Australian Government

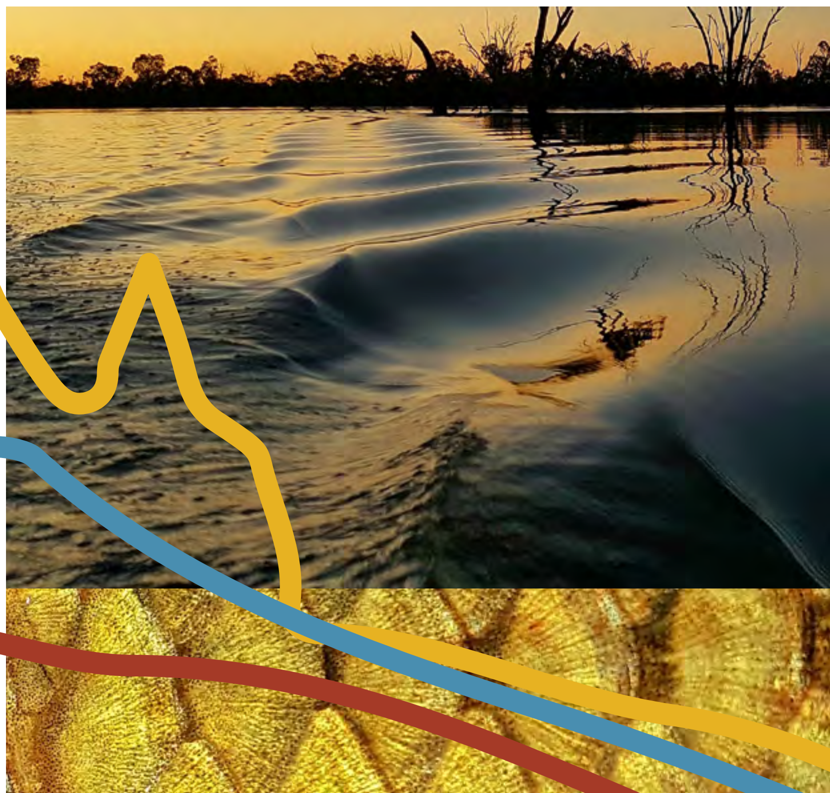
NATIONAL CARP CONTROL PLAN

FRDC

Submitted to the Department of Agriculture, Fisheries and Forestry representing the Australian Government

September 2022

The National Carp Control Plan



This document fulfils the requirements of a contract between the Fisheries Research and Development Corporation (FRDC) and the Australian Government to develop the National Carp Control Plan (NCCP). It will be used to inform decision making on whether to proceed with additional activities assessing the carp virus as a carp-control measure in Australia. The information and recommendations in this document represent the latest research and the associate limitations and assumptions of that research.

FRDC
Locked Bag 222, Deakin West ACT 2600
T: 02 6285 0400 E: frdc@frdc.com.au

The FRDC through investing in knowledge, innovation, and marketing aims to increase economic, social and environmental benefits for Australian fishing and aquaculture, and the wider community.
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Australian Government
Fisheries Research and Development Corporation

30 September 2022

The Fisheries Research and Development Corporation (FRDC) is pleased to present the National Carp Control Plan (NCCP, or the Plan) for consideration by the Australian Government.

The NCCP provides an extensive body of research and analysis to inform decision making about the potential use of a virus for biological control of European Carp, or common carp, in Australia. The Plan is the culmination of almost six years' work, including an extended interruption to laboratory studies during the COVID-19 pandemic. The research program underpinning the Plan involved 19 peer-reviewed studies and numerous planning investigations considering various aspects of carp biocontrol. This work represents the largest body of research ever undertaken to evaluate the possible use of a biological control agent for an aquatic pest. Results from this research provide an evidence base to help decision makers determine next steps regarding this important national issue.

Controlling an established pest fish that inhabits varied ecosystems across a vast swathe of south-eastern Australia presents a significant challenge. The Plan has taken a systems approach to dealing with this complex issue. Therefore, while the Plan's research outputs represent enduring contributions to knowledge for pest fish control, the broader process underpinning the Plan's development may also provide insights applicable to other issues at the interface of science, policy, and society.

Uncertainties regarding the release of the virus remain, but this is to be expected given the complexity of the work undertaken. The Plan identifies these uncertainties and sets out actions that may reduce them in an effort to assist further government decision making. Nonetheless, a decision on whether or not to release the virus will always involve some uncertainty. Decision makers will wish to consider residual uncertainties in the context of the scale of the carp problem, and in relation to other relevant factors such as costs, and the regulatory and policy environment.

We commend the Plan to your attention and look forward to the next stages of this important process.

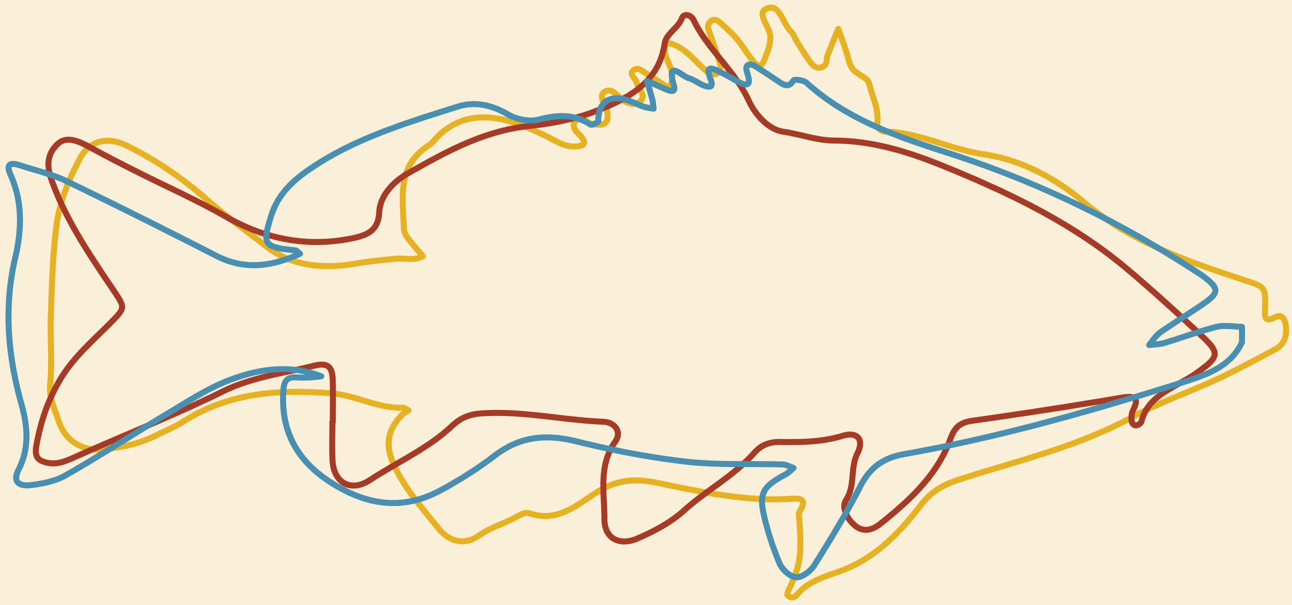
Yours sincerely

Patrick W Hone

Patrick Hone
FRDC Managing Director

Fisheries Research and Development Corporation
Postal address: Locked Bag 222, Deakin West ACT 2600 Australia
Office location: Fisheries Research House, 25 Geils Court Deakin ACT
T: 02 6285 0400 **E**: frdc@frdc.com.au **www**.frdc.com.au

The National Carp Control Plan



The National Carp Control Plan (NCCP)

Fisheries Research and Development Corporation (FRDC)
Locked Bag 222, Deakin West ACT 2600
T: 02 6285 0400 F: 02 6285 0499
E: frdc@frdc.com.au W: www.frdc.com.au

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GLOSSARY

Aggregations/aggregating — groups of animals or fish gathering in close proximity to each other, often for a specific biological purpose.

Anoxia — in relation to waterbodies, anoxia is a condition in which no dissolved oxygen remains in the water (compare 'hypoxia').

Biological control/biocontrol — using pest species' 'natural enemies', such as disease-causing organisms, predators, or parasites, to control their numbers and reduce the economic, environmental, and social harm they cause.

Biological control/biocontrol agent — the organism used to attack a pest species in a biocontrol program (see 'biological control/biocontrol').

Biomass — the total mass of a particular species occurring in an area or habitat. Measuring a species' abundance in terms of biomass would typically involve a description such as 'the wetland contained 5 tonnes of carp', and contrasts with describing abundance in terms of the number of individuals present (e.g. 'the wetland contained 5000 carp'). Biomass may be expressed on a per-area basis (e.g. '50 kg of carp per hectare').

Blackwater events — occur when flooding washes organic material into waterways, where it is consumed by bacteria, leading to a rise in dissolved carbon in the water. During a blackwater event, the water appears black due to the release of dissolved carbon compounds, including tannins, as the organic matter decays, similar to the process of adding water to tea leaves. Rising levels of dissolved carbon causes a sudden depletion of dissolved oxygen in water, which is essential for aquatic organisms that need to breathe underwater. (Source: https://www.waterquality.gov.au/issues/blackwater-events.)

Cyanobacteria/cyanobacterial blooms — microorganisms that are related to bacteria but are capable of photosynthesis and can be toxic to other species. Cyanobacteria are commonly called 'blue-green algae'. Under suitable conditions, cyanobacteria can form large 'blooms', covering large areas of waterbodies and potentially harming human and animal health.

Cyprinid herpesvirus 3 (CyHV-3) — a double-stranded DNA virus belonging to the family Alloherpesviridae. Throughout this report, CyHV-3 is referred to as 'the carp virus'.

Dissolved oxygen — the amount of oxygen present in water, typically expressed as milligrams per litre (mg/L). Most gill-breathing aquatic animals require dissolved oxygen to stay above certain levels (which vary between species) to remain healthy.

Effectiveness (in the context of the NCCP) — the extent to which the carp virus will reduce carp abundance and the environmental damage they cause in natural ecosystems.

Epidemiology — the scientific discipline that studies disease at a population scale.

Genetic biocontrol — methods or technologies that use biology to change the genetics of a target species population to achieve control of that population.

Genetic resistance — occurs when organisms possess genes or gene variants (alleles) that give protection against a particular disease-causing organism (e.g. virus or bacteria).

Hypoxia — a condition in which an environment (e.g. waterbody) is deprived of an adequate supply of oxygen for plants or animals. In contrast to 'anoxia', which describes a condition with no oxygen, hypoxia refers to oxygen concentrations that are lower than optimal for some biological process, such as cellular respiration.

Immunity (herd) — is a form of population-level disease resistance that occurs when a sufficiently high proportion of the organisms in a population are protected against an infectious disease because they have either previously been infected and survived, or have received a vaccine. Essentially, the immune systems of these organisms are then 'primed' to recognise and fight the disease. Under herd immunity, even individuals who have not previously been infected or vaccinated receive protection, because there are insufficient susceptible individuals in the population for effective transmission. Herd immunity differs from genetic resistance, which is bestowed by genes or gene variants that make an individual invulnerable to a particular infection and/or disease.

Latent (relating to viral infection) — some viruses possess the ability to 'hide' from the immune system of an infected host, while remaining within the host's body. Latent infections generally do not cause clinical signs of disease, as the virus is dormant or resting. When conditions become suitable (e.g. the host becomes stressed), the latent virus may re-activate (see 'recrudescence') and recommence an active infection.

Legacy nutrients — nutrients that are retained in a natural system (e.g. in the sediments within a waterbody) for extended time periods following their initial addition to the system.

Naïve (relating to epidemiology/immunology) — an individual or immune system that has not previously been exposed to a particular antigen.

Oxbow — a curved or U-shaped lake formed when a meandering river section becomes isolated from the main channel.

Pathogen — a disease-causing organism, especially a microorganism.

Piscivorous (of an animal) — fish-eating.

Prey switching — when an animal (predator) changes its primary source of food.

Recrudescence — the re-activation of latent viral infection (see 'latency').

Serological — blood tests that look for antibodies to a particular disease-causing organism (pathogen).

Transmission (in the context of disease) — the transfer of a virus or other disease-causing organism from an infected to a susceptible individual.

Trojan Y Chromosome approach/technology — a form of genetic biocontrol which introduces sufficient Y chromosomes into a population to bias the sex ratio towards males, thereby reducing and eventually eliminating the reproductive success of the target species or population.

ABBREVIATIONS AND ACRONYMS

AIIMS	Australian Interagency Incident Management System
APVMA	Australian Pesticides and Veterinary Medicines Authority
BIMS	Biosecurity Incident Management System
CCA	Catchment Control Areas
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CyHV-3	Cyprinid herpesvirus 3
EPBC Act	*Environment Protection and Biodiversity Conservation Act 1999*
ICS	Incident Control System
IMS	Incident Management Systems
kg/ha	kilograms per hectare
MDB	Murray–Darling Basin
MNES	Matters of National Environmental Significance
NCCP	National Carp Control Plan
OIE	World Organisation for Animal Health
RSPCA	Royal Society for the Prevention of Cruelty to Animals
WTP	willingness to pay

KEY POINTS

Introduced European Carp, or common carp, are a serious pest in Australia's fresh waters, damaging aquatic plants, muddying water, and harming native animals through predation and competition for food.

Research by the National Carp Control Plan (NCCP) has identified that carp occur at high densities across extensive areas of south-east Australia. The national biomass of carp ranges from 200,000 tonnes and possibly up to approximately 1 million tonnes under ideal breeding conditions featuring consecutive high rainfall years.

The NCCP was established to investigate the carp virus's potential to reduce carp populations at a continental scale. The NCCP completed an extensive research and investigations program involving 19 research projects and five investigations overseen by expert advisory groups and scientists. While many uncertainties remain, and preclude an unequivocal recommendation of feasibility at this point, NCCP research confirms that the carp virus has potential as a biocontrol agent. The body of evidence assembled by the NCCP research program is sufficient to enable Australian governments, should they choose, to proceed with additional targeted planning and research activities to inform an eventual decision on whether or not the virus should be used for biocontrol. Such a pathway could reduce, but would not eliminate, remaining uncertainties.

NCCP modelling indicates that, if successfully deployed, the virus could reduce and suppress carp populations by approximately 40–60% (and by up to 80% in less resilient carp populations). These modelled outcomes depend on some assumptions about how the carp virus will move through Australian carp populations, and on the potential development of resistance or immunity via several possible mechanisms. NCCP research indicates reduction of carp impacts may benefit from an integrated approach in which virus deployment is preceded by targeted harvesting, particularly in high-density carp populations. If the virus is eventually released as a biocontrol agent in Australia, an adaptive management approach is recommended which involves ongoing assessment of epidemiological performance to inform virus release operations. This approach would mitigate against departures from the predicted epidemiology.

Preliminary research indicates Australian carp may not possess the gene variants (alleles) that bestow heritable genetic resistance to the virus, meaning that the carp virus could potentially be effective for considerably more than 10 years. However, this work was exploratory, and did not constitute a comprehensive survey of Australian carp genetics. More broadly, the genetic basis for resistance to the carp virus remains imperfectly understood (though considerable international research in this area is ongoing). One uncertainty regarding genetic resistance is the role carp-Goldfish hybrids could play in its evolution. These hybrids are less susceptible than non-hybrid carp to the disease caused by the virus, and this relative invulnerability could bestow a selective advantage. Therefore, the rate at which genetic resistance to the virus would evolve among Australian carp remains largely uncertain, although the NCCP has developed the genetic tools to improve knowledge in this area. The potential emergence of herd immunity is also an uncertainty.

The carp virus will not infect humans or any other mammal, and there is considerable evidence the carp virus will not infect other non-target species (e.g. native fish). However, a very high level of confidence in the species-specificity of any biological control agent is required before its release. Additionally, concern regarding the virus's specificity to carp is relatively common in the Australian community. Unless addressed, such concerns could negatively affect social licence for carp biocontrol. For these reasons, additional non-target species susceptibility testing of selected fish species is recommended if governments wish to proceed with activities to inform an eventual decision on whether or not to proceed with carp biocontrol.

Broadscale and long-term water-quality impacts resulting from carp biocontrol operations are unlikely. Local water-quality impacts are likely under particular conditions, and in some ecosystem types (mainly those with low or no flows). Some aquatic habitats in the Murray–Darling Basin (MDB) already have water-quality parameters (particularly dissolved oxygen levels) that are marginal for native fish species. Further degradation of these parameters by decomposing carp could cause fish kills in these areas unless effectively managed. Carcass management strategies and methods can theoretically mitigate water-quality risks as demonstrated in NCCP case studies, noting that capacity to manipulate river flows specifically to benefit carcass management may often be limited or non-existent and physical collection of carcasses presents challenges.

If Australian governments choose to proceed with the additional activities required to inform a final decision, and this process eventually lead to virus release, implementation of carp virus biocontrol would likely involve two to three years of coordinated deployment focused initially on the MDB, with ongoing adaptive management beyond initial deployment.

A future carp biocontrol program would require investment. An NCCP case study of possible virus deployment in the Murray and Murrumbidgee systems roughly estimated that virus deployment and subsequent post-release management would cost around $190 million (at 2019 costings). This area covers more than 30% of the carp biomass in Australia including the highest densities of carp. If governments choose to proceed with activities to inform decision making, more accurate and detailed costings will be required.

Although uncertainties and risks remain, these are likely to be reduced through a pathway of targeted further research, implementation planning, adoption of NCCP recommendations, and by development of detailed post-release monitoring plans and an implementation governance structure that enables adaptive management. At the national scale, further regulatory approvals will be required if governments proceed with the assessment pathway. Community consultation, public communications, and stakeholder engagement are also important given the possible impacts and high level of interest in carp biocontrol.

EXECUTIVE SUMMARY

The National Carp Control Plan (NCCP) was established to help governments make decisions about the potential use of a virus called Cyprinid herpesvirus 3 (CyHV-3, hereafter 'the carp virus' or 'the virus') to control European Carp, or common carp, *Cyprinus carpio* (hereafter 'carp'), in Australia. Controlling pest species by using their 'natural enemies' (such as viruses) is called 'biological control' or 'biocontrol'.

To inform a decision about carp biocontrol feasibility, the NCCP addresses the following questions:

1. Will biocontrol using the carp virus be effective?
2. What are the risks associated with carp biocontrol and how can they be managed?
3. How could carp biocontrol be implemented?

In addition to addressing these key feasibility questions, the NCCP provides a preliminary assessment of the impacts, costs, and benefits of carp biocontrol and provides conclusions and recommendations.

Will carp virus biocontrol be effective?

The carp problem is extensive: Carp are one of Australia's most significant pest species. They were introduced to Australia in the mid-19th century, and are now the dominant large-bodied fish in most Murray–Darling Basin (MDB) waterways. The species is also abundant in many eastern coastal rivers, while isolated populations occur in Western Australia.

Ecological impacts attributed to carp in Australian ecosystems include decreased water clarity, destruction of aquatic plants that provide food and habitat for native species, and food chain domination. Carp removal or reduction will not necessarily result in a direct reversal of these effects, but is nonetheless expected to bring environmental, economic, and social benefits.

Controlling carp requires a clear understanding of their distribution and abundance in Australian waterways. To achieve this, the NCCP undertook the most comprehensive estimate of total carp biomass ever attempted. This research revealed that, over summer 2017–18, approximately 205,000 tonnes of carp were inhabiting mainland Australia (excluding Western Australia). Three consecutive flood years, which would favour carp population growth, could increase total carp biomass to approximately 1 million tonnes. Carp density is generally highest in lowland, regulated rivers, but can also be high in unregulated northern parts of the MDB.

Effective, long-term carp control is difficult. Carp are widespread, abundant and possess biological traits that mean their populations tend to rebuild rapidly following reductions. No 'silver bullet' for carp control currently exists, nor will biological control constitute such a solution.

Epidemiological modelling indicates that biocontrol could effectively reduce and suppress carp populations, especially if combined with other methods: Modelling conducted under the NCCP indicates that biocontrol using the carp virus could reduce carp populations by approximately 40–60% (and 60–80% in less resilient in carp populations). These projected reductions are generalisations and both greater and lesser reductions are expected across the numerous carp sub-populations that constitute Australia's total carp biomass. This modelling depends on assumptions regarding key epidemiological rates. These assumptions were informed by peer-reviewed science, and where possible tested using laboratory experiments. Nonetheless, further targeted research on the population structure of Australian carp, and on interactions between carp and the virus in natural or semi-natural settings (potentially conducted at an overseas institution) could further develop and refine understanding of the virus's likely effectiveness as a biocontrol agent. Additionally, if virus release eventually proceeds, an adaptive management approach will be needed to maximise effectiveness and manage risks.

Carp in Australia undergo large 'boom and bust' population fluctuations, but the virus's suppressive effects are expected to persist during conditions conducive to population increases. Furthermore, a 'Carpageddon' scenario featuring major, approximately simultaneous carp mortalities across a large geographic area is unlikely. NCCP research highlights that the virus is likely to produce substantial, seasonally restricted kills focused on targeted carp aggregation sites. The years following initial deployment should then produce ongoing kills comprised mainly of juvenile carp. Ensuring that sufficient carp within targeted sub-populations are infected during initial virus deployment would be critical for successful biocontrol implementation.

Controlling high-density carp populations may require a multi-method approach: High carp abundances and complex, interconnected population structures mean that the species is very resilient to control efforts. Consequently, any single control measure (including the virus) is unlikely to be successful across carp's entire Australian range if used in isolation. While any level of carp reduction could be beneficial, NCCP modelling indicates that, in Australia's highest-density carp sub-populations, a combined approach in which a portion of the total carp present are harvested before virus deployment offers a more rapid and effective opportunity to reduce carp densities and impacts below ecologically damaging levels. This multi-method approach would provide particular benefit in the lower Murray River where carp density is highest, and to a lesser extent, in the mid-Murray. Because the NCCP focused primarily on assessing the feasibility of viral biocontrol, the magnitude and timing of the fishing effort needed to attain effective carp reduction in high-density populations is unknown, but could be clarified by additional modelling.

Carp biocontrol risks

The carp virus will not affect humans or other mammals: The risk of direct human infection by the carp virus is extremely low. There is no indication that the virus has ever infected, or will ever infect, human beings or any other mammal. No additional investigation of this risk is warranted.

There is evidence that the carp virus will not infect or harm other non-human species, but further work is recommended: The World Organisation for Animal Health (OIE) notes that carp and carp hybrids (e.g. hybrids of carp and Goldfish) are currently the only species that fulfil its criteria for listing as susceptible to infection by the carp virus. The virus's DNA has been detected in a range of northern hemisphere freshwater fishes, a mussel, and a crustacean, but this does not necessarily indicate infection. Furthermore, international experience with the virus over more than two decades has not identified disease caused by the carp virus in any species other than European Carp, and carp hybrids, although viral DNA has been detected in numerous fish and invertebrate species. Australian testing by the Invasive Animals Cooperative Research Centre and CSIRO, with recent re-testing of Murray Cod and Silver Perch, found no evidence of infection in tested animals.

Despite the evidence supporting the virus's specificity to carp, the NCCP recommends some additional non-target species susceptibility testing before a decision is made regarding virus release. NCCP research identified that concerns regarding carp-virus species specificity were relatively common in the Australian community. Likewise, decision makers will need to know this issue has been investigated as thoroughly as is reasonably possible. Therefore, additional testing using an optimally designed viral challenge is recommended to improve confidence in the virus's specificity to carp before making decisions on virus release.

Broadscale and long-term water-quality impacts are unlikely, but impacts may occur in some habitat types: Research has identified and investigated likely impacts of decomposing carp on water quality. Water-quality impacts depend on dead-carp densities and their distribution in waterways, so water-quality research is built on carp mortality predictions generated by epidemiological modelling. Risks investigated included declines in dissolved oxygen, undesirable nutrient increases, harmful algae blooms, proliferation of disease-causing microbes, and impaired capacity to treat water. These variables are relevant for understanding the potential implications of carp kills for both ecosystem health and water use by humans and livestock.

In flowing river channels, carp decomposition is unlikely to compromise water quality beyond acceptable tolerances. However, in still or slow-flowing areas away from main channels, water quality could be reduced, especially when carp densities exceed 300 kilograms per hectare (kg/ha). Reducing high-density sub-populations by targeted physical removal prior to virus deployment could both enhance carp control success and mitigate risks to water quality by reducing the total number of dead carp resulting from disease outbreaks. Unregulated dryland rivers in the northern MDB face particular water-quality risks, as these waterways dry to isolated pools that provide drought refuges for threatened species, endure extended low- or zero-flow periods, and already experience impaired water quality. Virus-induced carp kills (with associated in-situ carcass decomposition) under cease-to-flow conditions in these systems could result in fish kills if not appropriately managed, yet detecting outbreaks a nd managing carp carcasses (for example, through physical collection) present particular challenges in these generally remote and sparsely populated areas.

Water treatment is unlikely to be compromised at the carp densities expected in most areas. However, water treatment and disinfection would become untenable at very high carp densities (approximately 2000 kg/ha). Carp densities of this magnitude are rare in Australian ecosystems, but could potentially occur in 'point-source' form if dead carp accumulate in small areas as a result of water currents or wind.

Proliferation of harmful bacteria, including those that cause botulism, is possible following carp kills, particularly if water quality more broadly is degraded. Outbreaks of bacterial disease have not been reported in Australia following fish kills, but this risk remains possible, and the biology of botulism outbreaks in particular makes predicting them difficult. Managing carp carcasses would provide the most effective mitigation measure against outbreaks of bacterial disease including botulism.

Carp biocontrol will have social and economic impacts: Carp biocontrol would have both positive and negative socio-economic impacts. Positive impacts would result primarily from improved aquatic ecosystem health following carp reductions. Beneficiaries of improved aquatic health include the tourism industry and a diverse range of river and waterway users, including recreational fishers.

Some stakeholder groups may experience negative impacts, or are already experiencing them in anticipation of implementation. NCCP social impact research outlines effects on commercial carp fishing businesses, tourism operators, native fish aquaculture businesses, and koi carp enthusiasts and businesses. For some stakeholder groups, negative impacts might be offset to some extent by opportunities that carp biocontrol could generate. For example, commercial fishers who target carp might play a valuable role in an integrated carp control program by fishing to reduce high-density carp populations prior to virus deployment.

Implementing carp biocontrol

The NCCP implementation strategy provides a high-level outline for virus deployment and biocontrol operations across carp's mainland eastern Australian distribution. The strategy is designed to clarify the feasibility of managing risks associated with carp biocontrol. Implementation would occur over 10 years with most activity focused on virus deployment and carcass management during the first two to three years.

National implementation objectives include:

a. widespread reduction and suppression (for at least 5–10 years) of carp populations and the damage they cause in Australian aquatic ecosystems,

b. management of environmental risks,

c. management of risks to water quality for town water supply, stock and domestic water needs, irrigation, and cultural and recreational purposes, and

d. effective and efficient virus deployment and carcass management, where the latter is required.

The NCCP implementation strategy provides national guidelines to achieve objective (a) and an approach and process to achieve objectives b to d (given these objectives will need to involve jurisdictions and more detailed planning).

Active virus deployment is critical for effective biocontrol: Deployment (if it eventually occurs) would require science, planning, coordination, and resources. Initial deployment would involve introduction of the virus into carp aggregations throughout each carp sub-population. Carp sub-populations and aggregations should be mapped prior to deployment. Sufficient numbers of infected carp would need to be introduced into each sub-population to (i) maximise initial knockdown, and (ii) enable ongoing transmission during subsequent years. Deployment during drier (but not drought) conditions that have reduced and concentrated carp populations at known aggregation locations is likely to maximise carp reductions.

Following initial deployment, infection, disease, and death is expected to move through an infected sub-population over approximately four to eight weeks, coinciding with water temperatures within the permissive range for the disease caused by the carp virus (approximately 16–28 °C) (Technical Paper 2; NCCP research project 4). Major carp kills occurring simultaneously across large geographic areas are not expected, as the demonstrated importance of physical contact as a transmission mechanism (NCCP research project 6) should ensure that the virus spreads relatively gradually through targeted sub-populations. After the initial virus deployment, ongoing strategic virus release may be required based on an adaptive management approach.

Carcass management strategies and methods could mitigate water-quality risks, but challenges remain: Numerous carcass management methods have been considered in NCCP case studies and investigations. Many strategies and methods involve strategic use of water regulation to flush, concentrate, and/or strand carcasses, thereby removing or reducing the need for manual carcass collection. However, river managers may not always have the freedom to manipulate flows specifically to benefit carp control operations. Manual carcass collection and removal will still be required at times and places where more mechanised strategies are not adequate and in-situ decomposition is likely to cause negative water-quality impacts. Manual collection of carcasses will, however, be challenging in remote areas or those where access is otherwise difficult.

Specific carcass management methods will depend on local characteristics and conditions, environmental sensitivities, river flow, and weather at the time of a carp kill. Employing an adaptive approach to biocontrol operations will promote the evolution of more effective carcass management methods as the program proceeds. Additionally, while the virus's biology indicates that it is unlikely to move rapidly or unpredictably across large areas, the possibility of unplanned outbreaks cannot be discounted, meaning surveillance will be an important component of effective carcass management strategies.

Coordinated management is necessary: Coordinated management is critical for the successful implementation of a national biocontrol program. Australia has successful operational coordination systems already in use (Incident Management Systems, or IMS). If deployment occurs, carp biocontrol will be a planned and managed event, rather than an emergency incident, but IMS can be readily adapted to the biocontrol context. Furthermore, IMS have been tested and proven through time, and are already used by all jurisdictions that would ultimately be involved in a possible carp biocontrol program.

