MANAGING THE CHOWILLA CREEK ENVIRONMENTAL REGULATOR FOR FISH SPECIES AT RISK

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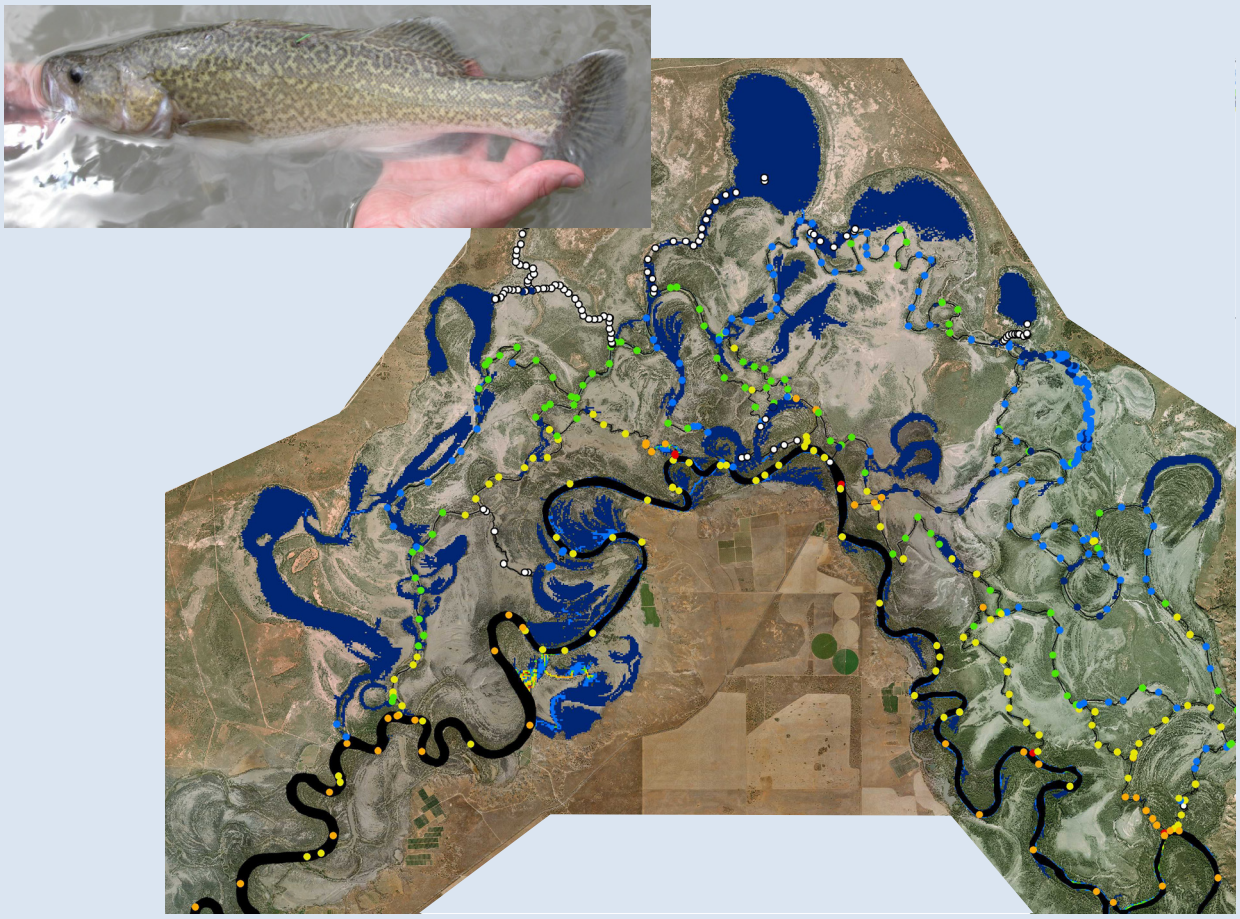

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Cover photographs from top: Juvenile Murray cod (Brenton Zampatti), hydrodynamic modelling of Chowilla floodplain and the River Murray (Water Technology, Melbourne).

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KEY MESSAGES

Background

- As part of the Living Murray Program to rehabilitate Icon sites, the Chowilla Regulator is designed to back water up over the floodplain, to provide a managed inundation.
- The aquatic habitats of Chowilla, particularly the diversity and permanence of streams with fast-flowing water velocity, were once common in the lower River Murray but have become extremely rare in over 800 km of the lower river since construction of the Locks created a series of weirpools.
- The diverse habitats in Chowilla, and the nearby Lindsay-Mullaroo system, contain the most significant populations of Murray cod, an EPBC listed species, in the lower River Murray, as well as other threatened and less common species. Data suggests that these habitats may be drought refugia for Murray cod, where spawning and recruitment occurs in drought years which sustains the riverine population.
- The Chowilla Regulator is proposed to operate every two to four years depending on the ecological condition of the floodplain, for approximately three months in spring which coincides with the major spawning period of native fish.
- The Regulator is planned to simulate the inundation of a flood but when using inflows of 10,000-20,000 ML/d it does not maintain the diverse flowing water habitats of a natural flood that are key features for fish, especially for spawning and survival of young (recruitment).
- Managed inundations using the Regulator will favour common native fish species and the non-native carp, but present risks for less common and threatened species, such as Murray cod.

Management and Mitigation of Risk for Native Fish

- The primary risks of the Regulator for native species results from the reduction in flowing water habitats, an increase in carp populations, and the disconnection of river and floodplain hydrology (i.e. inundation of the floodplain whilst the river is not flooding).
- Depending on the frequency and level of managed inundations, the Chowilla Regulator has a spectrum of risk for native fish:
    - At one end, if operated frequently (1-in-2 to 1-in-4 years) at a high inundation level, as proposed, there is a high risk of a decline in native fish species that are threatened or are less common.
    - At the other end, if it is operated less frequently (e.g. 1-in-10 years) at a lower level of inundation or during high river flows (35,000-50,000 ML/d) that maintain the diversity of fish habitats, long-term impacts on native fish are not likely.
- A major risk is the increase in regional carp populations which will place additional risk on native fish populations and aquatic environments.
- Mitigation of risks for native fish species includes: using the Regulator less frequently and at a low level of inundation; using natural high flows as much as possible; synchronising hydrology on a site and landscape scale (e.g. avoiding re-regulated flow from Lake Victoria); and increasing hydrodynamic diversity, and potentially fish recruitment, within Chowilla in the years when the Regulator is not used.
- Many native fish species respond to changes in flows and habitats at a landscape-scale (100s of kilometres) rather than Icon-site scale; as such, rehabilitation of fish habitats at a landscape-scale is recommended, including i) restoring flowing water habitats in the upper weirpools along the lower River Murray, and ii) providing a large in-channel rise (15,000-20,000 ML/d) annually along the length of the River Murray channel to stimulate spawning and recruitment of native fish.
- Monitoring and responsive adaptive management is a key to mitigating risks and optimising benefits for all biota. It is recommended that a Working Group be established that specifically uses Basin-wide expertise in ecology and biometrics, initially to design the monitoring and operating program, and then provide ongoing advice and annual peer review.

EXECUTIVE SUMMARY

Background

The Chowilla anabranch system and floodplain is located on the lower River Murray in South Australia adjacent to Lock 6. The anabranch system is a complex of perennial and ephemeral aquatic habitats consisting of creeks, backwaters, billabongs and lakes. Between 20 - 90% of River Murray flows are diverted through the Chowilla system under low flow conditions (i.e. < 10,000 ML/d). The main perennial creeks provide diverse aquatic habitats that include fast and slow flowing reaches, abundant aquatic macrophytes and numerous adjacent wetlands and backwater habitats. The habitat diversity reflects the character of the River Murray prior to the construction of the locks and weirs and it remains one of a few strongholds of native fish in the lower River Murray.

Chowilla has an extensive floodplain that is degraded due to reduced flooding frequency and elevated saline water table, the latter partly caused by hydraulic pressure of the high water level of Lock 6. The Chowilla Regulator is currently being built at the downstream end of the floodplain, in Chowilla Creek, to back water up over the floodplain thereby using relatively small volumes of water to inundate large areas of floodplain. The Regulator is proposed to be used for three months in spring; the operating frequency is yet to be determined but initial proposals have considered every two to four years.

Although there are predicted to be benefits for the terrestrial floodplain of the increased inundation provided by the new regulator (Nichol *et al.* 2010), a managed inundation using inflows up to 20,000 ML/d (Q_{SA}[1]) differs substantially from a natural flood and this produces some significant risks for fish. The proposed timing of the managed inundation, in spring, also coincides with the main spawning period of native fish. The South Australian Murray Darling Basin Natural Resources Management Board recognised this in the development of the project and in 2007 commissioned an assessment of risk for native fish (Mallen-Cooper *et al*. 2008).

The assessment concluded that five native fish species would likely benefit from the managed inundation and two species would be unaffected, but these were all common species. Four native fish species, including three threatened species, were identified at risk: namely Murray cod, freshwater catfish, silver perch and golden perch. Furthermore, it was concluded that non-native common carp would significantly benefit. The primary risks of the Regulator for the four native species results from the loss of hydrodynamic diversity (i.e. velocity profiles and flow patterns), an increase in carp populations, and the disconnection of river and floodplain hydrology (i.e. inundation of the floodplain whilst the river is not flooding).

The risk assessment identified *core habitats* that contained fast-flowing creeks with hydrodynamic diversity, which had significant populations of Murray cod and other native fish species. The study showed that in natural floods the hydrodynamics of the fast-flowing creeks are retained; that is, a natural flood is not a vast, still water-body but is a complex hydraulic environment with fast- and slow-flowing habitats as well as still water-bodies in wetlands and lakes. In comparison, a managed inundation using the Chowilla Regulator, with River Murray inflows to South Australia of 10,000 to 20,000 ML/d (Q_{SA}), backed water up onto the floodplain, greatly reducing water velocity and hydrodynamic diversity. The implications for the species at risk were that spawning and nursery habitats were reduced and the populations of these species would decline.

The present project was initiated to provide a conceptual framework to understand and mitigate these identified risks, provide further detail of risks and benefits, and to assess specific mitigation strategies.

Aims and Methodology

The project focused on the four native species identified at risk and aimed to assess the:

[1] Q_{SA} is River Murray discharge entering South Australia, which is upstream of all inlets to the Chowilla Floodplain.

1. Potential to retain the flowing water in the *core habitats*, and hence hydrodynamic diversity, by operating the Chowilla Regulator with Lock 6 raised by 0.62 m.
2. Impact of Lock 6 weirpool (backwater) on flowing water habitats in the Lindsay River and Mullaroo Creek.
3. Effects of restoring variable flow in Pipeclay and Slaney creeks, two of the main creeks of Chowilla.
4. Risk and benefits of Regulator operation.
5. Mitigation strategies of Regulator operation.

The methodology was to use conceptual models and hydrodynamic modelling to predict fish responses and use this to assess risk and benefits using qualitative scores of *Consequence* and *Likelihood,* as per standard risk assessment techniques. From this assessment we could then determine a framework for mitigation, monitoring and operations.

Findings

Conceptual models

Comprehensive conceptual models of fish ecology were developed from studies undertaken in the Chowilla system, lower and mid reaches of the River Murray and the Darling River. From these models 57 hypotheses were identified and these were cross-referenced with risks and benefits to refine priorities; this provides a framework for a monitoring program. A review of carbon dynamics of rivers highlighted that this area is poorly understood in large dryland rivers like the lower River Murray, yet it ultimately underpins floodplain river ecology and restoration efforts. Further investigation of carbon dynamics is recommended to optimise the contribution of the Chowilla Regulator to the restoration of the floodplain and the river.

Hydrodynamic modelling

In the Lindsay River and Mullaroo Creek, which has a significant Murray cod population, the hydrodynamic modelling indicated that there was little impact when Lock 6 was raised, if Lock 7 was also raised.

Raising the Lock 6 weirpool by 0.62 m (i.e. maximum practical) at 10,000 to 20,000 ML/d increases the head differential between the inlets of Chowilla and the outlet at the Regulator which provides significant benefits in retaining flowing water habitats, provided the Regulator is operated at a low level: 75% of the *core habitats* are retained by operating the Chowilla Regulator at <18.5 m AHD.

Predicted Responses of Fish

Using the conceptual models and the hydrodynamic modelling, the response of fish was predicted under three operating scenarios:

1. No change to infrastructure; lotic habitats increased in spring by raising Lock 6 (E-flows of 10,000 – 20,000 ML/d Q_{SA} and Lock 6 raised by 0.62 m).
2. Chowilla Regulator - lower height range (< 18.5 m AHD); >75% lotic habitats maintained in an event (E-flows of 10,000 – 20,000 ML/d Q_{SA} and Lock 6 raised by 0.62 m).
3. Chowilla Regulator – upper height range (> 18.5 m AHD); <25% lotic habitats maintained in an event (E-flows of 10,000 – 20,000 ML/d Q_{SA} and Lock 6 at normal pool).

Under the no change scenario the floodplain is expected to degrade further (Overton *et al*. 2005) but the health of the littoral and aquatic vegetation is expected to remain relatively stable (excluding reaches of creeks with saline groundwater intrusion which significantly degrades littoral and riparian vegetation). Despite the degradation of the floodplain, native fish present in Chowilla are not expected to decline. This is largely because for those species that spawn in Chowilla there is ongoing recruitment (survival of larvae and young) within the Chowilla creeks and existing wetlands, and this is not dependent on flooding. Other species, such as golden perch, that spawn in response to in-

channel rises (e.g. 15,000-20,000 ML/d) or floods, are dependent on landscape-scale events. There is little control of large floods in the lower River Murray but in-channel rises are heavily regulated and can potentially be re-regulated back into the river as environmental water allocations. The extent that flow-cued species will increase or decline in the future is dependent on management of the river at a wider scale than the Icon site.

Using the Chowilla Regulator in the *lower height range* (Scenario 2) enables the retention of valuable flowing water habitats, particularly if it is operated with the Lock 6 weirpool raised. Movement of Murray cod out of the Chowilla creeks (emigration) is expected to be limited and spawning is likely to continue. Recruitment of Murray cod may be less, due to reduced nursery areas, which include littoral (channel edges) and epibenthic (near bottom) zones that have complex hydrodynamics of slow–flowing areas adjacent to faster flowing currents.

Effects on freshwater catfish under this scenario are minimised, although increased access of carp to catfish habitats could have a negative effect. In a managed inundation event golden perch would be cued to migrate upstream by the increase of flow into Chowilla during the filling phase, but low outflows at the Regulator would limit immigration into the system, so net emigration is expected during a managed event. Golden perch will recolonise Chowilla but the extent that the abundance returns to pre-event levels depends on dispersal rates and the frequency of Regulator operation, both of which can be answered with monitoring. The responses of silver perch are likely to be similar to golden perch but much less is known of this species as it is much less abundant.

Using the Chowilla Regulator in the *upper height range* provides substantially more inundation of the floodplain but also has the most significant risks for less common and threatened fish species. Habitats with flowing water that have moderate and fast velocity (>0.17 and >0.3 m/s) contain key spawning and nursery habitats for Murray cod. These habitats are reduced in almost direct proportion to the height of the Regulator when using inflows up to 20,000 ML/d (Q_{SA}), so that at the maximum height there are virtually no habitats with moderate or fast velocity. In these conditions there are two alternative models for the response of Murray cod: i) fish retain site fidelity, despite the changed hydrodynamic environment, or ii) fish move out of the Chowilla creeks with net emigration during an event. In both models survival of larvae would be poor because of reduced nursery habitats, which would result in poor recruitment in that year

Some return movement and recolonisation over time is expected but, as discussed for golden perch, the extent that this occurs would depend on the frequency of managed inundations. For example, a 1-in-10 year frequency of operation would likely have no long-term impact whilst a 1-in-2 year frequency would very likely reduce abundance. A major risk for the Icon site and for the region is that Chowilla appears to be an effective recruitment zone for Murray cod which is likely influencing the abundance of cod more broadly, so a reduction in recruitment in Chowilla may result in a less abundant population more widely in the River Murray.

Effects on golden perch and silver perch when the Chowilla Regulator is used in the *upper height range* are similar to the *lower height range*, although greater emigration is expected and a longer period of time would be required between events for recolonisation. For freshwater catfish the risk increases greatly due to the expected increase in carp spawning and feeding activity. Depending on the abundance of carp, this leads to disturbance of catfish nests and nursery habitats.

Risks and Benefits

Using the conceptual models, hydrodynamic modelling and the predicted responses of fish, 42 risks and 13 benefits were identified. While these numbers are not a quantitative comparison the authors consider that there is a net risk for less common and threatened fish species, if the Regulator is operated frequently in the upper height range with inflows less than 20,000 ML/d (Q_{SA}).

The direct risks relate to the responses of fish as described above, and include impacts on spawning, recruitment and movement. There are also indirect risks largely driven by the decoupling of floodplain and river hydrology when the Regulator is used at low to moderate flows (e.g. < 35,000 ML/d). Disruption to carbon pathways between floodplains and channels is an important indirect risk but is poorly understood.

Increasing carp populations is a significant risk of operating the Chowilla Regulator. Carp will still spawn in natural floods, but the additional risks of the Chowilla Regulator are that: i) inundated floodplains will occur more often than at present; ii) the impounded water has more still-water habitats that will provide more suitable spawning areas and increase recruitment; and iii) managed inundations with lower hydrodynamic diversity (depending on operational regime), particularly the reduction in fast-flowing creeks adjacent to floodplains, will be a less favourable environment for predators of carp such as Murray cod. A separate Carp Management Strategy has been prepared (Stuart *et al*. 2011) which recommends using timing and frequency of use of the Regulator as the main mitigation method.

Of all the risks identified the overarching risk is inadequate monitoring. If monitoring is not well-designed or not sufficiently resourced, risks will not be detectable and any decline of native fish will not be evident. Monitoring also provides an integral feedback loop in the adaptive management process that should underpin Regulator operation.

The potential benefits of the project include: improving fish passage at the two main inlet regulators (Pipeclay and Slaney weirs); improving fish recruitment by increasing lotic habitats and improving littoral zones (achieved by providing more flow in the two main creeks, Pipeclay and Slaney); using floodplain carbon dynamics to enhance fish recruitment in natural events; and the experimental scope and potential flexibility of the project. An important associated risk of the first three benefits is an increase in carp spawning and recruitment, so an experimental approach will be needed to assess the balance of risk and benefit in these strategies.

Mitigation

There are eight main mitigation strategies. Five directly relate to operation of the Regulator, these are: frequency (regime), timing and duration, conservation of lotic habitats, inflow source and discharge, and rates of recession. Three are broader strategies that include: contingency flow, monitoring and adaptive management, and improving fish habitat and opportunities for recruitment at a landscape scale.

Using these strategies the project has high potential for mitigation of risks, as long as it is supported by well-designed monitoring. Frequency of operation is potentially the most powerful mitigation tool. Since the Regulator is an environmental rehabilitation project that can be ‘switched’ on and off, all risks for fish can potentially be managed by switching the Regulator ‘off’. Based on the conceptual models and the analysis of risks and benefits, operating the Regulator less frequently, at a low level or at very high inflows (e.g. 35,000 – 50,000 ML/d) provides less risk for fish. Balancing this with ecological outcomes on the floodplain is dependent on monitoring.

Timing and duration can be used to minimise the impact of carp by using the Regulator in winter, outside the spawning season of carp. Conserving lotic habitats and hydrodynamic diversity can be achieved by using the Regulator at low levels with Lock 6 raised. This provides an alternative strategy for operation of the Regulator that reduces risk for native fish, but the inundation of the floodplain is limited and assessment of the terrestrial benefits is required. Operating the Chowilla Regulator at higher levels reduces the extent of the *core habitats* and increase risks for fish.

A potential mitigation for the risk of reduced Murray cod recruitment is increasing lotic habitats and hydrodynamic diversity in the years when the Regulator is not used, using the upgraded Pipeclay and Slaney weirs to pass more flow. This option would need monitoring in the field to assess the response of Murray cod and the risk of increased carp spawning.

A significant risk is the disconnection of floodplain and river hydrology and the mitigation is to link Regulator operation as much as possible with landscape–scale processes. Hence; use water from floods upstream rather than re-regulated water from Lake Victoria and use high inflows (e.g. 35,000-50,000 ML/d) to produce more synchronised hydrographs upstream and downstream of the floodplain – all of which would provide more benefits for native fish.

The risk of native fish stranded on the floodplain can potentially be mitigated by operating the Regulator to manage the hydrograph on the floodplain and the rate of recession. Allocating a

contingency flow provides additional flexibility to manage the recession and also enables dilution of poor water quality, if required.

Mitigating risk can be viewed as constrained spatially and temporally to the Icon site. Considering the issue of mitigating risk more broadly, however, provides greater opportunities for improving native fish habitat and populations. The aim would be to improve the resilience of native fish populations and hence reduce the risks of managed inundations for fish. Two major strategies are: i) restoring lotic habitats in the upper weirpools along the lower River Murray by lowering the weir pools by 0.5 to 1.0 m (or greater if possible) either permanently or in spring during the main fish spawning season, and ii) providing a large in-channel rise (15,000-20,000 ML/d) annually along the length of the River Murray channel to stimulate spawning and recruitment of native fish. The latter could potentially benefit several Icon sites, including Barmah-Millewa, Gunbower-Koondrook-Perricoota, Chowilla/Lindsay Wallpolla, River Murray channel, and the Lower Lakes, Coorong and Murray mouth.

Monitoring and Operation

The Chowilla Regulator Project is one of the largest floodplain rehabilitation projects in Australia and is unprecedented in inundating a permanent flowing anabranch system that supports threatened native fish species. As such, the project represents a manipulative experiment on a grand-scale, with a regulator that can be operated variably or completely removed. This control over infrastructure provides two major opportunities: i) to use it as an experimental facility, and ii) to apply very responsive adaptive management.

Monitoring ties into the Regulator operating strategy. The initial recommended operation is a risk-averse event (winter inundation). Following that, however, and viewing the project as a manipulative experiment that has the ultimate mitigation of switching the Regulator 'off', we recommend testing the extremes of operation: i) a maximum spring/summer flood using stored water (Lake Victoria) with minimum lotic habitats retained (i.e. the maximum predicted risk), and ii) maximising fish outcomes using maximum inflows from the River Murray and maximising lotic habitats and hydrodynamic diversity.

The alternative is to balance floodplain inundation with minimising risks for fish in every managed event. This has the long-term risk that the incremental loss of native fish populations is not detected. Monitoring is then reduced over time and the detection ability is reduced. The two approaches, of testing the extremes of operation or minimising risk in every event, need further discussion with stakeholders and managers to reach agreement on the future operation.

The conceptual models and assessment of risk highlight the complexity and knowledge gaps of fish ecology and carbon dynamics of the lower River Murray and large dryland floodplain rivers in general. To manage the Chowilla Regulator effectively, monitoring needs to be well-designed. As such, we recommend the formation of a Working Group drawing upon the ecological and statistical expertise from across the Basin, to specifically develop a monitoring and investigations program, and an operating strategy for the Chowilla Regulator. The Working Group would then provide ongoing advice and annual peer review.

In conjunction with this experimental template of operation, a generic operating strategy is recommended that uses the principles for mitigating risk (frequency, timing and duration, conservation of lotic habitats, inflow source and discharge, and rates of recession) along with two additional principles: i) use natural modelled floods (MDBA BigMOD) as a template to simulate the natural rise, fall, and fluctuating peaks of flood events on a daily basis, and ii) be responsive to monitoring, including at a daily scale. A draft monitoring and operations framework has been developed as a flow chart (page 88) which incorporates feedback loops for risk management, monitoring and refining conceptual models.

Conclusion

The aquatic habitats of Chowilla, particularly the hydrodynamic diversity of lotic habitats are, along with the Lindsay-Mullaroo system, unique in the lower River Murray and provide the only remaining examples of permanent flowing water habitats in over 800 km of river. These habitats were a permanent feature of the main channel of the River Murray prior to the construction of Locks and

Weirs. The Chowilla and Lindsay-Mullaroo systems contain the most significant populations of Murray cod, an EPBC Act listed species, in the River Murray downstream of the Darling River junction. Data suggests that these habitats may be drought refugia for this species, where spawning and recruitment occurs in drought years which sustains the riverine population.

Inundating the Chowilla floodplain using a regulating structure results in significantly different hydrodynamics (water volumes, velocities, flow paths, etc.) compared to a natural flood. Furthermore, the Regulator can inundate the floodplain in isolation from broader scale (i.e. the river-scale) hydrological processes. Operation of the Chowilla Regulator at levels >18.5 m AHD with inflows < 20,000 ML/d Q_{SA} presents significant risks to Murray cod and other large-bodied native fish, and significant benefits for non-native common carp. Operation of the Regulator at <18.5 m AHD in conjunction with raising Lock 6 by 0.5 m may mitigate these risks at these flows. Operation of the Regulator is experimental and as such requires robust monitoring and investigations to measure benefits and avert risks, and test the hypotheses on which these predictions have been made. A Working Group is recommended that draws on the Basin–wide expertise in aquatic ecology and biometrics to help with the design of the monitoring program, operating strategy, and provide ongoing peer review.

The Chowilla Regulator is presently being constructed and is likely to be operable from 2013. The risks of managed inundations using the Chowilla Regulator will depend on how it is used and the frequency of use. The operational flexibility of the Chowilla Regulator and the ability to switch the Regulator ‘on’ and ‘off’ present a clear opportunity for adaptive management. Fundamental to the success of the project and to sustaining, and potentially improving, native fish populations will be a well designed monitoring program and linking the project with landscape-scale river rehabilitation.

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1 INTRODUCTION

The Chowilla Anabranch and Floodplain (hereafter Chowilla) is a significant ecological asset of the Murray Darling Basin and an Icon Site of the Living Murray Program. It covers an area of 17,700 ha near Lock 6, with 75 % in South Australia and 25 % in New South Wales. The floodplain ecosystem is valuable in its present state, but is also degraded in some areas. Five key threats have been identified (DWLBC 2006):

I. altered flow regimes;
II. elevated saline groundwater (up to 3 m higher than pre-regulation);
III. obstructions to fish passage;
IV. grazing pressure; and
V. pest plants and animals.

To address the threat of altered flow regimes and alleviate the effects of elevated groundwater, the Chowilla Regulator is currently being built by the South Australian Department for Water for the Murray-Darling Basin Authority, at the downstream end of the floodplain. The Regulator will back water up over the floodplain thereby using relatively small volumes of water to inundate large areas of floodplain. The Regulator is proposed to be used for three months in spring every two to four years, although the frequency will be responsive to water availability and a range of ecological objectives.

The objectives for fish in the Icon Site Management Plan for Chowilla (DWLBC 2006) include:

- Maintain the diversity and distribution of native fish species throughout Chowilla.
- Reduce barriers to fish passage throughout the floodplain-creek system.
- Maintain successful recruitment of small- and large-bodied native fish.

These objectives are complementary with the Native Fish Strategy (Murray-Darling Basin Commission 2004), which recognises that native fish populations have declined, and aims to conserve and rehabilitate these populations.

Although there are obvious benefits for the terrestrial floodplain of the increased inundation provided by the new Regulator, a managed inundation differs substantially from a natural flood and this produces some significant risks for fish. The proposed timing of managed inundations, in spring, also coincides with the main spawning period of native fish. The South Australian Murray-Darling Basin Natural Resources Management Board (SAMDBNRMB) recognised this in the development of the project and in 2007 commissioned an assessment of risk for native fish (Mallen-Cooper *et al*. 2008).

The assessment concluded that five native fish species would likely benefit from the managed inundation and two species would be unaffected, but these were all common species. Four native fish species, including three threatened species, were identified at risk: namely Murray cod, freshwater catfish, silver perch and golden perch. Furthermore, it was concluded that non-native common carp would significantly benefit. The primary risk of the Regulator for the four native species resulted from the loss of hydrodynamic diversity (i.e. velocity profiles and flow patterns), an increase in carp populations, and the disconnection of river and floodplain hydrology (i.e. inundation of the floodplain whilst river is not flooding).

The risk assessment identified *core habitats* that contained fast-flowing creeks and hydrodynamic diversity, which had significant populations of Murray cod and other native fish species. The study showed that in natural floods the hydrodynamics of the fast-flowing creeks are retained; that is, a natural flood is not a vast, still water-body but is a complex hydraulic environment with fast- and slow-flowing habitats as well as still water-bodies in wetlands and lakes. In comparison, a managed inundation using the Chowilla Regulator backed water up onto the floodplain, greatly reducing water velocity and losing hydrodynamic diversity when using low inflows. The implications for the species at risk were that spawning and nursery habitats were reduced and the populations of these species would, in the short- and long-term, decline. More of the key habitats would be retained at higher

flows, with correspondingly less risks, and the report recommended using the regulator with high inflows as well as less frequently.

The present project was initiated to provide a conceptual framework to understand and mitigate these identified risks, provide further detail of risks and benefits, and to assess specific mitigation strategies. The project focused on the four native species identified at risk and aimed to assess:

1. Potential to retain the flowing water in the *core habitats*, and hence hydrodynamic diversity, by operating the Chowilla Regulator with Lock 6 raised by 0.62 m.
2. Impact of Lock 6 weirpool (backwater) on flowing water habitats in the Lindsay River and Mullaroo Creek.
3. Effects of restoring variable flow, in Pipeclay and Slaney creeks, two of the main creeks of Chowilla.
4. Risk and benefits.
5. Mitigation, monitoring and operating strategies.

2 BACKGROUND

2.1 Chowilla Regulator Project

The main feature of the project is the Chowilla Regulator, which is being built at the downstream end of the anabranch and floodplain system to raise water levels onto the floodplain and simulate natural flood levels. The regulator and associated structures would:

- hold water at different levels, up to the level of the Lock 6 abutments at EL 19.87 m (the Lock 6 weirpool is normally at EL 19.25 m);
- enable controlled inundation of up to 50% of the floodplain;
- be operated in spring and early summer, initially for three months duration every second to fourth year, depending on available inflows, the condition of the floodplain and the frequency of natural flooding. Stop-logs of the regulator would be removed for the other nine months to enable uninterrupted flow of water and passage of fish;
- have fishways that function when the Regulator is operating, at low and high flows;
- be similar in length and height to Lock 6.

By inundating the floodplain more frequently and to higher levels than at present, the Chowilla Regulator aims to water floodplain vegetation to provide a range of ecological benefits, including diluting the salt in the upper soil layers and recharging upper freshwater lenses (DWLBC 2006). It would not decrease the level of the elevated saline groundwater.

New gates are being constructed at Pipeclay and Slaney weirs, which are the two main inlets that control flow into Chowilla. Fishways are also being constructed at these sites which will provide permanent fish passage. Ancillary structures are also being built to contain water on the floodplain, including blockbanks and a small regulator on Woolshed Creek (URS 2007).

2.2 Operation of the Chowilla Regulator

The frequency of operation of the Chowilla Regulator is flexible but the intent is to reinstate a natural regime of floodplain inundation so that the frequency of operation is likely to be one in three to four years (South Australian Murray-Darling Basin Natural Resources Management Board, 2009). The Chowilla Regulator can potentially be operated at any flow up to the removal of Lock 6 at 55,000 ML/d (Q_{SA}[2]). In practice the Chowilla Regulator would also need to be removed at these high flows, which would take some time, so that the practical upper limit for operation would likely be less than 55,000 ML/d. The minimum practical inflow (Q_{SA}) for operation of the Chowilla Regulator to achieve some floodplain inundation appears to be approximately 10,000 ML/d. Within this maximum and minimum flow range the Chowilla Regulator can also be operated at any height up to the same height as Lock 6.

If the Regulator is used with high inflows (e.g. 35,000 ML/d to 50,000 ML/d Q_{SA}) the hydrographs upstream and downstream of the Chowilla floodplain would be synchronised with floodplain inundation as per a natural flood (Fig. 1) but the inundation area on the floodplain would be greater. If the Regulator is used with low inflows (e.g. 10,000 ML/d Q_{SA}) these features of the hydrology are not synchronised (Fig. 1); that is, from an ecological perspective, inundation of the floodplain and river hydrology is decoupled. Between these two extremes of operation there is a spectrum of changing synchronisation or decoupling. Modelled hydrology of the River Murray from 1891 to 2006 (South Australian Murray-Darling Basin Natural Resources Management Board, 2009) using 'current' levels of abstraction of flow suggests that half of the managed events could have high levels of synchronisation and half of the events would have low levels of synchronisation.

When the Chowilla Regulator is not being used the new gates at Pipeclay and Slaney weirs can be operated independently. This provides the opportunity to vary the flow in these two major creeks of Chowilla to provide ecological benefits. The two new fishways at these sites would operate continuously.

[2] Q_{SA} is River Murray discharge entering South Australia, which is upstream of all inlets to the Chowilla Floodplain.

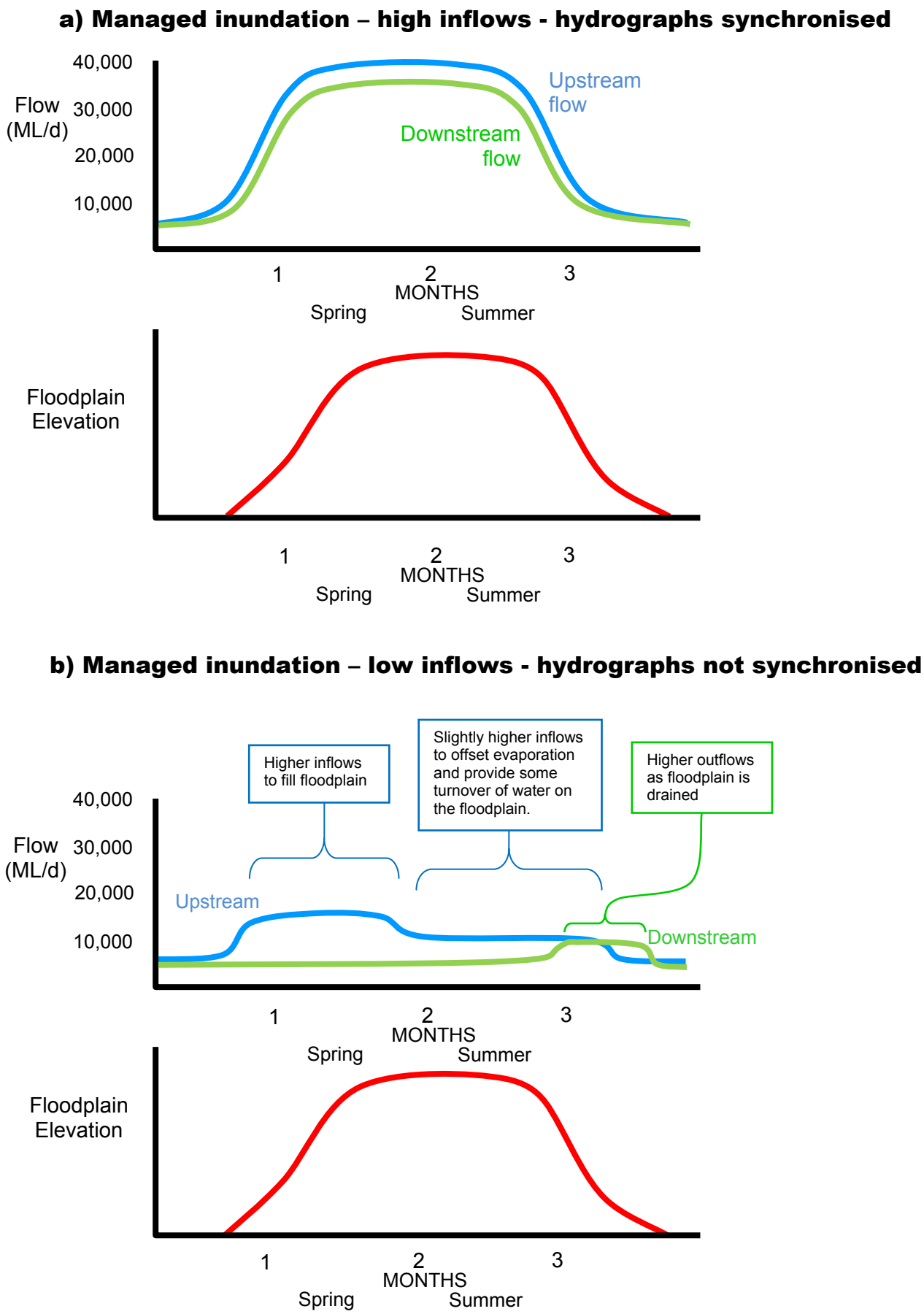

Fig. 1. Conceptual diagram of managed inundations with (a) high and (b) low inflows, showing the changes in synchronisation and magnitude of upstream and downstream hydrographs, and floodplain elevation.

2.3 Geography and Hydrology of the Chowilla Floodplain

Chowilla Creek is an anabranch system with several inlets upstream of Lock 6, and a single outlet downstream of Lock 6 (Fig. 2, Fig. 3). The major inlets are near Lock 6, comprising Pipeclay Creek and Slaney Creek, which have regulating weirs, and Swiftys Creek (Bank I). The minor inlets at the upstream end are Salt (Punkah) and Hypurna Creeks, and near Lock 6 there is Bank E, Boat Creek and Pilby Creek.

There are five major outlying ephemeral lakes (Fig. 2, Fig. 3). Lake Limbra, Lake Littra and Werta Wert are slightly deeper lakes. Lake Littra and Gum Flat have close connections to flood flows in nearby Punkah Creek and the other lakes are a long distance from flood flows in Chowilla Creek.

At low flows more than 50% of total river flow passes through Chowilla. At higher flows, up to 25,000 ML/d, less than 10% of the flow passes through Chowilla. At flood flows greater than 55,000 ML/d, when Lock 6 'drowns out', approximately one-third of the total flow passes through Chowilla. The outlying ephemeral lakes start to be inundated at approximately 40,000 ML/d and the whole floodplain is inundated when flows reach 100,000 ML/d.

Flows and the impact of regulation have been reviewed in the Icon Site Environmental Management Plan 2006-2007 (DWLBC 2006) and by Mallen-Cooper *et al*. (2008). One particular aspect that is useful for management of the Chowilla Regulator is the daily change in water level, as this is one the major tools that can be applied to manage an inundation event. Based on modelled 'natural' data 95% of the time the rises are less than 0.13 m per day and the falls are less than 0.20 m per day. Over the period of modelled data (1891-2006) there have been extreme events with falls between 0.3 and 0.74 m per day but these are very rare. The mean change in water level per day is less than 5 cm rise and 6 cm fall. During high flows (e.g. > 65,000 ML/d) when the floodplain is naturally inundated the change in daily level is small and generally less than 0.10 m per day (Fig. 4). Greater changes in levels occur at lower flows (e.g. < 60,000 ML/d).

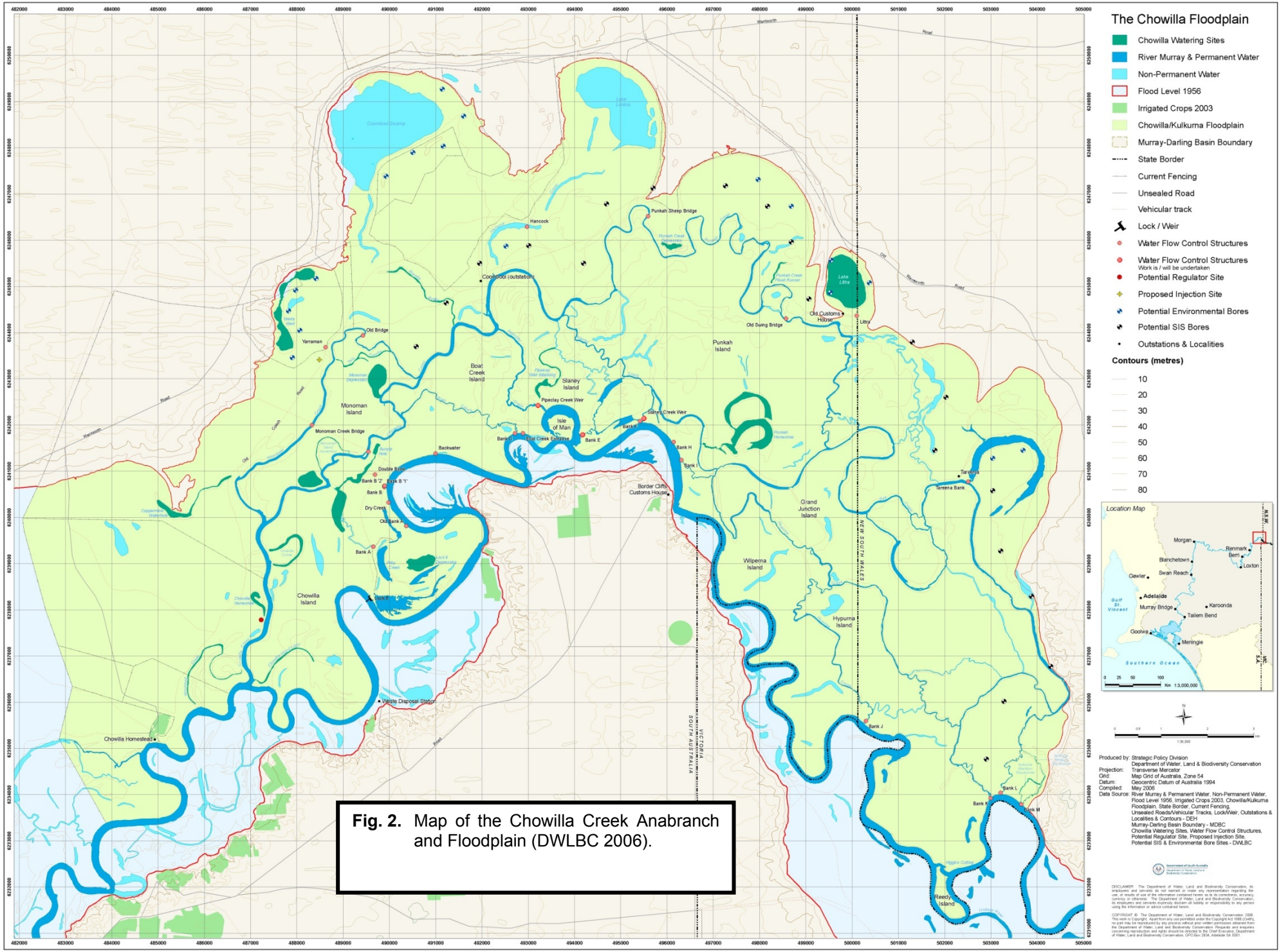

Fig. 2. Map of the Chowilla Creek Anabranch and Floodplain (DWLBC 2006).

