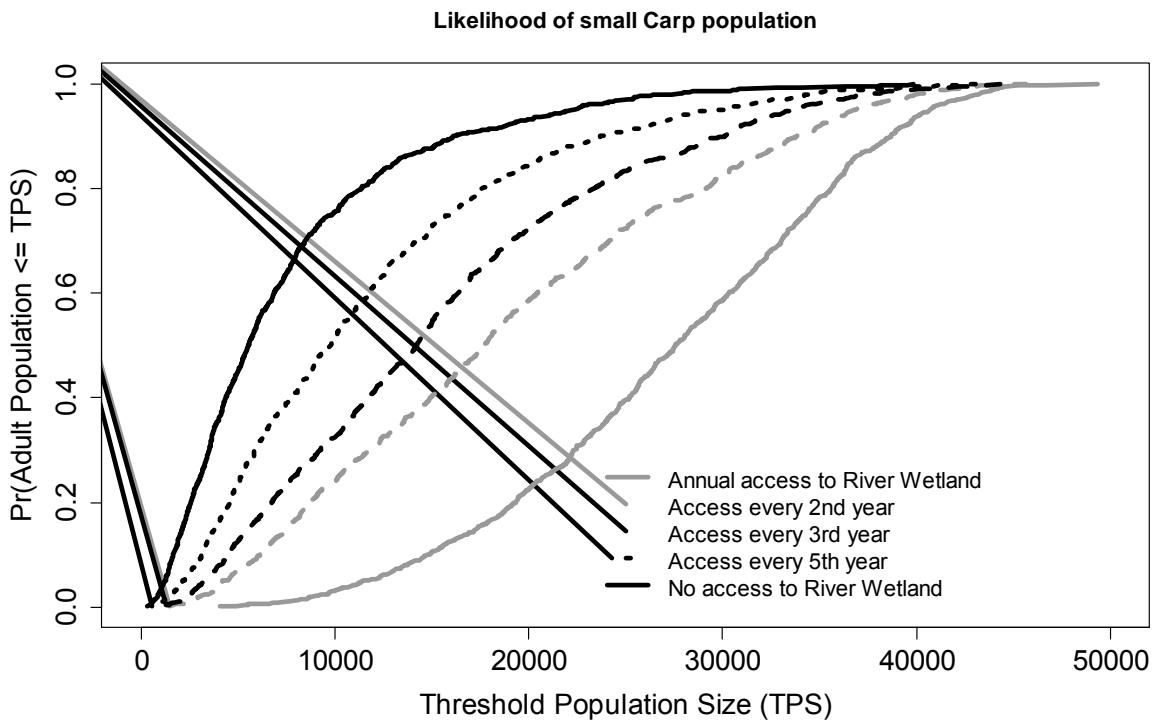


Figure 19. Bench flows and irrigation flows in the Murray River for a theoretical wetland: (a) mean population sizes, (b) likelihood of large population size and (c) likelihood of small population size



(b) Likelihood of large population size.



(c) Likelihood of small population size.

Figure 19 (continued)



### 6.7.2 Floodplain inundation

If a major flood occurs during the simulation (i.e. at Year 25), the Carp recruitment response is significant and the adult population increases to the carrying capacity of the system (Figure 20a). The flood resets some of the scenarios; annual access to a river wetland following a flood maintains high densities of Carp, whereas Carp decline in the other scenarios following a flood. With a restricted access to river wetland scenario of once every 5 years, the population declines rapidly. With a flood included, the chance of a large population for all scenarios is very high (Figure 20b), while the chance of the population being small is not altered greatly (Figure 20c). From this simple example, we can see that Carp will respond to alternate watering of preferred spawning habitats; however, the response when a flood occurs highlights that there is little that can be done when large-scale floodplain access occurs. There is, however, increasing population size, corresponding to the frequency of flooding included in any flow sequence, with annual access to the floodplain habitats providing the largest populations. Such sequencing is very important, especially with potentially very frequent artificial inundations proposed through the use of floodplain regulators.

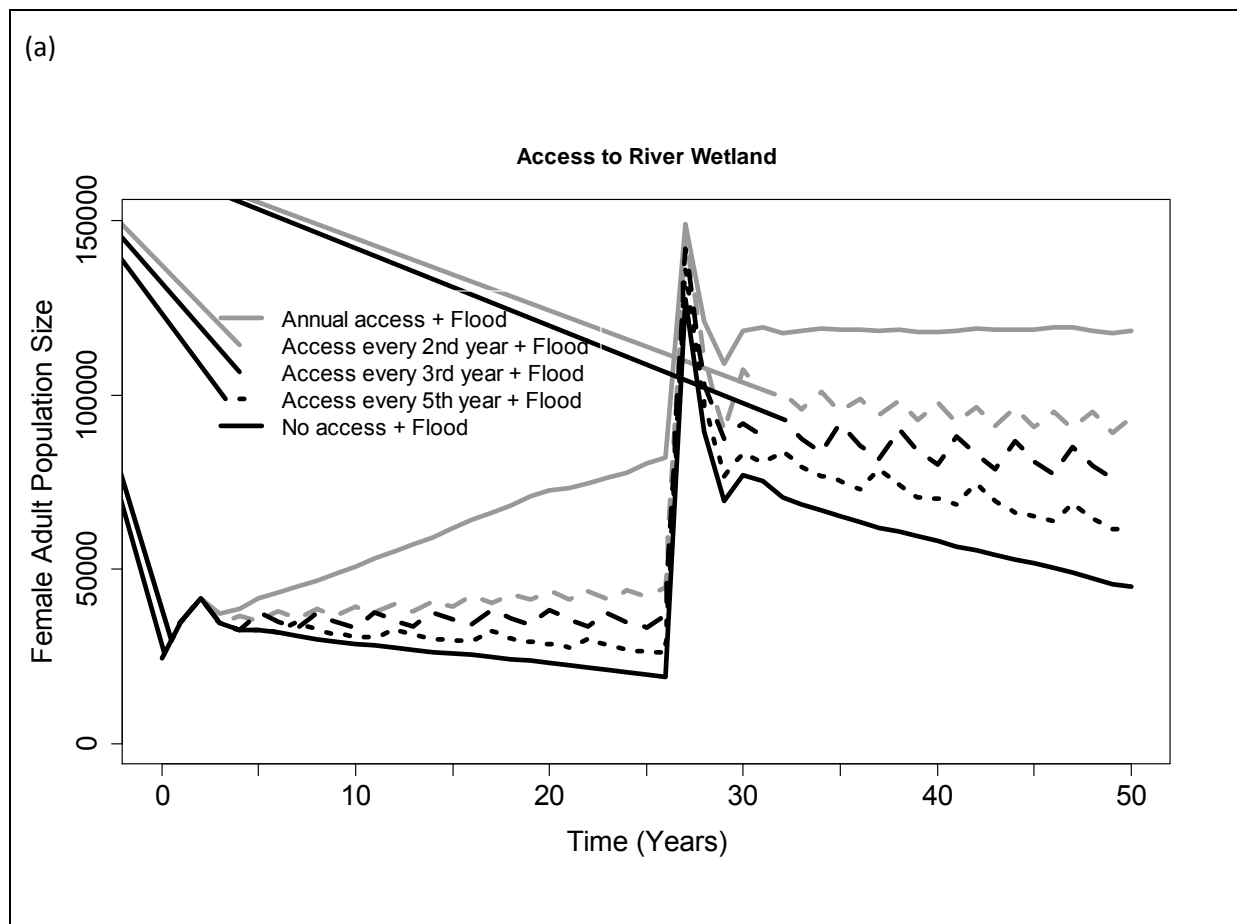


Figure 20. Flood scenario with benches flow and irrigation flow in the Murray River for a theoretical wetland

(A) Mean population sizes, (B) likelihood of large population size and (C) likelihood of small population size.

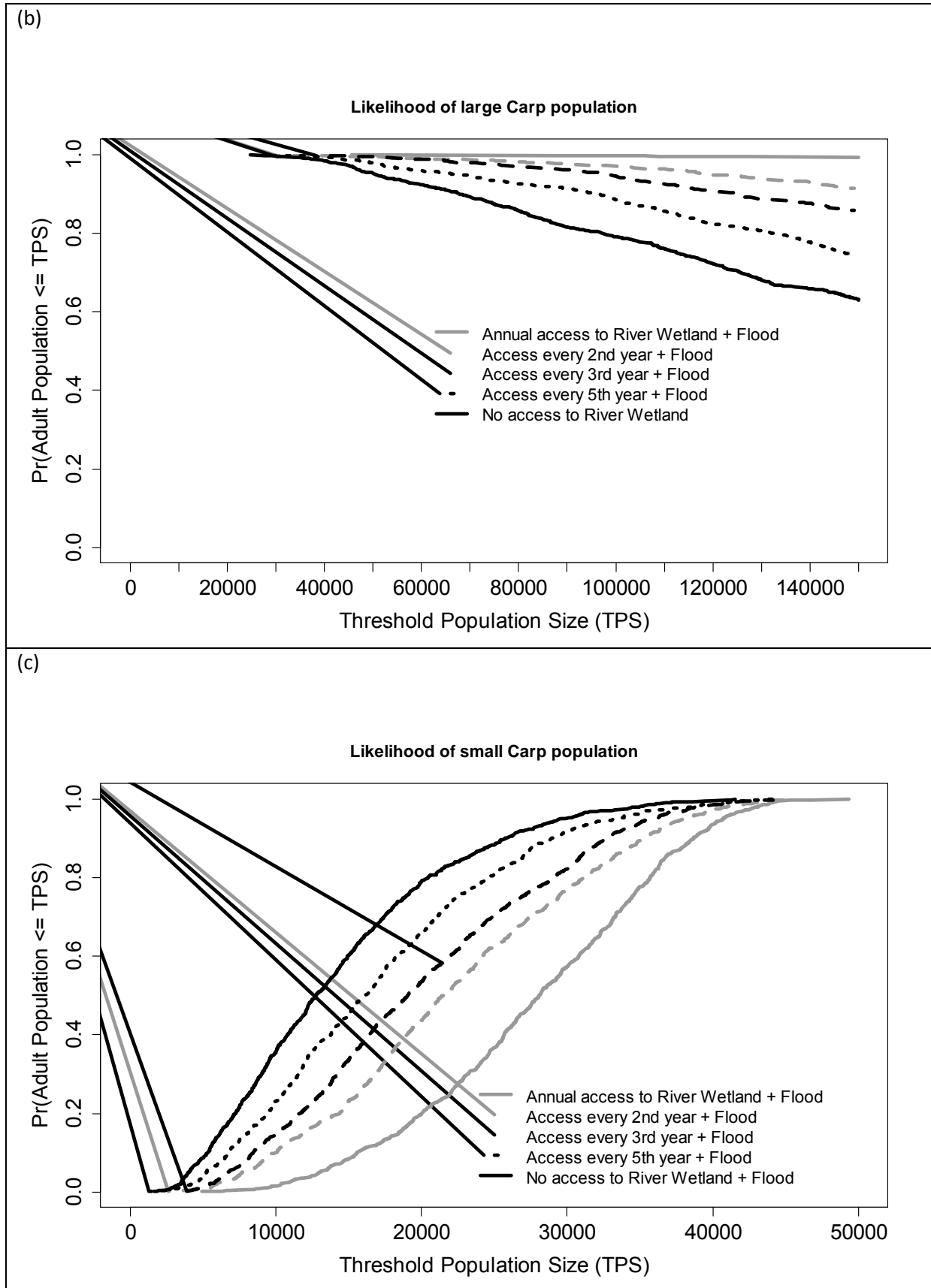


Figure 20 (continued)

## 7 Case studies

There are a wide range of scenarios that involve the management of Carp and flow. These are often complicated and need to be modelled on an individual basis. We considered, however, that modelling four case studies particularly relevant to priority areas/habitats in the MDB would illustrate the model outputs. In order to simplify the key issues at these sites, the following steps were undertaken for each:

1. development of a conceptual schematic diagram of the site
2. identification of the key habitats
3. determination of the areas of each habitat
4. determination of the likely flow regime and sequences
5. modelling of the Carp population outputs.

### 7.1 Lower Murray River downstream of Lock 1

The first case study consisted of Lakes Alexandrina and Albert (the ‘Lower Lakes’, see Section 4.1.11), together with the main channel of the Lower Murray River between Wellington and Lock 1 (Section 4.1.8) and associated wetlands (Section 4.1.12) (Figure 21).

The Lower Lakes cover an area of ~840 km<sup>2</sup> and receive freshwater inflows, mainly from the Murray River. They contain submerged aquatic plants in near-shore habitats (~0.55 m depth at +0.75 m AHD) dominated by *Potamogeton* spp., *Ruppia* spp. and various types of algae and fringing emergent vegetation (~0.15 m depth) dominated by *Phragmites australis* (Gehrig et al. 2011). The Lakes’ open water zone is sparsely vegetated (Gehrig et al. 2011). There are a range of wetlands along the ~200 km of the Murray River between the Lower Lakes and Lock 1 (Blanchetown; Section 4.1.12) that contain a wide range of inundated submerged, terrestrial and aquatic vegetation (Nicol et al. 2013). The Lower Lakes support a large biomass of Carp, which may then move into the river upstream, including the wetlands when they are inundated. High Carp biomasses have been found aggregating below Lock 1 (Figure 10).

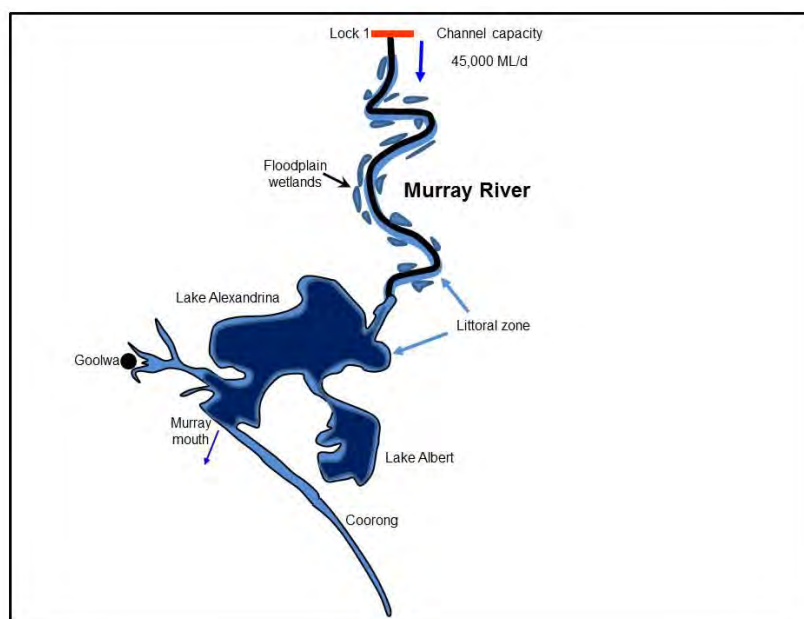


Figure 21. Schematic diagram of the lower Murray case study (including the Lower Lakes, the Lower Murray River, the wetlands and Lock 1)

Hydrological data for the Lower Lakes and the Murray River aquatic habitats below Lock 1 from 2000–2013 and the Lock 1 fishway operating regime helped guide this case study. From 2000–2010, flow in the Murray River downstream of Lock 1 was variable but generally characterised by prolonged periods of low discharge (i.e.  $\leq 5000$  ML/day) (Figure 22a). Two within-channel flow pulses of  $\sim 40,000$  ML/day and  $15,000$  ML/day occurred in December 2000 and February 2001, respectively (Figure 22a). By July 2001, flow had decreased to  $\sim 5,000$  ML/day and remained relatively constant at this level until May 2007, with the exception of two within-channel flow peaks of  $\sim 13,000$  ML/day and  $11,000$  ML/day in September 2003 and October 2005, respectively. From May 2007 until early 2010, flow in the Murray River downstream of Lock 1 was the lowest on record, ranging from  $100$ – $3000$  ML/day. In late 2010, flow increased dramatically, peaking at Lock 1 at  $79,000$  ML/day in March 2011. Flow at Lock 1 was elevated for much of the period from late 2010–2013, with a subsequent peak of  $54,000$  ML/d in May 2012.

Variable flow at Lock 1 over the period from 2000 to 2013 was reflected in water levels in the river channel downstream of Lock 1 and in the Lower Lakes. The Lower Lakes experience high levels of evaporation due to an expansive surface area ( $\sim 840$  km<sup>2</sup>) and shallow depth (Lake Alexandrina mean depth =  $2.9$  m). When evaporative loss is not countered by inflow, water levels in the Lower Lakes recede. Furthermore, hydrological connection between the Lower Lakes and the  $\sim 200$  km of river channel between Wellington and Lock 1 dictates that water levels in the river channel are heavily influenced by water levels in the Lower Lakes.

From 2000–2006, water levels in the river below Lock 1 and in the Lower Lakes ranged over typical regulated levels (i.e.  $0.4$ – $0.9$  m AHD in Lake Alexandrina) (Figure 22b). Following the extended period of low flow from 2001 to 2007, water levels in Lake Alexandrina and in the river channel below Lock 1 receded rapidly in 2006–2007. Diminishing flow from 2007–2009 resulted in further recession, with the water level in Lake Alexandrina falling below sea level (i.e.  $0$  m AHD) for the first time in recorded history. Water level was rapidly restored to typical regulated levels in late 2010 following large increases in flow over Lock 1, coupled with extensive floodplain inundation (bordering the river channel) in early 2011. The water level has since remained within the typical regulated range (Figure 22b).

Variable flow and water levels had a marked effect on aquatic habitat availability over the period 2000–2013. Under low flows (i.e. predominantly  $\leq 5000$  ML/day) and typical regulated water levels in the Murray River downstream of Lock 1, numerous wetlands are inundated and connected to the main channel. Furthermore, the river channel itself is predominantly lentic in nature, and submerged and emergent aquatic macrophytes are common (Nicol et al. 2013). The Lower Lakes are also characterised by a diverse range of aquatic habitats, including vegetated lake edges and off-channel wetlands (Nicol et al. 2013). Reduced flow and water level recession downstream of Lock 1 impacted aquatic habitat availability and quality; notably, the area of Lake Alexandrina diminished, with the remaining water disconnected from fringing emergent vegetation and accompanied by the near complete loss of submerged vegetation and elevated salinity (Kingsford et al. 2011). Furthermore, numerous wetlands that were typically inundated and connected to the river channel under normal regulated conditions were disconnected and desiccated.

The advent of high flows in 2010/11 was accompanied by equally dramatic changes in habitat availability. Water levels in Lake Alexandrina returned to typical levels, reinundating and reconnecting previously desiccated wetlands and fringing emergent vegetation. Submerged vegetation remained absent from the main channel of the Murray River below Lock 1 (Nicol et al. 2013), but previously desiccated wetlands were reinundated and reconnected, and broader areas of the floodplain were inundated over an extended period in early 2011.

Diminished water levels downstream of Lock 1 impacted the operation of the Lock 1 fishway and, subsequently, the biological connectivity with the Murray River upstream. From January 2007 to August 2010, water levels were below the designed operational range (minimum and maximum

head differential of 0.15 and 2.75 m AHD, respectively) of the vertical-slot fishway, impacting entrance conditions and subsequently fishway function (Figure 22a, see also Appendix 3, Figure A3.6). A Denil extension was added to the vertical-slot fishway in June 2009 in an effort to of fish passage.

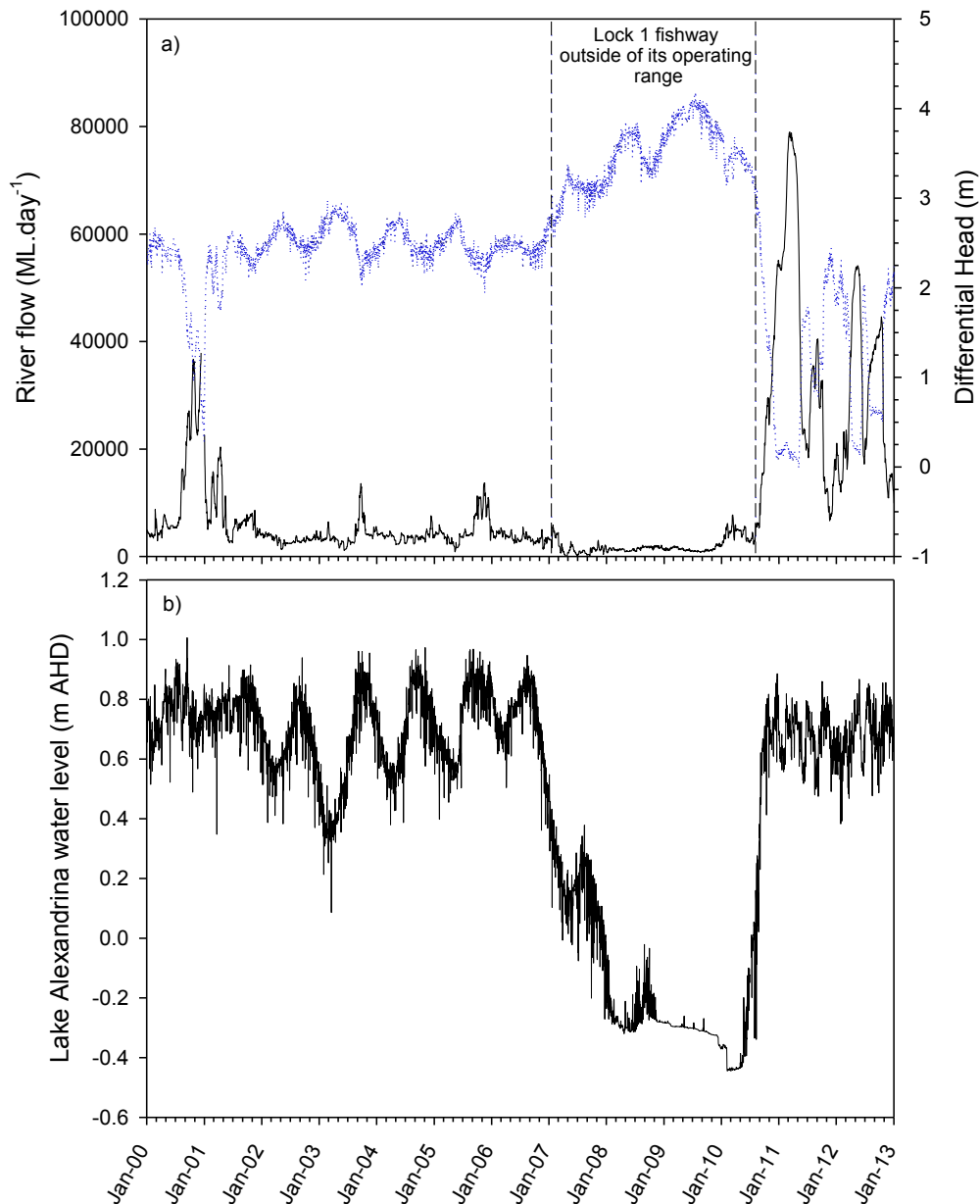


Figure 22. (a) Daily flow (ML/day) in the Murray River (black line) and head differential (m, blue dashed line) at Lock 1 (fishway operating range shaded grey), and (b) water level (m, AHD) in Lake Alexandrina upstream of Tauwitchere Barrage over the period January 2000 to January 2013. Lake Alexandrina water level and Lock 1 flow and water level data sourced from [www.waterconnect.sa.gov.au](http://www.waterconnect.sa.gov.au).

The hydrological data at Lock 1 extends back to 1963. Given the above exploration of the impacts of the lower inflows in to the Lower Lakes during the Millennium Drought, as well as the known removal of Carp through both commercial catch and Carp trap removals (Tables 4 and 8 and Figure 23), we wanted to understand the likely impacts of flow on a 'Lower Lakes' Carp population. The flow required to inundate various off-channel habitat types is well understood (Table 9). The historical flow sequence (Figure 24), combined with the flow bands for inundation, allows the extent and duration of inundated habitat types to be calculated for the Murray River below Lock 1.

Table 8. Commercial Carp catch in the Lower Lakes per year from 1984/85 to 2013/14

<sup>a</sup>Numbers were estimated by multiplying tonnes by 1000 to convert to kilograms, then dividing by 2 (assumes the average weight of Carp caught is 2 kg; commercial fisher estimate).

Year	Total catch (tonne)	Estimated numbers <sup>a</sup>	Carp trap removals
1984/85	302.0355	151,017	
1985/86	268.0516	134,025	
1986/87	284.3246	142,162	
1987/88	444.6483	222,324	
1988/89	358.4465	179,223	
1989/90	375.289	187,644	
1990/91	492.128	246,064	
1991/92	999.316	499,658	
1992/93	661.5402	330,770	
1993/94	825.0229	412,511	
1994/95	815.579	407,789	
1995/96	763.3238	381,661	
1996/97	752.2138	376,106	
1997/98	617.0888	308,544	
1998/99	439.7673	219,883	
1999/00	263.0298	131,514	
2000/01	261.9115	130,955	
2001/02	208.3896	104,194	
2002/03	403.1997	201,599	
2003/04	573.011	286,505	
2004/05	554.432	277,216	
2005/06	745.598	372,799	
2006/07	692.208	346,104	
2007/08	707.919	353,959	23,434
2008/09	782.5211	391,260	53,512
2009/10	581.377	290,688	18,898
2010/11	386.987	193,493	73,516
2011/12	304.004	152,002	125,093
2012/13	328.998	164,499	121,234
2013/14	417.946	208,973	130,012

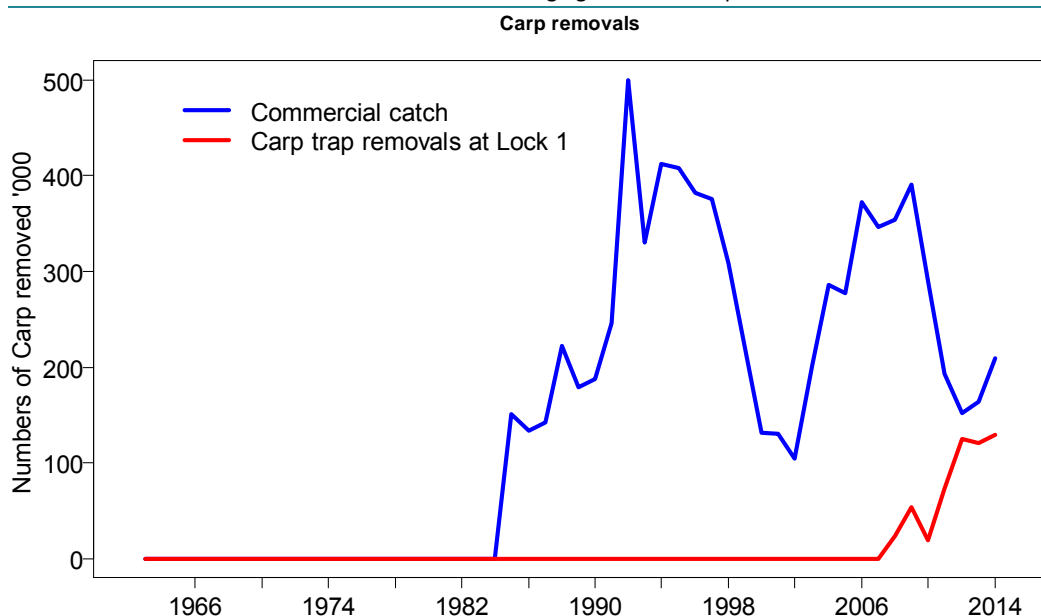


Figure 23. Lower Lakes commercial catch (see Table 8) and Carp trap removals at Lock 1 (see Table 4) over the same period as the flow data

This case study considers habitat types [river channel base flow (H4), ephemeral wetland (H8); permanently connected wetland (H9); natural floodplain inundation (H10); and terminal lakes (H13)] and quantifies the impacts of flow on Carp populations in the Murray River downstream of Lock 1 (incorporating the Lower Lakes). Historical flow data (1963–2014) was used for the flow sequence (Figure 24) to examine the response of Carp populations in this system. The flow sequence has wetter and dryer periods, providing a broad spectrum of flow conditions. If the flow remained at a given level for 25 days or more, then the growth rate specified for the habitat type was achieved. Flow thresholds determine access to the three non-channel habitat types (H8, H9 and H10, Table 9), and the contribution of each habitat type to reproductive success is given in Table 10. Two scenarios were modelled, one assuming Carp utilise both river and floodplain, and a second assuming Carp exclusively use floodplain habitats when available. The length of the river section of this system is ~200 km, bounded by Lock 1 upstream, with a carrying capacity of 200,000 adults, equivalent to 1 Carp/m of river length.



Table 9. Area of habitat types in the Lower Lakes inundated for each flow threshold

H4 = river channel base flow; H8 = ephemeral wetland; H9 = permanently connected wetland; and H10 = natural floodplain inundation.

Flow band (ML/day)	Habitat type			
	H4	H8	H9	H10
3,000	3658.0202	0	0	0
7,000	3658.0202	92.7866	3191.8821	897.2754
10,000	3658.0202	92.9862	3198.8519	897.2754
20,000	3658.0202	102.1472	3204.3820	917.0702
30,000	3658.0202	154.2675	3362.3604	993.7296
40,000	3658.0202	247.1734	3551.3217	1272.7718
50,000	3658.0202	289.2051	3621.3797	1695.8976
60,000	3658.0202	289.7563	3652.1122	2419.7286
70,000	3658.0202	376.3644	3823.6011	9547.9985
80,000	3658.0202	411.4628	3844.8727	11163.0561

Table 10. Flow bands contribution to Carp reproductive success for each habitat type inundated in the Lower Lakes

H4 = river channel base flow; H8 = ephemeral wetland; H9 = permanently connected wetland; and H10 = natural floodplain inundation.

Flow band (ML/day)	Habitat type			
	H4	H8	H9	H10
Combination of river and floodplain				
3,000	1	0	0	0
7,000	0.4666	0.0118	0.4071	0.1144
10,000	0.4662	0.0118	0.4076	0.1143
20,000	0.4641	0.0130	0.4066	0.1164
30,000	0.4478	0.0189	0.4116	0.1217
40,000	0.4191	0.0283	0.4068	0.1458
50,000	0.3948	0.0312	0.3909	0.1831
60,000	0.3651	0.0289	0.3645	0.2415
70,000	0.2102	0.0216	0.2197	0.5485
80,000	0.1917	0.0216	0.2015	0.5851
Mutually exclusive: when floodplain is available, Carp exclusively utilise it				
3,000	1	0	0	0
7,000	0	0.0222	0.7633	0.2146
10,000	0	0.0222	0.7636	0.2142
20,000	0	0.0242	0.7587	0.2171
30,000	0	0.0342	0.7455	0.2203
40,000	0	0.0487	0.7003	0.2510
50,000	0	0.0516	0.6459	0.3025
60,000	0	0.0455	0.5741	0.3804
70,000	0	0.0274	0.2781	0.6945
80,000	0	0.0267	0.2494	0.7240

The carrying capacity for Carp in the Lower Lakes (Lake Alexandrina 662 km<sup>2</sup> and Lake Albert 177 km<sup>2</sup>) is likely to be very large (total area ~840 km<sup>2</sup>). A population estimate of 180,000 adult Carp >500 mm, [with an upper maximum (95% CI) of 415,154 individuals] was made using tag recaptures for Lake Albert (Thwaites et al. 2010). The number of Carp <500 mm TL/LCF present in the lake was unknown. Given the relative sizes of Lakes Albert and Alexandrina and assuming an even distribution of habitats and Carp, this would give an overall estimate of 846,000 adult Carp (upper maximum

estimate of 1.95M) for the Lower Lakes. The carrying capacity is expected to be higher than any point estimate of the population size, given that this estimate is confounded by the commercial removal of Carp in the Lower Lakes. The river carrying capacity of 1 Carp/m equates to 1 Carp per 200 m<sup>2</sup> because the Murray River is ~200 m wide towards the Lower Lakes. Applying this density to the Lower Lakes yields a carrying capacity of  $840,000,000/200 = 4,195,000$ , rounding it down to 4,000,000 adults, where  $840,000,000 \text{ m}^2 = 840 \text{ km}^2$ .

