Population modelling of native fish outcomes for the Reconnecting River Country Program: Golden Perch and Murray Cod

Final report for the NSW Department of Planning and Environment, Reconnecting River Country Program

Charles Todd, Henry Wootton, John Koehn, Ivor Stuart,

Robin Hale, Ben Fanson, Clayton Sharpe and Jason Thiem

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Acknowledgement

We acknowledge and respect Victorian Traditional Owners as the original custodians of Victoria's land and waters, their unique ability to care for Country and deep spiritual connection to it. We honour Elders past and present whose knowledge and wisdom has ensured the continuation of culture and traditional practices.

We are committed to genuinely partner, and meaningfully engage, with Victoria's Traditional Owners and Aboriginal communities to support the protection of Country, the maintenance of spiritual and cultural practices and their broader aspirations in the 21st century and beyond.

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Population modelling of native fish outcomes for the Reconnecting River Country Program: Golden Perch and Murray Cod

Final report for the NSW Department of Planning and Environment Reconnecting River Country Program

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Contents

Tables

Figures

Summary

Context

Connectivity between rivers and their adjacent wetlands and floodplains is an important feature of healthy, functioning freshwater ecosystems. These connections support important ecological, hydrological and chemical processes. However, many rivers globally are no longer connected with floodplains and wetlands for as often or as long as they need to be, and these important processes are lost or compromised. Also, many rivers are managed in the context of balancing competing human and environmental needs for water. Consequently, the health of many river systems has declined.

To help restore rivers in Australia's Murray–Darling Basin (MDB), flexibility in managing the flows to support both human and environmental needs is required. As part of meeting this challenge, the New South Wales (NSW) Reconnecting River Country Program (RRCP) is considering physical, policy and operational constraints that limit river flow and floodplain connectivity in southern NSW and exploring how these constraints can be best managed to support healthy, productive waterways. The RRCP has three focal river zones:

- Murray River—Hume Weir to Yarrawonga Weir
- Murray River—Yarrawonga to Wakool Junction
- Murrumbidgee River— Burrinjuck Dam to Murray Junction

In the RRCP, decisions about how to best balance economic, social, cultural and environmental outcomes will be made based on: (i) comprehensive assessments of potential benefits and costs/impacts; (ii) an options evaluation process and community engagement; and (iii) collaboration on program design.

Floodplains can provide important foraging, spawning and nursery habitats for many riverine fish species. Moreover, the connection between these habitats and river channels also indirectly benefits many key processes supporting healthy fish populations (such as food and energy transfer). More generally, the growth, survival, reproduction and movement of many fish is inherently linked to characteristics of the hydrological regime. Relaxing constraints on the delivery of environmental flows will therefore likely have important benefits for native fish. However, these benefits are likely to vary from one species to another, based on their respective water requirements, and how different management approaches affect both hydrological conditions, and connections between rivers and floodplains. Information about how native fish species might respond to different flow scenarios is therefore an important input into the RRCP decision-making process.

This report presents a detailed analysis of the predicted outcomes for populations of two native fish species, Murray Cod (*Maccullochella peelii*) and Golden Perch (*Macquaria ambigua*), as a result of relaxing constraints in the RRCP program. Population modelling, which is an important tool widely used in conservation and natural resource management, was used to predictively explore likely outcomes for these two species in RRCP flow scenarios specified by the NSW government. This report describes the collation and synthesis of the latest scientific information to derive a conceptual understanding of how these two species respond to hydrological changes, and then application of this knowledge to construct population models to explore likely responses to the various potential hydrological scenarios in RRCP. The key results and findings in relation to predicted fish population outcomes under the various RRCP flow scenarios are outlined, and the assumptions and limitations associated with this approach have been highlighted. In addition, the predicted modelled trajectories were compared with those observed in independent empirical datasets, to assess the validity of the population models, and the learnings from that are also presented.

Methods

The population models were developed via an iterative process consisting of: (i) developing and updating species-specific conceptual models via a series of workshops with expert fish ecologists and environmental water managers, (ii) using this knowledge to adapt the population models for each of the core RRCP areas and hydrological scenarios, (iii) incorporating life history responses to flow and temperature cues, (iv) including flow–productivity effects, (v) including an anoxic blackwater construct (for Murray Cod only), (vi) defining and reporting the ecological benefits of the modelled RRCP flow scenarios, (vii) comparing model predictions with independent empirical datasets; and (viii) providing advice to NSW DPE regarding the model application and the results.

Models were run for Golden Perch and Murray Cod in a series of river reaches, including the three main RRCP focal zones of the Murray River (Lake Hume to Yarrawonga, and Yarrawonga to Wakool Junction) and the Murrumbidgee River (Gundagai to Murray Junction – fish populations were not modelled upstream of Gundagai to Burrinjuck Dam). The RRCP focal zone Yarrawonga to Wakool Junction was modelled as Yarrawonga to Torrumbarry and Torrumbarry to Wentworth. For the purposes of this report, we use the term 'Total RRCP Populations' to represent all modelled RRCP focal zones with the addition of the Murray River downstream from Wakool Junction to Wentworth. All the reaches modelled were included in the following: the Murray River from Lake Hume to the Murray Mouth (Golden Perch), the Murray River from Lake Hume to Wentworth (Murray Cod), the Edward River (both species), the Lower Darling River (Golden Perch), the Murrumbidgee River upstream of Balranald to Gundagai (both species), and Yanco Creek (Murray Cod).

In this study, river system hydrologic modelling has been used to obtain a realistic indication of the potential river flow and floodplain inundation outcomes from the RRCP over the long term under the varying climate conditions experienced in the Murray–Darling Basin. The models used for this work represent current system operations, current environmental water recovery data, and historical climate data over the period 1 July 1895 to 30 June 2019 (124 years). The environmental flow limit options explored in the modelling corresponded to 15,000 (current temporary operational limit), 25,000, 30,000, 40,000 and 45,000 ML day^{-1} flow limits in the Murray River downstream of Yarrawonga weir and 25,000, 30,000 and 40,000 ML day^{-1} flow limits in the Murray River at Doctors Point. In the Murrumbidgee River, the modelled flow scenarios corresponded to 22,000 (current temporary operational limit), 32,000, 36,000 and 40,000 ML day^{-1} flow limits at Wagga Wagga. The models include the representation of a range of environmental flows, including baseflows, small freshes, large freshes, and small overbank events, up to the flow limits modelled. The environmental flows represented in the models reflect the environmental water requirements described in the Murray – Lower Darling and Murrumbidgee Long Term Water Plans (DPIE 2020a, b). The Murray modelling was a collaboration between the Murray–Darling Basin Authority (MDBA) and the NSW Department of Planning and Environment (DPE), and the Murrumbidgee modelling was undertaken by NSW DPE.

The Murray and Murrumbidgee flow scenarios were integrated, as recommended by the NSW Government, and are summarised as the Base case and Options 1–4 in Table S1.

Table S1. Relaxed-flow-constraints scenarios at indicator gauges within two reaches of the Murray River and within the Murrumbidgee River.

Modelled flow scenario	Doctors Point (Albury) (ML day^{-1})	Yarrawonga Weir (ML day^{-1})	Murrumbidgee (Wagga Wagga) (ML day^{-1})
Base case	25,000	15,000	22,000
Option 1	25,000	25,000	32,000
Option 2	30,000	30,000	36,000
Option 3	40,000	40,000	40,000
Option 4	40,000	45,000	40,000

Population model outputs were generated for: (i) the total population size for Golden Perch and Murray Cod for all modelled reaches within the Total RRCP Populations (Total Murray to Wentworth and Total Murrumbidgee) under each RRCP flow scenario, (ii) the total adult population size and recruit (1-year-old) population size for each species for all modelled reaches that cover the RRCP focal zones under the various RRCP flow scenarios, (iii) plots of distributions of the mean population sizes and (iv) the expected mean population size (presented as bar plots) for each species, at a broad spatial scale as well as for each modelled reach that covers the RRCP focal zones. The expected mean population size and the expected trajectories of the mean population size were the summary results used to compare the various modelled scenarios. The models were run over >120 years of modelled hydrological and temperature data from 1896 to 2019. These data were assessed for their effects on elements of the life history of each species (e.g. spawning triggers and movement cues), including the effects of hypoxic blackwater events on Murray Cod, in the process developing a powerful tool for predicting the effects of the relaxed-flow-constraints scenarios examined by the RRCP on fish population dynamics.

Main messages

The population modelling predicted significant benefits to Golden Perch populations (up to an average 30% increase in the expected mean population size for the Total RRCP Populations; Table S2) and an overall neutral benefit to Murray Cod populations under relaxed-flow-constraints scenarios, with small benefits observable at localised sites (see Murray Cod results in main text).

Table S2. Summarised outputs from the mean trajectories of the population modelling for Golden Perch and Murray Cod populations across the Total RRCP Populations (inclusive to Wentworth) under the various relaxed-flow-constraints scenarios, Options 1–4.

Species	Catchment	Relaxed-flow-constraints scenario	% difference from the Base case in the expected value of:		
			mean population size	10% quantile population size	minimum population size
Golden Perch	Total RRCP Populations*	Option 1	10	25	34
		Option 2	16	25	32
		Option 3	23	39	40
		Option 4	30	54	43
	Murray River	Option 1	10	19	30
		Option 2	16	20	29
		Option 3	23	37	30
		Option 4	29	45	28
	Murrumbidgee River	Option 1	7	6	14
		Option 2	16	8	38
		Option 3	26	8	28
		Option 4	34	31	43
Murray Cod	Total RRCP Populations*	Option 1	0	1	1
		Option 2	0	1	2
		Option 3	0	0	0
		Option 4	0	1	1
	Murray River	Option 1	1	2	2
		Option 2	1	2	2
		Option 3	0	0	1
		Option 4	0	2	2
	Murrumbidgee River	Option 1	0	0	–2
		Option 2	0	0	–3
		Option 3	0	–2	–1
		Option 4	0	–2	–1

*Total RRCP Populations defined as the RRCP focal zones and Wakool Junction to Wentworth.

Golden Perch

- Increased flows under RRCP hydrological scenarios significantly enhanced the population outcomes (as indicated by the modelled juvenile and adult numbers and the overall population distribution curves – Figure 18; Figure 19 and Figure 20) for Golden Perch for all river reaches (Figure S1).
- The population model predictions for Golden Perch demonstrated that the highest RRCP hydrological flow limit scenario (i.e. Option 4) has the greatest benefit (30% increase in the expected mean population size compared with Base case flows) in each of the RRCP reaches. The Murray River (to Wentworth) had a 29% increase over the Base case under Option 4 (Table S2), and the Murrumbidgee River had a 34% increase over the Base case under Option 4). For several reaches, there were even larger benefits (e.g. 49% increase in the expected mean population size for the Lower Murray below Wentworth and a 40% in the expected mean population size in the mid Murrumbidgee (Gundagai to Hay).
- Generally, Option 4 had the best outcomes for most reaches, with the exception of Gundagai to Hay, in which Option 3 had the greatest predicted benefits (a 47% increase in the expected mean population size). This was likely due to Option 3 allowing for greater longitudinal connectivity, which is critical in this reach because one rule of the population model is that there is no recruitment in the upper Murrumbidgee (see Gundagai to Hay 1-year-old outputs). Also, there are likely subtle differences in the timing, frequency and size of modelled environment flow deliveries between Options 3 and 4. Option 4 also had strong modelled population benefits in the lower Murrumbidgee River (Hay to Balranald), which likely related to maximum connectivity with the mid Murray River (Torrumbarry to Wentworth). Concurrently, Option 4 had the strongest modelled population benefits in the reaches Yarrawonga to Torrumbarry and Hume to Yarrawonga. Yarrawonga to Torrumbarry likely benefited from greater connecting flows resulting from the knock-on effect of more individuals moving into the Hume to Yarrawonga reach. The Edward River had the lowest response: a 7% increase in the expected mean, possibly because the Edward River is a smaller system and is likely limited by fish passage and end of system attracting flows, affecting Golden Perch immigration rates from downstream source populations.
- Specific river reaches within the modelled areas had asymmetrical influence over regional- and interbasin-scale population dynamics. For example, the Edward River and the Murray River upstream of Torrumbarry, and the Murrumbidgee River upstream of Hay appear as 'sink' reaches, relying on immigration from downstream.
- Sensitivity analyses indicated that the modelled predictions were stable under various biological scenarios (e.g. various fish movement rates, various population sizes; see Appendix 4), increasing confidence in the predicted fish population responses to flow changes.

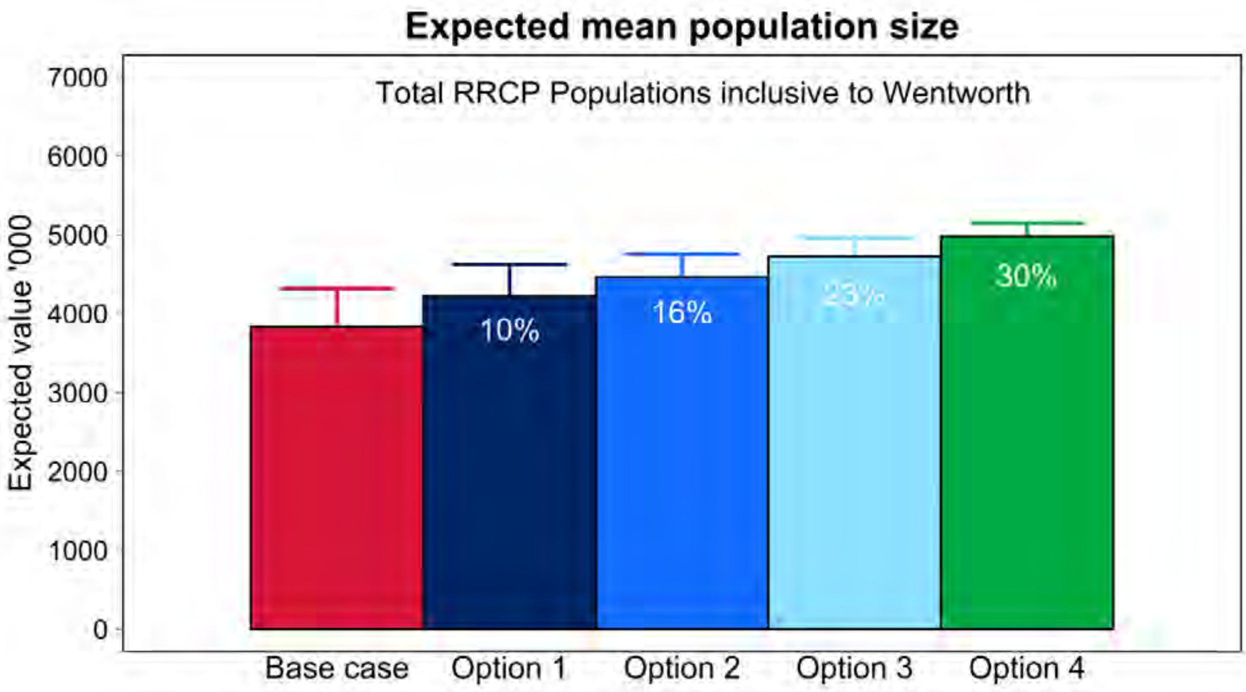

Figure S1. Summary of the predicted Golden Perch responses to flow scenarios (Base case to Options 1–4) aggregated across all modelled RRCP focal zones, together with the Wakool Junction to Wentworth reach. Each of the five bar graphs shows the expected value (+1 sd) of the mean population size for the adult population. The values printed on the bars for Options 1–4 are the predicted percentage increases in the population above that of the Base case. The expected mean adult population size is predicted to be 10% higher under Option 1, and 30% higher under Option 4, than under the Base case.

Murray Cod

- The modelling indicated that changes in flow under the RRCP hydrological scenarios would not change the expected mean population size for Murray Cod populations (Figure S2). However, there were benefits for this species in the Hume to Yarrawonga reach for some options, and there were marginal benefits in the Edward River. Recruitment responses were also strongest in these two reaches. The reasons for the relatively small benefits indicated by the model outcomes are likely related to spawning and recruitment being less dependent on increased discharge (ML day^{-1}) or floodplain connection within the model construct.
- The greatest effect on Murray Cod dynamics comes from hypoxic blackwater events, though these events did not vary across the RRCP hydrological scenarios.

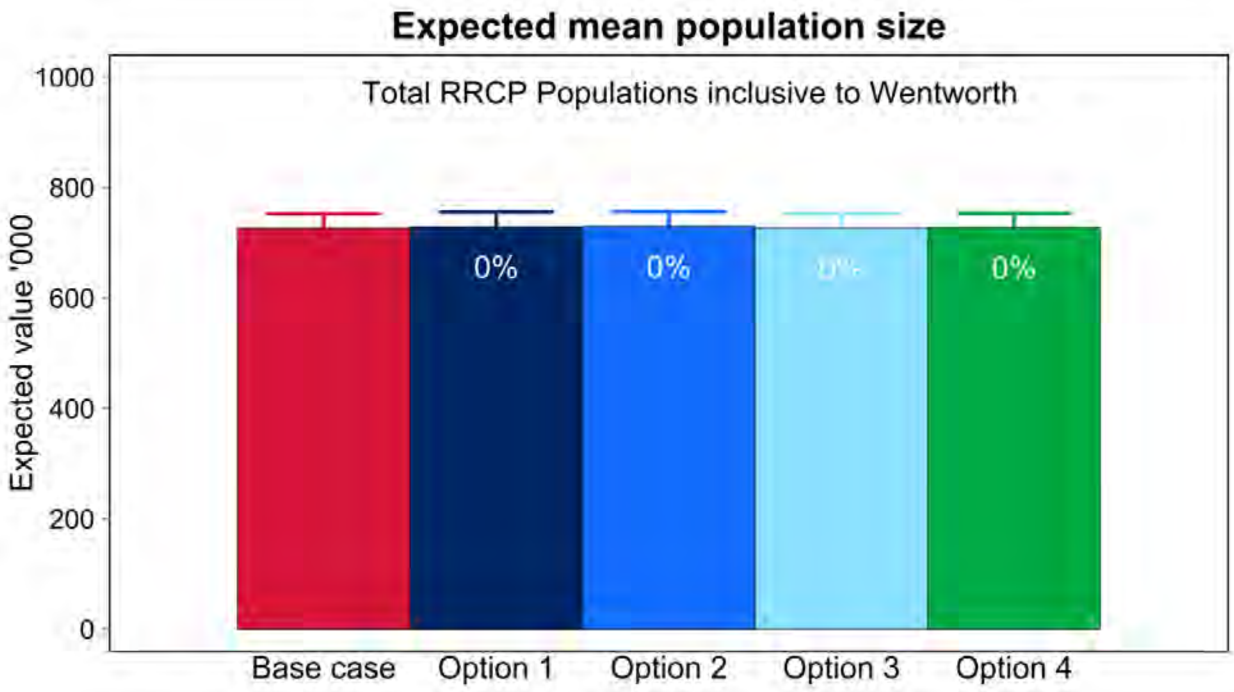

Figure S2. Summary of predicted Murray Cod responses to flow scenarios (Base case to Options 1–4) aggregated across all modelled RRCP focal zones, together with the Wakool Junction to Wentworth reach. Each of the five bars shows the expected value (+1 sd) of the mean population size for the adult population in the Total RRCP Populations. The values printed on the bars for Options 1–4 are the predicted percentage increases in the population above that of the Base case. The expected mean adult population size is invariant across all options.

Synthesis

Population modelling, supported by long-term modelled flow data, has proven to be a powerful approach to predicting the outcomes for the RRCP relaxed-flow-constraints hydrological scenarios for native fish. The modelling predicted clear benefits for Golden Perch from the maximum RRCP flow scenario (Option 4) (an average 30% increase in the expected mean adult population size). There were diminishing gains as the flow magnitude of the scenarios decreased. For Murray Cod, the models predicted a lower level of benefit from the RRCP relaxed-flow-constraints scenarios. This is likely to have been due to the lower reliance of Murray Cod on increased discharge (i.e. spring pulses and flooding) for recruitment, and to their high sensitivity to hypoxic blackwater events. For the RRCP program, relaxed flow constraints result in clear predicted benefits to Golden Perch populations, and likely other flow-dependent species, and constitute a major recovery pathway. Managed flows greater than 45,000 ML day^{-1} (the highest proposed flow limit at Yarrawonga) were not modelled under the present program and may have even greater benefits for native fishes. Modelling the effects of flow rates under climate change would also be instructive for predicting future population trends.

Model validation

While population models are useful for informing decision-making, they do not perfectly reflect reality. Hence, it is important to show that models are sufficiently realistic to meet their intended purposes and can be used as part of the decision-making process. A detailed model validation exercise was undertaken by comparing the predictions of the population models with empirical field survey data (provided by the Arthur Rylah Institute for Environmental Research (ARI) and the NSW Department of Primary Industries – Narrandera Fisheries Centre (DPI Fisheries)) for several focal reaches (Appendix 6: Validation). For both Golden Perch and Murray Cod, there were reasonable correlations between the model predictions and the observed datasets, and in general both showed similar temporal trends, especially in more comprehensive datasets such as that of the Yarrawonga to Torrumbarry reach for Golden Perch. Where misalignments between model predictions and empirical datasets were observed, these were likely due to factors that were known to have occurred but were not currently considered in the model construct (e.g. blackwater events and stocking for Golden Perch), or they indicated that some refinement of the model rules (especially the movement rules for Golden Perch) or the model inputs (especially blackwater events) would be beneficial. In some instances, misalignments may also have been due to factors causing variability in the empirical data, such as changes in electrofishing detection as a function of changes in flow level. Future refinements of the model construct and model inputs would likely increase certainty that the models can accurately predict the outcomes of various flow scenarios, especially in reaches where the misalignments were most significant (e.g. in the Gundagai to Hay reach for Golden Perch, and in the Edward River reach for both species). Model validation is critical but rarely undertaken, often due to a lack of independent datasets against which to compare model predictions. Our approach, utilising long-term datasets, provides detailed insight into the locations for which the population modelling results can be interpreted with a higher degree of certainty than where more caution is needed.

Recommendations

In relation to the four RRCP flow scenarios examined, the population model predictions for Golden Perch indicate that, in the RRCP reaches of the Murray and Murrumbidgee rivers, the RRCP hydrological scenario of 45,000 ML day^{-1} at Yarrawonga and 40,000 ML day^{-1} at Doctors Point and Wagga Wagga (i.e. Option 4) has the greatest benefits overall (an average 30% expected increase in mean adult population size, and up to 49% for some spatial areas, compared with the Base case). For the NSW DPE, we recommend that RRCP flow scenario Option 4 is likely to be the most beneficial for Golden Perch populations in the future.

The population modelling has revealed several of the important pathways/mechanisms that help to support Golden Perch populations, including emigration between the Lower Murray–Darling Basin system and upstream tributaries, such as the Murray River above Torrumbarry, the Edward and Wakool rivers, and the Murrumbidgee system. The population models identified the flows and spatial areas that can influence these processes, indicating a strong link between the scenarios and outcomes supporting native fish recovery.

For Murray Cod, the population models indicated that avoiding hypoxic blackwater is the most influential factor in recovering populations. We recommend utilising this knowledge in annual watering plans to better support broad fish population dynamics.

Supporting recommendations

The population models for Golden Perch and Murray Cod represent some of the most sophisticated tools for exploring future scenarios and likely ecological responses to a broad range of management interventions. Further technical refinements are suggested (e.g. the addition of key missing spatial areas, such as the Goulburn River and the Menindee Lakes, as well as modifications to the flow–ecology drivers), as are additional flow scenarios (e.g. without-development flow time series that is flows without dams and extraction for consumptive use as well as climate change scenarios). Subsequent application of the models may provide much-needed insights into the drivers of fish population dynamics over broad spatial and temporal scales, shedding further light on the likely outcomes of the proposed pathways for fish recovery.

1. Introduction

Connectivity between rivers and their adjacent wetlands and floodplains is an important feature of healthy, functioning freshwater ecosystems. These connections support important ecological, hydrological and chemical processes. However, many rivers globally are no longer connected with floodplains and wetlands for as often or as long as they need to be, and these important processes are lost or compromised. Also, many rivers are managed in the context of balancing competing human and environmental needs for water (Vörösmarty et al. 2010). Consequently, the health of many river systems has declined.

To help restore rivers in Australia's Murray–Darling Basin, flexibility in managing the flows to support both human and environmental needs is required (Dudgeon et al. 2006; Vörösmarty et al. 2010). As part of meeting this challenge, the New South Wales (NSW) government is considering the Reconnecting River Country Program (RRCP) in Southern NSW, in three focal regions: Murray River from Hume to Yarrawonga, Murray River from Yarrawonga to Wakool and Murrumbidgee River system (downstream of major storages: Burrunjuck and Blowering dams). The RRCP will consider the physical, policy and operational constraints that limit the flow of these river systems, and how these constraints can be best managed to support healthy, productive waterways. The RRCP is part of a broader program, the Sustainable Diversion Limit Adjustment Mechanism (SDLAM), and the RRCP and other SDLAM Supply Measures will allow for more effective use of water for the environment. Relaxing constraints may allow environmental watering to deliver higher flow peaks and hence the potential to improve native fish outcomes in the southern-connected Murray–Darling Basin, as well as the more efficient use of water.

Decisions about how to best balance economic, social, cultural and environmental outcomes in the RRCP will be made based on comprehensive assessments of potential benefits and costs/impacts, an options evaluation process and community engagement and collaboration on program design. DPE Biodiversity, Conservation and Science (BCS) is leading the assessment of the environmental benefits of RRCP projects for native vegetation, native fish, waterbirds and ecosystem function (productivity), and potential risks such as potential increase in Common Carp (*Cyprinus carpio*) populations, invasive weed spread and hypoxic blackwater events. These assessments are part of the initial stage of the Reconnecting River Country Program, during which a range of flow and mitigation options are explored; benefits and costs/impacts of these options are assessed and the program socialised with a broad range of stakeholders.

Environmental benefits assessments will provide quantitative predictions of the likely medium- to long-term ecological responses to RRCP flow limit options, using the best available science at a range of spatial scales. The outputs will help the RRCP projects by:

(a) informing evaluation of project flow limit options and government decision making on the preferred flow limits in the future;

(b) building stakeholder and community understanding and confidence in the range of likely environmental benefits and risks of relaxing constraints;

(c) defining the project benefits for inclusion in Strategic and Final Business Cases; and

(d) potentially informing the SDLAM reconciliation process.

The relaxation of constraints in the RRCP project is expected to have positive outcomes for native fish in these areas and across the Southern MDB by providing improved connectivity with floodplains and between habitats, increasing productivity and food availability, and enhancing instream conditions for movement and spawning in the Murray and Murrumbidgee rivers and their floodplain anabranches and creeks. However, the benefits of relaxing constraints will likely vary based on the water requirements of different species, along with how different management approaches change hydrological conditions in general, and connections between rivers, wetlands and floodplains more specifically. Information about how native fish species might respond to different flow scenarios is therefore an important input into the RRCP decision-making process.

The ARI has undertaken extensive and peer reviewed work using stochastic population models to provide medium- to long-term quantitative predictions of fish population responses to a range of management actions, including the provision of environmental water (Sherman et al. 2007; Koehn and Todd 2012; Todd et al. 2018). The models and approaches used in these studies can be modified and applied to the RRCP project flow options in the Murray and Murrumbidgee catchments.

The objective of this project is to use stochastic population models to provide quantitative predictions of the likely medium-to long-term changes to populations of Golden Perch (*Macquaria ambigua*) and Murray Cod (*Maccullochella peelii*) (this report), and non-native Carp (Wootton et al. in prep.) to RRCP project flow limit options in the Murray and Murrumbidgee catchments for NSW DPE. These models predict Golden Perch, Murray Cod and Carp population responses at a range of spatial scales to enable evaluation of likely risks and benefits of RRCP flow limit options within each project area. Note that Carp modelling is presented in a separate report (Wootton et al. in prep.).

This report first provides background information about stochastic population models and how they were broadly used in this project. It then describes:

- fish population model development and application within the project area
- how the latest scientific knowledge was incorporated into the project via technical workshops
- key findings and results, in terms of predicted responses of the two focal species to different potential future flow scenarios under the RRCP
- the limitations of the modelling process, and underlying assumptions when interpreting results

1.1. Background to population models and model outputs

Population models are an important mathematical tool widely used in conservation and natural resource management. ARI has developed and used the predictive capacity of population models for a variety of native fish and crustacean species to demonstrate likely outcomes for management interventions at a range of spatial and temporal scales (Todd et al. 2005, 2017, 2018, 2020; Sherman et al. 2007). In addition, population models have also been used to simulate population trajectories of non-native fish under a range of hydrological scenarios (Forsyth et al. 2013; Koehn et al. 2018; Brown et al. 2020; Stuart et al. 2021a).

Population models provide an immediate opportunity to predictively explore likely outcomes for the specified range of RRCP flow scenarios and thus provide managers with a reliable mechanism for prioritising flows that restore native fish communities. Quantitative predictions of fish population responses at medium- to long-term temporal scales (10–120 years) to relaxed-flow-constraints scenarios were made for rivers in the Murray and Murrumbidgee catchments. This included an evaluation of relative population responses under the various RRCP flow limit options. Population models are a representation of the ‘real’ world and hence can also account for other major factors that influence population processes, such as fish passage, angler harvest, and cold-water pollution.

Construction of the population models relies on collaborative approaches by fish ecologists, modellers, river managers and other subject-matter experts (e.g. blackwater and productivity ecologists) to collectively build an understanding of how river systems operate. A conceptual model is developed that uses knowledge of the species’ ecology to design management operations that inform the structure of the population models. As each management and spatiotemporal question is unique, the population models are adapted for project-specific objectives, fish species, and sites. Model outputs can be expressed as distribution comparisons, or abundances of adult or juvenile fish over biologically relevant spatial areas and time frames.

Population models can afford a high level of scientific credibility, rank outcomes and reduce uncertainty for proposed works, especially in situations where collecting field data is impractical. Hence, mathematical models provide one of the most cost-effective ways to predict environmental outcomes for various proposed management regimes. Examples of the types of outputs, their interpretations, and implications for river operations from the modelling include:

- fish population (abundance) trajectories for each of the proposed relaxed-flow-constraints scenarios in the Murray and Murrumbidgee catchments (see Figure 1 for a conceptual example) that will allow managers to make a comparison between the likely benefits of each
- outputs of various fish population measures (e.g. age classes, size classes, numbers of adults or recruits)
- scientifically robust interpretations and explanations of results (including uncertainty, sensitivity and power analysis), and clear explanations of benefits of the restoration options
- robust and transparent evaluation of the population responses (relative to Baseflow) to the various RRCP flow scenarios and hydrological recommendations designed to enable native fish population recovery.

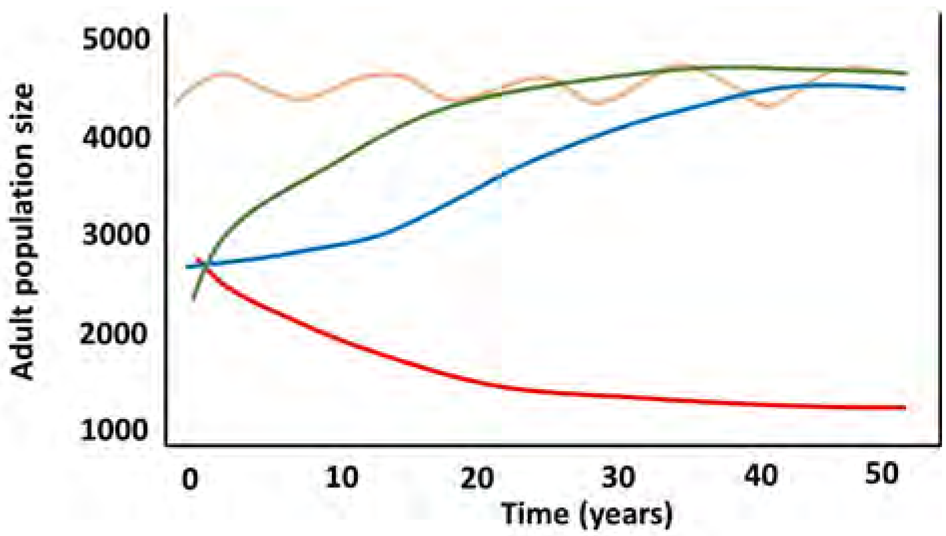

Figure 1. A conceptual example to demonstrate the model outputs of population trajectories for four different management scenarios, with each coloured line representing a different management scenario (or a combination thereof). Three of the scenarios start with comparable population sizes, before one decreases (red), and the other two increase but at different rates (green and blue). The size of the population stays relatively consistent through time in the fourth scenario (light brown).

The population models developed to assess the specified range of RRCP flow scenarios are stochastic population models, which means that some of the parameters vary randomly to account for natural variation within the modelled system. For each scenario assessed, 1000 iterations of the model were processed to explore the underlying variation of the model, thus generating 1000 different population trajectories. See Figure 2 for examples of a single trajectory, 10 trajectories, 100 trajectories and 1000 trajectories. The output from 1000 trajectories is summarised in Figure 3.

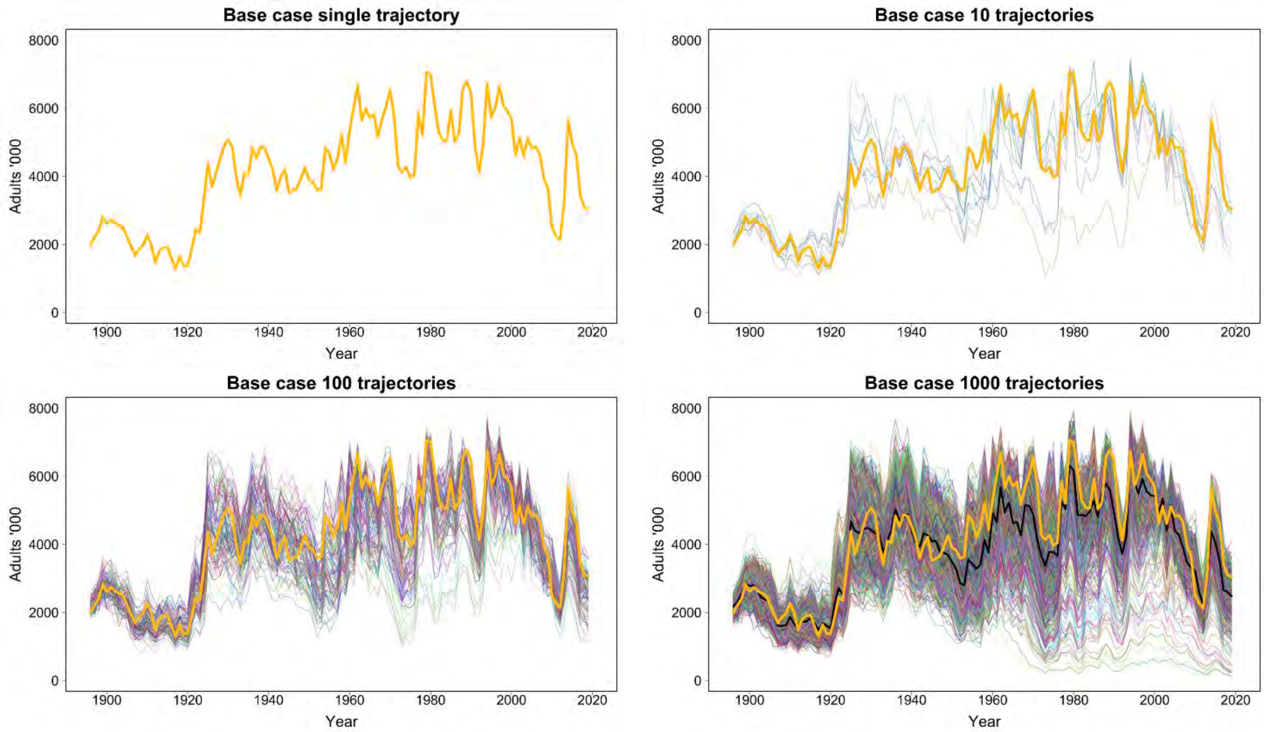

Figure 2. Top left: a single trajectory for the Total RRCP Populations of Golden Perch for the Base case scenario; top right: 10 trajectories for the Total RRCP Populations of Golden Perch for the Base case scenario; bottom left: 100 trajectories for the Total RRCP Populations of Golden Perch for the Base case scenario; and bottom right: 1000 trajectories for the Total RRCP Populations of Golden Perch for the Base case scenario, with the mean trajectory across all model iterations indicated in black.

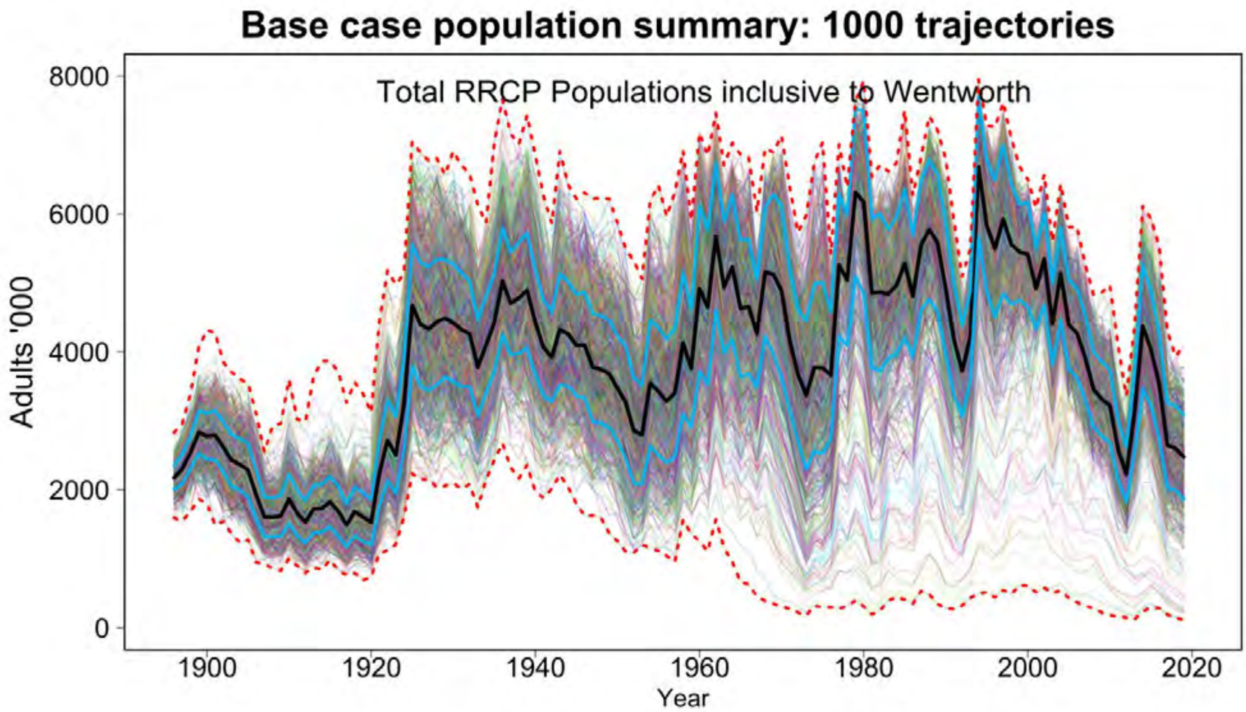

Figure 3. Summary of 1000 trajectories for the Total RRCP Populations of Golden Perch for the Base case scenario. The black line indicates the mean adult population size through time; blue lines indicate ±1 standard deviation from the mean; and the red dotted lines indicate the maximum and minimum across all trajectories through time.

To compare the base case scenario with the four options, we present the mean trajectories of five scenarios in one graph, even though this approach does not fully capture the variation around the mean trajectories. A common approach to assist in comparing various scenarios is to compile the distribution of minimum population sizes for each scenario. The minimum population size from each trajectory is recorded and converted into a cumulative distribution, forming the distribution of the minimum population sizes. Graphing these distributions provides a visual comparison of each scenario that transparently contrasts the likely benefits or detriments of each scenario. A conceptual example of these contrasts is provided in Figure 4 and Figure 5. Such distributions can indicate effectiveness at meeting a specified threshold population level and can be used to evaluate the likely success or failure of a given scenario. A distribution of minimum population sizes closer to zero represents a higher likelihood of the population being lower compared with a distribution further from zero, which has a comparative likelihood of the population being higher (preferred outcome; see Figure 5 and Figure 6). As the distribution of the minimum populations sizes is a cumulative probability distribution, it is possible to calculate the expected value of the minimum population sizes, and to compare these values among the various scenarios, as well as to calculate the percentage change (see e.g. Figure 7). Finally, it is possible to examine a variety of criteria with which to partition the data; for instance, the 10% quantile population size may be used instead of the minimum population size, as may the mean population size, or the maximum population size. See Figure 8 to Figure 11 for examples of use of the distribution of the mean and maximum population sizes.

In this report, modelled outputs are summarised by presenting graphs of: the mean trajectories of the RRCP flow scenarios (Base case and Options 1–4) (similar to Figure 4); distributions of the mean of each trajectory of the RRCP flow scenarios (Base case and Options 1–4) (similar to Figure 8); and bar charts of the expected mean population size, with percentage change from the Base case scenario, for the RRCP flow scenarios (Options 1–4) (similar to Figure 9). All other model outputs can be found in the Appendices.

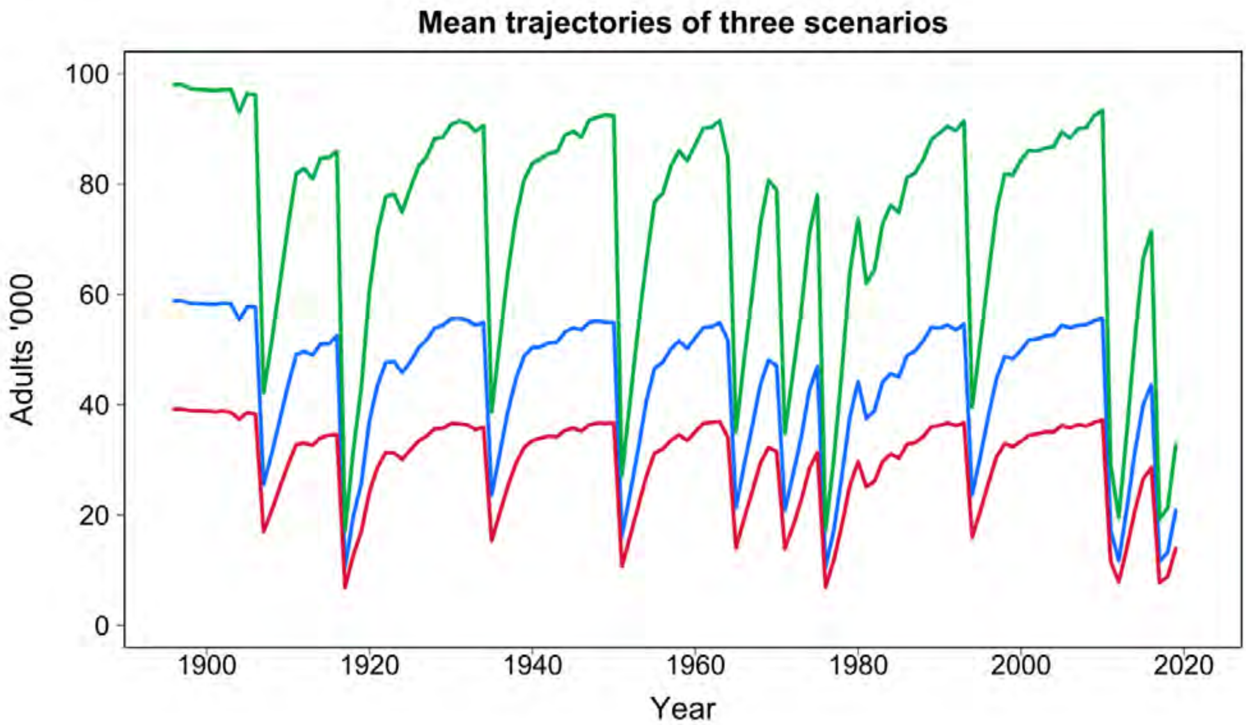

Figure 4. An example of the mean adult population trajectories for three hypothetical scenarios. The green line indicates the population outcome with optimised management, the blue line the population outcome with management addressing some threats, and the red line the poorest population outcome.

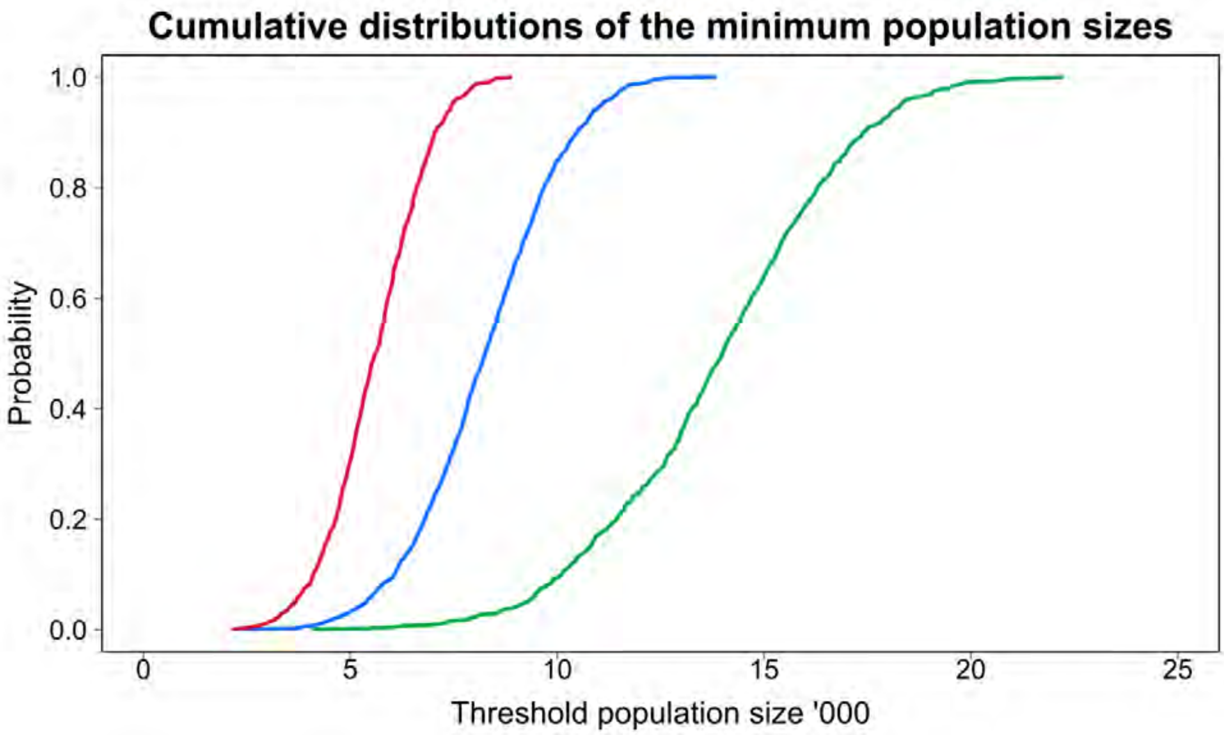

Figure 5. An example of the utility of comparing the distributions of the minimum population sizes for the three hypothetical scenarios in Figure 4. The green line indicates the population outcome with optimised management, the blue line the population outcome with management addressing some threats, and the red line the poorest population outcome. These distributions represent the likelihood of the population falling below an identified minimum threshold, with theoretical extinction occurring when this falls to zero.

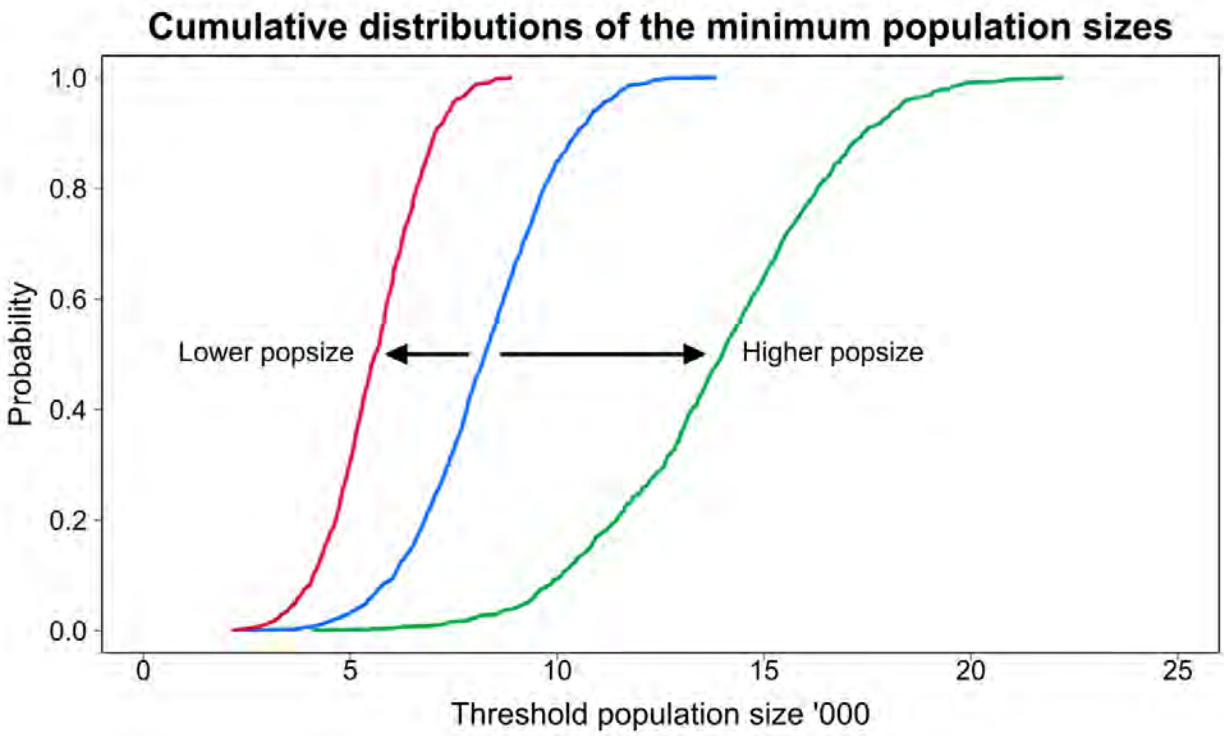

Figure 6. Indicative consequences when comparing the cumulative distributions of the minimum population sizes for the three hypothetical scenarios in Figure 4.

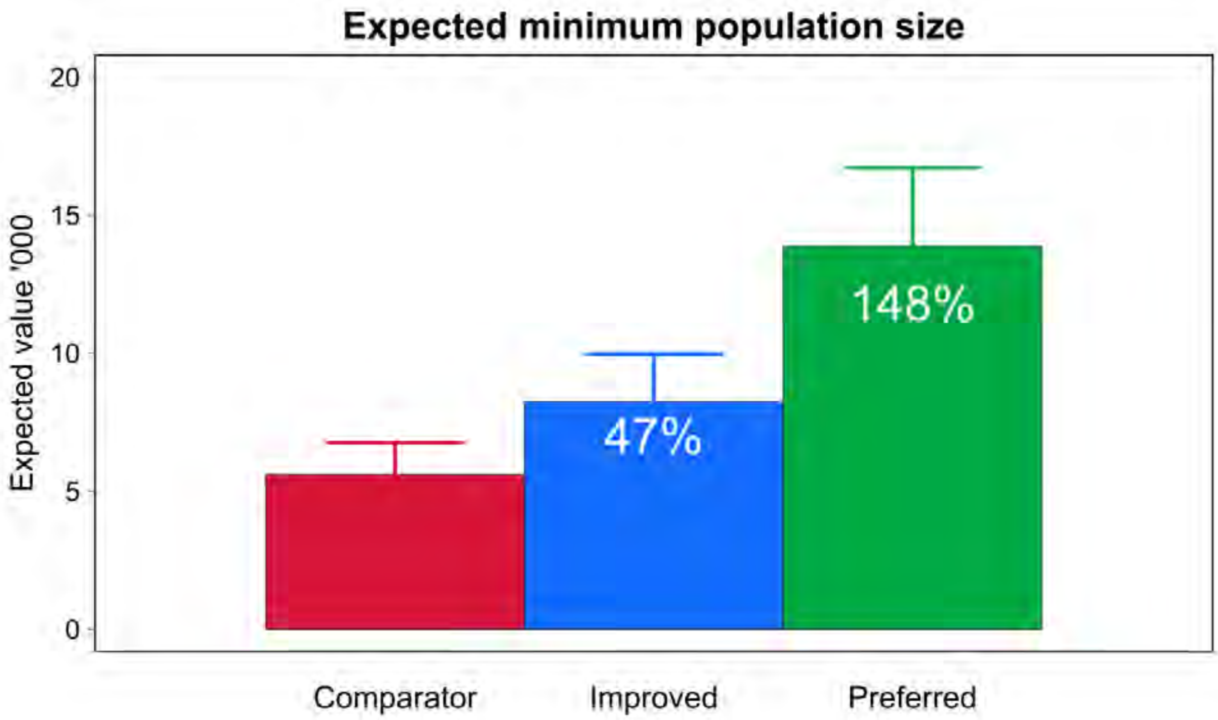

Figure 7. Bar chart of the expected minimum population size (+1 sd) for the three hypothetical scenarios in Figure 4, where the percentage difference is always in reference to the comparator (red) on the left; for model outputs this will be in comparison with the Base case scenario. The green bar indicates the population outcome with optimised management, the blue bar indicates the population outcome with management addressing some threats, and the red bar indicates the comparator or Base case scenario.

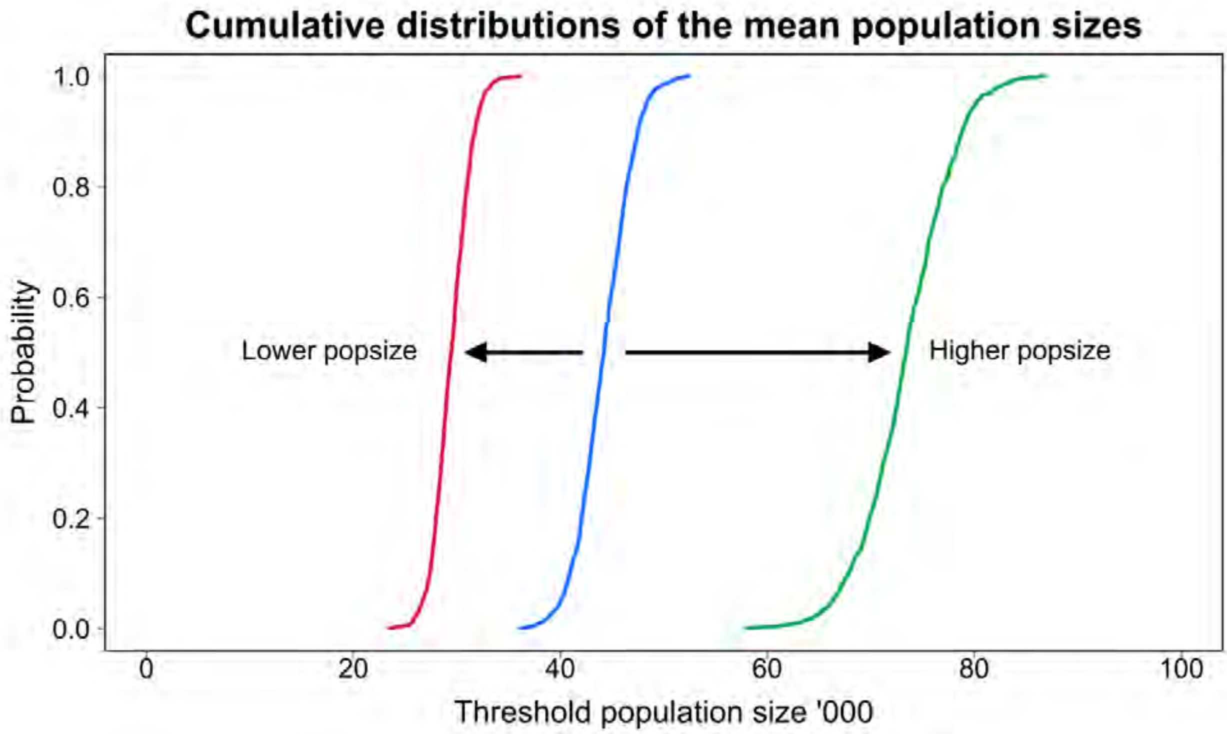

Figure 8. Indicative consequences when comparing the distributions of the mean population sizes for the three hypothetical scenarios in Figure 4.

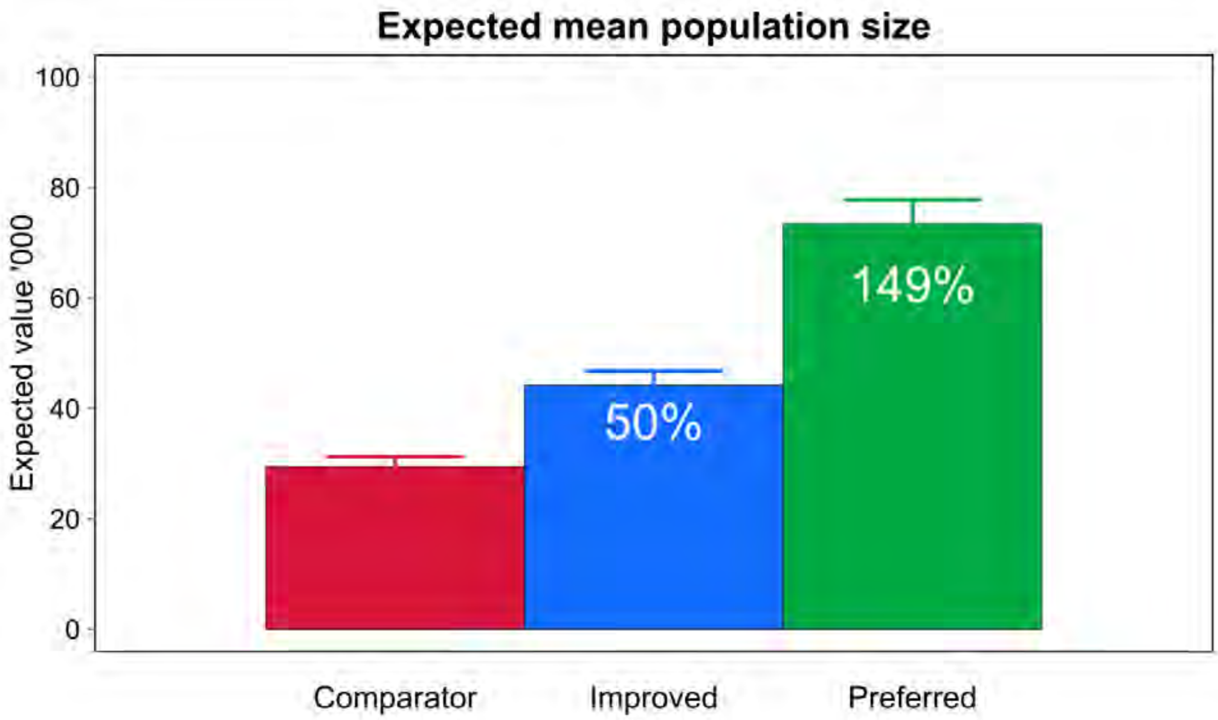

Figure 9. Bar chart of the expected mean population size (+1 sd) for the three hypothetical scenarios in Figure 4, where the percentage difference is always in reference to the comparator (red) on the left; for model outputs this will be in comparison with the Base case scenario. The green bar indicates the population outcome with optimised management, the blue bar indicates the population outcome with management addressing some threats, and the red bar indicates the comparator or Base case scenario.

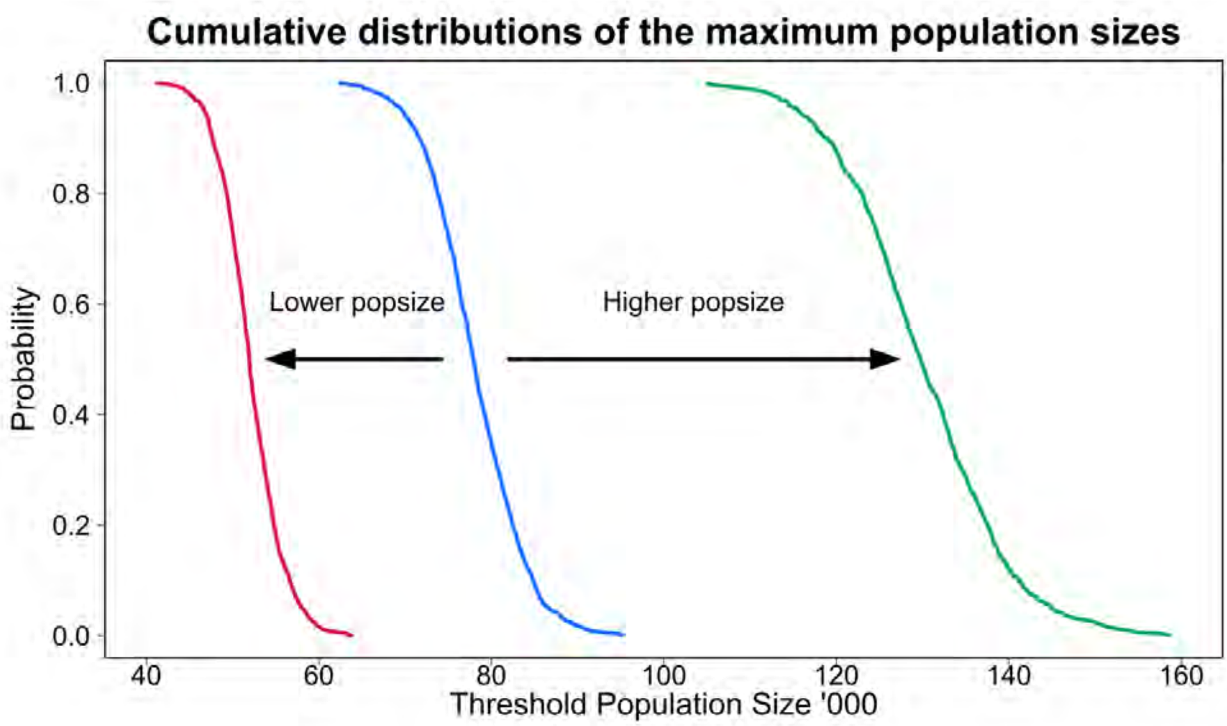

Figure 10. Indicative consequences when comparing the cumulative distributions of the maximum population sizes for the three hypothetical scenarios in Figure 4.

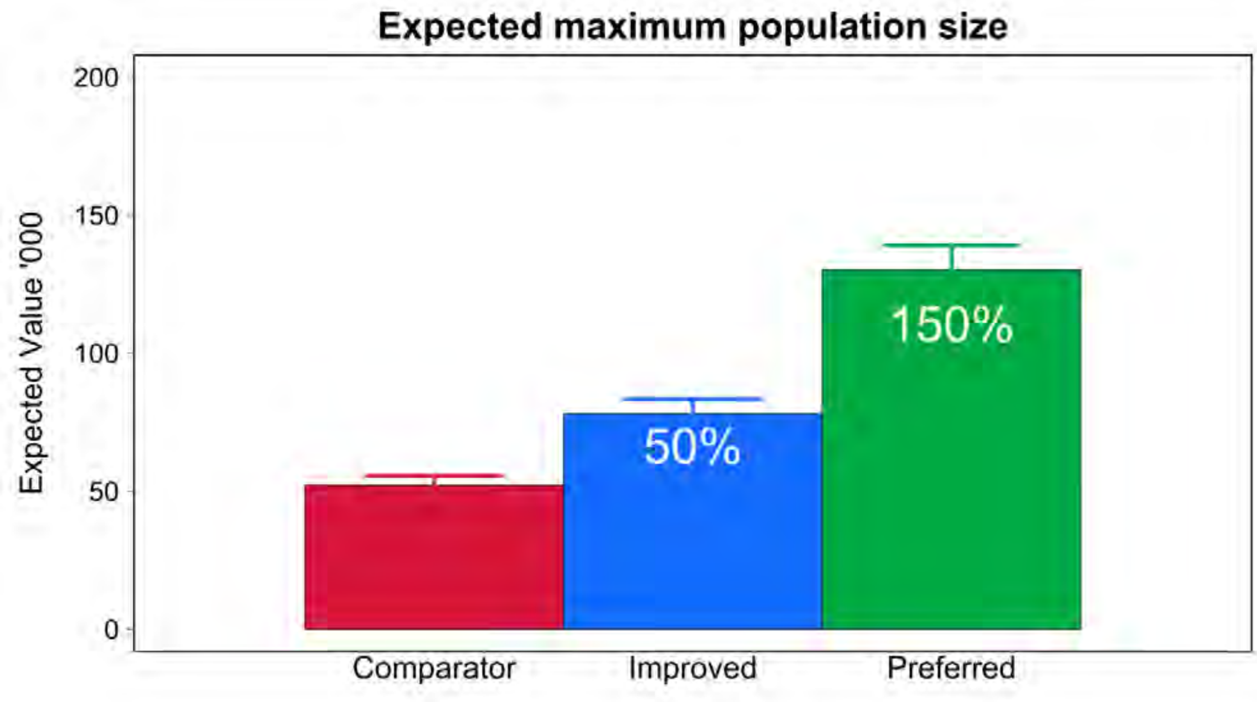

Figure 11. Bar chart of the expected maximum population size (+1 sd) for three hypothetical scenarios in Figure 4, where the percentage difference is in reference to the comparator (red) on the left; for model outputs this will be in comparison with the Base case scenario. The green bar indicates the population outcome with optimised management, the blue bar indicates the population outcome with management addressing some threats, and the red bar indicates the comparator or Base case scenario.

1.2. Validation

While current knowledge and theories are frequently embedded in models, no model will perfectly reflect reality (McCarthy et al. 2001; Deitze et al. 2018). The challenge is, therefore, to show that a model is sufficiently realistic to meet its intended purpose(s) (Rykiel 1996) and can be confidently used as part of a decision-making process that will achieve the desired conservation outcomes. Without addressing this challenge, there is a risk of the model being used to inform erroneous decisions (Augusiak et al. 2013), which could have detrimental, costly, or irreversible consequences (Getz et al. 2018). Therefore, it is important to validate models in order to determine the accuracy of predicted outcomes, and their ability to capture functional relationships and emergent phenomena (McCarthy et al. 2001; Deitze et al. 2018). While validation of the main predictions of a model is important, ideally the assumptions made (in terms of model structure and conceptual knowledge) and the secondary predictions (i.e. outputs that are not standard or used to make management decisions) should be assessed to understand the reliability of the model (Bart 1995).

A powerful way of assessing model performance is to check model predictions against data that are independent from the model-fitting process (Deitze et al. 2018). This independence is important, because it eliminates the possibility of model circularity influencing the validation operations, whereby model predictions may reflect the training data rather than be an accurate representation of the population processes. For several of the RRCP focal zones, there has been extensive sampling of fish populations since 2000 by scientists from NSW Fisheries and the ARI. Model validation is frequently not undertaken, usually because of a lack of independent datasets for comparison (Todd et al. 2008; Rogosch et al. 2019). Having access to these long-term datasets therefore represents an important, and quite unique opportunity to compare the predictions of the native fish population models of the RRCP scenarios with data that are independent from the model-fitting process.

Model validation is an important component of the project, using an approach developed by members of the core RRCP ARI Project Team, with input from a wider group of fish ecology and biostatistical experts from ARI (Jarod Lyon, Zeb Tonkin, Jian Yen), NSW Fisheries (Jason Thiem) and the University of Melbourne (Mick McCarthy, a globally renowned quantitative ecologist with experience in validating population models). The two RRCP ARI Project Team members responsible for leading the validation component (Ben Fanson and Robin Hale) were not involved in the construction or development of the stochastic population models.

As the validation component of this study was reliant on the outputs of the modelling, both the methodology for and the results of the validation process have been included in the Results section, with key results being further explained in the Discussion. This allows the reader to concentrate on the modelling component, then logically move to consider the validation of the modelling outcomes.

2. Methods

2.1. Program logic

The population models were developed via an iterative process consisting of: (i) developing and updating species-specific conceptual models via a series of workshops with expert fish ecologists and environmental water managers, (ii) using this knowledge to adapt the population models for each of the core RRCP areas and the additional study areas (the Lower Darling and Lower Murray rivers) and hydrological scenarios, (iii) incorporating life history responses to flow and temperature cues, (iv) including flow–productivity effects, (v) including an anoxic blackwater construct (for Murray Cod only), (vi) defining and reporting the ecological benefits of the modelled RRCP flow scenarios, and (vii) comparing model predictions with independent empirical datasets; (viii) providing advice to NSW DPE regarding the model application and the results.

2.2. Fish species

The fish population modelling within the RRCP project examined (native) Golden Perch and Murray Cod (the two species of concern in this report) and, in a separate report, (non-native) Carp (Wootton et al. in prep.). All three species are widespread in the MDB, and the two native species are highly important to First Nations people as angling and totemic species. Murray Cod has a national conservation listing and hence must be managed for both conservation and recreational fishery objectives (Koehn and Todd 2012). Populations of both native species have declined due to a range of factors, including alienation of floodplains, reduced annual river flows and flow pulses, and loss of lotic (flowing) habitats (Koehn et al. 2020).

2.3. Spatial area and population units

The models predict Golden Perch, Murray Cod and Carp population responses at a range of spatial scales to predict the effects of the RRCP flow limit options within each project area. The three core RRCP focal zones are:

- Murray River—Hume Weir to Yarrawonga Weir
- Murray River—Yarrawonga to Wakool Junction
- Murrumbidgee River—Burrinjuck Dam to Murray Junction

The RRCP focal zone Yarrawonga to Wakool Junction was modelled as two separate populations from Yarrawonga to Torrumbarry and Torrumbarry to Wentworth. To better represent the ecology of the two native species, the downstream boundary of Wakool Junction was extended to Wentworth. In addition, as Golden Perch are a highly mobile species (known to move large distances), and the Lower Murray and the Lower Darling rivers are known to support important populations, the Golden Perch model was extended to include the Lower Murray (including the lower lakes) and the Lower Darling rivers. For the purposes of this report, we use the term 'Total RRCP Populations' to represent all modelled RRCP focal zones with the addition of the Murray River downstream from Wakool Junction to Wentworth. All the reaches modelled were included in the following: the Murray River from Lake Hume to the Murray Mouth (Golden Perch), the Murray River from Lake Hume to Wentworth (Murray Cod), the Edward River (both species), the Lower Darling River (Golden Perch), the Murrumbidgee River upstream of Balranald to Gundagai (both species – fish populations were not modelled upstream of Gundagai to Burrinjuck Dam due to thermal pollution and this reach not contributing to native fish recovery), and Yanco Creek (Murray Cod).

2.4. Conceptual models

We examined, collated and reviewed published and unpublished ecological information and knowledge to identify uncertainties and to develop conceptual models of the life histories of Golden Perch and Murray Cod. Much of the available knowledge has already been gathered (through extensive literature searches and workshops) and collated in recent studies (e.g. Koehn et al. 2020). This information was updated with additional expert opinion in RRCP project workshops in early 2021 to ensure that the latest ecological knowledge relevant to the RRCP sites under consideration could be used. Application of contemporary conceptual models was a critical step, particularly when determining (i) the spatial scale of species' movements in relation to the model structure (i.e. metapopulations), (ii) parameterisation, and (iii) management units. For each of the subpopulations, the local context (including factors such as fishway passage availability, flow rates, physical structure of the environment, and fish movement patterns) was considered.

These conceptual models informed the structure of the population models and the rules within them, and in addition revealed the population drivers that might be influenced by the specific flow rules reflecting the proposed RRCP flow changes. For example, knowledge of the movements of Golden Perch is vital in establishing rules that will allow for the movement of the various life stages between the river reaches in the meta-population model. Similarly, conceptual understanding of the impacts of hypoxic blackwater events are important in representing Murray Cod population dynamics.

2.4.1. Golden Perch conceptual model

Golden Perch are a flow pulse specialist, with many components of their life cycle being driven by river flow and hydraulic diversity (Koehn et al. 2020). They require increases in discharge to initiate spawning (Lake 1967) and thus are a good candidate for exploring flow–ecology modelling questions. As sub-adults and adults, Golden Perch are a highly mobile species, with movements being triggered by fluctuations in discharge, and they often undertake river valley and intervalley movements (O'Connor et al. 2005; Koehn and Nicol 2016; Zampatti et al. 2019). Their larvae can also drift long distances downstream, and strong recruitment is associated with dense plankton communities, often in floodplain lakes and in the lower reaches of rivers (Sharpe 2011; Stuart and Sharpe 2020; Zampatti et al. 2021). The various proposed RRCP flow scenarios are thus likely to broadly impact the expression of Golden Perch populations throughout their life history: these impacts were explored via model rules developed for each population unit (see sections 2.8 and Appendix 2 for details). For example, increased flows under the various RRCP flow scenarios above the Base case levels are likely to affect the timing and intensity of spawning, the rates of larval drift, and the timing and volume of movement events. A species with a life history spanning large spatial scales requires modelling of a metapopulation (i.e. a population of populations) in order to confidently capture its population dynamics (i.e. movement) between discrete areas: Golden Perch do not successfully recruit in all areas (i.e. form sinks in some areas), but move from known recruitment areas (source areas) to sink areas as part of their life history strategy (Figure 12). Thus, a metapopulation model was used, based on this conceptualisation of movements and ecology, in which larval drift, juvenile and adult movement, and spawning migrations were considered across all RRCP reach areas (Figure 12).

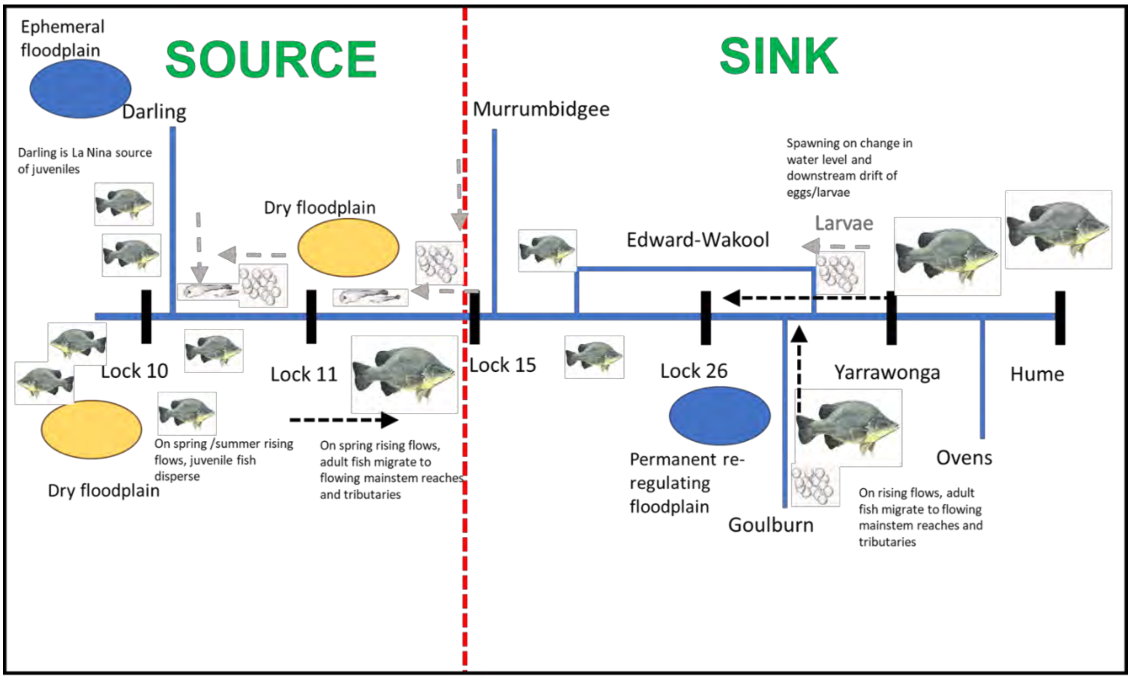

Figure 12. A conceptual model to demonstrate the 'source–sink' population dynamics of Golden Perch in the connected Southern MDB. In this context, 'sink' means that, despite local spawning, fish populations appear to be mostly maintained by emigration and hatchery stocking, rather than local recruitment. The productivity of these upstream reaches and floodplains still supports survival of stocked and emigrating juveniles.

2.4.2. Murray Cod conceptual model

Murray Cod are demersal, riverine specialists that are associated with permanent rivers, lotic (flowing) reaches and in-stream woody habitats (Koehn 2009a, 2009b; Koehn and Nicol 2014). Their life history can be completed at the scale of reaches (i.e. 5–50 km), though there can be occasional longer movements (Koehn et al. 2009; Koehn and Nicol 2016). Therefore, the use of single population models for each RRCP reach was considered appropriate, as genetic data and long-term monitoring suggests that inter-reach movements likely broadly balance out at a population scale (i.e. there are no source–sink dynamics). This approach has been utilised for other Murray Cod flow assessment modelling (Tonkin et al. 2021).

Adult Murray Cod spawn and fertilise eggs that adhere to hard substrate (e.g. hollow logs, and clay banks) in flowing areas. Eggs are guarded by the parental male until hatching, with larvae surviving on large yolk-sacs for up to a week as they drift downstream or disperse locally (Cadwallader and Gooley 1985; Koehn and Harrington 2006). Survival of eggs and larvae is known to be affected by temperature (Ryan et al. 2002), and also hydraulic characteristics (Tonkin et al. 2021), but recruitment is generally associated with perennial flowing rivers with high baseflows and no major water level drops during the spawning season (Figure 13; Stuart et al. 2019, 2021b; Stuart and Sharpe 2021). As such, the differing RRCP flow scenarios are likely to have less impact on the recruitment and broad-scale movement of Murray Cod than on that of Golden Perch. However, hypoxic blackwater can have major detrimental effects on Murray Cod populations (Ellis et al. 2021), as can temperature (Todd et al. 2005), and RRCP flow scenarios may contribute to the prevalence and strength of hypoxic blackwater events.

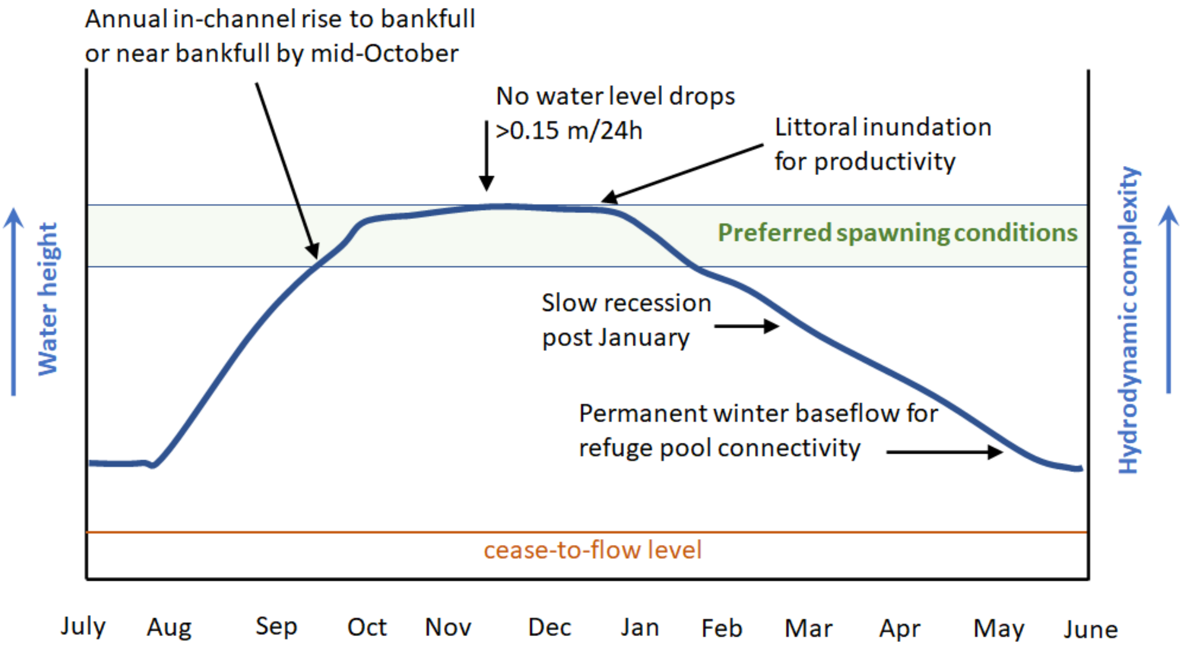

Figure 13. A conceptual model hydrograph for Murray Cod life history. The important elements are: (i) perennial lotic flows, (ii) spring rise and steady peak without major water-level drops, (iii) an attenuated summer recession to (iv) a high winter baseflow.

2.5. Ecological and operational workshops

Regular meetings of the Steering Group/Technical Committee have occurred from project inception. These meetings have supported a series of workshops held from February to April 2021 (involving the ARI Project Team, the NSW DPE, and experts from NSW DPI Fisheries and other local and water agencies) that were undertaken to:

1. revise and update the ecological knowledge and develop ecological conceptual models for Golden Perch and Murray Cod in each of the RRCP areas

2. assess and modify the model structures needed for RRCP flow scenarios

3. develop operational conceptual models and agree to the hydrological scenarios to be modelled in each of the RRCP areas

4. establish data needs, including river flows and water temperatures, and the most appropriate gauge sites for each RRCP area

5. develop the ecological flow and temperature rules within the models and scenarios

These workshops provided high-level expertise and ensured that the modelling was based on the most up-to-date ecology and riverine operational knowledge.

2.6. Model spatial zones and hydrological scenarios

The spatial zones for the RRCP, the flow limit options, and the fish species modelled are summarised in Table 1. The spatial scales of the population models are shown in Figure 14–Figure 17, where Figure 14 and Figure 15 describe the spatial scale and spatial location of the Golden Perch populations within the metapopulation model, and Figure 16 and Figure 17 describe the spatial scale of individual population locations modelled for Murray Cod. Note that the term ‘flow’ is used to specifically describe ‘discharge’ rather than hydraulic aspects.

Table 1. Reconnecting River Country Program (RRCP) project areas, flow limit options assessed, and areas for native fish population modelling.

RRCP project reach	Flow limit options assessed (ML day^{-1})	Spatial scale for predicting native population responses		
		RRCP focal area (Golden Perch and Murray Cod)	Sub-reach within RRCP focal area	Reaches outside RRCP focal zones
Murray: Hume to Yarrawonga	25,000 at Doctors Point (current Water Sharing Plan (WSP) limit matched to 15,000 at Yarrawonga) 25,000 (current WSP limit matched to 25,000 at Yarrawonga) 30,000 (matched to 30,000 at Yarrawonga) 40,000 (matched to 40,000 and 45,000 at Yarrawonga)	River Murray and floodplain from Hume Weir to Yarrawonga Weir (NSW and Victorian sides)		Murray River: Wakool Junction to Wentworth (this partitioning was necessary as Torrumbarry to Wentworth could not be split ecologically for both species)
Murray: Yarrawonga to Wakool Junction	15,000 downstream Yarrawonga (current operational limit) 25,000 30,000 40,000 45,000	River Murray floodplain from Yarrawonga Weir to Wakool Junction (NSW and Victorian sides)	Yarrawonga to Torrumbarry (both species) Torrumbarry to Wakool Junction (both species) Edward River (both species)	Lower Murray below Wentworth (this was necessary because it influences Murray Golden Perch populations) Lower Darling (necessary because it influences Murray Golden Perch populations)
Murrumbidgee	Modelled flows at Wagga Wagga to match flows at Yarrawonga and Doctors Point 22,000 (matched to 15,000 at Yarrawonga) 32,000 (matched to 25,000 at Yarrawonga) 36,000 (matched to 30,000 at Yarrawonga) 40,000 (matched to 40,000 and 45,000 at Yarrawonga)	Murrumbidgee River: Gundagai to Murray Junction	Hay Weir to Balranald Weir (both species) Murray Cod Gundagai to Berembed Weir Berembed Weir to Gogeldrie Weir Gogeldrie Weir to Hay Weir Yanco Ck Golden Perch Gundagai to Hay Weir	

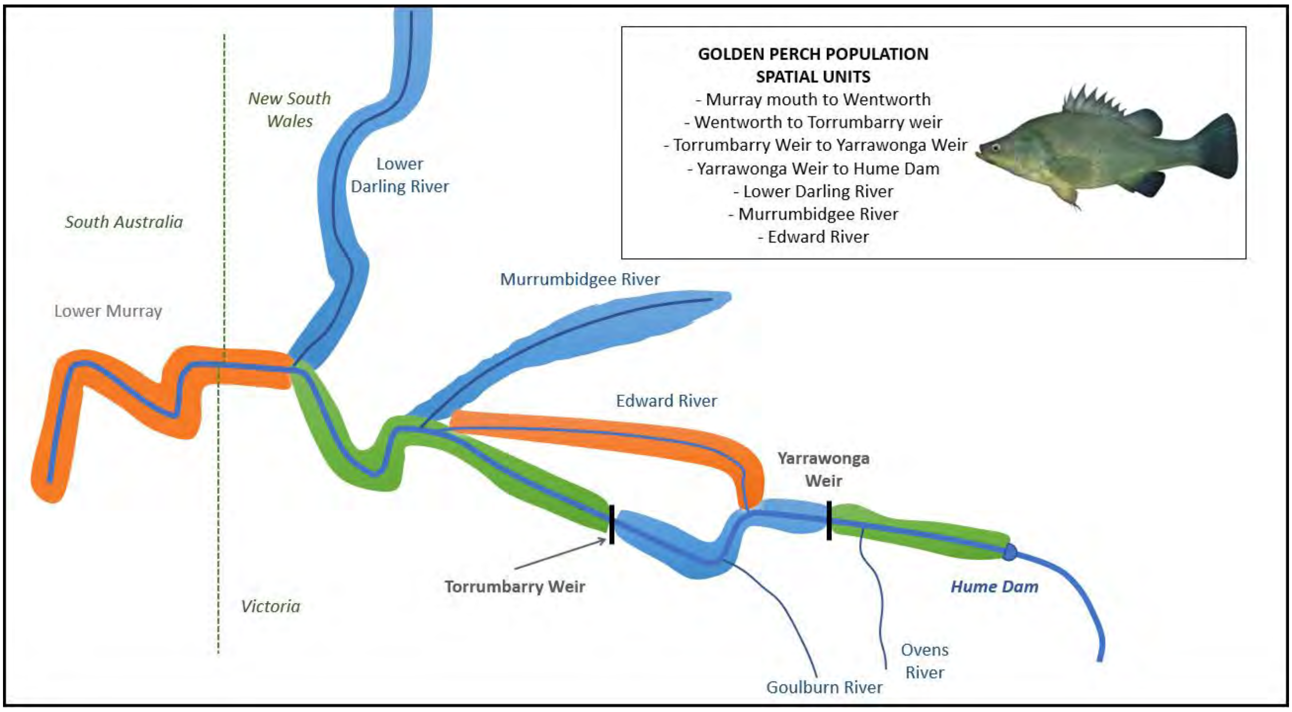

Figure 14. Spatial structure of the Golden Perch metapopulation modelled in the Southern MDB, with the Murrumbidgee River split into two population units in Figure 15.

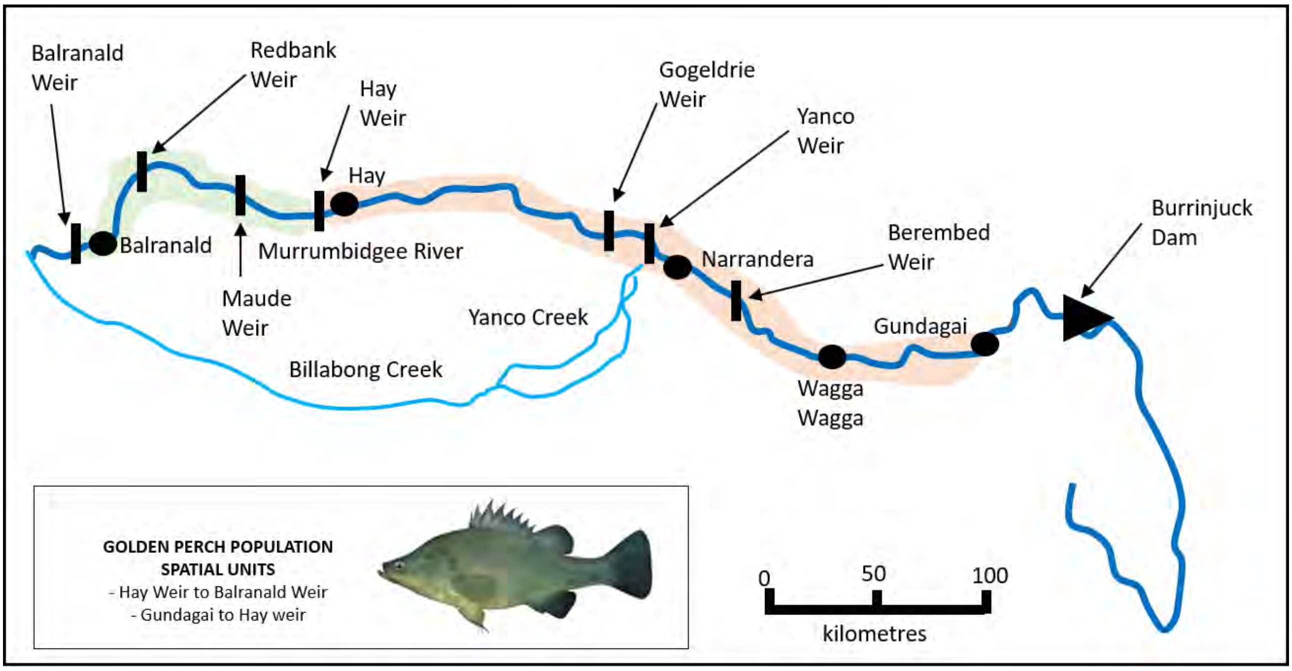

Figure 15. Golden Perch metapopulation spatial structure in the Murrumbidgee River.

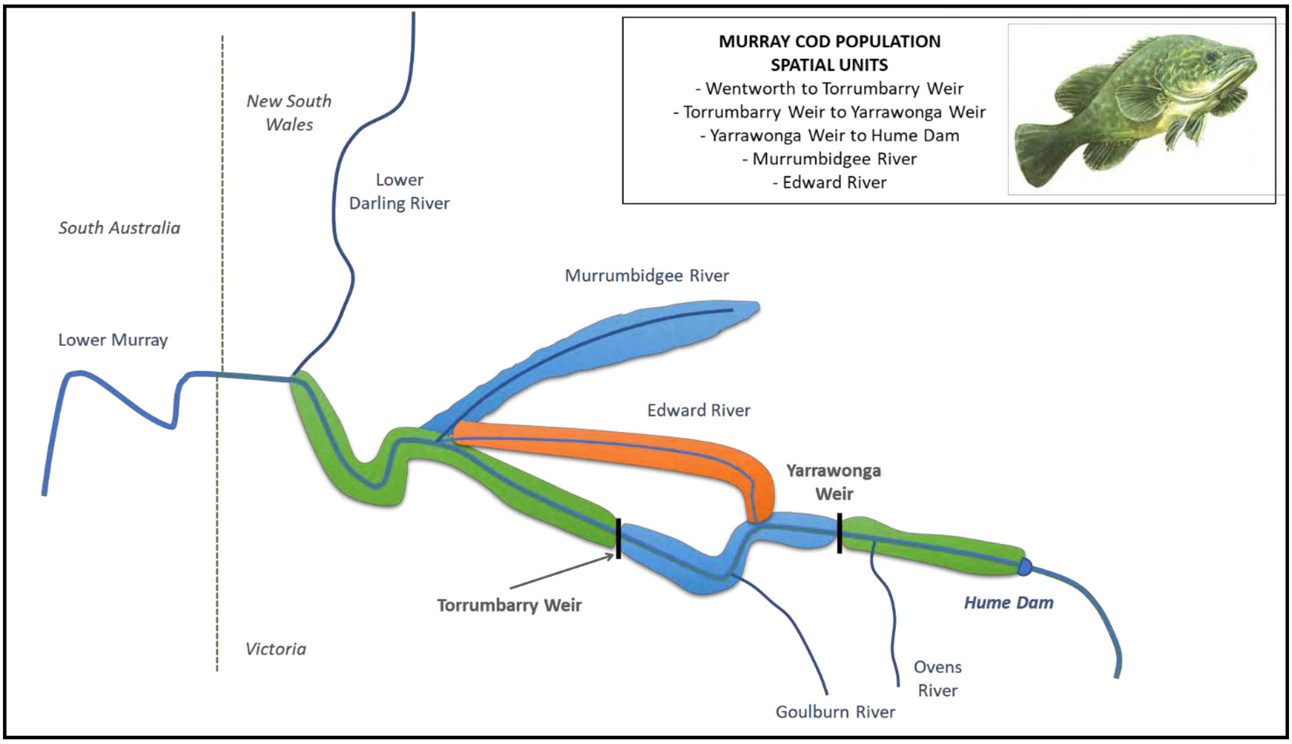

Figure 16. The spatial structure of Murray Cod populations modelled in the Lower MDB, with the Murrumbidgee River split into smaller population units in Figure 17.

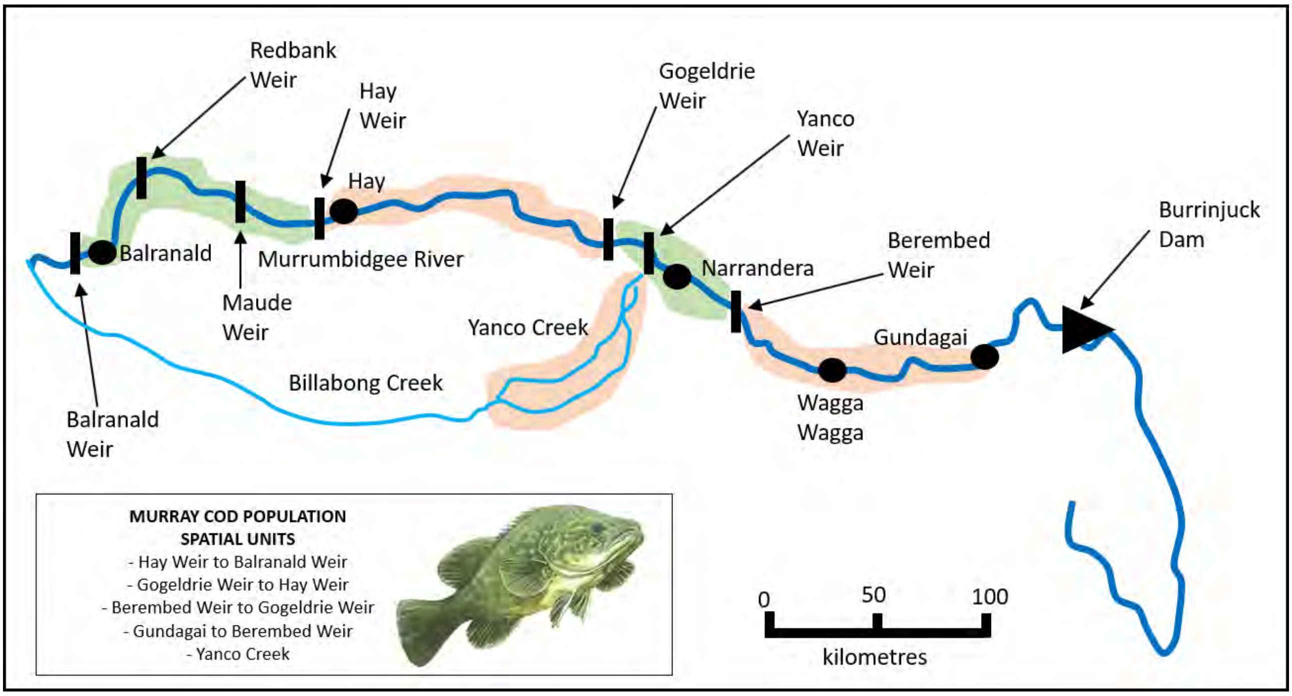

Figure 17. The Murray Cod population spatial structure in the Murrumbidgee River is split into and modelled as five populations.

2.7. Model descriptions

Brief descriptions of the population models for Golden Perch and Murray Cod are included here, with full descriptions and model rules provided in Appendix 2.

The Murray Cod population model is a stage/age matrix construct previously developed for the MDB (Todd and Koehn 2007; Koehn and Todd 2012). The model summarises the life history of Murray Cod by explicitly representing 50 age classes (Koehn and Todd 2012), where Murray Cod are assumed to become sexually mature at 5 years of age and fecundity is assumed to increase with age as a function of the average length of each age class (Rowland 1998a, 1998b). A 1:1 sex ratio was assumed, with the annual spawning season modelled from the beginning of October to the end of December and spawning being triggered by an 18°C water temperature threshold. The model tracks female fish and assumes male input is not limited, for ease of conceptual understanding, the model output is doubled and reported as total adults (i.e. males and females). As the life history of Murray Cod is largely contained at the reach level, and inter-reach movement is relatively infrequent (Thiem et al. 2021; see above), populations across RRCP reach areas are modelled independently.

The Golden Perch population model (30 age classes) is based on a similar model architecture to that of Murray Cod but is one single metapopulation model with populations interconnected, whereas the Murray Cod model is a series of single population models. The Golden Perch model also differs in some key components that reflect the specific ecology of this species (Koehn et al. 2020). Here, flow-dependent movements of the life stages of this highly mobile species (Reynolds 1983; Koehn and Nicol 2016) are modelled specifically, and links (e.g. immigration and emigration) between discrete populations are captured within the single metapopulation structure. Within the model, flow and temperature data regulate effects on the early-life-history survival and movement (larval drift), productivity on larval survival and young-of-the-year (also referred to as fingerlings), and flow-cued movements of juvenile and adult fish. This creates a dynamic metapopulation structure in which populations are linked across both small (i.e. adjoining populations) and large scales (i.e. across the whole metapopulation over multiple years). A 1:1 sex ratio was assumed (as for Murray Cod, the modelled output was doubled), and the annual spawning season was modelled from the beginning of October to the end of February, with spawning being triggered by site-specific flow cues and a temperature threshold of 17°C.

2.8. Model rules

An assessment of how life-history parameters for Golden Perch and Murray Cod were likely to be influenced by discharge in each reach was considered for each population and reflected in a series of model rules constructed for each key life-history stage (described below and in Appendix 2). Modelled daily flows and temperature records were used to generate estimates of key life-history parameters. For Murray Cod, estimates of recruitment of 1-year-olds considered egg, larval and fingerling survival, and were based on published statistical relationships, with flow characteristics generated from the Yarrawonga to Tocumwal reach of the Murray River (Tonkin et al. 2021). Golden Perch spawning periodicity and strength, juvenile survival, and larval and adult movement were also modelled via flow–ecology relationships for each population (Todd et al. 2005). Movement of Golden Perch was modified in specific locations where sufficient information was available (e.g. known factors, such as ineffective fish ladders or large weirs). The Golden Perch movement rules are defined in Appendix 2. Movement decisions at river junctions were determined from the daily ratio of bank full flows of the destination reaches (Koster et al. 2021). Golden Perch larval and 1-year-old-plus survival was also based on flow-derived estimates of basal productivity (see Appendix 2).

Stochastic mechanisms were used to capture both demographic and environmental processes: a binomial distribution was used to model the survival of juveniles and adults between discrete time steps (Todd et al. 2020), and a Poisson distribution was used to model recruitment of 1-year-olds (Murray Cod only: see Todd et al. 2020). Environmental stochasticity was incorporated by randomly varying survival and fecundity in each year (Todd et al. 2020); survival rates were drawn from normal distributions, and age-specific fecundity was calculated by applying age–length information to hatchery data (Rowland 2005). For both species, a density-dependent mechanism was used to scale the upper population limits in each population. The strength of the density dependence in each reach was determined by catch–mark–recapture data from the Murray River at Yarrawonga (Lyon et al. 2019) and via expert opinion from within the working group.

2.9. Data

Hydrology, temperature and gauges

Daily flow (hydrology) and temperature data were obtained from the most appropriate gauges for each population; see Table 2. Metapopulation sub-units for Golden Perch represented for the modelling reported in this document. and Table 3 (population units for Murray Cod), data provided by NSW DPE. To generate data inputs, river system hydrologic modelling was used to obtain a realistic indication of the potential environmental flow outcomes from the RRCP flow scenarios over the long term under the varying climate conditions experienced in the MDB. The models used for this work represent current system operations, current environmental water recovery, and historical climate over the period 1 July 1895 to 30 June 2019 (124 years). The models include the representation of a range of environmental flows, including baseflows, small freshes, large freshes and small overbank events, up to the flow limits modelled. The environmental flows represented in the models reflect the environmental water requirements described in the Murray – Lower Darling (DPIE 2020a) and Murrumbidgee Long-Term Water Plans (DPIE 2020b). The Murray modelling was a collaboration between the MDBA and NSW DPE, and the Murrumbidgee modelling was undertaken by NSW DPE. The Murray and Murrumbidgee flow scenarios were integrated, as recommended by NSW DPE, and are summarised as Base case and Options 1–4 in Table 4 below.

Modelled flow and temperature data were provided by NSW DPE and these data were analysed within the framework of the model to determine spawning conditions, and the subsequent survival of the resultant eggs, larvae and future life stages. Daily flow at relevant gauges were also used to assess movement between Golden Perch populations at river junctions. It is important to note that the historic gauged data was modelled between 1896 and 2019, but that the data series assumes current regulation and extraction rates throughout the 124-year modelled period. In future iterations of the present report, additional scenarios for 'without development (natural)' and potentially 'climate change' may be possible where hydrological data become available.

Table 2. Metapopulation sub-units for Golden Perch represented for the modelling reported in this document.

River/reach	Spatial boundary	Indicator gauge
Lower Murray below Wentworth	Murray mouth to Wentworth	Lock 9 downstream
Torrumbarry to Wentworth	Wentworth to Torrumbarry Weir (includes lower Wakool River)	Torrumbarry
Yarrawonga to Torrumbarry	Torrumbarry Weir to Yarrawonga Weir	Yarrawonga downstream
Hume to Yarrawonga	Yarrawonga Weir to Hume Dam	Doctors Point
Lower Darling River	Menindee Lakes to Wentworth	Burtundy
Edward River	Edward River	Stevens Weir
Hay to Balranald	Hay Weir to Balranald Weir	Hay Weir
Gundagai to Hay Weir	Gundagai to Hay Weir	Wagga Wagga

Table 3. Population units for Murray Cod represented for the modelling reported in this document.

River/reach	Spatial boundary	Indicator gauge
Torrumbarry to Wentworth	Wentworth to Torrumbarry Weir (includes lower Wakool)	Torrumbarry
Yarrawonga to Torrumbarry	Torrumbarry Weir to Yarrawonga Weir	Yarrawonga downstream
Hume to Yarrawonga	Yarrawonga Weir to Hume Dam	Doctors Point
Edward River	Edward River	Stevens Weir
Hay to Balranald	Hay Weir to Balranald Weir	Hay Weir
Gogeldrie to Hay	Gogeldrie Weir to Hay Weir	Gogeldrie Weir
Berembed to Gogeldrie	Berembed Weir to Gogeldrie Weir	Berembed Weir
Gundagai to Berembed	Gundagai to Berembed Weir	Wagga Wagga
Yanco Creek	Yanco offtake to Billabong Creek	Yanco offtake

2.10. Hypoxic blackwater

Hypoxic blackwater data inputs were provided by NSW DPE (DPE 2022) for the appropriate locations relating to Murray Cod modelling. These inputs comprised time series of the probability of a hypoxic blackwater event occurring within each model year, and the number of predicted days within each hypoxic event where the average oxygen concentration of the water within a given reach would be <2 mg L^{-1}. Mortality was estimated from these inputs by scaling each event by the most severe event in the dataset, and then multiplying by a factor of 0.8 to give a maximum possible mortality of an 80% reduction in adult survival rates (effectively applying mortality to a maximum of 80% of the spatial extent of each reach during a blackwater event). This mortality was then applied to juvenile and adult Murray Cod in that year within the affected reach. Mortality associated with hypoxia was not applied in Golden Perch modelling, as Golden Perch are thought to be less susceptible to (more able to escape from) hypoxic events (Thiem et al. 2020).

2.11. Productivity

A basal productivity mechanism was used in the population model construct for Golden Perch to inform the survival of larval and juvenile fish during the sensitive early life phases. Ecosystem productivity is particularly important for the larvae of Golden Perch, because they are small, and as a result have small yolk sacs and must feed frequently to survive (Arumugam and Geddes 1987). Here, the variation in daily flows (ML day^{-1}) around bank full levels in each reach were used to predict variation around standard survival rates. Results from a complementary productivity modelling project that mechanistically predicts carbon flux through selected areas of the MDB (Siebers et al. 2022) were used to inform the mechanism used here. Variation around the smaller-scale production estimates produced by the complementary project was used to validate the correlative flow-based mechanism, which allowed for the estimation of productivity across the metapopulation structure. For Murray Cod, a published statistical model was used to relate flows to egg, larval and fingerling survival (Tonkin et al. 2021). Specifically, five hydraulic characteristics affect estimates of recruitment strength, where flow variability and higher summer flow negatively impact recruitment, and higher spring and winter flow as well as antecedent maximum annual flow positively impact recruitment (Tonkin et al. 2021).

2.12. Commercial and recreational harvest

Both Golden Perch and Murray Cod have historically been subject to commercial fishing in NSW, SA and Victoria. Only SA continues a commercial fishery, and it is for Golden Perch alone (Ferguson and Ye 2012; Earl 2020). For NSW, catch data were sourced directly from NSW DPI Fisheries and from the published literature (Reid et al. 1997). Catch data were obtained from the published literature for SA (Reynolds 1976a, 1976b; Earl 2020). Commercial catch data for Victoria was not included in this study. Estimated catch weight was converted to fish numbers via an average weight calculation for each species, and reductions in numbers were thus applied to population sizes in model runs. The commercial harvest of Golden Perch in South Australia (in the lower lakes) has been included in the modelling. Recreational harvest was also included for both Golden Perch and Murray Cod. A yearly recreational harvest rule was applied to all populations of both species across model runs via a size-selectivity function from the 1950s onwards. The yearly recreational harvest rate was 5% for Golden Perch model runs, 10% for Murray Cod less than 1 m in total length, and 5% for Murray Cod equal to or greater than 1 m in total length.

2.13. Model runs

Models were run for each RRCP scenario (Table 4) for both species. As described above, the Golden Perch model was run as a metapopulation for each RRCP scenario, whereas Murray Cod populations were run as separate models (i.e. every population was run independently for each RRCP scenario). Each model run was conducted over the temporal extent of the input flow–temperature data (i.e. 1896–2019), with the initial population sizes as set by the working group. Each run consisted of 1000 iterations in which model attributes were varied, based on the flow and temperature inputs for the five scenarios modelled that drive the various rules around spawning, productivity, larval drift, and movement (see Table 2 and Table 3 for the gauges used for each population to assess the life-history responses, and Table 4 for descriptions of each flow scenario modelled). This provided information on the model sensitivity and enabled the estimation of expected values (see Results; also see Appendix 4 for the sensitivity analysis). Scenarios were combined across the two Murray and Murrumbidgee River spatial scales to form the total hydrological dataset for each RRCP scenario in this study. Maximum daily flows (ML day^{-1}) for each scenario are given at three indicator gauges across the project system in Table 4.

Table 4. RRCP flow scenarios at indicator gauges within two reaches of the Murray River combined with the Murrumbidgee River.

Modelled flow scenario	Murray River at Doctors Point (Albury) (ML day^{-1})	Murray River downstream of Yarrawonga Weir (ML day^{-1})	Murrumbidgee (Wagga Wagga) (ML day^{-1})
Base case	25,000	15,000	22,000
Option 1	25,000	25,000	32,000
Option 2	30,000	30,000	36,000
Option 3	40,000	40,000	40,000
Option 4	40,000	45,000	40,000

2.14. Model assumptions and limitations

As the data and knowledge upon which the models are developed is incomplete, every model has inherent assumptions. It is important that these assumptions are recognised and, where possible, their impacts explored through sensitivity analyses (Appendix 4).

Either for model simplicity or due to lack of information, the modelling undertaken in this study did not include some of the impacts that occur in the study reaches, such as: loss of fish due to water extraction pumps, effects of some barriers to fish passage, thermal shock (impacts of sudden changes in temperature), impacts on energetics or productivity, and water quality impacts. Some off-channel (floodplain) areas were not included in the model construct, and neither was stocking.

2.15. Sensitivity analyses

To assess that the results from the Golden Perch population model were robust, some key assumptions of the Golden Perch model were explored through sensitivity analysis. The effects of different movement rates, different initial population sizes, and different levels of immigration of fingerlings from the Northern MDB were assessed, and the results are presented in Appendix 4. The purpose of this sensitivity analysis was to investigate whether factors such as changes to connectivity, which can change population outcomes, will also change our assessment of the relaxed-flow-constraints scenarios. Convergence of early modelling outcomes (e.g. total population sizes) in the post-1980s period was also investigated. Sensitivity analysis has previously been undertaken for the Murray Cod model (Todd et al. 2005), with the current construct of the Murray Cod model being based on published statistical relationships with flow characteristics (Tonkin et al. 2021). However, the Murray Cod model is dependent on the input of modelled hypoxic blackwater and remains sensitive to the outputs of the blackwater model (given the potential mortality of up to 80% of the adult population).

3. Results

3.1. Population model responses to the relaxed-flow-constraints scenarios

Key results from the Golden Perch and Murray Cod modelling for each hydrological scenario and each RRCP area in the Murray and Murrumbidgee rivers are provided. All population outputs (graphs representing a total of 382 scenario results) are included in Appendix 3, and all sensitivity analysis outputs are included in Appendix 4.

3.1.1. Golden Perch

The results from the Golden Perch modelling applying the relaxed-flow-constraints scenarios for the Murray River and the Murrumbidgee River (Table 4) are presented in the following two sections: adult Golden Perch; and recruitment of Golden Perch.

3.1.1.1. Adult Golden Perch

The modelling outputs for the numbers of adult Golden Perch for the Total RRCP Populations are shown in Figure 18; those for the Total Murray Populations (i.e. populations in the Murray River to Wentworth, and in the Edward River) are shown in Figure 19; and those for the Total Murrumbidgee Populations (i.e. populations in the Murrumbidgee River and Yanco Creek) are shown in Figure 20. These aggregated results generally show the Base case mean population size to be less than that in all other scenario options, and that Option 4 provides the greatest benefits to Golden Perch at these aggregated spatial scales. The outputs for the RRCP individual reaches are included in Figure 21–Figure 26. Option 4 presents as the flow option that provides the greatest benefits to Golden Perch populations in most reaches. The exception is the upper Murrumbidgee River (Gundagai to Hay), where Option 3 is the best (Figure 26). Note that there is no recruitment in that reach, with populations likely maintained by immigration (see the Gundagai to Hay 1-year-old population output in Appendix 3).

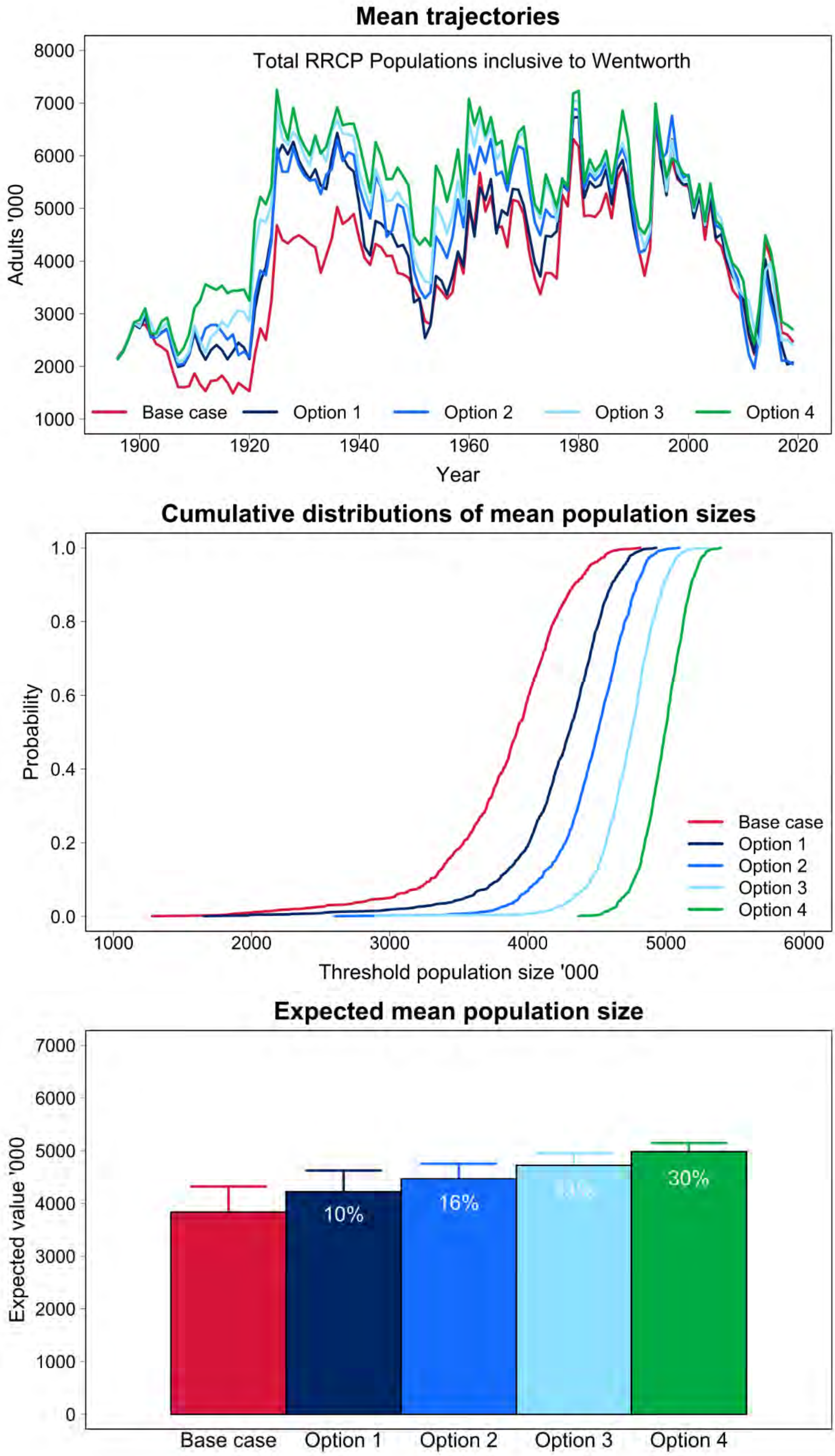

Figure 18. Modelled Golden Perch adult populations aggregated across all modelled RRCP focal zones, together with the Wakool Junction to Wentworth reach, for the RRCP flow scenarios Base case – Option 4. Top panel: mean adult population size through time. Middle panel: associated distribution of the mean adult population sizes. Bottom panel: expected mean adult population size, with the percentage change from Base case shown in each bar.