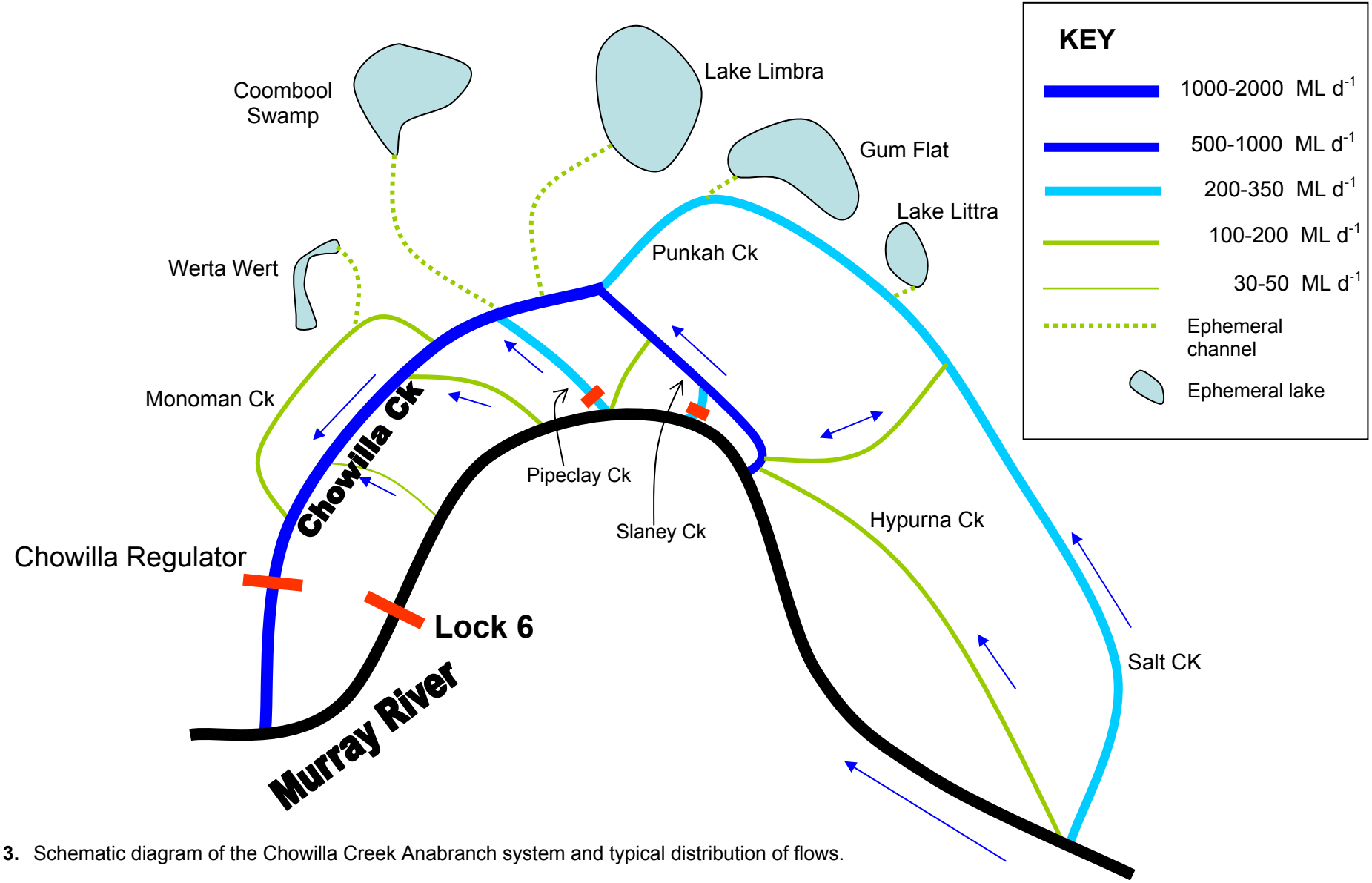

Fig. 3. Schematic diagram of the Chowilla Creek Anabranch system and typical distribution of flows.

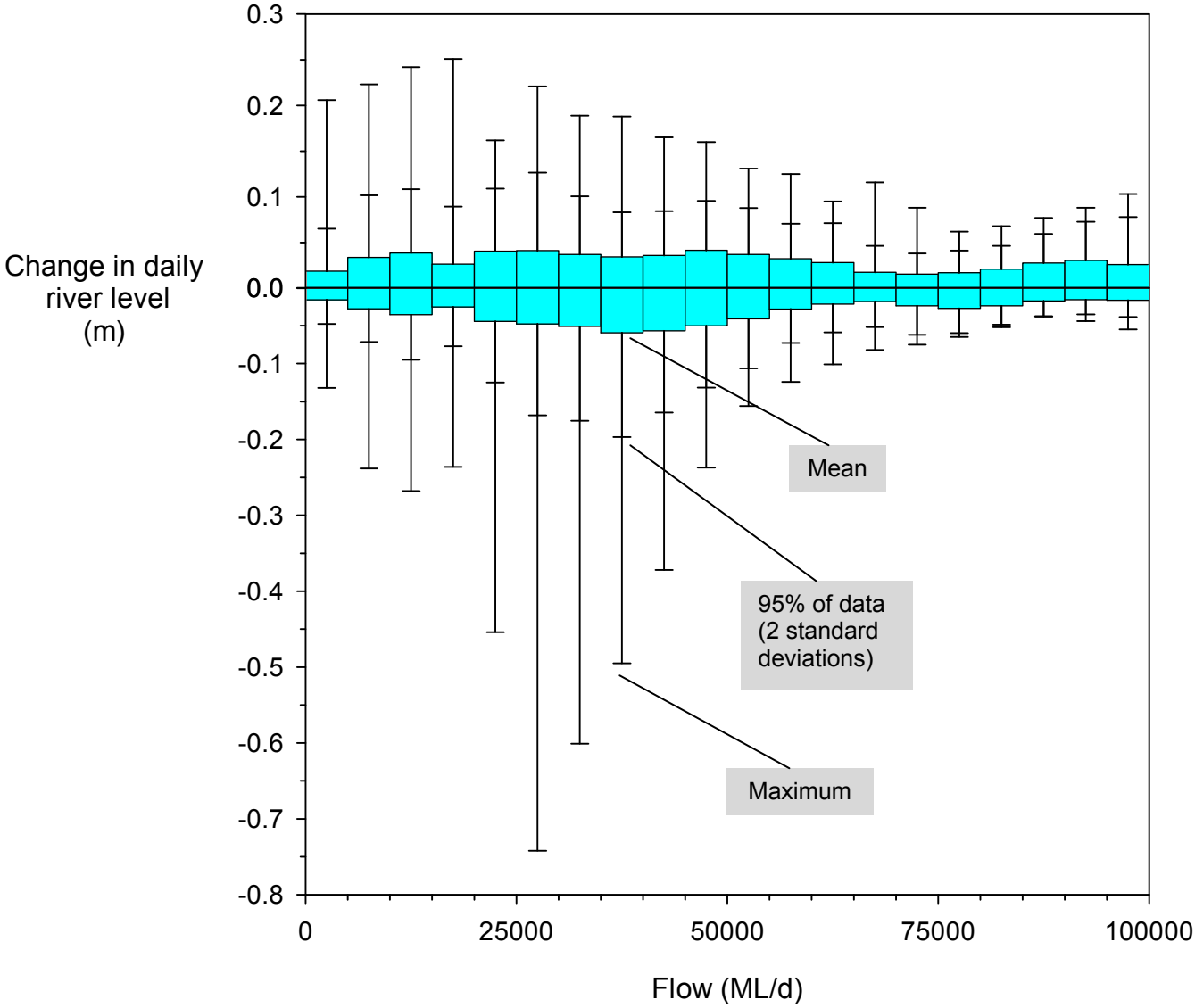

Fig. 4. Modelled 'natural' flow data (1891-2006; MDBA BigMod) showing daily change in water level in the River Murray near Chowilla. For each 5000 ML/d increment the mean, two standard deviations (i.e. 95% of the data) and the maximum values of positive (rising levels) and negative (falling levels) daily changes are shown.

2.4 Aquatic habitats

The Chowilla system is a permanently flowing anabranch system with ephemeral creeks and lakes that create a wide diversity of habitats. The permanent habitats include: creeks that have slow and fast-flowing reaches which vary in discharge, depth, width, instream woody debris, riparian vegetation and aquatic vegetation; and numerous adjacent wetlands, billabongs and backwater areas. The flowing-water habitats and the mosaic of diverse habitats have become rare in the River Murray in South Australia, which is a series of deep, relatively uniform, slow-flowing weirpools except at moderate to high flows.

Ephemeral lakes form the outer floodplain and these vary in flooding frequency, depth and connection to main channels, while there are smaller off-channel habitats such as billabongs that vary in size and inundation period. The aquatic habitats of Chowilla are described in detail by Zampatti *et al*. (2011).

The diversity of habitats reflects the character of the River Murray prior to the construction of the locks and weirs. This diversity supports abundant and diverse fish and as such, the Chowilla system remains one of a few strongholds of native fish in the lower River Murray. These factors contribute to the recognition of the Chowilla system as a Living Murray Icon site.

2.5 Fish diversity and abundance

There were studies of fish in Chowilla before the recent drought (Lloyd, 1990; Nichols and Gilligan 2003) and a four year study during the drought from 2004-2007 (Zampatti *et al*. 2011), while fish sampling of the region presently continues with Icon site Condition Monitoring (B. Zampatti pers. comm.). Table 1 presents a list of the species that are present and a qualitative score of their abundance in Chowilla, which is relative to their trophic level (i.e. large top-level predators are expected to be less numerous than small omnivorous fish). Of particular significance is the abundance of Murray cod and golden perch. Murray cod are consistently more abundant in Chowilla than in the nearby River Murray. Golden perch, on average, are also more abundant in Chowilla (Zampatti *et al*. 2011). These two species are particularly associated with fast-flowing creeks in Chowilla. These creeks and the mosaic of habitats closely associated with them are considered *core habitats* (Fig. 5) and are likely to be key spawning and nursery habitats for Murray cod.

The Murray cod population appears to be similar in abundance and size distribution to that present in the nearby Mullaroo Creek system in Victoria, which is recognised as a significant region for Murray cod (J. Koehn, pers. comm.).

Fish species that have distributions which overlap with Chowilla but have not been recorded are also listed (Table 1). There is a single record of a Murray hardyhead, a threatened species, from Lake Littra (Nichols and Gilligan 2003).

Table 1. Fish species in Chowilla (red are non-native species).

		Abundance in Chowilla Abundant ●●● Common ●● Rare ●
Medium- and Large-bodied species (100-1400 mm)		
Bony herring	*Nematalosa erebi*	●●●
Murray cod	*Maccullochella peelii peelii*	●●
Golden perch (callop)	*Macquaria ambigua*	●●
Silver perch	*Bidyanus bidyanus*	●
Freshwater catfish	*Tandanus tandanus*	●
Spangled perch	*Leiopotherapon unicolor*	●
Common carp	*Cyprinus carpio*	●●
Small-bodied species (< 100 mm)		
Unspecked hardyhead	*Craterocephalus stercusmuscarum fulvus*	●●●
Carp gudgeons [1]	*Hypseleotris* spp.	●●
Australian smelt	*Retropinna semoni*	●●●
Murray rainbowfish	*Melanotaenia fluviatilis*	●●●
Flathead gudgeon	*Philypnodon grandiceps*	●●
Dwarf flathead gudgeon	*Philypnodon* sp.	●
Gambusia	*Gambusia holbrooki*	●●
Goldfish	*Carassius auratus*	●●
Oriental weatherloach	*Misgurnus anguillicaudatus*	●
Species not regularly recorded in Chowilla but within range		
Murray hardyhead	*Craterocephalus fluviatilis*	(1 record from Lake Littra)
Shortheaded lamprey	*Mordacia mordax*	
Pouched lamprey	*Geotria australis*	
Olive perchlet	*Ambassis agassizii*	
Purple-spotted gudgeon	*Mogurnda adspersa*	
Southern pygmy perch	*Nannoperca australis*	
Flatheaded galaxias	*Galaxias rostratus*	

[1] A species complex that includes five or more species yet to be taxonomically defined (Bertozzi *et al*. 2000).

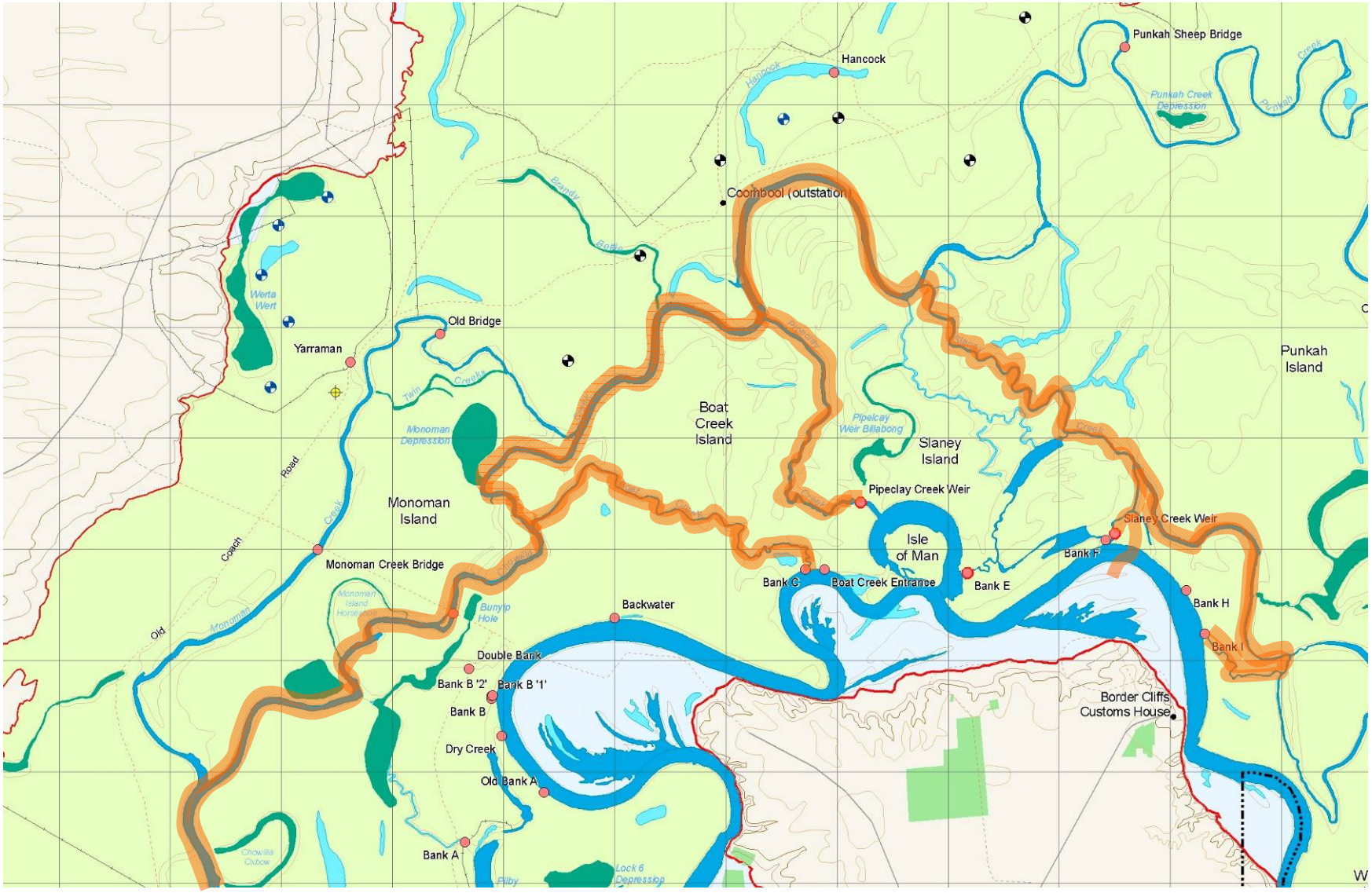

Fig. 5. *Core habitats* (shown in orange) that have complex hydrodynamics, including fast- and moderate-flowing reaches.

3 METHODOLOGY

The project method had five steps:

1 Background material.

The material was collated, reviewed and used for the conceptual models.

2 Conceptual models.

Broad conceptual models were developed for the fish species previously identified 'at risk' (Mallen-Cooper *et al*. 2008) and carp, a non-native species that was identified as a significant risk. The models included movement, spawning and recruitment of these species in Chowilla and, where feasible, other sites in the southern Murray-Darling Basin.

3 Hydrodynamic modelling.

The hydrodynamic modelling, done by Water Technology, incorporated flow, velocity and depth, of the Chowilla system, Lindsay-Mullaroo system and the adjacent River Murray from Lock 5 to Lock 7. The scenarios included:

i. 'Natural' flows without Locks (i.e. pre-regulation).

To enable comparisons with present conditions and the operation of the Chowilla Regulator.

ii. Present regulated river (i.e. 'do-nothing' scenario).

This scenario did not have any of the planned infrastructure but had access to the same environmental flows.

iii. Present regulated river with Pipeclay and Slaney weirs adjustable (i.e. with no Chowilla Regulator).

This scenario was aimed at assessing the scope to use Pipeclay and Slaney weirs on a regular basis to enhance fish habitats.

iv. Chowilla Regulator raised incrementally using maximum inflows of 10,000 ML/d, with Lock 6 at a) normal pool and b) raised 0.62 m (i.e. maximum).

This represents a low-inflow scenario where upstream and downstream hydrographs and floodplain inundation are poorly synchronised.

v. Chowilla Regulator raised incrementally using maximum inflows of 20,000 ML/d, with Lock 6 at a) normal pool and b) raised 0.62 m (i.e. maximum).

This represents a moderate-inflow scenario where upstream and downstream hydrographs and floodplain inundation would be more synchronised than the low-inflow scenario.

Note that a high-inflow scenario (e.g. 45,000 ML/d) was not modelled as the assumption is that the hydrodynamics and synchronisation of hydrology would be similar to a natural flood.

vi. Modelling of the upper Lock 6 weirpool with lower weirpool levels to generate more flowing-water habitats and hydraulic diversity.

These scenarios investigated the rehabilitating of flowing-water habitats as a potential mitigation and offset.

4 Workshop.

The workshop aimed at applying the conceptual models to the hydrodynamic modelling with the specific objectives of:

i. Identifying risks and benefits for fish (likelihood, consequence, certainty) of the various operating scenarios, based on an event scale and regime scale.

ii. Identifying knowledge gaps.

iii. Providing a monitoring framework that links back to short- and long-term operations.

iv. Providing a recommended operating strategy that minimises risks for fish and provides floodplain benefits.

5 <u>Prepare Report</u>

4 CONCEPTUAL MODELS

4.1 Introduction

Conceptual models are representations of complex systems that use available data and the present understanding of causal factors to show links, interactions and processes. They are usually pictorial or diagrammatic but can also be a concise description in text, which we have used here. The strength of conceptual models is that they link components of a system together to present a holistic view. The model, and the process of constructing the model, can highlight knowledge gaps, identify research and monitoring priorities, and clarify and synthesise thinking.

A potential weakness of conceptual models is that the relative strengths of various links, based on the data, are often not explicit and the model can sometimes be viewed as having more validity than the data suggests. Conceptual models need to be viewed as a tool that needs constant review and updating. They are presented in this report as a resource to describe the present understanding, and they need to be constantly refined as new data becomes available.

Conceptual models are presented in this section for the native fish species that have previously been identified as negatively impacted by the Chowilla Regulator (Mallen-Cooper *et al*. 2008), including Murray cod, golden perch, silver perch and freshwater catfish, and for the non-native carp which is expected to benefit from managed inundations. Bony herring is a large-bodied native fish species that is present in Chowilla but a conceptual model is not presented here as it is not considered at risk and is likely to benefit from large-scale managed inundations.

The objective of the conceptual models is to inform management of the Chowilla Regulator and is not intended for a wider readership. Hence, the conceptual models are presented as text summaries in point form to provide a higher level of detail to aid management, rather than a pictorial or diagrammatic model. As Murray cod is a species of particular interest for this project, a diagrammatic model of spawning and recruitment is added to the text model for added clarity.

To identify the strengths and weaknesses of each model a section on *Caveats* is included. The models are then used to identify knowledge gaps, or components of the model with the least data, and these form the hypotheses for monitoring which are coarsely ranked as *Moderate, High*, or *Very High* priority. The hypotheses are worded as topics for clarity in the context of the present report, rather than formal hypotheses for experimental design.

A significant question for the present project is 'How will fish respond to a changed environment during a managed inundation?' The conceptual models help address this issue. For two of the native fish species, Murray cod and golden perch, there are well-studied populations elsewhere in the southern Murray-Darling Basin that could inform the response of fish in Chowilla. Hence, the key features of these populations are summarised to help identify habitat flexibility and adaptability to change.

For the conceptual models of fish the following definitions are used:

> **Recruitment:** high survival of larvae and young fish in the first year (i.e. 0+).
>
> **Lotic:** refers to flowing water, but includes a diverse mosaic of hydraulic habitats with fast-flowing reaches and slow-flowing edges, backwaters and bends, which produce a variety of depth, water velocity and turbulence that occurs vertically, horizontally and longitudinally in the water column.
>
> **Lentic:** refers to stillwater, such as weirpools or lakes and has less diverse hydraulic habitats.

Conceptual models of carbon transport and productivity are discussed as these have a direct bearing on the benefits for fish on the floodplain and the river, as well as the broader ecological objective of rehabilitating the Chowilla floodplain to become a functioning part of the river ecosystem.

4.2 Carbon Dynamics

4.2.1 Introduction

In riverine ecosystems, the supply of organic carbon, the energy source for living organisms, comes from four major sources:

- Phytoplankton, free-living algae and photosynthetic micro-organisms in the water column,
- Periphyton, photosynthetic micro-organisms attached to the river substrate and other submerged surfaces such as rocks, snags, aquatic plants, and anthropogenic structures,
- Aquatic plants, submerged and emergent, and
- Terrestrial plants, plant litter that falls directly into the river channel or is moved there by wind or flood waters.

These are autotrophs, getting their energy from light and their carbon from CO_2. Fish and all other vertebrates are heterotrophs deriving their energy and carbon from autotrophs either directly or indirectly through other heterotrophs. Fish population dynamics in Chowilla, therefore, is dependent on carbon dynamics. The supply of carbon and early pathways from bacteria to phytoplankton to one of the first levels of heterotrophs, zooplankton, is of particular interest in fish ecology, as the survival of fish larvae is acutely dependent on the abundance, distribution, and size of plankton.

The fact that different native fish species in the lower River Murray and Chowilla have survival of larvae in low flow periods and in floods demonstrates that carbon is actively being utilised in these conditions and these early pathways producing plankton are also active. The supply of carbon to riverine foodwebs is, however, very poorly understood. The following is a brief review of current concepts in carbon dynamics in large rivers with a conceptual model for Chowilla.

4.2.2 Current Concepts of Carbon Dynamics in Large Rivers

In terms of generalised concepts, valuable components of past models - River Continuum Concept (Vanote *et al.* 1980), Serial Discontinuity Concept (Ward and Stanford 1983), and the Flood Pulse Concept (Junk *et al*. 1989, Ward and Stanford 1995) - have been synthesised in an attempt to create a cohesive view of riverine function at the large scale, termed the Riverine Ecosystem Synthesis (Thorp *et al.* 2006, Thorp *et al*. 2008). The main features of the RES, which is conceptually wide-ranging, involve dividing the river into 'functional process zones' (FPZ) delineated by geomorphological characteristics that are, in turn, reflected in ecological process. FPZs are arranged along a river in a general order that reflects characteristics evident in earlier models, but, as they are defined by internal consistency of process (and internal connectivity) they may be broken up and juxtaposed by artificial or natural discontinuities. The RES contains a number of tenets (Thorp *et al.* 2006) that contain propositions (generalised hypotheses) about processes within and across FPZs. These tenets are presented, often with limited published support, more as testable hypotheses for further research than as strong assertions or laws, and the RES as a framework within which to develop further research. However, it should be noted that Tenet 9 (Thorp *et al.* 2006) indicates that primary production within the channel (primarily algae), averaged over a year and the length of the river, produces "*>50% of the energy supporting metazoan* [~multi-celled animals] *production in channel and slackwater sites*". Several references quoted indicate low contributions from allocthonous (external) sources.

The challenge to further research represented by the (perhaps counter-intuitive) inference that floodplain vegetation contributes little to riverine carbon dynamics has resulted in scientific investigation (as distinct from conceptual development) in a number of rivers. A recent review (Tank *et al.* 2010) traversed the available literature thoroughly (some 376 refereed papers and book chapters) but failed to establish a unified view, let alone a general conceptual model, of the main sources, paths, or pools of organic carbon in riverine systems – echoing Webster and Meyer's (1997) observation that because of climate and other geographic exigencies, global comparisons of patterns were unlikely to provide informative predictors of stream function.

Tank *et al*. (2010) recognize the over-representation of temperate forested streams in North America and the biased view of carbon dynamics that may result. For instance, although there is a plethora of

papers dealing with the supply and fate of POM (Particulate Organic Carbon) from terrestrial plant litter only 7 examine potential floodplain inputs (as distinct from upland forest inputs) and none deals with a river remotely similar to, say, the lower River Murray. Of course there are very valuable transfers of learning between studies. Processes such as the breakdown of leaf material, microbial mediation, or the role of particular guilds of macroinvertebrates, are roughly similar in all rivers at a particular level of detail. But the juxtaposition of these processes and their relative importance in carbon dynamics at the large spatial (landscape) and time[3] scale appear to vary greatly. The review by Tank *et al* (2010) provides few synthesising oversights and a quantity of apparently contradictory conclusions drawn by researchers around the world. This appears to stem primarily from the fundamentally different nature of the rivers studied - from the Amazon (Junk *et al.* 1989) to episodic desert streams (Schade and Fisher 1997) – and the spatial and temporal bounds within which the carbon and its fluxes are quantified. Also the functional differences between particulate material deposited on/in the river substrate versus dissolved or suspended material (including phytoplankton) is not addressed. Whatever the cause, the development of an incontrovertible (or even uncontroversial) conceptual model for the River Murray system at Chowilla on the basis of other such models is extremely problematic.

4.2.3 Conceptual Model of Carbon Dynamics in Chowilla

In the absence of a reliable generalised model we may need to develop an understanding of carbon dynamics on a case-by-case basis. In the absence of data this has to be done on first principles. Perhaps most importantly, carbon dynamics in the lower River Murray remain a major knowledge gap and warrant urgent investigation.

The Murray system at Chowilla can be viewed as being comprised of three components differentiated by their hydrology and their ecological responses. They are the *channel* (the main river channel plus free-flowing anabranches), *water-shedding zones* (the areas that support terrestrial vegetation and which are left without significant surface water when a flood recedes), and *water-retaining zones* (billabongs, ephemeral anabranches, floodplain depressions, that hold standing water after the flood recedes and which, at least episodically, support aquatic ecosystems). The latter two, the floodplain components, differ in their response to flooding and in the types and quantities of organic carbon and other resources they supply. In the following model the responses in the three system components are tracked through the four phases of an inundation event:

1. Initial Inundation

Physical Outcome:

- Water moves onto the floodplain, wetting previously dry water-shedding and water-retaining sediments.
- Under flood conditions, alluvial sediment deposited on floodplain.

Water-shedding Zone:

- Upper soil water and stringers recharged, vegetation 'watered'.
- 'Wet' responses (of wet-dry processes) triggered. These include uptake into solution of nutrients, organics, and salt, made available by past evaporation at the soil surface or by death and decomposition of soul microbes (from past desiccation). Microbial biomass increases rapidly and diversifies in soil and overlying water.
- In addition to normal metabolic responses to watering, vegetation also responds to cues. In the case of red-gum this may take the form of seed-drop and dispersal.

Water-retaining Zone:

- Inundation of previously dry wetland sediment results in the typical 'wet' response described above.
- Buoyant plant litter is mobilised and CPOM may be moved.
- In wetlands that retained some water prior to inundation refugial conditions for fish populations are relieved.
- Wetland plant regrowth/seed dispersal stimulated.

[3] Cummins *et al*. (1983) and Tank *et al.* (2010) highlight the potential significance of rare events in the total carbon transport system of rivers.

Channel:

- Upper banks wetted (with some possible geomorphic consequences).
- Backwaters scoured with possible movement of organic material and biota (to floodplain or downstream).
- Some fish species (native and alien) stimulated to move onto floodplain.

2. Flooded Period

Physical Outcome:

- Although levels may fluctuate water covers water-shedding (and water-retaining) zone.
- At sites where saline groundwater incursion presents a threat, flood-water may provide an opposing head.

Water-shedding Zone:

- As the flooded period progresses microbial activity involved in breaking down of organic material can depress dissolved oxygen to zero switching decomposition to anaerobic (nitrogen concentration, pH, phenolics).
- Duration of inundation determines competitive advantage of flood-adapted species and also removes other invasive, non flood-tolerant, vegetation species amongst grasses, forbs, and sedges.

Water-retaining Zone:

- Wetting of wetland sediment initiates a productive succession which commences with the release of dissolved organic matter followed by blooms of micro-organisms (in 1-4 days) and microinvertebrates (microcrustacea, rotifers etc.) in 10-14 days. The latter represent a concentrated source of larval fish food if they come in contact.

3. Receding Inundation

Physical Outcome:

- In most circumstances the receding flows result in the return of a significant volume of water from the water-shedding zone as well as the “over capacity” water from wetlands to the river channel

Water-shedding Zone:

- If anoxic conditions have occurred recession of water results in aeration of upper strata of soil and remaining litter.
- Germination amongst terrestrial plants may commence – particularly along “flood-line”.
- Where flow in returning water is sufficiently powerful, forest litter is transported to the channel zone.

Water-retaining Zone:

- Wetlands return to maximum volume.
- Returning water from wetlands transport the results of enhanced productivity to channel system. This will consist of dissolved organic material and inocula of bacteria and/or microinvertebrates in ratios that are dependent on the duration of the flood.
- Fish would become isolated in wetlands. The biomass of fish and the diversity of species would be dependent on the size and depth of the wetland, duration of inundation, recession rates and the degree of connectivity.

Channel:

- Inputs from floodplain systems return to declining volumes of water in the channel. Where inundation has occurred in warmer periods (likely to be as a result of management) returning water may have a substantial oxygen debt or contain significant concentrations of phenolics. This seems unlikely at Chowilla due to limited tree cover.
- Backwaters are ‘reinstated’ perhaps inoculated with bacteria and microinvertebrates from flood inputs. This may create effective fish nurseries.

4. Post-inundation

Physical outcome:

- Water-shedding zones return to terrestrial-based ecosystems and wetlands commence gradual drying cycle through seepage and evaporation.

Water-shedding Zone:

- When partially dry, soils/sediments support increased aerobic microbial activity and an increase in adsorption of nutrients to inorganic and organic particles (potentially reducing availability). Movement of soil water to the surface followed by evaporation will lead to a gradual deposition of solutes at the surface. Complete dehydration will lead to the suppression of microbial activity and breakdown of microbial biomass.
- Where inundation has been seasonally appropriate, recruitment amongst many plant species will commence. Trees respond to adequate water supply including increased productivity (and possibly temporary reduction in leaf-fall/litter production).

Water-retaining Zone:

- High productivity, initiated by inundation, continues to progress as does an increase in diversity, particularly amongst wetland plants and invertebrates. Wetland productivity supports terrestrial diversity and biomass notably amongst birds and bats (with trees supplying suitable habitat diversity).
- Depending on the degree and duration of connectivity and the diversity of hydrological condition (e.g. permanence/ephemerality) there will be significant differences in the species composition and biomass of fish assemblages amongst wetlands. As fish are high-order predators in these systems, these differences will result in substantial variation amongst other organisms. For instance frog recruitment and diversity appear to be highly dependent on fish predation (Wassens and Maher 2010).

Channel:

- Any importation of floodplain litter reinforces the contribution of terrestrial primary production to the riverine food web. POM supports a number of invertebrate groups – insect larvae and crustaceans such as yabbies. Because of their resistance to complete breakdown, litter products provide a valuable long-term source of carbon.

4.2.4 Assessment of a Managed Inundation

With regard to carbon dynamics it seems likely that an artificial managed inundation will result in a favourable outcome compared to no flood (or the current situation) in all circumstances, subject to reasonable parameters of timing, duration, etc. The following discussion is loosely based on a comparison with a 'natural' flood (i.e. one generated by high flows moving down the river) covering a similar area of floodplain at Chowilla. The assessment is divided into Floodplain Hydraulics and Forms of Carbon.

FLOODPLAIN HYDRAULICS

Proportion of flood water returning to the River Murray channel. Given that the only geomorphic change is the weir at Chowilla, this statistic might be considered unchanged. However it should be noted that a 'natural' flood would require considerably more water to cover the same area for a period.

Area inundated. On the Chowilla floodplain itself this is the same as the 'natural' flood by definition. Effects in other nearby reaches are, of course, different.

Power. Stream power across any inundated floodplain will be a mosaic, dependent on the volume (depth) of water, roughness, and geomorphology at a number of scales. It is very likely that inundation backing up from a weir would exert significantly less power than one resulting from down-river movement of large volumes of water, even though, in flat wide floodplains such as Chowilla, much of the flow would be slow and lateral. Flow velocities at the recession phase of an artificial flood could be manipulated to some extent to manage the power of returning water. This factor should be included along with other local affects of the rate of return and the potential for down-stream outcomes in any investigation to determine an optimum draw-down pattern.

FORMS OF CARBON.

DOM. Floodwater dissolves soluble organic carbon from the floodplain soil and from dry organic material on the surface. Organic carbon, once in the water column, changes over time (e.g. through microbial action, dependent in turn on the level of dissolved oxygen, and by the action of sunlight breaking down phenolics) but essentially stays 'incorporated' in the water until it returns to the river channel or is 'lost' to other systems. Clearly a considerable proportion of the organic carbon available for solution is taken up early in an inundation event. Potentially, with the reduced volume to area ratio of the artificial inundation, return water might be expected to return a higher concentration of DOC to the channel in the immediate vicinity, though its effect may be less on a larger regional scale.

CPOM. The quantity of coarse organic material returned from inundation of a given area of a floodplain is mainly dependent on the productivity (particularly vegetation) of that area and the power of the flood water. As noted above, artificially flooding by backing up the river may result in less power from the movement of flood water. The Chowilla floodplain is sparsely treed, though it should be noted that most of the eucalypts present are relatively close to the banks of the main stream and anabranches, perhaps making litter relatively accessible to over-bank flows of sufficient power. The potential behaviour of coarse material from the grasses and forbs of the open floodplain is unknown. It seems likely that a 'back-up' flood will yield significantly less CPOM to the river than an equivalent area of 'flow-through' flood and certainly that the yielded CPOM would be restricted to the channel in the immediate vicinity. No scientific evidence (either way) exists.

FPOM. As might be expected, the behaviour of FPOM is probably between DOM and CPOM. But, as it is suspended in the water column rather than dissolved, its dynamics are to some extent dependent on water movement. Where FPOM is dealt with specifically in conceptual river system models (see Section 4.2.2), in-stream processing of CPOM upstream is often identified as an important source. The significance of this process in the Murray is unknown but is certain to have been substantially reduced by current management infrastructure and practice.

4.3 Fish Recruitment

The native fishes of the MDB demonstrate five life-history modes, reflecting the duration of spawning, spawning style and time, cues for spawning, fecundity and parental care:

1) *Circa-annual spawners, parental care, low fecundity* (relates to Humphries *et al.* (1999) Mode 1). Two large-bodied species (e.g. Murray cod, freshwater catfish) and one small-bodied species (purple-spotted gudgeon), which spawn in spring/early summer, and at the same time each year. Spawning is circa-annual and temperature related, from thousands to tens of thousands of eggs are laid demersally and subject to parental care.

2) *Circa-annual spawners, no parental care, high fecundity*. Represented by only one species, the large-bodied bony herring, which spawns in early summer and has litho-pelagic (i.e. demersal, then pelagic) larvae. Females spawn once but males may spawn multiple times.

3) *Circa-annual spawners, no parental care, low fecundity* (Humphries *et al.* (1999) Mode 3b). These are small-bodied species, with a single spawning event from late winter through summer. Mostly small-bodied species, including carp gudgeons and Murray rainbowfish.

4) *Flow-cued spawners, no parental care, high fecundity* (Humphries *et al.* (1999) Mode 2). Large-bodied species (e.g. golden perch, silver perch) that may spawn at any time between spring and autumn. Spawning is linked to a rise in flow and is related to temperature. Hundreds of thousands of semi-buoyant eggs are laid and no parental care is exhibited.

5) *Protracted spawners, no parental care, low fecundity* (Humphries *et al.* (1999) Mode 3a). Mostly small-bodied species (e.g. Australian smelt, flatheaded gudgeon) that have protracted, repeat or serial spawning from spring to autumn. Spawning cues are uncertain; from hundreds to thousands of pelagic or demersal eggs are laid and no parental care is exhibited

In general, the only species that require a increase in flow or a flood to spawn are the flow-cued spawners, golden perch and silver perch, and strong recruitment of these species coincides with in-channel rises in flow and overbank floods (Mallen-Cooper and Stuart 2003; Ye 2004). Although flooding is often a stimulus for production of fish in floodplain rivers (Junk *et al.* 1989), it appears that in the southern MDB most species use floodplains opportunistically and only four native species are obligate users of floodplains (or wetland / off-channel habitats): southern purple-spotted gudgeon, southern pygmy perch, flat-headed galaxias and Murray hardyhead. These species are all small-bodied and use permanent wetland habitats. They are also all threatened species, which probably reflects the degradation of these habitats. There is no evidence of native species being obligate users of ephemeral floodplains for spawning and recruitment (Humphries *et al*. 1999; King *et al*. 2003), although a number of common species (e.g. bony herring, Australian smelt) and less common

species (e.g. golden perch and catfish) will opportunistically use them. The one large-bodied species that specifically uses these habitats for spawning is the non-native common carp (King *et al.* 2003).

Most native fish species will spawn and recruit in the river channel, but it is highly likely that increased productivity from floodplain inundation benefits recruitment. Strong recruitment in some circa-annual and flow-cued spawners (i.e. Murray cod and golden perch) has been associated with overbank flows (Ye 2004; Rowland 1998; Ye and Zampatti 2007) and, if floods coincide with spawning, food from the floodplain may be transported back into the river channel, enhancing recruitment (Humphries *et al.*, 1999). Nevertheless, the role of the floodplain and overbank flows in the recruitment ecology of large-bodied fish in the lower River Murray remains little explored.

4.4 Murray cod

4.4.1 Conceptual model of Murray cod in Chowilla and the adjacent River Murray

- **Habitat**: 1+ to adult fish preferentially use lotic anabranch habitats with larger fish in larger streams; adult fish also use lentic main-stem habitats. Lotic habitats in anabranches are a permanent feature in low and high flows.
- **Spawning**: Occurs in spring (late September/early October), independently of flow, in both lotic and lentic habitats.
- **Recruitment**: Survival of larvae and 0+ fish is higher in hydraulically-diverse lotic habitats. Epibenthic and littoral zones in these habitats are important for young fish and these zones are clearly differentiated by low water velocity on the margins of high water velocity. Larvae either drift to, or actively seek, these zones in lotic habitats where food is more accessible, more diverse in size, and/or more abundant.

  During low flow periods and within-channel rises in flow, recruitment of larvae and 0+ fish is poor in the lentic main-stem habitat, possibly due to: low abundance of food for larvae, poor access to food due to the homogenous distribution of plankton in the low velocity habitat, or poor dispersal of the drifting larval which could lead to density–dependant factors. Recruitment improves in main-stem habitats during overbank floods which also coincides with the removal of weirs and increased hydraulic diversity.