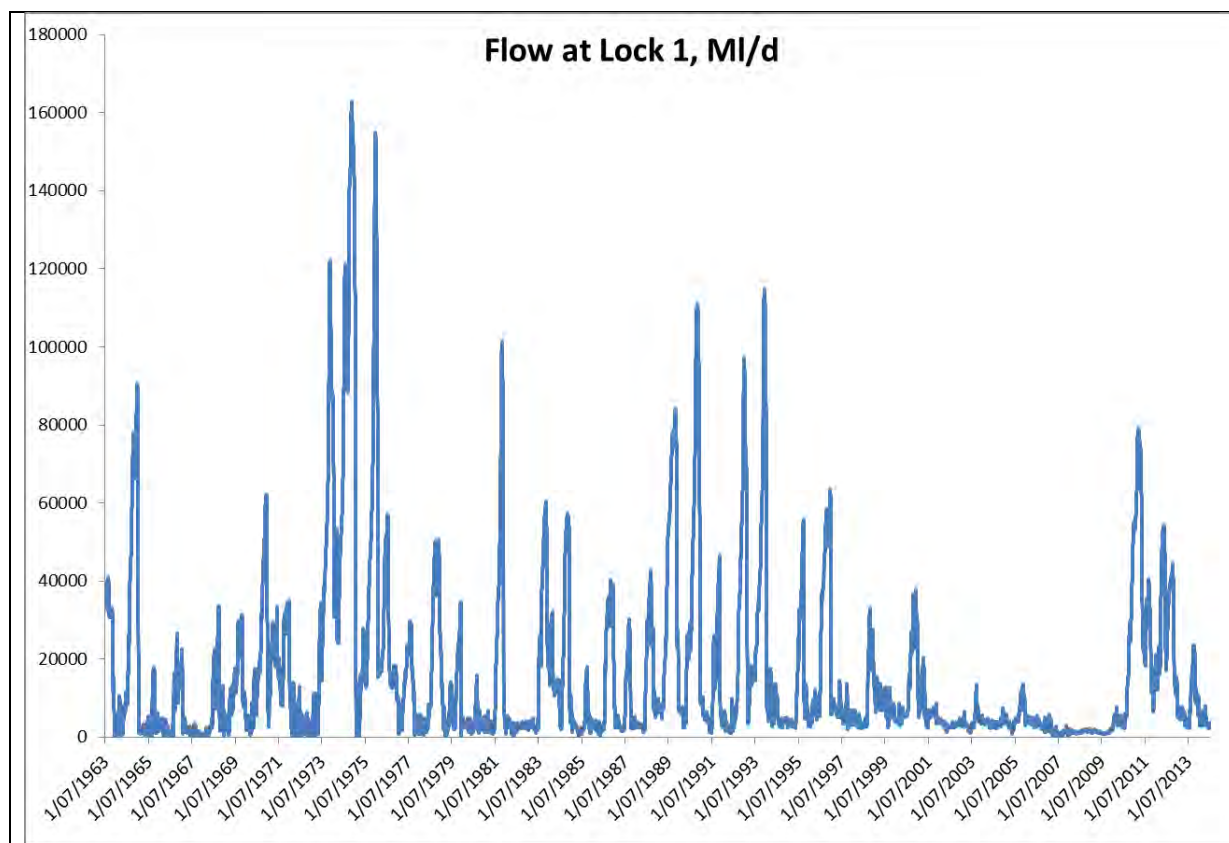


Figure 24. Daily flow data at Lock 1 in South Australia (1963–2014) in ML/day (data MDBA)

In addition to flows affecting the reproductive capacity of Carp, commercial fishing of Carp in the Lower Lakes as well as the introduction of the Carp trap in the fishway at Lock 1 reduces the population size through time.

In this case study, we consider Carp invading the Lower Lakes region, where each scenario begins with seeding with 100 Carp. We used the following scenarios to explore the dynamics of the Carp population in the Murray River below Lock 1 and the Lower Lakes: Scenario 1—river and lakes combined; Scenario 2—river and lakes combined with commercial catch; Scenario 3—river and lakes combined with commercial catch and Carp trap removals; Scenario 4—river and lakes combined with commercial catch and severe drought impacts on the Lower Lakes, where the carrying capacity decreases by 15%; Scenario 5—river and lakes combined with commercial catch, Carp trap removals and severe drought. The drought impacts on the Lower Lakes were estimated to decrease carrying capacity by 25%. As each scenario begins with a very small Carp population, the data used in the minimum population size risk curves is not collected until 15 time steps (years) after the start of the scenario, so that the minimum population size risk curve is not unduly influenced by the initial conditions.

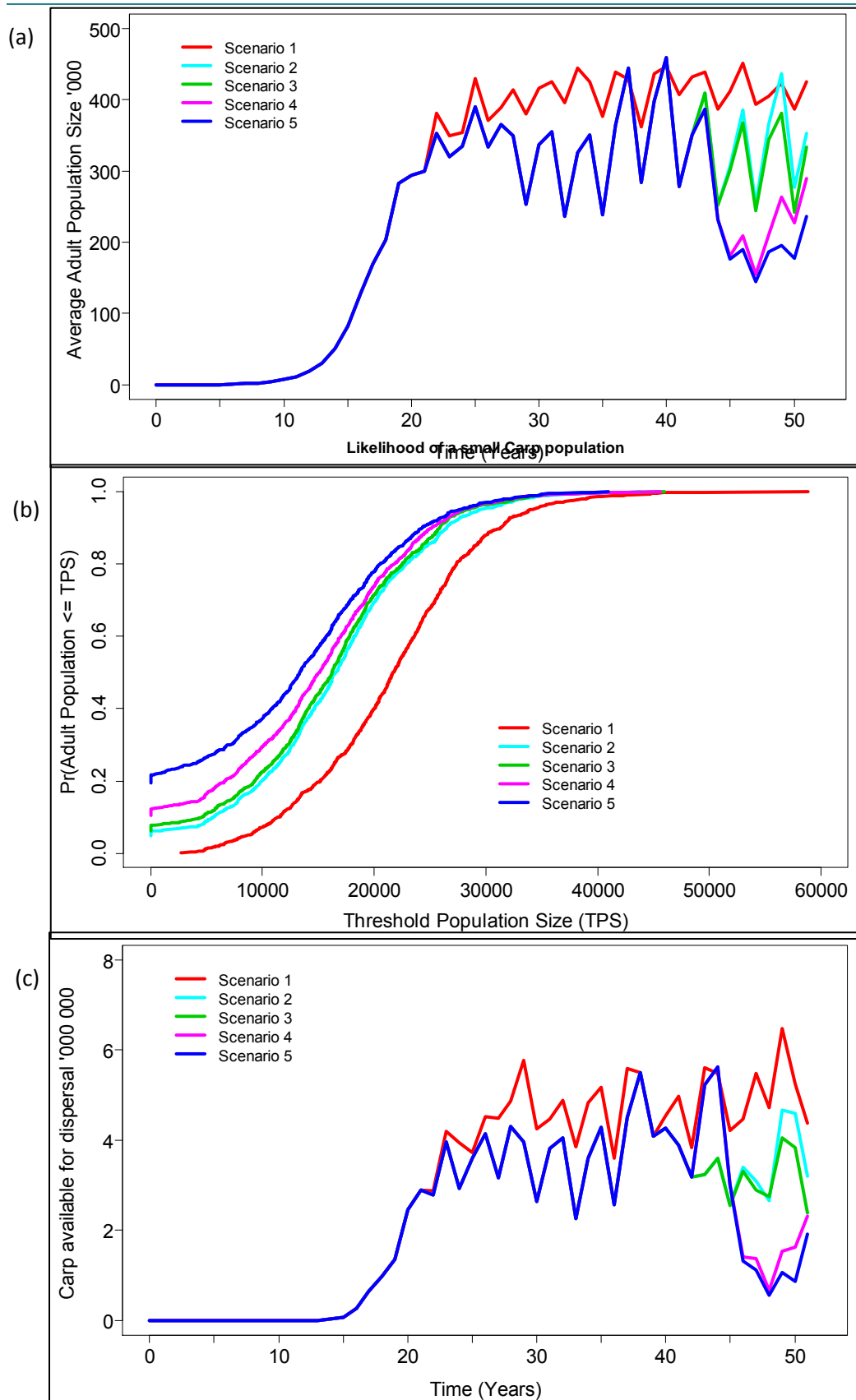


Figure 25. Population model outputs for the Lower Lakes and Murray River below Lock 1. (a) Average adult Carp population size for Scenarios 1–5 in the Lower Lakes and Murray River below Lock 1. (b) Minimum population size risk curves showing the likelihood that the Carp population will be small during the simulation period for the Lower Lakes and Murray River below Lock 1 for Scenarios 1–5. (c) Average number of Carp available for dispersal from the Lower Lakes and Murray River below Lock 1 for Scenarios 1–5.

The outputs from Scenarios 1–5 show a system dominated by the dynamics of Carp in the river and lakes combined. The population quickly rises following a decade of relatively low population size. This may coincide with the large floods of the mid 1970s; however, it is more likely that there is simply a critical mass of sufficient breeding fish in the population with no limits at the time on population growth. In Figure 25a, all scenarios indicate that a large population has developed in the Lower Lakes. However, when removals are accounted for we do see a shift from Scenario 1. This shift begins as soon as commercial harvesting starts; with the addition of Carp traps there is a further slight change (compare Scenarios 1 and 2). The drought years, and in particular the years 2007 to 2010 (Figure 22), where the Lower Lakes went below sea level, likely had an impact on the carrying capacity in the lakes. To what extent it affected the carrying capacity is unknown; however, we assumed a 15% decline in the adult carrying capacity and a 50% impact on one-year-olds (Scenarios 4 and 5). In combination with removals, the drought scenarios produce the lowest average population size of the lake scenarios (Figure 25a). The associated minimum population size risk curves (Figure 25b) capture these shifts from Scenario 1, where the likelihood of a small Carp population increases with more removals and lower carrying capacity, resulting in a higher likelihood of extinction for Scenario 5. The Carp population, however, did not go extinct in the Lower Lakes, but it is plausible that the population did decline to a relatively small size in the late 2000s.

The large Carp population in the Lower Lakes also produces large numbers of Carp available for dispersal (Figure 25c). The model does not follow the fate of these Carp, other than accounting for them by assigning them to the pool of Carp that do not have a place allocated to them in the Lower Lakes—Carp available for dispersal. Even with removals, the number of Carp available for dispersal is on average in the 100,000s. Not all of these Carp will find suitable habitat elsewhere; that is, some will get washed out to the ocean and some will try to move upstream and influence the number of Carp utilising the fishway at Lock 1.

In summary, the Murray River and Lower Lakes system is dominated by the Carp population of the Lower Lakes. Hence, environmental flows will have little impact overall on Carp population dynamics in the Lower Lakes, except possibly in years of low flow. In times of drought or low flow, large-scale removal of Carp may be beneficial in significantly reducing Carp numbers in the Lower Lakes, and in particular in reducing Carp available for dispersal.

## 7.2 Edward–Wakool

The Edward–Wakool river system provides a good example of complicated water management. The Edward–Wakool system consists of a mosaic of rivers, wetlands and floodplains and covers an area of more than 1000 km<sup>2</sup> between the Murray and Edward rivers (MDBA 2012; Figure 26). The Edward River is the largest anabranch of the Murray River and breaks away from the Murray River, flowing north to Deniliquin and then westward. Between the Edward River and the Murray River is a complex network of interconnecting regulated streams and ephemeral creeks and wetlands, of which the Wakool River is the largest. The Wakool rejoins the Edward River, then the Murray River 500 km downstream of Deniliquin. Ephemeral wetlands include billabongs, lagoons, depressions, creeks, flood runners and lakes. The system includes wetland and riverine habitats that are of cultural, economic and environmental significance to the Murray region (Green 2001). This includes large areas of flood-dependent vegetation communities dominated by River Red Gum, Black Box and Lignum *Muehlenbeckia florulenta*, including the Werai (11,000 ha) Forest.

Flow in the Edward–Wakool River System is supplemented with water from a number of secondary sources, and the region is crisscrossed with a range of ephemeral creeks. These include: Bullatale and Tuppal Creeks, which flow out of the River Murray between Tocumwal and the Barmah–Millewa Forest; Thule and Barbers Creeks (unregulated flow via the Gunbower Koondrook–Perricoota Forest); and Little Merran and Waddy Creeks (both regulated). The Poon Boon lakes provide another link between the Murray and Wakool rivers during larger flood events, and Billabong Creek provides

water from its own catchment, as well as regulated and flood flows from the Murrumbidgee River (Green 2001). The complex nature of flooding in the Edward–Wakool river system means that the characteristics of individual flood events vary.

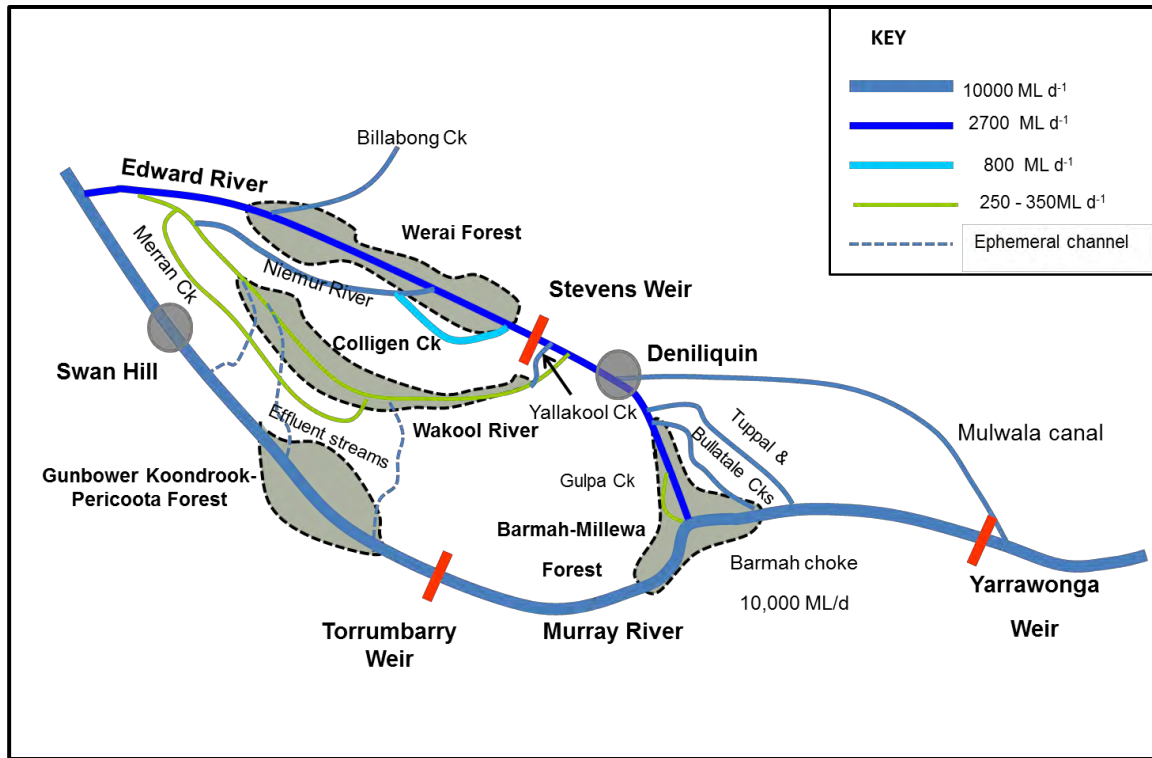


Figure 26. Schematic diagram of the Edward–Wakool river system

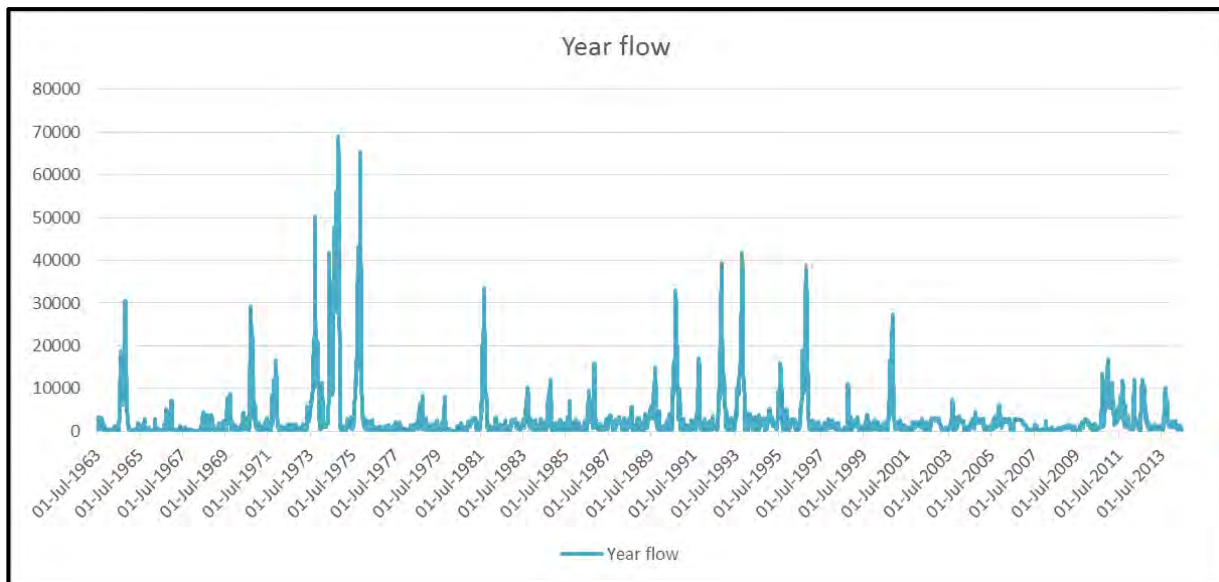


Figure 27. Historic flow sequence for the Edward–Wakool river system in ML/day (data MDBA)

To model the response of Carp populations in the Edward–Wakool to flow management, this case study considered three habitat types: (1) cover benches (H2), (2) summer irrigation flow (H3) and (3) natural floodplain inundation (H10). Historical flow data (State where obtained from and over what period) was used for the flow sequence (Figure 27) to examine the response of Carp populations in this system. The flow sequence has wetter and dryer periods, providing a broad spectrum of flow

conditions. The Wakool River does not effectively spill on to the floodplain until flows exceed ~20,000 ML/day, whereas the Werai Forest begins to be inundated with flows greater than 2400 ML/day flowing down the Edward River. In addition, the Wakool River is not thought to provide reproductive opportunities for Carp during summer irrigation flows—the river is incised and at best behaves similar to a cover benches flow during summer irrigation flows. The flow sequence (Figure 27) was analysed for both extent and duration of flows. If the flow remained at a given level for 25 days or more, then the growth rate specified for the habitat type was achieved. Extent was treated as a series of thresholds (flow greater than 400, 800, 1200, etc. ML/day) and was assigned a proportion of the reproductive output for the habitat type, with maximum output achieved at full inundation (see Table 11). The length of each river modelled was ~50 km, with a carrying capacity of 25,000 adults, equivalent to 0.5 Carp/m of river length.



Table 11. Flow bands contribution to Carp reproductive success for each habitat type inundated in the Edward–Wakool rivers

H2 = cover benches; H3 = summer irrigation flow; and H10 = natural floodplain inundation.

Flow band ML/day	Wakool River		Edward River		Combined	
	H2	H10	H3	H10	H3	H10
400	1	0	1	0	1	0
800	1	0	1	0	1	0
1,200	1	0	1	0	1	0
1,600	1	0	1	0	1	0
2,000	1	0	1	0	1	0
2,400	1	0	1	0	1	0
2,800	1	0	0.888,036	0.111,964	0.888,036	0.111,964
3,200	1	0	0.777,479	0.222,521	0.777,479	0.222,521
3,600	1	0	0.669,721	0.330,279	0.669,721	0.330,279
4,000	1	0	0.566,116	0.433,884	0.566,116	0.433,884
4,500	1	0	0.467,968	0.532,032	0.467,968	0.532,032
5,000	1	0	0.376,510	0.623,490	0.376,510	0.623,490
6,000	1	0	0.292,893	0.707,107	0.292,893	0.707,107
7,000	1	0	0.218,169	0.781,831	0.218,169	0.781,831
8,000	1	0	0.153,276	0.846,724	0.153,276	0.846,724
9,000	1	0	0.099,031	0.900,969	0.099,031	0.900,969
10,000	1	0	0.056,117	0.943,883	0.056,117	0.943,883
11,000	1	0	0.025,072	0.974,928	0.025,072	0.974,928
12,000	1	0	0.006,288	0.993,712	0.006,288	0.993,712
15,000	1	0	0	1	0	1
20,000	0.617,317	0.382,683	0	1	0	1
25,000	0.292,893	0.707,107	0	1	0	1
30,000	0.076,12	0.923,88	0	1	0	1
35,000	0	1	0	1	0	1

We consider two scenarios in this case study: (1) Wakool River Carp dynamics; and (2) Edward River Carp dynamics. The flow sequence impact on the Carp population in the Wakool River (Scenario 1) shows a sequence of rapid increases in the Carp population followed by periods of decline (Figure 28a), whereas the Edward River increased in size, particularly with the large flows in the 1970s. The number of Carp available for dispersal from the two rivers was significantly different—the Edward River produced large numbers of Carp available for dispersal in comparison with the Wakool River (Figure 28b). The associated minimum population size risk curve indicated that the Wakool River population had a high probability of being small during the simulation period and was quite different to the Edward River minimum population size risk curve (Figure 28c). The maximum population size risk curves indicated that the likelihood of being large was quite distinct for the Edward and Wakool rivers (Figure 28c).

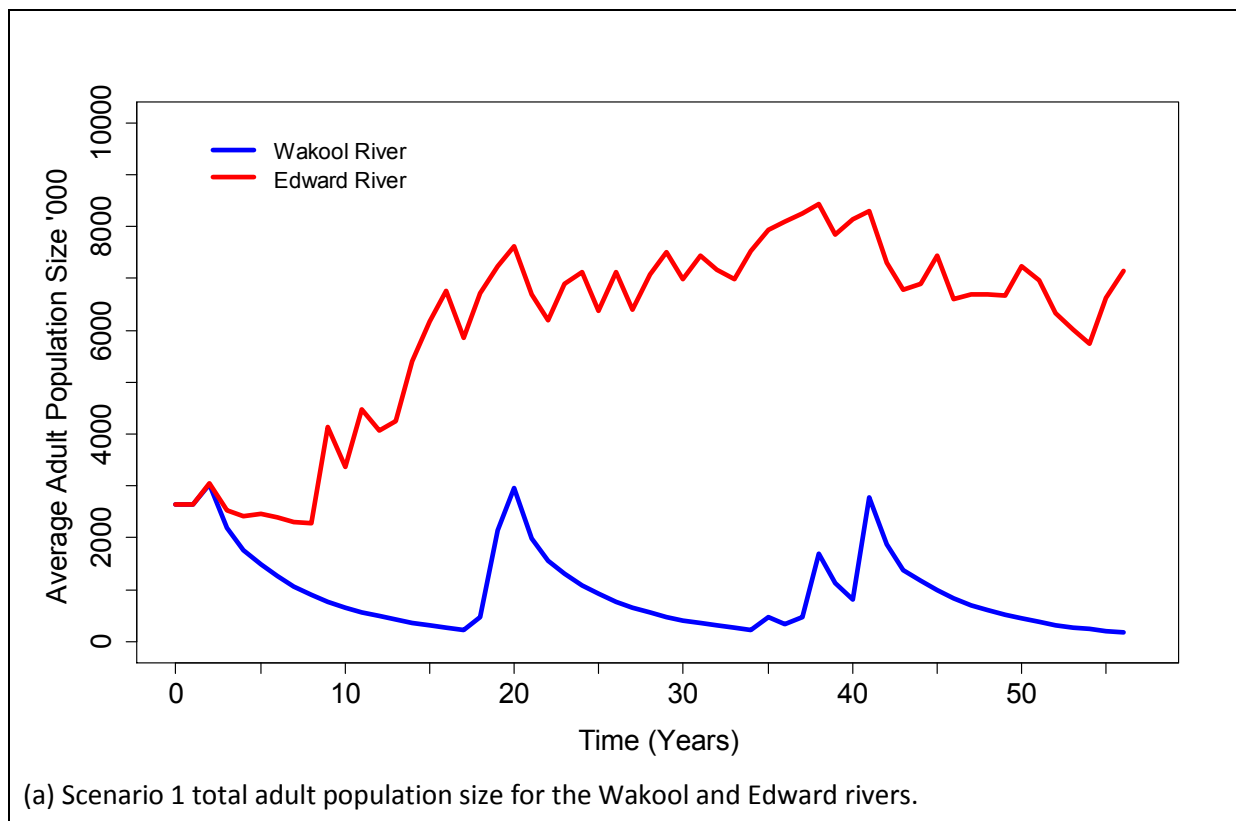
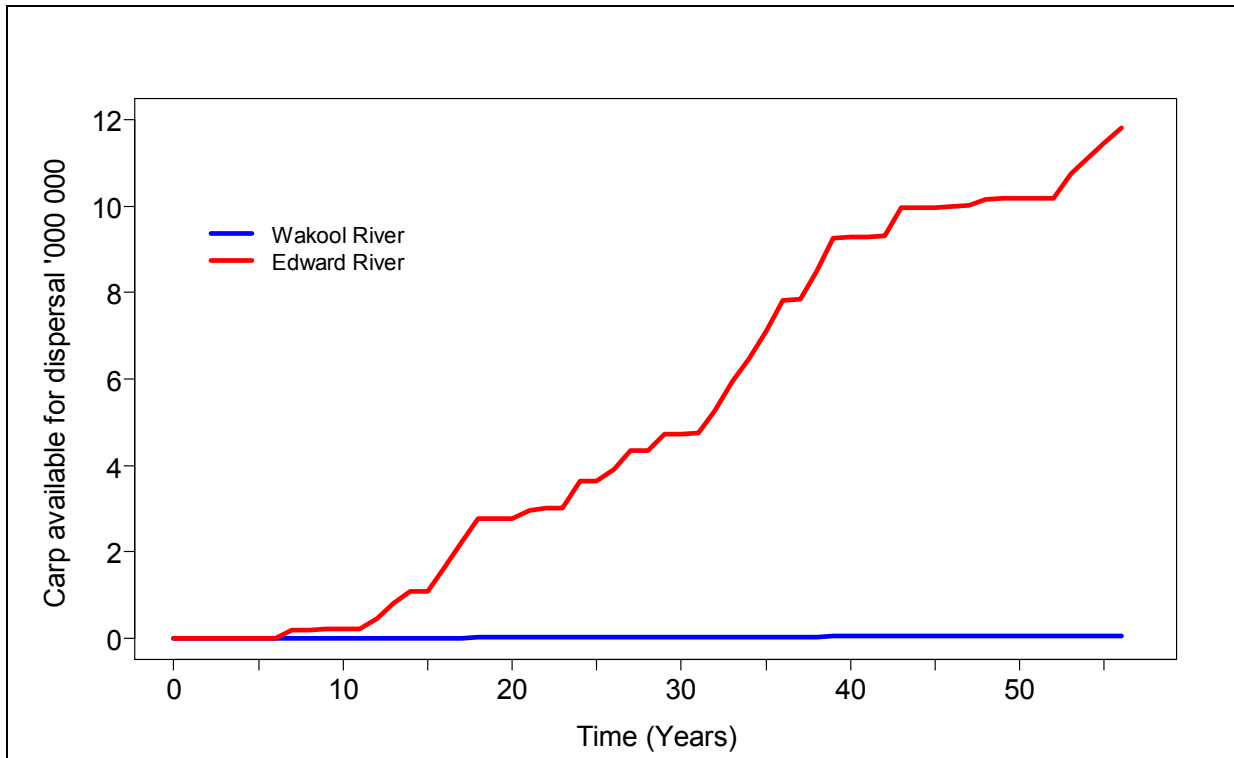
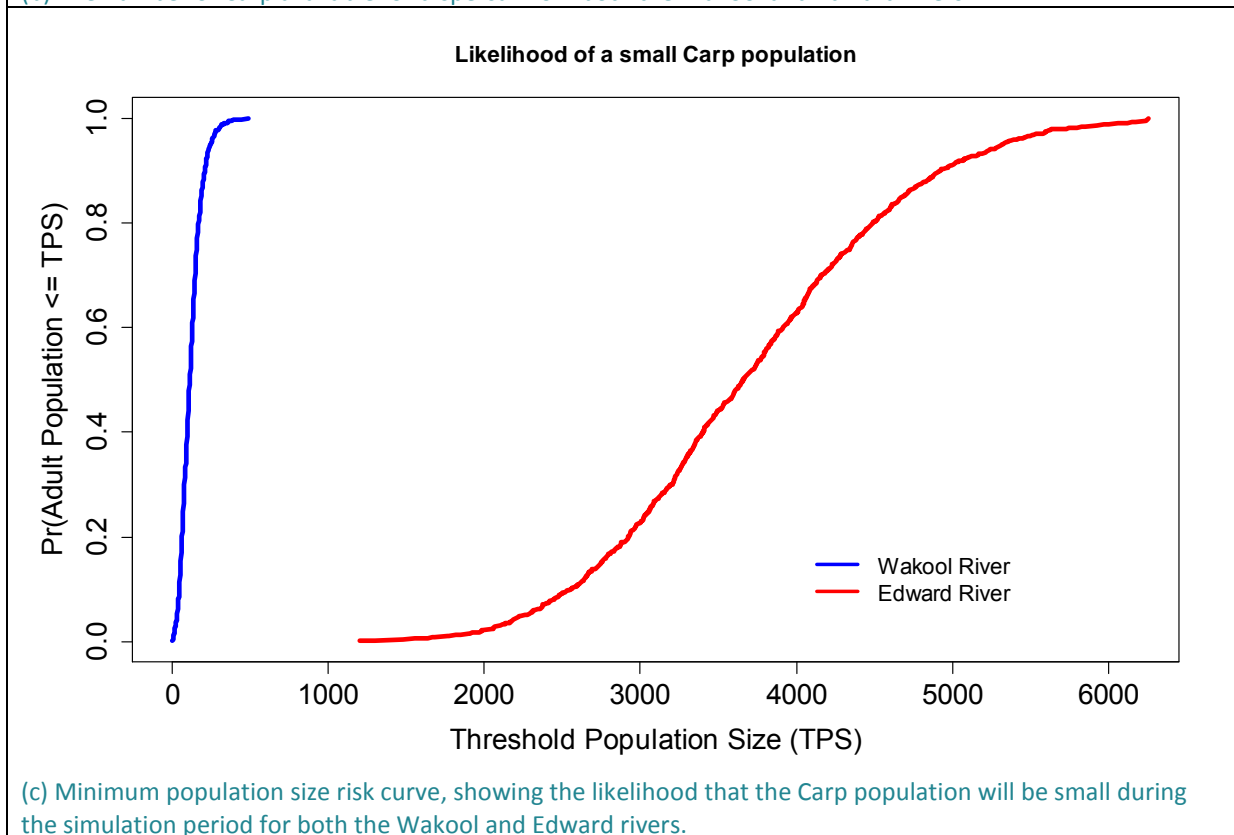


Figure 28. Population model output for the Wakool and Edward Rivers

(a) Scenario 1 total adult population size for the Wakool and Edward rivers, (b) the number of Carp available for dispersal from both the Wakool and Edward rivers, (c) minimum population size risk curve showing the likelihood that the Carp population will be small during the simulation period for both the Wakool and Edward rivers, and (d) maximum population size risk curve showing the likelihood that the Carp population will be large during the simulation period for both the Wakool and Edward rivers.



(b) The number of Carp available for dispersal from both the Wakool and Edward rivers.



(c) Minimum population size risk curve, showing the likelihood that the Carp population will be small during the simulation period for both the Wakool and Edward rivers.

Figure 28 (continued)

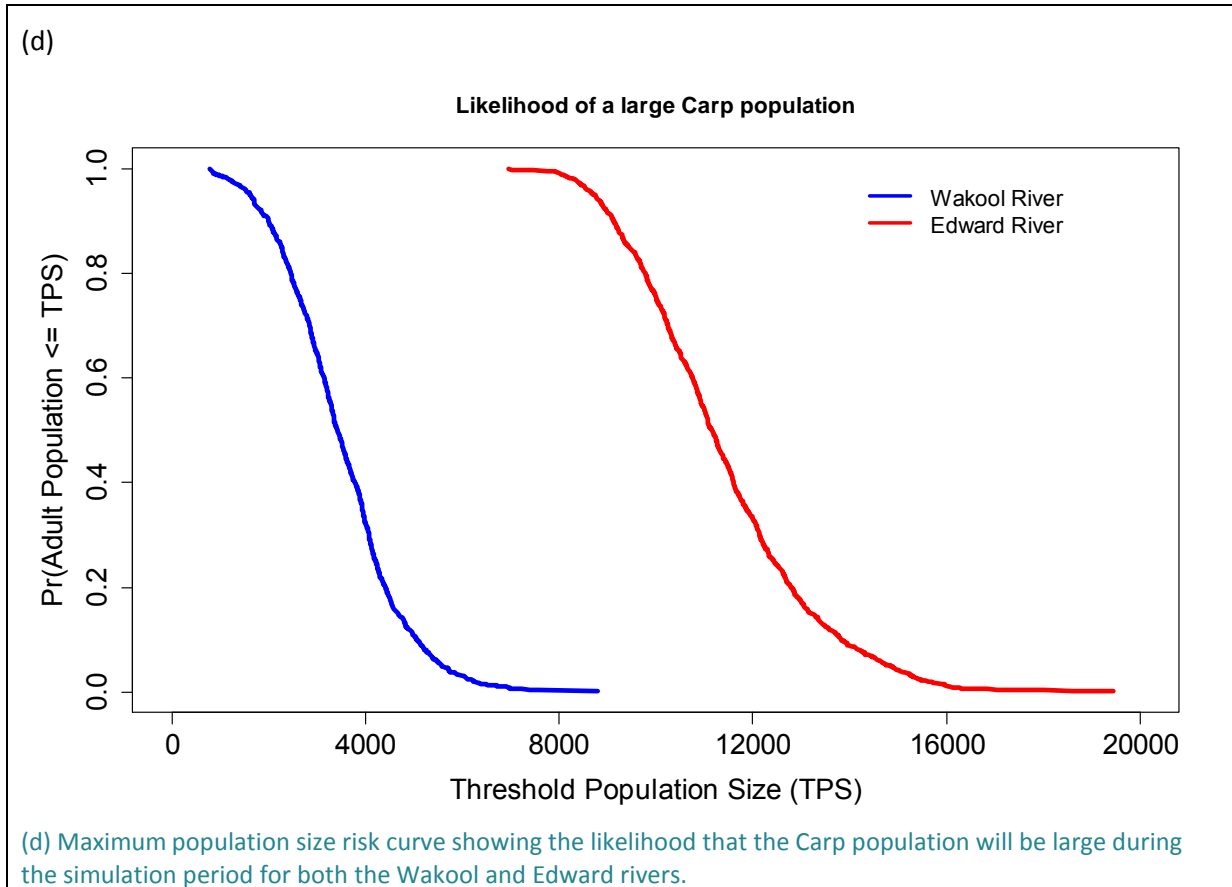


Figure 28 (continued)

In isolation, the Wakool River may have withstood a Carp invasion due to the lack of access to the floodplain except under high flows. On the other hand, with the same flow sequence the Edward River provides numerous opportunities for Carp to reproduce on a regular basis. Each river was modelled in isolation, which in reality would not be the case. For the Wakool River, the modelled decline in numbers between high flow events would, most likely, not have occurred because Carp from the Edward River would have been able to move freely between rivers. It is quite likely that the Edward River population helps to maintain the Carp in the Wakool River. While we haven't modelled the connectivity between the two systems in this case study, in a metapopulation construct this system connectivity could be modelled to examine the influence of Carp productivity in the Edward River on the Carp dynamics in the Wakool River.