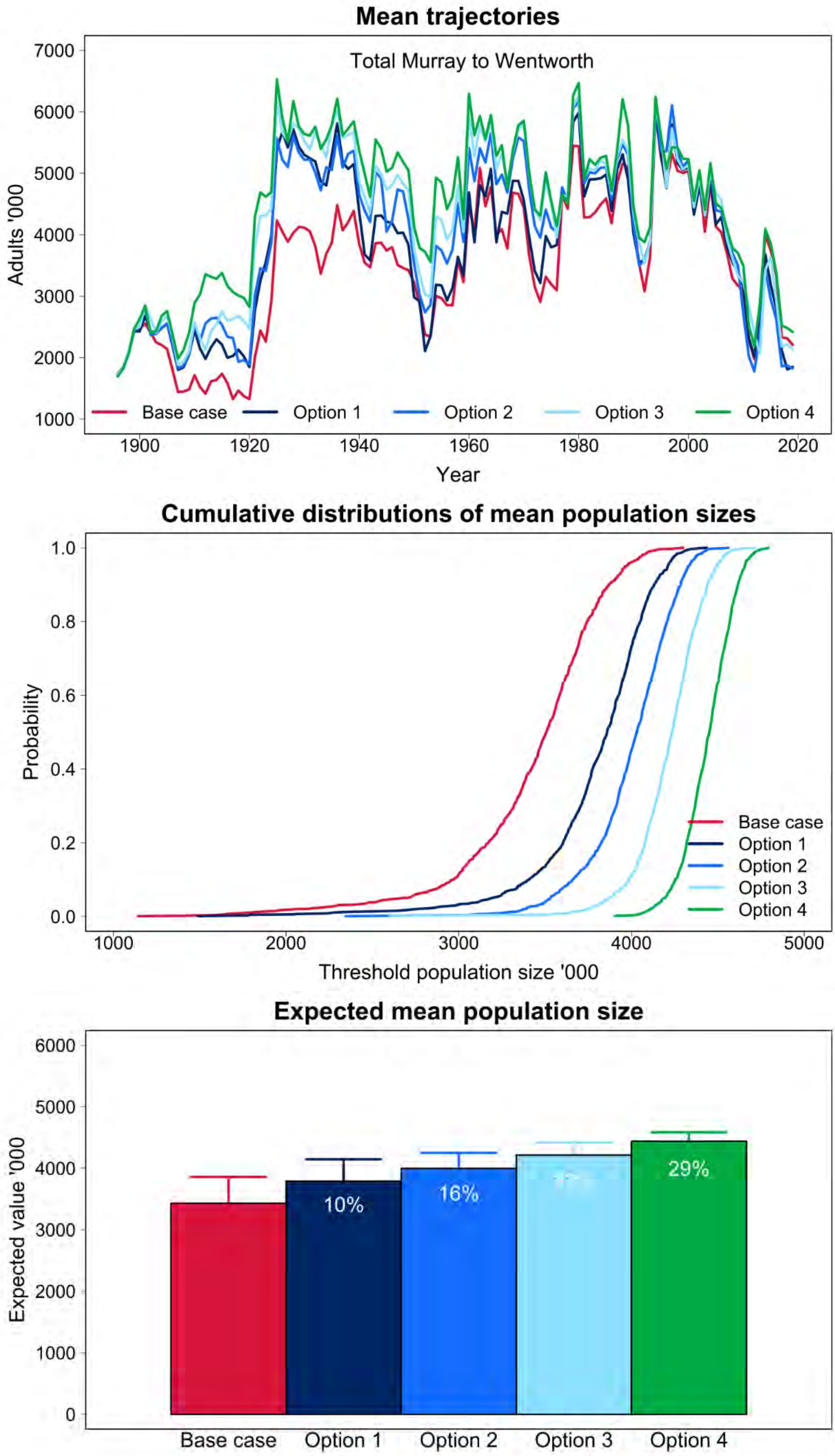

Figure 19. Modelled Golden Perch adult populations aggregated across the Murray River RRCP focal zones (including the Edward River), together with the Wakool Junction to Wentworth reach, for the RRCP flow scenarios Base case – Option 4. Top panel: mean adult population size through time. Middle panel: associated distribution of the mean adult population sizes. Bottom panel: expected mean adult population size, with the percentage change from Base case shown in each bar.

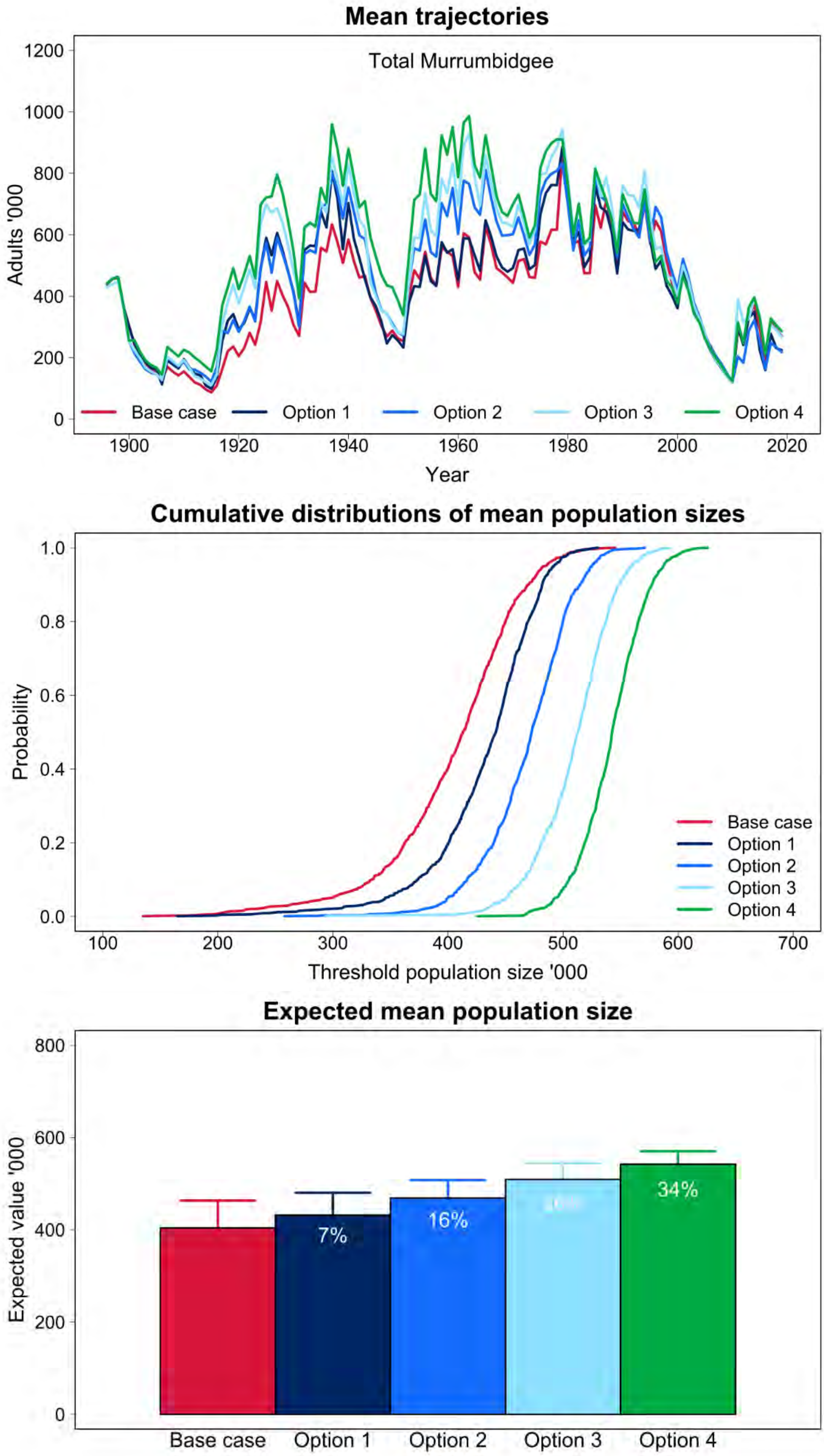

Figure 20. Modelled Golden Perch adult populations aggregated across the Murrumbidgee River RRCP focal area for the RRCP flow scenarios Base case – Option 4. Top panel: mean adult population size through time. Middle panel: associated distribution of the mean adult population sizes. Bottom panel: expected mean adult population size, with the percentage change from Base case shown in each bar.

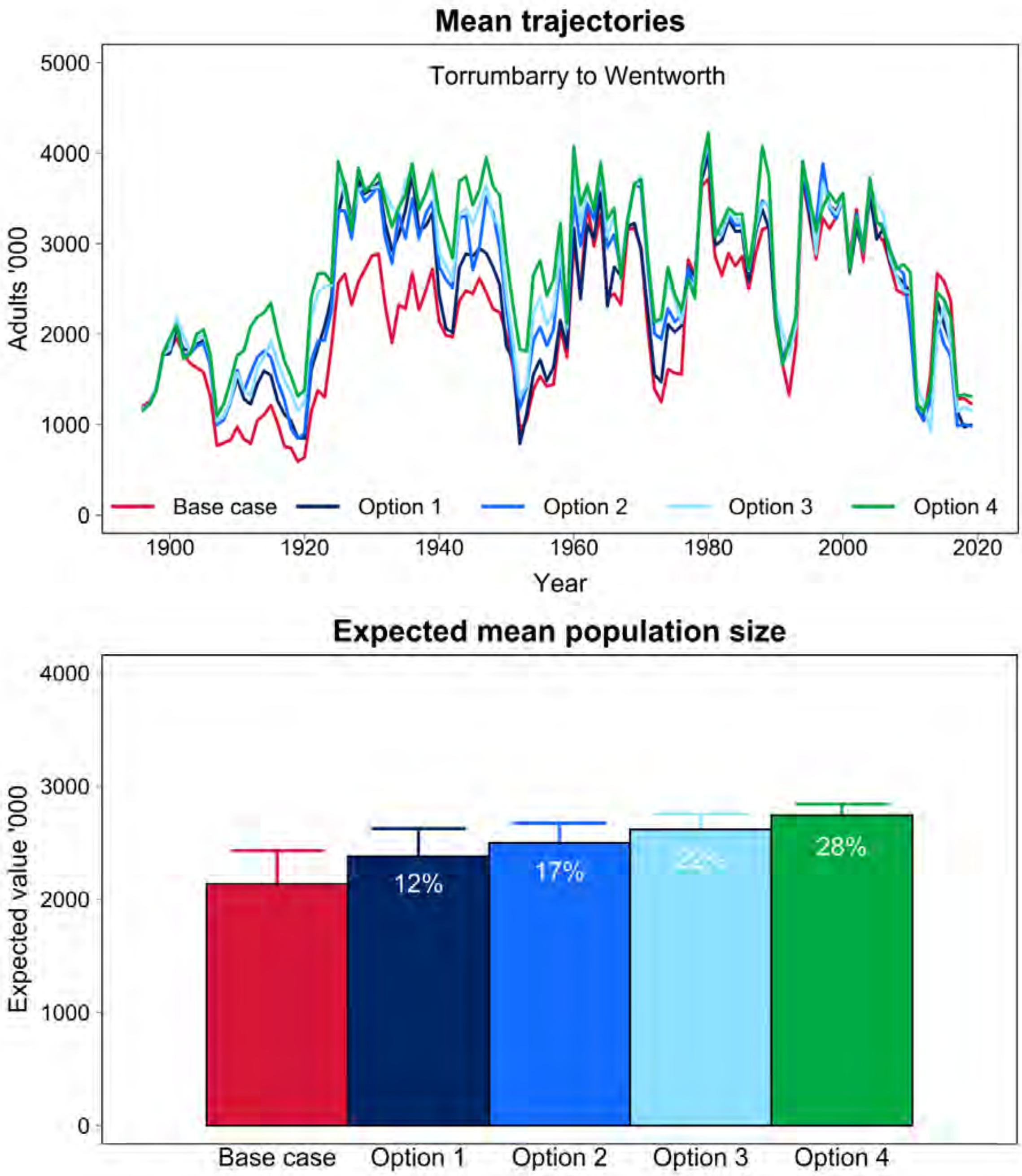

Figure 21. Modelled Golden Perch adult population in the Torrumbarry to Wentworth reach for the RRCP flow scenarios Base case – Option 4. Top panel: mean adult population size through time. Bottom panel: expected mean adult population size, with the percentage change from Base case shown in each bar.

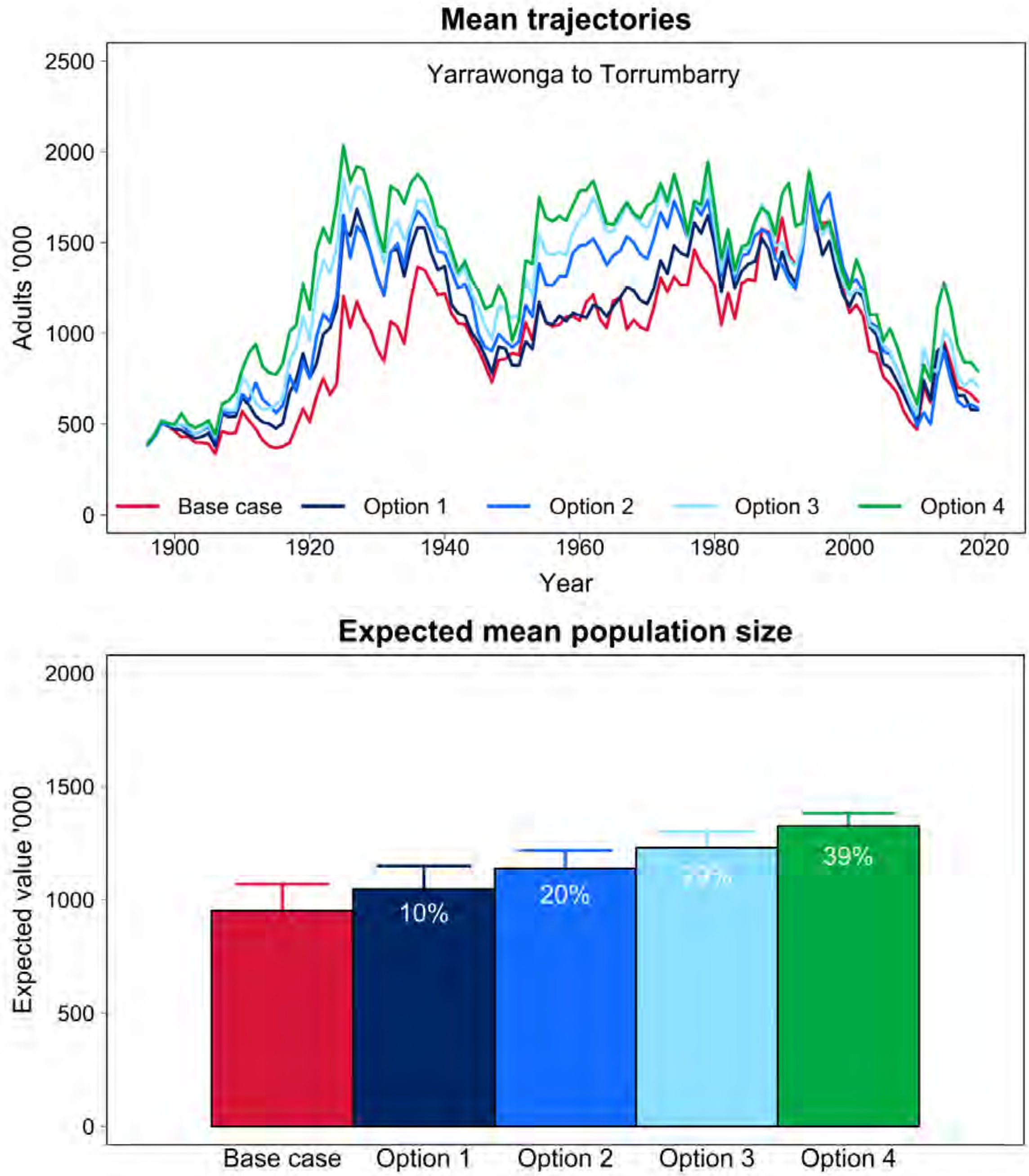

Figure 22. Modelled Golden Perch adult population in the Yarrawonga to Torrumbarry reach for the RRCP flow scenarios Base case – Option 4. Top panel: mean adult population size through time. Bottom panel: expected mean adult population size, with the percentage change from Base case shown in each bar.

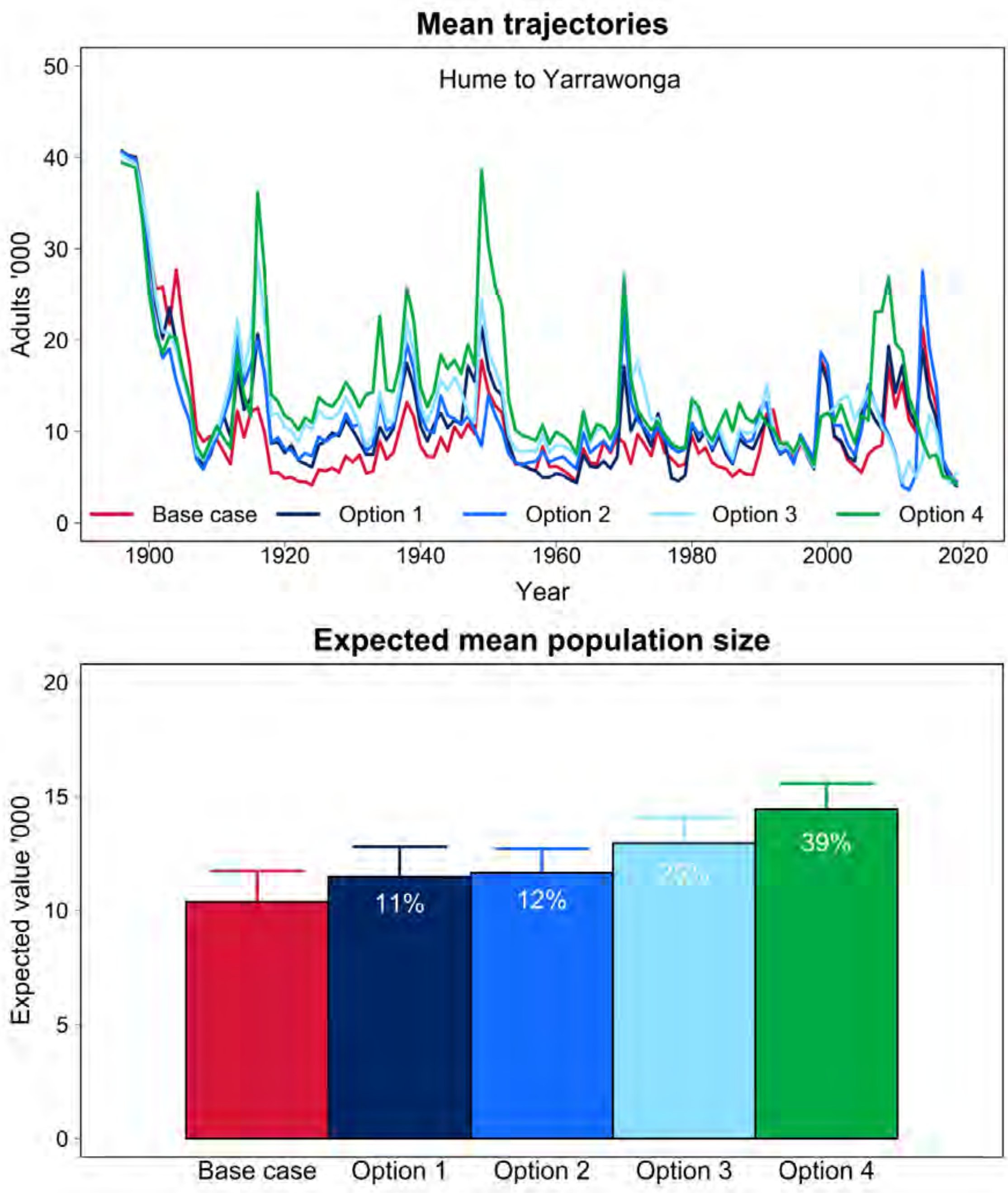

Figure 23. Modelled Golden Perch adult population in the Hume to Yarrawonga reach for the RRCP flow scenarios Base case – Option 4. Top panel: mean adult population size through time. Bottom panel: expected mean adult population size, with the percentage change from Base case shown in each bar.

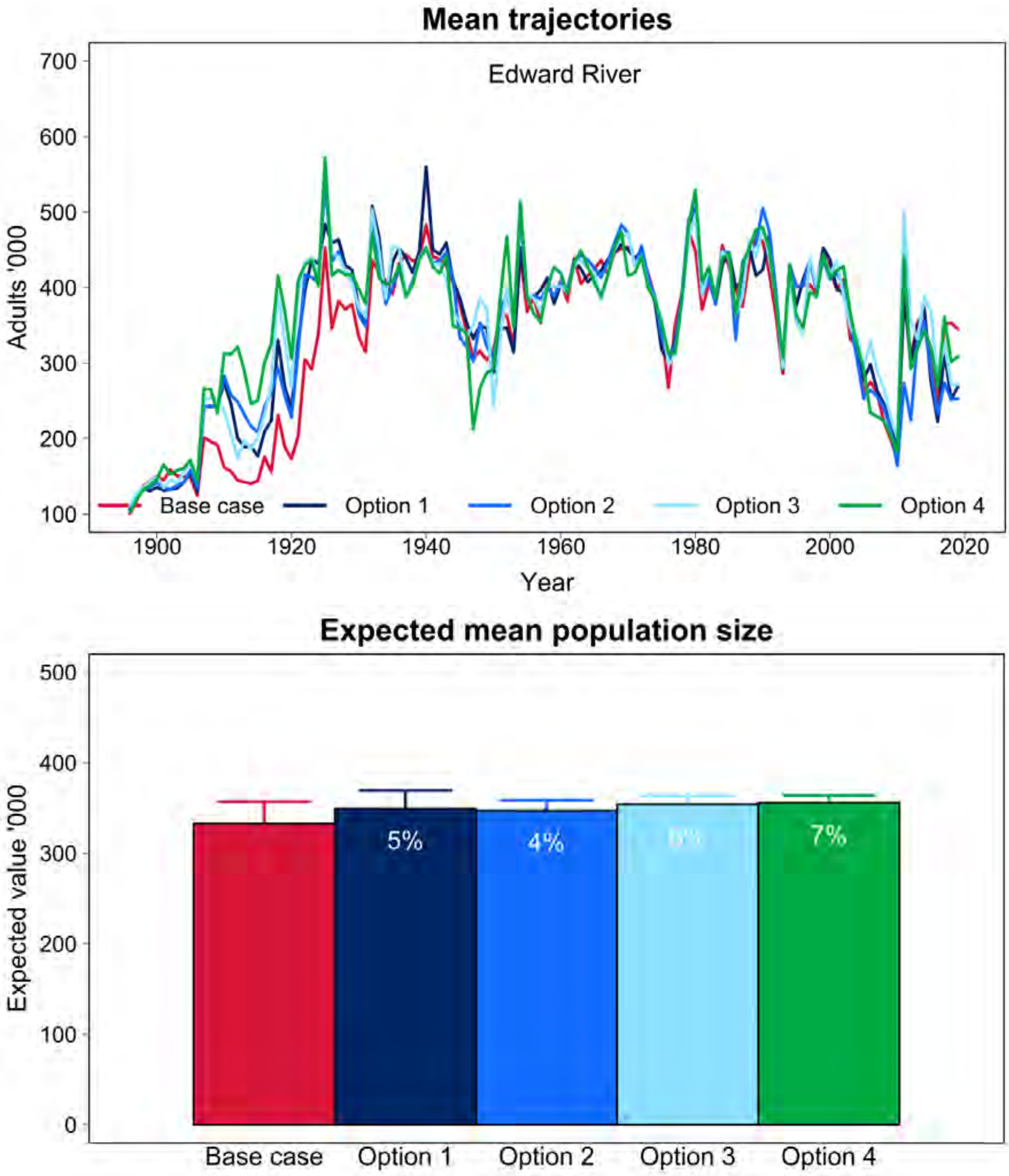

Figure 24. Modelled Golden Perch adult population in the Edward River for the RRCP flow scenarios Base case – Option 4. Top panel: mean adult population size through time. Bottom panel: expected mean adult population size, with the percentage change from Base case shown in each bar.

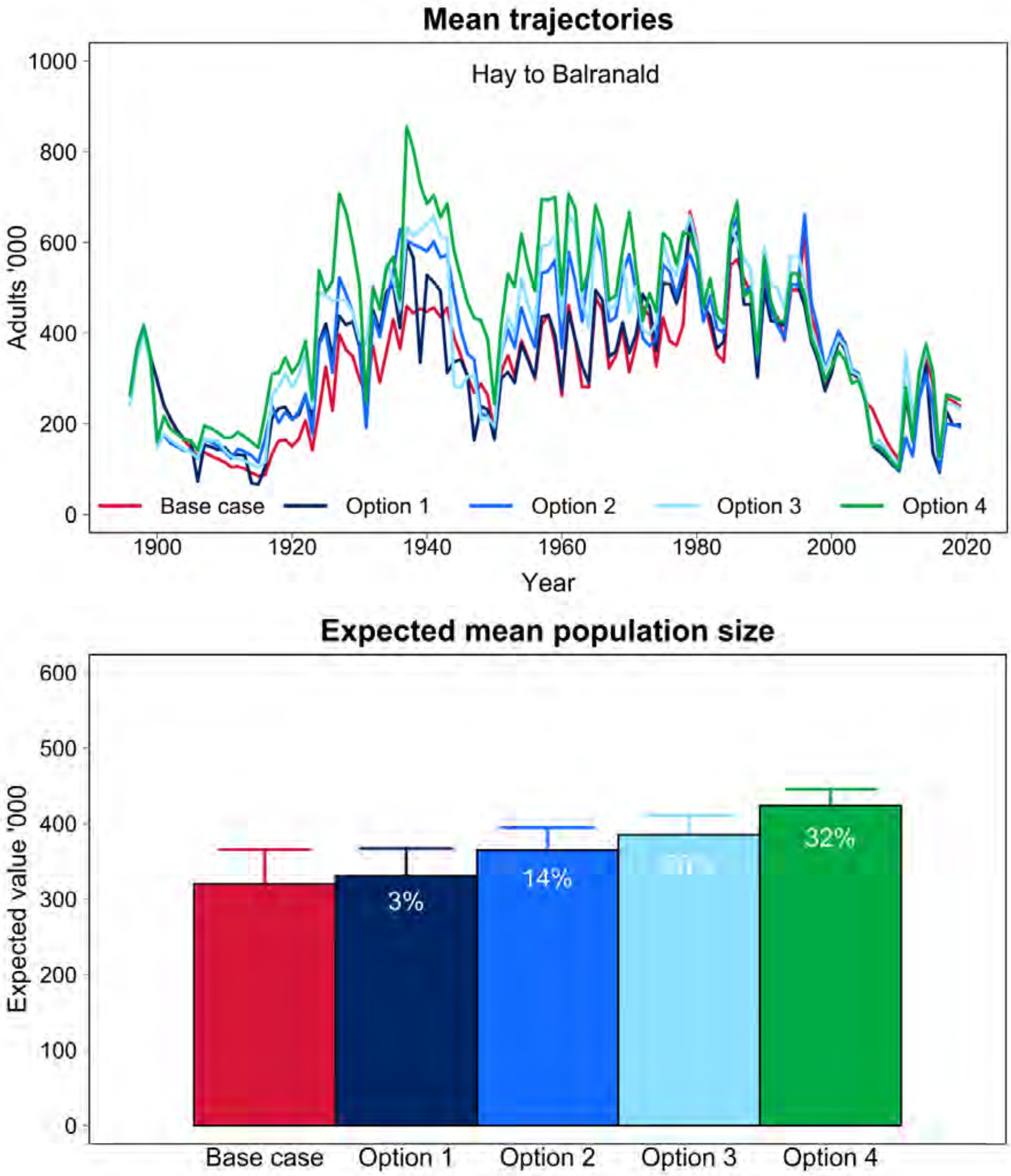

Figure 25. Modelled Golden Perch adult population in the Hay to Balranald reach for the RRCP flow scenarios Base case – Option 4. Top panel: mean adult population size through time. Bottom panel: expected mean adult population size, with the percentage change from Base case shown in each bar.

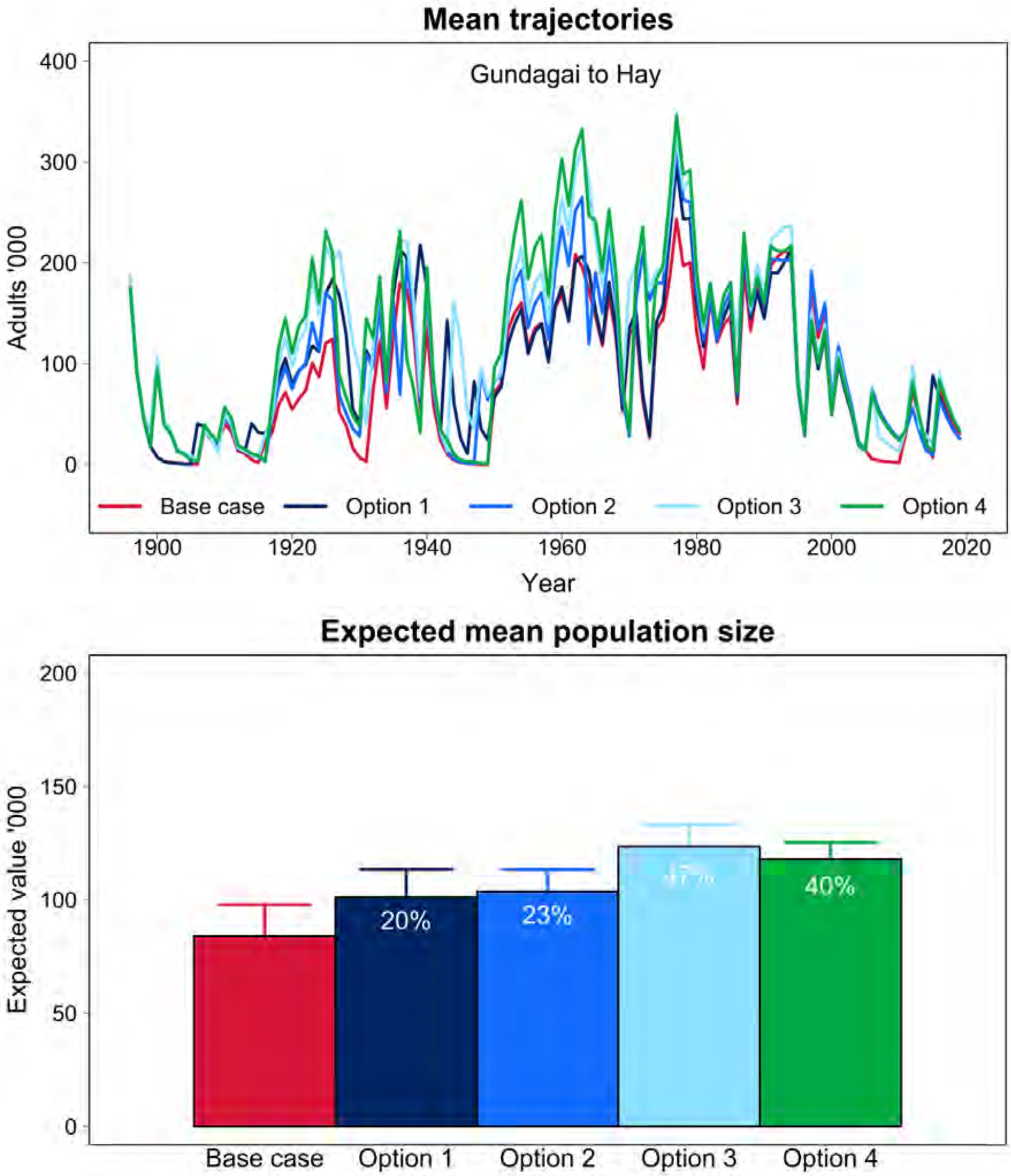

Figure 26. Modelled Golden Perch adult population in the Gundagai to Hay reach for the RRCP flow scenarios Base case – Option 4. Top panel: mean adult population size through time. Bottom panel: expected mean adult population size, with the percentage change from Base case shown in each bar.

3.1.1.2. Recruitment of Golden Perch

The modelling outputs for the numbers of 1-year-old Golden Perch ('recruits') for the Total RRCP Populations are shown in Figure 27, for the Total Murray Populations (to Wentworth, including Edward River) are shown in Figure 28, and for the Total Murrumbidgee Populations are shown in Figure 29. These figures show that there is consistent recruitment occurring in the Murray River, whereas recruitment is episodic in the Murrumbidgee River. Overall, the Base case mean 1-year-old population size is less than that for all other scenario options, and Option 4 provides the greatest recruitment benefits to Golden Perch at these aggregated spatial scales. Outputs for other individual river reaches are included in Appendix 3.

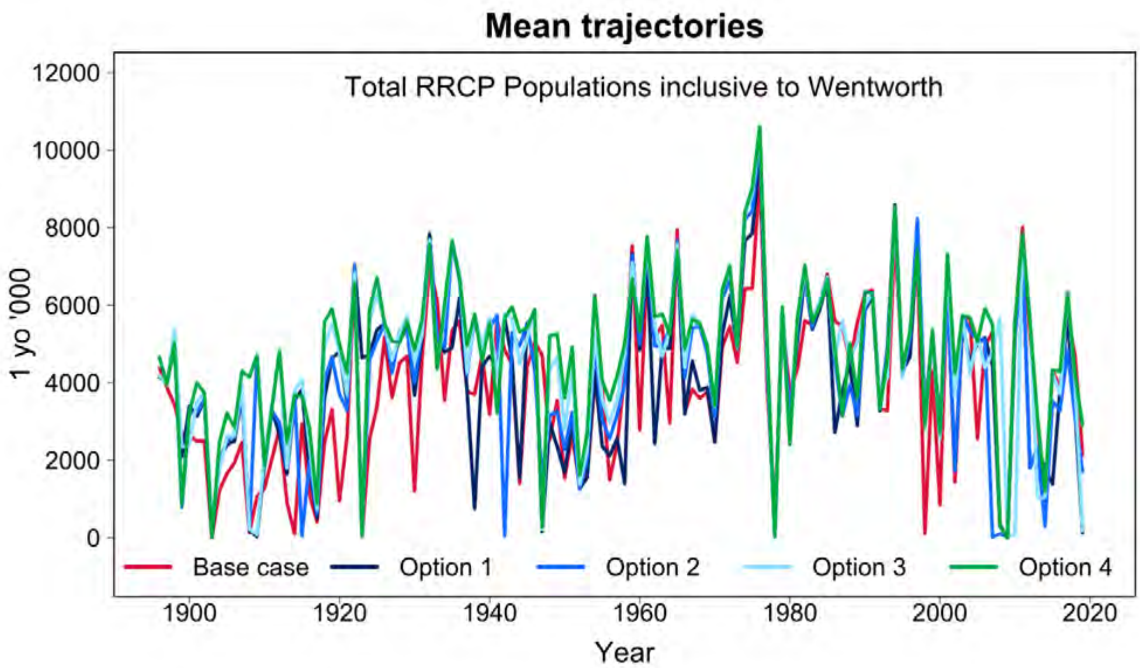

Figure 27. Modelled Golden Perch mean recruit (1-year-old) population size aggregated across all modelled RRCP focal zones, together with the Wakool Junction to Wentworth reach, for the RRCP flow scenarios Base case – Option 4.

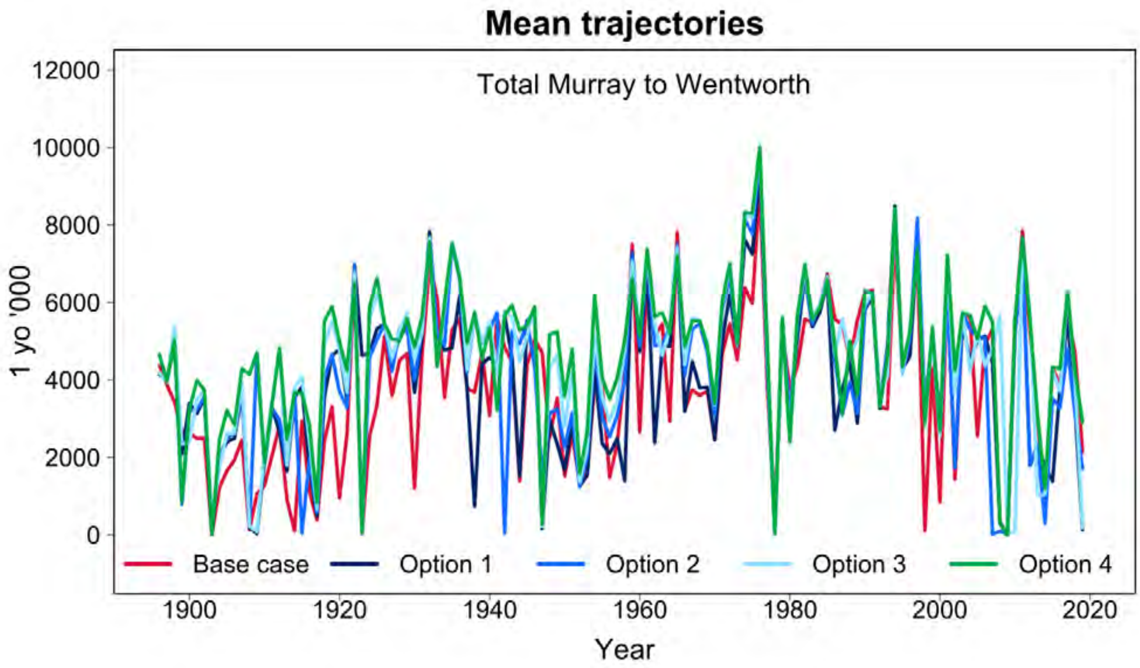

Figure 28. Modelled Golden Perch mean recruit (1-year-old) population size aggregated across the Murray River RRCP focal zones (including the Edward River), together with the Wakool Junction to Wentworth reach, for the flow scenarios Base case – Option 4.

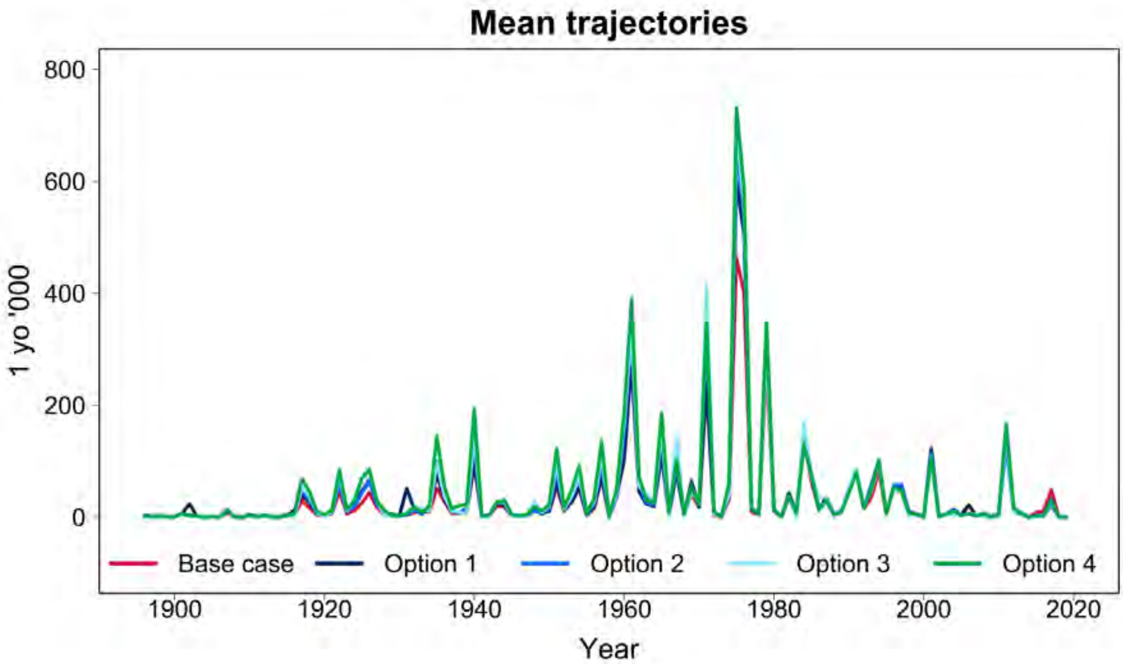

Figure 29. Modelled Golden Perch mean recruit (1-year-old) population size aggregated across the Murrumbidgee River RRCP focal area for the flow scenarios Base case – Option 4.

3.1.2. Murray Cod

The results from the Murray Cod modelling applying the relaxed-flow-constraints scenarios for the Murray River and the Murrumbidgee River (Table 4) are presented in the following two sections: adult Murray Cod; and recruitment of Murray Cod.

3.1.2.1. Adult Murray Cod

The modelling outputs for the numbers of adult Murray Cod for the Total RRCP Populations are shown in Figure 30; those for the Total Murray Populations (i.e. populations in the Murray River to Wentworth, and in the Edward River) are shown in Figure 31; and those for the Total Murrumbidgee Populations (i.e. populations in the Murrumbidgee River) are shown in Figure 32. These aggregated results generally show the Murray Cod population model outcomes to be invariant among the relaxed-flow-constraints scenarios, and that the greatest changes in population dynamics occur in response to blackwater disturbance. As the results for adult Murray Cod populations are largely invariant across the range of relaxed-flow-constraints scenarios, only a select number of reaches are presented here: two examples of invariant responses to the relaxed-flow-constraints scenarios (Yarrawonga to Torrumbarry – Figure 33, and Edward River – Figure 34) (blackwater-affected reaches) and three examples of varying responses to the relaxed-flow-constraints scenarios (Hume to Yarrawonga – Figure 35; Gundagai to Berembed – Figure 36; and Yanco Creek – Figure 37) (temperature-affected reaches). All other modelling outputs for adult populations in the individual RRCP river reaches are included in Appendix 3. Note that the Murray Cod population model outcomes show a high level of convergence, which is explained by a lack of variation in their adult population size response to the relaxed-flow-constraints scenarios across the whole time series (Figure 30).

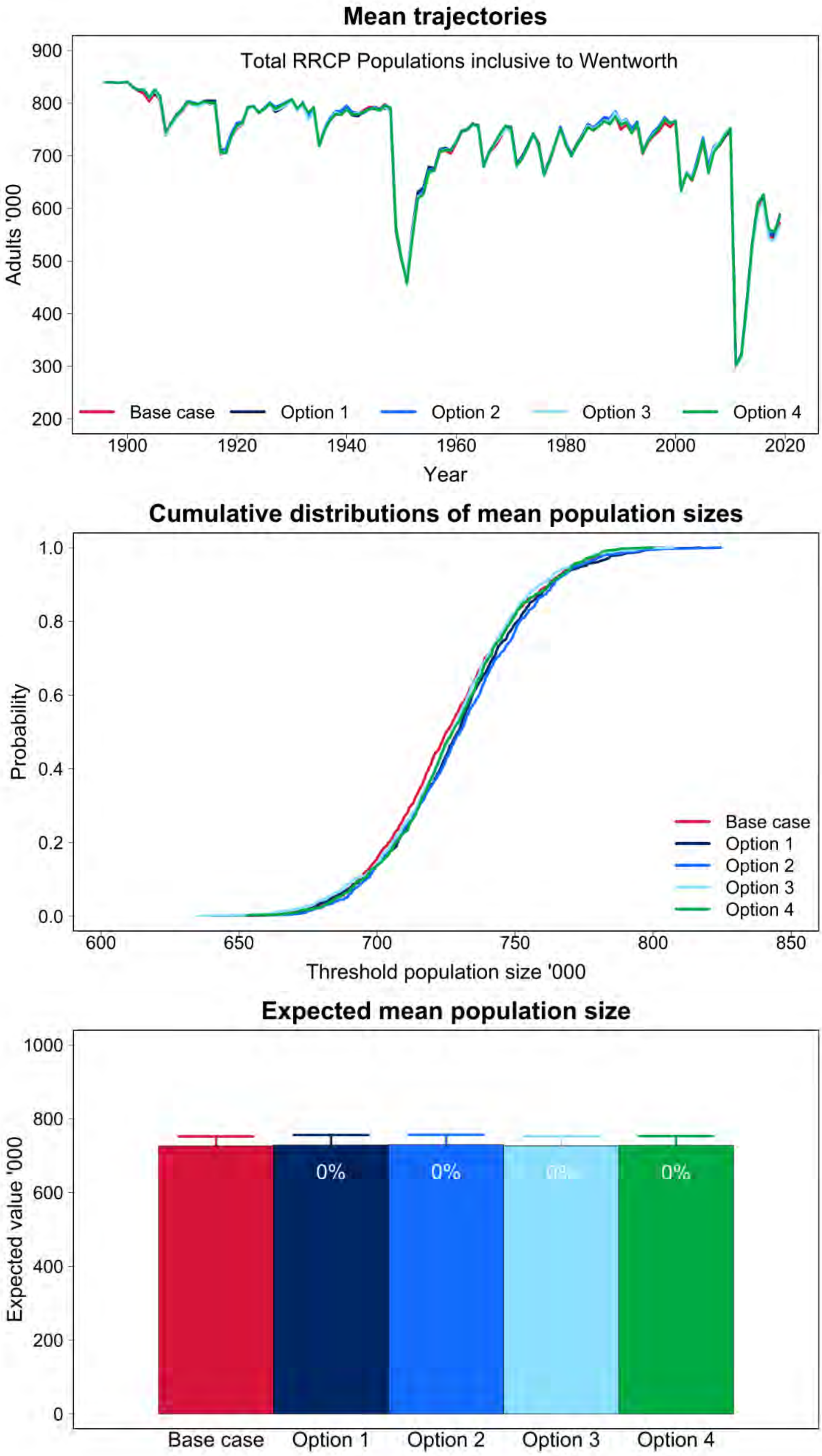

Figure 30. Modelled Murray Cod adult populations aggregated across all modelled RRCP focal zones, together with the Wakool Junction to Wentworth reach, for the RRCP flow scenarios Base case – Option 4. Top panel: mean adult population size through time. Middle panel: associated distribution of the mean adult population sizes. Bottom panel: expected mean adult population size, with the percentage change from Base case shown in each bar.

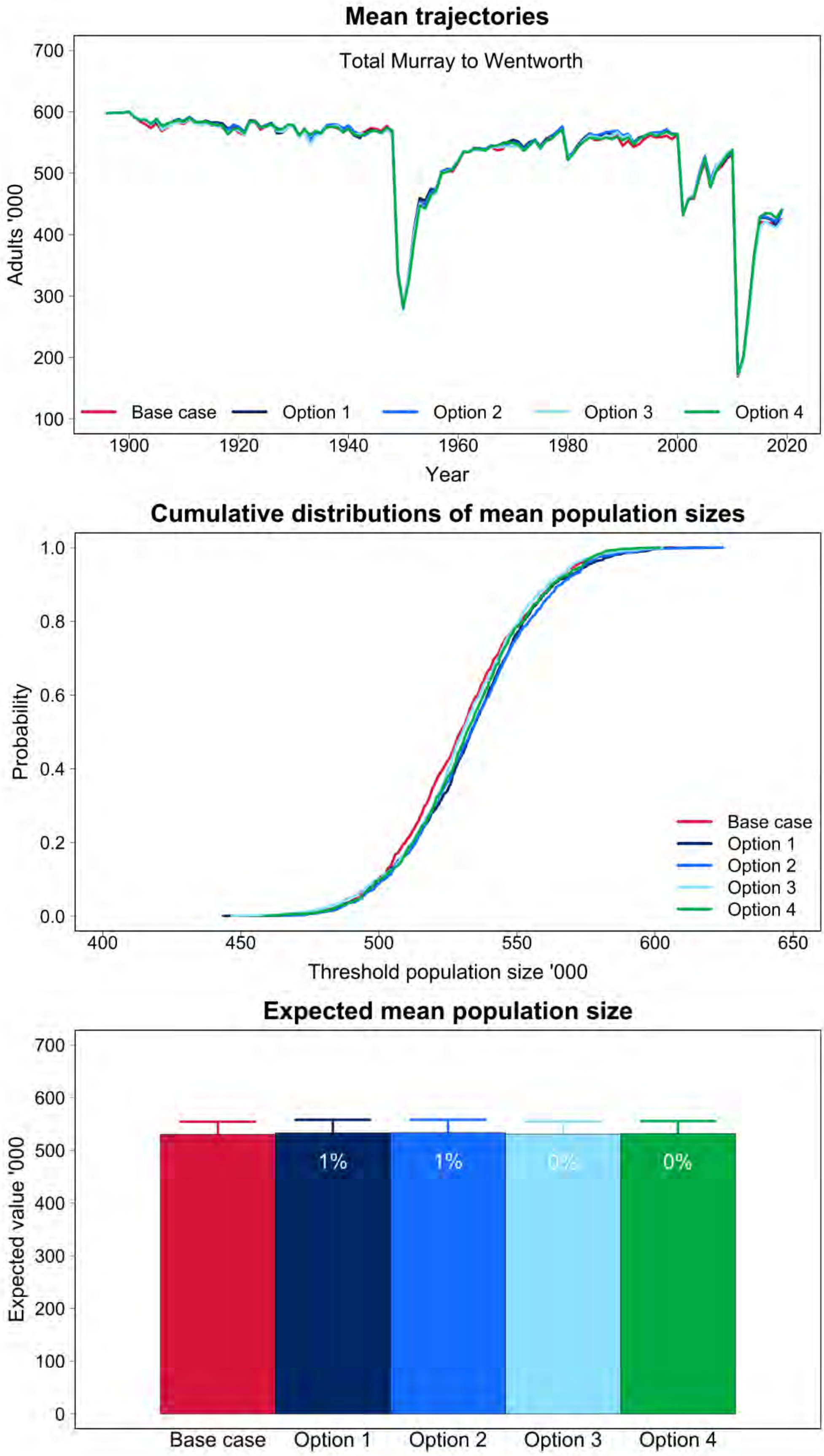

Figure 31. Modelled Murray Cod adult populations aggregated across the Murray River RRCP focal zones (including the Edward River), together with the Wakool Junction to Wentworth reach, for the RRCP flow scenarios Base case – Option 4. Top panel: mean adult population size through time, Middle panel: associated distribution of the mean population sizes and, Bottom panel: expected mean adult population size, with the percentage change from Base case shown in each bar.

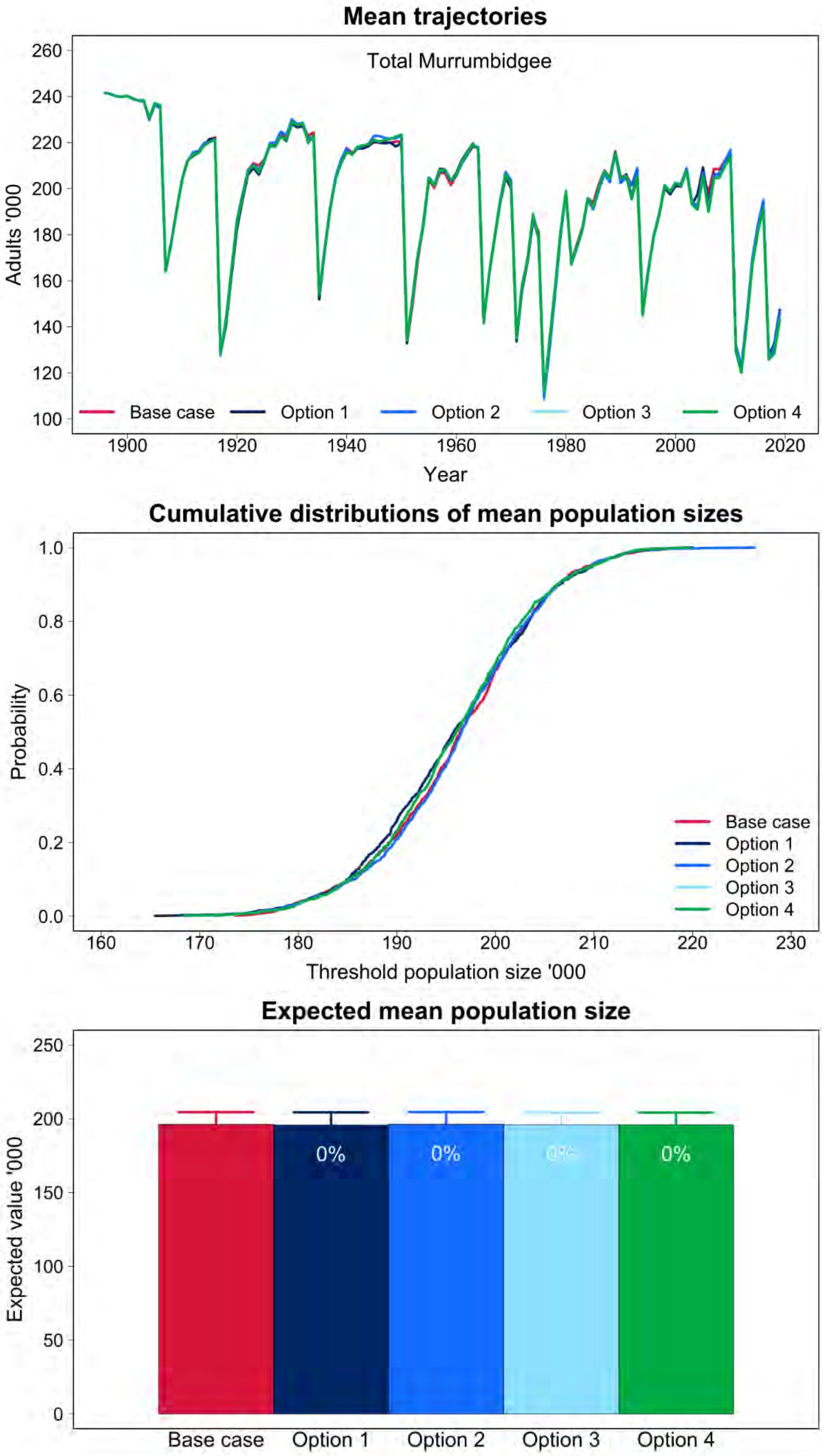

Figure 32. Modelled Murray Cod adult populations aggregated across the Murrumbidgee River RRCP focal area for the RRCP flow scenarios Base case – Option 4. Top panel: mean adult population size through time, Middle panel: associated distribution of the mean adult population sizes. Bottom panel: expected mean adult population size, with the percentage change from Base case shown in each bar.

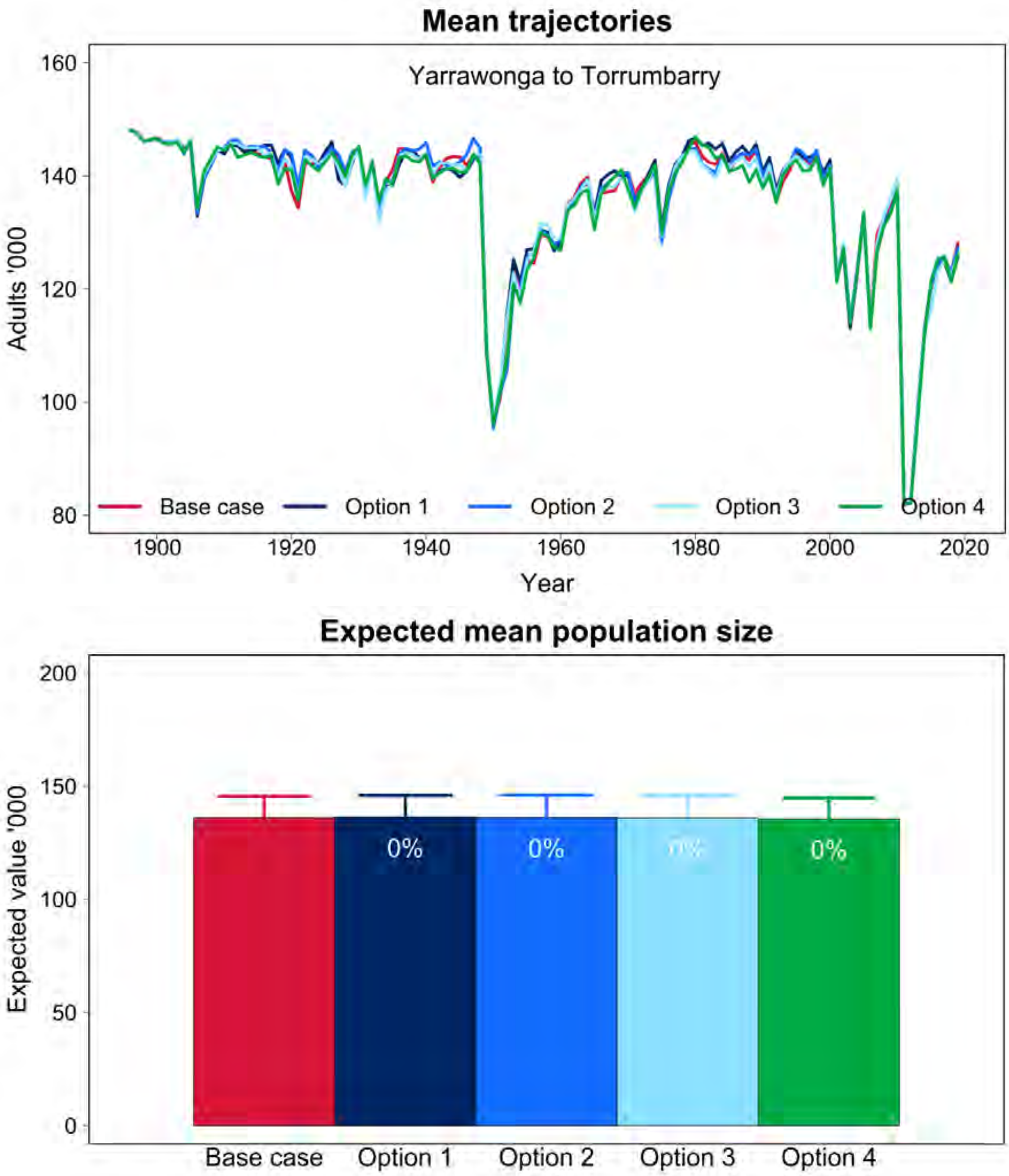

Figure 33. Modelled Murray Cod in the Yarrawonga to Torrumbarry reach for the RRCP flow scenarios Base case – Option 4. Top panel: mean adult population size through time. Bottom panel: expected mean adult population size, with the percentage change from Base case shown in each bar.

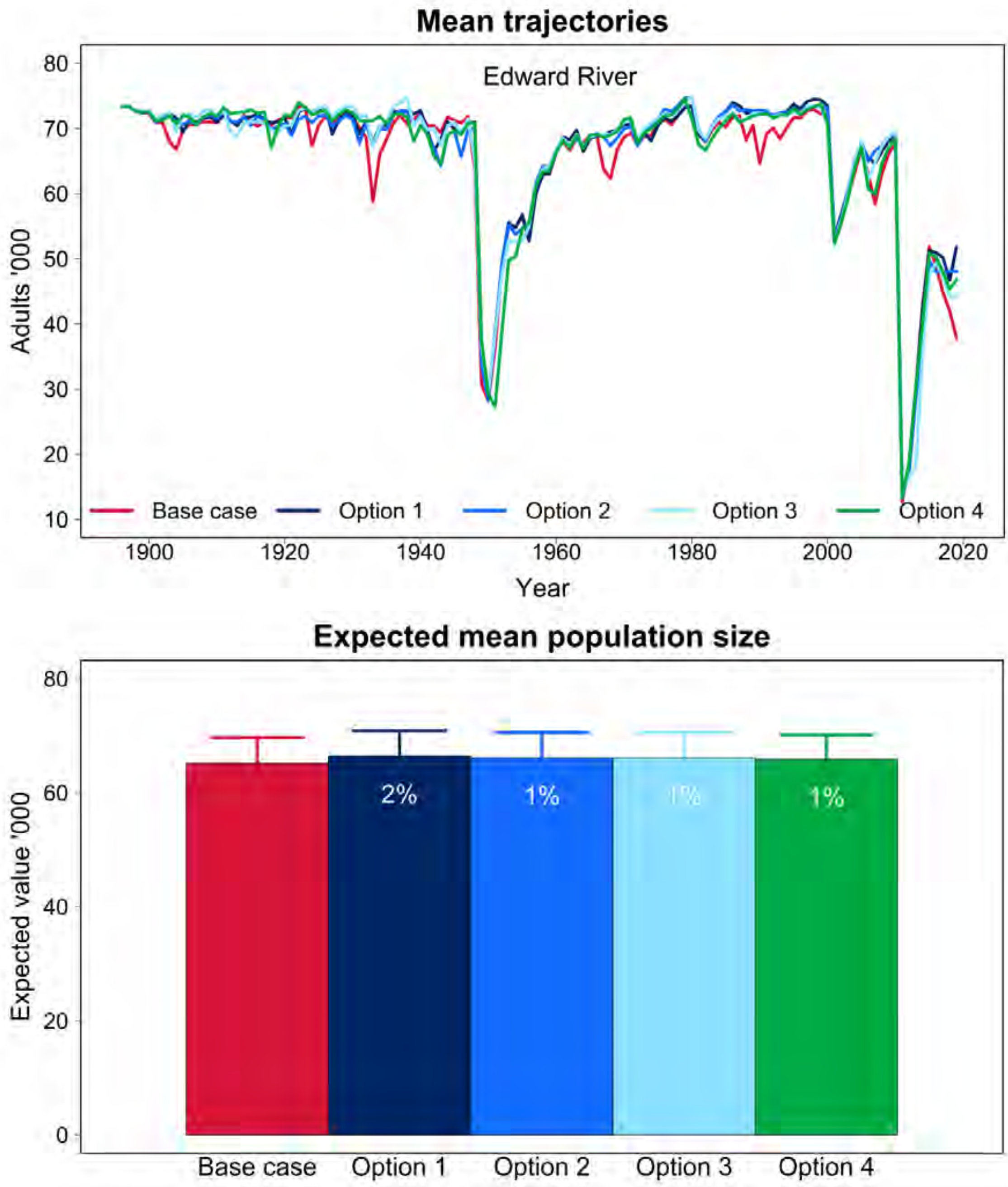

Figure 34. Modelled Murray Cod adult population in the Edward River for the RRCP flow scenarios Base case – Option 4. Top panel: mean adult population size through time. Bottom panel: expected mean adult population size, with the percentage change from Base case shown in each bar.

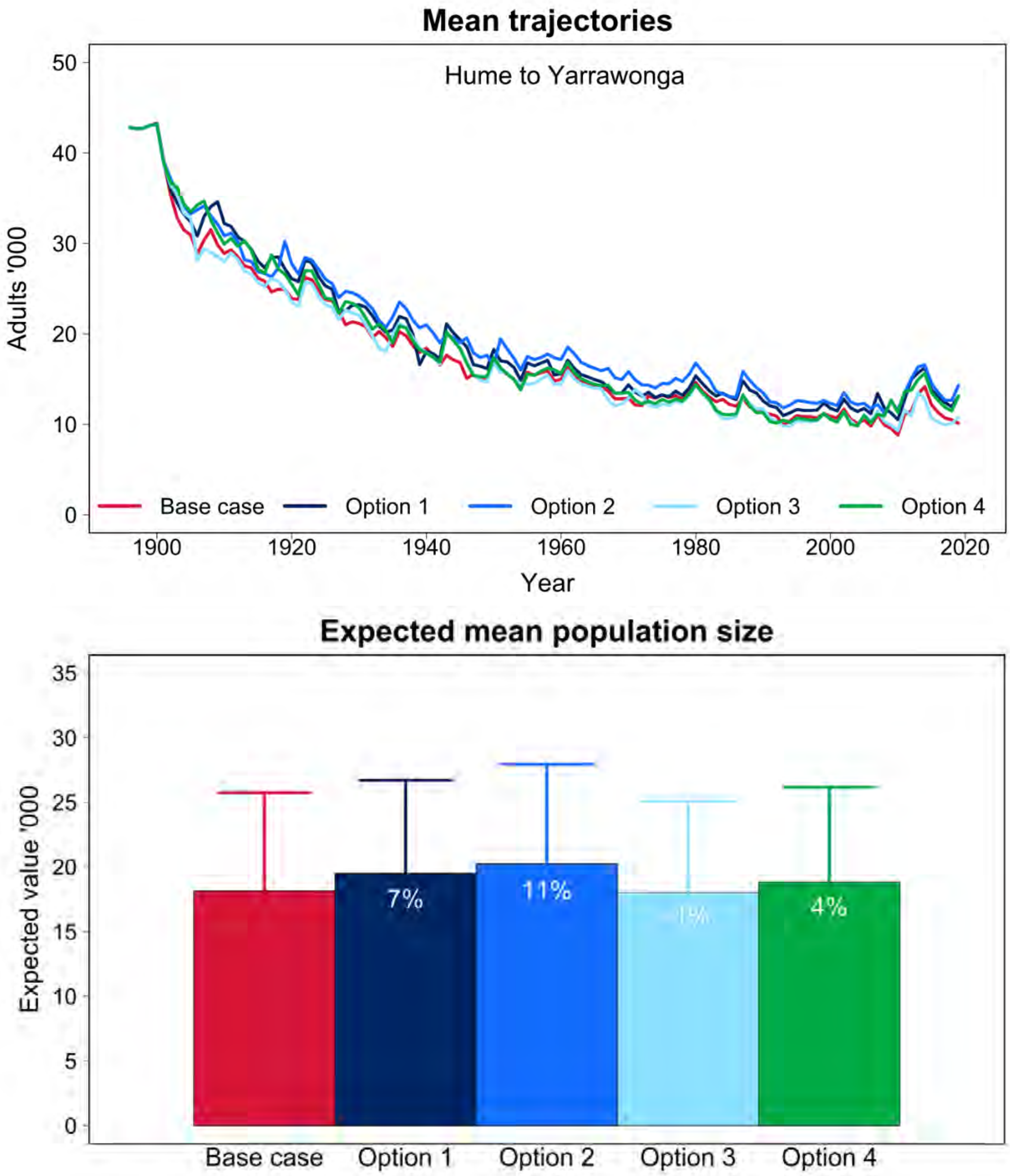

Figure 35. Modelled Murray Cod adult population in the Hume to Yarrawonga reach for the RRCP flow scenarios Base case – Option 4. Top panel: mean adult population size through time. Bottom panel: expected mean adult population size, with the percentage change from Base case shown in each bar.

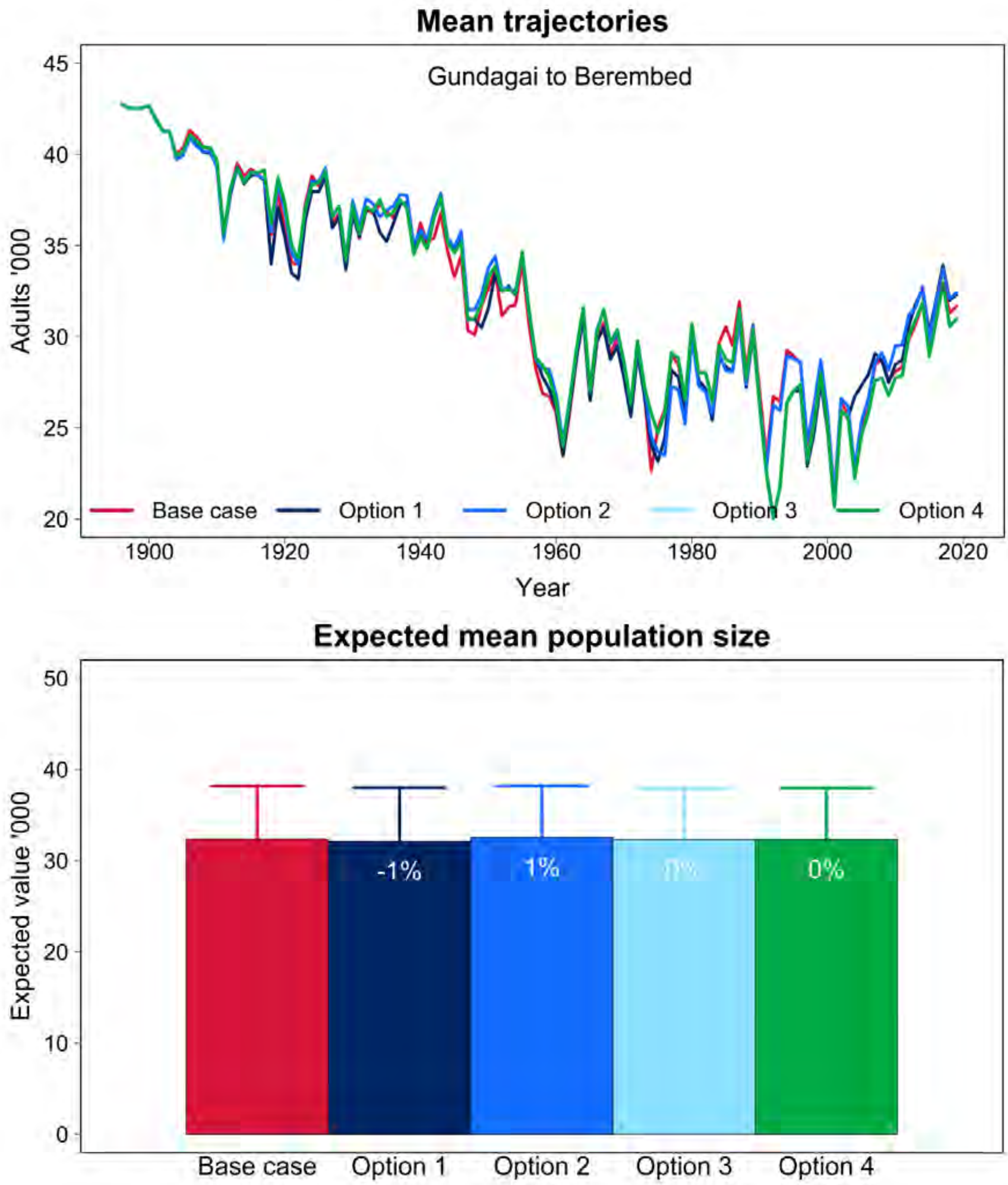

Figure 36. Modelled Murray Cod adult population in the Gundagai to Berembed reach for the RRCP flow scenarios Base case – Option 4. Top panel: mean adult population size through time. Bottom panel: expected mean adult population size, with the percentage change from Base case shown in each bar.

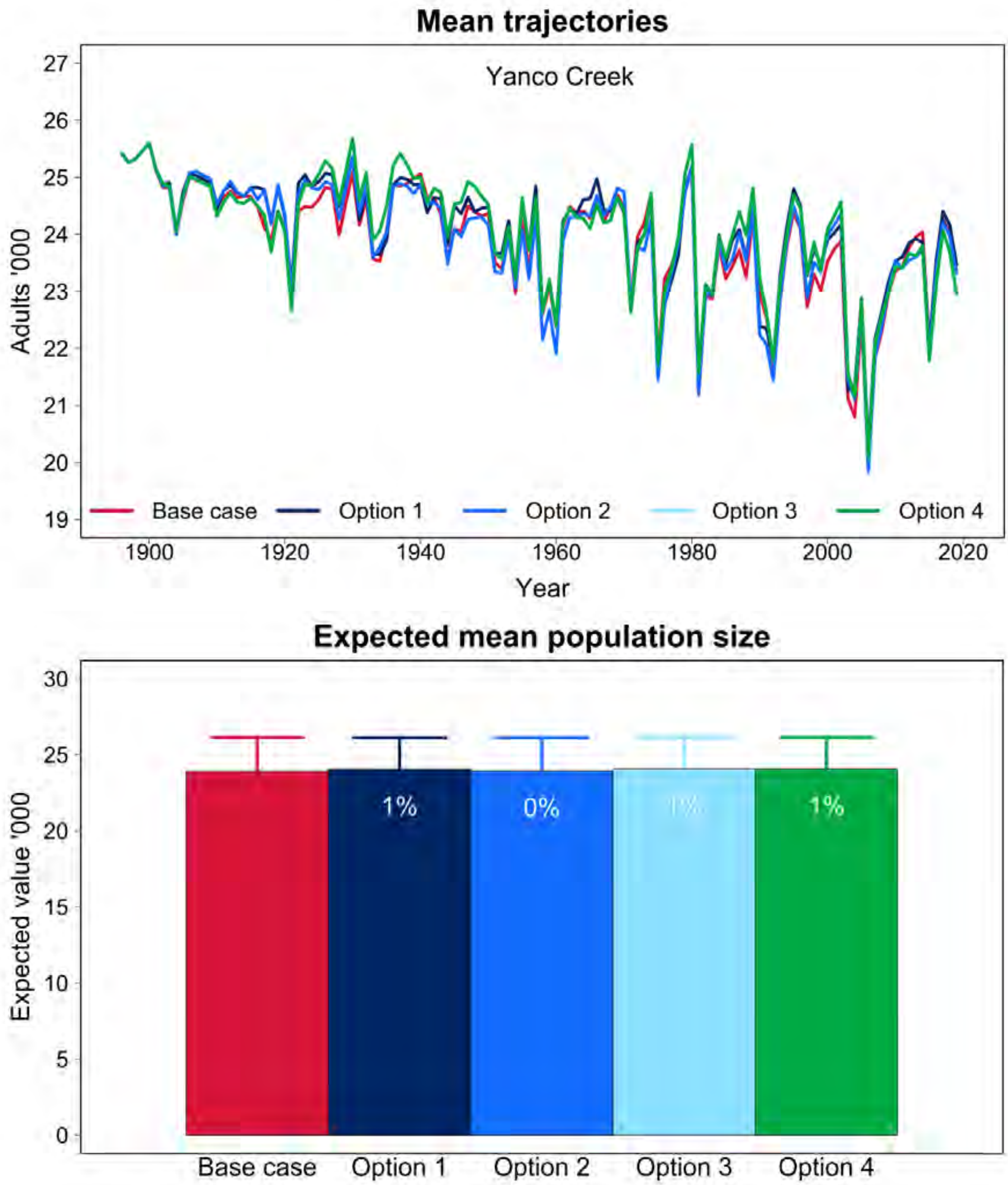

Figure 37. Modelled Murray Cod adult population in Yanco Creek for the RRCP flow scenarios Base case – Option 4. Top panel: mean adult population size through time. Bottom panel: expected mean adult population size, with the percentage change from Base case shown in each bar.

3.1.2.2. Recruitment of Murray Cod

The modelling outputs for the number of one year old (recruits) Murray Cod for the Total RRCP Populations is shown in Figure 38, the number of one year old Murray Cod in the Total Murray populations (to Wentworth, including Edward River) is shown in Figure 39 and the number of one year old Murray Cod in the Total Murrumbidgee populations is shown in Figure 40. Some of the results for 1 year old Murray Cod are invariant across the range of relaxed-flow-constraints scenarios (for example Yarrawonga to Torrumbarry – Figure 41). However, some populations exhibit a recruitment response to the scenarios, with mostly an increase from the Base case (Edward River – Figure 42; Hume to Yarrawonga – Figure 43; Gundagai to Hay – Figure 45; and Yanco Creek – Figure 46) and some a decrease (for example Berembed to Gogeldrie – Figure 44). Outputs for all individual river reaches are included in Appendix 3.

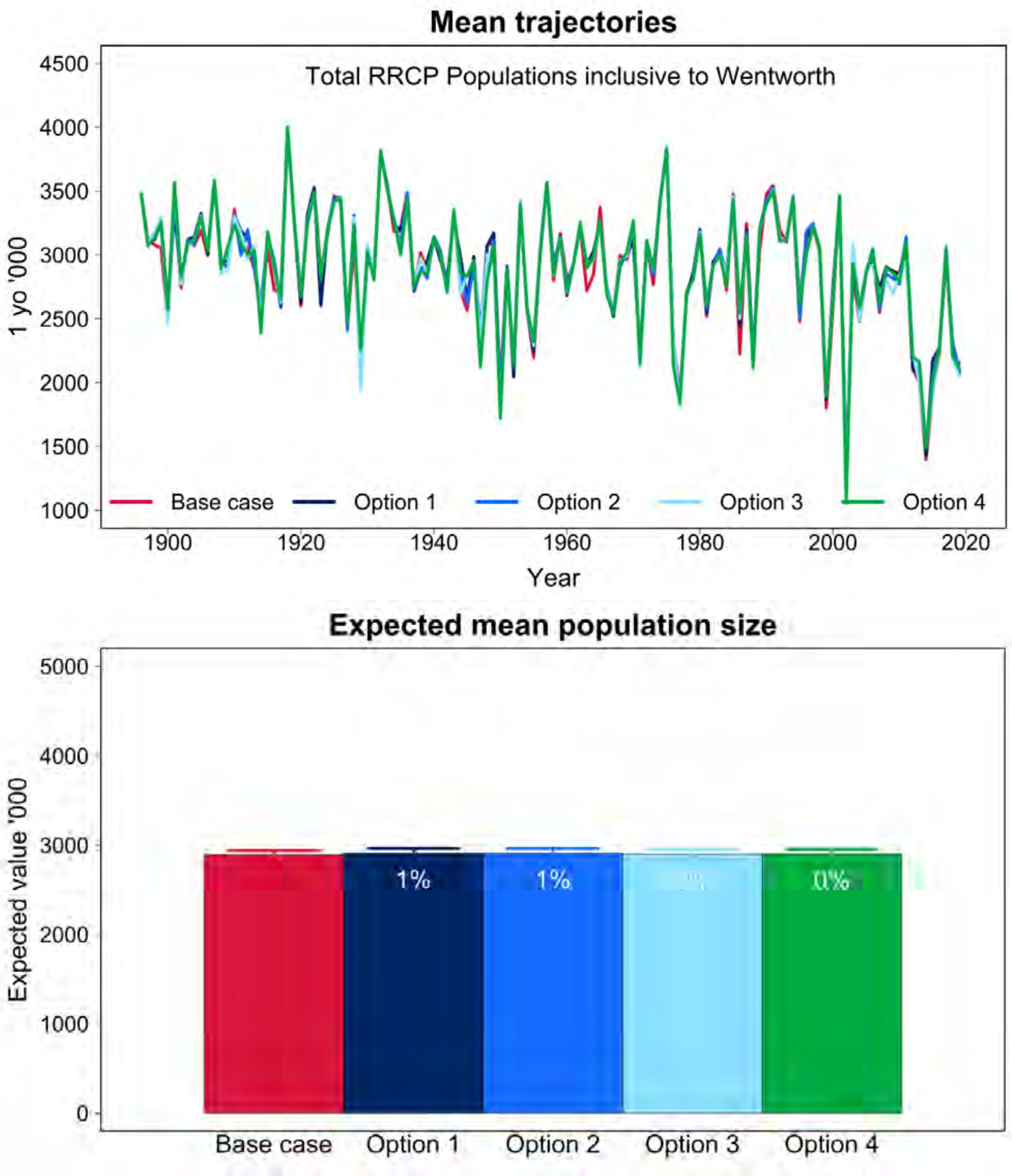

Figure 38. Modelled Murray Cod mean recruit (1-year-old) populations aggregated across all modelled RRCP focal zones, together with the Wakool Junction to Wentworth reach, for the RRCP flow scenarios Base case – Option 4. Top panel: mean recruit population size through time. Bottom panel: expected mean recruit population size, with the percentage change from Base case shown in each bar.

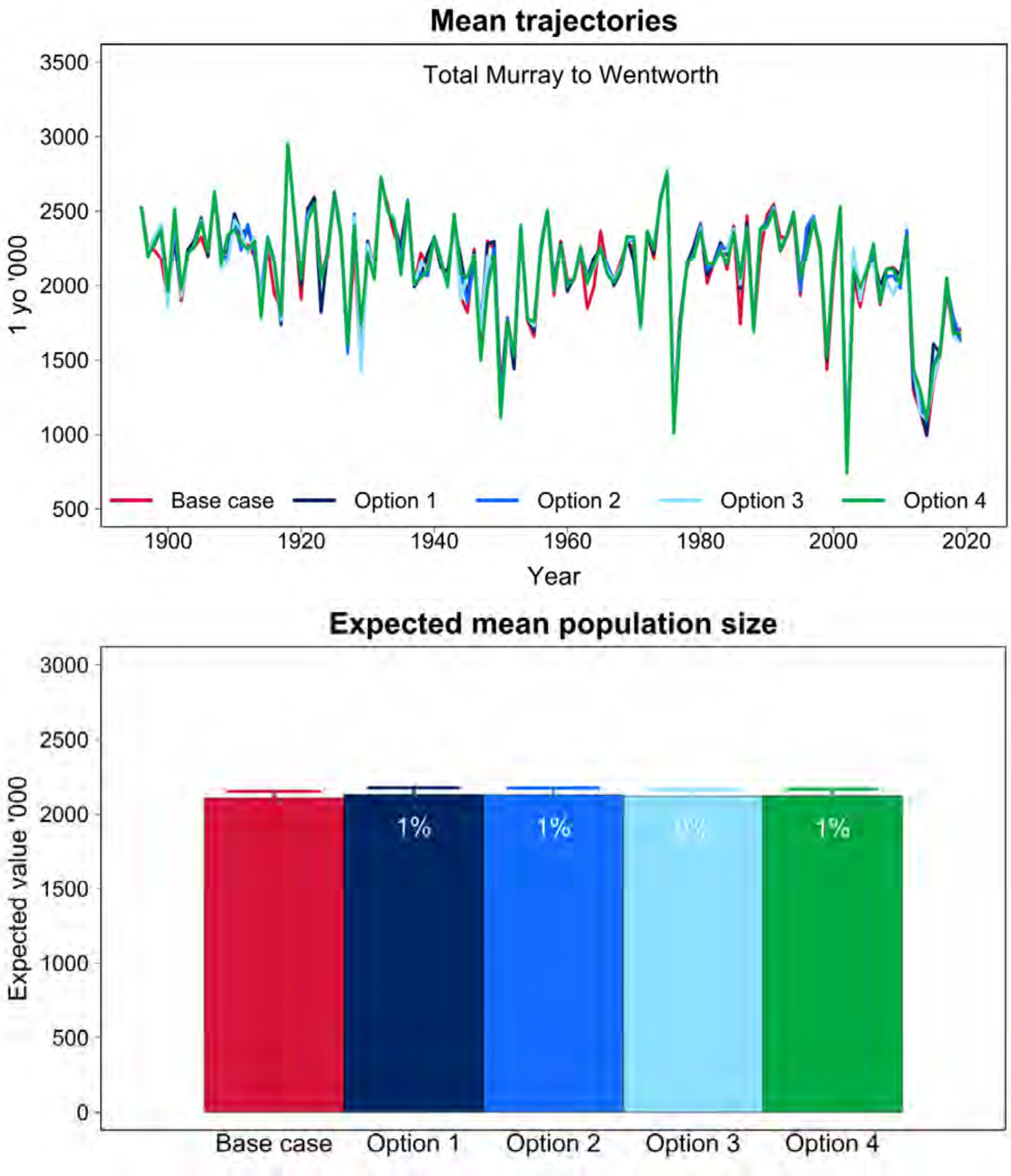

Figure 39. Modelled Murray Cod mean recruit (1-year-old) populations aggregated across the Murray River RRCP focal zones (including the Edward River), together with the Wakool Junction to Wentworth reach, for the flow scenarios Base case – Option 4. Top panel: mean recruit population size through time. Bottom panel: expected mean recruit population size, with the percentage change from Base case shown in each bar.

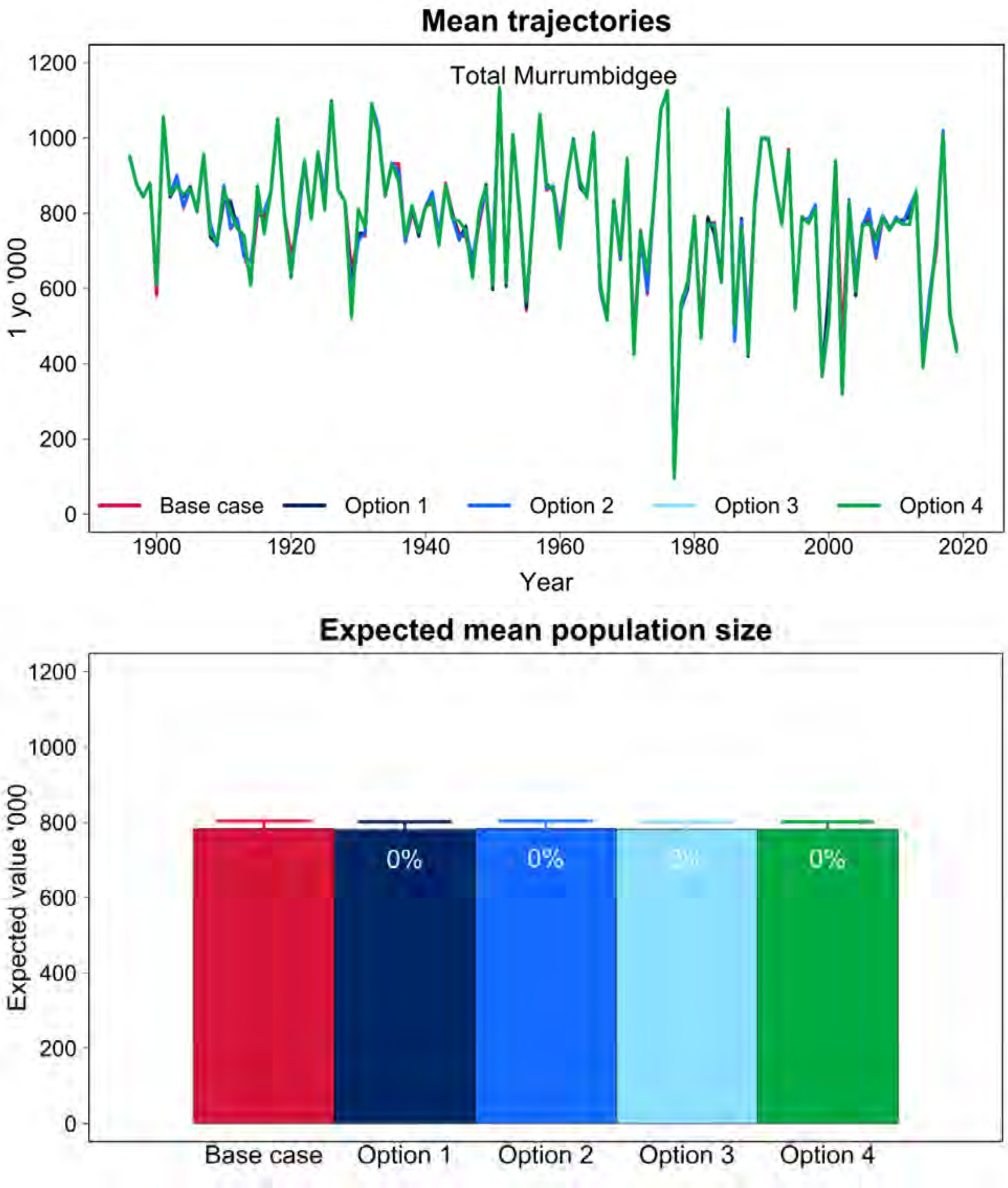

Figure 40. Modelled Murray Cod mean recruit (1-year-old) populations aggregated across the Murrumbidgee River RRCP focal area for the flow scenarios Base case – Option 4. Top panel: mean recruit population size through time. Bottom panel: expected mean recruit population size, with the percentage change from Base case shown in each bar.

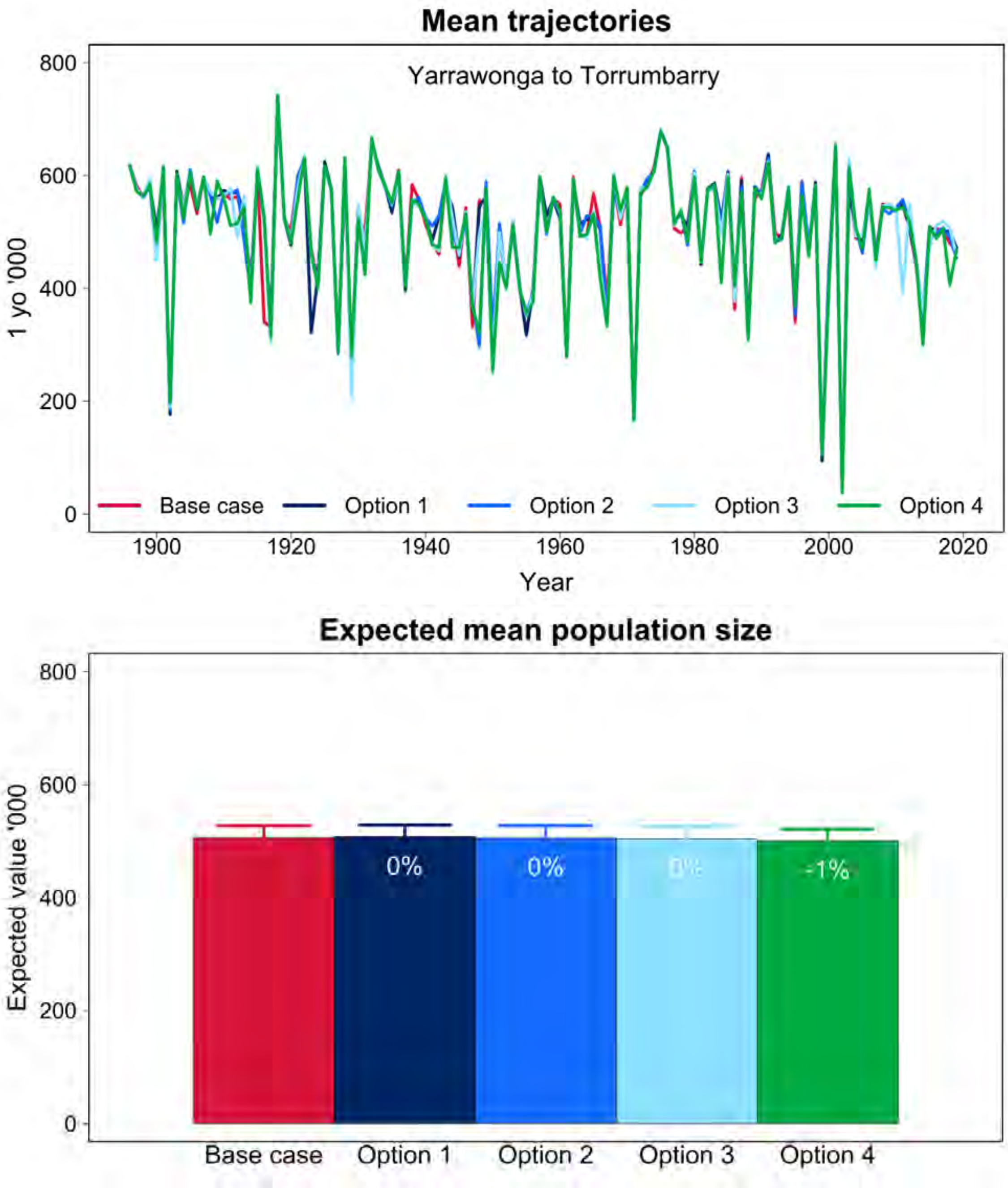

Figure 41. Modelled Murray Cod mean recruit (1-year-old) population in the Yarrawonga to Torrumbarry reach for the RRCP flow scenarios Base case – Option 4. Top panel: mean recruit population size through time. Bottom panel: expected mean recruit population size, with the percentage change from Base case shown in each bar.

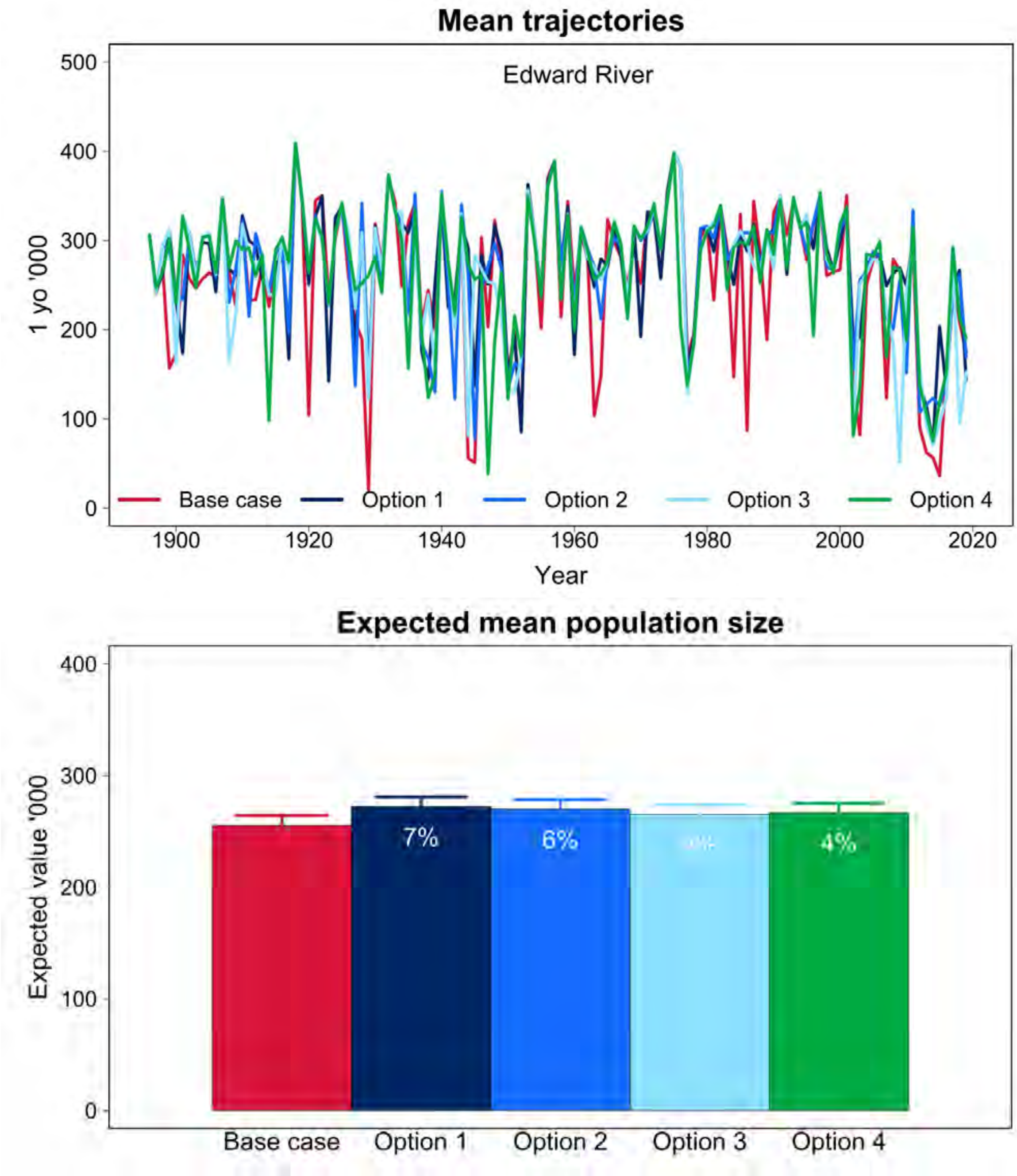

Figure 42. Modelled Murray Cod mean recruit (1-year-old) population in the Edward River for the RRCP flow scenarios Base case – Option 4. Top panel: mean recruit population size through time. Bottom panel: expected mean recruit population size, with the percentage change from Base case shown in each bar.

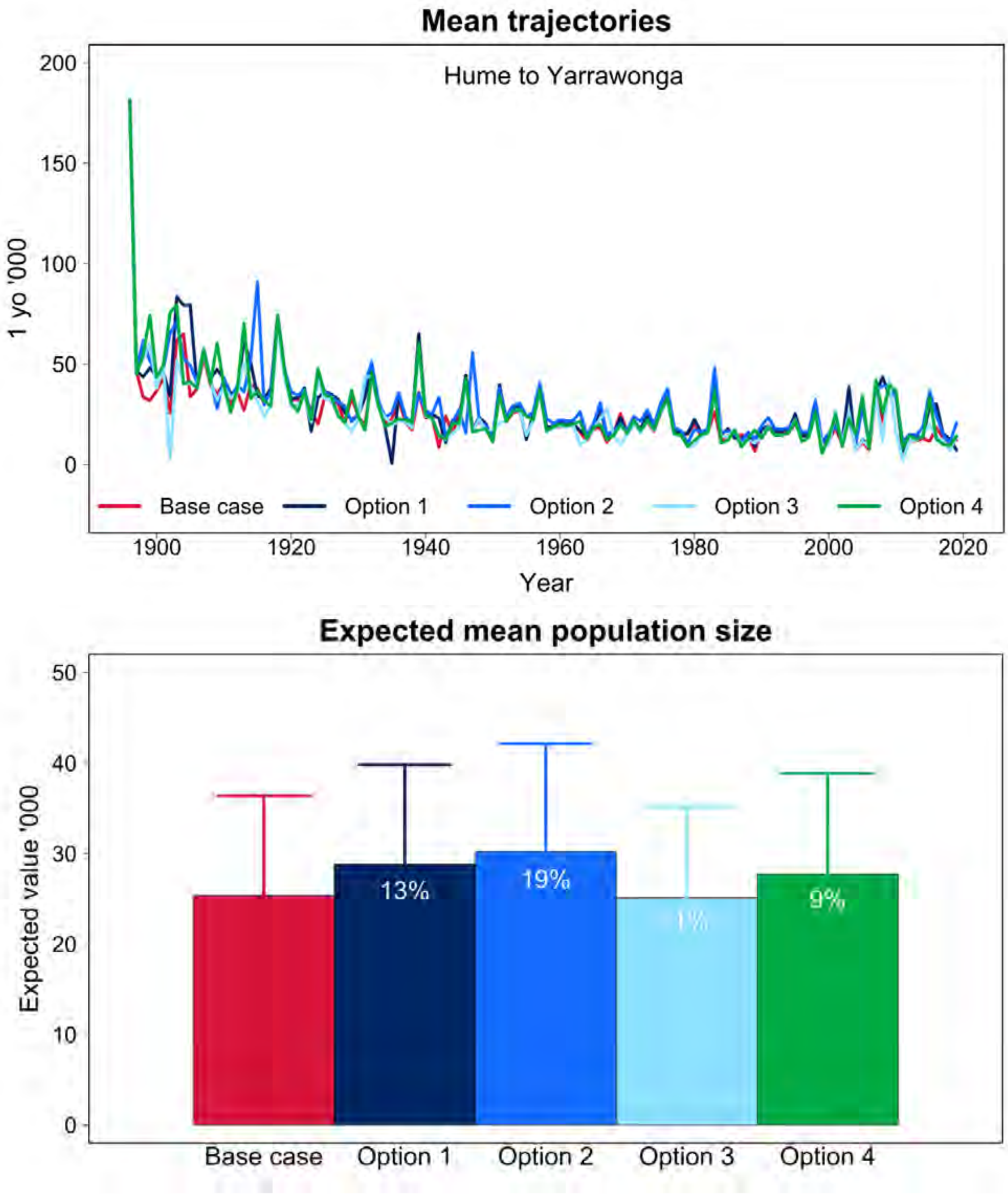

Figure 43. Modelled Murray Cod mean recruit (1-year-old) population in the Hume to Yarrawonga reach for the RRCP flow scenarios Base case – Option 4. Top panel: mean recruit population size through time. Bottom panel: expected mean recruit population size, with the percentage change from Base case shown in each bar.

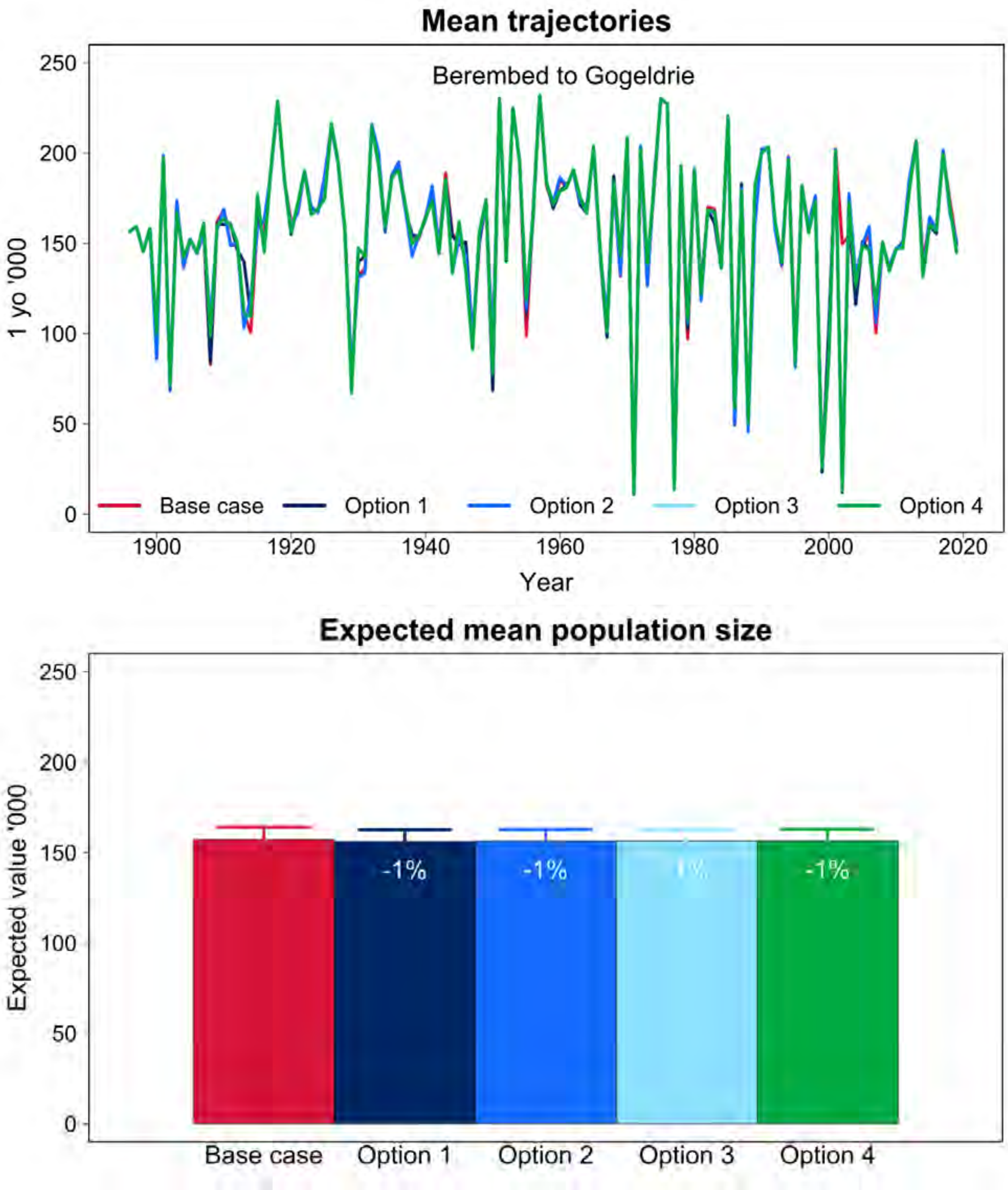

Figure 44. Modelled Murray Cod mean recruit (1-year-old) population in the Berembed to Gogeldrie reach for the RRCP flow scenarios Base case – Option 4. Top panel: mean recruit population size through time. Bottom panel: expected mean recruit population size, with the percentage change from Base case shown in each bar.

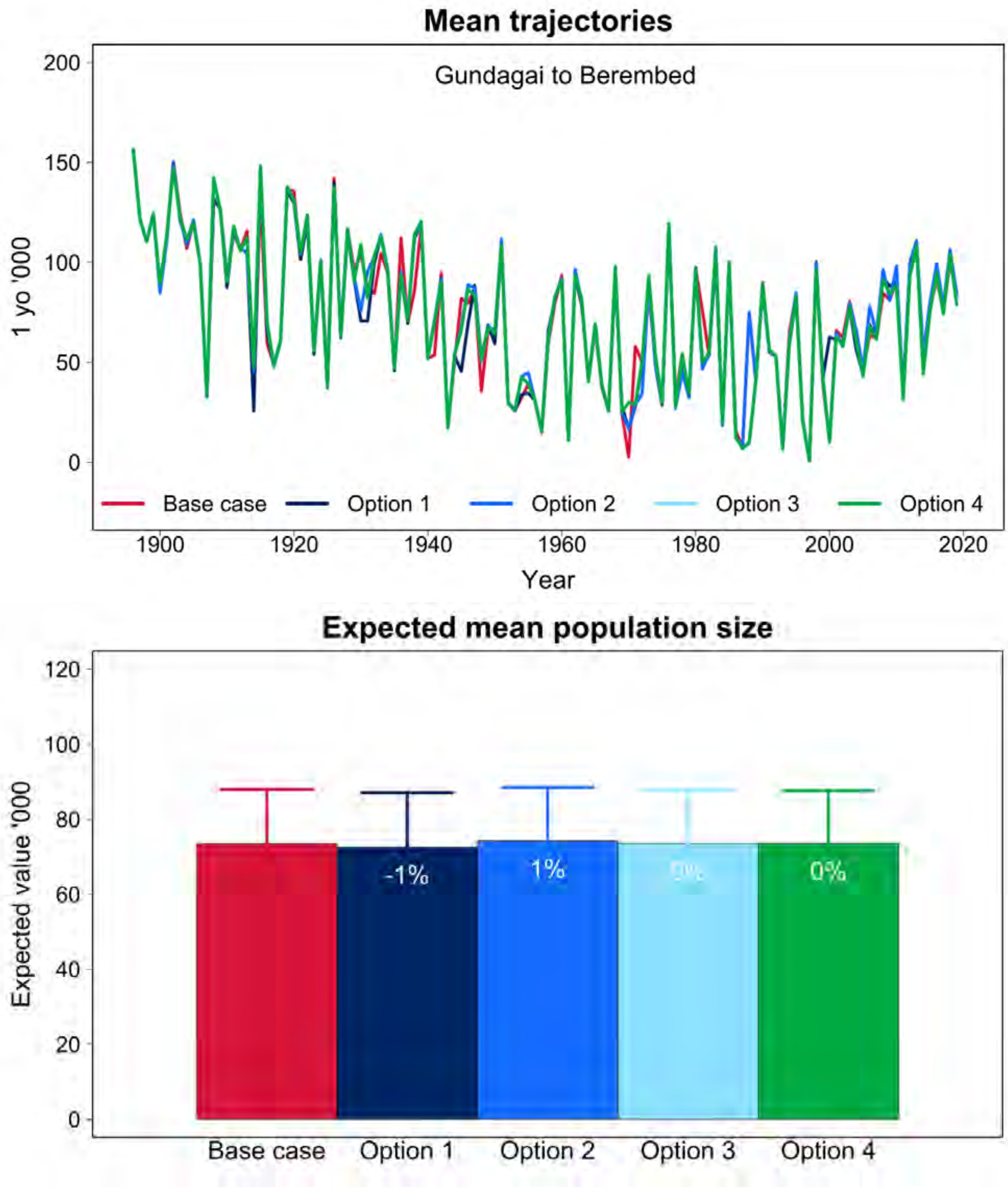

Figure 45. Modelled Murray Cod mean recruit (1-year-old) population in the Gundagai to Berembed reach for the RRCP flow scenarios Base case – Option 4. Top panel: mean recruit population size through time. Bottom panel: expected mean recruit population size, with the percentage change from Base case shown in each bar.

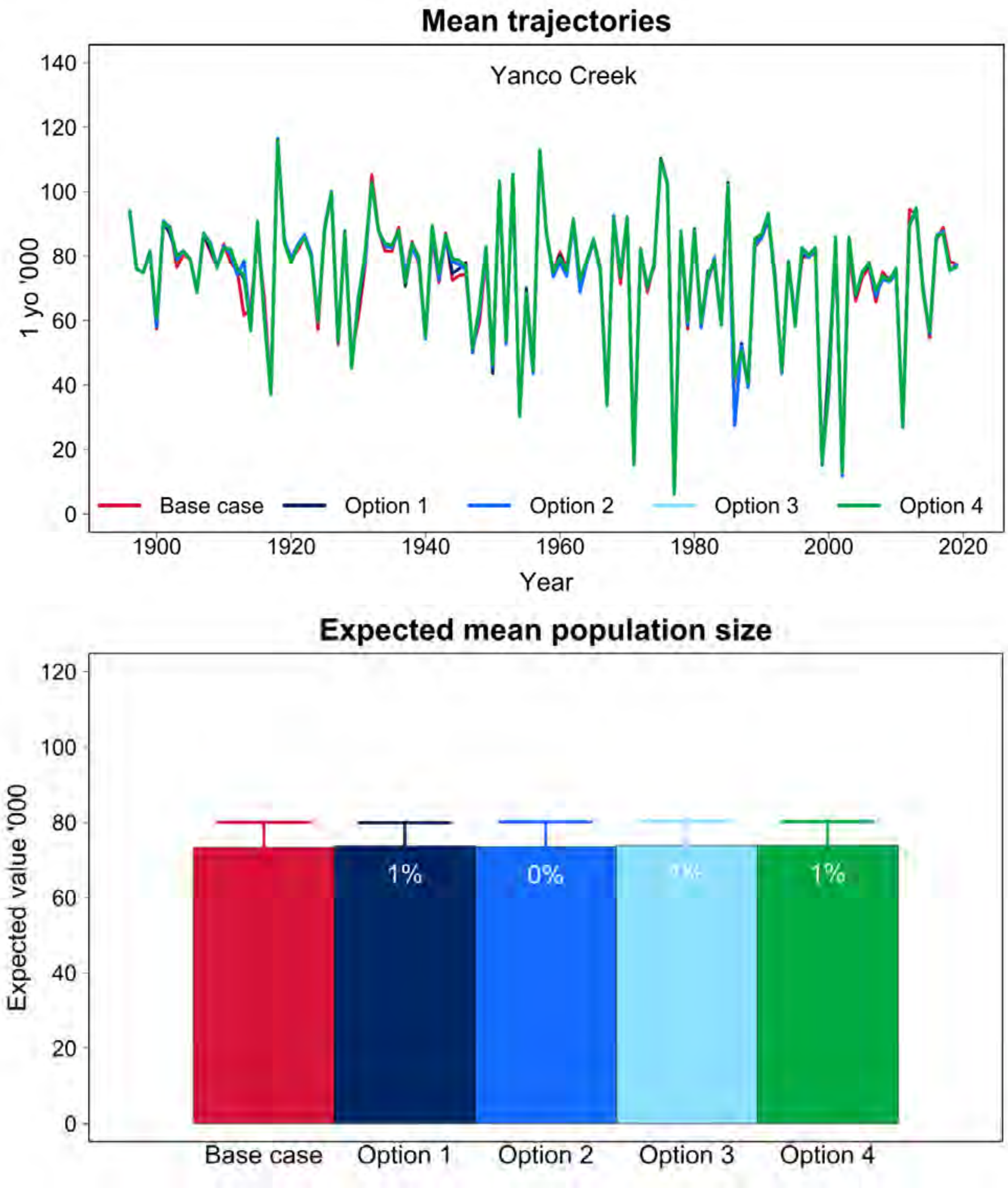

Figure 46. Modelled Murray Cod mean recruit (1-year-old) population in Yanco Creek for the RRCP flow scenarios Base case – Option 4. Top panel: mean recruit population size through time. Bottom panel: expected mean recruit population size, with the percentage change from Base case shown in each bar.

3.2. Model validation

This chapter presents the results of the work undertaken to compare the predictions of the native fish population models with the independent datasets held by NSW Fisheries and ARI. The methods that were used to undertake these comparisons are described here, followed by an outline of the results. The interpretation of these results and a summary of their implications for the broader RRCP native fish modelling project can be found in the subsequent Discussion chapter.

3.2.1. Overview of validation approach

Our broad approach involved comparing the outputs from the stochastic population models constructed for Murray Cod and Golden Perch (hereafter referred to as 'MODEL' data) with independent datasets collected from two different sources (hereafter referred to as 'OBSERVED' data; derived from the 'ARI' and 'NSW' datasets Table 5; Figure 47). The MODEL did not use any of the OBSERVED data as part of its formulation or training, so the OBSERVED data can be considered as a testing dataset. Implicitly, it was assumed that the OBSERVED data provided the best reflection of the actual population dynamics in the system (but see discussion of this assumption later). Before comparing the MODEL and OBSERVED datasets, several data preparation steps were undertaken, including ensuring temporal alignment of sampling and also that the same fish ages were included in comparisons (Appendix 6). From the NSW datasets, datasets were selected from riverine locations with more than five consecutive years of sampling from two or more sites (Appendix 6).