  A conceptual model of spawning and recruitment of Murray cod in Chowilla is shown in Fig. 6 as a flow chart.
- **Movement**: Adult fish (approx. > 750 mm) generally move within a small home range (5 km) in summer, autumn and winter. In spring adult fish either: i) continue to move little or ii) move actively up to 25 km between main-stem and anabranch habitats. These movements appear to be for spawning. The larger adult fish (> 950 mm) move between 5 and 25 km and smaller fish generally < 5 km. Most fish return to home sites. A low number (<10%) of large adult fish appear to move constantly (year round) between sites in the anabranch and the main-stem of river, spending short periods at each site.

  Proposed model for adult movement:

  1. Large males establish a small home range in Autumn / Winter and remain until spring after which they shift home range.
  2. Females move more in spring, visiting males at established spawning sites.

  Movement of sub-adult fish is very limited (< 5 km). Emigration rates for sub-adult and adult fish are very low in low-flow years (e.g. 45 tagged fish remained within 25 km; Zampatti pers. comm.); however, relatively homogenous genetics of the Basin population (Rourke *et al*. 2010) indicates a low (e.g. 10 fish per generation) but ongoing rate of dispersal. Larvae would contribute to provide emigration downstream and in a flood would likely drift further than the recorded movements of adult fish.

Caveats: The above model is based largely on data collected within an extended drought.

Data quality: The data on habitat, spawning and movement of adult fish are specific to Chowilla and are robust, while data on habitats and survival of larvae and 0+ fish are poor.

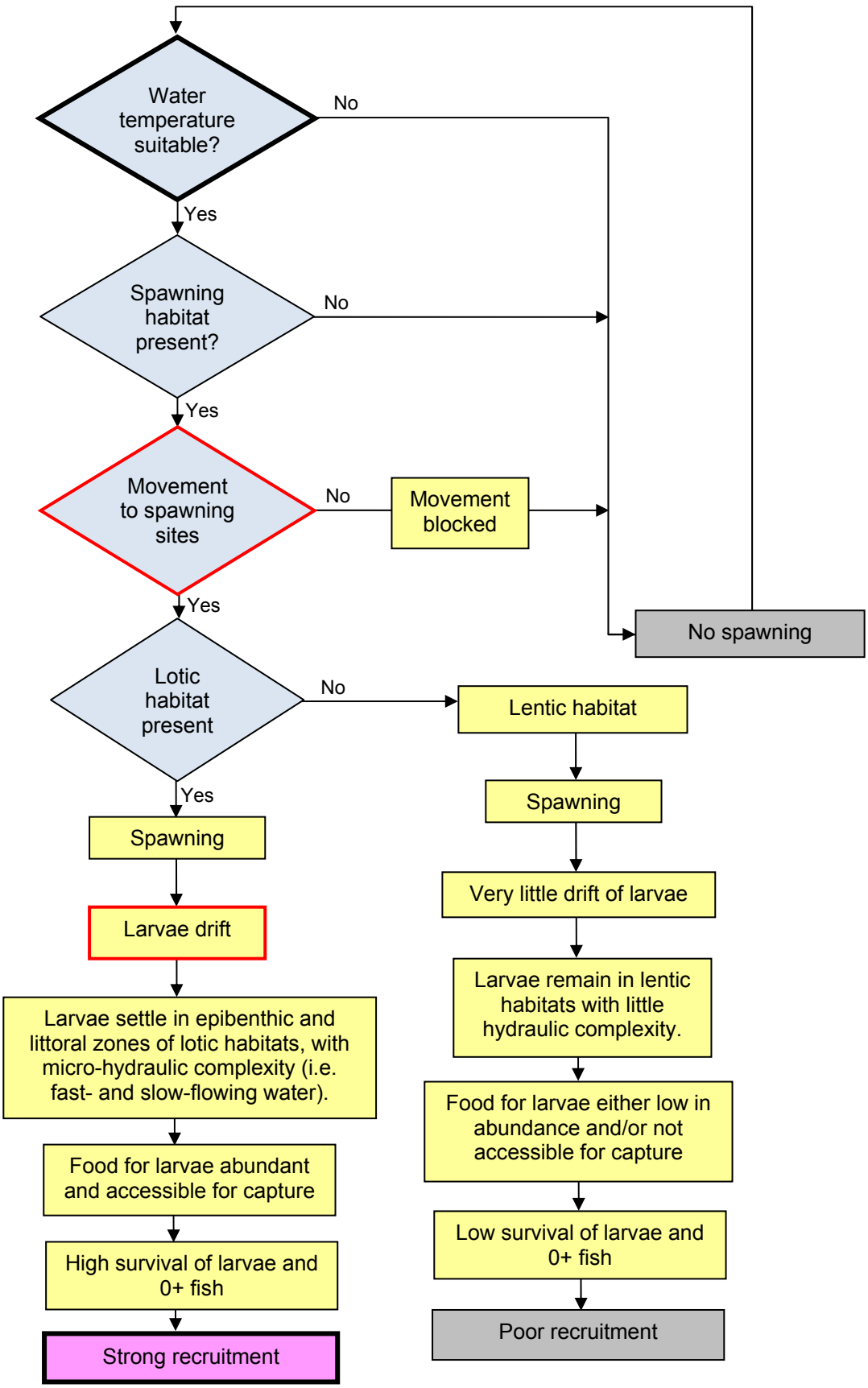

Fig. 6. Conceptual model of spawning and recruitment of Murray cod in Chowilla. Red outline of shapes indicate fish movement.

Table 2. Knowledge gaps and hypotheses for monitoring of Murray cod.

Knowledge gaps (components of the model with the least data)	**Hypotheses for monitoring**
Very High Priority	
• Survival of larval fish in relation to diet – in lotic, lentic and floodplain habitats (including food availability, composition and abundance in these habitats).	H_1
• Survival of larvae in relation to habitat use at low and high flows.	H_2
• Emigration and immigration of immature fish.	H_3
High Priority	
• Habitats of 0+ fish.	H_4
• Distance of larval drift.	H_5
• Movement of fish between Chowilla anabranch creeks and the River Murray	H_6
• Movement of fish in a natural flood, including lateral, longitudinal, emigration and immigration.	H_7
Moderate Priority	
• Limitations of spawning site abundance.	H_8
• Emigration and immigration of mature fish.	H_9

4.4.2 Features of studied populations of Murray cod elsewhere in the southern Murray Darling Basin

Lower Murray (downstream of Chowilla)

- **Lotic habitats only occur in high flows.**
- Uniform lentic habitats of continuous weirpools at the most common (entitlement) flows.
- River channel becomes a lotic habitat at high flows (> 20,000 ML/d); with significant overbank flows at > 40,000 ML/d.
- Present model is spawning every year.
- Recruitment occurs in high flow years when the river is a lotic habitat with overbank flows.
- Little movement data.

References: Ye and Zampatti (2007).

Lindsay River / Mullaroo Creek (lower River Murray)

- **Upstream lotic habitats (Mullaroo Creek) are a permanent feature** since 1934.
- Downstream lentic habitat (Lower Lindsay River) a permanent feature since 1930.
- Adult fish move from lentic to lotic habitats in autumn and remain there till spring.
- Spawning occurs in lotic habitats (larvae have been collected [C. Sharpe pers. comm.]).

References: Todd and Koehn (2007), Saddlier *et al*. (2008).

Lake Victoria (lower River Murray)

- **Off-stream lake storage filled during spring**.
- Lake Victoria is filled from the River Murray (Lock 9 weir-pool), mostly during spring.

- Inflows to the lake are often greater than passing flows in the River Murray.
- Murray cod are present in Lake Victoria but the source of this population is uncertain. The lake may be acting as 'sink' for larvae, juvenile and adult fish because of the high proportion of River Murray water that is used to fill the lake, and the fact that these fish are trapped in the lake due to the lack of passage at the inlet and outlet regulators. Alternatively, fish are spawning in the inlet channel, upstream and downstream of the inlet regulator, which provides between 0 to 20 kilometres of flowing water habitat, depending on the lake level and inflows.
- Records of commercial fishing show between 0-2490 kg of Murray cod were caught per annum from 1957-1994. However, the maximum catch is a relatively small commercial figure considering that up to 13,027 kg of cod per annum were caught in the adjacent River Murray in NSW in the same period (Reid *et al*. 1997). There are also nine years of the commercial catch data where less than 25 kg of Murray cod were caught per year in Lake Victoria, although other fish were caught. This indicates that the population was variable and there was not consistent recruitment within the lake habitat and the inlet channel, as is reported for populations in Chowilla and Mullaroo Creek.
- Despite the commercial data, the source of the Murray cod in Lake Victoria is unknown and little can be stated about the ecology, except it appears that Murray cod are not abundant compared with populations in the adjacent River Murray.

Lower Darling River

- **Lotic habitats commonly occur in spring** (flow data in Appendix 1) and lentic (pool) habitats created in very low and zero flows.
- Some lotic habitats occur in the lower Darling at low flows (e.g. 200 ML/d) because of the confined channel in some reaches.
- No movement data of fish.

References: Ellis and Meredith (2004), C. Sharpe, unpublished data.

Middle reaches of River Murray – Yarrawonga Weir to Torrumbarry Weir

- **Lotic habitats are a permanent feature**
- 280 km of lotic habitat (River Murray) a permanent feature, upstream of Torrumbarry weirpool, a lentic habitat that is 74 km long
- Tagged adult and juvenile fish move little (< 25 km) and remain in lotic habitats. Adult fish actively use deep floodplain channels for feeding.
- Spawning occurs in lotic main-stem habitats (larvae collected), but not in adjacent floodplain habitats (i.e. Barmah Forest)

References: King *et al*. (2005), Koehn and Harrington (2005a), Koehn and Harrington (2005b), Jones and Stuart (2007), Jones and Stuart (2008), Koehn (2009).

Broken Creek (middle River Murray)

- **Lotic habitats commonly occur in spring** (Appendix 2).
- Seasonally high flows each spring, from unregulated flows and localised rainfall, providing lotic habitats.
- Broken Creek flows into the River Murray downstream of the Barmah Forest Floodplain.
- A regulated stream with a number of weirs and fishways.
- Lentic habitats at low flows.
- A fish kill in 2002 caused by very low flows and anoxic water. Recovery of cod population needed 3 to 5 years, which may have been from survival of small, young fish in the fish kill or immigration from healthy populations in the adjacent River Murray.

References: (ARI 2005).

Lake Mulwala / Ovens River (upper River Murray)

- **Upstream lotic habitats (Ovens River) are a permanent feature**.
- Downstream lentic habitat in an impoundment (Lake Mulwala) is a permanent feature.
- Some adult fish move from lentic to lotic habitats in spring.
- Present model is spawning in lotic habitats with larvae drifting downstream
- Larvae collected in the river and in the impoundment but survival in each habitat is unknown.
- Lentic habitats of impoundment used by adults in non-spawning periods

References: Koehn and Harrington (2005a), Koehn and Harrington (2005b), Koehn (2009).

4.4.3 Implications for the management of Chowilla

In the Chowilla Floodplain and Lindsay-Wallpolla Islands Icon Site, significant populations of Murray cod are present in the anabranch creeks of Chowilla, and in the Mullaroo Creek- lower Lindsay River. The common habitat features of these and other sites with robust populations of Murray cod are that:

- Lotic (flowing) habitats are either permanent features or are present in the spawning season in spring.
- Healthy, diverse structural habitat is present which usually features riparian woodlands, geomorphic diversity, and large woody debris instream.
- Spawning occurs in both lentic and lotic habitats, but most adults preferentially move to lotic habitats in the spawning season (evidence from radiotracking of the Ovens and Lindsay rivers).
- Survival of larvae and subsequent recruitment appears strongly associated with lotic habitats and hydrodynamic diversity.

Hence, the patterns of habitats, distribution and recruitment of Murray cod present in Chowilla is seen elsewhere in the southern Murray-Darling basin and supports the view that the present habitats and hydrodynamic diversity are keys features that favour Murray cod. Specific nursery habitats have not been identified for Murray cod. Further research to describe the early life history of Murray cod could result in Lock 6, and Pipeclay and Slaney weirs being used to enhance these nursery areas.

Despite being a large-bodied fish species and capable of swimming long distances, emigration and immigration rates appear to be low. Hence, perturbations that result in a localised decline in abundance could have a long-term effect that takes years to recover. Murray cod also appear to frequently respond to hydrological change at a meso-scale (i.e. Icon Site scale), so they will be responsive to changes in flows and hydrodynamics within Chowilla.

4.5 Golden perch

4.5.1 Conceptual model of golden perch in Chowilla and the lower River Murray

- **Habitat**: 1+ to adult fish use lotic and lentic anabranch habitats and lentic main-stem habitats. Lotic habitats in anabranches are a permanent feature in low and high flows.

- **Spawning**: Occurs from spring to summer, with an increase in flow (e.g. > 10,000 ML/d, River Murray), in large lotic habitats. The source of water may be as important as the discharge as a spawning cue. Flow that originates from the middle reaches of the River Murray and the Darling River may provide a greater stimulus for spawning of this species at Chowilla than flow that originates from Lake Victoria (based on data of golden perch recruitment from 2004 – 2011, B. Zampatti unpubl. data).

- **Recruitment**:

Model 1 – Recruitment in lotic habitats:

Survival of larvae and 0+ is higher in hydraulically-diverse lotic habitats. Epibenthic and littoral zones in these habitats may be important for young fish and these zones are clearly differentiated by low water velocity on the margins of high water velocity. Larvae drift in lotic habitats and either settle passively or actively seek epibenthic and littoral zones, where food is more accessible, more diverse in size, and/or more abundant. Recruitment is greater at higher flows when there is an increase in lotic habitats and hydraulic diversity.

Model 2 – Recruitment in lentic habitats:

Eggs and larvae drift in lotic habitats and settle in recently-inundated floodplains or terminal lakes. These habitats are highly productive with high abundances of zooplankton, providing extensive food for fish larvae which consequently have high survival. This mechanism of recruitment is often referred to as the *flood recruitment model* (Lake 1967).

Model 3 – Recruitment in both lotic and lentic habitats:

A combination of Model 1 and 2. Larvae have flexible habitat requirements with behaviour that is effective in either lentic or lotic habitats. Low levels of recruitment occur in varying conditions and occasionally very high levels of recruitment occur in floods when conditions for larval survival are optimal (Mallen-Cooper and Stuart 2003).

- **Movement**:
  Adult fish have strong site fidelity within the Chowilla Anabranch system, with occasional ranging within Chowilla, mainly within channel habitats and rarely in backwaters. During elevated flows and water levels some adult fish make more active exploratory movements into small creeks and backwaters. Over spring, summer and autumn over a third of the population leaves Chowilla, with no apparent schooling, and make long-distance (20-270 km) unidirectional upstream movements in the River Murray, independently of any flow stimulus.

  Combined with other migration data, an applicable model for the lower Murray is:
  - Larvae drift downstream in moderate to high flows.
  - 0+ fish use settlement habitat and move little.
  - 1+ and older fish move upstream in response to increases in flow, in a staged migration to compensate for downstream drift as larvae.
  - Mature fish in their first year of maturity make early preparatory movements to spawning grounds upstream, from where they will establish a new home range and cyclical long distance migration patterns.
  - In high flows in spring adult fish migrate upstream to spawn followed by return movements.
  - Moderate to high emigration rates from the population, with occasionally very long-range dispersal of a few individuals, contributing to relatively homogenous genetics of the Murray-Darling population.

  Scale of management for this species needs to be on hundreds of kilometres with Chowilla and Lower Murray (e.g. downstream of Lock 15), and possibly wider, to be included as a single ecological unit.

Caveats: Above model is based largely on data collected within an extended drought. There are no specific data during floods at Chowilla.

Table 3. Knowledge gaps and hypotheses for monitoring of golden perch.

Knowledge gaps (components of the model with the least data)	**Hypotheses for monitoring**
Very High Priority	
• Flow and temperature cues for spawning.	H_{10}
• Survival and diet of larval fish – in lotic, lentic and floodplain habitats (including food availability, composition and abundance in these habitats).	H_{11}
• Distance of larval drift.	H_{12}
• Movement of fish in a natural flood, including lateral, longitudinal, emigration and immigration; use of lakes and floodplains.	H_{13}
High Priority	
• Chemical cues for spawning.	H_{14}
• Site selection for spawning.	H_{15}
• Habitats of 0+ fish.	H_{16}
• Movement of 0+ fish.	H_{17}
• Landscape-scale cyclical movements of fish.	H_{18}
• Emigration and immigration of immature fish.	H_{19}
• Emigration and immigration of mature fish.	H_{20}

4.5.2 Features of studied populations of golden perch elsewhere in the southern Murray Darling Basin

Lower Murray (downstream of Chowilla) (lentic at low flows, lotic at high flows)

- **Uniform lentic habitats of continuous weirpools at the most common (entitlement) flows**.
- Lotic characteristics of the river channel increase in the upper reaches of each weirpool at flows > 10,000 ML/d.
- Present model is that fish only spawn at flows > 10,000 ML/d.
- Recruitment occurs in high flow years when the river is a lotic habitat.
- Diverse movement patterns recorded. Reynolds (1983) study of tagged fish found that: 20% of tagged fish moved little; 60% moved less than 60 km – close to the length between weirs which are obvious limitations on movement; and 20% moved long distances, mainly upstream, in response to high flows when the weirs were removed.

References: Reynolds (1983), Ye (2004)

Middle River Murray (Yarrawonga Weir to Mildura Weir)

- **Temperate hydrology with regular spring increases in flow in most years**; high summer regulated flows upstream of Torrumbarry and more natural regime downstream of this site.
- Permanent, extensive main-stem lotic habitats (839 km of 1114 km).
- Lentic habitats in weirpools (275 km of 1114 km)
- Adult fish appear to migrate upstream and downstream to specific locations to spawn in spring; increasing river flow is a major stimulus for migration.
- Spawning occurs in lotic habitats (larvae collected) in spring.
- Immature fish (yearlings [1+] and older) and mature fish recorded migrating upstream in spring, summer and early autumn, in response to increasing flow.

- Recruitment is correlated to within-channel rises in flow; may also occur in floods but little data.

References: Mallen-Cooper (1999), Mallen-Cooper and Stuart (2003), King *et al*. (2009), O'Connor *et al*. (2005) Mallen-Cooper and Brand (2007).

Menindee Lakes and Darling River upstream

- **Semi-arid hydrology, with lotic habitats upstream and lentic habitats downstream.**
- Ephemeral deflation basin lakes, used for storage since 1965 with more permanent water in the lakes.
- Semi-arid hydrology with long periods of low flows.
- Large inflows from the Darling River are captured in Menindee, so the lakes act as a mainly-terminal system.
- Adult fish recorded migrating upstream in the Darling River in high flows.
- Low levels of spawning recorded in the lakes.
- Model 1: Fish spawn in the Darling River upstream; larvae drift into the lake and have high survival with the abundant zooplankton.
- Model 2: Resident fish spawn in the lake; larvae have high survival with the abundant zooplankton.

References: Ebner *et al*. 2009, C. Sharpe pers. comm.

Lake Cowal and Bland Creek

- **Semi-arid hydrology, with lotic habitats upstream when flowing and lentic habitat downstream.**
- A largely endorheic system that links with the Lachlan River only in very large floods (e.g. 1:20 year events).
- Episodic booms in the population after floods fill Lake Cowal, which is dry in droughts.
- Model 1: Fish are spawning in Bland Creek; larvae drift into the lake and have high survival with the abundant zooplankton.
- Model 2: Fish migrate downstream to the lake as it fills, and spawn in the lake; larvae have high survival with the abundant zooplankton.

References: Reid *et al.* (1997)

4.5.3 Implications for the management of Chowilla

The spawning of golden perch is strongly linked to high flows, including within-channel flows, and to landscape–scale events. The recruitment of this species in semi-terminal river systems (most notably Lake Cowal) and the presence of juveniles in floodplain habitats such as Menindee Lakes, suggests that inundated floodplains can act as nursery habitats for this species, as well as within main channels. Hence, using the Chowilla Regulator during high river flows that are extended along the length of the river has potential to enhance recruitment of golden perch. The timing and rate of the recession of floodwaters from Chowilla would be important to ensure fish are not trapped in isolated water bodies.

4.6 Silver perch

4.6.1 Conceptual model of silver perch in Chowilla and the lower River Murray

- **Habitat**: 1+ to adult fish use lentic main-stem habitats and lotic anabranch habitats.
- **Spawning**: Occurs in spring, with an increase in flow, in large lotic habitats.

- **Recruitment**: Eggs and larvae drift. Survival of larvae and 0+ is higher in hydraulically-diverse lotic habitats. Epibenthic and littoral zones in these habitats may be important for young fish and these zones are clearly differentiated by low water velocity on the margins of high water velocity. Larvae drift in lotic habitats and either settle passively or actively seek epibenthic and littoral zones, where food is more accessible, more diverse in size, and/or more abundant.

  Recruitment is greater at higher flows when there is an increase in lotic habitats and hydraulic diversity; this includes large flows contained within the channel.

- **Movement**:

  Using the present migration data, an applicable model for the lower Murray is:

  - Larvae drift downstream in moderate to high flows.
  - 0+ fish use settlement habitat on the margins of channels and move little.
  - 1+ and older fish move upstream in response to increases in flow, in a staged migration to compensate for downstream drift as larvae.
  - Adults migrate upstream to spawn in spring in response to increases in flows; return cyclical movements likely.
  - Low to moderate emigration rates from the population.

  Scale of management for this species needs to be on hundreds of kilometres with Chowilla and Lower Murray (e.g. downstream of Lock 15), and possibly wider, to be included as a single ecological unit.

Caveats: No spawning, recruitment or movement data that is specific for Chowilla and the Lower Murray. Model based largely on data extrapolated from the middle reaches of the River Murray.

Table 4. Knowledge gaps and hypotheses for monitoring of silver perch.

Knowledge gaps (components of the model with the least data)	**Hypotheses for monitoring**
Very High Priority	
• Flow and temperature cues for spawning	H_{21}
• Habitats of larvae	H_{22}
• Distance of larvae drift	H_{23}
• Movement of fish in a natural flood, including lateral, longitudinal, emigration and immigration	H_{24}
High Priority	
• Chemical cues for spawning	H_{25}
• Habitats of 0+ fish	H_{26}
• Landscape-scale cyclical movements of fish	H_{27}
• Emigration and immigration of fish	H_{28}

4.6.2 Implications for the management of Chowilla

Silver perch have a similar life history to golden perch and appear to spawn in response to high flows and to landscape–scale events. However, juveniles are seldom collected in floodplain habitats or semi-terminal lakes and spawning appears restricted to major river channels. Channel habitats with hydrodynamic diversity would appear to provide nursery habitats for this species. Operation of the Chowilla Regulator is not likely to benefit this species. Nevertheless, operation of Lock 6 and

Pipeclay and Slaney weirs could provide more suitable flowing channel habitat during landscape-scale flow events which has potential to enhance recruitment.

4.7 Freshwater catfish

4.7.1 Conceptual model of freshwater catfish in Chowilla and the lower River Murray

- **Habitat**: 1+ to adult fish use moderate to large lentic habitats in the main-stem and lotic anabranch habitats (small and large creeks).
- **Spawning**: Occurs in spring (late November /early December), independently of flow, in moderately-sized to large lentic and lotic habitats. Eggs are laid in nests of sticks or gravel and are guarded by the male.
- **Recruitment**: Survival of larvae and 0+ is higher in lentic and lotic habitats with macrophytes and riparian vegetation. Larvae are only very rarely recorded drifting in lotic habitats.
- **Movement**:

  An applicable model for the lower Murray is:

  - Larvae and juveniles likely disperse from adult spawning habitat to reduce competition, but over small distances (e.g. 0.1 to 10 km).
  - Adults have a small home range (e.g. 0.1 to 10 km) and migrate to nearby specific spawning sites in spring.
  - Very low emigration rates from the population, but sufficient to support relatively homogenous genetics of the Basin population.

Caveat: Very little movement data in the Murray-Darling.

Table 5. Knowledge gaps and hypotheses for monitoring of freshwater catfish.

Knowledge gaps (components of the model with the least data)	**Hypotheses for monitoring**
Very High Priority	
• Spawning habitats within Chowilla	H_{29}
• Habitats of larvae and conditions for high survival	H_{30}
• Emigration and immigration of fish	H_{31}
High Priority	
• Distribution within Chowilla	H_{32}
• Cues for adult fish to abandon nest prematurely	H_{33}
• Proportion of larvae that drift	H_{34}
• Habitats of 0+ fish	H_{35}
• Interaction with carp within Chowilla	H_{36}
• Movement of fish in a natural flood, including lateral, longitudinal, emigration and immigration	H_{37}

4.7.2 Implications for the management of Chowilla

Adult and juvenile freshwater catfish are seldom reported to extensively use ephemeral floodplain habitats, but are often reported in permanent lentic habitats. As such, they are not expected to utilise

temporarily flooded habitats in Chowilla but increased water levels and productivity may enhance survival of larvae and juveniles. Adult catfish are known to abandon nests due to water level fluctuations, usually due to rapid decreases in water level, which is a risk that will need to be carefully monitored in managed inundations. Negative interactions with carp are reported and any increase in the carp population could affect this species.

Like Murray cod, emigration and immigration rates appear to be low and localised decline in abundance could have a long-term effect on the population. Freshwater catfish also respond to hydrological change at a meso-scale and will be responsive to localised changes in flow and hydrodynamics within Chowilla.

4.8 Carp

4.8.1 Conceptual model of carp in Chowilla and the lower River Murray

- **Habitat**: Juvenile and adult fish preferentially use lentic habitats; nevertheless juvenile and adult fish also use lotic anabranch habitats.

  Spawning: Occurs from late winter to early summer, independently of flow, in shallow off-channel lentic habitats and within the channel in littoral regions of lotic and lentic habitats, usually with submerged vegetation. In Chowilla suitable habitats for spawning include: i) littoral zones of permanent creeks, ii) recently inundated creek margins, which has been observed, iii) wetlands adjacent to channels, which is expected, and iv) the outer lakes, which is possible.

- **Recruitment**: Survival of larvae and 0+ is high in inundated floodplain and littoral habitats with low velocity. Larvae and juveniles also drift from floodplains as they drain into mainstem habitats, where survival can be variable from year to year and may depend on growth rates on the floodplain.

- **Movement**: Adult fish inhabit permanent lotic and lentic habitats (including off-channel habitats) and may undertake seasonal spawning movements between channel and off-channel habitats. Some fish move long distances (> 100 km), which are fish that could colonise other areas, or equally could re-colonise Chowilla. Larvae can drift onto floodplain habitats as they fill, if there is suitable spawning habitat upstream; the presence of YOY in the outer lakes in the 2011 flood (B. Zampatti, unpublished data) shows that larvae either drift into the lakes or spawning occurs there.

  In Chowilla, spawning movements are likely to be to the creek margins and adjacent wetlands (see *Spawning* above) but the extent that adults actively move to the outer lakes is unknown.

  YOY actively move upstream after leaving the floodplain. Immature fish and young adults also actively move upstream aiding dispersal, leading to high emigration rates and the ability to colonise new habitats.

Caveat: Above movement model is based on data collected within the middle Murray as well as in Chowilla.

Table 6. Knowledge gaps and hypotheses for monitoring of carp.

Knowledge gaps (components of the model with the least data)	**Hypotheses for monitoring**
Very High Priority	
• Contribution of localised spawning events to broader populations	H_{38}
• Movement of adult and juvenile fish between the River	H_{39}

Murray and Chowilla	
• Movement of adult fish within Chowilla, especially to outer lakes and small wetlands	H_{40}
High Priority	
• Extent of spawning and recruitment during within-channel rises within Chowilla compared to floods	H_{41}
• Temporal extent of spawning season	H_{42}
• Minimum water temperature for spawning	H_{43}
• Survival and diet of larval fish	H_{44}
• Survival of 0+ fish on floodplain	H_{45}
• Survival of 0+ fish in main channel habitat	H_{46}
• Cues for lateral movement on & off floodplains	H_{47}
• Movement of fish in a natural flood, including emigration and immigration	H_{48}

4.8.2 Implications for the management of Chowilla

As a subset of the present project a Carp Management Strategy (Stuart *et al*. 2011) has been written that discusses management, assesses control options and provides a framework for implementation of strategies.

5 HYDRODYNAMIC MODELLING

5.1 Introduction

Hydrodynamic modelling was undertaken by Water Technology using MIKE FLOOD software (DHI), which dynamically links a two-dimensional (2D) MIKE21 model with a one-dimensional (1D) MIKE11 model. The 2D model utilises topographic data from LIDAR at a 30 m grid resolution. LIDAR generally has a vertical accuracy of approximately +/-0.1 m, however this accuracy is reduced slightly by resampling at a 30 m grid resolution for model purposes. The 2D model extended from the most upstream limit of the Chowilla Floodplain to the most downstream limit, and covered 28,800 hectares. The 1D model provides high accuracy of mean water velocity, which is a major determinant of fish habitat. The 1D model is based on 751 surveyed and interpolated cross-sections of stream channels, covering 142 km of floodplain channels, 135 km of the River Murray from Lock 5 to Lock 7, and 73 km of the Lindsay River and Mullaroo Creek.

5.2 Modelling Variables

The key modelling variables for fish habitats are water velocity and depth. Increments of these were selected for the modelling outputs to correspond to known attributes of fish habitats and fish behaviour in Chowilla (Table 7, Table 8). The velocity increments include moderate-flowing (0.18 – 0.30 m/s) and fast-flowing 0.31- 0.50 m/s) water that define the *core habitats*.

Table 7. Velocity increments for modelling.

Water velocity (m/s)	Fish habitat
0.00- 0.03	Backwaters
0.04- 0.10	Weirpools in the main river channel
0.11- 0.17	Slow-flowing
0.18- 0.30	Moderate-flowing
0.31- 0.50	Fast-flowing
> 0.50	Very fast

Table 8. Depth increments for modelling.

Depth (m)
0.0
0.01 – 0.10
0.11 – 0.30
0.31 – 0.50
0.51 – 1.00
1.01 – 1.50
1.51 – 2.00
> 2.00

Steam lengths of each velocity and depth class were interpolated from the 1D model by using the midpoints either side of a modelled point.

5.3 Modelling Scenarios

Six broad modelling scenarios were investigated:

i) Natural conditions, without the locks and weirs, to identify key hydrodynamic characteristics of fish habitats that could inform present management;
ii) Existing conditions, with the present locks and weirs, to provide a baseline for comparison;
iii) Pipeclay and Slaney weirs with new gates, to investigate the opportunities to vary hydrodynamics in two of the three main anabranch creeks in Chowilla;
iv) Chowilla Regulator under different Lock 6 levels and inflows to assess the extent that flowing water habitats could be maintained in the anabranch creeks during managed inundations;
v) Lower Lock 6 weirpool levels to identify the potential for rehabilitating flowing water habitats in the upper Lock 6 weir pool;
vi) Lindsay River and Mullaroo Creek to assess the impacts of backwater effects from raising the Lock 6 weirpool.

Scenario 1. Natural conditions

Model runs of natural conditions were without Locks 5, 6 and 7 (i.e. the extent of the model), Pipeclay and Slaney weirs, and known banks and levees. The model used the present channel profiles of the creeks and the River Murray although it is likely that these have changed to some extent since river regulation. A significant model input is the invert of the channel entries at Pipeclay and Slaney creeks as these determine when these creeks start to flow; survey data in the construction plans from 1929 showed that these have changed little.

Modelled Flow Increments: 1000, 2000, 5000, 7000, 10000, 15000, 20000, 40000, 60000 and 80000 ML/d.

Scenario 2. Existing Conditions

These model runs were with the Lock 6 water level set at 19.25 m AHD, which reflects present management where the weirpool is maintained at a fixed level independent of inflows. Inflow levels at Pipeclay and Slaney weirs were also fixed at the normal weirpool of 19.25 m AHD; at high flows there may be a slight hydraulic grade between the Lock 6 and these two structures, so that there may be greater flow passing down these two creeks, but it is considered minor.

Modelled Flow Increments: 1000, 2000, 5000, 7000, 10000, 15000, 20000, 40000 and 60000 ML/d. (Lock 6 is removed at flows greater than 60,000 ML/d, so that 80,000 ML/d under the *natural* scenario above is the same as under *existing*.)

Scenario 3. Existing Conditions with upgraded Pipeclay and Slaney Weirs Operational

In the model Slaney and Pipeclay weirs were operated dynamically to represent the design flows and realistic management (Table 2). The maximum flow is set at 2,000 ML/d to prevent erosion of the creek channel.

Table 9. Relationship between flow in the River Murray (entering South Australia) and flow passing Slaney and Pipeclay weirs which was used in the model.

Q_{SA} River Murray Flow entering South Australia (ML/d)	Slaney Flow (ML/d)	Pipeclay Flow (ML/d)
0	0	0
750	70	70
1750	500	500
4750	1000	1000
39750	2000	2000
172800	2000	2000

Modelled Flow Increments: 1000, 2000, 5000, 7000, 10000, 15000, 20000, 40000 and 60000 ML/d Q_{SA}.

Scenario 4. Chowilla Regulator

Four scenarios were run with the Chowilla Regulator (Table 10). The intent of these scenarios were to investigate the extent that *core habitats* in the anabranch creeks could be maintained whilst inundating the Chowilla floodplain. In all four scenarios flow through Pipeclay and Slaney weirs is maximised (Table 9) to mitigate loss of flowing water habitats. The first two scenarios were run at the normal Lock 6 weirpool level and the second two were run with the weirpool higher by 0.62 m; the intent of the latter scenarios was to produce a hydraulic head-differential between the weirpool and the Chowilla Regulator that could potentially maintain the *core habitats*. Modelled inflows were 10,000 ML/d, representing the maximum regulated flow that could be released from Lake Victoria, and 20,000 ML/d, representing whole or additional inflows from the River Murray upstream of Lock 7.

In the modelling runs the Chowilla Regulator was raised by a number of set increments: for the normal weirpool runs it was 16.5, 17.0, 17.5, 18.0, 18.5, 18.7, 18.9, 19.1, 19.25 m AHD, and for the high weirpool runs it was the same increments up to 18.5 m and then 19.0, 19.2, 19.4, 19.6 and 19.87 m AHD. This enabled the incremental changes in *core habitats* and inundation area to be investigated and to establish thresholds for operation of the Regulator.

Table 10. Modelling scenarios run with the Chowilla Regulator.

Scenario No.	Lock 6 level (m AHD)	Inflows
4d	Normal 19.25	10,000 ML/d
4d	Normal 19.25	20,000 ML/d
4e	High 19.87	10,000 ML/d
4e	High 19.87	20,000 ML/d

Scenario 5. Rehabilitating flowing water habitats

As one of the significant impacts of the Chowilla Regulator is the reduction of flowing water habitats in the Chowilla anabranches (Mallen-Cooper *et al*. 2008) we investigated options of rehabilitating flowing water habitats in other areas of the Icon site as methods of improving fish habitats generally and as potential offsets. Scenarios were run with the Lock 6 weirpool level lowered by 0.5 m and 1.0 m (Table 11) with the objective of investigating the increase in flowing water habitat in the upper weirpool.

Table 11. Modelling scenarios run with a lower Lock 6 weirpool.

Scenario No.	Lock 6 level (m AHD)	River Murray flows (Q_{sa})
5a	0.5 m below normal weirpool	0 to 60,000 ML/d
5b	1.0 m below normal weirpool	0 to 40,000 ML/d

Scenario 6. Assessing impacts on the lower Lindsay River and Mullaroo Creek

A potential impact of raising the Lock 6 weirpool is an increase in the backwater effect of the weir to the lower Lindsay River and Mullaroo Creek reducing the hydrodynamic diversity of fish habitat in this reach, which has a well-known Murray cod population. Model runs were done with the Lock 6 level raised by 0.62 m, firstly to assess the impact, then with Lock 7 raised by 0.15 m and 0.65 m to assess mitigation of any impact (Table 12).

Table 12. Modelling scenarios run of the Lindsay River and Mullaroo Creek.

Scenario No.	Lock 6 level	Lock 7 level
6a	Normal weirpool + 0.63	Normal weirpool
6b	Normal weirpool + 0.63	Normal weirpool + 0.15
6c	Normal weirpool + 0.63	Normal weirpool + 0.65

5.4 Modelling Results

5.4.1 Natural and Existing Conditions

Describing the hydrodynamics of the River Murray, anabranches and floodplains under natural conditions prior to river regulation provides an understanding of the important habitat characteristics of Chowilla and potentially how these interacted with the main channel. Modelling the existing conditions provides a baseline for comparison with the Chowilla Regulator and also provides some indication of the dynamism of the region (i.e. the ecological response over time) and the potential for fish communities to recover from changed conditions. The modelling identifies key elements of habitats and thresholds to maintain or optimise in managed inundations and operations of Pipeclay and Slaney weirs.

5.4.1.1 Major Findings

- Under natural conditions, without the locks and weirs, hydrodynamic diversity was a permanent feature of the main River Murray channel, including slow, moderate and fast-flowing reaches. It was not a uniform gently-flowing river. At flows of 5,000 ML/d or greater, which occurred for 95% of the time in unregulated conditions (MDBA model), more than 95% of the river channel had moderate (> 0.17 m/s) to fast-flowing (> 0.3 m/s) water velocities (Fig. 7, Fig. 10). This contrasts with the present river (Fig. 8), which at 5,000 ML/d has only 21% of the river channel with moderate to fast-flowing water velocities (Fig. 10).
- Even at a low flow of 2,000 ML/d, which was exceeded for 99% of the time, over 50% of the river channel had a mean velocity between 0.17 and 0.50 m/s under natural conditions (Fig. 9, Fig. 10) These data provide an indication of the longitudinal diversity of water velocity; it is also worth noting that the model is estimating mean channel velocity so that values of high velocity would include lateral diversity with low velocities on the margins and in backwaters.
- Under existing conditions, with the weirpools, the flowing habitats (>0.17 m/s) in the main channel are reduced by over 50% during entitlement flows of 3,000 to 7,000 ML/d (Fig. 9, Fig. 10). The river returns to a flowing habitat (>0.17 m/s) at flows of 15,000 ML/d and above (Fig. 9, Fig. 10).

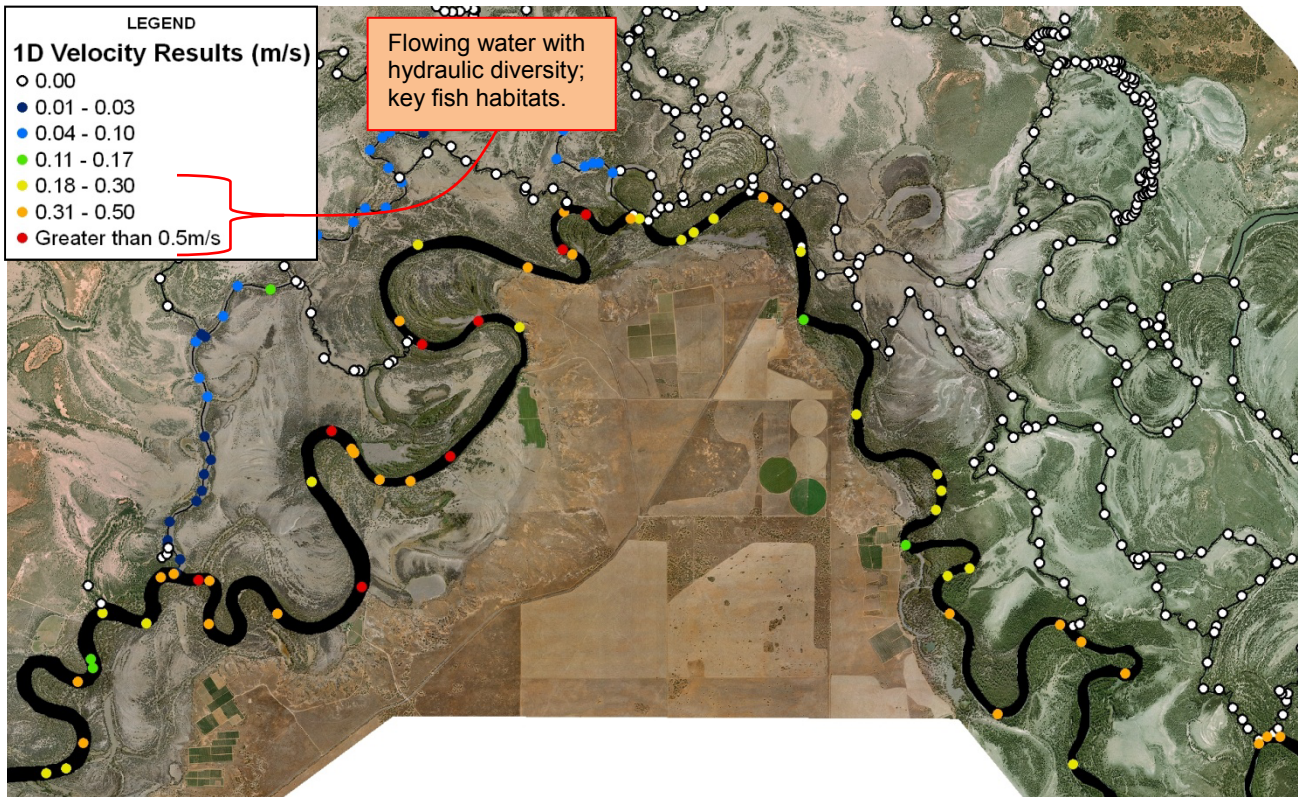

Fig. 7. Modelled mean water velocities of the River Murray and Chowilla at 5,000 ML/d under natural conditions with no locks or weirs.