In summary, both flooding of the Werai Forest and use of the Edward River for water transfer are likely to contribute to a higher Carp population in the Edward–Wakool river system. However, the value of the Werai Forest for native biota and the need to deliver water through the Edward–Wakool must be considered first when determining watering regimes. Native fish models, which are currently being developed, will assist water managers in determining whether the outcomes for native biota outweigh the risk of increased Carp populations.

### 7.3 Chowilla

Chowilla is a large undeveloped River Red Gum and Black Box floodplain in the Lower Murray River. It is listed under the Ramsar Convention and is an Icon Site of the Living Murray Initiative. Chowilla bypasses Lock 6 and has permanent lotic habitats, once characteristic of the historically unregulated Murray River in a region where serial main-channel weirs have created predominantly permanent

lentic habitats (Walker 2006). The floodplain and anabranch complex contains perennial and ephemeral creeks, backwaters, billabongs and lakes (Figure 29), and significant woodlands. The unique flowing water habitats of the Chowilla anabranch creeks support regionally significant populations of Murray Cod and high abundances of other species such as Golden Perch (Zampatti et al. 2011). In response to declines in the floodplain and woodland conditions, especially during the Millennium Drought, a large (79 m wide, 3 m head differential) regulator was constructed on lower Chowilla Creek to allow for artificial inundation of the floodplain, utilising lower volumes of water than those required for natural flooding (Figure 30). However, such artificial floodplain inundations are considerably different to natural flooding, and the potential impacts of these differences have been considered for native and invasive fishes (Mallen-Cooper et al. 2008, 2011). Engineered artificial floodplain inundation in the Chowilla system is considered to present substantial risks—especially for threatened Murray Cod and Freshwater Catfish as well as Golden Perch and Silver Perch—in addition to also constituting a high risk for the proliferation of Carp.

The Chowilla case study is a simplified study of two habitat types: summer entitlement (H5) and artificial floodplain (H11) and quantifies the impacts on Carp populations in the Chowilla system and surrounds. The two flow sequences underpinning this case study are taken from the hypothetical operating regime of the Chowilla regulator given in Appendix C of the operational strategy (Anon. 2014), the two sequences being (1) the modelled observed flow; and (2) the modelled regulator operation. Under normal variable flows, the Chowilla floodplain behaves like an ephemeral wetland that is inundated when flows increase and dries out again after flows recede. The example operational plan for regulating inundation of the Chowilla floodplain is to achieve significant inundation (approximately equivalent to 80 ML/day) in 3 out of every 5 years (Table 12). The length of the system modelled was 140 km bounded by Lock 7 upstream and Lock 5 downstream.

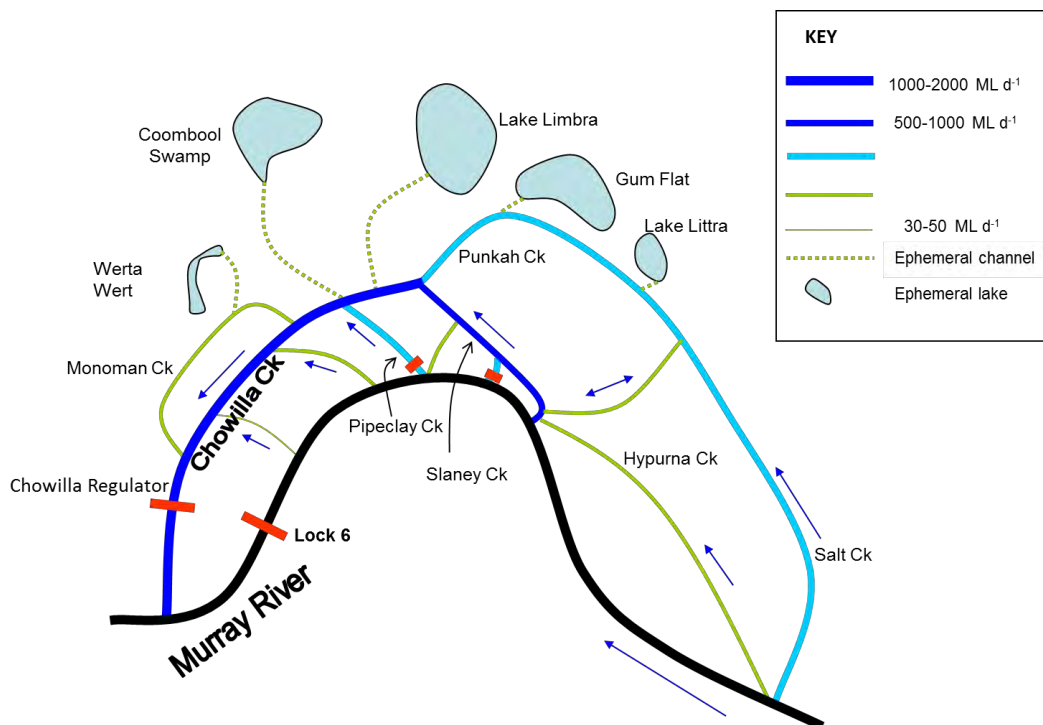


Figure 29. Schematic diagram of the Chowilla Creek anabranch system (adapted from Mallen-Cooper et al. 2008)

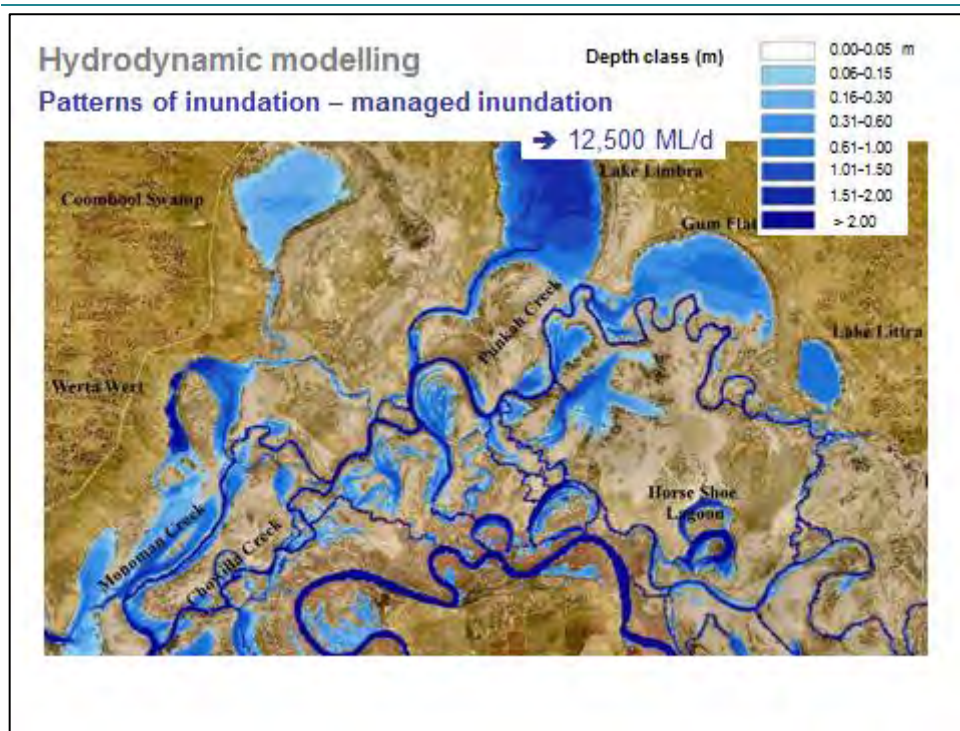


Figure 30. Area of artificial inundation (5361 ha) of the Chowilla floodplain for a flow of 12,500 ML/day (the approximate equivalent of 56,000 ML/day flood) (Mallen-Cooper et al. 2008)

Table 12. Summary of the hypothetical 15-year period of operation hydrograph for the Chowilla floodplain (Table 11. Appendix C; Anon. 2014)

Year	Flow	Duration (days)
1	Maximum extent managed inundation	120
2	EWA used to manage recession	–
3	Pulse flow via Pipeclay and Slaney Regulators	–
4	Mid-bank flow spike	77
5	Managed recession	94
6	Pulse flow via Pipeclay and Slaney Regulators	–
7	Mid-bank flow spike	129
8	Mid-bank + Maximum extent managed inundation	156
9	Pulse flow via Pipeclay and Slaney Regulators	–
10	Mid-bank flow spike	127
11	Pulse flow via Pipeclay and Slaney Regulators	–
12	Maximum extent managed inundation	83
13	Managed recession + maximum extent managed inundation	119
14	Pulse flow via Pipeclay and Slaney Regulators	–
15	Mid-bank flow spike	78

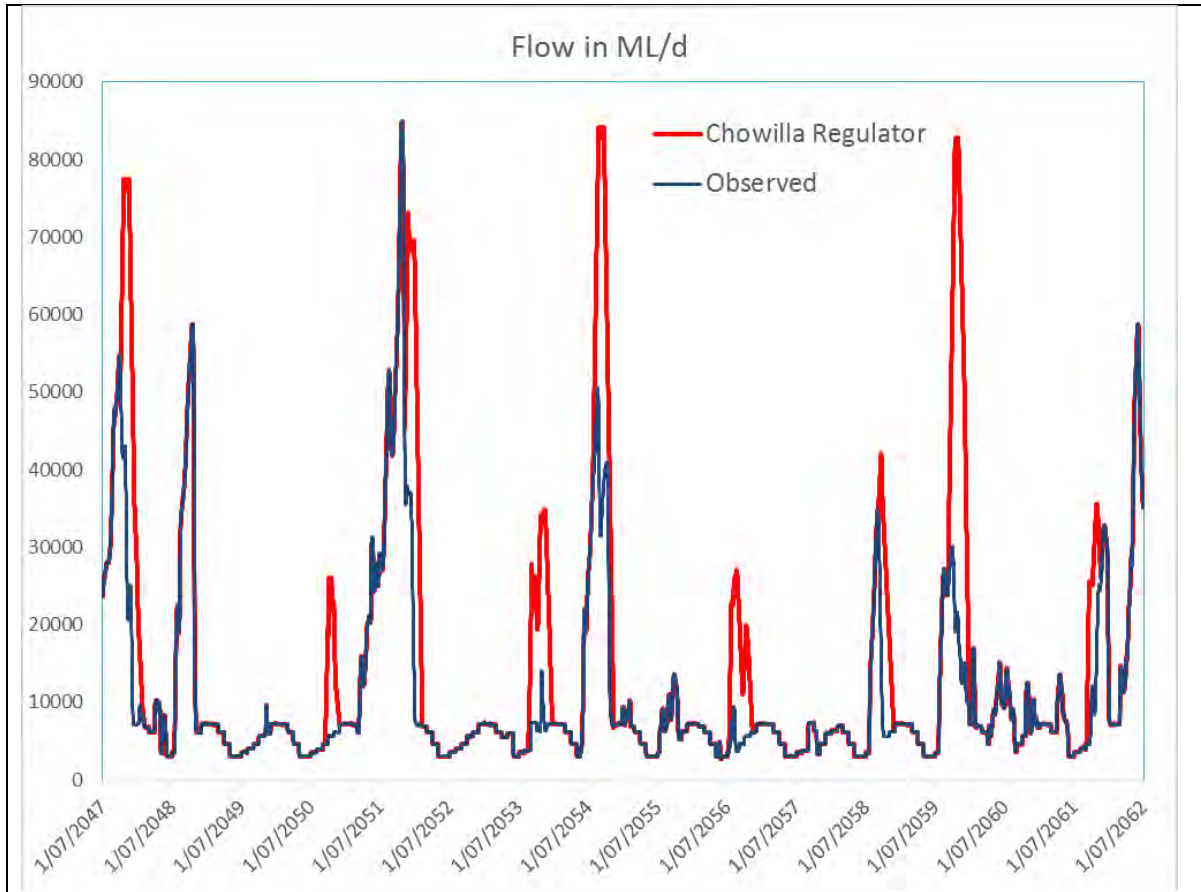


Figure 31. Modelled flow data for the Chowilla floodplain (from Anon. 2014; data supplied by T. Herbert)

The flow sequence determined the length of time water was on the floodplain as well as the extent of water of the floodplain. The larger the flow, the greater the extent; the longer the flow, the higher the likelihood of breeding success of Carp. The modelled flows (Figure 31) were analysed for both extent and duration of flows. If the flow remained at a given level for 25 days or more, then the growth rate specified for the habitat type was achieved. Extent was treated as a series of thresholds (flow >10,000 ML/day; >20,000 ML/day; etc.) and was assigned a proportion of the reproductive output for the habitat type, with maximum output achieved at full inundation (see Table 13). The flow information was aggregated into an annual summary of flow, with flow year dated from 1 July to 30 June.

We examined two scenarios: (1) a modelled future observed flow; and (2) a modelled future single operational example of the Chowilla regulator. The riverine capacity was estimated at 1 Carp/m. The section of river containing the Chowilla system is ~140 km in length; hence, it has a carrying capacity of 140,000 adult Carp. The adult carrying capacity was set at the riverine capacity unless the off-stream habitat type was permanently inundated.

The flow sequences examined maintained a relatively high riverine Carp population and, consequently, using risk curves did not provide much contrast between the different scenarios considered. The alternate metric of potentially emigrating Carp from the Chowilla locale, i.e. Carp available for dispersal, was used, and this metric changed between the two scenarios, providing insight into the use of the Chowilla regulator. The term potentially emigrating or available for dispersal was used because the model did not track the fate of Carp not residing in the riverine system, but calculated the number of Carp that were available for dispersal (some of which may not



survive to be true emigrants). The number of Carp available for dispersal remains a useful metric for comparing the Chowilla regulator operation.

Table 13. Flow bands contribution to Carp reproductive success for each habitat type inundated in the Chowilla Floodplain

H5 = summer entitlement; H11 = artificial floodplain.

Flow band (ML/day)	H5	H11
10,000	0.9174	0.0826
15,000	0.8354	0.1646
20,000	0.7545	0.2455
25,000	0.6753	0.3247
30,000	0.5983	0.4017
35,000	0.5241	0.4759
40,000	0.4531	0.5469
45,000	0.3858	0.6142
50,000	0.3227	0.6773
55,000	0.2643	0.7357
60,000	0.2109	0.7891
65,000	0.1628	0.8372
70,000	0.1205	0.8795
75,000	0.0842	0.9158
80,000	0.0542	0.9458
85,000	0.0306	0.9694
90,000	0.0136	0.9864
95,000	0.0034	0.9966
100,000	0.0000	1.0000

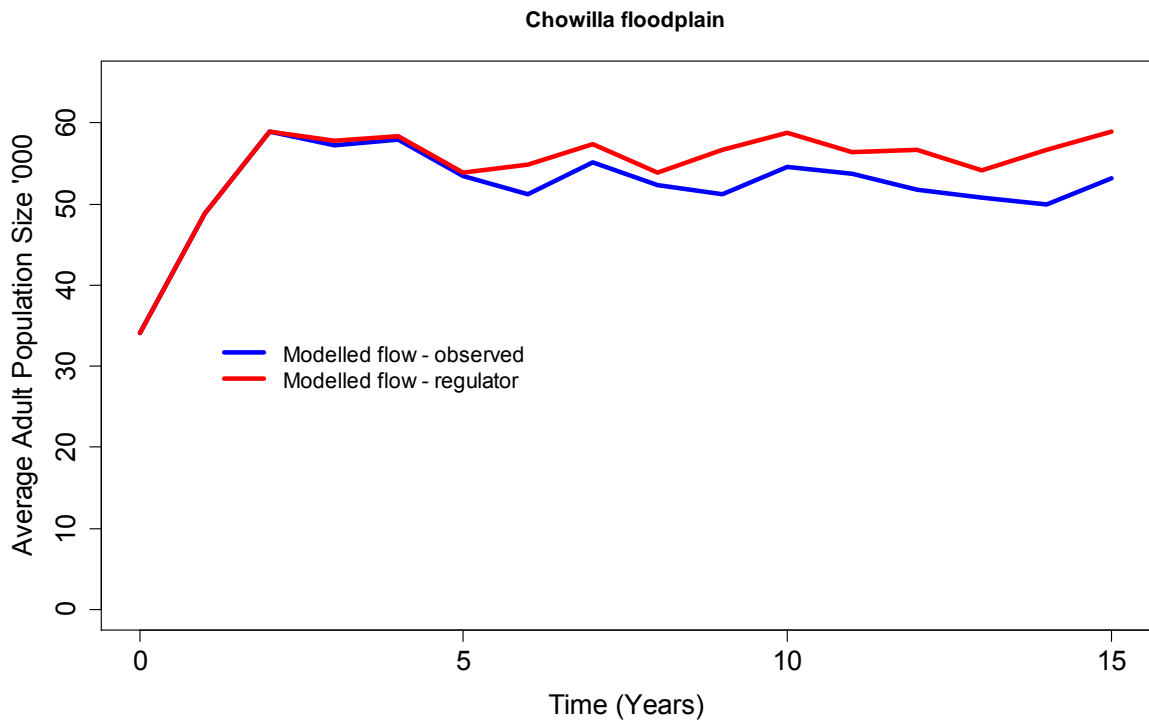


Figure 32. Mean Carp population size in response to the modelled Chowilla flow data

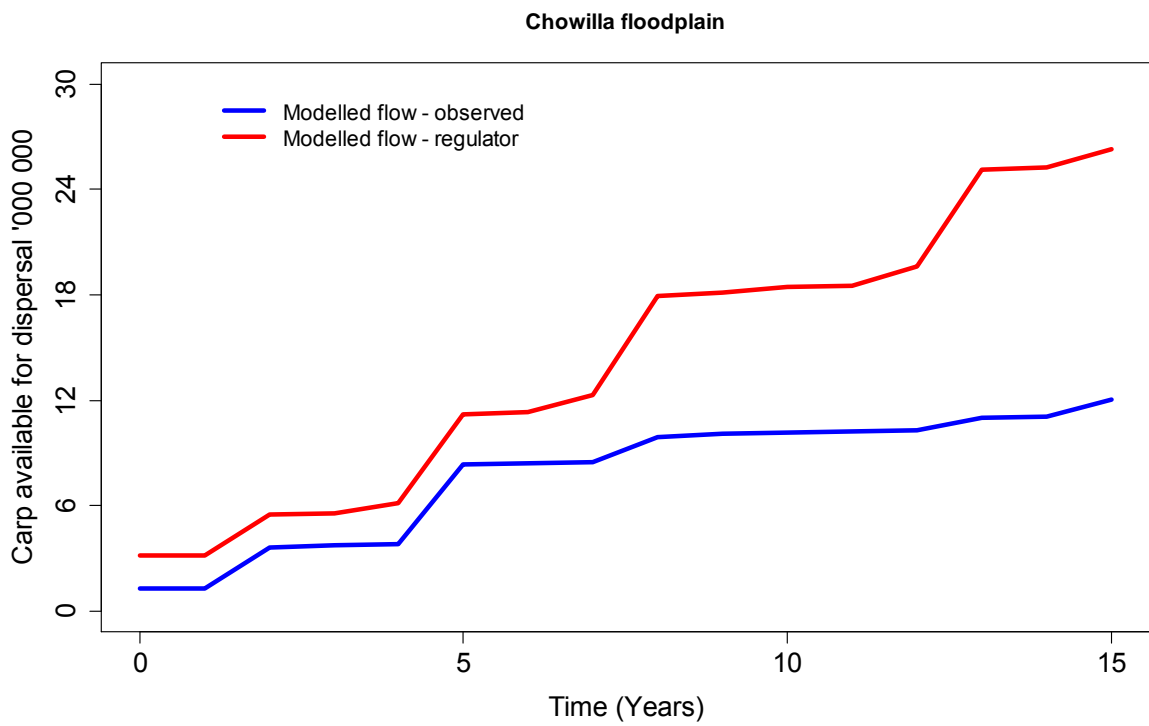


Figure 33. Mean biomass of Carp available to disperse in response to the modelled Chowilla flow data.

An assessment of Figures 32 and 33 indicated that the Carp population remained fairly stable under the two flow scenarios in the Chowilla reach. However, the number of Carp available for dispersal was markedly different between the two flow sequences. The modelled observed flow for Chowilla operations (Scenario 1) produced a substantial number of Carp available for dispersal over the relatively short modelled time frame (15 years compared with 50 years for other case studies). The modelled future single operational example of the Chowilla regulator (Modelled flow – regulator Figures 32 and 33) produced more than double the number of Carp available for dispersal. The outcomes from this case study highlight the potential of allowing Carp access to the floodplain, where large numbers of Carp may be produced for dispersal.

In summary, if Carp access the Chowilla floodplain throughout the operation of the Chowilla regulator, there will likely be significant recruitment and large numbers of Carp available for dispersal in 3 out of 5 years. Artificial floodplain inundation should be carefully considered, with frequent events minimised where possible, following assessments of impacts on other watering objectives. Alternative management options to those presented here should be explored further using this Carp model. Native fish models, which are currently being developed, will assist water managers in determining whether the risk of Carp population increase can be reduced while still benefiting native fish populations. The Carp model allows for alternative management to that presented here to be explored further.

## 7.4 Barmah–Millewa

Barmah–Millewa Forest is a large, complex floodplain wetland system in the Mid Murray River that is listed as internationally important under the Ramsar convention and is also an Icon Site for The Living Murray Initiative (Koehn et al. 2014a). Barmah–Millewa has a long history of water management, with numerous levee banks and regulators, and it has an allocated EWA of up to 150 GL per year. While flow regulation has greatly affected the natural flooding cycles, flooding does still occur, both naturally and enhanced by the EWA (see Appendix 3, Figure A3.13; King et al. 2010). In 2005/06, 513 GL of the Barmah–Millewa EWA was used to ‘piggyback’ the natural flow peak to increase its magnitude and duration. This led to positive outcomes for native fish (i.e. Golden Perch, Silver Perch, Murray Cod, Trout Cod and Southern Pygmy Perch; see King et al. 2010 for more details) and waterbird breeding, but also increased Carp recruitment (Koehn et al. 2014a).

It is recognised that the Barmah area attracts Carp from both upstream and downstream as a preferred spawning site (Stuart and Jones 2006a, 2006b), and as such the Barmah–Millewa region is modelled as the 150 km of river below containing the Barmah–Millewa floodplain and surrounds (Figure 34). When access is available to the Barmah–Moirra Lakes, it is typically over such timescales that all Carp in the Barmah–Millewa region would be expected to migrate there to spawn. When access is available to the Barmah–Millewa floodplain then Carp may access the floodplain for spawning directly from the river.

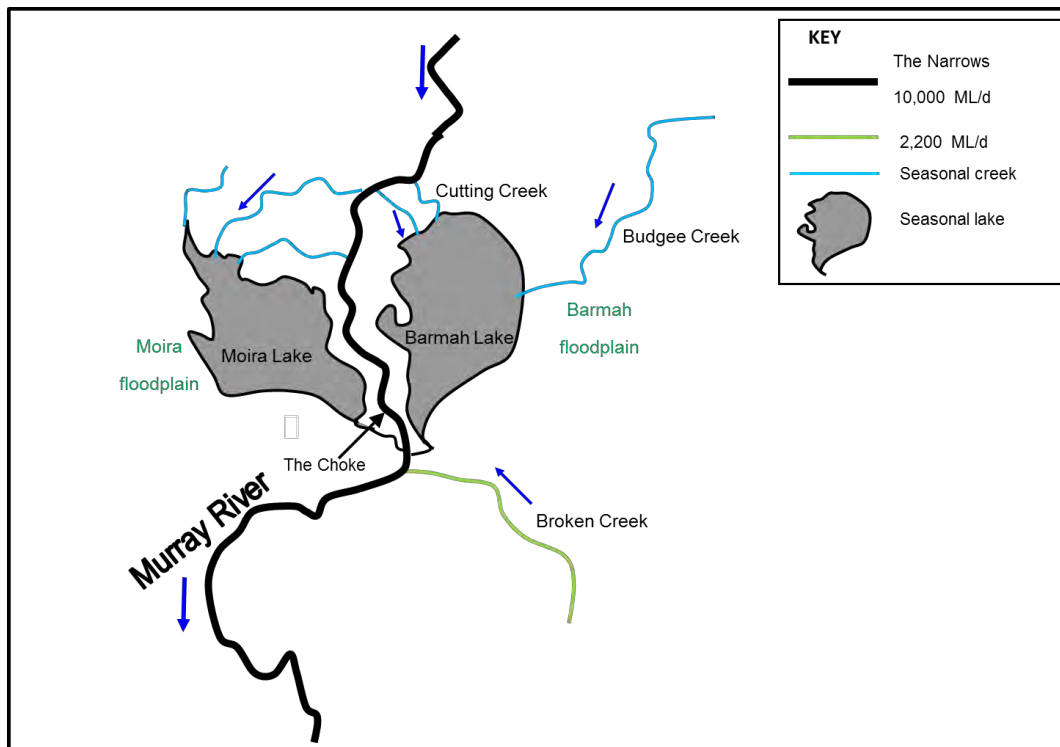


Figure 34. Schematic diagram of the Barmah–Millewa area, including Barmah and Moira lakes

This case study considers habitat types [summer irrigation flow (H3); river wetland (H6) and natural floodplain inundation (H10)] and quantifies the flow impacts on Carp populations in the Mid Murray River Barmah–Millewa floodplain (BMF) and surrounds. Flows were taken from the flow data at Yarrowonga (Figure 35). The flow sequence determined the length of time water was on the floodplain as well as the extent of water of the floodplain. The larger the flow, the greater the extent, and the longer the flow, the higher the likelihood of breeding success for Carp. The modelled flows (Figure 35) were analysed for both extent and duration. If the flow remained at a given level for 25 days or more, then the growth rate specified for the habitat type was achieved. Extent was treated as a series of thresholds and was assigned a proportion of the reproductive output for the habitat type, with maximum output achieved at full inundation (Table 14). The length of the system modelled was 150 km and of notionally three sections: 50 km around the Barmah–Millewa floodplain, 50 km upstream and 50 km downstream. The carrying capacity of 150,000 adults, equivalent to 1 Carp/m, was specified for the system. The Barmah and Moira lakes (BMLs) (H6) are connected every year due to summer irrigation flows and contribute to Carp population dynamics when the BMF (H10) is not inundated. When the BMF is inundated, the BMLs will remain attractive to Carp at low levels of inundation—we assume that as flows increase, more Carp will access the BMF, and as conditions change at the BML this will become less attractive to Carp. We postulate that Carp will begin to prefer the BMF once flows reach 12,000 ML/day and completely change to the BMF once flows reach 18,000 ML/day (Table 14). The sequence of BMF inundation is given in Table 15.

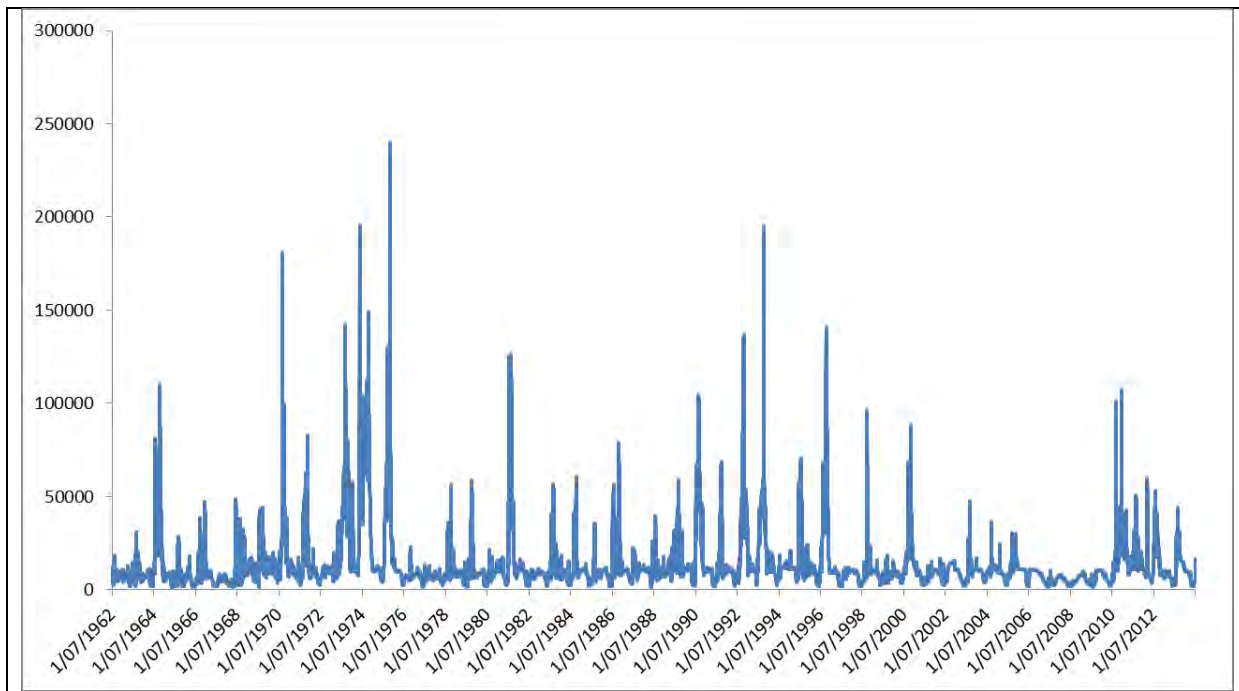


Figure 35. Yarrowonga flow data from July 1962 to June 2014; data MDBA

Table 14. Barmah–Millewa floodplain inundation for various flow thresholds (Barmah–Millewa flood maps: MDBA)

Flow threshold number (FTN)	Flow ('000 ML/day)	Area of inundation	Proportion of area inundated
1	8	2,306	0.037,5
2	9	2,921	0.047,5
3	10	3,842	0.062,5
4	11	6,015	0.097,8
5	12	8,004	0.130,2
6	13	9,315	0.151,5
7	14	10,100	0.164,3
8	15	11,471	0.186,6
9	18	16,625	0.270,4
10	20	20,699	0.336,7
11	25	25,327	0.412,0
12	30	30,193	0.491,2
13	35	34,360	0.558,9
14	40	38,143	0.620,5
15	45	41,912	0.681,8
16	50	44,137	0.718,0
17	55	47,146	0.766,9
18	60	48,770	0.793,4
19	65	50,418	0.820,2
20	70	53,060	0.863,1
21	75	54,901	0.893,1
22	80	56,623	0.921,1
23	85	58,240	0.947,4
24	90	59,765	0.972,2
25	95	61,207	0.995,7
26	100	61,473	1



Table 15. Barmah–Millewa floodplain flow threshold (FTN) sequence based upon Figure 35

Year	FTN	Year	FTN	Year	FTN	Year	FTN
1962	2	1975	24	1988	4	2001	15
1963	1	1976	23	1989	5	2002	3
1964	5	1977	5	1990	12	2003	8
1965	16	1978	2	1991	15	2004	6
1966	5	1979	10	1992	14	2005	5
1967	11	1980	11	1993	19	2006	10
1968	0	1981	4	1994	17	2007	3
1969	10	1982	13	1995	7	2008	0
1970	11	1983	2	1996	8	2009	2
1971	18	1984	10	1997	18	2010	3
1972	14	1985	13	1998	3	2011	14
1973	4	1986	4	1999	8	2012	9
1974	20	1987	11	2000	3	2013	9
						2014	10

We examined four scenarios: (1) summer irrigation flow and no access to BML and no access to BMF; (2) summer irrigation flow and access to BML and no access to BMF; (3) summer irrigation flow and no access to BML and access to BMF; (4) summer irrigation flow and access to BML and access to BMF.