Table 5. Description of the main datasets used for the validation component. The 'ARI' dataset was collected by scientists from the Arthur Rylah Institute for Environmental Research, which is part of the Department of Environment, Land, Water and Planning. The 'NSW' dataset was collected by the New South Wales (NSW) Department of Primary Industries, Fisheries.

Name	Data range	Description
ARI OBSERVED	2000–2019	This dataset was generated from a long-term (1999–2018) study (Lyon et al. 2021) estimating the population size for Golden Perch and Murray Cod in the 100km stretch of the Mid Murray between Lake Mulwala downstream to Tocumwal (Figure 1). Every year, 90–120 sites within this reach were electro fished by boat, and fish ≥220 mm were tagged. In all, 9801 Golden Perch (N = 539 recaptures) and 13,271 Murray Cod (N = 1537 recaptures) were caught. A Jolly–Seber capture–mark–recapture model was then used to estimate the population size for the 100-km section (see Lyon et al. 2021 for more details on this model). These data provide population size estimates and are the best available temporal dataset for population density. Sampling was consistently performed each year, and the model corrects for variation in detection rates.
NSW OBSERVED	1994–2021	This dataset contains boat electro fishing data from locations across NSW. The dataset includes a relative abundance measure (catch-per-unit-effort) and can be used for validating temporal trends and underlying processes. The spatial sampling was extensive, but the temporal sampling at times was patchy. Varying detection rates across years may be problematic for validation purposes, as this would likely bias population estimates.
MODEL	1984–2019	This dataset is the population model outputs. The validation used the population model outputs generated from an 'observed' flow scenario in which the observed flows (ML day^{-1}) at relevant gauges throughout the system were matched with modelled temperatures as generated by hydrological modelling (see section 2.9). For each population, population size estimates for each age class (1 year, 2 years, 3 years, adult) for every iteration were extracted from the model. Additionally, adult movement from Population 2 into Population 3 (from Yarrawonga to Torrumbarry) was also obtained.

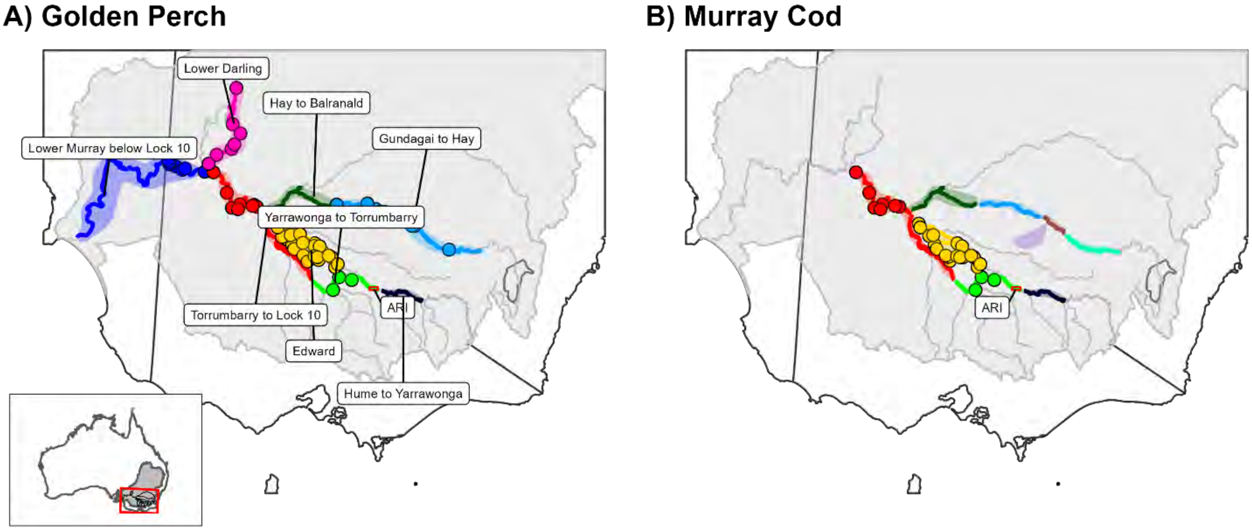

Figure 47. Maps of the study area, showing the NSW sampling sites for which data was retained for population analysis: A) for Golden Perch and B) for Murray Cod. Dots show the NSW sites from which OBSERVED data was used for the validation assessment. The red rectangle (labelled 'ARI' on the larger maps) indicates the location of the ARI study.

Description of population model outputs

For validation, the population model was run using 'observed' flow scenario inputs (from hydrological modelling as described in section 2.9) for each population area for both Golden Perch and Murray Cod. The 'observed' flow scenario inputs comprised observed daily flows (ML day^{-1}) paired with modelled temperature data at relevant gauges throughout the system. One thousand iterations were generated from the population model for each population. Each location was modelled independently for Murray Cod, while a single metapopulation model was used for Golden Perch to account for movement among locations. The population sizes N in each year t for age classes 1 year, 2 years and 3 years, and older ($N_{t,adult} = \sum_{i=3}^{I} N_{t,i}$) were calculated for each iteration, and then the finite population growth rate in each year *t*: $\lambda_t = \frac{N_t}{N_{t-1}}$ was estimated. Next, the median growth rates [and 95% confidence interval (CI)] for each t across iterations for each population area and species were calculated. To compare predicted (MODEL) and OBSERVED movement, adult movement from the 'Torrumbarry to Wentworth' reach to the 'Yarrawonga to Torrumbarry' reach was extracted (the two locations for which movement data was available in the 'ARI' dataset – Table 5). The rate of change in movement was used for comparisons (analogous to λ_t), taking the median and standard deviation across all runs.

Validation of population size and growth rate

The key objective of the population MODEL was to assess predicted fish population sizes under various flow conditions. However, the population models were not spatially explicit, so there was no defined area/volume to calculate the population size for a given population. Also, the selection of an initial population size would affect the size of the predicted population. Consequently, attempting to validate/compare population sizes directly was not possible without using arbitrary and potentially misleading correction/adjustment factors. Therefore, scaled abundance estimates (population size from the MODEL data, population density from the ARI OBSERVED data, and relative abundance from the NSW OBSERVED data) were compared, and the correlation between these estimates over time was assessed.

Predicted population growth rates can be extracted from the MODEL directly, but a statistical model was needed to estimate population growth rates from the ARI and NSW data. From the ARI dataset, population estimates (with uncertainties) were extracted for both species using the published Jolly–Seber capture–mark–recapture model (Lyon et al. 2021). As the aim was to compare population growth rates, it was necessary to obtain estimates of the finite population growth rate (λ). These data were not available, so they were calculated from the population estimates: $\hat{\lambda}_t = \frac{\hat{N}_t}{\hat{N}_{t-1}}$. To obtain some measure of the uncertainty, we assumed there was no correlation between N_t and N_{t-1} and used the delta method to estimate the standard error (SE) for λ (e.g. Mandel 2013). This SE estimate is likely to be conservative due to the probable positive correlation between estimates of *N*.

For the NSW dataset, we used a Bayesian state-based population model (Kéry and Schaub 2011) to obtain estimated growth rates from the relative abundance (catch-per-unit-effort; CPUE) data. Separate models were run for each population area. The model comprised two components: an observation model and a process model. The observation model was defined as:

$$n_{i,t} \sim Pois(\mu_{i,t})$$

where *i* = site, t = fish year. $\mu_{i,t}$ is the population density rate (number/hour) for year t and site *i*. A Poisson distribution was assumed, but it should be noted that additional variation in the process model was included, which mitigated overdispersion in the data. Note that the population density rate implicitly incorporates the detection rate of the electrofishing and assumes it to be constant. Therefore, $\mu_{i,t}$ is a relative abundance.

The next component of the statistical model was a process model. This component underlies the population dynamics and estimates the growth rate. This component is described as:

$$\begin{aligned} log(\mu_{i,t}) &= log(\mu_{i,t-1}) + EF_{i,t} + \bar{r} + r_t + \epsilon_{i,t} \\ r_t &\sim N(0, \sigma_r^2) \\ \epsilon_{i,t} &\sim N(0, \sigma^2) \end{aligned}$$

where $\mu_{i,t}$ is the mean abundance per hour electrofishing for year *t*. EF_{effort} is electrofishing effort in hours (log-transformed). $\bar{r}$ is mean population growth. Growth rate varies each year (r_t), following a normal distribution. It was assumed that sites had the same growth rate, with a process error ϵ_i, t, that was normally distributed. Summaries of the fit of these models are provided in the Appendix 6 (Figure A6.2).

All analyses were performed using R v3.3 (R Core Team 2019). Bayesian modelling was run using JAGS (Plummer 2004) and R2jags (Su and Masanao Yajima 2020). Non-informative priors were used for all models. Models were run for 40,000 iterations with a 1000 iteration burn-in. Model convergence was checked using the Gelman–Rubin statistic (all models had $\hat{R} \leq 1.05$; Gelman and Rubin 1992).

Validation of rates of movement between Yarrawonga and Torrumbarry

Given the high mobility of Golden Perch, assumptions around rates of movement are a key component of the MODEL for this species. The recruitment/migration parameter (PENT) was extracted from the Jolly–Seber model from the ARI dataset for Golden Perch, which mainly reflects immigration into the system rather than local recruitment (Lyon et al. 2021). Scaled MODEL immigration rates (from the Torrumbarry to Wentworth population to the Yarrawonga to Torrumbarry population) were compared with scaled immigration rates extracted from the ARI mark–recapture model. This comparison was focused on the correlation between the estimates as it was not possible to directly compare actual values.

Metrics used for validation

We assessed the concordance between the MODEL and the OBSERVED datasets (ARI, NSW) using multiple metrics (Table 6). The differing metrics indicate different kinds of concordance and the metric used depended on the parameter of interest (Table 6).

Table 6. Assessment metrics used for comparing the MODEL output dataset with the OBSERVED output dataset. The criteria clarify how the level of concordance between the MODEL and OBSERVED estimates were deemed 'weak' or 'strong' supports for the MODEL.

Parameter	Metric name	Description	Criteria	Comments
Population size migration rate	Pearson Spearman	Pearson and Spearman correlations to measure association	>0.4 = weak support >0.6 = strong support	Discrepancies between Pearson and Spearman correlations would indicate a potential for the peaks/troughs to be driving the correlations
Population growth rate	Mean Absolute Percentage Error (MAPE)	Assessment of magnitude of difference in population growth rate (log-scale), presented as percentage difference	<40% = weak support <20% = strong support	MAPE provides the average percentage difference between the MODEL data and OBSERVED data
	Bias	Assessment of whether the MODEL consistently over- or under-estimates population growth rates (based on the average log difference between the MODEL data and the OBSERVED data; a negative result indicates the MODEL predicts a lower population growth rate)	95% CI overlaps 0 OR <20% = weak support 95% CI overlaps 0 AND <20% = strong support	Bias provides insight into whether a MODEL might consistently over- or under-estimate population growth rates
	Growth rate directionality	The proportion of the time that MODEL data and the OBSERVED data predict the same growth rate direction	>80% = weak support >90% = strong support	Growth rate directionality provides some indication of whether or not model predictions are reliable. It may be that peaks and troughs are well predicted, but that smaller changes are not.

CI: confidence interval.

For population size and migratory rates, Pearson and Spearman correlations were used, which measure the association (–1 = perfectly negatively correlated; 0 = no association; 1 = perfectly positively correlated) between MODEL and OBSERVED abundances. The Pearson correlation assumes a normal distribution and a linear relationship, and hence is strongly affected by outliers. In contrast, the Spearman rank correlation is non-parametric and relies on ranked order, mitigating outlier effects. If MODEL and OBSERVED growth are tightly (positively) associated, both correlation indices will be close to 1. However, if the MODEL can only predict peaks, then the Pearson correlation may be near 1, but the Spearman correlation may be close to zero. Thus, discrepancies between the metrics can provide unique insights.

For growth rates, multiple metrics were used. Mean Absolute Percentage Error (MAPE) provides an estimate of the average difference between MODEL data and OBSERVED data. The log-difference between population growth rates were calculated and presented as the percentage difference:

$MAPE = (e^{\frac{\sum|log(\lambda_{MOD})-log(\lambda_{OBS})|}{n}} - 1) * 100\%$. Thus, smaller MAPE indicates better concordance between MODEL and OBSERVED estimates.

In addition to using MAPE to compare growth rates, it is also useful to assess any bias between the MODEL outputs and the OBSERVED outputs. Here, the following equation was used:

$BIAS = (e^{\frac{\sum log(\lambda_{MOD})-log(\lambda_{OBS})}{n}} - 1) * 100\%$. This yielded the average percentage difference. The further away from 0, the larger the bias.

As a coarser metric, how well the model predicted directional changes in growth rates was assessed, in particular, the sensitivity of the MODEL to predict positive and negative growth rates. For every year, the proportion of times the MODEL data and OBSERVED data agreed was estimated. Perfect concordance would be 1.

Incorporating uncertainty in estimates

A complicating component of the validation analysis is that there is uncertainty in all estimates. The population MODEL estimates are a distribution of estimates, not a single estimate. Similarly, growth rate estimates for ARI and NSW have uncertainty and are themselves distributions of possible values.

The approach taken here to incorporate this uncertainty was to obtain a distribution of the assessment metrics for each comparison. For the NSW data, 1000 iterations were randomly extracted from the Bayesian state model and paired with the 1000 model iterations. For each paired iteration, each assessment metric was calculated.

The same approach was repeated for the ARI datasets and the migration data, though each of these datasets had their own complications. For the ARI data, only standard errors for the growth rate estimates were available. It was assumed that each year growth rates were normally distributed according to the mean and standard error, and independent across years. One thousand iterations were randomly sampled and used as the input data. No uncertainty estimates for the ARI migration estimates were available, so we instead compared the ARI migration estimates with each MODEL iteration.

The result was 1000 values of each assessment metric for each comparison. The median, 2.5% quantile, and 97.5% quantiles of these values were obtained. When presenting the results, the estimates were given as median values (2.5%, 97.5%).

Presentation and interpretation of results

Assessing the results of model validation can be challenging, especially coming to a firm conclusion about whether a model is 'validated'. This is very much the case here, given the complexity of the models and the uncertainties in the datasets available for the model validation (e.g. due to the influence of the variability in detection of fish in the NSW datasets). For this reason, we present the model validation results here in three ways. The first of these is a qualitative description of the population trends predicted by the MODEL, and those observed in the empirical OBSERVED data. The purpose of this qualitative description was to compare the broad patterns and assess the level of congruence between the patterns in the MODEL dataset and those in the OBSERVED dataset, and to highlight the locations where there is less or more congruence. The second component is a quantitative comparison based on the various metrics outlined in Table 6. These comparisons have been used to add nuance to the qualitative description of the validation of the results, with the different metrics providing information about whether the MODEL dataset and the OBSERVED dataset differ in absolute or relative terms, or at the extremes. The third component is an assessment of the congruence (or lack of congruence) between the MODEL and OBSERVED datasets as a function of the hydrological conditions. The hydrological conditions considered here refer to the magnitudes of the difference in flow that are predicted between the lowest (i.e. Base case scenario) and the highest (i.e. Option 4) flow scenarios. This comparison allows us to assess how the MODEL dataset and OBSERVED datasets compare when we examine them across the hydrological conditions proposed under the RRCP. This final comparison was undertaken for the Yarrawonga to Torrumbarry reach, because this was the most comprehensively sampled reach (note, accounting to allow for detection variability was undertaken).

3.2.2. Validation results

Golden Perch—population size and growth rate

The MODEL and ARI dataset showed similar changes in the size of Golden Perch populations through time in the Yarrawonga to Torrumbarry reach. Populations were generally small in the final years of the Millennium Drought (pre-2010), and both showed increases following 2010–2011 and 2016–2017, when flooding occurred (Figure 48B). The MODEL had lagged peaks though, compared with the ARI data, which sharply peaked and slowly declined. The temporal misalignment can be seen more clearly by looking directly at the population growth rates (Figure 48C and D). For 2011 and 2017, both datasets had positive growth rates, but the ARI growth rates were substantially higher (e.g. both estimates are above the 1:1 line in Figure 48D). In contrast, the MODEL predicted positive growth rates in 2012 and 2013, but corresponding declines were observed in the ARI dataset. These growth rate discrepancies are reflected in the high MAPE values and the lack of apparent BIAS (Table 7).

The NSW dataset for the Yarrawonga to Torrumbarry reach (Figure 49C) was also broadly consistent with the MODEL, with the lowest population size observed in 2011, and larger population sizes in other years where data was available (2013–2014, 2016–2018). There were strong correlations between the MODEL and the OBSERVED NSW datasets, but the uncertainty was high (e.g. the median Pearson's correlation was 0.55, but the 95% CI was –0.49 to 0.93), which reflects the smaller number of samples available in the NSW dataset than in the ARI dataset.

In the Lower Darling (Figure 49D and Figure 50D), both the MODEL and NSW datasets showed a similar pattern of decreases (MODEL: 2000–2011; NSW: 2007–2008), followed by increases (MODEL: 2012–2013; NSW: 2009–2012). However, as the dates above indicate, there appears to be some temporal misalignment. Both correlation estimates suggested high congruence (~0.66). There was good accordance in the growth rates (Figure 50D aligning along the 1:1 line), although the MODEL-predicted growth rate in 2012 was much higher than the OBSERVED growth rate. This mismatch in 2012 resulted in a MAPE higher than that for the Yarrawonga to Torrumbarry reach, at ~60%. It should be noted that the NSW dataset only had data for three of the seven sites for 2012, resulting in a higher MAPE (~60%) than in the Yarrawonga to Torrumbarry reach, i.e. a higher uncertainty in the abundance and growth rate estimates for that year. Length–frequency histograms suggested that recruits were still entering the adult population in 2012 (Figure A6.3).

The most striking qualitative differences in population sizes were observed in the Edward River (Figure 49E and Figure 50E). The MODEL predicted a decrease in population size in 2012–2015, and the population size also decreased in the NSW OBSERVED datasets. However, post-2015, the MODEL predicted an increase in population size, whereas a decrease was observed in the NSW OBSERVED datasets. All assessment metrics reflected these mismatches between the MODEL predictions and the NSW data: low correlation, high MAPE, likely bias with the MODEL predictions, and low percentage of alignment in the direction of the population growth rate (Table 7).

In the Gundagai to Hay Reach (Figure 49F and Figure 50F), the MODEL predicted a decline over the years 2000–2010, before an increase in 2010–2011 and higher population sizes post-2011. In comparison, the NSW OBSERVED datasets show a relatively consistent increase from 2005. Correlations were ~0.5–0.6 (Table 6), which were driven by smaller population sizes during the drought, and increases afterwards. Both the MODEL and NSW OBVSERVED data captured these general patterns, but there was a lack of association in the growth rates (Figure 50), as reflected in the high MAPE. In particular, 2011 was an extreme outlier, with the MODEL predicting a >100-fold increase, while little change in population size was observed in the NSW OBSERVED data.

In the Lower Murray (Figure 49A and Figure 50A), NSW data were available for 2005–2006 and 2009–2012, during which times population sizes remained relatively consistent in the OBSERVED dataset. In contrast, the MODEL predicted more variability in the population size, with an increase over the years 2005–2006, a decrease over 2007–2010, and an increase post-2010. The Pearson and Spearman correlations were both low and indicated high uncertainty, and the MAPE value was high (Table 7).

Golden Perch—movement into the Yarrawonga to Torrumbarry population

Movement results from the ARI OBSERVED dataset and the MODEL were remarkably similar (Figure 51; Table 7). Both the MODEL and ARI indicated 2001, 2011 and 2017 as high movement years. While these high movement years strongly drove the Pearson correlation, the high Spearman correlation suggested that the MODEL was also doing well at lower migration rates.

Golden Perch—comparing MODEL predictions and OBSERVED data across flow conditions

There was no correlation (Pearsons and Spearman values were <0.35) looking across the whole dataset (Figure 52). However, there was a far stronger correlation when only looking at this relationship for OBSERVED flows of between 10,000 and 20,000 ML day^{-1} (Pearson and Spearman correlations both ~0.70). This suggests that there is a reduced concordance between the MODEL and the OBSERVED data for this reach at the lowest and highest observed flows, and an increased concordance at more intermediate observed flows. To place these flows into context, the mean annual flow (for August to November, when most environmental flows under the RRCP will occur) under the Base case scenario and Option 4 since 2000 are ~16,000 ML day^{-1} and 17,500 ML day^{-1}, respectively. Given the aim was to compare flow scenarios that differed in these intermediate flow ranges, rather than at the extremes, this suggests that the MODEL is likely to capture differences in abundances under the RRCP scenarios.

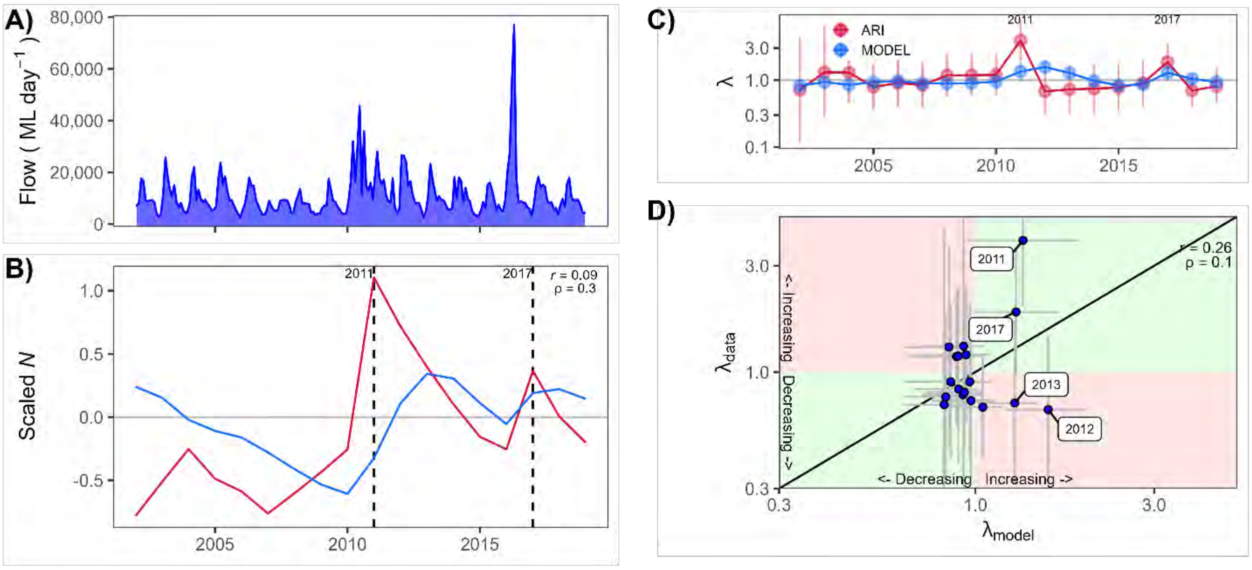

Figure 48. Relationship between MODEL and ARI estimates for Golden Perch: A) shows monthly average discharge: B) shows the relationship between the scaled population estimates between the MODEL (blue) and the OBSERVED (red) data. Correlation estimates for the population sizes are shown in the upper-right corner (*r* = Pearson correlation; ρ = Spearman correlation); C) shows the temporal pattern with the growth rates; D) shows the relationship between the growth rate estimates for the MODEL and the OBSERVED data. Green areas indicate concordance in growth rate direction (e.g. both increasing), and red areas indicate disconcordance (e.g. the MODEL data predicts increasing but the OBSERVED data suggest decreasing). Growth rates show the end year (e.g. '2011' is the change in population size from 2010 to 2011). The black line shows the 1:1 ratio. Correlation estimates for the growth rates are shown in the upper-right corner (*r* = Pearson correlation; ρ = Spearman correlation). Error bars show 95% CIs.

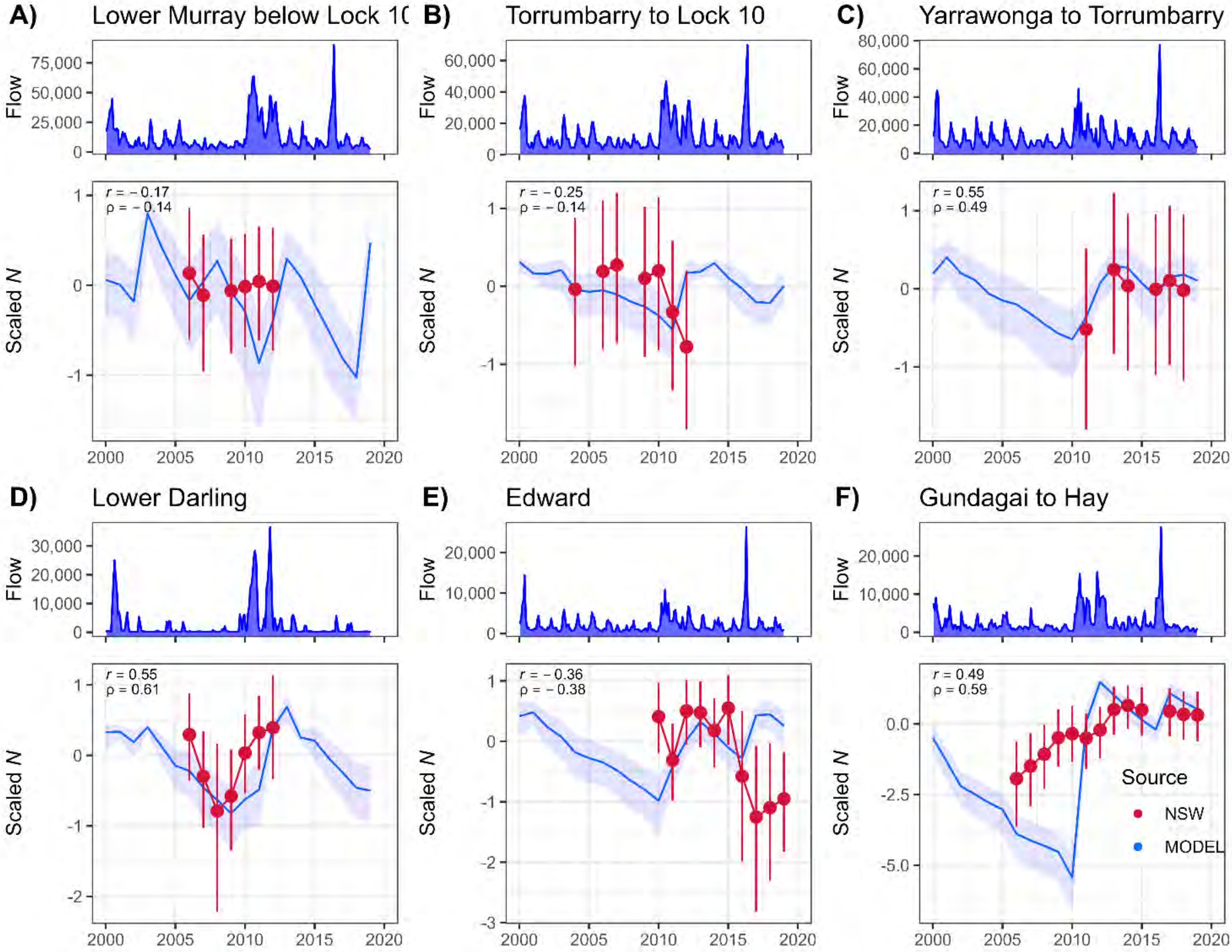

Figure 49. Temporal patterns in NSW OBSERVED data and MODEL estimates for Golden Perch. The top panels show mean monthly discharge. The bottom panels show the scaled abundance estimates (see Methods section for explanation) for MODEL and NSW estimates. Correlations (*r* = Pearson, ρ = Spearman) are shown for each panel (see Table 6). Error bars and shaded regions are 95% CIs. Units in the top panels are ML day^{-1}.

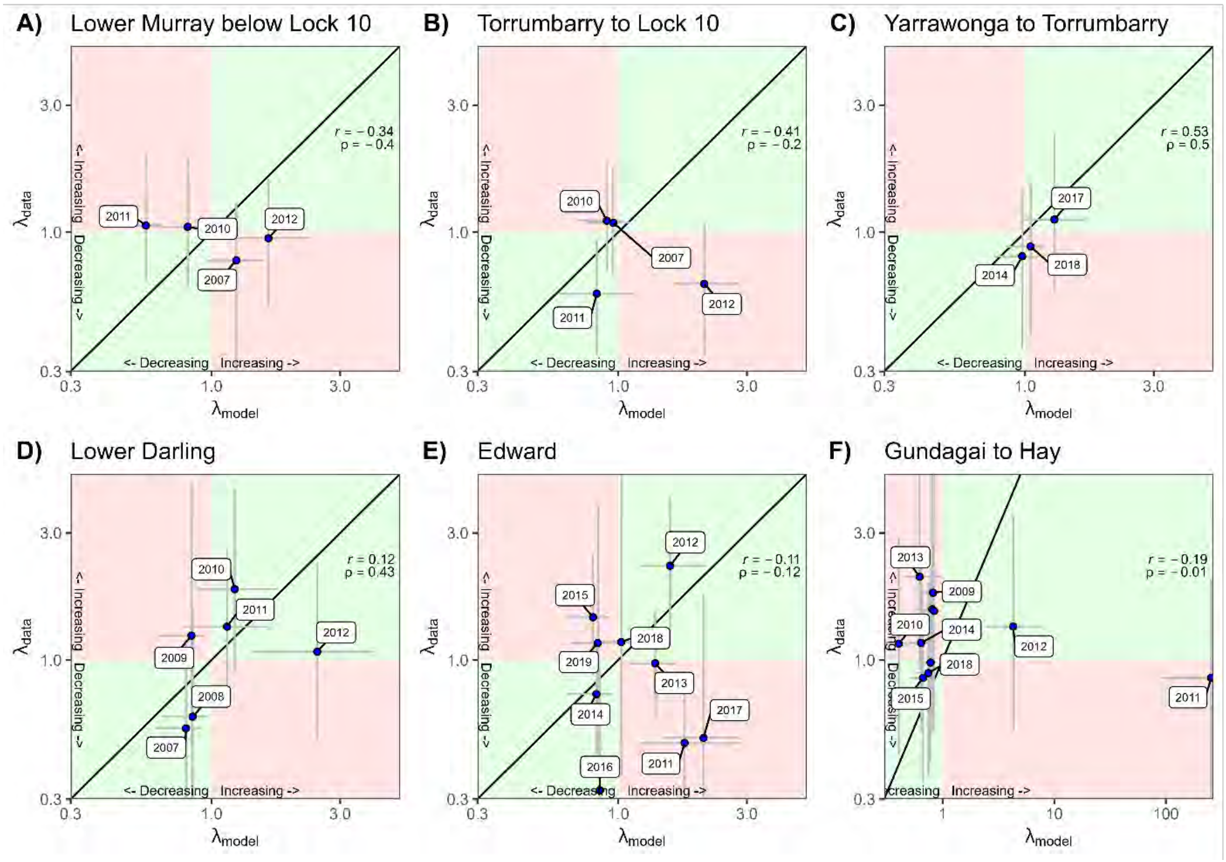

Figure 50. Golden Perch biplots showing the relationship between NSW OBSERVED data growth rates and predicted MODEL rates. See Figure 6 caption for details on each component.

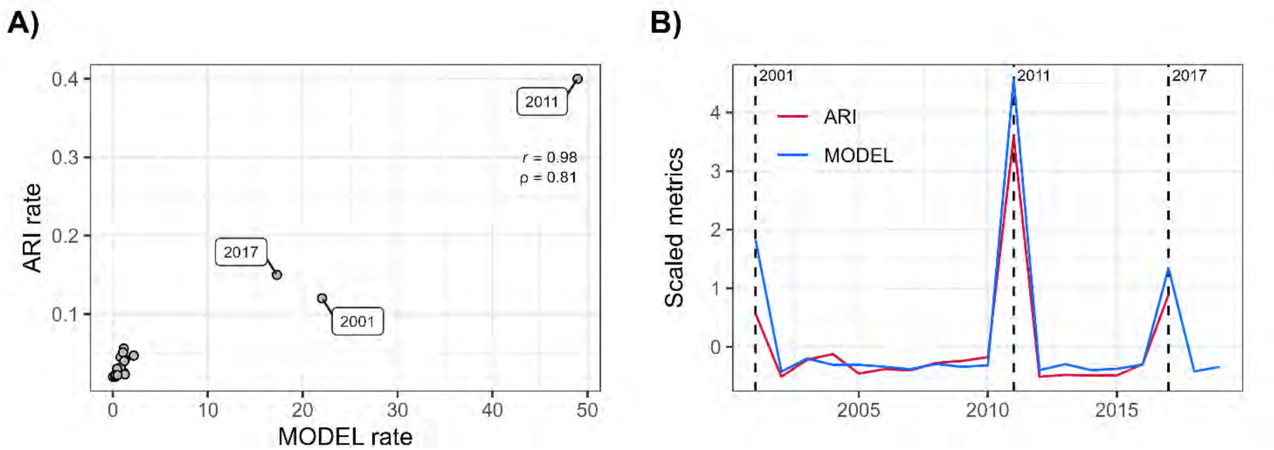

Figure 51. Relationship between MODEL and ARI OBSERVED dataset migration estimates for Golden Perch. Panel A) shows the correlation between MODEL migration estimates and ARI OBSERVED migration estimates (*r* = Pearson correlation; ρ = Spearman correlation). Panel B) shows the scaled migration rate for the MODEL and ARI OBSERVED estimates for the adult stage.

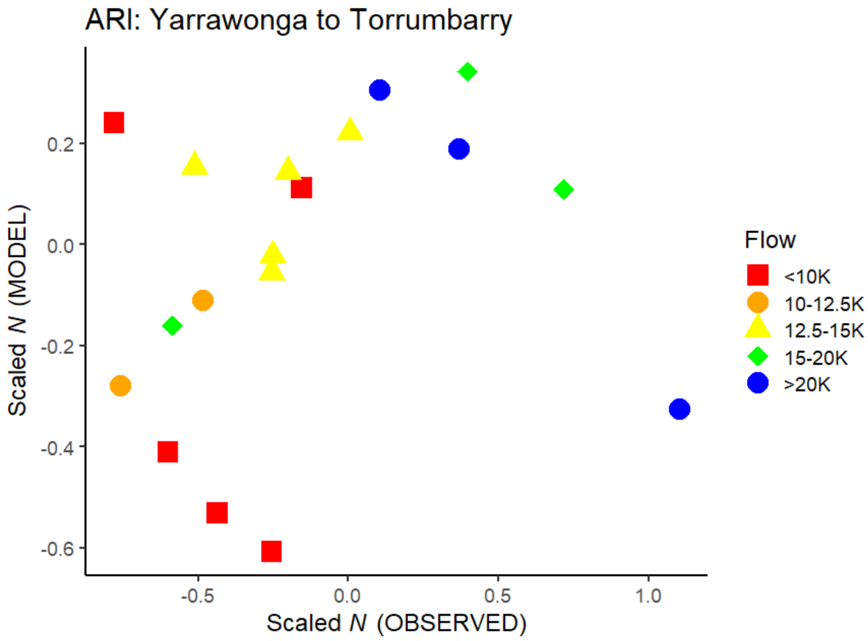

Figure 52. Golden Perch biplot of the relationship between scaled population size as predicted by the MODEL (Scaled *N*: MODEL) and in independent OBSERVED datasets (Scaled *N*: OBSERVED). Colours and shapes indicate observed flow, based on average daily discharge from August to November.

Table 7. Summary of assessment metrics for Golden Perch. Metrics shaded green indicate support for correlation between the MODEL data and the OBSERVED data from the specified study (as defined in Table 6). Weak support is indicated by light green and strong support is indicated by the darker green. Each metric provides different insights (see Table 6 for more details on each metric's comparative attributes). All output presented as the median and confidence interval (2.5%, 97.5%).

Parameter	Population ID	Study	Population size		Growth rate		
			Pearson	Spearman	MAPE	Bias	Direction
'Population size' growth rate	Lower Murray below Wentworth	NSW	-0.17 (-0.90, 0.80)	-0.14 (-0.94, 0.89)	59% (28%, 157%)	1% (-21%, 37%)	50% (0%, 75%)
	Torrumbarry to Wentworth	NSW	-0.25 (-0.69, 0.32)	-0.14 (-0.64, 0.36)	66% (32%, 122%)	34% (9%, 70%)	50% (0%, 75%)
	Yarrawonga to Torrumbarry	ARI	0.09 (-0.26, 0.40)	0.30 (-0.13, 0.59)	63% (41%, 92%)	-2% (-20%, 19%)	56% (33%, 72%)
		NSW	0.55 (-0.49, 0.93)	0.49 (-0.49, 0.94)	30% (8%, 102%)	13% (-15%, 69%)	67% (0%, 100%)
	Lower Darling	NSW	0.55 (-0.09, 0.95)	0.61 (-0.11, 0.96)	62% (22%, 162%)	9% (-8%, 28%)	67% (33%, 100%)
	Edward	NSW	-0.36 (-0.66, 0.06)	-0.38 (-0.64, 0.09)	101% (49%, 202%)	33% (20%, 48%)	44% (33%, 67%)
	Gundagai to Hay	NSW	0.49 (0.12, 0.73)	0.59 (0.12, 0.76)	225% (156%, 420%)	12% (-10%, 32%)	36% (18%, 55%)
Migration	Yarrawonga to Torrumbarry	ARI	0.98 (0.95, 0.99)	0.81 (0.76, 0.90)			

Murray Cod—population size and growth rate

In the Yarrawonga to Torrumbarry reach, the MODEL predicted that the population was relatively stable, with low interannual variability (Figure 53B). In comparison, in the ARI OBSERVED dataset, a decline was observed between 2000 and 2010, before an increase in 2014–2015 and a decline thereafter. Assessment metrics indicated a poor association, with both correlation metrics near 0 (Table 6). These patterns can be seen in the growth rates (Figure 53D). Most of the growth rates are in the bottom-right quadrant: whereas the MODEL predicted positive growth, negative growth was observed in the ARI dataset. The MAPE was ~40%, but was low due to growth rates being close to 1.0 in most years. Directionality was not consistent (Table 8), except for the mismatch between the MODEL predicting an increase and the ARI OBSERVED dataset showing a decrease (upper-right square). There was also a lack of strong associations between the MODEL and the NSW OBSERVED dataset for the Yarrawonga to Torrumbarry reach (Figure 54B; Table 8).

Only two other populations had sufficient NSW OBSERVED data for comparison (Figure 54; Figure 55). Torrumbarry to Wentworth had the highest correlation metrics (Table 8), mainly due a decrease predicted in the MODEL in 2010–2011 also being predicted in the NSW OBSERVED dataset (Figure 54A). However, the high MAPE was likely due to the differences in the population size and growth rate between the MODEL and OBSERVED data across the other years of comparison.

The results for the Edward River showed a similar decline in 2010–2011 that was both predicted by the MODEL and seen in the NSW OBSERVED datasets (Figure 54C; Figure 54C). While both the MODEL and NSW data showed some evidence of a rebound in numbers shortly after 2010–2011, the patterns may diverge after 2016 (although the uncertainty is high).

Murray Cod—comparing MODEL predictions and observed data in relation to flow conditions

There was no correlation between the MODEL predictions and the OBSERVED data (Pearson's and Spearman values between –0.1 and –0.2) (Figure 56). Unlike the findings for Golden Perch, the strength of these correlations was not increased when looking at this relationship only for observed flows between 10,000 and 20,000 ML day^{-1} (Pearson and Spearman correlations still between –0.1 and –0.2). This suggests that the MODEL is less likely to capture differences in abundances under the RRCP scenarios for Murray Cod than for Golden Perch in this reach.

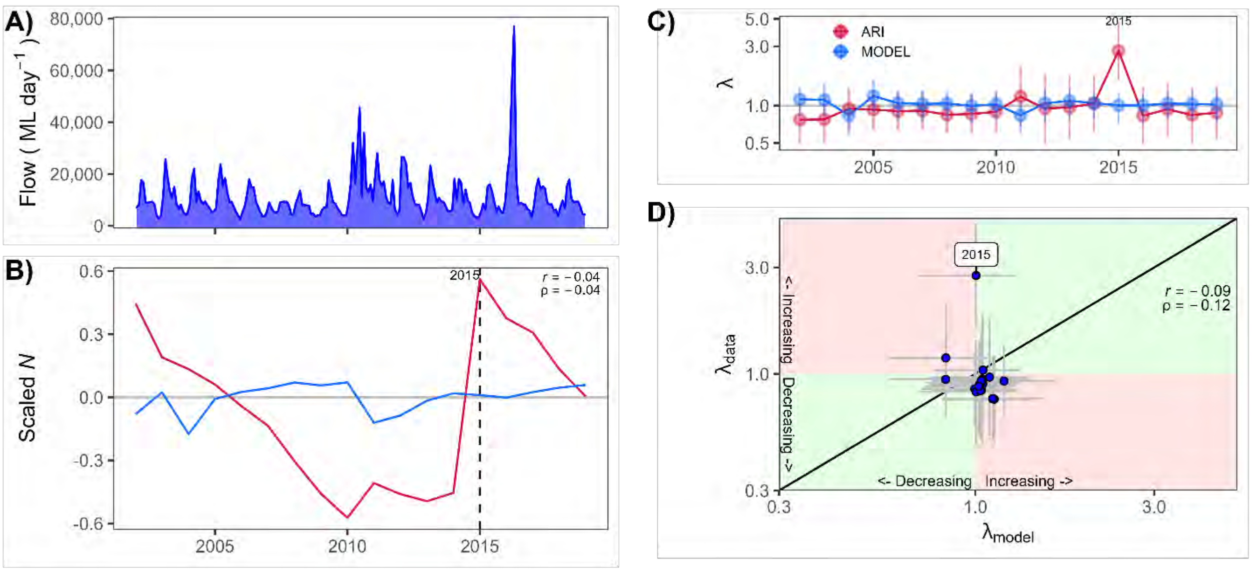

Figure 53. Relationship between MODEL and ARI OBSERVED estimates for Murray Cod. See Figure 6 caption for details.

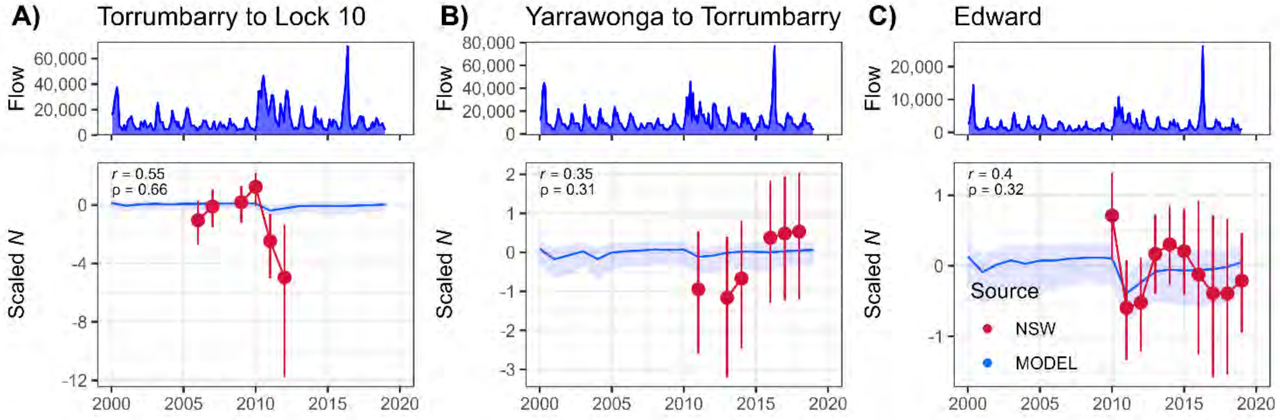

Figure 54. Temporal patterns in NSW OBSERVED data and MODEL estimates for Murray Cod. Each line shows the scaled abundance estimates. The error bars and shaded regions are 95% CIs. The units in the top panels are ML day^{-1}.

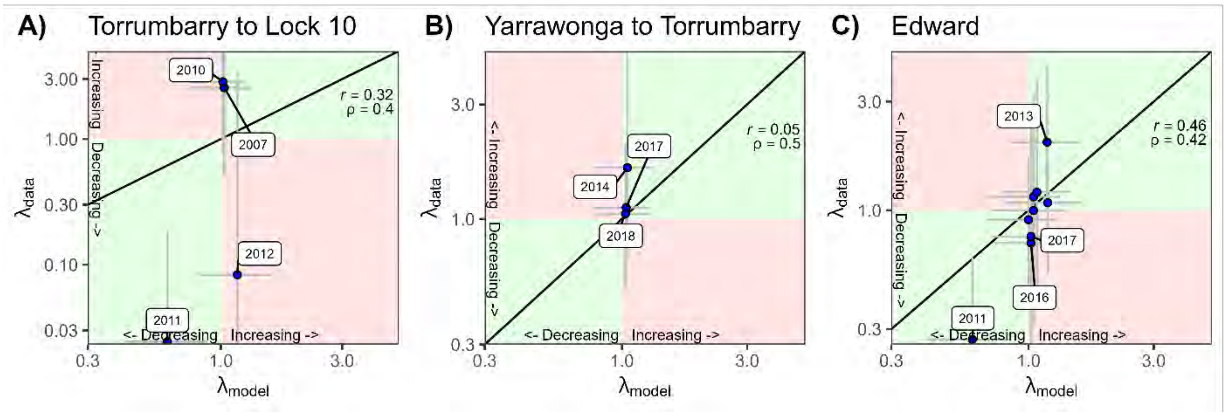

Figure 55. Murray Cod biplots showing the relationship between NSW OBSERVED data growth rates and predicted MODEL rates. Note that only growth rates with subsequent years of data are shown. See Figure 5 caption for details on each component.

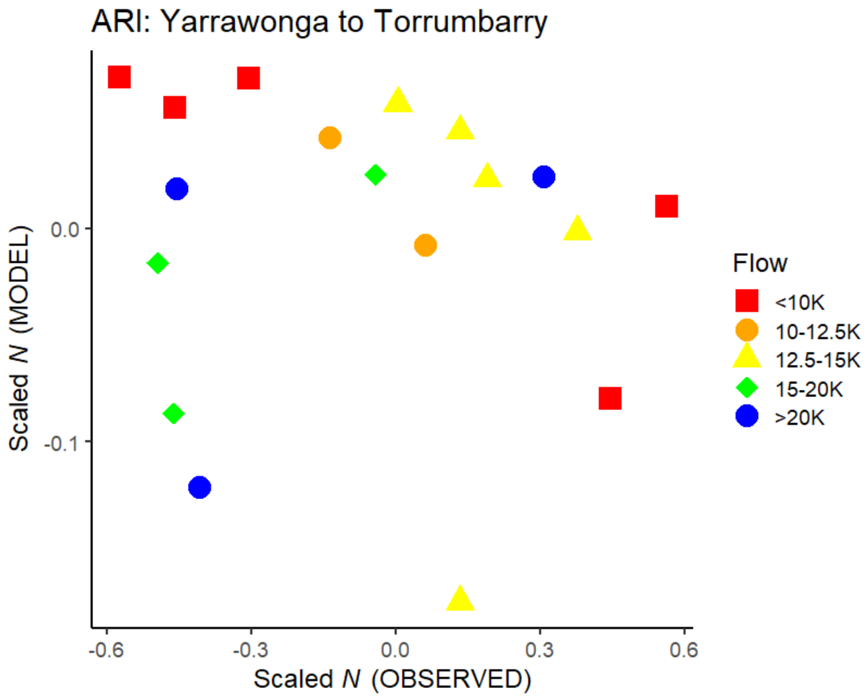

Figure 56. Murray Cod biplot of the relationship between scaled population size as predicted by the MODEL [Scaled *N* (MODEL)] and in independent datasets [Scaled *N* (OBSERVED)]. Colours and shapes indicate observed flow, based on the average daily discharge from August to November.

Table 8. Summary of assessment metrics for Murray Cod. Metrics shaded green indicate support for correlation between MODEL and specified OBSERVED data (as defined in Table 6). Weak support is indicated by light green and strong support by the darker green. Each metric provides different insights (see Table 6 for more details on each metric's comparative attributes).

Parameter	Population ID	Study	Population size		Growth rate		
			Pearson	Spearman	MAPE	Bias	Direction
Population size growth rate	Torrumbarry to Wentworth	NSW	0.55 (-0.15, 0.89)	0.66 (-0.09, 0.94)	598% (160%, 4555%)	144% (-4%, 1363%)	50% (25%, 100%)
	Yarrawonga to Torrumbarry	ARI	-0.04 (-0.60, 0.48)	-0.04 (-0.59, 0.52)	37% (25%, 52%)	6% (-7%, 19%)	44% (22%, 67%)
		NSW	0.35 (-0.77, 0.93)	0.31 (-0.83, 0.94)	38% (10%, 151%)	-17% (-47%, 23%)	67% (0%, 100%)
	Edward	NSW	0.40 (-0.22, 0.80)	0.32 (-0.31, 0.81)	56% (25%, 115%)	10% (-1%, 22%)	56% (33%, 89%)

4. Discussion

The RRCP program aims to balance economic, social, cultural and environmental outcomes to determine how best to mitigate the effects of current constraints on the flows of river systems to manage and support healthy, productive waterways. One of the key inputs to help inform this decision-making process is knowledge obtained from comprehensive monitoring and research programs. In this project, stochastic population models were used to predict native fish population responses to a suite of potential future hydrological scenarios under the RRCP program. These models have drawn on >120 years of modelled hydrological data for the Southern MDB and are based on the latest scientific knowledge about the focal species and their likely population responses to changes in hydrology. The models have proven to be an important tool to assist managers in decision-making with respect to environmental water management.

Key findings

Overall, the model outputs predict Golden Perch populations to exhibit improvements under several RRCP hydrological scenarios. The best outcomes for native fish from the scenarios tested were found to occur under the highest discharge option (i.e. Option 4; 45,000 ML day^{-1} flow limit at the Yarrawonga weir). Under that flow scenario, the model predicted an average increase of 30% in the mean Golden Perch population size totalled across all RRCP sites. There were even greater predicted benefits at regional scales (e.g. 39% increase in the expected mean population size for the river reaches Yarrawonga to Torrumbarry and Hume to Yarrawonga, and 49% increase for the Lower Murray (below Wentworth) reach. These results appear to be robust, as similar results were demonstrated throughout the numerous sensitivity analyses performed under a range of alternative model settings. Managed flows greater than 45,000 ML day^{-1} (the highest proposed flow limit at Yarrawonga) were not examined under the present program and such flows may have even greater benefits for native fishes. It is also worth noting that without-development flow scenarios that represent river flows in the absence of dams, weirs and extraction for consumptive use, were also not examined under the present program.

The likely benefits of RRCP flow scenarios for Golden Perch populations were evident for both juveniles and adults, with the model capturing a strong source–sink process occurring between reaches. The Mid Murray (Yarrawonga to Torrumbarry), the Lower Murray below Wentworth and the Lower Darling rivers were all sources, whereas the Murray River upstream of Torrumbarry Weir and the Edward River were sinks (Thiem et al. 2019). The sink areas relied on emigration of fish from downstream reaches to maintain Golden Perch populations, and the higher flow limit options appeared to provide enhanced movement cues for Golden Perch to undertake these upstream migrations. For example, a 40,000 ML day^{-1} flow limit (at Doctors Point) was required to maintain Golden Perch movement into the Hume to Yarrawonga reach, though this was slightly less evident in the Edward River, where a 25,000–30,000 ML day^{-1} flow limit at Yarrawonga was sufficient to maintain immigration to the reach. For the Murrumbidgee River, the 40,000 ML day^{-1} flow limit scenario provided slightly greater modelled emigration benefits than a 36,000 ML day^{-1} limit. Hence, under the RRCP flow options, there were predicted improvements in both recruitment and fish movement that have historically been strongly degraded by river regulation. It should be noted that in the reach Gundagai to Hay greater modelled emigration benefits came with a 36,000 ML day^{-1} limit.

The models suggest that some spatial areas are highly influential in terms of the broader population dynamics of Golden Perch. The Lower Murray is clearly important, as is the Lower Darling River and the northern MDB Darling River (including Menindee Lakes), modelled indirectly through the contribution of upwards of 1,000,000 juvenile fish during higher flow events. Another example of an influential spatial area is the Torrumbarry to Wentworth reach, which is a critical connection allowing Golden Perch to move freely throughout their range. This finding is supported by the empirical literature, which also suggests that certain areas of the MDB are particularly important as Golden Perch sources in some years (Sharpe 2011; Zampatti et al. 2018; 2021; Thiem et al. 2021). The known ecological responses to flows by Golden Perch (spawning, recruitment and movement; see Koehn et al. 2020) are consistent with these observations. For future management, model testing for a broader range of flow scenarios (including coordinated environmental flow releases from the Murray, Goulburn, Murrumbidgee and Lower Darling Rivers and testing removing/addressing barriers to fish movement) will likely reveal additional options for enhancing fish populations.

The model results show that the benefit of relaxing the flow constraints is predicted to be smaller for Murray Cod than for Golden Perch. This is likely because Murray Cod spawn and recruit in response to rising seasonal temperatures and flowing water hydraulic conditions, and there appears to be less reliance on major increases in river discharge (i.e. flooding) to cue these processes (Koehn and Harrington 2006; Stuart and Sharpe 2021): for example, Tonkin et al. (2021) found successful recruitment over a 20-year period in the Murray River, with only minor variation in recruitment between extreme flow conditions. The exception to this was in the Murrumbidgee River, where the models predicted increased survival of early life stages being associated with higher flow delivery. This aspect of the modelling likely requires refinement, as the early-life-stage survival rules were first developed for the Murray River and may be overestimated for the Murrumbidgee River. It is worth noting that the Edward-Wakool system of rivers and creeks was not modelled comprehensively—only the Edward River mainstem. There may be benefits from relaxed flow constraints for Murray Cod in smaller creeks and anabranches, where RRCP flow scenarios might provide more reliable winter–spring flows (currently, Murray Cod in creeks and anabranches may be affected by winter shut-downs in operational flows). Testing this hypothesis would require further modelling.

While the primary focus of this project was exploring the predicted responses to hydrological scenarios under the RRCP, the models also provide important insights into the long-term population trends for the two focal species. For Golden Perch, the outputs suggest there has been a decline in the size of populations over the past ~30 years, which is likely related to the rarity of high-flow events across the MDB since the late 1990s. The models provide an opportunity to test future hydrological scenarios and complementary measures (e.g. fishways) to identify the best combination of interventions for long-term fish population trajectories.

Model validation

Summary

Current knowledge and theory are embedded in the population models, but no model will perfectly represent reality (McCarthy et al. 2001; Deitze et al. 2018). Therefore, it is important to validate models to determine their limits of accuracy, and to understand their ability to capture functional relationships and emergent phenomena (McCarthy et al. 2001). We utilised empirical datasets for several of the RRCP focal zones to compare the model predictions of population size and growth rate, with the observed values. We also compared predicted and observed rates of movement into the Yarrawonga to Torrumbarry reach. The empirical dataset provides a unique opportunity to compare the predicted and observed values across the various RRCP focal zones, and to highlight priority areas where further development and refinement of the population models would be useful (Table A6.2).

For Golden Perch, there was good alignment between population size and growth rate for most of the six focal reaches with sufficient data to support these comparisons. The ARI Yarrawonga dataset is the longest independent dataset and is sufficiently detailed to support mark–recapture estimates of population abundance that account for variability in detection (Lyon et al. 2021). Temporal trends for the Yarrawonga to Torrumbarry reach population were very similar between the MODEL and OBSERVED data, with some evidence of the MODEL lagging the observed data by 1–2 years. There are four possible explanations for the lag: (1) the 2010–2011 floods may have led to a redistribution of fish, which may not have been captured correctly in the movement ‘reset’ rule in the MODEL; (2) the MODEL rules allow for movement between adjoining populations, but more extensive movement (i.e. across multiple populations within a year) may have occurred; (3) the MODEL rules may be overestimating the movement of fish into this reach from upstream (Hume to Yarrawonga); and (4) the Jolly–Seber modelling used for the ARI dataset (Lyon et al. 2021) may be overcompensating for changes in detection during the flood.

We found a very strong correlation between the MODEL prediction and the OBSERVED data for movement into the Yarrawonga to Torrumbarry reach. This correlation is not surprising, given that Golden Perch are a species known to move in relation to increased discharge (Koster et al. 2016). However, it is still an important confirmation that this process is being adequately captured in the MODEL rules.

We also found that the correlation between the MODEL-predicted and the OBSERVED population sizes in the Yarrawonga to Torrumbarry reach were weaker at the two extremes of the observed flows (mainly at the lower end) for Golden Perch. This is an important observation, as it provides evidence that the MODEL is likely producing realistic predictions for Golden Perch across the range of flows likely under the various RRCP scenarios. In comparison, the lack of correlation for Murray Cod suggests the MODEL results need to be interpreted with more caution for Murray Cod.

There were only weak correlations between the MODEL-predicted and OBSERVED Golden Perch population sizes for some reaches, especially the Edward River and Gundagai to Hay (Murrumbidgee River) reach populations (Table 6). These misalignments are likely due to the influence of factors on Golden Perch populations not currently being considered within the models. More specifically, the population size decrease observed in the Edward River in 2015–2016 was likely due to blackwater events that occurred in this system and elsewhere in the Southern MDB (Rees 2017). The influence of blackwater is not specifically included in the Golden Perch model; hence, the model does not predict the observed decrease. The mismatch could also be due to other factors, such as overestimated larval drift or immigration into this population. Similarly, the mismatch in the Gundagai to Hay reach is potentially because the MODEL does not include stocking, which is likely to be (at least partially) maintaining this population. The decline up to 2010 predicted by the model, therefore, may not reflect the actual population. The sharp response predicted by the MODEL thereafter, likely due to increase in upstream movement driven by flow, is also likely unrealistic, given the presence of many fish barriers, some largely impermeable, throughout the system.

The dataset for the Lower Murray was quite limited, and also only collected from the NSW section of this focal reach. Therefore, these results must be interpreted with some caution. A future expansion of the validation approach that considers datasets that might be available from the South Australian section of this reach would provide a more comprehensive assessment.

The MODEL generally predicted more stable Murray Cod populations than indicated by the OBSERVED data. For the Yarrawonga to Torrumbarry reach, a decrease during 2000–2010 was observed in the OBSERVED dataset, before an increase in 2014–2015 and a decrease post-2015. None of these changes were predicted by the MODEL. This could be related to the MODEL predictions representing average responses across whole reaches, including in this instance the section from Barmah downstream, where there were blackwater impacts, whereas the ARI observed dataset is from an area with no blackwater impacts. In the Torrumbarry to Wentworth reach, declines in Murray Cod population size occurred in 2010–2011, which is likely a response to blackwater impacts in this reach. However, the magnitude of the change was significantly less in the MODEL than in the OBSERVED dataset. Similar declines in both the MODEL and OBSERVED data occurred in the Edward River in 2010–2011, which is also likely to be a blackwater response. Blackwater events occurred throughout locations in the Southern MDB, both in 2010–2011 and in 2015–2016 (Whitworth et al. 2012; Rees 2017). However, blackwater events in the Edward River in 2015–2016 corresponded with declines in the OBSERVED data that were not predicted by the MODEL. These results indicate that further refinement of the inputs to characterise the effects of blackwater on Murray Cod are likely to lead to greater alignment between the MODEL and the OBSERVED data.

Potential biases in observed data

One major assumption in the validation exercise is that the OBSERVED data is a better representation of reality than the MODEL. As it was not possible to get exact population estimates, we had to use data from samples (extrapolated using catch-per-unit-effort data, etc.) and statistical models to produce estimates of population size and growth rates. The ARI Yarrawonga dataset followed standardised sampling protocols and corrected for varying detection rates (Lyon et al. 2021), so these estimates should be more robust than the NSW datasets, which had more variable sampling protocols and for which it was not possible to correct for detection rates. The NSW estimates thus have more potential bias that might distort temporal patterns (e.g. reduced capture probabilities due to river turbidity associated with increased river discharge or difficulties sampling during high-flow events: Lyon et al., 2014).

Opportunities for model refinement

The model construction, the model rules and the scenarios tested are all underpinned by the latest ecological knowledge of the study species. This knowledge was integrated with the flow data and the operational imperatives, to ensure that the effects of the flow changes being tested were closely linked to the drivers of population dynamics for each species. Knowledge of such flow–species relationships is not always perfect, however, and it is important to ensure that the model outputs are a result of the species' response and not of uncertainties in the models. In this study, detailed sensitivity analyses were undertaken that showed that the modelled outcomes were stable under various parameterisations (e.g. different rates of fish movement, different population sizes), indicating a consistent response to flows (Appendix 4). The sensitivity analyses should also be considered from the perspective that the main Golden Perch populations are located in the middle reaches, from a spatial perspective, and hence even under low rates of movement can still influence adjacent populations.

Both the sensitivity analysis and the validation work highlight the fact that there are some areas of uncertainty within the empirical data and the ecological knowledge. The purpose of the 'model rules' was to ensure that the best available knowledge was used transparently to construct the models, but equally to transparently capture the assumptions that have been made. The validation work has highlighted some aspects of the model rules (especially the movement rules for Golden Perch) and model inputs (especially blackwater) that could be further refined. The models could also be further refined as more knowledge comes to hand, especially in relation to their application in other reaches and at other sites. In many cases, the relationships between recruitment and hydrology differ between rivers (Tonkin et al. 2021). Some off-channel (floodplain) areas, including large areas of the Edward–Wakool system, were not included in the model, nor were the impacts of stocking or harvesting, some barriers to fish passage, thermal shock impacts, productivity, or water quality, or the rates of fish losses due to water extraction pumps.

The models provide a valuable way forward in managing rivers and flows by identifying the key processes and pathways by which populations are likely to be influenced (e.g. the provision of flows to cue fish movement from source-to-sink reaches), and by enabling evaluation of proposed interventions so as to provide the greatest potential benefits to local-, regional- and basin-scale native fish communities. There were clear predicted benefits for Golden Perch from increased RRCP flows. In the future, it will be possible to modify the model to assess likely responses to not only relaxing flow constraints but also a broad range of management actions (e.g. fishery management, habitat restoration, fish barrier removal, and threat mitigation). This would allow a more integrated approach to the management of rivers and the fish that inhabit them.

Conclusion

As predicted, the fish population responses varied across spatial regions and species due to differing life-history requirements. Nevertheless, according to the population model predictions, increased flow limits for environmental water delivery in the Murray and Murrumbidgee rivers would provide benefits to native fish populations, especially Golden Perch. The highest flow scenario tested (i.e. 45,000 ML day^{-1} in the Murray River at Yarrawonga and 40,000 ML day^{-1} in the Murrumbidgee River at Wagga Wagga) achieved the greatest benefits for Golden Perch, with diminishing gains as flow limits were reduced. This is instructive for selecting the optimal RRCP flow regime. Golden Perch populations responded more positively than Murray Cod populations due to their life-history requirements being more flow/floodplain dependent. Additional sensitivity analysis enabled greater confidence in the modelling results, by testing some of the uncertainties. For river managers, this population modelling allows a clear understanding of the trade-offs between the various RRCP flow scenarios by providing a transparent and flexible approach to selecting the flow regime that best meets the needs for tangible ecological restoration (Dalcin et al. 2022).

Recommendations

In relation to the four RRCP flow scenarios examined, the population model predictions for Golden Perch indicate that, in the RRCP reaches of the Murray and Murrumbidgee rivers, the 45,000 ML day^{-1} RRCP hydrological scenario (i.e. Option 4) has the greatest benefits overall (an average 30% expected increase in mean adult population size, and up to 49% for some spatial areas, compared with the Base case). For the NSW DPE, we recommend that RRCP flow scenario of Option 4 is likely to be the most beneficial for Golden Perch populations in the future.

The population modelling has revealed several of the important pathways/mechanisms that help to support Golden Perch populations, including emigration between the Lower Murray–Darling Basin system and upstream tributaries, such as the Murray River above Torrumbarry, the Edward and Wakool rivers, and the Murrumbidgee system. The population models identified the flows and spatial areas that can influence these processes, indicating a strong link between the scenarios and outcomes supporting native fish recovery.

For Murray Cod, the population models highlighted that avoiding anoxic blackwater is the most influential factor in recovering populations. We recommend utilising this knowledge in annual watering plans to better support broad fish population dynamics.

Supporting recommendations

The population models for Golden Perch and Murray Cod represent some of the most sophisticated tools for exploring future scenarios and likely ecological responses to a broad range of management interventions. Further technical refinements are suggested (e.g. the addition of key missing spatial areas, such as the Goulburn River and the Menindee Lakes, as well as modifications to the flow–ecology drivers), as are additional flow scenarios (e.g. natural flooding and climate change). Subsequent application of the models may provide much-needed insights into the drivers of fish population dynamics over broad spatial and temporal scales to highlight applied pathways for fish recovery.

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6. Appendices

Appendix 1. ARI Project Team

Key ARI personnel and their roles in this project are:

- Dr Ivor Stuart, Program Leader and Contact Officer
- Dr Charles Todd, Senior Scientist and Population Modeller
- Dr Henry Wootton, Scientist and Population Modeller
- Dr John Koehn, Senior Scientist and Ecologist
- Dr Robin Hale, Senior Scientist and Validation Module
- Dr Ben Fanson, Senior Scientist and Biometrician

Additional scientific support will variously be provided by other ARI staff, including Drs Scott Raymond, Jarod Lyon, Zeb Tonkin and Jian Yen. The project will also be supported by a range of other B appointed staff and experts, especially Dr Jason Thiem (NNSW DPI Fisheries) and Dr Clayton Sharpe (NSW Parks and Wildlife Service).

Dr Ivor Stuart

Senior Scientist, Applied Aquatic Ecology; Population Processes Program Leader

Qualifications

Dip. App. Sci., Grad. Dip. App. Sci., MSc, PhD

Awards

Eureka Prize (2004)
David Ashton Award (2004)
Victorian Engineering Excellence Highly Commended Award (2014)
International Distinguished Project Award for Laos fishways (2015)
Team member, International Distinguished Project Award (2018) for Laos fishways
Cardinia Creek Fishways Victoria Earth Award (2018)

Relevant expertise

- Fishway design
- Fish movement
- Environmental flows
- Fish population ecology
- Fisheries
- Native fish recovery and management
- Invasive animal control

Summary of competencies

Ivor is a freshwater fisheries biologist, with 30 years industry experience in flow planning, river management, fish passage and fish ecology. Ivor has worked in the tropical rivers of northern Australia, the arid rivers of western Qld and NSW, and the southern temperate rivers of Victoria and NSW. He has also worked in south-east Asia, developing fish passage programs for enhancing fisheries.

Ivor has received the Eureka Prize (2004), the David Ashton Award (2004) for applied fisheries research and the 2014 Victorian Engineering Excellence Highly Commended Award. In 2015, Laos PDR fishway team won the prestigious Distinguished Project Award. Ivor has published over 60 scientific journal articles and is on the editorial board of the international open access journal *Water*, which specialises in the ecology and management of water resources.

Relevant experience

Ivor has worked on >150 fish passage projects and brings a practical and transparent approach to fishway design with a strong emphasis on integration of local hydrology and fish ecology to improve outcomes. During river infrastructure projects, Ivor helps conceptualise fish ecology to identify important parts of a river's flow regime for managers to maintain fish populations. He has worked extensively in the Murray River, especially on the mainstem locks and adjacent floodplains and anabranches, where he helps conceptualise fish ecology to identify important parts of a river's flow regime to assist managers in maintaining fish populations.

Selected publications

Stuart, I., D'Santos, P., Rourke, M., Ellis, I., Harrisson, K., Michie, L., Sharpe, C. and Thiem, J. (2021). Monitoring native fish response to environmental water delivery in the lower Darling River 2020–2021. State of New South Wales and Department of Planning, Industry and Environment, New South Wales, Australia.

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Stuart, I.G. and Mallen-Cooper, M. (1999). An assessment of the effectiveness of a vertical-slot fishway for non-salmonid fish at a tidal barrier on a large tropical/sub-tropical river. *Regulated Rivers: Research and Management* **15**, 575–590.

Dr Charles Todd

Senior Scientist, Population Processes

Qualifications

PhD (2001) The University of Melbourne, Parkville, Victoria. *Tools for the conservation management of wildlife under uncertainty*

M. For. Sci. (1995) The University of Melbourne, Parkville, Victoria. *Potential impact of a farm forestry industry on the Goulburn regional economy*

BSc (1992) (Hons – Mathematics), La Trobe University, Bundoora, Victoria

Professional memberships and affiliations

Australian Society for Fish Biology: Secretary for the Australian Society for Fish Biology—Life Member and Hall of Fame inductee

Relevant expertise

- Mathematical modelling
- Risk assessment
- Population model development
- Uncertainty analysis
- Quantitative policy analysis
- Statistical modelling
- Threatened species assessment

Summary of competencies

Charles has 20 years' experience as a Senior Scientist in the Applied Aquatic Ecology Section at the Arthur Rylah Institute for Environmental Research. He provides expertise across ARI on developing population models to address key management and research questions affecting a variety of terrestrial and aquatic biota. His work has covered a range of issues, from threatened species to invasive species, from developing population models for small, localised endemic species to population models addressing management questions at the scale of the Murray–Darling Basin. Charles works closely with a variety of agencies, including local, interstate and international organisations. His particular interest lies in quantifying risk and uncertainty in management actions and providing advice on available management options to better manage the species of concern. He has developed population risk models for a number of MDB fishes to address management concerns, including: coldwater pollution; recreational fishing; invasive species; barriers to movement; and impacts of flow.

Relevant experience

- Lead—Lungfish Population Viability Analysis (PVA) Model
- Scientist—Murray–Darling Basin Authority Native Fish Models
- Scientist—Carp Biomass Project – National Carp Control Program
- Member—MER Basin Scale Fish Team

Selected publications

Tonkin, Z., Yen, J., Lyon, J., Kitchingman, A., Koehn, J.D., Koster, W.M., Lieschke, J., Raymond, S., Sharley, J., Stuart, I. and **Todd, C.** (2021). Linking flow attributes to recruitment to inform water management for an Australian freshwater fish with an equilibrium life-history strategy. *The Science of the Total Environment* **752**, 141863.

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Software

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https://www.ari.vic.gov.au/research/modelling/population-modelling-software

Dr Henry Wootton

Quantitative Ecologist; Population Processes

Qualifications

PhD (2022) The University of Melbourne, Parkville, Victoria. *Trawling for the unknown: an investigation of the impacts of harvest and oceanic warming on the life-histories of fish*

MSc (2010) The University of Melbourne, Parkville, Victoria. *Investigating disturbance type and severity on an ecologically important intertidal alga (Hormosira banksii) in South-eastern Australia*

BSc (2008) The University of Melbourne, Parkville, Victoria

Relevant expertise

Henry is an applied quantitative ecologist and evolutionary biologist who has extensive experience working on aquatic systems investigating how animals and populations respond to anthropogenic disturbance, environmental change, and management actions. He is keenly interested in the impacts of and adaptations to fishing, and alterations to natural processes such as human-induced flow variability and environmental change.

Summary of competencies

He asks questions using a diverse skillset, including the development and application of complex metapopulation models to study population-level responses to management actions. A good example of his quantitative modelling skillset can be found in a recent publication (Wootton et al. 2020: doi:10.1007/s11160-020-09617-9). He also has a strong track record of project delivery and publication. He is passionate about applied and quantitative ecology and is making this a focus of his very successful career.

He is currently working at the Arthur Rylah Institute (ARI) undertaking population modelling on Australian freshwater fish species to answer broad questions around the responses of populations to management actions. He is working in the modelling team with Dr Charles Todd, Dr John Koehn and Dr Ivor Stuart. He recently completed a PhD in the Quantitative Aquatic Ecology and Evolution lab at the University of Melbourne. The project investigated the impacts of harvest and warming on fish populations.

Selected publications

Wootton, H.F., Morrongiello, J.R., Schmitt, T. & Audzijonyte, A. (2022). Smaller adult fish size in warmer water is not explained by elevated metabolism. *Ecology Letters*, **25**, 1177-1188.

Wootton, H.F., Audzijonyte, A. and Morrongiello, J.R. (2021). Multigenerational exposure to warming and fishing causes recruitment collapse, but size diversity and periodic cooling can aid recovery. *Proceedings of the National Academy of Sciences of the United States of America* **118**(18), e2100300118 doi: 10.1073/pnas.2100300118.

Wootton, H.F., Morrongiello, J.R. and Audzijonyte, A. (2020). Estimating maturity from size-at-age data: are real-world fisheries datasets up to the task? *Reviews in Fish Biology and Fisheries* **30**, 681–697. doi:10.1007/s11160-020-09617-9

Wootton, H.F. and Keough, M.J. (2016). Disturbance type and intensity combine to affect resilience of an intertidal community. *Marine Ecology Progress Series* **560**, 121–133. doi:10.3354/meps11861

Woods, P.J., Macdonald, J., Barðarson, H., Baily, M., Bonanomi, S., Boonstra, W.J., Cornell, G., Cripps, G., Danielsson, R., Farber, L., Ferreira, A.S.A., Holma, M., Holt, R.E., Kokkalis, A., Ljüngström, G., Nieminen, E., Nordström, M., Oostdijk, M., Richter, A., Romagnoni, G., Sguotti, C., Simons, A., Shackell, N., Snickars, M., Tunca, S., Whittington, J.D., **Wootton, H.F.** and Yletyinen, J. (2021). A review of adaptation options in fisheries management to support resilience and transition under socio-ecological change. *ICES Journal of Marine Science* **79**, 463–479.

Todd, C.R., Koehn, J.D., Yen, J.D.L., Koster, W.M., Tonkin, Z., **Wootton, H.F.** and Barrow, J. (2020). Predicting long-term population responses by Murray Cod and Silver Perch to flow management in the Goulburn and Campaspe rivers: a stochastic population modelling approach. Arthur Rylah Institute, Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

Koehn, J.D., Todd, C.R., **Wootton, H.F.**, Stuart, I., et al. (in development). NSW Fish for the Future: Native Fish Population Modelling Progress Report April 2021. NSW DPI (Fisheries).

Code

Example code linked to the above publications is hosted on his Github https://github.com/Haychi-86

Dr John Koehn

Principal Research Scientist, Applied Aquatic Ecology

Qualifications

PhD (University of Melbourne 2006)

BSc (University of Melbourne 1980)

Professional affiliations

Australian Society for Fish Biology: Past President for the Australian Society for Fish Biology—Life Member and Hall of Fame inductee

Member of the editorial board for *Ecological Management and Restoration*

Special edition editor for *Marine and Freshwater Research*: *Climate change and the aquatic environment – the future for fish and fisheries in Australia* issue

Special edition editor for *Ecological Management and Restoration*: *The Native Fish Strategy: Bringing native fish back*. 15 (S1)

Awards

In 1997 he received the Gold Banksia and Catchment Management and Inland Waterways Banksia awards, and in 2000 he received Rivercare 2000 awards for scientific research.

Relevant expertise

- Leadership, innovation, research ability, project management and delivery
- Freshwater and fish ecology—habitats, movements, recruitment, population dynamics
- Murray–Darling Basin fishes
- Native fish population models
- Introduced fishes—especially Carp
- Conservation, threatened species, threatening processes, recovery planning, rehabilitation
- Knowledge transfer and communication, scientific advice to management and policy

Summary of competencies

John has established an international reputation as one of Australia's leading fish biologists through his research on the ecology and management of Australian freshwater fish. His research has resulted in over 250 scientific publications, most of which are refereed journal papers, books and conference proceedings. This original research has been of an applied nature and aimed at providing information to improve management. Recognition of his research achievements has been reflected in his inclusion on Ministerial committees (he is currently a member of the Scientific Advisory Committee for *Victoria's Flora and Fauna Guarantee Act 1988*), national recovery teams, advisory/expert committees (Murray–Darling Basin Commission drought expert panel, Murray, Ovens, Murrumbidgee environmental flow panels), the Murray–Darling Basin Commission Native Fish Management Strategy Advisory Panel and several fish taskforces). He was a key author of the Murray–Darling Basin Commission's Native Fish Strategy and has led or participated in a range of projects for Commonwealth, State and New Zealand research and management agencies. He is a past President of the Australian Society for Fish Biology and an honorary associate of the University of Melbourne. He was co-author of the scientific paper produced from the Cooperative Research Centre for Freshwater Ecology mark II, featured in the video *Special People*, produced by the Murray–Darling Basin Commission, and in the book *The Wizards of Oz*, in recognition of his contribution to fish research. He has often been invited to speak at conferences and workshops, to provide expert advice, to design and review projects, and to provide media comment and stories.

Relevant experience

He has led a range of large multidisciplinary project teams that have provided realistic management solutions related to the requirements of and threats to native freshwater fish (including altered flow regimes). Much of this research has been very innovative, leading to a large number of 'firsts' in this field in Australia (e.g. radio tagging fish, larval collections, electrofishing boat use, population models). He has been active in assessing the conservation status of and threats to many endangered species, as well as preparing and implementing recovery and management plans for them. He has published and provided advice on most of Victoria's freshwater fish species and the various threats to them.

Selected publications

Koehn, J.D. (2004). Carp (*Cyprinus carpio*) as a powerful invader in Australian waterways. *Freshwater Biology* **49**, 882–894.

Koehn, J.D. and O'Connor, W.G. (1990). *Biological Information for Management of Native Freshwater Fish in Victoria*. Government Printer, Melbourne.

Koehn, J.D., Brumley, A.R., Bomford, M. and Gehrke, P.C. (2000). *Managing the Impacts of Carp*. Bureau of Resource Sciences, Barton, ACT. 249 pp.

Humphries, P., King, A.J. and **Koehn, J.D.** (1999). Fishes, flows and floodplains: links between Murray–Darling freshwater fish and their environment. *Environmental Biology of Fishes* **56**, 129–151.

Koehn, J.D. and Harrington, D.J. (2006). Conditions and timing of the spawning of Murray cod (*Maccullochella peelii peellii*) and the endangered trout cod (*M. macquariensis*) in regulated and unregulated rivers. *Rivers Research and Applications* **22**, 327–343.

Koehn, J.D., Hobday, A.J., Pratchett, M.S. and Gillanders, B.M. (2011). Climate change and Australian marine and freshwater environments, fishes and fisheries: synthesis and options for adaptation. *Marine and Freshwater Research* **62**, 1148–1164.

Koehn, J.D., McKenzie, J.A., O'Mahony, D.J, Nicol, S.J., O'Connor, J.P. and O'Connor, W.G. (2009). Movements of Murray cod (*Maccullochella peelii peelii*) in a large Australian lowland river. *Ecology of Freshwater Fish* **18**, 594–602.

Koehn, J.D. (2009). Multi-scale habitat selection by Murray cod (*Maccullochella peelii peelii*) in two lowland rivers. *Journal of Fish Biology* **75**, 113–129.

Koehn, J.D. and Lintermans, M. (2012). A strategy to rehabilitate fishes of the Murray–Darling Basin, south-eastern Australia. *Endangered Species Research* **16**, 165–181.

Koehn, J.D., and Todd, C.R. (2012). Balancing conservation and recreational fishery objectives for a threatened species, the Murray cod, *Maccullochella peelii*. *Fisheries Management and Ecology* **19**, 410–425.

Koehn, J.D., Copeland, C. and Stamation, K. (eds). (2014). The Native Fish Strategy: Bringing native fish back. *Ecological Management and Restoration* **15** (S1).

Koehn, J.D., Hobday, A.J., Pratchett, M.S. and Gillanders, B.M. (eds) (2011). Climate change and Australian aquatic environments, fishes and fisheries. *Marine and Freshwater Research* **62**, 1148–1164.

Murray–Darling Basin Commission. (2004). *Native Fish Strategy for the Murray–Darling Basin 2003–2013*. Murray–Darling Basin Commission, Canberra, ACT. www.mdbc.gov.au

Dr Robin Hale

Senior Scientist, Applied Aquatic Ecology

Qualifications

BSc (Hons), PhD

Relevant expertise

- Wetland ecology
- Restoration ecology
- Monitoring program design and assessment
- Fish population biology
- Behavioural ecology

Summary of competencies

Rob is a freshwater ecologist with 18 years' research and industry experience in wetland ecology, restoration ecology, monitoring programs and assessment. He graduated with a PhD in ecology from the University of Melbourne in 2007 and held postdoctoral research positions at the University of Melbourne and Monash University for 12 years before joining the Arthur Rylah Institute (ARI) in 2019.

Rob is passionate about the conservation and management of aquatic ecosystems. His research portfolio is very strong (>80 scientific papers and technical reports) and diverse, spanning the broad areas of restoration, aquatic and population ecology, and environmental monitoring design and assessment. He is an editor of three international journals—*Freshwater Biology*, *Restoration Ecology* and *Frontiers in Conservation Science*. He has strengths and expertise in developing monitoring and research programs underpinned by conceptual models that outline key drivers of, and threats to, aquatic values. He has very strong quantitative skills and extensive experience in applying these to the design and evaluation of monitoring programs. Before joining the Applied Aquatic Ecology section, he worked as a biometrician at ARI for 6 months, providing statistical advice and expertise to a wide range of projects across the whole of the institute. Rob is a highly effective and reliable project leader who places a strong emphasis on frequent and professional interactions with project stakeholders.

Relevant experience

- Theme lead (2019–2020) for the frog and bird themes of the Wetland Monitoring and Assessment Program, which is a statewide program aimed at assessing ecological responses to environmental flow releases
- Led an ARC Linkage grant (2014–2017) examining how urban stormwater wetlands perform as habitats for aquatic taxa
- Led a statewide synthesis and meta-analysis of fish responses to instream habitat restoration for DELWP Water and Catchments (2019–2020)
- Member of team that designed the statewide DELWP Riparian Intervention Monitoring Program
- Co-led the development of a 10-year plan for monitoring aquatic and riparian health for the Murray Local Land Services
- Frequent provision of technical expertise, especially in relation to monitoring program design and evaluation for a wide range of industry bodies, e.g. Murray Local Land Services, Melbourne Water, Greening Australia, Hydro Tasmania, DELWP.
- Led a large experimental study to examine ecological responses to riparian restoration, funded by the Murray–Darling Basin Authority.

Selected publications

Papas, P., **Hale, R.** and 18 other co-authors. (2021). Wetland Monitoring and Assessment Program for environmental water. Stage 3 Final Report. Arthur Rylah Institute for Environmental Research Technical Report Series No. 297. Department of Environment, Water, Land and Planning. Heidelberg, Victoria. 318 pp.

Tonkin, Z., Kitchinghman, A., Fanson, B., Lyon, J., Ayres, R., Kearns, J., Koster, W., O'Mahoney, J., Hackett, G. and **Hale, R.** (2020). Quantifying links between instream woody habitat and priority fish species in south eastern Australia to inform future restoration. *Aquatic Conservation: Marine and Freshwater Ecosystems* **30**, 1385–1396.

Kitchingman, A., **Hale, R.**, Sharley, J., Zonkin, Z. and Reich, P. (2020). An overview of instream habitat interventions across Victoria: a collation of data, benchmark guidance, and outcomes evaluation. Unpublished Client Report for the Department of Environment, Land, Water and Planning. Arthur Rylah Institute for Environmental Research, Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

Mole, B., Morris, K., Moloney, P., Sparrow, A., Reich, P. and **Hale, R.** (2020). Riparian Intervention Monitoring Program, Second Progress Report. Unpublished Client Report for Water and Catchments, Department of Environment, Land, Water and Planning. Arthur Rylah Institute for Environmental Research, Department of Environment, Land, Water and Planning, Heidelberg, Victoria. 101 pp.

Koster, W.M., Dawson, D.R., Kitchingman, A., Moloney, P.D. and **Hale, R.** (2020). Habitat use, movement and activity of two large-bodied native riverine fishes in a regulated lowland weir pool. *Journal of Fish Biology* **96**, 782–784.

Hale, R., Mac Nally R., Blumstein, D.T. and Swearer, S.E. (2019). Evaluating how and where habitat restoration is undertaken for animals. *Restoration Ecology* **27**, 775–781.

Hale, R., Colton, M., Peng, P. and Swearer, S.E. 2019. Do spatial scale and life history affect fish–habitat relationships? *Journal of Animal Ecology* **88**, 439–449.

Hale, R., Brooks, S., Crowther, D. and Papas, P. (2018). Riparian and Aquatic Health Monitoring Program Years 1–3: South-West Slopes of NSW. Arthur Rylah Institute for Environmental

Research Technical Report. Department of Environment, Water, Land and Planning. Heidelberg, Victoria. 61 pp.

Sievers, M., **Hale, R.** and Morrongiello, J.R. (2017). Do trout respond to riparian change? A systematic review and meta-analysis with implications for restoration and management. *Freshwater Biology* **62**, 445–457.

O'Brien, A., Townsend, K., **Hale, R.**, Sharley, D. and Pettigrove, V. (2016). How is ecosystem health defined and measured? A critical review of freshwater and estuarine studies. *Ecological Indicators* **69**, 722–729.

Dr Ben Fanson

Scientist, Biometrician – Wildlife Ecology

Qualifications

Bachelor of Arts, Kalamazoo College, USA

Master of Applied Statistics, Purdue University, USA

Master of Biological Sciences, Purdue University, USA

PhD in Ecology and Evolution, Macquarie University, Sydney, Australia

Relevant expertise

- Biometric/statistical analysis
- Experimental design
- Nutritional ecology
- Life history theory

Summary of competencies

Ben Fanson began his ecologist training as a field technician, assisting in wildlife studies ranging from occupancy patterns in Spotted Owls to optimal foraging patterns in Black Rhinoceros in Kenya to mark–recapture estimates of Black Bears in Alaska, USA. Ben then obtained separate Masters in Biological Sciences and Applied Statistics from Purdue University (USA) in 2007, followed by a PhD in Ecology and Evolution from Macquarie University (AU) in 2012. During his studies and postdoctoral work at Deakin University, Ben researched the effect of the nutritional environment on life history traits (e.g. longevity, reproduction), and also worked as statistical consultant on over a dozen other projects. Currently, Ben works as a biometrician at ARI, providing statistical guidance on project design and analysis of multiple of projects utilising a myriad of statistical approaches. Ben provides scientific and statistical support across a range of ecological fields (fish ecology, community ecology, and wildlife biology). Ben uses a diverse array of statistical methods, such as mark–recapture state-based models, hierarchical mixed models, and Bayesian methods. Recently, Ben has been involved in numerous fish projects relating environmental flows to fish life history traits across the Murray–Darling Basin (e.g. Flow-MER).

Relevant experience

Provided statistical analysis and training across all sections at ARI

Analysed temporal patterns in shorebird abundance in Victoria using advanced statistical techniques

Collaborated with dozens of researchers analysing temporal patterns in hormones from Tasmanian Devils, Zebra Finches and Asian Elephants.

Co-authored an R package (hormLong) to facilitate analysis of hormonal data for wildlife endocrinologist

Researched the effect of nutritional environmental on the life history of animals, focusing on movement rates, immune function, reproductive output and survival

Selected publications

Dominiak, B.C. and **Fanson, B**. (2021). Transport from production facility to release locations caused a decline in quality of sterile Queensland fruit fly received for SIT application. *Entomologia Experimentalis et Applicata.*

Fanson, B.G., Fanson, K.V. and Biro, P.A. (2021). Macronutrient composition and availability affects repeatability of fly activity through changes in among- and within-individual (residual) variation. *Evolutionary Ecology* **35**, 387–399.

Zampatti, B.P., **Fanson, B.G.**, Baumgartner, L.J., Butler, G.L., Brooks, S.G., Crook, D.A., Doyle, K., King, A.J., Koster, W.M., Maas, R., Sadekov, A., Scott, P., Strawbridge, A., Thiem, J.D., Tonkin, Z. and Wilson, P.J. (2022). Population demographics of golden perch (*Macquaria ambigua*) in the Darling River prior to a major fish kill: a guide for rehabilitation. *Marine and Freshwater Research* **73**, 223–236.

Stuart, I., **Fanson, B.**, Lyon, J., Stocks, J., Brooks, S., Norris, A., Thwaites, L., Beitzel, M., Hutchison, M. and Ye, Q. (2021). Continental threat: how many common carp (*Cyprinus carpio*) are there in Australia? *Biological Conservation* **254**, 108942.

Thiem, J.D., Baumgartner, L.J., **Fanson, B.**, Sadekov, A., Tonkin, Z. and Zampatti, B.P. (2022). Contrasting natal origin and movement history informs recovery pathways for three lowland river species following a mass fish kill. *Marine and Freshwater Research* **73**, 237–246.

Koster, W.M., Stuart, I., Tonkin, Z., Dawson, D. and **Fanson, B**. (2021). Environmental influences on migration patterns and pathways of a threatened potamodromous fish in a regulated lowland river network. *Ecohydrology* **14**, e2260.

Dominiak, B.C. and **Fanson, B.G**. (2020). Current quarantine and suspension distances are excessive for incipient populations of Queensland fruit fly (*Bactrocera tryoni* (Froggatt))(Diptera: Tephritidae) in southern New South Wales, Australia. *Crop Protection* **138**, 105341.

Tonkin, Z., Kitchingman, A., **Fanson, B.**, Lyon, J., Ayres, R., Sharley, J., Koster, W.M., O'Mahony, J., Hackett, G. and Reich, P. (2020). Quantifying links between instream woody habitat and freshwater fish species in south-eastern Australia to inform waterway restoration. *Aquatic Conservation: Marine and Freshwater Ecosystems* **30**, 1385–1396.

Wright, D.W., Zampatti, B.P., Baumgartner, L.J., Brooks, S., Butler, G.L., D. A. Crook, D.A., **Fanson, B.G.**, Koster, W.M., Lyon, J., and Strawbridge, A. (2020). Size, growth and mortality of riverine golden perch (*Macquaria ambigua*) across a latitudinal gradient. *Marine and Freshwater Research* **71**, 1651–1661.

Brown, G.W., Robertson, P. and **Fanson, B**. (2020). Identifying a surrogate metric for monitoring the population status of a secretive habitat specialist, the heath skink *Liopholis multiscutata*, in south-eastern Australia. *Austral Ecology* **45**, 206–214.

Zampatti, B.P., **Fanson, B.G.**, Strawbridge, A., Tonkin, Z., Thiem, J., Crook, D., Butler, G.L., Balcombe, S., Koster, W., King, A., Crook, D., Woods, R., Brooks, S., Lyon, J., Baumgartner, L.J. and Doyle, K. (2019). Basin-scale population dynamics of Golden Perch and Murray Cod: relating flow to provenance, movement and recruitment in the Murray–Darling Basin: In Murray–Darling Basin Environmental Water Knowledge and Research Project—Fish Theme Research Report. Centre for Freshwater Ecosystems No. 223. Commonwealth Environmental Water Office, Canberra, ACT.

Forsyth, D.M., Pople, A., Woodford, L., Brennan, M., Amos, M., Moloney, P.D., **Fanson, B.** and Story, G. (2019). Landscape-scale effects of homesteads, water, and dingoes on invading chital deer in Australia's dry tropics. *Journal of Mammalogy* **100**, 1954–1965.

Brown, G.W., Murphy, A., **Fanson, B.** and Tolsma, A. (2019). The influence of different restoration thinning treatments on tree growth in a depleted forest system. *Forest Ecology and Management* **437**, 10–16.

Tonkin, Z., Sharley, J., **Fanson, B.**, Raymond, S., Ayres, R., Lyon, J., Balcombe, S. and Bond, N. (2019). Climate variability regulates population dynamics of a threatened freshwater fish. *Endangered Species Research* **40**, 257–270.

Dominiak, B., Galvin, T., Deane, D. and **Fanson, B.** (2019). Evaluation of Probodelt cone traps for surveillance of Dacinae in New South Wales, Australia. *Crop Protection* **126**, 104940.

Stoessel, D.J., Fairbrother, P.S., **Fanson, B.G.**, Raymond, S.M., Raadik, T.A., Nicol, M.D. and Johnson, L.A. (2019). Salinity tolerance during early development of threatened Murray hardyhead (*Craterocephalus fluviatilis*) to guide environmental watering. *Aquatic Conservation: Marine and Freshwater Ecosystems* **30**, 173–182.

See the following url for a full list:
https://scholar.google.com.au/citations?user=UOe8EskAAAAJ&hl=en

Appendix 2. Full population model descriptions

ESSENTIAL population modelling software

All models were developed and implemented in the software package ESSENTIAL (Todd and Lovelace 2019). ESSENTIAL enables both experts and non-experts to generate population model outputs and to assess outcomes.

Murray Cod single population construct

The model summarises the life history of Murray Cod by explicitly representing 50 age classes (Koehn and Todd 2012). A pre-breeding census construction was implemented (Burgman et al. 1993), with entry into the first age class (1-year age step) combining spawning, egg, larval and early juvenile survival, where early juvenile fish are defined as those less than 1 year old. Beyond 1 year of age, the survival rates define the transitions to each subsequent age class (up to 50 years). Murray Cod are assumed to become sexually mature at 5 years of age, with fecundity increasing depending on the maximum size of fish in the population (see the Murray Cod fecundity relationships derived for this study; Rowland 1998a, 1998b). The model only accounts for females, as males are not considered to limit the population in any way (Todd et al. 2005; Koehn and Todd 2012), although it is recognised that males are likely to play an integral role in the successful development of eggs hatching into larvae (Rowland 1998a, 1998b). A 1:1 sex ratio was assumed. While the model only accounts for females, the output is presented as total adults (male and female) by simply increasing the results by a factor of 2.

Both demographic and environmental stochasticity were included in the model (Akçakaya 1991; Todd and Ng 2001). Demographic stochasticity was incorporated using a binomial distribution to model the number of individuals surviving between consecutive time steps, and a Poisson distribution to model recruitment to the 1-year-old age class. Environmental stochasticity was incorporated by randomly varying the survival and fecundity rates each year. Survival rates were drawn from normal distributions transformed to the unit interval (Todd and Ng 2001), with specified means and standard deviations. Age-specific fecundities were drawn from a relationship estimated from hatchery data (Rowland 2005) and age–length data, with specified means and standard deviations. Todd and Ng (2001) provide a methodology for specifying correlations among survival rates; however, no information exists to quantify these correlations. Given the aquatic habitat in which fish live, it is reasonable to assume that the correlations are likely to be positive and close to unity. It was assumed that survival rates were perfectly correlated with each other and independent of fecundity rates, where fecundity rates were perfectly correlated with each other (Todd et al. 2004).

The model included processes for modelling the effects of density dependence, with the long-term average abundance set by the user at specific levels in each reach area. The form of density dependence used in the population model is based on the average population size that the system of interest can support over the long term. This is not a carrying capacity as such, as the density-dependence mechanism is designed to allow the population to exceed the threshold, with increasingly strong negative density dependence as the population size exceeds this threshold. The density dependence mechanisms mostly apply to 1-, 2-, and 3-year-old fish, which may reflect competition for food and habitat (see e.g. Todd and Koehn 2009; Koehn and Todd 2012).

The following equations define a Murray Cod population as specified by the population model:

$$FN_{i+1,t+1} = Bin\left(FN_{i,t}, dens_{i,t} \times BW_{j,t} \times S_{i,t}\right), \qquad i = 1\ldots49$$

$$FN_{1,t+1} = Poisson\left(S_{0,t} \times TE_{l,t} \times S_{l,t} \times TE_{e,t} \times S_{e,t} \times 0.5 \times EggNum_t\right)$$

$$EggNum_t = \sum_{i=5}^{i=50} Fec_{i,t} \times FN_{i,t}$$

$$N_{i,t} = 2 \times FN_{i,t}$$

$$dens_{i,t} = \begin{cases} AFPS \Big/ \sum_{k=25}^{k=50} FN_{k,t}, \text{ for } i = 25\ldots50 \text{ and } \sum_{k=25}^{k=50} FN_{k,t} > AFPS \\ AFPS \Big/ \sum_{k=15}^{k=50} FN_{k,t}, \text{ for } i = 15\ldots24 \text{ and } \sum_{k=15}^{k=50} FN_{k,t} > AFPS \\ AFPS \Big/ \sum_{k=10}^{k=50} FN_{k,t}, \text{ for } i = 10\ldots14 \text{ and } \sum_{k=10}^{k=50} FN_{k,t} > AFPS \\ AFPS \Big/ \sum_{k=i}^{k=50} FN_{k,t}, \text{ for } i = 2\ldots9 \text{ and } \sum_{k=i}^{k=50} FN_{k,t} > AFPS \\ 4 \times AFPS \Big/ \sum_{k=1}^{k=50} FN_{k,t}, \text{ for } i = 1 \text{ and } \sum_{k=1}^{k=50} FN_{k,t} > 4 \times AFPS \\ 1, \end{cases}$$

$$BW_{j,t} = BW_t \qquad j = i > 3$$

$$Length_{i,t} = MaxL_t \times \left(1 - \exp(-k_t \times \left(i + 1.535\right)\right) \qquad i = 5,\ldots,50$$

$$MaxL_t \sim N\left(ML, 40 \times ML/L_\infty\right)$$

$$L_\infty = 1360.465$$

$$k_t \sim 0.0674 + \beta\left(849.86, 884.55\right) - 0.49$$

$$Weight_{i,t} = \exp\left(a_t\right)/1000 \times Length_{i,t}^{3.36} \qquad i = 5,\ldots,50$$

$$a_t \sim N\left(-13.52, 0.1352\right)$$

$$Fec_{i,t} = -x_t + y_t \times Weight_{i,t} - 69.5 \times Weight_{i,t}^2 \qquad i = 5,\ldots,50$$

$$x_t \sim N\left(389, 2723\right)$$

$$y_t \sim N\left(5344, 53.44\right)$$

where *t* is an annual time interval, $FN_{i,t}$ and $N_{i,t}$ are the numbers of female adults and total adults, assuming an even sex ratio, in the i_{th} age class at time t; $S_{i,t}$ is a random variate describing environmental variation in the survival rates of Murray Cod in the i_{th} age class drawn from normal distributions transformed to the unit interval (Todd and Ng 2001), with no loss of information from the specified means and standard deviations; $S_{0,t}$, $S_{l,t}$, and $S_{e,t}$ are random variates describing environmental variation in survival rates of Murray Cod less than 1 year old, larvae, and eggs, respectively, similar to age-specific survival, where survival rates across all ages and stages are perfectly correlated; $TE_{l,t}$ is the proportional effect of temperature on survival of larvae, and $TE_{e,t}$ is the proportional effect of temperature (see Todd et al. 2005); $dens_{i,t}$ is the density-dependence factor for adults based on the total number of adults; $BW_{j,t}$ is the blackwater effect at time *t*, where *j* are fish greater than 3 years old; $EggNum_t$ is the total number of eggs produced at time *t*; AFPS is the average fish population size; $Fec_{i,t}$ is the fecundity for Murray Cod in the i_{th} age class, based on the age–length and length–fecundity relationships in Rowland 1998a and 1998b, where age–fecundity is perfectly correlated but not with survival (see Figure A2.1 and Figure A2.2); $Bin(n, s)$ is a random variate representing demographic variation in transition from one age class to the next, and it has a binomial distribution $Bin(n, s) = X \sim \text{Binom}(n, s)$, and $Poisson(m)$ is a random variate representing demographic variation in recruitment, and it has a Poisson distribution $Poisson(m) = X \sim \text{Poi}(m)$.

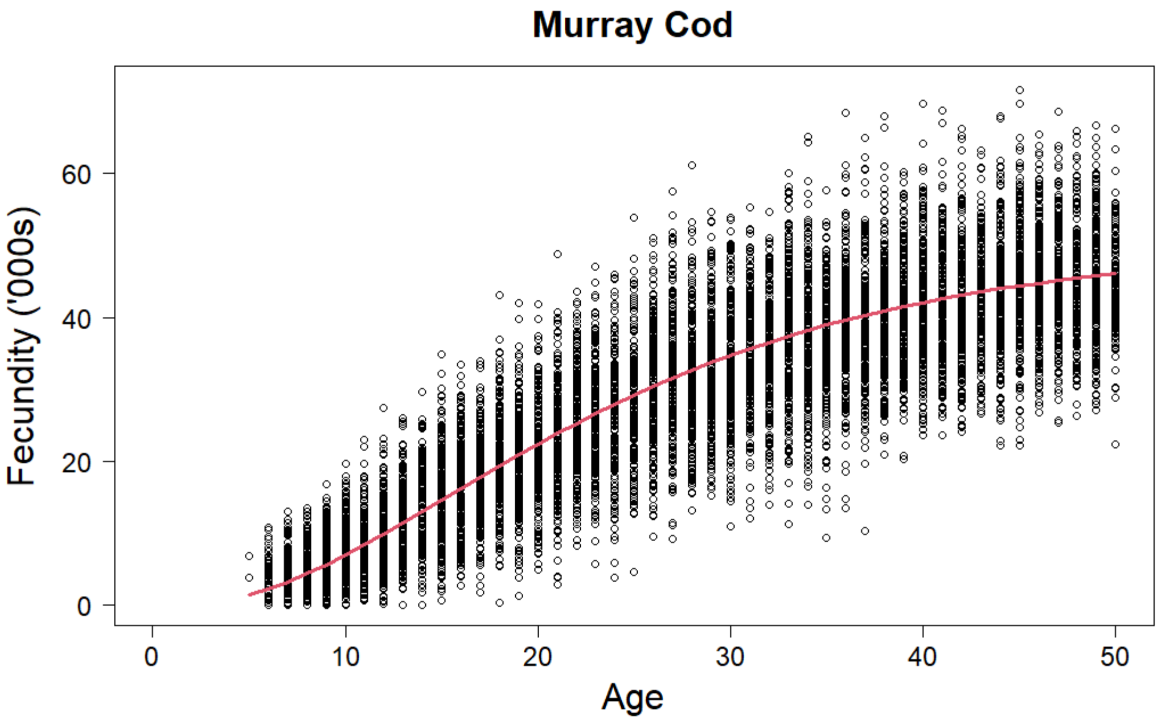


Figure A2.1. Age–fecundity used in the population model when the average maximum size of Murray Cod is 900 mm; this relationship is for smaller systems such as the Severn River.

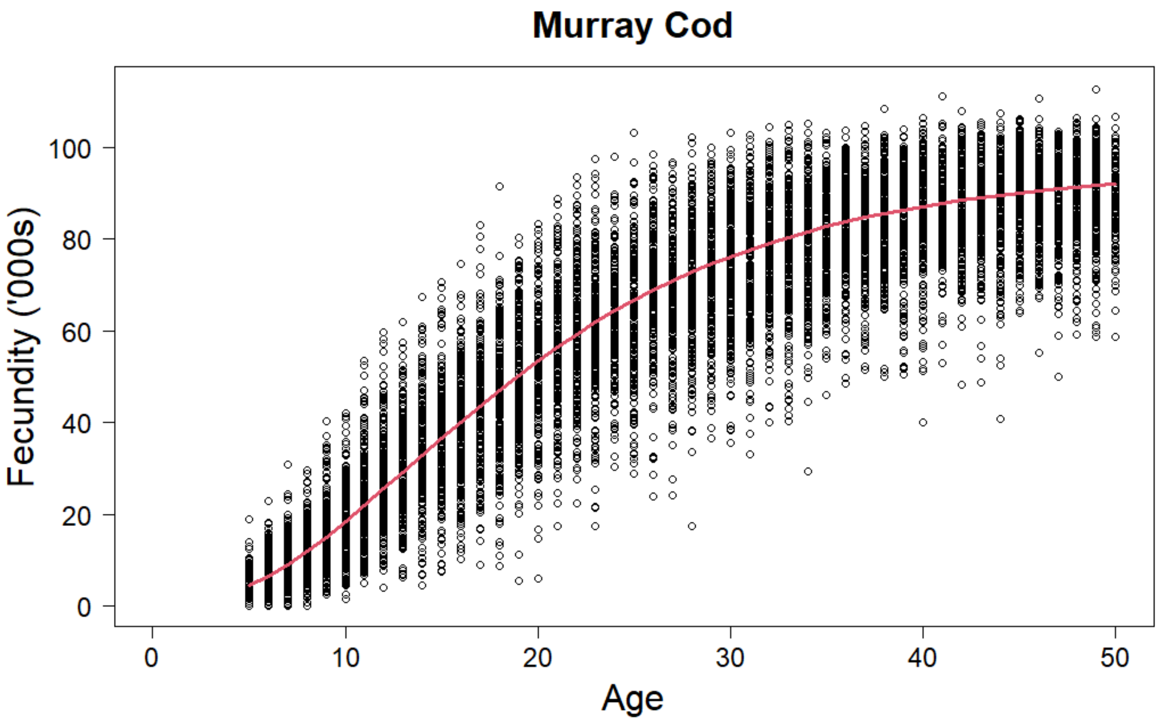


Figure A2.2. Age–fecundity used in the population model when the average maximum size of Murray Cod is 1200 mm; this relationship is for larger systems such as the Murrumbidgee River.

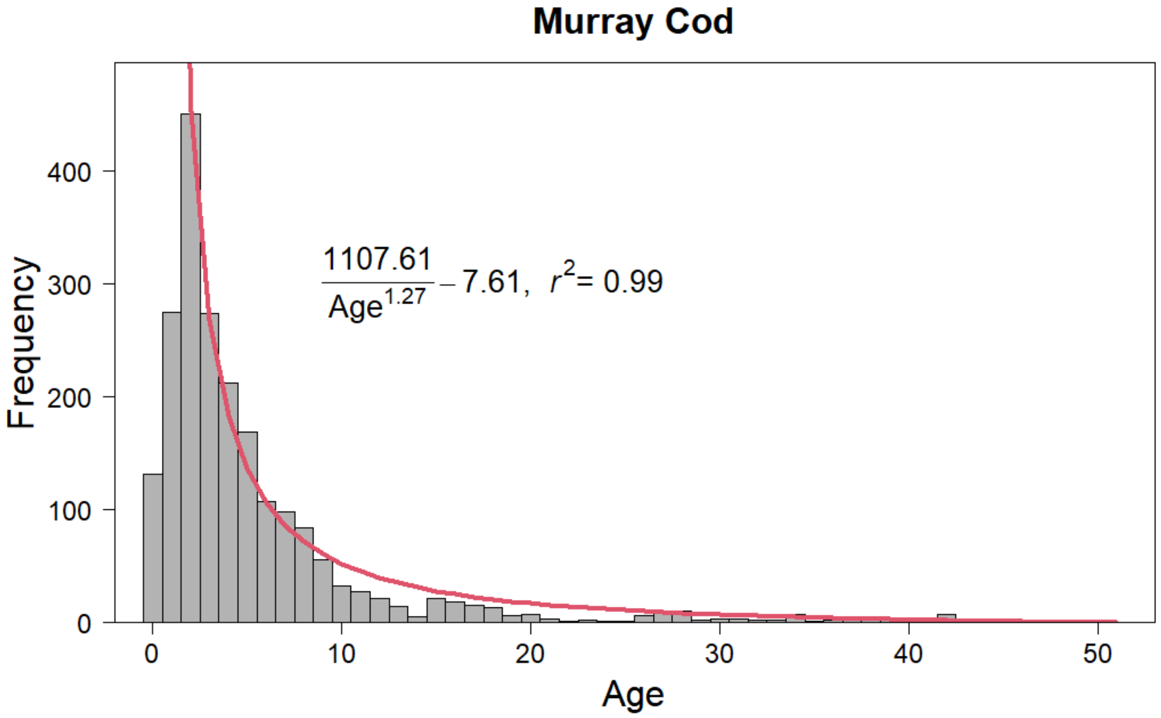


Figure A2.3. Age frequency of MDB Murray Cod collected between 1999 and 2016, with a fitted curve to generate age-specific survival rates.

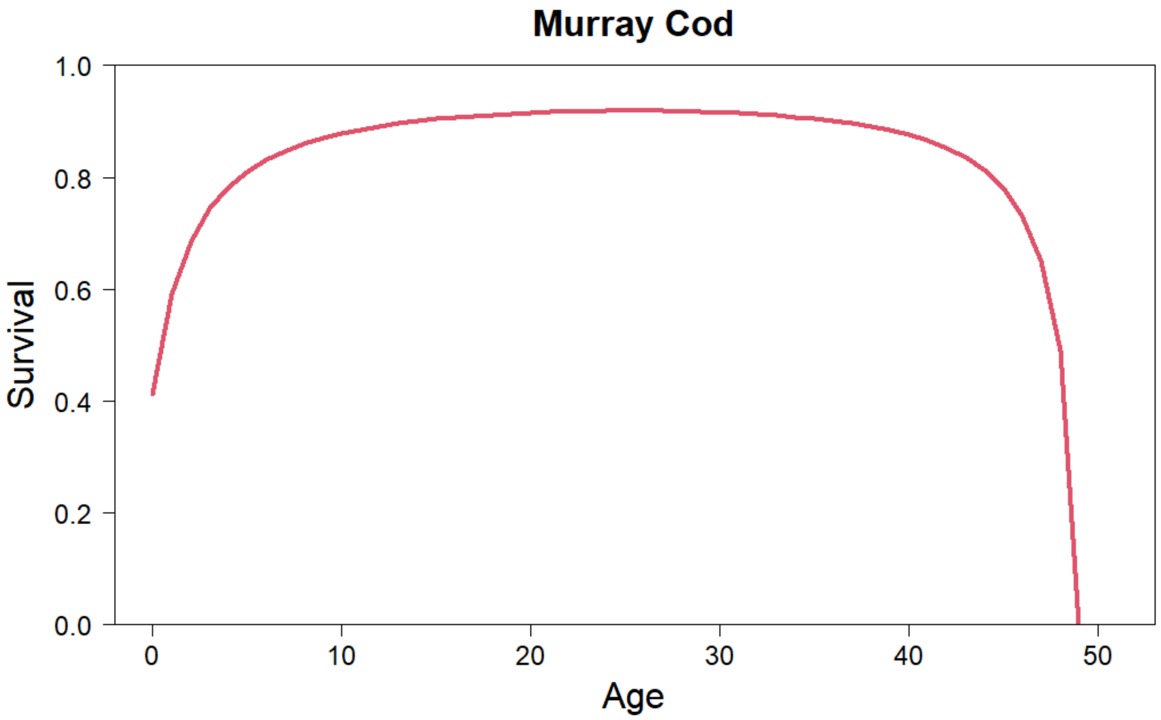


Figure A2.4. Age-specific survival rates for MDB Murray Cod generated from the ratio between age classes of the idealised age frequencies in Figure A2.3.

Age data obtained by analysing otoliths were used to generate estimates of age-specific survival (Ricker 1975; Todd et al. 2004, 2005; Todd and Lintermans 2015). A total of 1741 Murray Cod were aged from otoliths of fish sampled from the Murray–Darling Basin, collected between 1999 and 2016. An age class can be considered fully represented when the number of fish in the subsequent age class is less than the age class in question (Ricker 1975). The ratio between idealised age classes was taken as the 'average' or mean survival rate (Ricker 1975; Todd et al. 2004; Todd and

Lintermans 2015), and see Figure A2.3 for the curve generated from which the ratio between age classes provides the estimate of the age-specific survival rate (Figure A2.4). Survival rates for eggs, larvae and fingerlings (0+ fish) are unknown, and consequently, as stated in Todd et al. (2005), the rates estimated for the trout cod population model (Todd et al. 2004) were assumed to be appropriate for use in a Murray Cod population model, eggs ~ 0.5; larvae ~ 0.012 and 0+ fish ~ 0.12.

Golden Perch metapopulation construct

Golden Perch is a flow-dependent wide-ranging species (Zampatti et al. 2018; Koehn et al. 2020), and in order to capture their life cycle, a stage/age matrix model was constructed to capture the dynamics. A matrix construct was applied to the connected Murray–Darling Basin sites as a metapopulation model made up of eight populations, with immigration and emigration between adjoining upstream and downstream populations (Figures A2.6, A2.7, A2.8 and A2.9). This construct came from a number of workshops held as part of the Murray–Darling Basin Authority Fish Population Modelling project, with rules established for all of the linkages based on data (e.g. Mallen-Cooper and Stuart 2003) and expert elicitation (Koehn et al. 2018, 2020). This type of meta-population for Golden Perch has previously been used for Silver Perch in the Namoi River (northern NSW; Todd et al. 2019) and is deemed most suitable for this project. A conceptual model of Golden Perch life history in relation to important elements of the flow regime also informed the population model construct (Figure A2.5).