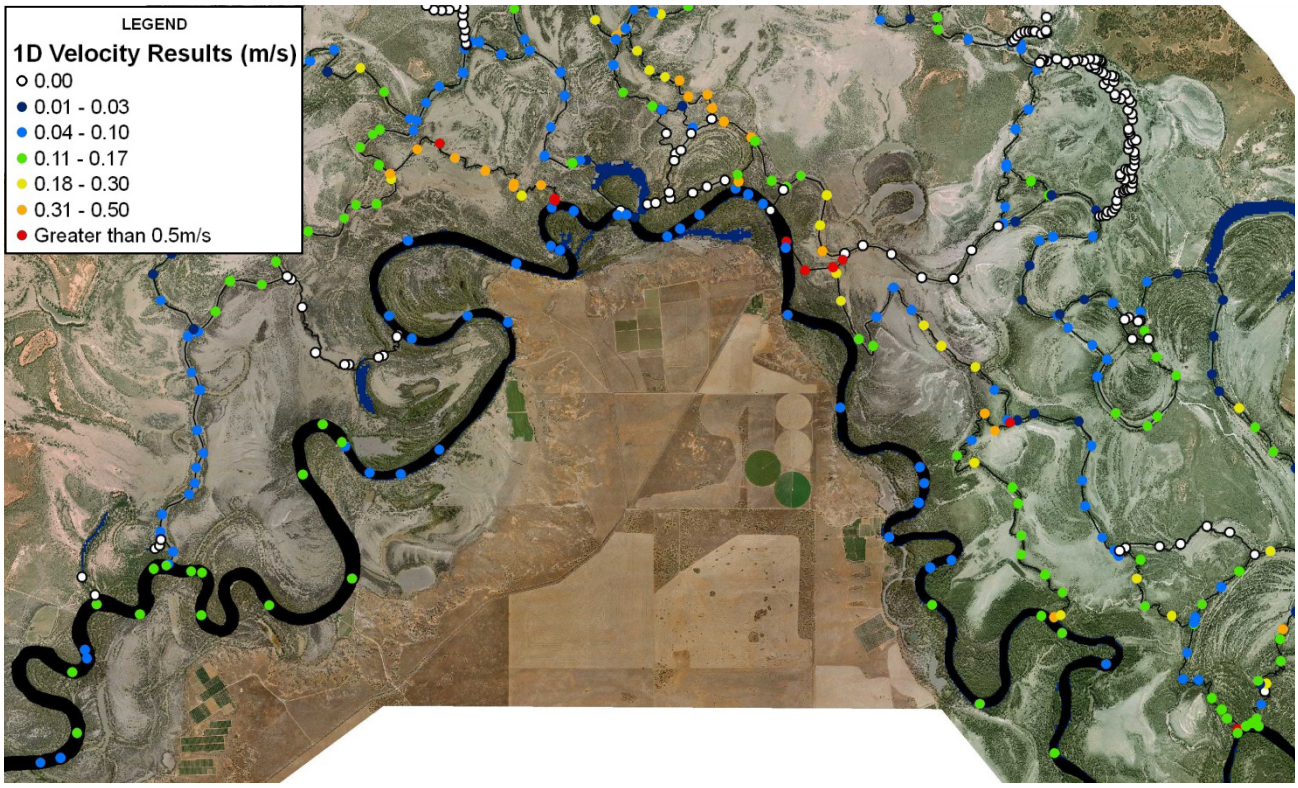

Fig. 8. Modelled mean water velocities of the River Murray and Chowilla at 5,000 ML/d under present conditions with locks or weirs.

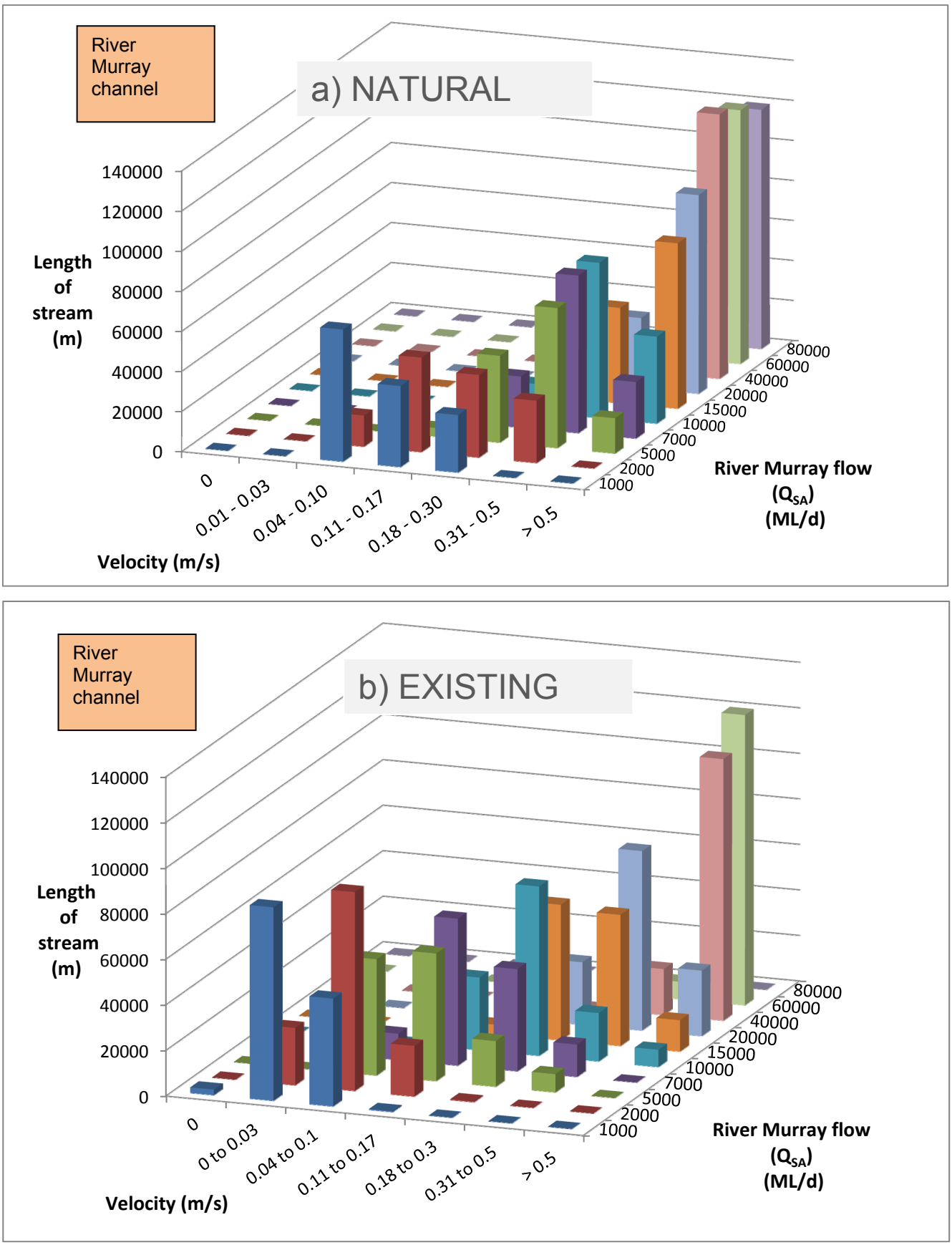

Fig. 9. Total stream lengths of mean water velocities of the River Murray channel only, under a) natural (i.e. no locks and weirs) and b) existing conditions with locks or weirs.

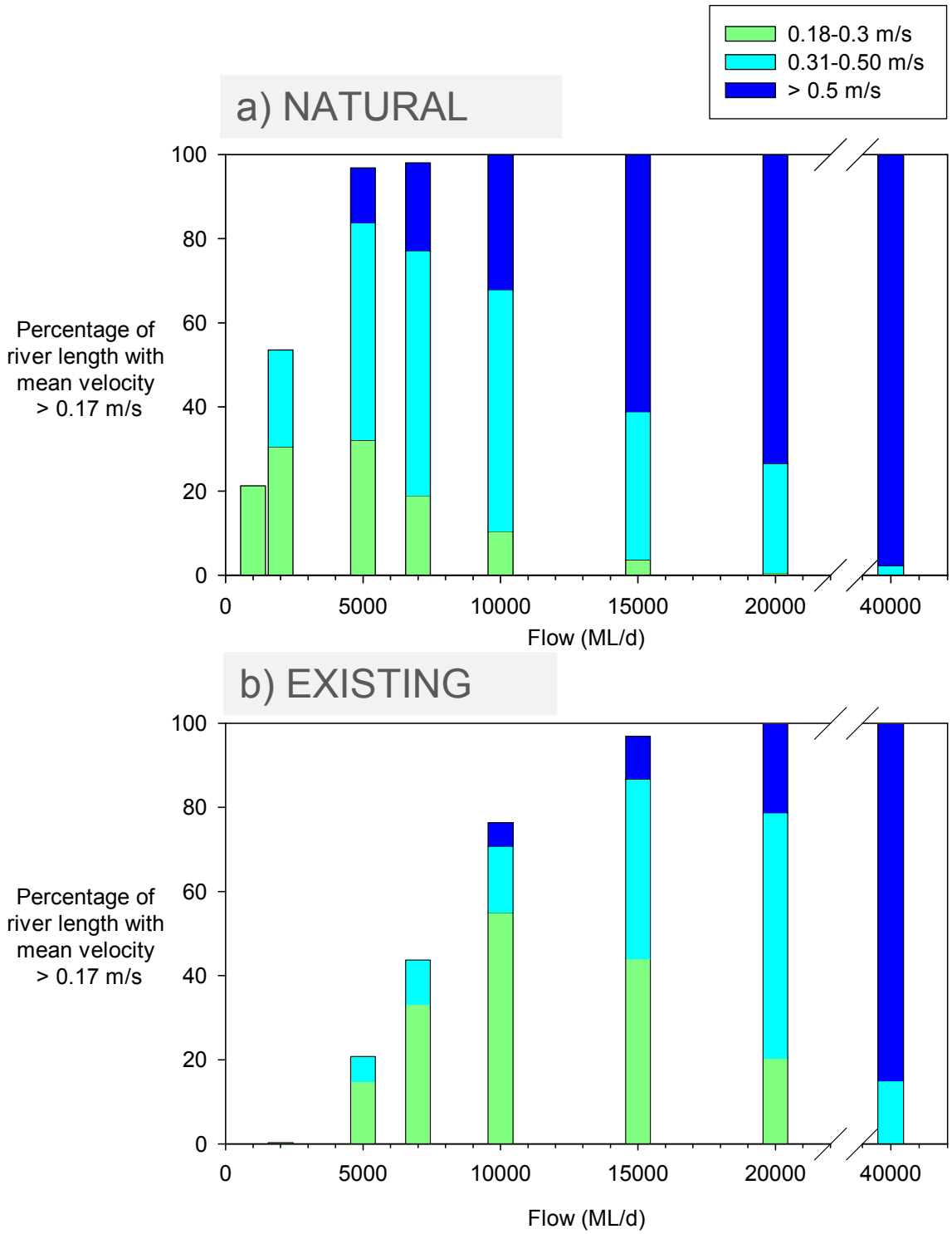

Fig. 10. Length of the River Murray (Lock 5 to Lock 7), with moderate- (0.17-0.30 m/s), fast- (0.31-0.5 m/s) and very-fast flowing (> 0.5 m/s) mean water velocity, in models of a) natural and b) existing conditions.

- The Chowilla anabranch was ephemeral under natural conditions and did not start to flow until flow in the River Murray was passing 5,000 ML/d. The anabranch creeks, however, were unlikely to dry completely as a flow of 5,000 ML/d flow was exceeded for 95% of the time. The anabranch creeks became a series of pools at flows less than 5,000 ML/d. Some of these pools were 1.5 to 2.0 m deep and would have provided permanent wetland habitats. These disconnected low-flow refugia present at low flows are not present in the same locations under present conditions, as there is now permanent flow in these creeks, but they may be present in the complexity of off-channel habitats adjacent to the Chowilla creeks.
- Under natural conditions hydrodynamic diversity was present in the anabranch creeks, previously identified as *core habitats*, at flows greater than 7,000 ML/d (Fig. 11), which occurred for 90% of the time. Nevertheless, under natural conditions the dominant flowing water habitats were present in the main channel, whilst the Chowilla creeks provided a diversity of low velocity and backwater habitats, as they do at present.
- The permanent hydrodynamic diversity that was present in the main river channel under natural conditions has now moved to the Chowilla anabranches under existing conditions (Fig. 12). This confirms previous descriptions of the Chowilla anabranch system as sharing characteristics of the River Murray prior to river regulation (Sheldon and Lloyd 1990).
- At 40,000 ML/d the floodplain begins to be inundated, starting with Lake Limbra (Fig. 13). The flood patterns and inundation under natural and existing conditions are almost identical. *Core habitats* are 85% moderate- to fast-flowing, and the other creeks of Chowilla have 50% moderate- to fast-flowing reaches and 50% slow-flowing reaches or backwaters (Fig. 13).
- At 60,000 ML/d there is significant inundation of the floodplain, including Lake Littra, Gum Flat, Werta Wert, Coppermine Waterhole and Woolshed Creek (Fig. 14). This is very similar under natural and existing conditions, which is expected as Lock 6 is usually removed at 60,000 ML/d and has little influence on river levels.
- At River Murray flows of 60,000 ML/d, approximately 20,000 ML/d passes through the Chowilla system.

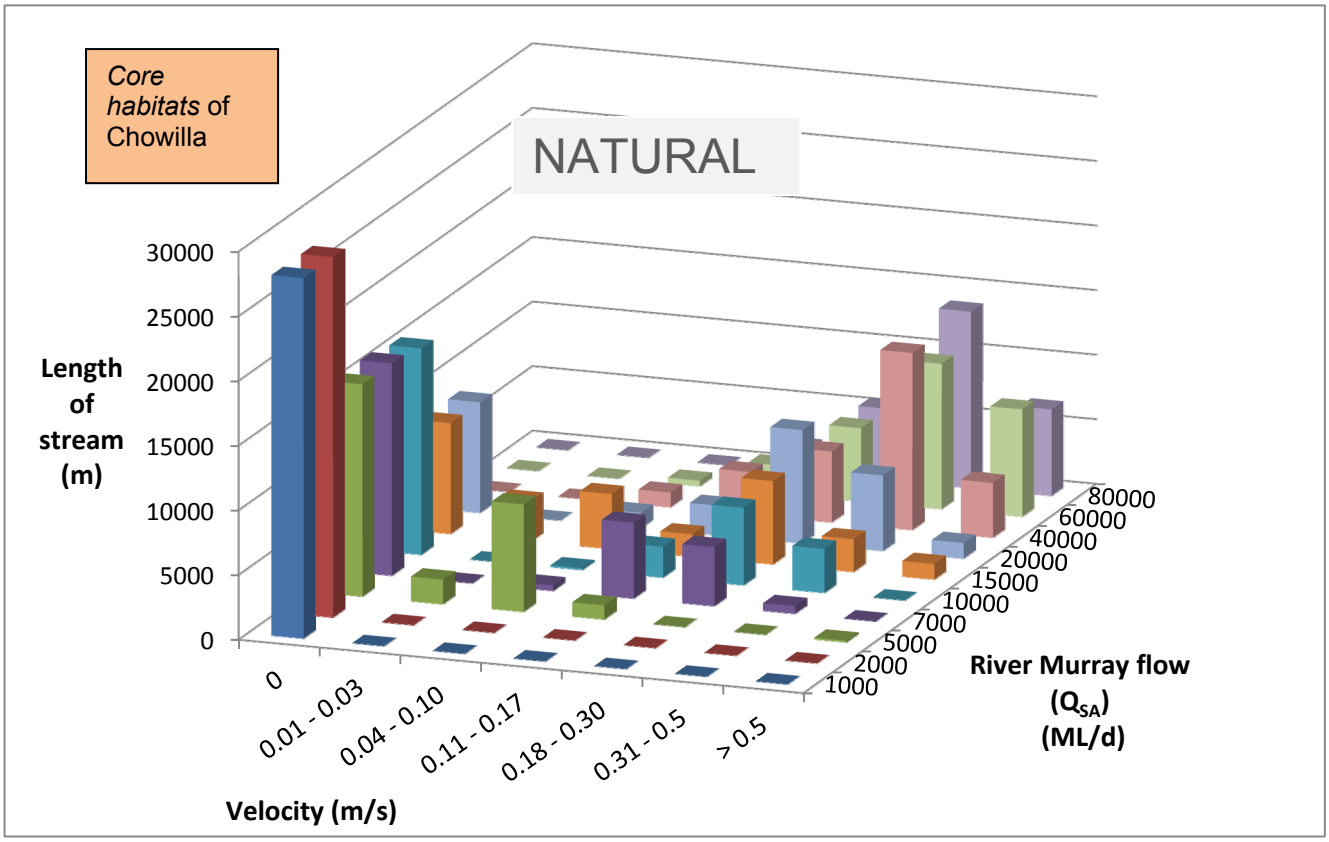

Fig. 11. Total stream lengths of mean water velocities of *core habitats* of Chowilla, under natural conditions with no locks or weirs.

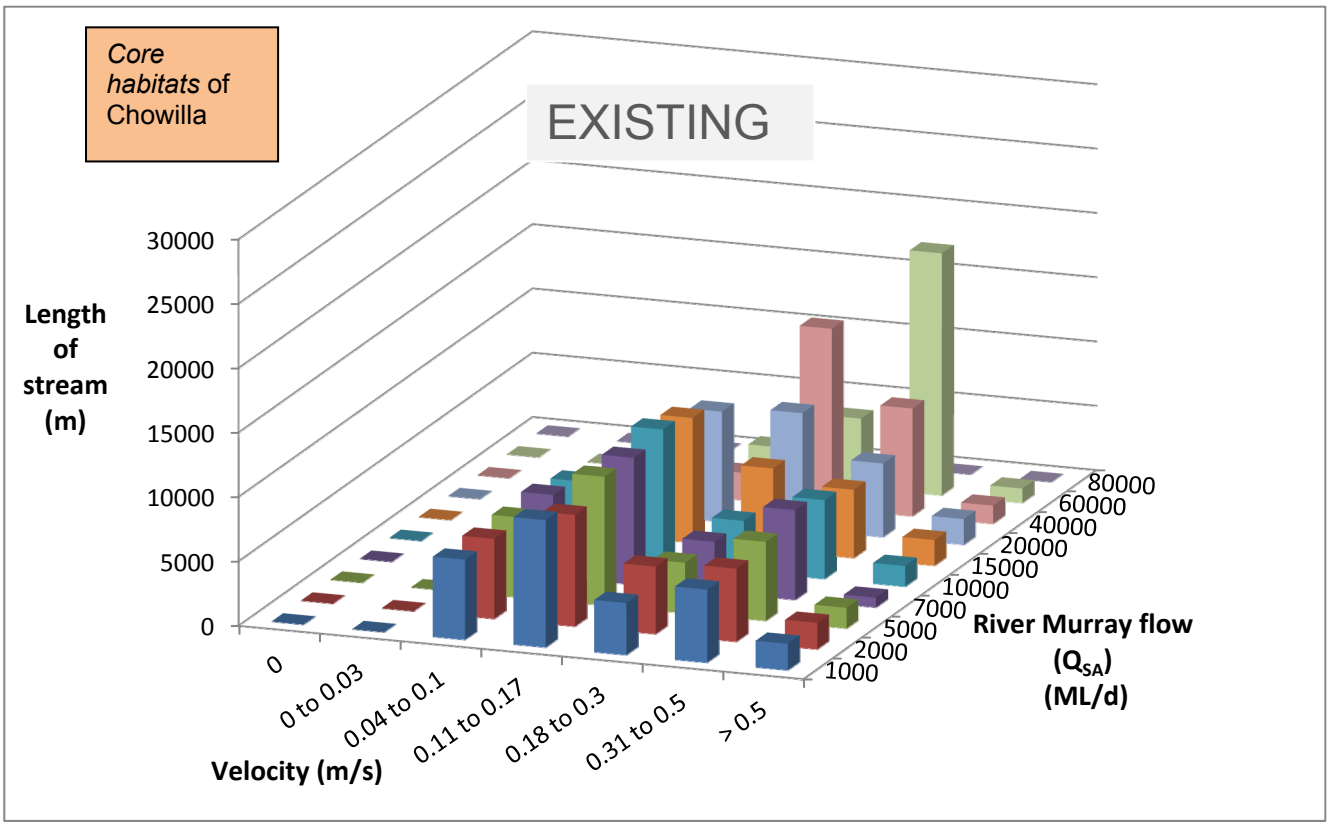

Fig. 12. Total stream lengths of mean water velocities of *core habitats* of Chowilla, under existing conditions with Lock 6 operated at 'normal' pool (19.25m AHD).

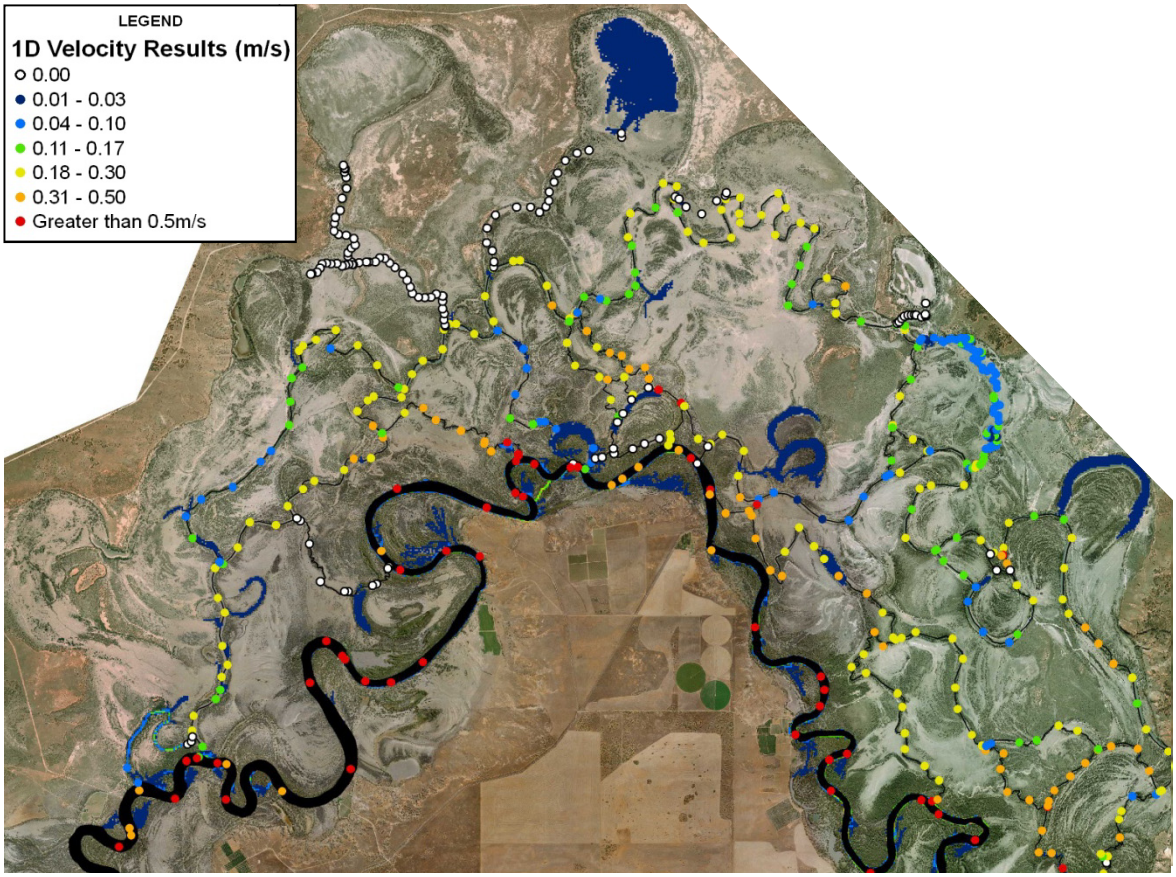

Fig. 13. Modelled (1D and 2D) water velocities of Chowilla at 40,000 ML/d under existing conditions.

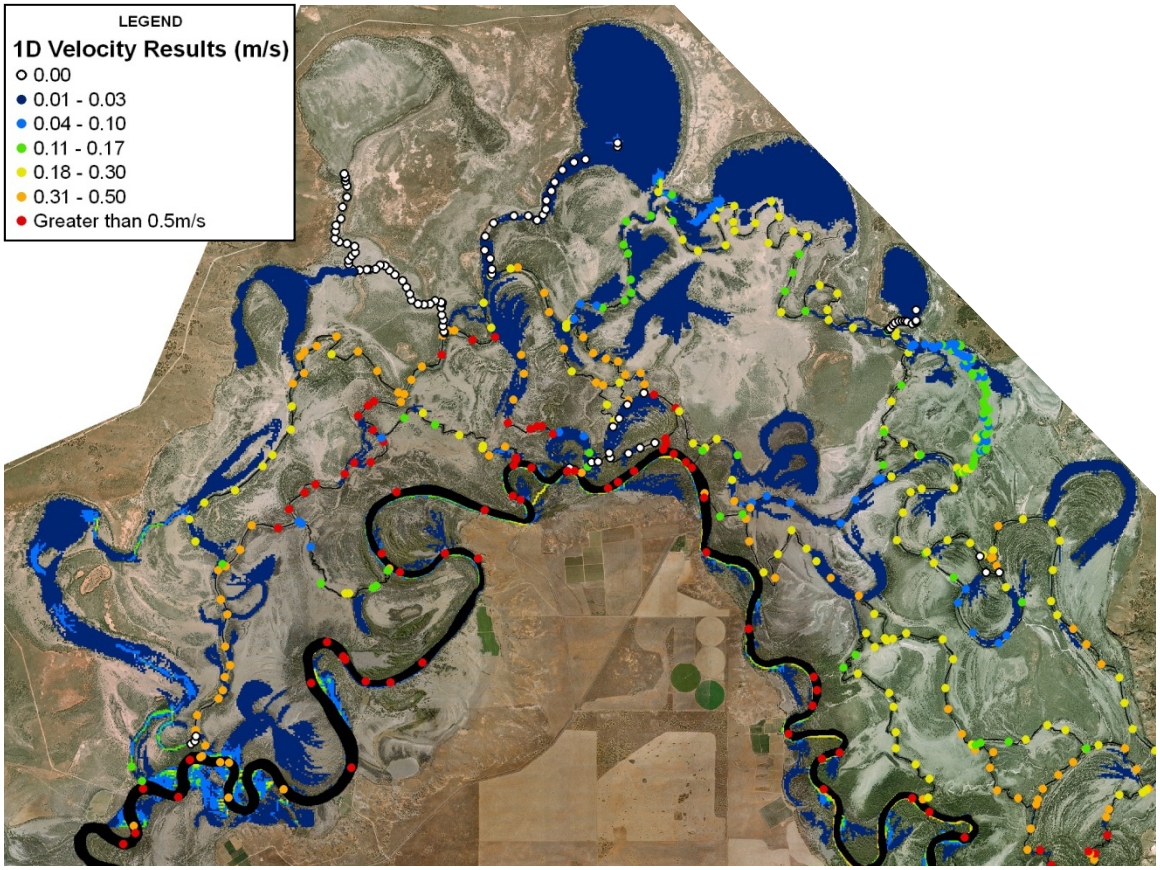

Fig. 14. Modelled (1D and 2D) water velocities of Chowilla at 60,000 ML/d under natural and existing conditions.

5.4.1.2 Ecological Implications

- Under natural conditions the River Murray main channel had a permanent diversity of slow-, moderate- and fast-flowing habitats. As the weir-pools stabilised water levels this diversity has disappeared for hundreds of kilometres from the main river channel, at low to moderate flows. It is now only permanently present in the lower River Murray in anabranch systems, with Chowilla providing the best example. This highlights the ecological value of the system and some of the features that make these aquatic habitats important for native fish.
- The anabranch creeks and wetlands of Chowilla would have provided a diversity of wetland habitats and some permanent refugia for fish species that are off-channel (or wetland) specialists (e.g. southern pygmy perch). Future management should reflect this diversity of wetting and drying regimes, where some wetlands did not dry out and were permanent refuges.
- The ephemeral nature of Chowilla suggests that large-bodied fish would have moved actively between the main channel and the anabranch creeks, especially as they provide flowing water habitats at river flows as low as 7,000 ML/d. The movement of fish into these habitats was probably seasonal to take advantage of food resources or spawning habitats that provided suitable nursery areas.
- At high flows the floodplain has diversity of slow-, moderate- and fast-flowing habitats and is not an inundated still body of water.
- Natural floods have high passing flow through channels that are adjacent to inundated floodplains; Chowilla notably passes one-third of high river flows. As floods do not uniformly rise and fall but fluctuate in level, it is very likely that this high passing flow is a significant mechanism of transport of carbon, and primary and secondary productivity off the floodplain and into the river.
- The flood dynamics (i.e. flow paths, distribution of velocities and depth, proportion of water passing through the Chowilla floodplain) are little changed with river regulation at flows greater than 40,000 ML/d.

5.4.2 Pipeclay and Slaney Weirs Adjustable

Modelling of Pipeclay and Slaney weirs with new gates was done with Lock 6 at normal pool (19.25 m AHD) and without the Chowilla Regulator operating. This was specifically aimed at investigating the opportunities to vary the hydrodynamics in two of the three main anabranch creeks in the *core habitats* of Chowilla.

5.4.2.1 Major Findings

- New gates on Pipeclay and Slaney weirs provide the capacity for more flow during regulated flow conditions.
- Within the *core habitats* the extent of reaches with moderate velocity and greater (> 0.17 m/s) increases 7-13 km, between river flows of 2,000 and 20,000 ML/d; this represents an increase of 26-47% (Fig. 15). The greatest increases in these habitats are in the flow range of 2,000-7,000 ML/d in the River Murray, which are typical regulated entitlement flows (Fig. 16).
- The increase in flow at Pipeclay and Slaney weirs, with only 5,000-7,000 ML/d River Murray flow, has the potential to create hydrodynamics in the *core habitats* that are similar to 40,000 ML/d under existing conditions (Fig. 15, Fig. 17).

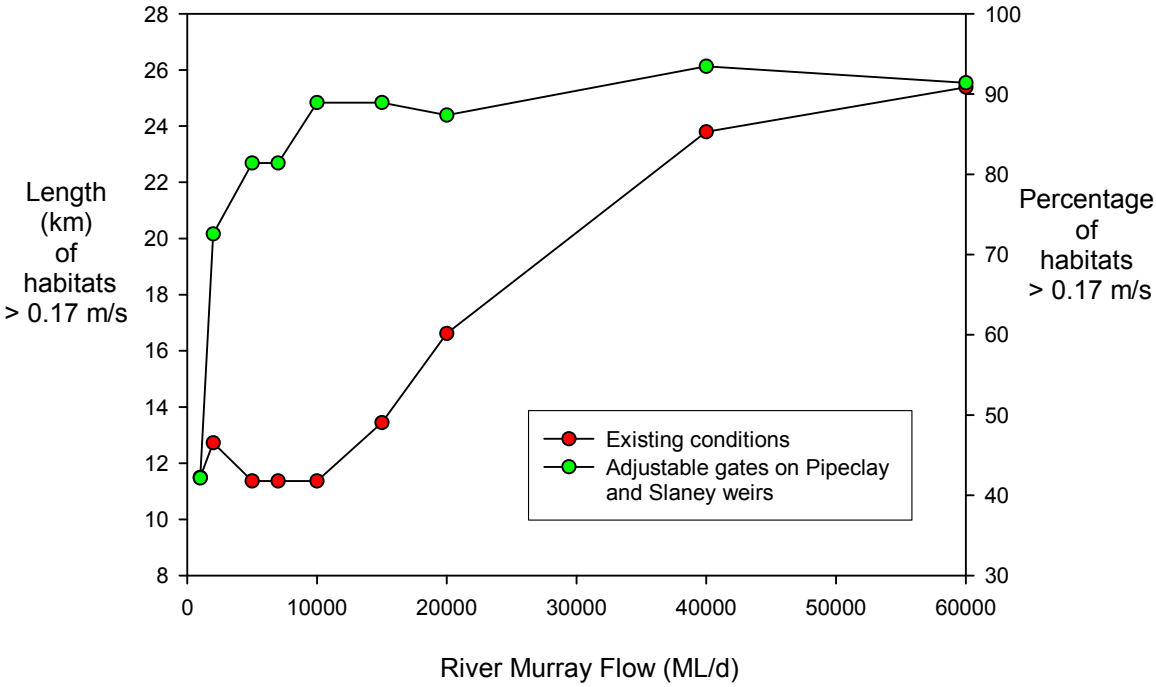

Fig. 15. Modelled length and percentage of *core habitats* that are moderate- to fast-flowing (velocity > 0.17 m/s), under existing conditions and with adjustable gates on Pipeclay and Slaney weirs.

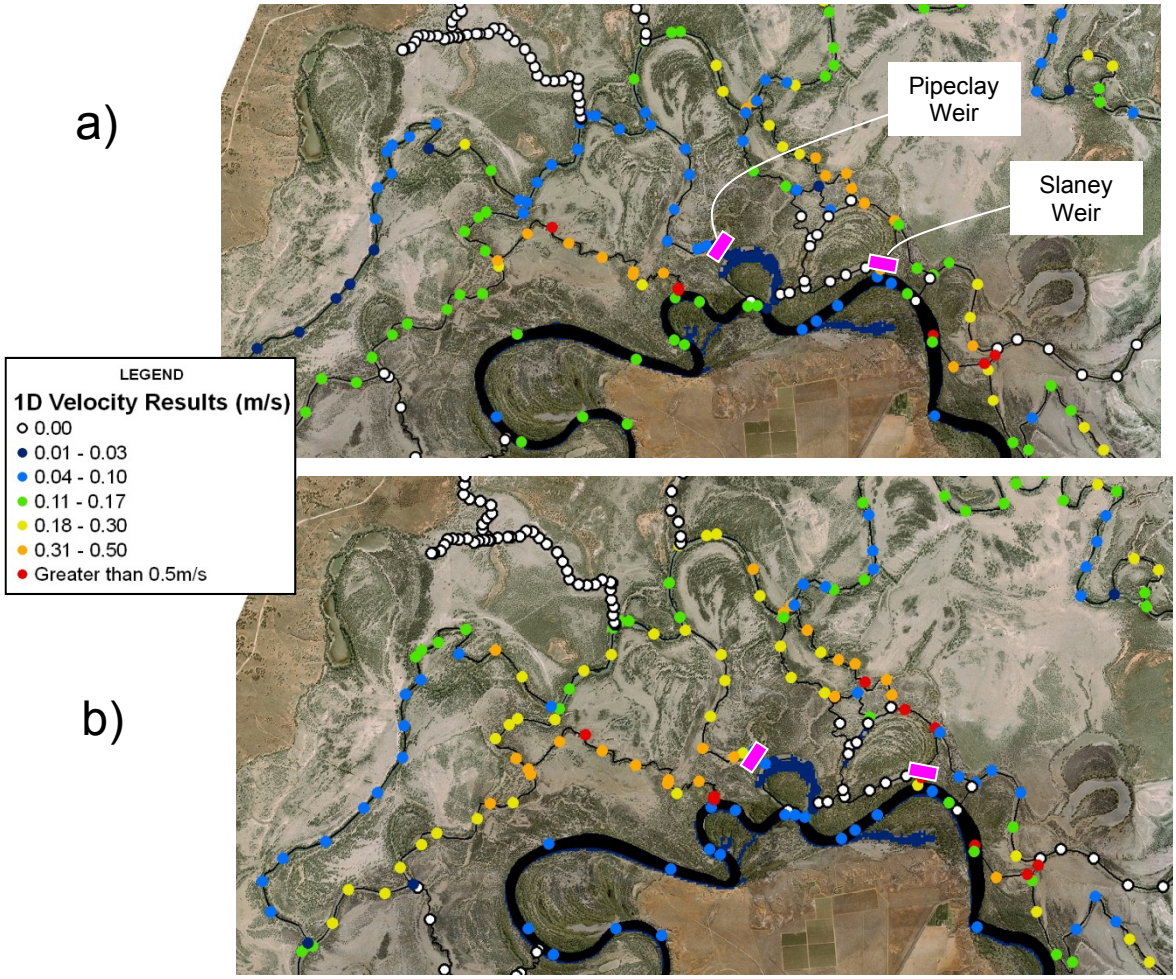

Fig. 16. Comparison of water velocity with 7,000 ML/d in the River Murray in *core habitats* under a) existing conditions and b) with adjustable gates on Pipeclay and Slaney weirs.

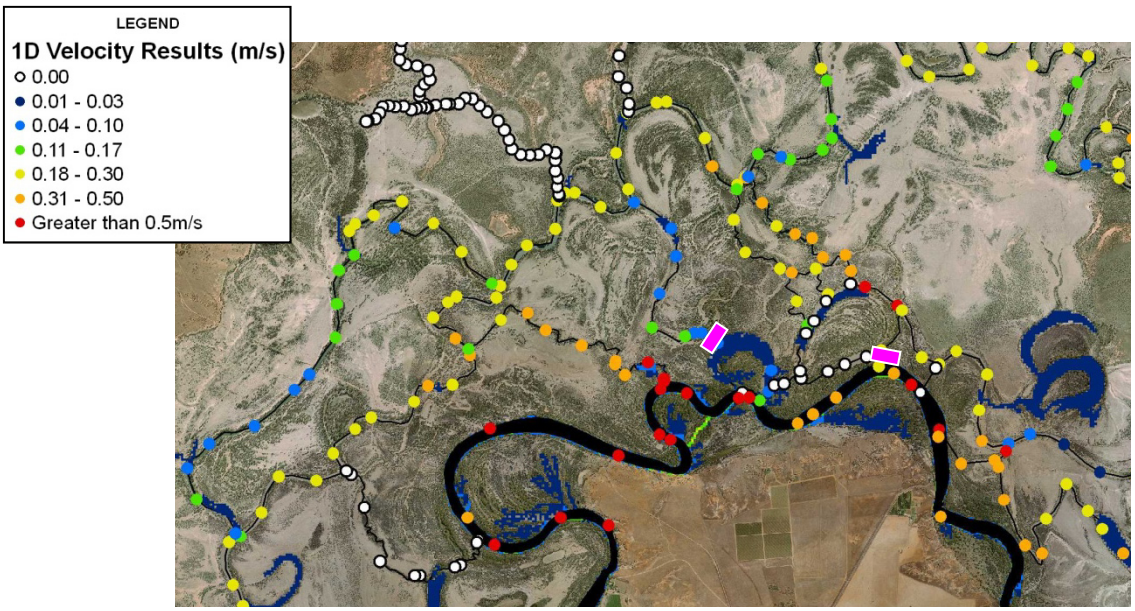

Fig. 17. Water velocity in *core habitats* under existing conditions with 40,000 ML/d in the River Murray.

5.4.2.2 Ecological Implications

- Improved flexibility of operation of Pipeclay and Slaney weirs provides the opportunity to simulate much higher river flows and increase the hydrodynamic diversity in the *core habitats* by increasing the extent of moderate- to fast- flowing reaches. However, a constraint is retaining the geomorphic stability of the stream.
- There is potential to increase streamflow variability and improve littoral zones in the *core habitats*. However, the role and ecological value of the littoral zone under natural conditions in these creeks is unknown and it is also possible that under the present stable flowing conditions the littoral zones that have developed are providing favourable habitats for fish recruitment. The streamflow down Pipeclay and Slaney creeks would have been more variable under natural conditions which could have produced either a diverse littoral zone of macrophytes or have favoured a lowered diversity with aquatic plants that tolerate variable levels (e.g. *Vallisneria*). Monitoring of these habitats would be necessary to assess the effect of increased streamflow variability.
- The increases in mean stream velocity also increases the habitats with margins and littoral zones of complex hydrodynamics. These form low velocity zones adjacent to high velocity zones where plankton could be more abundant and these could provide more feeding opportunities for fish larvae.
- For those species or life stages that respond to hydrological and hydrodynamic change on a meso-scale (e.g. the length of the *core habitats*), such as larvae and juveniles (0+) of Murray cod and freshwater catfish, there is potential to increase recruitment due to the increased hydrodynamic diversity. However, this would need to be treated as an experiment rather than a recommendation for management.
- A knowledge gap is the extent that meso-scale responses might still be dependent on landscape-scale processes. For example, the abundance of plankton in Chowilla might be dependent on primary and secondary productivity increases from upstream (i.e. floods or within-channel increases in flow) and transported to the anabranch creeks.

- Carp are responsive to water level fluctuations on a meso-scale and inundation of channel littoral zones which have macrophytes is likely to lead to increased spawning.