Achieving integrated pest management: Viral biocontrol has been the NCCP's primary focus. However, best-practice pest management usually requires an integrated approach in which multiple control measures work together to reduce pest impacts. Although any carp reductions are likely to be advantageous, NCCP modelling indicates that a multi-method, integrated approach may be particularly beneficial to reducing carp impacts in very resilient, high-density carp populations (NCCP research project 4). Control approaches that could work in concert with the virus include genetic control technologies, and various forms of physical removal through harvesting. Of these two approaches, physical removal is currently the most readily applicable. NCCP research indicates that, while some genetic technologies offer potential for carp control in Australia in the longer term, considerable and ongoing investment, beyond the NCCP's scope, would be required to overcome substantial biological and logistical barriers to deployment (NCCP research project 3).

Regional case studies illustrate implementation can be effective at a cost: NCCP case studies identified regional risks, opportunities, and strategies for virus deployment and carcass management. Case studies concluded that risks could be managed by applying a range of measures and technologies with coordination across government agencies and regional stakeholders. Case-study results highlight the value of local-scale involvement in carp biocontrol planning and implementation.

Case studies identified a range of potential carcass management methods. Manual carcass removal will likely only be required at particularly sensitive sites. A case study covering the southern Murray and Murrumbidgee systems estimated costs at roughly $190 million for a three-year virus deployment and management program. This cost estimate does not, however, include costs that may be involved in physically removing carp from high-density sub-populations prior to virus deployment.

Feasibility

Describing the feasibility of carp biocontrol using the virus requires a nuanced and qualified statement. Briefly restated, feasibility criteria are (i) effectiveness, (ii) risk identification and management, and (iii) implementation. When assessed against these criteria, results from NCCP research and investigations indicate feasibility, with qualifications. With strategic virus deployment, carp reductions of varying magnitudes and ongoing suppression appear achievable. From a risk perspective, water-quality impacts (for both ecosystem integrity and human/livestock use) appear manageable in many areas and habitat types, regional case studies have identified strategies for managing dead carp, and water treatment processes appear able to cope with all but the most extreme and unlikely dead carp loadings. To reframe these conclusions, no results have emerged to clearly indicate that further consideration of the virus as a biocontrol agent should cease.

Nonetheless, these broad indications of feasibility are subject to important uncertainties and caveats that preclude an outright and unqualified recommendation of feasibility. Some of these uncertainties could be reduced through targeted additional research, and this report includes suggestions for how this could occur (see next steps and recommendations that follow). Further investigation of the virus's specificity to carp is recommended as part of this additional research. Other uncertainties will likely be more difficult to resolve, and would need to be factored into an adaptive management framework if release eventually proceeds. Thus, while targeted further research is recommended, and could substantially improve the evidence base for decision making, it will not eliminate uncertainty or risk. Balancing these considerations, NCCP research provides sufficient evidence supporting the virus's potential as a biocontrol agent to continue with a pathway of activities to support an eventual decision on whether or not to proceed with virus release. Importantly, feasibility assessment under the NCCP has concentrated on the scientific and operational aspects of carp biocontrol; implementation costs and social and economic impacts reported here are approximate only, but will also be important considerations for decision makers.

Next steps and recommendations

If governments decide to proceed with further assessment and planning actions to support decision making on carp biocontrol the following activities are recommended.

GOVERNANCE

- Establish a national taskforce comprising state, territory, and local government representation to coordinate carp biocontrol implementation.
- Obtain Australian Pesticides and Veterinary Medicines Authority (APVMA) approval.
- Obtain other mandatory legislative approvals, including those required under the *Biosecurity Act 2015*, the *Biological Control Act 1984*, and relevant state and territory regulatory approvals.

A specific timeline for implementation is not provided as this will be determined by the Australian Government, along with state and territory governments, following their decisions about future carp biocontrol directions.

RESEARCH AND DEVELOPMENT FOR IMPLEMENTATION

The following implementation research is recommended should a decision be made to proceed towards the next assessment stages.

- Undertake additional non-target species susceptibility trials.
- Undertake field-based research aimed at understanding carp population structure and movements to inform epidemiological modelling and operational planning. This research would represent a 'zero-loss' investment, because knowledge of carp population structure would be required for any other future carp control measures, even if governments choose not to proceed with virus release.
- Undertake research on carp virus disease dynamics (particularly seasonal patterns of disease reactivation) under field conditions, or in experimental systems that simulate some of the variability found in nature. This research would enable further assessment of proposed virus release strategies and biocontrol efficacy. Within Australia, research using the virus can only take place in biosecure laboratories, so work of this nature would likely best be conducted internationally, in a location where the virus is already endemic.
- Develop methods for large-scale production, storage, and transport of the carp virus.
- Develop decision-support and mapping tools to support biocontrol operations.
- Assess the animal welfare implications of biological control using the carp virus.
- Clarify the carp virus's capacity to kill carp under saline conditions.
- Further investigate the evolution of resistance to the carp virus, including the potential role of carp-Goldfish hybrids in this evolution.
- Develop and assess ecological risk mitigation options for ephemeral dryland river systems and Ramsar wetlands including the South Australian Lower Lakes system and the associated marine system immediately outside the Murray River mouth.
- Develop and implement pre- and post-deployment monitoring and evaluation plans.

PUBLIC COMMUNICATIONS

- Develop a comprehensive communications and engagement plan.
- Continue NCCP science communication through the decision-making phase.

COMMUNITY CONSULTATION

- Publish the NCCP and undertake community consultation.
- Undertake tailored consultation, in addition to that completed under the NCCP, with Traditional Owners.
- Undertake specifically designed consultation with other stakeholder groups identified by the NCCP.

STAKEHOLDER ENGAGEMENT

- Actively engage Traditional Owners in decision making and enterprise development associated with carp biocontrol.
- Engage local knowledge and stakeholders in regional implementation planning.
- Acknowledge possible stakeholder impacts, including anticipatory impacts.

1 INTRODUCTION

Introduced European Carp, or common carp (*Cyprinus carpio*, hereafter 'carp') are a serious pest in Australia's aquatic habitats, damaging aquatic vegetation, muddying water, and harming native animals through predation and competition for food. Biological control using Cyprinid herpesvirus 3 (CyHV-3, hereafter 'the carp virus', or 'the virus') offers the potential to control carp over large areas. Before proceeding with virus release, however, fundamental questions of safety for humans and non-target animals, potential impacts on water quality, and broader environmental effects demand evaluation. To address these questions, the National Carp Control Plan (NCCP), funded by the Australian Government, coordinated the most intensive investigation ever devoted to a biological control agent to inform decisions on further planning and potential release. This report summarises the results of these investigations for decision makers. The report's purpose is to provide the information needed to decide whether to proceed with planning and other activities that will ultimately inform decisions on whether or not to release the virus to control carp in Australia.

The NCCP addresses the following feasibility questions to inform a decision about proceeding towards implementation:

a. Will biocontrol using the carp virus be effective?

b. What are the risks associated with carp biocontrol and how can they be managed?

c. How could carp biocontrol be implemented?

In addition to evaluating feasibility, the NCCP provides preliminary estimates of the costs and benefits of carp biocontrol and outlines an implementation strategy. The NCCP is supported by technical papers and project reports (Appendix 1). Readers seeking additional background information are directed to these resources.

This section of the report provides the background to carp in Australia and explains the carp virus's emergence as a potential biocontrol agent. Subsequent sections directly address one or more of the feasibility questions listed in points a–c. Section 2 outlines NCCP research conclusions about likely biocontrol effectiveness and risks (questions 'a' and 'b'). Section 3 provides strategic directions for implementation at the national scale (question 'c'). Section 4 illustrates how regional-scale carp biocontrol implementation could occur (question 'c'). Section 5 reports likely market and non-market costs and benefits accruing from carp biocontrol. Section 6 summarises NCCP findings to develop a feasibility statement. Section 7 outlines conclusions and recommendations for government.

1.1 A national problem

Although first introduced to Australia in the mid-19th century, carp only emerged as an environmental problem during the 1960s, when a genetic strain of carp called the 'Boolarra strain' escaped from a Victorian fish farm. The Boolarra strain's escape began approximately three decades of carp range expansion and population growth. Reasons for the Boolarra strain's success are varied, but flooding during the 1970s probably promoted carp dispersal and reproduction, while cross-breeding between Boolarra carp and genetic strains from earlier introductions may have created vigorous hybrids (see Technical Paper 1). Carp's ability to tolerate poor water quality probably also gave them a competitive advantage over native fish. Regardless of the mechanisms underlying their expansion, by the mid-late 1990s carp occupied a large area of south-eastern Australia, including most of the Murray–Darling Basin (MDB) and many eastern coastal catchments. A smaller population exists around Perth in Western Australia. Isolated populations also occurred in two Tasmanian lakes (Lakes Crescent and Sorrel). A physical removal campaign spanning more than 20 years resulted in the eradication of carp from Lake Crescent in 2007, while functional eradication of the Lake Sorrell population is imminent. The Lake Sorrell population is now strongly female-biased and many of the remaining males have a genetic disease that renders them sterile.

Carp's potential to become invasive was recognised soon after the Boolarra strain's escape, and the Victorian Government recommended carp eradication in 1962. Early control attempts included non-selective methods such as applying fish poisons to carp-affected waterways (Technical Paper 1). As carp expanded their geographic range, the focus shifted to various forms of capture and removal including netting, trapping, and community-based carp 'fish-outs'. While some of these approaches have achieved localised, short-term carp reductions, none have delivered long-term carp control over large areas (Technical Paper 1).

Definitive and concise statements about the ecological impacts of carp are difficult, because the species inhabits ecosystem types ranging from tidal subtropical upper estuaries to temperate, highly regulated dryland rivers. These varied ecosystem types will not experience the same impacts from a given carp density (Technical Paper 1). Additionally, overall carp abundance fluctuates markedly through time, as do the relative proportions of adult and juvenile carp within a given population. Carp impacts also occur with other environmental stressors, such as pollution and river regulation. All of these variables will affect the type and magnitude of impacts exerted by carp in a given ecosystem (Technical Paper 1; NCCP research project 15).

Despite this complexity, there is both scientific and anecdotal evidence that carp cause undesirable changes in at least some Australian freshwater ecosystems (see Technical Paper 1). The primary pathway by which carp damage aquatic ecosystems arises from the species' feeding style. Adult carp feed by syphoning sediment from the riverbed using their vacuum-like mouths, filtering out food items and ejecting the remaining material into the water around them. This feeding style reduces water clarity, adds nutrients to the water (potentially promoting harmful algal blooms), and destroys aquatic plants (Technical Paper 1). Carp also feed directly on small aquatic animals, causing local or regional extinction of some vulnerable species, and changing the composition of aquatic animal and plant communities. A recently recognised, but potentially important, impact is the monopolisation by carp of food resources and energy at the base of the food chain, preventing native fish population growth (Technical Paper 1). While these impacts will not occur in all places where carp occur, or at all times within a given location, they are reported in the scientific literature (Technical Paper 1). Importantly, these impacts also co-occur with other damaging processes, such as pollution, or with the legacy impacts of historical management practices (NCCP research project 15).

The concept of 'damage thresholds' (discussed in more detail in Section 2.1) provides a useful framework for understanding the ecological impacts of carp (Technical Paper 1). The concept posits that the ecological impacts of carp either manifest or intensify when carp densities (usually expressed as kilograms per hectare, kg/ha) exceed particular levels. Different ecosystem components or attributes have different damage thresholds. For example, a recent major review assessing carp impacts across the different continents and habitats in which they are invasive identified a carp density of 50 kg/ha for impacts on other fish species, 100 kg/ha for impacts on aquatic plants, and 150 kg/ha for negative impacts on water clarity (NCCP research project 4). These densities are indicative only and will vary substantially among different species and habitat types, and probably for a given species or habitat through time. Acknowledging the general and approximate nature of these thresholds, NCCP carp biomass estimates clearly demonstrate that carp densities exceed damage thresholds in many Australian aquatic habitats, indicating that carp pose real threats to aquatic biodiversity (NCCP research project 1).

1.2 The benefits of carp control

Long-term carp suppression is likely to benefit many species of aquatic flora and fauna. However, ecosystem responses to carp reduction will differ across the varied habitats comprising the species' Australian distribution. The potential for unexpected ecological consequences must also be acknowledged. For example, controlling carp might create opportunities for other invasive species that have hitherto been suppressed by carp to increase in abundance (NCCP research projects 12 and 15). Additionally, some faunal groups, such as fish-eating birds, may have come to rely upon carp as a food source. Sudden, major reductions in carp abundance could therefore result in food shortages for these species (NCCP research project 12). Such shortages could be short term, as small native fishes, the preferred food of many native predators, may increase their populations relatively rapidly in response to carp reductions. Some native invertebrates are very vulnerable to carp predation, and become locally or regionally extinct at even low carp abundances. Total carp eradication, which biocontrol will not deliver, would be required to restore populations of these species. Finally, the benefits of carp control are most likely to be fully realised when carp suppression is accompanied by action to address other, co-occurring environmental stressors.

These statements are not intended to devalue the worth of carp control; there is both scientific and anecdotal evidence that safe and effective carp control would benefit many Australian aquatic ecosystems. Improved water clarity and increased abundance of native aquatic plants and small animals have all been reported following carp control in Australian freshwater habitats. Modelling studies have also indicated that carp reduction could result in substantial improvements to native fish abundance, especially when combined with improved management of river flows. Biocontrol using the carp virus offers a potential, if partial, solution to a hitherto intractable problem.

1.3 Identifying the carp virus's potential as a biocontrol agent

Outbreaks of the disease caused by the carp virus were first recorded in German and Israeli aquaculture facilities during the mid-1990s. The virus's evolutionary origins are unclear, but it may have circulated in wild carp populations before emerging in aquaculture (Technical Paper 4.

Although currently occurring in 33 countries globally, the carp virus has never been deliberately used as a biological control agent. Disease outbreaks have instead resulted from the virus's unwanted entry to valued carp populations (including koi), or its unintended and unplanned introduction to invasive populations that are viewed as pests. Despite having caused major mortalities among wild carp in Japan, North America, and South Africa, the virus's impact on wild carp abundance in these locations is unclear. Some studies suggest relatively little impact, but data enabling comparison of carp populations before and after virus entry are scarce. Planned and deliberate introduction of the virus into carp sub-populations across the species' range is likely to have greater impact than unintentional, haphazard introduction.

International outbreaks prompted interest in the carp virus as a potential biological control agent for carp in Australia. The Invasive Animals Cooperative Research Centre initiated a research program during which CSIRO researchers studied the virus's capacity to effectively kill carp, and the potential for infections and disease to occur in species other than carp. Both avenues of research indicated that the carp virus had potential as a biocontrol agent; the virus killed a high proportion of infected carp, and appeared species-specific.

Information requirements for implementing a carp biocontrol program, however, exceed knowledge of host-specificity and laboratory-measured efficacy. Disease dynamics must be understood and potential ecological, social, and economic risks, including risks to water quality following carp kills, assessed. The Australian Government therefore funded the NCCP to develop the knowledge base required for informed decision making about biological control using the carp virus.

1.4 Investigating the potential for carp biocontrol in Australia

The aims of biocontrol programs typically include reduction in costs to agriculture and/or amelioration of environmental damage caused by target pests, each with attendant social and economic benefits. Regardless of the target and agent organisms and program aims, the basic value proposition for biological control usually lies in the capacity for highly specific biological control agents to spread through pest populations, providing sustained control over large geographic areas with minimal management intervention.

Because carp are an established pest inhabiting a large geographic area and attaining high population densities, a biocontrol agent targeting them needs the basic traits described above; specificity to the target species and a capacity to deliver cost-effective pest suppression across large areas. However, as the first attempt globally at viral biocontrol of a pest fish, carp control using the carp virus poses some unique challenges that differ from previous biocontrol programs targeting terrestrial vertebrates. In particular, because carp inhabit interconnected inland waterways, a viral biocontrol agent that transmits very rapidly and with high lethality among carp populations has the potential to cause major mortalities over large areas, with attendant risks to water quality as numerous carp decay in aquatic environments. Australia's only other vertebrate biocontrol programs — those targeting rabbits using the myxoma virus (MYXV) and rabbit haemorrhagic disease virus (RHDV, 'calicivirus'), and feral cats on Marion Island using feline panleukopenia virus (FPLV) — did not face this challenge because the target species were terrestrial and their decomposition posed few or no environmental risks. Carp biocontrol therefore demands a balance between effective, ongoing carp suppression at the continental scale and transmission dynamics that do not result in unmanageable densities of dead and decaying fish following initial deployment into high-density populations.

NCCP research indicates that the carp virus possesses the attributes required of a biocontrol agent to control carp. Modelling the virus's likely impacts on carp populations indicates that self-propagating transmission of the virus across large geographic areas, with subsequent widespread, major carp mortalities is unlikely. Rather, the virus is likely to only cause major carp mortalities when two factors — water temperature suitable for viral infection and disease in carp, and carp densities sufficient to enable effective transmission — co-occur (Technical Paper 2). Conditions conducive to outbreaks of the disease caused by the carp virus are most likely when carp gather to spawn in spring and early summer (depending upon latitude), meaning that the timing and location of kills may be relatively predictable. These traits provide an opportunity to effectively manage the water-quality risks associated with carp kills (Technical Paper 3). Because carp virus transmission is substantially reliant on direct physical contact between infected and susceptible carp, virus deployment will likely require more active and sustained ongoing releases than some other biocontrol agents (e.g. MYXV and RHDV used for rabbit biocontrol) to ensure effective carp suppression.

1.5 NCCP outline

Table 1 outlines to structure of the NCCP and the associated supporting documents.

Table 1: National Carp Control Plan (NCCP) content summary.

NCCP section or supporting document	Title	Subject matter
The National Carp Control Plan		
	Executive summary	Provides a stand-alone summary of the NCCP's underlying rationale, objectives, scope, methodological approaches, and conclusions.
1	Introduction	Summarises the introduction of carp to Australia and ensuing environmental impacts. Introduces Cyprinid herpesvirus 3 (CyHV-3, 'the carp virus') and describes its potential as a biocontrol agent for carp in Australia. Explains the NCCP's role in assessing the feasibility of carp biocontrol.
2	NCCP research	Summarises NCCP research approaches and key results related to effectiveness and risks.
3	Implementation strategy	Outlines how carp virus biocontrol could be implemented at a strategic national scale.
4	Regional case studies	Integrates information from NCCP research and implementation planning in specific regional settings, providing concrete illustrations of the manner in which carp biocontrol could be implemented and managed in particular regions.
5	Costs and benefits of carp control	Integrates key results from, and explains implications of, market and non-market cost-benefit analyses conducted under the NCCP.
6	Feasibility assessment	Defines criteria for assessing carp biocontrol feasibility, provides a summary feasibility assessment based on information from research and planning, and delivers a feasibility statement.
7	Conclusion and recommendations	Outlines steps for governmental consideration if a decision is made to proceed towards carp biocontrol implementation. Recommendations relate to regulatory approvals, research, planning, socio-economic impacts, or community engagement.

NCCP section or supporting document	Title	Subject matter
Supporting documents		
Appendix 1	NCCP research	Outline of NCCP research approach and results.
Appendix 2	Monitoring and evaluation plan	Scope for monitoring and evaluation of carp virus biocontrol.
Technical Paper 1	Carp biocontrol background	Supports the NCCP introduction by providing contextual information on the ecological health of Australian rivers, carp ecology and introduction to Australia, carp control measures that have previously been proposed, trialled, or attempted, the legal status of carp in Australian states and territories, and background to biological control.
Technical Paper 2	Epidemiology and release strategies	Supports NCCP research and risk summaries (section 2) by explaining the epidemiological modelling that underpins predictions about the impacts of virus-induced disease impacts on carp populations.
Technical Paper 3	Carp biocontrol and water quality	Supports NCCP research and risk summaries (section 2) by explaining potential dead carp impacts on water quality. The paper summarises NCCP research and literature reviews addressing dissolved oxygen and nutrient concentrations, risk of dead carp fuelling harmful algal blooms, potential dead carp impacts on water treatment processes, and the risk that decomposing carp could promote growth of disease-causing bacteria, including those responsible for botulism.
Technical Paper 4	Carp virus species specificity	Supports NCCP research and risk discussions (section 2) by summarising and explaining research investigating the potential for the carp virus to infect species other than European Carp.
Technical Paper 5	Potential socio-economic impacts of carp biocontrol	Supports the socio-economic risk discussion (section 2) by summarising NCCP research on the potential social and economic risks posed by carp biocontrol, explaining implications for biocontrol planning and implementation, and proposing risk mitigation options.
Technical Paper 6	Implementation	Describes an implementation pathway for carp biocontrol.
Technical Paper 7	NCCP engagement report	Report on NCCP stakeholder engagement including workshops and web-based feedback.
Technical Paper 8	NCCP Murray and Murrumbidgee case study	Case study for virus deployment and carcass management for the Murray and Murrumbidgee regulated systems.
Technical Paper 9	NCCP Lachlan case study	Case study for virus deployment and carcass management of the Lachlan catchment.

2 NCCP RESEARCH

The NCCP has undertaken a broad-ranging research program including 19 peer-reviewed research projects and five planning investigations including regional case studies (see Appendix 1). The NCCP Strategic Research and Technology Plan 2017–19 provided the blueprint for design and planning of this research program. The Research and Technology Plan was developed shortly after the NCCP began (in early 2017), and provided a framework for identifying strategic research needs to inform a potential carp biocontrol program. The Research and Technology Plan identified three major themes (Environment, Communities, and Informing Possible Implementation), with research priorities identified under each theme. These priority areas guided development of research projects, with applications for research generally sought by select tender. The Strategic Research and Technology Plan was reviewed and endorsed by the NCCP Science Advisory Group (SAG). All NCCP research projects are listed in Appendix 1 together with a more detailed discussion of research program formulation and governance.

Most NCCP research is necessarily theoretical, requiring complex modelling of carp populations, the environments they inhabit, and the interplay between carp and virus (see Appendix 1). NCCP research therefore contains assumptions which are explained next.

A continental-scale carp biocontrol program would encompass many different aquatic habitats spanning a large geographic area. The ecological complexity entailed by this large and diverse control area means that some uncertainties remain. This section describes these uncertainties and their implications.

2.1 Effectiveness of the carp virus

Effective carp biocontrol needs to initially reduce existing carp populations and maintain suppression in the longer term. Three NCCP research projects provided knowledge essential to assessing effectiveness. First, the foundational knowledge about the target species' abundance, distribution, and population dynamics that underlies any pest control initiative was supplied by carp biomass estimation research. Biomass estimates were static 'snapshots in time' for the total weight of carp and its distribution across the various habitats comprising the species' eastern Australian distribution over spring and summer 2017–18. Second, a carp population model provides the capacity to project these static biomass values forward in time so that contemporary population estimates will be available in future years. Third and finally, epidemiological modelling integrated knowledge about carp populations and carp virus biology to predict the virus's impacts on Australian carp populations (see Technical Paper 2 for detailed discussion). Together, these projects provide the primary knowledge base for assessing the carp virus's likely effectiveness as a biological control agent.

Other NCCP research also relevant to understanding biocontrol effectiveness, or that generated data or information for use in the three studies described above, includes development of tools and methodological approaches to study genetic resistance to the carp virus (NCCP research project 7), and work clarifying the relative importance of different virus transmission pathways (NCCP research project 6). Results from these projects feed into epidemiological modelling by either testing key assumptions regarding transmission, or enabling ongoing assessments of efficacy if the virus is eventually released.

Assessing the likely efficacy of carp virus biocontrol is largely a question of applied epidemiology. Therefore, a brief explanation of the approach used for the NCCP epidemiological modelling is warranted. Readers seeking greater detail are directed to Technical Paper 2, and NCCP research project 4 (the epidemiological modelling project report).

Although referred to for convenience throughout this document as 'epidemiological modelling', the study developed four interlinked models (for hydrology, carp habitat suitability, carp demography, and carp virus epidemiology). This approach was chosen because the key traits of Australian carp populations that would influence the magnitude and extent of viral knockdown change markedly through time and across the landscape in response to the major environmental variations typical of inland Australian waterways. These environmentally driven fluctuations in carp populations are often referred to as 'boom and bust cycles'. While major changes in carp abundance are the most obvious feature of these cycles, they also exert more subtle demographic influences, such as changes in the relative abundance of different age classes and the population's inherent capacity to rebuild following reductions. These demographic traits will influence the population-level impacts of any future carp biocontrol program. The carp virus itself is also subject to environmental constraints, notably in relation to the water-temperature range (16–28°C) under which the virus can infect carp and cause disease.

Understanding the interplay between the demography of the host population(s), the environmental tolerances of the pathogen, and the environmental context against which they will interact is relevant to most infectious diseases, but is particularly pertinent to carp biocontrol because inland Australian rivers and their carp populations are so dynamic. Epidemiological modelling under the NCCP explicitly recognised the linkages between population characteristics, environment, and disease outcomes by using multi-model approach. The four models were developed and integrated for five catchments; the Lachlan River (NSW), the mid Murray River (Hume Dam to Wentworth, NSW), the lower Murray River (Wentworth, NSW, to Goolwa, South Australia), the Glenelg River (Victoria), and the Moonie River (Queensland). Collectively, these catchments represent much of the diversity in carp habitat found throughout the species' Australian distribution. A brief description of each model and its application follows.

1. The hydrological model reconstructed river flow, water temperature, waterway inundation, and connectivity. These four traits were identified as the key environmental drivers for the distribution of adult and sub-adult carp (flow, temperature) and larvae and juveniles (inundation and connectivity, which facilitate spawning) at an expert workshop funded by the Invasive Animals Cooperative Research Centre in 2014. Other factors (plankton productivity, dissolved oxygen levels and salinity) were also identified as affecting habitat suitability for carp. High-resolution data were not available for these factors across all catchments, so where necessary, surrogate variables were used or the parameter was left as a non-informative model node that could be populated in future if data become available.
2. The habitat suitability model built on the reconstructed hydrological datasets from (1) to classify the habitat suitability of each river reach or waterbody for both adult/sub-adult and larval/juvenile carp for the full study period (1990–2017 for most catchments). Habitat suitability rankings were the primary output from this modelling, but biomass density estimates (kg of carp per hectare) were also derived using conversion factors developed in consultation with freshwater ecology experts. The resulting density estimates enabling cross-validation of the modelling against carp densities estimated independently by the NCCP carp biomass project (NCCP research projects 1 and 2), with the two sets of estimates in close agreement. These habitat-derived carp density estimates (i.e. kg of carp per hectare) were then used as input in the carp demography model.

3. The carp demographic model used the carp density estimates described in point 2. Treating the density estimates as inputs to a demographic projection model meant that key processes and parameters influencing carp populations (e.g. density dependence, environmental carrying capacity) could be modelled. This approach would not have been possible under the simpler approach of deriving carp abundance from density estimates using average weights. As part of the demographic modelling, the structure of carp metapopulations (population groups that may join with, or be separated from each other through time by environmental or behavioural drivers) was also refined. Demographic modelling enabled reconstruction of carp metapopulations featuring six life-history stages (eggs, larvae, early young-of-the-year, late young-of-the-year, sub-adults, and adults). In turn, these reconstructions enabled determination of baseline population sizes for each catchment throughout the study period (which, as previously mentioned, was 1990–2017 for most catchments). Baseline population sizes are important, because they provide a point of reference against which the impacts of a possible carp biocontrol program could be measured.
4. The epidemiological modelling adapted an SEIR (Susceptible-Exposed-Infected-Recovered) infectious disease transmission model by replacing the 'Recovered' class with two classes — latently infected (L) and recrudescent (Z)—reflecting the carp virus's disease dynamics (see Technical Paper 2 and NCCP research project 4 for further discussion of latency and recrudescence). Integrating the epidemiological model and the demographic model enabled exploration of the effects of different epidemiological assumptions on carp mortality and population suppression.

Results from the epidemiological modelling described earlier were considered in terms of the potential for the predicted carp reductions to reduce the environmental damage caused by carp. This approach is consistent with the concept that pest control should aim to reduce the damage caused by pest species — killing pests even in very large numbers may deliver relatively few benefits if population density remains high enough to continue causing damage (NCCP research project 4). Studies evaluating the environmental impacts of carp across the different continents and habitat types in which they are invasive have identified some general 'threshold densities' above which carp damage manifests or intensifies (Technical Paper 1). Different ecosystem components or attributes have different damage thresholds. For example, a recent major global literature review identified a carp density of 50 kg/ha for impacts on fish species, 100 kg/ha for impacts on aquatic plants, and 150 kg/ha for negative impacts on water clarity (NCCP research project 4).

These general ‘one size fits all’ damage thresholds for entire groups of species (e.g. all fish), or variables such as water clarity are indicative only, and will vary substantially among ecosystems, and potentially for a given ecosystem through time (Technical Paper 1). Furthermore, these thresholds have been developed by considering carp impacts across different ecosystems and continents. While Australian studies were included in broader analyses by scientists estimating carp-impact densities, these threshold densities were not developed specifically for Australian aquatic habitats.

Acknowledging the desirability of a more advanced understanding of damage thresholds for Australian species and ecosystems (see Appendix 2), the concept has still been useful in considering the likely effectiveness of carp biocontrol. Furthermore, carp damage thresholds of varying magnitudes almost certainly *do* exist—to provide an extreme example, some Australian freshwater snail species become locally extinct in the presence of carp at any density, and therefore effectively have a damage threshold of 0 kg of carp per hectare (Technical Paper 1). Other species and ecosystem characteristics likewise probably have their own damage thresholds.

Despite the use of damage thresholds in this plan as a concept for benchmarking potential outcomes for carp biocontrol in different areas, any reduction in carp density may be beneficial. Even carp reductions that do not force populations below a threshold value may still free resources for use by other species and provide a foundation from which to leverage other control measures.