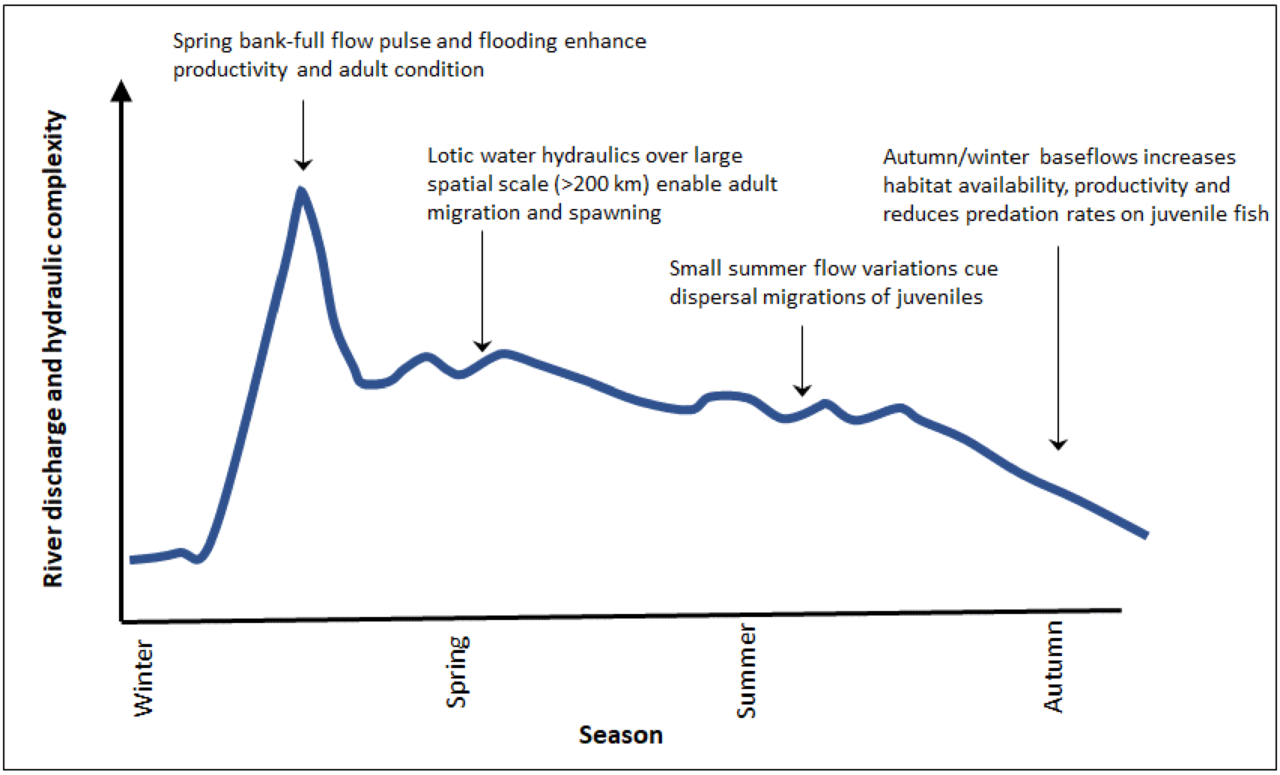


Figure A2.5. A conceptual model of important flow components within an annual flow regime and their relationship to the Golden Perch life history.

For each of the populations within the broader Murray and Lower Darling rivers metapopulation, a stage/age matrix model with four stages and 20 ages was constructed to represent the life cycle of Golden Perch: eggs; larvae; juveniles (ages 0–3 years); and adults (ages 4–20 years). Sexual maturity in the model occurs at 4 years of age (Mallen-Cooper and Stuart 2003), and egg production increases with age (Rowland 2005). Both demographic and environmental stochasticity were included in the model. Variation in the survival and reproduction of individuals was modelled by demographic stochasticity (Akçakaya 1991). Demographic stochasticity was incorporated using a binomial distribution to model the number of individuals surviving between consecutive time steps, and a Poisson distribution to model recruitment to the 1-year age class.

Environmental stochasticity was incorporated by randomly varying the survival and fecundity rates each year. Survival rates were drawn from normal distributions transformed to the unit interval (Todd and Ng 2001) with specified means and standard deviations. Age-specific fecundities were determined from a relationship estimated from hatchery data (Rowland 1996) and age–length data with specified means and standard deviations. Todd and Ng (2001) provide a methodology for specifying correlations among survival rates; however, no information exists to quantify these correlations. Given the aquatic habitat in which fish live, it is reasonable to assume that the correlations are likely to be positive and close to unity. It was assumed that the survival rates were perfectly correlated to one another and independent of the fecundity rates; fecundity rates were also assumed to be perfectly correlated with one another (Todd et al. 2004), and a pre-breeding census construction was used (Burgman et al. 1993). The density-dependence construct applies across all adult age classes equally. The following equations are for a single Golden Perch population:

$$FN_{i+1,t+1} = Bin\left(FN_{i,t}, dens_{i,t} \times S_{i,t}\right), \qquad i = 1\ldots29$$

$$FN_{1,t+1} = Poisson\left(dens_{0,t+1} \times S_{0,t} \times tempeffects_t \times S_{L,t} \times S_{E,t} \times 0.5 \times Eggs_t\right)$$

$$Eggs_t = \sum_{i=4}^{i=30} ST_t \times Fec_{i,t} \times FN_{i,t},$$

$$N_{i,t+1} = 2 \times FN_{i,t+1} \qquad i = 1\ldots30$$

$$dens_{i,t} = \begin{cases} \exp\left(-ds \times \left(\sum_{i=3}^{i=30} FN_{i,t} \middle/ DT - 1\right)\right), & \text{for } i = 2\ldots29 \text{ and } \sum_{i=3}^{i=30} FN_{i,t} \geq DT \\ 1, & \text{for } i = 2\ldots29 \text{ and } \sum_{i=3}^{i=30} FN_{i,t} < DT \end{cases}$$

$$DT = 1.25 \times AFPS$$

$$dens_{1,t} = \begin{cases} \exp\left(-ds_1 \times FN_{1,t}\right) & \text{for } \exp\left(-ds_1 \times FN_{1,t}\right) < 1 \\ 1, & \text{for } \exp\left(-ds_1 \times FN_{1,t}\right) \geq 1 \end{cases}$$

$$dens_{0,t+1} = \begin{cases} \exp\left(-ds_0 \times FN_{0,t+1}^{-d}\right) & \text{for } \exp\left(-ds_0 \times FN_{0,t+1}^{-d}\right) < 1 \\ 1, & \text{for } \exp\left(-ds_0 \times FN_{0,t+1}^{-d}\right) \geq 1 \end{cases}$$

$$FN_{0,t+1}^{-d} = S_{0,t} \times tempeffects_t \times S_{L,t} \times S_{E,t} \times 0.5 \times Eggs_t$$

$$Wei_{i,t} = \exp(W)\left(L_t^{\infty}\left(1 - \exp\left(-K_t\left(i - \mathrm{T}_t\right)\right)\right)\right)^{C_t} \qquad i \geq 4$$

$$W = -12.50$$

$$L_t^{\infty} \sim N(480.48, 6)$$

$$K_t \sim N(0.32, 0.06)$$

$$\mathrm{T}_t \sim N(-0.20, 0.3)$$

$$C_t \sim N(3.23, 0.03)$$

$$Fec_{i,t} = P_t Wei_{i,t}/1000 - q\left[Wei_{i,t}/1000\right]^2 \qquad i \geq 4$$

$$P_t \sim N(249.16, 16.61)$$

$$q = 20000$$

where t is an annual time interval $FN_{i,t}$, and $N_{i,t}$ are the numbers of female adults and total adults, assuming an even sex ratio, in the i_{th} age class at time t; $S_{i,t}$ is a random variate describing environmental variation in the survival rates of Golden Perch in the i_{th} age class drawn from normal distributions transformed to the unit interval (Todd and Ng 2001) with no loss of information from the specified means and standard deviations; $S_{0,t}$, $S_{l,t}$ and $S_{e,t}$ are random variates describing environmental variation in survival rates of Golden Perch less than 1 year old, larvae and eggs, respectively (similarly to age-specific survival, where survival rates across all ages and stages are perfectly correlated); $tempeffects_t$ is the proportional effect of temperature on survival of eggs and larvae (see Todd et al. 2005); $dens_{i,t}$ is the density-dependence factor applied to all age classes; ds and ds_i are the density scale for each location; $EggNum_t$ is the total number of eggs produced at time t; AFPS is the average population size; $Fec_{i,t}$ is the fecundity for Golden Perch in the i_{th} age class, based on an age–length relationship from 1347 aged Golden Perch, a length–weight relationship based on 2929 Golden Perch, and a weight–fecundity relationship in Rowland (1996), where age and fecundity are perfectly correlated with each other, but not with survival (see Figure A2.6); $Bin(n, s)$ is a random variate representing demographic variation in transition from one age class to the next with a binomial distribution $Bin(n, s) = X \sim \text{Binom}(n, s)$, and $Poisson(m)$ is a random variate representing demographic variation in recruitment with a Poisson distribution $Poisson(m) = X \sim \text{Poi}(m)$.

Age data obtained through analysing otoliths from the Murray River were used to generate estimates of age-specific survival (Ricker 1975; Todd et al. 2004, 2005; Todd and Lintermans 2015). A total of 2968 Golden Perch were aged from otoliths of fish sampled from the Murray River and catchments and collected over the years 1990 to 2015 (Mallen-Cooper and Stuart 2003; Tonkin et al. 2019). An age class maybe considered to be fully represented when the number of fish in the subsequent age class is less than the number of fish in the age class in question (Ricker 1975). The ratio between idealised age classes was taken as the 'average' or mean survival rate (Ricker, 1975; Todd et al. 2004; Todd and Lintermans 2015) (see Figure A2.7 for the curve from which the ratio between age classes provides the estimate of the age-specific survival rate in Figure A2.8. Survival rates for eggs, larvae and fingerlings (0+ fish) are unknown; consequently, it was assumed that 50% of eggs hatch, and the curve fitted to the age–frequency data was used to estimate larval and fingerling survival at 0.002 and 0.167, respectively, providing a potential population growth rate for Golden Perch of 1.4.

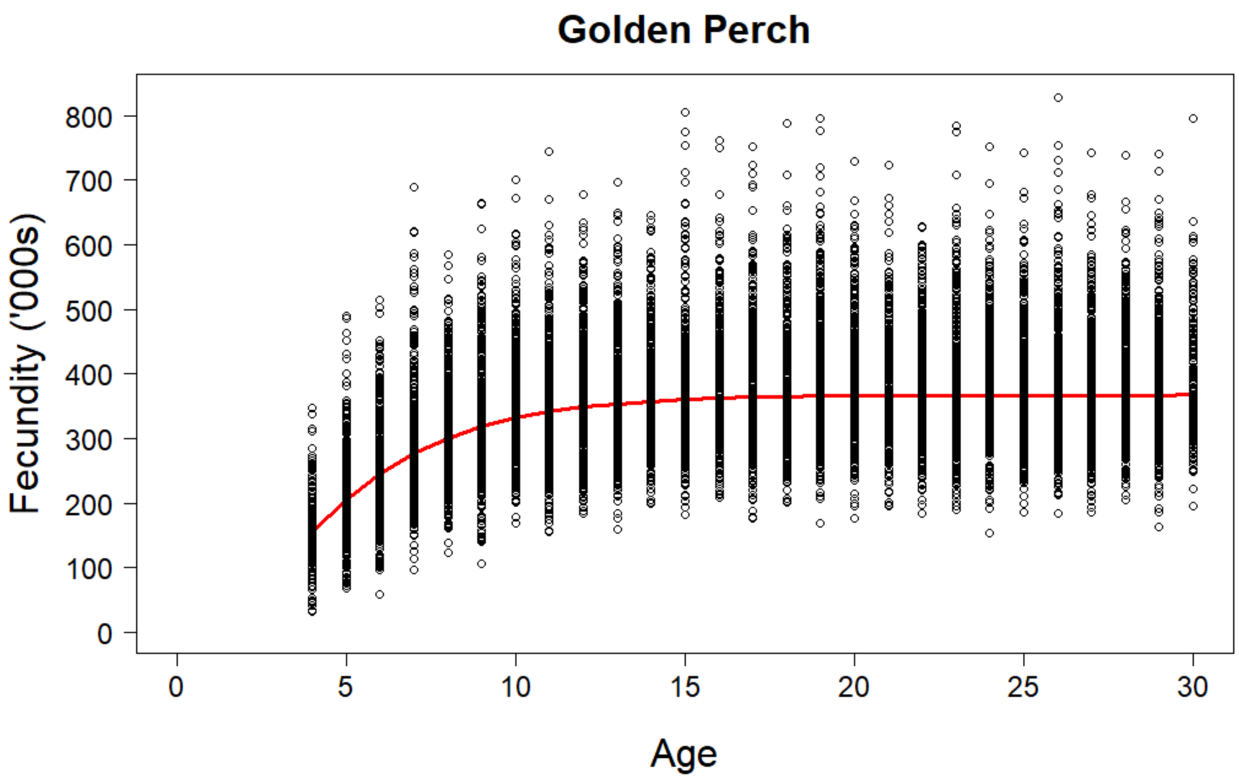


Figure A2.6. Age–fecundity relationship used in the Golden Perch single population and meta-population model.

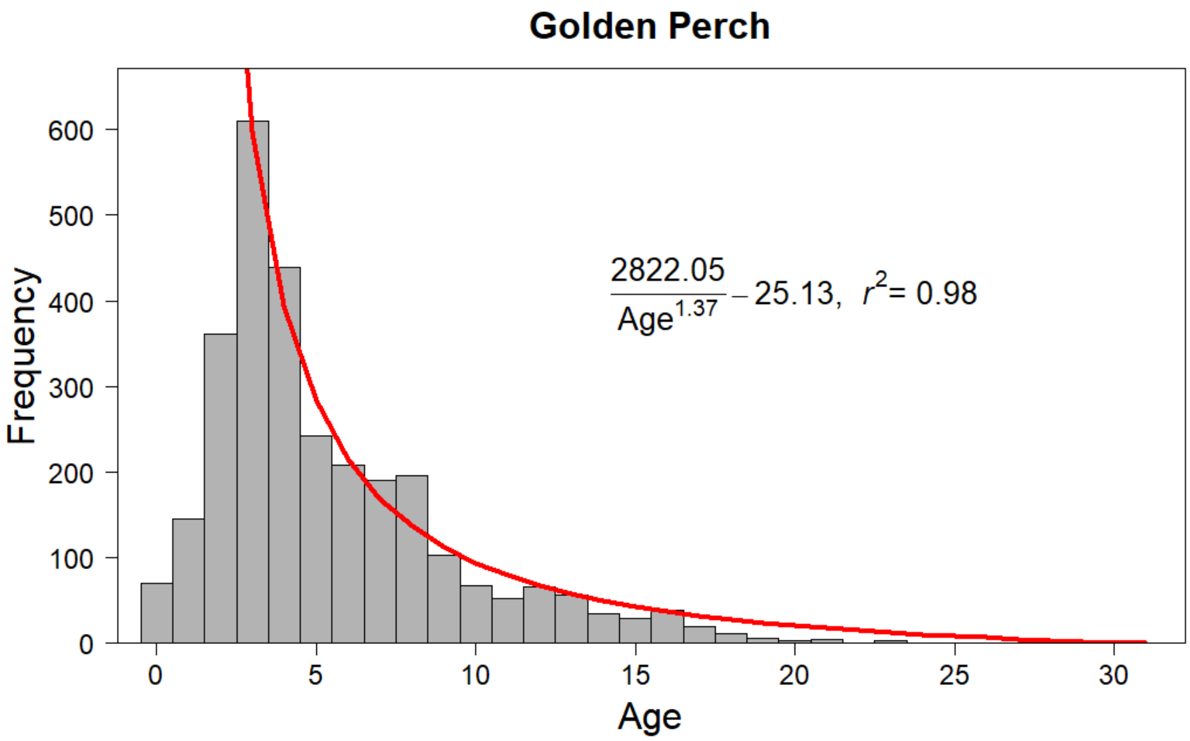


Figure A2.7. Age–frequency relationship with the fitted curve used to generate age-specific survival rates for Golden Perch.

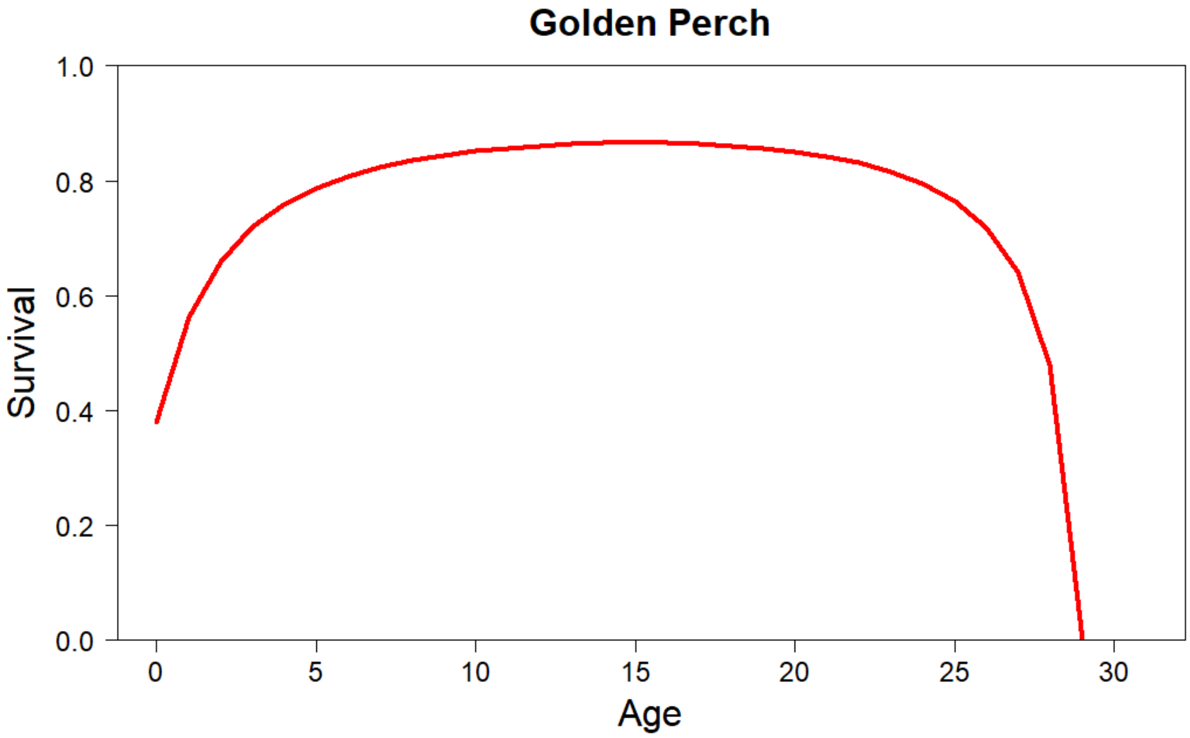


Figure A2.8. Age-specific survival rates for Golden Perch generated from the ratio between age classes (from the idealised age frequencies in Figure A2.7).

Model rules documentation

Golden Perch model rules extended

Each population unit has a specific set of rules defining the influence that flow and temperature have on the life history of Golden Perch within the section, and on its interaction with other sections immediately upstream or downstream. The broad areas of rule development relate to spawning, egg and larval drift, juvenile movement, adult movement, adult spawning run, and productivity.

Golden Perch spawning

Golden Perch spawning is triggered by rules specific to reaches within the MDB (defined below). Generally, spawning (October through till March) starts when two consecutive days are >17°C, combined with a flow signal, and then continues until the end of the spawning period. Survival of the spawned eggs over a period of 16 days (including the larval period) is calculated via a published temperature relationship (Michie et al. 2020). The proportion of fish spawning on any given day is dictated by a function that decays from the initial spawning peak, but also often depends on the flow on that day (see specifics for each population below).

In the Lower Murray population, fish only spawn on a flow of >18,000 ML day^{-1}, when lotic hydraulics are created. The proportion of fish spawning increases with the flow (>18,000 ML day^{-1} creates lotic conditions at the South Australian (SA)–Victoria border; C. Bice, SARDI, pers. comm.).

In the Torrumbarry to Wentworth population (includes lower Wakool), spawning starts on a flow of >14,000 ML day^{-1} (King et al. 2009). Once initiated, there is no effect of flows on the proportion spawning.

In the Yarrawonga to Torrumbarry population, spawning starts on a flow of >7000 ML day^{-1} (at Barmah choke), as lotic hydraulics are always present. Once initiated, there is no effect of flows on the proportion spawning (King et al. 2009; Z. Tonkin, ARI, pers. comm.).

In the Hume to Yarrawonga population, spawning occurs at low flows (>5000 ML day^{-1} at Doctors Point) due to the lotic nature of the hydrology (Tonkin et al. 2009). Spawning does occur, but there is low or no recruitment due to cold-water pollution.

In the Lower Darling population, spawning only occurs at flows of >2000 ML day^{-1} at the Weir 32 gauge (Sharpe and Stuart 2018). The proportion spawning increases with flow.

In the Hay to Balranald population, spawning is triggered by flows >1500 ML day^{-1}; lotic hydraulics are always present, so there is no real spawning relationship with discharge.

In the Edward River population, there is no known spawning, but it is assumed that fish can spawn at flows of >2600 ML day^{-1} at the Toonalook gauge (DPIE 2020a).

In the Gundagai to Hay population, spawning occurs with flows of ~1500 ML day^{-1}, as lotic hydraulics are always present.

Golden Perch egg and larval drift

Golden Perch egg and larval drift is calculated as a sum of the daily spawning rate across the spawning period: the proportion of fish spawning on each day is multiplied by the daily drift rate, and these calculations are summed over the spawning period. Eggs and larvae spawned on each day are allowed to drift for a period of 15 days. Note that all larvae stay in the Lower Murray River population, as there is no drift out.

Drift from Murray River populations (Murray River populations from Hume to Wentworth) into respective downstream populations: if the maximum flow on the day or for the following 15 days is greater than 35,000 ML day^{-1}, larval drift is 0.8. If flow does not reach this threshold, larval drift is 0.25 for the day.

Drift from the Yarrawonga to Torrumbarry population is driven by the flows as defined directly above; however, only 1% of larvae are retained in the system. The other 99% either drift to Torrumbarry to Wentworth or to Edward River (see directly below) or perish in the weir pool at Torrumbarry or via irrigation pumping.

Drift from the Hume to Yarrawonga population: there is 99% mortality when larvae drift to pop 3 (undershot weir mortality).

Drift from the Yarrawonga to Torrumbarry population into the Torrumbarry to Wentworth population: the daily drift proportion defined above is divided into proportions that represents the Murray River before and after the intersection with the Edward River. The lower proportion all drift to the Mid Murray (i.e. all drifting larvae go to the Mid Murray), and the upper proportion is divided into drift to the Mid Murray and the Edward River populations via the daily ratio of flow at Toonalook gauge to Torrumbarry gauge. The yearly drift value is summed from these two proportions.

Drift from the Yarrawonga to Torrumbarry population into the Edward River population is the remaining proportion of drift from Yarrawonga to Torrumbarry into Torrumbarry to Wentworth. Note that these larvae all die, as there is no known recruitment in the Edward River.

Drift from the Hay to Balranald population into the Torrumbarry to Wentworth population follows these rules: if flow is <500 ML day^{-1}, there is no larval drift on the day; if flow is >500 ML day^{-1}, it follows the relationship defined in Figure A2.9.

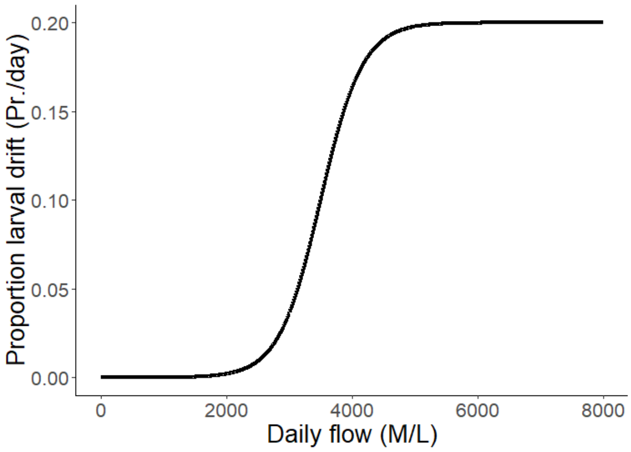


Figure A2.9. Relationship between flow and drift of Golden Perch larvae from the Lower Murrumbidgee River population into the Mid Murray River population.

Drift from the Gundagai to Hay population into the Hay to Balranald population follows these rules: if flow is <500 ML day^{-1}, there is no larval drift on the day; if flow is >500 ML day^{-1}, it follows the relationship defined in Figure A2.10.

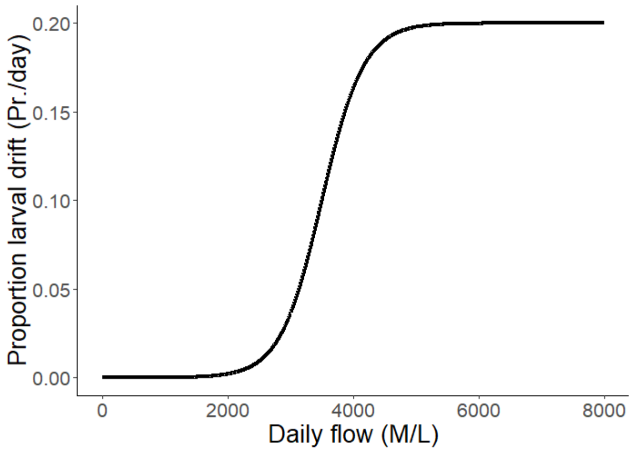


Figure A2.10. Relationship between flow and drift of Golden Perch larvae from the Upper Murrumbidgee River population into the Lower Murrumbidgee River population.

Drift from the Lower Darling population into the Lower Murray population follows these rules: if flow is <400 ML day^{-1}, there is no larval drift on the day; if flow is >400 ML day^{-1}, it follows the relationship defined in Figure A2.11.

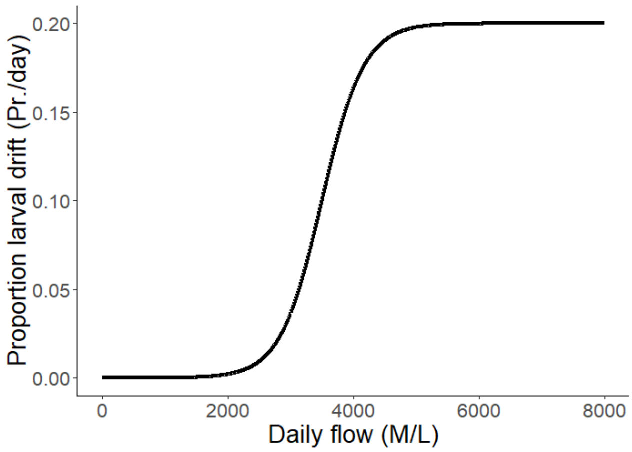


Figure A2.11. Relationship between flow and drift of Golden Perch larvae from the Lower Darling River population into the Lower Murray River population.

Drift from the Edward River population into the Torrumbarry to Wentworth population follows these rules: if the maximum flow on the day or for the following 15 days is >15,000 ML day^{-1}, larval drift is 0.8. If flow does not reach these levels, larval drift is 0.25 for the day.

Golden Perch juvenile and adult movement

Movement is calculated as the proportion of the adult and juvenile population that moves from one population to another in a single year time step. Fish can only move into adjacent populations in a given year time step, and this may underestimate fish movement—particularly for adult Golden Perch during high flows. The proportion of fish moving is dictated by specific flow rules in each area. Here, daily flows drive a daily movement value that is summed over each year time step (Figures A2.12 and A2.13). This defines the movement of fish in each population within a year, and the daily movement value is apportioned to possible destinations via an upstream: downstream movement ratio and also via relative flow ratios where movement 'decisions' need to be made (i.e. at intersections: see Table A2.1 for more detail). Note that 3-year-olds are counted as juveniles in the model, but the adult movement rate is applied to this year class.

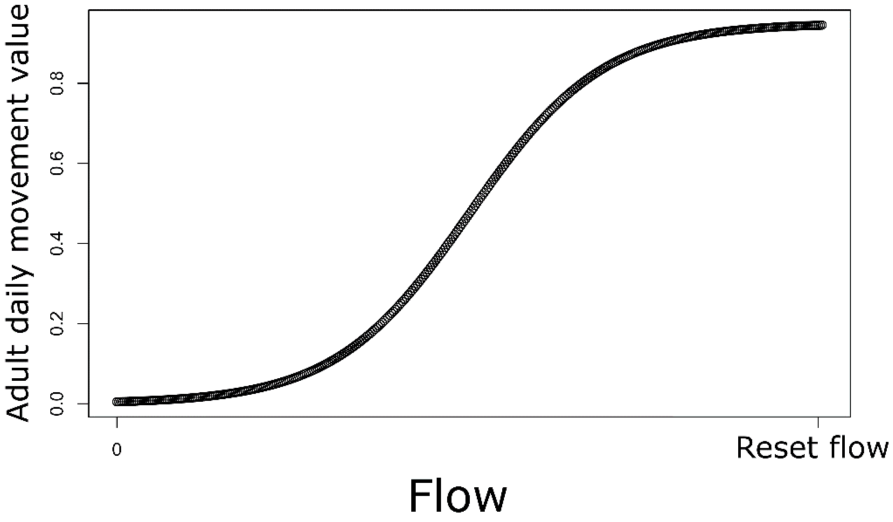


Figure A2.12. Adult daily movement value as a function of flow on that day. This relationship is scaled to the size of the reset flow value for each population. This relationship is based upon movement data at Torrumbarry weir.

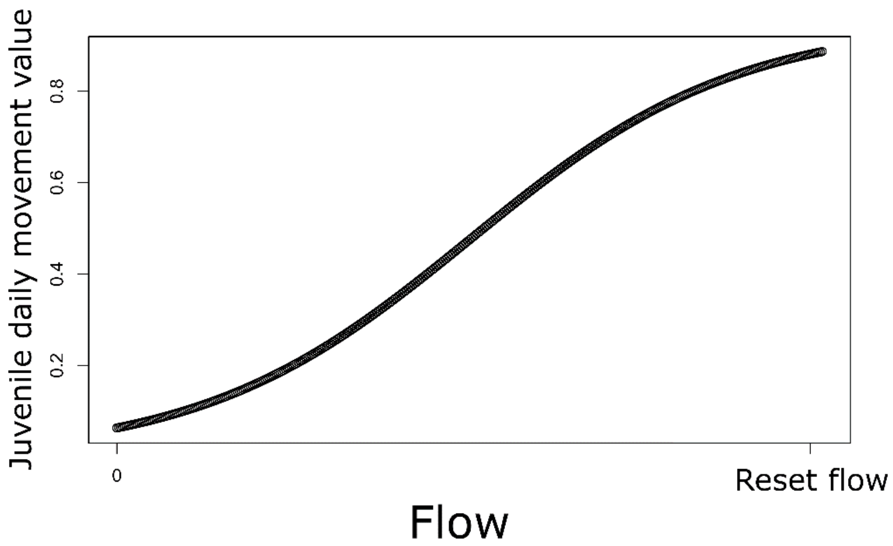


Figure A2.13. Juvenile daily movement value as a function of flow on that day. This relationship is scaled to the size of the reset flow value for each population. This relationship is based upon movement data at Torrumbarry weir.

Note that an overall movement rate is calculated for each population in each year (according to flow as above), and this overall rate (called '*Totalmovement*' in Table A2.1) is then split into movement to possible destination populations via a set of movement rules (Table A2.1). The underlying movement ratio is 3:1 upstream (u/s) to downstream (d/s) (determined from the expert opinion of the wider working group as there is no field data). These ratios are incorporated into the equations in Table. A2.1 as '*u/s movement*' or '*d/s movement*'. Movement 'decisions' where there is a river junction (i.e. where there are two or more destinations at the upstream or downstream end of a population) are based upon the ratio of the flows relative to the bank full flows from each destination. For example, the rule for fish moving from the Lower Murray River and making a movement decision into either the Darling or Mid Murray rivers is a ratio of the proportion of bank full flows in each destination reach. This gives the Lower Darling River a greater weighting, reflecting the greater 'attractiveness' of flows from this reach. The movement from the Lower Murray River population to the Mid Murray

River population is given by 1 – (movement from the Lower Murray River population up to the Lower Darling River population). The proportion of fish moving from the Lower Darling River population and up or down the Murray River is driven by the upstream: downstream movement ratio (as above).

Table A2.1. Movement rules for Golden Perch in the connected Lower Murray–Darling system.

Location	Destination	Rule
Lower Murray	Mid Murray	$Movement = Totalmovement * u/s\ movement * \frac{Pr.bankfull\ at\ Euston}{Total\ bankfull\ Pr.}$
	Lower Darling	$Movement = Totalmovement * u/s\ movement * \frac{Pr.bankfull\ in\ Darling}{Total\ bankfull\ Pr.}$
Mid Murray	Lower Darling	$Movement = Totalmovement * d/s\ movement * \frac{Torrumbarry\ flow}{Total\ flow}$
	Lower Murray	$Movement = Totalmovement * d/s\ movement * \frac{Collignan\ flow}{Total\ flow}$
	Upper Mid Murray	$Juv\ Movement = Totalmovement * u/s\ movement * \frac{Torrumbarry\ flow}{Total\ flow}$ $Adult\ Movement = Totalmovement * u/s\ movement * \frac{Torrumbarry\ flow}{Total\ flow}$
	Lower Murrumbidgee	$Juv\ Movement = Totalmovement * u/s\ movement * \frac{\text{Balranald}\ flow/2}{Total\ flow}$ $Adult\ Movement = Totalmovement * u/s\ movement * \frac{\text{Balranald}\ flow}{Total\ flow}$
	Edward	$Juv\ Movement = Totalmovement * u/s\ movement * \frac{\text{Toonalook}\ flow}{Total\ flow}$ $Adult\ Movement = Totalmovement * u/s\ movement * \frac{\text{Toonalook}\ flow}{Total\ flow}$
Upper Mid Murray	Upper Murray	$Movement = Totalmovement * u/s\ movement$*0.01
	Edward	$Movement = Totalmovement * d/s\ movement * \frac{\text{Toonalook}\ flow}{Total\ flow}$
	Mid Murray	$Movement = Totalmovement * d/s\ movement * \frac{Collignan\ flow}{Total\ flow}$
Upper Murray	Upper Mid Murray	$Movement = Totalmovement * d/s\ movement$
	Mid Murray	$Movement = Totalmovement * d/s\ movement * u/s\ movement$

Location	Destination	Rule
Lower Darling	Lower Murray	$Movement = Totalmovement * d/s\ movement * d/s\ movemeny$
Lower Murrumbidgee	Mid Murray	$Movement = Totalmovement * d/s\ movement$
	Upper Murrumbidgee	$Movement = Totalmovement * u/s\ movement$
Edward	Mid Murray	$Movement = Totalmovement * d/s\ movement$
	Upper Mid Murray	$Movement = Totalmovement * u/s\ movement$
Upper Murrumbidgee	Lower Murrumbidgee	$Movement = Totalmovement * d/s\ movement$

Reset flows

Reset flows are triggered by flow on a given day that is double the bank full flow in each reach. This triggers a 50% movement event (i.e. 50% of fish move) in that year in the specific reach. Here, 30% of fish move up and 20% downstream (50% of the total population move), and movement 'decisions' are dictated by the yearly proportions of daily bank full flows, where appropriate. Populations at the outer extremes of the metapopulation structure have a 50% movement into the adjoining population. Data on bank full flows come from the Murray–Lower Darling Long-Term Water Plan – part B (DPIE 2020a) or the Murrumbidgee Long-Term Water Plan – part B (DPIE 2020b).

Golden Perch adult spawning run

The rules for the adult spawning run are similar to the adult movement rules, but movement is estimated from the start of August until the end of January.

It does not include reset flows.

A proportion of adults will go on a spawning run and return to the original population.

- **20% of adult movers will return to original population**

Therefore, all results from adult movement are *0.2

Golden Perch productivity

Golden Perch productivity is described in the main text.

Murray Cod model rules extended

Murray Cod egg and larval survival

- Murray Cod: 10 days eggs / 10 days as drifting larvae
- Murray Cod spawning occurs after 2 days with temperature >18°C.

Equation for Murray Cod temperature–survival vector:

$\exp(\log_a + (temp \times \log_b)) / (1 + (\exp(\log_a + (temp \times \log_b))))$

Log_a = –16.902733

Log_b = 1.141874

Survival = product of temperature vector between current day and end of critical period (egg and larval period)

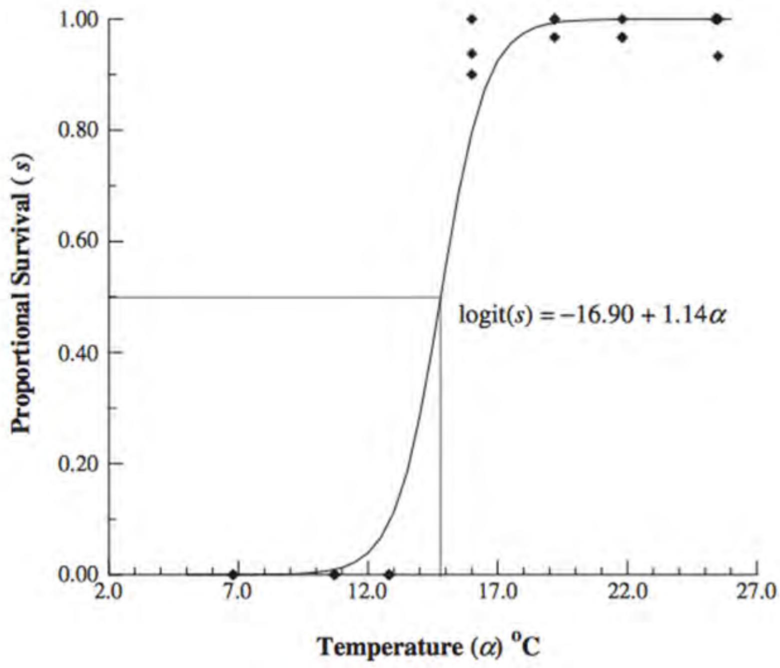


Figure A2.14. Proportional Murray Cod egg and larval survival with increasing temperature.

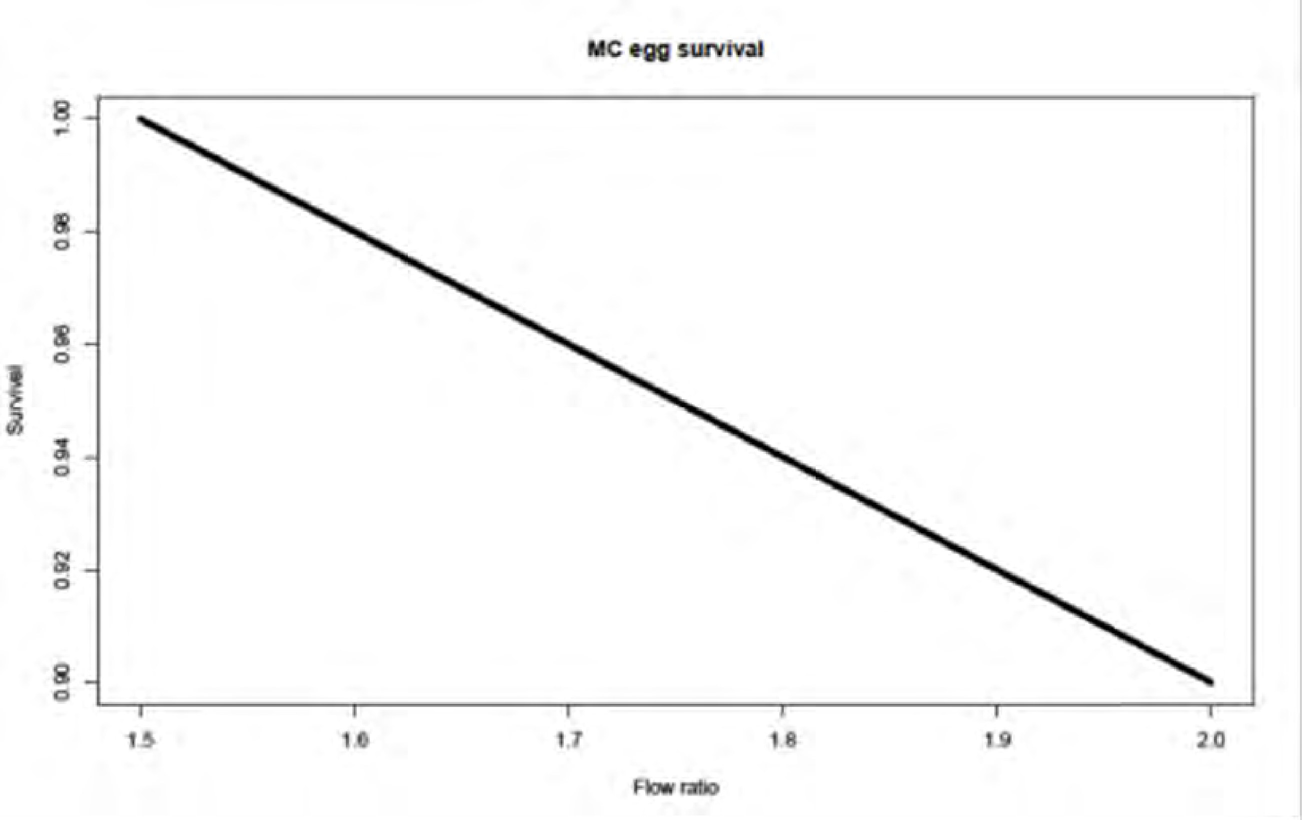


Figure A2.15. Murray Cod egg survival with increasing ratio of maximum flow within the 10-day critical period.

Appendix 3. All outputs from the modelling scenarios

All model outputs for Golden Perch and Murray Cod other than those included in section 3 are presented below: 1000-trajectory population summaries for the Base case scenario, mean abundance trajectories, cumulative distributions, and expected population sizes (mean, 10% quantile, minimum and maximum adult population size statistics) for individual populations and grouped populations (abundance statistics summed across populations). Trajectories of the mean recruit (1-year-old) populations are also presented. The percentage differences reported in the expected value figures for Golden Perch (Figures A3.1 – A3.12) and Murray Cod (Figures A3.25 – A3.36) are based on all 1000 trajectories of the respective figures, whereas the summary outputs of Table A3.1 are based on the mean trajectory of each scenario (Option 1 – Option 4: the percentage difference from Base case), for example the minimum population size is based on the minimum of the mean trajectory. Note that the mean of the mean trajectories is the same as the mean of the distribution of the mean from each trajectory, compare mean population size differences in Table A3.1 with TableA3.2.

Table A3.1. Reproduced Table S2. Summarised outputs from the mean trajectories of the population modelling for Golden Perch and Murray Cod populations across the Total RRCP Populations (inclusive to Wentworth) under the various relaxed-flow-constraints scenarios, Options 1–4. The mean, quantile and minimum value differences are calculated from the mean trajectories.

Species	Catchment	Relaxed-flow-constraints scenario	% difference from the Base case in the expected value of:		
			mean population size	10% quantile population size	minimum population size
Golden Perch	Total RRCP Populations*	Option 1	10	25	34
		Option 2	16	25	32
		Option 3	23	39	40
		Option 4	30	54	43
	Murray River	Option 1	10	19	30
		Option 2	16	20	29
		Option 3	23	37	30
		Option 4	29	45	28
	Murrumbidgee River	Option 1	7	6	14
		Option 2	16	8	38
		Option 3	26	8	28
		Option 4	34	31	43
Murray Cod	Total RRCP Populations*	Option 1	0	1	1
		Option 2	0	1	2
		Option 3	0	0	0
		Option 4	0	1	1
	Murray River	Option 1	1	2	2
		Option 2	1	2	2
		Option 3	0	0	1
		Option 4	0	2	2
	Murrumbidgee River	Option 1	0	0	–2
		Option 2	0	0	–3
		Option 3	0	–2	–1
		Option 4	0	–2	–1

*Total RRCP Populations defined as the RRCP focal zones and Wakool Junction to Wentworth.

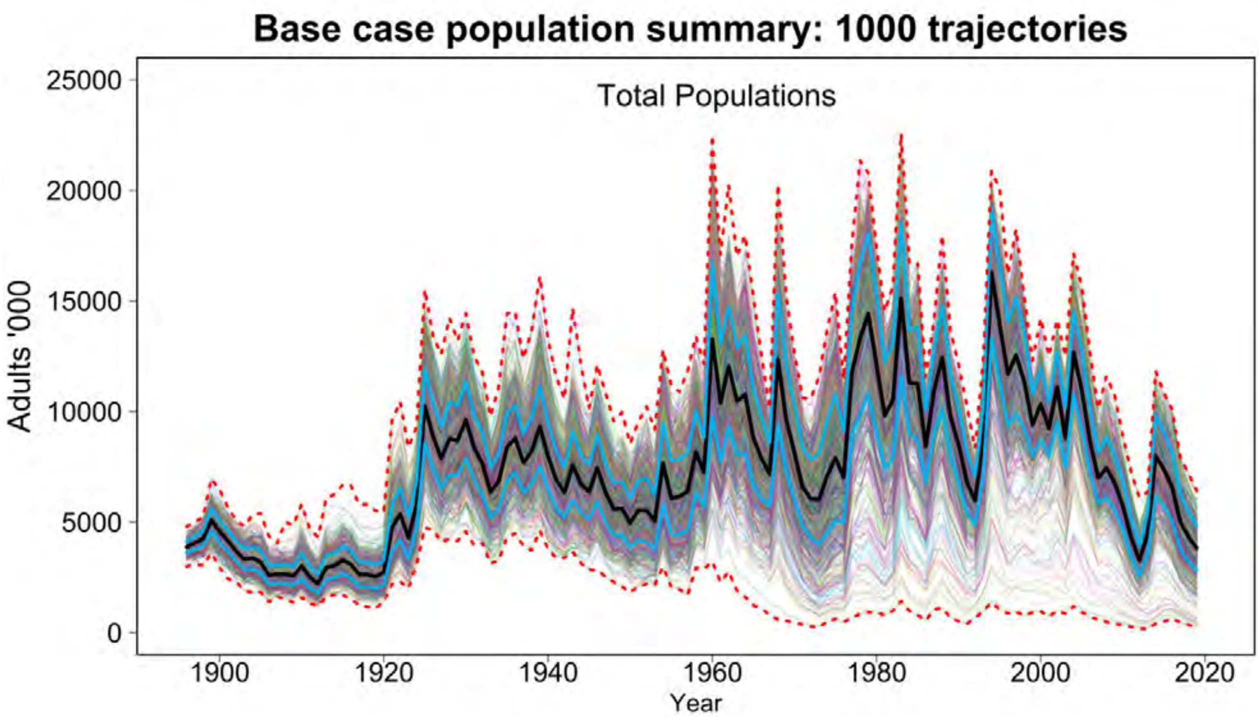
Table A3.2. Summarised outputs from all trajectories of the population modelling for Golden Perch and Murray Cod populations across the Total RRCP Populations (inclusive to Wentworth) under the various relaxed-flow-constraints scenarios, Options 1–4. The mean, quantile and minimum value differences are calculated from all trajectories.

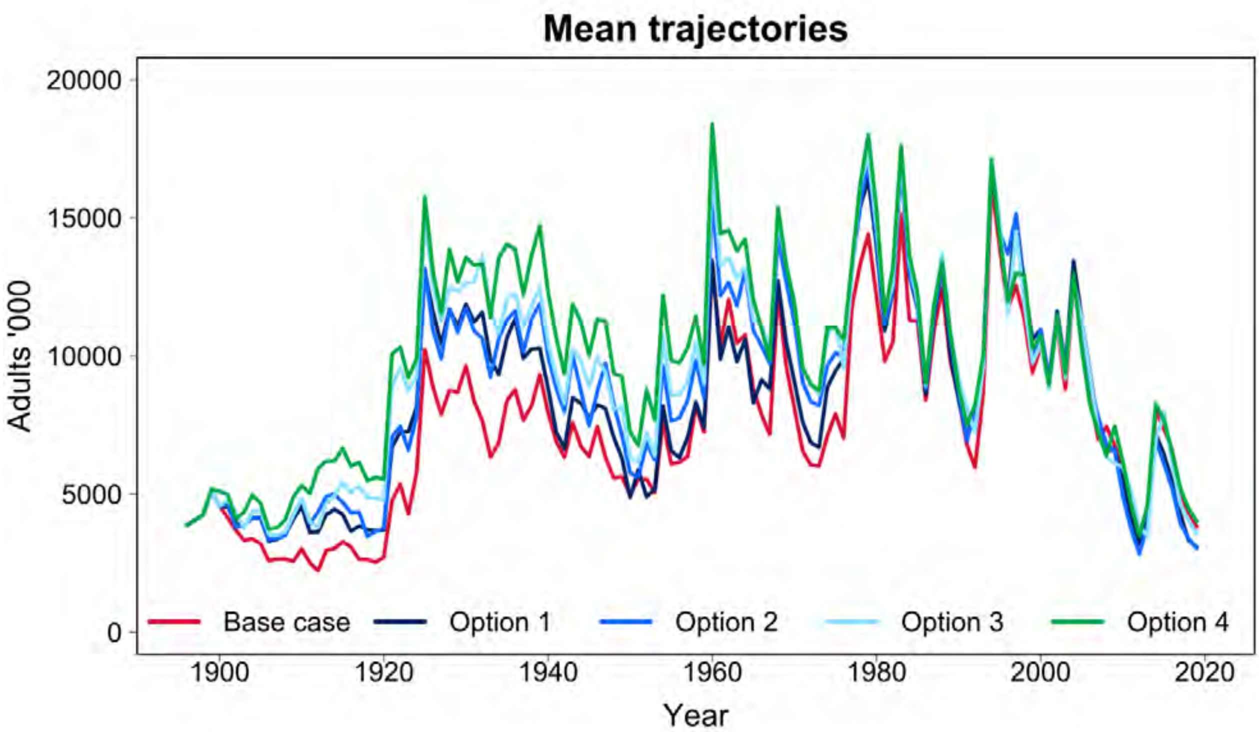
Species	Catchment	Relaxed-flow-constraints scenario	% difference from the Base case in the expected value of:		
			mean population size	10% quantile population size	minimum population size
Golden Perch	Total RRCP Populations*	Option 1	10	23	23
		Option 2	16	28	24
		Option 3	23	38	37
		Option 4	30	52	46
	Murray River	Option 1	10	22	21
		Option 2	16	26	22
		Option 3	23	38	34
		Option 4	29	52	38
	Murrumbidgee River	Option 1	7	9	9
		Option 2	16	10	22
		Option 3	26	13	20
		Option 4	34	31	39
Murray Cod	Total RRCP Populations*	Option 1	0	0	1
		Option 2	0	0	2
		Option 3	0	0	0
		Option 4	0	0	1
	Murray River	Option 1	1	1	2
		Option 2	1	1	2
		Option 3	0	0	1
		Option 4	0	1	2
	Murrumbidgee River	Option 1	0	0	-1
		Option 2	0	0	-2
		Option 3	0	0	-1
		Option 4	0	0	-1

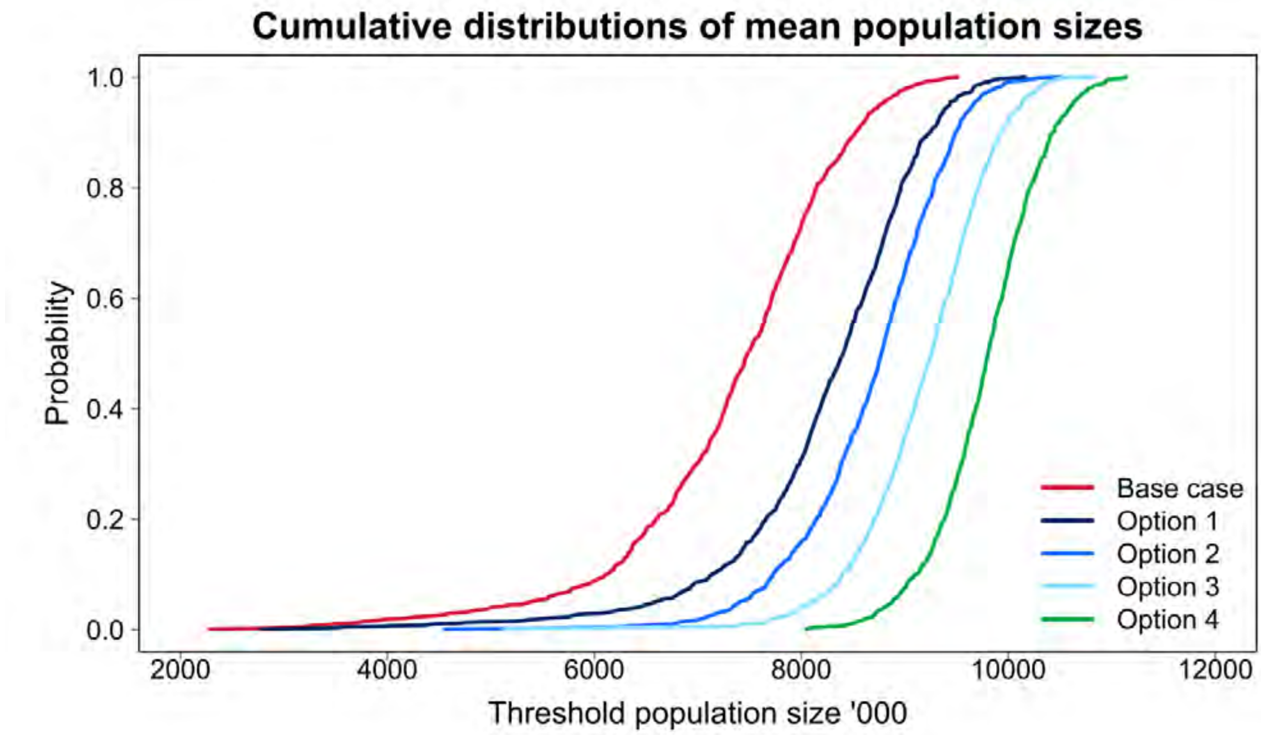
*Total RRCP Populations defined as the RRCP focal zones and Wakool Junction to Wentworth.

Golden Perch adult populations

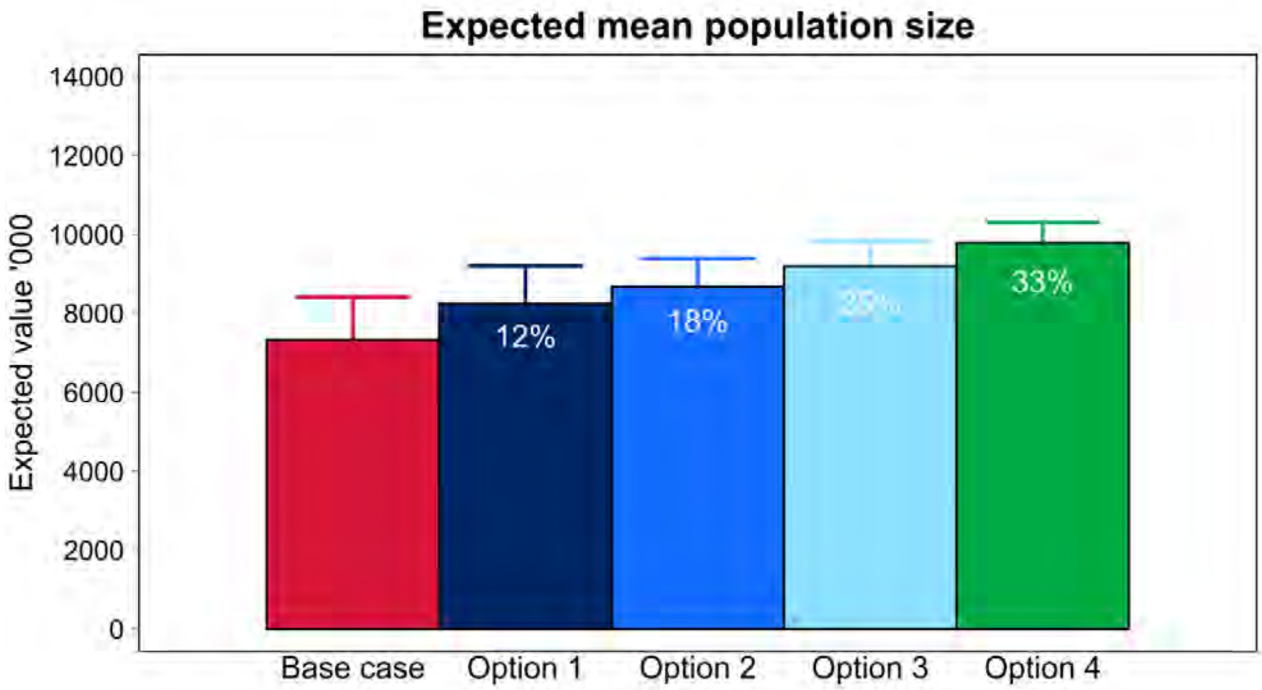
Golden Perch – Total populations



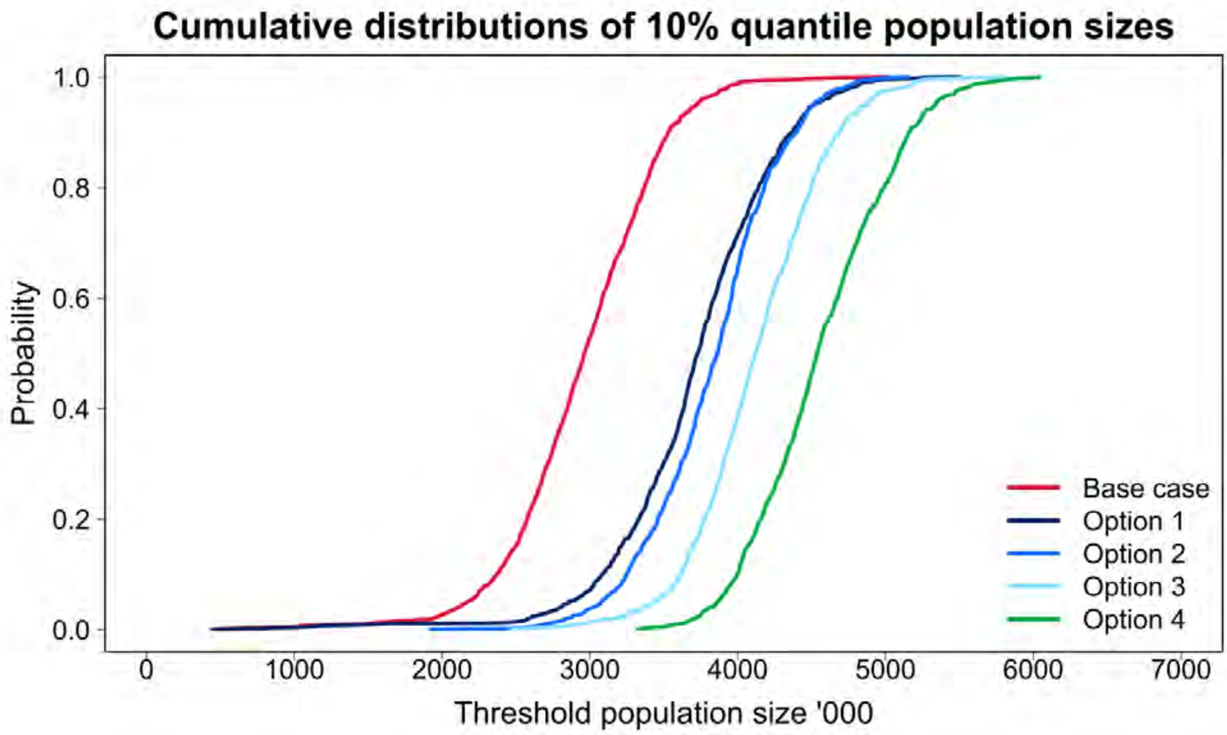


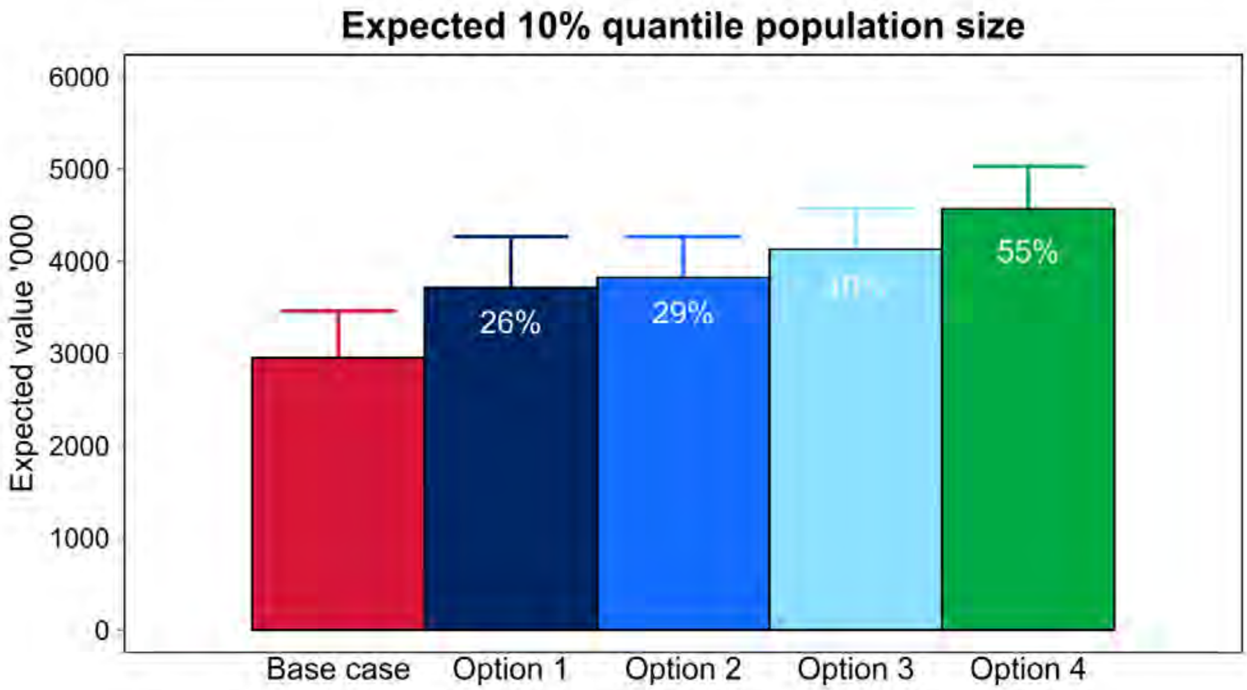


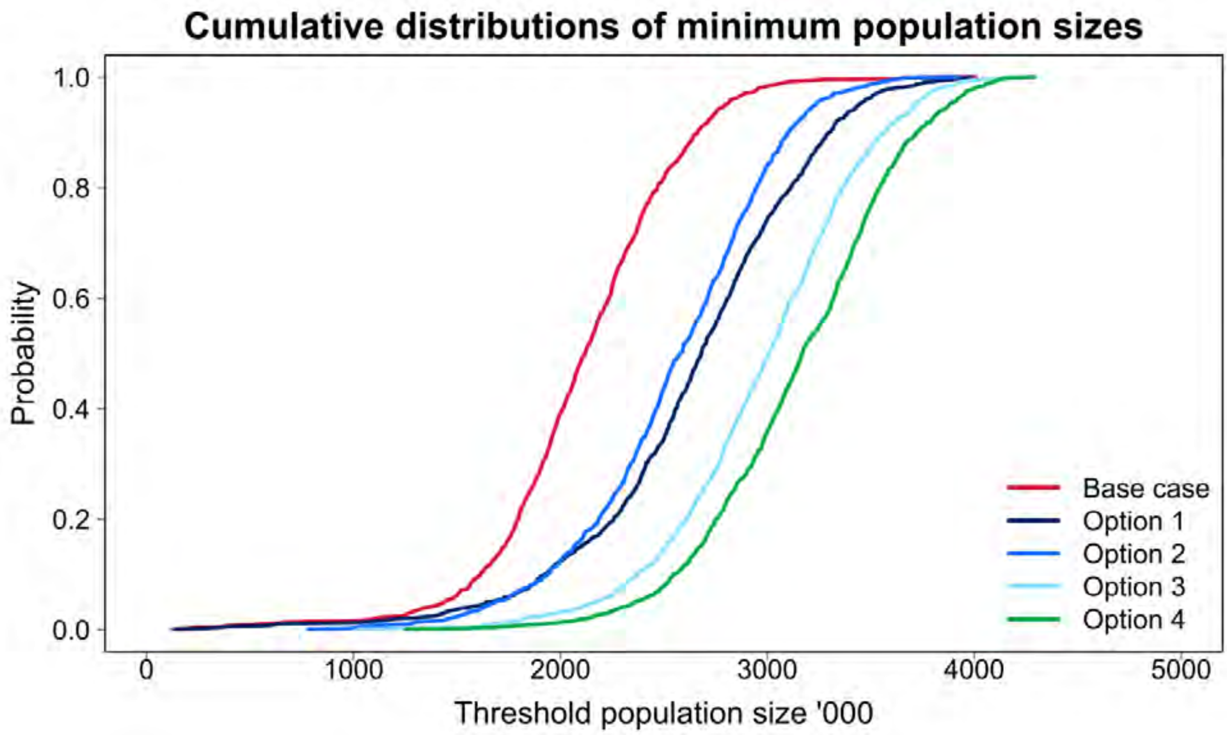
Cumulative distributions of mean population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
2000
4000
6000
8000
10000
12000
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4

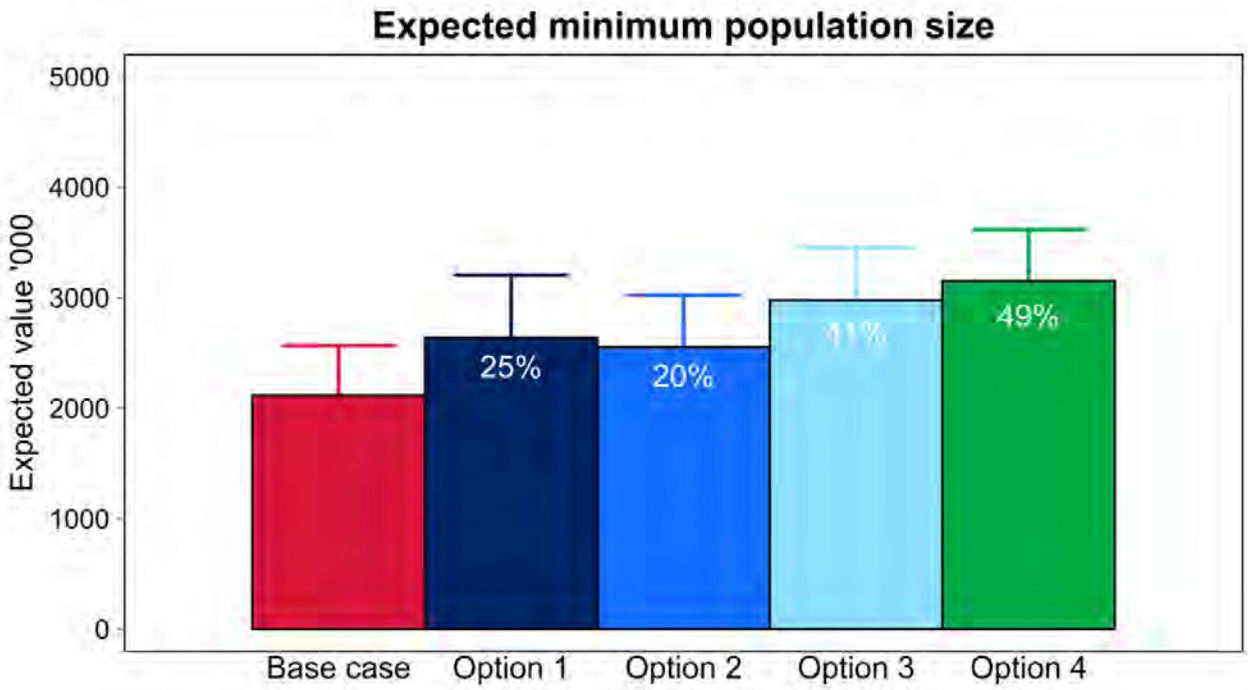


Expected mean population size
Expected value '000
14000
12000
10000
8000
6000
4000
2000
0
12%
18%
25%
33%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of 10% quantile population sizes
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
5000
6000
7000
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected 10% quantile population size
Expected value '000
0
1000
2000
3000
4000
5000
6000
26%
29%
55%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
1000
2000
3000
4000
5000
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected minimum population size
Expected value '000
5000
4000
3000
2000
1000
0
25%
20%
41%
49%
Base case
Option 1
Option 2
Option 3
Option 4

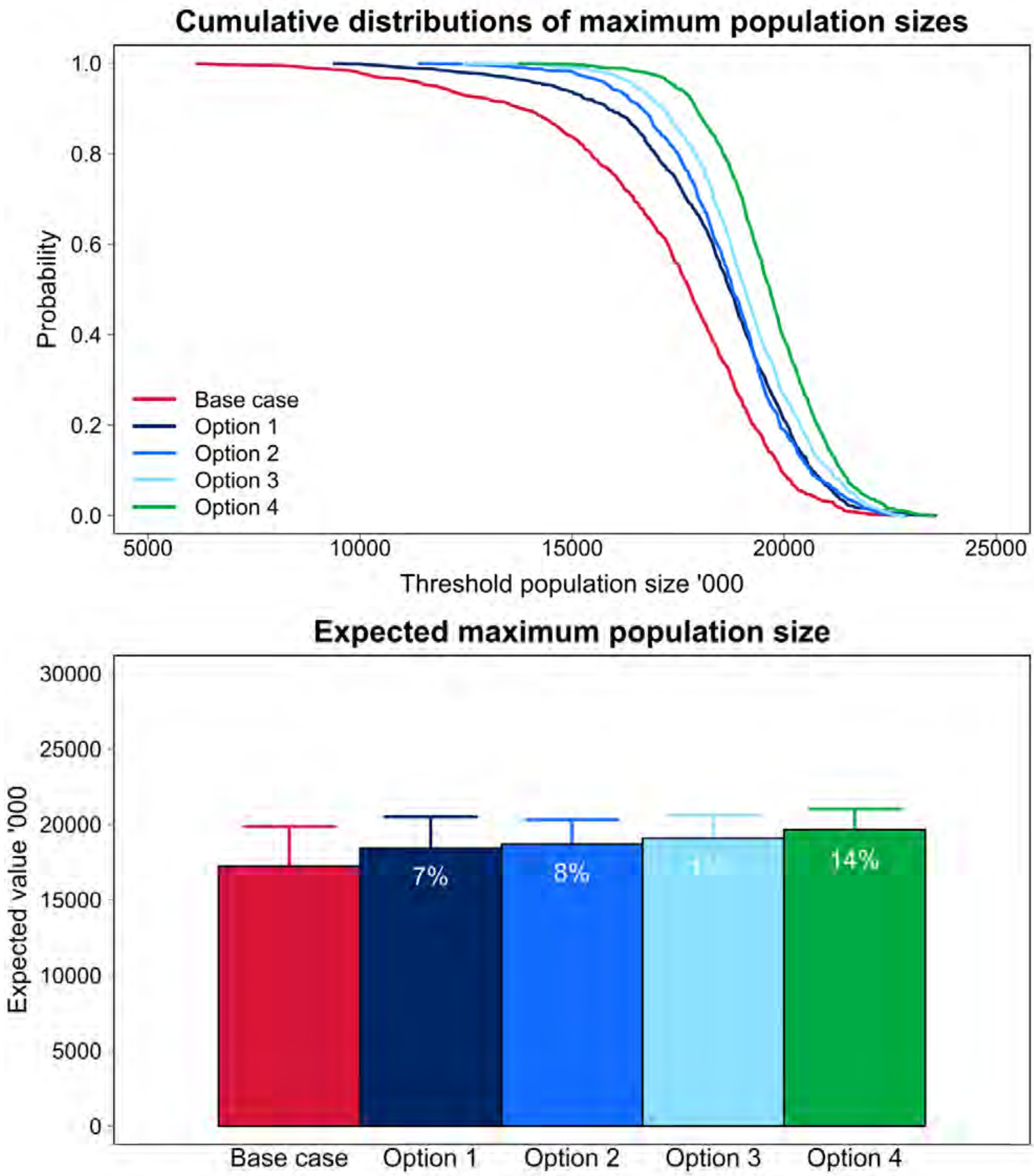
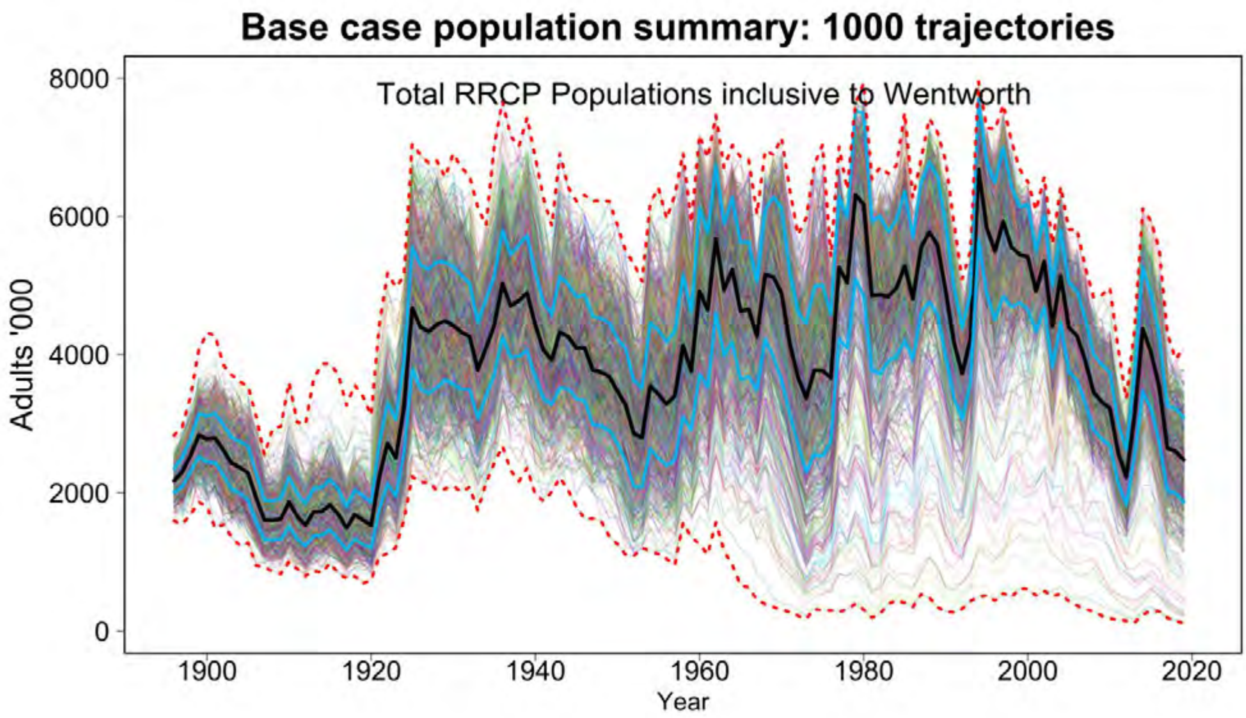
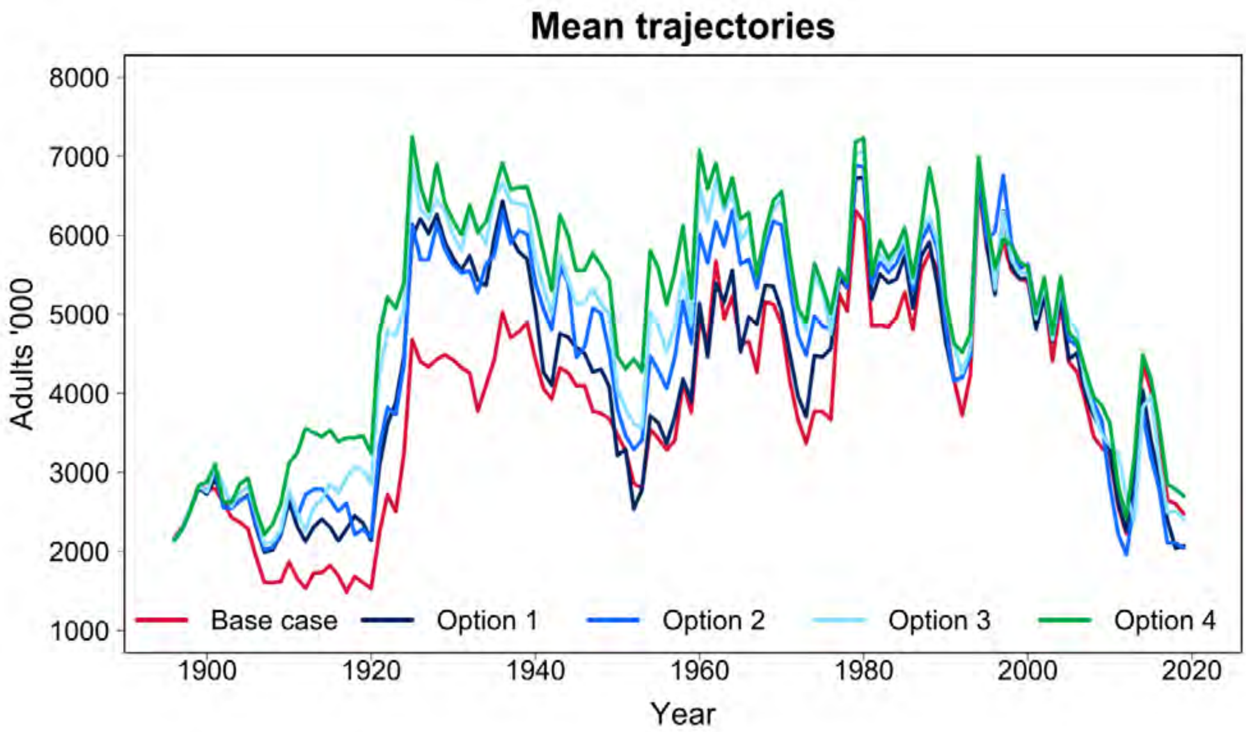
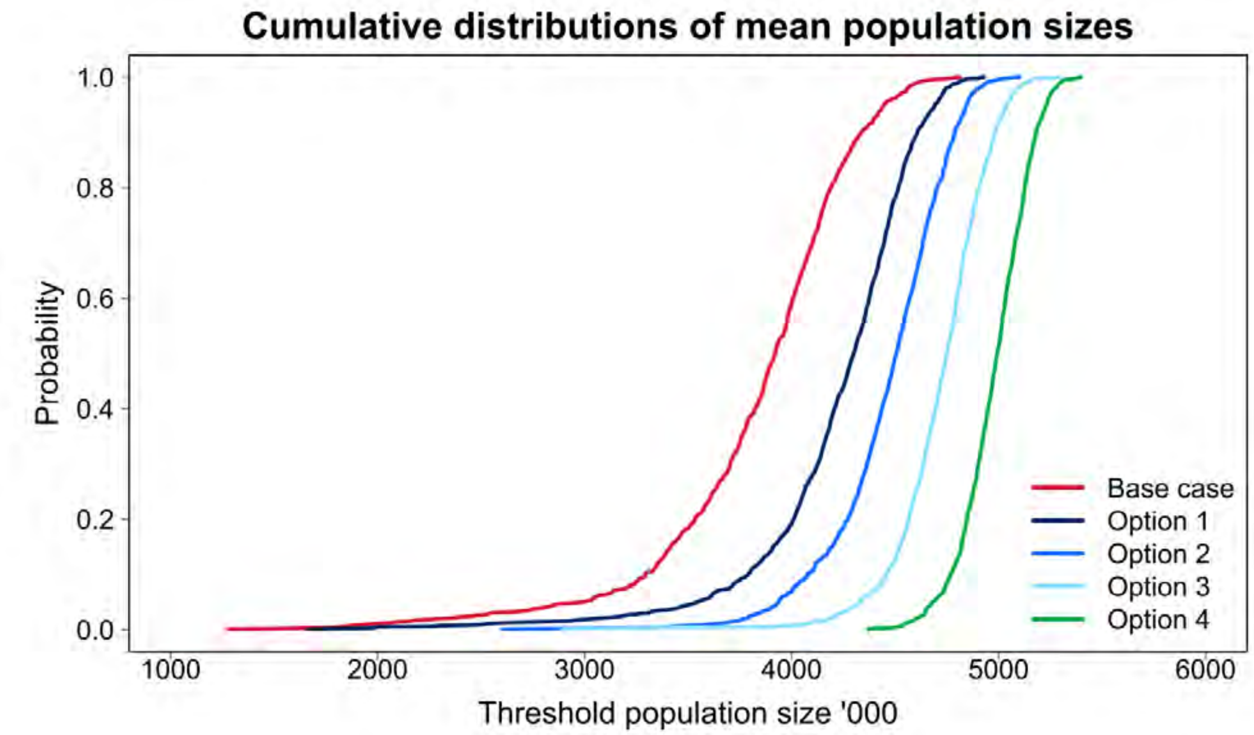


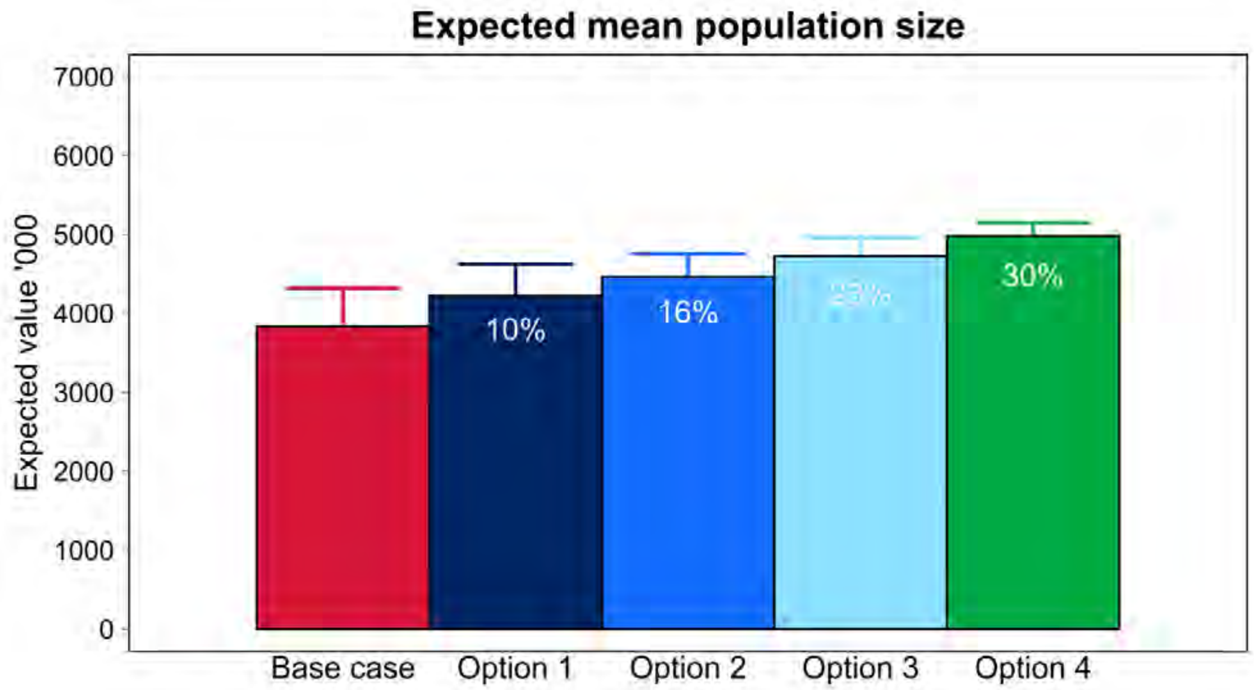
Figure A3.1. Golden Perch adult populations aggregated across all reaches in this study in the southern MDB for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult population trajectories for the Base case scenario; second panel: the mean adult population sizes; third panel: associated distributions of mean adult population sizes; fourth panel: expected mean adult population sizes, with the percentage change from the Base case shown in each bar; fifth panel: associated distributions of 10% quantiles of adult population sizes; sixth panel: expected 10% quantiles of adult population sizes; seventh panel: associated distributions of minimum adult population sizes; eighth panel: expected minimum adult population sizes; ninth panel: associated distributions of maximum adult population sizes; tenth panel: expected maximum adult population sizes.

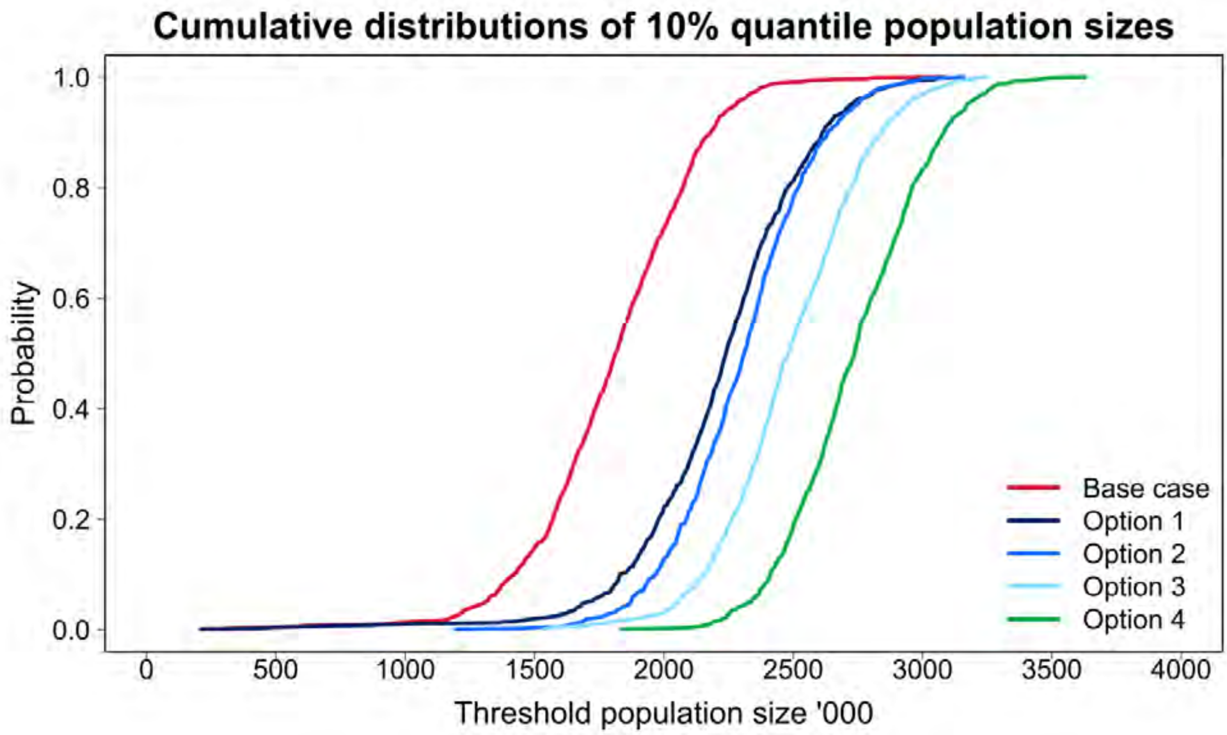
Golden Perch – Total RRCP populations inclusive to Wentworth



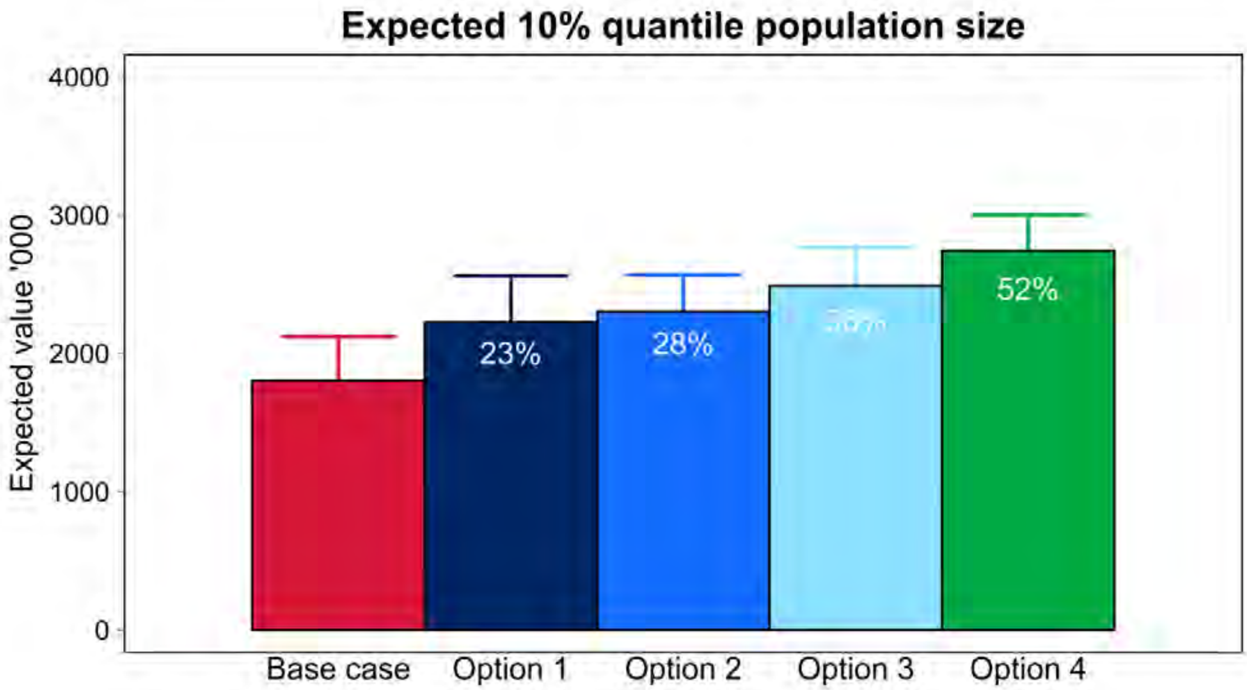



Cumulative distributions of mean population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
1000
2000
3000
4000
5000
6000
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4

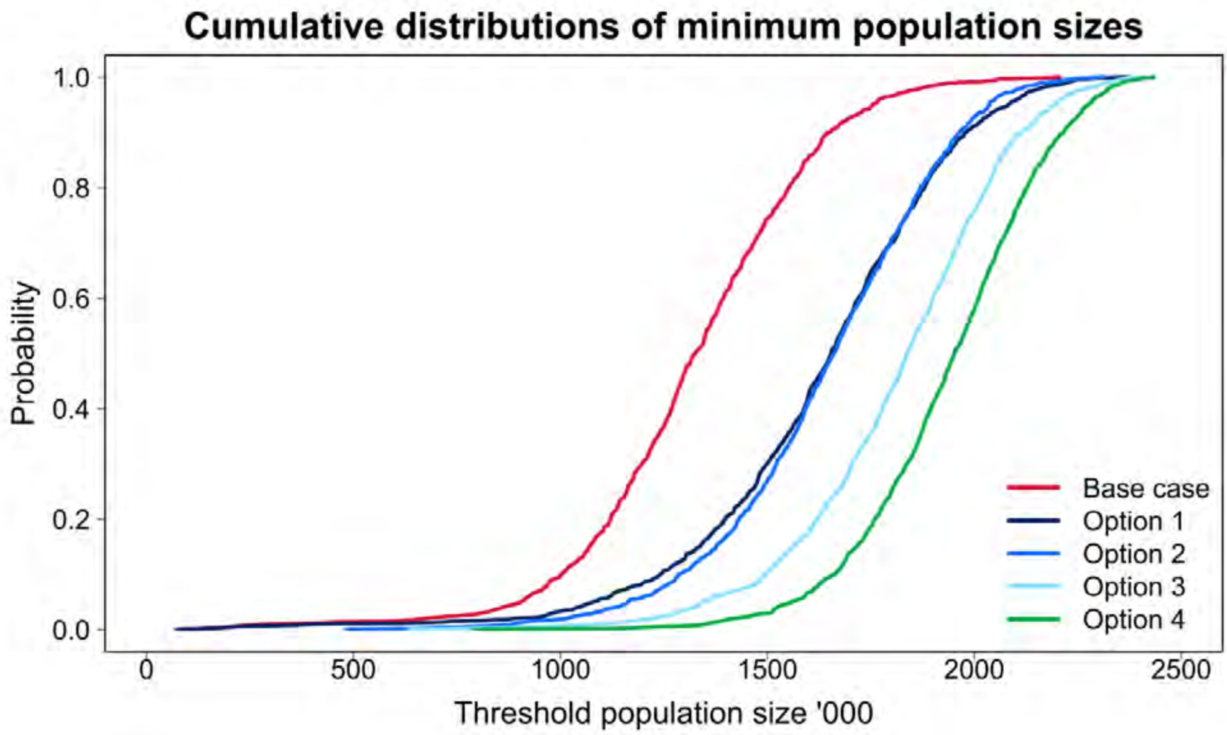

Expected mean population size
Expected value '000
7000
6000
5000
4000
3000
2000
1000
0
10%
16%
23%
30%
Base case
Option 1
Option 2
Option 3
Option 4

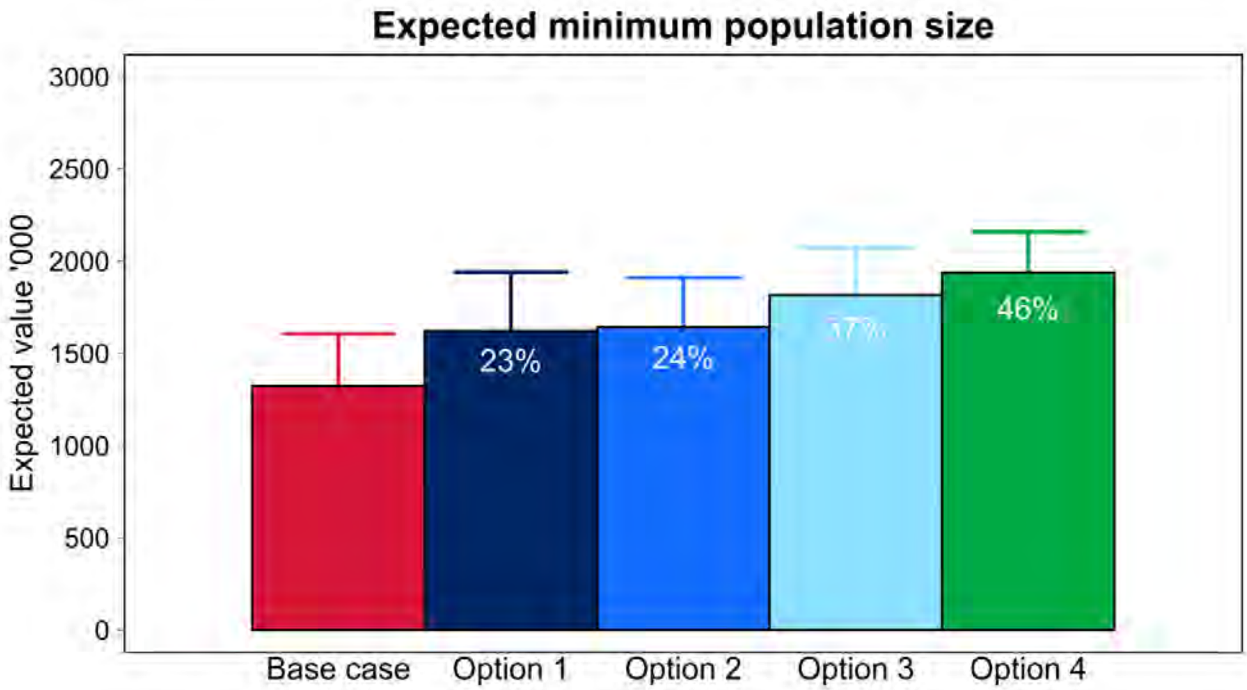


Cumulative distributions of 10% quantile population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
500
1000
1500
2000
2500
3000
3500
4000
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4



Expected 10% quantile population size
Expected value '000
4000
3000
2000
1000
0
23%
28%
52%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
500
1000
1500
2000
2500
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected minimum population size
Expected value '000
3000
2500
2000
1500
1000
500
0
23%
24%
37%
46%
Base case
Option 1
Option 2
Option 3
Option 4

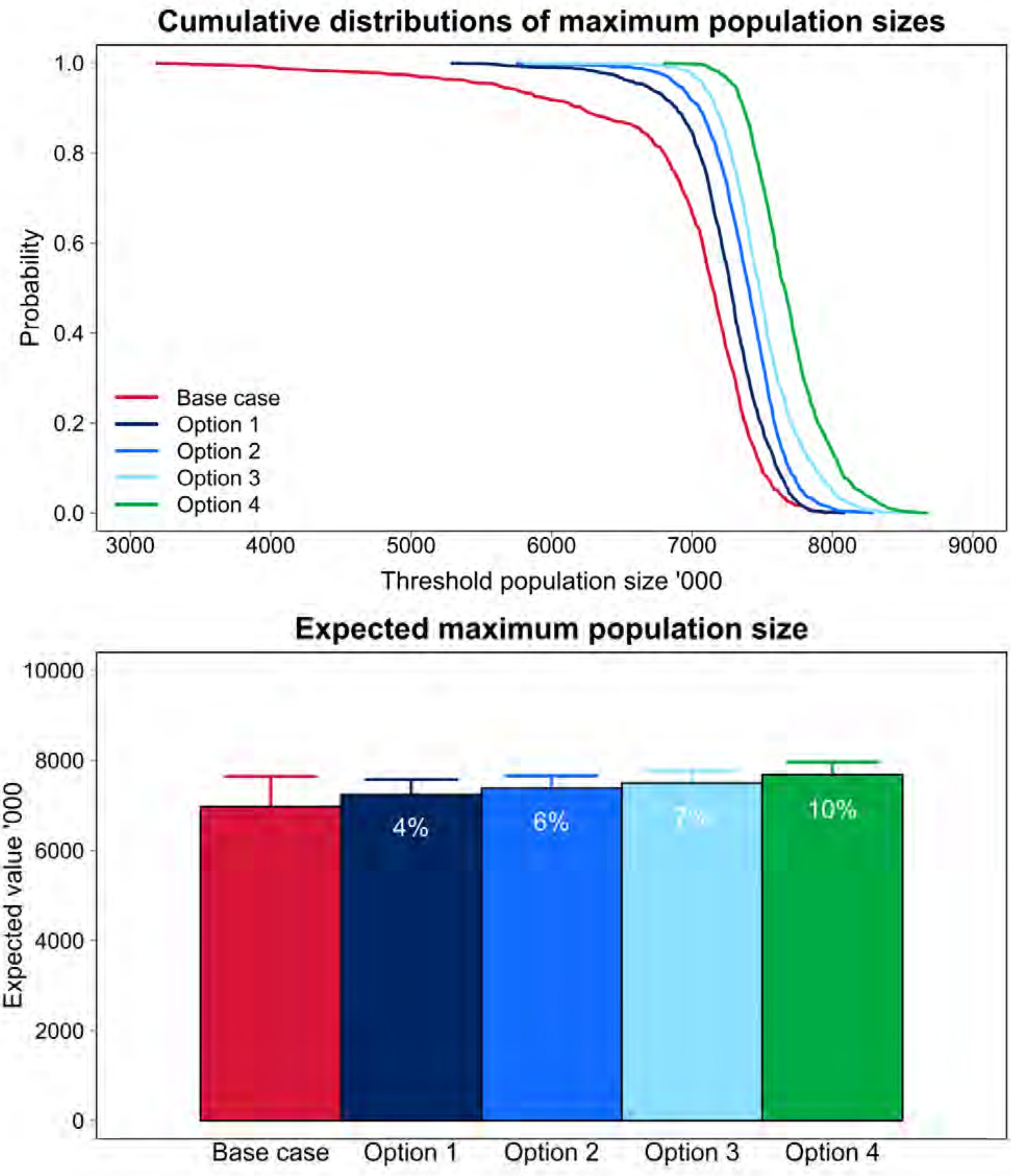
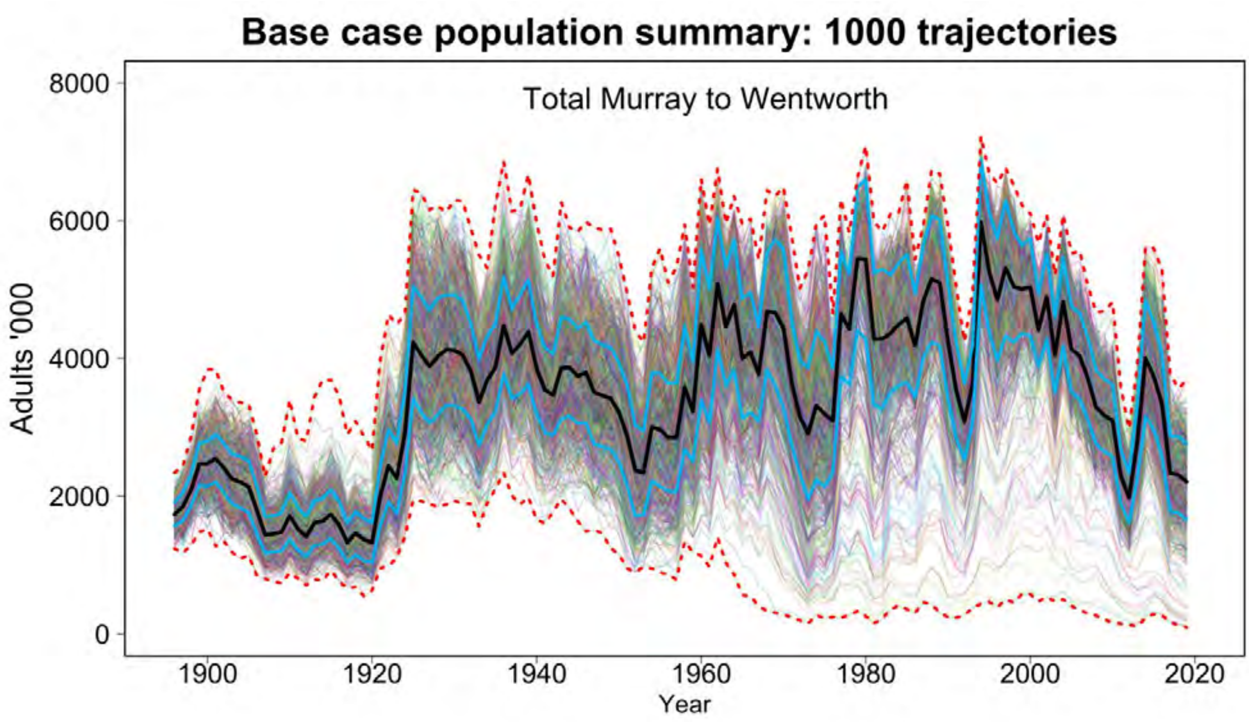
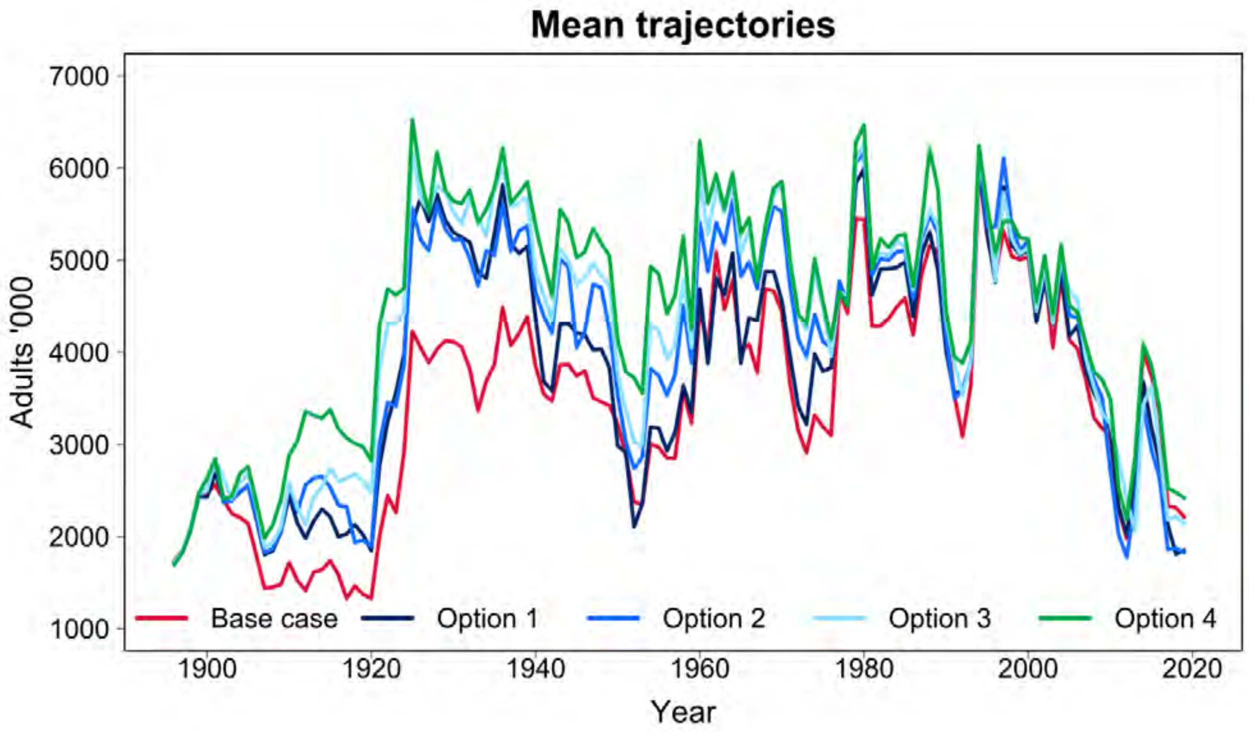
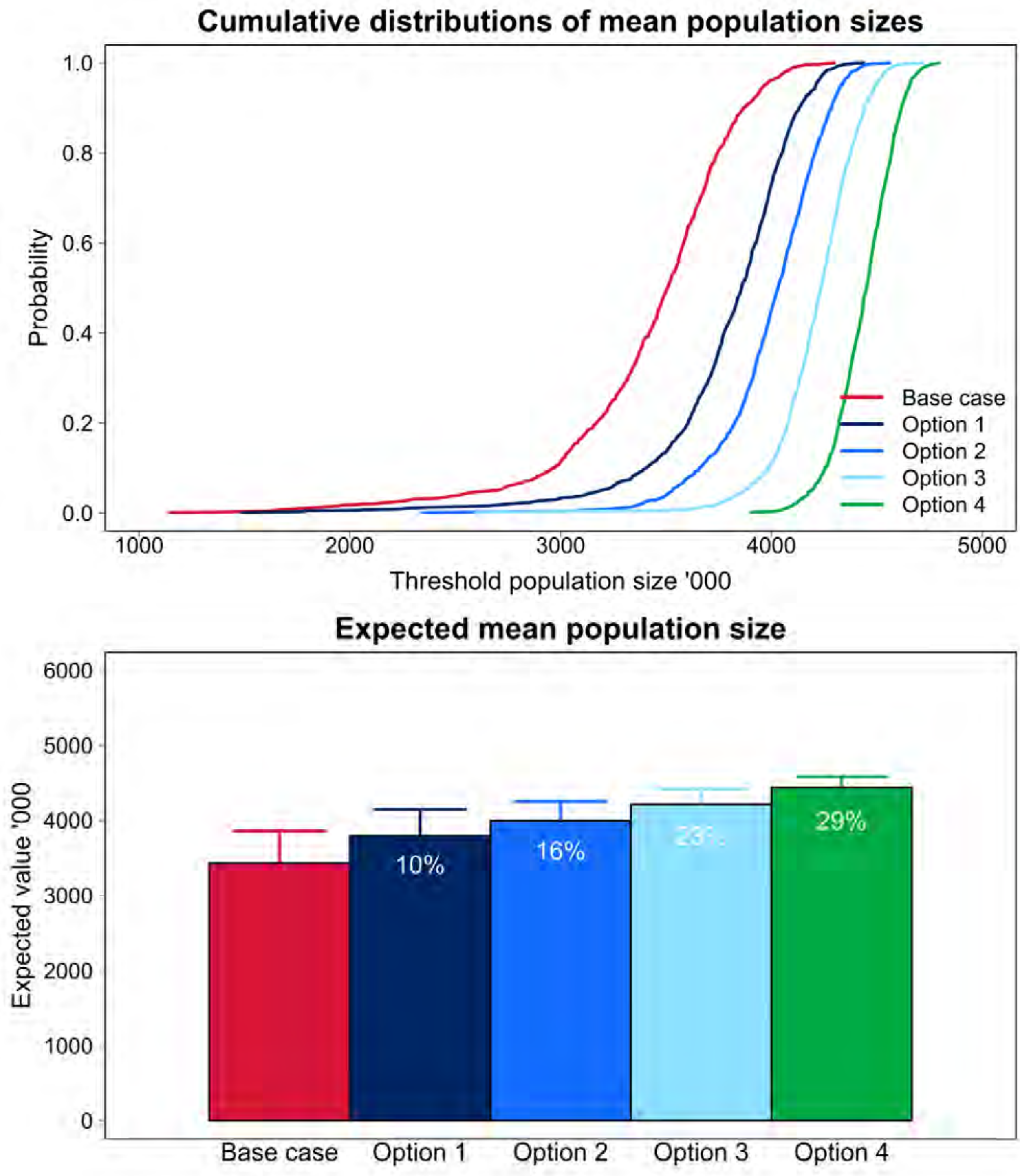


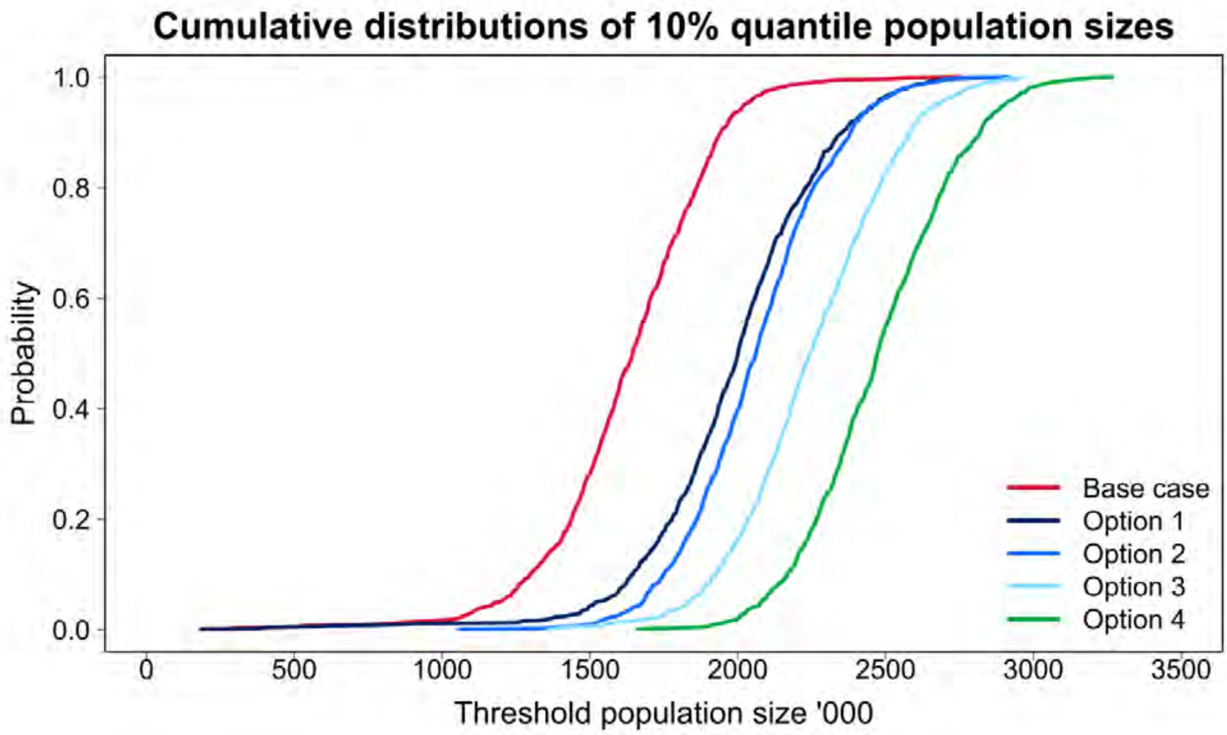
Figure A3.2. Golden Perch adult populations aggregated across all modelled RRCP focal zones, together with the Wakool Junction to Wentworth reach, for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult population trajectories for the Base case scenario; second panel: the mean adult population sizes; third panel: associated distributions of mean adult population sizes; fourth panel: expected mean adult population sizes, with the percentage change from the Base case shown in each bar; fifth panel: associated distributions of 10% quantiles of adult population sizes; sixth panel: expected 10% quantiles of adult population sizes; seventh panel: associated distributions of minimum adult population sizes; eighth panel: expected minimum adult population sizes; ninth panel: associated distributions of maximum adult population sizes; tenth panel: expected maximum adult population sizes.