5.4.3 Chowilla Regulator

As described earlier, the objective of these model runs was to investigate the extent that *core habitats* in the anabranch creeks could be maintained whilst artificially inundating the Chowilla floodplain. A reduction in the *core habitats* has previously been identified as a significant risk (Mallen-Cooper *et al.* 2008).

Interactions of two methods of maintaining the *core habitats* were modelled: 1) raising the Lock 6 weir pool by 0.62 m from a normal level of 19.25 m to 19.87 m, to increase the differential head between the weir-pool and the Chowilla Regulator, and 2) increasing the available inflow from the River Murray to South Australia, at the upstream end of the Chowilla system, from 10,000 ML/d to 20,000 ML/d. The Chowilla regulator was incrementally raised in these model runs to quantify changes in habitats.

5.4.3.1 Major Findings

Flood dynamics

- The present modelling confirms earlier studies that show a major, and expected, reduction in the hydrodynamic diversity in Chowilla when using the Regulator to optimise floodplain inundation, when compared to a natural flood (Fig. 18).
- Using the Chowilla Regulator under the proposed operating regime (i.e. 10,000 ML/d or 20,000 ML/d Q_{SA}; regulator height used to simulate >40,000 ML/d flood inundation) will represent a change to the dynamics of floodplain inundation that is far greater than the effects on floods of Lock 6 which, while acknowledging the impacts of Lock 6 on groundwater and the river channel, has had little effect on the dynamics of natural floods.
- Use of the Regulator with low outflows (e.g. 2,000 ML/d), as per the most common proposed operation with low inflows of 10,000 ML/d that is aimed at optimising water use, results in a very low turnover of floodwater compared to natural floods. Using the Chowilla Regulator at high flows (e.g. 40,000 ML/d Q_{SA}) would obviously greatly increase turnover of floodwater.
- The Chowilla region has always had permanent complex flowing water habitat, firstly in the main channel under natural conditions prior to Lock 6 (Fig. 9), and then in the anabranch creeks after construction of Lock 6 (Fig. 12). Using the Chowilla Regulator to maximise inundation of floodplains with low inflows (e.g. 10,000 ML/d) would be the first time that these permanent habitats would be disrupted in this area and the hydrodynamic complexity severely reduced.

Retaining core habitats

- The height of the Regulator is the dominant feature controlling the extent of hydrodynamic diversity, having much more influence than inflows up to 20,000 ML/d or the height of the Lock 6 weirpool.
- The extent of moderate- (> 0.17 m/s) and fast-flowing (>0.30 m/s) reaches in the *core habitats* initially <u>increases</u> when using the Chowilla Regulator at low levels, as flow is increased through Pipeclay and Slaney weirs (Fig. 19), and then <u>decreases</u> when using the Chowilla Regulator at higher levels, as backwater from the regulator influences water velocity.
- Raising the Lock 6 weirpool 0.62 m maintains more of the *core habitats* than varying river inflows between 10,000 and 20,000 ML/d (Fig. 19). This is largely because the higher weirpool enables more flow to pass through the gates of Pipeclay and Slaney weirs.
- If Lock 6 is raised by 0.62 m, 100% of the *core habitats* with mean water velocities > 0.30 m/s (i.e. key adult Murray cod habitat) are maintained when the Chowilla Regulator is used up to approximately <u>18.0 m AHD</u>, which applies to either 10,000 ML/d or 20,000 ML/d passing in the River Murray (Q_{sa}) (Fig. 19). The percentage comparison is made with existing conditions at 5,000 ML/d, which is a typical regulated entitlement flow in spring.

- 75% of habitats > 0.30 m/s are maintained when Lock 6 is raised by 0.62 m and the Chowilla Regulator is operated up to approximately 18.5 m AHD, which again applies to either 10,000 ML/d and 20,000 ML/d (Fig. 19).
- At the same Regulator height more of the *moderately–flowing* (0.18 - 0.30 m/s) velocities are maintained in the *core habitats* than the *fast-flowing* (> 0.30 m/s) velocities.
- The most favourable operating strategy to maintain *moderately–flowing* velocities is to have inflows of 10,000 ML/d and have Lock 6 raised by 0.62 m. In these conditions 100% of *moderately–flowing* velocities are maintained up to a Regulator height of 19.4 – 19.5 m AHD, although the key *fast-flowing* habitats are reduced by 90%. Approximately 75% of *moderately–flowing* velocities are maintained up to a Regulator height of 19.6 m AHD.
- To maintain 100% of *moderately–flowing* velocities with the other operating strategies (Lock 6 raised 0.62 m with 20,000 ML/d; Lock 6 normal with 10,000 ML/d; Lock 6 normal with 20,000 ML/d) the Regulator needs to be below 18.5 to 18.7 m AHD. To maintain 75%, the Regulator needs to be below 19.2 m AHD when 20,000 ML/d is used with Lock 6 raised, or below 18.7 to 18.9 m AHD when Lock 6 is at normal pool; in these conditions the key *fast-flowing* habitats are reduced by 67 to 89%.
- When the Chowilla Regulator is set at 18.5 m and the Lock 6 weirpool is raised, to retain 75% of the hydrodynamics of the *core habitats* > 0.30 m/s, depth in the creek channels increases and some outlying wetlands, such as Lake Limbra and Werta Wert, receive water (Fig. 20).

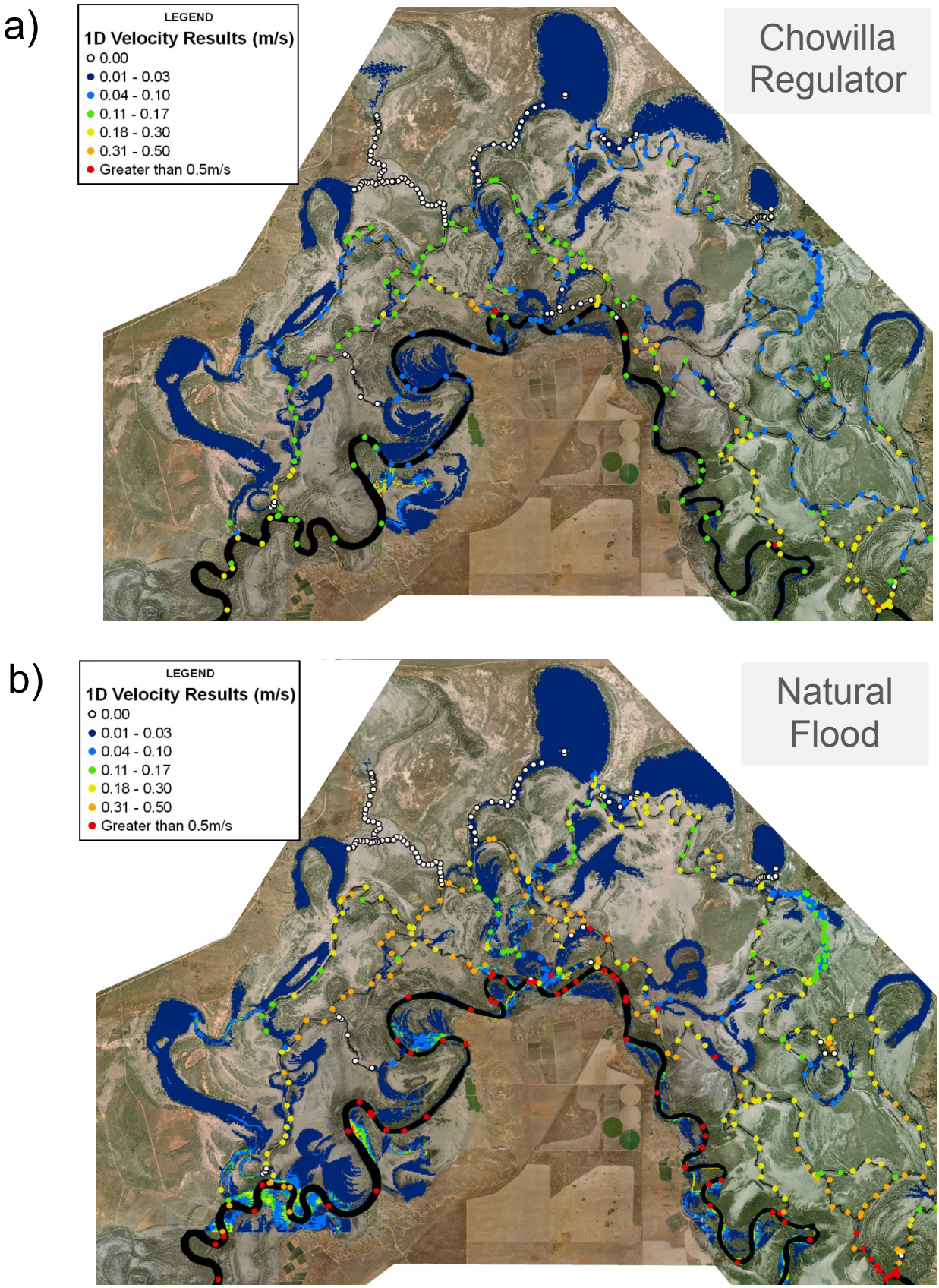

Fig. 18. Modelled (1D & 2D) velocities of Chowilla showing the reduction in hydrodynamic complexity when: a) using the Chowilla Regulator (19.2 m AHD; Lock 6 19.87 m AHD; Q_{SA} 10,000 ML/d) compared with b) a flood of 60,000 ML/d under present conditions.

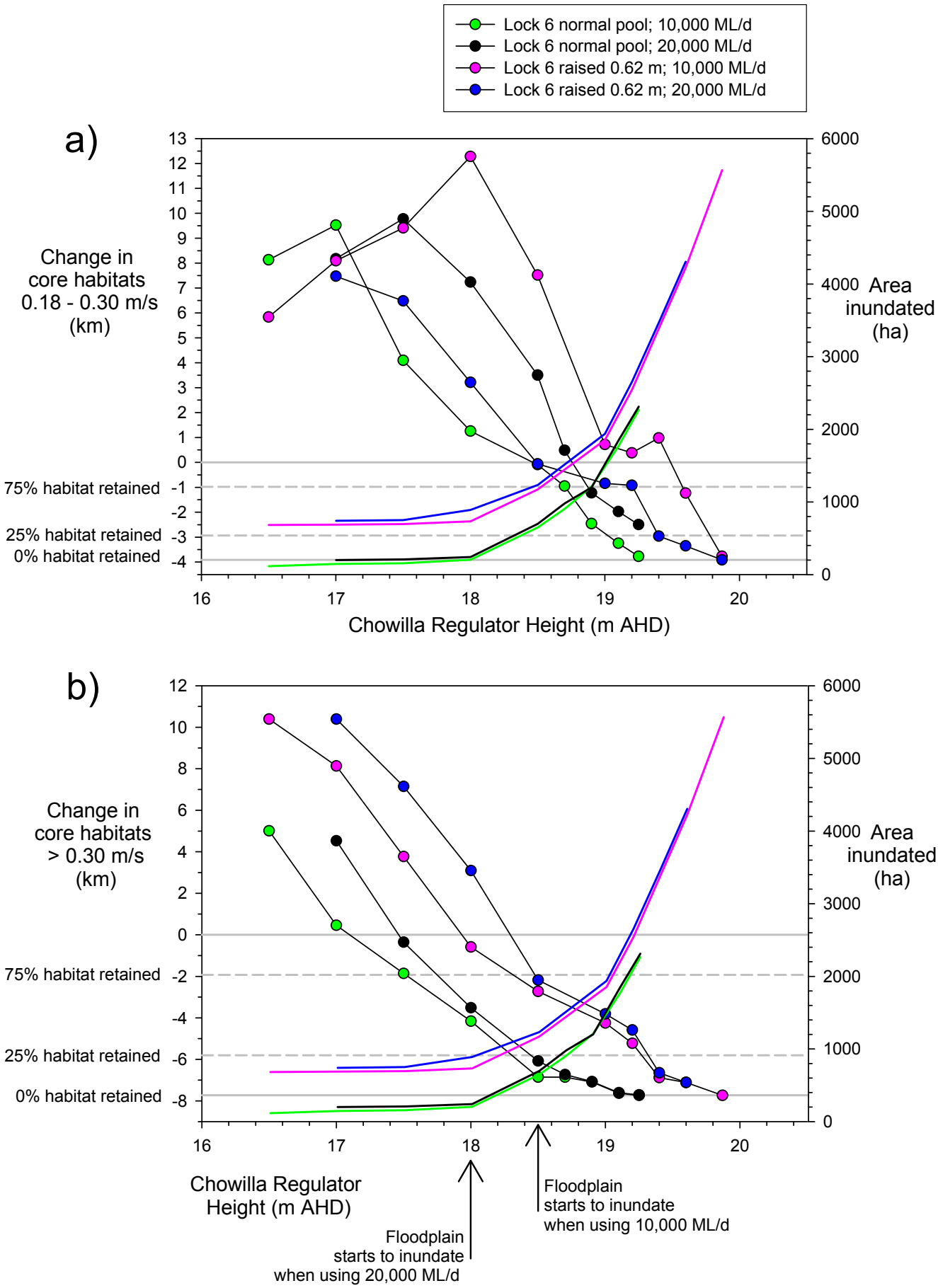

Fig. 19. Change in the percentage and distance of habitats (symbols and lines): a) 0.18-0.30 m/s and b) > 0.30 m/s, in the *core habitats*, using the Chowilla Regulator with 10,000 ML/d and 20,000 ML/d inflows and Lock 6 at normal pool and raised 0.62 m. Area inundated is shown with solid lines and no symbols.

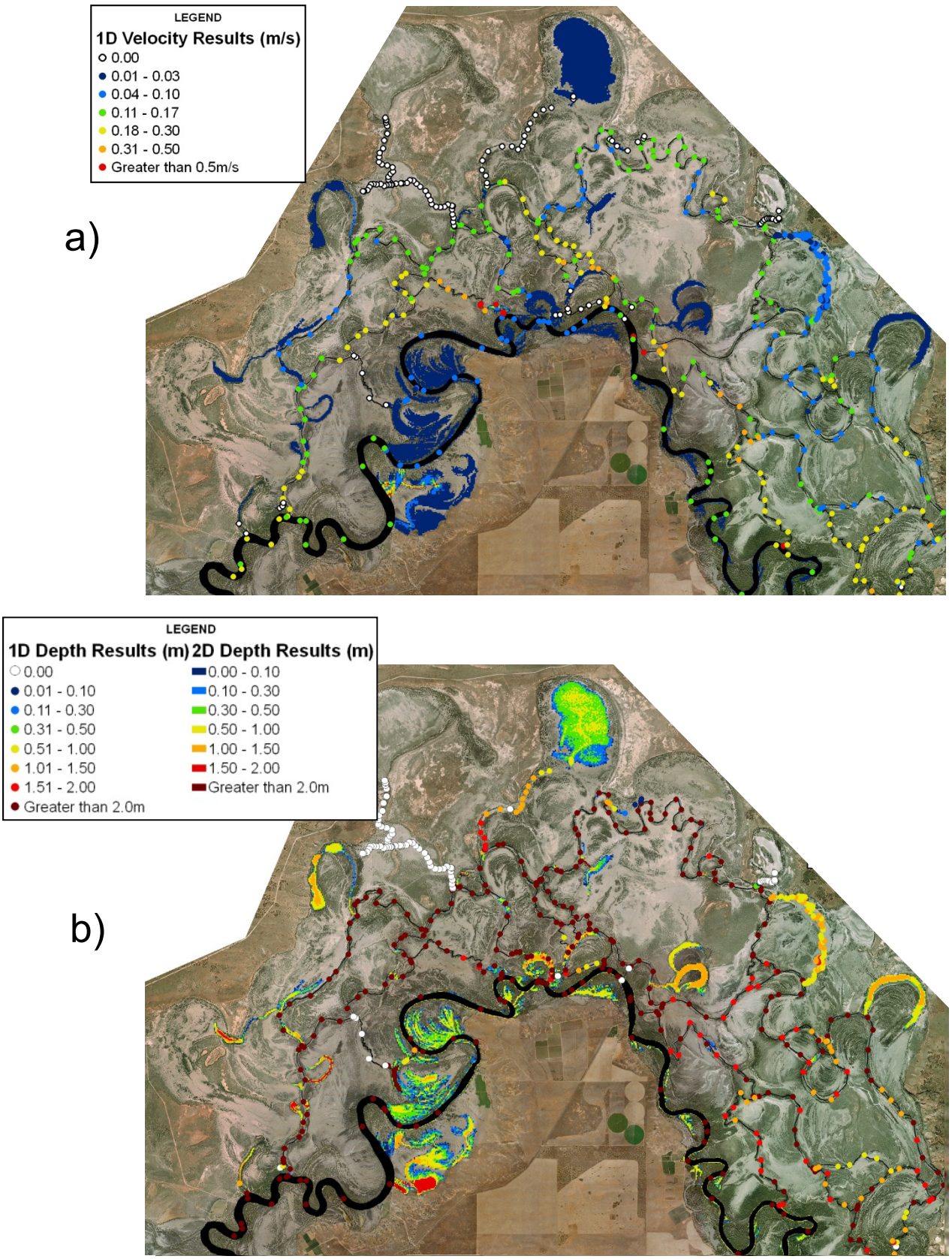

Fig. 20. Modelling results of Lock 6 raised 0.62 m and Chowilla Regulator set at 18.5 m, showing: a) velocity and b) depth. River Murray flow (Q_{sa}) is 10,000 ML/d.

5.4.3.2 Ecological Implications

Flood dynamics

- Carbon transport pathways will differ from a natural flood due to less throughput of flow.
- Dilution of carbon and primary productivity would be very low, both on the floodplain and as the water returns back to the river; hence, the risk of high oxygen demand, poor water quality and fish kills is higher than in a natural flood, both on the floodplain and in the river.
- The release of water from the floodplain back to the river would very likely not be synchronised with a flood or high flows in the river. For fish that spawn in response to high flows, larvae will not be present to take advantage of the released productivity. There will likely be high recruitment, however, of those fish species that spawn independently of flow during summer (the likely period of released water) and which appear to recruit successfully in deep lentic water-bodies, like the River Murray weir-pools. These species include the already common gudgeons and bony herring, but none of the species at risk.
- Operating the Chowilla Regulator to maximise floodplain inundation reduces the hydrodynamic variability compared to both natural floods and to existing conditions under low flows (i.e. "do nothing"). This reduces the diversity of fish habitats, particularly habitats suitable for larvae of those fish species that require complex flowing water habitats, such as flowing channels with slow-flowing margins. Such habitats include epibenthic zones with roughness, backwaters and adjacent off-channel wetlands. These habitats are potential nursery areas for larvae and juveniles where food, such as zooplankton, is more abundant and accessible.

  The results confirm findings from the previous modelling and risk assessment (Mallen-Cooper *et al.* 2008), that operating the Chowilla Regulator to maximise floodplain inundation will favour most small-bodied native fishes and will disadvantage all the large-bodied fish species except bony herring.

Retaining Core Habitats

- The *core habitats* are hydrodynamically diverse with low and high velocities. The higher mean velocities have a greater diversity than the low mean velocities because they include margins and backwaters with low velocity. This small-scale diversity is not shown with the 1D model or with the 2D model at the scale used, but it can be assumed from the mean velocity.
- Two components of the velocity range are significant in determining the relationship between hydrodynamic diversity and fish distribution: > 0.17 m/s, which defines flowing (lotic) water for fish habitats; and > 0.3 m/s, which is a key habitat for large-bodied fish but particularly for spawning adult Murray cod in spring. Extensive sampling in the Chowilla system between 2004 and 2007 has shown that adult Murray cod and other large-bodied fish select these fast-flowing habitats (Zampatti *et al*. 2011) and this has also been confirmed in the Lindsay-Mullaroo system with radiotracking (Saddlier *et al*. 2008).
- Reducing the extent of habitats with velocities > 0.3 m/s could reduce spawning of Murray cod. These fish may seek more suitable spawning sites, which could lead to increased emigration. Significantly, hydrodynamic diversity is reduced and this is very likely to impact on larval drift and nursery habitats for larvae; the potential flow-on effect is reduced survival of larvae, reduced recruitment and a poor year class. It is also possible that Murray cod will not seek alternative spawning sites and will spawn in the same locations, even though velocity is reduced; however, conditions for larval survival is reduced and recruitment would be expected to be worse than not using the Regulator.
- Operating the Chowilla Regulator with Lock 6 raised by 0.62m provides a greater increase on *core habitats* at low regulator levels (< 18.3 m) and greater preservation of *core habitats* at higher regulator levels, compared with increasing River Murray inflows from 10,000 ML/d to 20,000 ML/d. The advantage of using 20,000 ML/d is that it is likely to be a landscape–scale flow event that could stimulate golden perch and silver perch to spawn.

- Operating the Chowilla Regulator up to 18.5 m AHD, with Lock 6 raised 0.62 m enables 75% of flowing water habitats with velocities >0.30 m/s to be maintained. A reduction of 25% of these habitats is considered an acceptable risk in a short-term event such as a managed inundation, as the majority of the adult population is likely to be retained and immigration or return movement may occur over the following months or years (if no managed inundation occurs). The caveat is that monitoring is needed to verify this assessment of risk, both for the short-term response and for long term trends in the population. The monitoring would then provide feedback to adaptively manage the Chowilla Regulator to ensure that native fish species at risk are not impacted.
- Operating the Chowilla Regulator up to 19.0 m AHD with Lock 6 raised 0.62 m enables 50% of *fast-flowing* (>0.30 m/s) habitats to be maintained. Loosing half of the prime spawning habitat of Murray cod presents a significant risk, with further reduced spawning, recruitment and increased emigration. Such an event would need to be monitored very carefully for short-term and long-term impacts.
- Operating the Chowilla Regulator up to 19.4 m AHD reduces most of the habitat > 0.3 m/s and creates a high risk of a major impact on the spawning season of Murray cod. At this Regulator height the retention of habitat with 0.17 – 0.30 m/s is improved with Lock 6 raised 0.62 m but it is sensitive to inflows, ranging from 25% retention at 10,000 ML/d to over 100% at 20,000 ML/d. However, the ecological interaction of *moderate-flowing* and *fast-flowing* habitats is unknown, and the extent that adult fish would remain in these habitats or that nursery habitats would be retained are unknown.

5.4.4 Rehabilitating flowing water habitats

Model runs were conducted with the Lock 6 weirpool level lowered by 0.5 m and 1.0 m (Table 11). The objectives were to investigate the extent that the upper Lock 6 weirpool could be rehabilitated to a flowing river habitat – a principle that could be applied to any of the lower Murray Weirs - and assess the impact on existing flowing water habitats in the anabranch creeks of Chowilla.

5.4.4.1 Major Findings

- Lowering the Lock 6 weirpool by 0.5 m produces no detectable change in hydrodynamics at very low flows of 1,000 and 2,000 ML/d or at higher flows of 7,000 ML/d or greater, but flowing water habitats with velocities > 0.17 m/s increase by 3.7 km at a flow of 5,000 ML/d (Fig. 21).
- Lowering the Lock 6 weirpool by 1.0 m also has no impact on hydrodynamics at very low flows of 1,000 and 2,000 ML/d but produces an increase of 10.5 km in flowing water habitats (with velocities > 0.17 m/s) at 5,000 ML/d (Fig. 21). This is equivalent to 18% of the 58 km-long weirpool and almost doubles the extent of flowing water habitats of the Icon site by adding to the existing 11.6 km of the *core habitats*. At higher flows of 10,000 and 15,000 ML/d there is a minor increase of 1.2-3.5 km kilometres in flowing habitats.
- Higher velocity habitats of > 0.3 m/s occur in the upper weirpool at flows of 10,000 ML/d and greater, with both the weirpool lowered by 0.5 m and 1.0 m.
- At flows ≥ 20,000 ML/d, decreasing weir-pool height by 0.5 or 1.0 m produces little change in hydrodynamics, as flow rather than weirpool level is determining water velocity. At these higher flows the river has a high proportion of flowing habitats > 0.17 m/s, similar to the unregulated conditions without the locks (Fig. 10).
- With the weirpool lowered by 0.5 m or 1.0 m it is possible that, at low flows, the inlets of the upper creeks in the Chowilla system (e.g. Salt Creek) are above the weir-pool level and may not flow but further modelling would be needed to quantify this.

- The modelling showed reductions in the water velocity of the *core habitats* of the anabranch creeks. This is dependent, however, on discharge through Pipeclay and Slaney weirs and further modelling with different gate settings would be needed to quantify the extent that the *core habitats* would be affected.

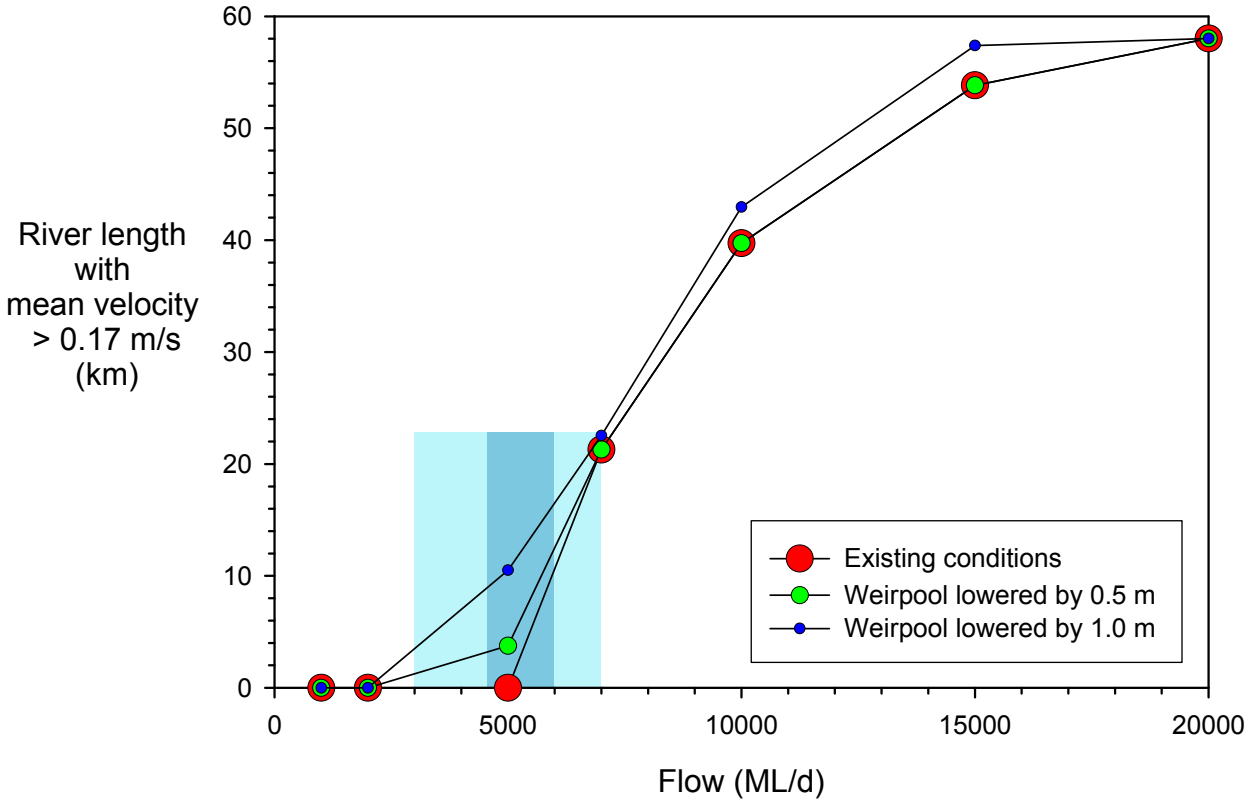

Fig. 21. Comparison of the extent of flowing water habitats (> 0.17 m/s) in the Lock 6 weirpool under existing conditions and with the weirpool lowered by 0.5 m and 1.0 m. The light blue box is the range of entitlement flows to South Australia and the darker blue box is entitlement flows in spring, which is the spawning season of Murray cod.

5.4.4.2 Ecological Implications

- Rehabilitating the hydrodynamic diversity of the main channel of the River Murray by increasing flowing water habitats would improve conditions for native fish, particularly for those species that have declined as a result of the river changing from a flowing river to a series of weirpools.
- Lowering the weirpool by 0.5 m only improves a relatively small reach of the upper weirpool at 5,000 ML/d so the response of fish populations would be very minor.
- The increase of 10.5 km of flowing water habitats provided by lowering the weirpool by 1.0 m at 5,000 ML/d would provide a major benefit for fish populations in the river, particularly for three large-bodied species considered at risk in the present project - Murray cod, golden perch and silver perch.
    - Significantly, this discharge is within the range of 'entitlement' flows in spring, when many native fish are active and spawning, as well as during other 'entitlement' flow periods (Fig. 21).

- The increase in flowing water habitats in spring would provide more suitable habitat for adult and juvenile fish of these species.
- Murray cod respond to hydrodynamic change on a meso-scale, so the increased flowing water could lead to increased spawning activity in the main channel of the River Murray. The increased mean velocity would likely facilitate drift of Murray cod larvae thus mitigating potential density dependent impacts; as well as increasing nursery habitats, such as littoral margins and epibenthic zones with complex hydrodynamics. These conditions could lead to increased recruitment of this species.

5.4.5 Assessing impacts on the lower Lindsay River and Mullaroo Creek

The results of the modelling and the conclusions were sent to MDBNRM Board on 9 October 2009 in a separate memorandum (Appendix 3). In summary, the memorandum stated that raising the Lock 6 weirpool by 0.63 m impacts on 50% of flowing habitats in Mullaroo Creek but this can be largely mitigated by raising the Lock 7 weirpool by 0.15 m. Further modelling was recommended to refine this mitigation strategy and to establish the hydraulic diversity that naturally occurs in the system, with the intent of establishing a baseline and bounds for future management.

6 PREDICTED RESPONSES OF FISH SPECIES AT RISK

6.1 Introduction

Each managed inundation event will be unique. There will be different inflows, inundation rates, water levels, recession times, temperatures, climate and water quality. To assess fish responses we considered two broad groups of managed events that either: i) retained the majority of *core habitats* (>75%) as lotic (flowing) or ii) retained a minority (< 25%) of the *core habitats* as lotic. These were compared to a *no change* scenario with no new infrastructure but with the same additional environmental flows (10,000 ML/d Q_{SA}); in this scenario more flow could be passed down the Chowilla Creeks by raising the Lock 6 weirpool, rather than using new gates on Pipeclay and Slaney creek weirs. The three scenarios are also used in Section 7 to assess risk and benefits.

The conceptual models and the hydrodynamic modelling were used to assess the response of fish species at risk, as well as the non-native carp, for these three scenarios, both in an event (short-term over a few months) and for a regime (long-term, with multiple events over many years). Each scenario includes a regime with more variable environmental flows in the main Chowilla Creeks, without the Chowilla Regulator in use and without additional flow in the River Murray. This is achieved either by using the upgraded Pipeclay and Slaney weirs or by raising Lock 6 with the existing Pipeclay and Slaney weirs. To provide background to the predicted responses of fish, the expected ecological changes in the three scenarios are summarised below:

1. **No change to infrastructure - additional environmental flows; lotic habitats increased in spring**

    - No Chowilla Regulator.
    - No upgraded gates on Pipeclay or Slaney weirs (i.e. very little control of flow except by varying the Lock 6 weirpool level).
    - No fishways on Pipeclay and Slaney weirs.
    - Natural floods included.
    - Environmental flows included (e.g. 10,000 ML/d inflows in spring).
    - Lotic habitats in anabranch creeks increased in spring (environmental flow increases the extent of flowing water habitat in Chowilla with Lock 6 raised).

    Expected Ecological Changes

    The impacts under this scenario would differ in floods and low flows. Present concepts of floodplain/river interactions in dryland rivers suggest that the productivity of inundated floodplains like Chowilla is more likely driven by endogenous carbon and nutrients, rather than exogenous sources such as floodwaters, although exogenous plankton are important in initiating productivity. In large natural floods the poorer vegetation health would, however, result in less allochthonous (external) floodplain carbon inputs and the degraded floodplain would have a less abundant 'seedbank' of plankton, which are important in sustaining productivity in floods. Therefore, the reduced carbon inputs and reduced plankton of the degraded floodplain would directly result in lower productivity returning to the main river in large natural floods. This could result in poorer recruitment of those fish species that spawn in floods. The caveat to this statement is that the extent that carbon inputs from floodplains are limiting productivity in natural floods in the River Murray is unknown, and the proportion of carbon that the Chowilla floodplain contributes to the River Murray is unknown. However, ecological theory clearly suggests that a healthy vegetated floodplain should benefit the ecology of the river in floods and a degraded floodplain would provide fewer benefits.

    Under the *no change* scenario the floodplain is expected to degrade further (Overton *et al*. 2005) but the health of the littoral and aquatic vegetation is expected to remain relatively stable (excluding reaches of creeks with saline groundwater intrusion which significantly degrades littoral and riparian vegetation). Despite the degradation of the floodplain, native fish present in Chowilla are not expected to decline as they are largely dependent on the

mosaic of habitats in the anabranch creeks and adjacent wetlands, and not inundation of the floodplain.

Ongoing low-level autochthonous (aquatic) carbon inputs and riparian allochthonous carbon inputs, such as leaf litter, would remain relatively unchanged. Hence, instream productivity during non-flood years should remain unchanged. With the addition of environmental flows in spring inundating stream margins and low-level benches, productivity would likely increase, leading to increased fish recruitment.

2. Chowilla Regulator - lower height range (< 18.5 m AHD), additional E-flows; >75% lotic habitats maintained

- Chowilla Regulator.
- >75% of lotic habitats maintained in managed inundations.
- Upgraded gates Pipeclay or Slaney weirs (with variable control of flow).
- Fishways at Pipeclay and Slaney weirs.
- E-flows included [e.g. 10,000 ML/d inflows].
- Lotic habitats increased seasonally when regulator not operating; additional E-flows required.
- Natural floods included.
- Operating regime: possibly used once every four years in spring with 10,000 ML/d (Q_{SA}) inflows (i.e. less frequent than described in the Brief to meet floodplain objectives).

Expected Ecological Changes

Under this regime low-lying wetlands and habitats on stream margins would improve or retain their ecological integrity. However, there is little large-scale inundation so the broader floodplain is expected to continue degrading but to a lesser extent than the *no change* scenario. Comments above for the *no change* scenario on the effects of floodplain productivity, carbon dynamics, and the interactions of the river and floodplain also apply to this scenario.

3. Chowilla Regulator – upper height range (18.5 -19.87 m AHD); additional E-flows; 25 - 0% lotic habitats maintained

- Chowilla Regulator.
- 25% of lotic habitats maintained in managed inundations at a Regulator level of 18.5 m AHD, with a decreasing percentage as the Regulator height increases.
- Upgraded gates Pipeclay or Slaney weirs (with variable control of flow).
- Fishways at Pipeclay and Slaney weirs.
- E-flows included [e.g. 10,000 ML/d inflows].
- Lotic habitats increased seasonally when regulator not operating; additional E-flows required.
- Natural floods included.
- Operating regime: used once every two to four years in spring with 10,000 ML/d inflows (i.e. frequency as described in the Brief to meet terrestrial floodplain objectives).

Expected Ecological changes

Using the Chowilla Regulator frequently and at the upper height range is predicted to improve terrestrial floodplain vegetation. However, the high saline water table and hydraulic pressure from the Lock 6 weirpool remain when the Regulator is not in use and floodplain vegetation on the edge of the inundated area (e.g. the upstream [eastern area] area of the floodplain) may be stressed by high salt levels in these conditions.

Managed inundations will increase carbon capture through primary productivity of phytoplankton and through the increase in the health and abundance of floodplain vegetation. The extent that this productivity is transported to the river is unknown but it is likely to be less than a natural flood simply due to the lower turnover of floodwater.

The increase in inundation area and frequency is likely to improve the 'seedbank' of plankton. This would then be available in natural floods and hence could improve the productivity of these events.

Aquatic macrophytes would be little affected in the long term but the health of riparian vegetation is likely to improve. Allochthonous carbon from the riparian zone is likely to increase but no major change in the carbon dynamics of low flows is expected.

6.2 Species Responses

6.2.1 Murray cod

No Change

Event

- Lotic habitats maintained, so that emigration and immigration (dependent on main stem recruitment) rates would remain stable.
- Present passage of Murray cod between the anabranch creeks and the main stem downstream of Lock 6 would continue.
- Using Pipeclay and Slaney weirs to increase lotic habitats, by raising Lock 6, has the potential to increase recruitment, although there is also a risk of increased carp recruitment.
- Present spawning and recruitment patterns continue, with ongoing recruitment each year.

Regime

- Terrestrial floodplain degrades but has little effect on local recruitment in non-flood years, because instream spawning habitats remain and nursery habitats remain (i.e. diverse hydrodynamics in littoral and epibenthic zones).
- Degraded floodplain would reduce carbon inputs to the river in large floods. If carbon is limiting, then productivity and fish recruitment in large floods would be reduced in the lower River Murray.

Chowilla Regulator; > 75% lotic habitats retained

Event

- The reduction of lotic habitats may cause some adult and immature fish to leave the Icon site but the majority of the adult population are likely to remain in Chowilla.
- Present spawning and recruitment patterns would continue in an event, possibly with slightly reduced recruitment due to the reduction of nursery areas.
- Present passage of Murray cod between the anabranch creeks and the main stem downstream of Lock 6 may be slightly restricted through the Chowilla Regulator fishway, but the majority of movement of fish seeking spawning sites is not likely to be interrupted.
- Using Pipeclay and Slaney weirs to increase lotic habitats, without the Chowilla regulator, has the potential to increase recruitment, although there is also a risk of increased carp recruitment.
- Fish passage through Pipeclay and Slaney weirs would improve connectivity, enabling dispersal of immature fish and movement of adult fish between the creeks and the river.

Regime

- Retaining 75% of lotic habitats and using Pipeclay and Slaney weirs in the years when the Chowilla Regulator is not operational is likely to retain the present population of Murray cod. This is because recruitment would be less in years when the Regulator is used (e.g. by 25 %) but could be more in other years, using Pipeclay and Slaneys weirs to increase hydrodynamic diversity.
- Of those fish that emigrate from Chowilla, there is likely to be some return movement as well as immigration over the following months or years with no managed inundation.

Chowilla Regulator; < 25% lotic habitats retained

Event

- There are two major models of movement and spawning with the Chowilla Regulator operating in this condition:

  Model 1.

  - The loss of the majority of lotic habitats leads to increased competition for preferred spawning sites, and increased movement out of the Icon site. This movement may result in emigration but some fish are likely to return after a single event. Due to less adult fish present during the event, total spawning for the Chowilla population is reduced.

  Model 2.

  - Fish have high fidelity for spawning sites and use the same spawning locations despite the change from a lotic to a lentic environment. Movement out of the Icon site is limited.
- In both models survival of larvae would be poor because of reduced nursery habitats and potentially density-dependent effects, resulting in poor recruitment.
- The passage of Murray cod between the anabranch creeks and the main stem downstream of Lock 6 may be slightly restricted through the Chowilla Regulator fishway, which may affect spawning.
- In years when the Chowilla regulator is not used, Pipeclay and Slaney weirs can be used to increase lotic habitats and this has the potential to increase recruitment, although there is also a risk of increased carp recruitment.
- Fish passage through Pipeclay and Slaney weirs would improve connectivity, enabling dispersal of immature fish and movement of adult fish between the creeks and the river.

Regime

- Under the two major models of movement and spawning:

  Model 1.

  - Over the short-term of a few managed events the total adult population would decline slightly but over the long-term there is a possibility that adult fish will permanently seek spawning sites elsewhere, which may be sub-optimal. The total resident population of Chowilla would decline.
  - The extent that this occurs would depend on the frequency of managed inundations; e.g. a 1-in-10 year frequency would likely have no long-term impact whilst a 1-in-2 year frequency would very likely reduce abundance.

  Model 2.

  - The existing population retains fidelity to Chowilla over the long-term but abundance declines with increasing mortality of the resident population, with a major decline over the scale of the life span of Murray cod (approx. 50 years). As in Model 1, the total resident population of Chowilla would decline.
  - Immigration does not replace mortality as new immigrants would be seeking optimum reliable habitat in spring.

  - As in Model 1, the extent that this occurs would depend on the frequency of managed inundations.
- In both models total recruitment over many years would be less. However, there is potential to compensate for this and increase recruitment when the Chowilla regulator is not in use, by increasing lotic habitats using Pipeclay and Slaney weirs. An experimental approach is needed to quantify recruitment with increased lotic habitats, and this may not necessarily increase nursery habitats of margins and adjacent backwaters. The recruitment patterns in years with and without the Chowilla Regulator would be a useful basis for adaptive management of the project.
- Chowilla appears to be an effective recruitment zone for Murray cod which is likely influencing the abundance of cod more broadly, so a major risk for the Icon site and for the region is that a reduction in recruitment in Chowilla may result in a less abundant population in the River Murray.

6.2.2 Golden perch

No Change

Event

- Lotic habitats maintained, so that emigration and immigration rates would remain stable.
- Using environmental flows of 10,000 ML/d, without the Chowilla Regulator, would stimulate fish to leave Chowilla and migrate upstream but present data suggests at least 15,000 ML/d is needed to stimulate spawning of this species.
- Present spawning and recruitment patterns continue, which are dependent on landscape–scale rather than meso-scale changes in flows. Recruitment each year would be dependent on large main-channel flows.
- Present passage of golden perch between the anabranch creeks and the main stem downstream of Lock 6 would continue, but passage is blocked at Pipeclay and Slaney weirs. Passage along the main stem is improved by a new fishway at Lock 6.