Other NCCP research considered alternative control methods to complement the virus and to clarify the relative value of carp virus biocontrol over other methods. One project evaluated the potential utility of genetic biocontrol technologies (NCCP research project 3) and another the effectiveness of harvesting or manual carp control approaches (NCCP research project 8). Key results and implications of effectiveness-related research under the NCCP are described next.

RESEARCH CONCLUSIONS—EFFECTIVENESS

- Over summer 2017–18, total carp biomass for eastern Australian was approximately 205,000 tonnes (NCCP research project 1). As a result of necessary simplifying assumptions in the modelling, biomass is likely underestimated (NCCP research project 1). These underestimates are particularly relevant given strong and persistent La Niña conditions in the years immediately preceding publication of the NCCP.
- Population modelling indicates that carp biomass will change markedly in response to climatic drivers (NCCP research project 2). In particular, higher flows, especially those that inundate floodplains, typically promote carp population growth. A ‘worst-case’ scenario for carp abundance, involving three consecutive years of flooding across carp’s entire Australian range, could result in a total carp biomass of just over 1 million tonnes (NCCP research project 2).
- Of the total carp biomass, a greater proportion is contained in waterbodies (e.g. lakes, reservoirs etc) than in rivers (see Figure 1) (NCCP research project 1).
- Planned virus release is unlikely to cause major, uncontrolled carp mortalities over large geographic areas (i.e. there will be no ‘Carpageddon’ scenario). Rather, large carp kills are only likely during spring and early summer, and in places where carp school densely (aggregate) prior to spawning (Technical Paper 2).

- Major kills involving numerous adult carp are only likely in the year of initial virus release, and potentially in the following one or two years. After this, the virus is expected to continue suppressing carp numbers, but mortalities should consist mainly of small juvenile carp, whose carcasses are likely to be less obvious in the environment (Technical Paper 2; NCCP research project 4).
- The degree to which the virus suppresses carp populations will differ both through time and from place to place. At times and places where carp populations are less resilient (e.g. during droughts, or in habitats that are inherently less suitable for carp), the virus could reduce carp populations by 60–80%. At times and places where carp populations are more resilient, populations could be reduced by around 40–60%. Sustained carp suppression could last at least 10 years, but the emergence of genetic resistance and/or herd immunity remain uncertainties.
- NCCP research has identified the tools and approaches needed to investigate the evolution of resistance to the virus among Australian carp. Targeted further work assessing the development of resistance (including the potential role of carp-Goldfish hybrids in this development) is recommended.
- Biocontrol is expected to reduce carp population densities below the intermediate damage threshold of 100 kg/ha across extensive areas of Australia's inland waterways (Technical Paper 2; NCCP research project 4). In some areas with very high carp densities, biocontrol alone may not be sufficient to reduce populations below theoretical damage thresholds. Targeted intensive harvesting prior to virus deployment is recommended for these areas, and will also serve to reduce the total biomass of dead carp ultimately resulting from viral disease (NCCP research project 4). In other locations where carp populations may already be below damage thresholds, deliberate release of the carp virus may not be necessary. Damage thresholds are used here as a general guide, acknowledging that development or refinement of threshold values tailored specifically to Australian aquatic ecosystems is desirable.
- The modelled impact of the virus on carp explicitly recognises Australian carp populations' propensity for large fluctuations in abundance ('booms and busts'), and indicates that the virus will continue to suppress carp populations even at the peak of 'booms'. That is, the virus's suppressive effects on carp populations will be moderated but not overwhelmed by conditions that encourage high carp abundance.
- A limited review of genetic biocontrol technologies identified the Trojan Y Chromosome approach as the technique most applicable to carp in Australia (NCCP research project 3). However, considerable technical and logistical barriers would need to be overcome before this technology could be deployed as a continental-scale carp control measure (NCCP research project 3). Notably, implementing Trojan Y would require a multi-decade commitment to breeding and stocking carp carrying the Trojan Y genetic construct (NCCP research project 3).
- A combined literature review and carp population modelling study indicated that physical removal has little capacity to provide sustained, continental-scale carp suppression if used as a stand-alone control measure (Technical Paper 1; NCCP research project 8). Similarly, the carp virus, if deployed in isolation from other measures, is unlikely to reduce high-density carp populations, such as those in the lower Murray River, below the intermediate damage threshold of 100 kg/ha (although even reductions that do not push carp abundance below this threshold may be beneficial). However, using the two approaches together, with targeted physical removal reducing carp abundance prior virus deployment, has considerable potential to suppress resilient, high-density populations that are otherwise very difficult to control (NCCP research project 4).

IMPLICATIONS FOR FEASIBILITY

- Implementing a biocontrol program using the carp virus is expected to require active, targeted virus deployment into pre-identified carp sub-populations under conditions appropriate for infection and disease.
- Viral biocontrol will provide greater suppression, over longer time periods, at times and places with less resilient carp populations (i.e. reduced capacity to 'bounce back' following population reduction). Virus release strategies have been designed to target these opportunities for increased impact.
- While any reduction in carp density brings potential ecological benefits, optimising suppression (and hence outcomes) across the species' entire range is likely to require a multi-method approach (NCCP research project 4). In particular, NCCP modelling indicates that targeted physical removal prior to virus deployment will optimise suppression in high-density carp populations. Assessing biocontrol feasibility was the NCCP's primary focus, meaning detailed assessment of a multi-method, integrated approach was beyond the program's scope. Nonetheless, the desirability of such an approach in at least some parts of carp's Australian range has planning and resourcing implications that will need to be more completely assessed if governments decide to proceed towards implementation.
- Genetic biocontrol technologies, and particularly the Trojan Y Chromosome approach, are potentially applicable to carp in Australia, but substantial biological and logistical challenges would need to be overcome prior to implementation, requiring considerable investment.

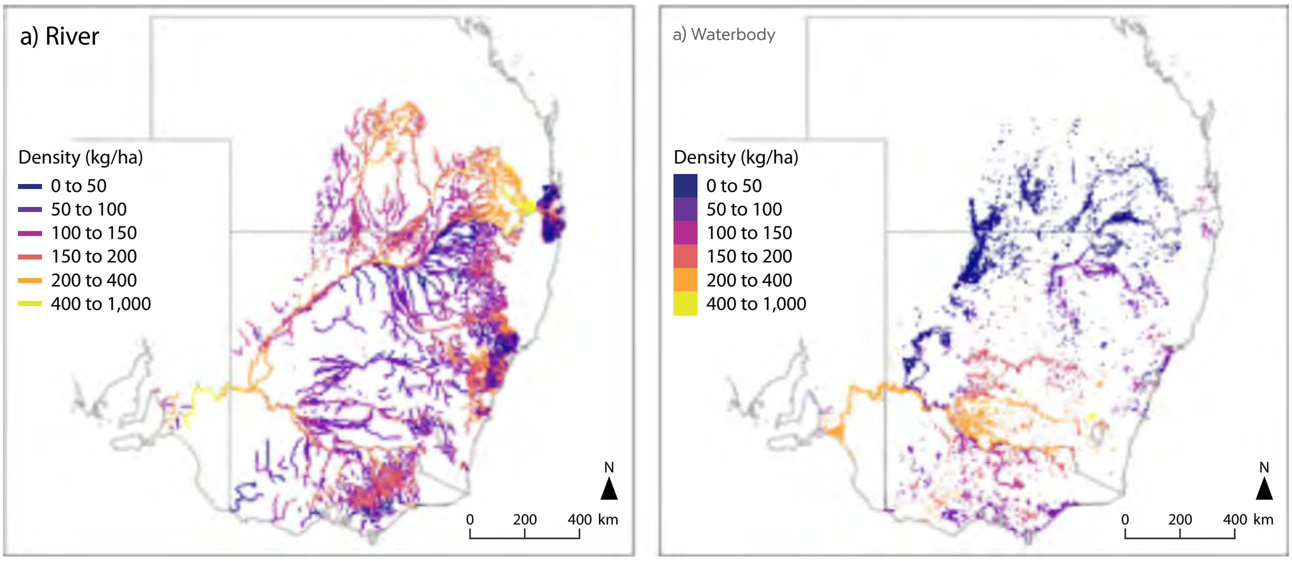


Figure 1: Density and distribution of carp in eastern Australia during spring/summer 2017–18, based on carp biomass estimation and mapping conducted under the NCCP. Carp also occur in some Western Australian coastal catchments.

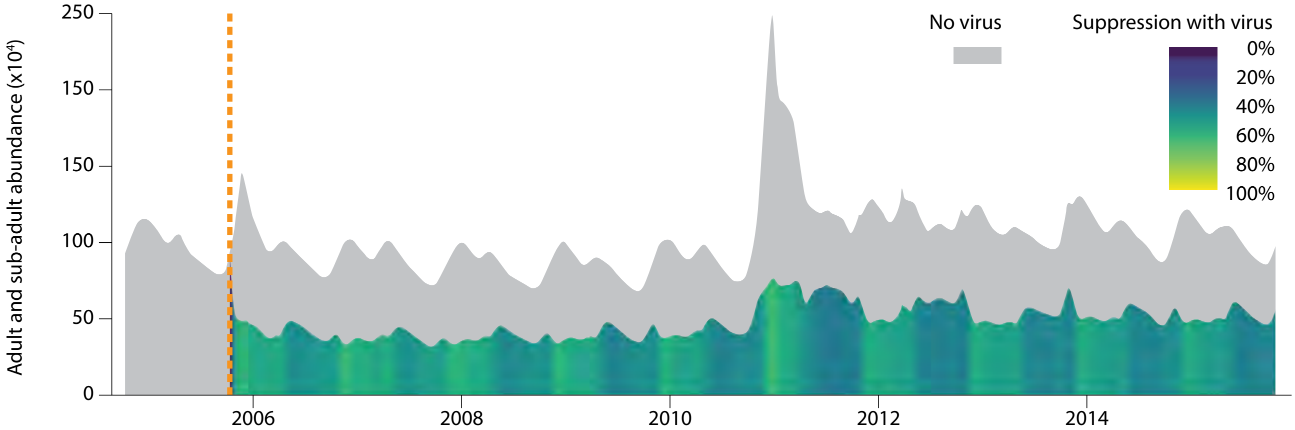


Figure 2: Modelled release of the carp virus into the mid-Murray River in 2000, assuming recrudescence and reasonable transmission. The shaded grey area represents carp populations in the absence of virus release.

KEY ASSUMPTIONS

Some key assumptions underpinning the NCCP epidemiological modelling and the consequences of those assumptions underlie the NCCP epidemiology conclusions as shown in Table 2.

Table 2: Key assumptions of the carp virus's impacts on Australian carp populations.

Assumption	Confidence that assumption is correct	Consequences if assumption is incorrect or inaccurate
Transmission primarily relies on physical contact between infected and susceptible carp. While other transmission pathways for the virus exist (e.g. infection of susceptible carp when they touch or ingest virus floating in the water) exist, experimental evidence from the NCCP and the broader scientific literature indicate that transmission through the water is likely to be relatively less important than physical contact between carp.	**High.** An NCCP experiment (NCCP research project 6) designed to test the relative importance of two transmission pathways (water-borne and physical contact between carp) confirmed that the latter is likely to be considerably more effective than the former. Transmission through the water can occur, but, in this experiment, the viral concentrations required to cause infection via this pathway were rarely achieved, even when diseased carp were confined in small (40 litre) volumes.	Variable depending on circumstances such as carp aggregation and water temperature, but overall carp mortalities would likely be greater if transmission through water is more effective than expected. If waterborne transmission occurred across long distances, carp kills could occur in unexpected locations, but this is unlikely. Nonetheless, the possibility of outbreaks in unexpected locations cannot be discounted. Such outbreaks could result from long-distance movement by latently infected carp, or from movement of infected carp by either humans or predatory animals/birds.
Direct physical contact between carp is frequent during spawning. The modelling assumes that, during spawning season, direct physical contact between carp occurs frequently.	**Medium.** While frequent physical contact among carp engaged in spawning behaviour is intuitively likely and based on well-understood reproductive biology, there are no data quantifying this.	The predicted strong seasonality of outbreaks may not be observed. If this assumption is incorrect, planning for deployment will be more difficult.
Latent infection with subsequent reactivation. The modelling assumes that carp surviving initial infection with the virus will develop a latent (i.e. dormant) infection that can be reactivated under suitable conditions, thereby infecting other carp. This reactivation of latent infections leading to disease — called 'recrudescence' — is one of the most important assumptions underlying the predicted impacts of viral disease on carp populations.	**Medium.** Latent and recrudescent carp virus infections are reported in the scientific literature. Additionally, results from an NCCP experiment supports the existence of latency and recrudescence over short time periods under laboratory conditions and with juvenile carp. Confirmation of latent carp virus infections with subsequent temperature-induced recrudescence, over longer time periods, in adult carp, and under variable environmental conditions (i.e. representing natural environments) is desirable.	If latent infections with subsequent reactivation do not occur, or if herd immunity means that they do occur, but do not cause substantial mortality, the virus's capacity to suppress carp populations in the medium to long term (i.e. 5–10 years) will be greatly diminished. The scenario would be one of a single major disease outbreak followed by rapid population recovery.

Assumption	Confidence that assumption is correct	Consequences if assumption is incorrect or inaccurate
No pre-existing resistance among Australian carp.	**Medium.** Preliminary work indicates that the genes conferring resistance to the carp virus are not present in Australian carp populations. However, this research was exploratory, and confirmation is desirable.	Viral effectiveness would be reduced, by an amount corresponding to the nature and prevalence of the resistance-conferring genes.
Viral transmission ceases completely outside permissive temperature range (below 16 °C and above 28 °C).	**Medium.** Carp maintained in a laboratory at 11 °C did not produce infectious virus, supporting this assumption (Technical Paper 2). Nonetheless, fish immunology is complex, and the different processes that could ultimately lead to a carp dying from the disease caused by the virus (i.e. an infected carp secreting virus, a susceptible carp becoming infected, then developing disease and dying) will all proceed at different rates as temperatures change. If new scientific knowledge documenting temperature effects on secretion, transmission, and survival emerges, this can incorporated into the modelling.	Transmission under temperature conditions that don't allow disease development could facilitate emergence of population-level immunity to the virus.

UNCERTAINTIES

- To effectively initiate outbreaks, infectious carp will likely need to participate in aggregations to ensure high contact rates between infectious and susceptible individuals. Yet, carp aggregations can be transient, sometimes lasting only a day or two before dispersing. Ensuring that infectious carp participate in aggregations could therefore be challenging. Virus deployment strategies based on releasing latently infected carp prior to the spring/early summer spawning period and allowing them to join aggregations naturally could help to overcome this challenge. Both the broader scientific literature and an NCCP laboratory experiment (NCCP research project 5) indicate that latently infected carp may experience temperature-induced reactivation of their infections, but further investigation is recommended.
- NCCP research project 5 was a short-term, laboratory-based study using juvenile carp. Patterns of recrudescence and onward infection over longer timeframes, in adult carp, and in the more variable and diverse environmental and temperature conditions characteristic of natural ecosystems could vary from those reported in this experiment. Furthermore, carp with a recrudescing infection could potentially experience behavioural changes that alter the likelihood of contact with susceptible individuals. Given these considerations, additional research assessing latency and recrudescence in adult carp, over longer timeframes, and under conditions more typical of a natural ecosystem is desirable. Even this additional research will not provide a complete understanding of carp virus disease dynamics, emphasising the importance of detailed and thorough post-release monitoring. Planning for a second year of virus deployment also mitigates against these uncertainties to some extent by providing a second opportunity to initiate outbreaks.

- Carp populations could develop herd immunity, reducing modelled effectiveness of the virus (Technical Paper 2).
- Some uncertainty remains about the role that carp-Goldfish hybrids could play in the evolution of resistance following virus release. Hybrids of European Carp can be infected by the carp virus, but are much less likely to develop serious disease than are 'pure' (i.e. non-hybrid) carp. Following a virus release, this relative invulnerability to disease could bestow a selective advantage on hybrids, potentially leading to their dominance in the population. However, the evolutionary fitness of carp-Goldfish hybrids and their potential role in the emergence of resistance remain knowledge gaps. NCCP research project 7 has developed genetic tools that could help to reduce this uncertainty.

2.2 Risks associated with carp biocontrol

Direct risks associated with carp biocontrol centre on the potential for decaying carp to degrade water quality, with a range of negative consequences. The other main direct risk is for carp virus impacts on non-target species. Secondary ecological risks are also described in the following sections.

2.2.1 Water-quality risks

Decomposing carp have the potential to negatively affect water quality. Most notably, decomposition can deplete dissolved oxygen, stressing or killing gill-breathing aquatic organisms (Technical Paper 3). Decomposition also releases nutrients and ammonia that can respectively fuel harmful algal blooms or are toxic to aquatic life. In combination, decaying carcasses, low or no dissolved oxygen, and algal blooms could potentially cause 'cascades' of negative impacts, including severe oxygen depletion and proliferation of disease-causing bacteria (Technical Paper 3). Modelling and risk assessment under the NCCP have investigated the likelihood that these damaging processes (termed 'exposure pathways') and their negative consequences ('risk assessment endpoints') could emerge following the virus's deployment as a biocontrol agent for carp in Australia (NCCP research projects 9 and 15).

RESEARCH CONCLUSIONS — RISKS

- Where carp densities are below approximately 300 kg/ha, and the water is flowing, key water-quality parameters are unlikely to be seriously impaired (Technical Paper 3). These conditions tend to prevail in most of the regulated river channels of the southern MDB, but are dependent upon broader climatic regimes (e.g. flows reduce or cease during drought) (Technical Paper 3). For perspective, Figure 1 illustrates the distribution of carp biomass during the summer of 2017–18.
- Where carp densities exceed approximately 300 kg, and the water is still or slow-moving, there is potential for low dissolved oxygen conditions and harmful algal (cyanobacterial blooms) to develop (Technical Paper 3). These conditions are most likely to prevail in waterbodies that are disconnected from flowing river channels (e.g. wetlands, lakes, reservoirs etc), and in unregulated rivers that cease to flow and dry to disconnected pools during dry periods (Technical Paper 3).
- Carp kills during dryer conditions will generally pose greater risks to water quality because dead carp are concentrated into a smaller total area (NCCP research projects 9 and 15). Conversely, the virus is likely to reduce carp populations most effectively if released during a relatively dry (not drought) period when carp are concentrated into smaller areas and not undergoing strong population growth (NCCP research project 4). This tension between protecting water quality and maximising carp reductions could be managed through careful implementation planning and management.

IMPLICATIONS FOR FEASIBILITY

- Initial virus deployment should occur during a period of low to moderate carp population density, thereby reducing the likelihood of high dead carp loadings that could compromise water quality.
- Initial virus deployment should occur during a year in which sufficient flow is available to dilute carp decomposition products and aid water-column mixing (noting that river managers may not always be able to manipulate flows specifically to benefit carp control).
- Main river channel habitats are unlikely to experience negative water-quality impacts following carp kills, whereas shallow, off-channel habitats and unregulated dryland rivers may, particularly where carp densities exceed 300 kg/ha.
- In some of Australia's highest-density carp populations, targeted harvesting before virus deployment may enhance carp suppression (NCCP research project 4). Reducing carp density before virus release could also mitigate water-quality risks in areas where carp biomass is high.
- In higher-risk habitats, two important risk mitigation options (manual collection of carcasses and use of water releases to flush away dead carp) are difficult or impossible to implement. There is consequently an argument for restricting planned virus release to the southern, regulated portion of the MDB where carp populations tend to be high and opportunities to use flow to aid carcass collection or flushing in some locations are increased. However, the risk remains that the virus would disperse, either by long-distance movement of latently infected carp, or through human agency, beyond the targeted release areas to locations where negative water-quality impacts are more likely. Therefore, if release proceeds, planning will need to incorporate surveillance and rapid-response measures across carp's mainland eastern Australian distribution, focusing on off-channel areas with carp biomass of 300 kg/ha or greater. Implementing such measures in remote areas, or where access is otherwise difficult, presents logistical challenges requiring adequate resourcing.
- The timing of initial virus deployment would need to be carefully planned to achieve an optimal balance between biocontrol effectiveness and risk management. Acknowledging that rainfall and flow will vary among catchments during any given year, this balance is most likely to be attained if initial deployment occurs under moderate flow conditions (i.e. neither flooding with full wetland inundation, nor drought), and when climatic conditions in the years preceding release have produced relatively low carp populations. Care will also be needed to ensure that virus-induced carp kills do not coincide with 'blackwater' events.

KEY ASSUMPTIONS

- NCCP water-quality modelling uses dead carp densities derived from the NCCP carp biomass and epidemiological modelling projects. Modelled water-quality impacts therefore rest on the fundamental assumption that these two projects' conclusions are approximately correct.
- The water-quality impacts of extreme dead carp densities were also modelled to understand likely impacts on water quality if dead carp densities are much higher than predicted. These investigations confirmed that very high dead carp densities seriously compromise water quality. Serious underestimation of likely dead carp biomass is, however, unlikely.

UNCERTAINTIES

- Nutrients from decaying carp could enter aquatic sediments and remain there, potentially forming a nutrient 'bank' that could contribute to future undesirable events, such as harmful algal blooms, well after carp carcasses have decayed (Technical Paper 3; NCCP research project 7).
- Assessing the extent to which 'legacy' nutrients in the sediment could contribute to environmental problems into the future is challenging, because the chemistry involved in the sequestration and subsequent release of these nutrients from the sediment is both complex and dependent upon local conditions (Technical Paper 3; NCCP research project 9).
- Nutrient accumulation is most likely at sites of high carcass density, such as where carcasses concentrate through current or wind action. Targeted carcass removal focused on these areas will be the most effective risk mitigation approach (Technical Paper 3; NCCP research project 9), but presents difficulties in some areas as outlined previously.
- NCCP water-quality modelling did not account for cumulative risks potentially posed by the downstream movement of water containing decomposition byproducts from successive upstream carp kills (NCCP research project 9).

2.2.2 Water treatment risks

Understanding potential impacts of carp biomass decomposition on water treatment plants and processes is essential for decision making on carp biocontrol. Producing drinking water involves two stages; 'treatment', which ensures water does not contain offensive odours or tastes, and 'disinfection', which kills potentially harmful microorganisms (Technical Paper 3; NCCP research project 14). Research co-funded by the NCCP investigated potential impacts of carp decomposition on both processes (NCCP research project 14).

RESEARCH CONCLUSIONS

- At carp densities typical of those estimated across the species' Australian range, standard water treatment and disinfection processes are effective (Technical Paper 3).
- At carp concentrations towards the upper limits of those estimated in Australian ecosystems, water remains treatable with the addition of powdered activated carbon (Technical Paper 3). Incorporating powdered activated carbon into the treatment process incurs additional costs, but is already routinely used in Australian water treatment plants to remove algal tastes and odours (Technical Paper 3).
- At carp densities substantially higher than those estimated to occur in Australian ecosystems, both water treatment and disinfection are untenable (Technical Paper 3). These very high dead carp densities are most likely to occur in a 'point-source' manner if wind or current caused dead carp to accumulate in a localised areas close to a treatment plant inlet (Technical Paper 3).

IMPLICATIONS FOR FEASIBILITY

- Dead carp densities likely to eventuate from use of the carp virus as a biocontrol agent pose little risk to the operability of water treatment plants.
- In areas with higher carp densities, some additional water treatment processes will likely be needed during peak carp mortalities.
- Carcass management activities will be required to prevent dead carp accumulating at high densities in restricted locations and decaying therein.

2.2.3 Carp virus species specificity

A detailed summary of species specificity information relevant to biocontrol using the carp virus is provided in Technical Paper 4. Key results and their implications for decision making are provided in the following sections.

RESEARCH CONCLUSIONS — SPECIES SPECIFICITY

- Specificity to the target organism is a fundamental requirement for most biocontrol agents.
- Some viruses can infect their hosts without causing disease. In these cases, the host is *infected* but not *affected* by the virus.
- The carp virus can neither infect nor affect any mammal, including human beings.
- Disease caused by the carp virus has only been reported in European Carp (including the ornamental variety), and in hybrids of European Carp (e.g. carp-Goldfish hybrids).
- CSIRO testing that preceded the NCCP (funded by the Invasive Animals Cooperative Research Centre) indicated that none of the 22 non-target species tested (see Technical Paper 4 for details) were either infected or affected by the virus, although some questions remained, leading to further work.
- A literature review commissioned by the NCCP (NCCP research project 11) raised the possibility that the carp virus may be able to infect species other than carp, though apparently without affecting them. This review recommended some additional work to increase confidence in the virus's species specificity before proceeding with virus release. Accordingly, Murray Cod and Silver Perch were re-tested for susceptibility to infection by the carp virus (NCCP research project 12). Attempts were also made to re-test Rainbow Trout, but captive fish experienced a water chemistry issue that led to major mortalities before any exposure to the virus occurred (NCCP research project 12). Therefore, at the direction of the relevant Animal Ethics committees, testing did not proceed for this species.

  No evidence of viral infection was found in the re-tested Murray Cod and Silver Perch (NCCP research project 12). However, NCCP research identified viral species-specificity as an important concern for the Australian community. NCCP research project 13 identified that 57% of 4680 people surveyed were concerned that the virus might be transmissible to fish or animals other than carp. Decision makers will also need to be as confident as possible that the virus will only infect carp. Consequently, additional testing is recommended before any decisions are made regarding virus release. This testing should include Rainbow Trout as a minimum, but a small number of additional species could also be identified for inclusion through consultation with scientific experts.

IMPLICATIONS FOR FEASIBILITY

There is no indication that the carp virus has ever infected human beings or any other mammal, or is likely to do so in future. Further investigation of this possibility is not required, and it does not affect the feasibility of carp biocontrol.

The situation regarding potential susceptibility of lower vertebrates — and particularly non-carp fish species — is more complex. While considerable evidence indicates that the virus is specific to carp, community concern regarding species specificity, combined with the absence of Rainbow Trout from the second round of non-target species susceptibility testing (NCCP research project 12), mean that a precautionary approach to this issue is warranted. Therefore, the NCCP recommends that the current level of confidence in the virus's species specificity is insufficient for a clear determination of feasibility, and that additional testing is conducted.

KEY ASSUMPTIONS

The key assumption underpinning carp virus species-specificity considerations is that following any future release, the virus would not evolve in ways that result in the acquisition of new host species. Predicting viral evolution is difficult, and the virus's capacity for evolutionary change over longer timescales cannot be tested in the laboratory. Nonetheless, the carp virus possesses several traits that make it much less likely than many viruses to infect species other than carp (see Technical Paper 4).

UNCERTAINTIES

Absolute guarantees about the species specificity of any virus, including the carp virus, are not possible, so uncertainty in this area will never be completely eliminated. Nonetheless, confidence in the virus's specificity to carp could likely be further improved. Additional, carefully controlled non-target species susceptibility trials could provide the additional evidence required to address community concerns and support a more definitive determination of the virus's host range. These additional trials are therefore recommended before decisions regarding virus release are made.

2.2.4 Ecological impacts

The NCCP research program has considered primary risks (i.e. water quality, including for stock and domestic use, and species specificity) and secondary ecological impacts. These secondary impacts were assessed by reviewing information available in the scientific literature, and through the structured elicitation of expert opinion. A brief summary of the ecological risk pathways and potentially impacted ecosystems and species identified and assessed through this process is provided in the following sections. Risk management and mitigation is outlined in sections 2 and 3.

PROLIFERATION OF DISEASE-CAUSING BACTERIA FOLLOWING CARP KILLS

If dead carp are left to decay in waterbodies following virus-induced carp kills, diverse bacterial communities are likely to use the carcasses as a substrate for growth (Technical Paper 3; NCCP research project 15). These bacteria would include those that had been inhabiting the intestinal tracts of the carp prior to death, various generalist 'spoilage' bacteria associated with decay, and potentially some disease-causing species such as Shiga-toxin producing *Escherichia coli* and various *Aeromonas* species (NCCP research project 15).

The potential proliferation of harmful bacteria following carp kills is largely a consequence of poor water quality (Technical Paper 3; NCCP research project 15). Therefore, the extent to which dissolved oxygen can be maintained, nutrient levels managed, and cyanobacterial blooms averted, will influence pathogenic bacteria risk levels. As with other water-quality hazards, major carp kills during low-flow conditions elevate risk. Additionally, temperature is an important determinant of microbial growth, with bacteria more likely to proliferate when water temperatures exceed approximately 20 °C (NCCP research project 15). Given the carp virus causes disease in carp most effectively at water temperatures between approximately 16–28 °C, carp kills would occur at temperatures suitable for bacterial growth. Therefore, proliferation of bacteria, including species harmful to humans and other animals, is at least theoretically possible following carp kills. Despite the capacity of fish kills to generate conditions suitable for bacterial growth, there are no recorded incidents of bacterial disease outbreaks caused by these opportunistic 'secondary' bacteria in humans, fish, or other faunal groups following fish kills in Australia (NCCP research project 15). Nonetheless, the possibility of such an outcome cannot be discounted, particularly if water quality deteriorates.

REDUCED AVAILABILITY OF CARP AS A FOOD SOURCE FOR NATIVE SPECIES

Carp are now the dominant large-bodied fish species in the MDB, and are also abundant in many coastal catchments. Consequently, piscivorous native species, including fish and waterbirds, may now rely on carp (especially juvenile carp) for a portion of their diets. The NCCP risk assessment (NCCP research project 15) concluded that nesting waterbirds are the group most likely to be affected by this exposure pathway, so the following discussion focuses on this faunal group.