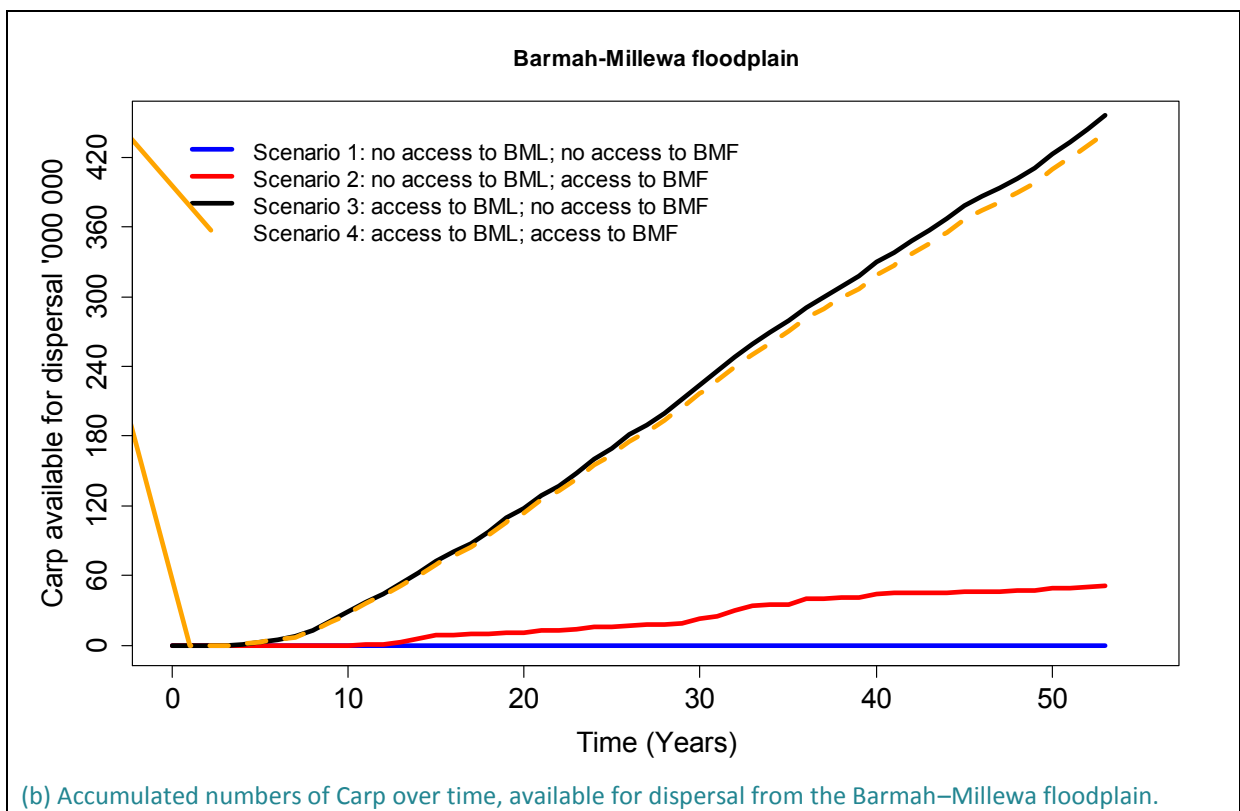
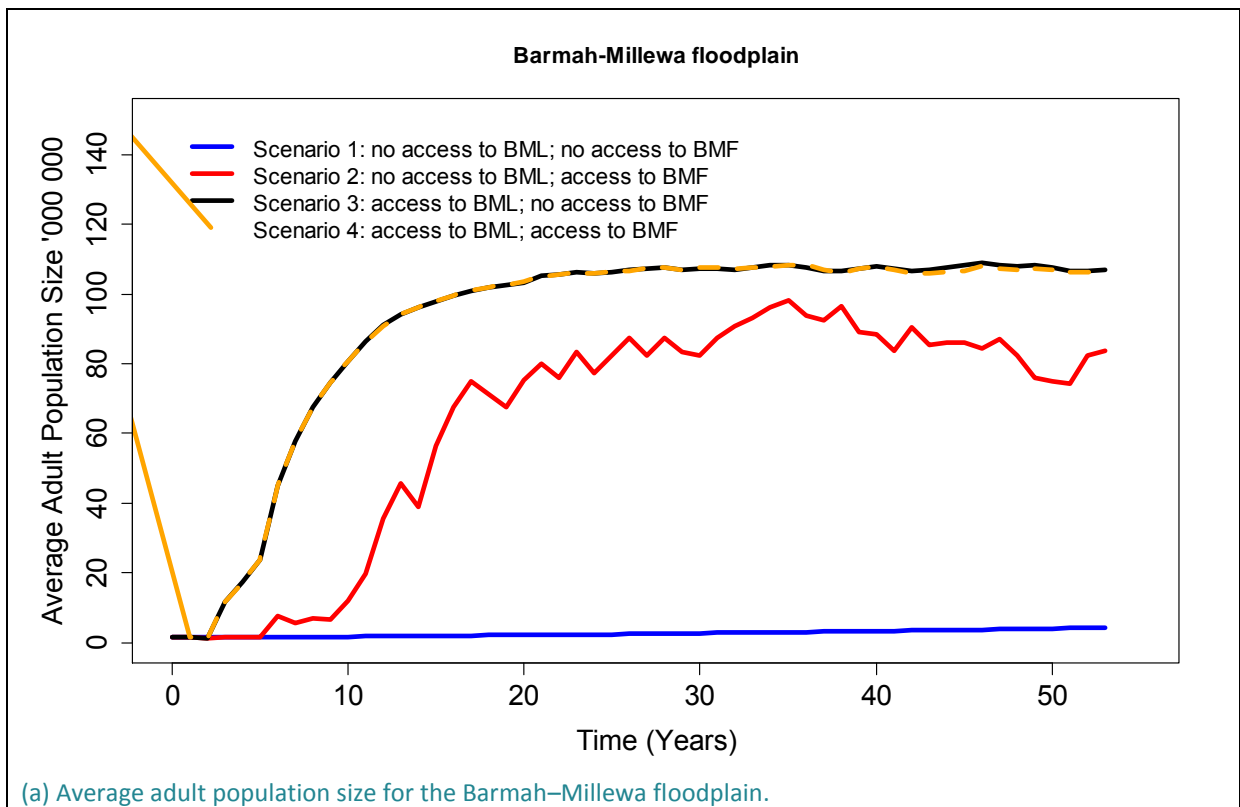


Figure 36. Population model output for Barmah–Millewa floodplain for Scenarios 1–4  
(Continued next page)

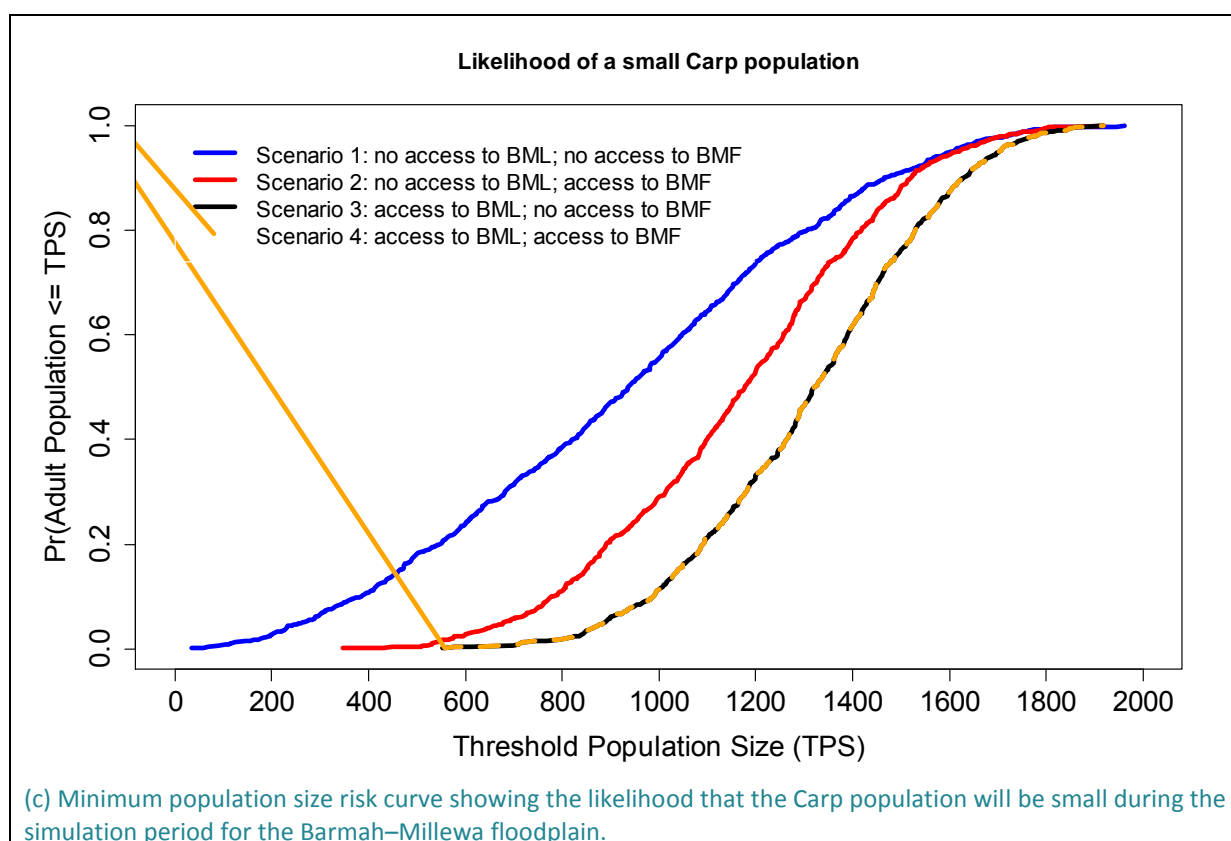


Figure 36 (continued). Population model output for Barmah–Millewa floodplain for Scenarios 1–4

The output from modelling Carp response to access to the Barmah–Millewa floodplain produced some interesting results. The Carp population slowly increased when only the summer irrigation flow was considered—virtually no Carp were available for dispersal and there was a higher likelihood of the Carp population being small compared with the other scenarios (Figure 36a, b and c). When Carp were given access to the Barmah–Millewa floodplain, the average adult population size increased, the number of Carp available for dispersal significantly increased, and the likelihood of the population size being small decreased (Figure 36a, b and c). The scenarios with access to Barmah–Moira Lakes produces the largest average adult population size of Carp, with an order of magnitude increase in the number of Carp available for dispersal and the least likelihood of the population size being small (Figure 36a, b and c). The exploration of these scenarios indicated that interaction between the Barmah–Millewa floodplain and the Barmah–Moira Lakes makes managing a Carp population in this region very difficult. Summer irrigation flows that consistently inundate the Barmah–Moira Lakes show this to be the worst possible scenario, with such large numbers of Carp available for dispersal it is likely that such a scenario will have a dramatic influence on Carp numbers in the rest of the Murray River. While it may be possible to limit access to the Barmah–Moira Lakes, it would be nearly impossible to limit access to the broader Barmah–Millewa floodplain. Although in comparison with the Barmah–Millewa floodplain scenario, it does not produce such dramatically large numbers of Carp available for dispersal, some years there were in excess of 5,000,000 Carp available for dispersal, and over the 40 years of Carp dispersal (Figure 36b) from the Barmah–Millewa region, 50,000,000 Carp were available for dispersal.

In summary, the Barmah–Millewa floodplain and the Barmah–Moira lakes are capable of producing very large numbers of Carp for dispersal to other areas of the MDB. Annual high irrigation flows that provide access to the adjacent wetlands during the Carp spawning season are likely to be artificially

supporting higher Carp numbers. Limiting access to the Barmah–Moira Lakes will help contain Carp numbers in years outside of the natural floodplain access, noting that it will be impossible to limit access to the broader Barmah–Millewa floodplain. However, once again the objectives of environmental water must be considered a priority. Managers should utilise native fish models, which are currently being developed, as well as information on the other requirements of other ecological objectives to determine whether the ecological benefits from watering the Barmah–Millewa floodplain and the Barmah–Moira lakes outweighs the potential impacts of an increased Carp population.

## 8 Risk assessments

### 8.1 Background to risk assessment

While the flexible life history of Carp enables them to spawn and recruit regardless of prevailing hydrological conditions, there is compelling evidence that Carp spawn and recruit more successfully in wetlands, slack waters and on freshly inundated floodplains compared with in main river channel habitats. Hence, the scale of recruitment is likely to be much greater during natural floods and large-scale managed artificial inundations. It is important to recognise that Carp are already very abundant in the MDB river systems and that their spawning and impacts will be ongoing, with or without environmental water.

Carp pose some serious environmental risks and these need to be addressed as part of broader environmental restoration efforts. Indeed, a key principle of integrated pest management is to assess and ameliorate the risks and impacts that Carp create. Environmental watering is planned and undertaken for the benefit of native biota, including fish, and these benefits should take precedence and outweigh the vast majority of risks that may be associated with Carp. The management challenge is to design environmental watering programs that maximise environmental benefits to native biota (e.g. native fish) while also carefully considering the risks posed by Carp and implementing actions to mitigate them. A risk assessment is important for achieving this balance between environmental recovery and Carp 'control'.

### 8.2 Risk analysis

Analysis of risks should be based on the Australian Standards (Standards Australia 2004); these Standards have been used recently to guide management decisions concerning Carp control and environmental watering (Mallen-Cooper et al. 2011; SMEC 2013). There are two components to risk: *likelihood* (probability of the risk occurring) and *consequence* (severity if risk occurs), with usually four levels of risk possible in standard risk assessments (low, medium, high, very high). The ecological *consequences* (e.g. loss of aquatic macrophytes) build on those outlined in previous risk assessments (SMEC 2013) and are based on published literature impact thresholds (Brown and Gilligan 2014). The scores for each likelihood (Table 16) and consequence (Table 17) are combined in a risk matrix to produce an overall risk score (Table 18).

Each of the scores is based on current scientific knowledge (published literature) and contributions from project scientists in a workshop setting (i.e. expert opinion). The risks associated with Carp occur at a range of geographic scales, time frames, river flow regimes and habitats, and the cause for each consequence and likelihood is based on the conceptual model of Carp life history (Appendix 3, Figure A3.1), the biological information presented in Appendix 2, and the ecological concepts of Appendix 3. Some of these categories (e.g. floodplain inundation) are directly related to habitat type (e.g. floodplain vegetation), so there is some overlap, but for the purposes of this document (i.e. to transparently evaluate risks) habitat and flow type are each presented separately.

We have used several different ways to assess and illustrate risks:

1. Standard risk assessments (Standards Australia 2004; Tables 16, 17, 18) for impacts on native values and Carp response/impacts to environmental water (Table 19).
2. Risks associated with particular habitat types are given by the population growth rates (Section 8.4; Table 20). Those habitats associated with overbank flooding clearly pose the greatest risks.
3. Risk curves derived from the population model provide a relative risk between scenarios and are presented for flow types and flow sequences (Section 8.3; Figure 36).

Table 16. Likelihood ratings for threats to native values

Likelihood rating	Descriptor	Definition
5	Very likely	Confident that Carp will impact native values (supported by published literature)
4	Likely	Carp are expected to impact native values (from published literature and expert opinion)
3	Possible	Carp are likely to impact native values (from expert opinion)
2	Unlikely	Carp are not expected to impact native values (from published literature and expert opinion)
1	Very unlikely	Carp are highly unlikely to impact native values (from published literature and expert opinion)
0	None	Confident that Carp will not impact native values (from published literature and expert opinion)

Table 17. Consequence levels of impacts on native values

Consequence severity level	Descriptor	Consequence to native values
5	Extreme	High-density Carp cause complete loss of macrophytes, water quality and native fish values, and changes to ecosystem function
4	Major	Extensive detrimental impacts of Carp on aquatic values include declining macrophytes, water quality and native fish values, and changes to ecosystem function
3	Moderate	Some impacts of Carp on aquatic values, which may include declining macrophytes, water quality and native fish values
2	Minor	Short-term impacts to native values and ecology
1	Low	Undetectable or inconsequential ecosystem impacts; native values and ecology maintained

Table 18. Risk matrix (Standards Australia 2004)

Risk key:



		Consequence				
		1. Low	2. Minor	3. Moderate	4. Major	5. Extreme
Likelihood	5. Very likely	M	M	H	VH	VH
	4. Likely	M	M	H	H	VH
	3. Possible	L	y	M	H	VH
	2. Unlikely	L	L	M	M	H
	1. Very unlikely	L	L	M	M	H
	0. None					



Table 19. Risk assessment of environmental watering levels/bands and Carp response/impacts

Risk key:

Low	Medium	High	Very high
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Risks		Baseflows (well within river channel)	Fresh (within river channel)	Bankfull (some low-lying wetlands inundated)	Overbank (major floodplain inundation)
Expected Carp response	Consequence	Likelihood	Likelihood	Likelihood	Likelihood
1. Longitudinal movement of adults	Low	Possible (L)	V. likely (M)	V. Likely (M)	V. Likely (M)
2. Spawning in river channel	Minor	Likely (M)	V. Likely (M)	V. Likely (M)	Possible (M)
3. Lateral movement of adults	Moderate	V. unlikely (M)	Unlikely (M)	V. Likely (H)	V. Likely (H)
4. Wetland spawning	Moderate	V. unlikely (M)	Unlikely (M)	V. Likely (H)	V. Likely (H)
5. Broad floodplain spawning	Major	V. unlikely (M)	Unlikely (M)	Unlikely (M)	V. Likely (VH)
6. High larval survival and drift	Major	V. unlikely (M)	Unlikely (M)	Likely (H)	V. Likely (VH)
7. Major Carp recruitment event	Extreme	V. unlikely (H)	Unlikely (H)	Possible (VH)	V. Likely (VH)
8. Juvenile dispersal	Major	V. unlikely (M)	Possible (H)	Likely (H)	V. Likely (VH)
Expected Carp impacts	Consequence	Likelihood	Likelihood	Likelihood	Likelihood
1. Carp impact on water quality (e.g. turbidity)	Major	Unlikely (M)	Unlikely (M)	Possible (M)	Likely (H)
2. Carp impact on macrophytes	Major	Possible (H)	Possible (H)	Likely (H)	Likely (H)
3. Carp impact on native fish	Major	Possible (H)	Possible (H)	Possible (H)	Likely (H)
4. Degradation of habitats	Extreme	Possible (VH)	Possible (VH)	Likely (VH)	Likely (VH)

### 8.3 Carp risks and flows

Flows can be treated as a surrogate for ‘available habitat’ and vice versa because neither is mutually exclusive. Here we evaluate the risk for four flow scenarios; while each is treated separately, in reality each flow type is reliant on the previous flow conditions (e.g. an overbank flow that has already passed through the previous flow stages). Natural systems and Carp population dynamics are highly reliant on antecedent conditions, so consecutive overbank flows may carry considerably more risk because there are more Carp to take advantage of the subsequent flood (Balcombe et al. 2012; Beesley et al. 2014). This has been illustrated by the risk curves for population changes (e.g. Figure 20).

The key risks concerning Carp population increases (without mitigating actions) in response to the various components of environmental water management can be summarised in Figure 37.

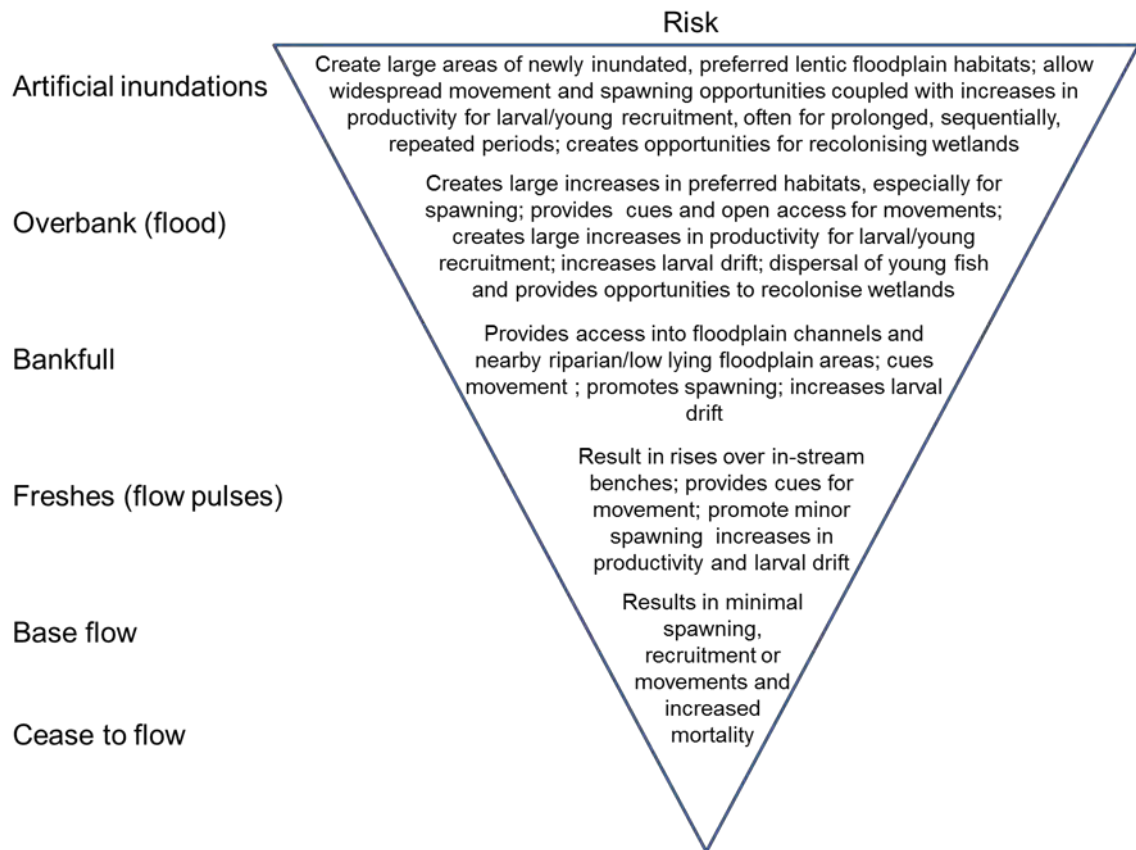


Figure 37. Risk for various environmental flow components

## 8.4 Carp risks and habitat types

The essence of changes to population abundance are encompassed in the following general population equation:  $N_{t+1} = \lambda N_t$ ,

where  $N$  is the population,  $\lambda$  is the population growth rate and  $t$  is time. Thus, the population at a future time ( $t + 1$ ) is a result of the population at time  $t$  multiplied by the population growth rate ( $\lambda$ ).  $\lambda$  can be derived mathematically and summarises the collective vital rates of fecundity and survival of each life stage of the species (e.g. eggs, larvae, juveniles, adults). Survival rates may be different for each life stage and the given habitats in which they occur.  $\lambda$  then allows for the calculation of a theoretical doubling time for the population: i.e. when  $\lambda = 2$ , the population doubles annually.  $\lambda > 1.2$  could be considered a significant population growth rate. Table 20 provides modelled estimates of Carp population growth rates (and hence risks of population growth) for a range of flow–habitat types. It is well known that floodplain habitats are preferred by adult Carp for breeding and feeding, and these are also recruitment ‘hot spots’. A range of habitat types have been evaluated for risk (Table 21) according to their calculated population growth rates (Table 20), and it is clear that flooded, floodplain habitats pose the greatest risk. Such flooding may occur with natural water levels (flooding), over which managers have little control. In other cases, such as flooding using regulators, managers have almost total control and so these operations need to be most carefully managed. The first three flow–habitat types (red) will all, on average, double Carp populations each year, while the following five flow–habitat types (orange) will double in less than 2 years.

Table 20. Risk in relation to modelled Carp population growth rates ( $\lambda$ ) associated with various flow–habitat types

Note  $\lambda > 2$  are highlighted in red and  $\lambda > 1.2$  are highlighted in orange; pop. = population.

Habitat–flow type	Theoretical pop. growth rate ( $\lambda$ )	Theoretical pop. doubling time (years)
Artificial floodplain inundation, e.g. Chowilla	2.60	0.73
River wetland, e.g. Barmah–Millewa	2.43	0.78
Natural floodplain inundation	2.41	0.79
Wetland permanently connected, e.g. adjacent weir pool	1.78	1.20
Lakes (terminal), e.g. Alexandrina	1.74	1.25
Wetland perennial, e.g. Kow swamp	1.52	1.66
Wetland ephemeral, e.g. Hattah lakes	1.46	1.83
Lakes (off-stream), e.g. Lake Victoria	1.42	1.98
Main Channel (Lower Murray) – cover benches	1.06	11.90
Main Channel (Mid Upper Murray) – summer irrigation flow	1.02	35.0
Main Channel (Mid Upper Murray) – cover benches	0.88	–
Main Channel (Lower Murray) – base flow	0.86	–
Irrigation Channels	0.80	–
Channel (Mid Upper Murray) – base flow	0.77	–

Table 21. Risk matrix for a range of situations and locations relating to Carp impacts and water management

Risk key:

Low	Medium	High	Very high
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		Consequence				
		Low	Minor	Moderate	Major	Extreme
Likelihood	Very likely				Spawning/recruitment hot spots Major wetland watering sites	Major overbank flooding Impounded floodplain waters – regulators Sequential floodplain watering
	Likely			Low population levels, isolated lakes or wetlands	Permanent and ephemeral wetlands	Adjacent connected wetlands, weir pools, terminal lakes
	Possible		Main channel base flow, impoundment	Main channel bench flow	Threatened species sites	Valuable wetland sites, large sites, high population levels
	Unlikely		Upland streams	Small isolated wetland		
	Very unlikely		Irrigation channel			
	None					

From the risk assessment of habitat types, we recommended that all situations in the *Extreme* and *Major* consequence categories (at least) meet the following management requirements:

1. Prepare a Carp management plan that includes a risk assessment and contingency measures relating to watering scenarios.
2. Create a Carp-flow coordination group with appropriate expertise to plan and manage watering events and mitigate outcomes for Carp.
3. Designate responsibility for Carp management actions.
4. Prepare a business case and funding to implement Carp plans.
5. Monitor the flow event to quantify the impact on Carp populations.

If these actions are undertaken for these two risk categories then this would represent a major step forward for dealing with issues relating to Carp and flows.

## 8.5 Synthesis of Carp risk assessment

For river managers who are planning environmental watering, undertaking a Carp risk analysis provides a useful formalised structure for considering effects on Carp populations and the options for reducing the associated risks. What is most obvious from the present risk assessment is that Carp spawning and recruitment (Carp responses) are greatest when water reaches the floodplain. It is also apparent that consecutive flood years multiply Carp benefits (and hence potential impacts). In contrast, some levels of Carp impacts (e.g. reduction of aquatic macrophytes) continue to occur, whether water is within the river channel or on the floodplain. Hence, there are disproportionate increases to Carp abundance under a flooding scenario, the continued presence of Carp can cause ongoing impacts, the degree of which will often depend on prevailing Carp densities.

Prioritising benefits and hydrological scenarios for native biota provides more beneficial ecological outcomes than simply managing flows to disadvantage Carp; hence, Carp should be a secondary consideration in most instances. Interestingly, the life history of Carp is strongly linked to floodplains and wetlands, so if flow events are contained within the river channel (e.g. baseflows, freshes and bankfull flows) then there are limited opportunities for Carp to migrate onto the floodplain for spawning. Carp are able to spawn in the river channel, but our modelling demonstrates that larval survival and recruitment is much less than under flooded conditions and that flowing main-river habitats are much less preferred than slack-water floodplain habitats.

In summary, the risks of major Carp spawning and its associated impacts are likely to be much less under within-channel flows. In contrast, within-channel flows may benefit a range of native fish species. For many native fish, a carefully designed in-channel hydrograph can still have significant spawning and recruitment benefits for native fishes (Humphries et al. 1999; Baumgartner et al. 2013; Zampatti and Leigh 2013a, 2013b). Overbank flows may also provide significant benefits to native fish (e.g. King et al. 2009), and such benefits need to be quantified and compared against potential Carp risk so that balanced watering decisions can be made. When there is a clear need to provide overbank flow to restore natural ecosystem processes there should be a transparent recognition, for all stakeholders, that Carp will likely benefit and that populations and impacts will expand. Under that scenario, there is acceptance that the benefits outweigh the risk (Carp), but that some benefit will unavoidably be conferred to Carp. To minimise these Carp outcomes, there are a variety of operational and intervention techniques that can be considered for reducing Carp populations (see Section 4.5), but the priority is to integrate actions, responsibilities and monitoring into a Carp management plan, especially for the highest-risk flow–habitat scenarios.

## 9 Discussion

Flow restoration for ecosystem health is a key tenet of The Basin Plan (MDBA 2010, 2011), and restoration of native biota (fish, vegetation, waterbirds) through water management is an important component (MDBA 2014). Carp, however, are now a conspicuous part of the MDB fish community, and there is considerable concern about their potential responses to environmental watering. Hence, Carp management needs to be considered in terms of pest management principles, but also in conjunction with water management. This will require dedicated attention to this issue, the development and implementation of site-specific Carp management plans, better definition of agency responsibilities and concerted efforts towards collaborative management. The development of an MDB-wide Carp management plan (aligned with the MDB Alien Fishes Plan; see Barrett et al. 2014) to accompany watering strategies, that also includes the identification of agency responsibilities, would greatly assist in this regard.

The primary aim of flow restoration, however, is to improve the condition of native biota and supporting ecosystem processes. Carp risk needs to be acknowledged and managed, but not at the expense of forgoing the benefits to the native biota. The ecological benefits provided to native fishes and other biota (of which there are many) need to be quantified in a similar way to the quantification of changes to Carp populations undertaken by this project (Koehn et al. 2014a).

As a very successful invasive fish species, the Carp has biological traits that sets it apart and gives it advantages over many MDB native fishes. Given the long breeding season of Carp, avoiding potential spawning is difficult, especially when achieving multiple objectives (for a range of sites and species). Hence, there is a need for careful management so as to disadvantage Carp (or at least minimise their impacts) but to benefit native fishes. Understanding Carp biology and population dynamics in response to flows and management interventions is critical for managing this conundrum and avoiding flow management paralysis based on the fear of enhancing Carp populations. Understanding fish–flow relationships cannot be gained through examining EWA-type flows alone. It requires examination of all aspects of the flow regime, including large-scale natural flooding. This provides the context for any Carp population changes and gives baseline levels from which to compare outcomes. This project has focused on how we can use contemporary knowledge of Carp biology and ecology, together with flow-related examples of population responses, to inform and develop a population model.

A Carp population model to examine potential flow-related population dynamics is a powerful tool to inform management. Empirical data on Carp populations, particularly their growth rates and abundance, is scarce, so modelling not only provides a robust alternative to examining population biology, but is also predictive, allowing the potential outcomes of competing management scenarios to be evaluated. The contemporary model used in this project is based on life stages and set in a stochastic framework suited to Australia's variable river and climatic conditions. The biological basis of the model is supported by the latest scientific data, further informed by regional examples and calibrated with empirical data (where possible) and expert opinion. This population abundance model enables a quantitative approach to comparing the potential outcomes of a range of management options at both site-specific and regional scales. This model and expert knowledge of habitat-specific Carp responses can be predictive within specific environmental watering scenarios and can provide advice on managing Carp and flows within an appropriate risk-management framework.

The most common environmental watering scenarios for the Murray River are likely to be: (1) within-channel river pulses; (2) some flows that may break out-of-channel/overbank in some regions, particularly in the Mid Murray at Barmah; (3) water allocations to specific sites/wetlands



(via channels or pumped); and (4) artificial inundations using floodplain regulators. These all impact Carp in different ways. The highest risk scenarios for Carp all relate to floodplain inundation (natural flooding and artificial inundations using regulators). Some high-risk scenarios such as natural flooding are infrequent, and in most cases managers have little control of natural events. For managed scenarios, such as the use of regulators to artificially inundate floodplains, there are high levels of control. There are two key components of floodplain inundation for which Carp responses are of particular concern: first, the sequencing of managed flows and floodplain inundations; and second, the return of Carp from the floodplain to the river metapopulation. Given the relatively short time required for Carp to reach sexual maturity (2–3 years), increased abundance in Carp populations can be greatly exacerbated by frequent, sequential overbank flooding. Hence, the proposed use of floodplain regulators (which can deliver high frequency managed flooding during within-channel river flows) clearly poses the greatest Carp risk from environmental watering.

The recommendations of previous work in relation to the Carp risk during managed artificial floodplain inundations clearly need much greater consideration (Mallen-Cooper et al. 2008, 2011). Other high-risk hydrological scenarios relate to watering or inundation of ephemeral and regulated wetlands, wetlands adjoining weir pools, and terminal and off-channel lakes. The impact of changes to Carp populations on the river metapopulation will depend on the return of Carp from off-channel habitats. In some cases this may be preventable, although this is likely to mean that there will be little return of fish of any species (particularly medium and larger species). Thus, some benefits to the native fish community may also be lost if the Carp exodus from floodplains is reduced or prevented.