Regime

- The long-term degradation of the floodplain would result in less productivity of large natural floods, which may influence the recruitment of golden perch in these events. This will depend on the extent that the Chowilla floodplain contributes to the productivity of large floods in the lower River Murray.
- Spawning and recruitment during within-channel flows that do not inundate floodplains would remain unaffected.

Chowilla Regulator; > 75% lotic habitats retained

Event

- At the beginning of an event the increase in flow would stimulate fish to migrate upstream and leave Chowilla, whilst fish downstream of Chowilla would have little stimulus to migrate into Chowilla. During an event, net emigration is expected and a reduced abundance of golden perch would occur.
- Using inflows of 10,000 ML/d would not likely provide sufficient stimulus for golden perch to spawn. However, a flow of 15,000 to 20,000 ML/d may stimulate spawning of this species, noting that the source of water (i.e. stored water versus natural floodwaters) may be as important as the discharge.
- If the Chowilla Regulator is used with natural floodwaters of 20,000 ML/d that are occurring on a landscape–scale, there is a possibility that recruitment of golden perch could be enhanced.

- Passage of golden perch at Pipeclay and Slaney weirs is improved with new fishways, enabling year-round dispersal and a rapid migration response to natural floods.

Regime

- Although there is net emigration of golden perch from the Icon site, golden perch exhibit moderate rates of dispersal so that immigration of fish is expected between events. As for Murray cod above, the extent that this occurs would depend on the frequency of managed inundations; e.g. a 1-in-10 year frequency would very likely have no long-term impact whilst a 1-in-2 year frequency would very likely reduce abundance.
- Similar to the *no change* scenario above, present spawning and recruitment patterns continue, which are dependent on landscape–scale rather than meso-scale changes in flows. Recruitment each year remains dependent on large main-channel flows.

Chowilla Regulator; < 25% lotic habitats retained

- The response of golden perch under this scenario is similar to the above scenario with 75% of lotic habitats retained, but emigration is likely to be higher due to the reduction in these habitats. Hence, it would take longer for immigration to return abundance to pre-event levels.

6.2.3 Silver perch

In many respects the response of silver perch is likely to be very similar to golden perch. The differences are that less is known of the biology of silver perch and they appear to be more a main-channel species (including large lotic creeks in the Chowilla system) whereas golden perch are found in a wider variety of habitats including lentic habitats such as floodplains and terminal lakes.

Whilst there may be some potential to enhance recruitment of golden perch using the Chowilla Regulator with natural floodwaters greater than 15,000 to 20,000 ML/d, the same does not necessarily apply to silver perch. Unlike golden perch, silver perch juveniles were not collected recently in 2011 from the floodplains of Chowilla (B. Zampatti, unpub. data) whereas they are consistently collected from main channel sites in fishways.

Similar to Murray cod and golden perch, the extent that this species returns to Chowilla after a managed event is dependent on the frequency of use of the Regulator. Juvenile silver perch have active longitudinal migrations, presumable to disperse from nursery areas and compensate for downstream drift as larvae. These fish would recolonise Chowilla after a managed event and, as for golden perch, a 1-in-10 year frequency would very likely have no long-term impact whilst a 1-in-2 year frequency would very likely reduce abundance.

Overall, the ecology of silver perch in the lower River Murray remains a major knowledge gap in our conceptual understanding of native fish ecology in the MDB.

6.2.4 Freshwater catfish

No Change

Event

- Lotic and lentic diversity of habitats maintained, with the same levels of instream diversity and aquatic macrophytes.
- Low-flow carbon dynamics continue relatively unchanged.

- Present spawning and recruitment patterns continue.
- Emigration and immigration rates remain stable.

Regime

- Terrestrial floodplain degrades but has little effect on local recruitment, because instream spawning habitats remain and nursery habitats remain.
- Degraded floodplain would reduce carbon inputs to the river in large floods but recruitment of this species does not appear to be strongly linked to floods.

Chowilla Regulator; > 75% lotic habitats retained

Event

- This species is often found in lentic habitats so the reduction of lotic habitats is not likely to increase emigration from the area.
- Present spawning would continue in a managed event. Nevertheless, freshwater catfish are sensitive to variations in water levels and will abandon nests if there is a reduction in water level during incubation of eggs.
- The extent that hydrodynamically diverse habitats enhance survival of catfish larvae is unknown, so the effect of reduced lotic habitats on recruitment is unknown.
- Increased access of carp to wetlands could lead to disturbance of nests and nursery areas, which would cause poor recruitment of freshwater catfish.
- Fish passage through Pipeclay and Slaney weirs would improve connectivity, enabling dispersal of immature fish and movement of adult fish between the creeks and the river.

Regime

- If water levels are managed to ensure spawning is completed, the long term impacts are mainly from negative interactions with carp. There are two possible models that relate to the direct impacts of carp and carp abundance:

  Model 1.

  - Increased access and abundance of carp has a direct negative impact on the spawning sites and nursery areas of freshwater catfish. These cause recruitment failure in repeated events. Frequent managed inundations causes an increase in the carp population with ongoing negative impacts on spawning and recruitment in every year and catfish habitats in general. Consequently, the freshwater catfish population declines.

  Model 2.

  - Spawning areas and nursery areas of freshwater catfish have minimal overlap with habitat of carp. Abundance and density of carp increase but not to an extent that impacts on recruitment of catfish.
- Both models are equally valid and will probably depend on the increased abundance and density of carp.

Chowilla Regulator; < 25% lotic habitats retained

Event

- As freshwater catfish do not appear to actively seek lotic habitats for spawning the additional reduction of these habitats is not likely to have an additional direct impact.
- The indirect impacts are greater because the additional inundation of the floodplain provides greater opportunities for carp to spawn and greater access to catfish habitats.
- Fish passage through Pipeclay and Slaney weirs would improve connectivity, enabling dispersal of immature fish and movement of adult fish between the creeks and the river.

Regime

- If the Regulator was used frequently, the increased opportunities for carp provided by the increased inundation areas would increase the probability of Model 1, described above, with a decline in the catfish population.

6.2.5 Carp

No Change

Event

- Carp population continues with present fluctuating recruitment patterns, including poor recruitment in drought years and high recruitment in flood years.

Regime

- Terrestrial floodplain degrades but has little effect on local recruitment, because instream spawning habitats remain and nursery habitats remain.
- Carp population is stable over time with generally high abundance throughout the lower River Murray.

Chowilla Regulator; > 75% lotic habitats retained

Event

- Inundating stream margins and low-lying floodplains, and increasing the extent of lentic habitats will create excellent conditions for spawning and recruitment of carp. The local population of carp will increase and these fish will also disperse to the River Murray.

Regime

- Frequent use of the Chowilla Regulator in spring will increase the abundance of carp.
- The extent of the population increase will be limited by: i) the available nursery areas, which is much less than the full inundation scenario with *less than 25% of lotic habitats retained,* and ii) the timing of inundation which can targeted to avoid the spawning period of carp (see Carp Management Strategy, Stuart *et al*. 2011).

Chowilla Regulator; < 25% lotic habitats retained

Event

- Widespread inundation of floodplains will provide extensive habitat for spawning and recruitment and a major increase in the abundance of carp can be expected.

Regime

- If the Regulator was used frequently in spring, the carp population would increase substantially.
- If the Regulator was used outside of the spawning season of carp, in winter, the increase in carp abundance would be minimal.

The response of carp to operation of the Chowilla Regulator is discussed further in the Carp Management Strategy (Stuart *et al*. 2011), which discusses the scenarios in more detail and provides a framework for implementation of strategies for management.

6.3 Knowledge Gaps

The predicted responses of fish highlight some specific knowledge gaps from the conceptual models that have direct implication for management of the Chowilla Regulator and should be a focus of monitoring efforts.

MURRAY COD

Movement

- Emigration: i) during an event, including response time (e.g. Is the response different for one week or one month of inundation?), and ii) over a regime of repeated spring inundations.
- Return movements and immigration of adult and juvenile fish after an event.

Recruitment

- Recruitment in Pipeclay and Slaney creeks with fluctuating flows and increased lotic habitats in spring.
- Recruitment during managed events and under *no change* scenario.

Population Dynamics

- Natural population variance over time.

GOLDEN PERCH

Movement

- Rates of emigration and immigration (adults and juveniles) under natural conditions and under managed inundations.

Recruitment

- Can recruitment be enhanced with a combination of natural high flows and the Chowilla Regulator?
- Can spawning by cued from stored water from Lake Victoria plus additional river flow or is it dependent on floodwaters from upstream passing uninterrupted along the main stem of the River Murray?
- Origin of juveniles (i.e. new recruits)

SILVER PERCH

- The knowledge gaps are similar to golden perch but their ecology in the lower River Murray is much less well understood.

FRESHWATER CATFISH

Habitats

- Distribution and habitat use of freshwater catfish in the Chowilla region.

Movement

- Movement of adults and juveniles between lotic and lentic habitats and between the River Murray and Chowilla system (Note: drift of freshwater catfish larvae has been observed in lotic habitats in Chowilla).

Interactions with carp

- Will carp impact on catfish nests and nursery areas in managed inundations?
- Do carp displace freshwater catfish?

CARP

- Would a winter flood prevent carp spawning and using floodplain habitats, and at what temperature should the winter flood end?
- A separate Carp Management Strategy (Stuart *et al*. 2011) provides more detail on specific knowledge gaps that would aid management.

7 ANALYSIS OF RISKS AND BENEFITS

7.1 Methodology

The analysis of risks and benefits is based on the Australian Standard (Standards Australia 2004). There are two components to risk, *Likelihood* or probability of the risk occurring and, *Consequence* or severity if the risk occurs. The risks identified in the present study have been categorised with five levels of *Likelihood* and *Consequence* (Table 13). Risk assessments are usually used to evaluate one project or scenario, consequently, in order to enable the comparison of three major scenarios we incorporated an additional *Likelihood* of *None*.

Consequence and *Likelihood* scores are combined in a risk matrix to produce an overall risk score (Table 14). For the present project we have produced an overall score for each risk but have also shown the individual scores, as they provide the reader with transparency and a more thorough understanding of the issue.

The principles and logic applied to risk can also be applied to benefits. We have used the same five levels of *Likelihood* and *Consequence* to produce a benefits matrix (Table 15).

In developing scores of *Likelihood* and *Consequence* all available information is used but this ranges from direct and applicable scientific data to diverse expert opinion. We have provided *Certainty* scores (Table 16) where possible, to inform the reader of the validity of overall scores of each risk.

The risks are listed in Table 17 and the benefits in Table 18, for each of the three broad scenarios described in Section 6.1:

1. No change to infrastructure - additional environmental flows; lotic habitats increased in spring.
2. Chowilla Regulator - low height, additional E-flows; >75% lotic habitats maintained.
3. Chowilla Regulator – maximum height; additional E-flows; < 25% lotic habitats maintained.

For each risk or benefit the overall rating is shown as a specific coloured box in each table, combined with scores for *Consequence, Likelihood* and *Certainty* where applicable. The risks and benefits occur at a range of geographic scales; for the present project we have shown where these occur at an Icon-site scale, a Landscape-scale, or both. Where the risks or benefits directly relate to hypotheses from the conceptual models, these are listed (and hyperlinked back to the relevant knowledge gap). Some benefits also have an associated risk and these have been listed. Footnotes have been used to clarify specific points.

Table 13. Consequence and Likelihood scores (Standards Australia 2004).

Consequence	Likelihood
Extreme	Very likely
Major	Likely
Moderate	Possible
Minor	Unlikely
Very minor (insignificant)	Very unlikely (rare)
	None[1]

[1] Likelihood of *None* added to enable comparison of three major scenarios; risk assessment usually evaluates one project.

Table 14. Risk matrix. (Standards Australia 2004).

Key:

Low
Medium
High
Very High

		Consequence				
		Very minor	Minor	Moderate	Major	Extreme
Likelihood	Very likely	M	M	H	VH	VH
	Likely	M	M	H	H	VH
	Possible	L	M	M	H	VH
	Unlikely	L	L	M	M	H
	Very unlikely	L	L	M	M	H
	None					

Table 15. Benefits matrix.

Key:

Low
Medium
High
Very High

		Consequence				
		Very minor	Minor	Moderate	Major	Extreme
Likelihood	Very likely	M	M	H	VH	VH
	Likely	M	M	H	H	VH
	Possible	L	M	M	H	VH
	Unlikely	L	L	M	M	H
	Very unlikely	L	L	M	M	H
	None					

Table 16. Certainty scores, which have been used where there is scientific inference but not for strategic or management risks and benefits.

Certainty (or confidence); applies to *Consequence* and *Likelihood*		
4	Very Certain	(supported by direct scientific data)
3	Moderately Certain	(supported by indirect scientific data)
2	Uncertain	(no available data; consensus of expert opinion)
1	Very Uncertain	(no available data; diverse expert opinion)

Table 17. Comparison of the risks of the Chowilla Regulator and No Change. Colours follow total risk score from Table 14. Certainty scores for Consequence and Likelihood are shown in brackets. Hypotheses for monitoring are from conceptual models or are additional ones that are specific to monitoring. *High* and *very high* risks are selected for monitoring, as well as native species of interest and new infrastructure.

Risks	Icon-site scale	Landscape scale	Consequence	No change (incl. new E-flows) Lotic habitats increased Likelihood	Chowilla Regulator (incl. new E-flows) 75% lotic habitats maintained Likelihood	Chowilla Regulator (incl. new E-flows) Lotic habitats not maintained Likelihood	Hypotheses for monitoring
Fish spawning and recruitment							
1. Repeated decrease in recruitment of Murray cod, population declines	■	■	Extreme (4)	V. unlikely (4)	Unlikely (3)	Likely (3)	H 1, 2, 3, 6
2. Repeated decrease in recruitment of golden perch, population declines	■	■	Major (4)	Unlikely (3)	Unlikely[1] (2)	Unlikely (2)	H 10, 11, 12, 13
3. Repeated decrease in recruitment of silver perch, population declines	■	■	Extreme (4)	Unlikely (1)	Unlikely[1] (1)	Unlikely (1)	H 21, 22, 23, 24
4. Repeated decrease in recruitment of freshwater catfish, population declines	■	■	Extreme (4)	Unlikely (3)	Unlikely (2)	Possible (2)	H 29, 30, 31, 33, 36
5. Carp population increases due to managed inundations[2]	■	■	Major (4)	Unlikely[3] (3)	V. Likely[4] (3)	V. Likely (3)	H 38, 39, 42, 43, 44, 45, 46, 47
6. Carp population increases due to natural floods		■	Moderate (4)	V. Likely (4)	V. Likely (3)	V. Likely (3)	H 39, 42, 43, 44, 45, 46, 47, 48

[1] Golden perch and possibly silver perch appear to require > 10,000ML/d in the lower Murray to stimulate spawning; hence, it is unlikely to occur in these scenarios but would occur under natural high flow events.
[2] At a landscape scale, provides major source for the lower Murray. Evidence includes: larval drift data, adult movement data from radio, PIT and plastic tags.
[3] Natural floods will still provide recruitment of carp, as per the flooding regime conditions prior to the drought.
[4] Likelihood increases for the managed inundation because of the frequency of events and the favourable low-velocity, shallow habitats for spawning.

Risks	Icon-site scale	Landscape scale	Consequence	No change (incl. new E-flows) Lotic habitats increased Likelihood	Chowilla Regulator (incl. new E-flows) 75% lotic habitats maintained Likelihood	Chowilla Regulator (incl. new E-flows) Lotic habitats not maintained Likelihood	Hypotheses for monitoring
7. Carp spawning and recruitment from littoral zone improvement (from fluctuating small within-channel flows)	■		Moderate[1] (3)	Possible (4)	Likely (4)	Likely (4)	H 41
8. Impounded water from Chowilla Regulator becomes a sink for larvae of important large-bodied species (Murray cod, freshwater catfish, golden perch, silver perch) from main stem and creeks; poor or lost natural recruitment due to poor survival in weirpool environment.	■	■	Extreme (2)	None	Possible (2)	Possible (2)	H 1, 5, 11, 12, 22, 23, 30, 34
9. Loss of hydraulic diversity in habitats reduces recruitment of large-bodied native fish species (N.B. could be the main mechanism of recruitment for Murray cod)	■	■	Extreme (3)	None	Possible (3)	Likely[2] (3)	H 1, 2, 4, 5, 11, 12, 16, 22, 26, 30, 34, 35
10. Oriental weatherloach colonises and increases in population	■	■	Moderate (3)	Likely (3)	V. Likely[3] (3)	V. Likely (3)	H49
11. Gambusia increases in population	■		Minor (3)	Unlikely (3)	Likely (3)	Likely (3)	
Fish movements							
12. Long-term emigration > immigration of Murray cod, population declines	■		Extreme (4)	V. unlikely (4)	Unlikely (2)	Possible (2)	H 3, 6, 9

[1] Compared with a large inundated floodplain.
[2] See section on modelling: hydraulic diversity is reduced at inundation levels that provide broad terrestrial floodplain benefits. At maximum inundation all lotic habitats become lentic.
[3] *Likelihood* greater for the Chowilla Regulator as the frequency of inundation will favour oriental weatherloach

Risks	Icon-site scale	Landscape scale	Consequence	No change (incl. new E-flows) Lotic habitats increased Likelihood	Chowilla Regulator (incl. new E-flows) 75% lotic habitats maintained Likelihood	Chowilla Regulator (incl. new E-flows) Lotic habitats not maintained Likelihood	Hypotheses for monitoring
13. Long-term emigration > immigration of golden perch, Icon-site population declines.	■		Major (4)	V. unlikely (4)	Likely (3)	Likely (3)	H 19, 20
14. Long-term emigration > immigration of silver perch, Icon-site population declines.	■		Major (4)	V. unlikely (1 or 2)	Likely (2)	Likely (2)	H 28
15. Fish passage through main stem fishways compromised through reduced attraction at i) Lock 6, and ii) downstream Locks due to suppression of the hydrograph.		■	Moderate (3)	None (4)	Likely	Likely (2)	H_{50}
16. Pipeclay and Slaney fishways not optimised; poor fish passage.			Major	N/A	Unlikely (3)	Unlikely (3)	H_{51}
17. Denil fishways at Pipeclay and Slaney do not pass all large Murray cod.[1]	■		Moderate (2)	N/A	Possible (2)	Possible (2)	H_{52}
18. No fishways at Pipeclay and Slaney			Major (3)	V. likely	V. unlikely	V. unlikely	
19. Poor water quality creates blackwater and causes fish kills.	■		Major[2] (3)	V. unlikely	Unlikely[3]	Unlikely	

[1] Large Denil fishway is a conservative design but is untested for Murray cod.
[2] A blackwater event could affect threatened species such as Murray cod and affect downstream fish populations in the release of blackwater.
[3] Refer to SA MDB NRM B blackwater study for detail.

Risks	Icon-site scale	Landscape scale	Consequence	No change (incl. new E-flows) Lotic habitats increased Likelihood	Chowilla Regulator (incl. new E-flows) 75% lotic habitats maintained Likelihood	Chowilla Regulator (incl. new E-flows) Lotic habitats not maintained Likelihood	Hypotheses for monitoring
20. Fish kills from stranding by isolation and evaporation of wetlands (mainly small fish but could also be large fish).	■		Moderate[1] (3)	Possible (3)	Likely[2] (3)	Likely (3)	H_{53}
21. Salinity – impacts on larvae with an increase in release of saline groundwater	■		V. minor (1)	V. unlikely (1)	V. unlikely[3] (1)	V. unlikely (1)	
Indirect effects on fish populations							
22. High natural within-channel flows (e.g. 15,000 ML/d) used by regulator in 'hybrid' events and hydrograph suppressed downstream; main stem spawning & recruitment failure of large-bodied fishes	■	■	Extreme[4] (4)	None	Possible (3)	Possible (3)	H_{54}
23. Decoupling of timing of release of carbon, nutrients, zooplankton pulse from high flows in the river downstream; few benefits for large-bodied native fish species	■	■	Moderate (2)	None	Possible (2)	Possible (2)	
24. Decoupling of riverine cues (flow and velocity) for migration (upstream, downstream, lateral) and direct and indirect utilisation of the floodplain	■	■	Moderate (3)	None	Likely (2)	Likely (2)	$H_{4, 7, 13, 16, 24, 37}$

[1] Score based on only small-bodied common species trapped in wetlands with no long-term impact on the Icon Site population. Score would be higher if less-common species or large-bodied fish were killed.
[2] More likely than *No change* because lakes could be operated separately more often.
[3] Potentially from point sources at the end of a recession.
[4] These flows are known to be important for the recruitment of golden perch.

Risks	Icon-site scale	Landscape scale	Consequence	No change (incl. new E-flows) Lotic habitats increased Likelihood	Chowilla Regulator (incl. new E-flows) 75% lotic habitats maintained Likelihood	Chowilla Regulator (incl. new E-flows) Lotic habitats not maintained Likelihood	Hypotheses for monitoring
25. Loss of floodplain vegetation leads to low carbon inputs to main channel in natural floods	■		Moderate (1)	Possible (1)	Unlikely[1] (1)	Unlikely (1)	
26. Connectivity reduced within floodplain by new small regulators at various sites; impacts on managed inundations and natural floods. Floodplain processes decoupled from main channels habitat	■		Moderate (2)	Possible (2)	Likely (2)	Likely (2)	H 7, 13, 24, 37
27. Connectivity – reduced between main stem and Chowilla by new barrier (Chowilla Regulator) and fishway not providing complete transparency for fish (esp. for Murray cod)[2]	■		Major (2)	None	Possible (2)	Possible ()2	H 7, 13, 24, 37
28. Increase in lentic weeds; reduced habitat for native fish.	■		Moderate (1)	V. unlikely (2)	Possible (2)	Possible (2)	
29. New levees affect natural floods, flow path	■		Minor (2)	None	Possible (2)	Possible (2)	
30. Bird predation of fish increases	■		V. minor (2)	V. unlikely (2)	Unlikely (2)	Unlikely (2)	
31. Operational failure due to increased complexity of managing water infrastructure	■		Moderate[3] (2)	None	Possible (2)	Possible (2)	

[1] However, there is also an alternative model that carbon is not limiting in the river.
[2] Data suggests that Murray cod are moving between the main stem and anabranch creeks in the spawning season, possibly to pair up.
[3] Operational failure includes reduced fish passage, poor management of flows and water quality, fish kills; range of risks are accentuated.

Risks	Icon-site scale	Landscape scale	Consequence	No change (incl. new E-flows) Lotic habitats increased Likelihood	Chowilla Regulator (incl. new E-flows) 75% lotic habitats maintained Likelihood	Chowilla Regulator (incl. new E-flows) Lotic habitats not maintained Likelihood	Hypotheses for monitoring
Strategic / Program Risks							
32. Monitoring: floodplain manipulations done without quantifiable objectives, hypotheses, or conceptual models clarified; project potential not realised.	■	■	Major (3)	None	Possible[1]	Possible	
33. Monitoring: natural floods occur without quantifiable objectives, hypotheses, or conceptual models clarified; project potential not realised.			Moderate (3)	Possible[3]	Possible[3]	Possible	
34. Monitoring: no controls for comparison – only trend analysis in time	■	■	Major[2] (3)	Possible	Possible	Possible	
35. Monitoring: detectability and variance of pop^{n}s unknown	■	■	Major (3)	Possible	Possible	Possible	
36. Monitoring: resources insufficient to collect adequate data	■	■	Major[3] (3)	Possible	Possible[4]	Possible	
37. TLM objectives not met	■	■	Major (2)	Possible	Possible	Possible	
38. NFS objectives not met	■	■	Major (2)	Possible	Likely[5]	Likely	

1 Depends on monitoring program and allocated resources.
2 If negative impacts present.
3 Floodplain declines despite intervention.
4 Depends on monitoring program and allocated resources.
5 Depends on application of mitigation strategies; primarily reducing frequency of regulator operation and providing main stems E-flows.

Risks	Icon-site scale	Landscape scale	Consequence	No change (incl. new E-flows) Lotic habitats increased Likelihood	Chowilla Regulator (incl. new E-flows) 75% lotic habitats maintained Likelihood	Chowilla Regulator (incl. new E-flows) Lotic habitats not maintained Likelihood	Hypotheses for monitoring
39. Fisheries (rec. and comm.) objectives not met	■	■	Major (3)	Possible	Possible	Likely	
40. E-water not optimised	■	■	Major (2)	Possible	Possible	Possible	
41. Cumulative impacts of Regulator use not identified, including event and regime scale.	■	■	Extreme (3)	None	Possible	Possible	
42. Operation of structure for purposes other than ecological restoration of the Chowilla Floodplain (e.g. water storage).	■	■	Extreme (2)	None	Possible	Possible	

Table 18. Comparison of the benefits of the Chowilla Regulator and No Change scenario. Colours follow benefits score from Table 15. Certainty scores for Likelihood and Consequence are shown in brackets. Hypotheses for monitoring are from conceptual models or are monitoring specific. *High* and *very high* benefits are selected for monitoring, as well as native species of interest and new infrastructure.

Benefits	Icon-site scale	Landscape scale	Consequence	No Change (incl. new E-flows) Lotic habitats increased Likelihood	Chowilla Regulator (incl. new E-flows) Low height 75% lotic habitats Likelihood	Chowilla Regulator (incl. new E-flows) Max. height No Lotic habitats Likelihood	Associated risk	Hypotheses for monitoring
1. Small-bodied fish recruitment, populations increase.	■		Minor (4)	Unlikely (3)	V. likely (3)	V. likely (3)	None	
2. Murray cod recruitment increases.	■	■	Extreme (3)	Likely[1] (3)	Unlikely[2](3)	V. unlikely (3)	None	H 1, 2, 4
3. Golden perch spawning and recruitment, population increases.	■	■	Major (3)	V. unlikely[3] (4)	V. unlikely[4] (3)	V. unlikely (3)	None	H 10, 11, 12, 16, 17
4. Increase in lotic habitats and in-channel flow variability via upgraded Pipeclay and Slaney weirs[5], increases recruitment and improves diversity of species and age classes (i.e. pop[n] *robustness*).	■		Major (3)	None	V. likely (4)	V. likely (4)	Yes, see Risk 7	H 1, 2, 4, 8, 11, 16, 22, 26, 30, 35
5. Increase in lotic habitats and in channel flow variability via variability in the Lock 6 weirpool, increases recruitment and improves diversity of species and age classes (i.e. pop[n] *robustness*).	■		Major (3)	Likely (4)	V. likely[6] (4)	V. likely (4)	Yes, see Risk 7	H 1, 2, 4, 8, 11, 16, 22, 26, 30, 35

1 If 10,000 ML/d of E-flows are used the area of flowing water habitat and habitat heterogeneity, which is associated with Murray cod spawning and recruitment, is doubled in Chowilla.
2 Likelihood higher if additional E-flows can be acquired to enable increase of lotic habitats seasonally when regulator is not operating.
3 Probability would be greater with higher inflows (e.g. 20,000 ML/d).
4 As for above footnote
5 Provides an increase in fish habitat for a diverse fish community, esp. large-bodied fish. More natural regime varying flow, depth, velocity; fish have more interaction with littoral zone and opportunity to use temporarily inundated habitats; more natural carbon transport between instream and terrestrial habitats.
6 More *likely* than *No Change* scenario because variable gates at Pipeclay and Slaney provide more benefit with raised weirpool.

Benefits	Icon-site scale	Landscape scale	Consequence	No Change (incl. new E-flows) Lotic habitats increased Likelihood	Chowilla Regulator (incl. new E-flows) Low height 75% lotic habitats Likelihood	Chowilla Regulator (incl. new E-flows) Max. height No Lotic habitats Likelihood	Associated risk	Hypotheses for monitoring
6. Improved littoral zone and edge habitats from: • low elevation use of regulator [e.g. 1.0 m], • increased and fluctuating flow from Pipeclay and Slaney, increases recruitment and diversity of species and age classes.	■		Moderate (3)	None	V. likely[1] (2)	V. likely (2)	Yes, see Risk 7	H 1, 2, 4, 8, 11, 16, 22, 26, 30, 35
7. Improved littoral zone and edge habitats from: • raised weirpool, increasing flow from Pipeclay and Slaney and into upper creeks	■		Moderate (3)	Likely (2)	V. likely (2)	V. likely (2)	Yes, see Risk 7	H 1, 2, 4, 8, 11, 16, 22, 26, 30, 35
8. New fish passage at Pipeclay and Slaney weirs improves connectivity.	■	■	Major (4)	None	V. likely (4)	V. likely (4)	Yes, see Risk 17	H[55]
9. Floodplain vegetation structure & diversity improves.[2]	■		Major (4)	V. unlikely (3)	Likely (3)	Likely (3)	Yes, see Risk 5	H 1, 4, 7, 11, 13, 16, 22, 24, 30, 37
10. Priming floodplain using Regulator prior to a natural event, either seasonal or yearly prime.	■		Moderate (2)	None	Possible (2)	Possible (2)	None	
11. Floodplain vegetation (esp. understorey)	■		Moderate[3] (1)	None	V. likely (1)	V. likely (1)	Yes,	H56

[1] Although aquatic macrophytes well established at present.
[2] Long-term vegetation response leads to more physical diversity on the floodplain or margins that fish use during natural floods and possibly managed inundations.
[3] However, there is also an alternative model that carbon is not limiting in the river.

Benefits	Icon-site scale	Landscape scale	Consequence	No Change (incl. new E-flows) Lotic habitats increased Likelihood	Chowilla Regulator (incl. new E-flows) Low height 75% lotic habitats Likelihood	Chowilla Regulator (incl. new E-flows) Max. height No Lotic habitats Likelihood	Associated risk	Hypotheses for monitoring
captures carbon in the soil for the next inundation and release to the river							see Risk 5	
12. Nutrient, carbon and zooplankton pulse from floodplain to the river downstream, in recession of a managed inundation benefits native fish	■		Moderate[1] (1)	None	V. likely (1 or 2)	V. likely (1 or 2)	Yes, see Risk 5	H_{57}
13. Experimental scope; large-scale manipulative experiment enables controlled hypothesis-testing of models to inform the management of other floodplain sites in the MDB	■	■	Extreme (3)	Possible	Likely[2]	Likely	Yes, see Risks 32 to 36	

[1] Mainly benefits small-bodied fish but large-bodied species may benefit if timing correlated with spawning and additional main stem flows.
[2] Depends on monitoring framework and resources.

7.2 Discussion

7.2.1 Risks

The hydrodynamic modelling, assessment of fish responses to managed inundations, and assessment of risks has focused on operating scenarios with low (10,000 ML/d) and moderate (20,000 ML/d) inflows to South Australia. At high inflows (e.g. 35,000-50,000 ML/d) the hydrodynamics and synchronisation of upstream and downstream hydrology with floodplain inundation are expected to be similar to natural flows of the same magnitude. Under these conditions the ecological responses of all biota are expected to be similar to a natural event and the risks for fish are also expected to be similar to a natural event, assuming that the Regulator provides effective fish passage.

When the Regulator is used with low and moderate inflows there are four main areas of risk:

i) fish spawning and recruitment,
ii) fish movements,
iii) indirect effects on fish populations, and
iv) strategic / program risks.

Most of the high and very high risks are in the first category and relate to reduced recruitment and subsequent population decline of species at risk, particularly Murray cod and freshwater catfish. Increased carp populations are a very high risk with a high degree of certainty.

Under the 'no change' or 'do nothing' scenario, which has no Chowilla Regulator or upgraded Pipeclay and Slaney weirs, the risks have low likelihoods of occurring; however because the consequences are *high* they are still ranked overall, as *high* risks. Under 'no change', carp will still spawn in natural floods, so the additional risks of the Chowilla Regulator are that: i) inundated floodplains will occur more often than at present; ii) the impounded water has more lentic habitats and areas of low water velocity that will provide more spawning and nursery areas depending on the operational regime, and increase recruitment; and iii) the managed inundation with low hydrodynamic diversity, particularly the reduction in fast-flowing creeks adjacent to floodplains, will be a less favourable environment for predators of carp such as Murray cod.

Movement of fish is a significant risk, particularly emigration during an event or over a series of events (regime). Certainty of this risk for Murray cod is, however, low and this represents a significant knowledge gap that needs to be considered in monitoring. Inadequate movement of native fish species off the floodplain during the recession of a managed inundation is a *high* risk, because these fish become trapped and they die as the floodplain dries. Nevertheless, this is a risk that can be potentially managed by operation of the Regulator (see Sections 8, 10). Some natural mortality of fish, especially small-bodied species, is expected in isolated lakes and wetlands and this would be part of the natural carbon dynamics of the floodplain.

The risks from indirect effects on fish populations will be subtle to detect but may be very significant. Nutrient and carbon pathways between floodplains and channels are very poorly understood in the River Murray yet they are integral to fish population dynamics, especially recruitment processes. Monitoring programs tend to describe abundance and diversity of biota (patterns), but more resources need to be allocated to investigating the processes behind these patterns (e.g. carbon dynamics of floodplains and rivers), as these underpin ecosystem function and hence restoration.

The decoupling of floodplain and river hydrology, by inundating a floodplain to simulate a large flood but having relatively low inflows in the river, provides a range of indirect risks. Mixed cues for fish movement and spawning are likely. Further decoupling, by compartmentalising lakes and operating them independently, increases these risks. Understanding floodplain processes, as mentioned above, through well-designed monitoring programs is a key to minimising this risk.

Program or strategic risks may ultimately be the greatest risk and these relate mainly to monitoring; put simply, if monitoring is inadequate, risks will be not be detectable and any decline of native fish

will not be detectable. There are also broader program risks of not meeting TLM (The Living Murray) and NFS (Native fish Strategy) objectives.

7.2.2 Benefits

Thirteen potential benefits of the project were identified but it is the consensus of the authors that the risks outweigh the benefits for native fish and that if the main objective of the project was to improve native fish populations, other environmental rehabilitation techniques, in addition to the proposed fishways at Pipeclay and Slaney weirs, would be used. These techniques are discussed in *Mitigation of Risks* (Section 8) under *Improving Fish Habitat and Opportunities for Recruitment*.

The potential benefits can be categorised as:

i) Improving fish passage (Pipeclay and Slaney weirs).
ii) Increasing lotic habitats, leading to increased fish recruitment.
iii) Improving littoral zones, leading to increased fish recruitment.
iv) Using floodplain carbon dynamics to enhance fish recruitment in natural events.
v) Experimental scope and flexibility.

Increasing the length and variability of lotic habitats, by releasing more water through Pipeclay and Slaney weirs, would very likely improve the littoral zone and has potential to improve recruitment of native fish, including Murray cod. A limitation of the hydrodynamic modelling, however, is that water velocity is provided as a mean value and the hydrodynamic diversity within a cross-section of the stream (e.g. slower margins as well as faster flow) remains unknown. It is possible that higher mean velocities may reduce diversity by reducing slow-flowing backwaters, margins and epibenthic zones, so ground-truthing at this level of detail should be undertaken when the weirs become operational. Although improving the recruitment of Murray cod is scored as *unlikely* to *very unlikely* it is still ranked as a *high* benefit because the *consequence*, improving the population of a threatened species, is *extreme*.

Increasing the length and variability of lotic habitats can be achieved at present by raising Lock 6 but the Chowilla Regulator provides an additional potential feature that, under a low height or high flow (e.g. 35,000 - 50,000 ML/d) scenario, there may be a greater amount of nursery habitats for native fish. The refurbished Pipeclay and Slaney weirs will also provide the capacity to pass more flow and be adjustable on a daily basis, hence improving the ability to introduce fine temporal scale of flow and water level variability in lotic habitats.

It is important to note that providing variability of lotic habitats also has an associated risk, which is increased spawning and recruitment of carp. Assessing the balance of these benefits and risks can only be achieved through monitoring. This highlights an inherent strength and benefit of the project – the experimental scope. The Chowilla Regulator with Pipeclay and Slaney weirs offer a wide scope for manipulative and repeatable experiments providing an excellent opportunity for adaptive management.

A potentially *high* benefit is utilising the carbon dynamics of the floodplain to enhance recruitment of fish in natural floods, either through 'priming' the floodplain or by synchronising the floodplain recession with high river flows. Exploiting this potential benefit, however, again highlights the need to have a deeper understanding of these processes. Monitoring the chemistry of floodplain soils and their biota, including the 'seedbank' of plankton, should be part of a broader monitoring program.

8 MITIGATION OF RISKS

8.1 Operation of the regulator

8.1.1 Frequency

Frequency of operation is probably the most powerful mitigation tool. Conceptually the regulator is an environmental rehabilitation that can be switched 'on' and 'off' (albeit, over weeks), in contrast to more permanent environmental rehabilitation such as revegetation, or resnagging. Because of this flexibility, all risks for fish can potentially be managed by switching the Regulator 'off', which makes the project very suitable for adaptive management.

Based on the conceptual models and the analysis of risks and benefits, operating the Regulator less frequently provides less risk for fish. However, this also depends on the type of managed event. An event with high inflows, using a raised Lock 6 and low Regulator level has much less risk than one with low inflows, normal Lock 6 level, and a high Regulator level.

8.1.2 Timing and duration

The timing and duration of a managed inundation event is one the most useful tools to mitigate the major risks of increased carp recruitment, poor water quality and loss of hydrodynamic diversity in spring. Timing the inundation to start and end in winter is recommended as: i) it would be outside the carp spawning season; ii) the cold winter water on the floodplain would have low microbial activity so that nutrients and carbon would be used slowly and the risk of poor water quality would be very low, and; iii) any loss in hydrodynamic diversity would be outside the Murray cod spawning season.

A managed event in winter is a low-risk strategy. It could be applied at the beginning of the project, or at other times when the risk from carp populations or poor water quality needs to be minimised.

8.1.3 Conserving and increasing flowing water (lotic) habitats

A major risk, particularly for Murray cod, is the loss of hydrodynamic diversity in the *core habitats*. If this occurs in spring it is likely to lead to poor recruitment. A mitigation for this impact is operating the Chowilla Regulator up to 18.5 m AHD with Lock 6 raised 0.62 m which, the hydrodynamic modelling indicates, enables 75% of the hydrodynamic diversity within the *core habitats* to be retained. Although increasing inflows from 10,000 to 20,000 ML/d (Q_{SA}) provided little improvement in maintenance of hydrodynamic diversity, higher flows of 35,000 to 50,000 ML/d might provide greater benefits, which could be assessed either in the field or by further modelling.

The second mitigation is an offset for this impact, which is to improve hydrodynamic diversity and Murray cod recruitment: i) in Chowilla in the years when the Regulator is not used, by passing more flow down Pipeclay and Slaney creeks and increasing habitat complexity with large woody debris, and ii) in the main stem of the River Murray by lowering the weirpools (see also 8.4.1 below) and again adding large woody debris. Both options are experimental. The first option would need assessment as passing more flow and increasing mean velocity does not necessarily create more hydrodynamic complexity within the cross-section or longitudinal-section of the stream channel, both of which may be required for spawning and nursery habitats. Increasing flow in these channels also increases the risk of carp spawning. These two offset options, within Chowilla and within the main stem, would require monitoring to assess their effectiveness, evaluate the risks and provide feedback for adaptive management of flows or weirpool levels.

8.1.4 Synchronising floodplain and river hydrology

Some of the risks for fish are generated by the decoupling of floodplain and river hydrology, which is accentuated when the Regulator is used with low inflows. This decoupling also limits the broader ecological benefits of river-floodplain interactions that occur in natural floods. We recommend that operation of the Regulator be biased to higher inflows (e.g. 35,000 ML/d to 50,000ML/d) and

synchronisation of floodplain inundation and river hydrology, both at a site-scale (upstream and downstream of Chowilla) and a landscape-scale (i.e. 100s of kilometres of river).

Although 20,000 ML/d (Q_{SA}) inflows provided little improvement in maintenance of hydrodynamic diversity within Chowilla, this magnitude of flow over a landscape scale, which is also synchronised with floodplain inundation, has potential benefits for spawning and recruitment of golden perch as well as other native species. A flow of 20,000 ML/d also improved the hydrodynamic complexity of the River Murray channel, creating more natural fish habitats less affected by the weirpools.

8.1.5 Inflow source and discharge

Inflow source and discharge can not only mitigate risks but can also influence the likelihood of achieving benefits for native fish. Higher inflows are preferred as these: i) create more natural hydrodynamics in the main river channel, lessening the effects of the weirpool and ii) provide a greater turnover of flow through Chowilla. Higher inflows are also more likely to be over a landscape scale and as mentioned above, for species that require a significant flow cue to spawn, this increases the likelihood of spawning.

The source of water, which relates to synchronising managed inundations with landscape-scale hydrology, is likely to be important in optimising benefits for native fish. Hence, water sourced from floods in the Darling River or middle River Murray is preferred to stored water from Lake Victoria. This principle would result in less flexibility in the timing of Regulator operation (as opposed to using stored water from Lake Victoria) but it would retain longitudinal integrity of flow, which is an important ecological consideration.