There is little scientific evidence quantifying the importance of carp in waterbird diets. Nonetheless, waterbird breeding usually occurs on inundated river floodplains, thus coinciding both temporally and spatially with carp spawning. The co-occurrence of numerous juvenile carp with waterbirds raising young makes it intuitively likely that juvenile carp form an important food source for waterbirds at these times. Carp reduction could therefore create food shortages for fish-eating waterbirds during their nesting periods (NCCP research project 15).

Treatment options to reduce the risk that carp control will result in food shortages for waterbirds centre on planning initial virus deployment on a catchment or regional basis to avoid waterbird nesting periods. Unfortunately, in at least some parts of carp's Australian distribution (e.g. along the Murray River), waterbird nesting periods and permissive temperatures for carp virus infection and disease coincide, making implementation of this control measure challenging. Supplementing local populations of forage species through hatchery rearing and release programs has also been suggested, but would be costly and both biologically and logistically complex (NCCP research project 15).

PREDATORY SPECIES SWITCHING FOCUS TO PREY ON NATIVE SPECIES FOLLOWING CARP REDUCTION

If piscivorous species do rely on carp as a food source, and this food source is substantially reduced by viral disease, then 'prey switching' may occur as predators refocus their hunting efforts from carp to native species, including small-bodied native fish, juveniles of large-bodied native fish, crustaceans, frogs, and freshwater turtle eggs and young. Potential mitigation measures for this risk are similar to those outlined under the heading 'Reduced availability of carp as a food source for native species'.

BOTULISM OUTBREAKS FOLLOWING CARP KILLS

Botulism is a serious illness caused by bacterial neurotoxins (Technical Paper 3; NCCP research project 15). The bacteria that cause botulism can persist for decades as dormant, harmless spores in aquatic sediments and other environments, including the intestinal tracts of animals. The basic prerequisites for a botulism outbreak are anoxic (no oxygen) conditions and a protein source to fuel bacterial growth (Technical Paper 3; NCCP research project 15). When these conditions occur, dormant spores germinate, with ensuing bacterial growth and toxin production, potentially leading to a botulism outbreak. Botulism outbreaks in wild birds and livestock occur sporadically in Australia (Technical Paper 3; NCCP research project 15).

Although there are seven botulism strains, concern in the carp biocontrol context lies primarily with strains C, D, and C-D mosaic (Technical Paper 3; NCCP research project 15). These strains affect birds, livestock, and, to a much lesser extent, fish, but are not harmful to humans. Strain E is very dangerous to humans and fish, but there is some doubt as to whether this strain occurs in Australia. If strain E is present in this country, it is likely rare and/or has a restricted distribution (Technical Paper 3; NCCP research project 15).

Botulism risk varies with both river flows and water temperatures. Botulism outbreaks are more likely at temperatures greater than 20 °C and in still or slow-moving water. The temperature band within which the virus causes disease most effectively in carp means that outbreaks will usually occur at temperatures above 20 °C (Technical Paper 3; NCCP research project 15). Overall, it is possible that botulism outbreaks could result from mass carp mortalities (Technical Paper 3; NCCP research project 15). This risk rating is conservative and precautionary, reflecting the capacity of major fish kills to produce the fundamental preconditions for a botulism outbreak under some circumstances (i.e. kills occurring in shallow, off-channel waterbodies with high carp densities) (Technical Paper 3; NCCP research project 15). Despite this biological plausibility, fish kills in Australian freshwater ecosystems have not generally triggered botulism outbreaks, with only one recorded outbreak (NCCP research project 15). Nonetheless, depending upon the virus release strategy used, carp kills resulting from planned release of the carp virus could be on an unprecedented scale for Australian systems. The 'possible' risk rating reflects a balance of these considerations. As for pathogenic bacterial risk more generally, treating botulism risk centres on removing carcasses, either manually or through planned water releases where feasible (NCCP research project 15).

EPHEMERAL OR DRYLAND RIVER SYSTEMS

Ephemeral waterbodies are those that either dry completely or shrink to a series of disconnected pools during low-rainfall periods. Ephemeral systems tend to occur in the drier northern and western portions of the MDB, and differ from regulated rivers that tend to have long stretches of permanent water. Ephemeral river systems are ecologically important because the isolated permanent or semi-permanent waterholes that remain in their channels during dry times provide drought refuges for many species, including those that are rare and threatened (NCCP research project 15).

Refuge waterholes generally have little or no flow, and often have generally poor water quality, even in the absence of fish kills (Technical Paper 3). Virus-induced carp kills could potentially exacerbate these conditions, compromising the refuge value of these habitats (Technical Paper 3). These impacts will need to be addressed through regional implementation planning.

RAMSAR WETLAND SYSTEMS

Twenty-five listed wetlands occur within carp's Australian distribution. These wetlands have high conservation values and are afforded protection by the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) and the Ramsar Convention. These wetlands also tend to have high carp biomass. The NCCP ecological risk assessment (NCCP research project 15) concludes that the following wetlands could possibly be impacted according to criteria established under the EPBC Act:

- The Coorong and Lakes Alexandrina and Albert estuarine wetlands (South Australia),
- Currawinya Lakes (Currawinya National Park) (Queensland),
- Gwydir Wetlands: Gingham and Lower Gwydir (Big Leather) Watercourses (New South Wales),
- Narran Lake Nature Reserve (New South Wales),
- Paroo River Wetlands (New South Wales),
- The Macquarie Marshes (New South Wales),
- Banrock Station Wetland Complex (South Australia),
- Barmah Forest (Victoria),
- Fivebough and Tuckerbil Swamps (New South Wales),
- Gunbower Forest (Victoria),
- Hattah-Kulkyne Lakes (Victoria),
- Kerang Wetlands (Victoria),
- New South Wales Central Murray Forests (New South Wales), and
- Riverland (South Australia).

Implementation planning will need to assess and mitigate possible impacts consistent with EPBC Act requirements. NCCP case studies demonstrated that risk mitigation measures are possible at Barmah Forest and Gunbower Forest (see section 4.4).

2.3 Socio-economic impacts

The feasibility assessment for carp biocontrol presented in the NCCP is limited to scientific and operational matters, and does not formally incorporate potential socio-economic impacts. Nonetheless, the NCCP research program considered these potential impacts (Technical Paper 5; NCCP research projects 13 and 15), and summarised results are presented for consideration by governments.

Positive and negative impacts of the NCCP will vary between stakeholder groups. Carp biocontrol may involve negative impacts for some stakeholder groups, particular in the short term as the virus is deployed and initial major carp mortalities occur. These initial negative impacts may be balanced by longer-term benefits flowing from improved environmental outcomes. Other stakeholders could experience more sustained negative impacts.

NCCP social impact research could only identify potential impacts, as opposed to quantifying actual impacts. Potential impacts were used because the research was conducted concurrently with NCCP biophysical research, and hence could not fully consider final research conclusions and the likely short- and long-term effects of carp biocontrol.

2.3.1 Traditional Owners

Many Aboriginal Nations have strong interest in carp-affected waterways. Many Aboriginal people living outside these regions also have cultural responsibilities to care for carp-affected country despite not currently living on that country.

The NCCP consulted Aboriginal Nations and organisations to discuss carp biocontrol. Consultation directly with Aboriginal communities was limited.

Negative (or potentially negative) impacts of carp biocontrol for Aboriginal people include:

- potential for disempowerment through lack of involvement in carp biocontrol planning, decision making, and implementation,
- potential for negative impacts on health of country if biocontrol has unforeseen harmful effects on ecosystems,
- potential for negative impacts on cultural activities and culturally important sites if biocontrol has unforeseen harmful effects on ecosystems, and
- potential for reduced employment opportunities if biocontrol is ineffective or is planned and implemented in ways that do not empower Aboriginal people.

Positive, or potentially positive impacts of carp biocontrol for Aboriginal people include:

- empowerment through active, meaningful, appropriately resourced involvement,
- potential for improvements in health of country if biocontrol is effective,
- potential for positive impacts on cultural activities and culturally important sites if biocontrol is effective, and
- potential for increased employment opportunities if biocontrol planning and implementation is empowering for Aboriginal people.

A key recommendation is that a specific engagement strategy be developed and implemented for Aboriginal communities which consults at the community as well as nations level. Aboriginal engagement should engage on enterprise outcomes as well as social licence to operate.

2.3.2 Tourism

The tourism sector is defined as any recreation-related business that is reliant on inland freshwater systems or regions for their income (e.g. houseboat operators, fishing guides, nature-based or adventure tourism, and accommodation with water frontage). Poor water quality, regardless of its cause, reduces visitation to freshwater destinations, resulting in negative economic impacts to the tourism sector. For example, the tourism industry has been, and continues to be, negatively impacted by major algal blooms occurring along the Murray River. Perceived declines in water quality can be as damaging to tourism businesses as real reductions. Technical Paper 5 addresses potential socio-economic impacts on the tourism industry, and potential mitigation measures, in detail.

2.3.3 Commercial carp fishers

Commercial carp fisheries in Australian states and territories are currently fairly small, with limited permits issued. Regulatory regimes vary widely across the jurisdictions in which commercial carp fishing is permitted.

Potential negative impacts of carp biocontrol on the commercial fishing sector include:

- uncertainty about the future resulting in psychological distress and mental health impacts,
- severe reduction in profitability, or complete loss of business viability,
- inability to invest in or sell fishing businesses,
- changes to World Organisation for Animal Health (OIE) trade policies that could reduce access to international markets or reduce profitability,
- difficulty or inability to obtain or service finance,
- loss of market access,
- impact on public reputation, and
- increased business costs.

Potential positive impacts or opportunities of carp biocontrol for the commercial fishing sector include potential inclusion of live harvest in an integrated control strategy to support biocontrol. Technical Paper 5 and NCCP research project 13 address potential socio-economic impacts on commercial carp fishers, and potential mitigation measures, in detail.

2.3.4 Native fish aquaculture

Native fish aquaculture is a small but growing industry, which is expanding in both domestic and export markets. Many of these markets are highly sensitive to any change in real or perceived product quality. Viability of the sector is reliant upon price premiums attracted by their products' 'clean and green' image. The sector supplies fingerlings for stocking, export fingerlings for grow-out overseas, and some businesses grow stock into table-size fish for domestic consumption. Markets include conservation restocking, stocked recreational fishing, and consumption.

Potential negative impacts of carp biocontrol on the native fish aquaculture sector include:

- uncertainty about future business viability, including potential for complete loss of viability,
- increased business costs,
- changes to OIE trade policies following virus release in Australia, and
- loss of market access due to negative perceptions (i.e. loss of 'clean and green' image) and/or regulatory barriers.

Potential positive impacts of carp biocontrol on the native fish aquaculture sector include:

- expanded business opportunities if native fish restocking is implemented as an environmental restoration measure alongside carp biocontrol, and
- potential opportunities to address existing regulatory constraints.

Technical Paper 5 details potential socio-economic impacts on the native fish aquaculture industry, and potential mitigation measures.

2.3.5 Koi hobbyists and businesses

Keeping decorative koi carp (an ornamental genetic strain of carp) involves thousands of people and supports many businesses in those jurisdictions where koi may be legally kept (New South Wales and Western Australia). Koi keeping has a long cultural history, and koi keepers have strong connections to their pet fish and to koi communities in other countries.

Potential negative impacts of carp biocontrol on the koi sector include:

- uncertainty about the future resulting in psychological distress, and mental health impacts,
- higher day-to-day business costs resulting from the need to increase biosecurity measures,
- higher koi keeping costs for hobbyists,
- reduced social interaction,
- psychological and financial impacts of loss of koi, for both hobbyists and businesses, and
- longer-term viability of the koi hobby in Australia.

Technical Paper 5 and NCCP research project 13 address potential socio-economic impacts on koi hobbyists and businesses, and potential mitigation measures, in detail.

The NCCP has commissioned a biosecurity strategy for the koi sector to guide risk mitigation following potential release of the carp virus in Australia (NCCP planning investigation 2). The project concluded that:

- improved biosecurity protocols could reduce the risks of adverse impacts on the koi sector, and
- koi sector representatives are concerned that implementing enhanced biosecurity protocols would be costly for both hobbyists and businesses, and would unduly inhibit koi exchanges and events.

2.3.6 Recreational fishers

Recreational fishing is a key driver of visitation and tourism revenue in many freshwater and estuarine areas inhabited by carp. Changes in fishing conditions and opportunities contribute to changing visitor numbers. Within the recreational fishing sector, a relatively small number of fishers specifically focus on carp fishing (coarse fishing, a term originating in the United Kingdom to denote fishing for species other than the salmonids historically recognised as premium sporting or 'game' species). Recreational fishers have been highly engaged in discussions about carp control and in actions to raise awareness of carp as a pest species, for example through conducting regular community-based 'carp buster' competitions.

Potential negative impacts of carp biocontrol for recreational fishers (and particularly those who target carp) include:

- reduced fishing opportunities and/or fishing activity for those wishing to catch carp,
- reduced carp numbers for coarse fishers, and
- reduced profitability for some recreational fishing suppliers or guide businesses if carp constitute a substantial component of their business.

Potential positive impacts of carp biocontrol for recreational fishers include:

- increased fishing success and enjoyment for fishers wishing to catch native species,
- increased revenue for fishing-related businesses if carp control leads to improved ecosystem health and enhanced native fish abundance, and
- opportunities for recreational fisher involvement in carp control and aquatic habitat restoration.

Technical Paper 5 and NCCP research project 13 detail potential socio-economic impacts on recreational fishers, with potential mitigation measures for negative impacts.

3 IMPLEMENTATION STRATEGY

3.1 Introduction

This section describes how carp virus biocontrol could be successfully implemented across Australia. The implementation strategy provides a national framework or strategic 'intent' for more detailed planning should the Australian Government decide to proceed towards implementation. The strategy does not provide detailed implementation actions as jurisdictions and regions are best placed to complete implementation planning according to jurisdictional legislation and local conditions and constraints.

The implementation strategy is based on NCCP research (section 2), and case studies (section 4). Additional information is provided in Technical Paper 6. The case studies reported in section 4 illustrate how implementation could occur in particular regions.

3.2 Implementation objectives

Implementation objectives for carp biocontrol have been developed from NCCP research results and feasibility assessment. The objectives are:

a. widescale reduction and suppression of carp populations for the medium to long term (5–10 years),

b. effective environmental risk management with no unacceptable impacts on Matters of National Environmental Significance (MNES) under the EPBC Act,

c. management of water-quality risks for town water supply, stock and domestic water needs, irrigation, and cultural and recreational purposes, and

d. effective and efficient virus deployment and carcass management, where the latter is required.

This section provides specific national strategies to achieve objective (a), which is fundamentally informed by technical and scientific considerations and therefore within the scope of NCCP research and investigations. Objectives (b), (c), and (d) are primarily informed by policy, jurisdictional, local, and operational considerations and are therefore addressed conceptually to provide indicative approaches for regional planners. The NCCP case studies demonstrate how these objectives could be achieved in particular regional contexts.

3.3 Implementation outcomes

AT LEAST 40-60% MORTALITY IN TARGETED CARP SUB-POPULATIONS

NCCP modelling indicates that initial virus deployment into targeted carp sub-populations will cause disease outbreaks that reduce those populations by on average 40-60% relative to pre-deployment levels (and 60-80% in less resilient in carp populations) (see Technical Paper 2, NCCP research project 4, and section 2.1 for details, including assumptions and uncertainties).

ONGOING SUPPRESSION OF TARGETED CARP SUB-POPULATIONS

Following virus deployment and associated carp reductions, suppression is expected to result from the combined effects of the initial knockdown and reactivation of latent infections.

3.4 Implementation phases

If governments ultimately decide to proceed towards undertaking a carp biocontrol program, NCCP implementation is proposed over a 10-year timeframe with activities primarily focused in the first four years. Specific timings are dependent on implementation planning and adaptive management. The phases or periods of implementation include:

1. planning — one or two years of implementation planning before virus deployment,
2. operations (initial deployment) — two or three years of virus deployment and carcass management, possibly preceded by harvesting to 'thin out' high-density carp sub-populations,
3. operations (post deployment) — five to seven years of significantly reduced operations and ongoing surveillance, and
4. completion.

The phases listed in points 1–4 occur sequentially, however overlaps and delays between the different phases are expected (for example, suitable pre-conditions for deployment may take some time to eventuate). The following sections apply the knowledge generated by NCCP research and planning investigations to address the third feasibility question, namely "how could carp biocontrol be implemented?".

3.4.1 Planning

The NCCP implementation strategy sets out the national strategic intent and approach to virus deployment and management, and provides the basis from which jurisdictions and regions will undertake more detailed implementation planning. Implementation planning will identify the operational measures and resources required to deploy the virus and manage associated risks. Regulatory approvals will also need to be obtained during the planning stage. Guidelines for the planning phase are given in Technical Paper 6.

LEGISLATIVE APPROVALS

Objectives (b) and (c) (from section 3.2) will be guided by numerous legislative approval processes and then implemented according to those approvals. Legislative approvals requiring completion during the planning stage include those necessary under:

- the EPBC Act,
- legislation administered by the APVMA,
- the *Biosecurity Act 2015*,
- the *Biological Control Act 1984*, and
- relevant state and territory regulatory approvals.

STRATEGIC ASSESSMENT UNDER THE EPBC ACT

On 19 January 2018, a delegate of the then Minister for the Environment and Energy entered into an agreement with the then Department of Agriculture and Water Resources to undertake a strategic assessment of the NCCP. The strategic assessment will be undertaken in accordance with section 146 of the EPBC Act (see dcceew.gov.au/environment/epbc/strategic-assessments/strategic/national-carp-control-plan).

Additional planning, risk assessment and drafting of statutory documents will be required to undertake the strategic assessment should government decide to undertake further work towards implementation of the NCCP.

For the purposes of the strategic assessment, the Plan is to be a document that will describe how the NCCP will be implemented by each state and territory to ensure impacts on Protected Matters are acceptable. A Strategic Assessment Report will be prepared to assess how the implementation of the Plan will ensure the appropriate level of consideration and management of impacts on Protected Matters. A draft Strategic Assessment Report and draft Plan will need to be made available for public comment. Following the public comment period, a Supplementary Report (addressing public comments) and a revised Plan and Strategic Assessment Report (if necessary) will be submitted to the Minister for consideration.

After considering the Strategic Assessment documents the Minister may decide to endorse the Plan if satisfied that the reports adequately address the impacts. If the Minister endorses the Plan, the Minister may then approve the taking of an action, or class of actions, in accordance with the Plan and the EPBC Act. The effect of any such approval decision is that any actions or class of actions would not need further approval by the Minister under the EPBC Act if taken in accordance with the endorsed Plan.

This process takes approximately 18 months. This timeframe depends on the timely preparation of the relevant strategic assessment documents and management of the public consultation process. In past strategic assessments, including those where governments were the proponent, the preparation of this documentation has been undertaken by ecological consultants, with expertise in EPBC Act assessments.

MANAGEMENT AREAS FOR OPERATIONS

Planning would begin by determining Catchment Control Areas (CCAs) for implementation across the designated area of virus deployment. CCAs will be defined by:

- operational considerations such as spans of control,
- prioritised areas for virus release,
- connections and barriers between waterways and carp populations, and
- natural characteristics of the catchment.

DEVELOPMENT OF IMPLEMENTATION PLANS

If governments decide to proceed towards implementation, jurisdictions and regions (as defined by CCAs) will need to develop regional implementation plans detailing specific operational approaches, requirements, and constraints including regional central command and forward command locations (Technical Paper 6). Regional implementation plans will reflect the relevant directions, policies, legislative requirements and frameworks of the appropriate state or territory plan.

ESTABLISHING OPERATIONAL COORDINATION

During the planning phase operational coordination would need to be established according to jurisdictional and regional planning and proposed Australian incident management procedures (Technical Paper 6).

3.4.2 Operations (initial deployment)

Operations would follow implementation planning and would take two to three years to complete. The operational phase would involve the following major tasks:

1. virus preparation,
2. establishment of regional and jurisdictional implementation teams,
3. operational preparation,
4. communications and engagement, and
5. initial deployment field operations.

This phase of viral biocontrol would be the most resource intensive, as it includes the substantial tasks of virus deployment and carcass management (outlined in the following sections). This phase might usefully be preceded by targeted, intense harvesting of carp in high density sub-populations to reduce their abundance prior to viral biocontrol (NCCP research project 4). Details of operations related to implementation are provided in Technical Paper 6.

3.4.3 Operations (post deployment)

Operations in the year after initial deployment would involve a significant reduction in the number of carp kills and the size of the carp in those kills. Kills during this phase are likely to substantially comprise juvenile carp, presenting reduced water-quality risks (Technical Paper 3; NCCP research project 4).

Post-deployment operations involve moving from 'response' arrangements with full incident management systems to a 'maintenance and learning' phase during which active operational activity is substantially reduced. Australian experience with viral biocontrol of vertebrate pests indicates that these programs are most effective when delivered with a long-term, strategic approach to managing the evolving relationship between virus and host. Regional disease surveillance and operational response capability may still be required and could be conducted, with appropriate resourcing, by state/territory agencies. Alternatively, dedicated regional coordination centres could be retained with reduced staffing levels.

Jurisdictions are probably best placed to lead any activities during this period. The need for coordination at the national level would be reduced, but ongoing national monitoring and evaluation would still be required.

3.4.4 Completion

The completion phase would begin when all necessary national actions to deploy the carp virus and manage associated risks have been completed. Completion is likely to begin approximately 10 years after initial virus deployment, but experience during adaptive management could change this projection. Upon completion, jurisdictions would be able to manage risks as part of their usual operations. Ongoing surveillance, monitoring, and research is proposed following completion.

3.5 Virus deployment strategy

3.5.1 Critical success factors

Virus deployment will aim to achieve the first implementation objective, namely:

- widescale reduction and suppression of carp populations for the medium to long term (5–10 years).

Critical success factors for carp virus deployment and carp biocontrol are identified in the following sections. These factors exploit the biological characteristics of carp and the carp virus to maximise knockdown and suppression.

USING VIRUS AND CARP BIOLOGY TO MAXIMISE EFFECTIVENESS

Virus deployment aims to maximise the impacts of viral disease on carp populations by achieving both an initial knockdown and ongoing suppression as modelled by NCCP research (NCCP research project 4).

Four primary biological preconditions will likely determine the virus's impact on carp populations:

- the permissive water temperature for viral infection and recrudescence,
- recrudescence of latent infections,
- carp aggregation behaviour to achieve virus transmission between carp, and
- the proportion of carp infected within a given sub-population (see Technical Paper 2 and NCCP research project 4 for more detailed discussion of these variables).

The carp virus's capacity to kill carp is temperature dependent. The virus only causes disease in carp at temperatures between approximately 16 and 28 °C. Disease is particularly likely in a narrower temperature range between approximately 21 and 25 °C (Technical Paper 2). Within carp's Australian distribution, these water temperatures mainly occur through spring and early summer.

As water temperatures move outside the permissive range, the virus becomes latent within infected carp and does not replicate (see Technical Papers 2 and 6 for descriptions of latency and its potential role in carp biocontrol). The scientific literature and results from a preliminary and limited laboratory experiment under the NCCP indicate that, as water temperature increases into the permissive range during spring in the years following initial deployment, a proportion of latently infected carp will experience reactivation of their infection (recrudescence) (Technical Paper 2; NCCP research project 4). These individuals may or may not get sick and/or die, but most should shed virus, potentially infecting naïve carp with which they have physical contact (NCCP research project 4).

This sequence of latency and recrudescence will be a crucial determinant of the virus's capacity to deliver long-term carp suppression (Technical Paper 2). If latent infections recrudesce and infect naïve carp, the virus should deliver effective ongoing carp suppression for at least 5–10 years, and probably longer, albeit with uncertainties regarding genetic resistance and herd immunity (NCCP research project 4). Recrudescent carp virus infections are documented in the scientific literature, and results from a short-term laboratory experiment under the NCCP also support the existence of recrudescence, although their applicability to the timescales and environmental conditions under which recrudescence would need to occur in the field should be interpreted cautiously (Technical Paper 2; NCCP research project 4). If recrudescence does not occur, or if it does occur but herd immunity reduces mortality rates, the carp virus will deliver large initial mortalities in the year or two following release, but is unlikely to provide longer-term suppression (NCCP research project 4).

Physical contact between infected and naïve carp is almost certainly the most effective transmission pathway for the carp virus (Technical Paper 2; NCCP research project 4; NCCP research project 6). A laboratory experiment under the NCCP (NCCP research project 6) supports this contention, demonstrating that physical contact between carp is required for efficient transmission of the carp virus. In contrast, transmission through water required extremely high viral concentrations that were only rarely obtained even when infected carp with disease symptoms were housed in small (40-litre) volumes of water. The emphasis placed on direct physical contact as the primary transmission route in NCCP epidemiological modelling is therefore supported by experimental evidence. Although the virus can survive in the water column outside its carp host for a relatively short period, this transmission pathway is likely to be substantially less important than direct physical contact between infected and naïve carp (Technical Paper 2; NCCP research project 4; NCCP research project 6).

The requirement for physical contact between carp to ensure transmission presents both opportunities and challenges. The need for physical contact to ensure effective transmission contributes to a geographically and seasonally restricted outbreak pattern that facilitates carcass management. However, transmission through physical contact also means that engineering disease outbreaks of sufficient magnitude to knock down carp populations may be challenging.

Carp spawning behaviour provides the most likely opportunity to initiate outbreaks of the disease caused by the carp virus. Adult carp move to access suitable spawning habitat in early spring, forming large aggregations immediately prior to spawning. Aggregations place numerous carp in close physical proximity. The virus will be deployed by introducing infected carp into aggregations within targeted sub-populations. Two primary potential deployment techniques for getting infected carp into aggregations have been identified by NCCP research and planning investigations. These techniques (i) are capture, injection and release of a subsample of aggregating fish in spring, and (ii) capture, injection and release of latently infected carp during winter prior to onset of aggregating behaviour. An adaptive management approach following virus release (if governments choose to proceed) is most likely to enable refinement and optimal targeting of deployment methods.

Photo Luis Garcia (Wikimedia).

TARGETING AGGREGATIONS ACROSS CARP SUB-POPULATIONS

The most effective virus deployment strategy will target as many aggregations as possible within a given carp sub-population. Depending upon the virus-deployment technique used, deployment may need to occur during a relatively narrow time-period when carp aggregating behaviour and permissive water temperatures coincide. Sufficient virus needs to be introduced into each sub-population to (a) trigger an outbreak that provides initial knockdown, and (b) ensure that a proportion of infected carp develop latent infections to trigger outbreaks in future years. If insufficient aggregations within each carp sub-population are not infected during this period, carp suppression is likely to be suboptimal.

ACHIEVING BROADSCALE INFECTION

Broadscale deployment of the carp virus is required to ensure that as many carp as possible are exposed to the virus while still immunologically naïve (Technical Paper 2). The requirement for broadscale deployment does not initially extend to geographically isolated populations, such as those in coastal catchments. Over time, however, isolated carp populations could still be controlled through secondary deployment of the virus at jurisdictional discretion.

While broadscale virus deployment and impact is desirable, logistical constraints and priorities would almost certainly preclude simultaneous deployment across carp's entire Australian distribution. However, targeting carp meta-populations (connected groups of sub-populations) offers an opportunity to achieve broadscale impacts, while operating at more manageable spatial scales.

The regulated systems within the MDB contain high carp densities, and are proposed as the focus of the initial virus deployment. In areas where carp may not routinely aggregate in large numbers (e.g. some unregulated systems in the northern MDB), initiating outbreaks could be particularly challenging.

3.5.2 Duration of initial carp virus deployment

Initial virus deployment is proposed for the first year with contingency for a second year of deployment based on an evaluation of first-year deployment success. A second year of deployment may be required given the uncertainty regarding the narrow 'window of opportunity' during which permissive water temperatures and carp aggregation align. The extent of virus deployment and carcass management required in the second year would be determined by evaluating first year outcomes.

3.5.3 Location of initial carp virus deployment

If carp biocontrol eventually proceeds, initial virus deployment would likely focus on regulated river systems of the MDB, including irrigation areas (subject to irrigation operations), see Figure 3. Deployment timing would be informed by local surveillance, monitoring, and environmental/weather conditions. Specific decisions about deployment timing and locations would need to be agreed by all jurisdictions and the Australian Government. Deployment and subsequent management would occur over two years across the following management zones and geographic locations.

Mid zone of operations

- the Gwydir River and adjoining waterbodies and lakes from Copeton Dam to the confluence with the Barwon River,
- the Namoi River and adjoining waterbodies and lakes from Keepit Dam to the confluence with the Barwon River,
- the Macquarie River and adjoining waterbodies and lakes from Burrendong Dam to the confluence with the Barwon River,
- the lower sections of the Balonne and Warrego River systems, and
- the Barwon and Darling Rivers to Menindee Lakes.

Southern zone of operations

- Murray River and adjoining waterbodies and lakes from Hume Dam to the Lower Lakes. Including the lower sections of the following tributaries:
  - Ovens,
  - Goulburn,
  - Campaspe,
  - Loddon,
  - Broken, and
  - Lower Darling from Menindee Lakes;

  including the following tributary/anabranch systems
  - Edward-Wakool,
  - Chowilla, and
  - Darling Anabranch.
- Murrumbidgee River and adjoining waterbodies and lakes from Burrinjuck Dam to the confluence with the Murray River (note there are large carp populations throughout the upper Murrumbidgee catchment and these could be included in the first year of deployment).
- The Lachlan River and adjoining waterbodies and lakes from Wyangala Dam to the confluence with the Murrumbidgee River including the first section of Wyangala Creek.

Murrumbidgee River. Photo Bidgee (Wikimedia).