Initially, the present project focused on specific flow types, but it became apparent that, although general recommendations can be made for flow and habitat types, operational details can be very site-specific; thus, there is a need for individual site risk assessments relating to watering scenarios. These will form a key component of flow-related Carp management plans, including assessments of risk, and strong involvement of the infrastructure operators is required in planning development and implementation. This process can be informed by the model outputs for the scenarios tested herein. There is also a need for principles and guidelines for Carp management to be developed in conjunction with EWAs and other complementary management actions.

It is difficult to manage any fish population, including Carp, in the absence of adequate field data. We therefore recommend establishing a monitoring regime that provides data on Carp population dynamics in relation to their overall status and also their responses to interventions such as environmental water management. Not only will these data inform management, but they can also be used to support the validation, calibration and future refinement of the population model. At present there appears to be no dedicated Carp monitoring program for any of the high-priority floodplain regulators or nearby riverine sites. Although Carp are a very well-studied fish species, their impacts on native fishes and on many components of the Australian ecosystem are still not well quantified. There is a need to quantify such impacts so that they can receive proper recognition and management attention (Koehn et al. 2000).

Bio-economic modelling provides a quantitative framework for considering the benefits and costs of alternative levels of investment in invasive species management. It does this by linking the level of investment in the costs of intervention (control) to the value of the benefits derived; typically a product of the number of individuals that have to be removed to achieve some specified density (Choquenot et al. 2004). Determining threshold population levels (e.g. kg/ha) against which targets and investments can be made is important for Carp (pest) management plans (Koehn et al. 2000). While it was outside the scope of the present project to quantify the potential impacts of currently available Carp 'control' techniques on overall populations, we conclude that the options are currently limited. The present technologies need to be carefully

implemented and tailored to maximise their site-scale impacts. There is also a need to quantitatively and realistically assess the impacts of each Carp ‘control’ option on overall populations.

A major gap in the management of fish and environmental water is the ability to quantifiably evaluate the negative impacts of Carp alongside the benefits to native biota. There are no detailed, site-specific native fish management plans or population models; hence, development of these is urgently required for quantifying the overall benefits of environmental water. Greater certainty of the benefits to native fishes will increase confidence in our understanding of the relative impacts of Carp and the need for management actions. In summary, native fish models would enable Carp management to be considered in a more balanced way.

The rehabilitation of MDB native fishes cannot be achieved by the provision of environmental water only, or the removal of Carp alone (Koehn et al. 2104b). In some cases there are other overriding issues or threats that need to be addressed before the benefits from environmental water can be maximised—for example, actions to address issues such as cold-water pollution (Lugg and Copeland 2014), connectivity (Baumgartner et al. 2014), blackwater (King et al. 2012) and fisheries stocking and management (see Koehn and Todd 2012) can complement the benefits from environmental flows in terms of supporting the recovery of native fishes.

Climate change will also have a wide range of impacts on fishes and their habitats (Balcombe et al. 2011; Koehn et al. 2011; Morrongiello et al. 2011) and this needs to be integrated into future water management (Aldous et al. 2011). Reductions in flows are predicted to be minor compared with those already imposed by river regulation and water extraction (McMahon and Finlayson 2003), but there will be changed flow patterns, with more extreme droughts and floods (CSIRO 2008). It is difficult to predict how these changes will impact either native fish or Carp populations, but they are likely to alter habitats and increase pressure on the use of EWAs.

Environmental water management is a relatively new science in which managers and scientists are all learning. There have been substantial changes to water management in the MDB over the past two decades, potentially with major benefits to native biota and the river ecosystem. There is still much to be learnt, however, both from science and management perspectives on how to maximise these benefits. There is a need to plan carefully and then to learn as we go. Potential risks, such as any increases in Carp abundance, must be weighed up against other benefits, and there is great scope for reducing the benefits to Carp while achieving broader river restoration goals. This study illustrates the utility of a population model to ‘quantify’ changes in Carp populations resulting from a range of flow scenarios, including environmental water management. Additional tools such as conceptual and population models (both for Carp and native fish) will greatly assist this management by allowing exploration of the relative outcomes of various options. While the development of this modelling has been a major step forward, there are several additional opportunities that could greatly progress water and Carp management in the future:

1. The development of a metapopulation model for Carp. While this current model can be utilised at any scale, the integration of different habitats, areas and flows would provide outputs with greater amenity for flow managers.
2. Application of this model to the northern MDB, which has some key ecological differences from the southern MDB that need to be explored and incorporated. (Work is expected to begin on this soon.)
3. Development of population models incorporating flows for a range of native fish species. (Work has just been initiated for eight species.)
4. Ultimately, a fish community model that can include interactions between species and watering options could be developed.

Current thinking indicates that planning for environmental flow and Carp management is best conducted over longer time frames (e.g. 10 years), which can easily be accommodated with the use of modelling. Together with outputs from the newly initiated Native Fish Population Models Project, managers will soon be able to make comparisons of benefits and risks to make more informed decisions regarding watering actions.

## 10 Key messages for management

A range of recommendations relating to both the general principles as well as more detailed aspects of watering are provided below. As the details of individual watering events and scenarios can be very site-specific, however, local assessments for the management of flows and Carp may also be required.

- Priority objectives for environmental water management in the MDB are to benefit native biota, and this focus must be maintained.
- Carp are a highly visible and abundant invasive fish species that can readily respond to flows, especially overbank flooding. The long potential spawning season for Carp overlaps with that of many native fishes and also with likely watering times for other biota; hence, careful management is needed.
- Natural flooding does promote Carp and native fish population growth, but water managers have little control over these flows.
- Carp are now a major component of MDB fish fauna, and their recruitment may be an inevitable by-product of some environmental watering activities. The responses observed in Carp populations are influenced by existing high abundances. In general, however, in-channel environmental flows will have minimal impacts on Carp populations, but will have benefits to native fish populations. Furthermore, existing large reproductive Carp populations in the Lower Lakes of the Murray River mean that environmental flows into South Australia will have limited further impact on Carp numbers in the Lower Murray River.
- Habitats and flows that result in high population growth rates pose the highest risk for increases in Carp populations, and these all involve the inundation of floodplain, wetland and lake habitats.
- Artificial floodplain inundation using regulators is likely to pose the greatest risk of increasing Carp populations. Such inundations may export Carp from floodplains and substantially increase the river Carp metapopulation, while benefits to most native fish species may be limited. Frequent, sequential inundations of the floodplain and the cumulative impacts from the multiple large-scale sites constitute the greatest risk of increasing Carp populations in the Murray River. Nevertheless, water managers have high levels of control over this type of management action and hence have the ability to manage such inundations carefully.
- Watering for non-fish outcomes could be considered during winter months (water temperatures <16°C) to minimise Carp recruitment. This may mean, however, that positive outcomes for native fish should not necessarily be expected.
- There is a need for Carp to be managed in conjunction with watering through the development and implementation of adequate Carp management plans for all high-risk watering activities and sites, with actions based on pest management principles. These site

plans would benefit from being set within the context of a coordinated, Basin-wide Carp management plan.

- In order to quantify the responses of Carp to flows and to manage populations, there is a need for data from regular monitoring. The data can also be incorporated into population models that can be used to forecast potential changes in Carp and native fish abundances over the appropriate temporal (decadal) timescales.
- There is a need for quantifying the benefits of flow management actions for native species so that these can be balanced against any impacts from Carp. A step towards this has occurred through the initiation of a project to develop native fish population models that will allow the benefits of environmental flows for fish to be explored.

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## Appendix 1 Environmental watering options and benefits for native fish

Table A1.1. Examples of the benefits to Murray–Darling Basin fish of various environmental watering options and examples of environmental watering

Watering option	Benefits for fish	References
Increase magnitude or extend duration of flooding	Input of organic carbon and material for ecosystem productivity Increased wetland and floodplain habitat area and food production Increased spawning and recruitment of some species Adult movement of some species onto floodplain and within channel Increased egg/larval and juvenile dispersal?	King 2004; Tonkin et al. 2011; King et al. 2009, Rayner et al. 2009; King et al. 2010; Rolls and Wilson 2010; Tonkin et al. 2011; Beesley et al. 2012; Hammer et al. 2013; Leigh and Zampatti 2013a, 2013b
Create within-channel flow pulses	Increased spawning and recruitment of some species Adult movement of some species within channel Increased body condition and growth Increased egg/larval dispersal and juvenile movements	O'Connor et al. 2005; King et al. 2009; King et al. 2010; Lyon et al. 2010; Tonkin et al. 2011; Rolls et al. 2012, Rolls and Wilson 2010; Baumgartner et al. 2013; Zampatti and Leigh 2013a, 2013b
Water individual wetlands	Habitat maintenance and refuge during droughts Increased food production in wetland only Increased recruitment of wetland fish species Increased connectivity between the river and wetland	Lyon et al. 2010; Hammer et al. 2013; Ellis et al. 2013
Impound water on floodplains using structures	Habitat maintenance and refuge during droughts Increased food production in wetland only Increased recruitment of wetland fish species Note: risk to some fish species, potential increase in Carp	Mallen-Cooper et al. 2008, 2011; Koehn et al. 2014a
Maintenance (base flows)	Refuge area during dry periods	Hammer et al. 2013

## Appendix 2 Ecological knowledge of Carp

There is a need to use the best available knowledge and science to understand Carp as an invasive species so that they can be effectively managed as a pest species (Koehn et al. 2000). This information also provides the ecological context and structure for models, and the scenarios and parameters for use of the population model to set priorities and address issues within the management framework.

### A2.1 General biology

Carp are well known for their tolerance of a wide range of temperatures, salinities and oxygen (Opuszynski et al. 1989; Stecyk and Farrell 2007), as well as their mobility (Koblitskaya 1977; Brown et al. 2004) omnivorous diet (Crivelli 1981), extreme fecundity (Sivakumaran et al. 2003; Bajer et al. 2012), and tendency to exploit unstable areas as spawning/nursery habitat (Bajer and Sorensen 2010). Their generalist habitat requirements have allowed them to thrive in disturbed habitats (Gehrke and Harris 2001), with their species' attributes being different to MDB native fishes (Koehn 2004), and their adaptations being important to Carp invasion success (Bajer and Sorensen 2010). The biological information for Carp, summarised in the Section below, can help in the development of conceptual models for informing environmental flow delivery. The need for decadal flow planning based on fish biology has recently been highlighted (Baumgartner et al. 2013; Koehn et al. 2014a), whereby aspects of reproductive and movement biology were used to generate a 10-year environmental flow plan. This type of approach, bringing fish biology into long-term planning, will also be likely to have great benefits to native fish communities.

#### A2.1.1 Ageing of Carp

A variety of techniques have been trialled to determine the most reliable and accurate method for estimating the age of Carp, including measuring scales, opercula bones, vertebrae, dorsal spines, pectoral fin rays and otoliths. Of these, the otolith (asteriscus) has proven to be the most accurate and reliable (Vilizzi and Walker 1999; Phelps et al. 2008; Winkler et al. 2011). The age of young Carp can be determined reliably by counting daily growth rings from polished otoliths to ~3 months of age, and numerous studies have refined methods so as to achieve high accuracy (Vilizzi 1998; Smith and Walker 2004a, 2004b). Although Carp present considerable challenges for estimating age, sectioned otoliths are a reliable and validated method (Brown et al. 2004). An accurate ageing technique allows successful spawning to be directly associated with river and flow conditions; thus, the impacts of various management interventions can be evaluated. Alternatively, accurate ageing can better inform population models, and such modelling can be employed to provide some level of prediction concerning Carp response to a range of management scenarios.

#### A2.1.2 Longevity of Carp

In the North American Mid-west, ageing of Carp from sectioned otoliths has yielded an estimation of a maximum age of 34 years (Bajer and Sorensen 2010). This longevity gives Carp the ability to exert consistent propagule pressure for many years and to produce large numbers of offspring (Bajer and Sorensen 2010). In Australia, Carp commonly reach 15 years of age (Brown et al. 2004), with a maximum age of 29 years being recorded from a large female Carp (760 mm FL) and 8.5 kg] in the mid Murray and Barmah area (Jones and Stuart 2008).

### A2.1.3 Growth

Carp growth rates vary with geographic location, from year to year, and throughout the year: growth is faster in the warm water temperatures of spring and summer, particularly following flooding (Hume et al. 1983). In South Australia, Carp in the Murray River grow faster and larger than those from the Barmah–Millewa area—this is probably related to warmer water temperatures (Vilizzi and Walker 1999; Brown et al. 2003). Female Carp grow faster and larger than males, an adaptation for producing greater numbers of eggs (Stuart and Jones 2002; Smith 2005). However, heterogeneity in length-at-age was high for both male and female Carp in the Barmah Forest area (Brown et al. 2005). Larval Carp grow very rapidly, but similar to adults, growth can be vary between habitats and years, with fish spawned early in the season (e.g. September) having a longer growing period than those spawned late (e.g. February; Smith 2005). A 50-day-old Carp might have a 40 mm FL and weigh 1.5 g (Vilizzi 1998; Smith and Walker 2004b). As most initial field confirmations of spawning and recruitment are determined from length data, this needs to be considered in relation to length–age relationships. The maximum size recorded for a Carp from the Murray River is 760 mm FL and 8.5 kg (Stuart and Jones 2002), but greater sizes have been reported from wetlands.

### A2.1.4 Survival

A major knowledge gap in the basic life history of Carp is quantitative age-specific mortality schedule data. This data gap is particularly the case for the egg and larval stages, for which there is little information on mortality rates. Notwithstanding, a high proportion (at least 60–80%) of eggs are assumed to be lost to fungal infection and invertebrate grazing (Smith 2005), and a natural mortality rate of 96% has been estimated for age-0 Carp on the Murray River at Barmah (Brown et al. 2005). Young-of-the-year Carp (30–150 mm FL) are assumed to be highly susceptible to piscivorous birds [e.g. cormorants, darters, Pelicans (*Pelecanus conspicillatus*), egrets and herons] and predatory native fish (primarily Golden Perch and Murray Cod). The natural mortality rates are thought to decrease with age, and a rate of 83% has been estimated for age-1 Carp at Barmah (Brown et al. 2005).

Once Carp reach 2 years of age and 300+ mm FL, there are few predators except large Murray Cod, Pelicans and commercial and recreational fishers (Koehn et al. 2000; Koehn 2004). Carp may also die in large numbers during wetland drying events, and while in shallow water they are vulnerable to a variety of predators (e.g. Pelicans, Feral Pigs *Sus scrofa*, Foxes *Vulpes vulpes*, Lace Monitors *Varanus varius* and a variety of avian raptors). Stranding of Carp in wetlands is likely to disproportionately impact on mature female fish, and thus may have a large impact on populations and possibly be a potential way to control Carp biomass (Brown et al. 2005; Jones and Stuart 2008). In general, few Carp show external signs of disease or distress (project team, unpublished data).

## A2.2 Reproductive biology

### A2.2.1 Maturation

For wild Carp, sexual maturity has been recorded at a young age: ~1 year for males, 2 years for females (Swee and McCrimmon 1966; Brumley 1996; Sivakumaran et al. 2003; Brown et al. 2005; Bajer and Sorenson 2010). In the Murray River at Barmah, maturity of 50% of Carp was observed at: 307 mm FL and 1.1 years for males and 328 mm FL and 2.7 years for females (Brown et al. 2005). In the same study, maturity of 95% of Carp was observed at 379 mm FL and 1.2 years for males and 392 mm FL and 4.7 years for females. For a small proportion of fish in optimal growing conditions, maturity can even be reached at age 0+ and 230 mm FL for males and 280 mm FL for females (Brown et al. 2005). The ability of Carp to reach early maturity is common to populations



in other parts of the MDB, and we note that there can also be considerable variation in the size/age at first maturity depending on local conditions.

### A2.2.2 Fecundity

Fecundity is the average number of eggs a female Carp can spawn annually, and many females carry over a million mature eggs (Sivakumaran et al. 2003). For Carp, fecundity is unusually complex because females are 'fractional' or 'batch' spawners, meaning they can release batches of eggs throughout the breeding season; because egg production is almost constant, it is difficult to determine fecundity in any one year. Female Carp can also develop eggs in an asynchronous manner: some fish develop their eggs early in the season and some late.

There is a clear relationship in many fishes between maternal size and greater egg size, larval hatch size and larval survival; thus, it is likely that large female Carp strongly influence annual recruitment patterns (Birkeland and Dayton 2005). Large female Carp are relatively more important for egg production for two reasons: (i) larger females carry more eggs than smaller females and (ii) larger females produce larger eggs, which is likely to be advantageous for larval survival (Sivakumaran et al. 2003). For example, a single large (e.g. 6 kg) female Carp may release 100,000 to 220,000 eggs in a batch (Sivakumaran et al. 2003), but this is only a fraction of her total annual fecundity of 1.5 million eggs (Hume et al. 1983). A smaller (1.25 kg) female fish may carry only 80,000 eggs. Eggs may make up a maximum of 35% of the body weight (Sivakumaran et al. 2003) for female Carp (see Figure A2.1).

### A2.2.3 Sex ratio

As for many aspects of Carp biology, the sex ratio of fish is variable spatially and temporally. Female Carp tend to slightly outnumber males (1.5:1) in wetlands and at riverine access areas to wetlands, but males outnumber females (2:1 to 7:1) at more distant riverine reach sites (Stuart and Jones 2002). Similarly, there can be more females than males (1.7:1) in the Lower Murray River (Smith 1999). There are also many cases of equal sex ratios (1:1) in the MDB (Brown et al. 2005). Perhaps the most interesting sex ratio data comes from Lock 1, Murray River, South Australia, where prespawning females outnumbered males (2.6:1) during the spawning season, but the female:male ratio gradually declined (to 0.6:1) by April (Conallin et al. 2008).



Figure A2.1. A large, gravid female Carp (photo: Clayton Sharpe)



#### A2.2.4 Spawning

Carp have an unusually long spawning season of up to nine months, beginning in say mid-August (depending on local conditions) and finishing by April (Sivakumaran et al. 2003; Stuart and Jones 2006b). In the Lower Murray River, the spawning season may be even more extended (Smith 2005), but the peak spawning period is from October to December (Smith and Walker 2004b; Zampatti et al. 2011). Within a population, there are always females with ovaries close to maturation (Sivakumaran et al. 2003), and some female Carp may spawn repeatedly within a single season (Sivakumaran et al. 2003; Smith and Walker 2004b; Brown et al. 2005). At Lock 1 the gonadosomatic index for female Carp peaked at 19% in December before declining to 8% in April (Conallin et al. 2008).

Carp eggs mature during winter for the spring spawning season, which begins when the water temperature rises to 15–16°C and the photoperiod is >10 h of light (Smith and Walker 2004b). This allows earlier spawning times than is possible for many large native MDB species that prefer warmer temperatures for spawning (Koehn and O'Connor 1990; Adamek 1998; Koehn et al. 2000), and it also allows them to take advantage of spawning areas downstream of water storages that release cold water (Koehn 2001). Favourable conditions for spawning include a rise in water temperature (16–24°C) (Swee and McCrimmon 1966; Crivelli 1981; Smith and Walker 2004b), and there is an upper spawning threshold of 29°C (Hume et al. 1983).

Carp prefer shallow littoral habitats, where they lay their adhesive eggs onto submerged and emergent vegetation, but Carp can also spawn on a wide range of substrate types (see Figure A2.2). Spawning in the main river channel is common, but Carp actively select off-stream floodplain habitats, such as the Barmah–Millewa floodplain, the Macquarie Marshes, and wetlands adjacent to the Lower Murray River in South Australia (Koehn and Nicol 1998; Stuart and Jones 2006b; Gilligan et al. 2010; Conallin et al. 2012).

Carp use floodplain habitats as spawning sites and nurseries (Koblitskaya 1977; Kanitskiy 1983; Balon 1995; King et al. 2003; Stuart and Jones 2006b). They prefer shallow, warm, well-vegetated, lentic or slow-flowing waters for spawning (Crivelli 1981; Kanitskiy 1983; Koehn et al., 2000), and although they may spawn in the absence of flooding in the Lower Murray River (Smith and Walker 2004b), increased spawning and larval and juvenile abundance have been linked with floodplain inundation (King et al. 2003; Stuart and Jones 2006b; Humphries et al. 2008). These areas have very low densities of egg and larval predators due to their rapidly expanding areas and shallow depth (Bajer and Sorensen 2010) and they frequently have severely hypoxic conditions during hot and dry periods and flooding during wet seasons, reducing predatory pressure and recruitment bottlenecks (King et al. 2003; Stuart and Jones 2006b; McNeil and Closs 2007).

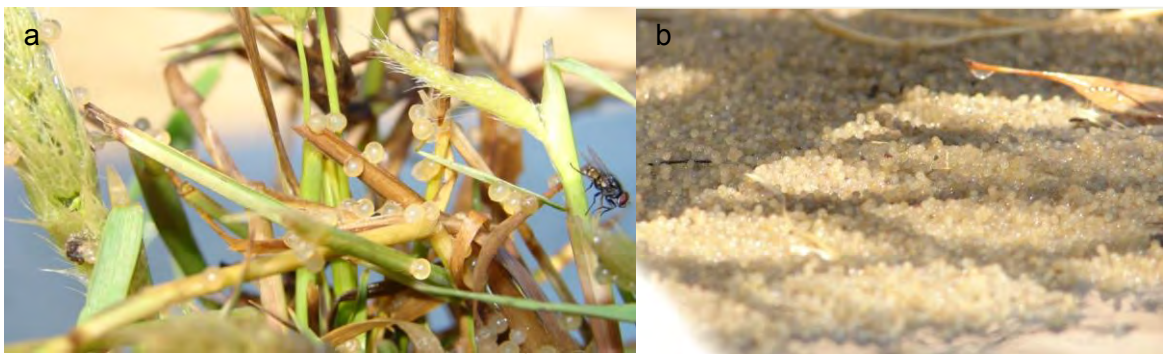


Figure A2.2. Carp eggs (a) attached to vegetation (photo: Ivor Stuart); (b) laid on the substrate (photo: Ivor Stuart)

### A2.2.5 Recruitment

Recruitment is the survival of young fish to sexual maturity (1 or 2 years of age for Carp—see above). A surrogate measure of recruitment that is often used is the number of post-larval fish or juveniles detected in their first year. Each year there is variation in the number of fish that 'recruit', depending upon spawning conditions, flow and environmental conditions, and survival/mortality processes. A strong year-class or cohort can be easily tracked through the population size structure by observing the length-frequency, especially for small fish (<100 mm). However, the most accurate way to determine in which years recruitment has occurred is to age the fish from sectioned otoliths, thereby isolating the strong recruitment years (e.g. Crook and Gillanders 2006). Often successful Carp recruitment is associated with specific events, such as flooding (Brown et al. 2003).

Across the MDB, 12 Carp recruitment hotspots have been identified: Mid Darling, Lower Macquarie, Wimmera, Lower Gwydir, Koondrook–Perricoota–Gunbower, Lower Border Rivers, Lower Castlereagh, Great Cumbung Swamp, Upper Wakool, Barmah–Millewa Forest, Lake Victoria–Chowilla and Lake Brewster (Gilligan unpubl. data). This study was largely undertaken during low flow conditions, and Carp also spawn at a wide range of other sites, including some that have been shown to exhibit major population explosions (see Appendix 3 for examples).

Increased Carp recruitment with floodplain inundation is well documented in the MDB (Humphries et al. 1999; King et al. 2003; Brown et al. 2003, 2005; Stuart and Jones 2006b; Crook and Gillanders 2006; Conallin et al. 2012), with these areas providing conditions where survival of Carp larvae is high (Zampatti et al. 2011). Hatching of Carp eggs is rapid (two days at 25°C). Larvae can develop rapidly (Adamek 1998) and are tolerant to starvation (Geurden et al. 1999); however, they are extremely vulnerable to predation (King et al. 2003). Larvae and juveniles can drift from floodplains into mainstem habitats, where survival can be variable from year to year and may depend on growth rates on the floodplain (Zampatti et al. 2011). Following periods of natural and enhanced flows in the Murray River, Macdonald and Crook (2013) found that the Barmah–Millewa area was the major source of Carp recruits for the Murray River main channel, with increased young-of-the-year fish compared with low-flow years. Carp show a positive response to river regulation, with juveniles being more abundant in regulated rivers than in unregulated rivers, suggesting that recruitment of these species is favoured by the more stable conditions in highly regulated rivers (Gehrke and Harris 2001).

### A2.3 Movements and dispersal

The scientific literature concerning the movement ecology of Carp has grown markedly in the last decade. From early tag–recapture work in the Lower Murray River, Carp were considered non-migratory (Reynolds 1983); however, more specific studies with radio-tags, acoustic tags, fishway monitoring and otolith microchemistry have indicated that they move widely. Larvae can drift downstream, juveniles (young-of-the-year actively move upstream, and adults can move long distances (>100 km), leading to high emigration rates and the ability to colonise new habitats (Stuart et al. 2011; Zampatti et al. 2011; Koehn and Nicol 2014, in press). In essence, Carp are a highly mobile species with attributes that allow for rapid population expansion and recolonisation (Koehn and Nicol 1998, in press).

The reproductive success of Carp is linked with its strong migratory drive to gain access to the shallow spawning habitats (Bajer and Sorensen 2010). During the warmer months, large numbers of adults and juveniles move upstream to spawn, feed or disperse (Mallen-Cooper 1999).

Carp are capable of moving large distances at any of their life stages (Jones and Stuart 2008), with adult Carp between riverine and floodplain habitats. Adults also move longitudinally along rivers at a local scale of a few kilometres through to hundreds of kilometres (Stuart and Jones 2006a). Carp are common in fishways (Mallen-Cooper 1999), where a rising water temperature of >18°C cues their migrations.

Juvenile Carp, (from young-of-the-year) are also highly mobile, and larvae can drift considerable distances downstream from nursery habitats before dispersing, during which process they move through fishways in very large numbers (up to tens of thousands per day) (Stuart and Jones 2006a; Crook et al. 2013).

The recent completion of the Murray River fishway program gives Carp an unprecedented ability to migrate freely along over 2000 km of river. The tagging of Carp with Passive Integrated Transponders (PIT tags), together with tag readers at fishways will be important in further understanding movement patterns (Baumgartner et al. 2014). Carp moving through fishways also provide a unique opportunity for removal with devices such as the Williams' cage (Stuart et al. 2006)—at Lock 1 (Blanchetown, South Australia) ~130 tonne were removed in 2013–2014 at up to 5 tonne per day (Barry Cabot, SA Water, pers. comm.).

## A2.4 Habitats

Like many native fishes, Carp are also associated with structural woody habitats, but while they may be similar in some general habitat preferences, they also show considerable differences. Within the river channel, Carp generally prefer shallower, slower-flowing habitats (<0.20 m/s, even still water), close to the bank, and with wood higher in the water column than other large-bodied native species (Koehn and Nicol 2014). These preferences are more similar to those of Golden Perch than they are to those of Murray Cod or Trout Cod. They are also more likely to inhabit off-stream waters such as wetlands and billabongs. Juvenile and adult fish preferentially inhabit lentic habitats; however, they have been known to also use lotic anabranch habitats (Zampatti et al. 2011). Carp are in fact a habitat generalist, with weaker attachments to particular habitats than many native fishes.

## A2.5 Resistance and resilience

Carp can readily be described as a species that has high tolerance to a range of environmental variables (Koehn 2004; Section 2, Table 2). These 'resistance' attributes allow them to survive a wide range of environmental conditions. A further range of 'resilience' attributes (dispersal ability, distribution, abundance, reproductive capacity) allows the species to bounce back after difficult environmental events (e.g. drought). In an assessment of the capability of 15 fish species in south-eastern Australia to withstand drought conditions, Carp rated both the most resistant and the most resilient (Crook et al. 2010). These attributes may also apply to other environmental conditions and are indicative of the survival abilities of this species.

## Appendix 3 Ecological concepts

### A3.1 Conceptual models

Conceptual models are representations of complex systems (or components of them) that use available data and present causal factors to show links, interactions and processes. They are often pictorial or diagrammatic, but more specific models can also be concise text descriptions. They express ideas about components and processes deemed important in a system, document assumptions about how components and processes are related, and identify gaps in our knowledge; hence, they are working hypotheses about system form and function (Manley et al. 2000). The strength of conceptual models is that they link components of a system together to present a holistic view and highlight complementary actions. These models might include the components outlined above. The development of conceptual models provides an explicit synthesis of the best available biological knowledge that incorporates key ecological attributes and needs. The process of developing such models engages the experts on that species, and allows them to provide the most up-to-date information (often not yet published), together with expert opinion where necessary. Documentation of conceptual models is also important because our knowledge and experience often accumulates change incrementally; without documentation this is not recorded and made readily available for use in management.

### A3.2 Carp life cycle

The life cycle of Carp can be simplified into five stages (Figure A3.1), each with specific life purposes and attributes (Table A3.1) that can then be used as a basis from which to construct the population model. These life stages will respond differently to changed conditions, prefer different habitats and have different dispersal mechanisms.

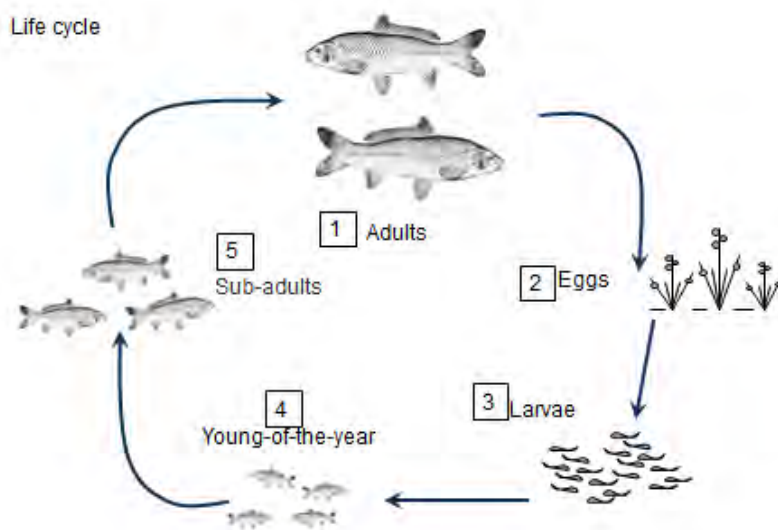


Figure A3.1 Schematic diagram of the various stages in the Carp life cycle

Note: young-of-the-year and subadults may both be referred to as 'juveniles'

Table A3.1. Key concepts relating to the life stages of Carp outlined in Figure A3.1

Life stage	Comments
1 Adults	Occupy both flowing (river) and still-water habitats, but prefer low water velocities. Have wide environmental tolerances and are highly mobile. Are ecologically different from other MDB native fishes. School and form overwintering and prespawning aggregations. Prefer to spawn in vegetated, shallow, still-water habitats.
2 Eggs	Attached to submerged vegetation in still, warmer water. Hatch in 2 days at 25°C.
3 Larvae	Some drift or may be flushed from slow-flowing areas. Develop rapidly.
4 Young-of-the-year	May recolonise (upstream/downstream) or drift downstream. Note: this includes 'fingerlings' and 'fry'.
5 Subadults	May recolonise. Transition from pelagic to benthic feeding.

### A3.3 Population dynamics

Population dynamics for fish populations involves the distribution, abundance, structural, and temporal and spatial changes in relation to habitat and landscape requirements. The most important concept of populations revolves around the basic population equation:

$$N_{t+1} = N_t + B_t - D_t + I_t - E_t,$$

where  $N$  = Number of fish;  $B$  = Births;  $D$  = Deaths;  $I$  = Immigration;  $E$  = Emigration;  $t$  = Time.

Other components of population dynamics are:

- Populations are often mainly reliant on the number of female fish ( $N_f$ ), which indicates the actual reproductive stock.
- Fecundity ( $F$ ) = the number of eggs per female.
- Total number of eggs ( $N_e$ ) =  $F \times N_f$
- The life stages of the species (see Figure A3.1).
- Survival rates ( $S$ ) between each life stage of the species.
- Recruitment, which is the replacement of an adult into the population (i.e. survival through all life stages), but survival to age 0+ is often used as a surrogate for this because the greatest mortalities occur at egg and larval stages. Note that successful spawning does not necessarily result in successful recruitment (i.e. there may be a failure of survival at the egg or larval stages).

The population may be limited by the 'carrying capacity' of the habitat or ecosystem, and this will be dependent on a range of critical (e.g. thresholds to survival) and non-critical conditions (such as quality and quantity of food supply). The response of a fish population in relation to any environmental change, such as a change in flow, will be dependent on both the initial population and the magnitude of the response initiated. If the resident population is small (as in the case of a threatened species), then the magnitude of the overall response will be low, and possibly difficult to detect. If there is no resident population (i.e.  $N = 0$ ), then no response can be

expected, even if the flow has provided the desired conditions. Conversely, a large resident population will result in a visibly large response, as is the case for many Carp populations.