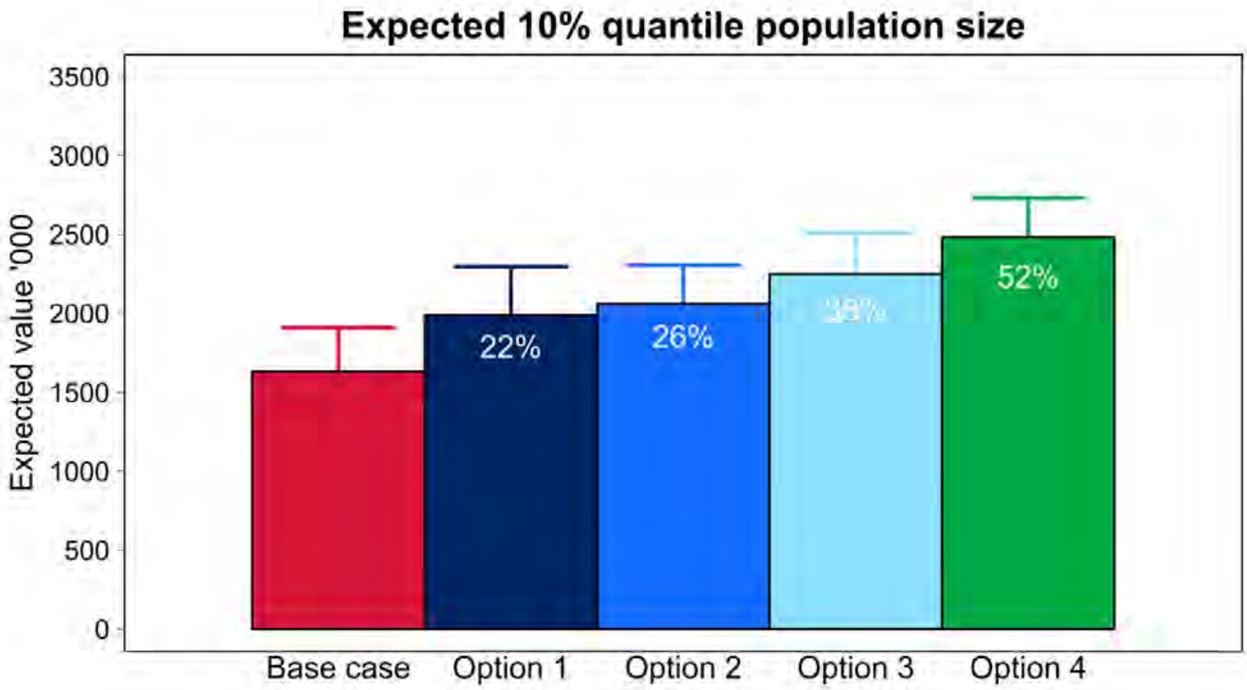
Golden Perch – Total Murray River populations inclusive to Wentworth

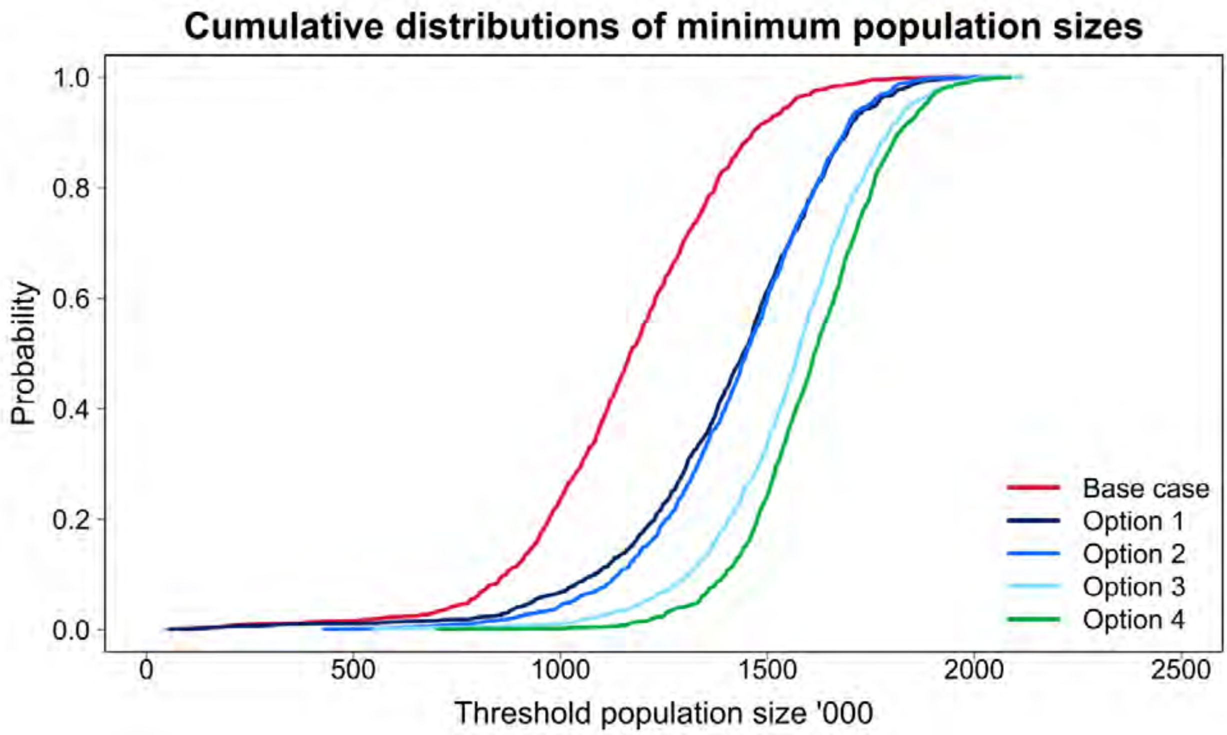




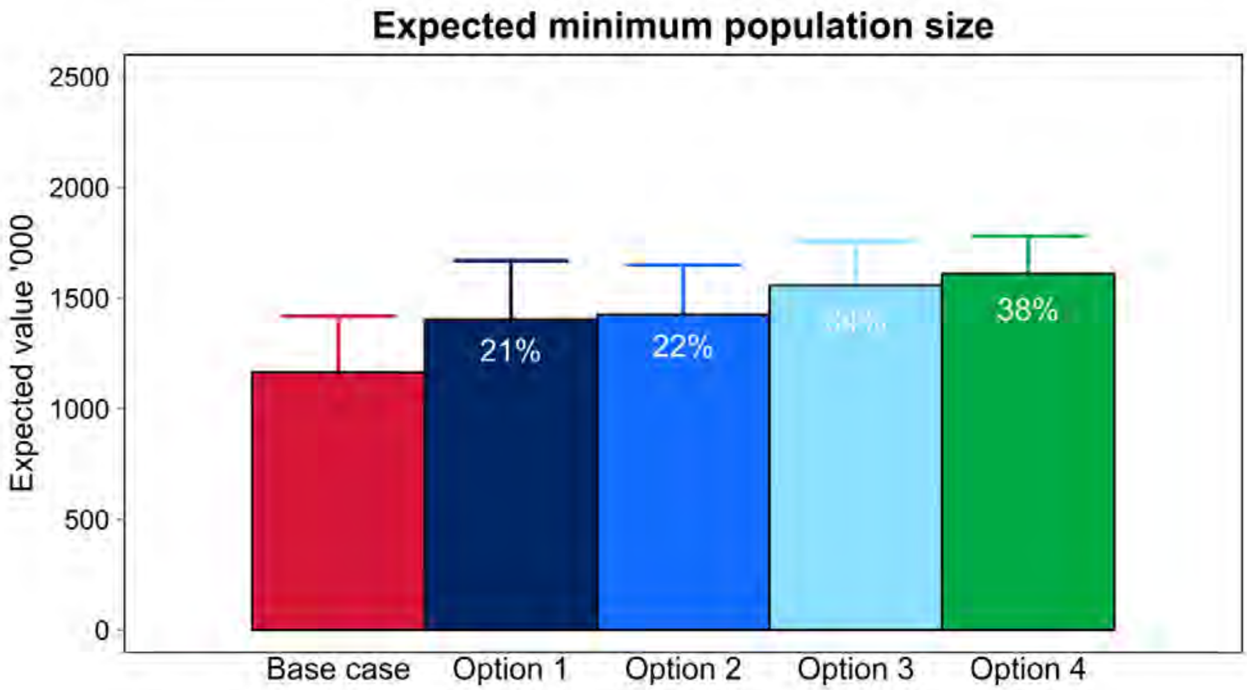

Cumulative distributions of mean population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
1000
2000
3000
4000
5000
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4
Expected mean population size
Expected value '000
6000
5000
4000
3000
2000
1000
0
10%
16%
29%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of 10% quantile population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
500
1000
1500
2000
2500
3000
3500
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected 10% quantile population size
Expected value '000
3500
3000
2500
2000
1500
1000
500
0
22%
26%
38%
52%
Base case
Option 1
Option 2
Option 3
Option 4



Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
500
1000
1500
2000
2500
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4



Expected minimum population size
Expected value '000
2500
2000
1500
1000
500
0
21%
22%
38%
Base case
Option 1
Option 2
Option 3
Option 4

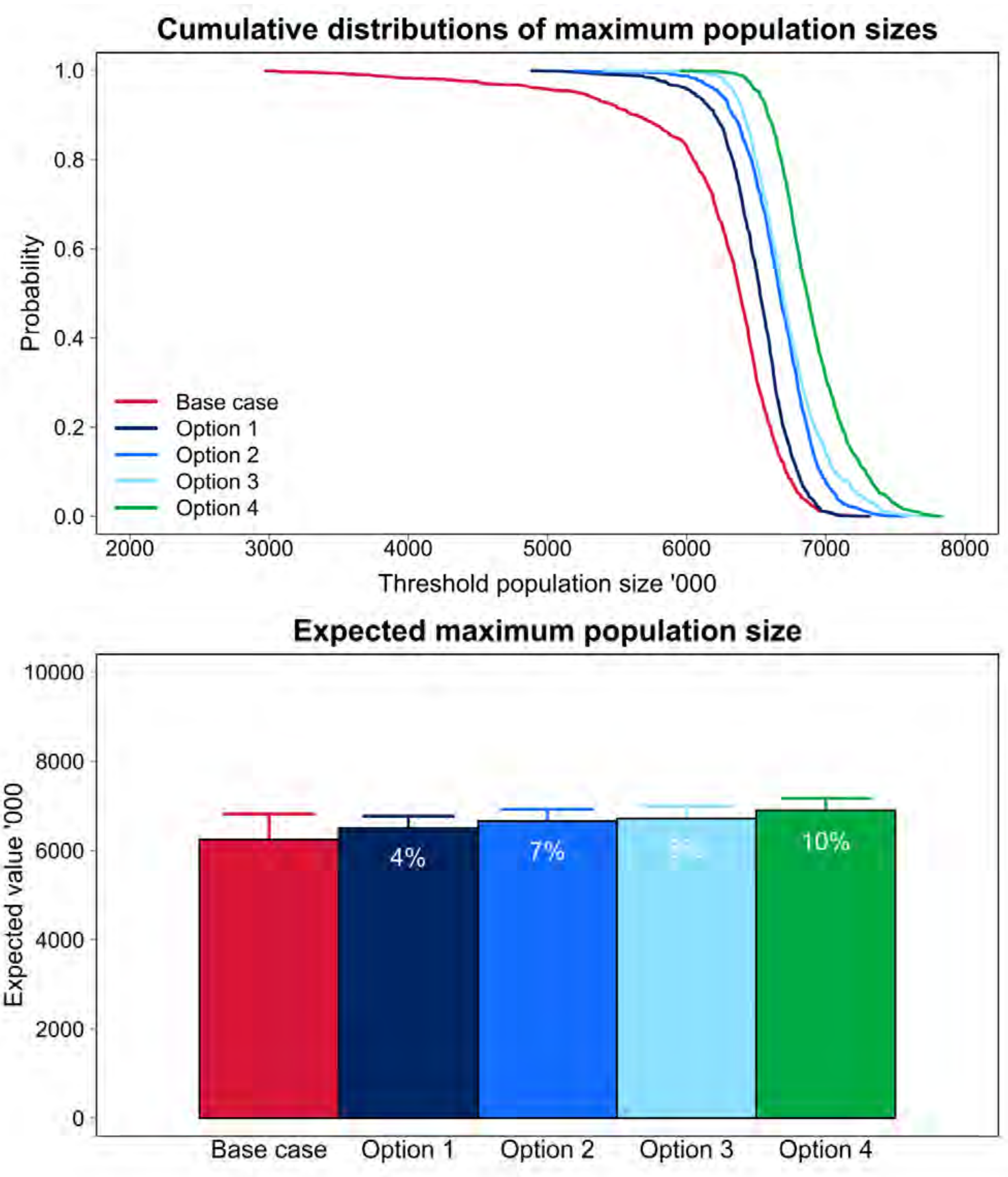
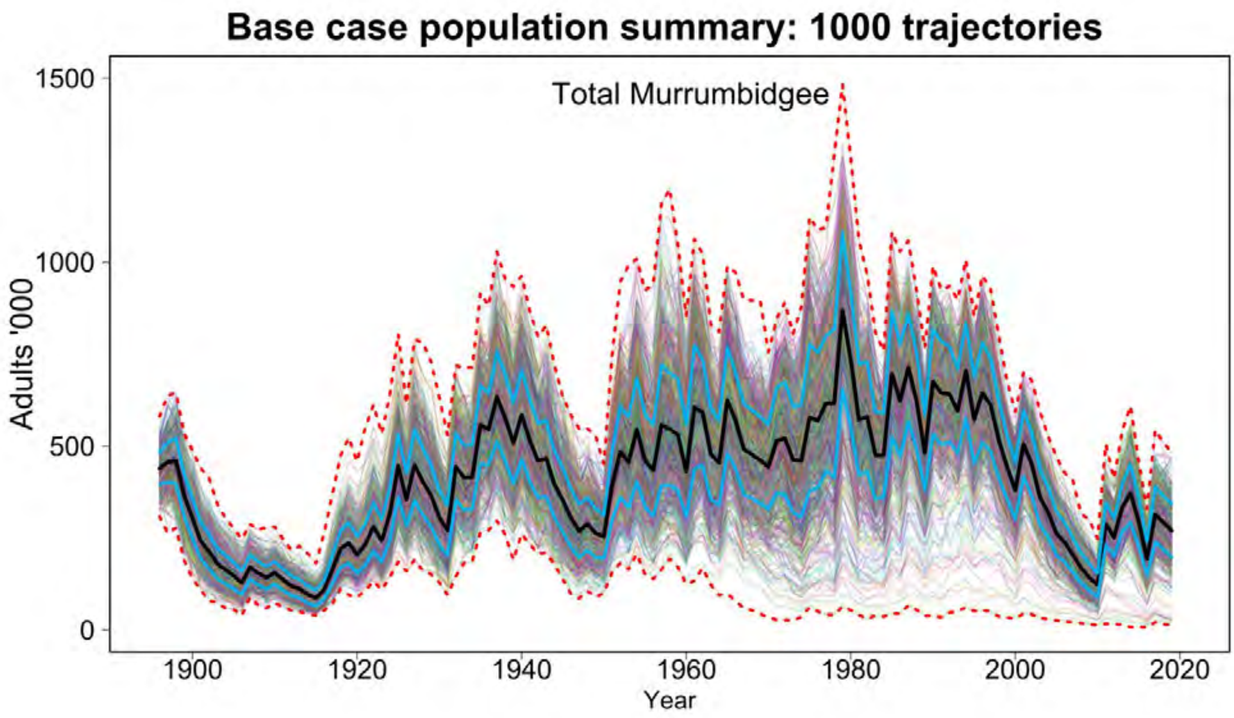
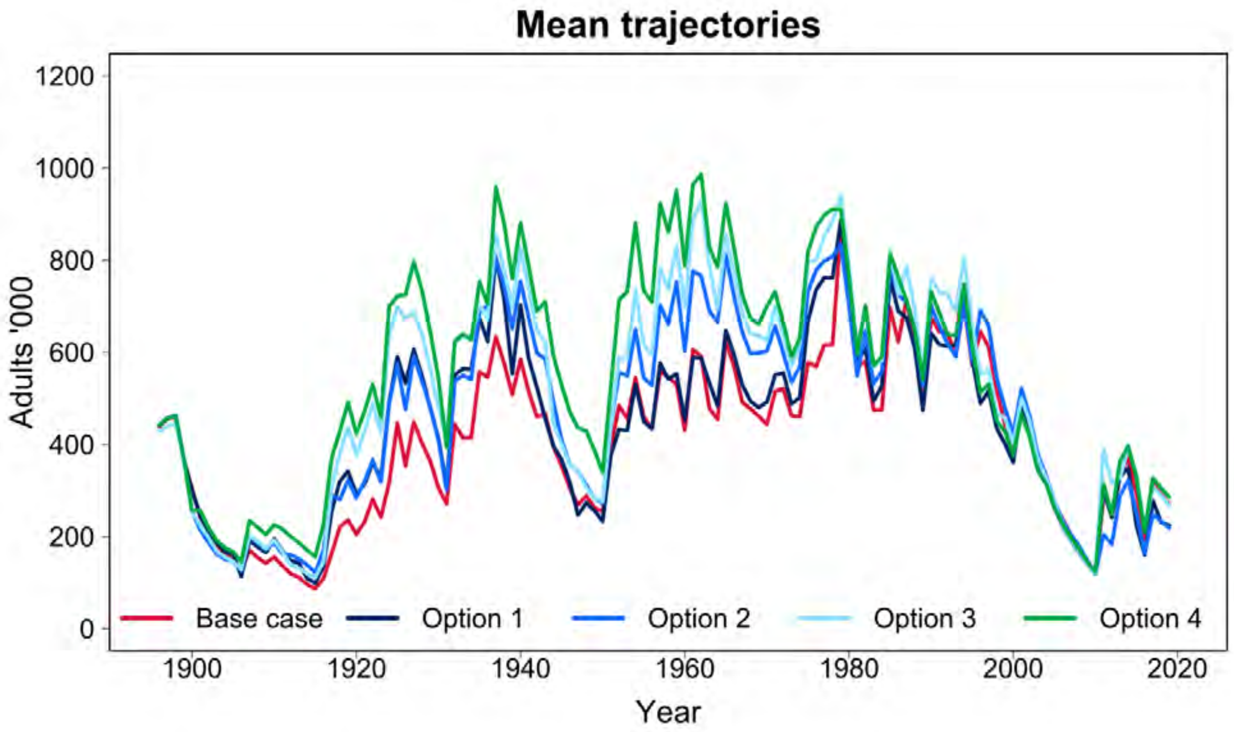
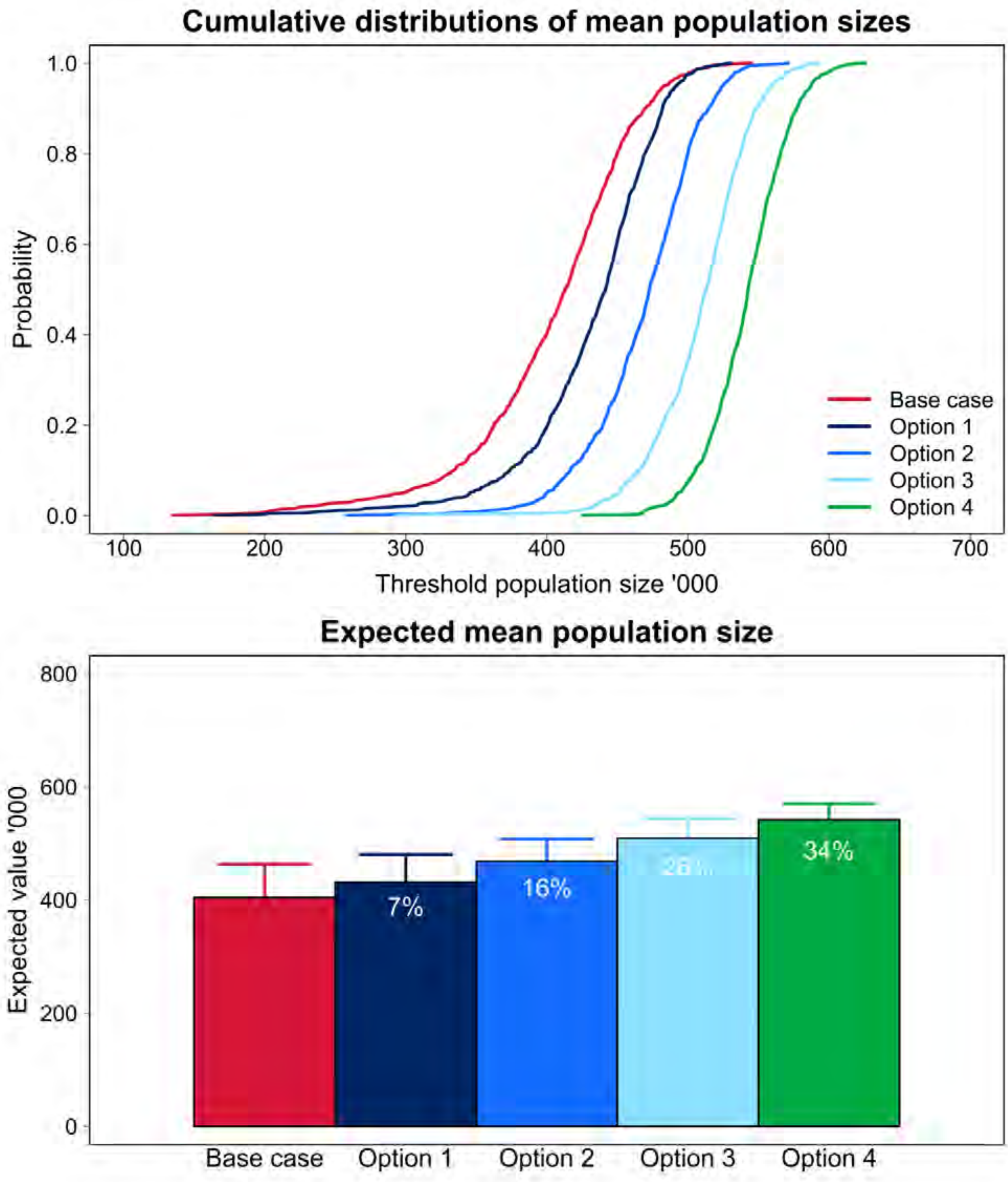


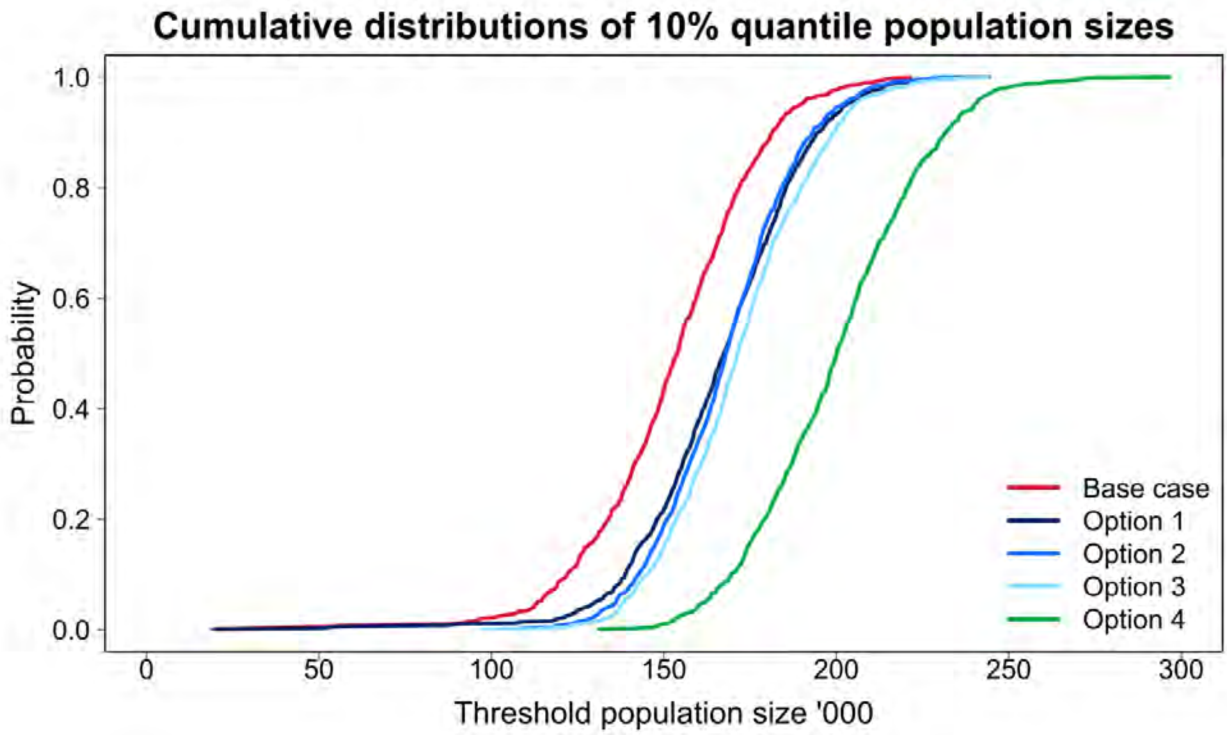
Figure A3.3. Golden Perch adults aggregated across the Murray River RRCP focal zones (including the Edward River), together with the Wakool Junction to Wentworth reach, for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

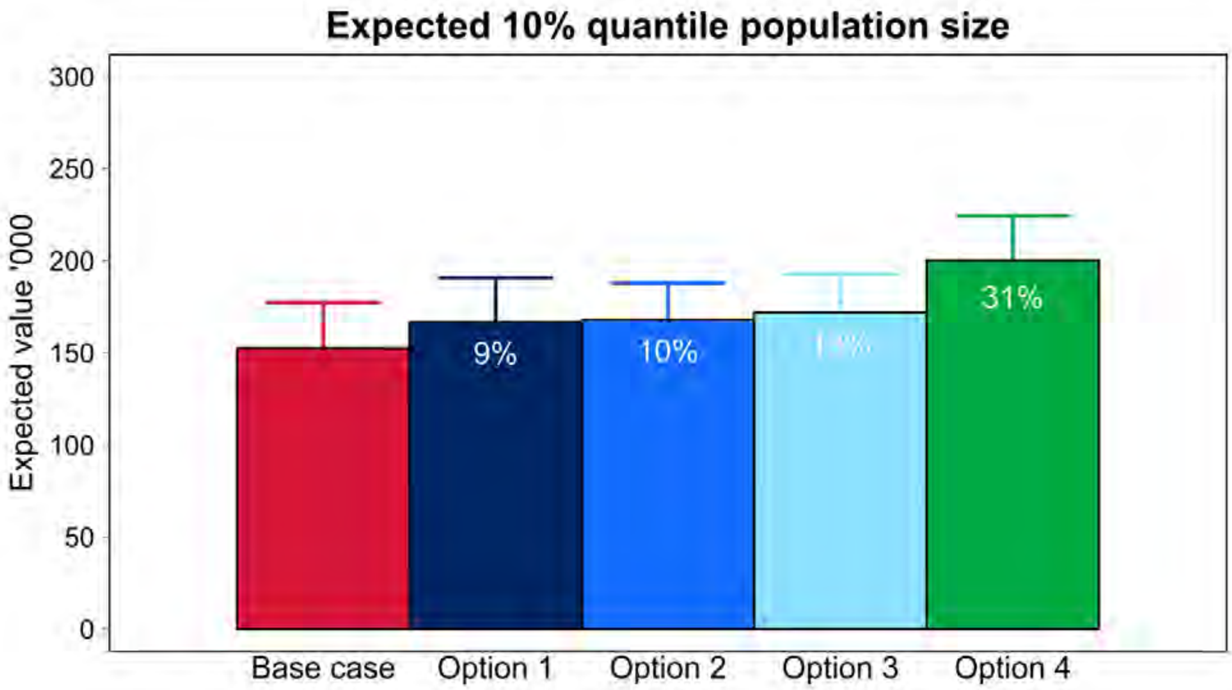
Golden Perch – Total Murrumbidgee River populations

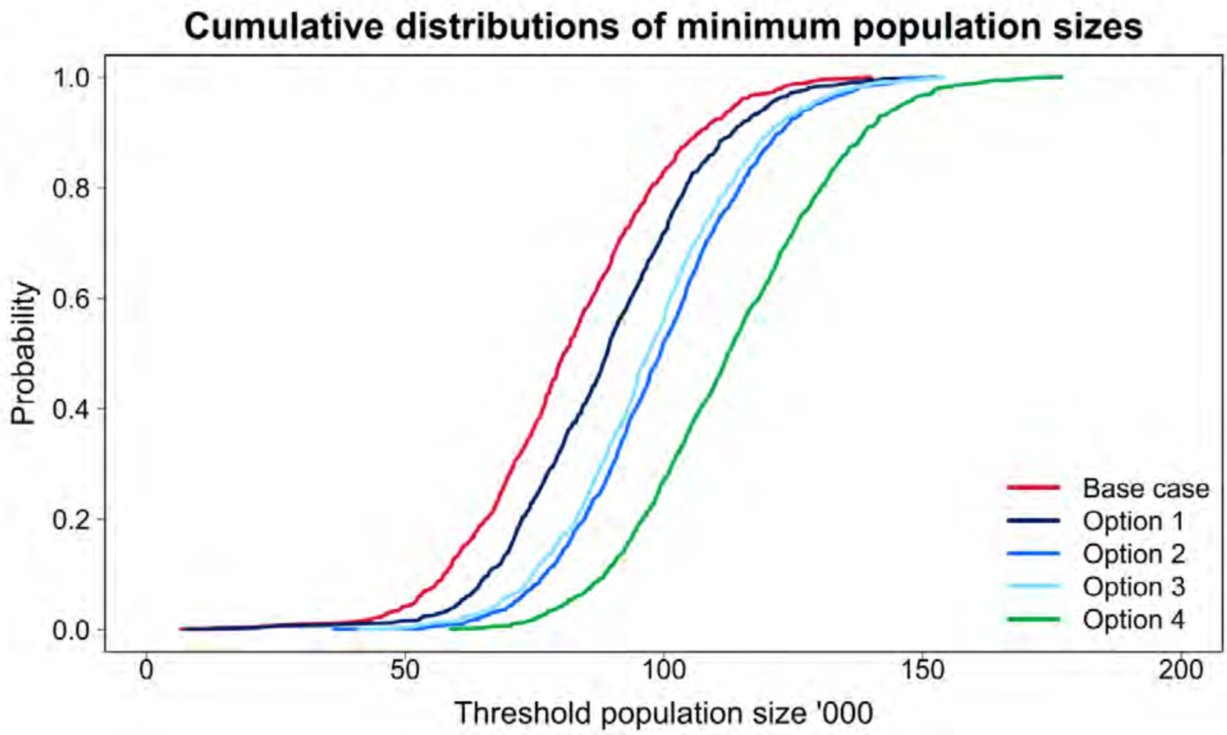


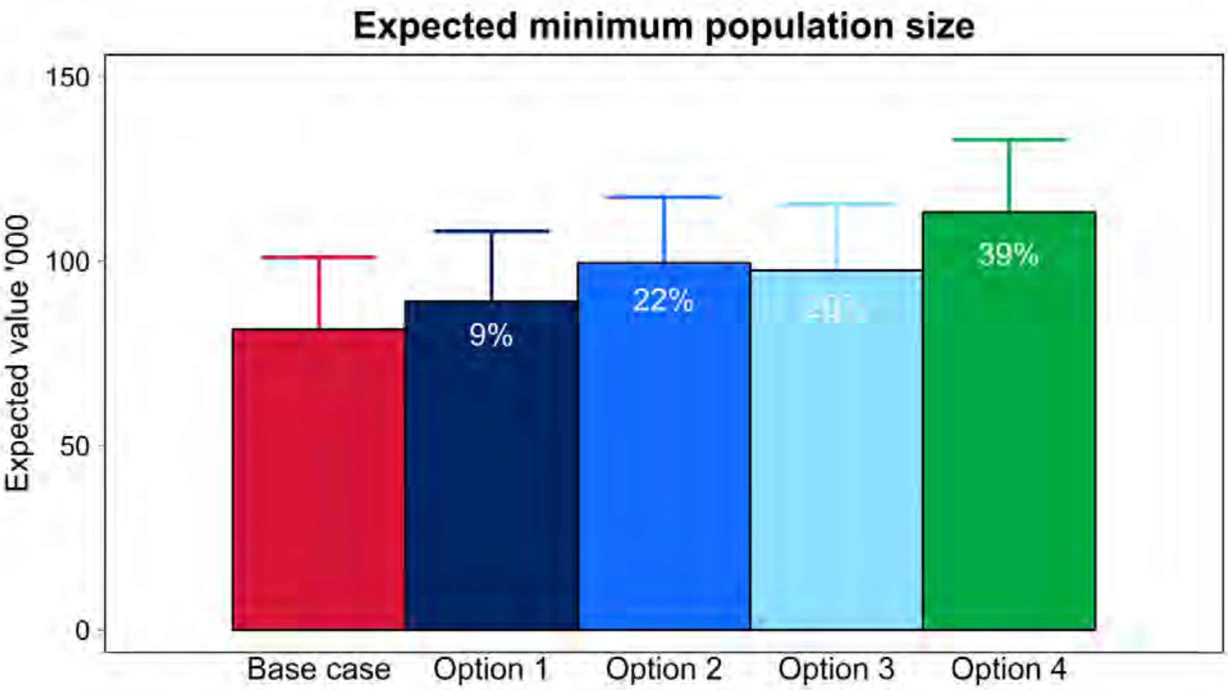



Cumulative distributions of mean population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
100
200
300
400
500
600
700
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4
Expected mean population size
Expected value '000
800
600
400
200
0
7%
16%
26%
34%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of 10% quantile population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
50
100
150
200
250
300
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected 10% quantile population size
Expected value '000
300
250
200
150
100
50
0
9%
10%
31%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
50
100
150
200
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected minimum population size
Expected value '000
150
100
50
0
9%
22%
39%
Base case
Option 1
Option 2
Option 3
Option 4

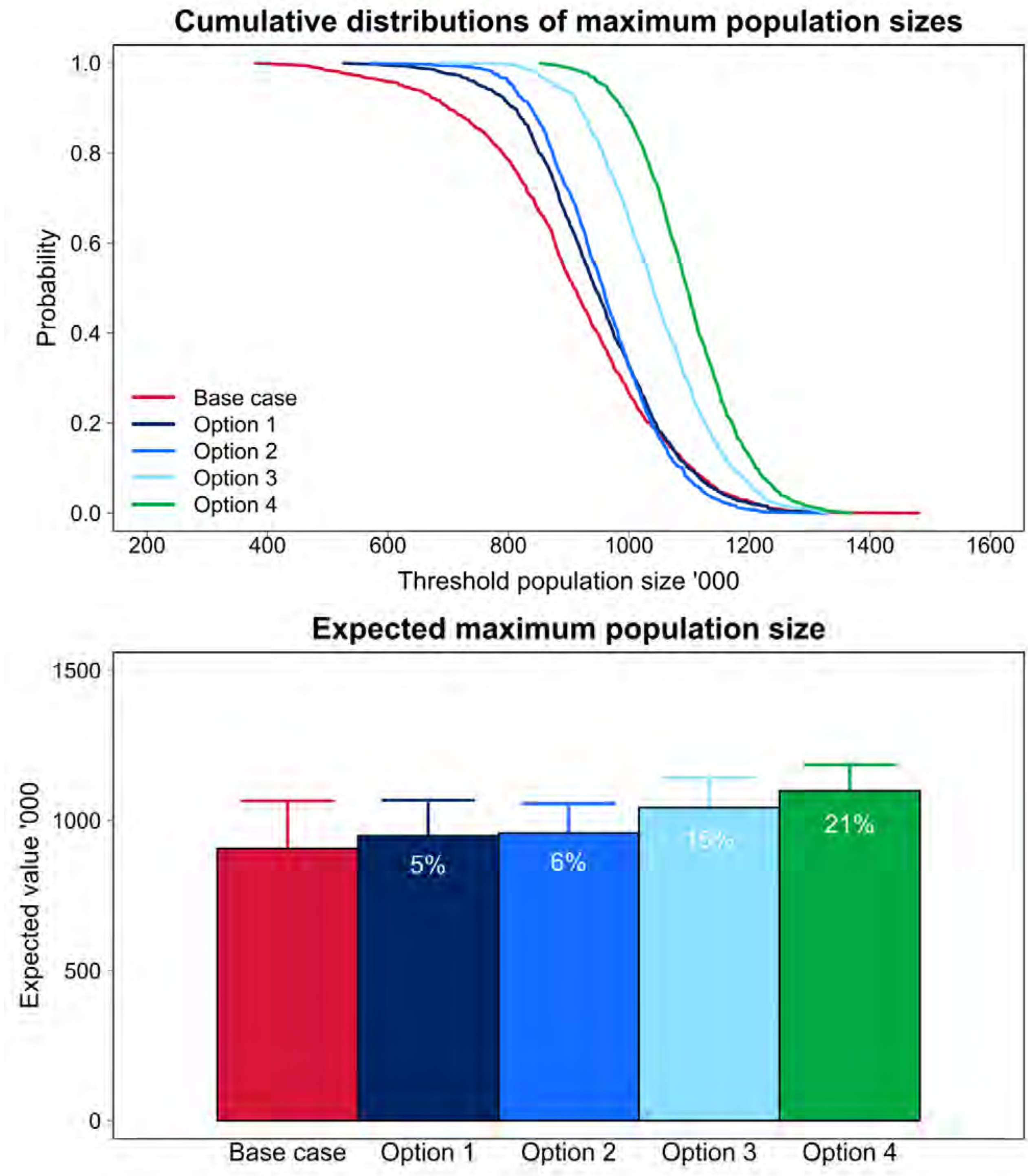
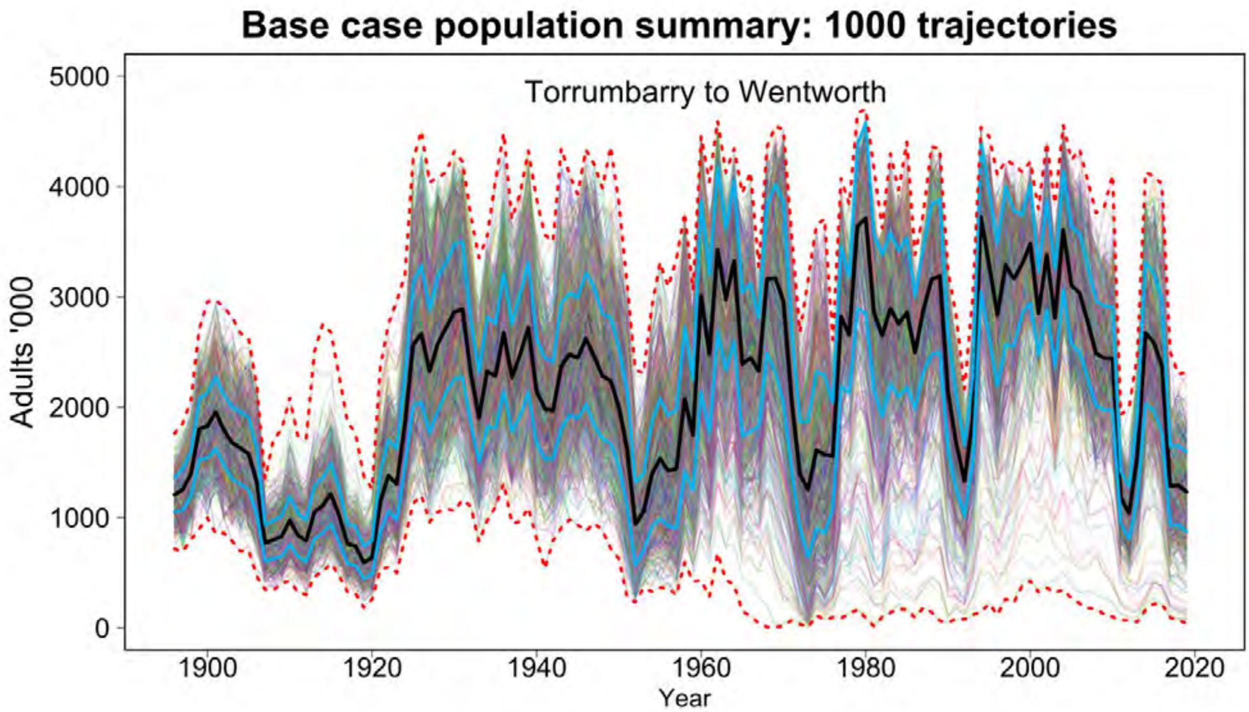
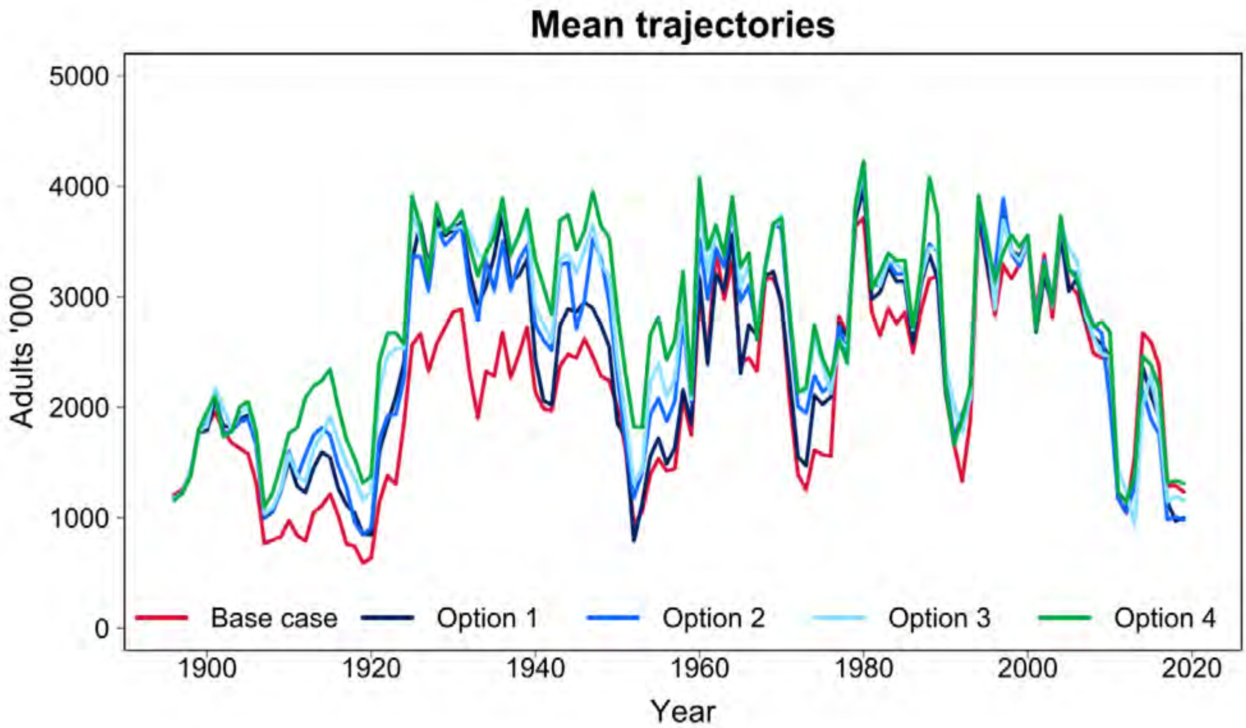
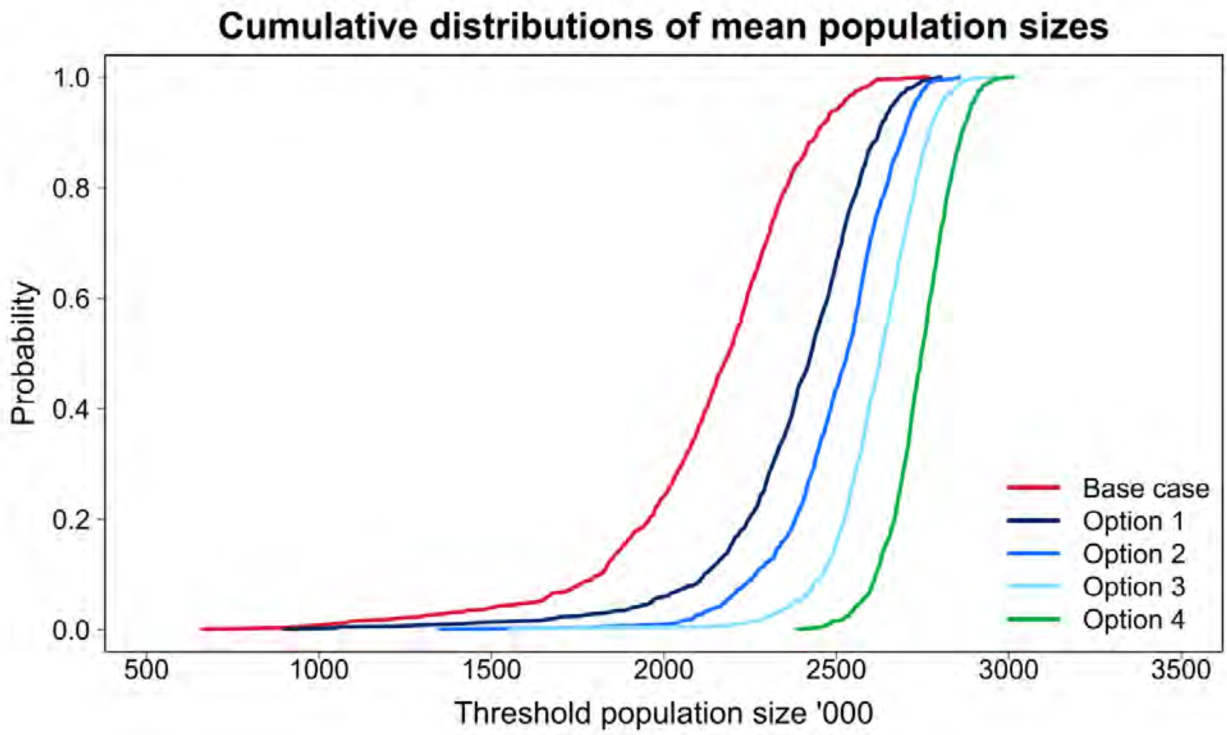


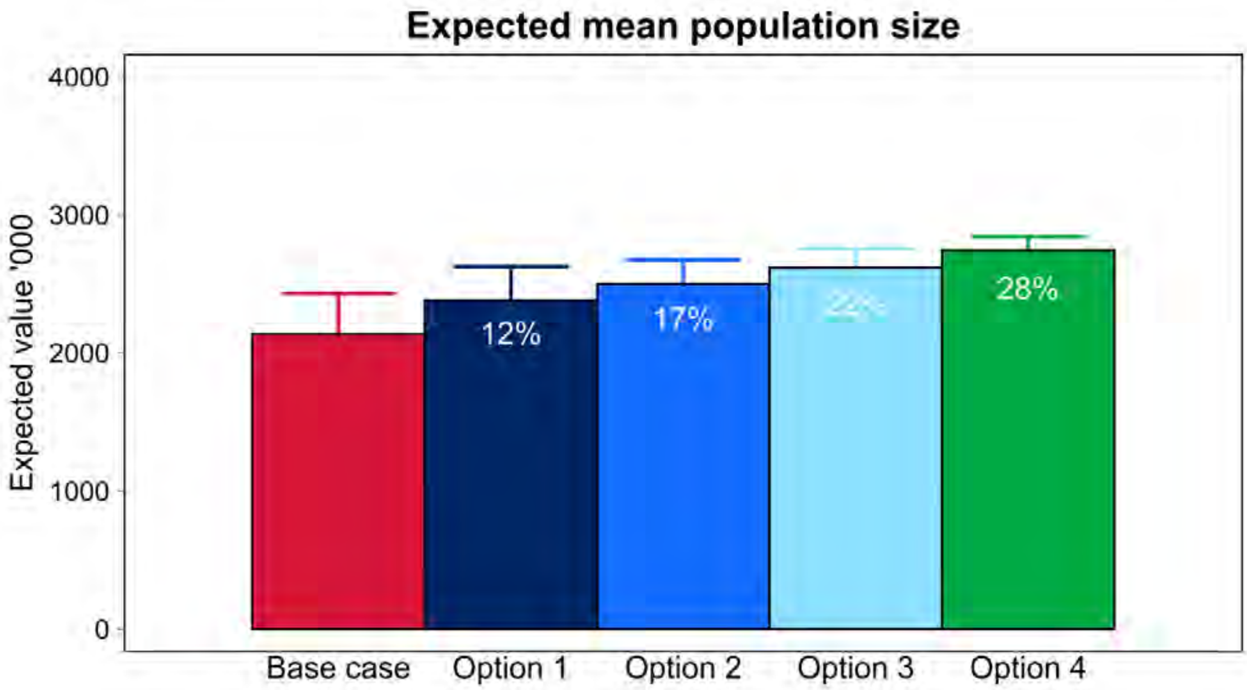
Figure A3.4. Golden Perch adults aggregated across the Murrumbidgee River RRCP focal zone for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

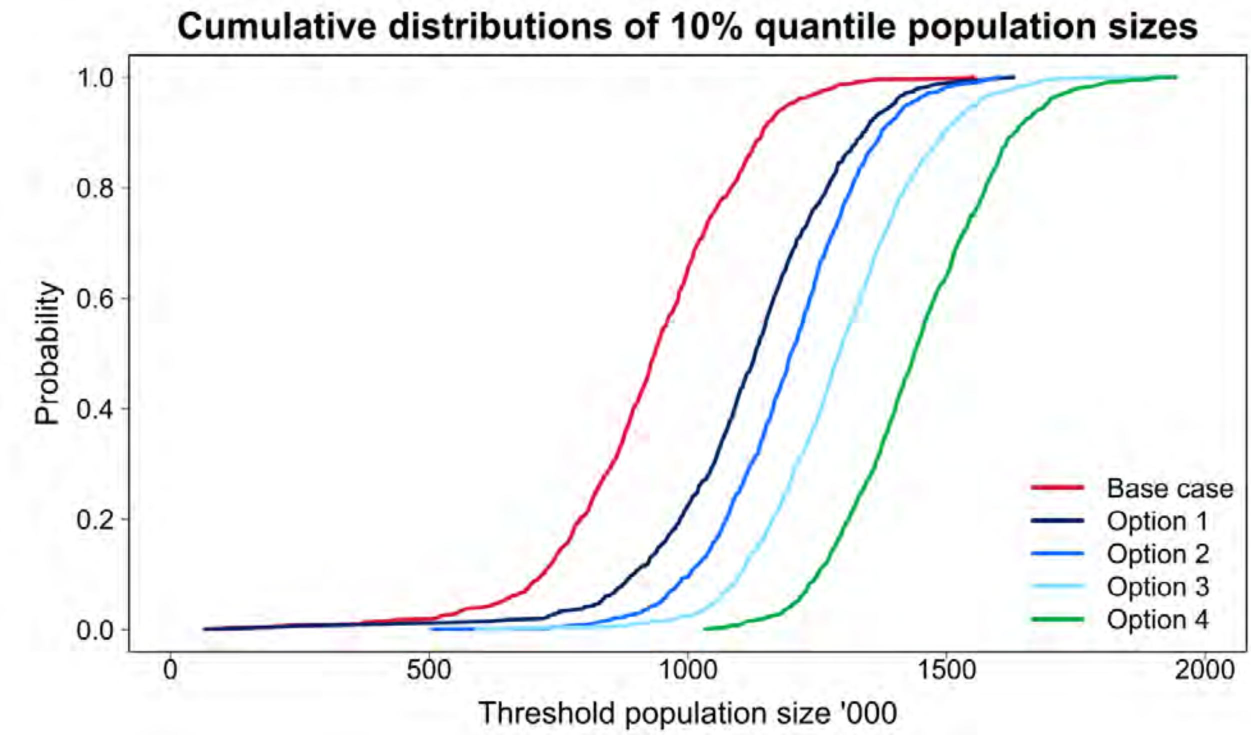
Golden Perch – Torrumbarry to Wentworth

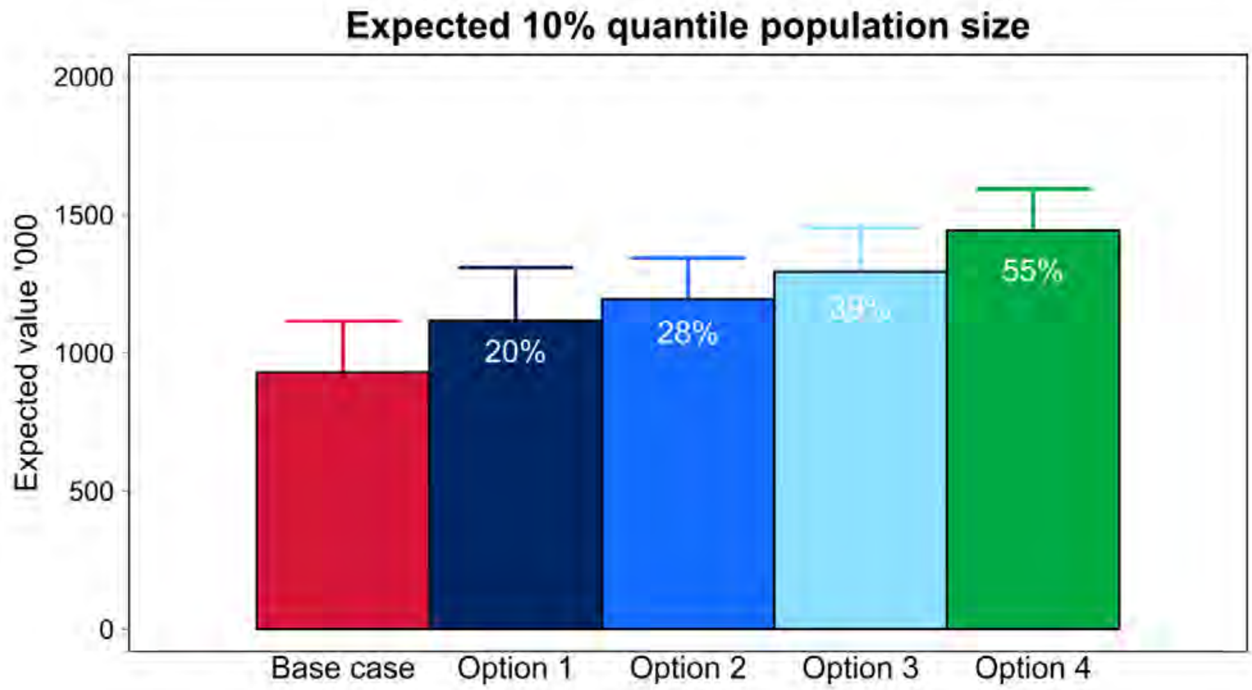


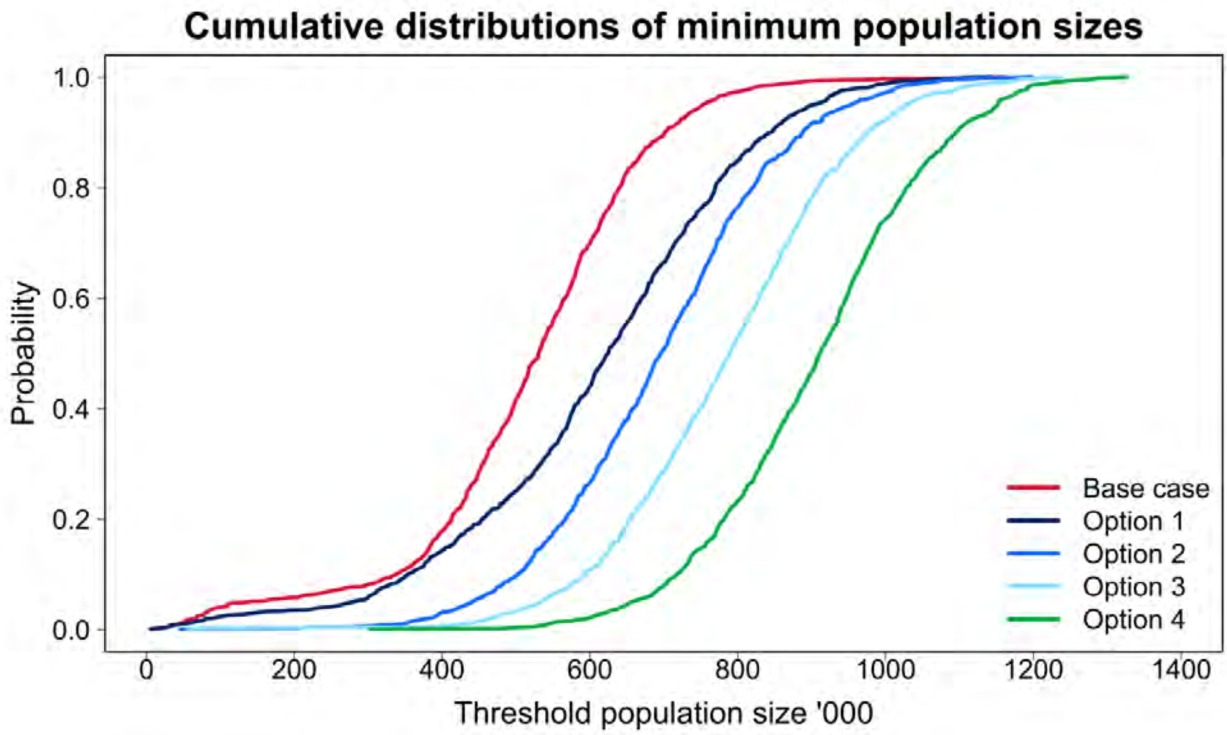


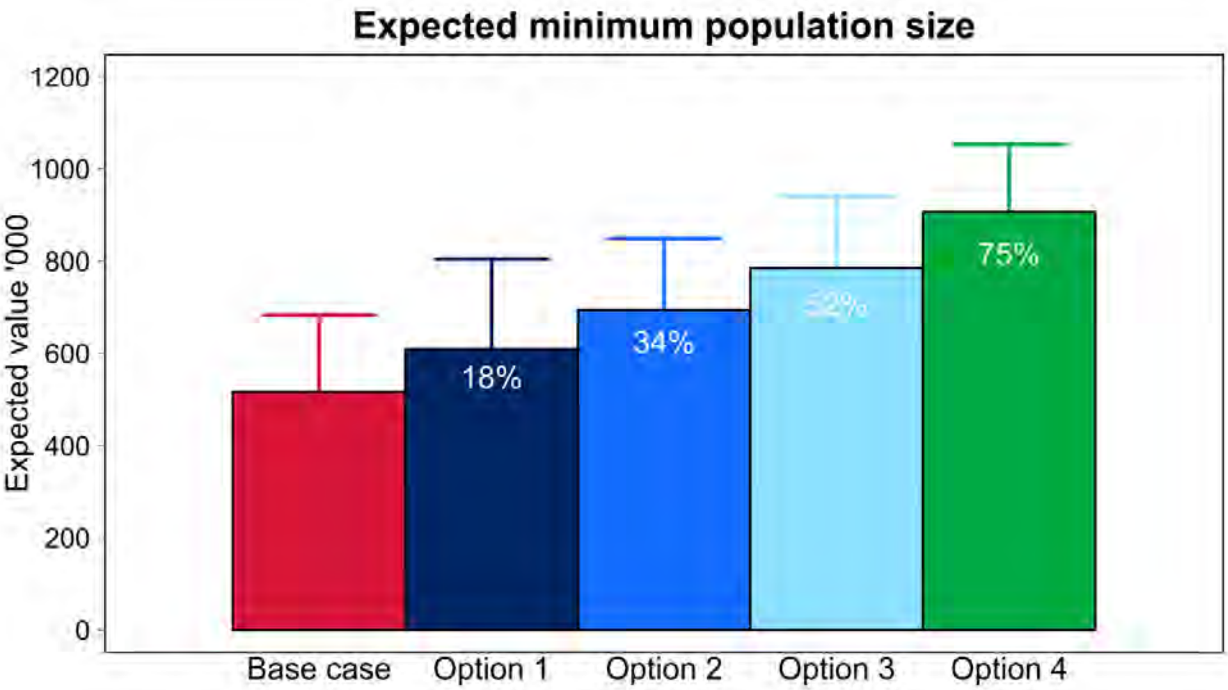

Cumulative distributions of mean population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
500
1000
1500
2000
2500
3000
3500
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected mean population size
Expected value '000
4000
3000
2000
1000
0
12%
17%
28%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of 10% quantile population sizes
Probability
Threshold population size '000
1.0
0.8
0.6
0.4
0.2
0.0
0
500
1000
1500
2000
Base case
Option 1
Option 2
Option 3
Option 4


Expected 10% quantile population size
Expected value '000
2000
1500
1000
500
0
20%
28%
39%
55%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
200
400
600
800
1000
1200
1400
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected minimum population size
Expected value '000
1200
1000
800
600
400
200
0
18%
34%
52%
75%
Base case
Option 1
Option 2
Option 3
Option 4

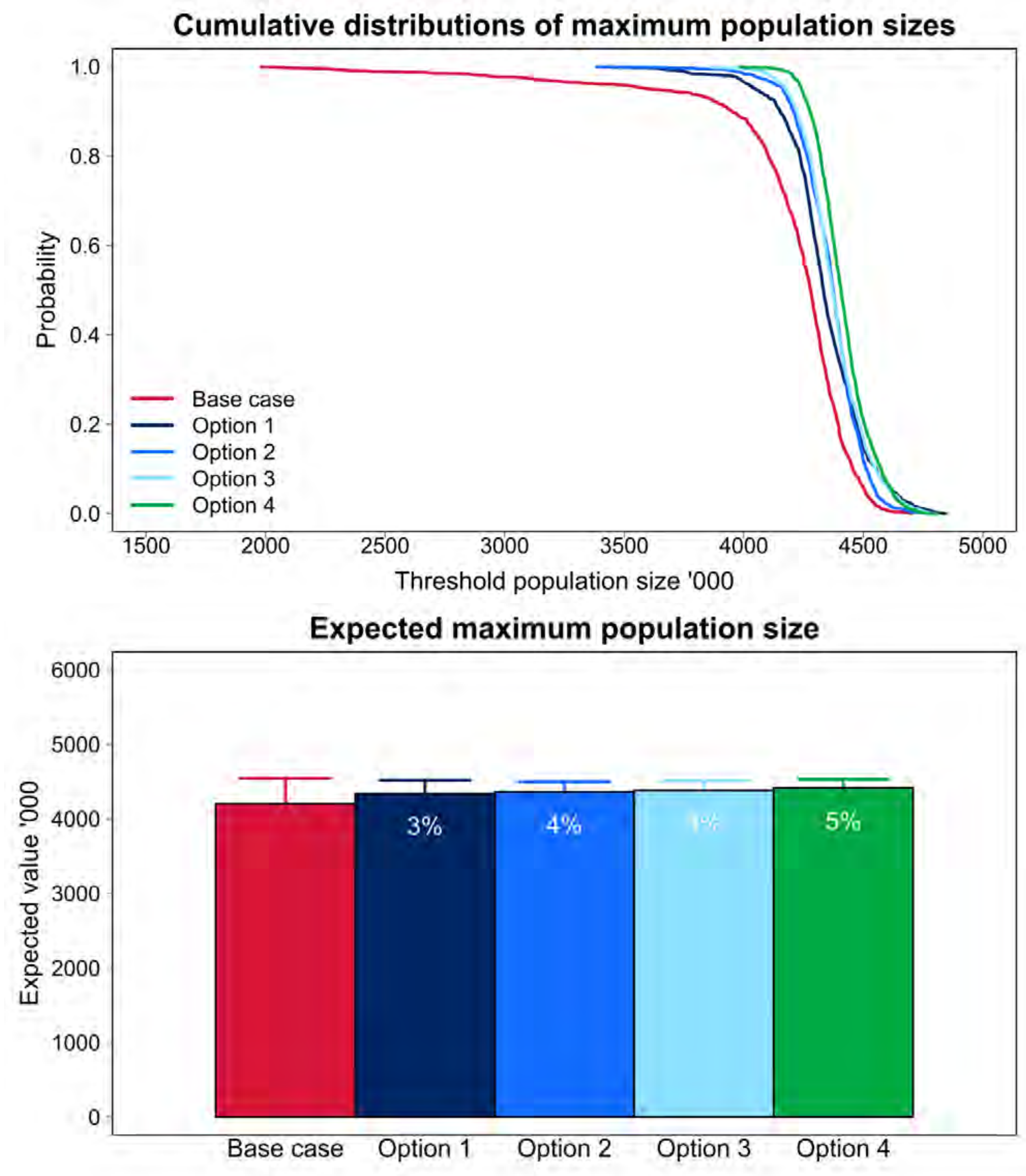
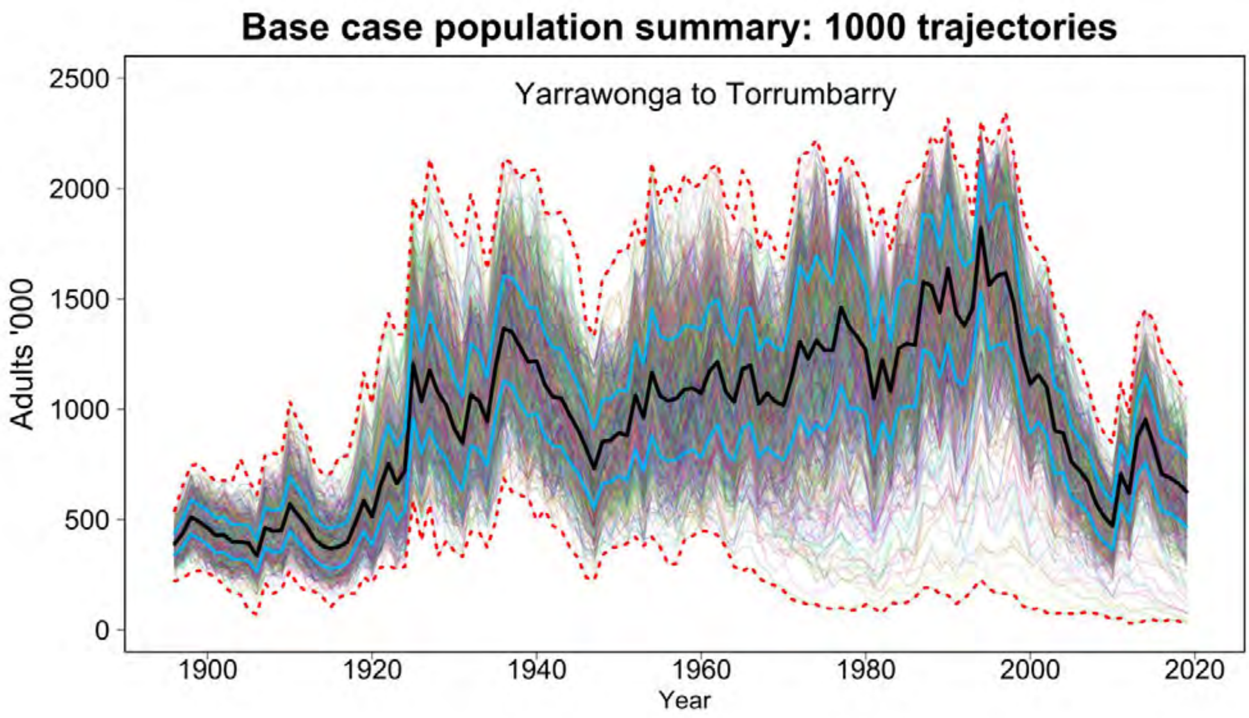
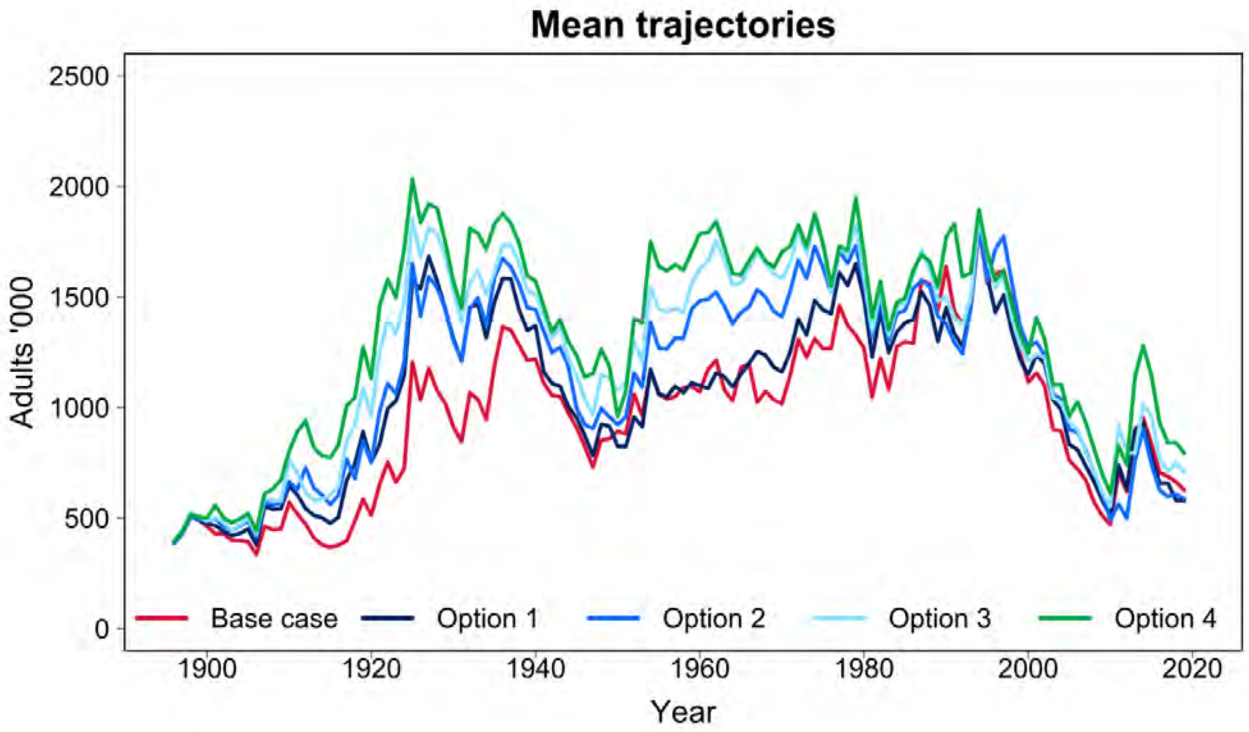
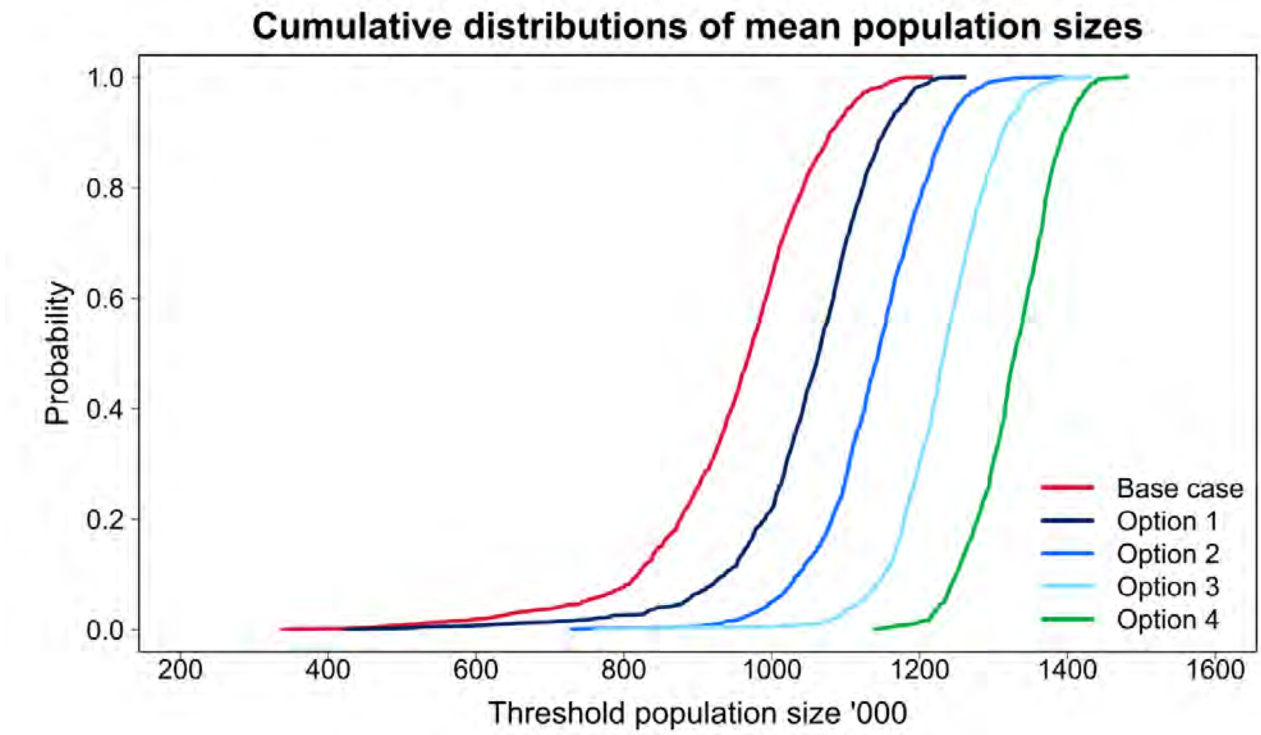


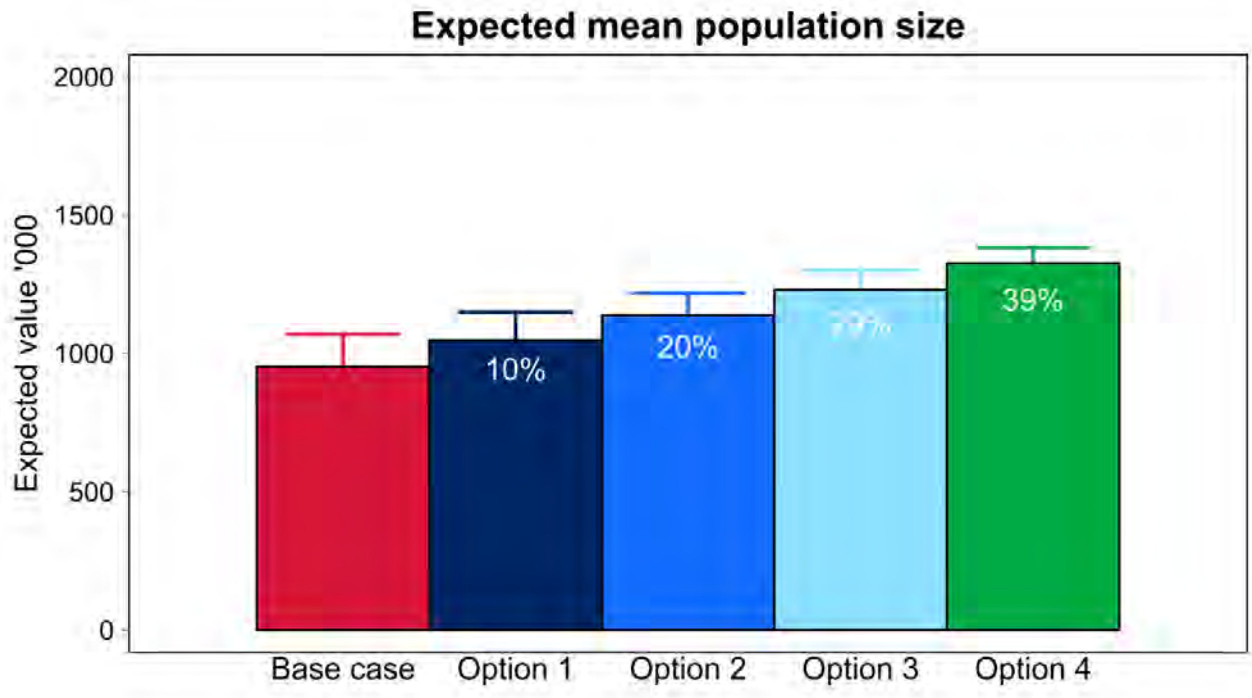
Figure A3.5. Golden Perch adults in the reach Torrumbarry to Wentworth for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

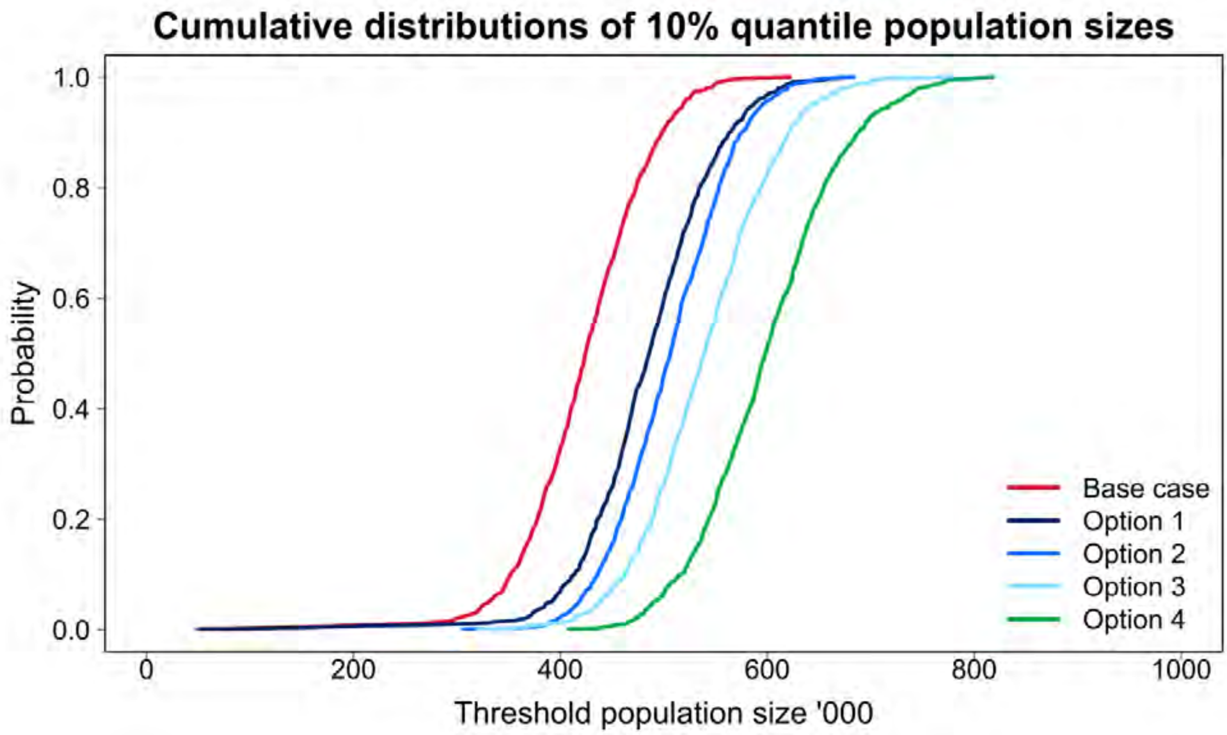
Golden Perch – Yarrawonga to Torrumbarry

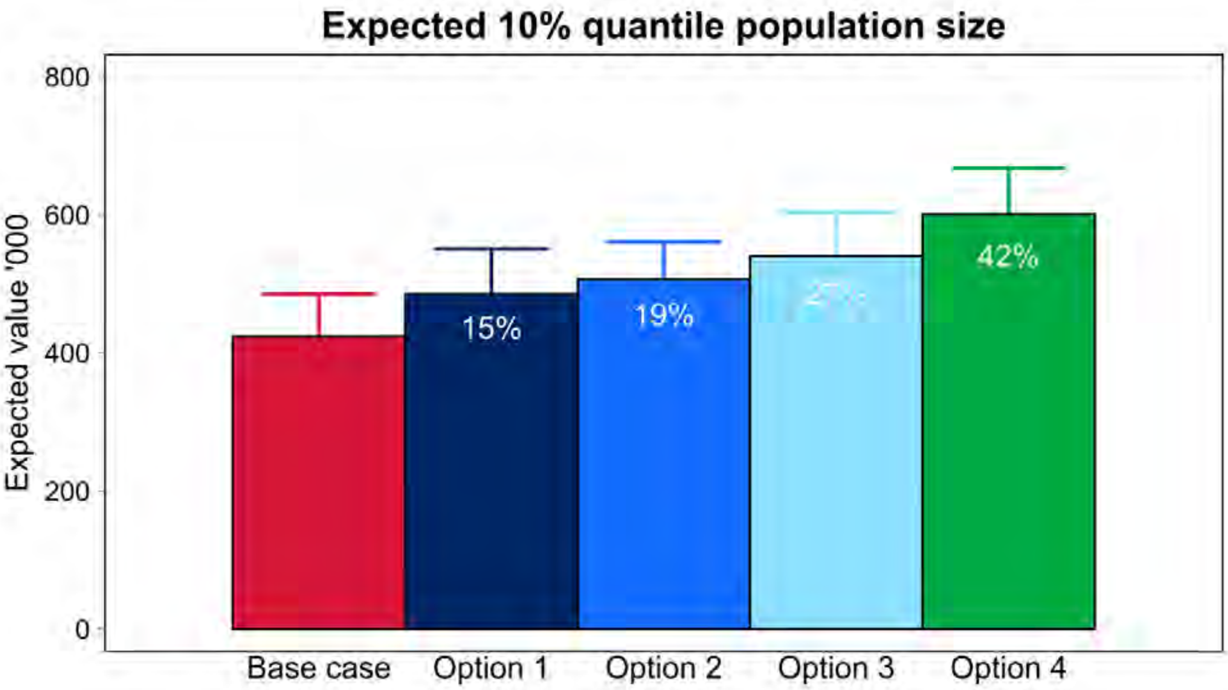


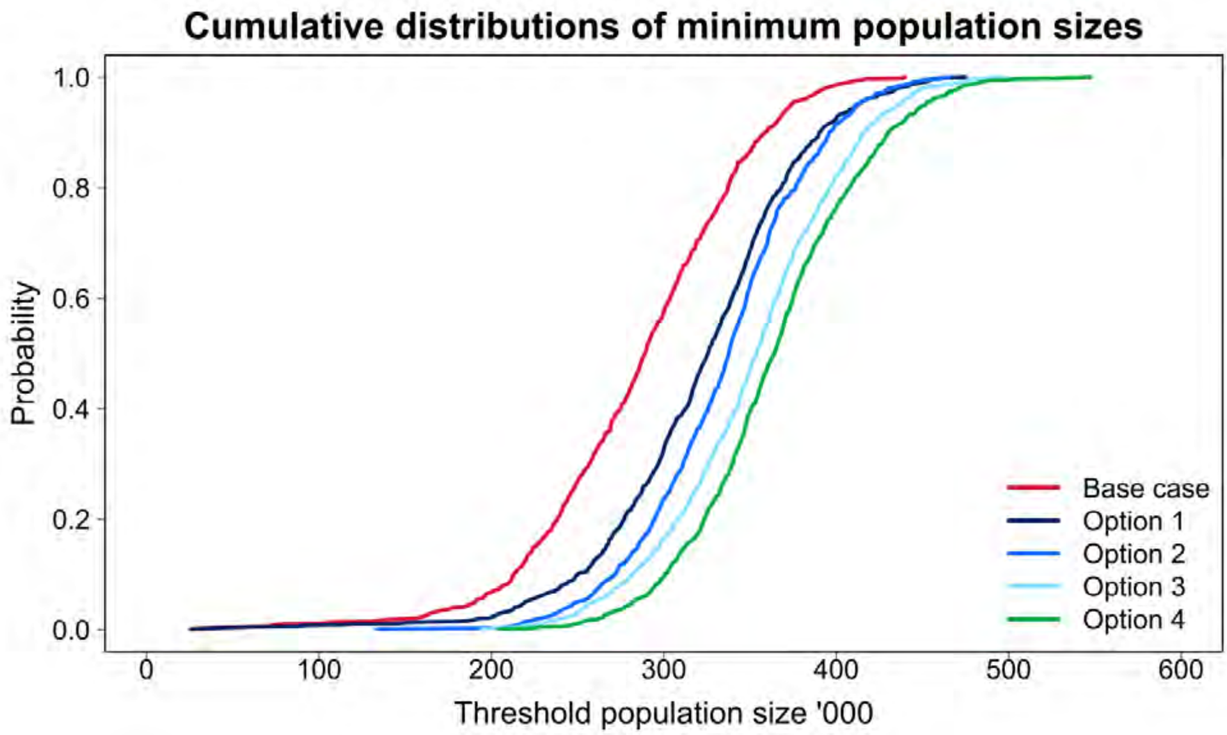


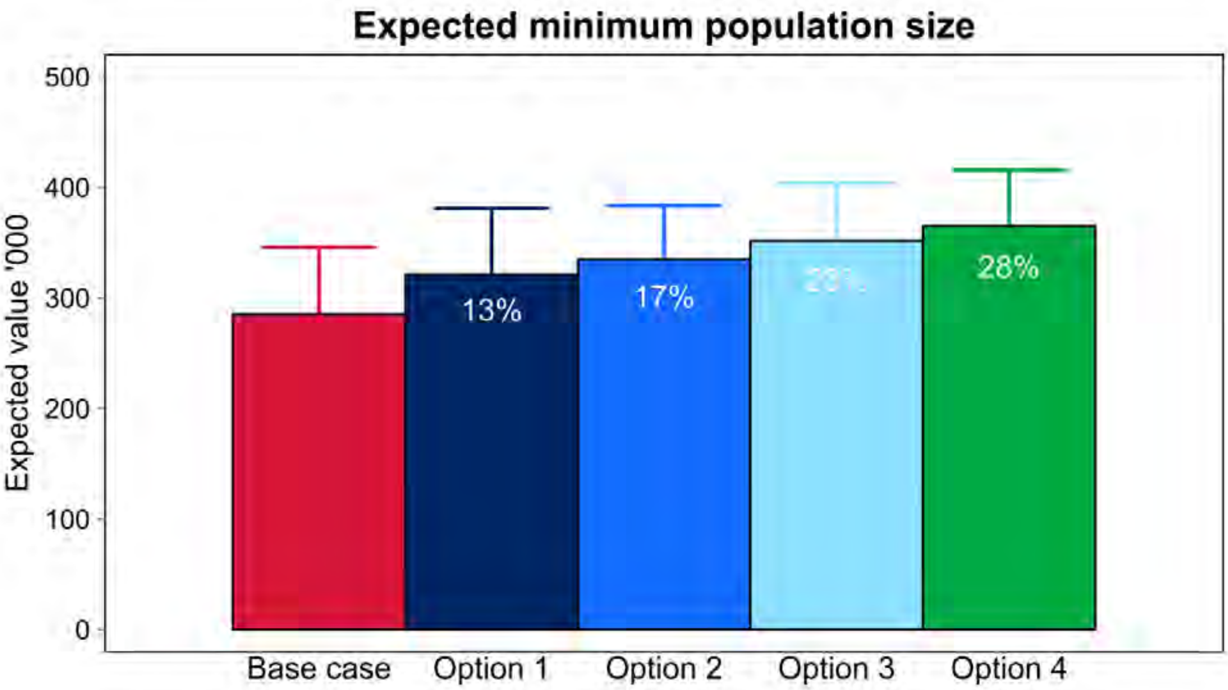

Cumulative distributions of mean population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
200
400
600
800
1000
1200
1400
1600
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected mean population size
Expected value '000
2000
1500
1000
500
0
10%
20%
39%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of 10% quantile population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
200
400
600
800
1000
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected 10% quantile population size
Expected value '000
800
600
400
200
0
15%
19%
42%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
600
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected minimum population size
Expected value '000
500
400
300
200
100
0
13%
17%
28%
Base case
Option 1
Option 2
Option 3
Option 4

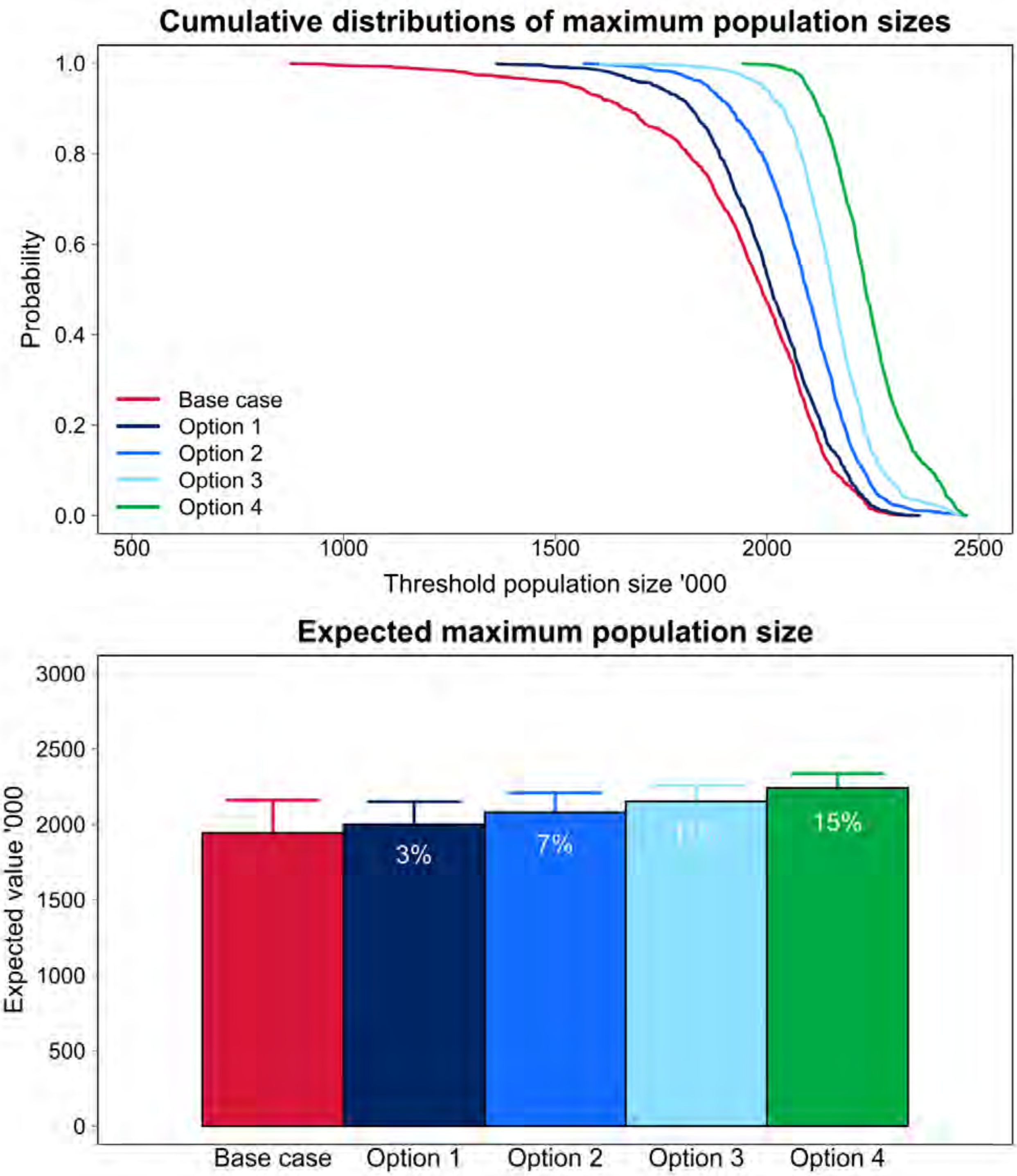
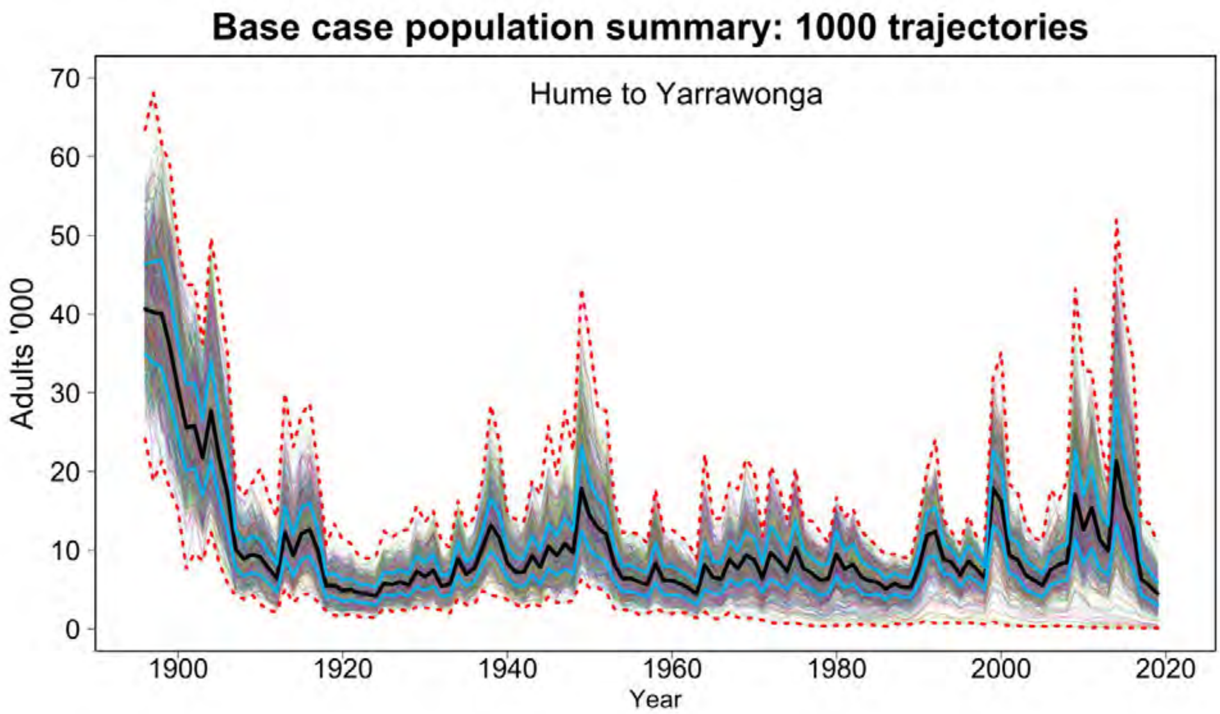
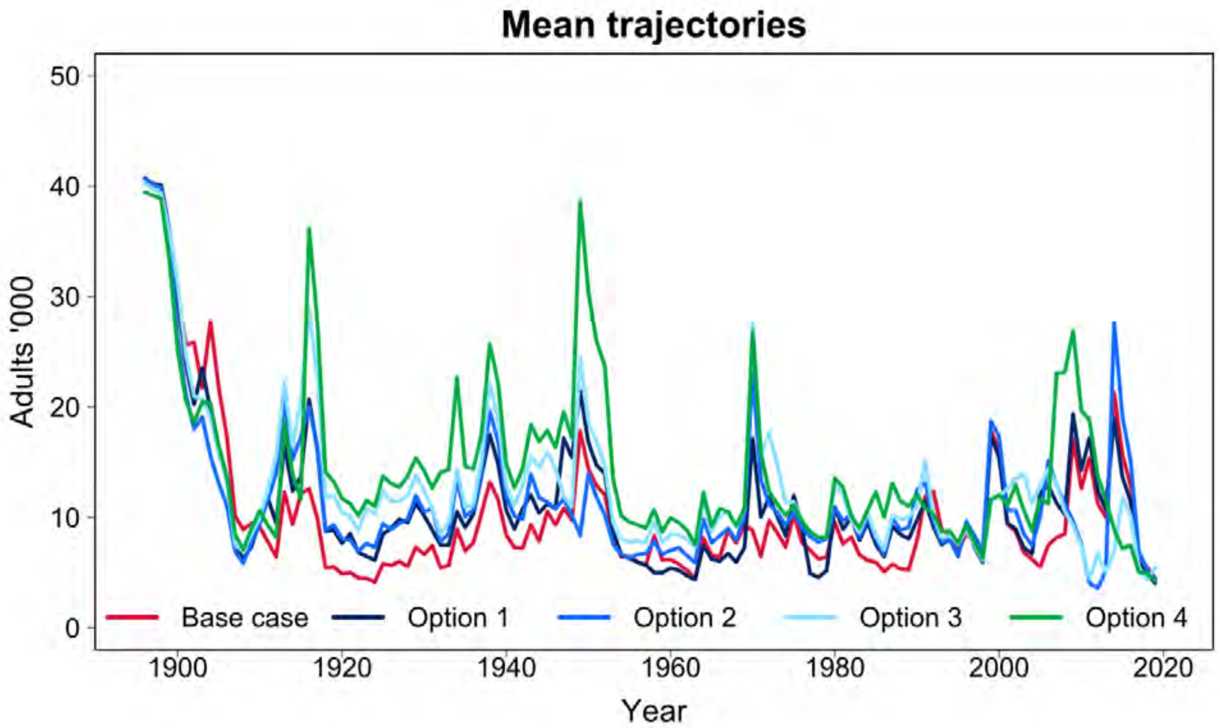
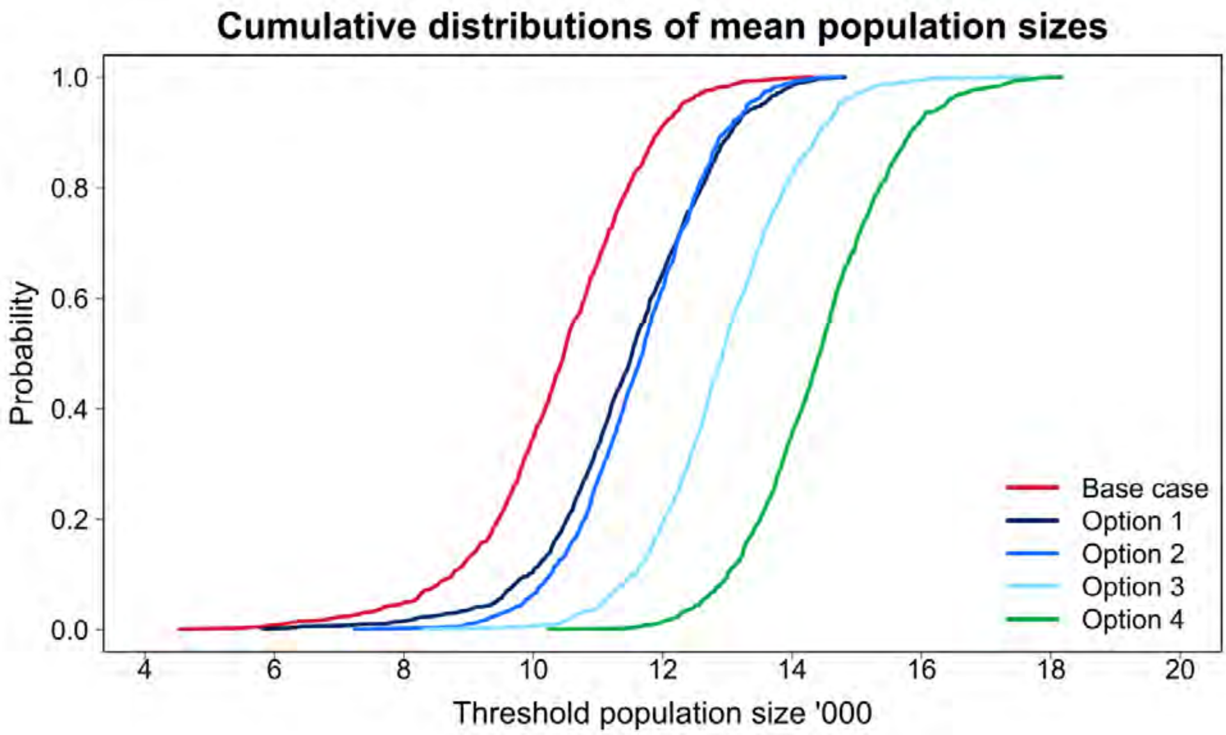


Figure A3.6. Golden Perch adults in the Yarrawonga to Torrumbarry reach for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

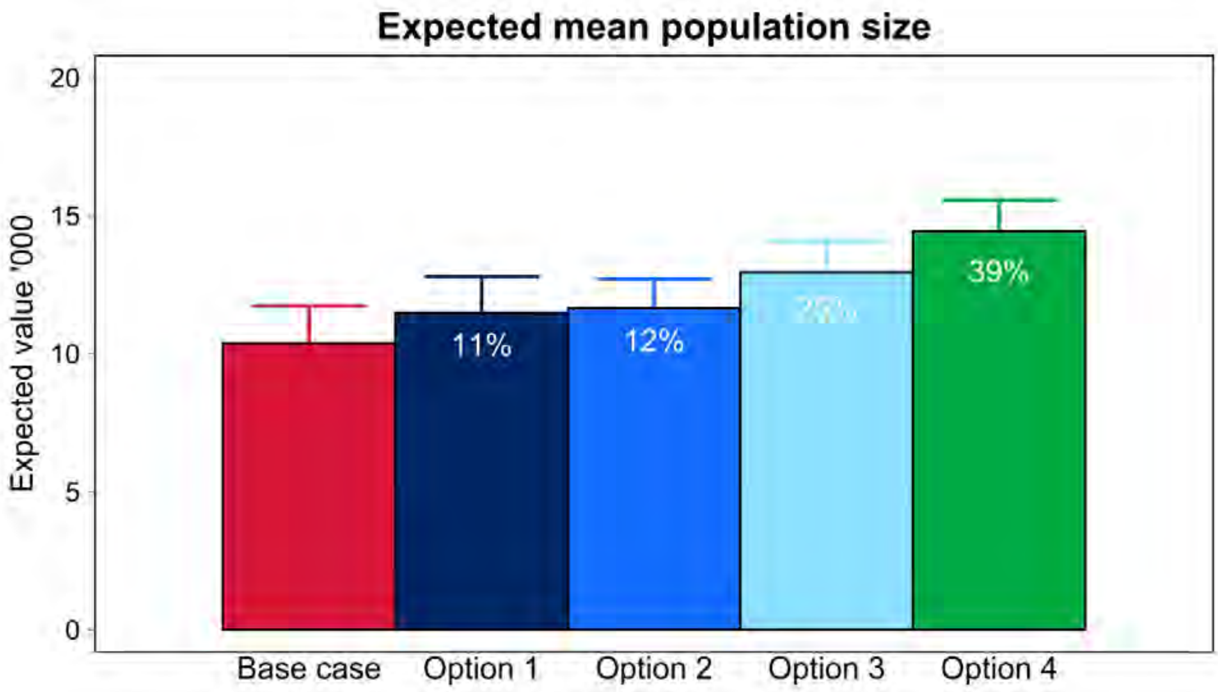
Golden Perch – Hume to Yarrawonga

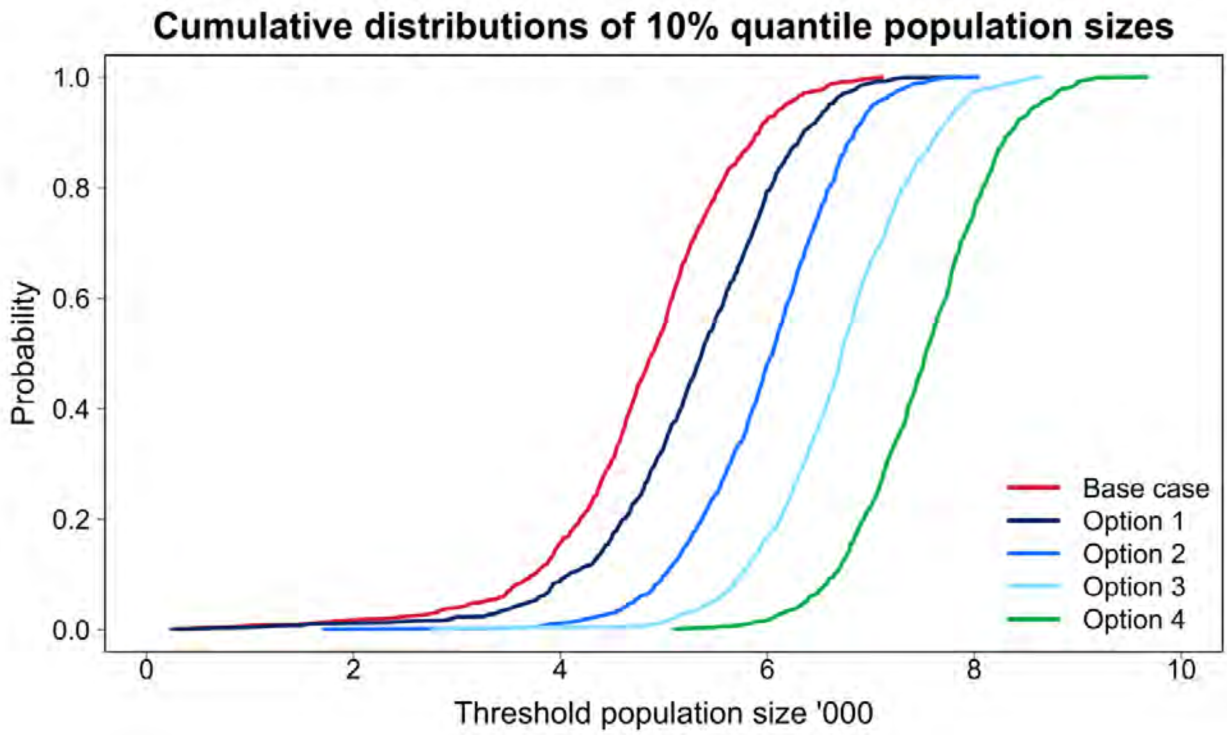


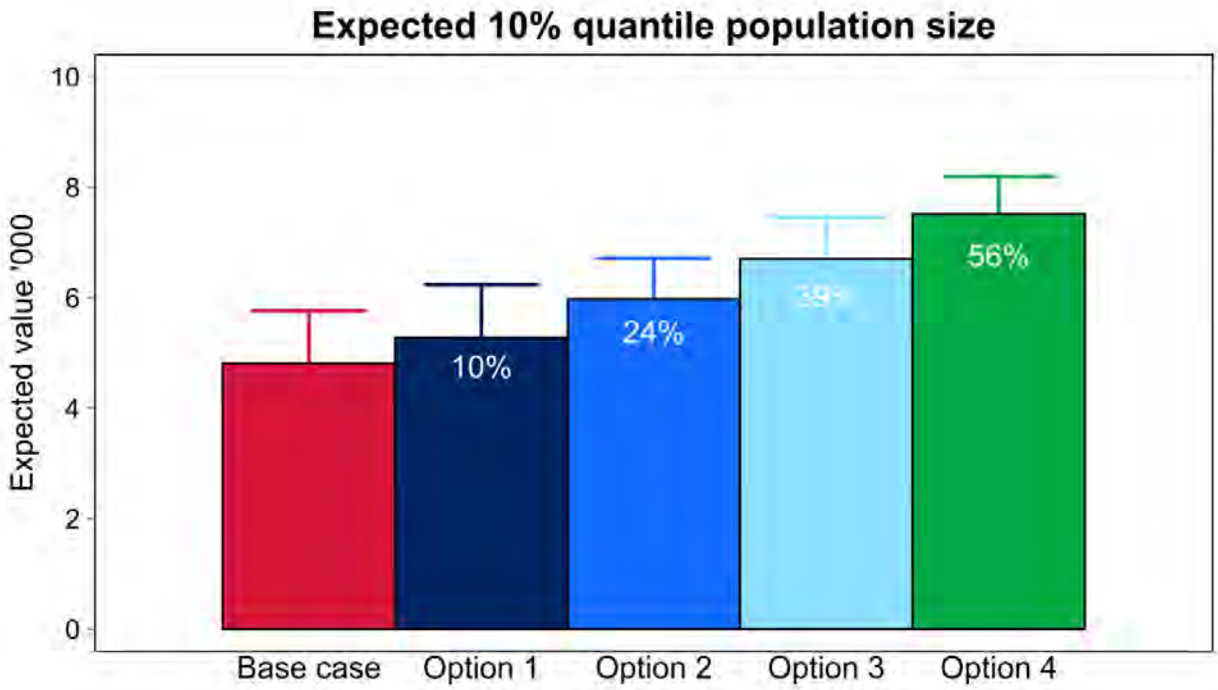


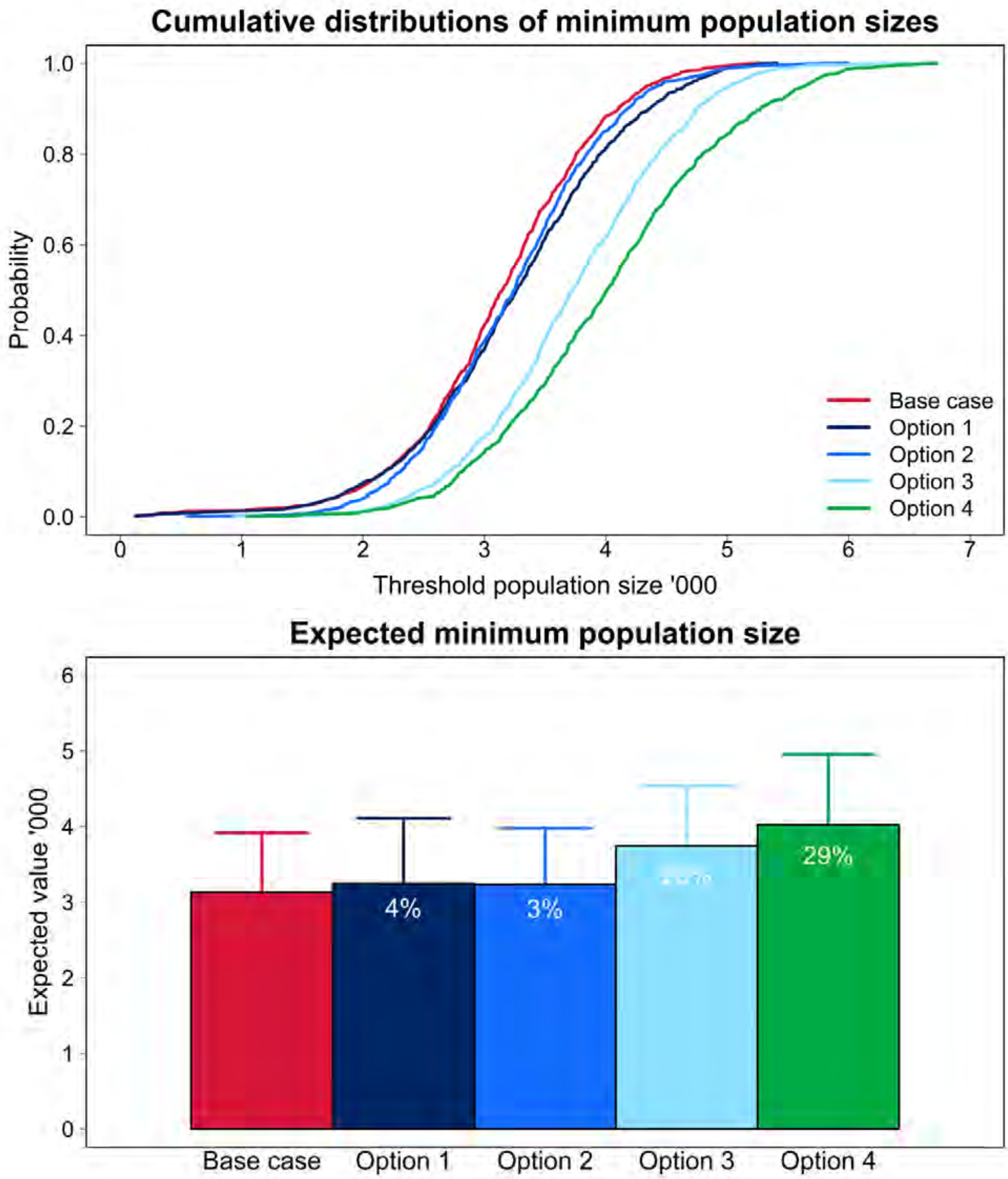

Cumulative distributions of mean population sizes
1.0
0.8
0.6
0.4
0.2
0.0
Probability
4
6
8
10
12
14
16
18
20
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4

c


Expected mean population size
20
15
10
5
0
Expected value '000
11%
12%
39%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of 10% quantile population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected 10% quantile population size
Expected value '000
10
8
6
4
2
0
10%
24%
56%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4
Expected minimum population size
Expected value '000
6
5
4
3
2
1
0
4%
3%
29%
Base case
Option 1
Option 2
Option 3
Option 4