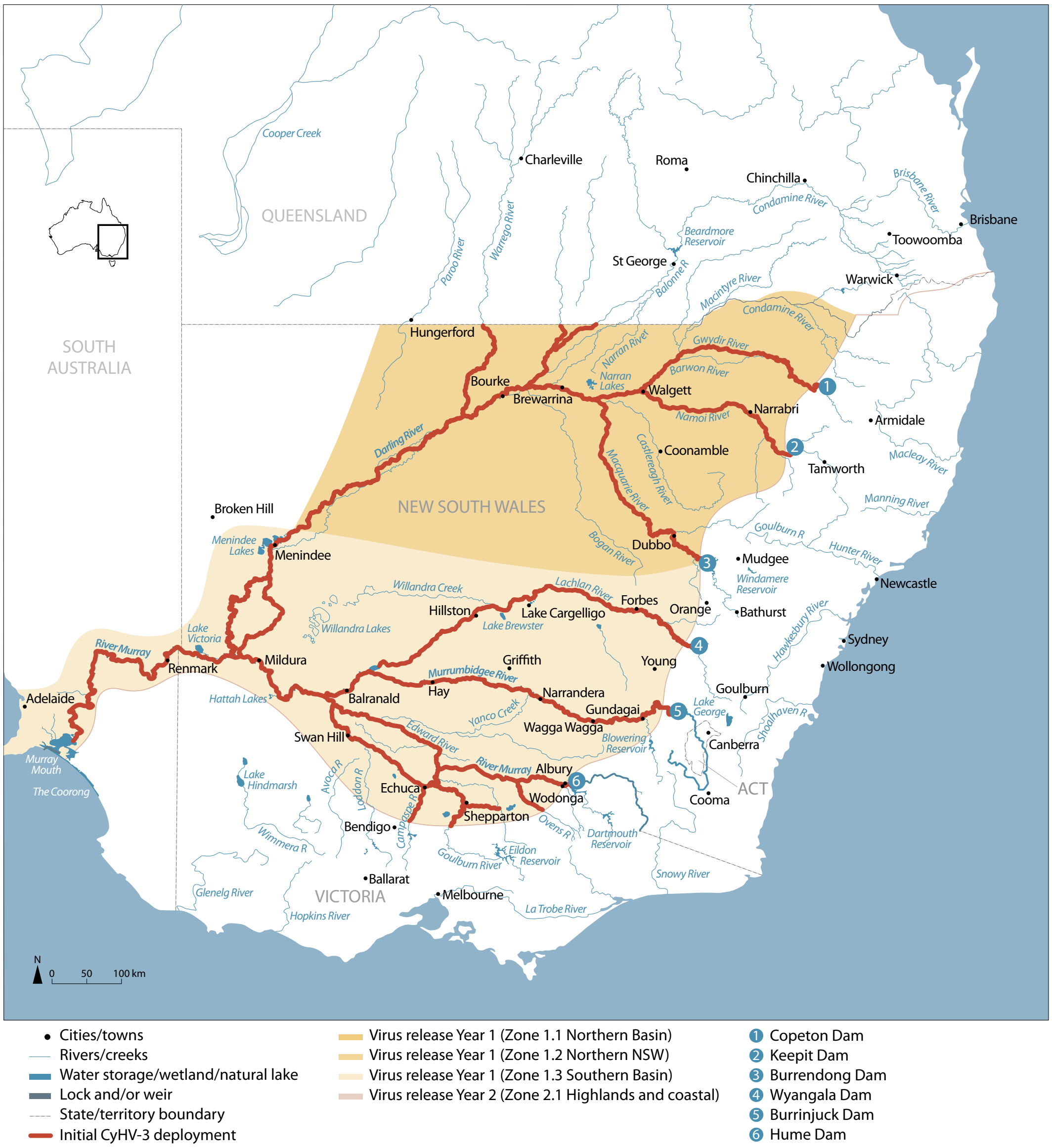


Figure 3: Initial deployment of the carp virus into regulated systems in south-eastern Australia.

The mid zone or northern New South Wales zone will reach permissive water temperatures for viral infection and disease earlier than the southern zone, so deployment could begin and finish slightly earlier in the north.

A potential variation on the release strategy focusing on regulated river systems first would be to include Queensland's unregulated ephemeral systems in the initial release (Figure 4). These rivers dry to disconnected refuge pools, usually during the season when virus release would need to occur (NCCP research project 15). Refuge pools have important biodiversity values, which could be compromised by decomposing carp at high densities. Furthermore, these pools typically feature dissolved oxygen and temperature profiles that are already marginal for native fish (Technical Paper 3; NCCP research project 15). Dryland ephemeral rivers consequently present a different risk profile to regulated systems. A virus release strategy that includes these sensitive systems in the initial deployment would aim to induce major carp mortalities in a predictable manner while personnel and resources for intensive carcass removal are present. Initial carp mortalities could reduce the overall population, thereby reducing the likelihood of major kills that could compromise water quality in future years. Nonetheless, the challenges associated with implementing such an approach in these remote systems where vehicle access is often very difficult should not be underestimated.

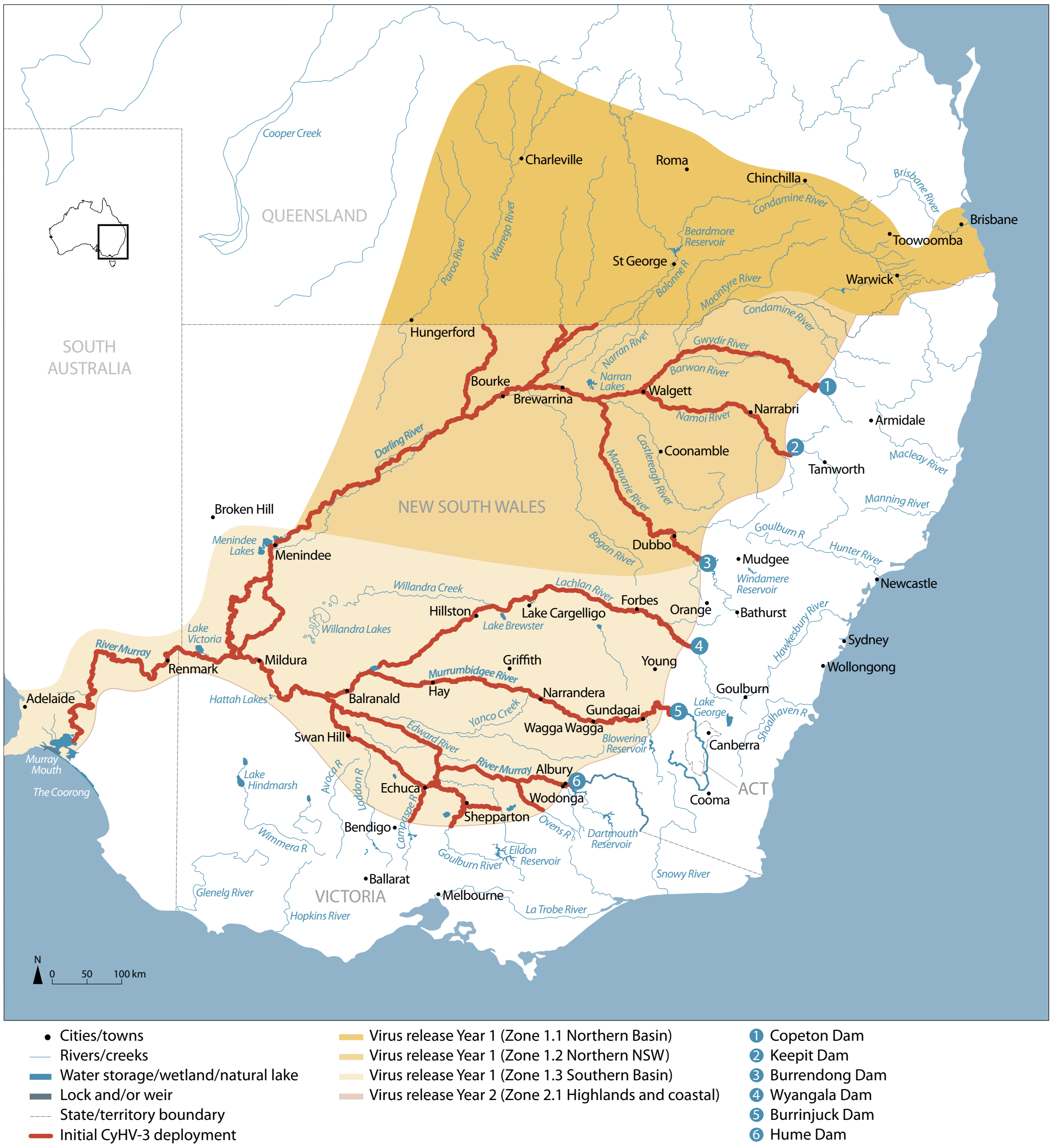


Figure 4: Initial deployment of the carp virus — regulated rivers in the MDB and major unregulated rivers in the northern Basin including Queensland.

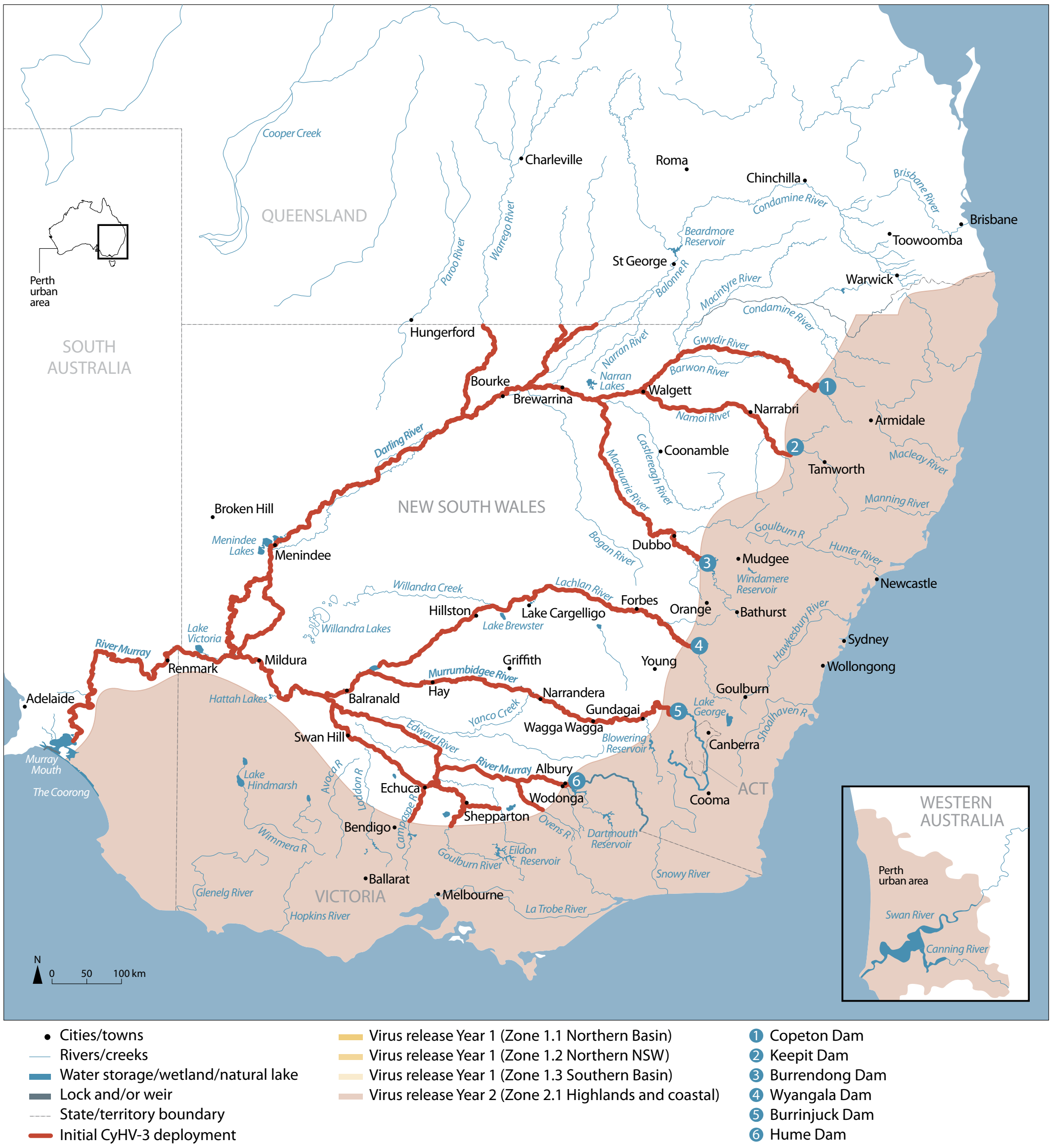


Figure 5: Secondary deployment of the carp virus — unregulated upland catchments of the MDB and coastal catchments including Western Australia.

3.5.4 Secondary carp virus deployment

In the second or third year following initial deployment, the carp virus would be deployed into aggregations within sub-populations in other catchments across the full extent of carp's Australian distribution. This control region is shown in Figure 5 and includes:

- unregulated upland catchments in the MDB, and
- coastal catchments across New South Wales, Victoria, Queensland and (potentially) Western Australia.

Specific locations for deployment can be determined by relevant jurisdictions consistent with national objectives for carp control.

3.5.5 Carp virus deployment methods

There are two potential methods for introducing the virus into carp populations:

1. As carp begin to aggregate in spring, fish in targeted aggregations would be captured, usually by electrofishing, injected with the virus, and released back into the waterway in which they were caught. As many aggregations will be infected as possible across each carp sub-population.
2. In late winter, prior to the onset of aggregating behaviour, dispersed carp would be captured within targeted sub-populations, injected with the virus to initiate a latent infection, and released. As the water warms, the latently infected carp are expected to join spawning aggregations. Because aggregations coincide with warming water temperatures, latently infected carp should experience reactivation of their infections as spawning occurs, thereby infecting other carp in the aggregation and initiating an outbreak. Uncertainties remain about exactly how a virus deployment approach based on latently infected carp would function under field conditions. For example, the extent to which carp experiencing a reactivating viral infection will participate in spawning aggregations is unknown. Some of these uncertainties could potentially be resolved by studying patterns of latency and recrudescence under conditions of environmental variability similar to those that would occur in the field and over timescales of weeks to months. Because Australian research using the carp virus can only take place in biosecure laboratories, studies of this nature would probably best be undertaken internationally, in a location where the virus is already endemic and where its use in scientific experimentation is therefore less restricted. Such experiments would not, however, obviate the need for a thorough post-release monitoring scheme linked to an adaptive governance and management structure to facilitate ongoing evolution of release strategies if carp biocontrol does proceed.

Selecting between these two deployment methods will be an operational decision based on conditions and capability. An adaptive approach should be used during the initial release, with a combination of methods tested depending on regional environmental conditions and operational constraints.

3.6 Carcass management

Carcass management, where required, would follow initial virus deployment. Carcass management is essential to achieve the following implementation objectives:

- management of environmental risks and no unacceptable impacts on MNES,
- management of risks to water quality for town water supply, stock and domestic water needs, irrigation, and cultural and recreational purposes, and
- effective and efficient management of carp virus deployment and carcass management.

Carcass management operations would be implemented within each CCA and would follow deployment operations.

Carcass management will be determined by the maintenance of water quality at levels that mitigate significant risks or specific outcomes. Where possible clear risk thresholds or triggers should be developed to guide operations.

Factors guiding selection of carcass management strategies include:

- predicted dead carp biomass,
- threats to the operability of infrastructure,
- social amenity,
- cost to deploy a method and return on investment,
- resource availability,
- waterway features,
- prevailing water quality in the operational area,
- flow and water movement,
- downstream and upstream assets and impacts,
- potential environmental impacts,
- forecast weather,
- unloading and transport access for equipment, and
- disposal option(s) available.

Technical Paper 6 outlines more specific carcass management strategies and methods. Detailed carcass management strategies will be determined in subsequent implementation planning stages based on specific regional conditions and policies.

To achieve efficient carcass management, methods that do not require manual collection and removal of carcasses should be prioritised where possible. Non-removal methods such as the use of water flow and wind conditions are less labour-intensive and more likely to be rapidly deployed, but may not always be achievable as a result of water availability and the degree to which flows at a given location can be manipulated or regulated.

3.6.1 Carcass management strategies

Potential carcass management strategies are outlined in the following sections. Some of these approaches involve manipulating live carp movements before infection and/or death, ultimately facilitating carcass removal. Section 4 (regional case studies) illustrates the potential application of some methods.

MANIPULATING MOVEMENT AND DISTRIBUTION OF LIVE CARP BEFORE VIRUS RELEASE

- Manipulating river flow and water level, including the use of permanent infrastructure (e.g. weirs, wetland regulators) to promote carp aggregation or concentration.
- Removing live carp from targeted sub-populations before virus release in areas where carp density and habitat traits pose risks to water quality, or in other areas where strategically effective.

MOVEMENT AND DISTRIBUTION OF INFECTED LIVE CARP

- Using permanent and temporary infrastructure (e.g. floating booms and nets) to restrict movement of infected live carp into areas or habitat types where water-quality impacts are more likely to occur and/or have serious consequences.
- Using permanent and temporary infrastructure to contain infected live carp in areas or habitat types where water-quality impacts are less likely to occur and/or have serious consequences.

MOVEMENT AND DISTRIBUTION OF CARP CARCASSES AND NUTRIENTS

- Using regulated water flows and permanent infrastructure to assist the flushing of carp carcasses and nutrients.
- Using regulated flow conditions and permanent and temporary infrastructure to intercept and remove carp carcasses at strategic locations.
- Using regulated water flows and permanent and temporary infrastructure to divert carp carcasses away from locations where water-quality impacts are more likely to occur and/or have serious consequences.
- Using permanent and temporary infrastructure to contain carp carcasses in situ at locations where water-quality impacts are less likely to occur and/or have serious consequences.

STRATEGIC REMOVAL AND DISPOSAL OF CARP CARCASSES

- Physically remove a proportion of carp carcasses from locations where their accumulation cannot be avoided and water-quality impacts are more likely to occur and/or have serious consequences.
- Physically remove a proportion of carp carcasses from strategic locations (e.g. where carcasses accumulate and there is ease of access or facilities for collection).

MITIGATING IMPACTS OF DECOMPOSING CARP CARCASSES

- Aerating waterways.
- Flushing cyanobacterial blooms.
- Native fish breeding and restocking plans (with particular focus on micro-endemic species and to mitigate potential prey-switching impacts, noting considerable logistical and biological challenges in some cases).

3.7 Implementation management and coordination

The NCCP will adopt existing cross-jurisdictional management systems that have been extensively applied in Australia and are used by all relevant authorities likely to be involved in carp biocontrol. These systems are relevant for both planned events (such as carp biocontrol) and emergency responses. These systems include:

- the Australian Interagency Incident Management System (AIIMS) Incident Control System (ICS) 2017 that underpins the management and leadership system for all emergency responses across Australia, and
- Biosecurity Incident Management System (BIMS) that is applicable for biosecurity emergency responses and largely aligns with AIIMS ICS except in areas where operations are specific to biosecurity (e.g. destruction and disposal).

Carp biocontrol implementation management should also be guided by the following principles:

- national coordination—led by the Commonwealth and delivered by each state/territory in which carp control is undertaken,
- scalability of management—each state/territory will expand and contract both scale and complexity of management in parallel with expansion and contraction of field operations,
- field operations within a functional management unit or CCAs—management will be situated primarily within local areas of operations (catchment or part thereof) with coordination at the whole-of-state/territory level,
- designated lead agencies—each jurisdiction undertaking carp biocontrol will nominate a single lead agency responsible for coordinating control activities including financial management,
- designated supporting agencies—jurisdictional lead agencies may nominate a supporting agency to represent their jurisdiction at national-level forums,
- jurisdictional delegation—each state/territory will use their authorities, delegations, and legislation to deliver the NCCP, and
- adoption of critical management systems.

Additional information on management arrangements, principles, and procedures is detailed in Technical Paper 6.

3.8 Integrated pest management

Viral biocontrol has been the NCCP's primary focus. Nonetheless, best-practice pest management usually requires an integrated approach. A range of carp control measures, including physical removal and genetic technologies, may have increased effectiveness when deployed against carp populations suppressed by viral disease. Physical removal methods could also be used to reduce carp populations before virus deployment to mitigate water-quality impacts in sensitive locations.

Integrating viral biocontrol with genetic biocontrol technologies is not currently feasible, as none of the potentially applicable genetic approaches are sufficiently advanced to enable field deployment. The Trojan Y Chromosome approach has been assessed as the most promising genetic control method (NCCP research project 3), but substantial investment in research and infrastructure (hatcheries) over approximately 10 years would be necessary to prepare even this technology for field deployment.

3.9 The role of science in management

An ongoing scientific management approach is critical for optimising biocontrol effectiveness and risk management. Remaining uncertainties about carp virus biocontrol could be reduced or managed by targeted additional research that could inform deployment strategies and ongoing management. During deployment, an adaptive, science-based operational approach will increase effectiveness and reduce risks and costs. For example, disease dynamics will probably differ slightly among regions and carp populations and a science-based management approach will be critical for detecting these differences and understanding their implications for biocontrol effectiveness.

To enable evidence-based adaptive management, the following actions and governance arrangements are recommended:

- a national technical advisory committee to frame and guide monitoring and evaluation and advise on initial deployment,
- national knowledge management and decision-support tools that can integrate modelling and monitoring data,
- regional investigations into carp aggregations and movements during planning periods,
- fish biology and water-quality expertise located within regional implementation teams, and
- a national monitoring and evaluation plan which includes the following assessments to inform ongoing management
  - viral effectiveness under varying environmental and carp demographic conditions,
  - impacts of carp decomposition on water quality,
  - the evolving relationship between carp and the virus, and
  - ecological responses during the deployment phase and in the longer term.

Science needs to be integrated into decision making and operational systems. The proposed adoption of AIIMS includes science and planning functions directly into decision making. Investing in an ongoing role for science in carp biocontrol is likely to significantly reduce implementation costs.

4 REGIONAL CASE STUDIES

4.1 Introduction

This section outlines how carp biocontrol could be implemented across four case study regions:

- the Lachlan catchment in New South Wales,
- the South Australian Riverland (Locks 1 to 3 on the Murray River),
- the mid-Murray (Barmah to Koondrook Perricoota), and
- the southern connected basin portion of the Murray and Murrumbidgee River systems (below Hume Dam).

Case-study locations do not span carp's entire eastern-Australian distribution, but focus on high carp biomass areas in the MDB's southern connected systems. Case study areas are high priority for virus deployment as described in section 3. Technical Papers 5, 6, 8, and 9 provide more detailed information.

Case studies were developed through numerous stakeholder workshops within each case-study area. Stakeholders involved in workshops included water managers, water users, environmental water holders, commercial fishers, tourism operators, landholders, local and state government officers, natural resource managers, and water utilities. Workshops used NCCP research results to inform planning and discussions.

Workshops had the following focus questions:

- How much of a problem are carp in the area?
- What are the opportunities for carp control in the area?
- What are the environmental values and locations in the area?
- Where are the social and infrastructure risks from carp biocontrol?
- Where should carp control be implemented and why?
- What are the risks from carp carcasses and how could they be managed?
- Do the NCCP biomass estimates for the area seem accurate?
- What are stakeholder views about use of the carp virus to control carp in the workshop area?

4.2 Lachlan case study

4.2.1 Description of area

The Lachlan case study area includes the entire Lachlan River catchment as shown in Figure 6. The Lachlan catchment encompasses 22 local government areas.

The catchment's main river is the Lachlan and its tributaries. Major off-channel waterbodies include Lakes Cargelligo and Brewster, and Cumbung Swamp. The Lachlan system does not connect directly through to the Murrumbidgee and Murray systems.

Parts of the Lachlan catchment are regulated with permanent waterbodies and flows but substantial ephemeral areas remain. There are many regulators and weirs, including major dams, on the Lachlan River and its tributaries.

4.2.2 The carp problem

The Lachlan catchment has a significant carp problem. Carp are widespread through the catchment, and are most abundant in permanent off-channel waterbodies. There are 70 carp sub-populations located throughout the catchment, highlighting the system's disconnected nature. Some parts of the catchment above Wyangala Dam remain carp free.

High carp densities (more than 500 kg/ha) occur in sections of the Lachlan river from Forbes to Hillston and in the major off-channel waterbodies. Carp biomass and its distribution within the catchment as estimated during summer 2017–18 is shown in Table 3 (drawn from NCCP research project 1).

Table 3: Indicative biomass of European Carp, *Cyprinus carpio*, and its distribution in the Lachlan River catchment, New South Wales. All biomass estimates in this table are drawn from NCCP research project 1.

Location	Tonnes
Upstream of Wyangala	145
Wyangala to Jemalong	1,901
Lake Cowal and upper drainage area	917
Jemalong to Brewster	866
Lake Cargelligo	208
Lake Brewster	1,077
Willandra Creek	7,491
Brewster to Great Cumbung	4,977
TOTAL	**17,582**

Carp abundance in the Lachlan catchment varies considerably in response to hydrological conditions. During dry conditions carp become concentrated into permanent waterbodies or die in ephemeral systems.

Lachlan River. Photo Mattinbgn (Wikimedia).

4.2.3 Risks assessment

Table 4 summarises the main risks and impacts associated with carp biocontrol in the Lachlan catchment, with mitigation options.

Table 4: Risk summary, with mitigation options, for carp biocontrol in the Lachlan River catchment, New South Wales.

Risk	Possible impacts	Risk mitigation
Environmental		
Native fish nursery sites (e.g. Agassiz's Glassfish [olive perchlet] and Southern Pygmy Perch).	Low if water quality maintained and normal Lachlan River flows.	Strategic carcass management upstream by booms.
Macquarie Perch breeding in the Abercrombie River.	Low if water quality maintained and normal Lachlan River flows.	Strategic carcass management upstream by booms.
Pelican rookery at Lake Brewster.	Could be impacted if water quality not maintained.	Virus deployment during a non-breeding season.
Lake Cowal.	Low due to variable carp populations.	No virus deployment.
Endangered Ecological Community downstream of Wyangala Dam.	Low due to cold water temperatures.	No virus deployment.
Social		
Town water offtakes.	Low due to treatment capability.	Water treatment and carcass management.
Major towns: Forbes, Booligal, Condobolin, Hillston and Cargelligo.	May impact amenity.	Focused carcass management.
Lake Brewster.	Low as no public access. Could affect water quality.	Water regulation to manage carcass impacts.
Lake Cargelligo.	High amenity value and likely high number of carcasses. Possible short-term impacts.	Use of wind and booms to corral carcasses to specific shorelines to reduce impacts.
Irrigation offtakes.	Numerous offtakes likely low impact.	Intake screening.
Weirs.	Low impact.	Operational approvals.

4.2.4 Implementation constraints

The Lachlan catchment has several characteristics that will shape and constrain carp biocontrol operations. In the catchment's ephemeral streams, carp population density is sufficiently low that virus deployment may not be warranted. A substantial portion of the Lachlan River is also affected by cold-water pollution from Wyangala and Carcoar Dams. Water temperatures in these reaches are below the permissive range for the disease caused by the carp virus.

The Lachlan River is not navigable, so physical collection of carp carcasses would generally be restricted to shore-based operations. Adjoining major floodplain waterbodies are navigable but have extensive shallow areas that would restrict operations.

Access to some parts of the catchment is restricted by private property and limited public road access. Operations would therefore be confined to strategic locations at weir points and settlements.

4.2.5 Management arrangements

Carp biocontrol operations for the entire Lachlan catchment could be managed through one CCA (Figure 4). Central command could be located in Forbes and forward commands could be located at Condobolin, Hillston and Oxley. The Oxley forward command could be included in the Murrumbidgee CCA. Most operational activity would occur at locations along the 300 kilometres of river between Forbes and Booligal.

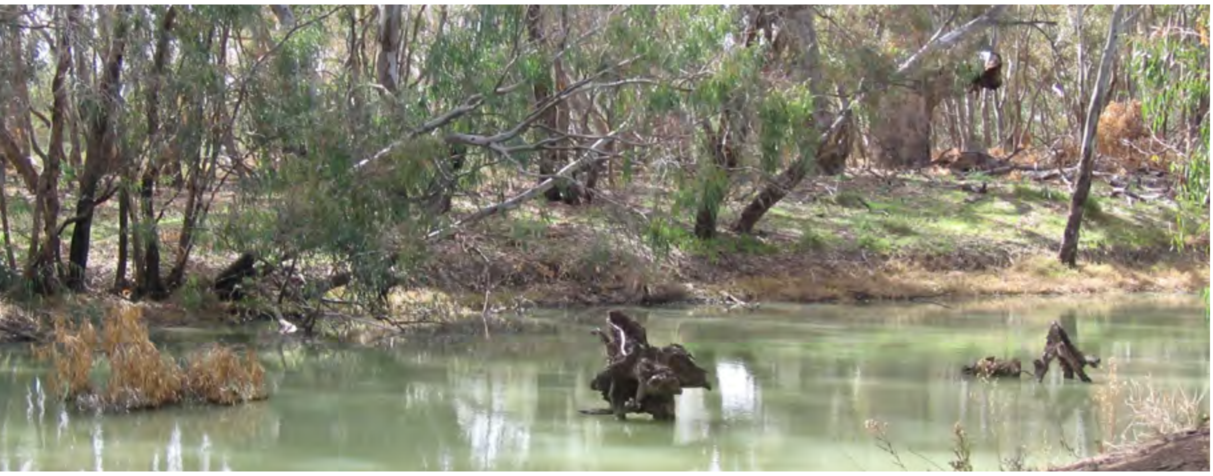
4.2.6 Carp virus deployment strategy

The following sections of the Lachlan catchment would be targeted for carp virus deployment:

- Lachlan River and adjoining systems between Forbes and Booligal at numerous weir points,
- Lake Brewster,
- Lake Cargelligo,
- Booberoi Creek, and
- strategic locations on the Abercrombie River where carp aggregations are known to occur.