### A3.4 Carp population variability

As has been shown from the regional examples (Section 4.1), Carp population numbers can vary considerably, especially in isolated waters. Abundances can also vary over time in river populations, as exhibited in data from the Mid Murray region shown below (Figure A3.2). This data was collected using boat electrofishing in the Murray River downstream of Lake Mulwala (but upstream of Barmah–Moirā). Carp numbers decreased steadily as the drought progressed (post-1999), increased after a small flow supplemented by an environmental flow in 2005–2006 (King et al. 2010), and increased sharply following substantial natural flooding in 2010 and 2011. Examination of Carp data collected by the Sustainable Rivers Audit (Davies et al. 2012) also showed similar variation in abundances (Figure A3.3).

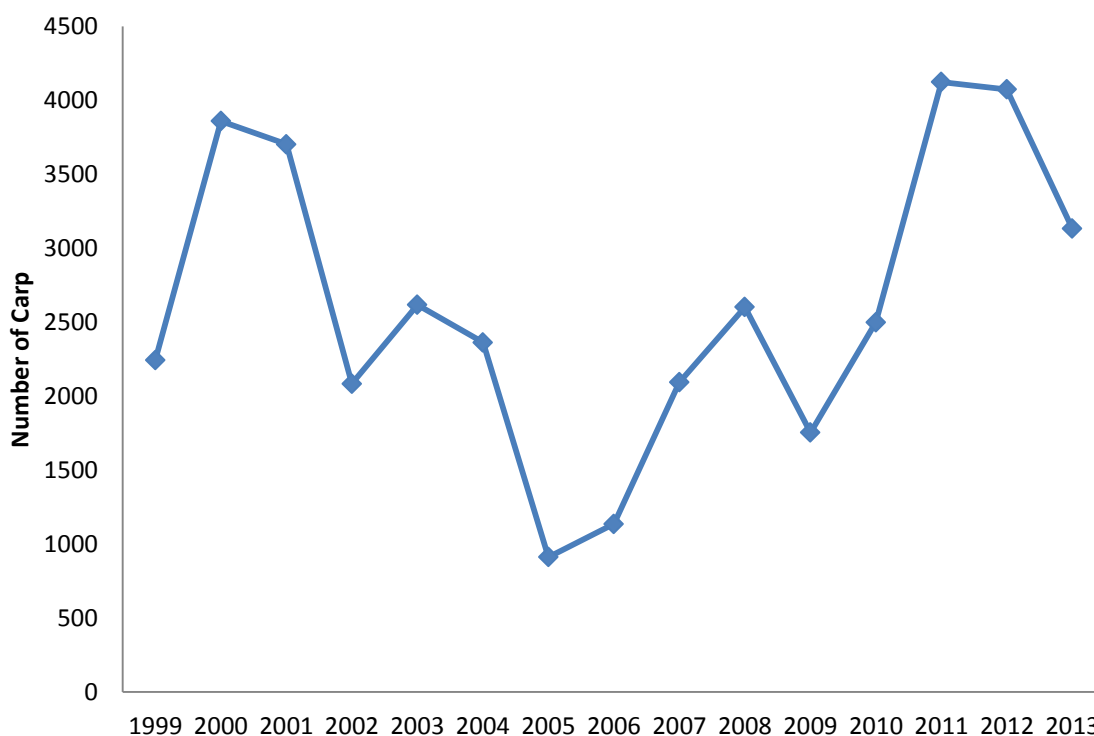


Figure A3.2. Total numbers of Carp per year collected by electrofishing standard sites in the Mid Murray River, 1999–2013 (ARI unpubl. data)

### A3.5 Spatial scales

The spatial scale of ecological processes, connectivity and fish population dynamics needs to be considered in population modelling. For example, dynamics (and hence management) can occur at individual sites (e.g. an individual wetland) or over whole river reaches (e.g. Yarrawonga to Barmah) or catchments (Edward–Wakool system). These scales can be grouped geographically, by operational area (e.g. if they are dependent on a single riverine structure) or even by eco-



hydrological region [e.g. the endorheic Avoca and Lachlan river systems. In part the scaling issue is determined by the scale of movement of the fish in question. In this case, Carp are known to be active and move widely over larger scales (Koehn and Nicol 1998, in press; see below); hence, connectivity is important over large reaches. This concerns both the longitudinal connectivity of fish moving upstream, downstream, laterally into floodplain channels and also onto the floodplain itself. The spatial extent of habitats increases with flows, particularly wetland areas.

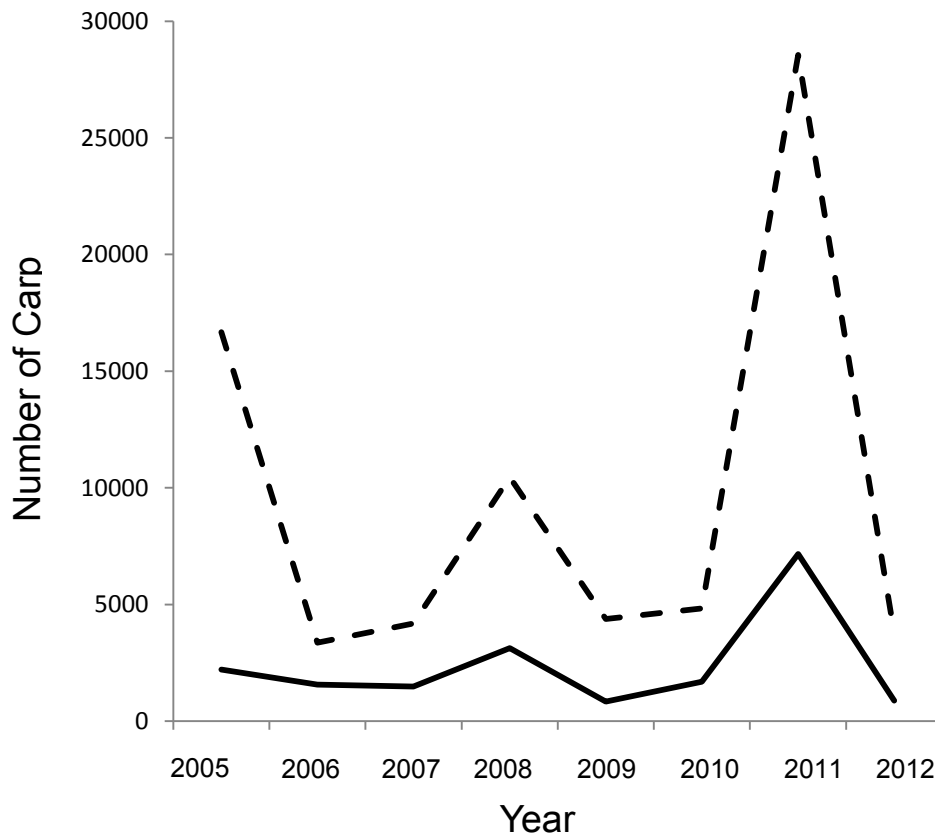


Figure A3.3 Total numbers of Carp caught per year by the Sustainable Rivers Audit for the whole (dotted line) and Lower Murray–Darling Basin (solid line) 2005–2012

### A3.6 Movements and aggregations

Carp movements have been described as highly variable and, as illustrated in Figure A3.4 and Table A3.2, they have a range of purposes. Of particular importance are the movements across spatial scales (both up and down river) and between river and wetland habitats when connections are available. Each movement may be affected differently by flows (Table A3.2). The large-scale movements that link smaller sites to a riverine metapopulation help explain how the MDB could have been invaded in such a relatively short period of time (Koehn et al. 2000). Carp schooling and social behaviour result in the forming of aggregations in the river, below barriers, potentially over winter, and at entrances to wetlands (Figure A3.5; Table A3.3). Aggregations of Carp below a weir/barrier (e.g. Section 4, Figure 10) is likely to be movement-based rather than a spawning aggregation. Aggregations in wetlands and off-stream waters can create a reservoir of adult Carp that can disperse with the next flooding event.



'Natural' dispersal of Carp occur through the following mechanisms or pathways:

- within channels (longitudinal and lateral)
- overtopping of channels onto floodplains (wide-ranging access)
- drift of eggs (adhesive, so less widespread), larvae and young-of-the-year
- movements of juveniles and adults
- interconnectedness between habitats.

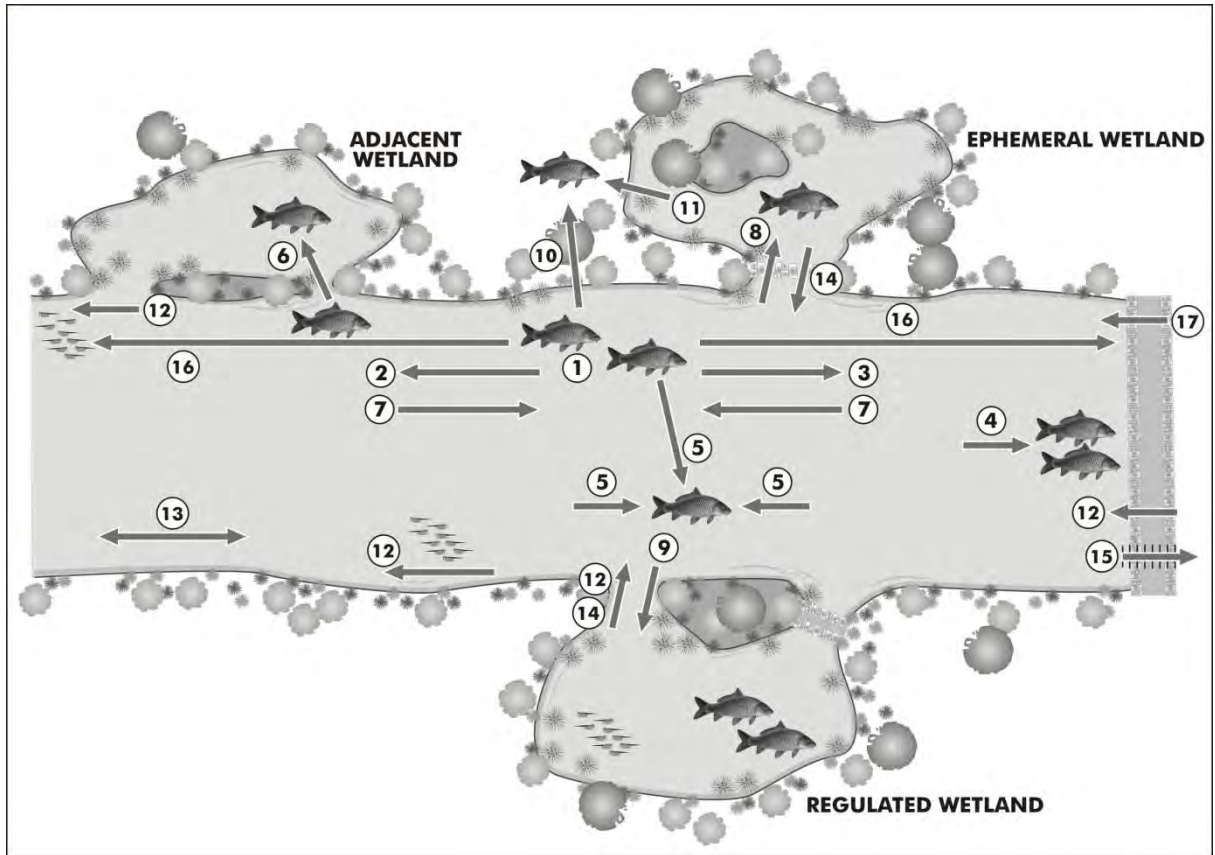


Figure A3.4. A diagram of the different types of movements likely for Carp  
 Descriptions of these movements are given in the accompanying Table A3.2.

Table A3.2. Description of movement types for Carp, as illustrated in Figure A3.4  
Flow types from Figure 3: 1—Cease to flow; 2—Base flow; 3—Fishes; 4—Bankfull; and 5—Overbank.

No.	Description	Life stage	Flow type
1	Local movements	Adult	2
2	Downstream prespawning movement	Adult	3, 4, 5
3	Upstream prespawning movement	Adult	3, 4, 5
4	Riverine movement to below barriers	Adult; subadult	3, 4, 5
5	Prespawning movement to regulated floodplain access points	Adult	4, 5
6	Movement to littoral zone/permanent adjoining wetland	Adult	4
7	Return movements (homing)—upstream or downstream	Adult	2–5
8	Access to floodplain ephemeral channels and wetlands	Adult; subadult	4, 5
9	Access to regulated wetlands	Adult	4, 5
10	Movements from river to floodplain	Adult	4, 5
11	Movements from wetlands to floodplain	Adult	5
12	Downstream larval/young-of-the-year drift	Larvae/young- of-year	5, 4
13	Juvenile recolonisation (upstream or downstream)	Subadult	2–5
14	Adult/juveniles entering river from refuge wetlands	Adult; subadult	4, 5
15	Upstream movement through fishways	Adult	2–5
16	Large-scale interregional movements	Adult	2–5
17	Downstream movements	Adult; subadult	

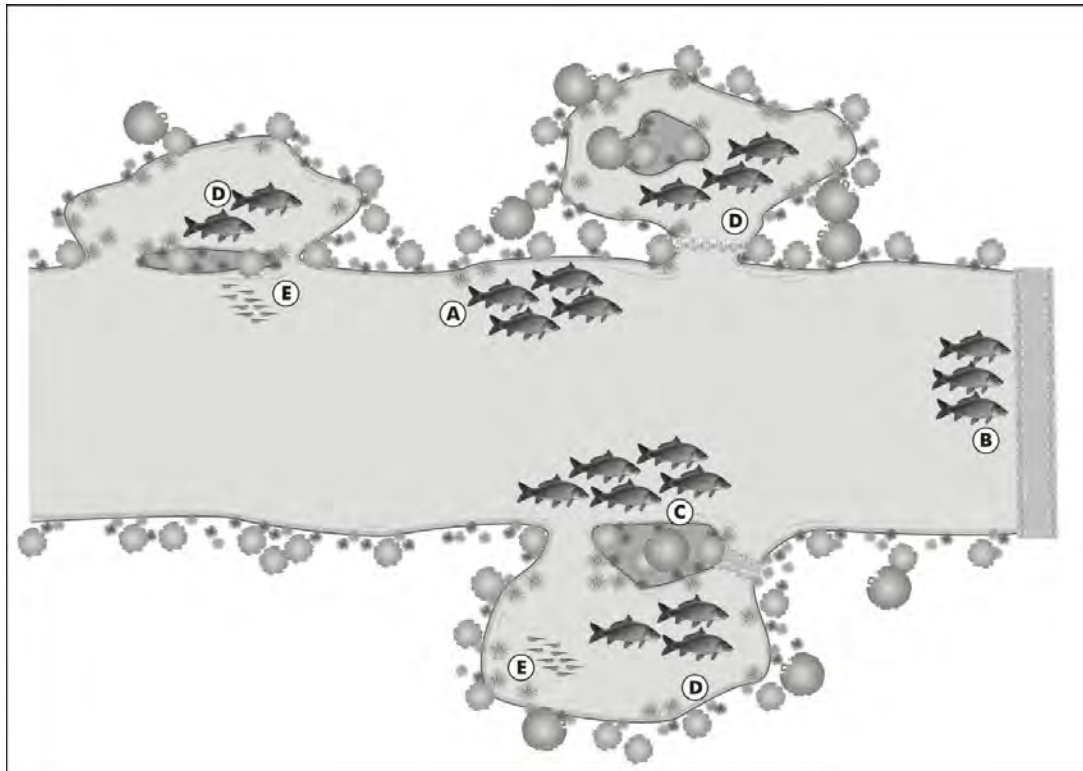


Figure A3.5. A diagram of different types of aggregations for Carp  
 Descriptions of these movements and aggregations are given in the accompanying Table A3.3.

Type	Description
A	Winter aggregations—female-dominated when near wetlands
B	Spring aggregations—female-dominated early, then male-dominated
C	Prespawning aggregation at regulated floodplain access
D	Spawning aggregation in wetlands
E	Accumulations of eggs and larvae in still waters
A	Winter aggregations—female-dominated when near wetlands

Table A3.3. Description of aggregations of Carp as illustrated in Figure A3.5

Like many fishes, most Carp movements occur over relatively small scales, with more occasional larger movements (Crook 2004). Carp are, however, highly mobile compared with many other native species (Koehn and Nicol 1998, in press), and interregional movements regularly occur, with these now being monitored with PIT-tagged Carp moving through Murray fishways (see Baumgartner et al. 2014; Figure A3.6). While movements appear to be seasonal in nature (see Figure A3.6), they can occur throughout the year (Koehn and Nicol 1998; in press). Colder water temperature appears to provide limitations to movement, with little movement through fishways in the colder months of June and July regardless of flows (Figure A3.6). Early in the spawning season, as water temperatures start increasing, some small groups of Carp will move into available wetlands and spawn. Adults appear to move before juveniles. Juvenile movement is

based on dispersal, with young-of-the-year movement off floodplains to upstream and downstream in December to March. This may be dependent on flows, with downstream movements (up to 100 km) being more rapid than those upstream (Stuart and Jones 2006a). The drift of larvae and young-of-the-year is another important downstream dispersal mechanism for the species, the effects of which will depend on flows and the flooding/flushing of larvae from floodplain and riparian habitats.

Movements are also likely to be affected by longer-term components of the flow regime. Data from the Lock 1 fishway was examined to ascertain whether the increase in the relative abundance of Carp observed in 2008–2009 (the most severe part of drought) was caused by fish accumulating downstream due to a non-functional fishway. This appears to be a feasible explanation because passage of Carp increased with increased flows in the following years (Figure A3.6). This data does need to be interpreted with some caution, however, as other factors were also at play. The grey-shaded area in Figure 20 denotes a period when tailwater levels were essentially too low for fish to enter the fishway. This was actually marginal from January 2006 and only got worse until the Denil fishway extension was installed in 2009. Detections of PIT-tagged Carp during the peak migration period were minimal in 2008–2009, indicating that fish could not use the fishway. Consequently, even though we used data from 5–7 km downstream of Lock 1, it is likely that the increase in abundance was in part still due to fish accumulating below the barrier. The PIT reader was also not functioning from December 2010 to June 2011. Thus our conceptual hypothesis would be that fish are making an annual migration from the Lower River and Lakes and were impeded by Lock 1.

An important question remains: ‘what proportion of the Carp population moves?’ Downstream of Lock 1 (river and lakes), 2970 Carp have been PIT-tagged, and there have been 1212 unique PIT-tagged Carp recorded on the Lock 1 PIT reader—41% of the tagged population. This data may have some biases, however, as many of the fish were PIT-tagged at sites immediately downstream of Lock 1 where they were already accumulating while migrating.

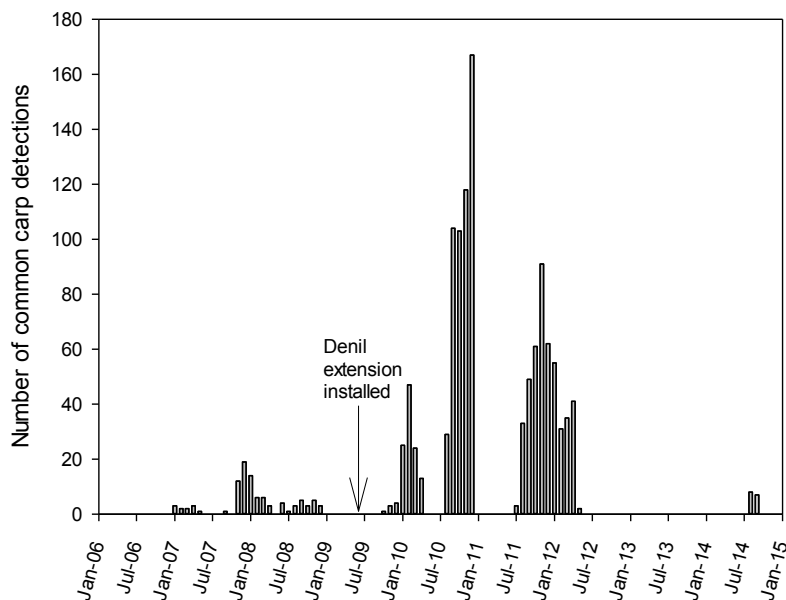


Figure A3.6. Detection of PIT-tagged Carp at Lock 1 fishway (in the Lower Murray River) from January 2006 to January 2015 (Brenton Zampatti, SARDI, unpubl. data)

One of the key concerns is that Carp that leave the river and move onto the floodplain to spawn and recruit may return to add considerable numbers to the metapopulation of the river. Carp are known to move to key spawning areas (Koehn and Nicol 1998; Stuart and Jones 2006a; D. Gilligan, IACRC unpubl. data), so this means that the adult population reaching the wetland may not only have originated from the adjacent river reach, but also have migrated from both upstream and downstream reaches. These adults may then return to their original river positions, along with their offspring (either as larvae or juvenile fish, depending on the time spent in the wetland habitat; Figure A3.7). Due to the greater productivity in the wetland, spawning, survival (recruitment) and growth rates may be higher than in the river (see Section 6.7) and provide a large export of young Carp (Figure A3.8).

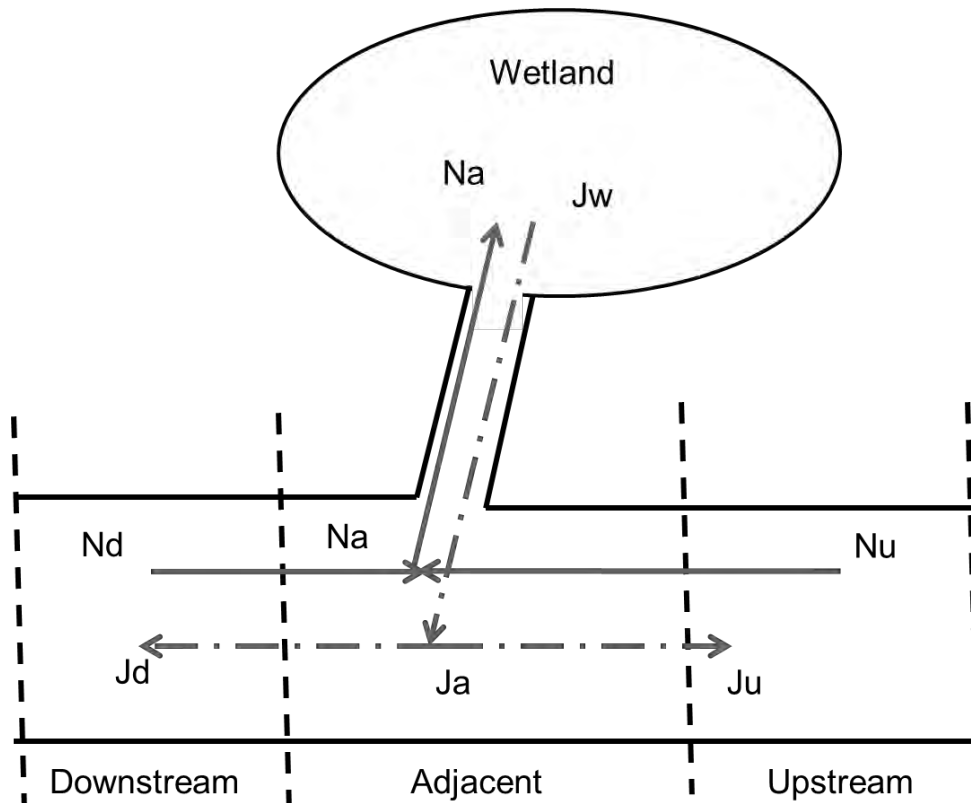


Figure A3.7. Schematic of Carp movements from the river into the wetland to spawn, then the return of adults and juvenile Carp to the river

N = Number of adults, J = number of juveniles. Notations: d = downstream, a = adjacent, u = upstream, w = wetland.

Among Australian native freshwater fish populations, there are occasional examples of movement patterns varying between males and females, most notably in the catadromous Australian Bass (*Percaletes novemaculeata*) and Tupong (*Pseudaphritis urvilli*) (Koehn and Crook 2013). However, there is some evidence that male and female Carp also display variable movements. In a tagging study at Barmah Lake, a major Carp spawning ground, intermediate-sized male Carp moved further than adult males or females, which stayed nearer the spawning habitats (Stuart and Jones 2006a). While at Lock 1 in the Lower Murray River, female Carp with high egg-to-body ratios [gonadosomatic index GSI] are the predominant fish moving through the fishway immediately before the breeding season (2.6 females to 1 male), but this female-

dominated sex ratio declines, along with GSI each month, to a low of 0.61 females to 1 male in April (Conallin et al. 2008; Figure A3.9). From these data it is apparent that female Carp migrate in larger numbers than males (from the riverine area to spawning zones) in the lead-up to spawning and that it is males that dominate movement in fishways post-spawning. These data indicate how reproductive status may influence the movement patterns outlined above.

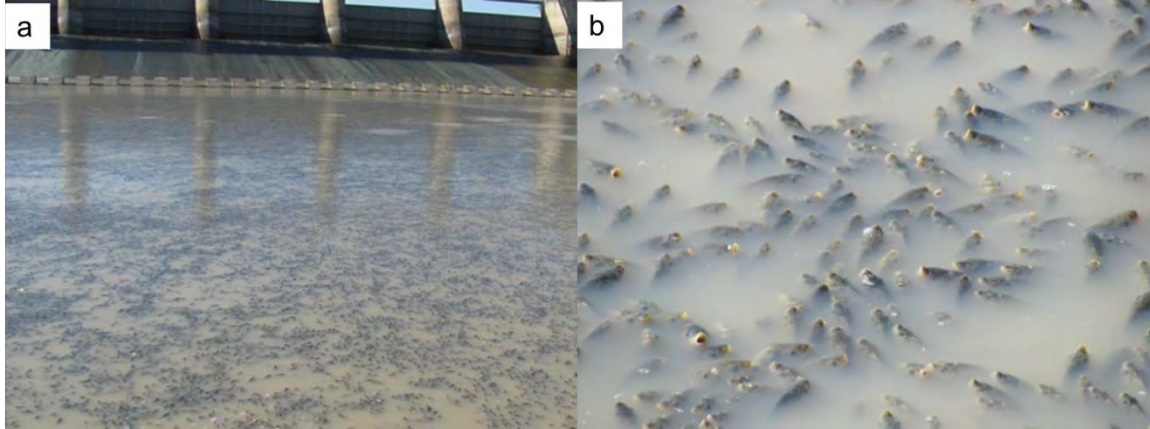


Figure A3.8. Juvenile Carp that may add to the river population from (a) behind a regulator; and (b) on the floodplain (photos provided by Ivor Stuart)

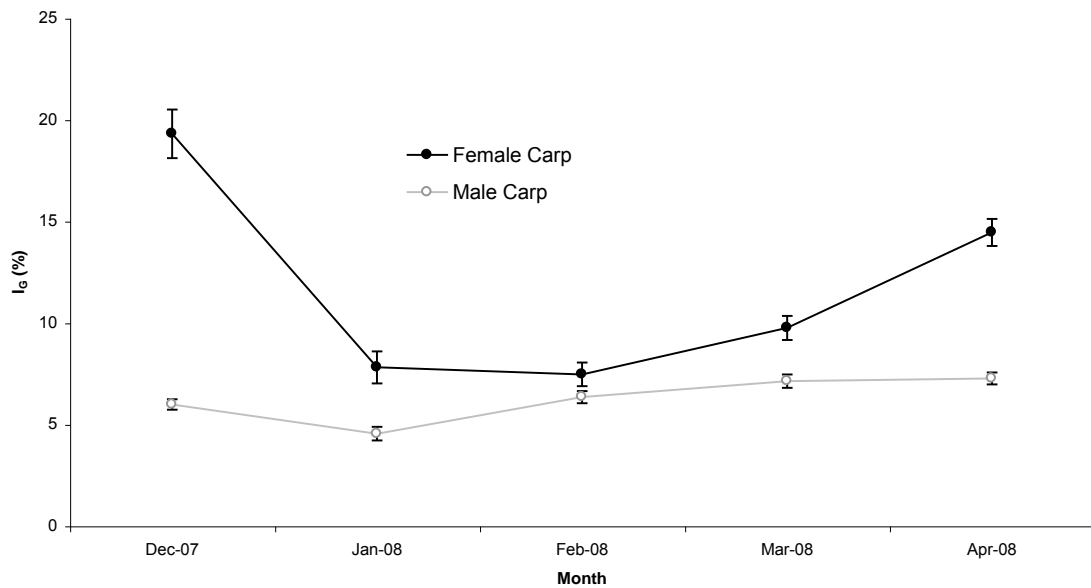


Figure A3.9. Gonadosomatic Index ( $I_G$ ) for male and female Carp collected monthly at Lock 1 fishway from December 2007 to April 2008 (from Conallin et al. 2008)

### A3.7 Seasonality

The general seasonality of issues relating to Carp is illustrated in Figure A3.10. It is recognised that some timing may vary across the range of Carp and that there is also variation in the seasonality for the spawning of large-bodied native species (Murray Cod, Trout Cod, Golden



Perch, Silver Perch), but this figure does illustrate the overlaps that occur and, hence, the difficulty in providing environmental water that avoids certain 'Carp events'. For example, Carp spawning, water temperatures >16°C (approximate threshold for spawning) and movements occur over much of the year.

Event	J	A	S	O	N	D	J	F	M	A	M	J
Pre spawning condition												
Spawning season												
Spawning Movements												
Adult Movements												
Juveniles Movements												
Larvae present												
Spawning aggregations												
Winter aggregations												
Water temp > 16°C												
Spawning large-bodied native fishes												
Spawning small-bodied native fishes												

Figure A3.10. Seasonal assessment of key events in the Carp life cycle

### A3.8 Regional differences

The MDB is large and covers a range of climatic and geomorphic zones that can provide considerable range of conditions for Carp. This is particularly evident for the northern and southern connected MDB, but there is also variation in conditions within the geographic scope of this project—the southern MDB. Examples of differences in rainfall and temperatures are given in Table A3.4, but there are also considerable differences in habitats, including within individual rivers. For example, habitats in the Murray River in the lower reaches have been modified from flowing reaches into a series of lentic weir pools (Walker 2006), which are more likely to favour Carp.



Table A3.4. Mean monthly rainfall and temperature records for three geographical locations within the MDB: St George (Southern Queensland), Albury (Southern NSW) and Murray Bridge (South Australia)

Statistic and location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean monthly rainfall													
St George	88.0	54.0	46.9	33.2	43.2	25.5	33.1	27.2	22.7	43.1	55.4	54.2	533.2
Albury	33.5	48.5	42.3	39.4	48.3	61.9	66.1	64.2	57.0	49.2	62.5	41.3	615.4
Murray Bridge	16.3	18.7	20.4	28.8	35.3	38.6	35.7	36.9	36.5	33.6	25.1	23.8	349.7
Mean monthly temperature													
St George	34.8	33.4	31.7	28.0	23.2	19.8	19.6	22.2	26.6	29.6	31.8	33.7	27.9
Albury	32.2	31.1	27.5	22.4	17.6	14.1	13.2	15.0	18.3	21.5	25.9	29.2	22.3
Murray Bridge	29.2	29.3	26.7	23.5	19.6	16.7	16.2	17.5	19.9	22.9	25.7	27.6	22.9

### A3.9 Habitats

The MDB encompasses a wide diversity of ecosystems and habitats that occur over a range of scales and exist in patches across the landscape. There are many broad habitat types (e.g. river, wetland, permanent, ephemeral), but their amenity to any fish species or life stage depends on the species' requirements at the time, the landscape position, and the habitat area, condition/quality and accessibility (see Koehn and Kennard 2014). At the larger scale, in the southern connected MDB there are a variety of rivers, creeks, anabranches, wetlands and floodplains, and these form a complex mosaic of:

1. *Permanent river channel habitats* (e.g. Murray River); they tend to have a high diversity of habitat, including variable depth and width, instream wood ('snags'), riparian vegetation and aquatic vegetation.
2. *Endorheic rivers*, which drain to a wetland or swamp (Lachlan and Avoca rivers). Endorheic rivers by nature tend to have considerable variation in flow, with long periods of zero flow; they often only connect to the main river catchment in large floods (e.g. 1-in-20-year flood event for the Lachlan to link to the Murrumbidgee).
3. *Wetland mosaics and streams*: include forest flood-runners, billabongs, wetlands and lakes; (usually shallow; <3 m deep) permanent lakes, and irrigation channels. The permanent billabongs are generally deeper than the wetland complexes, with a discrete littoral zone, often with aquatic vegetation.
4. *Dry floodplain* (forest floodplain): provides shallow aquatic habitat only in floods or artificial inundations.

An illustration of the range of habitat types (both natural and constructed, e.g. including the weir pools mentioned above) of the southern connected MDB is given in Figure A3.11. These habitats are considered for each life stage of Carp (see Appendix 2) in the parameterisation of the population model. Descriptions of each habitat type are as follows:

- river wetland—on the adjacent floodplain that may be inundated; may be permanent or ephemeral
- main channel: low flow—inundated at all flows
- main channel: benches—inundated at higher within-channel flows
- connected wetland—permanently connected to the river, e.g. adjacent to weir pools
- weir pools—water impounded behind locks in the Lower and Mid Murray
- regulated wetland—water impoundment controlled by a regulator
- off-channel wetland—with periodic connections
- terminal lakes—permanent Lower Lakes (see Section 4.1.11).