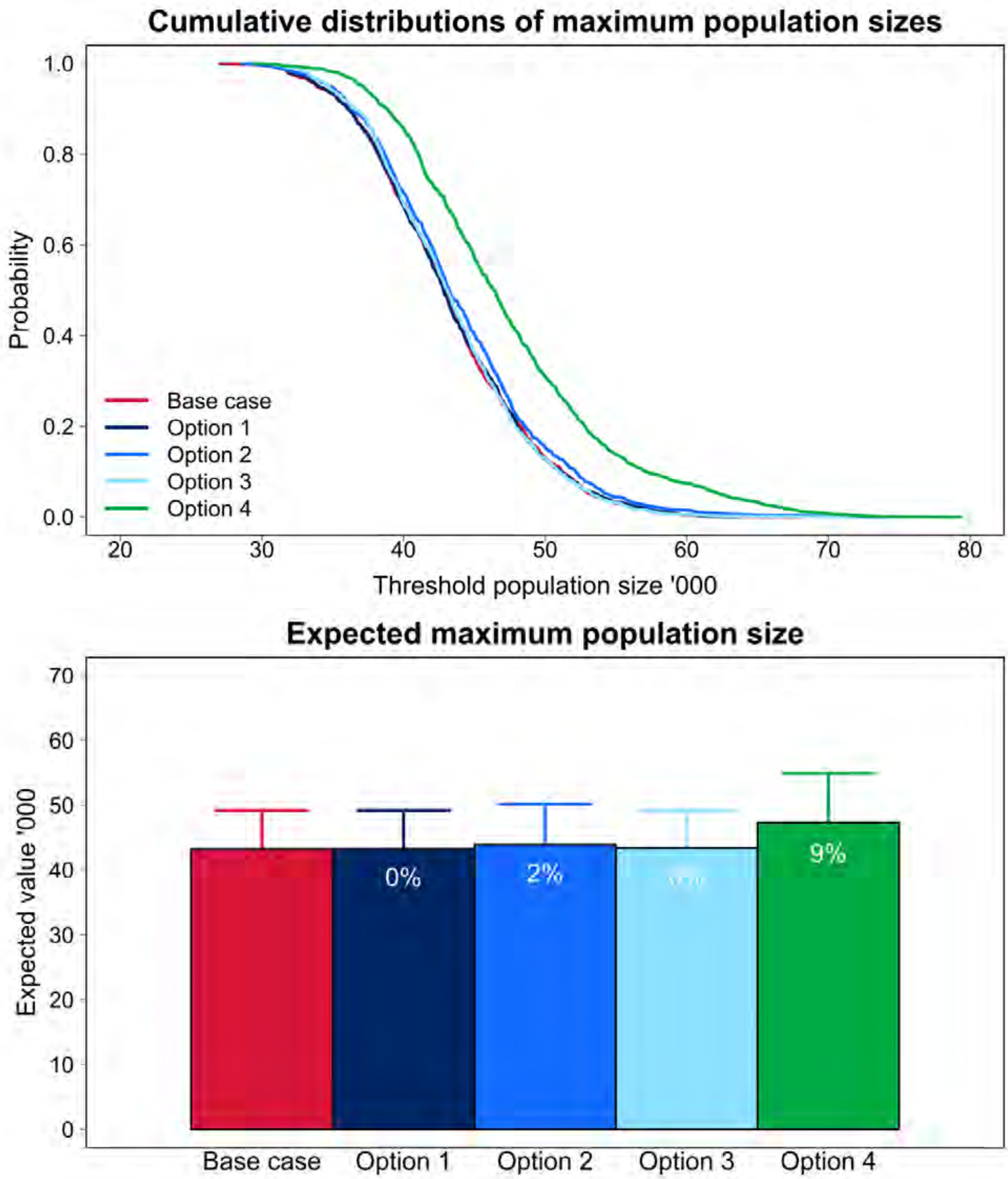
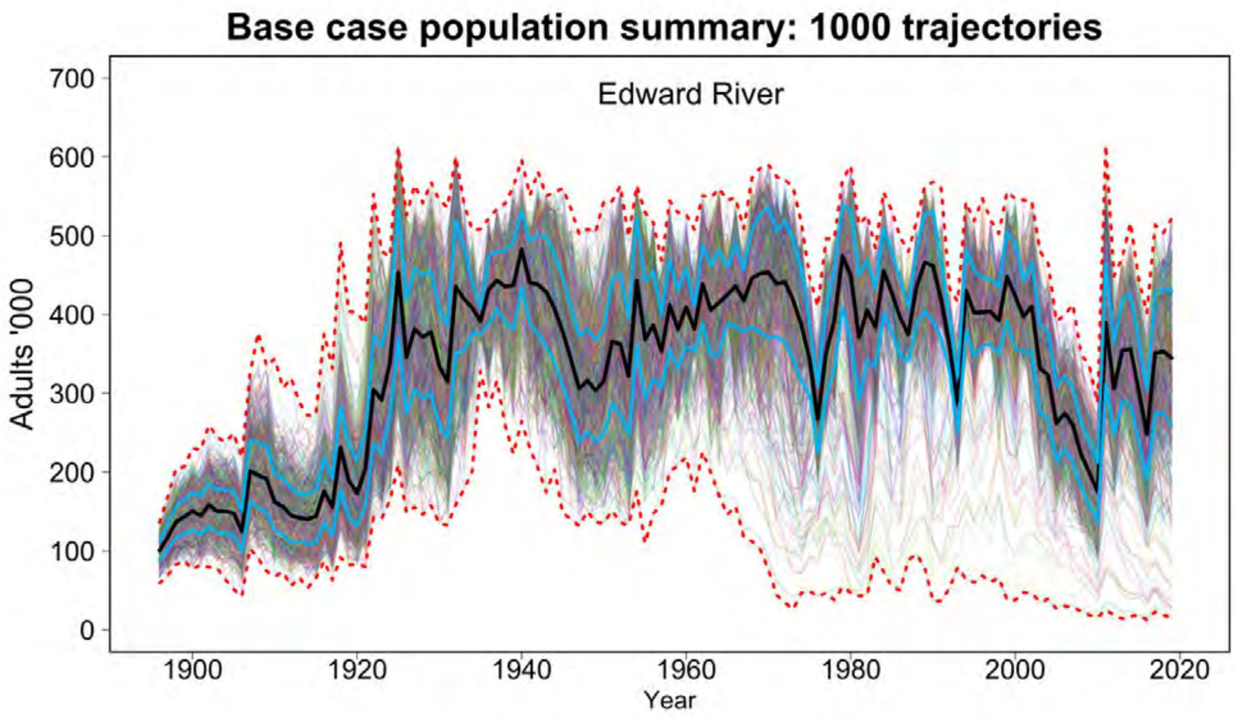
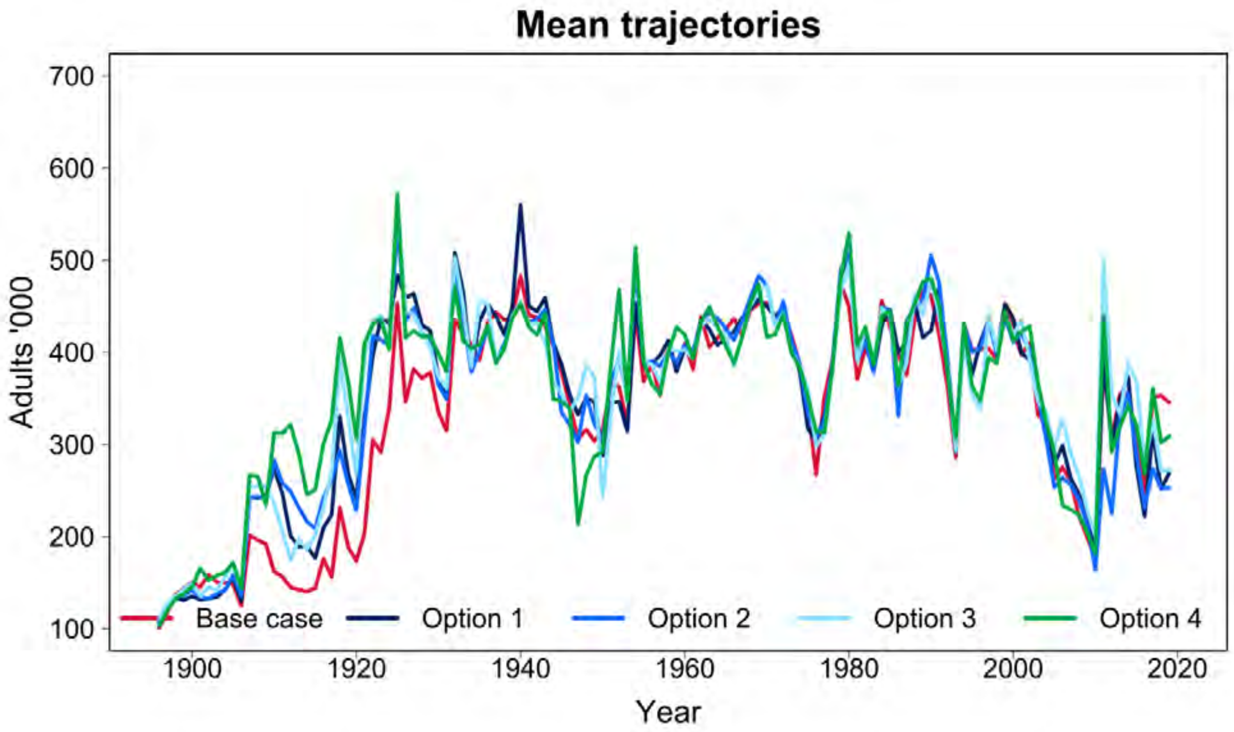
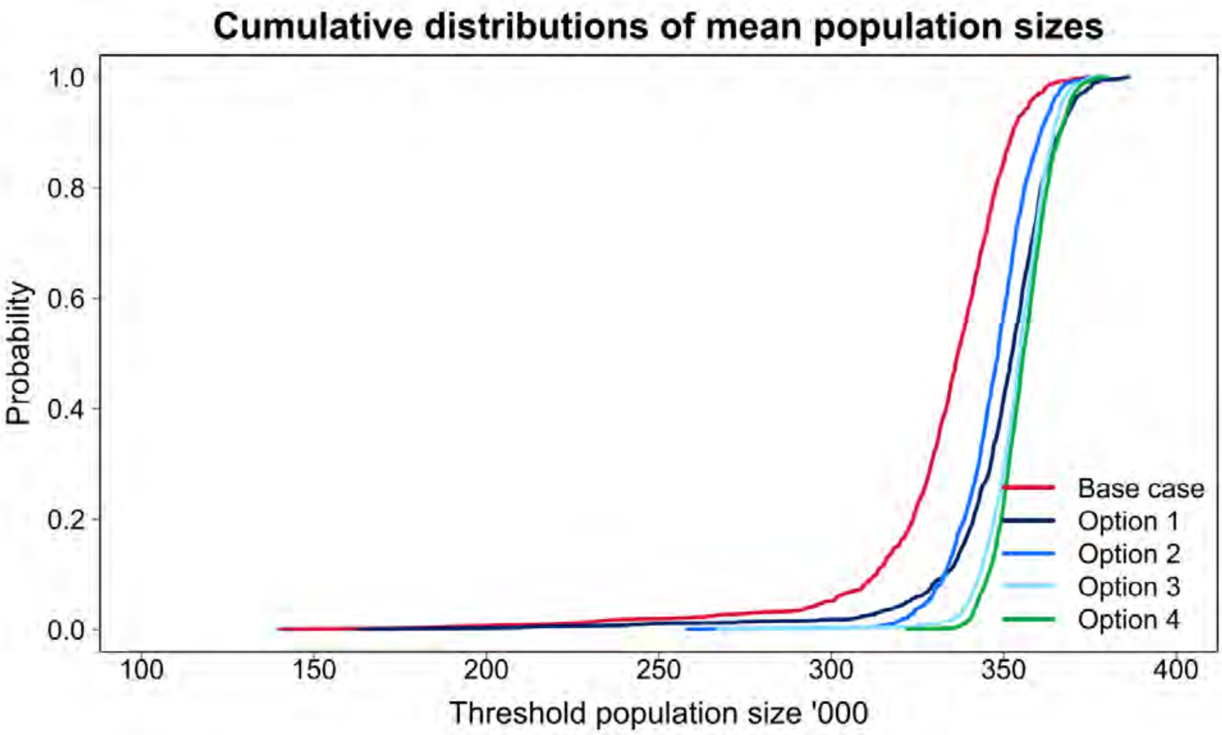


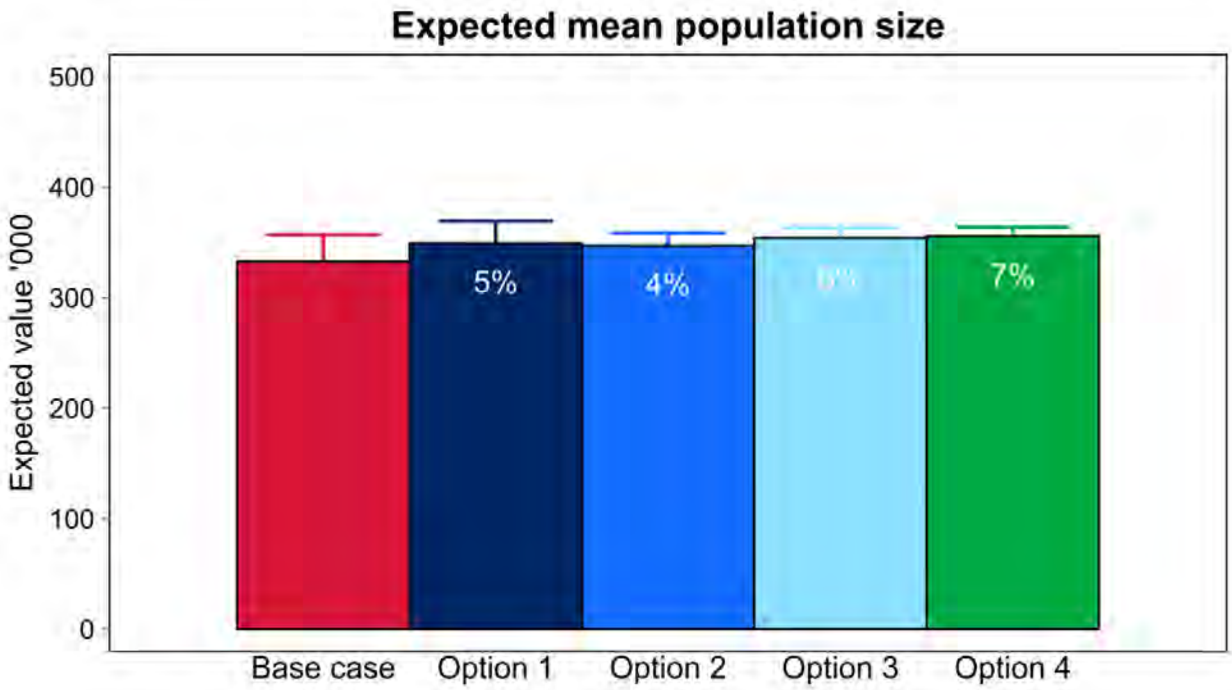
Figure A3.7. Golden Perch adults in the Hume to Yarrawonga reach for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

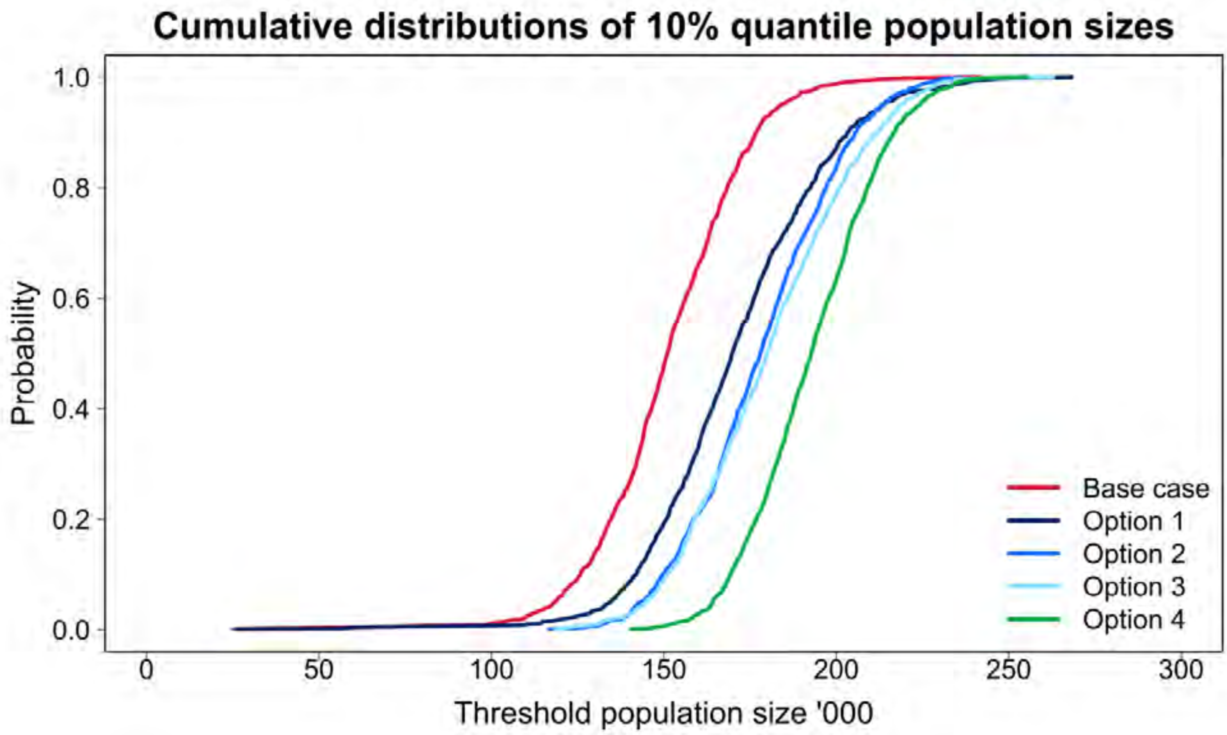
Golden Perch – Edward River

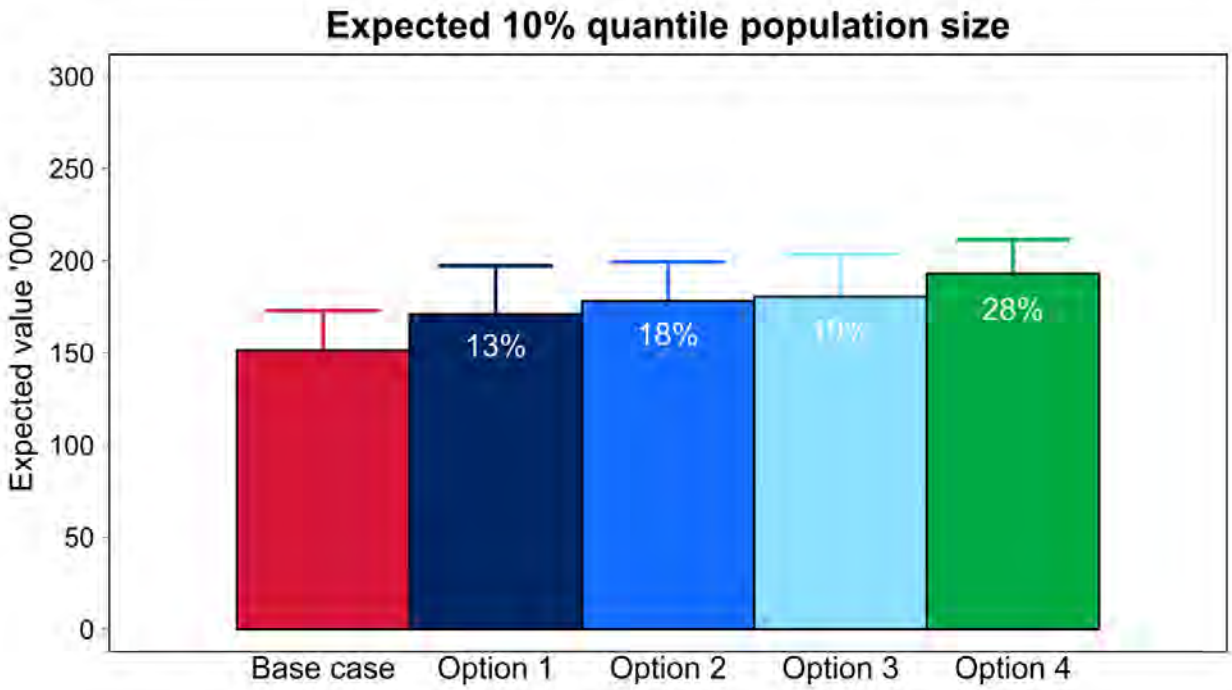


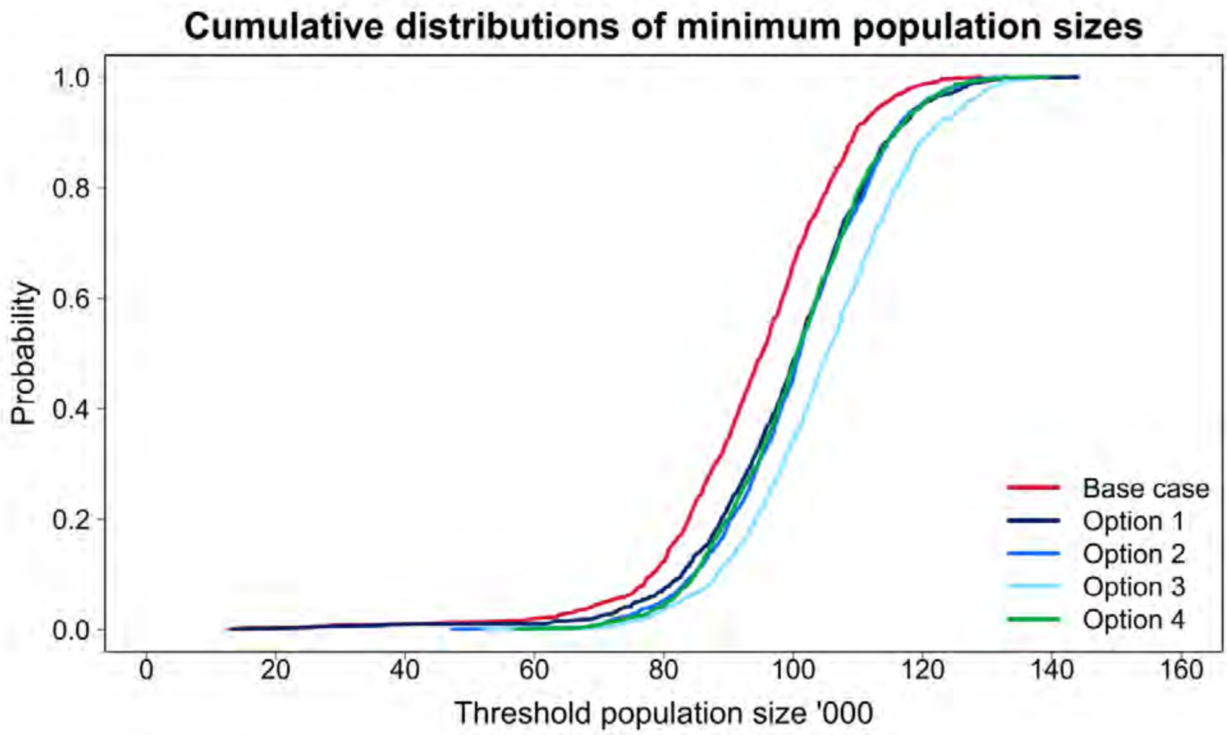


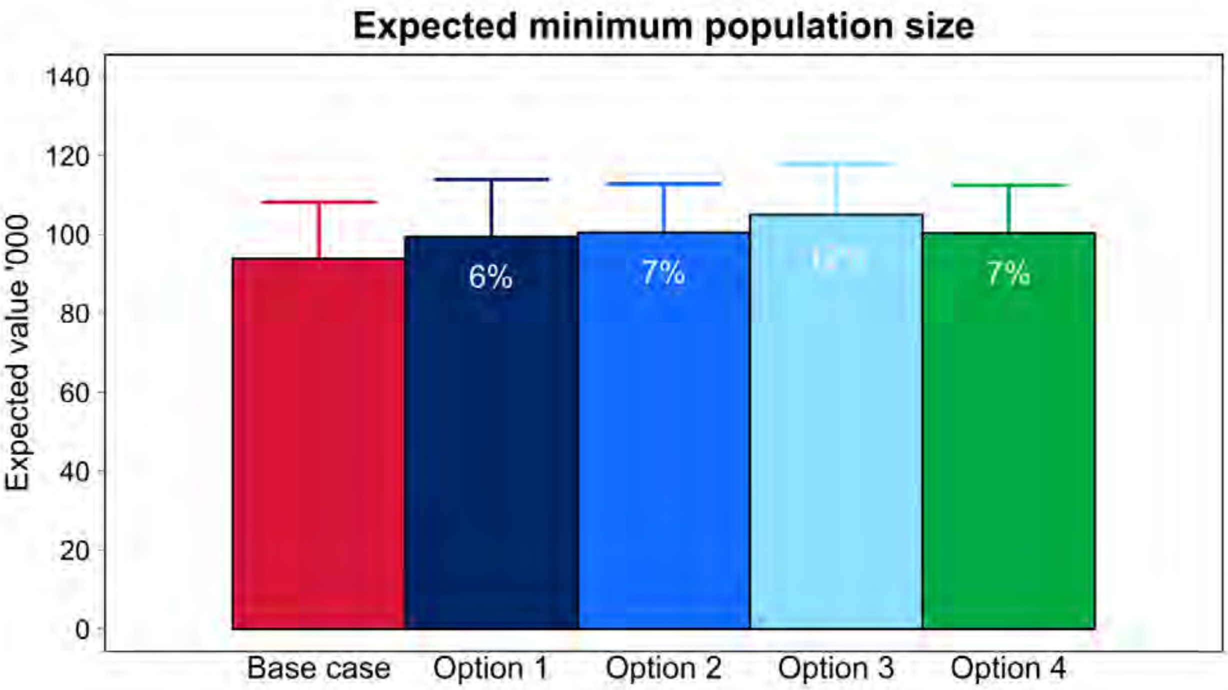

Cumulative distributions of mean population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
100
150
200
250
300
350
400
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected mean population size
Expected value '000
500
400
300
200
100
0
5%
4%
7%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of 10% quantile population sizes
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
50
100
150
200
250
300
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected 10% quantile population size
Expected value '000
0
50
100
150
200
250
300
13%
18%
28%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
120
140
160
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected minimum population size
Expected value '000
140
120
100
80
60
40
20
0
6%
7%
7%
Base case
Option 1
Option 2
Option 3
Option 4

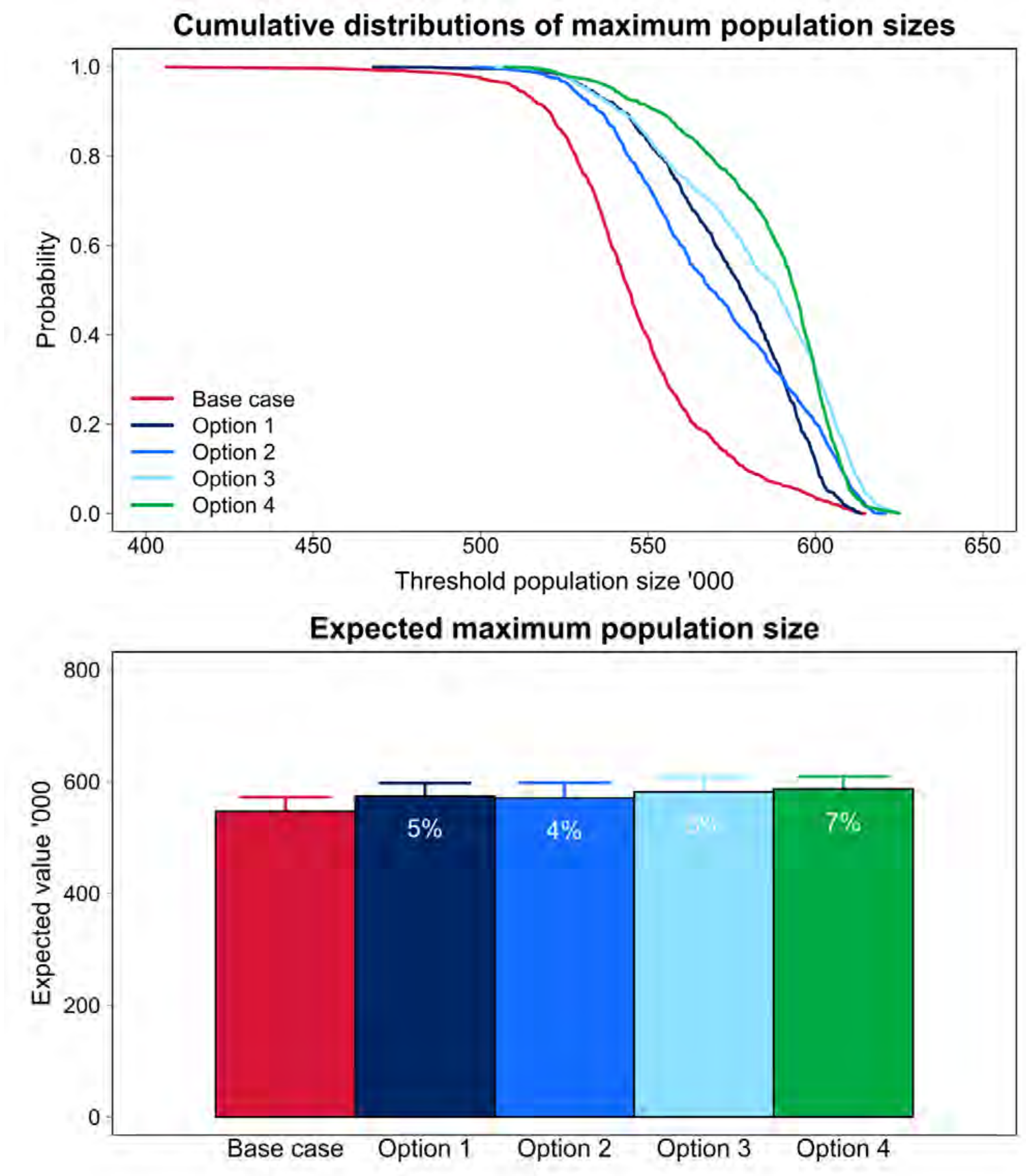
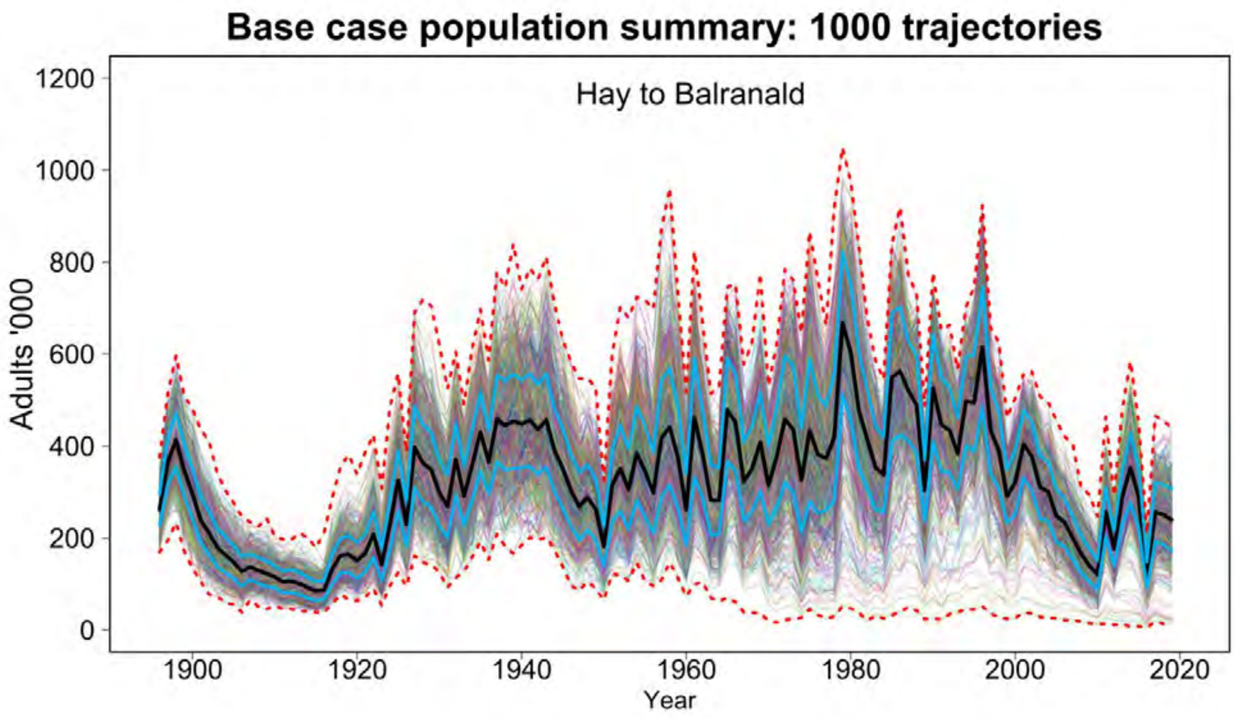
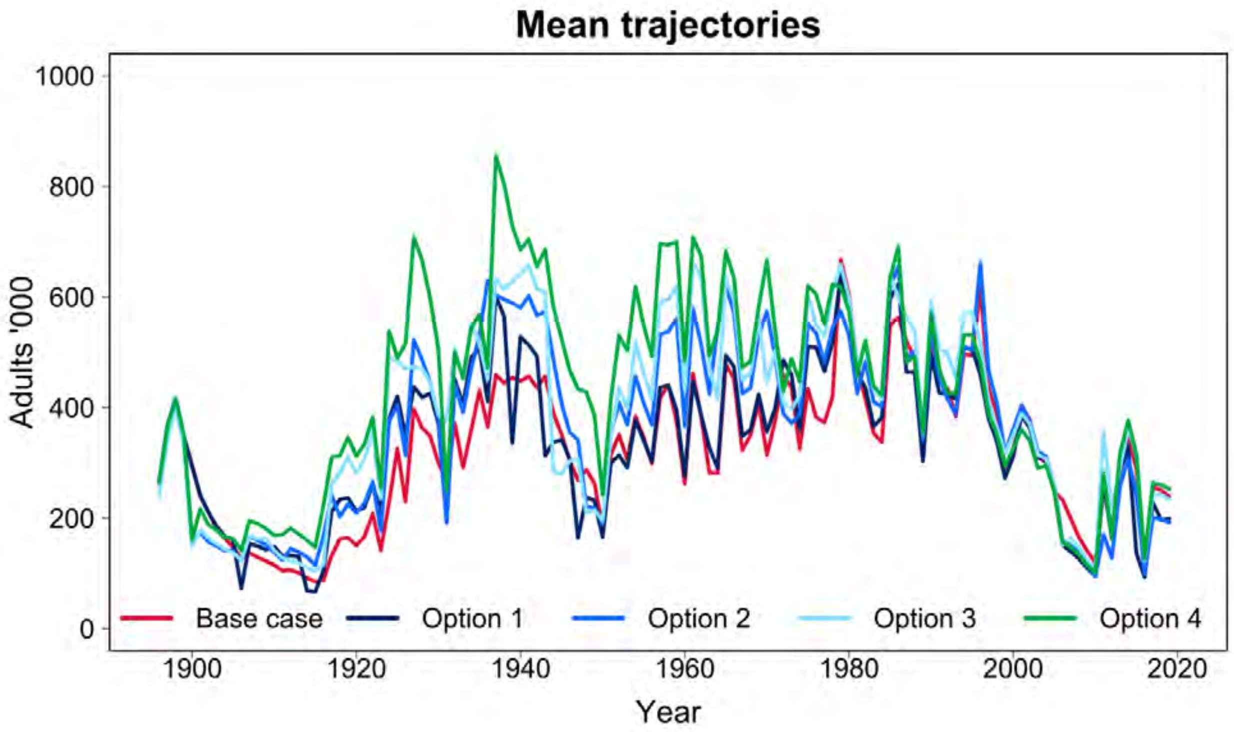
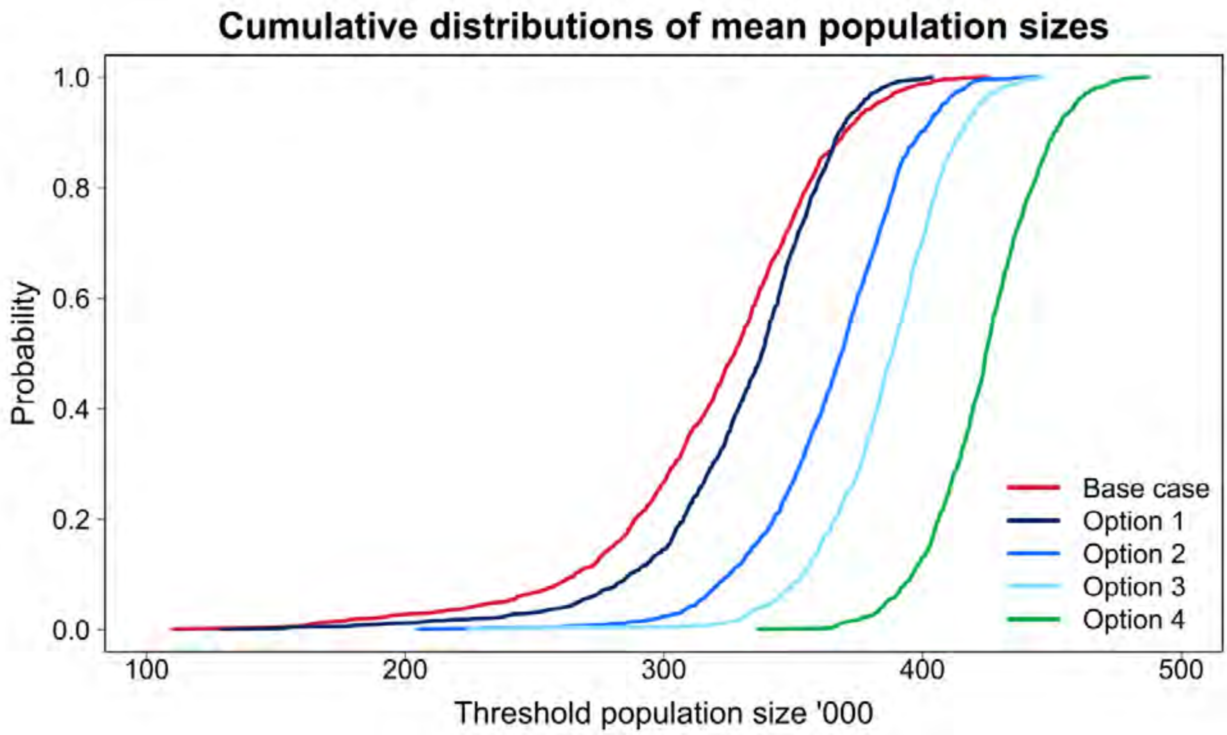


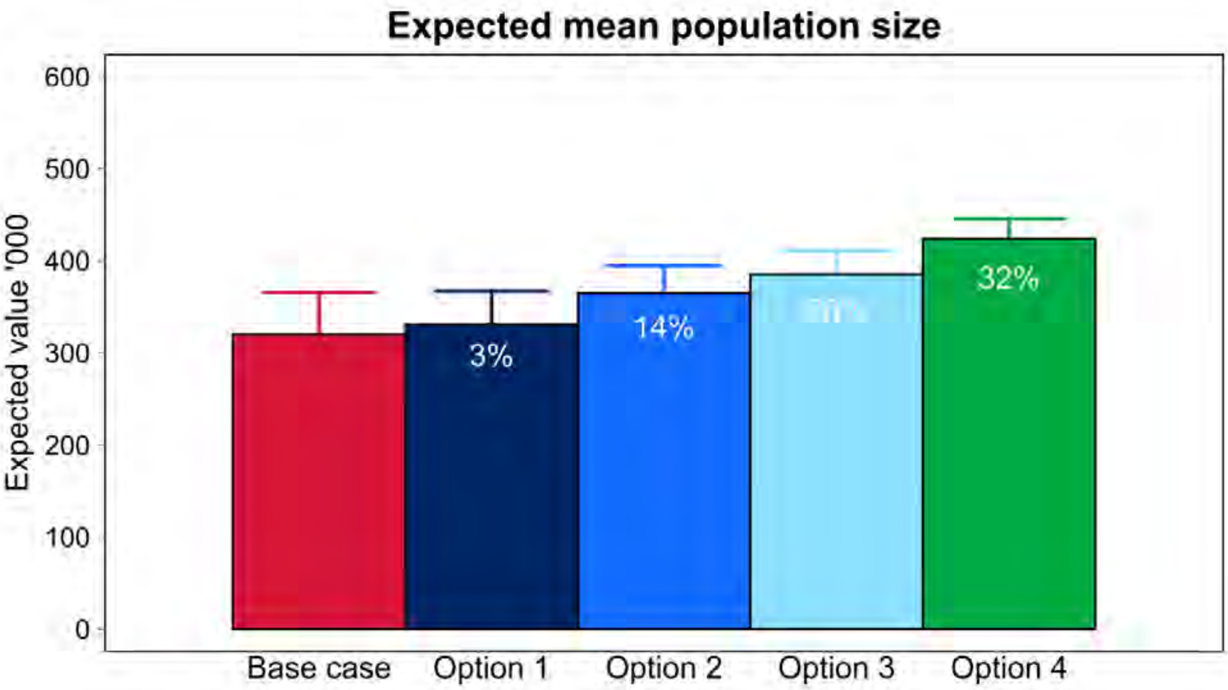
Figure A3.8. Golden Perch in the Edward River for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

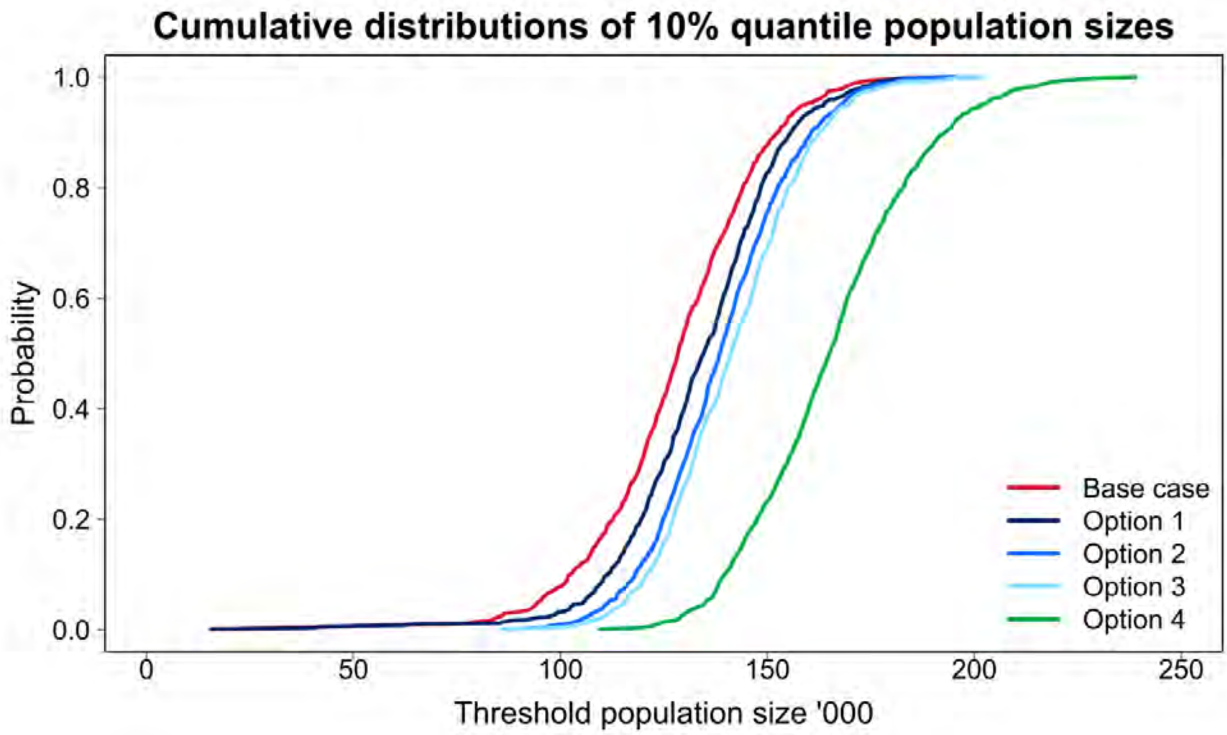
Golden Perch – Hay to Balranald

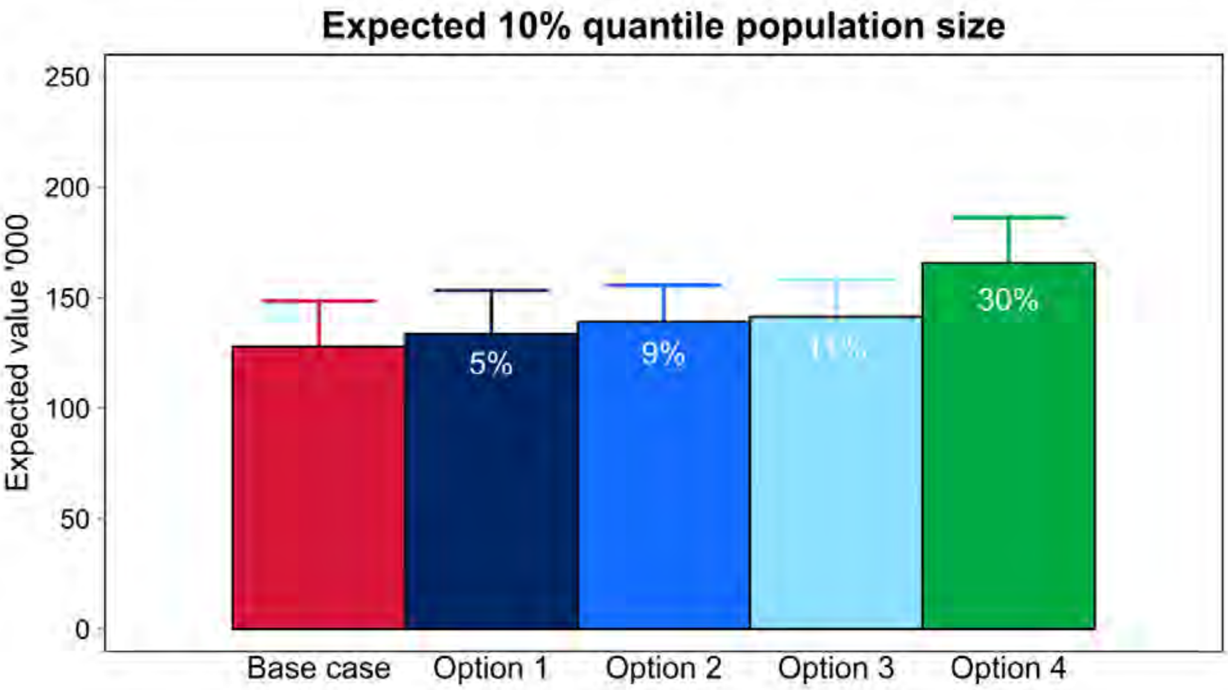


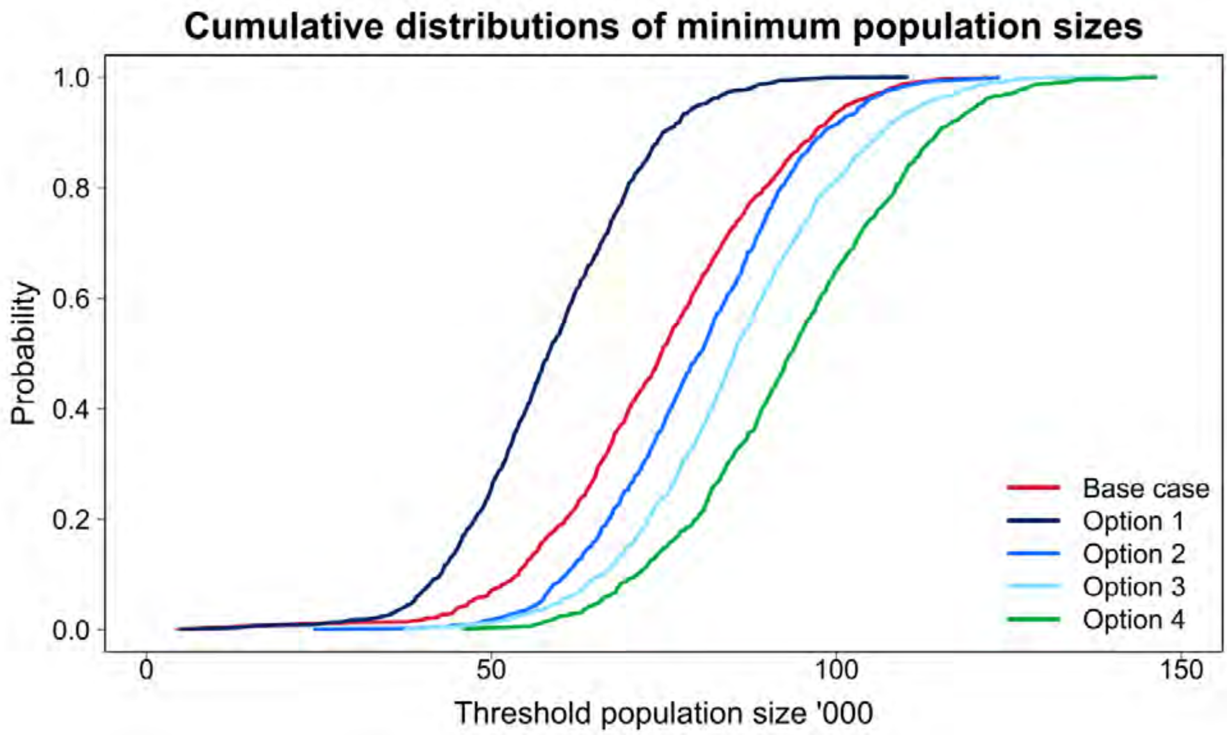


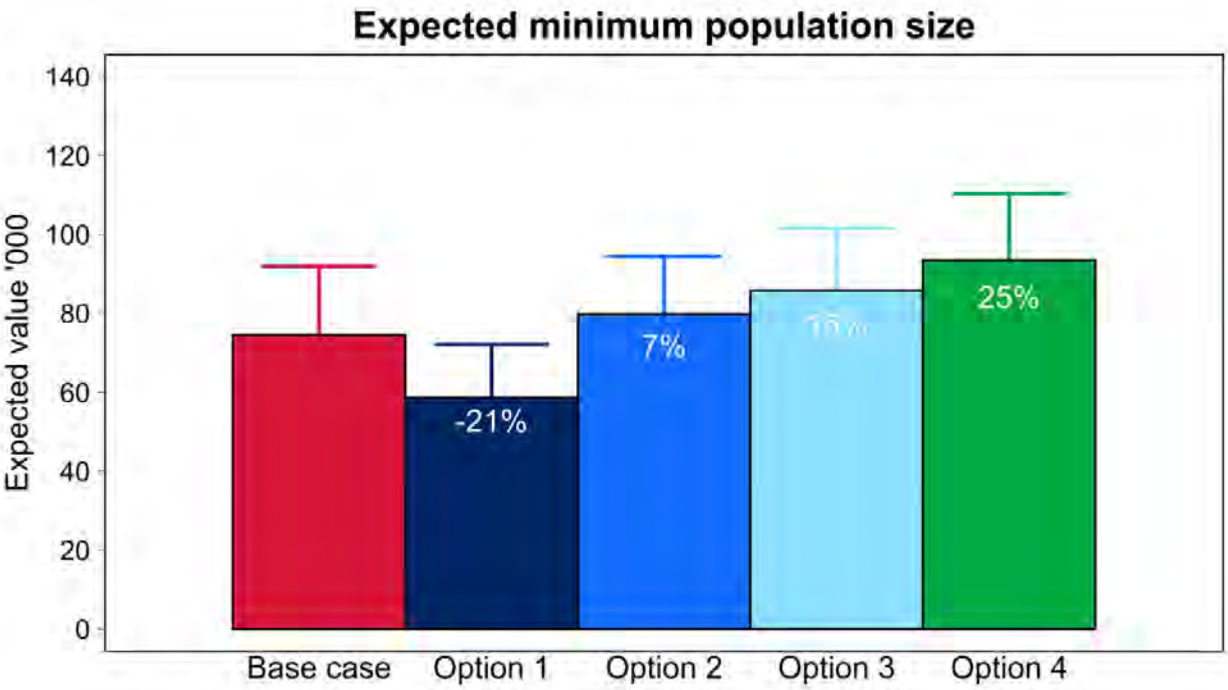

Cumulative distributions of mean population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
100
200
300
400
500
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected mean population size
Expected value '000
600
500
400
300
200
100
0
3%
14%
32%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of 10% quantile population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
50
100
150
200
250
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected 10% quantile population size
Expected value '000
250
200
150
100
50
0
5%
9%
30%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
50
100
150
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected minimum population size
Expected value '000
140
120
100
80
60
40
20
0
-21%
7%
25%
Base case
Option 1
Option 2
Option 3
Option 4

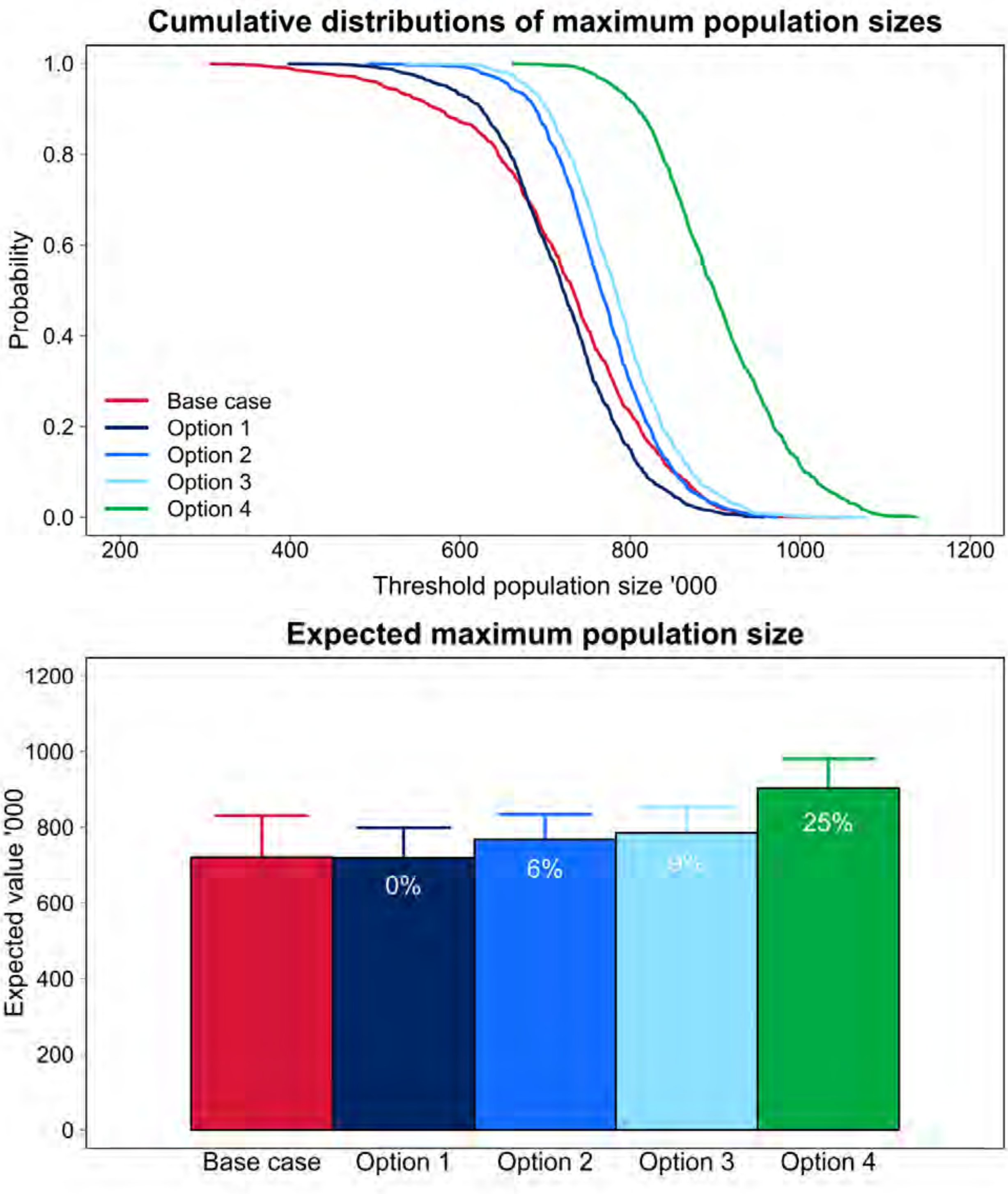
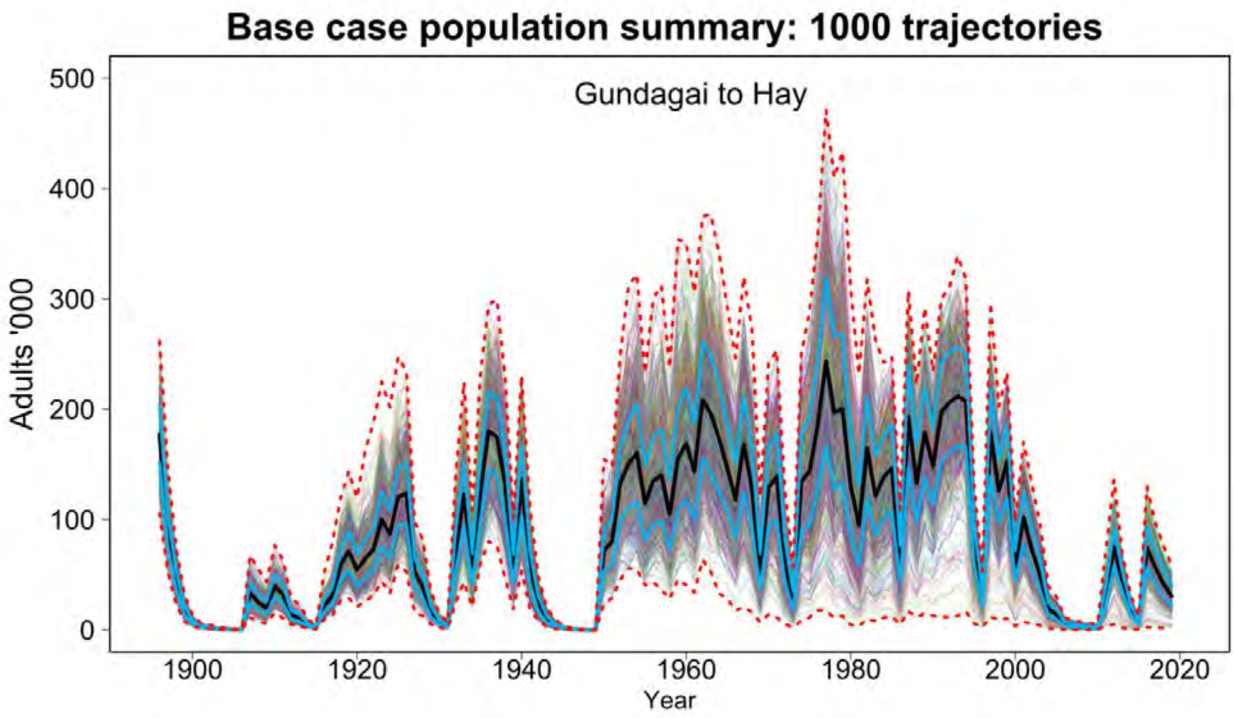
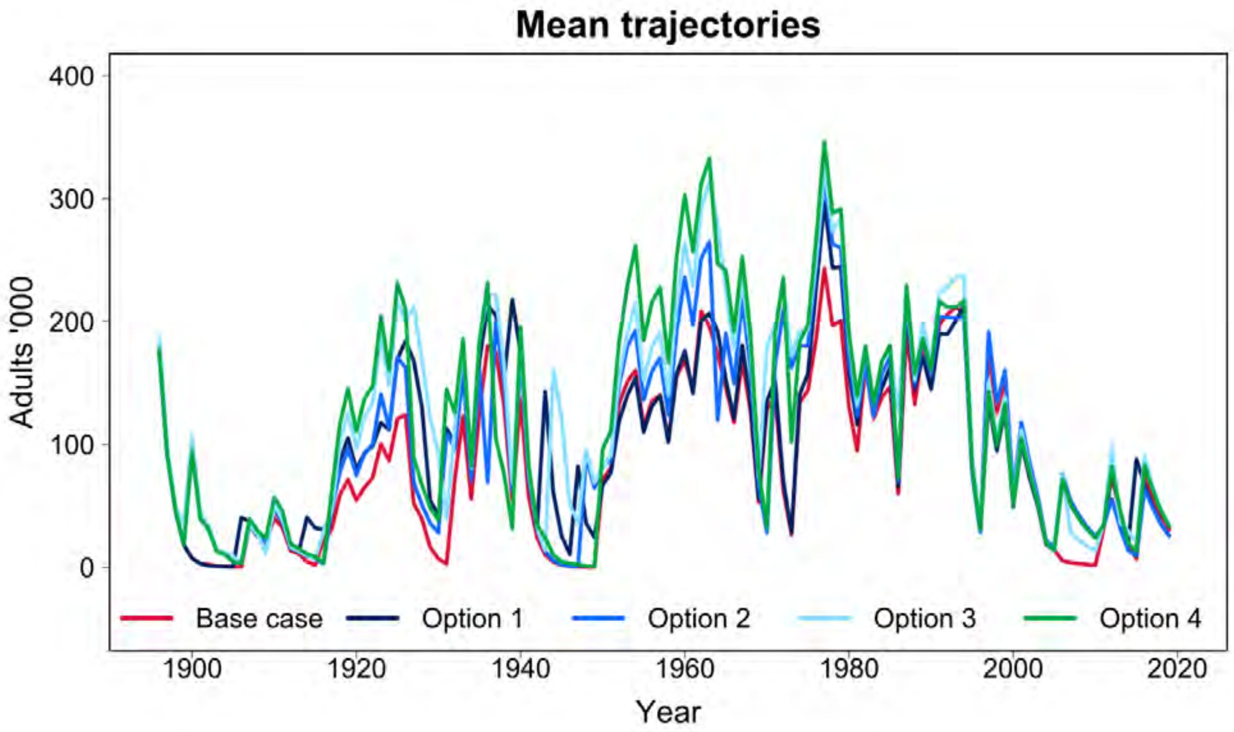
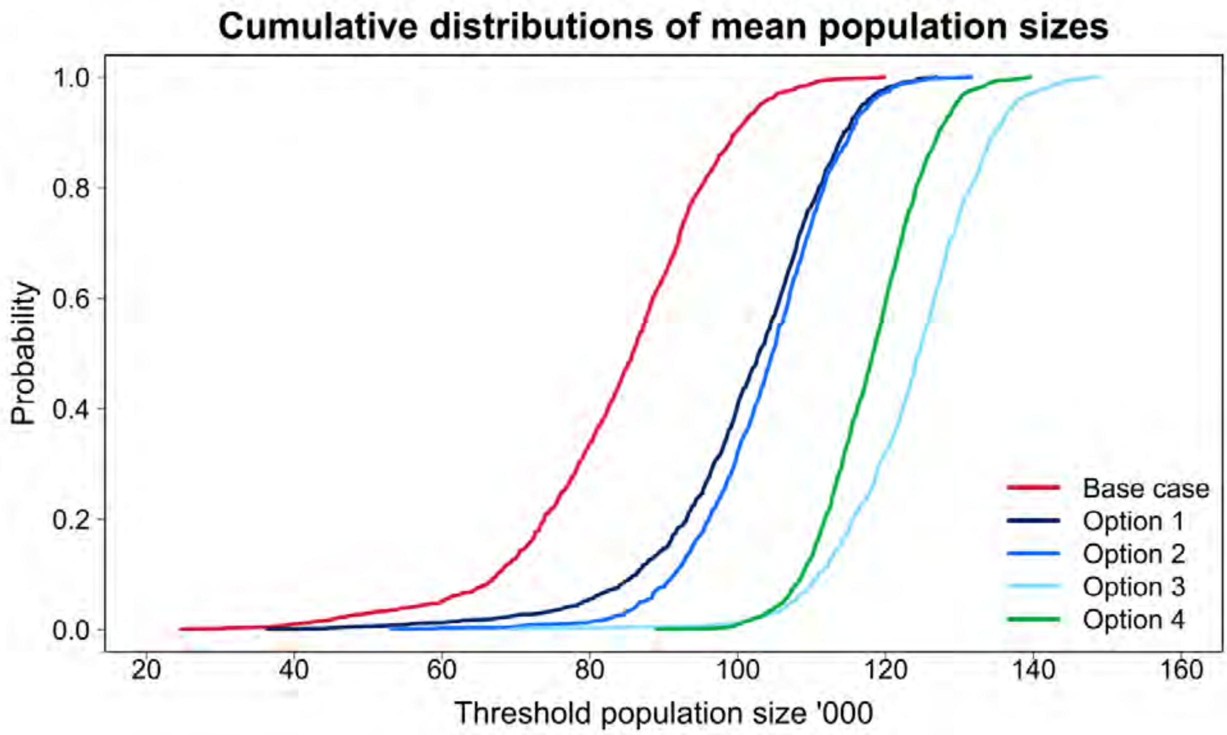


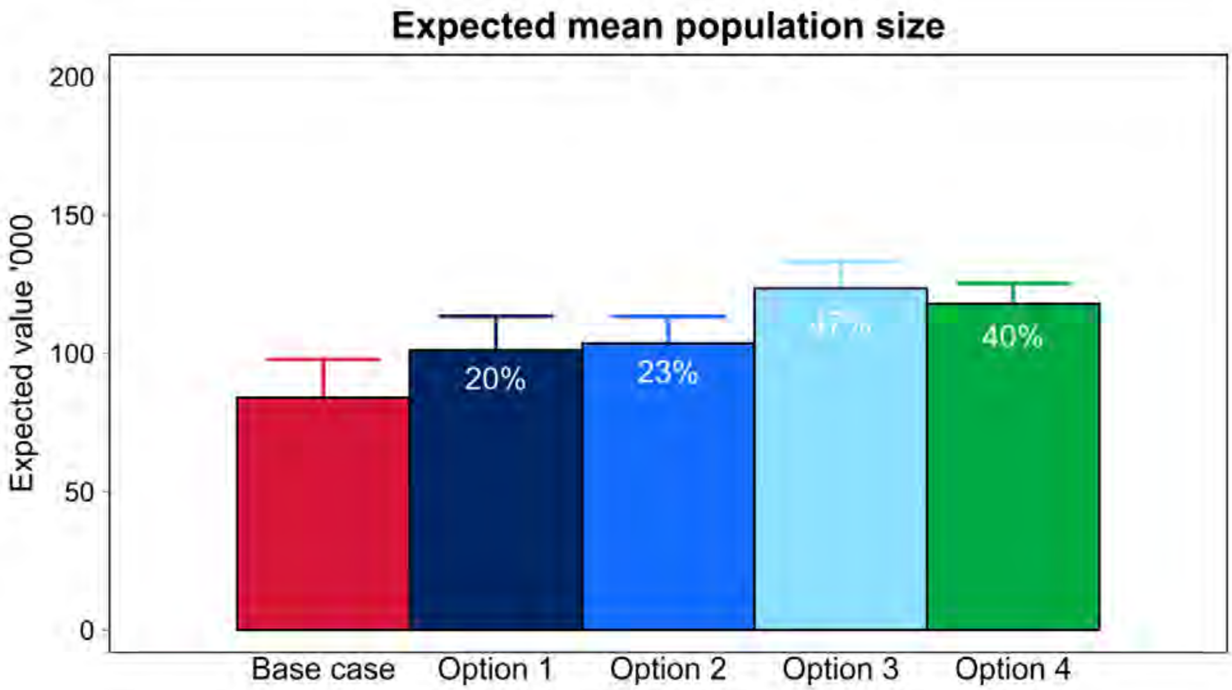
Figure A3.9. Golden Perch adults in the Hay to Balranald reach for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

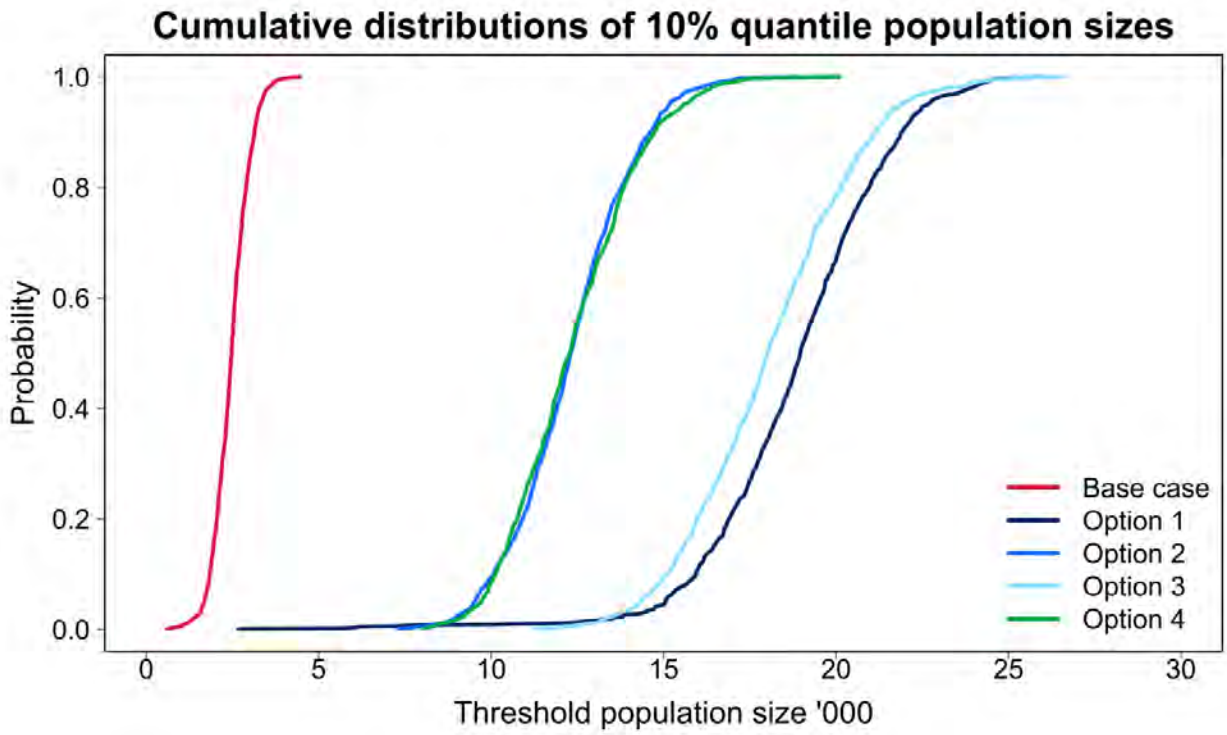
Golden Perch – Gundagai to Hay

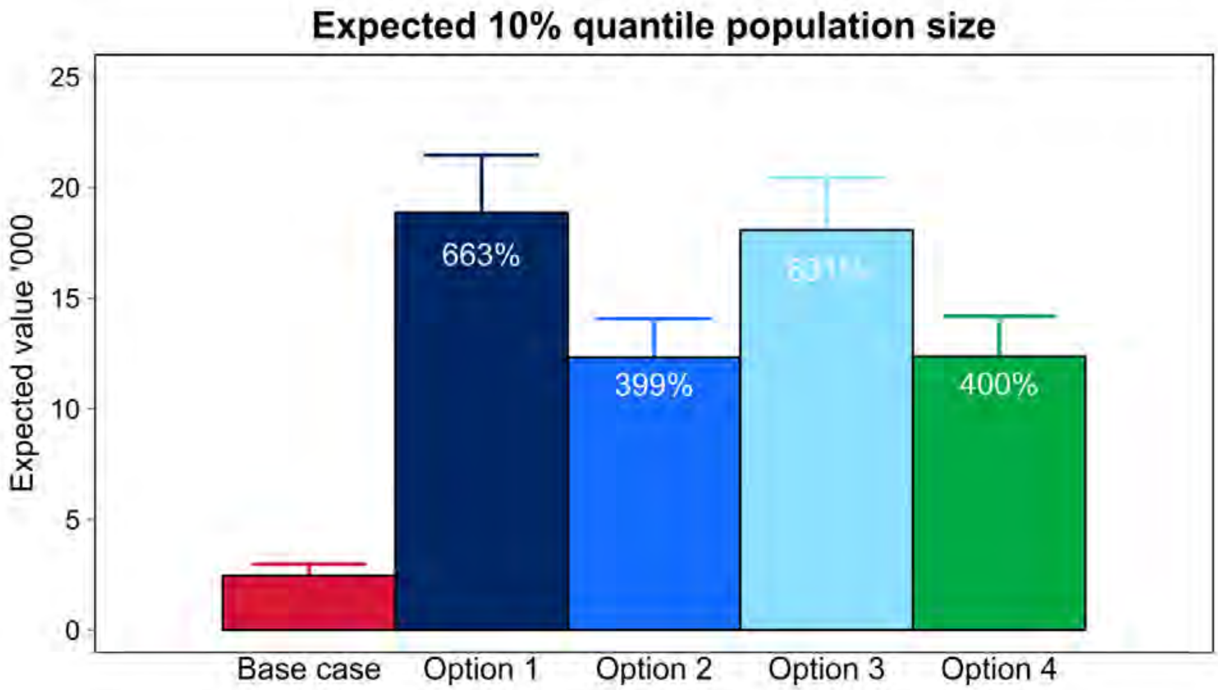


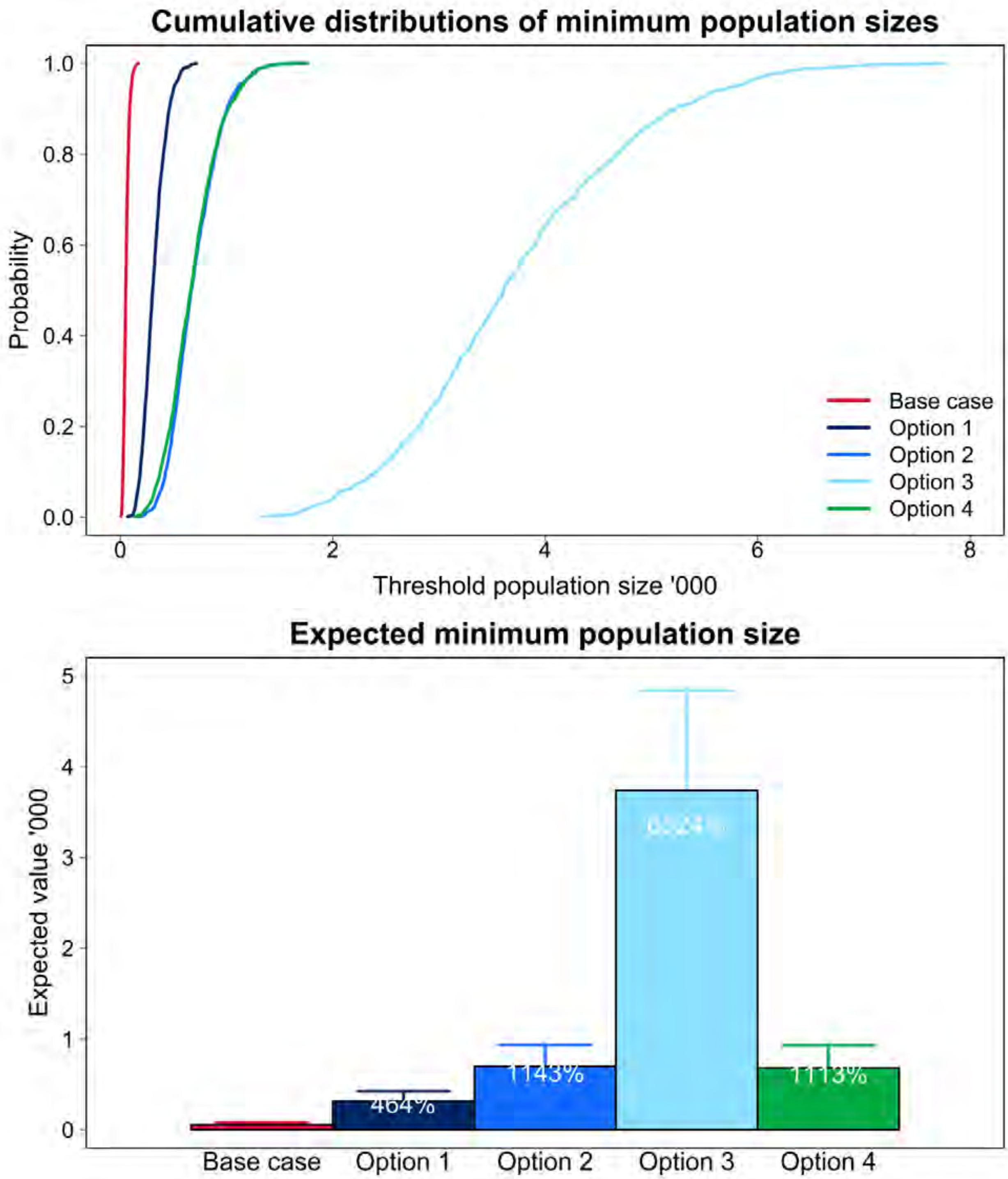



Cumulative distributions of mean population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
20
40
60
80
100
120
140
160
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected mean population size
Expected value '000
200
150
100
50
0
20%
23%
40%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of 10% quantile population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected 10% quantile population size
Expected value '000
25
20
15
10
5
0
663%
399%
400%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4
Expected minimum population size
Expected value '000
5
4
3
2
1
0
464%
1143%
1113%
Base case
Option 1
Option 2
Option 3
Option 4

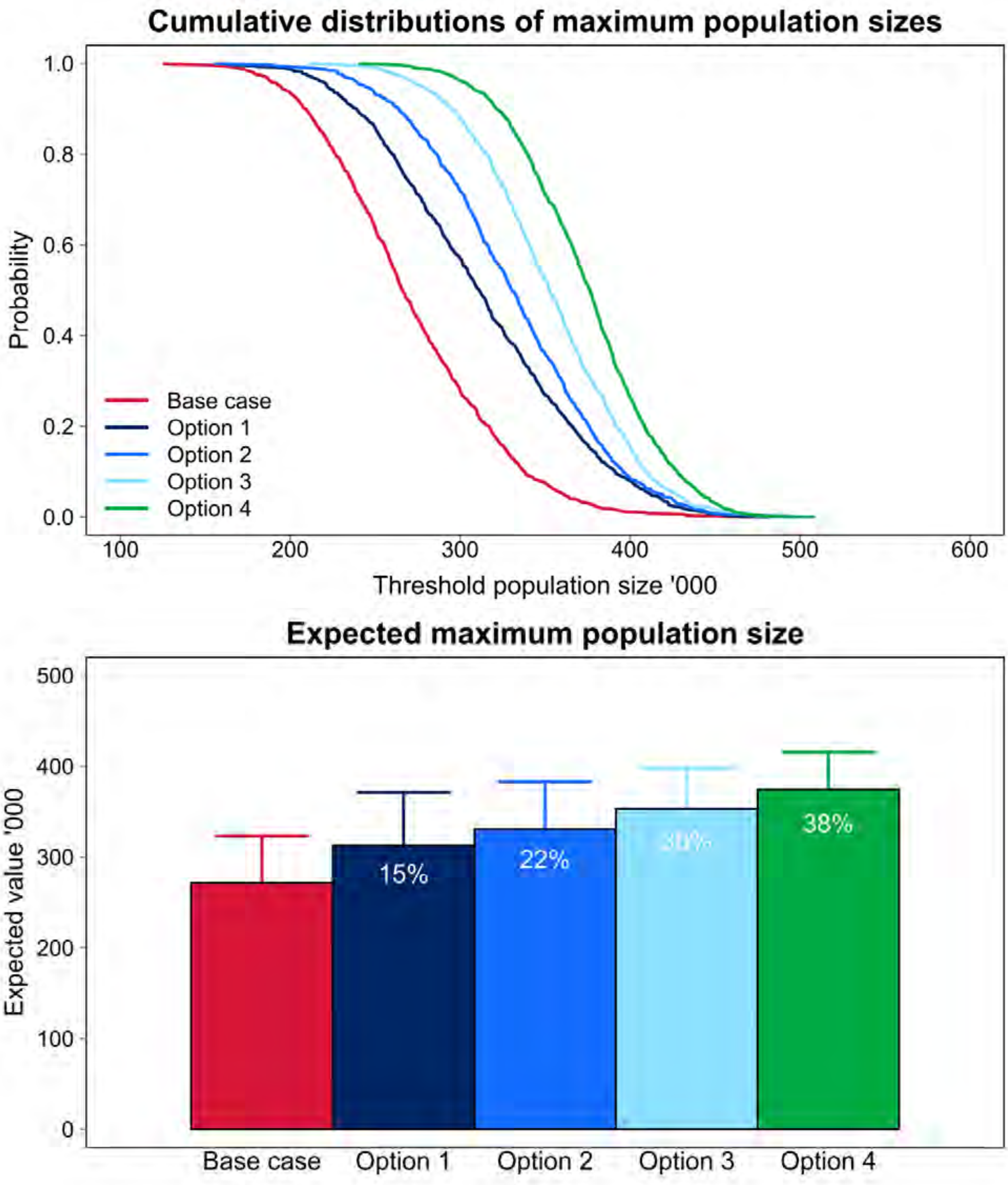
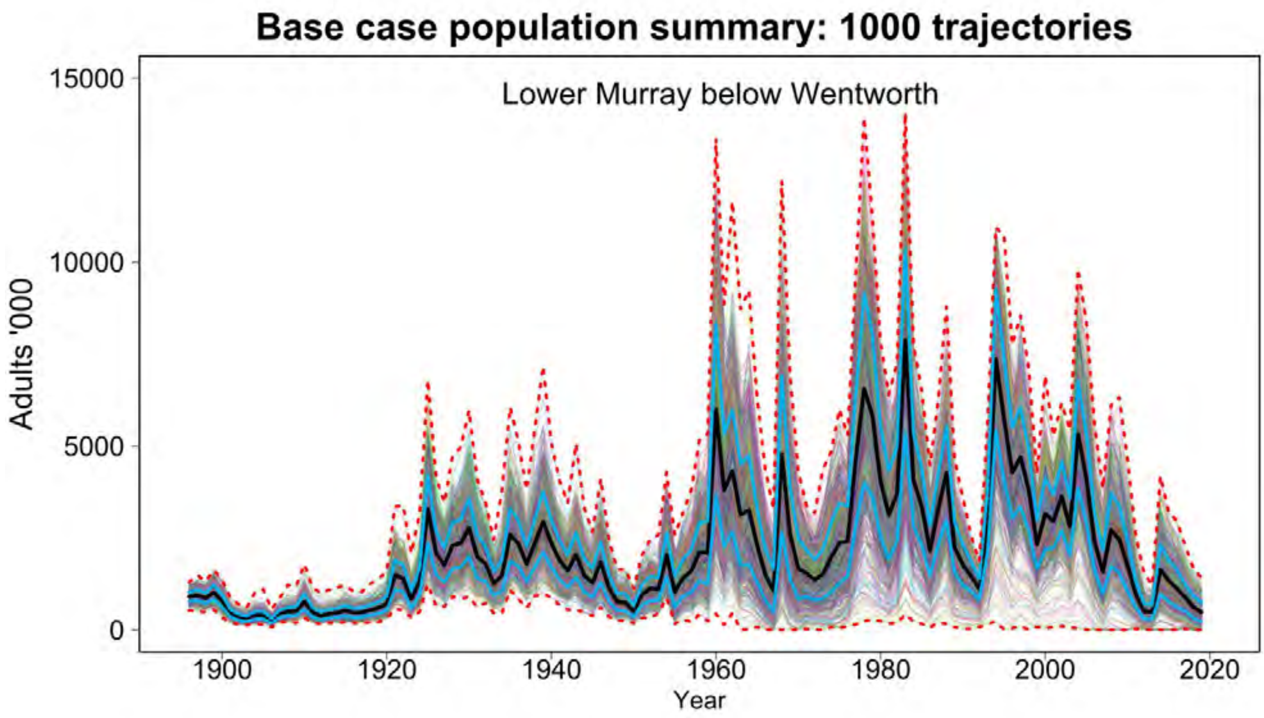
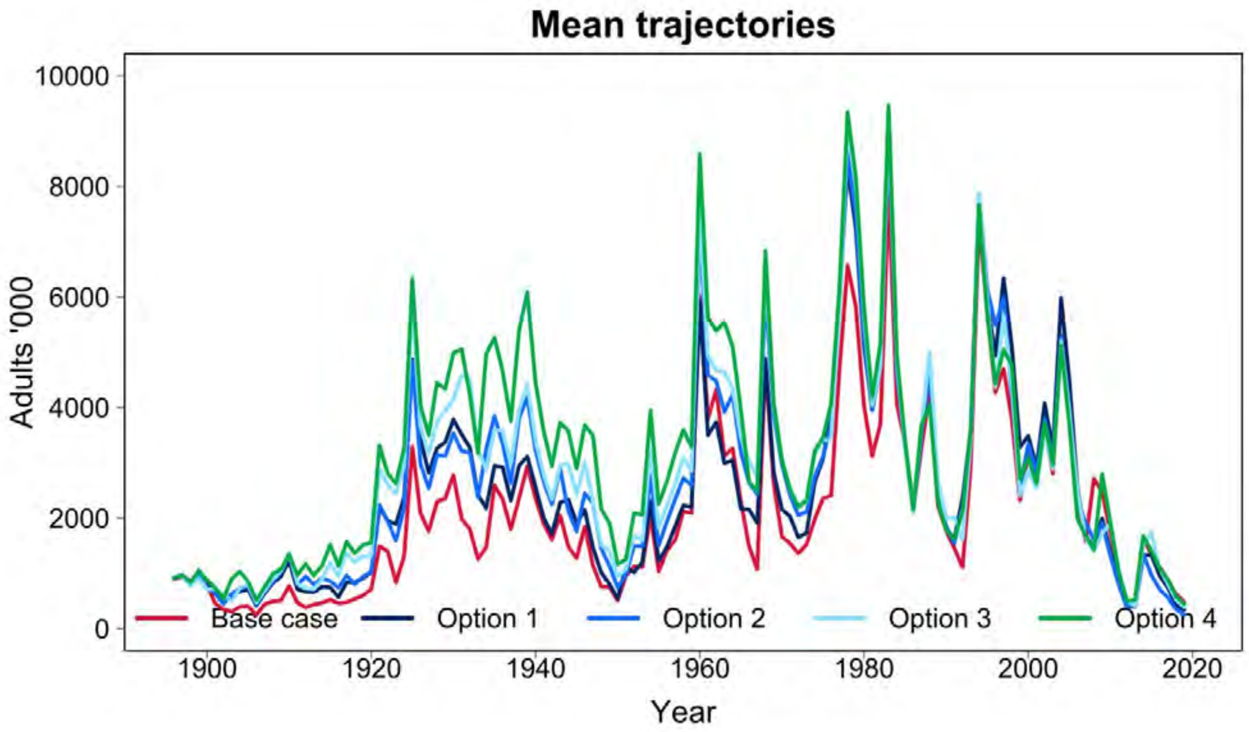
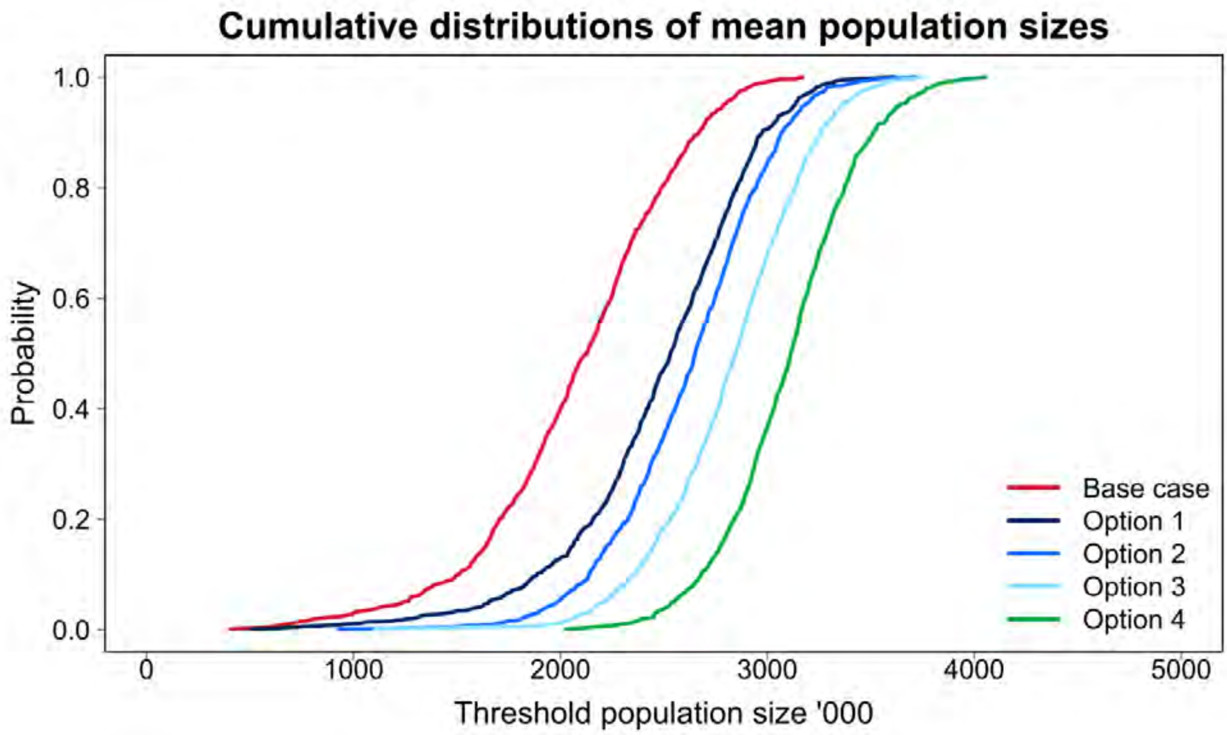


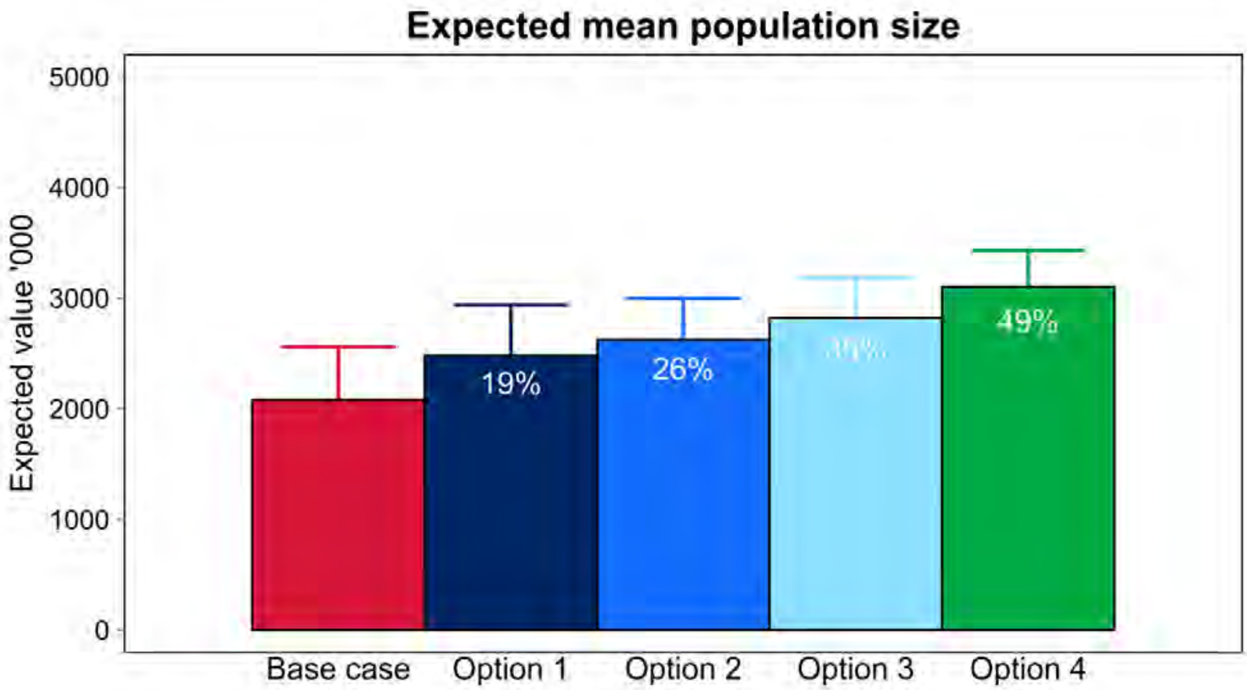
Figure A3.10. Golden Perch adults in the Gundagai to Hay reach for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

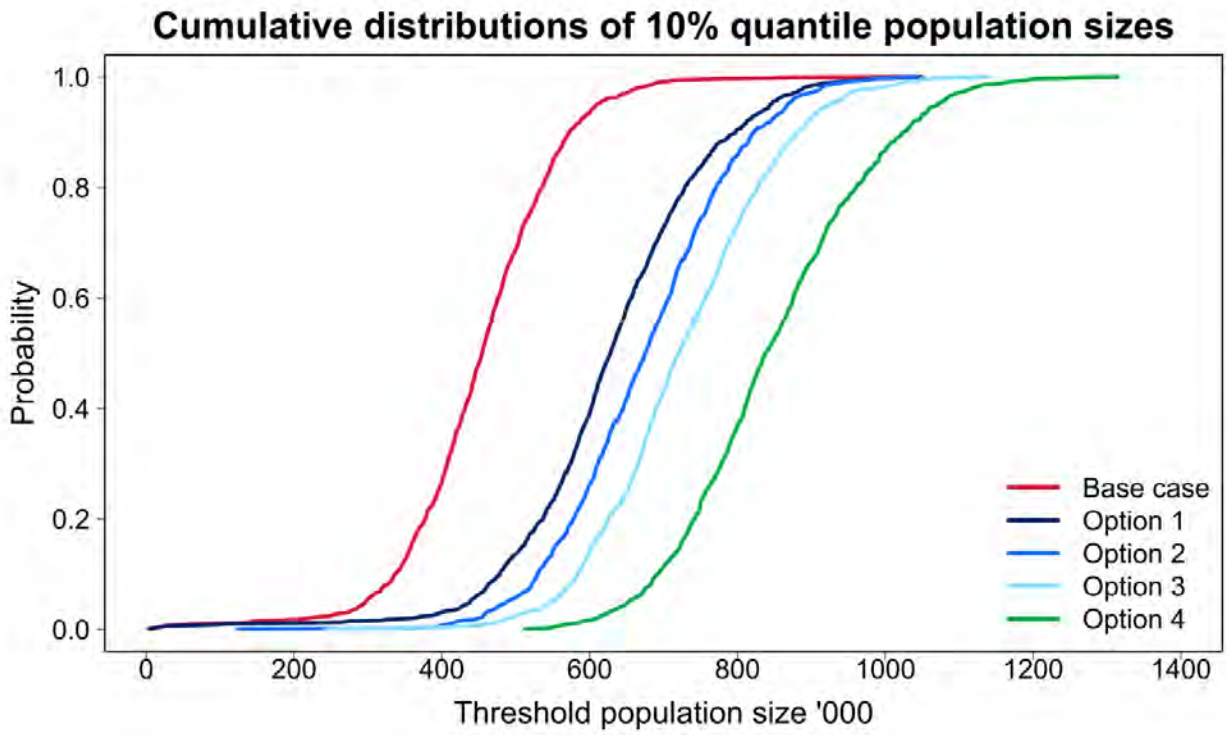
Golden Perch – Lower Murray below Wentworth

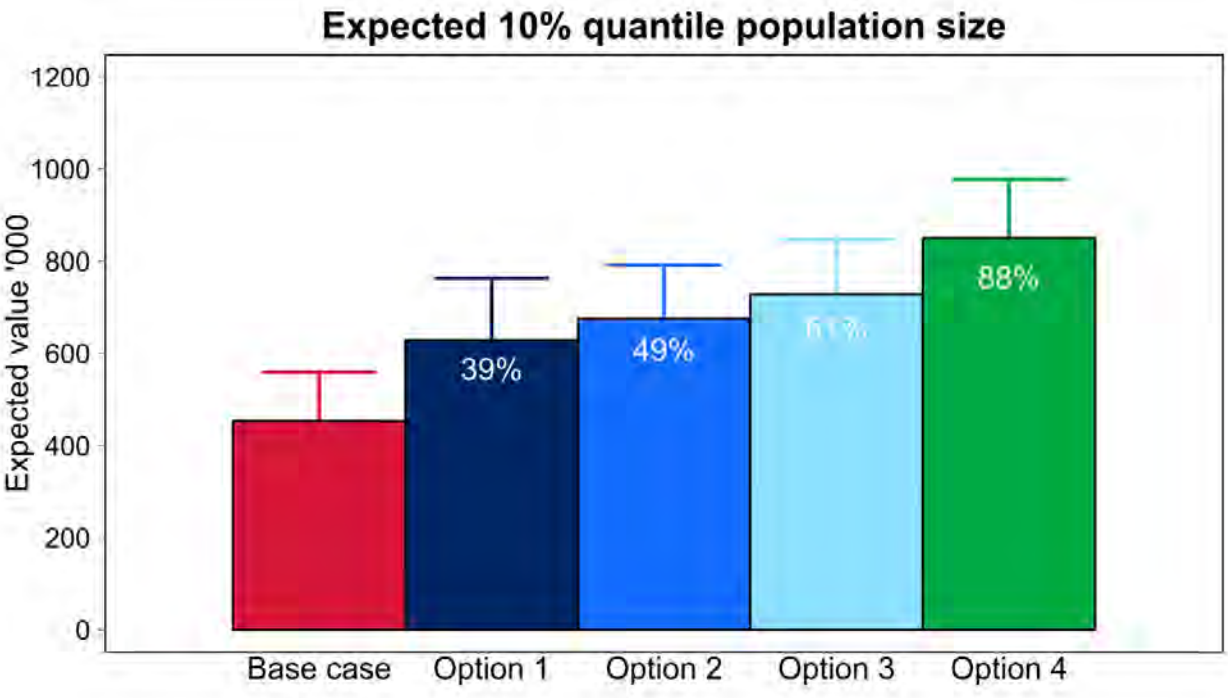


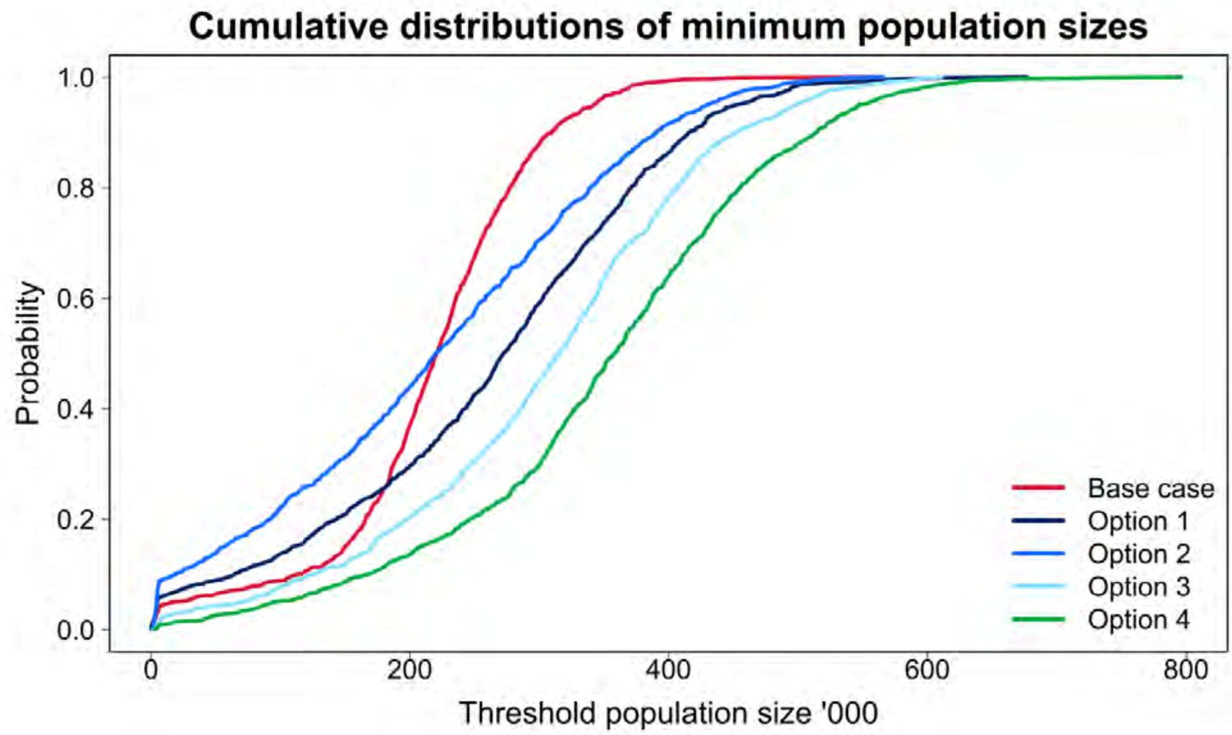


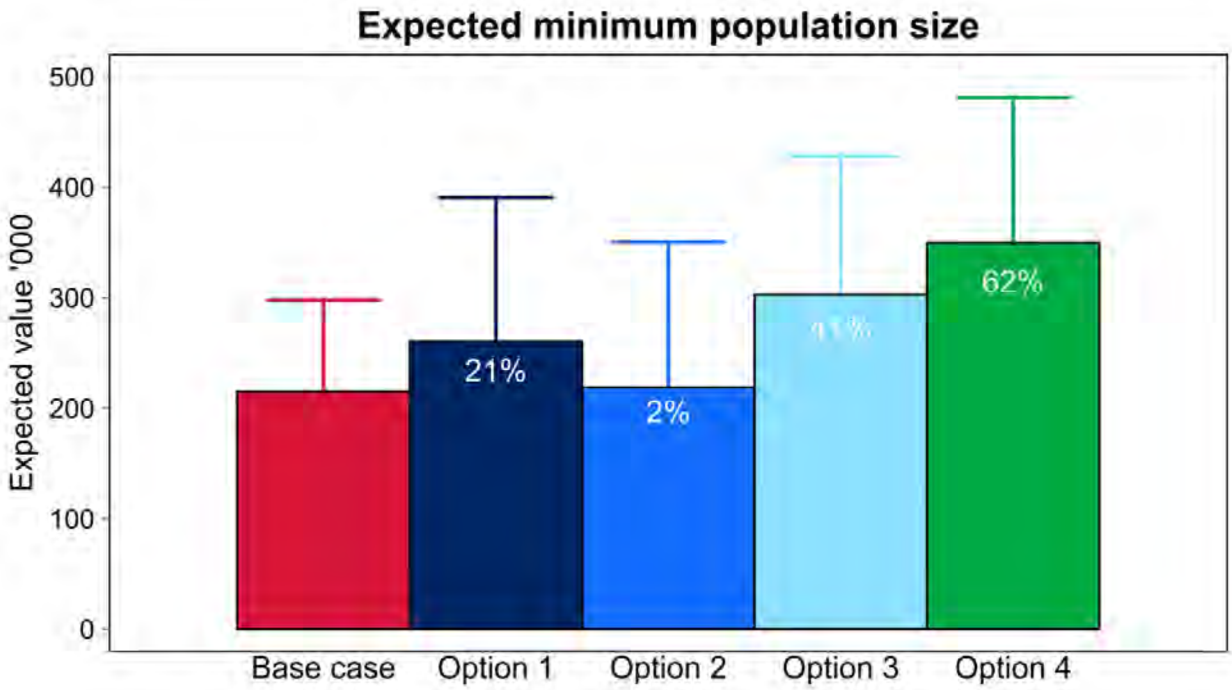

Cumulative distributions of mean population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
1000
2000
3000
4000
5000
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected mean population size
Expected value '000
5000
4000
3000
2000
1000
0
19%
26%
49%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of 10% quantile population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
200
400
600
800
1000
1200
1400
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected 10% quantile population size
Expected value '000
1200
1000
800
600
400
200
0
39%
49%
88%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
200
400
600
800
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected minimum population size
Expected value '000
500
400
300
200
100
0
21%
2%
62%
Base case
Option 1
Option 2
Option 3
Option 4

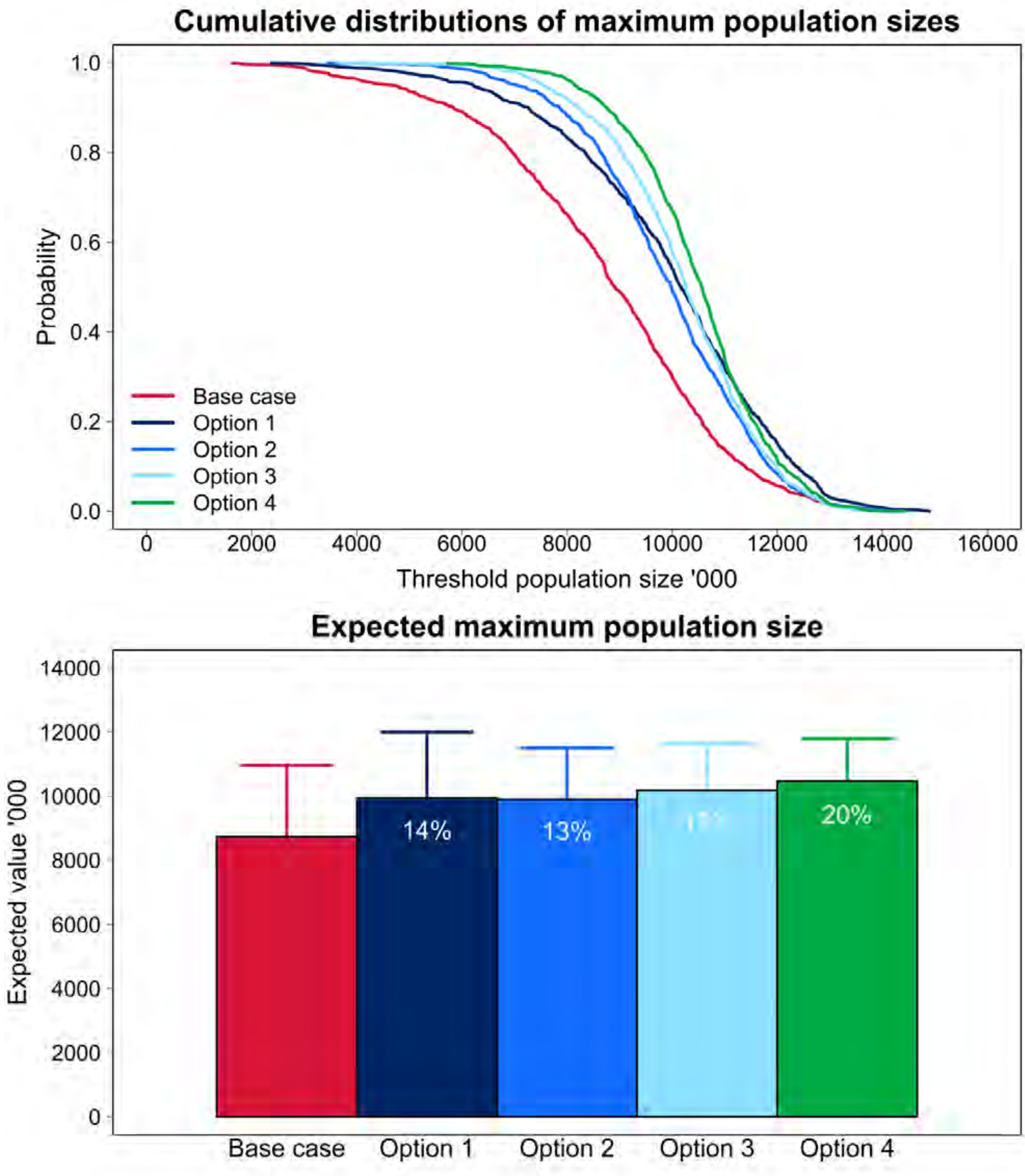
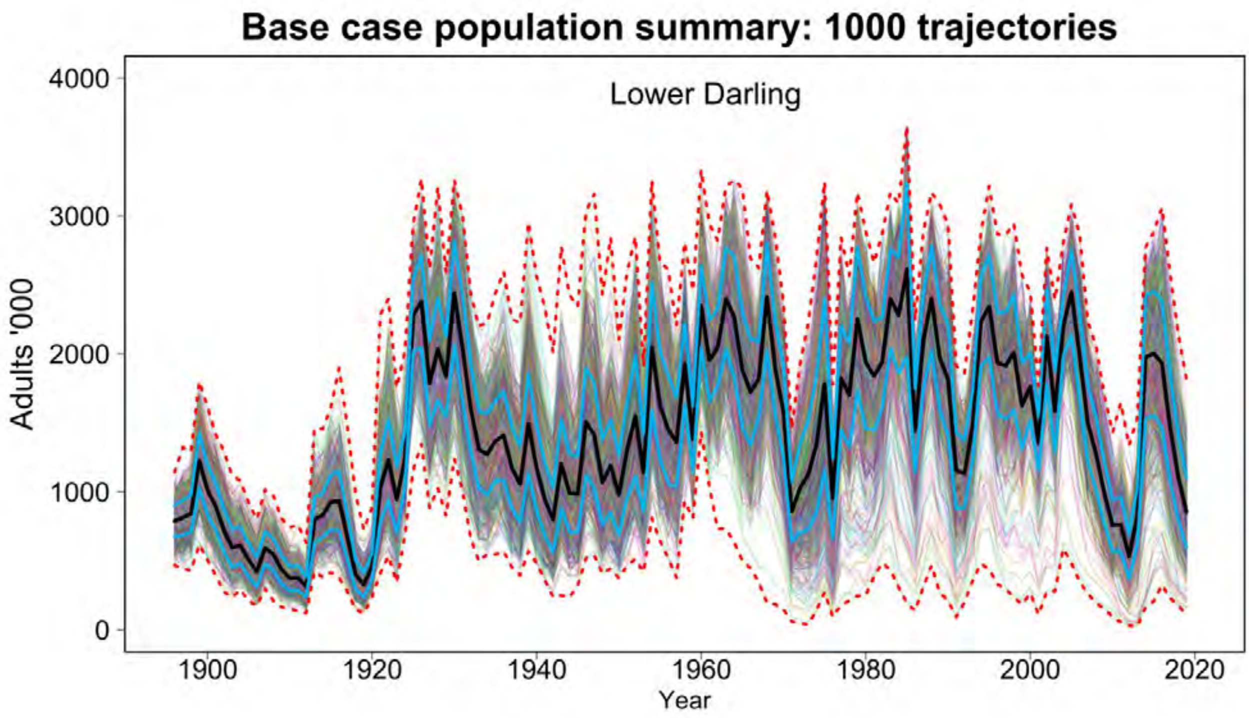
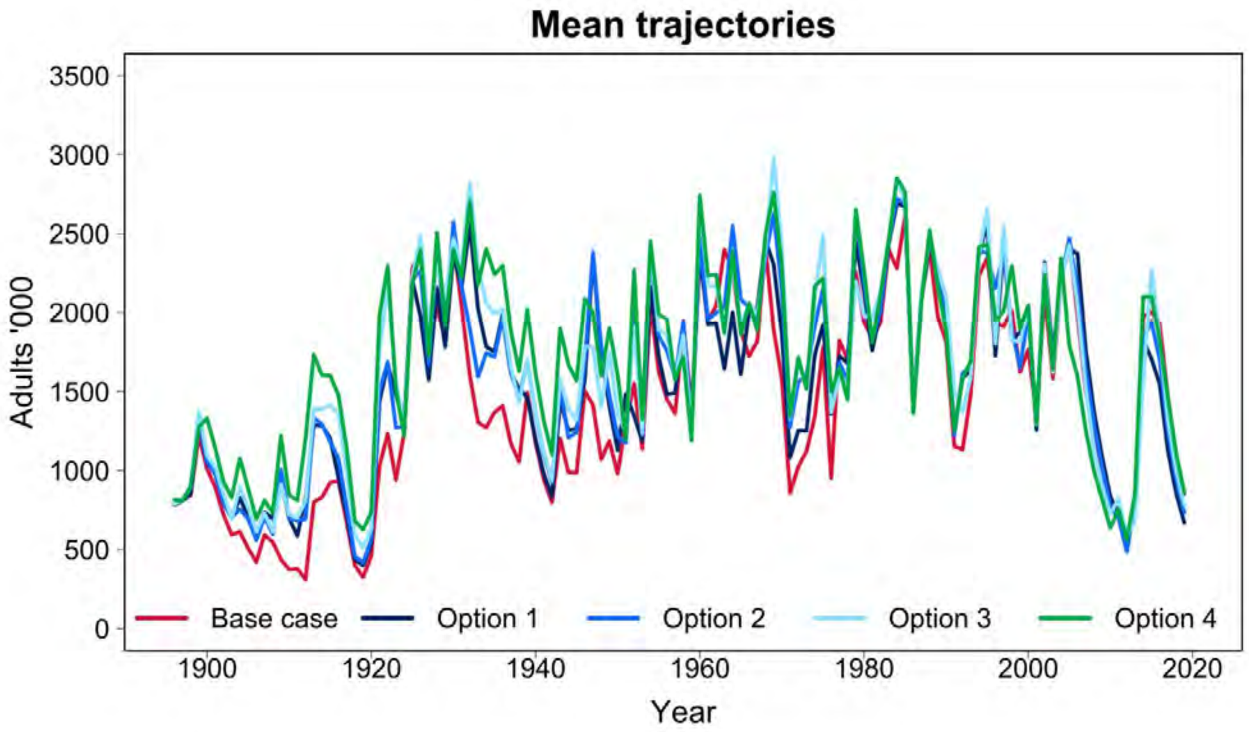
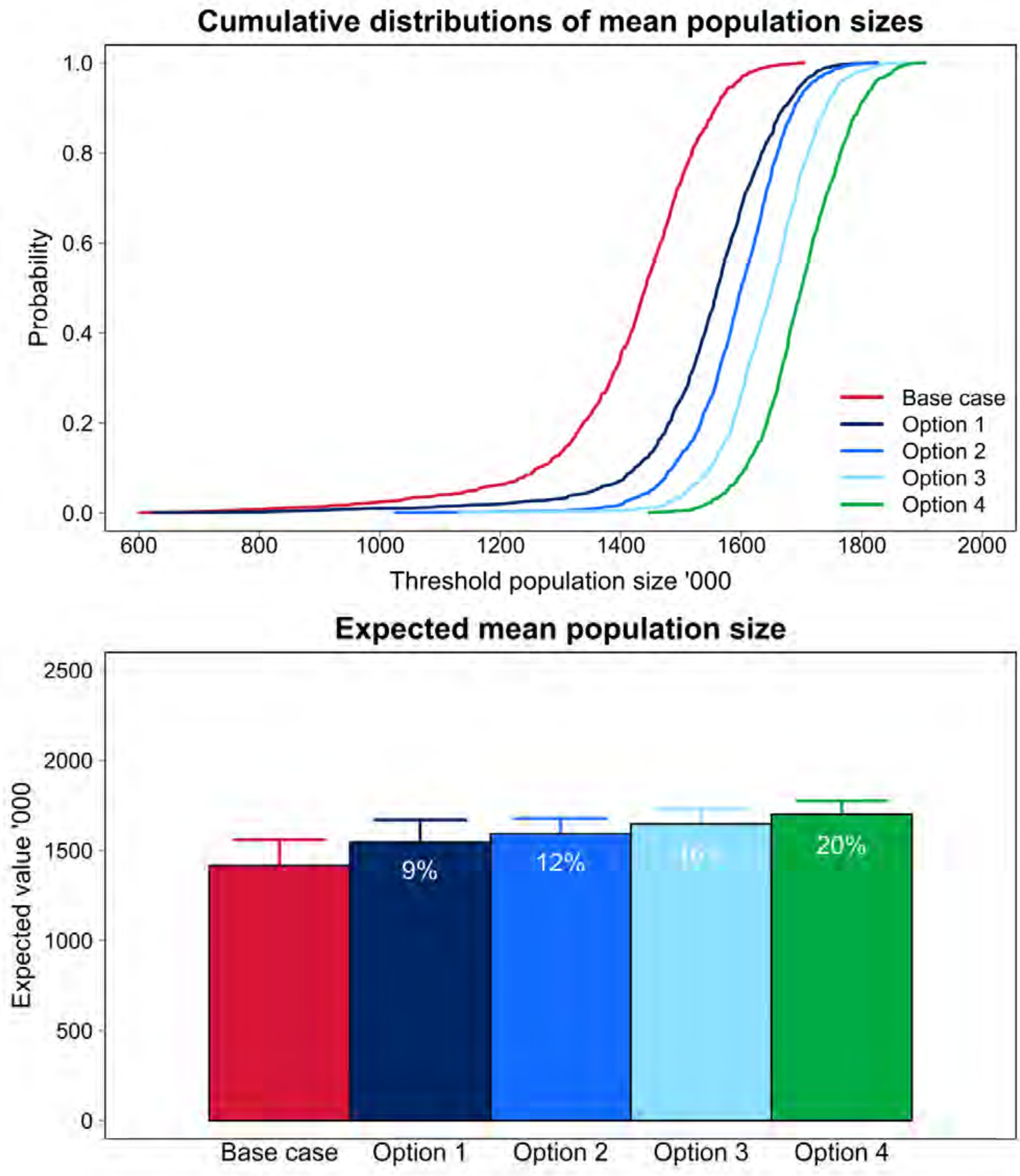