Carp aggregations also occur below Wyangala Dam and from Carcoar Dam to Forbes, but these areas are affected by cold-water pollution. Biocontrol using the carp virus therefore may not be successful in these reaches.

The areas listed above hold the Lachlan catchment's highest carp biomass and are also carp spawning sites. Risks in these areas can be managed with appropriate coordination and resourcing. These locations encompass more than 20 carp sub-populations.



Lachlan River. Photo Mattinbgn (Wikimedia).

4.2.7 Carcass management strategy

Carcass management in the Lachlan catchment would focus on areas where the virus had been deployed into carp aggregations and where risks are highest. Operations more generally would focus on the 300-kilometre zone between Forbes and Booligal.

Only a proportion of all carcasses may need to be removed from the river providing favourable flow conditions are available to maintain water quality. More carcasses may need to be removed from Lakes Brewster and Cargelligo, where flow is limited or non-existent. The following measures and tactics could be applied to manage risks:

- strategic cross-river booms to corral carcasses drifting downstream into shore-based removal locations,
- containment booming and removal of carcasses from aggregations below weir pools, and
- regulation of Lake Brewster to isolate carp carcasses.

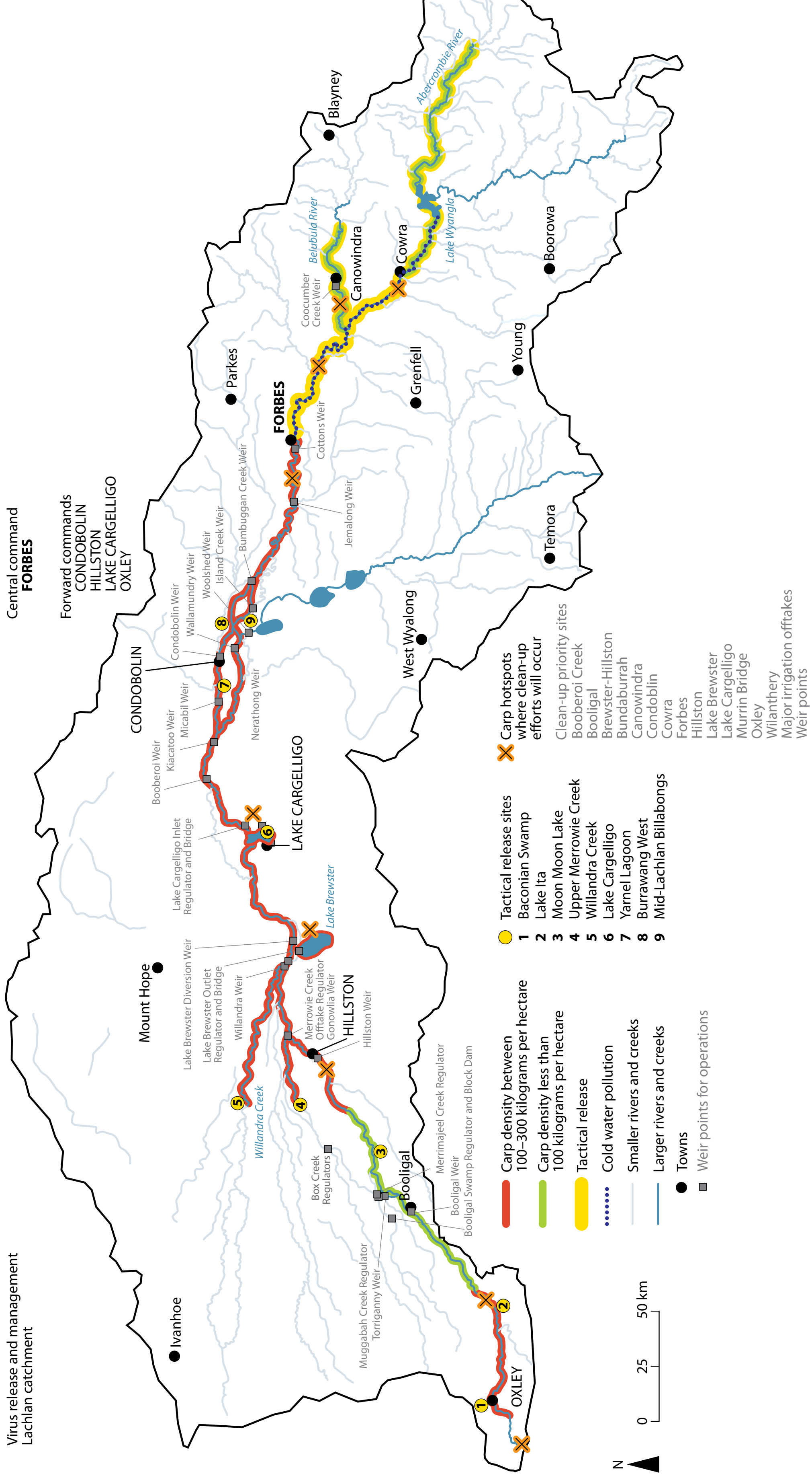
Workshops highlighted considerable opportunities to synchronise water-regulation planning with potential virus deployment. Using water releases to assist with carcass management would reduce the need for costly and laborious manual carcass removal activities, but river managers are unlikely to be able to alter operations specifically for carp control.

4.2.8 Conclusions

NCCP research and stakeholder workshops indicate that biological control using the carp virus could effectively reduce carp abundance in the Lachlan catchment. Strategic approaches to carcass management generally appear logistically achievable (with some constraints), and are expected to mitigate risks. If carp biocontrol proceeds, operations in the Lachlan catchment would be focused on various locations along the 300-kilometre river stretch between Forbes and Booligal.

Expert workshops emphasised the importance of communications and engagement within the region in advance of, and during, operations. There is considerable local knowledge and expertise in the region that should be utilised in biocontrol implementation. Traditional Owners and recreational fishing groups have expressed interest in planning, decision making, and operational participation.

Figure 6: Potential carp biocontrol implementation in the Lachlan catchment.



4.3 Riverland/lower Murray Lock 1 to Lock 3 case study

4.3.1 Description of area

The mid-Murray case study covers the Murray River between Locks 1 and 3, including Lake Bonney. Carp attain high population densities in the case study area, inhabiting the Murray River channel, adjoining wetlands and oxbows, and Lake Bonney. Commercial activity in the region includes extensive irrigated agriculture, river-based tourism, and commercial carp harvesting in Lake Bonney. Major townships include Waikerie and Morgan.

4.3.2 The carp problem

Over the 2017–18 summer, carp densities in the case study area ranged from 200–500 kg/ha (NCCP research project 1). Carp dominate waterbodies such as Lake Bonney.

4.3.3 Risk assessment

Table 5 summarises the main risks and impacts associated with carp biocontrol in the Riverland/lower Murray area, with mitigation options. Risks are substantially social in nature.

Table 5: Risk summary, with mitigation options, for carp biocontrol between Locks 1 and 3 in the lower Murray River, South Australia.

Risk	Possible impacts	Risk mitigation
Environmental		
Off-channel regulated wetlands.	Invertebrates and amphibians, Murray Cod.	Regulation of flows, carp attractants, carcass removal.
Oxbow systems e.g. Devils Pound.	Invertebrates and amphibians. Reduced dissolved oxygen, algal blooms.	Carcass removal with boats.
Murray River channel.	Murray Cod.	Strategic booms and upstream collection of carcasses.
Social		
Houseboats (hundreds).	Odour, amenity.	Strategic booms and upstream carcass collection. Effectively communicating the extent of affected areas to potential customers.
Waikerie township.	Odour, amenity.	Strategic booms and upstream carcass collection. Small boat carcass removal.
Holiday shacks between Morgan and Blanchetown and off-channel marina.	Odour, amenity.	Strategic booms and upstream collection of carcasses.
Private irrigation offtakes (domestic use).	Water quality.	Screens on intake structures.
Major irrigation offtakes.	Water quality.	Screens on intake structures.
Morgan Lagoon.	Odour, amenity.	Booms and small boats to corral carcasses for collection.
Lake Bonney.	Six hundred tonnes of carp. Odour and amenity.	Booms and small boats to corral carcasses to boat ramps and edges for operations.

4.3.4 Implementation constraints

This case study area imposes several implementation constraints associated with access and infrastructure. Large shallow wetlands, lakes, and oxbow systems are difficult to access with boats and shore-based equipment. Lake Bonney also presents a challenge for operations. The lake is large and shallow with high carp biomass and high salinity. Lake Bonney is also subject to intensive recreational use. The lake experiences strong winds that will affect carcass management operations by blowing dead carp to downwind locations. The wind also naturally oxygenates the lake, potentially mitigating water-quality impacts.

Major river regulation infrastructure is located at each of the locks. Carp carcasses will likely concentrate at these locations. Carp control operations must be conducted without affecting river operations.

4.3.5 Possible pre-deployment density reduction

The lower Murray contains high carp densities. Consequently, the 40–60% carp reductions expected to follow virus deployment may still leave higher densities than would occur in less resilient populations. While any carp reduction has the potential to deliver ecological benefits, such benefits may be enhanced if virus deployment in the lower Murray is preceded by targeted, intensive harvesting to reduce carp 'starting density'. Assessing the timing, magnitude, and operational planning aspects of this 'pre-fishing effort is beyond the NCCP's scope, but could usefully be investigated by some limited additional modelling (NCCP research project 4).

4.3.6 Management arrangements

Operations may involve a control centre located at Waikerie and forward command locations at Lake Bonney and Morgan.

4.3.7 Carp virus deployment

The carp virus should be deployed through the whole river system and adjoining wetlands and oxbow systems.

4.3.8 Carcass management

Priority carcass management locations include areas above water treatment plants, water offtakes, areas around townships and holiday shacks, locks, spot locations in which carcass accumulation is likely (e.g. Pelican Point), and wetlands holding environmental values.

4.3.9 Conclusions

The Riverland area has high carp biomass that could be substantially reduced by carp biocontrol. These reductions could potentially be enhanced by targeted, intensive harvest before virus deployment. Risks in this area are predominantly social, reflecting high levels of tourism and recreational use.

Social risks could be managed with strategic boom placement and collection of carp carcasses. Screens on irrigation intakes provide a solution to mitigate risks such as pump blockage. Lake Bonney would require more sophisticated carcass management using corralling and booming in navigable parts of the lake to direct carcasses to convenient collection points. Workshops highlighted the importance of local communication and engagement, especially with the tourism sector. Workshops also highlighted the importance of working with water authorities and local governments in potential carp virus biocontrol.

4.4 Mid-Murray case study

4.4.1 Description of area

The mid-Murray case study area extends from Picnic Point to the Gunbower wetlands on the Murray River. This section of the Murray forms a highly connected permanent system with large adjoining wetlands including Barmah and Moira Lakes, Gunbower Creek and associated lagoons, and Kow Swamp. The area's flow patterns and geomorphology are ideal for carp.

4.4.2 The carp problem

The region supports high carp densities and spawning hotspots, including Barmah and Moira Lakes and Gunbower Creek. The area's carp population tends to concentrate at these spawning sites during spring and early summer.

4.4.3 Risks assessment

Figure 7 provides a spatial scan of the risks associated with virus release in the study area. Table 6 summarises these risks at particular locations.

Table 6: Risk summary, with mitigation options, for carp biocontrol in the mid-Murray River region (Pelican Point to Gunbower Forest wetlands).

Risk	Possible impacts	Risk mitigation
Environmental		
Ramsar wetlands (Barmah).	Endangered species, bird nesting.	Regulation of flows, timing of virus deployment, strategic carcass removal, carcass dispersal.
Gunbower Creek and lagoons.	Bird nesting, wetland ecology.	Carcass removal with boats.
Kow Swamp.	Bird nesting.	Flow regulation, strategic booms and upstream collection of carcasses, carcass removal.
Social		
Kow Swamp.	Significant cultural site, water quality.	Flow regulation, strategic booms, and upstream collection of carcasses.
Echuca township and associated tourism and recreation including events.	Odour, amenity.	Strategic booms and upstream collection of carcasses, regular small boat carcass removal.
Torrumbarry weir pool.	Odour, amenity.	Strategic booms and upstream collection of carcasses, regular small boat carcass removal.
Gunbower small landholdings.	Odour, amenity, water quality.	Screens on intake structures.
National irrigation channel offtake.	Water quality.	Strategic booms and upstream collection of carcasses.

4.4.4 Possible pre-deployment density reduction

The mid-Murray case-study area holds generally high carp densities. Consequently, the 40–60% carp reductions expected to follow virus deployment may still leave higher densities than would occur in less resilient populations. While any carp reduction has the potential to deliver ecological benefits, such benefits may be enhanced if virus deployment in the mid-Murray is preceded by targeted, intensive harvesting to reduce carp 'starting density'. Assessing the timing, magnitude, and operational planning aspects of this 'pre-fishing' effort is beyond the NCCP's scope, but could usefully be investigated by some limited additional modelling (NCCP research project 4).

4.4.5 Implementation constraints

The study area's features and values impose environmental, physical, and social constraints on biocontrol implementation. Important considerations include:

- high levels of year-round tourism and recreational use,
- large shallow inaccessible waterbodies such as Kow Swamp,
- significant cultural values,
- Ramsar wetlands and endangered species,
- requirement to maintain navigable waterways,
- numerous shallow lagoons with poor physical access and high carp biomass, and
- numerous small adjoining landholders.

4.4.6 Management arrangements

The regional control centre could be located at Echuca with forward command centres at Picnic Point and Cohuna.

4.4.7 Carp virus deployment

Virus deployment is illustrated in Figure 8. The case study indicates that eight major carp sub-populations should be targeted for virus deployment.

4.4.8 Carcass management

Carcass management in the region is illustrated in Figure 9. Managing high-risk zones around the Echuca township and Gunbower and Torrumbarry weirs will require adequate resourcing. Cross-channel booms that corral and direct carp carcasses to collection points would constitute the main management method. Booms would be located upstream of high-risk areas. Around Echuca township regular small boat operations would be required to remove as many carcasses as practical. At Barmah and Moira Lakes, risks could be substantially managed by carcass dispersal using flow regulation supplemented by strategic carcass removal at aggregation locations.

4.4.9 Conclusions

The mid-Murray case study illustrates that the carp virus could be deployed and managed successfully in a high-use, complex, connected system with important environmental and social values. The case study area poses some significant challenges to implementation, especially in locations such as Kow Swamp and Gunbower Creek. These locations will require further implementation planning. As with the lower Murray, carp biocontrol outcomes in the mid-Murray could potentially be enhanced if targeted intensive harvesting occurred before virus deployment. Carp biocontrol in the mid-Murray case study area would be relatively costly, reflecting the area's complexity and high carp biomass.

Figure 7: Mid-Murray carp biocontrol case study risks and opportunities scan.

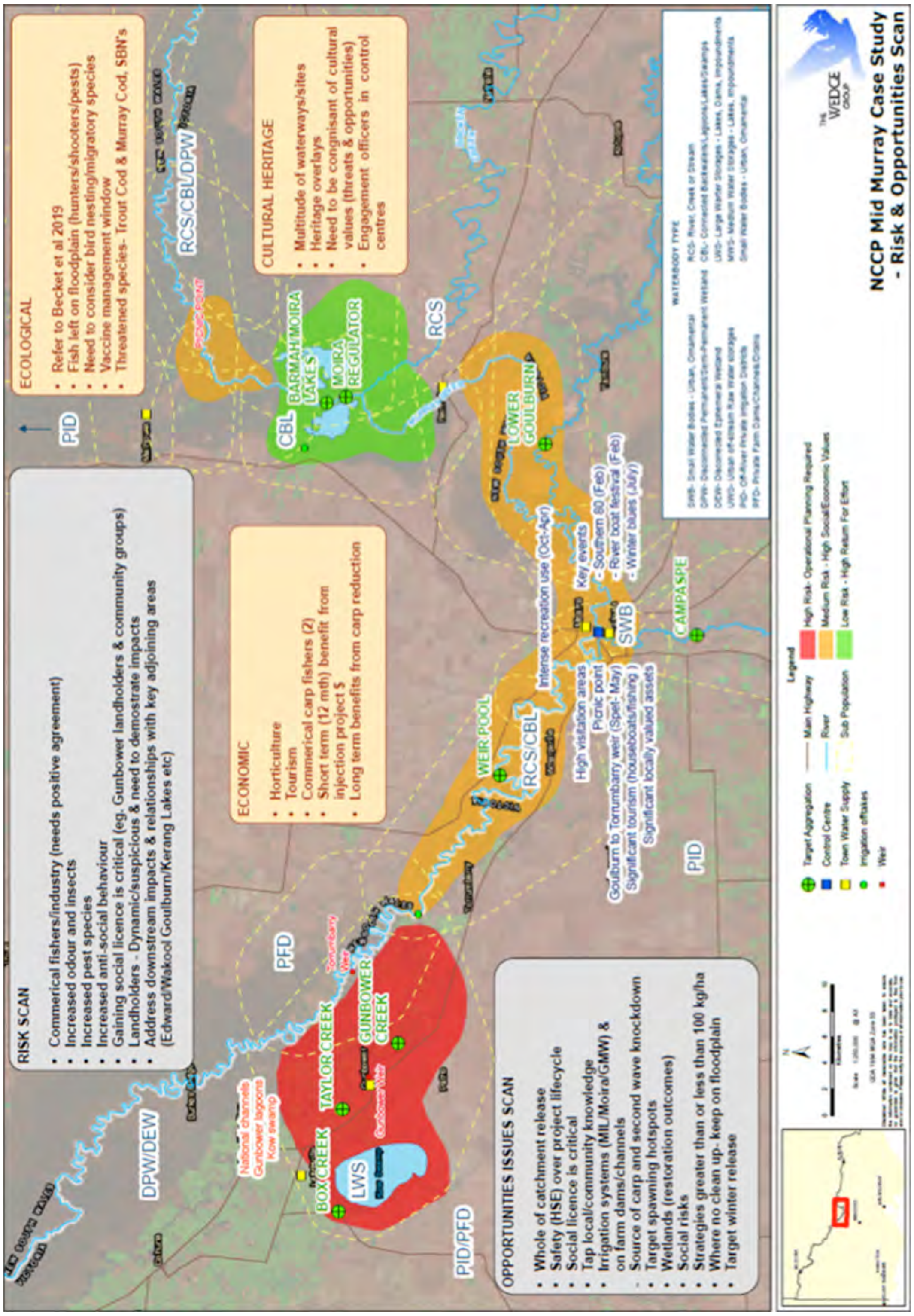


Figure 8: Mid-Murray deployment strategy into carp sub-populations.

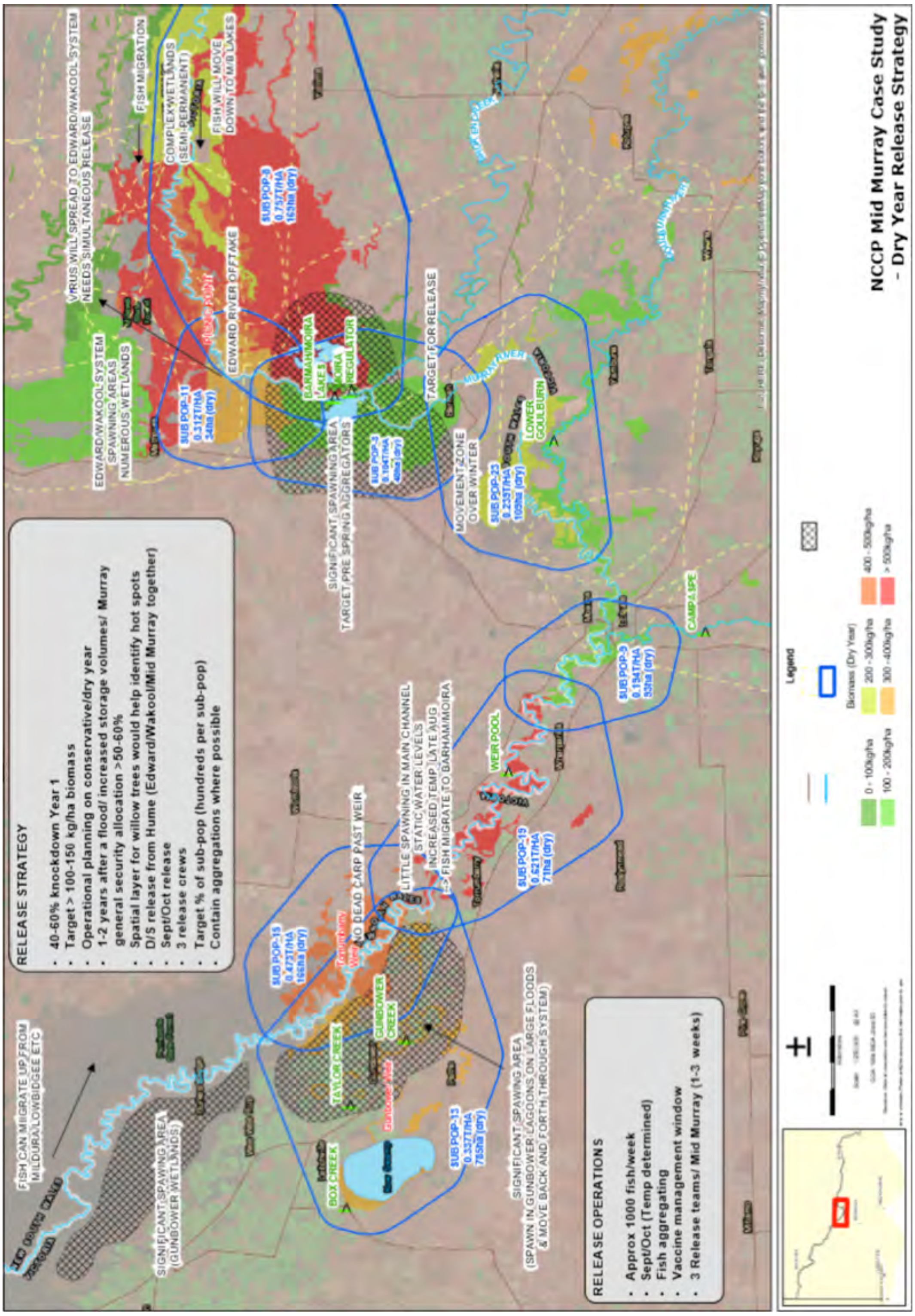
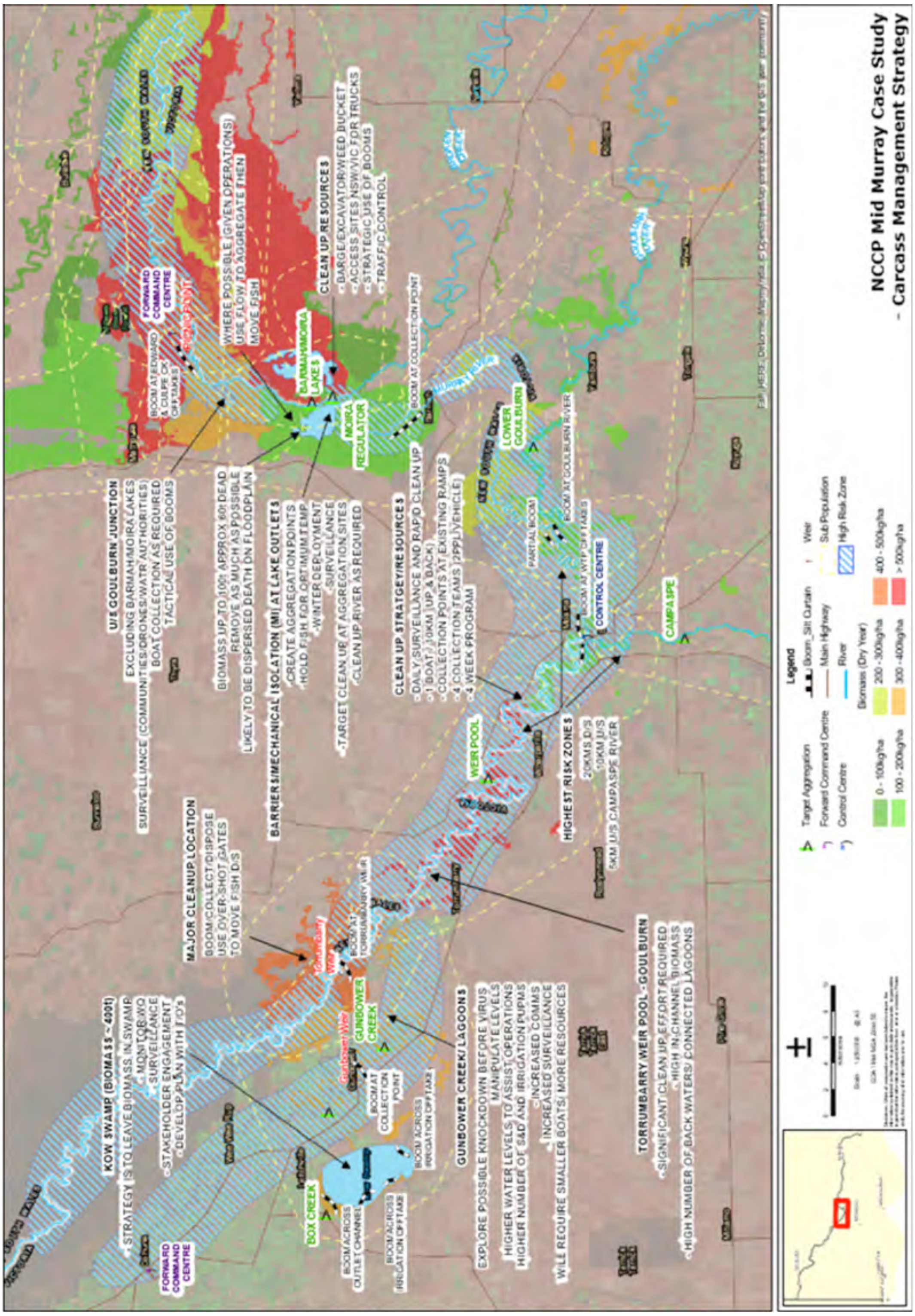


Figure 9: Mid-Murray carcass management strategy.



4.5 Murray and Murrumbidgee system below Hume Dam case study

4.5.1 Description of area

The case study area represents the southern zone for initial deployment of the carp virus, and encompasses the previous mid-Murray case study, demonstrating how carp biocontrol could be scaled up. This area contains the highest carp biomass and densities of all the case study areas. The area also includes anabranch systems and the lower reaches of tributaries into the main rivers. Parts of the area have high environmental values including Ramsar wetlands.

4.5.2 The carp problem

Carp are abundant in both Murray and Murrumbidgee River systems. During summer 2017–18, carp densities in the area ranged from 100–500 kg/ha (NCCP research project 1). The case study area encompasses numerous carp aggregation and spawning hotspots.

4.5.3 Risk assessment

Figure 10 summarises high-level risks for virus deployment and management. Highest risk areas are located in the lower sections of the Murray River where carp biomass is greatest. Other high-risk areas include waterbodies and reaches that experience periodic low flows, such as the Edward-Wakool anabranch system (EW1 in Figure 10) and the lower Murrumbidgee wetlands (MB6 in Figure 10).

4.5.4 Possible pre-deployment density reduction

This case study area holds some of Australia's highest carp densities. Consequently, the 40–60% carp reductions expected to follow virus deployment may still leave higher densities than would occur in less resilient populations. While any carp reduction has the potential to deliver ecological benefits, such benefits may be enhanced if virus deployment in the Murray and Murrumbidgee system below Hume Dam is preceded by targeted, intensive harvesting to reduce carp 'starting density'. Assessing the timing, magnitude, and operational planning aspects of this 'pre-fishing' effort is beyond the NCCP's scope, but could usefully be investigated by some limited additional modelling (NCCP research project 4).

4.5.5 Management arrangements

Potential management arrangements for operations are outlined in Figure 10. All operations could be managed in four CCAs or regions. Each region would have a central command and at least two forward command locations.

Coordination would be required across regions at the state/territory level. During operations, resource deployment may at times need to be concentrated on particular sites to address emerging risks. Surge operational capacity will also be required.