8.1.6 Rate of Recession

At an Icon-site scale the recession of a managed inundation is a critical period to manage the specific risk of native fish, particularly large-bodied species, being trapped on the floodplain. The present model of floodplain movements of large-bodied native species in the middle reaches of the River Murray is that these fish will leave the floodplain at the first significant drop in water level, which in a natural flood would provide the cue the recession is beginning. The approach at other Icon sites (e.g. Koondrook-Perricoota and Gunbower), where managed inundations are being used, is to use this model as a basis for experimentation and adaptive management. Such an approach can be used at a regime or event scale. At an event scale the recession can be managed on a weekly or even daily basis; for example, if radio tracked or sampled fish were found to be remaining on the floodplain after a significant drop in water level, then the Regulator could be used to provide a series of further drops in water level. At a regime scale lessons from one event can be used in the next.

The model of fish behaviour on floodplains described above is based on data from the middle reaches of the River Murray and the transferability of those findings is unknown. The hydrology of floods in the lower River Murray is different to the upper and middle reaches; the falling limb of the hydrograph is often quicker than the rising limb in the lower River Murray and this is likely to affect fish behaviour.

8.2 Contingency flow

Contingency flow is recommended to help manage two risks: poor water quality and native fish being trapped on the floodplain. Both need to be linked to monitoring but the principle is to keep an allocation in Lake Victoria for dilution if poor water quality with low dissolved oxygen is anticipated or eventuates, and also to provide additional cues for fish to leave the floodplain.

8.3 Monitoring and Adaptive Management

A key to mitigation is detecting and quantifying the risk; hence, this depends on a well-designed monitoring program. If the monitoring program is aimed solely at detecting population changes the main mitigation would be to cease operation of the Chowilla Regulator and infrastructure until fish populations recover. If, however, the monitoring program also aims to understand ecological processes (see Section 9 for further discussion), a range of options become available. Long-term

mitigation of risk comes from seeking an understanding of processes and having a responsive adaptive management strategy.

8.4 Improving fish habitat and opportunities for recruitment

Mitigating risk in the present project has so-far been spatio-temporally constrained to the Icon site and the time frame of an event or regime. Considering the issue more broadly, however, provides greater opportunities for improving native fish habitat and populations. The aim would be to improve the resilience of native fish populations and hence reduce the risks of managed inundations for fish.

8.4.1 Restoring lotic habitats along the lower River Murray

The hydrodynamic modelling showed that lowering weirpools has potential to restore the hydrodynamic diversity that was a characteristic of the lower River Murray prior to construction of the locks and weirs. Increasing the extent of flowing water habitats in the upper weirpools would provide a major improvement in fish habitat, especially if it could done along the length of the lower River Murray either permanently or in spring. Such a river rehabilitation project could be linked with resnagging of the upper weirpools to provide further improvement in habitat. A significant advantage of this approach is that no environmental water is needed; only the hydrodynamics are changed.

8.4.2 Providing a large in-channel rise along the length of the lower River Murray

Large in-channel rises in discharge are a significant component of the hydrology of the lower River Murray that has been severely impacted by regulation of flow. Golden perch and possibly silver perch spawn in response to these flows, as well as overbank floods, in spring and summer. It appears that flows of 15,000-20,000 ML/d in the lower River Murray are the minimum required to stimulate spawning and recruitment of golden perch. Interestingly, 15,000 ML/d is the threshold where the hydrodynamics of the River Murray appear to change from slow-flowing weirpools to a moderately-flowing (>0.17 m/s) river and at 20,000 ML/d the river appears to change again to mostly fast-flowing (>0.3 m/s).

As discussed earlier the source of the water and retaining longitudinal integrity of flow are important. Ideally, the flow would be unaltered from the Darling River or middle River Murray to the sea. There would obviously be multiple environmental benefits along the length of the river, including freshwater flow to the Coorong and improved estuarine conditions for a range of freshwater and estuarine fish.

9 MONITORING

9.1 Introduction

The Chowilla Regulator Project is one of the largest floodplain rehabilitation projects in Australia and is unprecedented in inundating a permanent anabranch system that supports threatened native fish species. The overarching risk of regulator operation is that to achieve the desired inundation levels of the floodplain with limited volumes of water there is also a major disconnection of ecological processes at the river-scale (i.e. inundation of floodplain whilst river is not flooding). As such, the project represents a manipulative experiment on a grand-scale, with a regulator that can be operated variably or completely removed. This control over infrastructure provides two major opportunities for monitoring: i) to use it as an experimental facility, and ii) to apply very responsive adaptive management.

We advocate an adaptive management approach to the operation of the Chowilla Regulator that involves the explicit recognition of uncertainty through the adoption of alternative hypotheses regarding the effects of regulator operation. Adaptive environmental assessment and management (Holling 1978) or adaptive management (Walters 1986) is a structured approach that incorporates scientific methodologies in the design, implementation and evaluation of management strategies whilst at the same time recognises the importance of institutional and social structures to management decisions (Schreiber *et al*. 2004) For a more detailed explanation of adaptive management, particularly in the Australian context, see Bearlin *et al*. (2002), Schreiber *et al*. (2004), and Kingsford *et al*. (2011).

Monitoring of the risks and benefits of the Chowilla Regulator to native and non-native fish should be question-driven (see Lindenmayer and Likens 2010). Questions will need to be explicitly articulated and scientifically-robust monitoring programs designed to answer these questions. Importantly, such an approach should embrace ecosystem science in order to develop an understanding of the drivers that influence ecological pattern and process (Likens *et al*. 2009).

In this section we outline a broad spatio-temporal approach to monitoring and the range of parameters that will need to be monitored to answer questions regarding the hypotheses proposed in the present report. For the experimental designs that could be applied to the monitoring we recommend a specific working group and workshop that incorporates fish ecologists, biometricians and managers to agree on objectives, refine hypotheses and develop methodologies and experimental designs.

9.2 Monitoring Approaches

Monitoring the risks and benefits of the Chowilla Regulator will need to be conducted over broad and fine temporal and spatial scales. Lindenmayer and Likens (2010) define long-term monitoring as "repeated field-based empirical measurements collected continuously . . . for at least 10 years" and there is general consensus that decadal scale investigations may be necessary to understand the response of floodplain ecosystems to restoration activities/management interventions (Gawlick 2006; Likens *et al*. 2009). It is at least this temporal scale of investigations that will be required at Chowilla to account for the longevity and life-history processes (e.g. recruitment and movement) of large-bodied fish such as Murray cod, which can live for over 48 years, or golden perch, which can live for over 26 years. At the fine timescale of days, weeks and months, event–based monitoring will be required to answer specific short-term questions regarding the risks and benefits of regulator operation.

Large rivers and their biota respond to environmental changes over small and large spatial scales, and this needs to be reflected in monitoring and management (Kingsford *et al*. 2011). Monitoring at the large spatial scale is the most resource-intensive and is frequently overlooked. However, connectivity occurs over large spatial scales and plays a key role in freshwater ecosystems. Sites such as Chowilla are also influenced by large spatial scale (river-scale) hydrological and geomorphic processes and the large-scale cumulative effects of river regulation.

Consequently, monitoring in Chowilla should account for the small spatial-scale lateral and longitudinal connections between the Chowilla floodplain and the broader river channel, as well as the large spatial-scale longitudinal and lateral connections along the river channel and floodplain wetlands of the Murray and Darling rivers. These connections vary with flow and monitoring needs to consider this temporal variability.

The methodology of *Condition Monitoring* of the Chowilla Icon site for The Living Murray (TLM) aims to describe the composition and relative abundance of fish assemblages, but provides little data on the reasons for observed patterns. Utilising such an approach to monitor the benefits and risks of Chowilla Regulator may identify when a risk occurs but not why it occurred, thus omitting a critical feedback loop to adaptively manage regulator operation to minimise risk.

Observational monitoring will need to be complemented with structured, question-driven monitoring that provides information on ecological process and hence has predictive capacity. Importantly a combination of observational monitoring (patterns) and question-driven monitoring (process) will enable evidenced-based decisions to be made regarding regulator operation and may also provide opportunities to improve fish populations in the Chowilla region.

9.3 Passive versus Active Adaptive Management

Adaptive management can generally be described as either passive (i.e. adventitious learning) or active (i.e. incorporating experimentation). Kingsford *et al*. (2011) propose a strategic adaptive management process that incorporates structured passive (trial and error) and active (experimentation) adaptive management. The process is applied by Kingsford *et al.* (2011) to the management of protected areas but the four key steps are generic - 1) setting the desired ecological condition, 2) management options, 3) operation, and 4) evaluation and learning – and could equally be applied to the Chowilla Regulator project (see Kingsford *et al*. 2011 for more details).

The present project has identified risks and benefits for fish, and potential mitigations. There are two approaches to using this information in regulator operation and monitoring: 1) *Passive* - using the predictive models to constantly minimise impacts and monitor the response, or 2) *Active* - deliberately test the extremes (Table 19). The main problem of a *passive* approach is that by minimising risk in every event any reductions in native fish abundance are minimised and would be difficult to detect – which could lead to the incremental loss of fish populations (Table 19). In this scenario monitoring resources are also reduced over time and the detection ability is further reduced.

Choosing an *active* approach, testing the predicted minimum and maximum risk, maximises the probability of detection in monitoring, enabling the risk to be quantified. It is worth noting that the risk is not permanent and that if, for example, the majority of native fish emigrated from the Icon site, fish would return over time without the Regulator operating.

An *active* approach, that acknowledges that the project is also a large-scale manipulative experiment with inherent risks, would potentially be the most appropriate way to operate and monitor the Chowilla Regulator. The project has, however, a range of terrestrial and aquatic ecological objectives so that strictly applying an active approach may not be practical. The extent that each of these approaches is utilised would need to be assessed in the experimental design workshop that includes the managers.

9.4 Framework for a monitoring program

Effective monitoring programs are characterised by clear questions that are underpinned by a conceptual model of an ecosystem or population, and strong partnerships between scientists, policy makers and managers (Lindenmayer and Likens 2010). To this end, a strategic adaptive management approach (Kingsford *et al.* 2011) or similar is recommended as a framework for the development of a monitoring program to assess the risks and benefits of the operation of the Chowilla Regulator on native and non-native fish.

Table 19. Summary of two approaches to monitoring and assessing risks in operating the Chowilla Regulator.

Approach 1. 'Passive' Adaptive Management	Approach 2. 'Active' Adaptive Management
Use the predictive models to minimise impacts, adaptively managing each event 1. Winter event – to test infrastructure, systems and minimise risk in first event. 2. Use any available water, adaptively manage to maximise floodplain and minimise risk for fish.	**Test and monitor extremes early in the program** 1. Winter flood – minimum predicted risk. 2. Maximum summer flood using stored water (Lake Victoria), minimum lotic habitats retained – maximum predicted risk. 3. Maximising fish outcomes using maximum inflows from the River Murray.
Benefits Risks minimised from Day 1. High capacity for short-term adaptive management, with good short-term (e.g. 1-5 yrs) outcomes.	**Benefits** Quantifies risk. Monitoring resources can be more targeted.
Risks Incremental loss of fish population not detected. Monitoring reduced over time. Detection ability reduced.	**Risks** Predicted short-term risks are high: blackwater, fish kills, carp, emigration of native fish. Note: risk is not permanent.
Mitigation If incremental loss of fish population is detected, then can apply mitigation strategies. No mitigation if risk is not detected.	**Mitigation** Do not operate regulator until fish return (e.g. 5 years).
Effectiveness of Mitigation High, if risk detected. Not effective if risk is not detected.	**Effectiveness of Mitigation** High - capacity to monitor fish early in the program.

9.4.1 Monitoring Data

From the conceptual models and risk assessment we have developed 57 hypotheses (Appendix 4). Many of these hypotheses, however, could be tested using the same dataset or, the same method may be used to collect multiple datasets (e.g. fish larvae of multiple species). Table 20 shows how these datasets, hypotheses from conceptual models, and risks overlap for monitoring.

Table 20. Monitoring datasets shown by species, with hypotheses from the conceptual models and the risk assessment.

Dataset	Murray cod		Golden perch		Silver perch		Freshwater catfish		Carp	
	Hypoth.	Risks	Hypoth.	Risks	Hypoth.	Risks	Hypoth.	Risks	Hypoth.	Risks
Spawning (larval presence)	H 8	R 27	H 10, 14, 15	R 2	H 21, 25	R 3	H 29	R 4	H 38, 41, 42, 43	R 5, 7
Larval ecology	H 1, 2	R 1, 8, 9, 23, 25	H 11, 12	R 2, 8, 9, 23, 24, 25	H 22, 23	R 3, 8, 9, 23, 2324, 25	H 30, 34	R 4, 8	H 44	R 5, 7
Recruitment ecology (0+ & juveniles)	H 4	R 1, 9	H 16, 17	R 2, 9	H 26	R 3, 9		R 4	H 45, 46	R 5, 7
Movement (long. & lateral; emigration, immigration, cyclical, return after disturbance)	H 3, 6, 7, 9	R 12, 15, 16, 17, 24, 26, 27, 29	H 13, 19, 20	R 13, 15, 16, 24, 26, 27	H 24, 27, 28	R 14, 15, 16, 24, 27	H 31, 33, 37	R 16, 26	H 39, 47, 48	R 5
Distribution & abundance		R 1		R 2		R 3	H 32	R 4	H 38	R 5

9.4.2 Monitoring Methods

The five key biological and ecological parameters that would need to be measured are spawning, recruitment, movement, distribution and abundance. There will also be a broad range of additional parameters that could be measured to answer specific questions pertaining to fish ecology in relation to regulator operation. Nevertheless, the parameters and techniques outlined below relate specifically to detecting responses to the hypothesis from the risks (Table 17) and benefits (Table 18). Many of these parameters have previously been measured in the Chowilla region and more broadly in the lower River Murray (Leigh *et al.* 2010, Zampatti *et al.* 2011, Leigh and Zampatti, 2011). Sample sizes, sites, frequency of sampling and other details related to experimental design will need to be established as part of a working group/workshop process.

1. <u>Spawning</u>

   - Presence of larval fish (drift nets, light traps and larval tows).

2. <u>Recruitment ecology (0+ and older)</u>

   - Habitats, food and survival of larvae and 0+ (specific techniques).

- Origin of recruits (otolith microchemistry).
- Length and/or age structure of population (electrofishing, fyke nets).

3. Movement

- Short and long-term, and site and river-scale movements of golden perch, Murray cod and common carp (radio and/or acoustic telemetry, passive integrated transponder (PIT) tags).

4. Abundance and Distribution

- Spatio-temporal variation in the distribution and abundance of key species (boat electrofishing and fyke nets).

5. New Infrastructure (i.e. Chowilla Regulator and Pipeclay and Slaney Weir Fishways)

- Assessment of fishway function (top and bottom trapping using custom-designed traps and PIT tagging).

9.4.3 Spatial and Temporal Scales

Selecting spatial and temporal scales for monitoring should be done as part of the experimental design workshop. However, a few broad issues are worth noting that can inform discussions at the workshop.

Spatial scales

- Need to incorporate Icon Site and Landscape spatial scales, which acknowledges that fish can respond at a meso-scale with the Icon site, or can move over 100's of kilometres and respond to floods that originate from 1000 km upstream.
- Habitat types within the Icon site, including:
  - i) permanent large fast-flowing creeks,
  - ii) permanent small fast-flowing creeks,
  - iii) permanent large slow-flowing creeks,
  - iv) permanent small slow-flowing creeks,
  - v) permanent wetlands
  - vi) ephemeral outer lakes

Temporal scales

- Need to use a template of *event* (short-term) and *regime* (long-term) time scales.
- Event-based monitoring needs to assess the response of fish (e.g. survival of young fish and movement of adult fish) intensively during and for 12 months after each event, then less intensively.
- The major categories of events to monitor are:
  - Managed Inundation Event, with minimum inundation.
  - Managed Inundation Event, with maximum inundation.
  - Variable flow in Pipeclay and Slaney creeks without Chowilla Regulator operating.
  - No managed event and low spring flows.
  - Natural flood.
- Practically, the more intensive monitoring is likely to be in the first 10 years, so a program should aim for three events to intensively monitor within this period.

9.4.4 Monitoring Budget

A typical budget for this scale of project involving investigation of spawning, recruitment, movement, distribution and abundance of fish at a meso- and landscape-scale would be $0.5–0.6 mil. per annum. The most effective process to determine the budget is to refine the experimental design first, as this will determine resources needed.

10 OPERATING STRATEGIES

In order to minimize the risks and optimise benefits for fish, six guiding principles were outlined in Section 8 (Mitigation of Risks) for operation of the Regulator:

i) *Frequency* (minimise frequency of Regulator use or of operational regimes which do not maintain lotic habitats and hydrodynamic diversity for fish).
ii) *Timing and duration* (winter floods to minimise carp spawning and poor water quality).
iii) *Conserving and increasing lotic habitats* (minimise loss by raising Lock 6 and operating the Regulator at low levels).
iv) *Synchronising floodplain and river hydrology*.
v) *Inflow source and discharge* (relates to maximising synchronisation with landscape–scale hydrological events).
vi) *Rate of recession* (to minimise fish stranded on the floodplain).

At a more detailed operational level there are two additional principles:

vii) Use natural modelled floods (MDBA BigMOD) as a template to simulate the natural rise, fall (typically 5-15 cm per day) and fluctuating peaks of flood events on a daily basis.
viii) Be responsive to monitoring, including on a daily basis.

Using an 'active adaptive management' approach, as outlined in Monitoring (Section 9), the operational strategy needs to use the above principles and be linked with a comprehensive monitoring program. A draft monitoring and operations framework is shown in Fig. 22. The framework applies to managed inundation events, natural floods and to varying flows in Pipeclay and Slaney creeks, although for the latter scenario some parts of the flow chart will not apply, such as monitoring carp on floodplains, recession management and validating hydrodynamic modelling of Mullaroo Creek. The framework is focused around responses to managed events and natural floods within the Icon site, and, as such, it is missing links with landscape–scale monitoring. The experimental design workshop will refine the scale of monitoring required and this can then be incorporated into the framework.

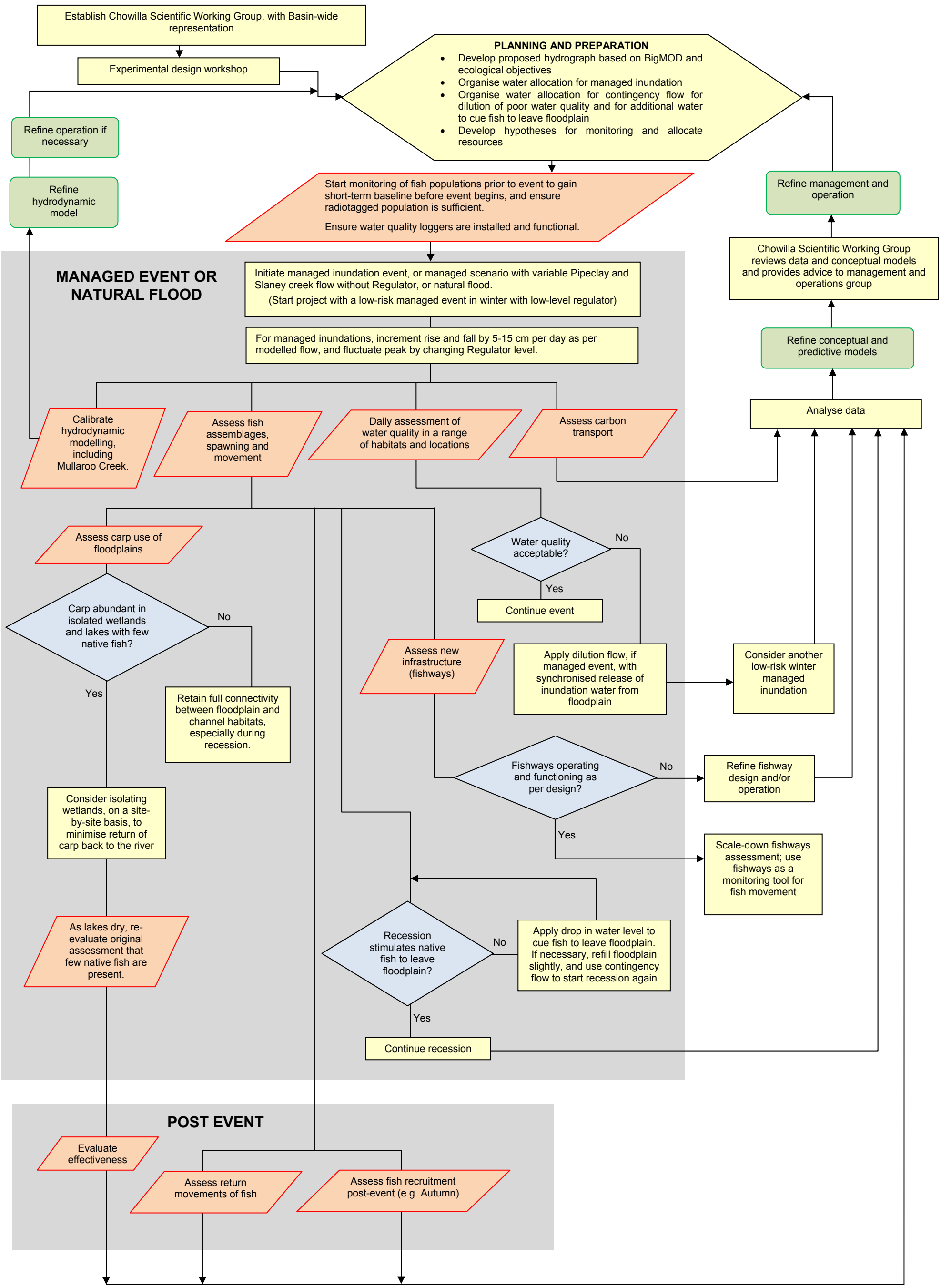

Fig. 22. A draft monitoring and operations framework. Orange parallelograms are data inputs or monitoring.

11 CONCLUSION

The aquatic habitats of Chowilla, particularly the diversity and permanence of moderate- and fast-flowing water, were once common in the lower River Murray but have become extremely rare in over 800 km of the lower river since construction of the Locks created a series of weirpools. These habitats in Chowilla, and in the nearby Lindsay Mullaroo system, contain the most significant populations of Murray cod, an EPBC Act listed species, in the River Murray downstream of the Darling River junction. Data suggests that these habitats may be drought refugia for this species, where spawning and recruitment occurs in drought years which sustains the riverine population.

Inundating the Chowilla floodplain using a regulating structure results in significantly different hydrodynamics (water volumes, velocities, flow paths, etc.) than a natural flood. Furthermore the Regulator is likely to inundate the floodplain in isolation to broader scale (i.e. the river-scale) hydrological processes. Operation of the Chowilla Regulator at levels >18.5 m AHD presents significant risks to Murray cod and other large-bodied native fish, and significant benefits for non-native common carp. Operation of the Regulator at <18.5 m AHD in conjunction with raising Lock 6 may mitigate these risks. The operational strategy with the least risk is to use the Regulator with very high inflows (e.g. 35,000 ML/d to 50,000 ML/d Q_{SA}) so that the hydrographs upstream and downstream of the Chowilla floodplain are synchronised with floodplain inundation and the hydrodynamics are similar to a natural flood (Note: modelling of very high inflows is needed to confirm this).

Operation of the Regulator is experimental and as such requires robust monitoring and investigations to measure benefits and avert risks, and test the hypotheses on which these predictions have been made. A Working Group is recommended that draws on the Basin–wide expertise in aquatic ecology and biometrics to help with the design of the monitoring program and provide ongoing peer review.

The Chowilla Regulator is presently being constructed and will be operable from 2013. The risks of managed inundations using the Chowilla Regulator will depend on how it is used and the frequency of use. The Chowilla Regulator also represents a clear opportunity for adaptive management as it is an environmental rehabilitation tool that can be manipulated and switched ‘on’ and ‘off’. The keys to the success of the project and to sustaining, and potentially improving, native fish populations will be a well designed monitoring program and linking the project with landscape-scale river rehabilitation.

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APPENDIX 1.

Flow in the lower Darling River.

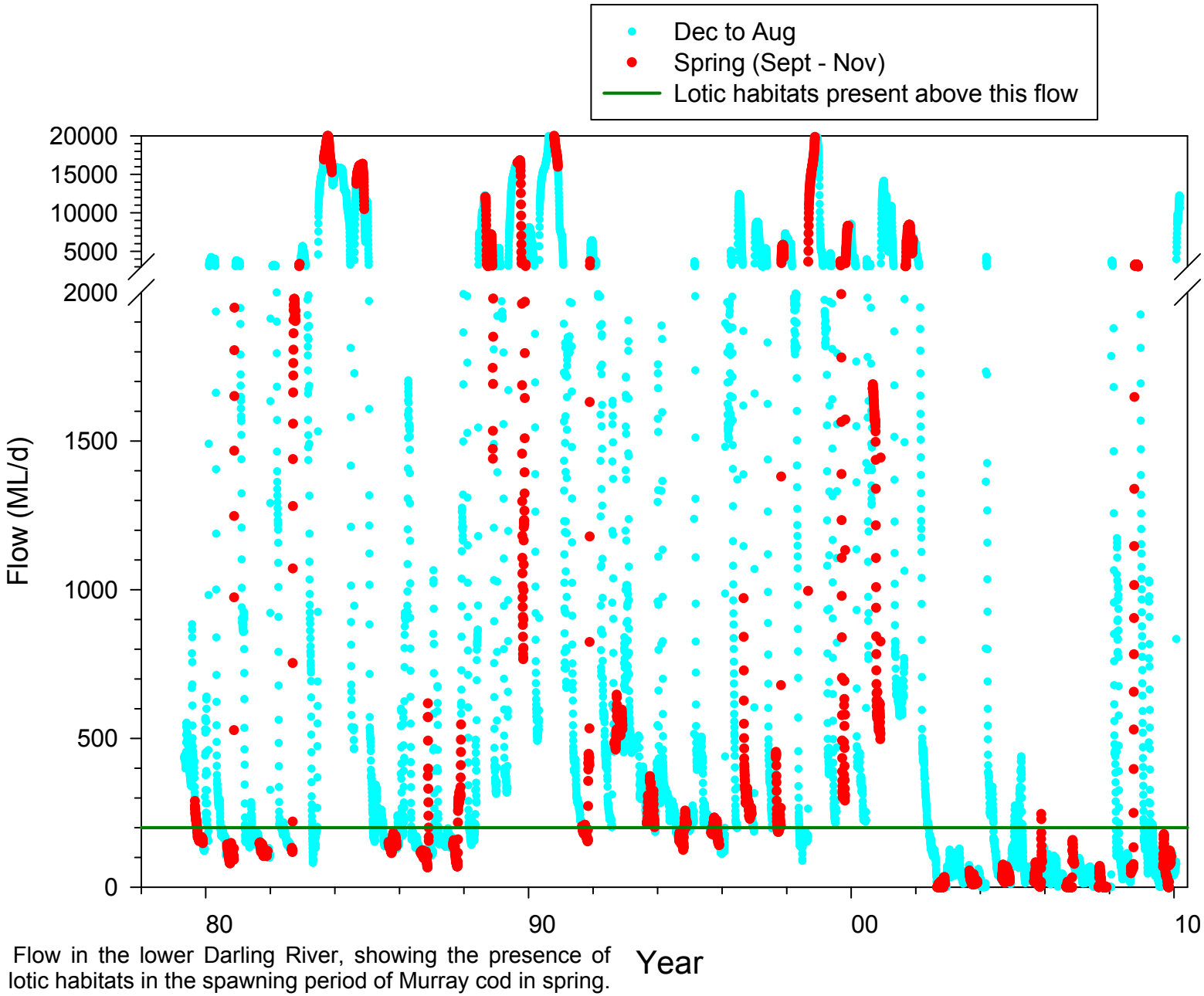

Fig. A1-1. Flow in the lower Darling River, showing the presence of lotic habitats in the spawning period of Murray cod in spring.

APPENDIX 2.

Flow in a middle River Murray tributary with Murray cod; Broken Creek at Rices Weir.

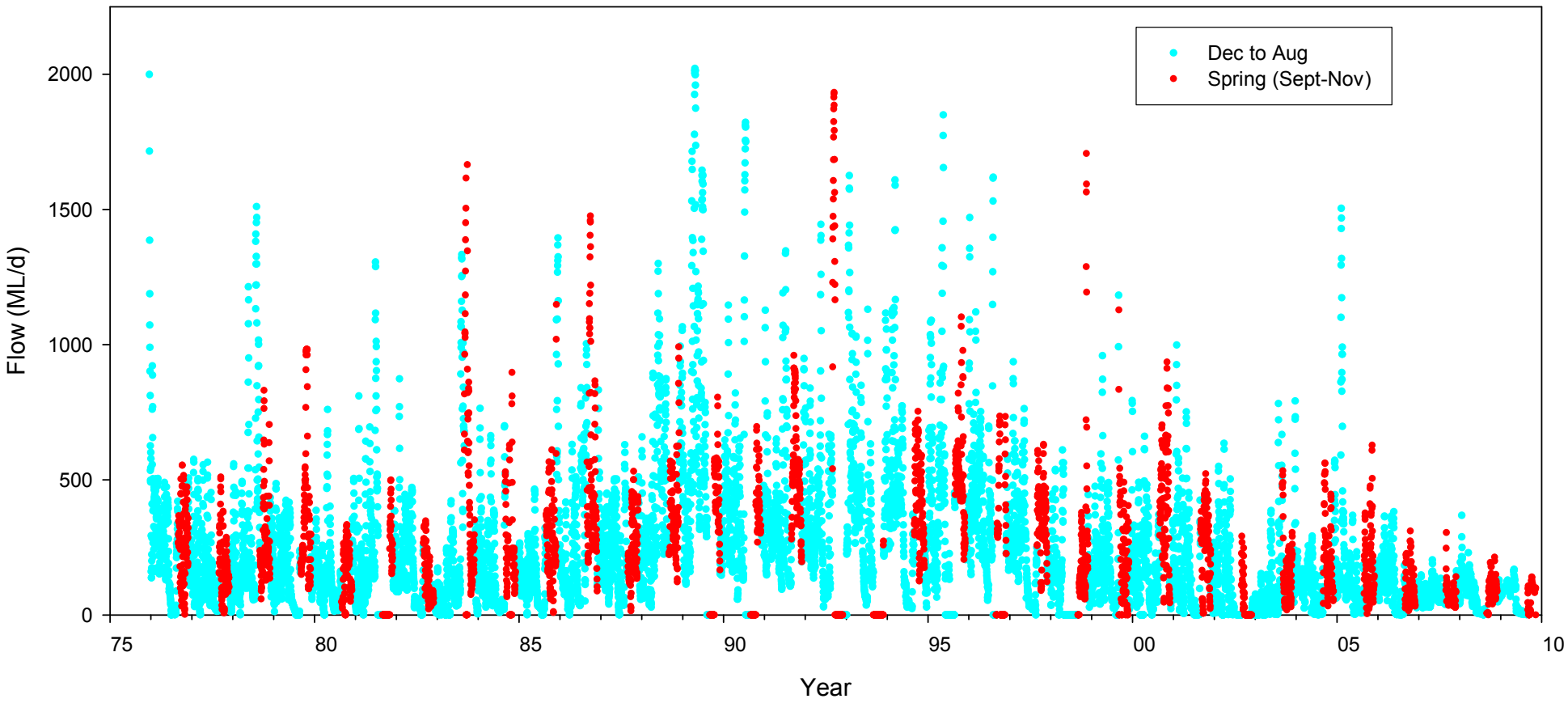

Fig. A2-1. Flow in Broken Creek at Rices Weir, showing the presence of relatively higher flows with lotic habitats in the spawning period of Murray cod in spring.

APPENDIX 3.

Memorandum: Effects of raising the Lock 6 weirpool on fish populations in the Lindsay River and Mullaroo Creek, October 2009.

Memorandum

Date: 9 October 2009

To: Tony Herbert

From: Martin Mallen-Cooper

Subject: **Effects of raising the Lock 6 weirpool on fish populations in the Lindsay River and Mullaroo Creek**

1 INTRODUCTION

As part of the project 'An evaluation of the proposed Chowilla Creek Environmental Regulator on large-bodied fish species' the SA MDB NRM Board requested advice on the effects of raising the Lock 6 weirpool on fish populations in Lindsay River and Mullaroo Creek (Fig. 1). The project team (Dr Martin Mallen-Cooper, Dr John Koehn, Brenton Zampatti, Dr Terry Hillman, Dr Alison King, Ivor Stuart, Stephen Saddlier and Clayton Sharpe) examined hydrodynamic modelling by Water Technology:

i) To identify whether there was an impact on fish habitats, and

ii) If there was an impact, to examine the potential for mitigation.

Most of the team (MMC, JK, TH, AK, IS, CS) reviewed the modelling in a teleconference (4 Sept 2009) and the whole team reviewed this memo.
The intent of this memo is to provide the SA MDB NRM Board with some guidance on the impacts of raising Lock 6 on the Lindsay-Mullaroo system, prior to completion of the whole project. The contents of this memo will be expanded in the final report.

2 MODELLING

2.1 Model validation

Water Technology validated various aspects of the Lindsay and Mulcra Island Hydraulic Model (Water Technology 2009). In the Mullaroo Creek the validation included comparing the results of modelled water level and mean water velocity with six gauged sites (Fig. 2). The water level varied less than 0.1 m between the model and gauged data, while the modelled water velocity was either accurate or underestimated by up to 0.15 m/s (Fig. 3). A significant issue for fish habitats in Mullaroo Creek is maintenance of fast-flowing habitats so it is useful that the model produces a slight underestimate of water velocity, as this provides a conservative assessment of the impacts of a changed hydraulic regime.

2.2 Effects on fish habitats of raising the Lock 6 weirpool

1.2.1 Methods

For the present project the 1D model was used which provides mean velocities of surveyed cross-sections along the stream. The mean value does not describe the littoral zone; hence slow-flowing habitats can occur on the edge of fast-flowing habitats. The velocity data was post-processed and categorised into velocity classes based on fish habitats:

0.00- 0.03 m/s	backwater.
0.04- 0.10 m/s	very slow-flowing.
0.11- 0.17 m/s	slow-flowing.
0.18- 0.30 m/s	moderate-flowing.
0.31- 0.50 m/s	fast-flowing.
> 0.50 m/s	very fast.

The data was graphed as:

i) Maps of points.
ii) Longitudinal profiles.
iii) Areas of velocity classes.

Four scenarios were modelled:

1) Existing conditions with normal Lock 6 and 7 weirpools.

2) Lock 6 pool raised to maximum (0.63 m above normal pool) with Lock 7 at normal pool – to assess the impact on the hydraulic regime of Mullaroo Creek and Lindsay River.

3) Lock 6 pool raised to maximum (0.63 m above normal pool) with Lock 7 weirpool raised by 0.15 m – to assess the potential to mitigate any loss of fast-flowing habitats in Mullaroo Creek.

4) Lock 6 pool raised to maximum (0.63 m above normal pool) with Lock 7 weirpool raised by 0.65 m – to assess the maximum potential to mitigate any loss of fast-flowing habitats in Mullaroo Creek.

2.2.2 Results and Discussion

Comparison of velocity profiles along the Mullaroo Creek and Lindsay River under normal pool levels and with Lock 6 raised (Fig. 4 and 5; Fig. 8; Fig.9) shows that there is a 50% reduction of the fast-flowing habitats (0.31 to 0.5 m/s) in Mullaroo Creek, which are a key habitat for adult Murray cod. The slow-flowing habitats of 0.10 to 0.17 m/s, which may provide significant edge habitats for small-bodied fish and larvae, are also reduced by 50%. Raising the Lock 7 weirpool by 0.15 m appears to largely mitigate this loss of fast-flowing habitats (0.31 to 0.5 m/s) and produces a slightly greater area of these habitats compared with the existing conditions (Fig. 6; Fig. 8; Fig. 9). However, there is a change in hydraulic diversity with less very slow-flowing habitats (0.04 - 0.10 m/s) which are known to be important for small-bodied fish and early life stages of many fish species (Humphries *et al*. 2006).

Raising the Lock 7 weirpool by 0.65 m produces water velocities that are much higher than the existing conditions (Fig. 7; Fig. 8; Fig. 9) and are likely much higher than in any conditions, as the Lock 7 weirpool does not rise more than 0.45 m above normal pool (Fig. 10) except in floods when the weir is removed and the tailwater is much higher. The high water velocities in this modelling scenario are likely to be detrimental to fish habitats.

2.2.3 Recommendations

Modelling and validation

- Run hydraulic model with Lock 7 raised by 0.10 m and Lock 6 raised by 0.63 m to assess whether the extent of slow-flowing habitats can be maintained as well as the fast-flowing habitats.

- Run hydraulic model with natural floods with Lock 7 raised 0.25 m and 0.45 m (i.e. natural maximum) with the correspondingly raised tailwater, to assess the natural fluctuations in hydraulic diversity. This would set the bounds for future management.

- Acknowledging that the 1D model produces an estimate of mean velocity and that localised hydraulic diversity within the cross-section of a stream is important for fish,

provide reference sites for ADCP measurements that can be used to validate and refine the model during a managed inundation.

- Survey and quantitatively assess the surface area of slackwaters of Mullaroo Creek and Lindsay River and when they commence-to-fill. This is a recommendation from Conallin and Meredith (2006) and is also recommended by the present project team.
- Raise Lock 7 by 0.15 m this season (or 0.1m if the above hydraulic model reveals a more favourable outcome) and further validate the model with gauging, ADCP and estimates of surface areas of slackwater habitats.
- Investigate the use of Computational Flood Dynamics (CFD) to produce a 3D model of sections of the river to use as a predictive tool. (N.B. complex woody debris and macrophytes are not needed for the model).

Management, monitoring and research

- Assess the use by fish, especially small life stages, of slackwater habitats in Mullaroo Creek and Lindsay River (also a recommendation by Conallin and Meredith 2006) and assess zooplankton biomass; noting that loss of these habitats may be an impact of raising Lock 6 and 7.
- Assess the hydraulic impacts of raising Lock 6 and 7 on the fishways at these structures.
- Increase large woody debris at key locations to improve hydraulic diversity as a mitigation strategy that would also serve as habitat rehabilitation when the weirpools are not raised. Specialist input will be needed to identify the key locations.
- Future management with weirpool raising needs to consider raising Lock 7 in spring and returning to normal pool in summer, as there may be benefits for large-bodied fish. An adaptive management approach would be needed to assess fish movement and spawning activity.
- Integrate these recommendations with future management and recent initiatives by DSE for the broader Lindsay–Mullaroo system.

Summary

Raising Lock 6 by 0.63 m (i.e. maximum) causes a reduction in fast-flowing habitats that are considered significant for large-bodied fish and the impact warrants mitigation. Raising the Lock 7 weirpool by 0.15 m appears to largely mitigate this impact but there is a loss of very slow-flowing habitats which are important for small-bodied fish and larvae. Recommendations include further modelling to refine this mitigation strategy and to establish the hydraulic diversity that naturally occurs in the system, with the intent of establishing a baseline and bounds for future management.

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Conallin A. & Meredith. S 2006. Slackwater Environments of Mullaroo Creek: are they important habitat for fish? Report No. 07/06. Prepared for the Mallee Catchment Management Authority. 17 p.

Humphries P., Cook R.A. Richardson A.J. & Serafini L.G. 2006. Creating a disturbance: manipulating slackwaters in a lowland river. *River Research and Applications* **22**: 525–542.