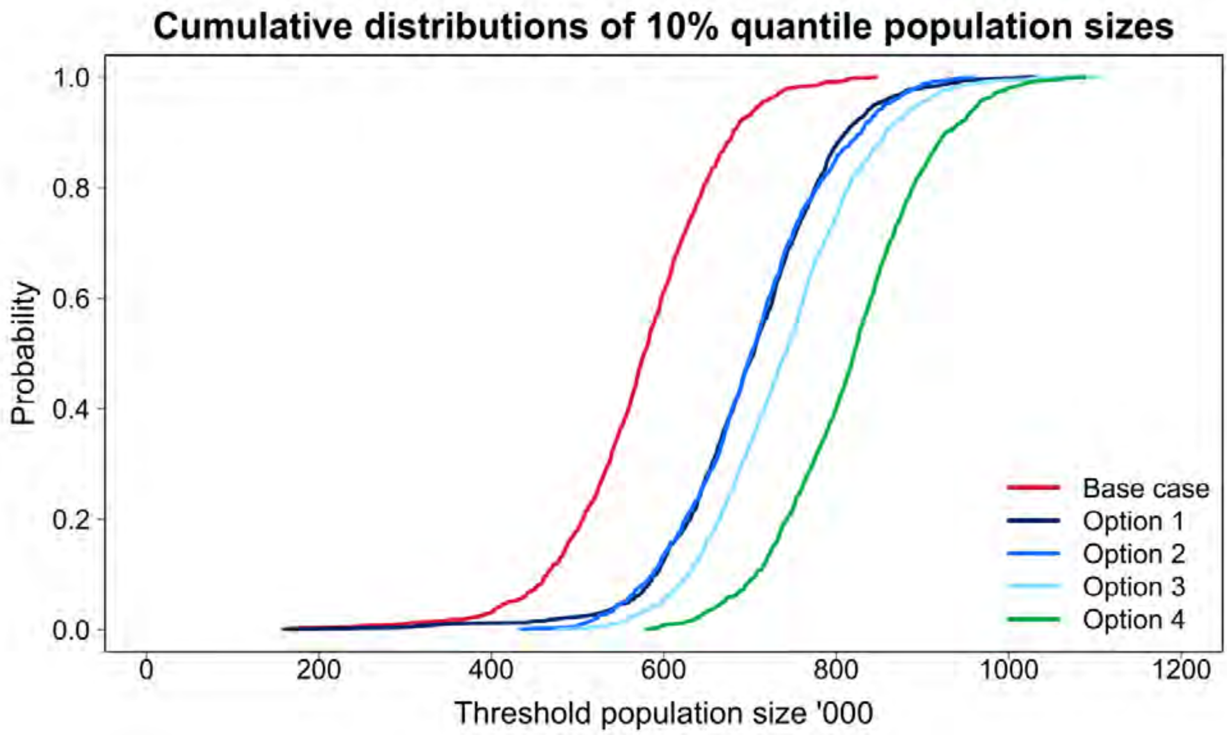
Figure A3.11. Golden Perch adults in the Lower Murray below Wentworth reach for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

Golden Perch – Lower Darling

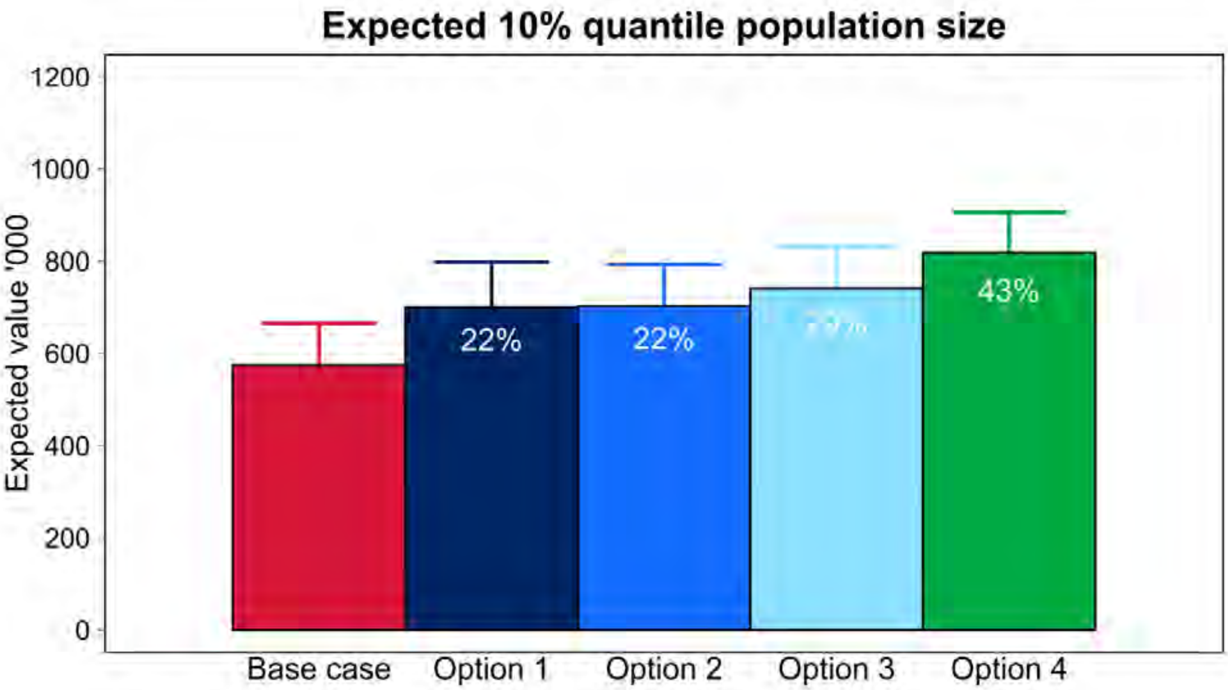




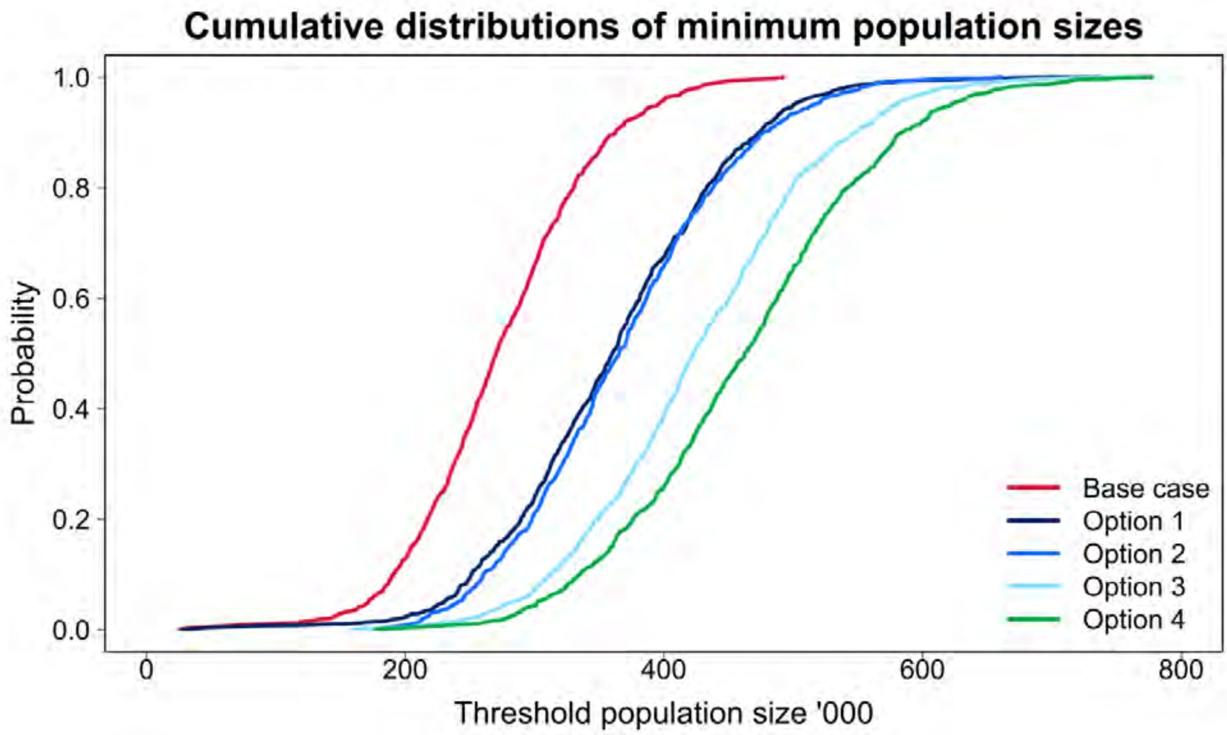

Cumulative distributions of mean population sizes
Probability
Threshold population size '000
1.0
0.8
0.6
0.4
0.2
0.0
600
800
1000
1200
1400
1600
1800
2000
Base case
Option 1
Option 2
Option 3
Option 4
Expected mean population size
Expected value '000
2500
2000
1500
1000
500
0
9%
12%
20%
Base case
Option 1
Option 2
Option 3
Option 4

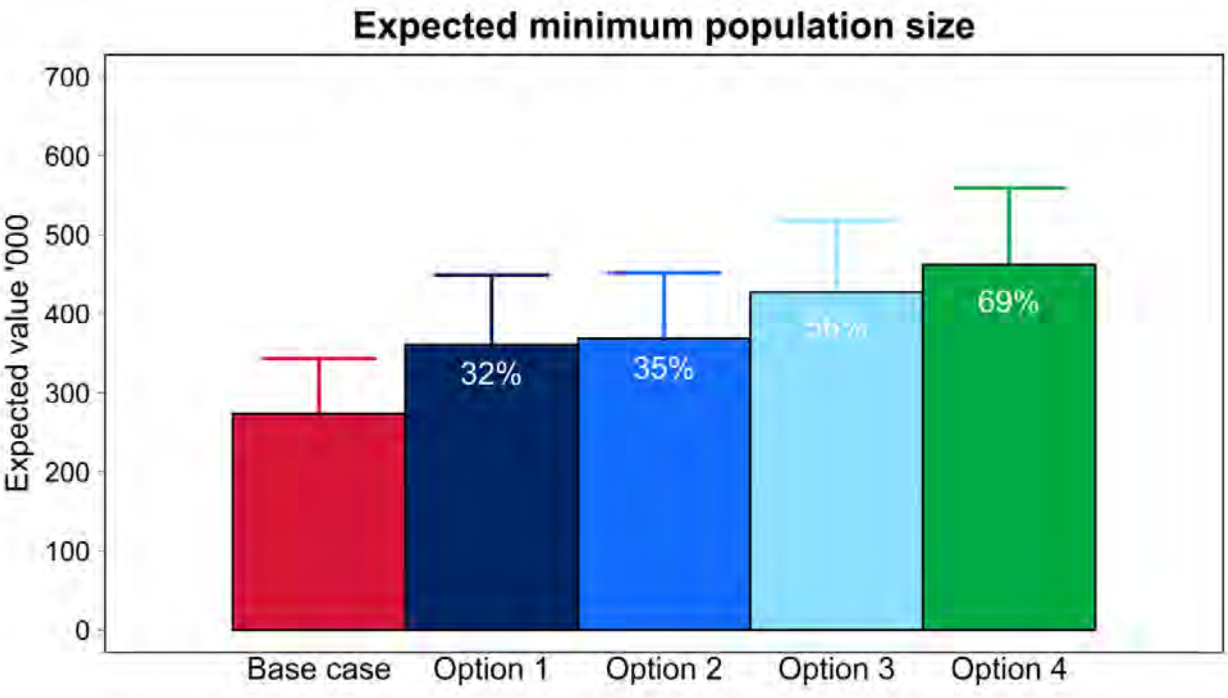


Cumulative distributions of 10% quantile population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
200
400
600
800
1000
1200
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4



Expected 10% quantile population size
Expected value '000
1200
1000
800
600
400
200
0
22%
22%
43%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
200
400
600
800
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected minimum population size
Expected value '000
700
600
500
400
300
200
100
0
32%
35%
69%
Base case
Option 1
Option 2
Option 3
Option 4

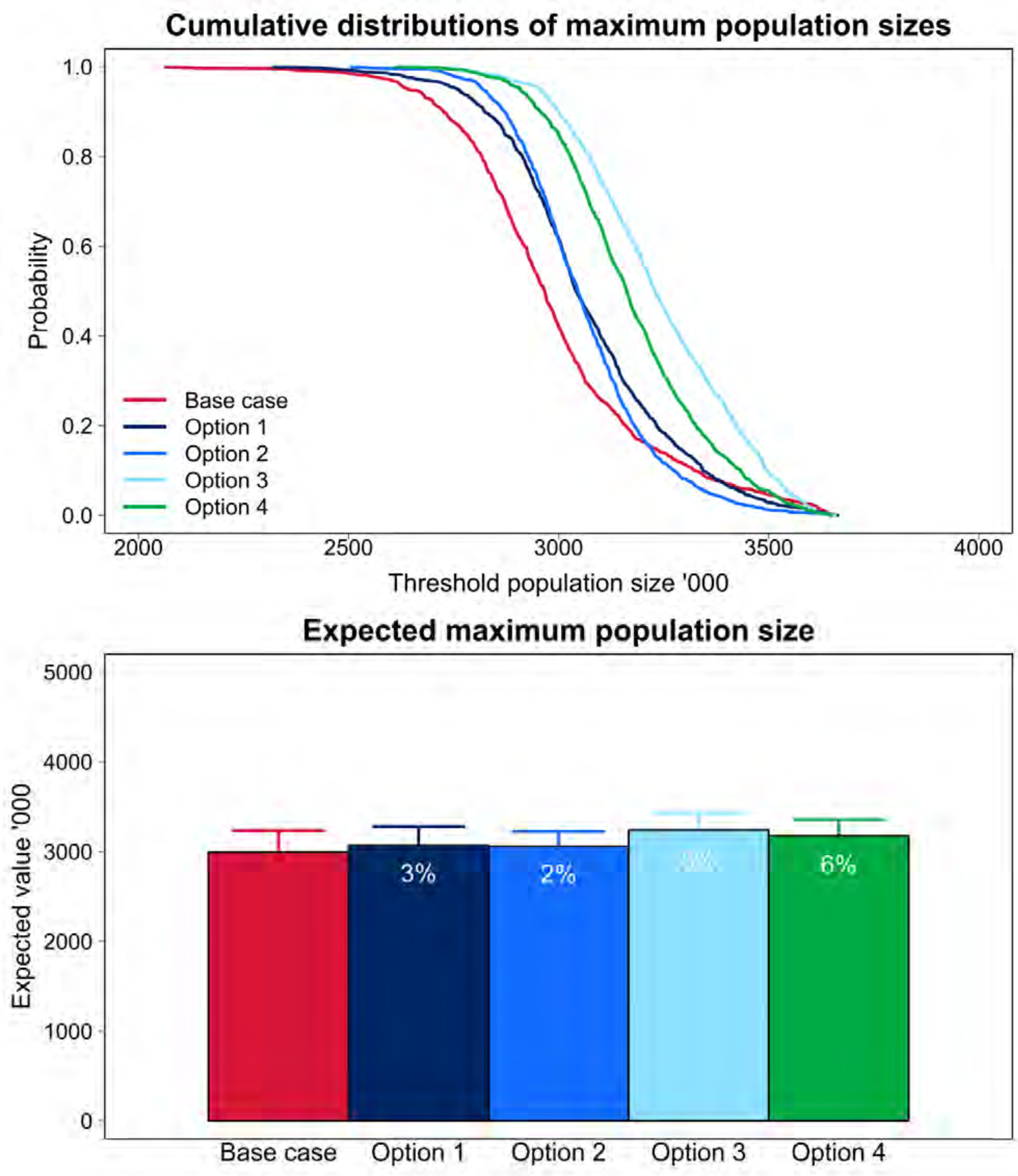


Figure A3.12. Golden Perch adults in the Lower Darling reach for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

Golden Perch Recruits

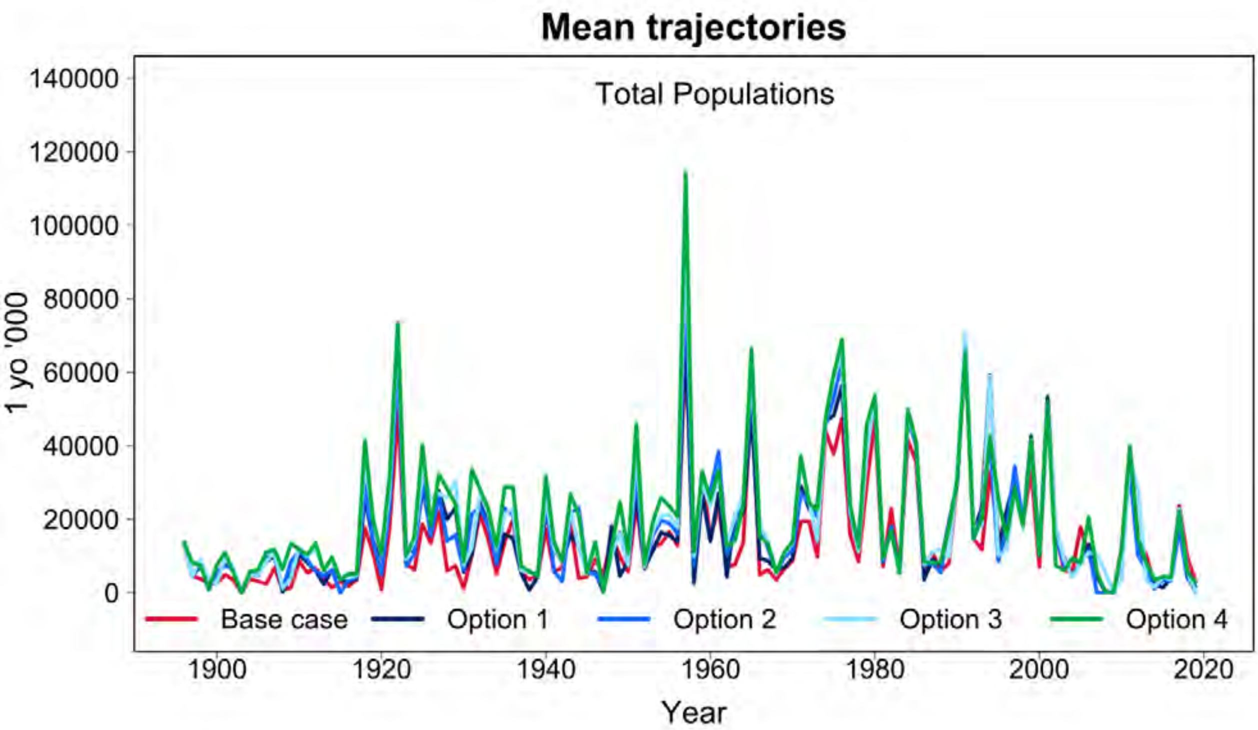


Figure A3.13. Golden Perch recruits mean population size aggregated across all reaches in this study in the southern MDB for the RRCP flow scenarios Base case – Option 4.

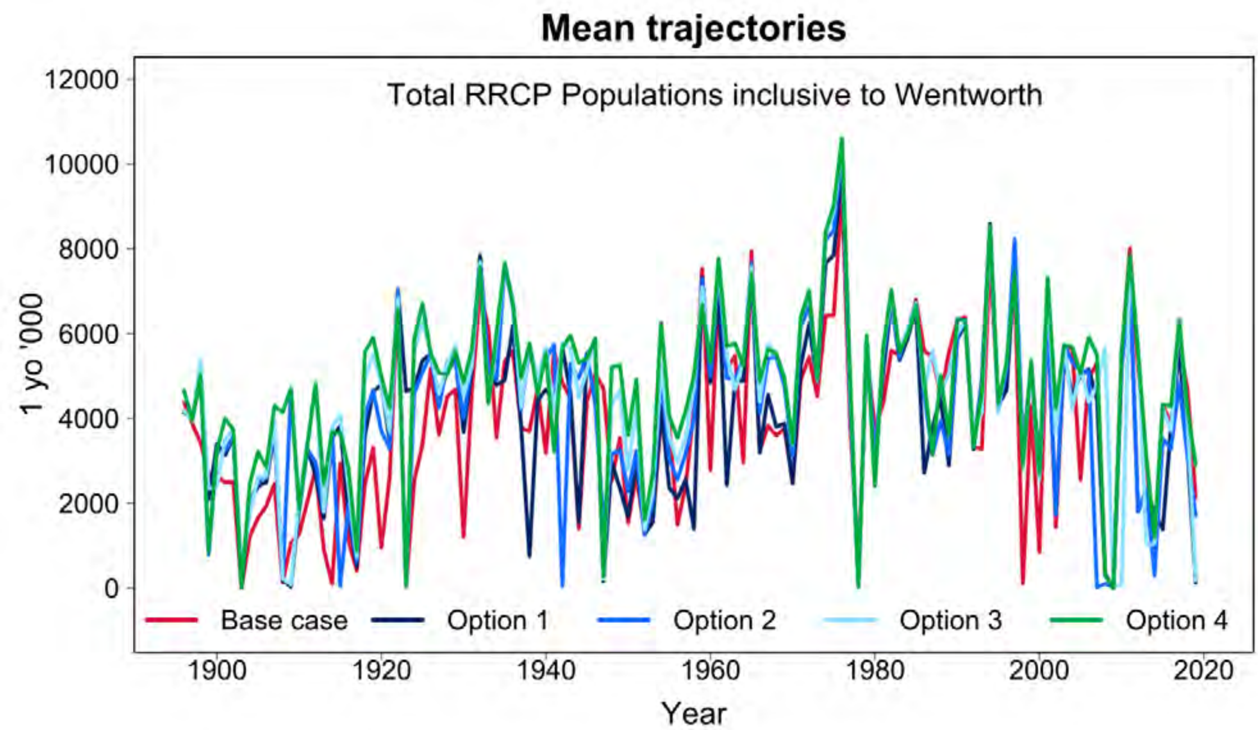


Figure A3.14. Golden Perch recruits mean population size aggregated across all modelled RRCP focal zones, together with the Wakool Junction to Wentworth reach, for the RRCP flow scenarios Base case – Option 4.

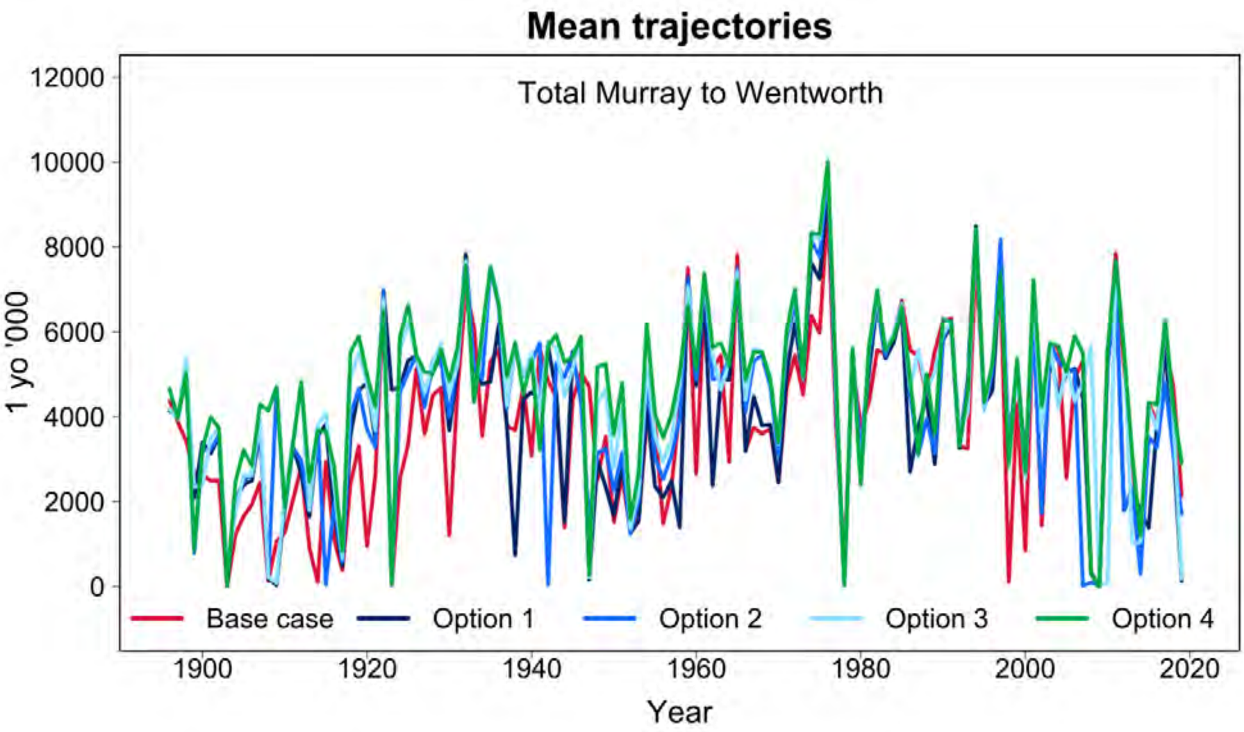


Figure A3.15. Golden Perch recruits mean population size aggregated across the Murray River RRCP focal zones (including the Edward River), together with the Wakool Junction to Wentworth reach, for the RRCP flow scenarios Base case – Option 4.

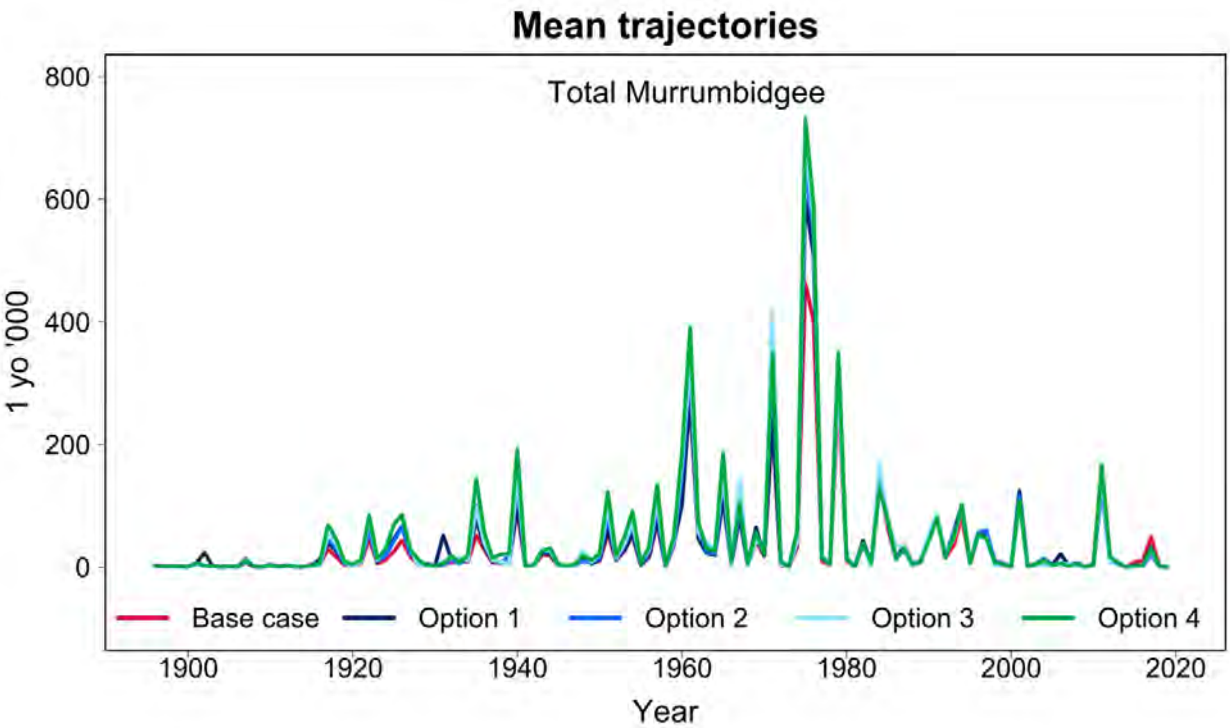


Figure A3.16. Golden Perch recruits mean population size aggregated across the Murrumbidgee River RRCP focal zone for the RRCP flow scenarios Base case – Option 4.

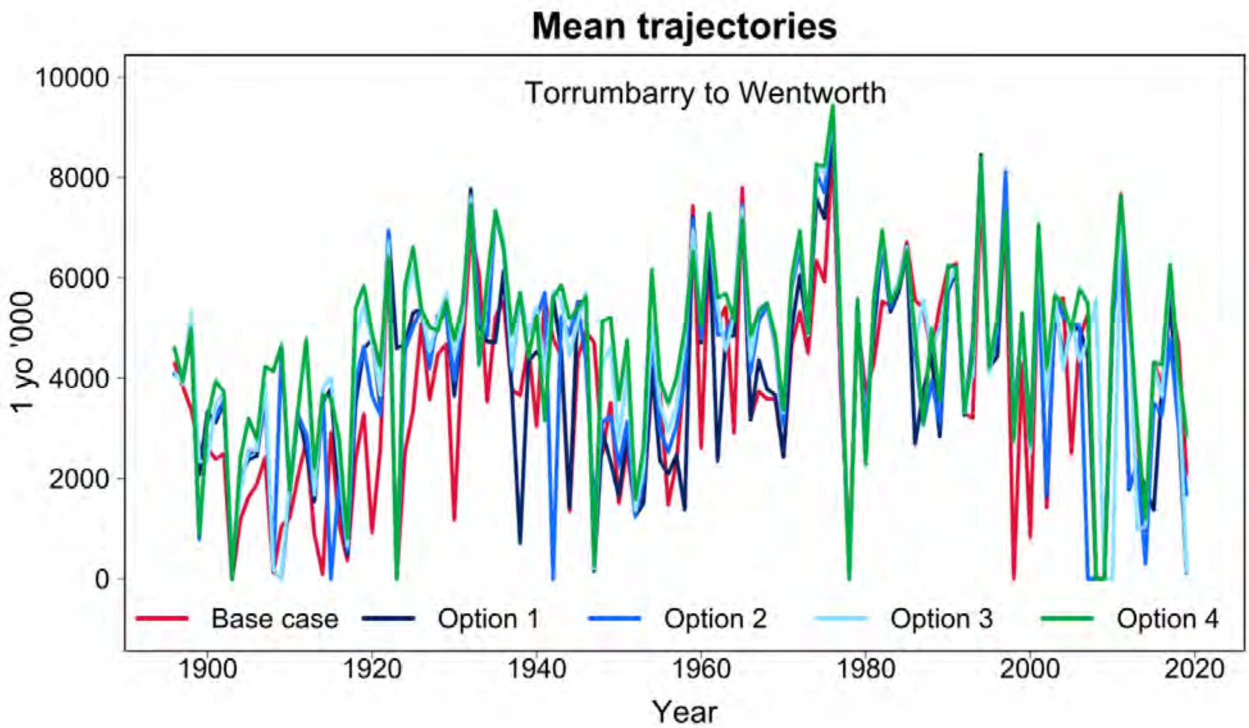


Figure A3.17. Golden Perch recruits mean population size in the Torrumbarry to Wentworth reach for the RRCP flow scenarios Base case – Option 4.

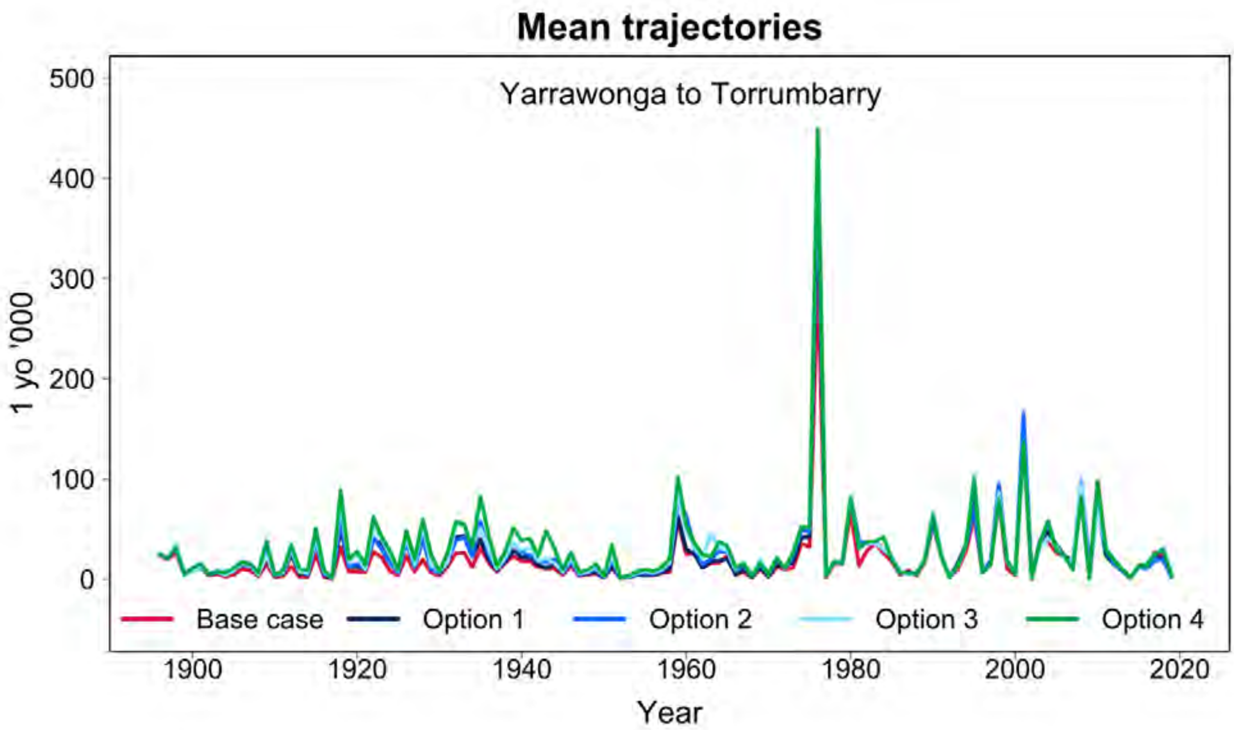


Figure A3.18. Golden Perch recruits mean population size in the Yarrawonga to Torrumbarry reach for the RRCP flow scenarios Base case – Option 4.

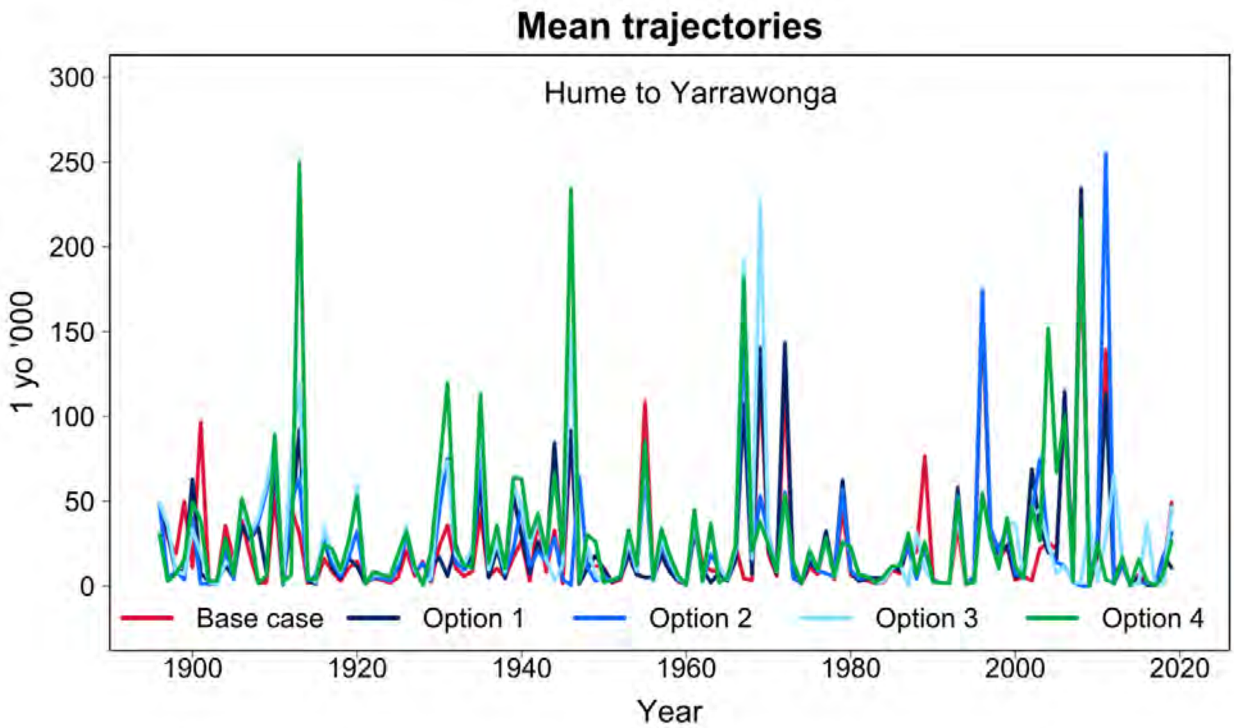


Figure A3.19. Golden Perch recruits mean population size in the Hume to Yarrawonga reach for the RRCP flow scenarios Base case – Option 4.

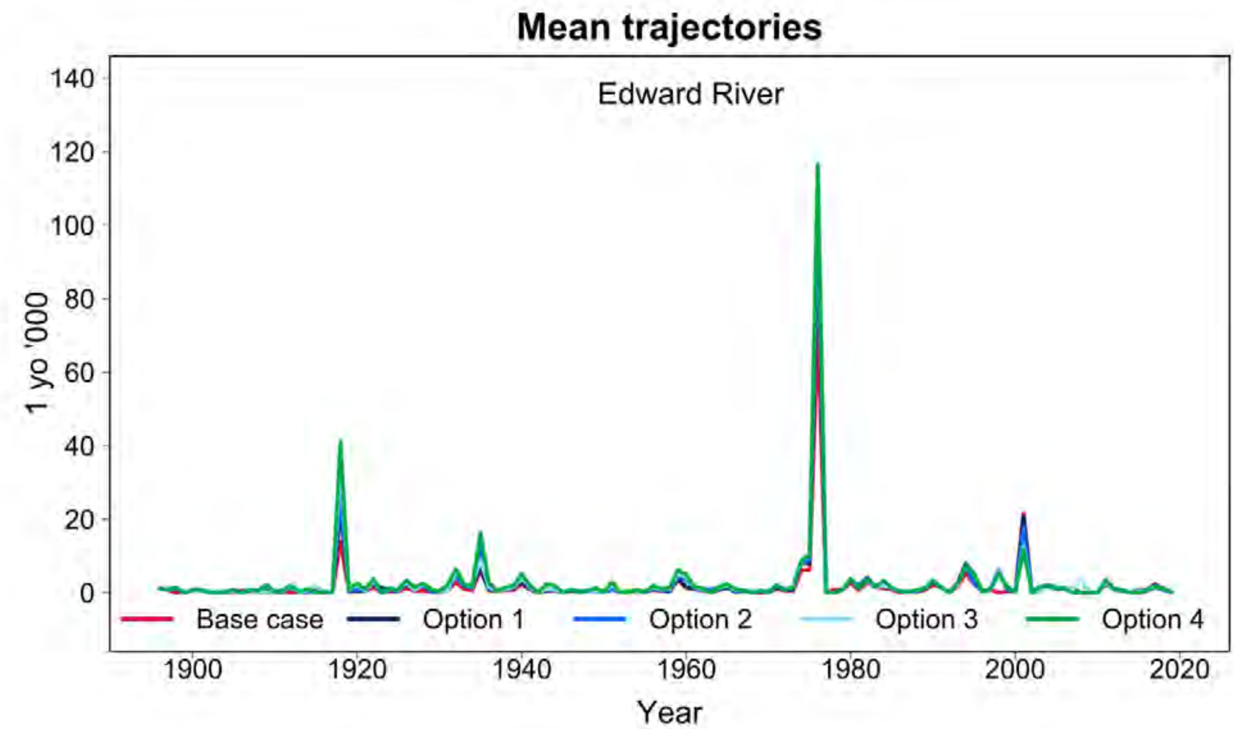


Figure A3.20. Golden Perch recruits mean population size in the Edward River for the RRCP flow scenarios Base case – Option 4.

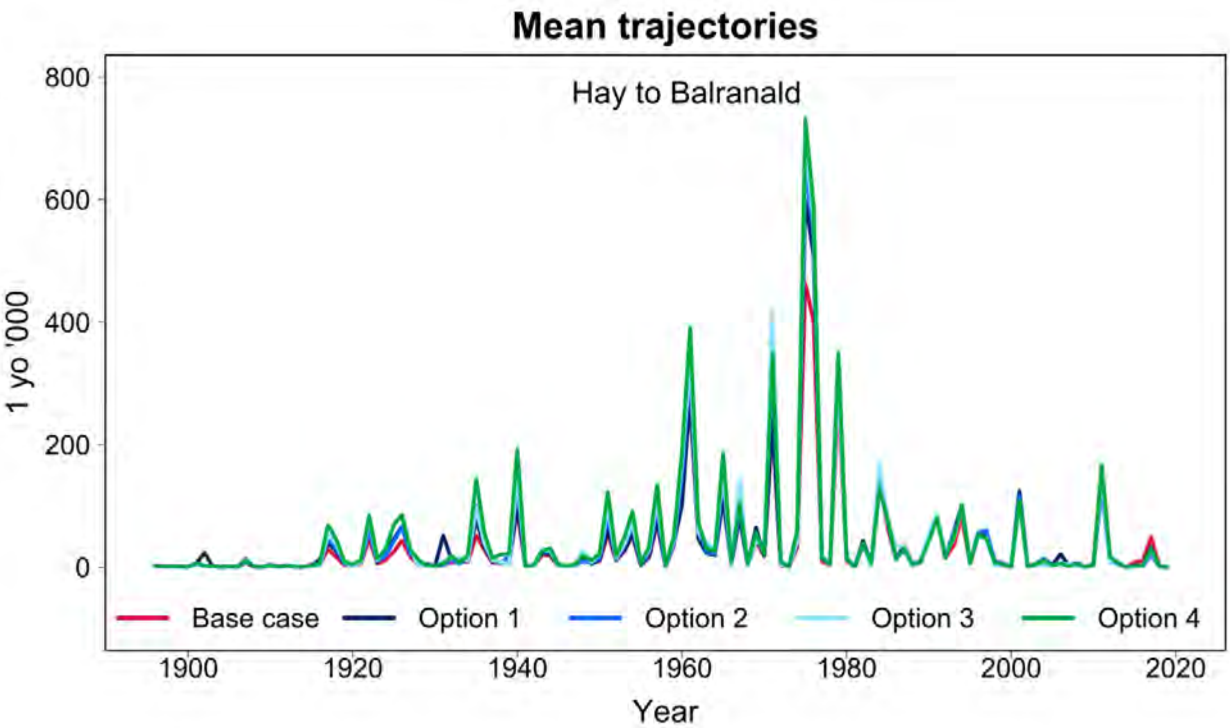


Figure A3.21. Golden Perch recruits mean population size in the Hay to Balranald reach for the RRCP flow scenarios Base case – Option 4.

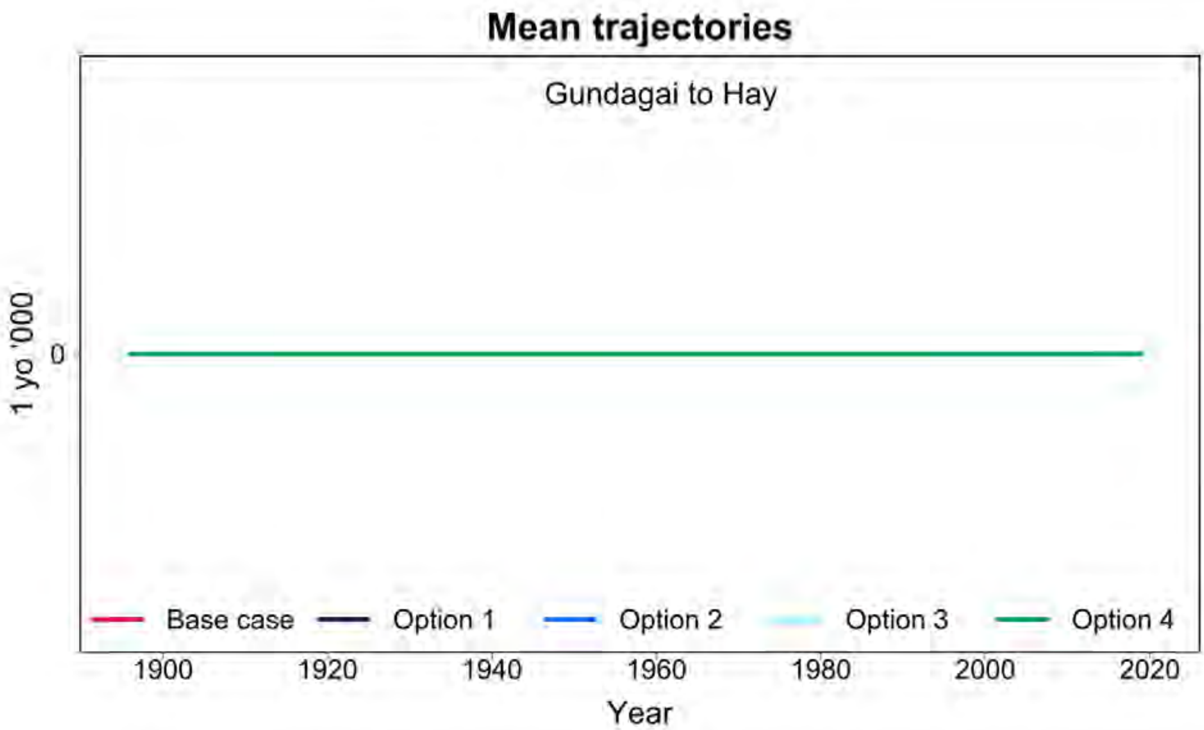


Figure A3.22. Golden Perch recruits mean population size in the Gundagai to Hay reach for the RRCP flow scenarios Base case – Option 4.

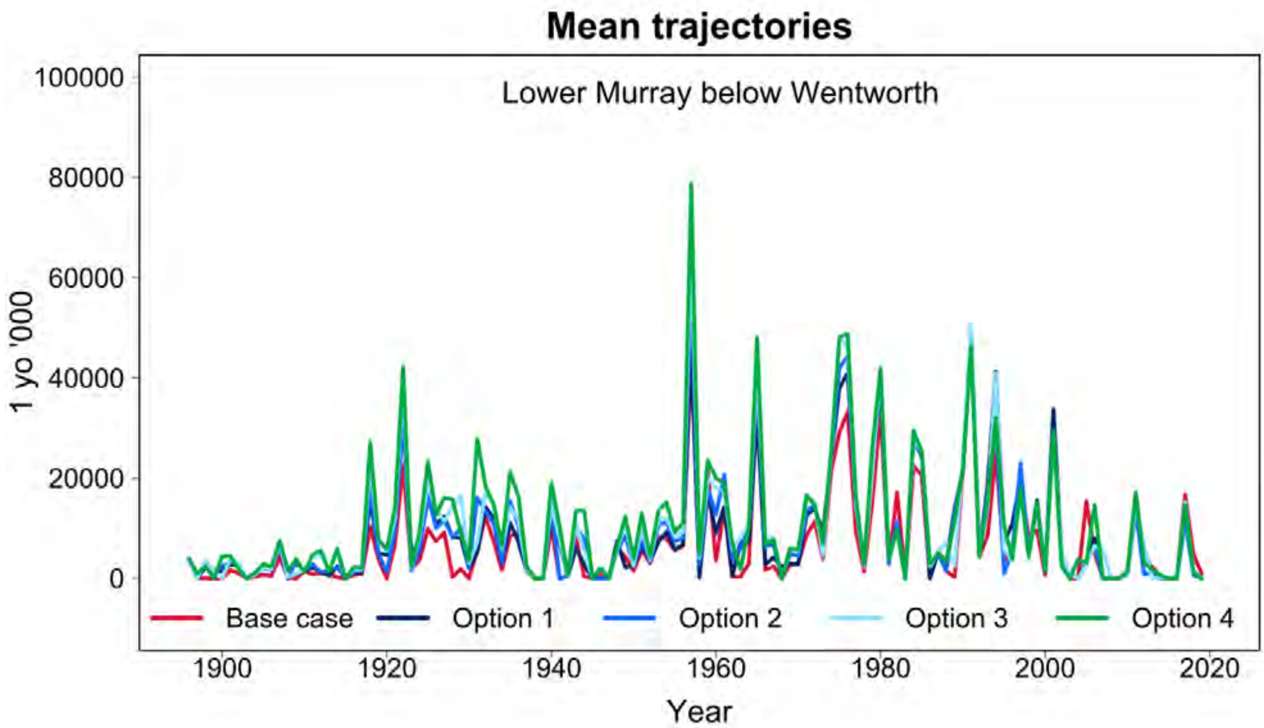


Figure A3.23. Golden Perch recruits mean population size in the Lower Murray below Wentworth reach for the RRCP flow scenarios Base case – Option 4.

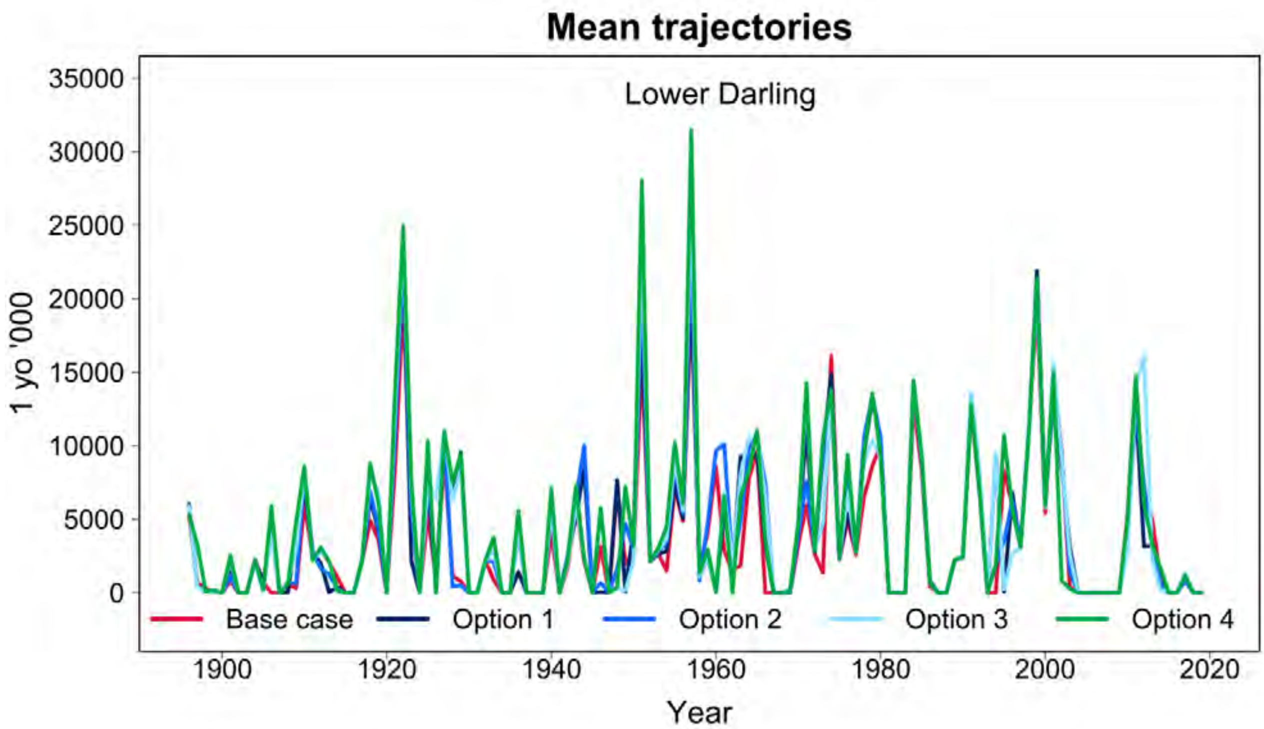
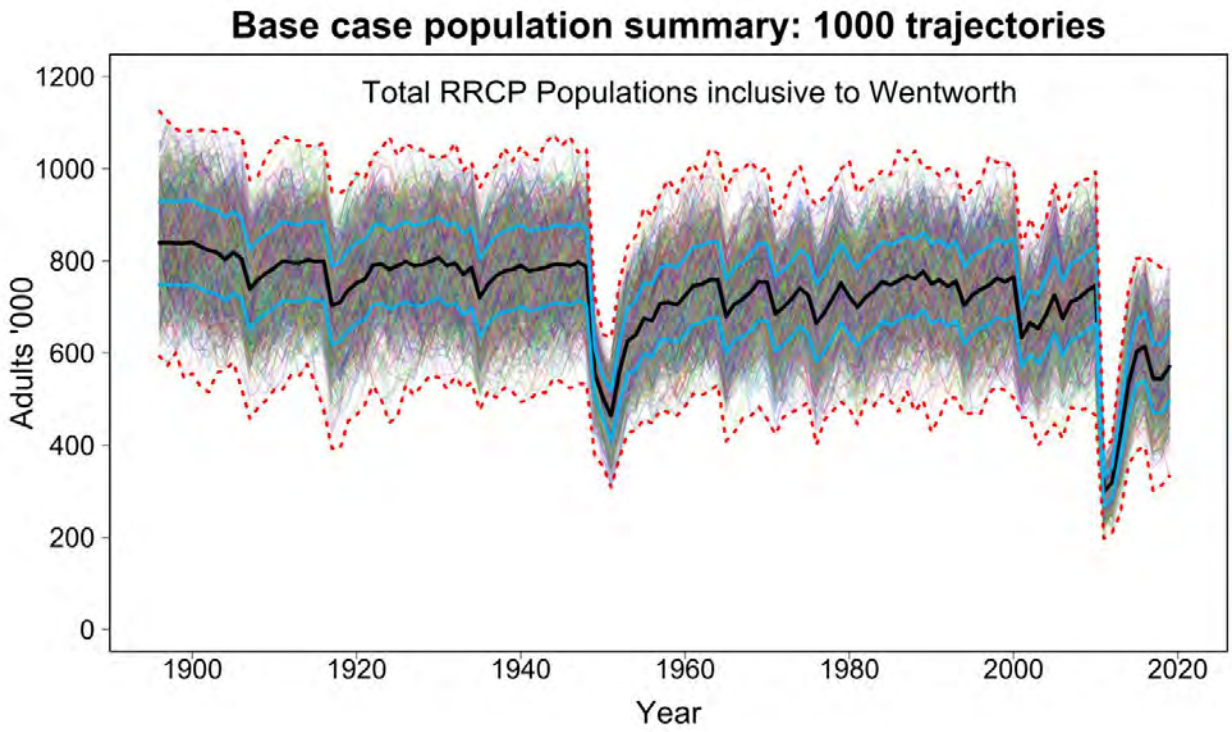
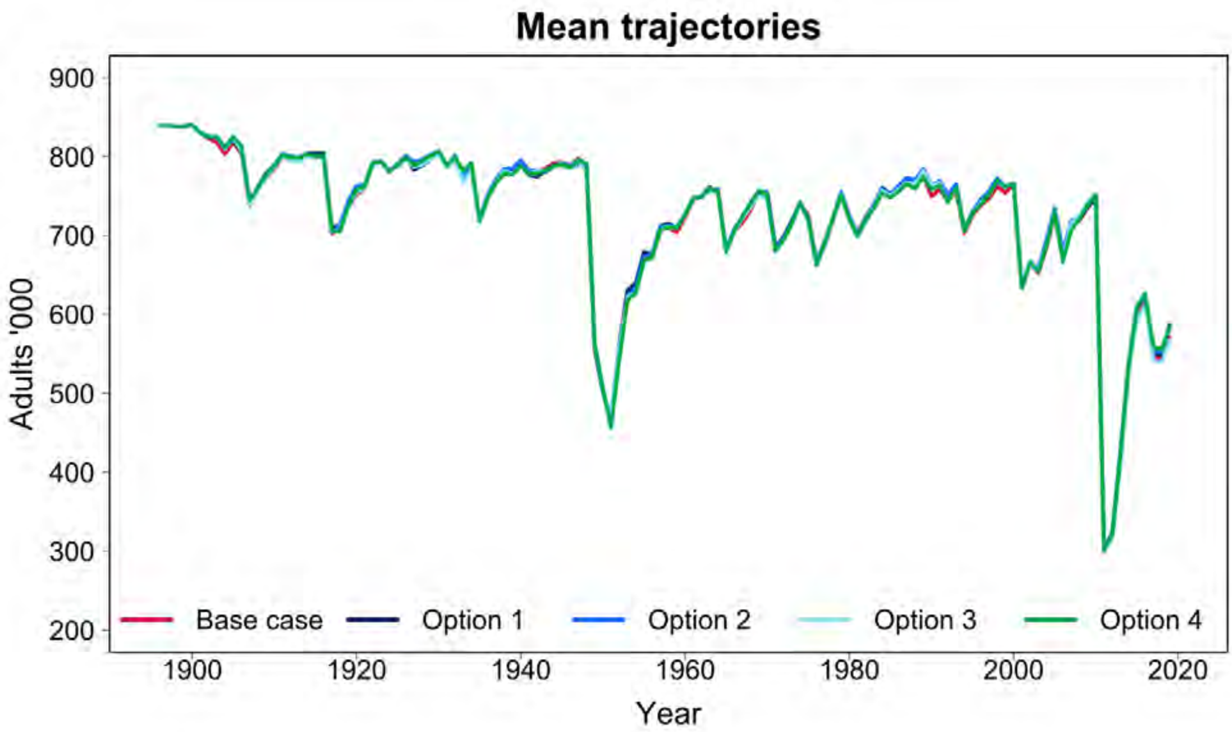


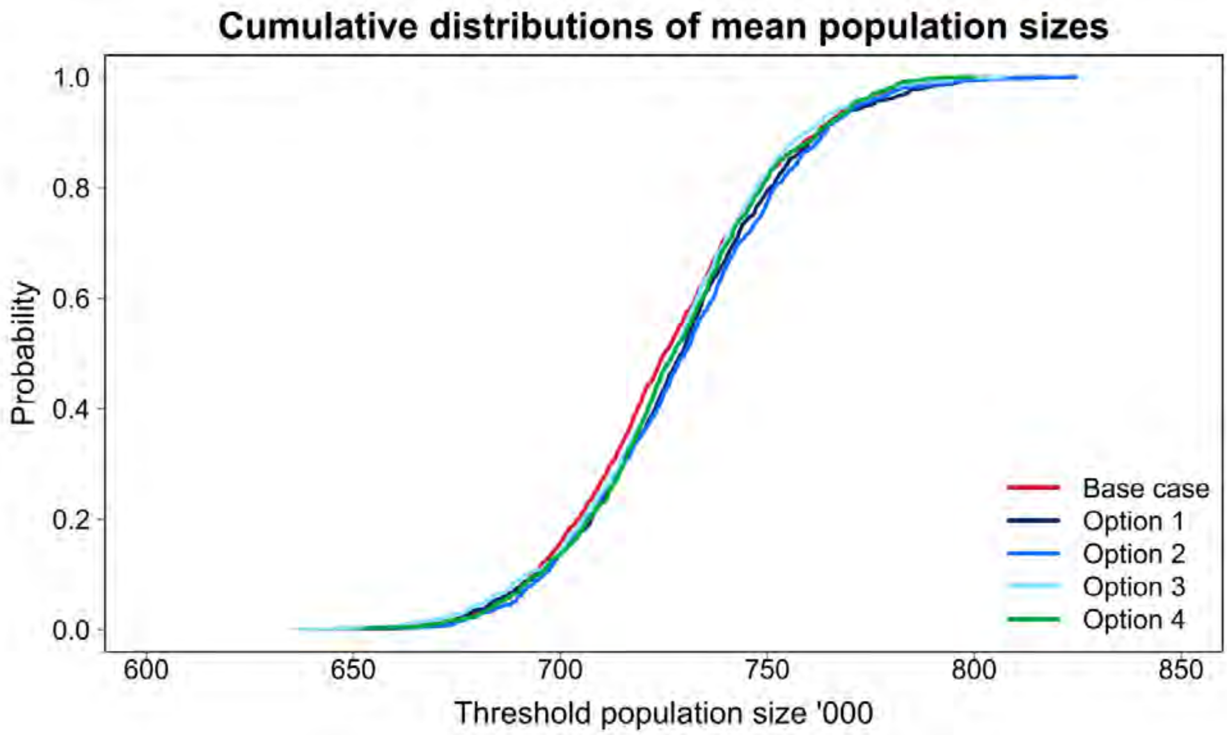
Figure A3.24. Golden Perch recruits mean population size in the Lower Darling reach for the RRCP flow scenarios Base case – Option 4.

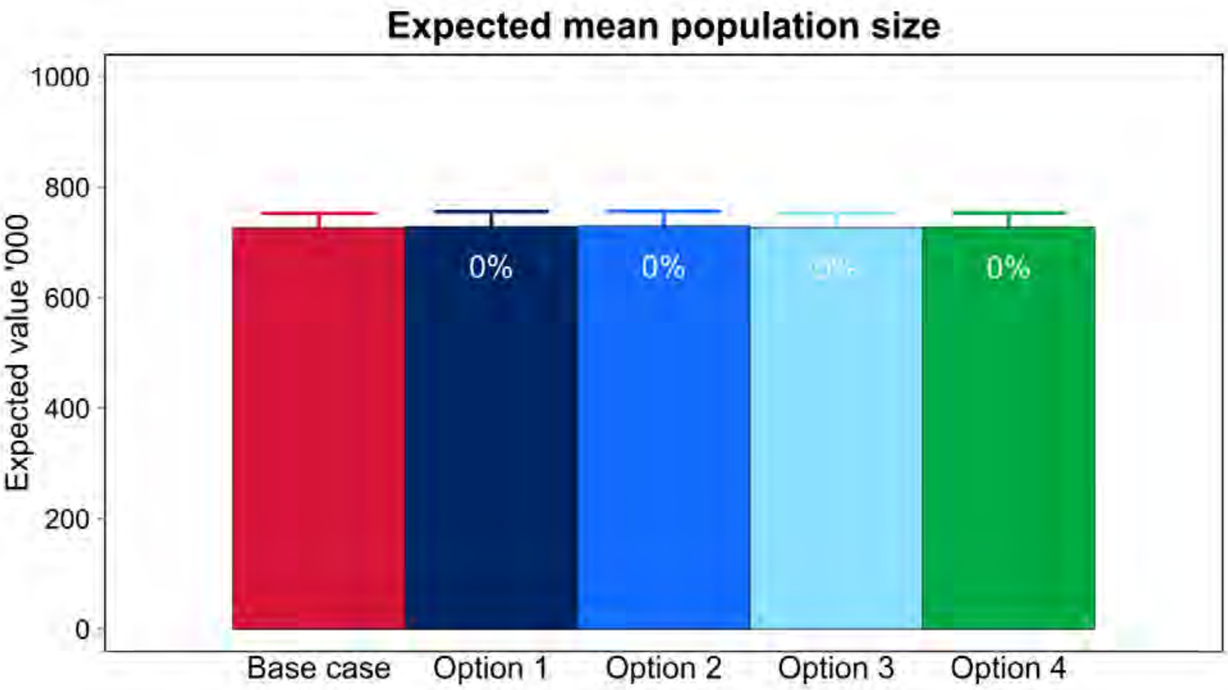
Murray Cod Adults

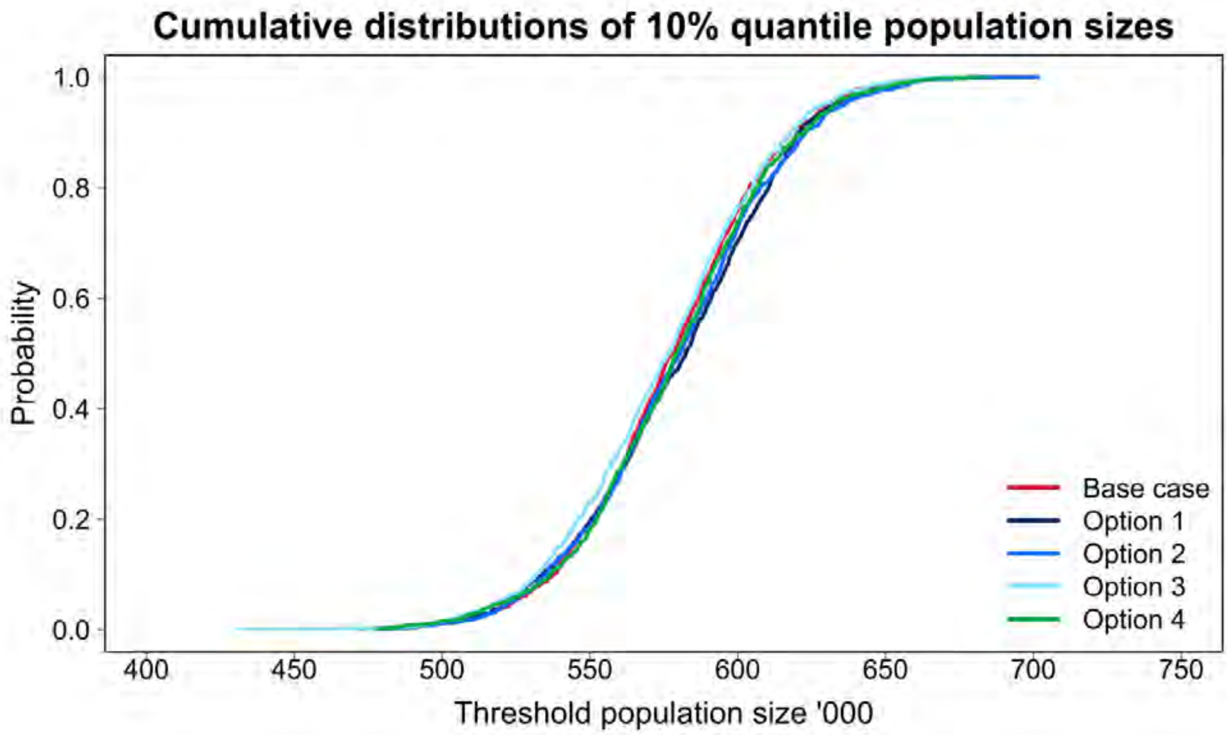
Murray Cod – Total RRCP populations inclusive to Wentworth

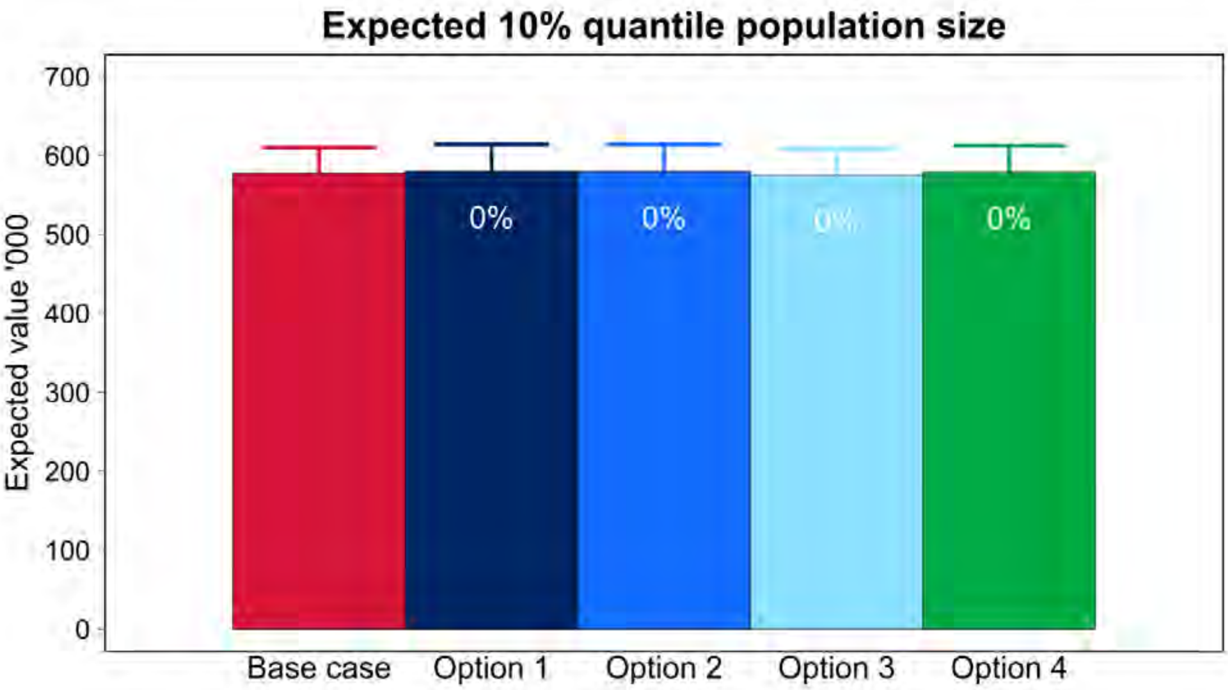


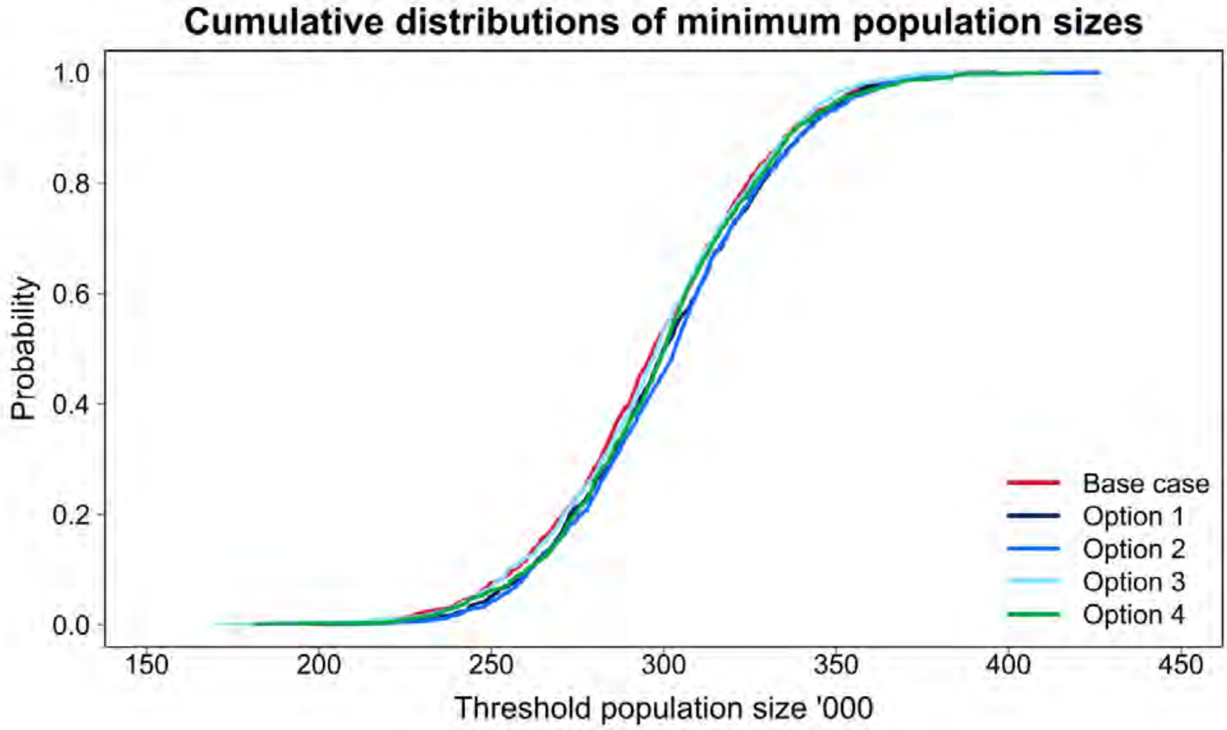


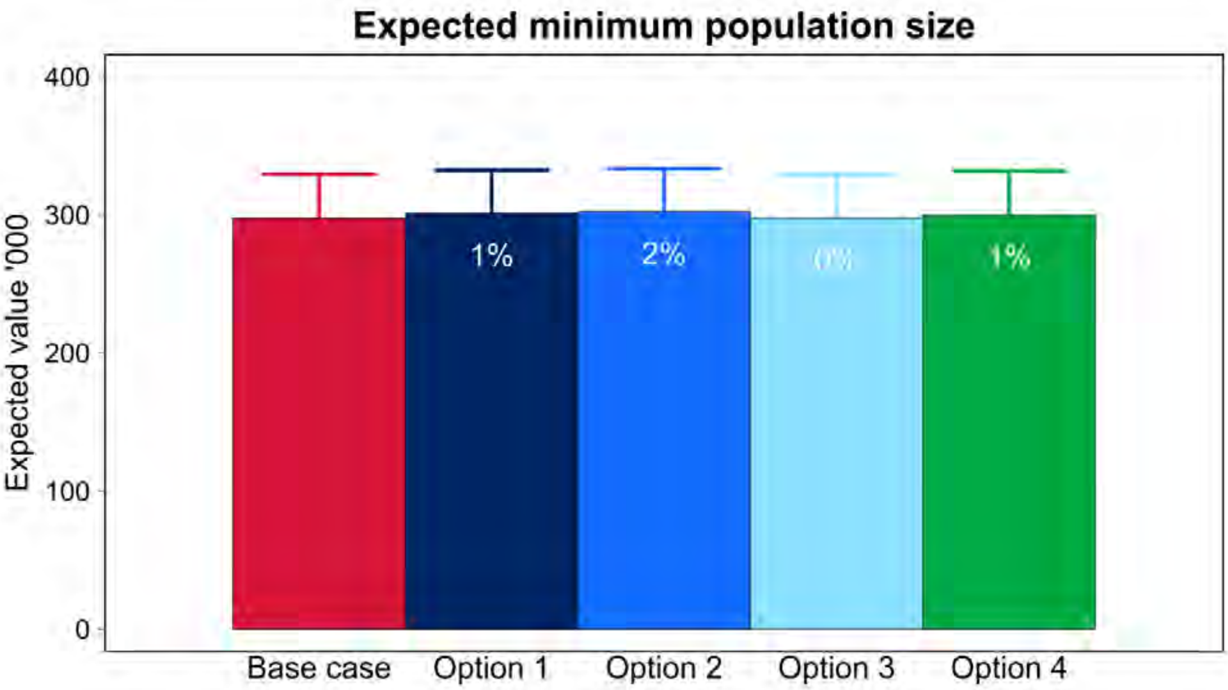

Cumulative distributions of mean population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
600
650
700
750
800
850
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected mean population size
Expected value '000
1000
800
600
400
200
0
0%
0%
0%
0%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of 10% quantile population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
400
450
500
550
600
650
700
750
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected 10% quantile population size
Expected value '000
700
600
500
400
300
200
100
0
0%
0%
0%
0%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
150
200
250
300
350
400
450
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected minimum population size
Expected value '000
400
300
200
100
0
1%
2%
0%
1%
Base case
Option 1
Option 2
Option 3
Option 4

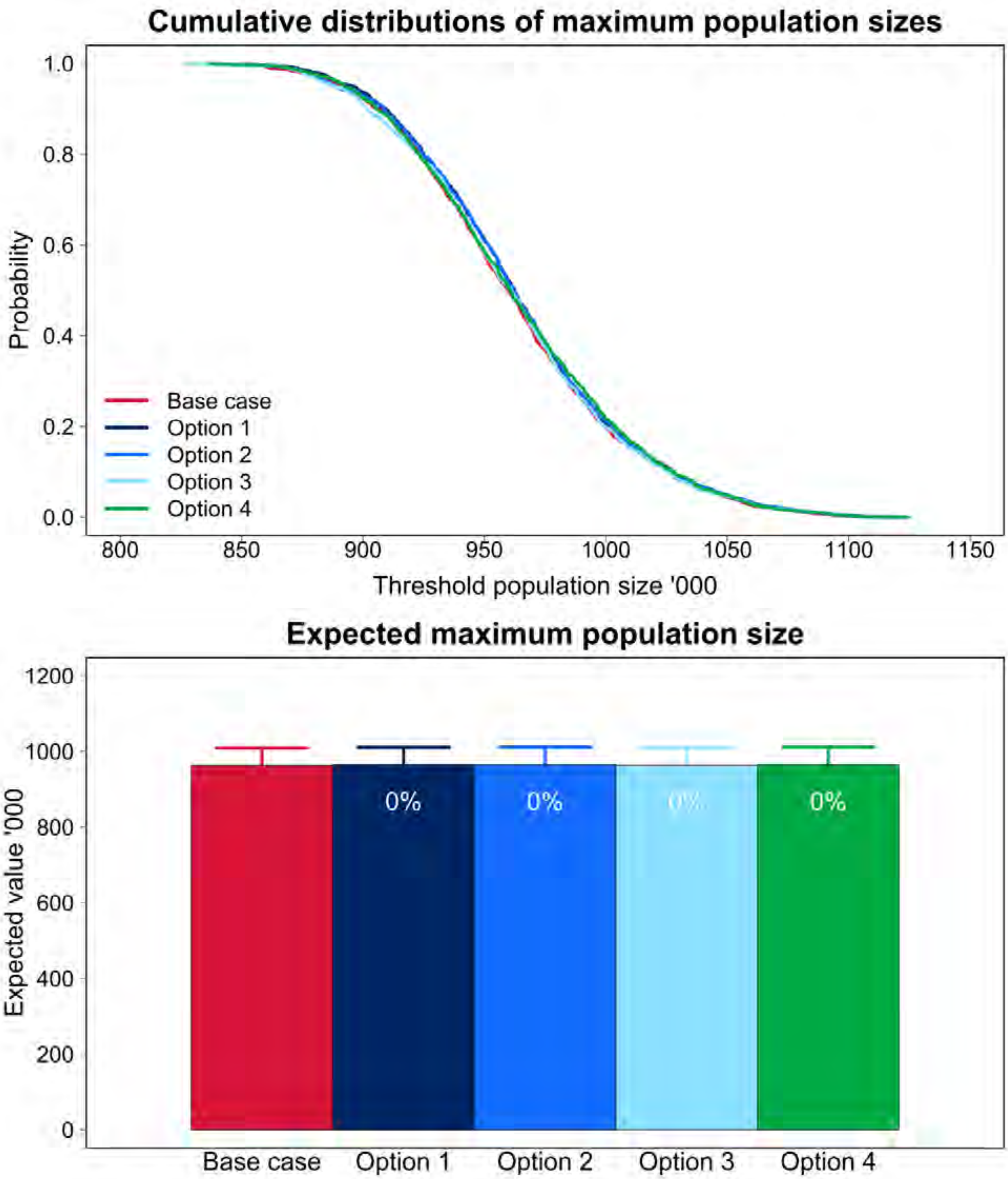
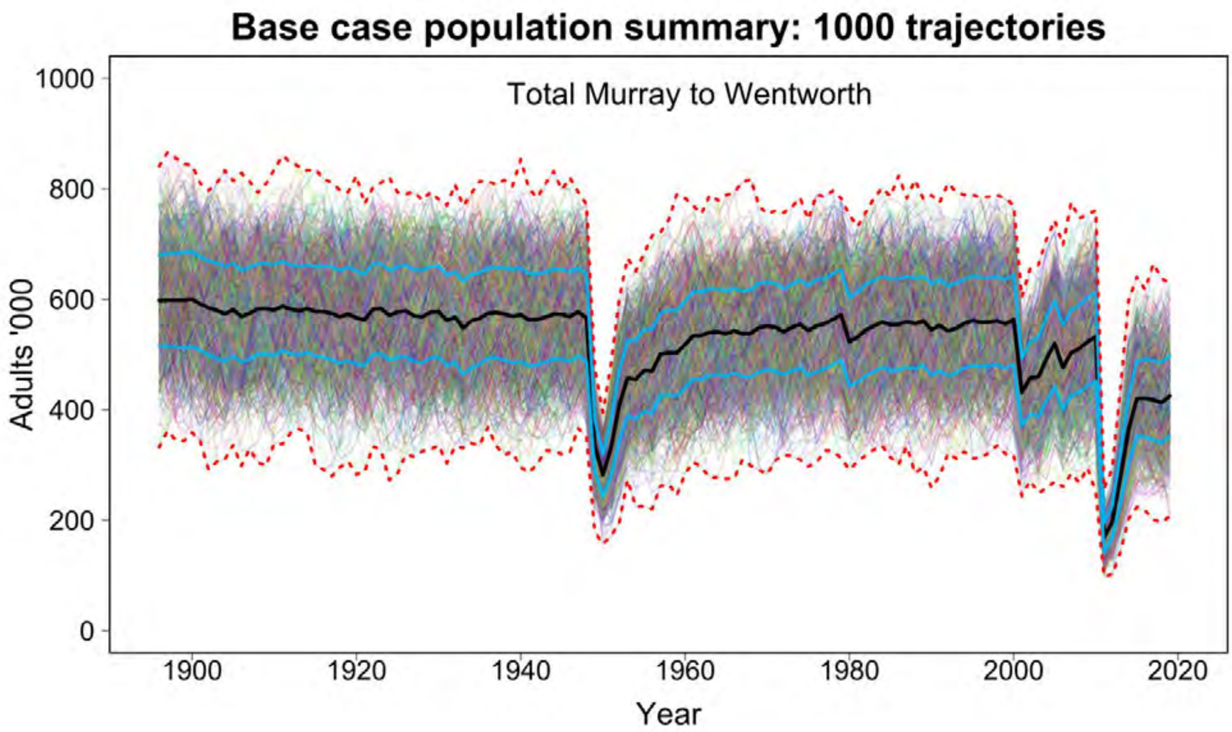
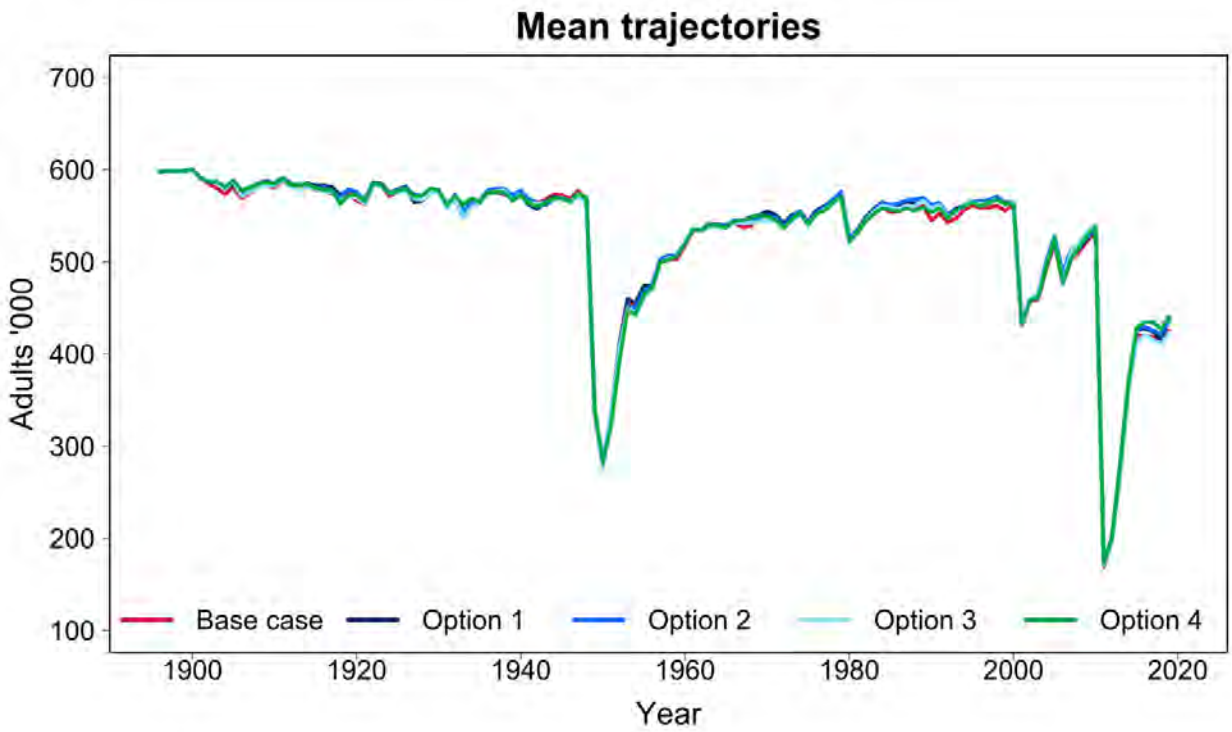
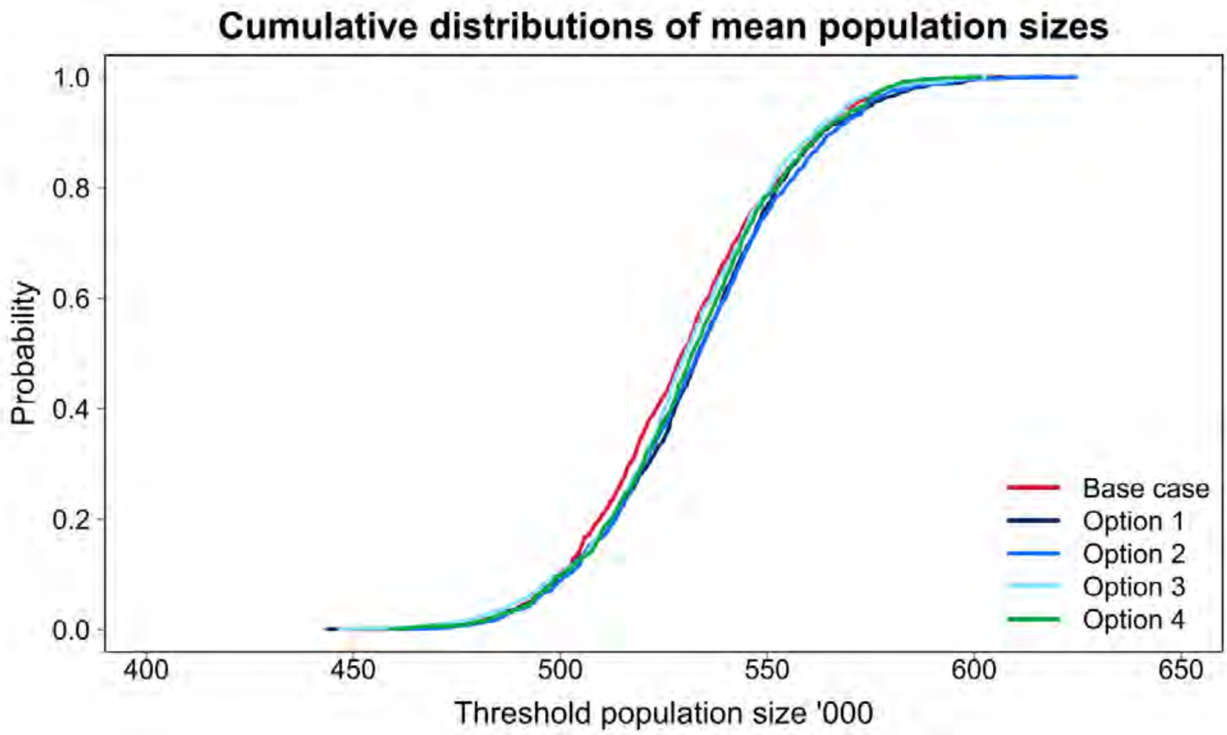


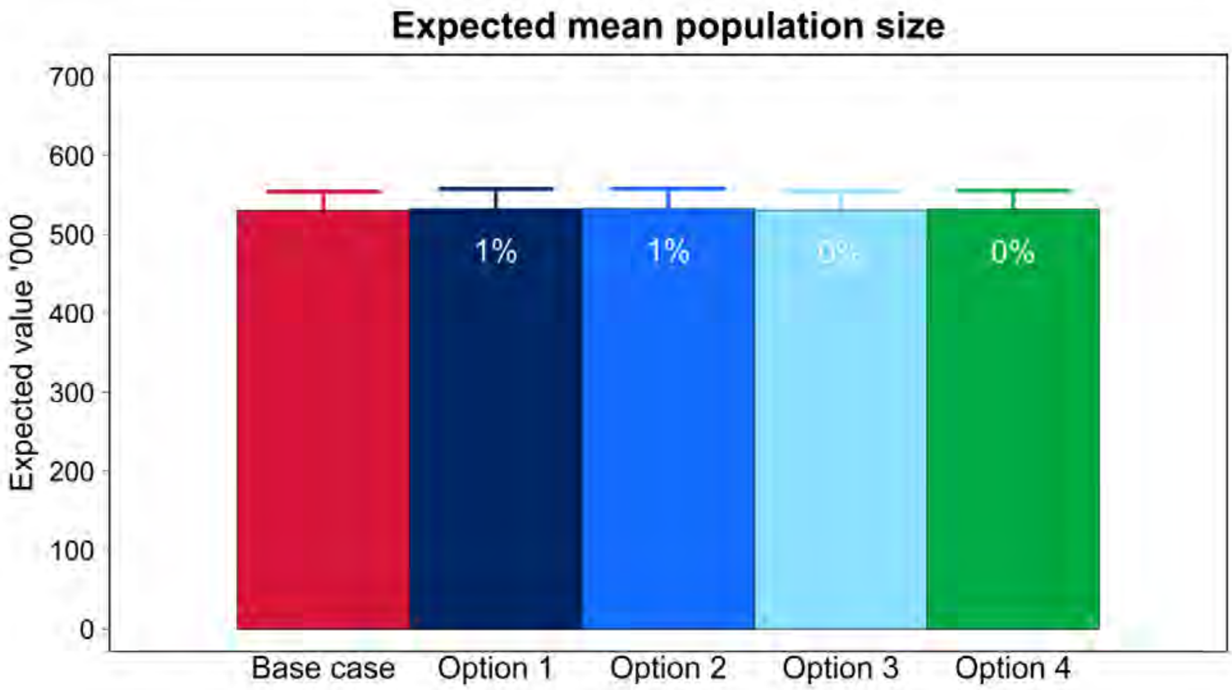
Figure A3.25. Murray Cod adults aggregated across all modelled RRCP focal zones, together with the Wakool Junction to Wentworth reach, for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

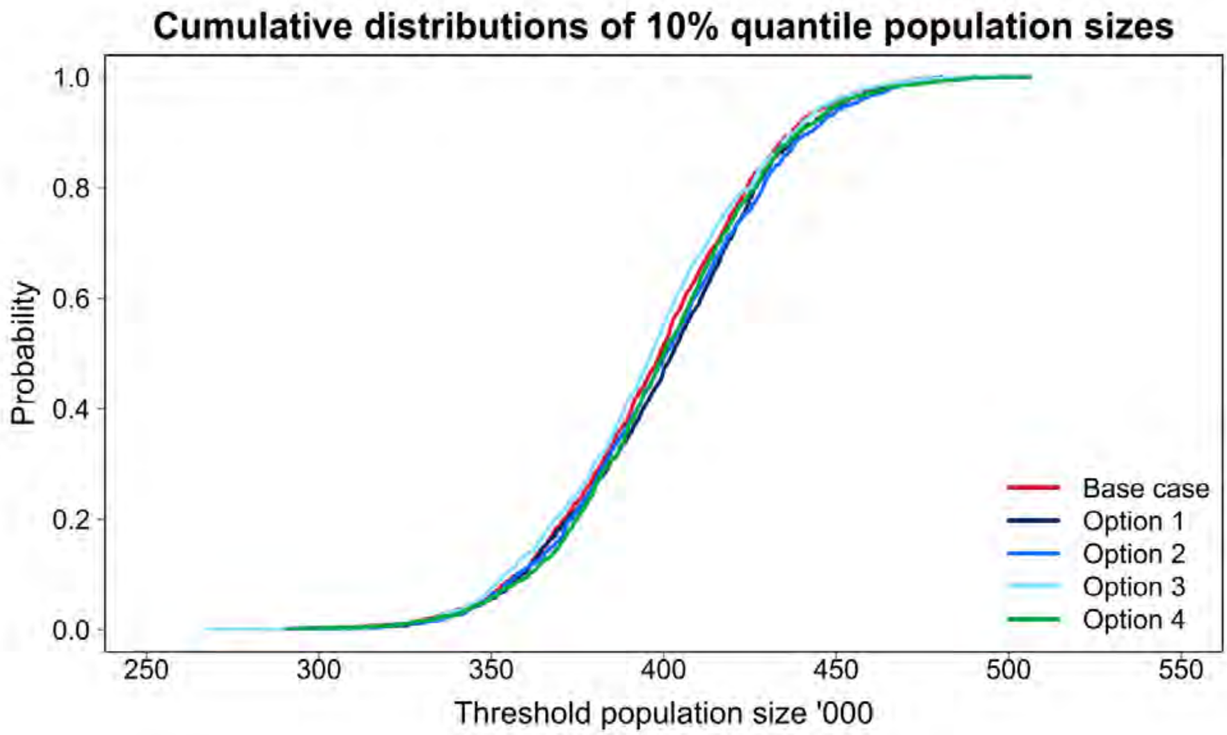
Murray Cod – Total Murray River populations inclusive to Wentworth

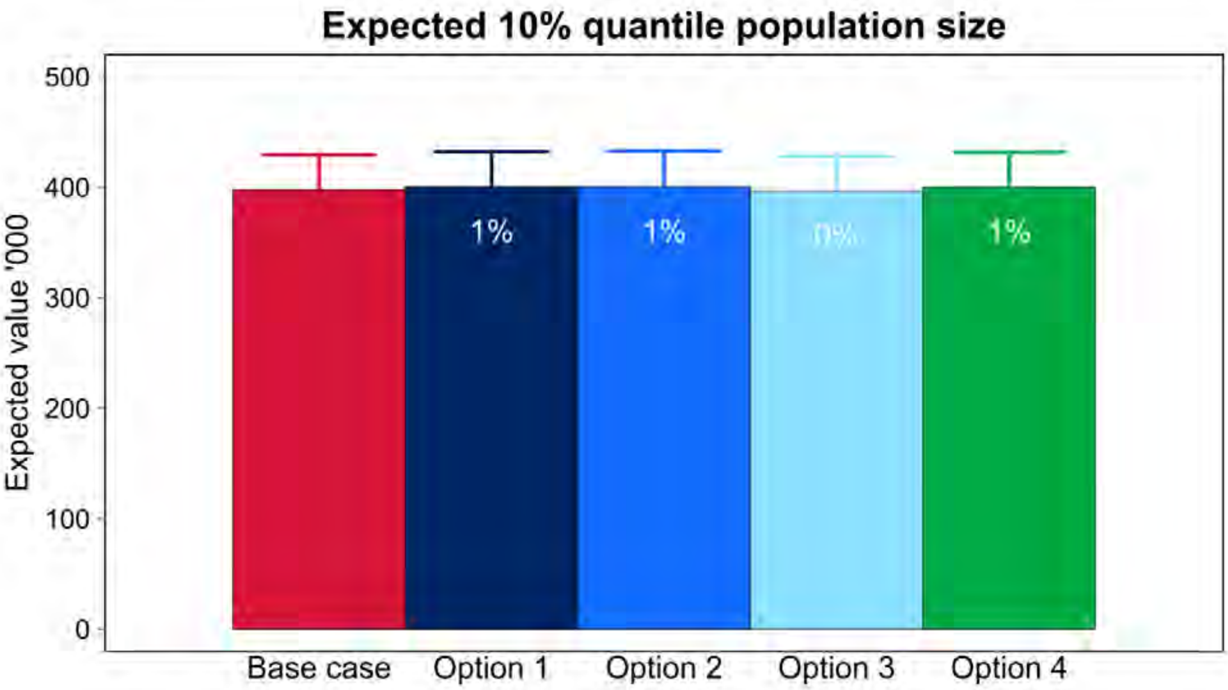


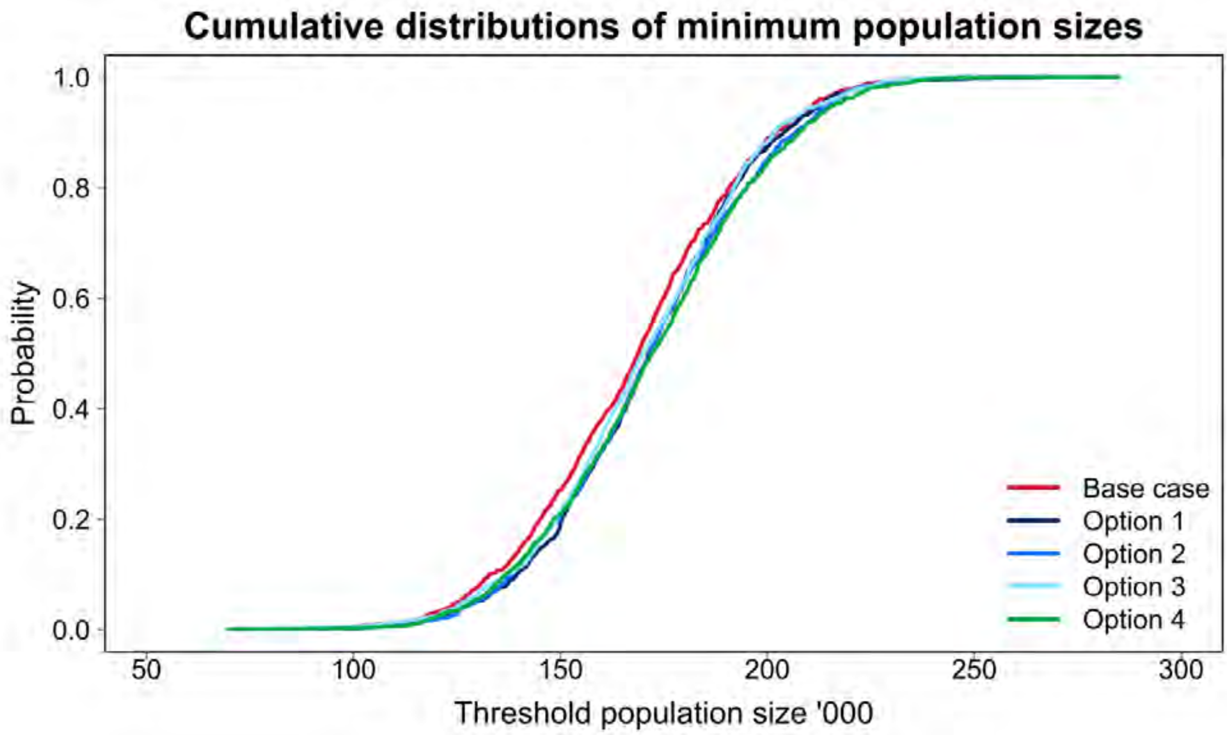


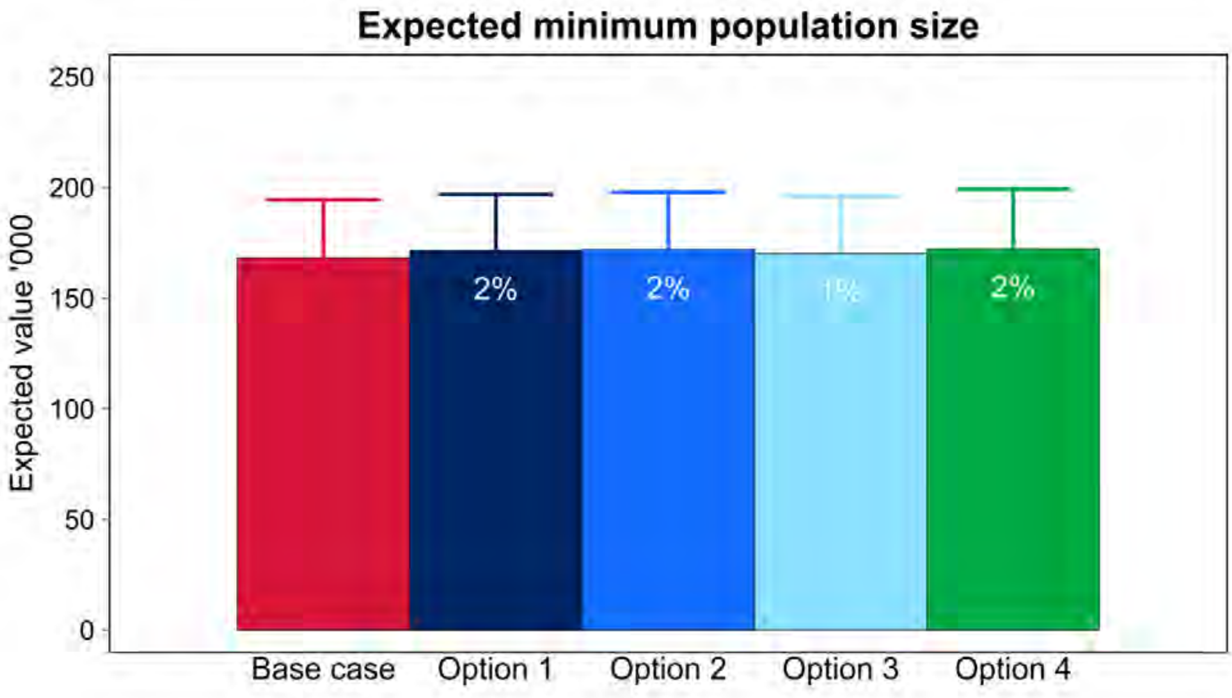

Cumulative distributions of mean population sizes
1.0
0.8
0.6
0.4
0.2
0.0
Probability
400
450
500
550
600
650
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected mean population size
700
600
500
400
300
200
100
0
Expected value '000
1%
1%
0%
0%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of 10% quantile population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
250
300
350
400
450
500
550
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected 10% quantile population size
Expected value '000
500
400
300
200
100
0
1%
1%
0%
1%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
50
100
150
200
250
300
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected minimum population size
Expected value '000
250
200
150
100
50
0
2%
2%
1%
2%
Base case
Option 1
Option 2
Option 3
Option 4

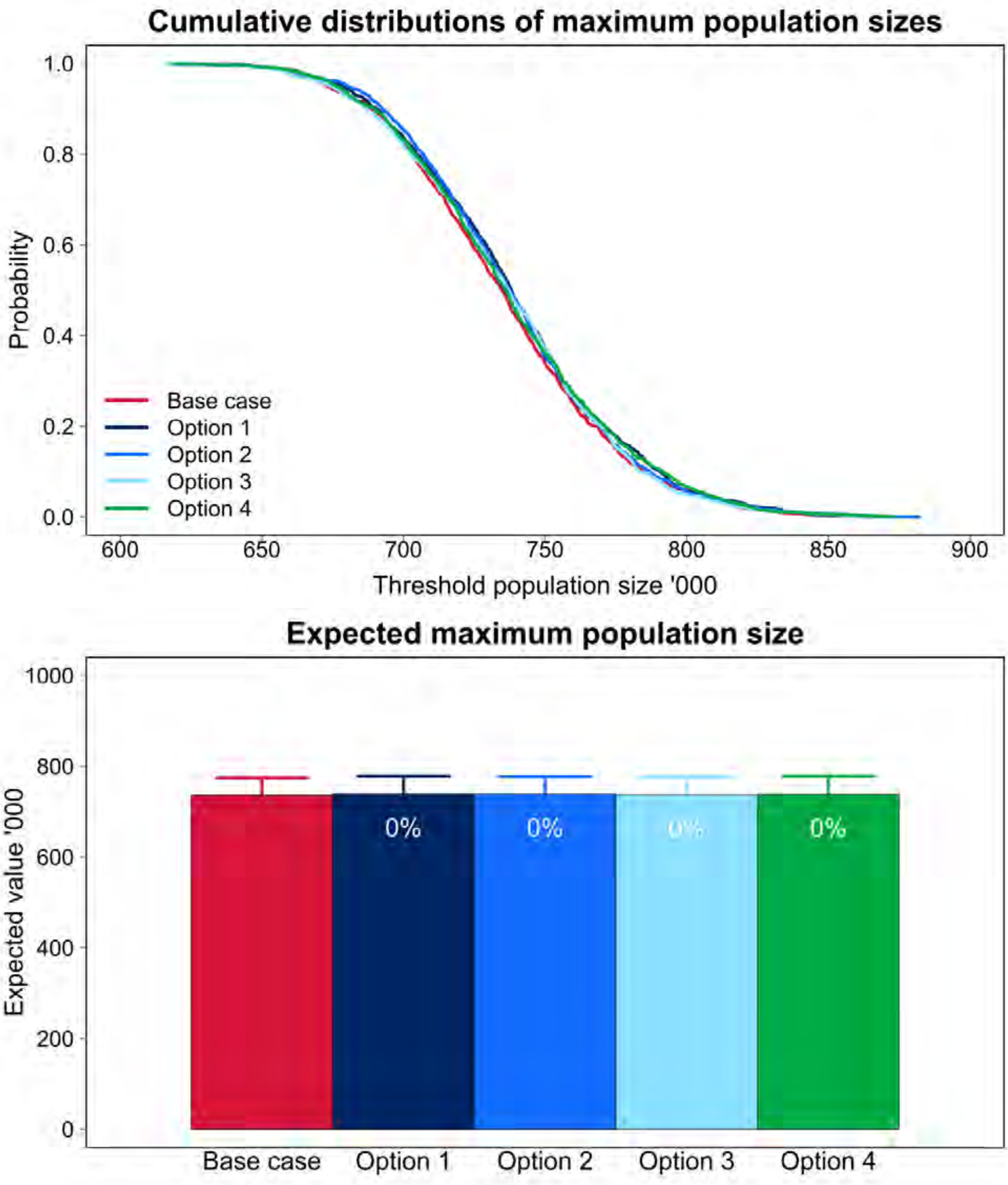
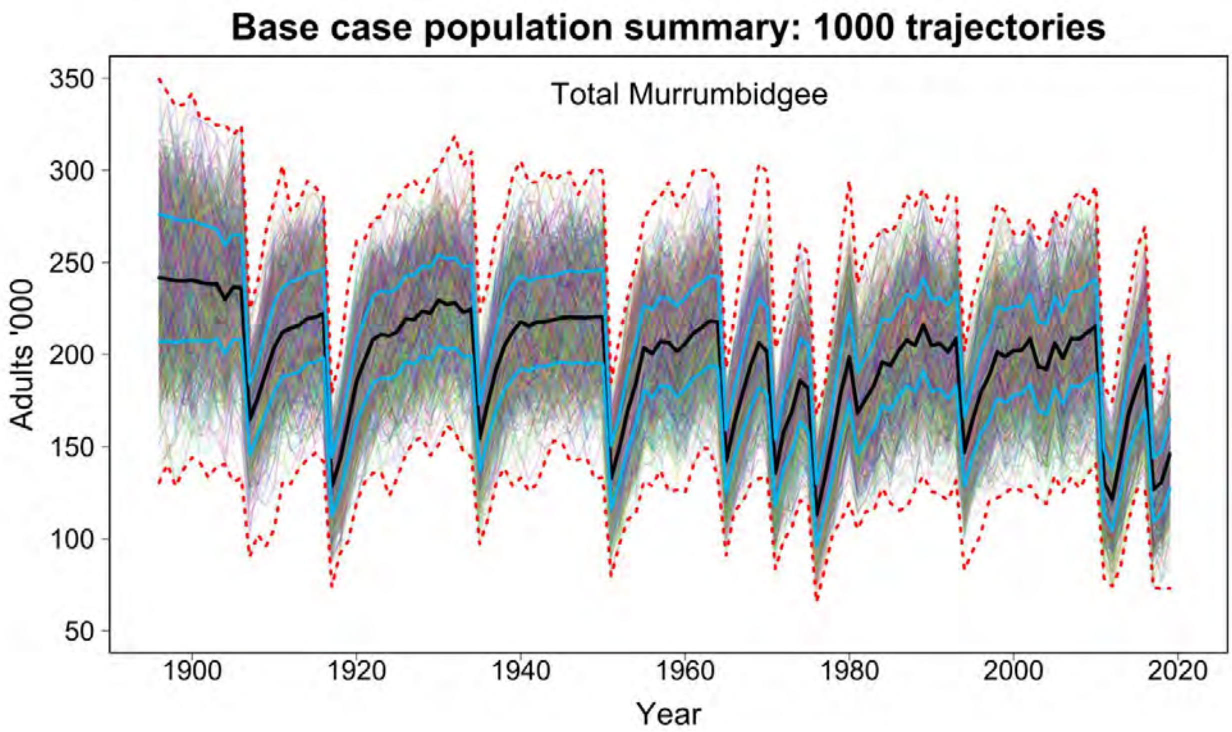
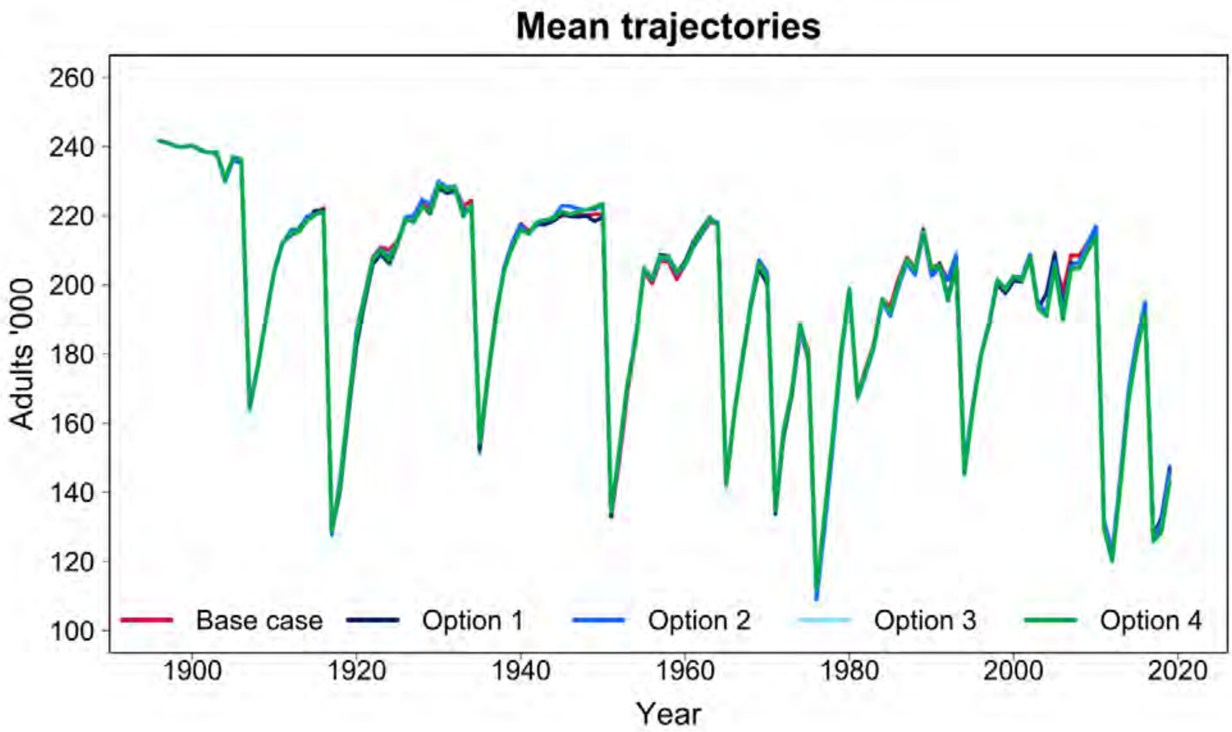
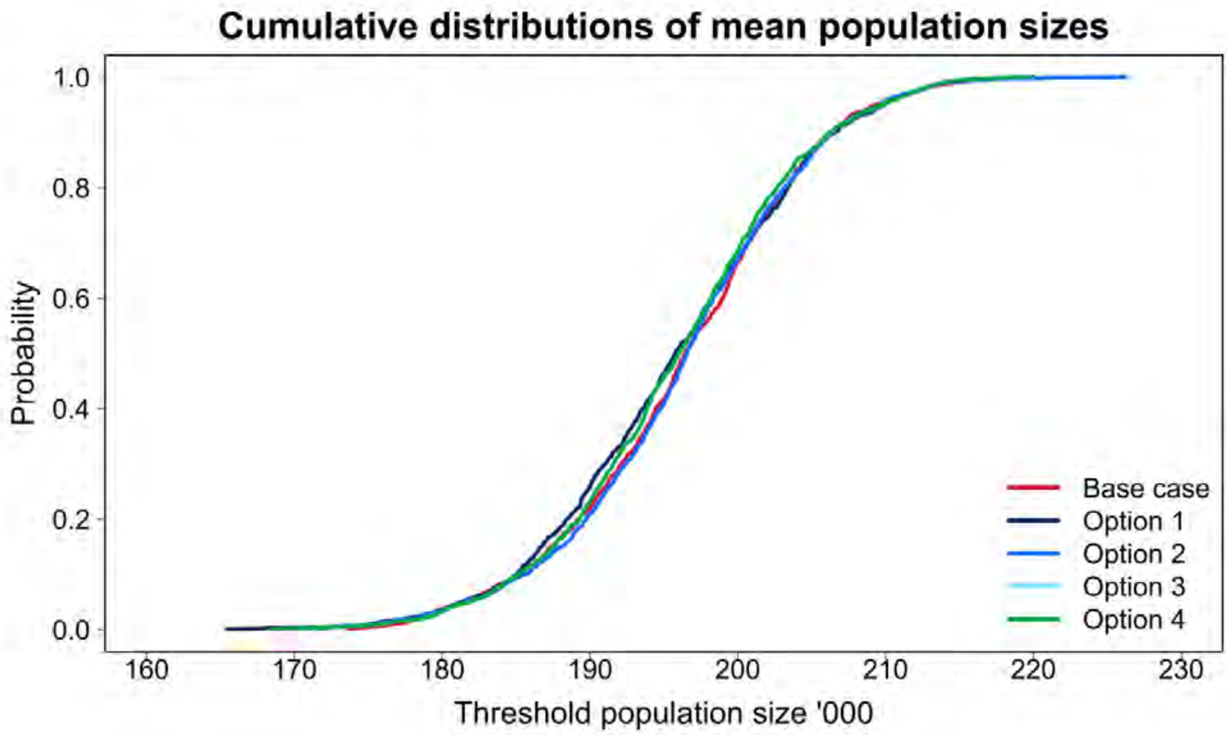