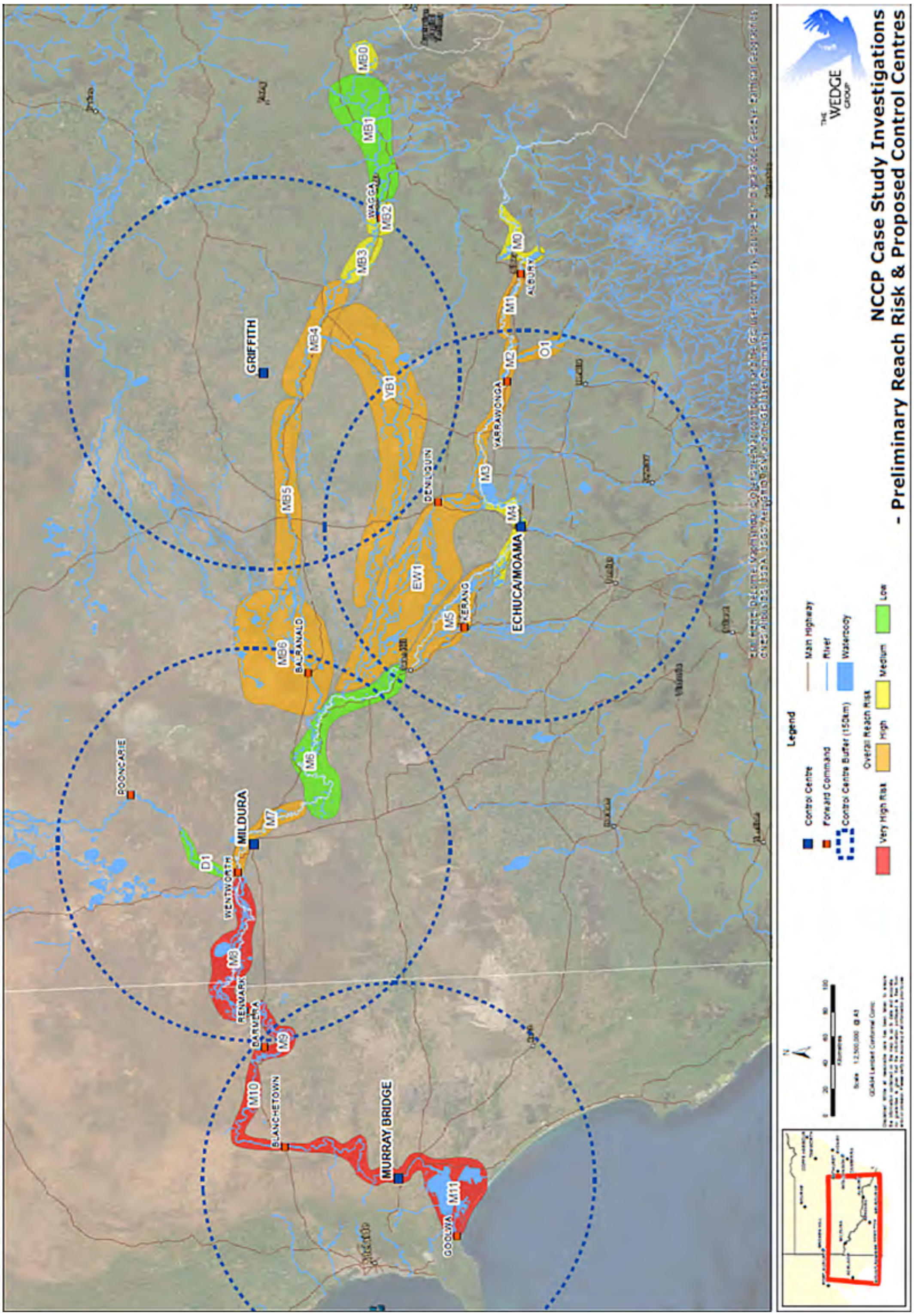
4.5.6 Operational costs

The cost of implementing carp biocontrol in the case study area was estimated at approximately $190 million over three years with range of assumptions (NCCP planning investigation 5).

4.5.7 Conclusions

This case study highlights the potential for effective and efficient management of carp biocontrol operations across large areas by directing and coordinating operations through smaller regions.

Figure 10: Murray and Murrumbidgee NCCP implementation to address risks.



5 COSTS AND BENEFITS OF CARP CONTROL

5.1 Introduction

This section summarises information from NCCP research assessing:

- the current costs and benefits consequent upon the presence of carp in Australia (i.e. the 'status quo'),
- costs and benefits arising from implementing a biocontrol program using the carp virus, and
- longer-term costs and benefits associated with reduced carp abundance, if a carp control program was successful.

Both market (i.e. readily monetised) and non-market (i.e. less readily monetised, yet still valuable) costs and benefits were considered.

Costs and benefits of carp biocontrol are difficult to assess accurately because carp:

- inhabit a diverse range of Australian aquatic ecosystems,
- vary markedly in abundance among different habitats, and within a given habitat through time, and
- cause habitat-specific ecological impacts that interact with a range of other, non-carp stressors.

Consequently, developing cost-benefit assessments for a limited number of case study locations is likely to provide more meaningful information than a nation-wide estimate with a large error margin. The case study approach also provides a methodological 'template' that can be applied to additional regions as required.

Research under the NCCP has identified that, while the virus has potential to reduce and suppress carp abundance, ecological outcomes in areas with very high carp densities could potentially be enhanced by targeted and intensive carp harvesting before virus deployment. The NCCP was explicitly focused on assessing the feasibility of carp biocontrol, so, beyond a general acknowledgement of the potential usefulness of an integrated approach, costings and plans for a targeted 'fish down' are not presented in this report. Any costs incurred by such an initiative would need to be quantified separately. Using targeted harvesting to reduce carp densities before virus deployment could bring both additional costs and opportunities to reduce expenditure. For example, carcass management activities could potentially be reduced in some areas if carp populations were 'thinned' by harvesting before biocontrol operations began.

5.2 Costs of carp in Australia

Impact costs of carp in Australian waterways have been assembled from available data under the following themes:

a. reduced water quality,
b. erosion and increased incidence of algal blooms,
c. impacts on invertebrates and both native and exotic aquatic plants,
d. competition with native fish species, and
e. introduction of pests and diseases.

Total impact costs were generated by including maintenance costs for water treatment and infrastructure, planning and management costs for affected water and land, opportunity costs for tourism, and secondary impacts for primary producers (NCCP research project 19).

Cost assessments indicate that carp do not create substantial market costs in the Australian economy (NCCP research project 19). Rather, most direct and indirect carp impacts are more strongly aligned with non-market costs. Irrigation sectors, water authorities, and primary producers did not report carp as a significant financial threat. Water-treatment plants reported an estimated average increased water-treatment cost of $211,494 per plant per year due to source sedimentation. This 'per-plant' figure represents a total annual cost of $21,360,894 for treatment of turbid water when multiplied across 101 treatment plants in New South Wales and Victoria (NCCP research project 19). However, the proportion of this total sedimentation directly attributable to carp is unknown.

Non-market impact costs were calculated based on a per-household willingness to pay (WTP) for primary changes over 10 years following carp suppression. These changes were identified by an ecological expert elicitation panel, with units of change identified as additional expected native fish per kilometre of river, per expected additional 10,000 hectares of wetland free of carp, and per additional expected 1000 waterbirds. The range of possible total WTP calculated for Australia is $24,372–$2,076,074,706 for fish, $39,187–$313,498,906 for wetlands, and $5,422–$601,833,024 for birds (NCCP research project 19).

Calculating total WTP of Australian households requires predicting how many units of expected environmental outcomes will be realised for each affected area. To do so with the greatest accuracy, using the implementation strategy as a guide, a tailored clean-up strategy must be developed, informed by logistical considerations specific to the area, and water-quality implications predicted by the same or 'best fit' case-study area. Each area to be considered must then synthesise epidemiological predictions from the same or 'best-fit' case-study area, and ecological response predictions from the same or 'best-fit' case-study area. Two case study examples are provided later in this section.

In addition to market and non-market surveys, a literature review of economic, environmental and/or social impacts related to the direct and indirect impacts of carp was undertaken. Estimates associated directly with the impact costs of carp ranged from $11.18 to $500 million per annum Australia-wide. The latter estimate must be viewed with caution, as the methods used to calculate it are not clearly described. Additional estimates were made for the value of impacts where carp may be a contributing factor, including erosion damage, reduced amenity, biodiversity impacts, and water-quality impacts including algal blooms. Erosion was estimated to cost irrigators $1.9 million over eight years for channel repairs, while loss of consumer surplus due to algal blooms was estimated to cost $185 million to $250 million per annum. Amenity, biodiversity, and water-quality impacts were assessed based on a household WTP for qualitative or quantitative improvements. Willingness to pay for a 1% improvement to an attribute ranged between $0.46 to $13.27. Improvements in amenity also attracted a one-off WTP of $28.75 to $54.16 for recreational fishing, and $59.97 to $104.07 for rivers to be 'swimmable'.

5.3 Benefits of carp in Australia

Carp in Australia generate financial benefits through three key uses; recreational fishing, commercial fishing, and the ornamental koi industry. A small but active community of Australian recreational fishers specialise in targeting carp (and other species) using coarse-fishing techniques (NCCP research project 13). Other recreational fishers catch carp as part of more general fishing activity, in which carp may or may not be one of the target species (NCCP research project 13). Recreational fishers who like or prefer catching carp are likely to constitute a small proportion of total recreational fishing participation in Australia (NCCP research project 19). The economic contribution of recreational carp fishing in Australia has not been estimated. Positive economic impacts from carp fishing competitions (e.g. 'carp-buster' events), also not quantified, may benefit communities through generation of tourism industry income. Importantly, benefits associated with community-based carp-buster events may arise largely from participants' desire to 'get rid of carp' (NCCP research project 19).

Commercial exploitation of carp centres around two key products; fertiliser (Charlie Carp) and carp for table consumption in Australia and abroad. Profitability of carp fishing in Australia has not been estimated.

The commercial ornamental koi sector differs from the other sectors discussed here in that it relies on maintenance of captive imported and locally bred animals rather than preservation of wild populations of carp. The legality of owning and transporting carp varies from state to state in Australia.

5.4 Regional costs of carp biocontrol

The whole Murray and Murrumbidgee systems and the mid-Murray case studies were used to estimate the cost of implementing a carp biocontrol program using the carp virus. The total cost estimate for the whole Murray and Murrumbidgee systems is roughly $190 million. The rough cost estimate for the mid-Murray is approximately $14 million. These costs are approximate and indicative only, and reflect 2019 costings and numerous assumptions. If governments choose to continue work towards a final decision on whether or not carp biocontrol should proceed, the methods and processes used to develop these estimates can be used as a template for refining cost estimates.

The costs described here are based on the following key a ssumptions:

- one year for implementation planning and coordination at the regional level,
- two years of initial deployment,
- the second year of initial deployment assumes 60% of year one costings,
- twelve months of community engagement and establishment of regional operations platforms,
- six months of operations in each year of deployment, with peak resource application September to December annually,
- deployment in a year with average water levels,
- deployment will target populations where average biomass exceeds 150 kg/ha,
- mortality rate of 60%, and
- clean-up operations targeting identified medium- and high-risk (ecological and socio-economic) reaches.

Potential impacts not included in the costs of virus release include:

- loss of amenity for regional communities and tourists due to fish carcass odour in affected waterways,
- increased incidence of algal blooms and/or blackwater events that may reduce aesthetic and recreational amenity values and biodiversity for some affected waterways,
- increased bird mortalities associated with botulinum toxin cycles if carcasses and/or water quality in wetlands and other low-flow waterbodies cannot be managed,
- increased water treatment costs resulting from dead fish blocking plant inlets and/or above-threshold ammonia levels from decomposing fish, and
- increased costs for protection of the koi industry.

Pre-release costs were calculated for factors including

- extensive local consultation and stakeholder engagement,
- local statutory planning functions,
- establishment of operational posts (control centres and forward command centres),
- production, transport, and storage of virus,
- training of virus deployment personnel,
- training and response resources for clean-up personnel, and
- establishment and maintenance of communication channels between monitoring, release, and clean-up personnel.

Virus release costs include:

- virus transport and distribution,
- financial remuneration for personnel, and
- hire and/or purchase of tools and equipment.

The two potential viral deployment methods described in section 3.5 incur similar costs.

Following infection of carp populations, costs are largely associated with carcass management, monitoring, communications, and associated operations including:

- contracting personnel to coordinate, patrol, and collect carp from waterways,
- disposing of dead carp, including hire and/or purchase of equipment to direct, confine, collect, or contain dead carp,
- planning and coordinating dead carp disposal including transport routing, access, and designation/design of disposal areas, carcass transport and processing, and
- sourcing and retaining 'surge' resources for response to unforeseen events.

Ongoing (post initial deployment and clean-up) costs include:

- monitoring, assessment, and reporting of carp biomass and aggregation dynamics, hydrological conditions, and long-range meteorological predictions to ensure successful long-term suppression,
- additional modelling, or use of existing models for ongoing management,
- capacity to produce, transport and store virus, and maintain effectiveness through targeted follow-up activities,
- monitoring and reporting virus efficacy (transmission, virulence, potential emergence of host resistance),
- water-quality monitoring and reporting for human and livestock use,
- ecological health monitoring and evaluation of carp suppression,
- monitoring and evaluation of workplace health and safety effectiveness for personnel,
- regular reporting of carp control activities to key stakeholders, and
- monitoring community attitudes towards carp control activities and results for development of effective communication.

5.5 National costs

Accurately identifying a total national cost for carp biocontrol implementation is not currently possible. A total national cost estimate could be generated by adding jurisdictional and national costs to regional costs. Key factors to consider in developing regional costs include:

- A region's geographic, landscape, and ecological features, including characteristics of its carp populations. For example, costs are likely to be highest in regulated systems of the southern MDB, as these have high carp biomass and could receive carp decomposition products from upstream. Consequently, substantial risk mitigation efforts may be required in this region. Tailored risk mitigation approaches are also likely to be needed for ephemeral systems in the northern portions of the MDB, given the particular risk profile presented by these habitats.
- Can a region provide enough financial, technical, and human resources on its own, or will these need to be subsidised?
- Can regions coordinate to mitigate costs and risks?
- Does a region lie within a jurisdiction that has/can obtain contingency and surge resources if needed?
- How extensive will year two and follow up operations need to be?

5.6 Cost-mitigating factors

Opportunities may exist mitigate the costs associated with carp carcass management by using carcasses as raw material for marketable products rather than placing them in landfill (or otherwise disposing of them). To explore potential economic uses of carp carcasses, an NCCP research project trialled several potential products and processing techniques (NCCP research project 17). Products identified as potentially feasible were subject to further cost-benefit analysis. Composting, rendering as mixed inputs to animal feeds, and hydrolysate were the most commercially viable options. Composting was identified as having the greatest net cash benefit per kg input of carp ($0.438–$0.338) (NCCP research project 17).

Before developing plans to utilise carp carcasses, potential constraints imposed by jurisdictional environmental protection legislation will need to be considered. For example, in some Australian states, the carcasses of carp killed by the virus may be classified as industrial waste, potentially limiting options for their use.

6 FEASIBILITY ASSESSMENT

The feasibility of proceeding towards carp biocontrol implementation is assessed against the criteria detailed in Table 7. The NCCP assesses scientific and operational feasibility. Feasibility criteria involving financial and policy considerations are not assessed, as these are matters for consideration by governments. The feasibility criteria detailed in Table 7 cover the critical questions for carp biocontrol based on the aims of biocontrol programs generally, previous research, input from NCCP advisory groups, and NCCP research results.

The ecological benefits of carp biocontrol are not included as a feasibility criterion, as accurately assessing the ecological benefits of carp reduction is complex and context specific (Technical Paper 1; NCCP research project 18). The NCCP is underpinned by the fundamental assumption that carp have adverse impacts on freshwater ecosystems, consistent with extensive research and evidence, and that reducing these impacts will improve environmental outcomes (see section 1, and Technical Paper 1).

Table 7 outlines each criterion and any relevant standards defining it.

Table 7: Feasibility criteria and relevant standards.

Feasibility criteria	Definitions and standards
1. Will carp virus biocontrol be effective?	
That there will be widescale reduction and suppression of carp populations for the medium to long term (5–10 years) in Australian aquatic ecosystems.	Long-term carp suppression is defined as 5–10 years, based on the likely shorter suppression durations afforded by other currently available methods. 'Widespread' is defined as occurring across major catchment systems and multiple jurisdictions. Modelled outcomes are likely to suppress carp populations by 40–60% on average.
2. What are the carp virus biocontrol risks and how can they be managed?	
The carp virus will not affect human health, or domestic or stock animal health, as a result of direct infection (i.e. this criteria does not relate to potential secondary impacts, such as those associated with degraded water quality).	The World Organisation for Animal Health (OIE) defines a notifiable impact as occurring if a species is infected by the pathogen in question. Infection is defined as "the entry and development or multiplication of a pathogenic agent in the body of humans or animals".
There are very low risks that the carp virus will infect and cause disease and/or sub-clinical effects in any non-target species.	The OIE defines a notifiable impact as occurring if a species is infected by the pathogen in question. Infection is defined as "the entry and development or multiplication of a pathogenic agent in the body of humans or animals".
There will be no significant impacts on the quality of water used for town water supplies, stock and domestic consumption, irrigation, and cultural and recreational purposes.	Significant impacts are defined under the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (available at https://www.waterquality.gov.au/guidelines/anz-fresh-marine).
3. How can carp virus biocontrol be implemented?	
Implement effective and efficient operations to manage risks and potential impacts.	Guidelines on effective and efficient operations are outlined in the Australian Interagency Incident Management system (AIIMS) Incident Control System (ICS).

NCCP research and planning investigations provide the evidence for assessment against the feasibility criteria. Table 8 summarises the assessment of feasibility against these criteria.

Table 8: Summary assessment of feasibility against specific criteria.

Feasibility criteria	Evidence	Expected outcomes	Feasibility assessment
1. Will carp virus biocontrol be effective?			
i. That there will be widescale reduction and suppression of carp populations for the medium to long term in Australian aquatic ecosystems.	Epidemiological modelling; transmission experiment; latency experiment; carp biomass estimates; population modelling.	Forty to sixty per cent knockdown of carp following initial virus deployment (60–80% in less resilient in carp populations). Carp suppression could continue for at least 10 years, and should persist through booming or highly productive carp population growth periods. Nonetheless, uncertainties regarding the development of genetic and/or herd immunity, and the extent to which recrudescence of latent infections will occur under field conditions remain. Carp populations will likely be reduced below theoretical damage thresholds across extensive areas of Australia's inland waterways (see section 2.1), however this may not occur in high density sub-populations. Benefits may be enhanced if virus deployment in the lower Murray is preceded by targeted, intensive harvesting to reduce carp 'starting density'. Assessing the timing, magnitude, and operational planning aspects of this pre-fishing effort is beyond the NCCP's scope, but could usefully be investigated by some limited additional modelling (NCCP research project 4). Some uncertainty remains about the likelihood of achieving sufficient virus transmission within carp aggregations during the first year of deployment. A second year of deployment may therefore be required.	Feasible (indicative) based on epidemiological modelling, and providing some additional validation and refinement of assumptions underpinning that modelling is conducted.

Feasibility criteria	Evidence	Expected outcomes	Feasibility assessment
2. What are the carp virus biocontrol risks and how can they be managed?			
i. The carp virus should not infect or cause disease in non-target species.	CSIRO and Invasive Animals CRC non-target species susceptibility testing preceding the NCCP; review assessing the carp virus's potential to infect humans; carp virus species specificity review (for non-human species); non-target species susceptibility testing on Murray Cod and Silver Perch.	Additional non-target species susceptibility testing focused on rainbow trout at minimum would provide necessary additional knowledge of the virus's host range.	Additional testing is recommended to inform a clearer feasibility recommendation.
ii. The carp virus must not affect humans or stock health through direct infection (note, this criterion does not refer to impacts on water quality caused by decomposing carp carcasses).	Human health review.	The virus will not infect humans or other mammals.	Feasible based on human health literature review.
iii. Manage prolonged, adverse impacts on water quality for town water supply, stock and domestic water supply, irrigation, and cultural and recreational purposes.	Anoxia and blue-green algae water quality research; water treatment research; ecological risk assessment; regional case studies.	Prolonged broadscale impacts unlikely. Challenges remain in some ecosystem types discussed throughout this report (e.g. northern MDB ephemeral systems). Risks could be managed with sufficient resourcing as per the NCCP implementation strategy and case studies. Water treatment plants can deal with existing carp densities. Some risks can be managed by communication and education. No significant infrastructure risks have been identified.	Feasible (indicative) based on the NCCP water quality modelling and its assumptions and sufficient carcass management.

Feasibility criteria	Evidence	Expected outcomes	Feasibility assessment
3. How can carp virus biocontrol be implemented?			
i. Implement effective and efficient measures and actions that mitigate risks and impacts associated with the release of the carp virus.	Ecological risk assessment; NCCP implementation strategy; regional case studies.	NCCP case studies illustrate that risk mitigation is possible subject to effective coordination, planning, and resourcing.	Feasible based on NCCP case studies and conclusions from water quality, biomass, and epidemiological modelling.

Describing the feasibility of carp biocontrol using the virus requires a nuanced and qualified statement. Briefly restated, feasibility criteria are (i) effectiveness, (ii) risk identification and management, and (iii) implementation. When assessed against these criteria, results from NCCP research and investigations indicate feasibility, with some qualifications. With strategic virus deployment, carp reductions of varying magnitudes and ongoing suppression appear achievable. From a risk perspective, water-quality impacts (for both ecosystem integrity and human/livestock use) appear manageable in many areas and habitat types, regional case studies have identified strategies for managing dead carp, and water treatment processes appear able to cope with all but the most extreme and unlikely dead carp loadings. To reframe these conclusions, no results have emerged to clearly indicate that further consideration of the virus as a biocontrol agent should cease.

Yet, as has been noted throughout this report, these broad indications of feasibility are subject to important uncertainties and caveats. In particular, the following key uncertainties preclude a definite recommendation of feasibility at this time.

a. Further non-target species susceptibility testing is recommended.
b. Investigation of viral latency and recrudescence in adult carp under variable environmental conditions and over timescales similar to those that would be required to initiate outbreaks and sustain carp suppression in natural ecosystems is desirable. Modelled carp suppression outcomes depend on reactivation of latent infections. Therefore, while latent and recrudescent infections are consistent with knowledge of the carp virus's biology and have been indicatively supported by a short-term laboratory experiment using juvenile carp in the NCCP, further confirmation is recommended.
c. Confirmation of some key epidemiological rates, again ideally generated from longer-term experiments under conditions of environmental variability similar to those encountered in the field, would usefully inform and validate epidemiological modelling.
d. Improved understanding of the possible existence of alleles conferring resistance to the carp virus in Australian carp, and the potential role of carp-Goldfish hybrids in the evolution of resistance, is desirable.
e. In addition to these specific issues, broader uncertainties remain regarding the viability of carcass management in waterways that are remote and/or difficult to access (e.g. the ephemeral systems of the northern MDB). Concerns regarding the likely effectiveness of clean-up in these systems is compounded by their relative sensitivity to water-quality impacts.
f. In a point allied to (e), major and unmanaged carp kills in still-water environments (e.g. off-channel wetlands) could establish the preconditions for avian botulism outbreaks. Given the highly probabilistic nature of botulism outbreaks, quantitatively predicting the likelihood of these events is difficult. Effective carcass management could prevent development of the preconditions for botulism outbreaks, but may be challenging in these habitats. Sufficient resourcing for carcass-management operations may be able to address these concerns.

Points a–d could be addressed with additional, targeted research, potentially leading to a more definitive feasibility determination. A pathway for such research is set out in the Recommendations section of this report. Yet even additional research would not eliminate all uncertainty or risk, necessitating a flexible and responsive adaptive management framework if virus release did eventually proceed.

The above considerations preclude an outright recommendation of feasibility at this time. Yet concluding that carp biocontrol is non-feasible would not accurately represent the results of most of the NCCP science, and risks prematurely discarding one potential option for managing a serious environmental problem for Australian aquatic ecosystems.

7 CONCLUSIONS AND RECOMMENDATIONS

NCCP research and planning investigations have developed a knowledge base from which Australian governments could, if they choose to do so, proceed with further activities to inform decision making on potential use of the virus in Australian biocontrol operations.

A continental-scale biocontrol program targeting an established pest fish inevitably involves risk and uncertainty. As noted in section 6, NCCP research and investigations have clarified risks and reduced, but can never eliminate, uncertainty.

Biocontrol using the virus will not eradicate carp, nor will it provide a stand-alone solution for controlling carp in perpetuity. However, successfully implementing carp biocontrol could achieve the following national outcomes and opportunities:

- reduced environmental damage caused by carp,
- a 'window of opportunity' during which ecological restoration measures could be implemented to benefit native fish and aquatic habitats while carp impacts are reduced, and
- an opportunity to develop and refine other carp control measures that could then be deployed against carp populations reduced by viral disease.

If governments decide to proceed with additional activities to further inform decision making, the next stages will involve additional research, legislative approvals and more detailed planning and risk mitigation.

7.1 Governance recommendations

If governments decide to proceed with further activities to support decision making, the following governance tasks are recommended as a minimum to proceed with assessment and coordination:

1. Establish a national taskforce (potentially the existing Freshwater Vertebrates and Invertebrates Working Group of the Environment and Invasives Committee) consisting of state/territory and local government representatives to coordinate planning. The taskforce should include representatives from biosecurity, water, environment, and agriculture portfolios. Key tasks would include policy and regulation, communications and engagement, and operations.
2. Develop and implement an NCCP communications and engagement plan.
3. Progress state, territory, and Commonwealth legislative approvals, as necessary supporting information becomes available.
4. Obtain APVMA approval. This task will involve Australian Government negotiation with the NSW Department of Primary Industries to complete the APVMA approval.
5. Seek approval under other relevant legislation including the *Biosecurity Act 2015*, the *Biological Control Act 1984*, and relevant state and territory regulatory approvals.

A specific timeline for implementation is not provided as this would be determined by the Australian Government and state/territory governments.

7.2 Research and development recommendations

The NCCP research program has made substantial progress towards understanding the carp virus's potential role as a biocontrol agent in Australia. As noted in section 6, several key uncertainties are likely amenable to resolution through carefully planned and targeted research. Recommendations for this research are provided in the following sections.

7.2.1 Additional non-target species susceptibility testing

Although considerable evidence indicates that the carp virus only infects carp, concerns regarding the potential for infection in other species are relatively common in the Australian community. To address these concerns, and improve the level of evidence available to decision makers, a final round of non-target species susceptibility testing is recommended. At minimum, this testing should include rainbow trout. The experiments should be carefully designed to ensure that test subjects are exposed to the virus under optimal conditions for infection.

7.2.2 Improving understanding of carp virus latency and recrudescence

During the NCCP research program, a need for improved understanding of the dynamics of carp virus latency and recrudescence under field conditions has emerged as a key area in which additional knowledge would substantially benefit decision making. These aspects of carp virus infection and disease are important for two reasons.

First, if carp biocontrol does eventually proceed, releasing latently infected carp into waterways during seasons (most likely winter) when water temperatures are below the permissive range for the disease caused by the carp virus may be an effective virus deployment strategy. Latent infections are expected to recrudesce as water temperatures enter the permissive range in spring, which is also when carp in many areas aggregate to spawn. If carp with reactivating infections joined spawning aggregations, they would likely have physical contact with numerous other carp, thereby initiating outbreaks (Technical Paper 2; NCCP research projects 4 and 6).

Second, modelled carp suppression outcomes depend upon recrudescence of latent infections. Under NCCP modelling, if latency does not occur, carp populations rapidly rebuild after initial major outbreaks, meaning the virus would offer only very short-term carp suppression (NCCP research project 4).

Scientific knowledge of carp virus biology supports the occurrence of both latency and recrudescence, as do results from a short-term laboratory experiment under the NCCP (NCCP research project 5). However, the two considerations outlined above are critical to the effectiveness of carp virus biocontrol. Therefore, studying latency and recrudescence in natural ecosystems (or at least in conditions imitating them) could substantially improve understanding of carp biocontrol efficacy. The broad aims of such research would be twofold; to determine whether latency and recrudescence do in fact occur over the timescales (likely weeks to months) on which they would need to operate in a biocontrol program, and to improve understanding of how these processes interact with critical carp behaviours. For example, a key question is whether carp experiencing recrudescence would join spawning aggregations. Additionally, such research should use adult carp, as this is the life-history stage in which latency primarily needs to operate for the virus to be maximally effective as a biocontrol agent.

Conducting research as outlined previously in Australia is difficult. As an exotic (to Australia) virus notifiable to the OIE, all research using the virus in Australia must occur within biosecure laboratories, removing the possibility of field experiments and constraining the scale of laboratory experiments. However, international research institutions in countries where the virus is endemic, and where biosecurity provisions regarding its scientific use are therefore less stringent, possess facilities that could enable research as described earlier. Such facilities include outdoor pond/lake systems and large indoor tanks that would provide an opportunity to study virus dynamics under conditions more representative of natural ecosystems than is generally feasible in the laboratory. If governments choose to proceed with activities to support decision making about carp biocontrol, further consideration of this research would be a useful priority.

7.2.3 Validating epidemiological modelling with real data

By coupling models of carp virus transmission and disease dynamics with those simulating carp demography and ecology, NCCP modellers have produced cutting-edge work with real capacity to inform a pathway to implementation. As with all modelling, assumptions were necessary (see discussion in section 2, and Technical Paper 2), and, while these were informed wherever possible by information available in the scientific literature, the unique challenges posed by carp biocontrol mean that some uncertainty remains.

One of the most useful pieces of research that could be undertaken to inform implementation is further investigation of carp population structure. The carp virus's epidemiology in Australian systems will be influenced by carp population structure and demography, because factors such as population density, age structure (the relative abundance of different age classes in the population), and connectivity between carp sub-populations will influence the knockdown resulting from viral disease (see section 2.1). Consequently, NCCP epidemiological modelling is linked to a carp demographic model. This model is based on the best available scientific information and has been evaluated by carp biology and ecology experts. Nonetheless, additional field-based research investigating carp demography and population structure would refine this model, enabling improved operational planning for virus deployment and outbreak response. Additionally, research to better resolve carp population structure and demography would be a 'zero-loss' investment, because this information would be useful for any future carp control measures if governments choose not to proceed with biocontrol.

Similarly, recently available data on carp virus outbreaks from Japanese waterways provide an opportunity to test and validate the epidemiological modelling. Japanese aquatic habitats differ in some important respect from those in Australia, but applying the models to the Japanese data nonetheless represents a useful opportunity to test assumptions and outcomes, and is recommended. Likewise, the potential approach outlined in section 7.2.2 for studying viral disease dynamics under natural or semi-natural conditions would also yield data to inform the modelling, particularly with regard to some key epidemiological rates.

7.2.4 Developing methods for large-scale production, storage, and transport of the carp virus

APVMA approval requires that virus production, packaging, and distribution processes are standardised, quality-controlled, limit opportunities for mutation or inclusion of adventitious agents, and generally conform to standards similar to those expected of animal health vaccines. From a logistical perspective, the capacity to produce large quantities of virus in forms that enable effective transport and deployment throughout the control area is an essential operational requirement for carp biocontrol.