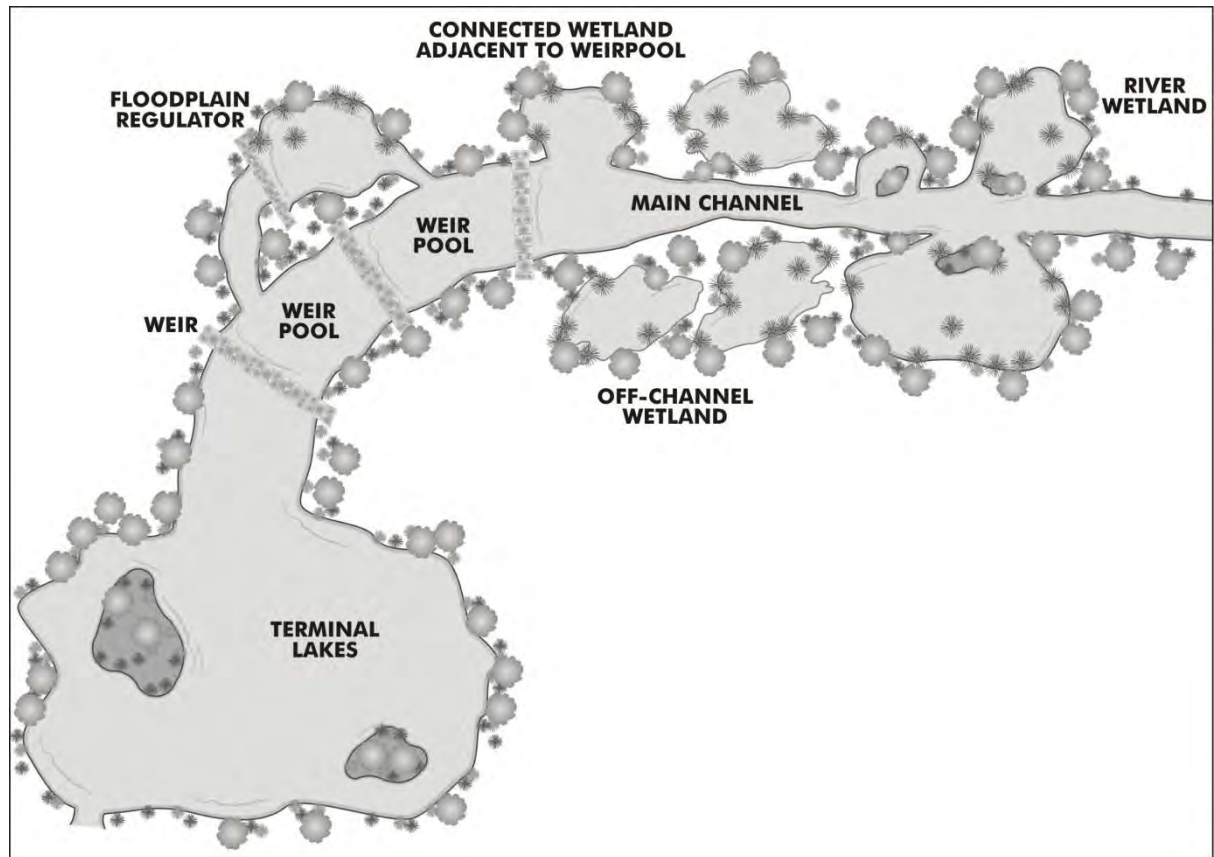


Figure A3.11. The different habitat types identified for Carp in the Murray River

### A3.10 Ecosystem function and processes

There are a range of wider ecosystem functions and processes that can be greatly affected by flows and provide benefits not only to fish directly, but via overriding impacts on the ecosystem. These include biotic processes (such as productivity, recruitment, connectivity) and abiotic processes (such as hydrology and geomorphic changes). For example, productivity, or the supply of organic carbon (from algae and photosynthetic microorganisms, submerged and emergent aquatic plants or terrestrial plant litter) provides the energy source for living organisms and may influence the carrying capacity of a fish population.

### A3.11 Refugia

Fish that survive in refugia can recolonise and repopulate when conditions become more favourable. This type of ecology is common in temporary rivers (Hermoso et al. 2013; Kerezszy et al. 2013), but also applies to off-stream or isolated waters such as floodplain billabongs (from which resident Carp populations may be able to re-enter the main river system). Resident refuge populations can also provide a reproductive stock from which wider populations can recover when flows are available (see Figure A3.7).

### A3.12 Flow regimes

The flow regime is made up of a series of components (Figure A3.12), which can have considerable variability over both the short and longer term (see Figure A3.13). These components can affect each stage of a fish's life cycle differently (see Figure A3.1), and the quantity, timing and quality of flows can all have differing impacts; it is necessary to understand these when delivering environmental water (Bunn and Arthington 2002). EWAs can be used to restore these components to existing flows (e.g. flow peaks and variation), or to meet a particular watering objective for native biota (e.g. a movement cue). These components of the flow regime also enable a range of riverine ecological functions and processes to support fish populations.

There is an intimate connection between the impacts of a flow volume, the channel morphology (capacity) and the hydrodynamics (velocity, turbulence) at any particular site. While water delivery is measured in volumes, it is the water height (e.g. river rise; bankfull; height to fill for wetlands) that is usually more meaningful to fish responses. The differences in the volume of water needed to elicit the same height response at different river sites (especially progressing downstream) need to be accounted for when delivering flows for ecological outcomes. For example, bankfull in the Mid Murray (Barmah) is ~8000 ML/day, with large floodplain inundation at >11,000 ML/day (Figure A3.13a), whereas bankfull in South Australia is ~40,000 ML/day (Figure A3.13b).

The differing types of flow levels that are likely to be considered as EWAs are illustrated in Section 2, Figure 3. Each of these flows may impact Carp in different ways (see Section 2, Table 1). Large overbank flows will rarely be an objective of EWAs, although they may be used to prolong natural high flows and create within-channel flow pulses. Bankfull flows may cause flooding of some smaller wetlands, and artificial floodplain inundations may occur through the use of floodplain regulators. While EWAs may be considered to be 'controlled', it must be remembered that the flow regime also consists of many 'uncontrolled' events (especially larger floods), to which Carp are also likely to respond strongly. Environmental water often builds on or extends other natural flow events, including overbank flooding (see King et al. 2010). Thresholds, such as height to fill levels for access to wetlands and overbank flooding need to be assessed on an individual site basis. Flow sequences and variable river flows (see Figures A3.12, A3.13) also need to be taken into account. Flows delivered down the main channel are often forgotten, and these are important because they potentially affect a large number of sites as they progress downstream. Multiple effects can be achieved at multiple sites if the flow pulse is preserved as it travels downstream. Water that inundates the floodplain can also provide benefits to the in-channel ecosystem if it is returned to the river channel. Works and measures such as the use of floodplain regulators and pumping can provide floodplain inundations, but not many of the other attributes of a natural flood (see Koehn et al. 2014a).

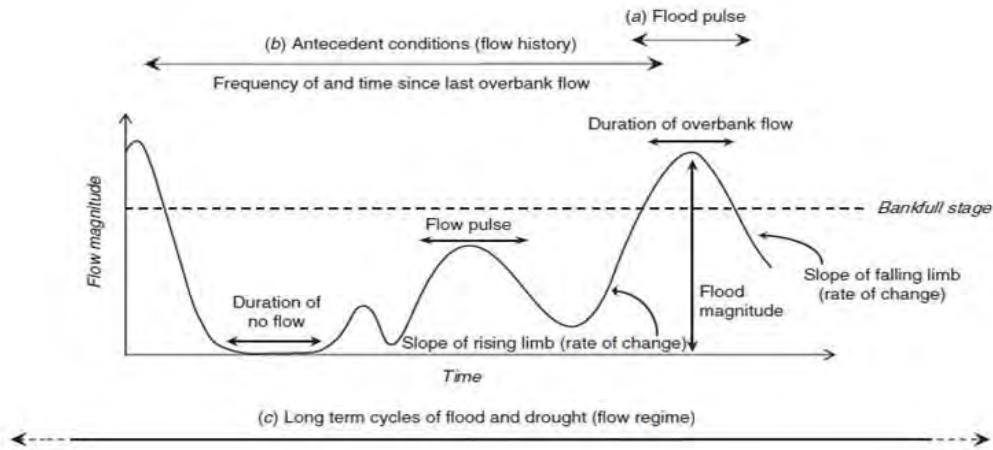


Figure A3.12 Components of a flow regime

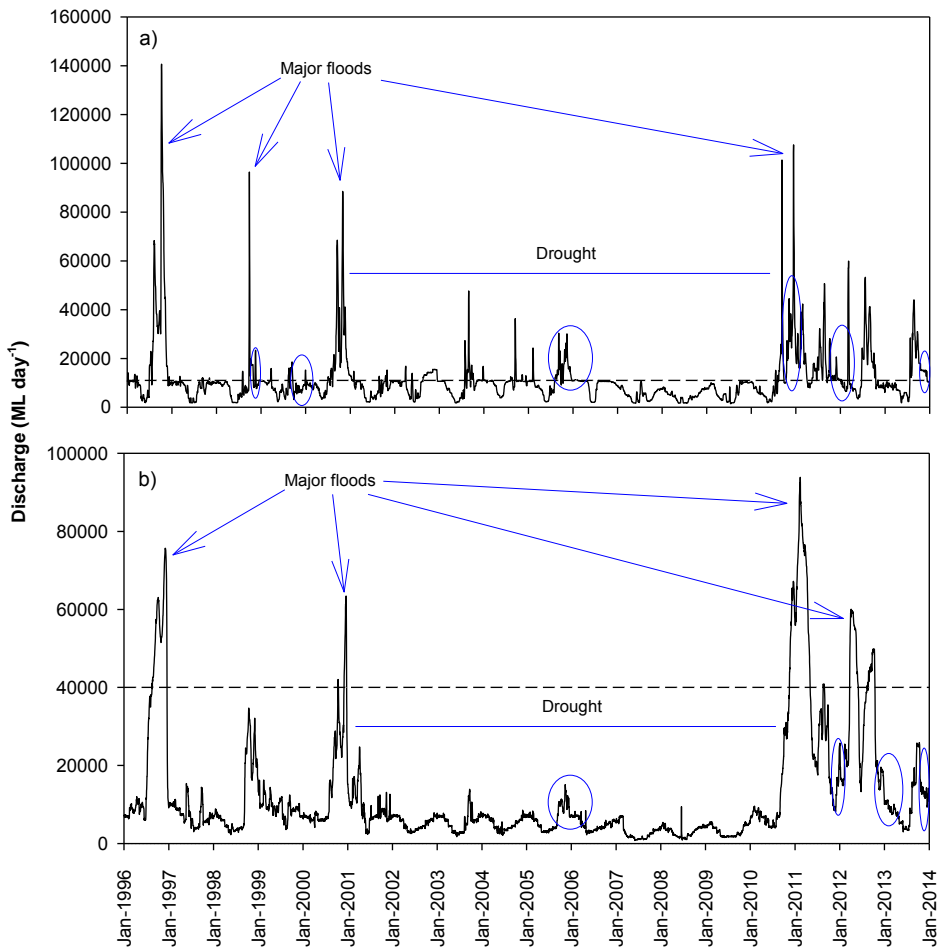


Figure A3.13 Mean daily discharge (ML/day) at (a) Yarrawonga, Mid Murray River, and (b) the Lower Murray River at the South Australian border from January 1996 to January 2014. Bankfull flow is represented by a dotted line for the Mid Murray (11,000 ML/day) and Lower Murray at the South Australia border (40,000 ML/day). Environmental water allocations (EWAs) are indicated by circles.

## Appendix 4 Proforma Carp management plan

Given the variation in approaches to Carp management plans and the major gaps for site-specific plans at high priority sites (e.g. MDB-wide Carp management plan, Barmah–Millewa, Koondrook–Perricoota, Lower Lakes, Darling River), this project has included the following proforma structure that may be used to facilitate the development of future plans.

### 4.1 Background material

Collate and review background material, existing documents/case studies, hydrological data and site-specific information regarding Carp population dynamics to inform the management plan and to assist in developing a site-specific conceptual model and the use of a Carp population model, where this is useful for quantifying differences in outcome or for selecting between management options.

### 4.2 Identify ecological assets

Clearly identify the values of the site (e.g. native fish, water quality, aquatic vegetation) that may be impacted by Carp and then define the management goals for restoration of the site (e.g. sustained reduction of Carp biomass from 400 to 100 kg/ha). This goal will be fundamental for developing and evaluating the on-ground Carp interventions and the overall management plan.

### 4.3 Carp population conceptual model

Develop a site-specific conceptual model of Carp spawning and recruitment that may result from managed and natural floodplain inundation at the proposed watering site. Where possible, the model should utilise site-specific data (i.e. Carp population dynamics, hydrological data, local fish survey data, stakeholder observations) and consider the broader responses of Carp to any watering event (e.g. on a river-reach scale). The use of schematic diagrams as illustrated in our case studies (Section 7) may be useful in this process.

### 4.4 Hydrodynamic/inundation modelling

The hydrology of the site should be examined using a hydrodynamic model that includes the influence of current and future flow management on Carp behaviour and recruitment. The model should consider various flow components (Appendix 3, Figure A3.12), the level of inundation associated with each band (e.g. Section 7.1, Table 9), and the suitability of the inundated area for Carp spawning and recruitment (Appendix 2). The model should aim to identify and compare areas that are likely to increase spawning and recruitment opportunities for Carp (e.g. shallow, slow-moving water) under each type of flow. The model should be used in conjunction with the Carp population dynamics model (see below) to predict the likely responses of Carp, at this event scale, to natural floods and managed inundations, and to quantify and inform the appropriate control action (if required).

## 4.5 Carp population dynamics modelling

Develop a Carp population model to determine how Carp may respond to proposed water scenarios within the targeted system. This model should be linked to the hydrodynamic/inundation model (see above) and consider the scale of associated ecological processes, type and quality of available habitat, connectivity, seasonal movement patterns and population dynamics, including: distribution; abundance; structure; carrying capacity; and temporal and spatial changes in relation to habitat and landscape requirements.

## 4.6 Risk assessment

Undertake an assessment of risks and apply to proposed watering scenarios. Ideally, the analysis of risks should be based on the Australian Standards (Standards Australia 2004), which have been used recently to guide management decisions concerning Carp control and environmental watering (Mallen-Cooper et al. 2011; SMEC 2013; see Section 7).

## 4.7 Workshop

Conduct a workshop with the aim of refining and applying the Carp conceptual model and population dynamics model to the hydrodynamic modelling scenarios with the following specific objectives:

- Ensuring representation from a broad range of stakeholders, including: scientists, natural resource managers, water management agencies and community groups.
- Identifying the existing Carp population biomass or abundance (e.g. 400 kg/ha) and clearly defining the project goals that will reduce Carp impacts (e.g. sustained biomass reduction to 100 kg/ha through limiting spawning and recruitment).
- Identifying the range of potential operational, hydrological and physical management options for controlling Carp.
- Identifying any constraints to on-ground actions, such as unwanted impacts on native fish.
- Identifying high-priority geographic areas for management action based on both Carp biology and management levers (e.g. floodplain regulators).
- Collating information on site characteristics, flows (including sequences) and Carp populations.
- Assessing the range of management options and potential practicality, effectiveness and viability of reducing Carp recruitment, population size and impacts.
- Identifying any previous evidence for the success of these management options.
- Assessing the preferred Carp management techniques for potential impacts on other floodplain biota (including native fish) or floodplain processes.
- Recommending the most applicable Carp control measures to maximise the potential for achieving the project objectives.
- Developing an initial costing for implementing and evaluating management actions.
- Assessing information on the implementation of Carp control measures—identifying the most appropriate spatial and temporal scales, and potentially suitable locations.
- Providing cost estimates for the implementation of the recommended measures.



- Briefly identifying key monitoring and evaluation criteria for measuring fish population response.
- Refining risk assessment based on the results of the stakeholder workshop.

## 4.8 Report

Report on likely Carp responses to the proposed watering scenarios and identify appropriate Carp management measures by:

- Providing Carp population dynamics and hydrodynamic/inundation model output for proposed watering scenarios.
- Identifying the risks associated with each scenario.
- Identifying the range of potential management options, including operational (e.g. timing, duration, rates of flooding) and physical (e.g. use of barriers, retention in deflation basins, traps, fishways).
- Providing information on the potential of these measures to prevent recruitment and/or reduce population size.
- Providing advice on the effectiveness and viability of these measures.
- Developing a detailed design and costing for implementing and evaluating management actions, including the appropriate monitoring regimes.
- Providing an assessment of impacts of preferred control measures on other floodplain biota (including native fish) or floodplain processes.
- Providing a detailed description of the most applicable measures, including evidence for their success.
- Providing detailed information on the application of the recommended measures, including information on appropriate spatial and temporal scales for implementation and the identification of physical locations or location types where they would be most suited.
- Developing and setting Carp population thresholds (e.g. 100 kg/ha) and targets for maintenance/restoration of natural assets (e.g. native fish populations, water quality or aquatic plants).
- Providing evidence of how the proposed control measures minimise the risks associated with the delivery of water.

## Appendix 5 Site-specific Carp management plans reviewed

Table A5.1. Site-specific Carp management plans reviewed

\*This is a site management plan that is not Carp-specific. However, it does mention Carp management in brief throughout the report.

Authors	Location	Hydrology scenarios	Carp management	Other considerations	Key recommendations
Stuart and Mallen-Cooper (2011)	Pike–Mundic Floodplain Complex, Murray River, South Australia (7000 ha)	<ol style="list-style-type: none"> <li>Existing conditions (i.e. no change from 7000 ML/day entitlement flow to South Australia)</li> <li>Natural flood (50,000 ML/day)</li> <li>Managed inundation for 120 d (1000 ML/day inflow)</li> </ol>	Discusses operational (e.g. timing, duration and rates of flooding), physical (e.g. barriers, drying, traps) and 'blue-sky' (e.g. daughterless Carp) control/eradication methods and associated costs	<ul style="list-style-type: none"> <li>Conceptual model of Carp life history within the Pike–Mundic complex (primarily derived from Chowilla Floodplain Carp data)</li> <li>Potential risks and benefits for native flora and fauna</li> <li>Broader catchment scale impacts associated with localised Carp recruitment</li> </ul>	<p>Utilise operational strategies to disadvantage Carp spawning/recruitment while maintaining/enhancing the habitat/hydrological conditions for native fish:</p> <ul style="list-style-type: none"> <li>operate regulators to maintain a mosaic of flow habitats</li> <li>reduce frequency of managed inundations, but take advantage of natural floods</li> <li>prioritise managed inundations for winter, but seek to understand broader ecological consequences</li> <li>plan for managed recession before water temperatures reach ~15°C</li> <li>adopt operational regimes that maximise flowing water habitats.</li> </ul> <p>Physical interventions are not recommended until baseline knowledge gaps regarding basic Carp biology are filled.</p> <p>Implement a monitoring framework to gather basic information to inform future changes in hydrology and management.</p>

Authors	Location	Hydrology scenarios	Carp management	Other considerations	Key recommendations
Stuart et al. (2011)	Chowilla Floodplain, Murray River, South Australia (~17,700 ha including anabranch and floodplain systems)	<ol style="list-style-type: none"> <li>1. Within-channel stable flows (7000 ML/day entitlement flow to South Australia)</li> <li>2. Natural flood (e.g. 30,000 ML/day)</li> <li>3. Managed inundation (&gt;75% flowing water retained)</li> <li>4. Managed inundation (&lt;25% flowing water retained)</li> </ol>	Discusses operational (e.g. timing, duration and rates of flooding), physical (e.g. barriers, drying, traps) and 'blue-sky' (e.g. daughterless Carp) control/eradication methods and associated costs	<ul style="list-style-type: none"> <li>• Conceptual model of Carp life history within the Chowilla Floodplain</li> <li>• Potential risks and benefits for native flora and fauna</li> <li>• Broader catchment scale impacts associated with localised Carp recruitment</li> <li>• Carp spawning hotspots within the system</li> </ul>	<p>Utilise operational strategies to disadvantage Carp spawning/recruitment while maintaining/enhancing the habitat/hydrological conditions for native fish:</p> <ul style="list-style-type: none"> <li>• reduce frequency of managed inundations (1 in 10 years rather than 1 in 2 or 1 in 4) to reduce opportunities for Carp spawning and recruitment</li> <li>• take advantage of any natural flooding at the river reach scale to flood Chowilla, to optimise benefits for native fish species considered at risk</li> <li>• for a managed inundation, operate the Chowilla environmental regulator to prioritise winter inundation</li> <li>• plan for managed recessions before water temperature reaches ~15°C</li> <li>• adopt a managed operating regime that maximises flowing water habitat (Mallen-Cooper et al. 2011).</li> </ul> <p>Physical interventions are not recommended until baseline knowledge gaps regarding basic Carp biology are filled. If future monitoring indicates physical control is applicable, then it is recommended to trial exclusion techniques, desiccation, and tracking Judas Carp to determine exploitable behaviours. The application of any physical control techniques should be applied in a monitored adaptive management framework.</p>

Authors	Location	Hydrology scenarios	Carp management	Other considerations	Key recommendations
Stuart (2009)	Yatco Lagoon, Murray River, South Australia  (~346 ha over two lagoons)	N/A (see 'Other considerations')	Discusses physical control methods (e.g. screens, wetting/drying, traps)	<ul style="list-style-type: none"> <li>Hydrological scenarios were only related to fish passage and management of Carp screens in low and medium flows; removal of Carp screens when high flow events occur was also suggested</li> <li>Conceptual model of Carp life history in Yatco Lagoon—indicating potential control strategies for each of the species' life stages</li> <li>Potential risks and benefits for native flora and fauna</li> </ul>	<ul style="list-style-type: none"> <li>Major emphasis on Carp control rather than total eradication.</li> </ul> <p>Two key recommendations:</p> <ul style="list-style-type: none"> <li>minimise the number of adult and subadult Carp entering and exiting the wetland system</li> <li>minimise the damage to wetland values by adult Carp.</li> </ul> <p>Three main strategies were implemented to achieve these recommendations:</p> <ul style="list-style-type: none"> <li>screens to exclude adult and subadult Carp (&lt;250 mm TL) in low to moderate flows; removal of screens in periods of high flow</li> <li>introduction of wetting and drying schemes</li> <li>harvesting of Carp aggregations at regulators using William's Carp separation cage.</li> </ul>

## Managing flows and Carp

Authors	Location	Hydrology scenarios	Carp management	Other considerations	Key recommendations
Stuart et al. (2010)	Murrumbidgee Demonstration Reach (UMDR)  Bredbo, NSW to Casuarina Sands, ACT (~100 km)	N/A (see 'Other considerations')	Discusses physical control methods (e.g. screens, traps, electrofishing, Judas Carp, netting, recreational fish-outs, chemical poisoning, wetting/drying, bio-manipulation, aquatic restoration, introduction of diseases and 'blue-sky' (e.g. daughterless Carp) techniques)	<ul style="list-style-type: none"> <li>Hydrological scenarios were only described as low to moderate flows maintained throughout the year, with floods occurring occasionally at varying magnitudes</li> <li>Conceptual model of Carp life history in the UMDR— indicating potential control strategies for each of the species' life stages</li> <li>Potential risks and benefits for native flora and fauna</li> </ul>	<p>The overall aim is to rejuvenate native fish communities and aquatic vegetation via the targeted reduction of Carp.</p> <p>More specifically:</p> <ul style="list-style-type: none"> <li>promote community awareness</li> <li>investigate the effectiveness of various control techniques (e.g. Carp separation cages on regulators)</li> <li>record targeted and sustained reduction of Carp abundance via monitoring and evaluation programs</li> <li>limit Carp recruitment without negatively impacting native fish recruitment</li> <li>gain a better understanding of Carp movements and population dynamics via tracking and evaluation programs.</li> </ul>

Authors	Location	Hydrology scenarios	Carp management	Other considerations	Key recommendations
Braysher et al. (2009)	Dewfish Demonstration Reach, Condamine River, Queensland (~90 km reach)	N/A	<ul style="list-style-type: none"> <li>• Manage the impacts and abundance of alien species populations (specifically Carp) via the application of physical control mechanisms (e.g. Carp screens, traps) and water level manipulation</li> <li>• Limit the potential for reinfestation from likely sources within the reach</li> <li>• Reduce the likelihood of further human-assisted invasions of Carp and other species (community awareness)</li> </ul>	<ul style="list-style-type: none"> <li>• Potential risks and benefits for native flora and fauna</li> </ul>	<ul style="list-style-type: none"> <li>• Water level manipulations of managed weir pools where possible during active spawning.</li> <li>• Carp exclusion from emergent vegetation to reduce access to spawning habitat.</li> <li>• Carp trapping at remediated weirs (modified to allow fish passage).</li> <li>• Permanent in-stream traps that utilise bait (grain), but prevent bycatch of waterbirds or native species.</li> <li>• Bio-manipulation—stocking with large-bodied native fish could reduce spawning success.</li> <li>• Netting program and use of Judas Carp to target spawning aggregations.</li> <li>• Community awareness programs (broader community, schools and recreational groups, e.g. angling clubs).</li> <li>• Implementation of Carp disposal bins.</li> <li>• Monitoring programs for identifying Carp hotspots within the catchment.</li> </ul>

Authors	Location	Hydrology scenarios	Carp management	Other considerations	Key recommendations
Stuart (2012)	Edward–Wakool system (~500 river-km; 1000 square kilometres between the Murray and Edward rivers)	N/A	<p>Carp management in the Edward–Wakool region is:</p> <ol style="list-style-type: none"> <li>operational (e.g. flow management) and/or</li> <li>intervention-based (e.g. Williams’ Carp separation cages on fishways and regulators).</li> </ol> <p>The three major objectives are to:</p> <ol style="list-style-type: none"> <li>minimise opportunities for spring/summer floodplain spawning by adult Carp (intervention/operational)</li> <li>maximise flowing water habitats, which are preferred by native fish (operational), and</li> <li>minimise damage by adult Carp on riverine/wetland values (intervention/operational).</li> </ol>	<ul style="list-style-type: none"> <li>Potential risks and benefits for native flora and fauna</li> <li>Conceptual model of Carp life history in the Edward–Wakool system</li> <li>Identification of key knowledge gaps associated with Carp management specifically for the Edward–Wakool area (e.g. identifying Carp spawning habitats and timing/location of Carp aggregations)</li> </ul>	<p>Operational control methods recommended:</p> <ul style="list-style-type: none"> <li>bio-manipulation (recovery of native predatory fish via the synchronisation of flow spikes in known spawning periods)</li> <li>reduce frequency of blackwater events</li> <li>rate of recession (floodplain draining of Carp breeding areas to expose and kill eggs)</li> <li>rate of recession (draining of wetlands and floodplains to strand and kill adult Carp).</li> </ul> <p>Intervention control methods recommended:</p> <ul style="list-style-type: none"> <li>electrofishing removal</li> <li>cage trapping in regulators</li> <li>Judas Carp tracking programs</li> <li>netting key Carp habitats and aggregations (commercial fishing techniques)</li> <li>screens on wetlands</li> <li>exclusion barriers (e.g. sonic and electrical barriers, bubble curtains)</li> <li>chemical poisoning (e.g. rotenone)</li> <li>diseases</li> <li>molecular and biological control (e.g. ‘daughterless’ Carp technology, lethal genes, sterile offspring).</li> </ul>



Authors	Location	Hydrology scenarios	Carp management	Other considerations	Key recommendations
Braysher et al. (2008)	Tahbilk Lagoon, Victoria (162 ha)	N/A	<ul style="list-style-type: none"> <li>Discusses some physical control techniques and promotes an integrated approach to Carp control</li> <li>Recommends the use of flow to benefit native catfish and is suggestive of how flows can be delivered to disadvantage Carp</li> </ul>	<ul style="list-style-type: none"> <li>Generalised conceptual model of Carp life history, including potential control strategies for each stage; potential risks and benefits for native flora and fauna</li> </ul>	<ul style="list-style-type: none"> <li>Use a mobile Williams' Carp separation cage to target various migration bottlenecks (i.e. road crossing, flow-control structures); institute formal monitoring, reporting, maintenance, and Carp disposal program. Collect baseline data for native fish. Formalise responsibilities for daily operation.</li> <li>Develop sophisticated flow-control options for restoring flows to the lagoon while limiting Carp recruitment and maximising benefits for native fish ecology. Install Carp vertical screens in flow-control structures.</li> <li>Utilise an adaptive management approach to account for the flexible life history of Carp and demonstrate Carp management approaches to the community.</li> <li>Implement a monitoring and evaluation program that will demonstrate the effects of Carp management. This should include the installation of PIT tag readers and the development of a small multi-agency team to lead restoration initiatives.</li> </ul>
*DSE (2003b)	Hattah–Kulkyne Lakes Ramsar Site (955 ha in 12 lakes)	N/A	Considers restriction of Carp entry	N/A	<p>Recommendation presented as a management objective:</p> <ul style="list-style-type: none"> <li>investigate the effectiveness of mechanisms for restricting the entry of Carp, while allowing native fish to enter Hattah Lakes via Chalk Creek, with a view to selecting a cost-effective control mechanism.</li> </ul>

## Managing flows and Carp

Authors	Location	Hydrology scenarios	Carp management	Other considerations	Key recommendations
*DSE (2003a)	Gunbower Forest Ramsar Site  (Ramsar site ~19,450 ha, with wetlands covering ~9,855 ha)	N/A	N/A	N/A	<p>Recommendations presented as management objectives:</p> <ul style="list-style-type: none"> <li>• prepare and implement priority plant and animal control programs in accordance with the Mid Murray Forest Action Plan and strategies and Action Plans developed by the CMA</li> <li>• coordinate pest plant and animal control efforts with adjacent landholders and management agencies.</li> </ul>
*Riverine Recovery Program: van Uitregt (2014) (DEWNR)	Beldora–Spectacle Lakes, South Australia  (Management area: 1965 ha; wetland area: 287.8 ha)	A 5-year wetland wetting and drying plan is presented	Considers restriction of Carp entry and timing of wetting/drying cycles of the wetlands to restrict Carp recruitment, but at the same time promote native fish recruitment	Potential risks and benefits for native flora and fauna associated with wetting/drying cycles and the application of the proposed Carp screens	<ul style="list-style-type: none"> <li>• Implementation of optimised fish screens with integrated one-way gates (push traps) at each of the inlet/outlet regulators.</li> <li>• Wetting and drying cycles over a 5-year period to be implemented in order to restrict Carp recruitment and promote native fish and vegetation recovery.</li> </ul>

Authors	Location	Hydrology scenarios	Carp management	Other considerations	Key recommendations
*Department of Environment, Water and Natural Resources (Berri): Scott and Sutor (2012)	Pilby Wetland Complex (Pilby Lagoon: 10.8 ha; Pilby Creek: 33 ha; Lock 6 depression: 5 ha)	A 5-year wetland wetting and drying plan is presented	Considers restriction of Carp entry and timing of wetting/drying cycles of the wetlands to restrict Carp recruitment	Potential risks and benefits for native flora and fauna associated with wetting/drying cycles and the application of the proposed Carp screens	Maintain or improve the diversity and abundance of native fish and reduce the abundance of introduced fish species via: <ul style="list-style-type: none"> <li>• implementation of a hydrological regime (wetting/drying) that incorporates variable hydrology in order to promote food production, support the establishment and improvement of habitat condition and support recruitment of native fish</li> <li>• operate and maintain current Carp screens on the inlet structure that are of the vertical 'jail bar' style, whereby allowing large-bodied native species, e.g. Bony Herring (<i>Nematalosa erebi</i>) to enter the wetland, but exclude Carp</li> <li>• Implementing a monitoring program to assess the best time of year for wetting/drying cycles of the wetland so as to determine when spawning and recruitment is most predominant.</li> </ul>
*Riverine Recovery Program (DEWNR 2013)	North Caurnamont (~62 ha)	A 5-year wetland wetting and drying plan is presented	Considers restriction of Carp entry and timing of wetting/drying cycles of the wetlands to restrict Carp recruitment, but at the same time promote native fish recruitment	Potential risks and benefits for native flora and fauna associated with wetting/drying cycles and the application of the proposed Carp screens	<ul style="list-style-type: none"> <li>• Implementation of optimised fish screens with integrated one-way gates (push traps) at each of the inlet/outlet regulators.</li> <li>• Wetting and drying cycles over a 5-year period to be implemented in order to restrict Carp recruitment and promote native fish and vegetation recovery.</li> </ul>