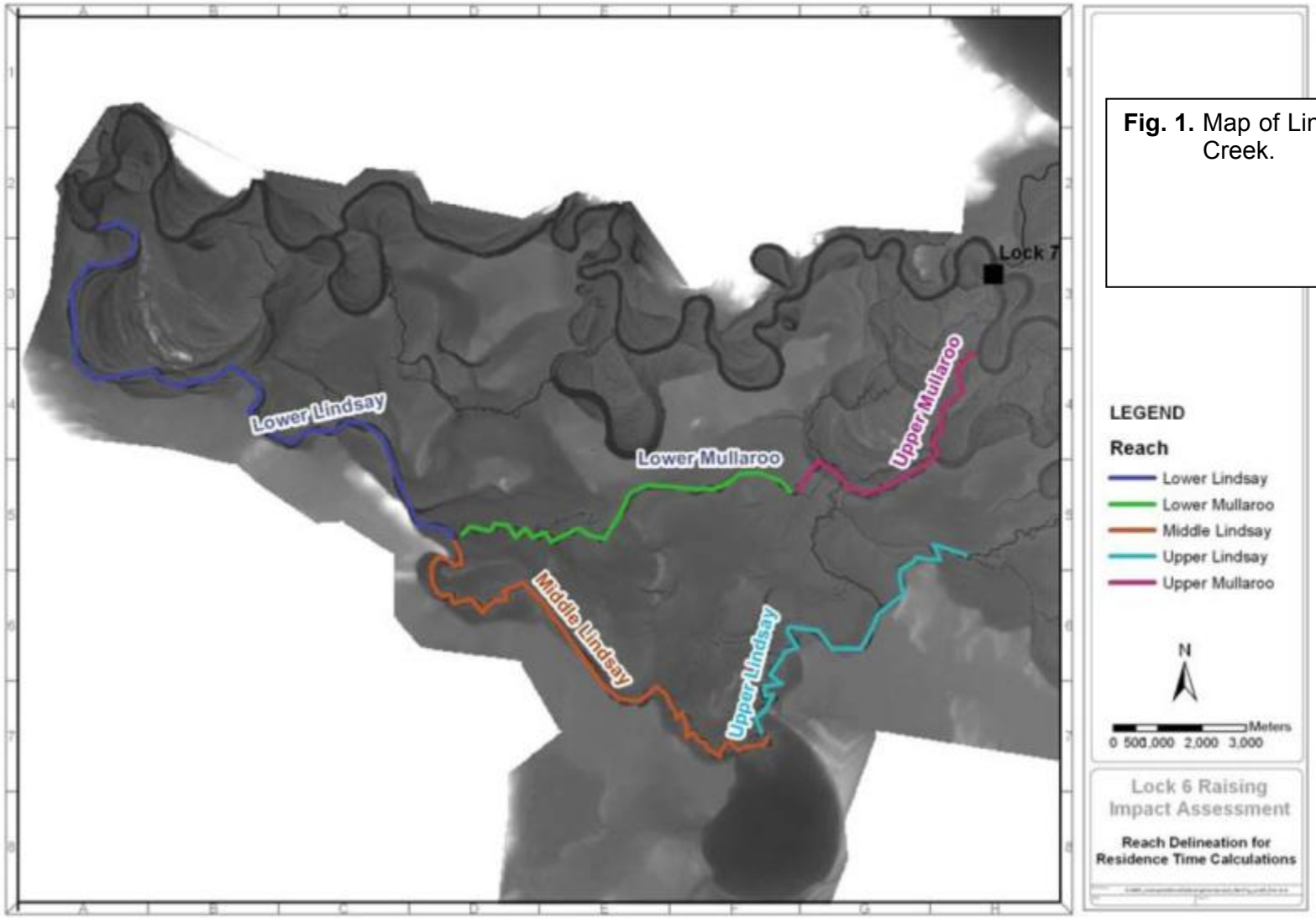

Fig. 1. Map of Lindsay River and Mullaroo Creek.

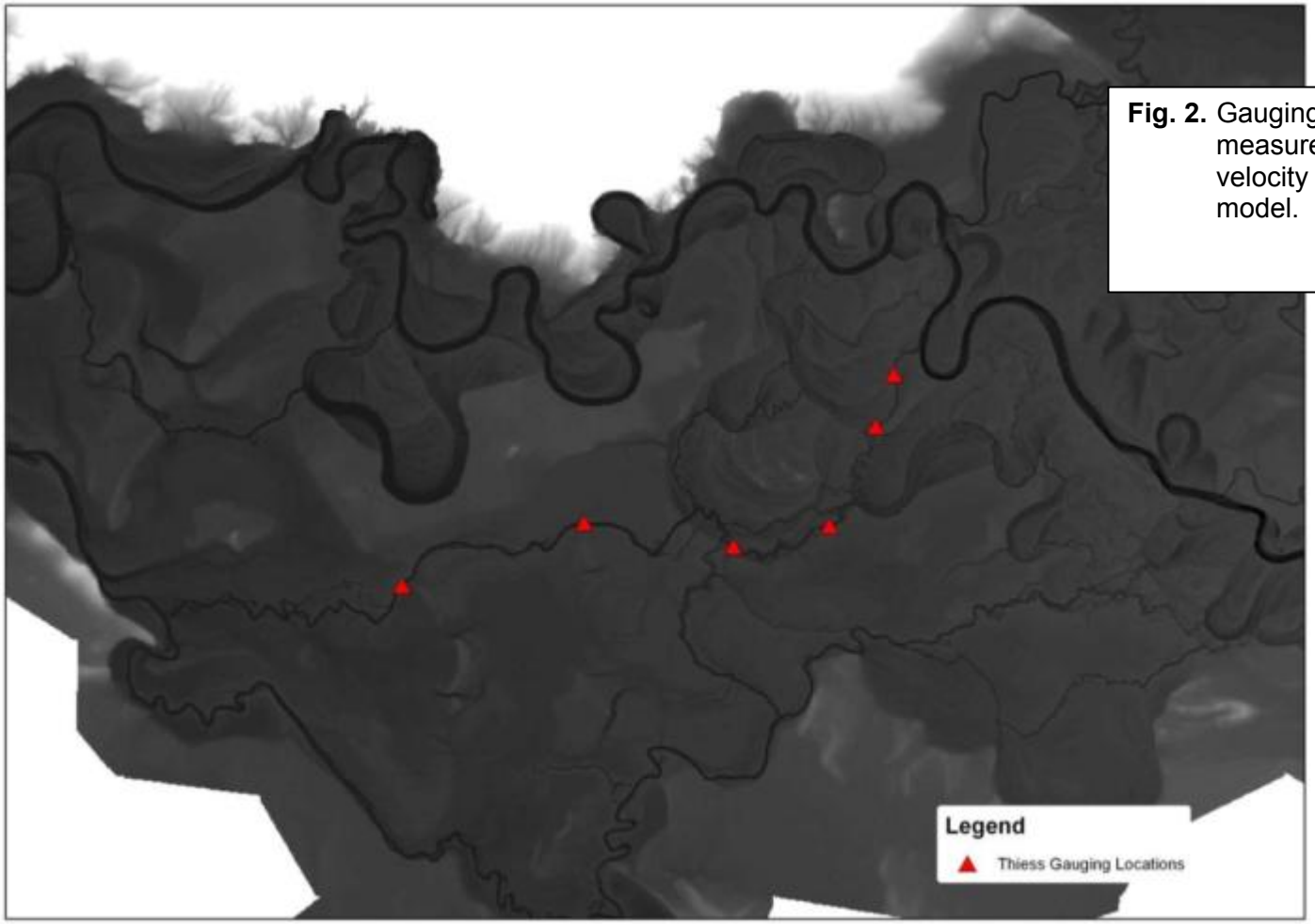

Fig. 2. Gauging stations used by Theiss to measure water level and mean water velocity for calibration of hydraulic model.

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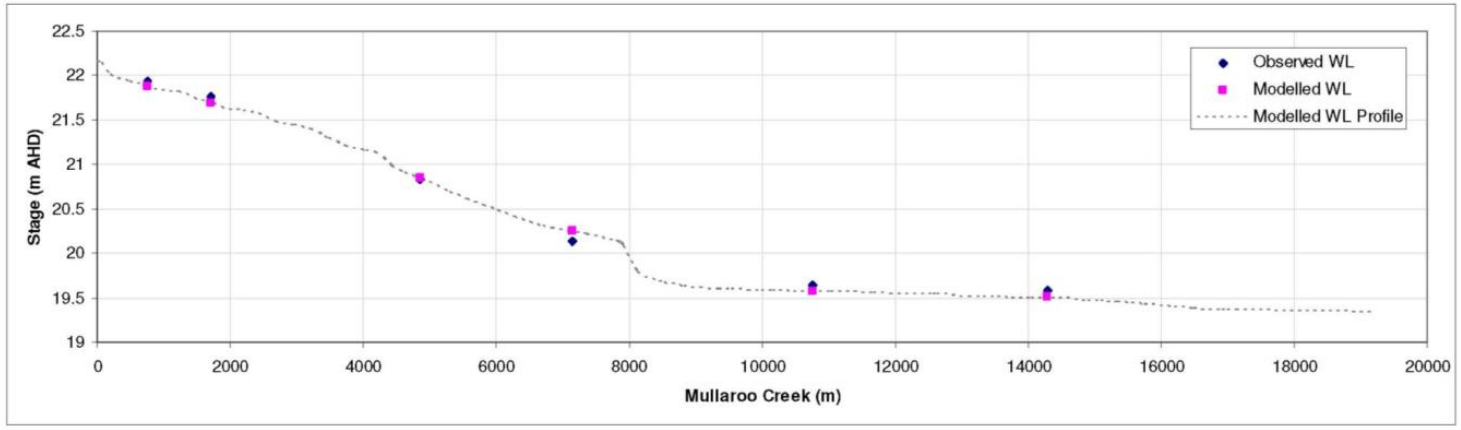
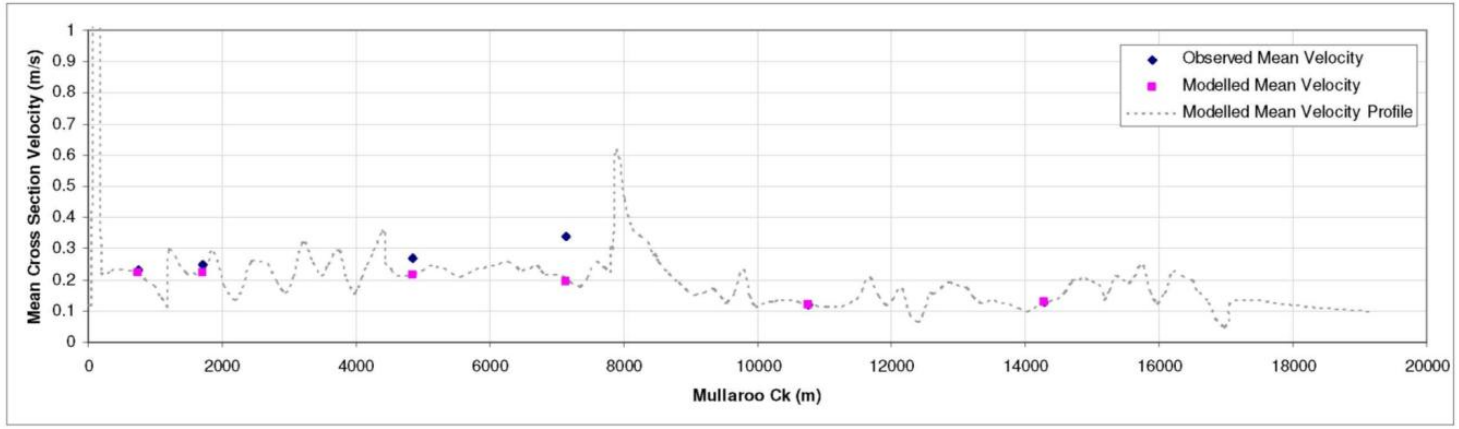


Fig. 3. Comparison of modelled and real water level and mean water velocity at six sites in Mullaroo Creek.

Figure 2-27 Mullaroo Creek Profile



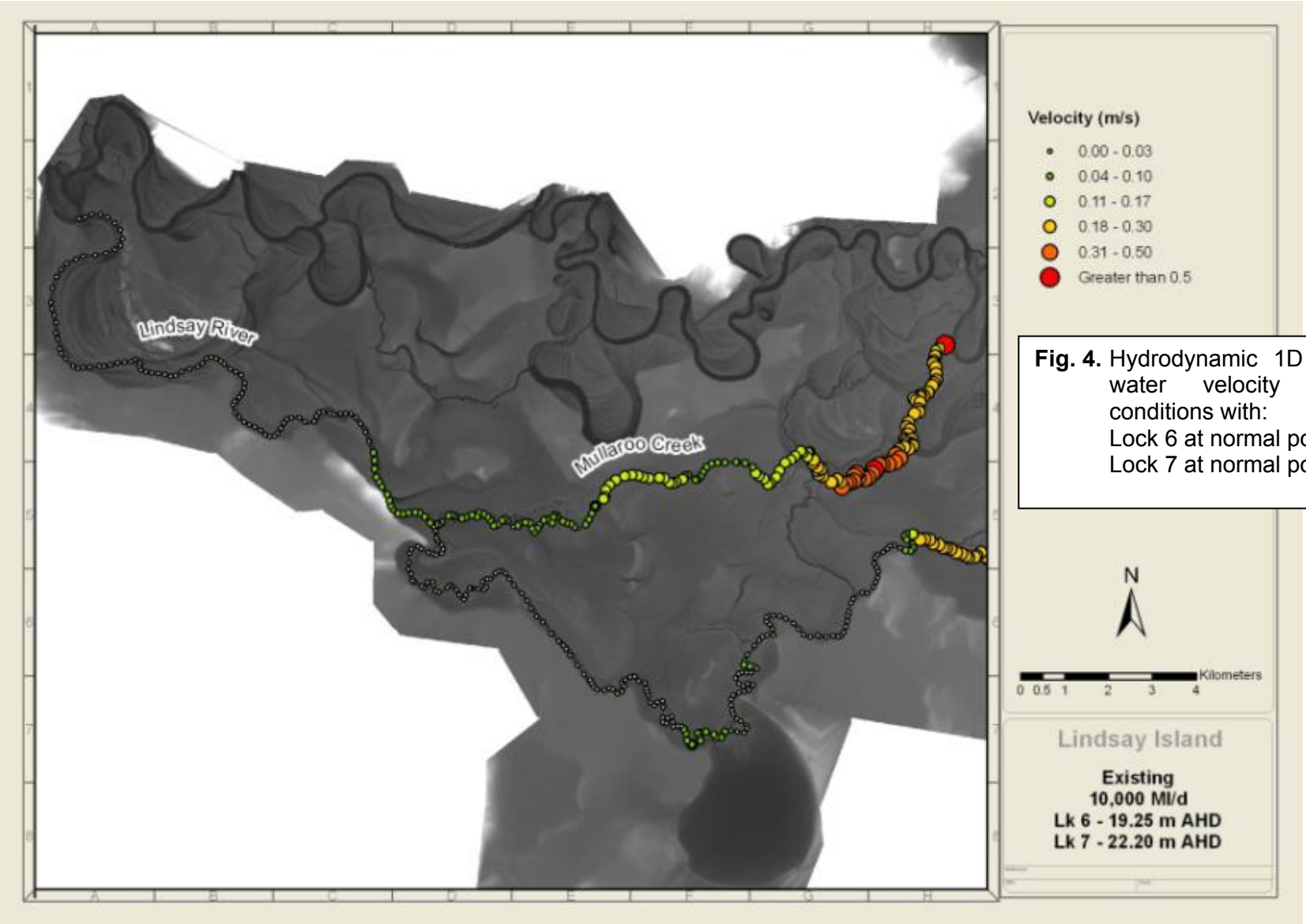


Fig. 4. Hydrodynamic 1D model of mean water velocity under existing conditions with:
Lock 6 at normal pool
Lock 7 at normal pool.

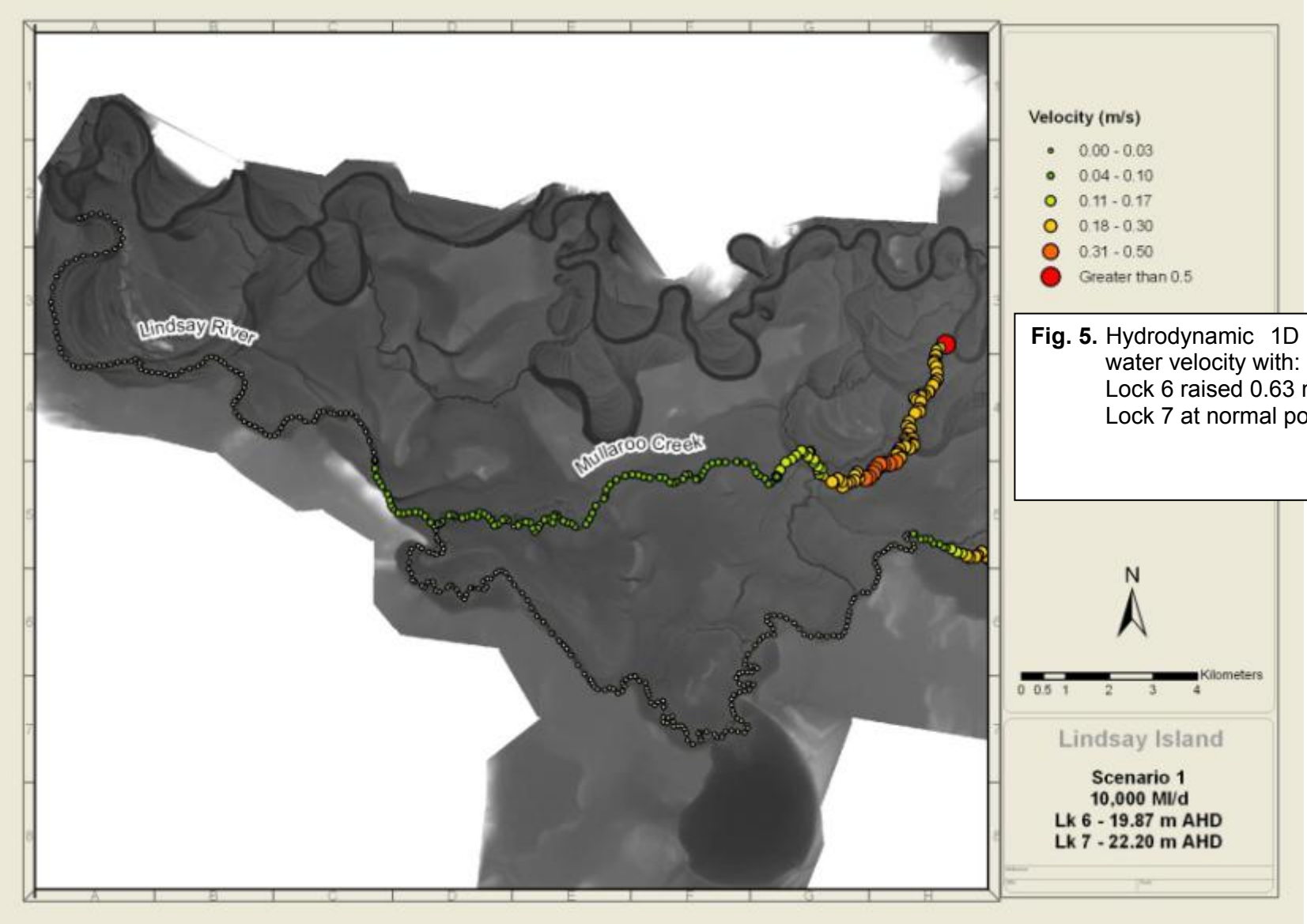


Fig. 5. Hydrodynamic 1D model of mean water velocity with:
Lock 6 raised 0.63 m (maximum)
Lock 7 at normal pool.

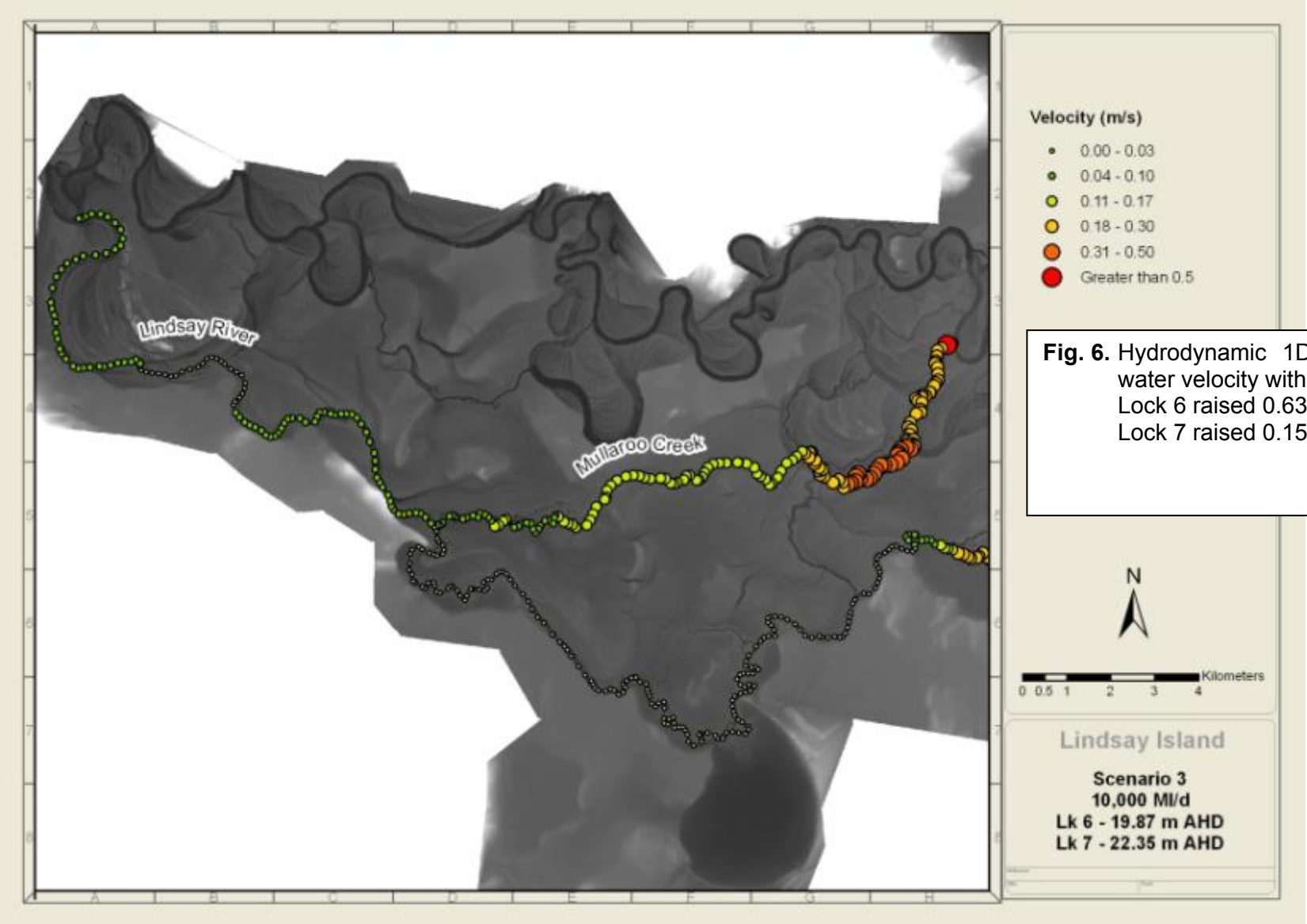


Fig. 6. Hydrodynamic 1D model of mean water velocity with:
Lock 6 raised 0.63m (maximum)
Lock 7 raised 0.15m.

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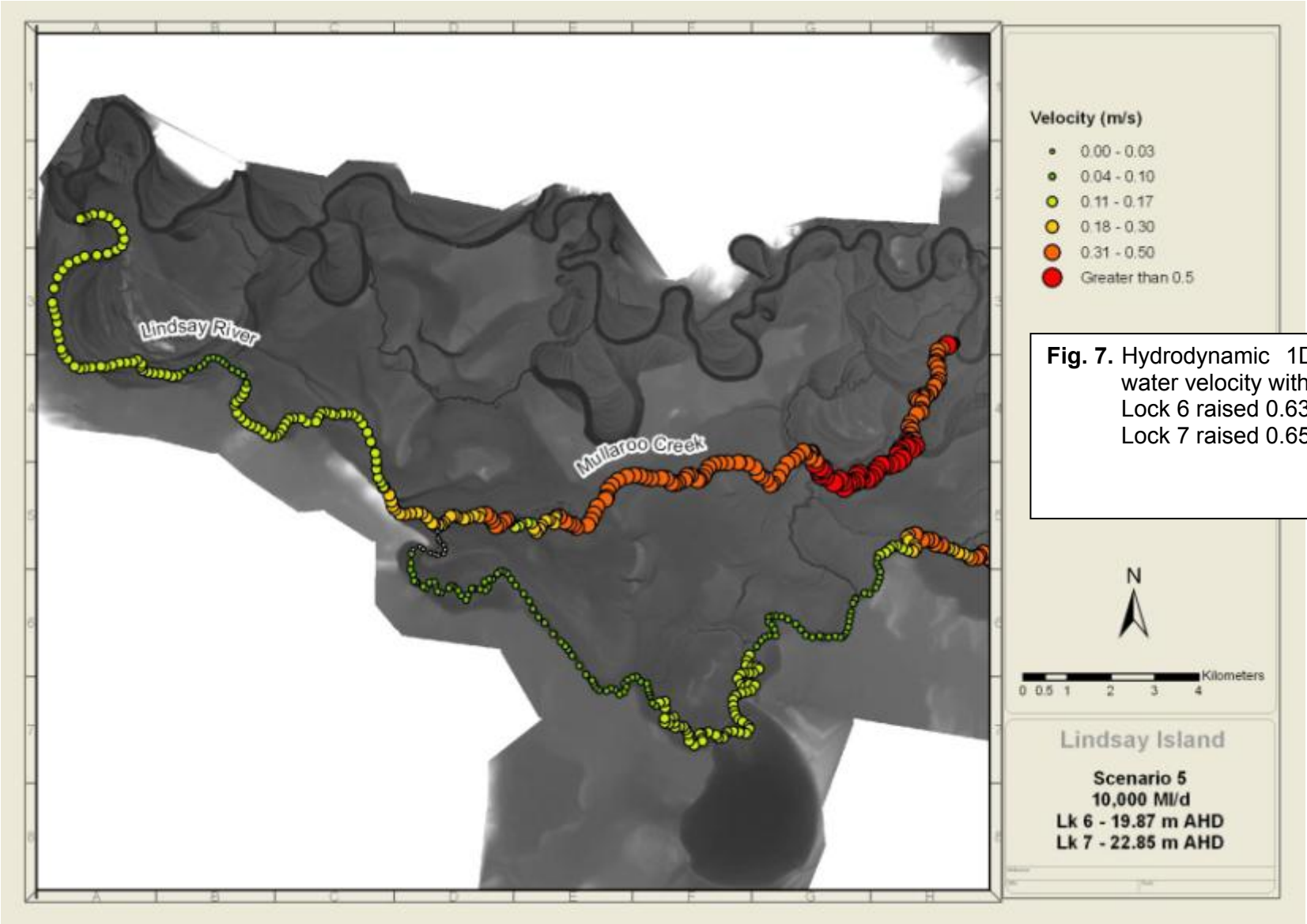

Fig. 7. Hydrodynamic 1D model of mean water velocity with:
Lock 6 raised 0.63m (maximum)
Lock 7 raised 0.65m.

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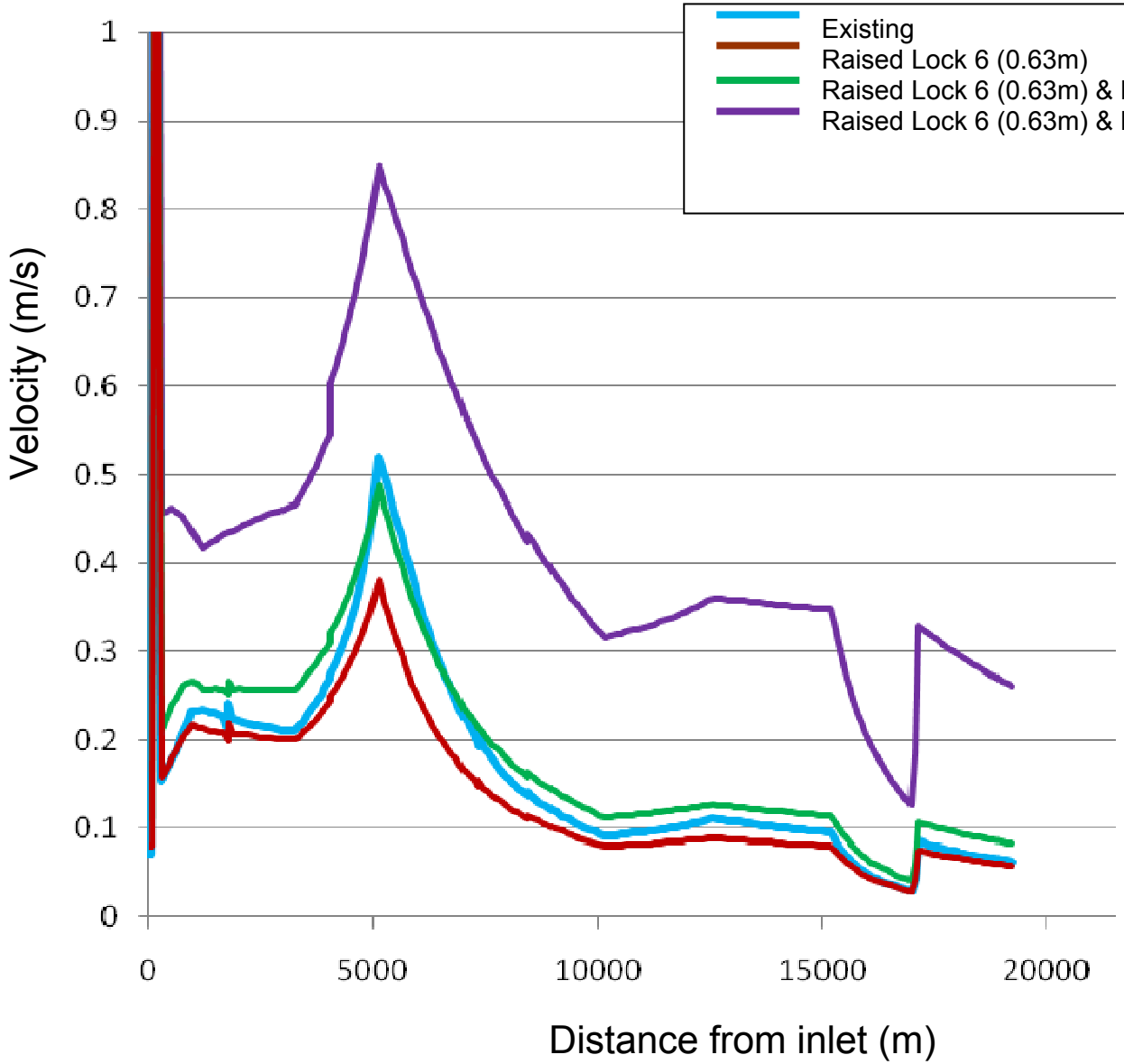

Fig. 8. Hydrodynamic 1D model of mean water velocity showing interpolated longitudinal profile under existing conditions and three scenarios of weirpool raising.

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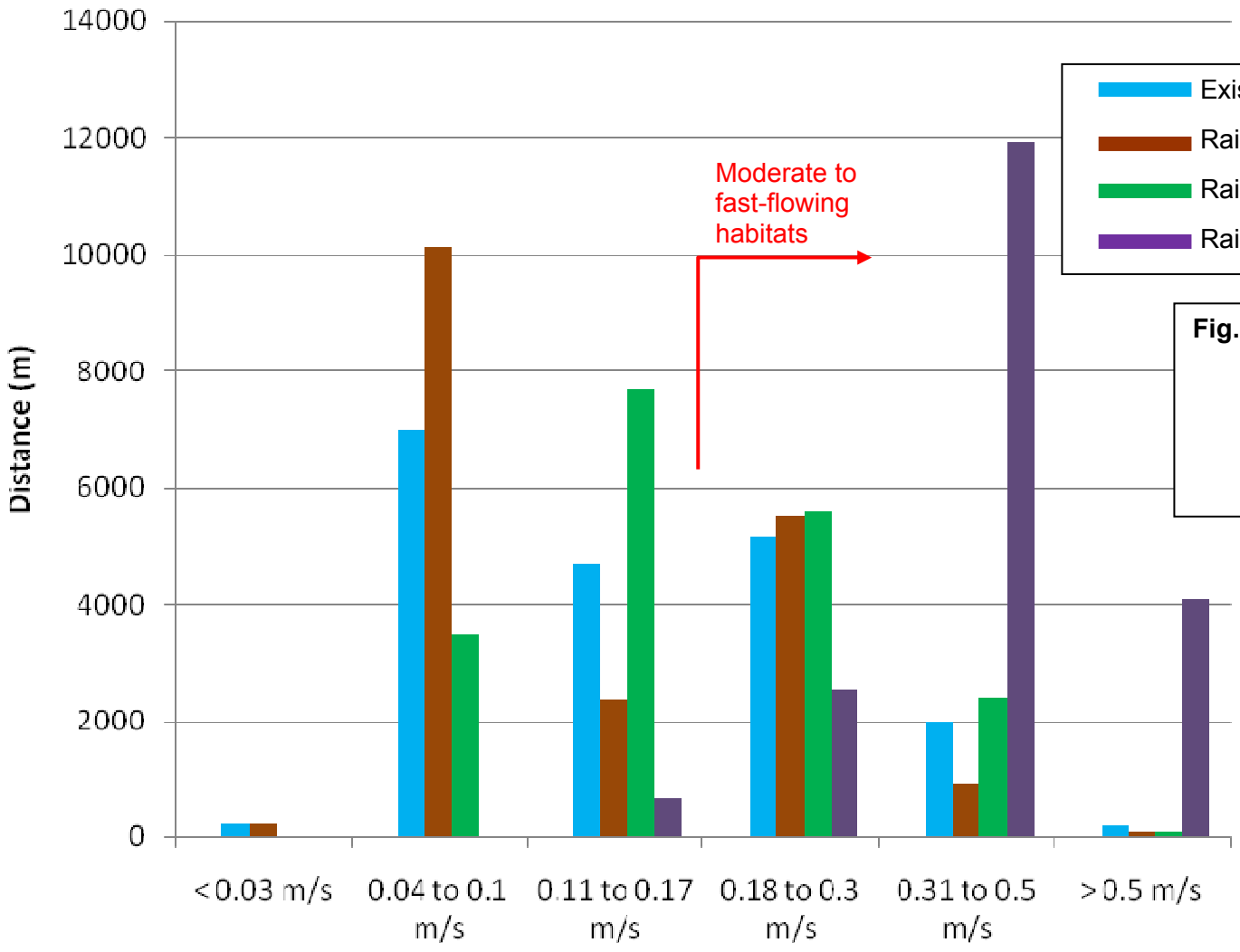

Fig. 9. Hydrodynamic 1D model of mean water velocity showing total interpolated stream lengths for each velocity class, under existing conditions and three scenarios of weirpool raising.

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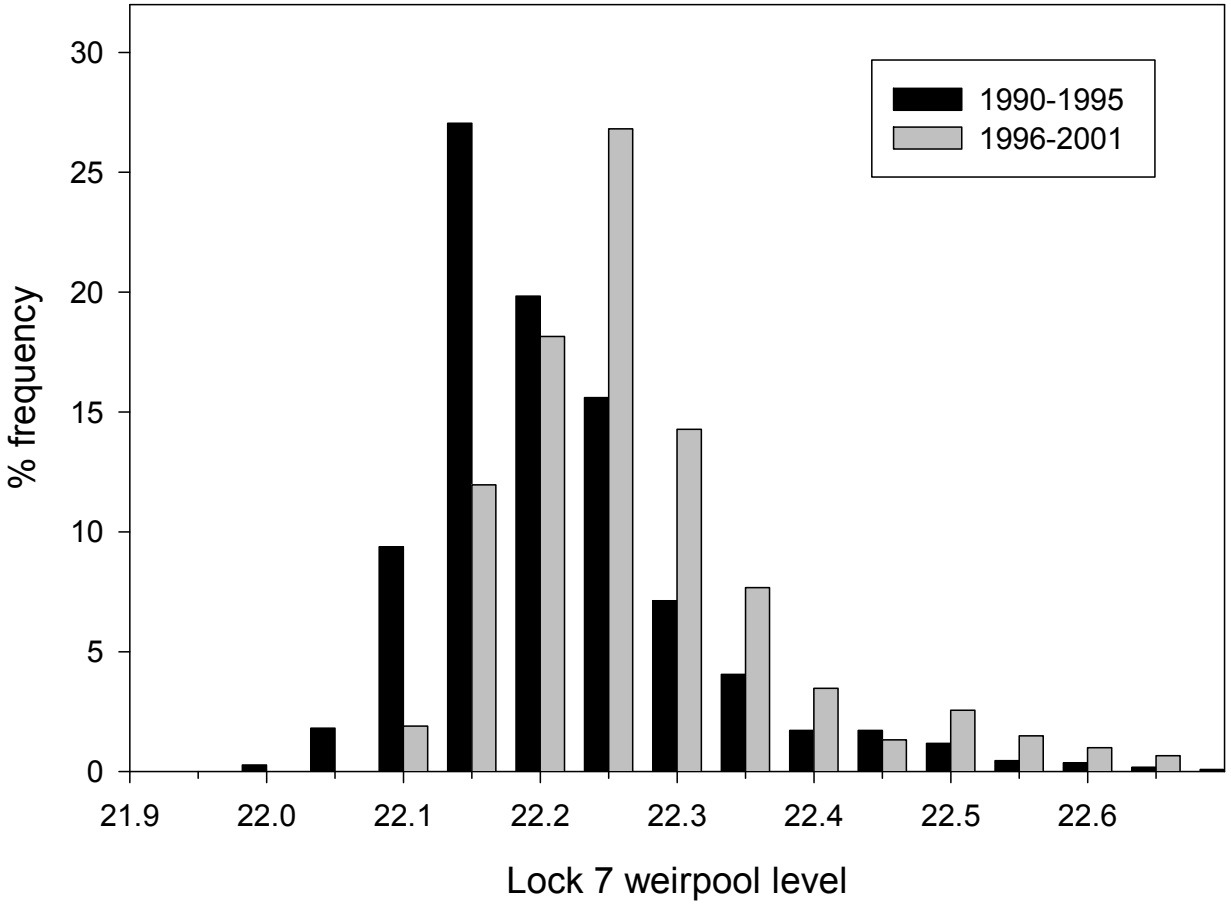

Fig. 10. Frequency of Lock 7 weirpool levels in regulated (non-flood) conditions.

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APPENDIX 4.

Hypotheses from conceptual models and assessment of risk and benefits

Appendix 4

Hypotheses from conceptual models and assessment of risk and benefits

[1] Survival of larval Murray cod in relation to diet - in lotic, lentic and floodplain habitats (including food availability, composition and abundance in these habitats).

[2] Survival of larval Murray cod in relation to habitat use at low and high flows.

[3] Emigration and immigration of immature Murray cod.

[4] Habitats of 0+ Murray cod.

[5] Distance of drift of larval Murray cod.

[6] Movement of Murray cod between Chowilla anabranch creeks and the River Murray.

[7] Movement of Murray cod in a natural flood, including lateral, longitudinal, emigration and immigration.

[8] Limitations of spawning site abundance for Murray cod.

[9] Emigration and immigration of mature Murray cod.

[10] Flow and temperature cues for spawning of golden perch.

[11] Survival and diet of golden perch larval fish - in lotic, lentic and floodplain habitats (including food availability, composition and abundance in these habitats).

[12] Distance of drift of larval golden perch.

[13] Movement of golden perch in a natural flood, including (lateral, longitudinal, emigration and immigration); use of lakes and floodplains.

[14] Chemical cues for spawning of golden perch.

[15] Site selection for spawning of golden perch.

[16] Habitats of 0+ golden perch.

[17] Movement of 0+ golden perch.

[18] Landscape-scale cyclical movements of golden perch.

[19] Emigration and immigration of immature golden perch.

[20] Emigration and immigration of mature golden perch.

[21] Flow and temperature cues for spawning of silver perch.

[22] Habitats of silver perch larvae.

[23] Distance of drift of larval silver perch.

[24] Movement of silver perch in a natural flood, including (lateral, longitudinal, emigration and immigration).

[25] Chemical cues for spawning of silver perch.

[26] Habitats of 0+ silver perch.

[27] Landscape-scale cyclical movements of silver perch.

[28] Emigration and immigration of silver perch.

[29] Spawning habitats of freshwater catfish within Chowilla.

[30] Habitats of freshwater catfish larvae and conditions for high survival.

[31] Emigration and immigration of freshwater catfish.

[32] Distribution of freshwater catfish within Chowilla.

[33] Cues for adult freshwater catfish to abandon nest prematurely.

[34] Proportion of freshwater catfish larvae that drift.

[35] Habitats of 0+ freshwater catfish.

[36] Interaction of freshwater catfish with carp within Chowilla.

[37] Movement of freshwater catfish in a natural flood, including lateral, longitudinal, emigration and immigration.

[38] Contribution of localised spawning events of carp to broader populations.

[39] Movement of adult and juvenile carp between the River Murray (broad scale e.g. Lower Lakes to Darling) and Chowilla.

[40] Movement of adult fish within Chowilla, especially to outer lakes and small wetlands.

[41] Extent of spawning and recruitment of carp during within-channel rises within Chowilla compared to floods.

[42] Temporal extent of carp spawning season

[43] Minimum water temperature for spawning of carp

[44] Survival and diet of larval carp

[45] Survival of 0+ carp on floodplain

[46] Survival of 0+ carp in main channel habitat

[47] Cues for lateral movement of carp on & off floodplains

[48] Movement of carp in a natural flood, including emigration and immigration.

[49] Oriental weatherloach colonisation.

[50] Fish passage through main stem fishways compromised through reduced attraction at i) Lock 6, and ii) downstream Locks due to suppression of the hydrograph.

[51] Pipeclay and Slaney fishways not optimised; poor fish passage.

[52] Denil fishways at Pipeclay and Slaney do not pass all large Murray cod.

[53] Fish kills from stranding by isolation and evaporation of wetlands.

[54] Small flood pulses captured by regulator and suppressed downstream; main stem spawning & recruitment failure of large-bodied fishes.

[55] New fish passage at Pipeclay and Slaney weirs improves connectivity.

[56] Floodplain vegetation (esp. understorey) captures carbon in the soil for the next inundation and release to the river.

[57] Nutrient, carbon and zooplankton pulse from floodplain to the river downstream, in recession of a managed inundation benefits native fish.