Potential approaches to producing the virus that meet both APVMA requirements and operational challenges have been discussed by the NCCP Operations Working Group, and a project proposal procured. However, virus production and storage capabilities are logistical questions relevant to the implementation, rather than feasibility assessment, phase of a biocontrol program, and the proposal was consequently not funded under the NCCP. If governments elect to proceed towards implementation, this work will be essential.

7.2.5 Ongoing mapping and investigation of carp aggregations

Understanding the timing and location of carp aggregations is critically important to ensure effective carp virus biocontrol. Scientific knowledge about carp aggregations is currently limited. The NCCP completed a citizen science project that collected important information on the location and characteristics of carp aggregations (NCCP planning investigation 1). Continuation of this project, and research using the data it generates, is recommended.

7.2.6 Decision-support and mapping tools for operational activities

If carp biocontrol is implemented, a suite of decision-support and mapping tools will enhance operational planning and response capabilities. Prospective tools for development have been scoped under the NCCP.

The most important operational support tool will be an online Geographic Information System (GIS) incorporating carp biomass data from both wet and dry years, carp aggregation locations and spawning hotspots, areas important for human use and biodiversity, and carp sub-populations. This GIS would in turn provide the basis for developing a range of decision-support tools to assist operational managers to visualise and explore diverse virus deployment and carcass management scenarios. The ecological and administrative complexity of carp biocontrol operations will mean that visualisation capacity of this nature is essential for effective operational management. Building this system would require modelling and mapping of carp sub-populations through the entire range of biocontrol operations. The NCCP epidemiological modelling project has mapped and modelled carp sub-populations in selected case study catchments, so methodological approaches and data requirements are now well-known.

7.2.7 Assessing carp virus salinity tolerance

Carp inhabit numerous waterways with elevated salinity. Most obviously, coastal waterways such as the Gippsland Lakes (Victoria), Albert and Logan Rivers (Queensland), and the Lower Lakes (South Australia) are saline to varying degrees, and are inhabited by carp. Some inland waterways inhabited by carp are also saline. The carp virus's salinity tolerance is currently poorly understood, so it is possible that the virus's capacity to infect or kill carp could be reduced or eliminated under saline conditions. Research investigating the virus's likely effectiveness in saline conditions would therefore usefully inform operational planning.

7.2.8 Assessing animal welfare implications of carp biocontrol

The Royal Society for the Prevention of Cruelty to Animals (RSPCA) acknowledges the need for pest animal control, but notes that control methods should be as humane as possible for all species, including fish. Under laboratory conditions, carp can take up to 16 days to die from the disease caused by the carp virus (NCCP research project 6). Disease progression involves gill necrosis (breakdown) and haemorrhaging, and probably involves some level of suffering.

Assessing the welfare implications of carp biocontrol in consultation with animal welfare experts is recommended. Preliminary discussions involving the NCCP Science Advisory Group, external scientists with expertise in animal welfare, and representatives of the RSPCA have yielded some initial ideas about how such an assessment could be conducted. The recommended next step is to convene a meeting or workshop expanding upon this early work.

7.2.9 Monitoring the evolving relationship between carp and virus

Following virus deployment, Australian carp populations and the carp virus would begin a co-evolutionary 'arms race'. Tracking this evolving relationship is an important aspect of measuring a biological control program's progress. A pilot study under the NCCP has developed the tools necessary to track the evolution of genetic resistance in Australian carp population if virus release did eventually occur (NCCP research project 7).

Primary areas of uncertainty in predicting the emergence of resistance in Australian carp populations are:

- The potential role that carp–Goldfish hybrids, which are less likely to die following infection with the carp virus than are 'pure' carp, could play in promoting resistance remains uncertain. The Australian freshwater research community has considerable expertise in carp and Goldfish ecology and genetics, and a useful and low-cost next step in addressing this uncertainty could involve convening an expert workshop to review this issue. This recommendation is included in the NCCP monitoring and evaluation plan shown at Appendix 2.
- Research to further investigate the potential existence of the alleles conferring genetic resistance to the carp virus among Australian carp populations is recommended. Exploratory NCCP research found no evidence of these alleles (NCCP research project 7), but did not constitute a comprehensive genetic survey of Australian carp populations. This research did, however, develop the tools required for further assessing this question.

7.3 Implementation planning recommendations

Implementation planning is recommended to address the following important issues:

- mitigation of high to moderate ecological risks identified for ephemeral dryland river systems and Ramsar wetlands including the South Australian Lower Lakes systems and the associated marine system immediately outside of the Murray River mouth (NCCP research project 15),
- improving regionally specific knowledge of carp movement and aggregation behaviour, and
- developing plans and estimating costs associated with potential targeted 'fish down' activities in high density sub-populations.

Further recommendations and guidelines for implementation planning are given in Technical Paper 6.

7.4 Community relations recommendations

The general community and specific stakeholder groups have a high level of interest in the NCCP. If governments choose to proceed with activities to further inform eventual decision making on carp biocontrol, ongoing community consultation and stakeholder engagement is important. All stakeholders have indicated that they would appreciate continued communications and engagement.

Traditional Owners have an important connection to inland waterways and carp control. In NCCP workshops, Traditional Owners have expressed a strong desire to not only be informed about progress towards biocontrol implementation, but also to be actively involved in decision making. The NCCP has begun the process of engaging with Traditional Owners on carp biocontrol. Ongoing dedicated engagement is recommended as planning towards implementation proceeds.

Communications recommendations include:

- continue NCCP science communication through the next phases of research, approvals, and decision-making phase, if governments choose to proceed with these activities,
- develop a comprehensive communications and engagement plan that includes strategies for specific stakeholder groups listed in the NCCP, spans all phases of biocontrol implementation, and is integrated with jurisdictions and regions, and
- communicate reasons for not proceeding towards virus deployment, if Australian governments choose this approach.

Community consultation recommendations include:

- undertake specifically designed and more extensive consultation with Traditional Owners, and
- undertake specifically designed consultation with other stakeholder groups identified by the NCCP.

If governments decide to proceed with activities to support decision making, stakeholder engagement recommendations include:

- actively engage with Traditional Owners in decision making and enterprise development about possible carp biocontrol and its management,
- engage local knowledge and stakeholders in regional implementation planning, and
- acknowledge possible stakeholder impacts, including anticipatory impacts.

APPENDIX 1 OVERVIEW OF NCCP RESEARCH

MEETING A COMPLEX RESEARCH CHALLENGE

Controlling established pests is always challenging. Pest species tend to be hardy and adaptable, and are often widespread. Freshwater pest fish pose particular control challenges because they inhabit inter-connected and often ecologically sensitive environments. Major fish kills can therefore have implications for water quality in freshwater ecosystems. More subtly, established high-impact pests often shaped ecosystems around themselves and become integral to new modes of ecosystem function. Removing these species (or, more realistically, reducing their abundance) can have unforeseen consequences for ecosystems and the human communities that depend upon them for livelihoods and recreation.

Given this complexity, NCCP research needed to span biological, physical, economic, and social questions. Important research areas included understanding carp population size and distribution, the virus's likely effects on these populations, potential impacts of dead carp on water quality and water treatment, community and stakeholder views on carp control, and development of virus release and carcass management strategies. By engaging with these issues, the NCCP research program has produced new knowledge that will inform decision making on future directions for carp biocontrol.

RESEARCH PROGRAM OVERVIEW

The NCCP research program consists of 19 peer-reviewed projects and five investigations spanning the biophysical sciences, social sciences, and applied economics. The research program's 'blueprint' is the NCCP Strategic Research and Technology Plan (available at https://www.frdc.com.au/knowledge-hub/national-carp-control-plan), which defines three key themes for NCCP research; environment, communities, and informing possible implementation. These key themes emphasise the multi-disciplinary and applied nature of the NCCP research program. Under each theme sit one or more priority areas that guided development of targeted research projects.

The NCCP research program has made progress towards resolving the uncertainty and complexity inherent in viral biocontrol of an established pest fish. For perspective, no other biological control proposal has received such an intensive research effort to inform decisions on possible release. NCCP research has developed new knowledge that provides:

- the most comprehensive estimate of Australian carp biomass ever obtained,
- a national-scale understanding of the carp virus's likely dynamics in, and impacts on, Australian carp populations,
- understanding of how the carp virus could be deployed to maximise effectiveness,
- clearer insights into the impacts various dead carp concentrations could have on water quality and water treatment processes, and
- potential pathways for implementation.

Inevitably, given the scale and complexity of the carp problem, uncertainties and knowledge gaps remain. The NCCP identifies the key uncertainties for each research theme and explains implications for decision making. Where relevant, actions to reduce these uncertainties are described.

RESEARCH MANAGEMENT

Recognising the need for a broad-ranging investigation, in 2016 the Australian Government provided $10.211 million for the NCCP's development. The Fisheries Research and Development Corporation (FRDC), a statutory corporation under the *Primary Industries Research and Development Act 1989*, was contracted to develop the NCCP, with the then Commonwealth Department of Agriculture and Water Resources (DAWR, now the Department of Agriculture, Fisheries and Forestry (DAFF)) acting as program manager. A steering committee, comprising senior officials from DAWR, the Department of the Environment and Energy, and the Department of Industry, Innovation, and Science, provided strategic oversight at the programmatic level. Soon after the NCCP's inception, four advisory groups, combining jurisdictional representation with subject-matter expertise, were established to oversee the program's research (Science Advisory Group — see next section), policy, communications, and operations components. By late 2018 the NCCP's Policy Advisory Group had completed its functions, and oversight of policy matters relevant to the NCCP was adopted by the Commonwealth's Environment and Invasives Committee.

THE NCCP SCIENCE ADVISORY GROUP

The NCCP's Science Advisory Group (SAG) has been the principal body overseeing the research program and providing advice to the NCCP Secretariat and National Coordinator. The SAG was formed to provide advice to FRDC on the planning and implementation of the research program. Since its inception in December 2016, and up to the conclusion of the main portion of the NCCP's research program in late 2019, the SAG met quarterly to fulfil its functions. The SAG's tasks included setting research priorities to address knowledge gaps, reviewing and providing feedback on proposals to fill research needs, and reviewing and providing feedback on research outputs. These functions were facilitated by quarterly Principal Investigator Workshops, at which researchers working on NCCP projects presented project updates and results to audiences that include members of SAG and other NCCP advisory groups.

In addition to review by the SAG, NCCP project final reports were reviewed by at least two independent subject-matter experts. These expert reviews were then considered by SAG, which made a final decision on whether or not to formally 'accept' the project reports. The SAG formally accepted a research project if (i) all project objectives were met, and (ii) comments from external reviewers and the SAG (where applicable) were adequately addressed. This process ensured that all NCCP research project final reports were subject to a review process approximately analogous to that involved in peer-reviewed scientific journal publications. Table 9 summarises the SAG's deliberations on NCCP research project final reports.

In order to adequately serve the advisory needs of the NCCP, SAG members were nominated to represent relevant scientific expertise from Queensland, New South Wales, South Australia, Victoria, the Australian Capital Territory, Tasmania, and Western Australia. Disciplines and subject areas represented on the SAG included fish ecology, biology, virology, and epidemiology, human health, and socio-economics. The SAG also included representatives from the then Department of the Environment and Energy (now the Department of Climate Change, Energy, the Environment and Water), and DAFF.

As the main body of NCCP research concluded in in 2019, limited additional research questions emerged that, if successfully answered, were likely to reduce some key uncertainties. Consequently, a provisional NCCP was submitted to DAFF in January 2020, with an agreement to update the document on completion of the additional research projects. Completion of these additional research projects, most of which required biosecure laboratory facilities, was delayed by the COVID-19 pandemic, which saw Australian laboratories accredited for research on exotic viruses prioritising COVID-19 research. These projects were completed from early–mid 2022. A modified SAG, referred to as the NCCP 'Special SAG', was convened to assess these projects and advise on their integration into the NCCP. The Special SAG included scientists with the expertise necessary to evaluate the newly completed projects, or with broad, cross-program interests in NCCP research and its application. These discussions occurred over four meetings during early–mid 2022, and the new projects, with the modified SAG's assessment of them, have been included in Table 9.

Table 9: NCCP research project final report acceptance status.

Project number: Project title	Status	Additional comments from SAG or Special SAG
2016-132: Impact costs of carp and expected benefits and costs associated with carp control in the Murray–Darling Basin.	Not fully evaluated, but SAG input to drafts.	The Final Report for this project was submitted in August 2020, well after the original NCCP SAG had concluded its functions and ceased meeting. Therefore, this project was not formally considered for SAG acceptance, but SAG did provide input on drafts, which was accepted and implemented by the project investigators, and engaged with the project team through the project's life, primarily at NCCP Principal Investigator Workshops.
2016-152/2018-189: Building community support for carp control: Understanding community and stakeholder attitudes and assessing social effects/Socio-economic impact assessment and stakeholder engagement.	Not fully evaluated, but SAG input to drafts.	Final Reports for these two linked projects were submitted in December 2019, after the original NCCP SAG had concluded its functions and ceased meeting. Therefore, this project was not formally considered for SAG acceptance, but SAG did provide input on drafts, which was accepted and implemented by the project investigators, and engaged with the project team through the projects' lives, primarily at NCCP Principal Investigator Workshops.
2016-153: Preparing for carp herpesvirus: A carp biomass estimate for eastern Australia.	Accepted.	
2016-158: Development of strategies to optimise release and clean-up strategies underpinning possible use of herpesvirus 3 (CyHV-3) for carp biocontrol in Australia.	Accepted.	

Project number: Project title	Status	Additional comments from SAG or Special SAG
2016-170: Development of hydrological, ecological and epidemiological modelling to inform a CyHV-3 release strategy for the biocontrol of carp in the Murray–Darling Basin.	Accepted (with conditions).	SAG acknowledged that this is an innovative, complex, and detailed body of work. However, given this complexity and detail SAG requested that the published version include a more detailed discussion of current knowledge regarding the epidemiology of CyHV-3 infections and disease outcomes, and clarification of the model assumptions and parameter estimates, particularly regarding immunology, transmission and the role of water temperature effects. The complexity of this work, and the importance of its underlying assumptions, have been acknowledged throughout the NCCP, accompanied where relevant by recommendations for further research to either test key assumptions or to generate key epidemiological rates to inform the models. This research is currently being published in the peer-reviewed scientific literature, with two papers published at the time of writing (September 2022).
2016-180: Assessment of options for utilisation of virus-infected carp.	Accepted.	
2016-183: Cyprinid herpesvirus 3 and its relevance to humans.	Accepted.	
2017-054: Social, economic, and ecological risk assessment for use of Cyprinid herpesvirus 3 (CyHV-3) for carp biocontrol in Australia.	Accepted.	
2017-055/2017-056: Expanded modelling to determine anoxia risk in main river channel and shallow wetlands/Investigation of nutrient interception pathways to enable circumvention of cyanobacterial blooms following carp mortality events.	Accepted.	
2017-094: Review of carp control via commercial exploitation.	Accepted.	
2017-104: The likely medium- to long-term ecological outcomes of major carp population reductions.	Accepted.	

Project number: Project title	Status	Additional comments from SAG or Special SAG
2017-127: Defining best practice for viral susceptibility testing of non-target species to Cyprinid herpesvirus 3: A discussion paper based on systematic quantitative literature reviews.	Not accepted.	SAG acknowledged the extent of the work, which informed design of further studies for non-target species testing for the NCCP. The SAG did not accept this project on the basis that the work did not meet the objective of determining ‘best practice’ in non-target species susceptibility (as defined by OIE) testing through a practical set of targeted recommendations, but rather provided broad advice for testing of non-target species resistance. To provide more targeted advice on next steps for non-target species testing, a small committee including the Principal Investigator for this study and SAG members with relevant subject-matter expertise was formed. The deliberations of this group led to project 2019-176, which aimed to re-test the susceptibility of Murray Cod, Silver Perch, and Rainbow Trout to infection by the carp virus.
2017-135: Essential studies on Cyprinid herpesvirus 3 (CyHV-3) prior to release of the virus in Australian waters: Excretion and seasonality.	Not accepted (by NCCP Special SAG)*	This work aimed to provide preliminary ‘proof of concept’ that carp could be infected by the virus, then returned to temperatures below the permissive range to induce a latent infection that would reactive when temperature rose into the permissive range. The work used juvenile carp, and was not intended to provide definitive proof that latency and recrudescence would occur under field conditions. Rather, the experiment was intended as a short-term test of the concept to determine whether or further investigation may (or may not) be useful. The NCCP Special SAG did not to accept this project, not because of its preliminary and short-term nature, but due to some concerns regarding the experiment’s execution. These concerns centred on morbidities in some fish tanks that the Special SAG considered had not been adequately explained, water-temperature fluctuations that occurred around tank-water exchanges, and inadequate or unclear explanation of these issues in the project report. Nonetheless, the Special SAG further noted that these limitations do not mean that the study’s results should be completely discounted, but rather that they should be presented in context as requiring cautious interpretation.

Project number: Project title	Status	Additional comments from SAG or Special SAG
2017-148: Identifying synergistic genetic biocontrol options for *Cyprinus carpio* in Australia.	Accepted.	
2017-237: Risks, costs and water industry response.	Accepted.	
2018-120: Population dynamics and carp biomass estimates.	Accepted.	
2019-176: Determination of the susceptibility of Silver Perch, Murray Cod and Rainbow Trout to infection with CyHV-3.	Not accepted (by NCCP Special SAG)*	This project aimed to distil the broad recommendations of project 2017-127 into a more defined and practical scope by re-testing three non-target fish species using best-practice methods. The Special SAG did not accept this work for several reasons. Major mortalities in Rainbow Trout due to inadvertent exposure to chlorinated water at the research facility well before challenge with the virus meant that this species could not be tested. Consequently, the project was unable to meet one of its objectives — testing the susceptibility of rainbow trout to the carp virus. Other key reasons for non-acceptance centred on unexplained mortalities in both test (i.e. exposed to the virus) and control (not exposed to virus) fish, and insufficient data to support a determination of susceptibility or otherwise in test fish. Recognising the importance of determining the virus's specificity to carp with the highest level of confidence practically achievable, the NCCP recommends additional non-target species susceptibility testing to inform decision making on carp biocontrol.
2020-104: Evaluating of the role of direct fish-to-fish contact on horizontal transmission of Koi herpesvirus	Accepted (by NCCP Special SAG)*	
2019-163: NCCP: Understanding the genetics and genomics of carp strains and susceptibility to CyHV-3	Accepted (by NCCP Special SAG)*	

* The NCCP Special SAG was an NCCP Advisory Group formed to assess projects that began later in the overall duration of the NCCP program, and which therefore attained completion after the original NCCP SAG had completed its functions and ceased meeting. The Special SAG included members with the subject-matter expertise necessary to assess the remaining projects, as well as those with broad scientific interests across NCCP research and its implications.

RESEARCH APPROACH

Projects within the NCCP research program use a range of research approaches, including experimentation in biosecure laboratories, field-based research assessing carp abundance, decomposition and associated water-quality impacts, reviews of the scientific literature, diverse modes of social enquiry, and economic modelling. Some crucial NCCP research projects use computer modelling, in which mathematical representations of key environmental variables play out in many different combinations. Modelling was essential to the NCCP for two main reasons. First, modelling enables exploration of phenomena that occur over long timescales and large geographic areas, such as medium- to long-term impacts of the virus on carp populations. These phenomena would be difficult or impossible to study using a traditional experimental approach. Second, the carp virus must remain in a biosecure laboratory until all necessary legislative approvals are gained, severely limiting opportunities for field experimentation. Wherever possible, NCCP modelling has been underpinned by data from field observations, helping to ensure that the modelled system mimics key aspects of Australian aquatic ecosystems as accurately as possible. Additionally, some of the modelling that helps to understand how the virus could impact carp populations is data-driven, which means that researchers search large datasets to identify underlying patterns, rather than beginning with predefined assumptions (see Technical Paper 2 for more detailed discussion of data-driven modelling).

Despite these attempts to ensure that the modelling accurately represents the study systems, assumptions and simplification remained unavoidable. Whenever assumptions are made in modelling, there is a chance that they could be incorrect to some degree. Incorrect assumptions in modelling studies can have consequences for the accuracy of conclusions ranging from minor to severe, depending upon the exact nature of the assumptions. Often, the validity of model outputs can only be assessed by collecting and analysing relevant data from the study system(s). Therefore, the NCCP has identified and communicated key assumptions underpinning research conclusions, and has recommended further work to enable cross-checking/ground-truthing of these assumptions where practical.

RESEARCH AND INVESTIGATIONS PROJECTS

NCCP research and investigations projects are shown in Figure 11, grouped by the broad themes of understanding biocontrol effectiveness, understanding and managing risks, and assessing benefits and costs.

Figure 11: NCCP research and investigations and outputs. Research projects that are peer reviewed are in 'roman' text. Investigations that are not peer reviewed are in '*italic*' text. Numbers in the white boxes refer to NCCP research project numbers as cited throughout the Plan's text.

Understanding carp virus effectiveness	1. Understanding carp virus effectiveness	4. Assessing the carp virus's capacity to reduce and suppress Australian carp populations
	2. Understanding how carp biomass changes over time in wet and dry conditions	5. Refining understanding of virus efficacy
	3. Exploring genetic biocontrol option that could work synergistically with the carp virus	6. Clarifying virus transmission pathways
	A. *Mapping carp aggregations*	7. Investigating the genetics of resistance to the carp virus
		8. Investigating the role of physical removal as a carp control technique
Understanding risk	9. Water quality risk assessment of carp biocontrol for Australian waterways	12. Additional testing of Murray Cod, Silver Perch, and Rainbow Trout to determine susceptibility to infection by the virus
	10. Understanding whether the virus can affect humans	13. Understanding stakeholder views and impacts
	11. How to determine whether the virus affects non-target species	
Understanding risk / Managing risk	14. Determining and managing water treatment risks	15. Systemic ecological and social risk assessment
Managing risk	16. Exploring clean-up methods and engineering solutions for fish kills internationally	B. *Biosecurity risk control measures for the koi industry*
		C. *Engineering options for the NCCP*
		D. *Lachlan case study*
		E. *Murray and Murrumbidgee case study*
Managing risk / Benefits and costs	17. Options to utilise dead carp	
Benefits and costs	18. Predicting medium- and long-term benefits of carp control	19. Estimating benefits and costs

NCCP outputs

National Carp Control Plan (NCCP)

Technical Papers
1. Background
2. Epidemiology
3. Water quality
4. Species specificity
5. Socio-economic impacts
6. Implementation
7. Engagement report
8. Murray case study
9. Lachlan case study

Final reports

APPENDIX 2 MONITORING AND EVALUATION PLAN

Monitoring design for carp biocontrol using CyHV-3

Introduction

Monitoring and evaluation are essential to successful implementation of any biological control program, including carp control using Cyprinid herpesvirus 3 (CyHV-3). Monitoring enables evaluation of biocontrol success and return on investment, measured against economic, social, and environmental criteria. Crucially, monitoring also enables detection of potential declines in biocontrol effectiveness, such as might emerge from the evolution of host resistance, or attenuation of viral virulence. These declines signal the need to implement additional control measures.

This appendix to the NCCP outlines key monitoring priorities, with the aim of delineating a broad scope for a carp biocontrol monitoring program. Monitoring associated with a carp biocontrol program could encompass three broad themes:

a. changes in carp abundance, distribution, and population structure following virus release,
b. ecological and biophysical responses to carp reductions, and
c. the evolving relationship between carp and the virus, including the latter's progress through, and prevalence in, Australian carp populations.

Conceptually, these three monitoring themes can be divided into those that address questions of population and community ecology (a and b) and those that primarily address questions in the disciplines of virology, epidemiology, and immunology (c). Carp population ecology (point a) and ecological responses to carp reduction (point b), are linked by the concept of 'damage thresholds', which posits that there are threshold carp densities at which impacts on various ecosystem attributes or components begin to manifest (Technical Paper 2; NCCP research project 4).

Monitoring to refine carp threshold densities

The threshold densities at which carp impacts begin to manifest will likely differ considerably among ecosystem components. For example, the carp densities at which impacts on aquatic plants manifest will almost certainly differ from those at which, say, aquatic invertebrates, are affected. Similarly, a given ecosystem attribute or component may exhibit different response thresholds in different areas of carp's Australian range. Understanding the ecological mechanisms underpinning these differing responses to carp reduction should be a key goal of the ecological monitoring that accompanies carp biocontrol. Considerable research effort has been devoted to identifying these damage thresholds internationally, particularly in the United States, but they remain poorly understood in Australia. An improved understanding of these thresholds would be of considerable utility in developing quantitative management targets as carp control activities proceed (if the virus is eventually used a biocontrol agent in Australia). A well-designed ecological monitoring program represents an opportunity to efficiently gather information on carp-impact threshold densities.

Variables for ecological monitoring

Recognising the importance of damage thresholds as a structuring concept for ecological monitoring, key attributes for inclusion in a monitoring program are likely to include:

- carp population density and recruitment dynamics,
- waterbody physico-chemical attributes,
- plankton (both phytoplankton and zooplankton),
- macrophytes,
- aquatic invertebrates,
- fish (non-carp species),
- birds, and
- amphibians.

For each of these attributes, Stocks and Gilligan (2017) and Brooks (2018) list testable hypotheses, key evaluation questions, and potential monitoring designs and sampling protocols. Neither Stocks and Gilligan (2017) nor Brooks (2018) have undergone formal peer review, but would likely provide useful 'blueprints' for developing a national-scale ecological monitoring program. Therefore, expanding upon these reports through workshops or other collaborative mechanisms is recommended as the next step towards developing an ecological monitoring plan for carp biocontrol.

Monitoring the evolving relationship between carp and virus

In any viral biocontrol program, tracking the agent's progress through the host population and monitoring the evolving host-virus relationship is essential for measuring impact on the target pest. These tasks require diagnostic tools that can:

a. detect the virus's presence in carp populations or sub-populations,
b. monitor recurrent outbreaks once the virus becomes established in carp populations, and
c. assess exposure to the virus among carp at the population level, and how this variables change through time. This monitoring component encompasses tracking the evolving relationship between carp and the virus, including the potential emergence of genetic resistance.

In relation to (a), environmental DNA (eDNA) approaches could be useful if their capacity to detect the carp virus at low levels could be confirmed. As for ecological monitoring, the variables listed in points a–c are only a general guide to the kinds of responses that should be monitored. NCCP research has identified cost-effective tools and approaches for monitoring the potential emergence of genetic resistance (NCCP research project 7), but more detailed consultation with subject-matter experts is recommended to develop a detailed plan for monitoring host-virus relationships if governments eventually decide to proceed towards carp biocontrol implementation. This aspect of monitoring is particularly important, as it provides the only means to detect and counteract declines in biocontrol effectiveness.

Baseline monitoring (pre virus release): The foundation for success

Inherent in the concept of monitoring the impact of any intervention is the need for information on pre-intervention conditions to form a 'baseline' against which change can be measured. Thus, both ecological response and host–virus relationship monitoring would need to begin before any future deployment of the virus against Australian carp populations.

A pilot ecological response monitoring program, collecting baseline ecological data from 24 sites across four river systems (i.e. six sites per river system) within the New South Wales portion of the Murray–Darling Basin has already begun (Stocks and Gilligan, 2017). This network of monitoring sites could be expanded to cover a larger portion of carp's Australian distribution. More detailed guidelines for development of ecological and biophysical monitoring programs are provided by Stocks and Gilligan (2017) and Brooks (2018).

Finally, pre-release reference samples of both carp and virus should be retained. Just as pre-release ecological monitoring establishes a baseline against which responses to carp reductions can be assessed, maintaining pre-release samples of virus and host provide a benchmark against which post-release evolutionary change can be measured. Advice from subject-matter experts should be sought regarding appropriate sampling designs for collection of these reference samples.

Monitoring costs

Detailed monitoring plans have not been developed, so detailed costings are not available. However, funding for monitoring and associated data handling could be allocated to participating states and territories, with coordination to ensure that monitoring results feed back into adaptive management.

Conclusions

A well-designed monitoring program is essential for evaluating the success of any biocontrol program, and hence for calculating return on investment. Monitoring also provides the only realistic opportunity for managers to detect declining biocontrol effectiveness and implement new control measures. Thus, monitoring needs to encompass:

a. changes in pest abundance, distribution and recruitment,

b. ecological responses to pest reductions, and

c. the evolving relationship between the biological control agent (virus) and host.

For carp control, structuring monitoring for the ecological response component (point b) around the organising concept of damage thresholds will help to ensure that monitoring delivers optimum value for managers. Under the NCCP, frameworks for monitoring both changes to carp populations (point a) and ecological responses (point b) have been developed. These frameworks could be refined and expanded if governments continue with further activities to inform a decision on whether or not carp biocontrol should proceed. Both state/territory and Commonwealth natural-resource and fisheries-management agencies have abundant expertise in monitoring variables encompassed by points (a) and (b) and could usefully contribute to this work. A conceptual framework for monitoring the evolving relationship between carp and virus is less developed, but basic requirement are known, and the expertise to build such a program is available. Finally, monitoring the three key themes listed in points a–c is only useful if baseline conditions against which future changes can be monitored are available. Therefore, establishment of appropriate sampling designs and collection of baseline data and samples will be key priorities if governments proceed with activities to inform decision making on carp biocontrol, and particularly if, after additional research and attainment of legislative approvals, implementation of a carp biocontrol program appears possible.

REFERENCES

Brooks, S. (2018). Monitoring and evaluating ecosystem responses to release of Cyprinid herpesvirus 3. Unpublished report to the National Carp Control Plan (draft only).

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