## Appendix 6 Description of Carp management mechanisms

Table A6.1. Description of Carp management mechanisms

Management mechanism	Description
Exclusion screens (French et al. 1999, Hillyard et al. 2010)	<ul style="list-style-type: none"> <li>• Vertical jail bar configuration (10 mm) with apertures between the bars of 31 mm.</li> <li>• Specifically designed to restrict movements of Carp <math>\geq 250</math> mm TL (body width <math>&gt;31</math> mm), but will restrict movements of any species with similar or larger body dimensions. Notwithstanding, the vast majority of small-bodied native species can pass through these screens.</li> <li>• To mitigate or minimise restrictions on the passage of native species, a strong understanding of the movement patterns and size range of the resident fish assemblage is required.</li> <li>• Flow control structures are required and screens are fabricated from galvanized steel, which may be aesthetically unpleasing.</li> </ul>
Jumping and pushing traps (Stuart et al. 2006; Thwaites et al. 2010)	<ul style="list-style-type: none"> <li>• Designed to separate Carp from native species by exploiting the innate jumping and pushing behaviour of Carp. Native species have not been observed displaying these behaviours.</li> <li>• Most effective when targeting annual migrations between river channels and off-channel habitat.</li> <li>• Requires cages and infrastructure to mechanically lift and empty captured fish, hence, expensive and aesthetically unpleasing.</li> <li>• Given that very few Carp were captured during the present survey, this control method may not be cost effective.</li> <li>• Push traps may have application for allowing large Carp to exit the wetland and not return. This will require further investigation.</li> </ul>
Targeted harvesting	<ul style="list-style-type: none"> <li>• Electrofishing, netting (fyke, gill) and trapping (box traps).</li> <li>• Unlikely to eradicate all invasive species, but will aid in controlling/reducing numbers.</li> <li>• Depending on the level of effort required to achieve a satisfactory reduction in the biomass of invasive species, this may be an expensive option.</li> <li>• Although there may be some native species bycatch, these fish can be release unharmed.</li> </ul>

Management mechanism	Description
Wetland draining/drying	<ul style="list-style-type: none"> <li>• Draining and drying can be extremely effective in eradicating invasive species.</li> <li>• Not species-specific, so will destroy native species.</li> <li>• A draining cycle is required for Carp screens to be effective.</li> </ul>
Water level manipulations (Shields 1957; Yamamoto et al. 2006)	<ul style="list-style-type: none"> <li>• Used to expose and desiccate eggs, which are deposited on fringing vegetation.</li> <li>• Can be effective for Carp, which spawn on submerged vegetation.</li> <li>• Requires flow and water level control structures.</li> <li>• Timing of manipulations is critical because there is the potential to impact native species spawning.</li> </ul>
Disconnection	<ul style="list-style-type: none"> <li>• Disconnect the wetland at the inlet and utilise fish-smart irrigation off-take techniques to pump water into the wetland (irrigation pumps and fine-mesh self-cleaning foot valve strainers capable of pumping up to 16 ML/day: <a href="http://www.sure-flo.com/scs_page.html">http://www.sure-flo.com/scs_page.html</a>)</li> <li>• Off-the-shelf technology in wide-scale use throughout the USA.</li> <li>• Will stop large- and small-bodied fish (native and invasive) from entering the wetland.</li> <li>• Depending on the mesh utilised and the time when pumping occurs, there may still be some potential to introduce eggs and larvae, but these will likely be destroyed in the pump—this will need to be monitored and managed to minimise or mitigate the risk.</li> <li>• Potential issues with the mesh basket becoming fouled with entrained debris/fish; hence, regular cleaning is necessary. This can be minimised by using relatively low- to medium-flow pumps, by positioning of the off-take, by managing the delivery of water to avoid high-debris loads (e.g. after high-rainfall events) and by installing a fine-mesh self-cleaning foot valve strainer.</li> </ul>
Tracking Judas Carp (Inland Fisheries Service 2008)	<ul style="list-style-type: none"> <li>• Has been shown to be effective in controlling Carp in Tasmania because the behaviour of tracked Judas fish mirrors that of untagged fish, thereby permitting focused harvesting efforts.</li> <li>• Requires expertise for surgical implantation of tags into Judas tracking fish and specialised tracking equipment.</li> <li>• Can provide good movement and habitat association data.</li> <li>• Tag weights should be &lt;2% of body weight; therefore, there is limited application with small-bodied species.</li> <li>• Can be expensive.</li> </ul>

Management mechanism	Description
Chemical piscicides such as rotenone (Sanger and Koehn 1997; Clearwater et al. 2008)	<ul style="list-style-type: none"> <li>• Can be extremely effective at eradicating invasive species; however, it is not species-specific and will destroy native species.</li> <li>• Native species rescue should be considered. Fish can be removed prior to draining, stored in culture facilities and released once the chemical has been neutralised.</li> <li>• Will require large quantities of chemicals and potentially several applications, so can be expensive; however, may have some application if the wetland is drained down to a single pool or a series of isolated pools.</li> <li>• Wetland will need to be isolated and residual chemical treated to avoid downstream mortalities.</li> <li>• Requires specialised training and permits.</li> <li>• May be difficult to acquire permits due to the presence of native species.</li> </ul>
Barrier netting (Inland Fisheries Service 2008)	<ul style="list-style-type: none"> <li>• Fine-mesh netting is deployed to restrict access of fish to preferred spawning habitat, i.e. fringing vegetation.</li> <li>• Has been effective in Tasmania at reducing the spawning success of Carp; however, Carp may use the netting as spawning substrate, and deposited eggs will need to be destroyed by the application of lime.</li> <li>• The volume of fine-mesh netting required to net off all fringing habitat can be expensive and aesthetically unpleasing.</li> <li>• Labour-intensive to install, remove and maintain.</li> <li>• Limited application for Eastern gambusia (<i>Gambusia holbrooki</i>) and Small-bodied Redfin (<i>Perca fluviatilis</i>)</li> <li>• Timing is critical because there is the potential to impact native species spawning.</li> </ul>
Electrical barriers (Verrill and Berry 1995)	<ul style="list-style-type: none"> <li>• Used to restrict movements of fish by establishing an electrical field between two electrodes. Fish are shocked and either turn around or are briefly paralysed and flow downstream before recovery from paralysis.</li> </ul>

## Appendix 7 Model structure and development

After reviewing the available models, it was decided that the best model construct for the purpose of this study required a mechanistic understanding of the dynamics of Carp early life history, as recruitment strength drives Carp dynamics. This exploration of early life history also required an examination of the habitats utilised by Carp in this phase of their development and the likely productivity associated with habitats. We used the life history and available data for Carp to guide the construction of a stochastic, age-based, population model with an explicit description of egg, larval, fingerling and young-of-the-year survival (Figure A7.1). The stochastic age-based model allows the availability of various habitat types to drive the dynamics, and the flows determine the availability of habitat.

This construct allowed for a variety of scenarios to be considered, such as mechanistic-type scenarios where access to certain habitats occurs at different frequencies or specific flow-time series. Such examination can help comprehension of the scale of Carp dynamics under natural or modified modelled flow scenarios for the likely impact on Carp dynamics, and can consequently be used to inform specific flow management. The life history of Carp is well known (see Appendix 2). In general Carp are: long-lived (up to 34 years old); fast-growing, attaining a maximum size of ~80 cm; exhibit variable fecundity with size; and are sexually mature by the age of 3.

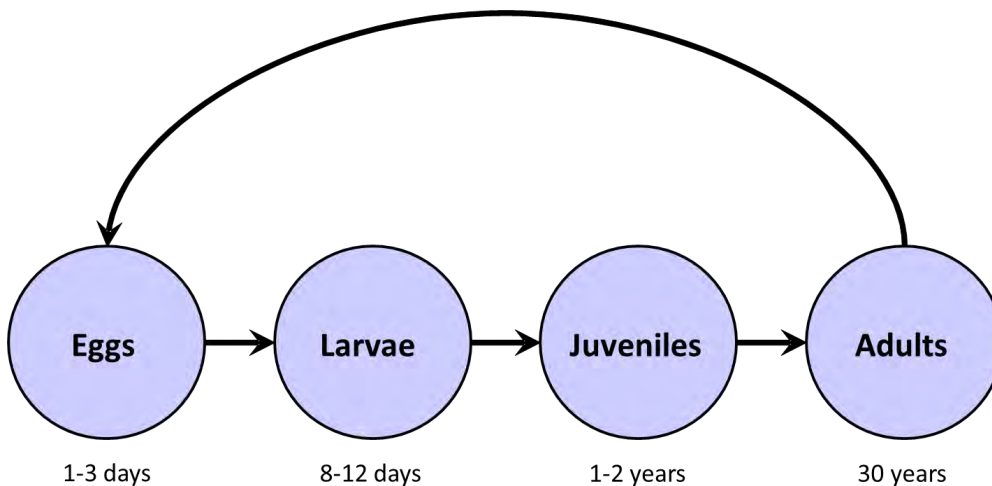


Figure A7.1. Life history of Carp and the associated period spent in each developmental phase

An age-structured matrix requires estimates of age-based survival rates and age-based fecundity as a function of recruitment to 1-year-olds. Age data obtained through analysing otoliths can be used to generate estimates of age-specific survival (Ricker 1975; Todd et al. 2004, 2005). An age class may be considered to be fully represented when the number of fish in the subsequent age class is less than the age class in question (Ricker 1975). Age data was obtained from 8635 Carp otoliths collected from around Victoria. Carp age ranged from 0 to 29, and a curve was fitted to the age data to allow age-specific survival rates to be estimated (Figure A7.2 and Table A7.1). Note that survival rates were not estimated beyond age 28 in the fitted relationship, which guided the number of age classes used in the model construct. Variation around the mean estimates in Table A7.1 remained unknown; the coefficient of variation in the survival rates was kept constant across all age classes to fully explore the variable habitat impacts on recruitment.

An age–fecundity relationship was generated from 133 aged Carp, with fecundity estimates ranging from 32,000 to 1,540,000 eggs. The relationship between age and fecundity varies little as age increases (Figure A7.3), but varies greatly within age classes. When we assumed the distribution of eggs within a specified age was log-normally distributed with a standard deviation of 200,000, and randomly generating fecundity given age, the resultant spread of fecundity appeared plausible given the data (Figure A7.4).



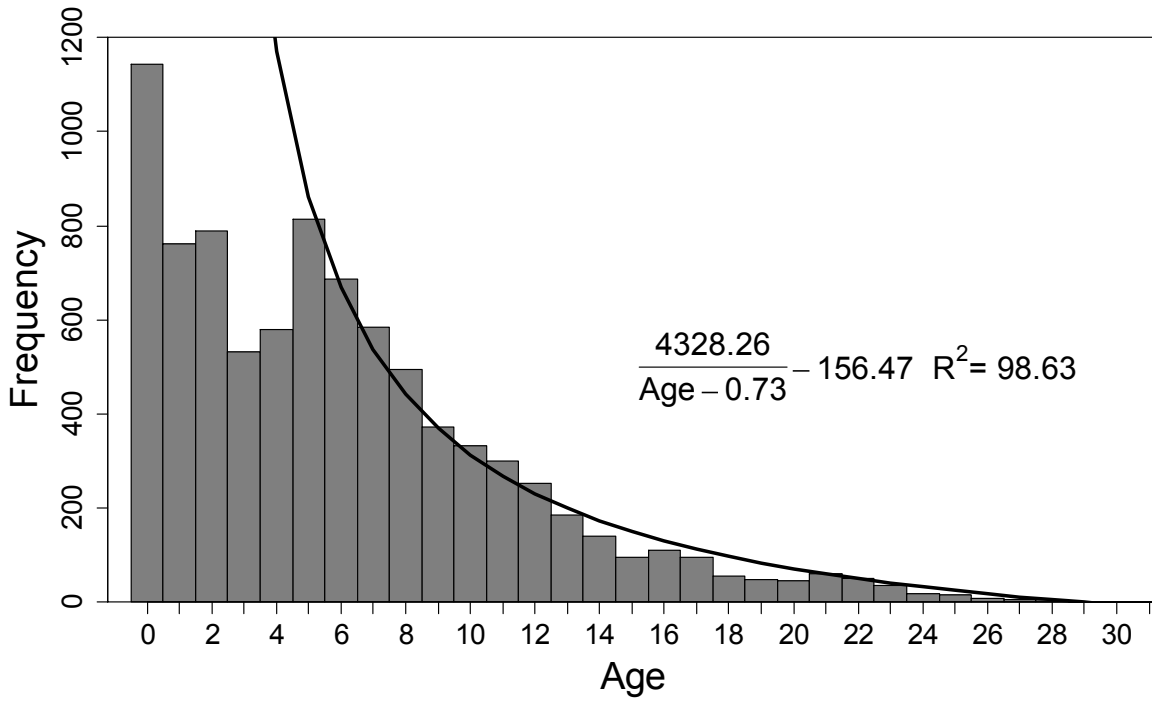


Figure A7.2. Age frequency data with curve fitted to a fully represented section of the data

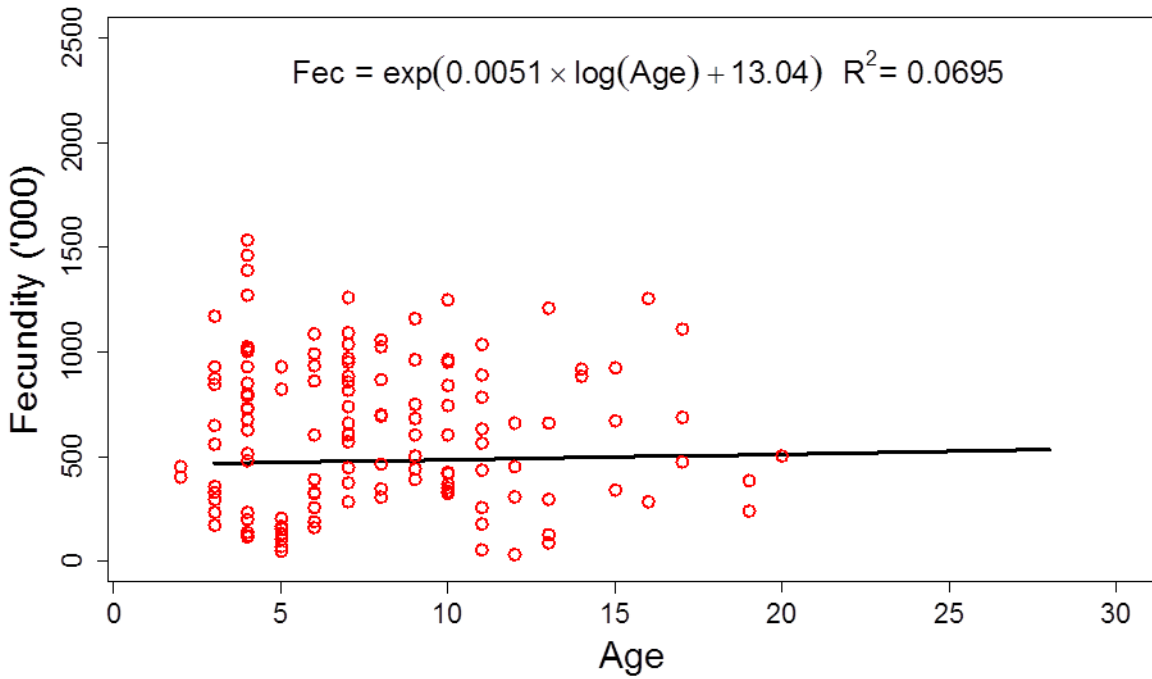


Figure A7.3. Age–fecundity data with relationship fitted

Table A7.1. Estimated survival rates and associated standard deviation (S.D.) based upon hypothesised coefficient of variation (CV)

Age	Mean survival	S.D.	CV	Age	Mean survival	S.D.	CV
1	0.20	0.02	0.1	15	0.87	0.09	0.1
2	0.54	0.05	0.1	16	0.87	0.09	0.1
3	0.67	0.07	0.1	17	0.86	0.09	0.1
4	0.74	0.07	0.1	18	0.86	0.09	0.1
5	0.78	0.08	0.1	19	0.85	0.09	0.1
6	0.80	0.08	0.1	20	0.85	0.08	0.1
7	0.82	0.08	0.1	21	0.83	0.08	0.1
8	0.84	0.08	0.1	22	0.82	0.08	0.1
9	0.85	0.08	0.1	23	0.80	0.08	0.1
10	0.86	0.09	0.1	24	0.77	0.08	0.1
11	0.86	0.09	0.1	25	0.72	0.07	0.1
12	0.86	0.09	0.1	26	0.64	0.06	0.1
13	0.87	0.09	0.1	27	0.48	0.05	0.1
14	0.87	0.09	0.1	28	0.00	0.00	0.1

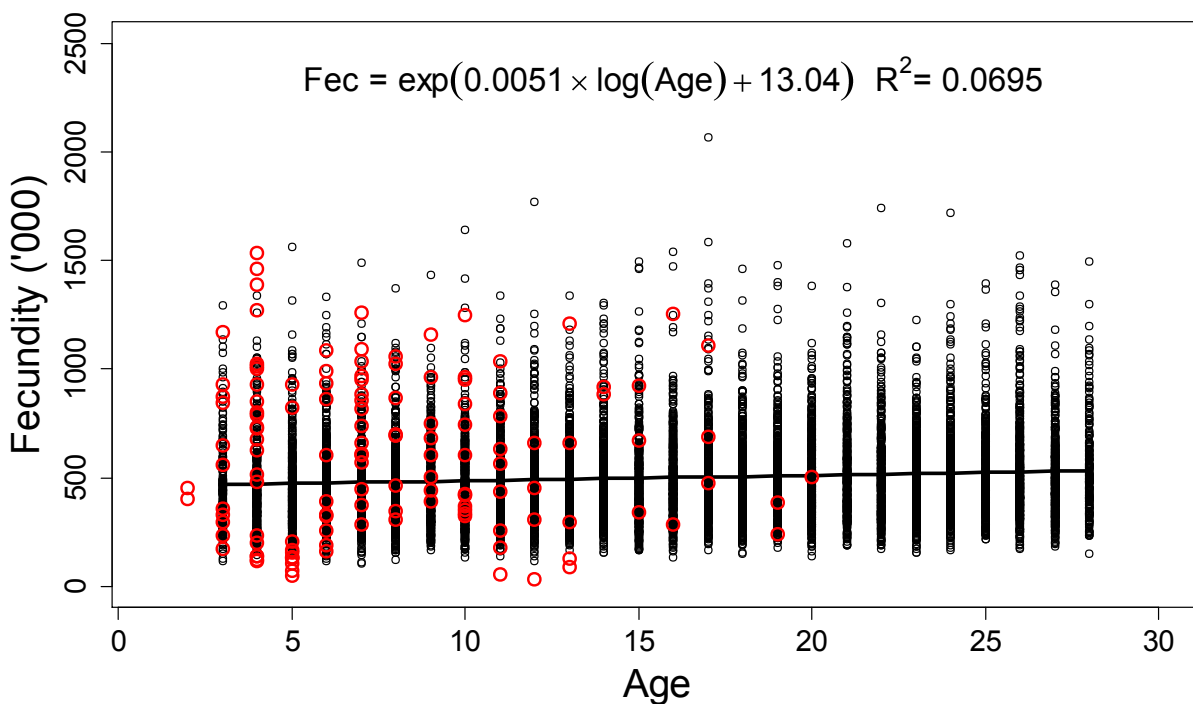


Figure A7.4. Generated fecundity given age in black and the original fecundity data in red

The analysis of the age frequency data generated estimates of 27 survival rates, so these could be readily used in a matrix construction with 28 age classes (where the final age class was specified to be 0, indicating that no animal lives beyond the age of 28). The matrix construct is a female-only model, and it is assumed that there are enough males in any situation to fertilise all eggs from female fish and that there is an even sex ratio. The construction of a 28 age class population model used calculated age-specific survival and fecundity rates, and estimated survival rates for eggs, larvae, fingerling, young-of-the-year and juvenile fish in order to complete the mathematical life cycle (Figure A7.5).

$$\begin{bmatrix} 0 & 0 & R_3 & R_4 & \cdots & R_{26} & R_{27} & R_{28} \\ s_1 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 \\ 0 & s_2 & 0 & 0 & \cdots & 0 & 0 & 0 \\ 0 & 0 & s_3 & 0 & \cdots & 0 & 0 & 0 \\ 0 & 0 & 0 & s_4 & \cdots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & s_{26} & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & s_{27} & 0 \end{bmatrix}$$

Figure A7.5. Age structured matrix model for Carp

Recruitment is in the top row and survival rates in the subdiagonal, where recruitment to 1-year-olds is given by  $R_{age} = Fec_{age} \times S_{eggs} \times S_{larvae} \times S_{flings} \times S_{yoy}$ .  $Fec_{age}$  = the fecundity at a given age,  $S_{eggs}$  = eggs survival,  $S_{larvae}$  = larvae survival,  $S_{flings}$  = fingerling survival and  $S_{yoy}$  = young of year survival.

Solving the equation  $(CarpModel - \lambda I) = 0$ , where the  $CarpModel$  is the matrix specified in Figure A7.5, yields the underlying growth rate (or finite rate of increase) for Carp model. To solve this equation, an estimate of recruitment ( $R_i$ ) for each age is required. Recruitment is the process of spawning, hatching, developing, growing and surviving to become a 1-year-old, and is given by:

$$R_{age} = Fec_{age} \times S_{eggs} \times S_{larvae} \times S_{flings} \times S_{yoy}$$

where  $Fec_{age}$  is the fecundity at a given age,  $S_{eggs}$  is egg survival,  $S_{larvae}$  is larvae survival,  $S_{flings}$  is fingerling survival and  $S_{yoy}$  is young-of-the-year survival.

Specifying the survival rates for different habitats would allow the model to explore the contribution of these different habitats to Carp dynamics. We hypothesised that different habitats would yield different estimates of the early life history survival rates. We employed an expert elicitation process to estimate the impact that the different habitat types would have on the early life history stages and to generate estimates of early life history survival for a number of habitat types. Once survival rates were estimated, the associated growth rate for each habitat type could be calculated. This provided an expression of risk in terms of likely response in population dynamics from each habitat type. The results from the expert elicitation process are given in Table A7.2. Any growth rate  $>1.4$  potentially exhibits very strong population growth, and strong recruitment is expected from these habitat types, as is shown by the population growth rate and the expected time taken for the population to double. Note that population growth rates less than one indicate a population decline; hence, a doubling time is not applicable. The 14 flow–habitat types used are defined in Section 6.3 and Appendix 8.

Table A7.2. Percentage survival elicited from expert opinion and the associated growth rate for each habitat type

Habitat	Egg survival (%)	Larval survival (%)	Fingerling survival (%)	Young-of-the-year survival (%)	Population growth rate	Population doubling time
H1	0.72	1.82	3.31	6.31	0.77	–
H2	1.36	3.84	5.88	7.25	0.88	–
H3	2.45	5.24	6.89	11.00	1.02	35.00
H4	1.50	2.83	5.25	8.15	0.86	–
H5	2.69	5.24	7.36	12.01	1.06	11.90
H6	12.07	10.00	21.41	15.50	2.43	0.78
H7	4.68	7.10	14.84	14.76	1.52	1.66
H8	7.96	5.70	16.83	7.96	1.46	1.83
H9	6.45	6.54	14.84	21.12	1.78	1.20
H10	10.90	8.15	20.31	21.39	2.41	0.79
H11	12.19	11.65	13.51	26.31	2.60	0.73
H12	5.21	5.91	13.09	13.69	1.42	1.98
H13	6.37	7.52	15.03	17.05	1.74	1.25
H14	0.71	2.20	6.70	5.65	0.80	–

Populations cannot increase indefinitely—at some point resources become limited. While early life history analysis indicates that some habitats exhibit strong recruitment potential, once these recruits move into the river channel (as flows or water regimes change) they will be competing for resources with all the age classes of other Carp. In the river channel we hypothesise that every metre of river can support one adult Carp, so if our system of interest is 200 km then we set the adult-carrying capacity at 200,000 Carp. If space becomes limited with an increasing population, Carp must move or die. Flow can be used to define which habitats become available for Carp in any given year. If the system of interest has a number of different habitat types, we can define the access to these habitats through varying levels of flow.

In summary, the Carp model is a stochastic population model with 28 age classes and estimates of survival and fecundity for each age class (see Figures A7.2–A7.5 and Table A7.1), where ages 1 and 2 have fecundity set to zero. The underpinning matrix model (Figure A7.5) has age-specific recruitment in the top row. Recruitment is a function of the numbers of eggs spawned, eggs that hatch, larvae that survive, fingerlings that survive and young-of-the-year that survive to become 1-year-olds. Fecundity, the number of eggs spawned per fish, has been estimated (Figures A7.3 and A7.4); however, the proportion of eggs that hatch and the rest of the early life history survival has not been directly measured. Combined, these factors are known as early life history survival or  $s_0$ . An expert elicitation process was undertaken to parameterise the

early life history components. This was done for a number of habitats, because different habitats are likely to vary in productivity levels and thus have different contributions to recruitment strength (Table A7.2). Once  $s_0$  has been estimated, analysis of the underlying matrix model can be performed to calculate the growth rate associated with each habitat. Assigning the number of female adults that get access to each habitat type determines the strength of recruitment in any given year. Flows determine which habitat types become available in the given year. Thus, the model can be used to examine the given flow components and the expected response by Carp to them.

Additionally, the model can be used to assess the possible consequences for Carp populations (abundances, biomasses, structures) caused by the impacts of watering management actions. These include impacts over both short (years) and longer time frames (decades). Movement between habitat types is modelled through changes in flow, because the availability of habitat types (and access to them) is also dependent on flow, and the size of the flow determines the number of Carp that have access to that habitat (also dependent on the number of Carp at a given time step). Different spatial scales can be modelled e.g. the northern and southern MDB; the Upper and Lower Murray River. As new information becomes available, other relevant biology can be included, such as temperature tolerances of eggs and larvae.

Stochasticity in population modelling uses the process known as Monte Carlo simulation, in which random numbers are generated from distributions describing variation in population parameters. The purpose is to determine how random variation, lack of knowledge, or error affects the sensitivity, performance and/or reliability of the predictions (Wittwer 2004). Monte Carlo simulation is categorised as a sampling method, because the inputs are randomly generated from probability distributions to simulate the process of sampling from an actual population (Wittwer 2004). Including mechanistic descriptions of demographic and environmental variation in an underlying projection matrix construct produces a stochastic population model. Demographic stochasticity is modelled by incorporating variation in the survival and reproduction of individuals (Akçakaya 1991) through a binomial distribution to model the number of individuals surviving between consecutive time steps, and using a Poisson distribution to model recruitment (Todd et al. 2005). Environmental stochasticity is modelled by randomly selecting survival and fecundity rates from specified distributions for each time step (Todd and Ng 2001).

The model uses a Monte Carlo simulation technique in which the user determines the number of iterations produced. Typically, in order to examine the consequences of a potential management action, each scenario is run (iterated) a minimum of 1000 times. The purpose of the large number of iterations is to provide sufficient sampling from the parameter distributions to allow full exploration of the variation of the distribution and to examine the likelihood of extreme events (Ferson et al. 1989; Burgman et al. 1993). The data generated from the simulation can be represented as probability distributions (or histograms) or converted to error bars, reliability predictions, tolerance zones, and confidence intervals (Wittwer 2004).

Recording the minimum population size from each iteration or trajectory and then plotting the associated normalised cumulative frequency distribution produces a graph of probabilities versus population size—this is the minimum population size risk curve. This represents both the chances of extinction (probability of falling to zero) and the chances of falling below some non-zero population threshold (Burgman et al. 1993). Additionally, risk curves can be readily compared and assessed in terms of increasing or decreasing risk by a shift to the left or right, respectively, of the minimum population size risk curve (Figure A7.6). A method for quantifying changes in risks is to calculate the average minimum population size for each curve and then comparing these values (McCarthy 1995; McCarthy and Thompson 2001; Todd et al. 2004).

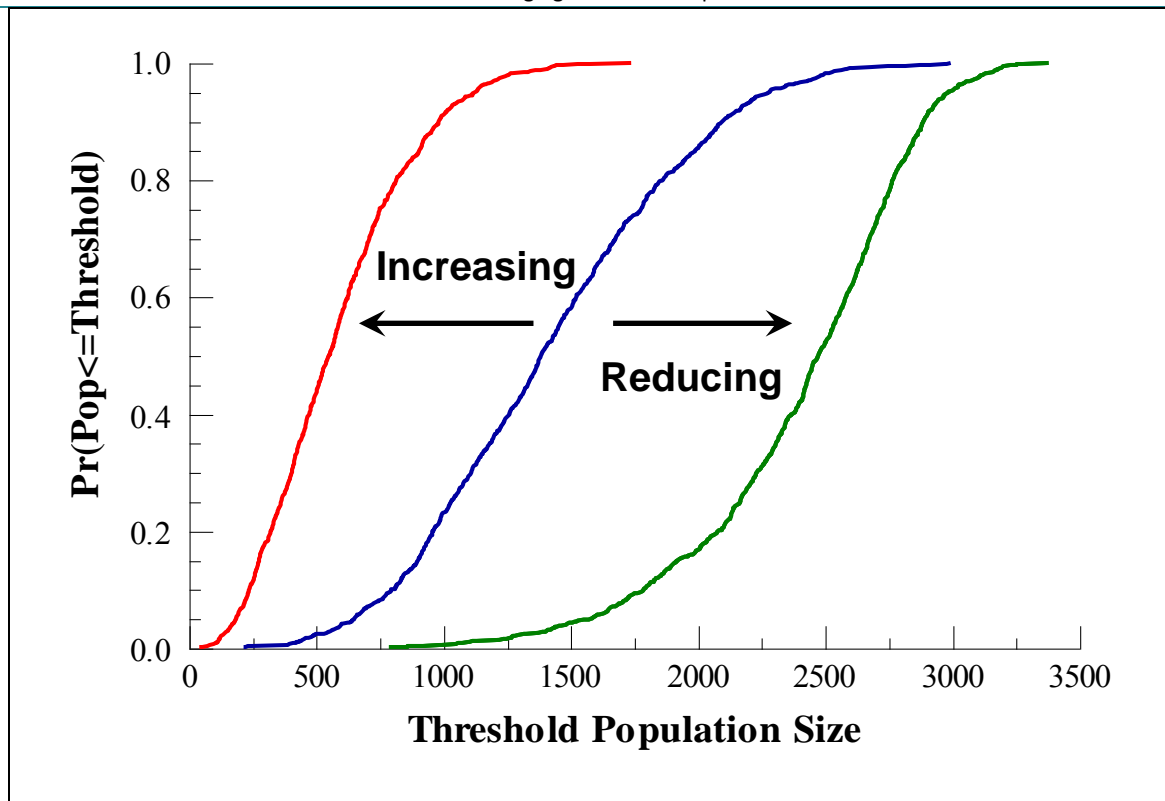


Figure A7.6. Minimum population size risk curves (risk increases as the risk curve shifts to the left and risk decreases as risk curves shift to the right)

Given that one of the objectives of the project is to examine a number of management scenarios, it is useful to report on the statistics of:

- risk curves associated with the distribution of the minimum population size (e.g. specific elements of the population such as adult fish or recruitment, etc.);
- risk curves associated with the distribution of the maximum population size, exploring the probability of a population being large;
- the average trajectory through time.

All statistics reported are for total population, even though the construct is a female-only model.

The construction of all models and modelling of all scenarios was undertaken using the software package *Essential* (Todd and Lovelace 2008). *Essential* is a highly flexible stochastic modelling platform that allows both expert model development and general use by way of access to a limited suite of parameters. Data generated can be accessed for all parameters over all time steps and iterations. Specific applications of *Essential* have been developed for Trout Cod and Murray Cod population models (Todd et al. 2004; Koehn and Todd 2012).

The mechanical development of the specific Carp model fits within a process (Section 6, Figure 18) that links other aspects of this project, including the expert workshops and case studies (Section 7).

## Appendix 8 Habitat types used for Carp scenario modelling

Table A8.1. Description of habitat types used for Carp scenario modelling

No.	Habitat type	Description
H1	Main Channel (Mid Upper Murray)—base flow	Low level not topped up by irrigation flows <50% bankfull. Only occurs during severe drought
H2	Main Channel (Mid Upper Murray)—cover benches	50–70% bankfull irrigation flow
H3	Main Channel (Mid Upper Murray)—bankfull	70% to bankfull irrigation flow
H4	Main Channel (Lower Murray)—base flow	Weir pools at operating height, low flows
H5	Main Channel (Lower Murray)—cover benches	Increase weir pool extent/influence (entitlement + irrigation flows + weir pools)
H6	River Wetland, e.g. Barmah–Millewa	Adjacent low-lying wetlands (without broader floodplain inundation)
H7	Wetland Perennial, e.g. Kow Swamp	E.g. Barren Box Swamp. Off-stream wetlands with permanent water
H8	Wetland Ephemeral, e.g. Hattah Lakes	Off-stream wetlands, high elevation wetlands dry out if not reconnected
H9	Wetland permanently connected, e.g. adjacent weir pool	Wetlands now inundated permanently because of the weir pools follow weir pool dynamics, e.g. all unregulated weir pool wetlands in Lower Murray
H10	Natural floodplain inundation	Broad floodplain inundation (as per high-level natural flood)
H11	Artificial floodplain inundation, e.g. Chowilla	Inundated by regulators
H12	Lakes (off-stream), e.g. Lake Victoria	Lakes Victoria, Cargelligo; permanent water bodies
H13	Lakes (terminal), e.g. Alexandrina	Permanent water bodies at the end of the system
H14	Irrigation channels	High flow in irrigation season, then mostly dry/residual pools







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