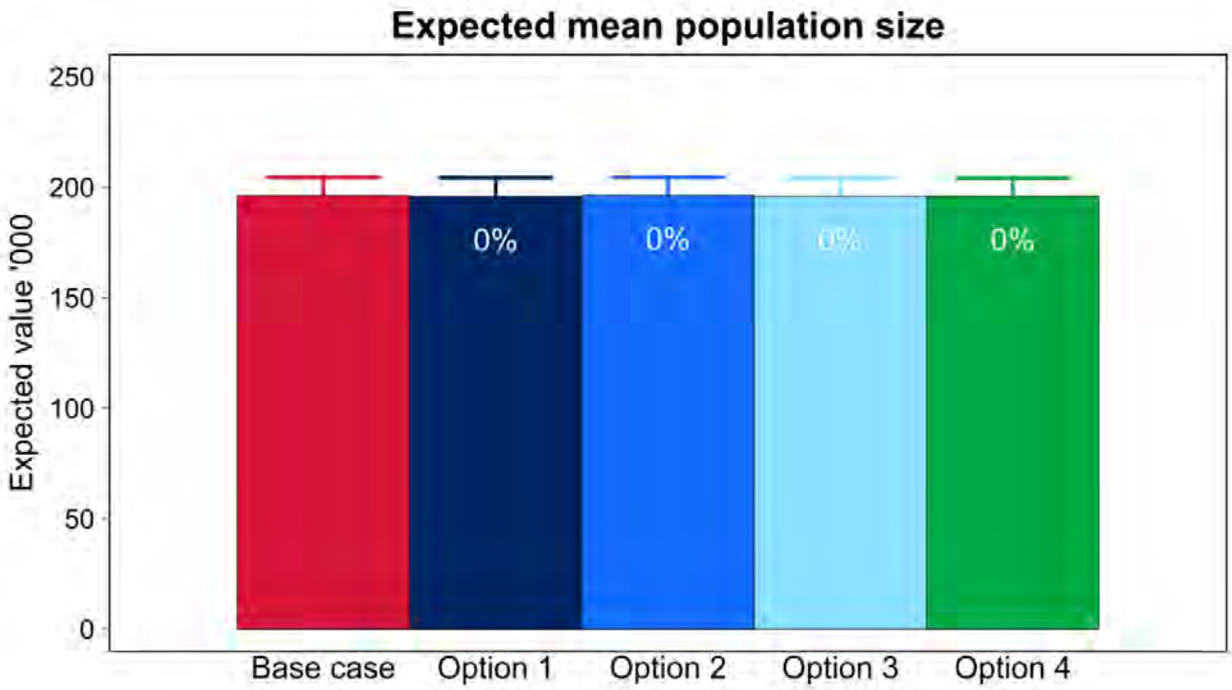
Figure A3.26. Murray Cod adults aggregated across the Murray River RRCP focal zones (including the Edward River), together with the Wakool Junction to Wentworth reach, for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

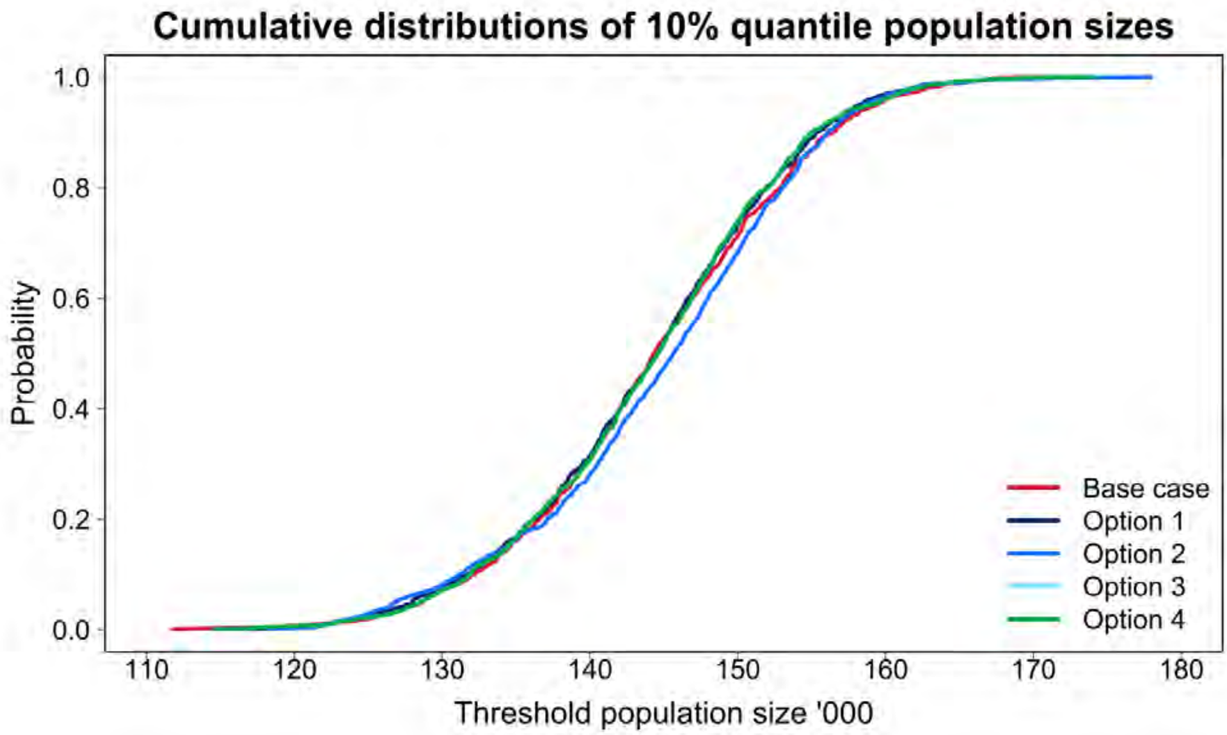
Murray Cod – Total Murrumbidgee River populations including Yanco Creek

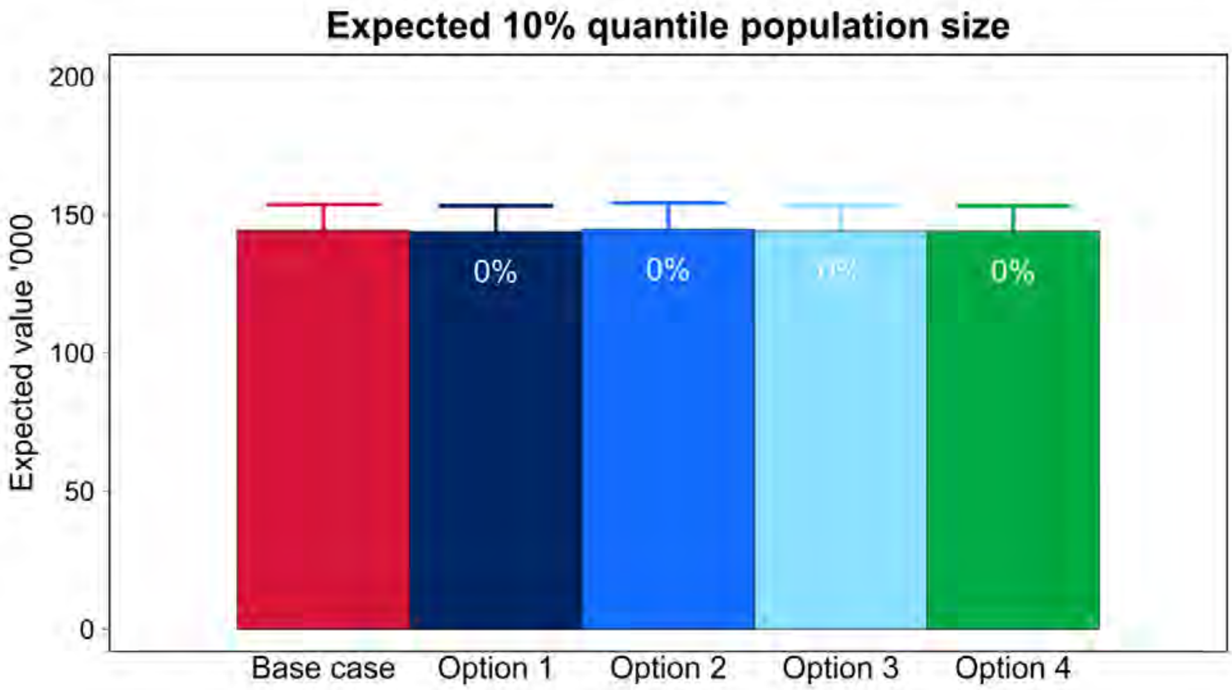


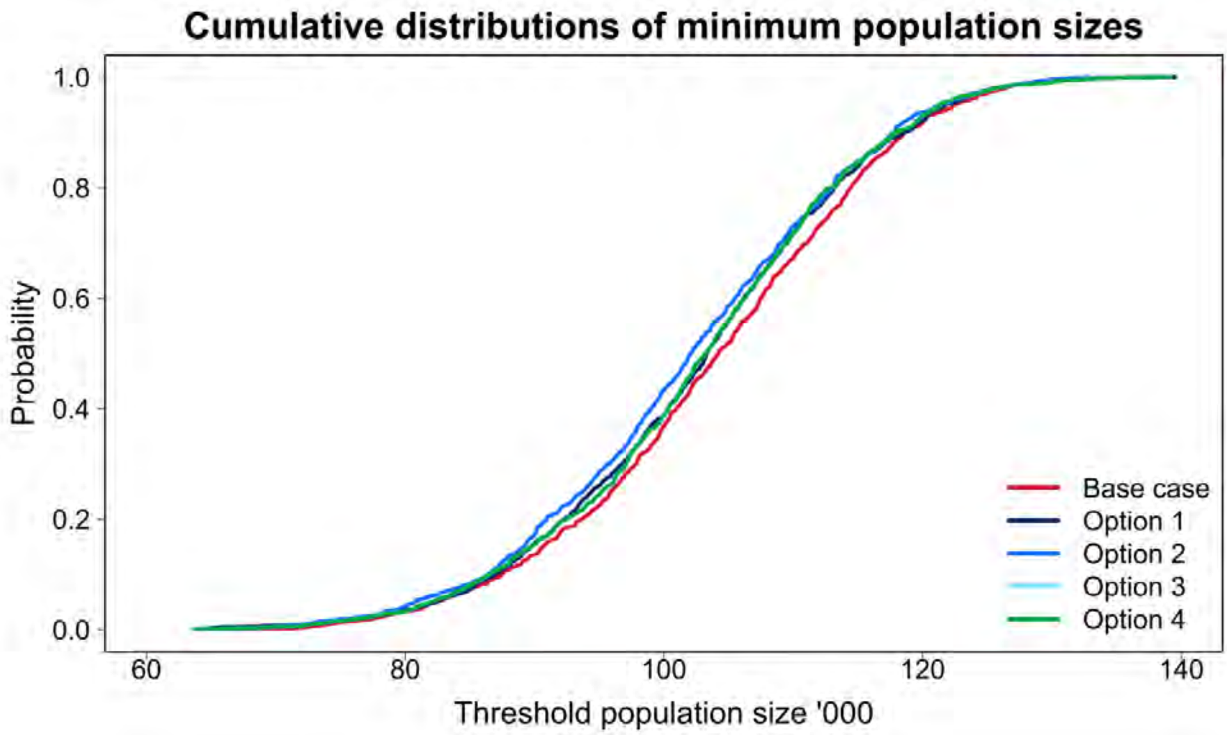


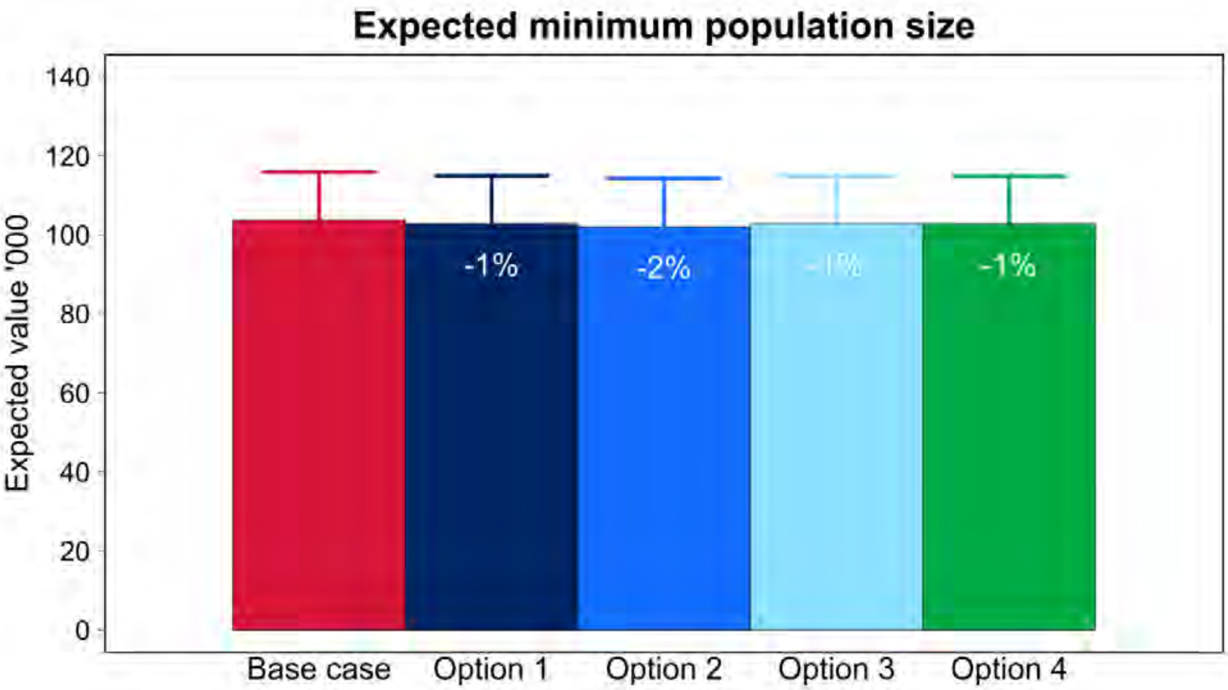

Cumulative distributions of mean population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
160
170
180
190
200
210
220
230
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected mean population size
Expected value '000
250
200
150
100
50
0
0%
0%
0%
0%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of 10% quantile population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
110
120
130
140
150
160
170
180
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected 10% quantile population size
Expected value '000
200
150
100
50
0
0%
0%
0%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
60
80
100
120
140
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected minimum population size
Expected value '000
140
120
100
80
60
40
20
0
-1%
-2%
-1%
-1%
Base case
Option 1
Option 2
Option 3
Option 4

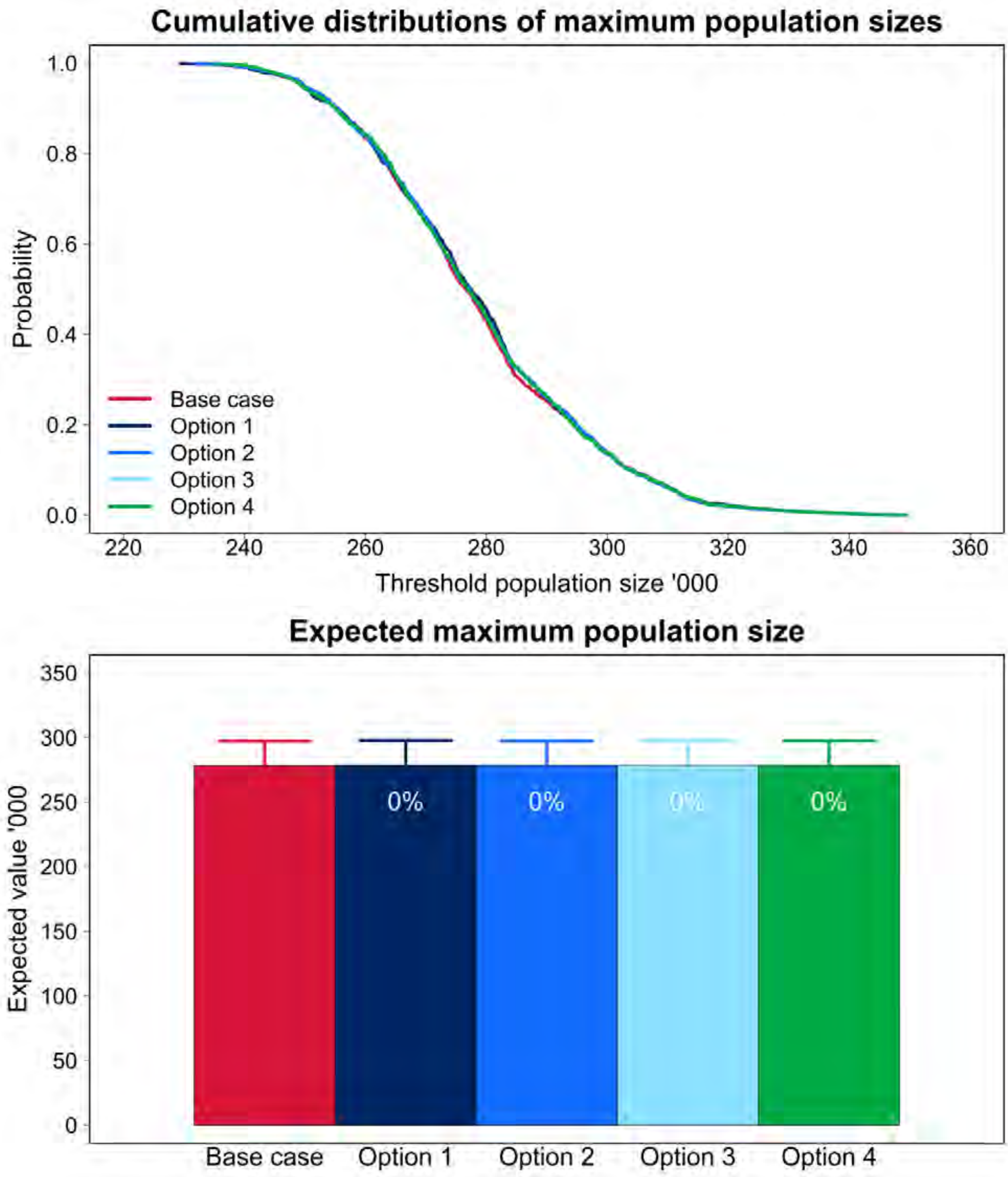
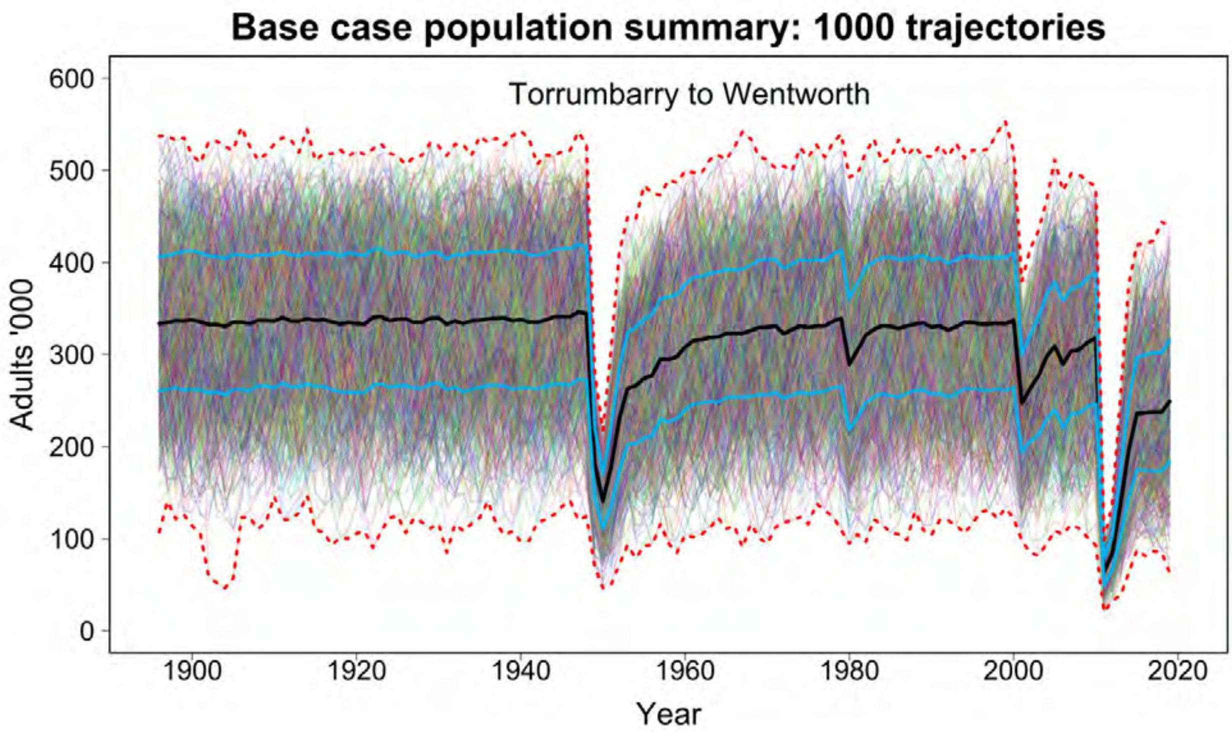
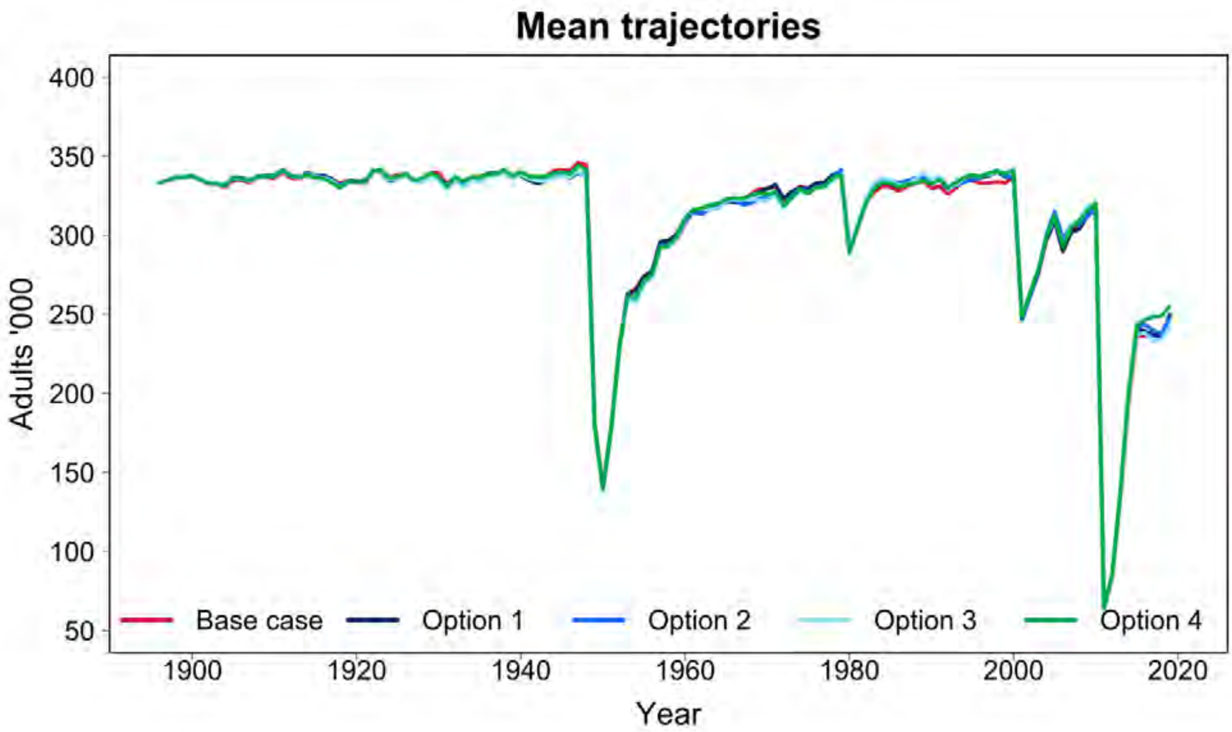
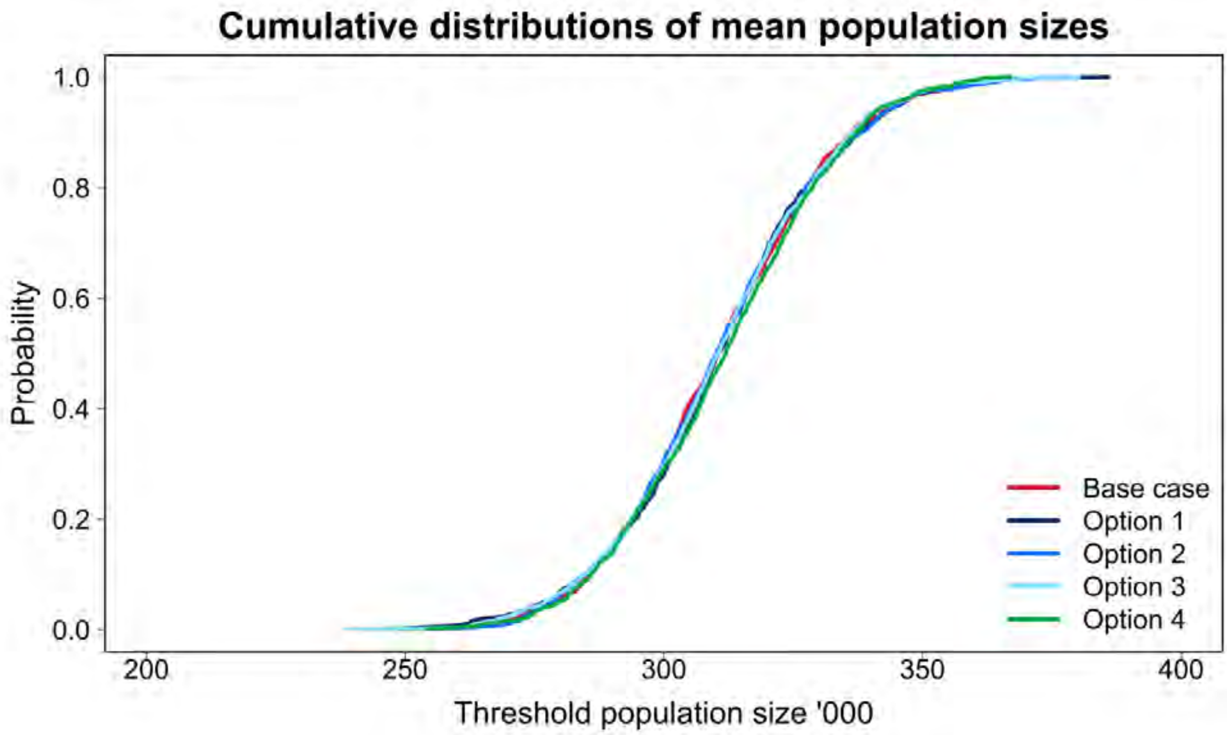


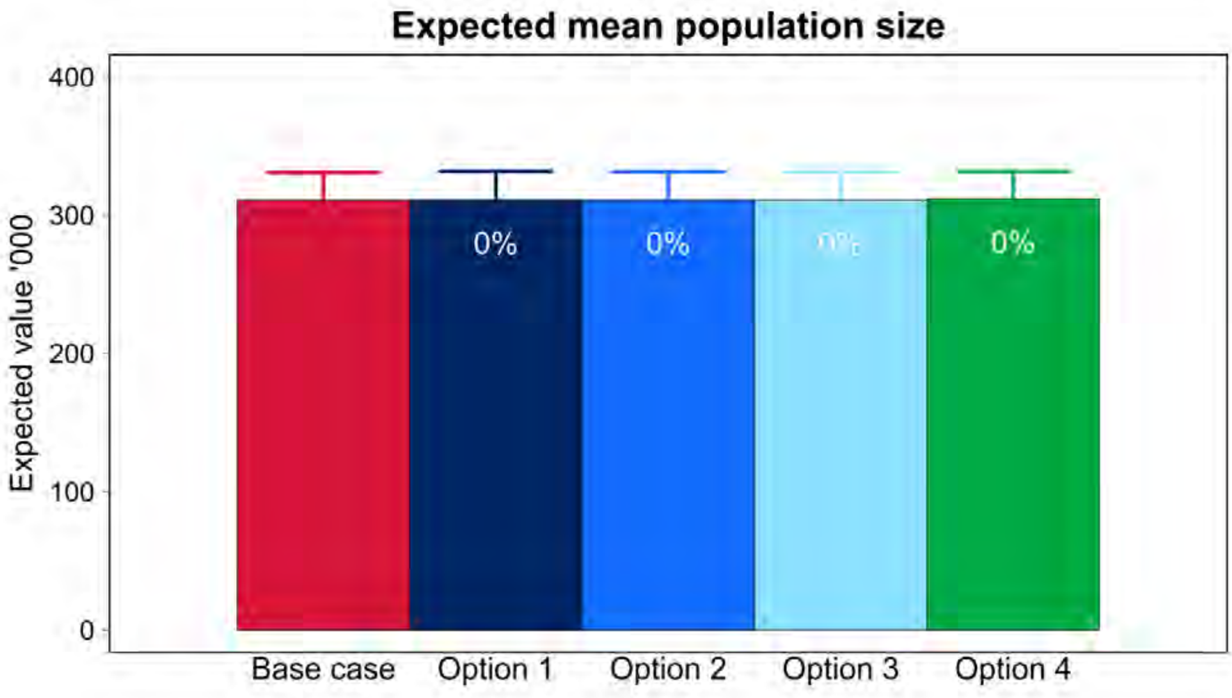
Figure A3.27. Murray Cod adults aggregated across the Murrumbidgee River RRCP focal zone for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

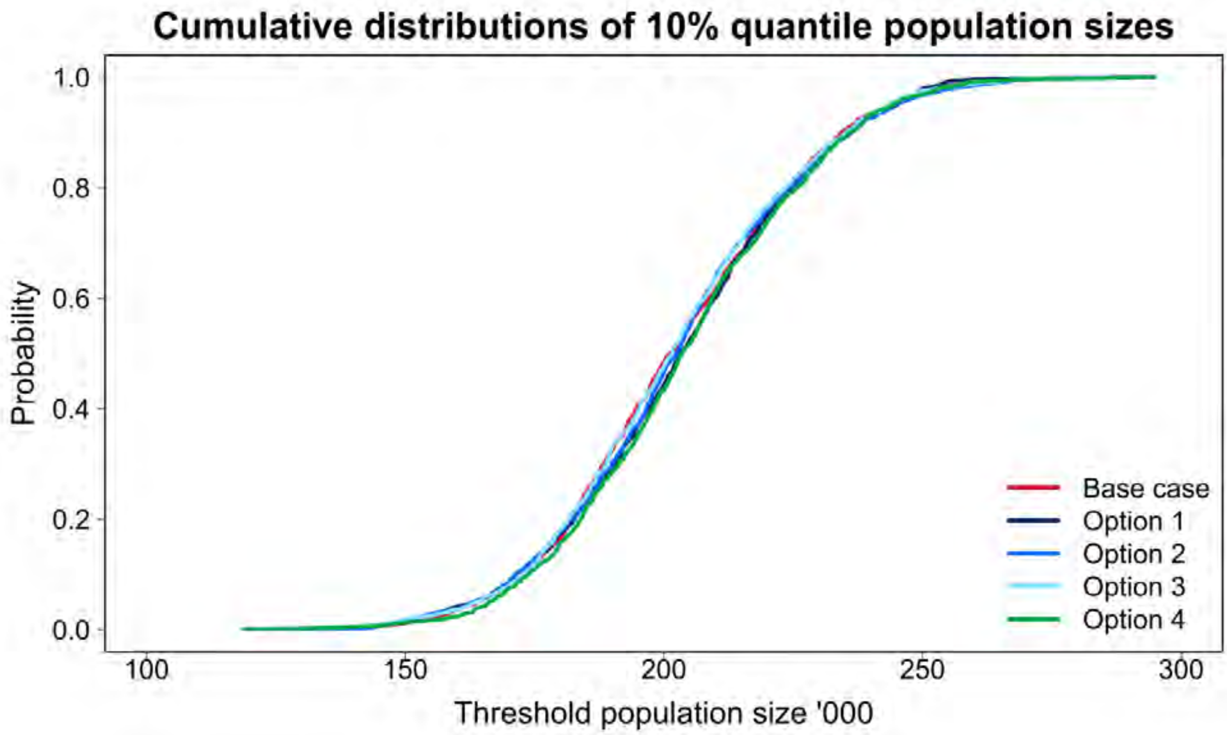
Murray Cod – Torrumbarry to Wentworth



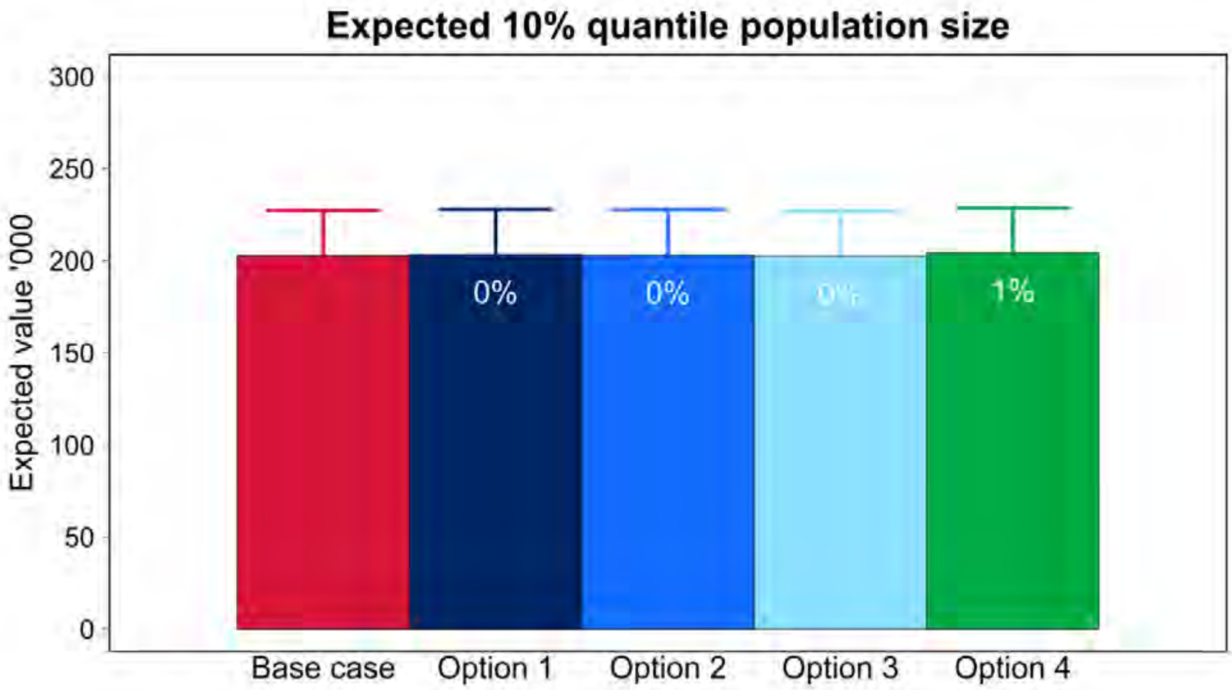



Cumulative distributions of mean population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
200
250
300
350
400
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4

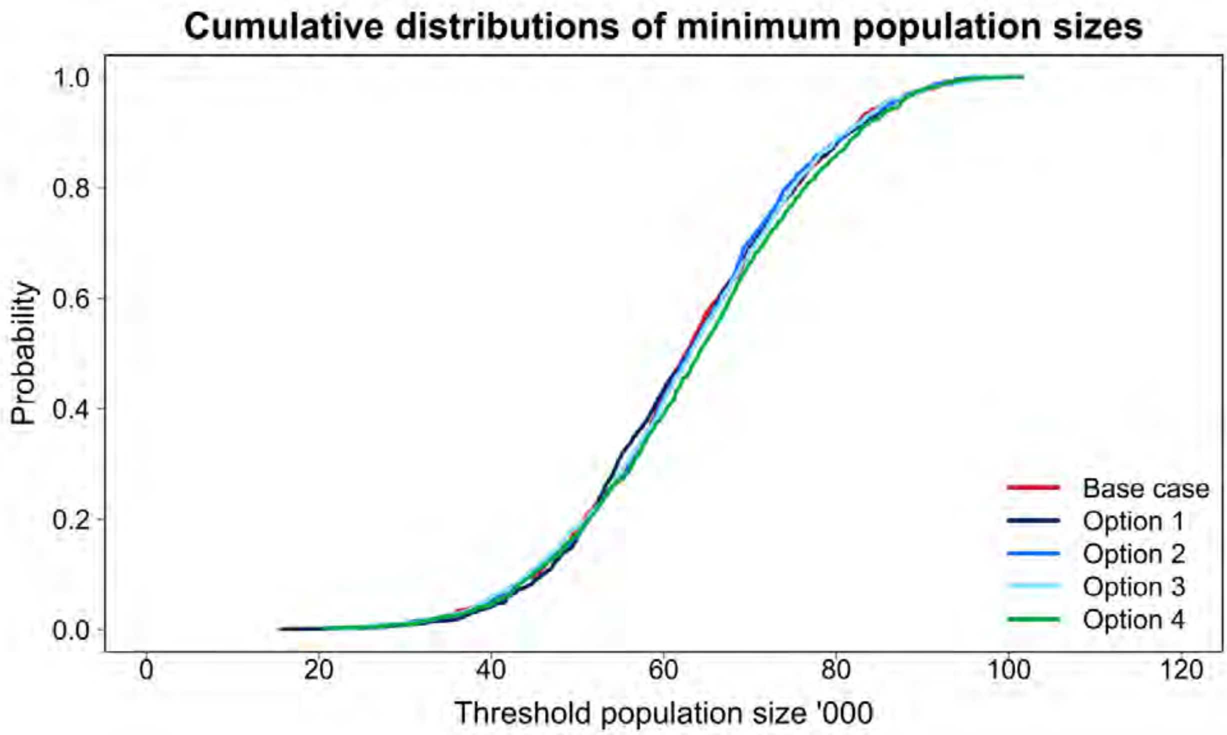

Expected mean population size
Expected value '000
400
300
200
100
0
0%
0%
0%
Base case
Option 1
Option 2
Option 3
Option 4

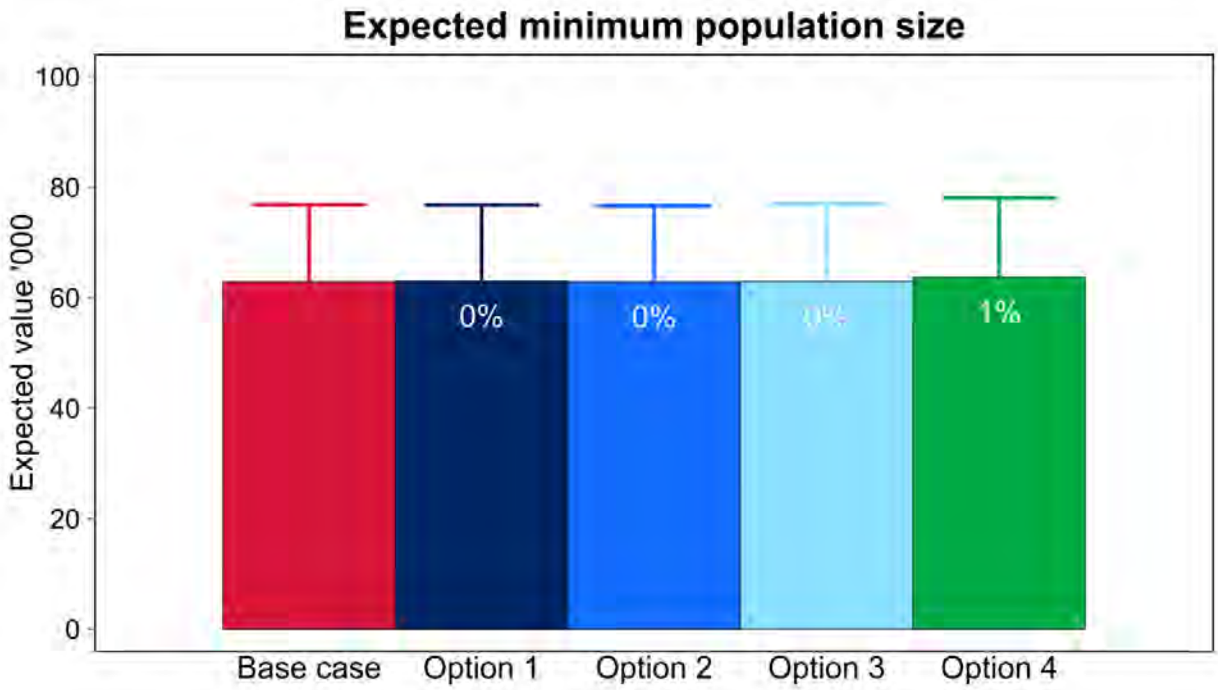


Cumulative distributions of 10% quantile population sizes
Probability
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4



Expected 10% quantile population size
Expected value '000
0%
0%
1%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
120
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected minimum population size
Expected value '000
100
80
60
40
20
0
0%
0%
1%
Base case
Option 1
Option 2
Option 3
Option 4

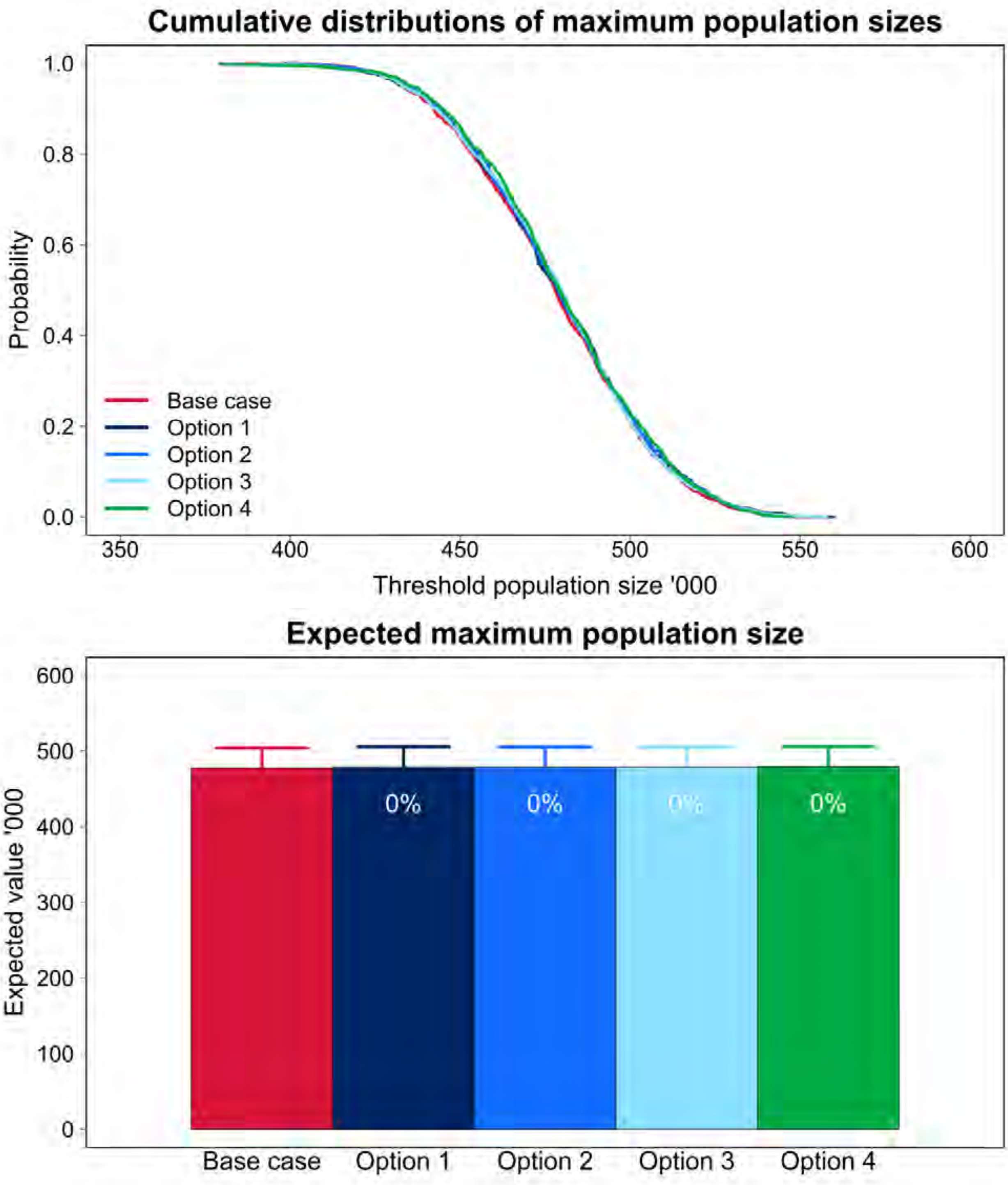
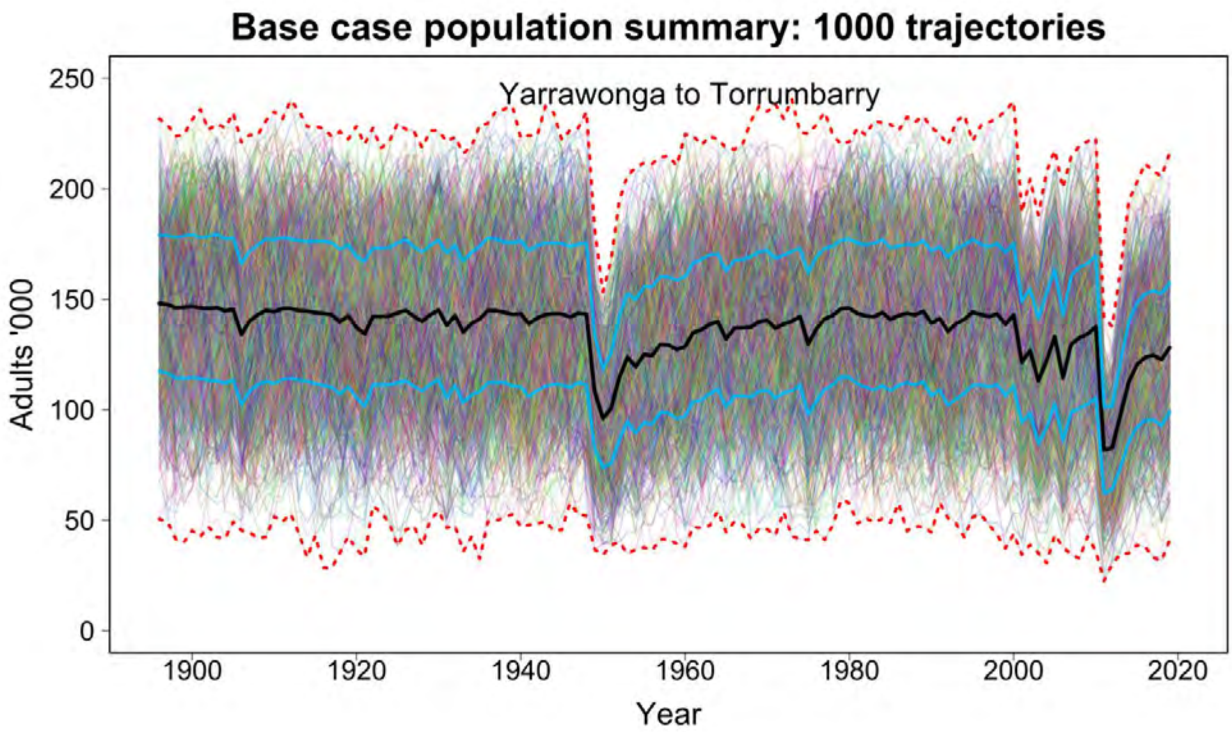
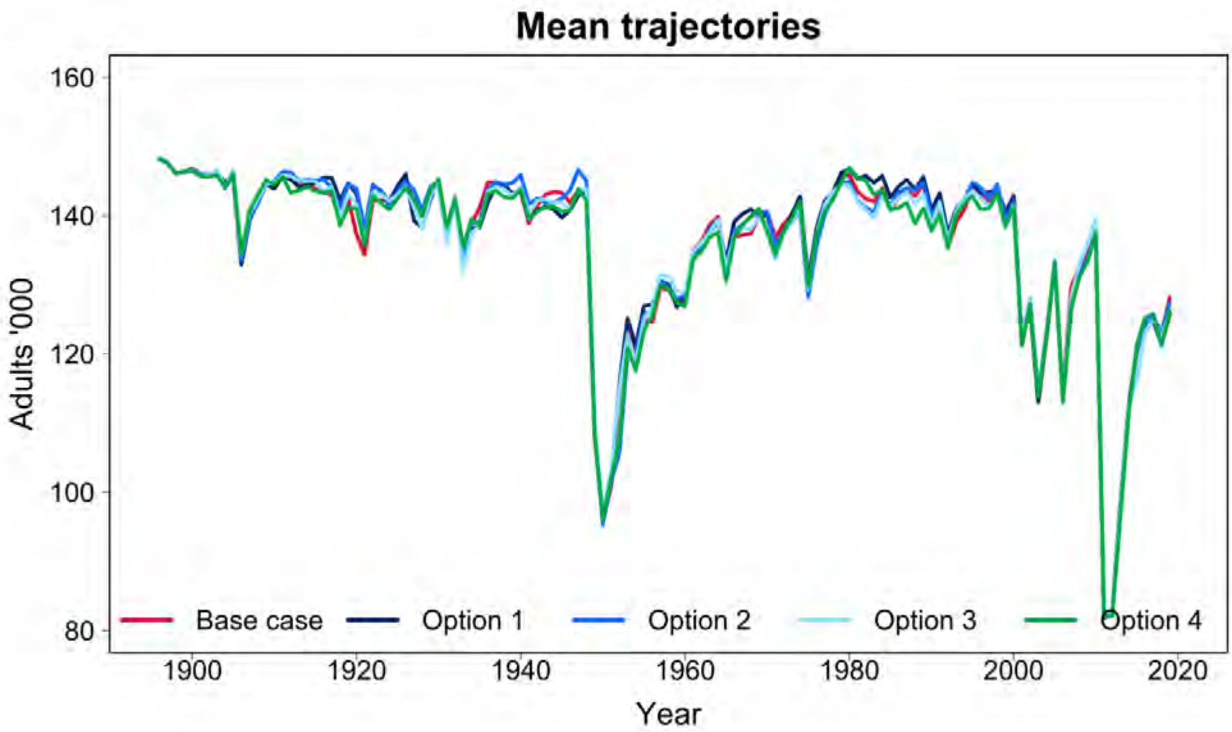
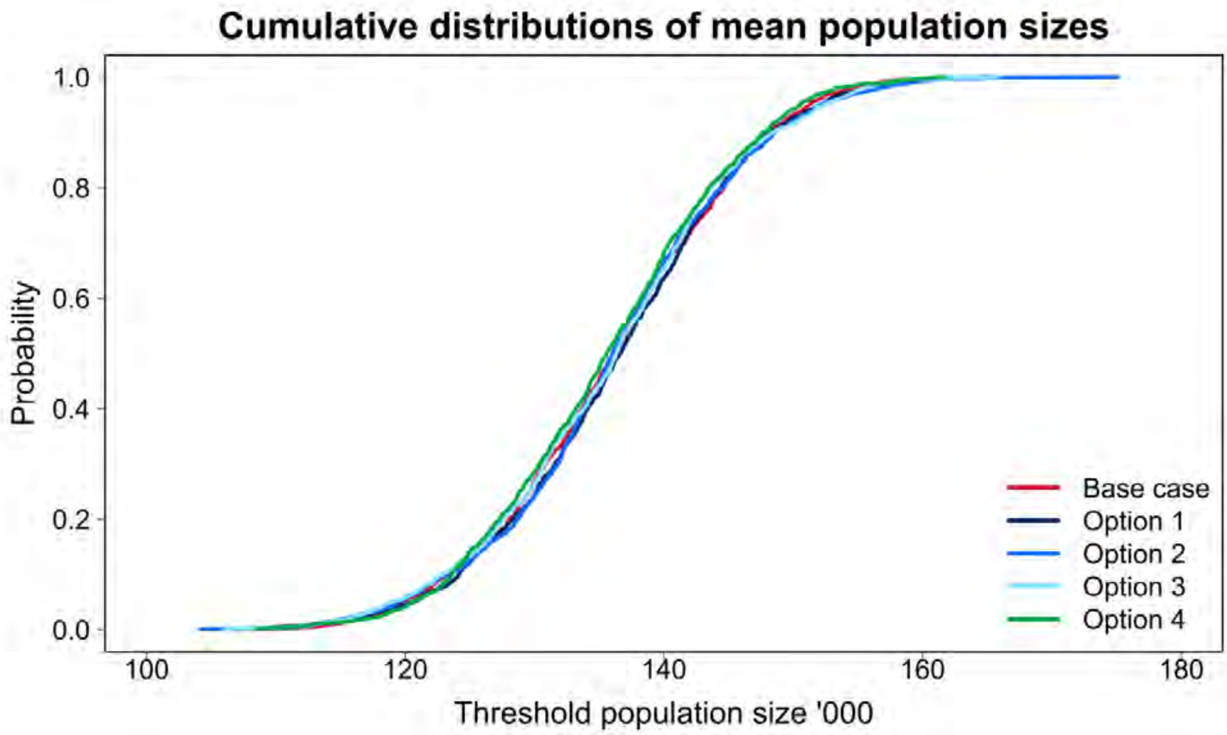


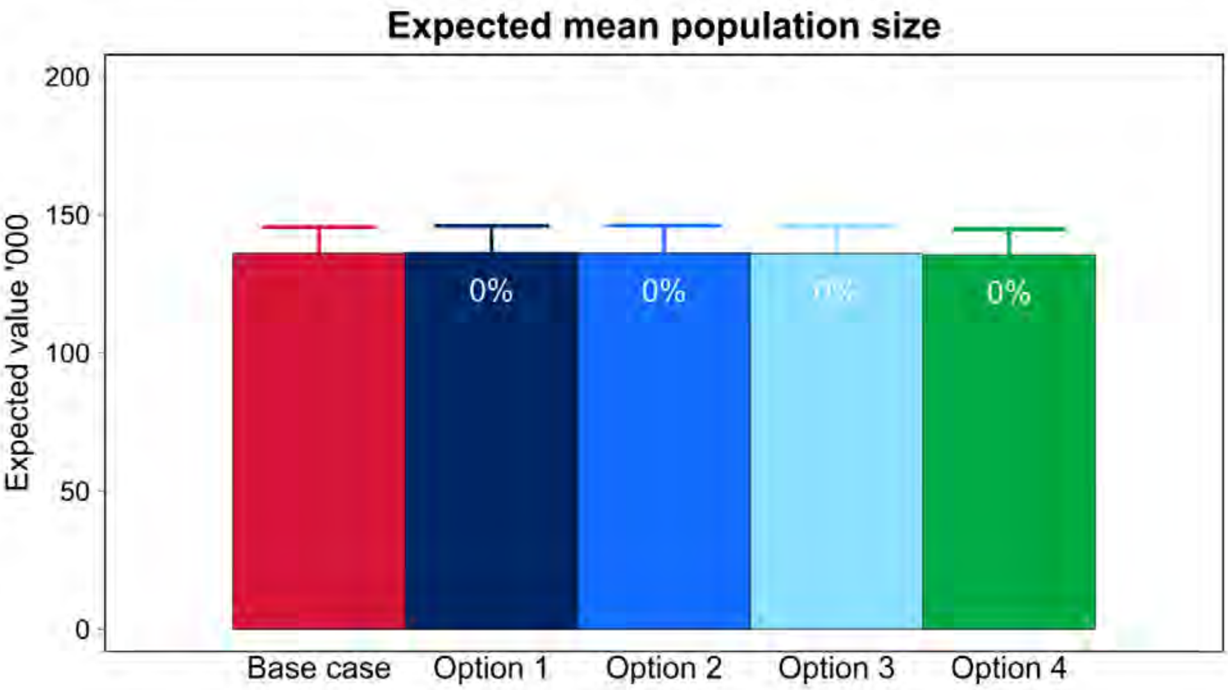
Figure A3.28. Murray Cod adults in the Torrumbarry to Wentworth reach for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

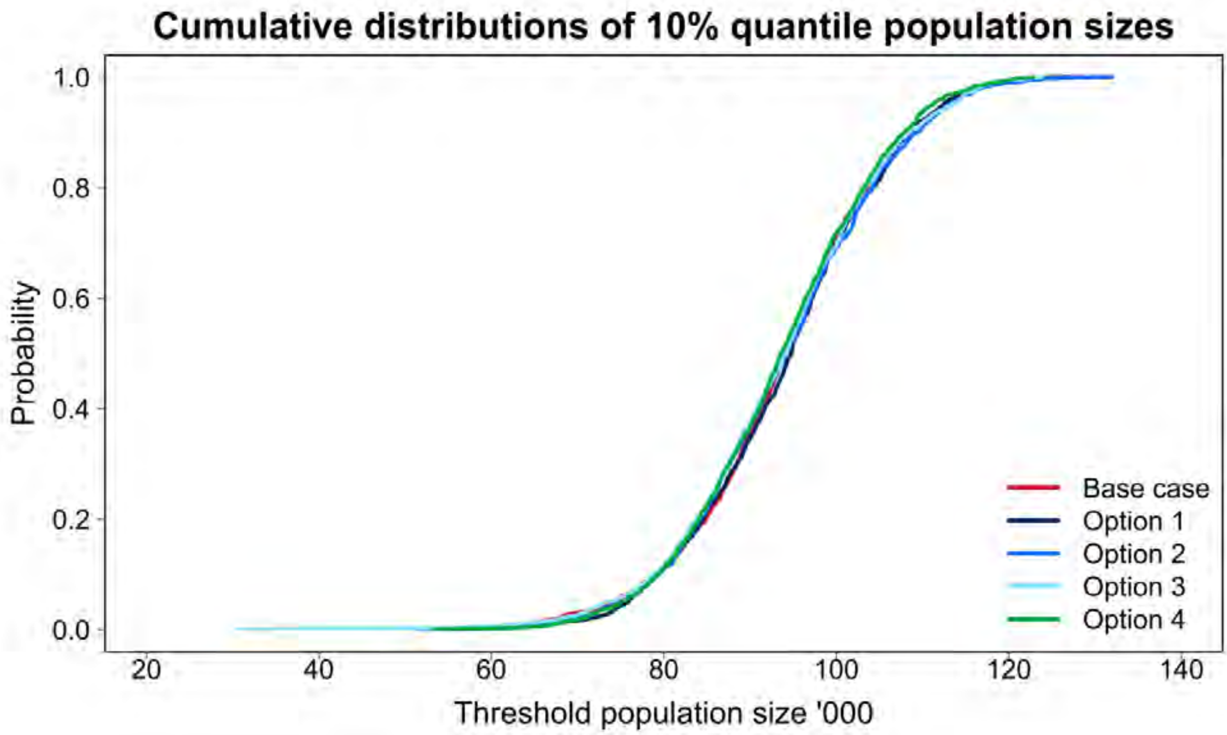
Murray Cod – Yarrawonga to Torrumbarry

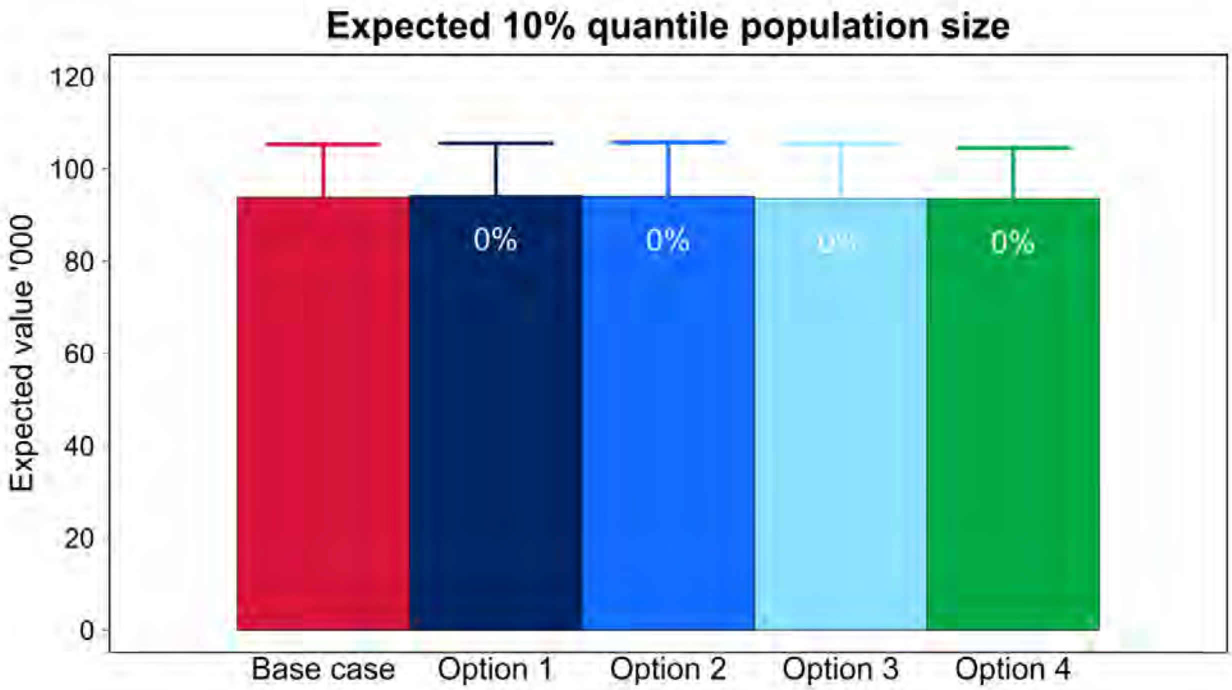


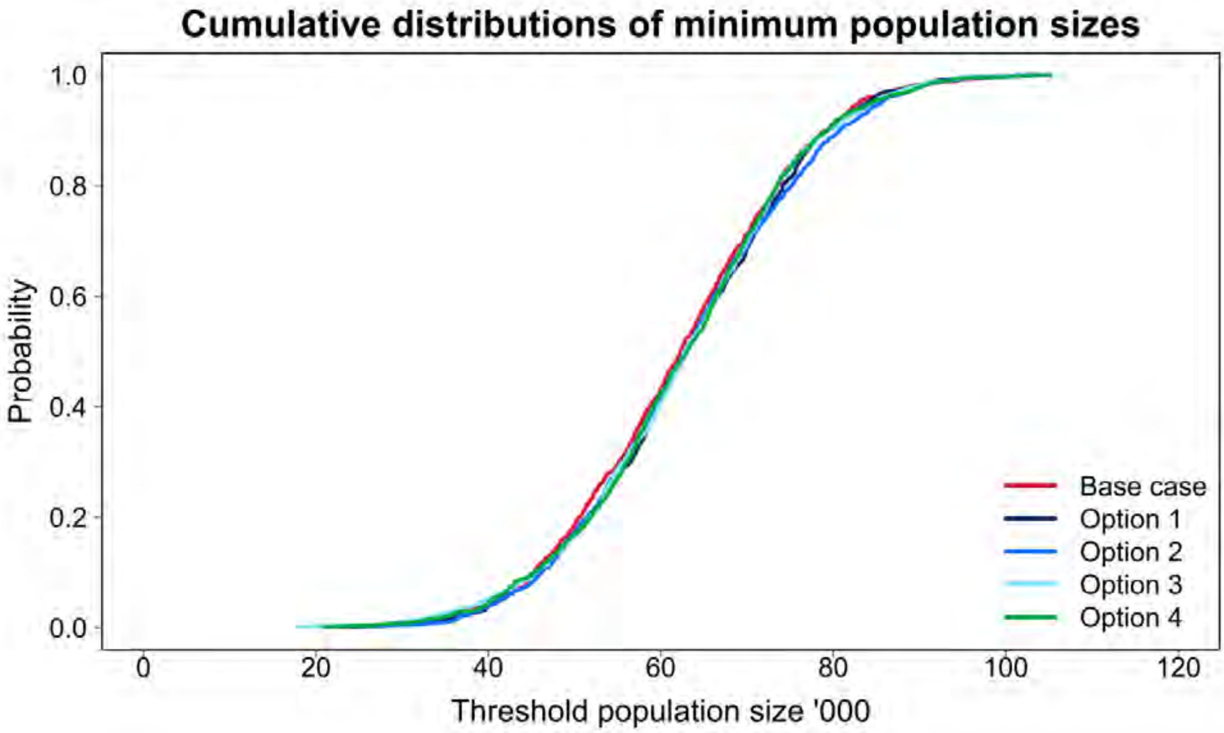


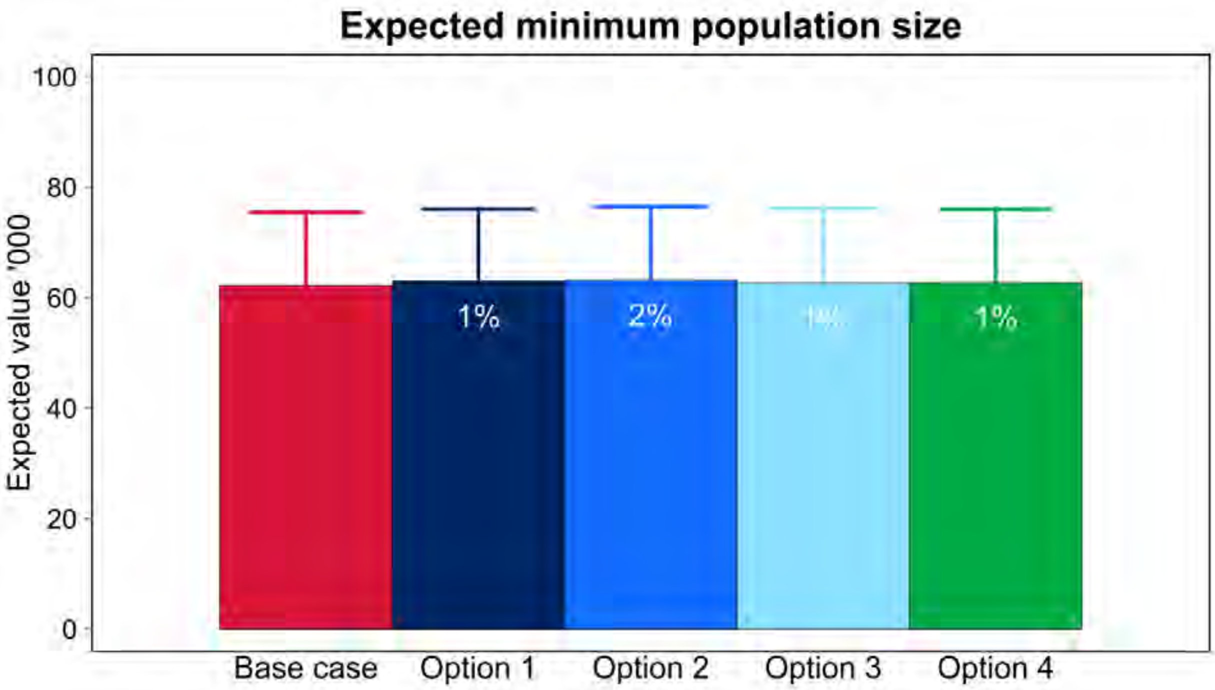

Cumulative distributions of mean population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
100
120
140
160
180
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected mean population size
Expected value '000
200
150
100
50
0
0%
0%
0%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of 10% quantile population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
20
40
60
80
100
120
140
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected 10% quantile population size
Expected value '000
120
100
80
60
40
20
0
0%
0%
0%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
120
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected minimum population size
Expected value '000
100
80
60
40
20
0
1%
2%
1%
1%
Base case
Option 1
Option 2
Option 3
Option 4

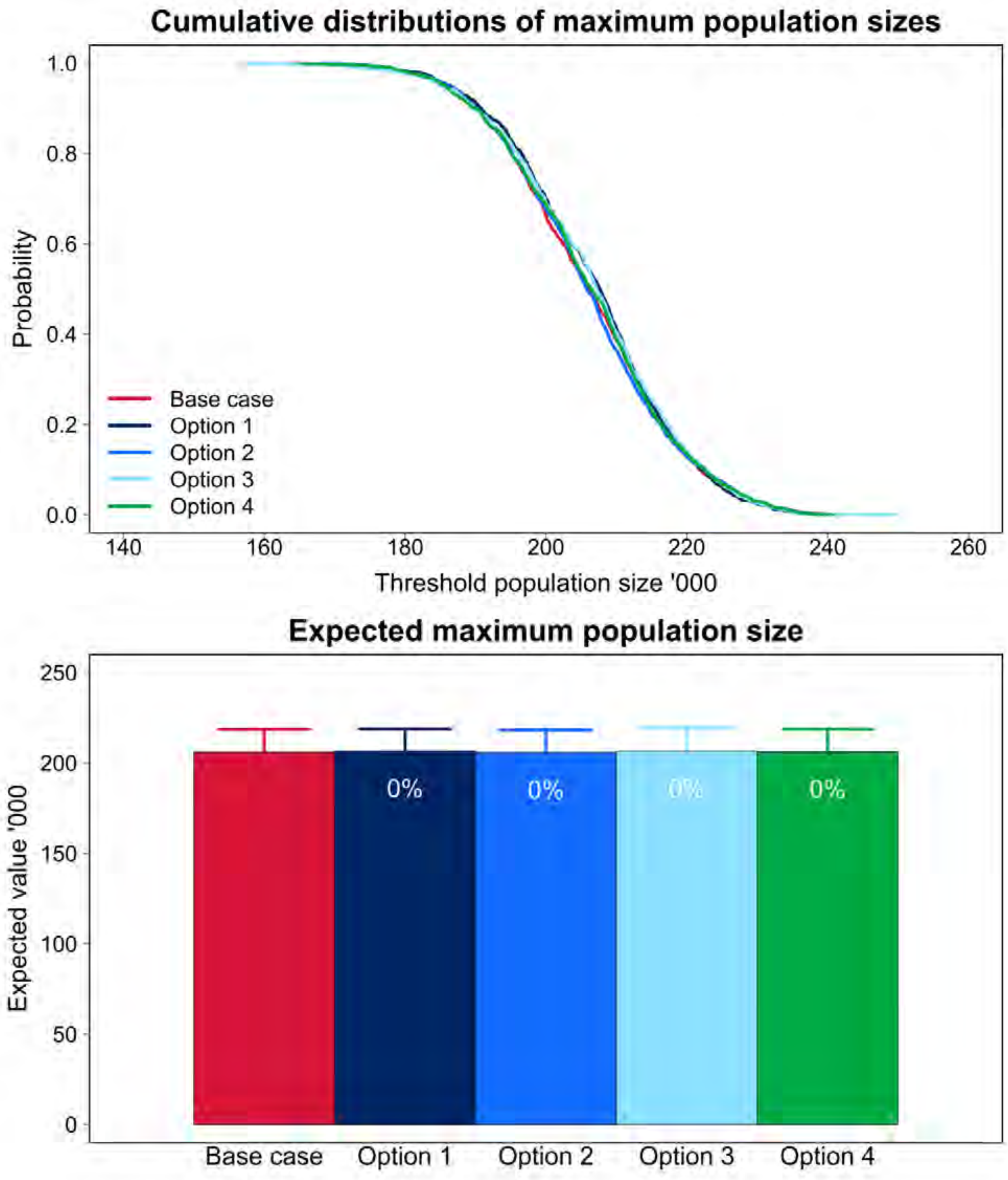
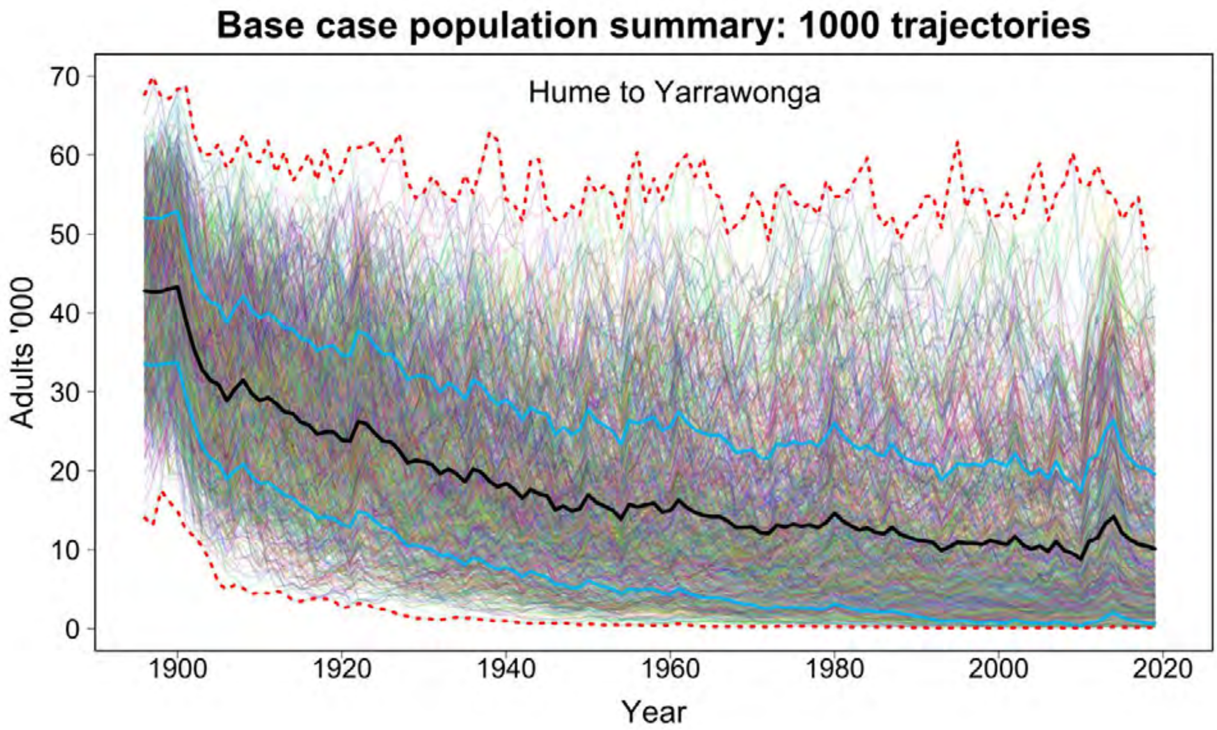
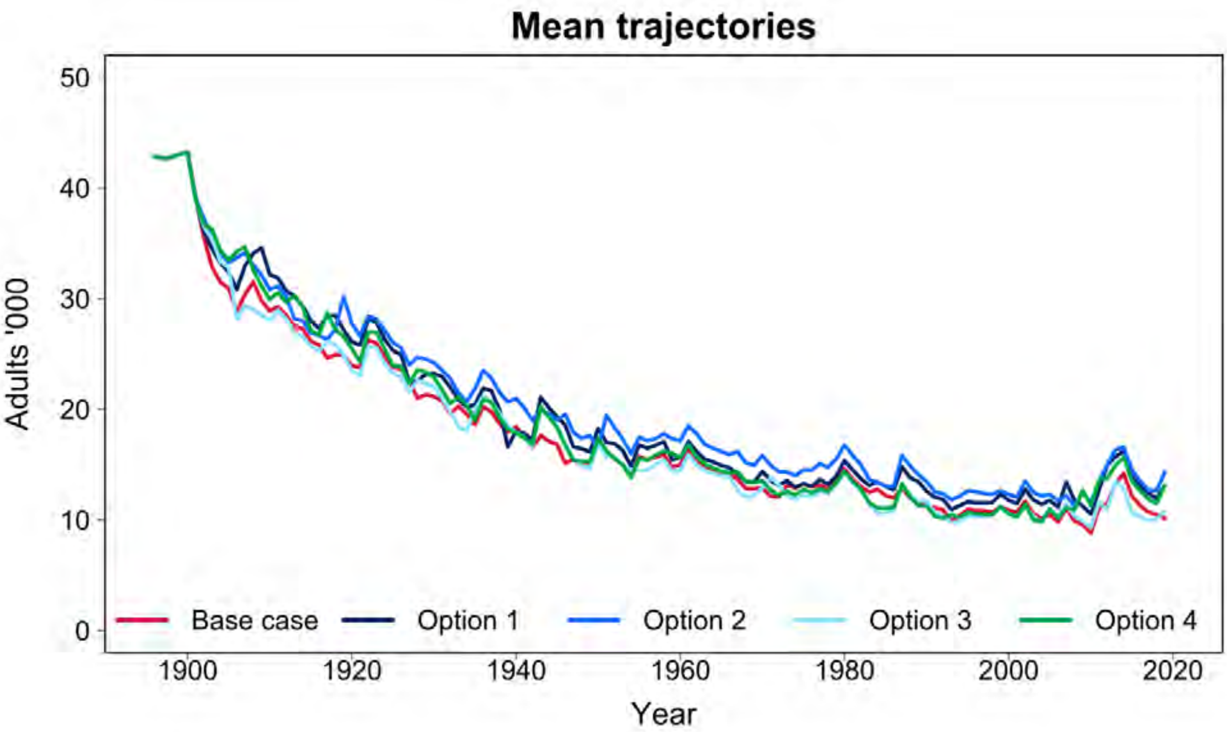
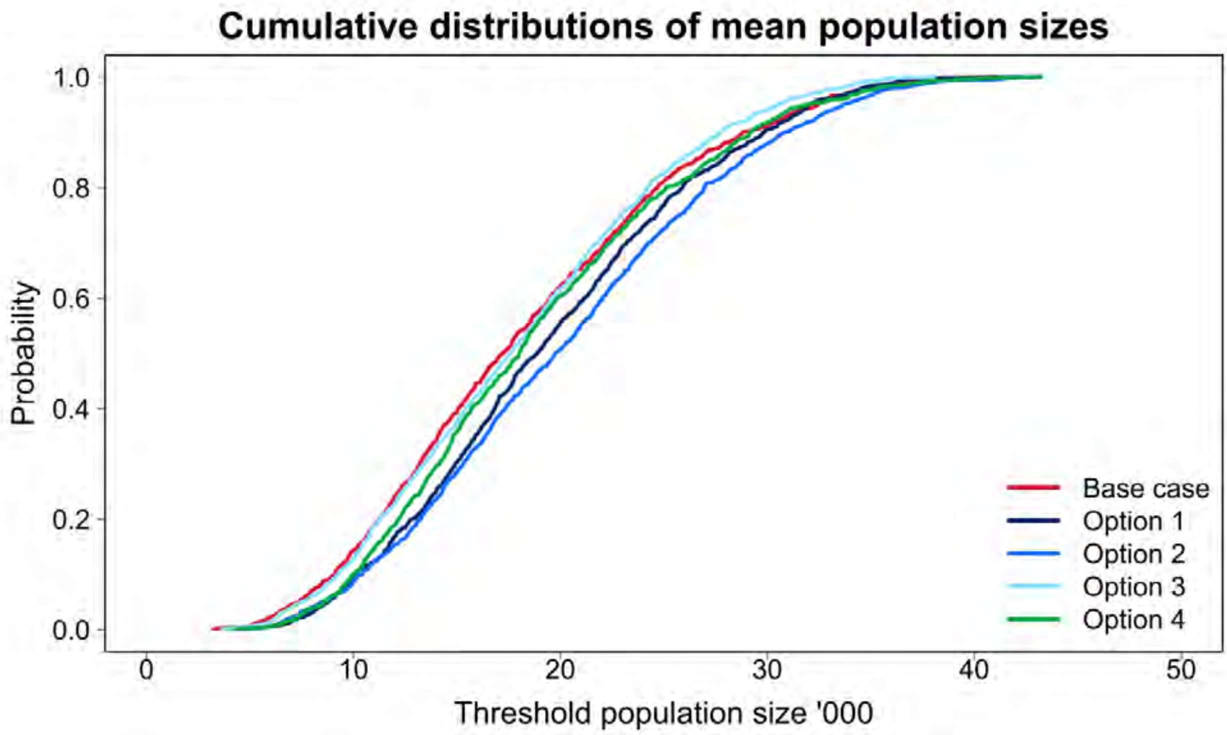


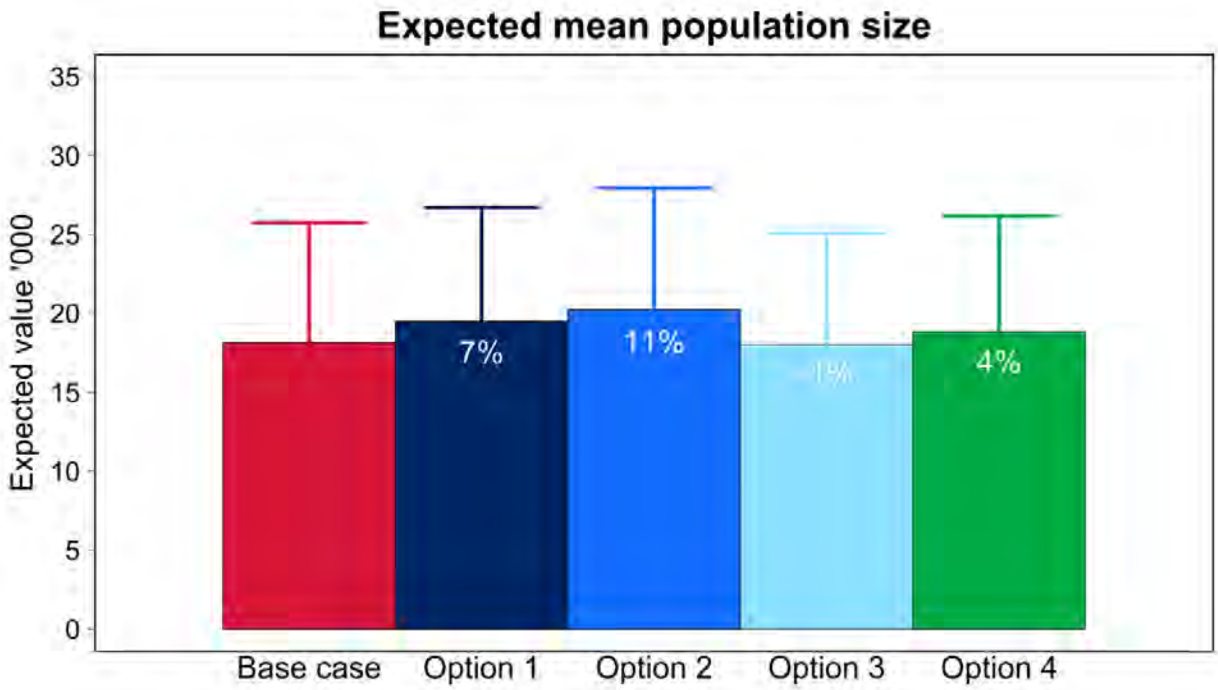
Figure A3.29. Murray Cod adults in the Yarrawonga to Torrumbarry reach for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

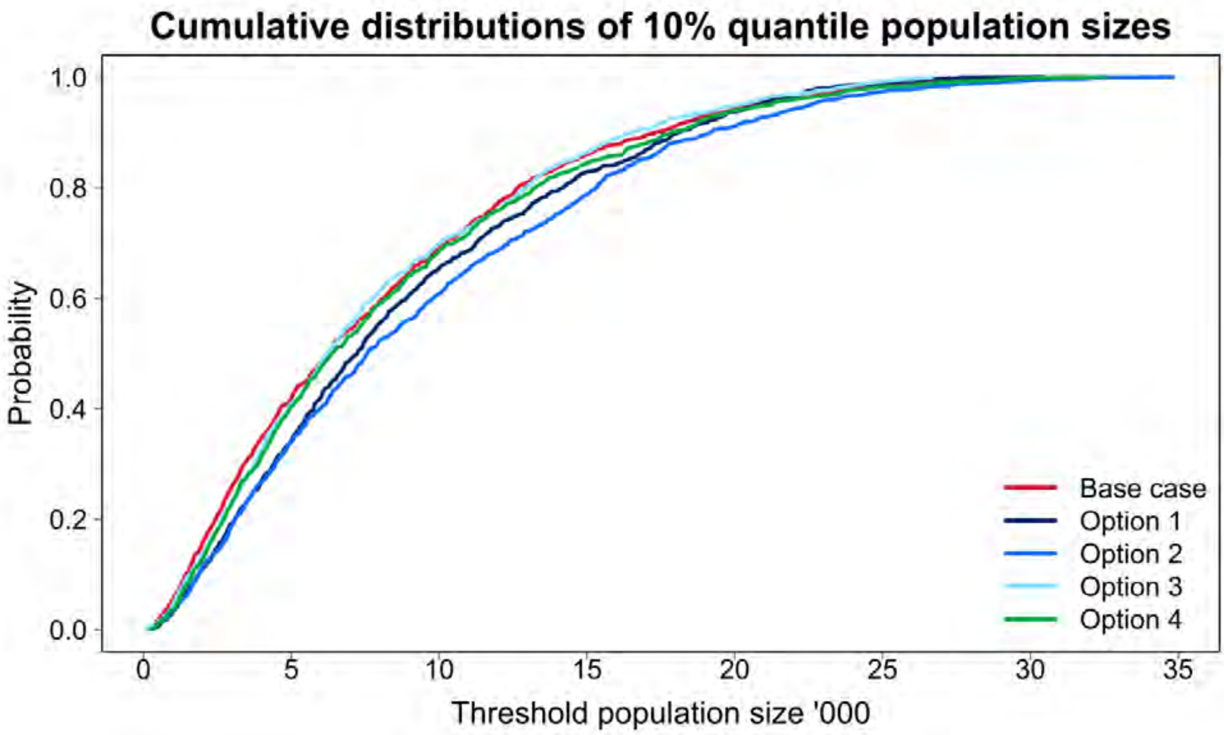
Murray Cod – Hume to Yarrawonga

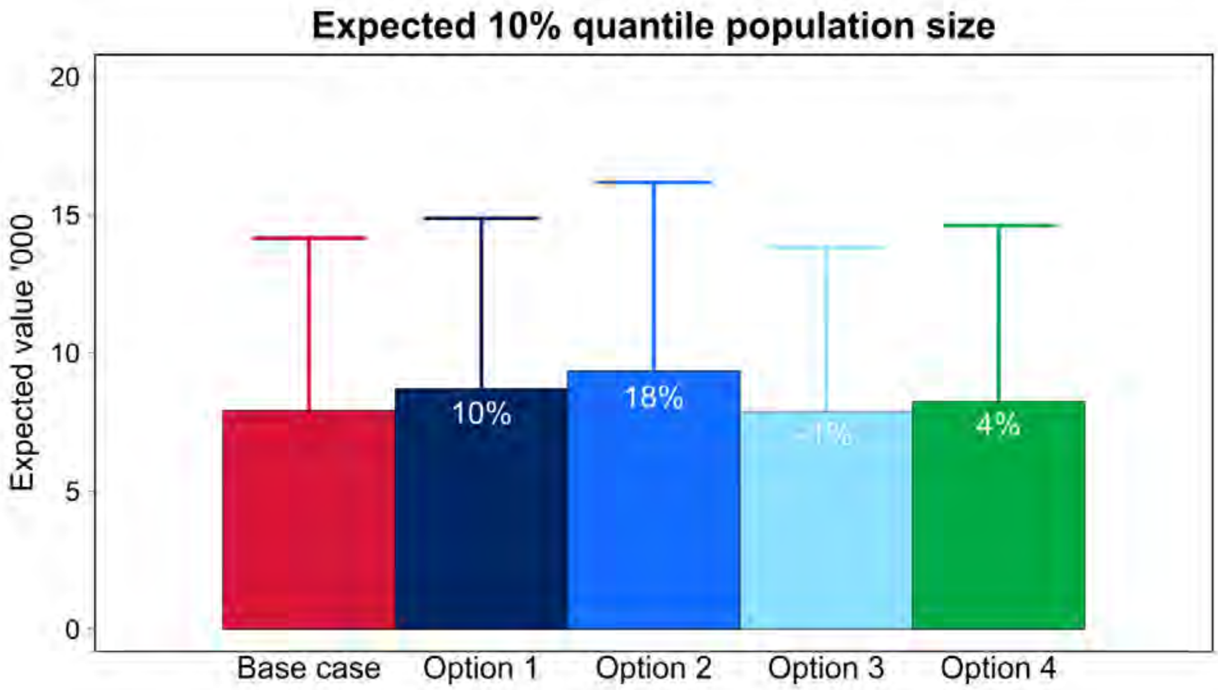


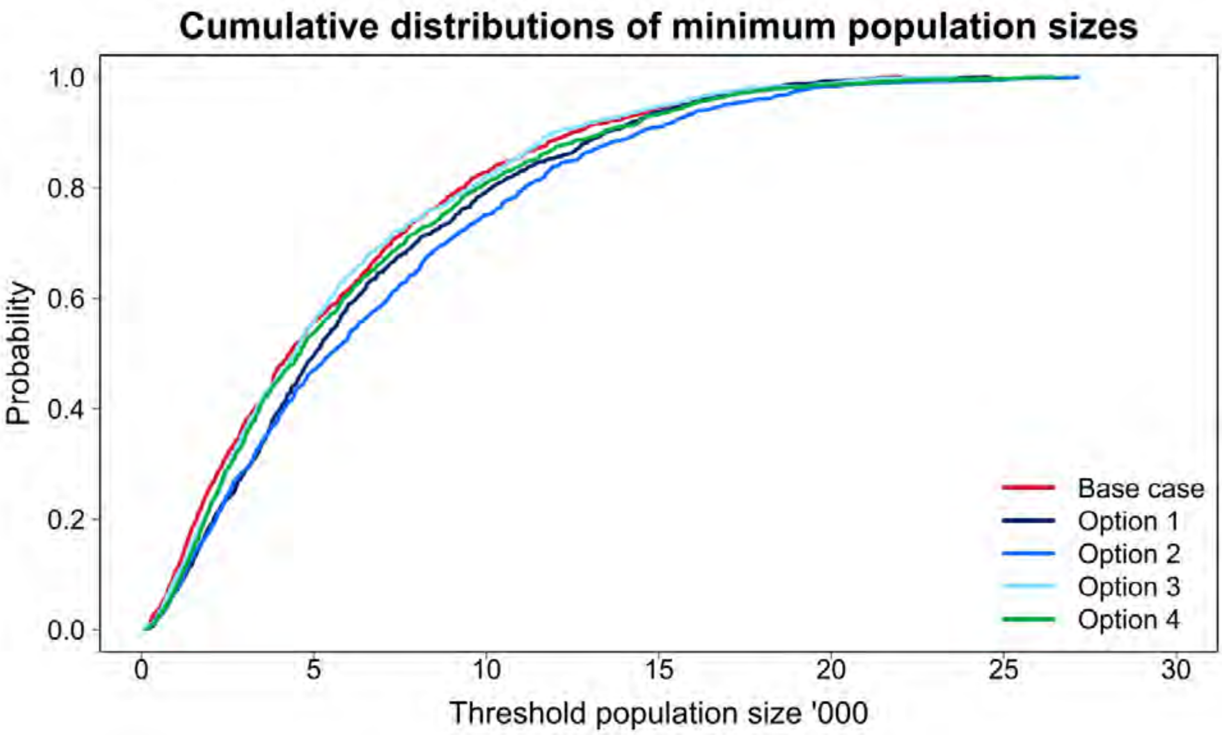


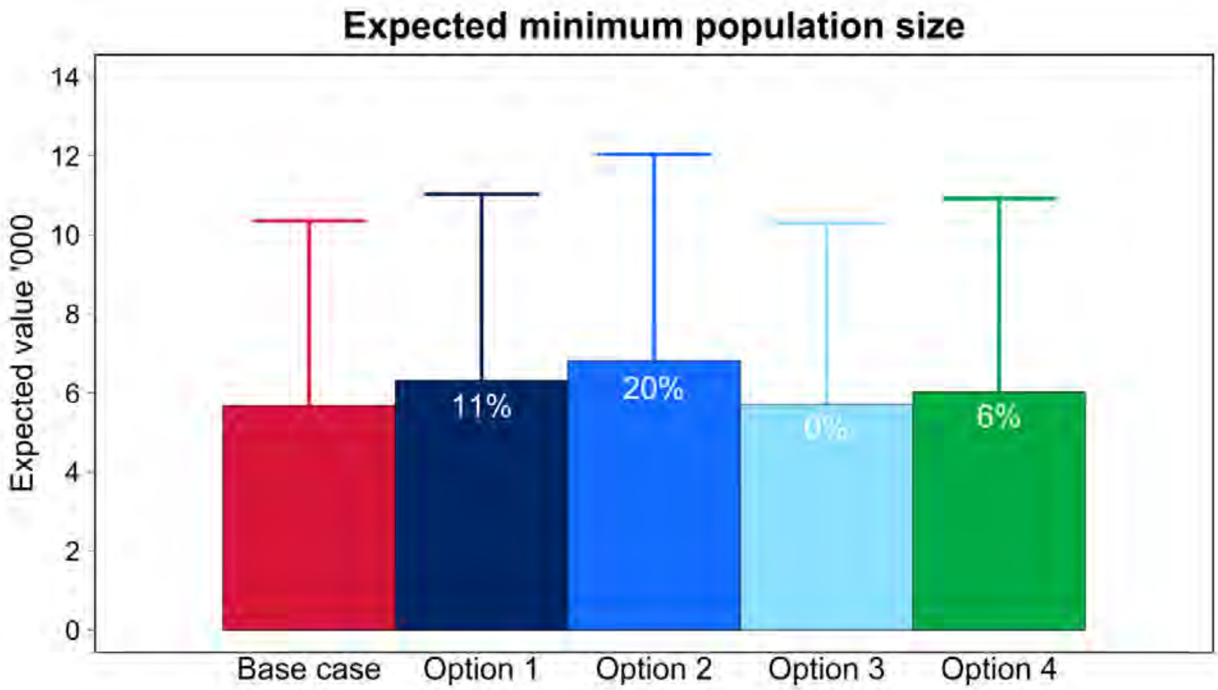

Cumulative distributions of mean population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected mean population size
Expected value '000
35
30
25
20
15
10
5
0
7%
11%
1%
4%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of 10% quantile population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
35
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected 10% quantile population size
Expected value '000
20
15
10
5
0
10%
18%
-1%
4%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
Threshold population size '000
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
Base case
Option 1
Option 2
Option 3
Option 4


Expected minimum population size
Expected value '000
14
12
10
8
6
4
2
0
11%
20%
0%
6%
Base case
Option 1
Option 2
Option 3
Option 4

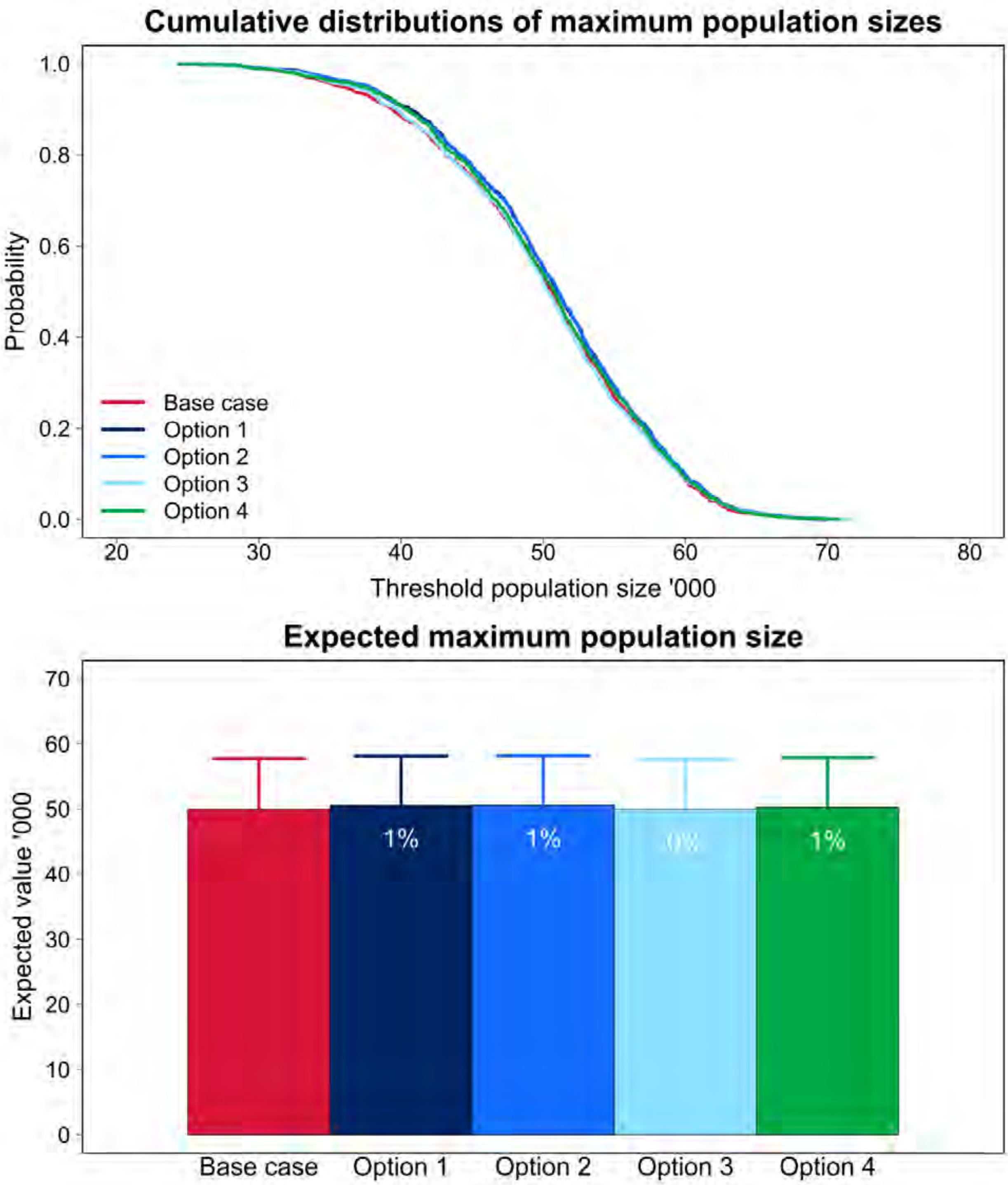
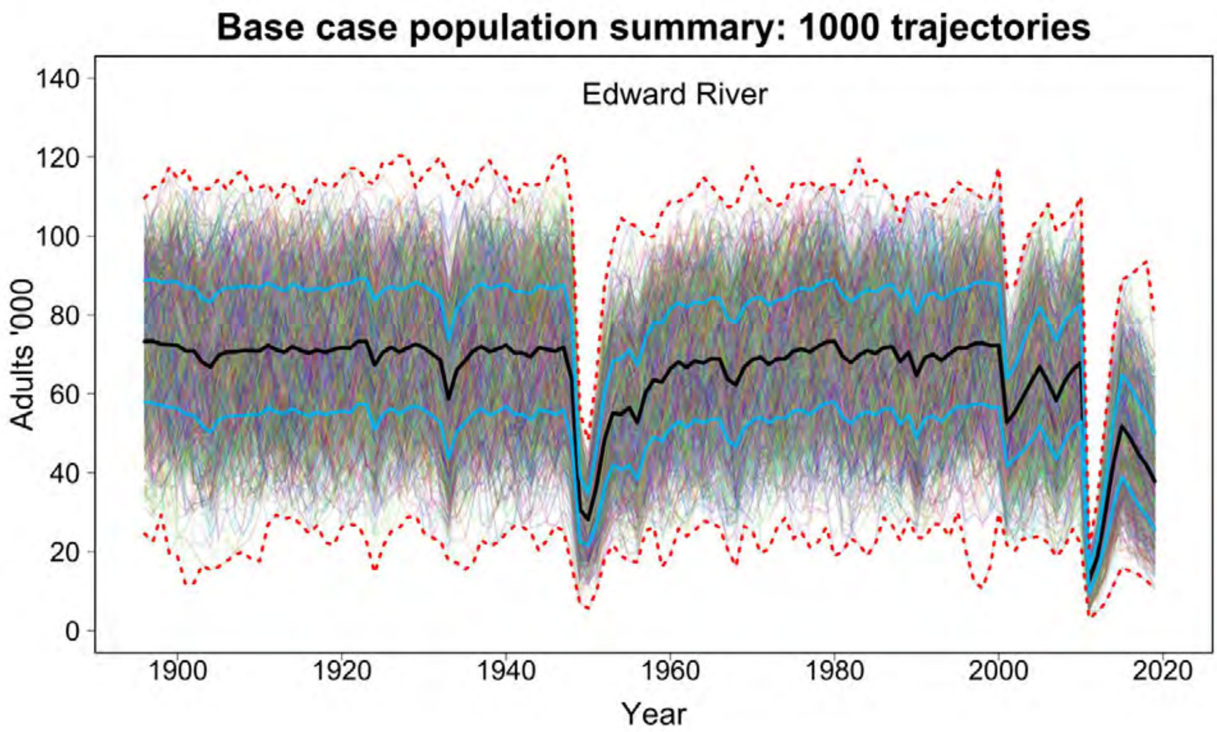
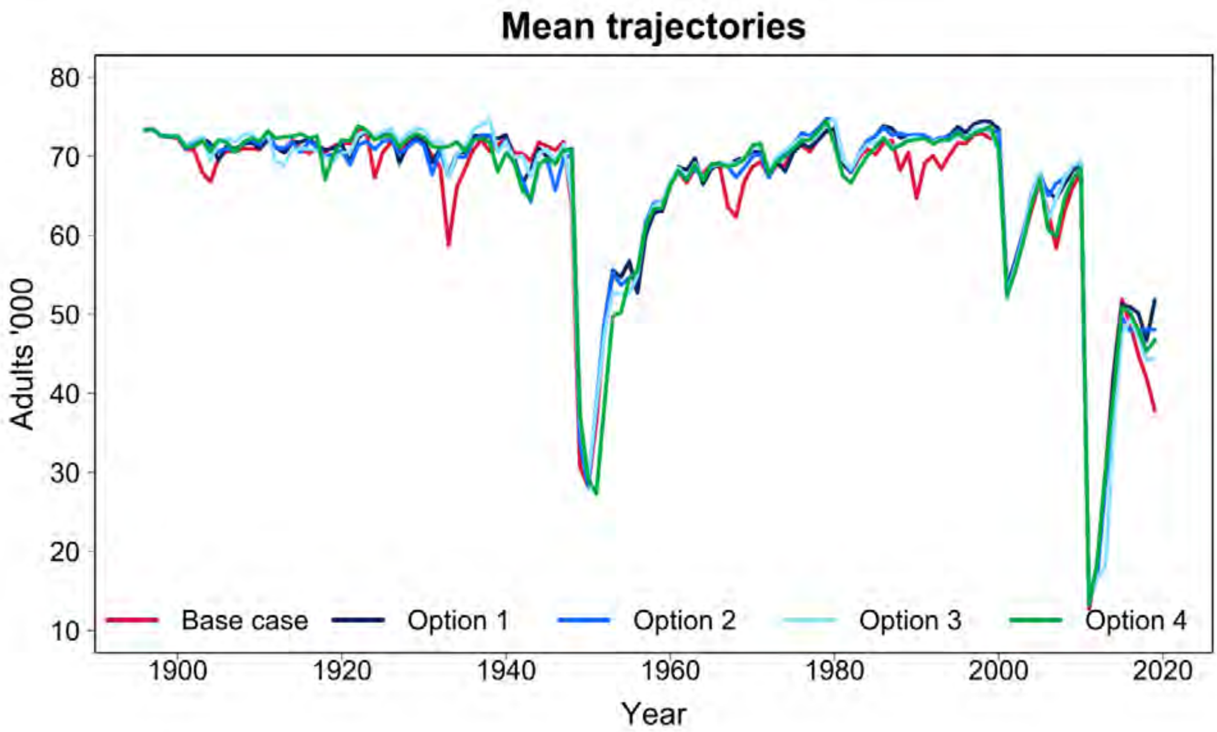
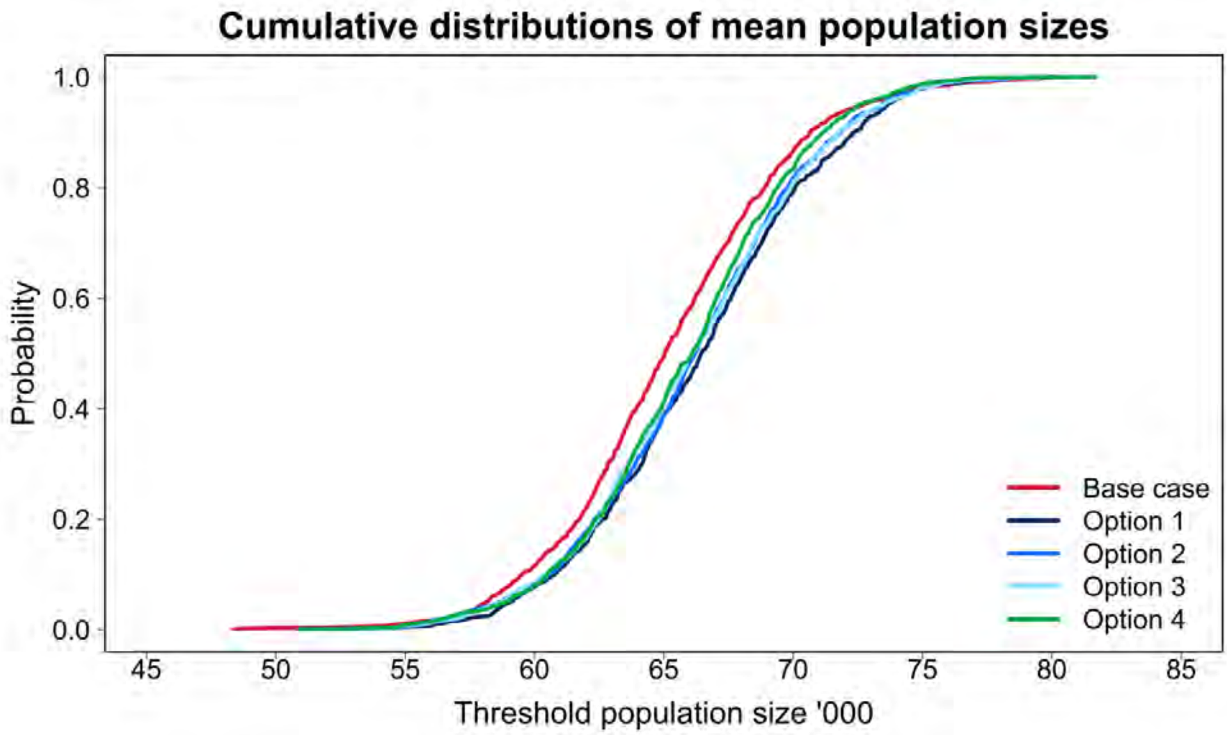


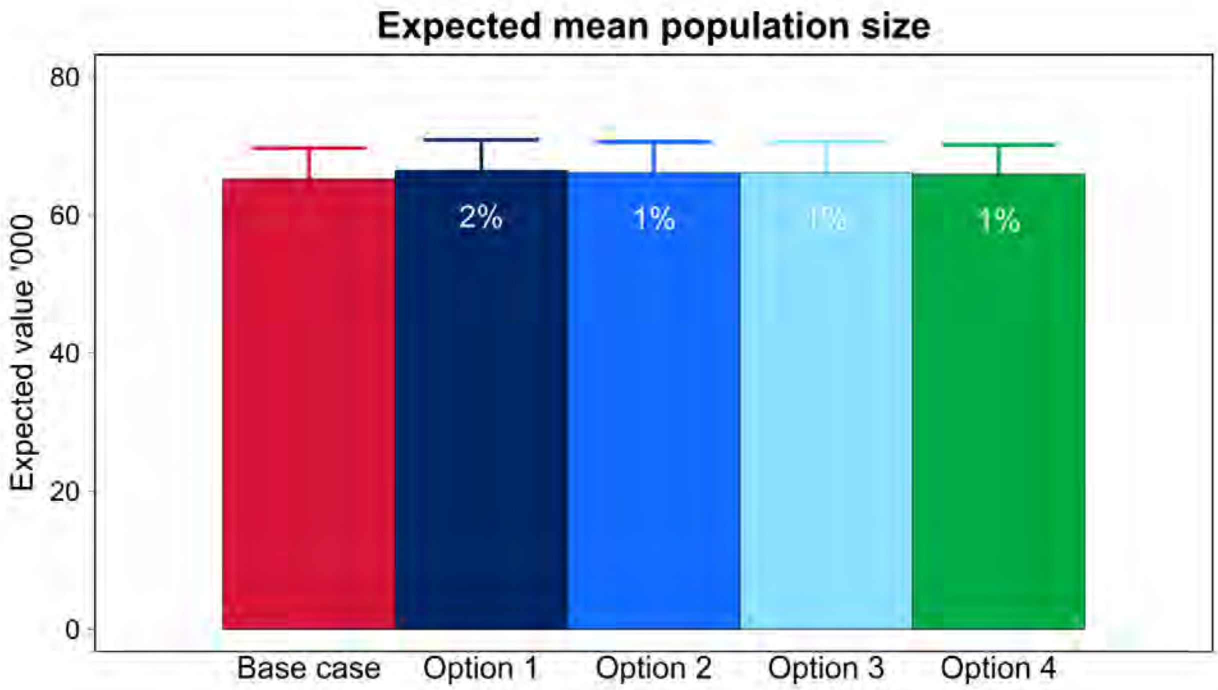
Figure A3.30. Murray Cod adults in the Hume to Yarrawonga reach for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

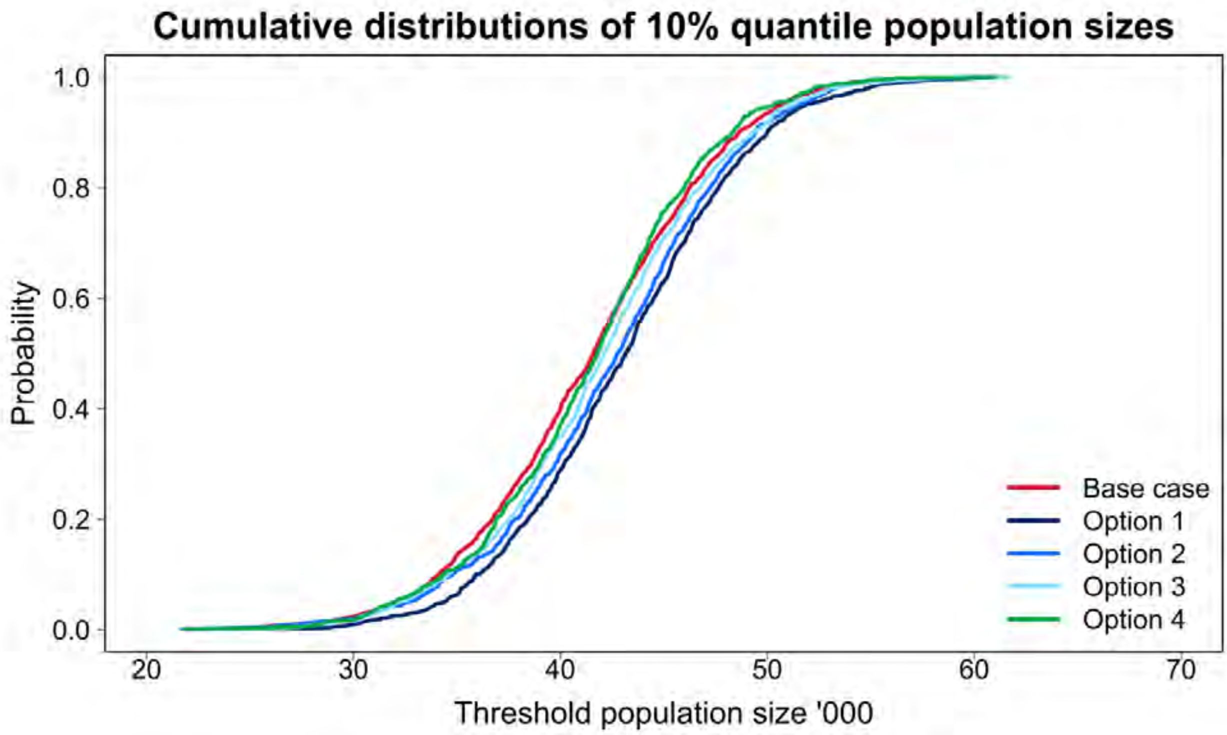
Murray Cod – Edward River

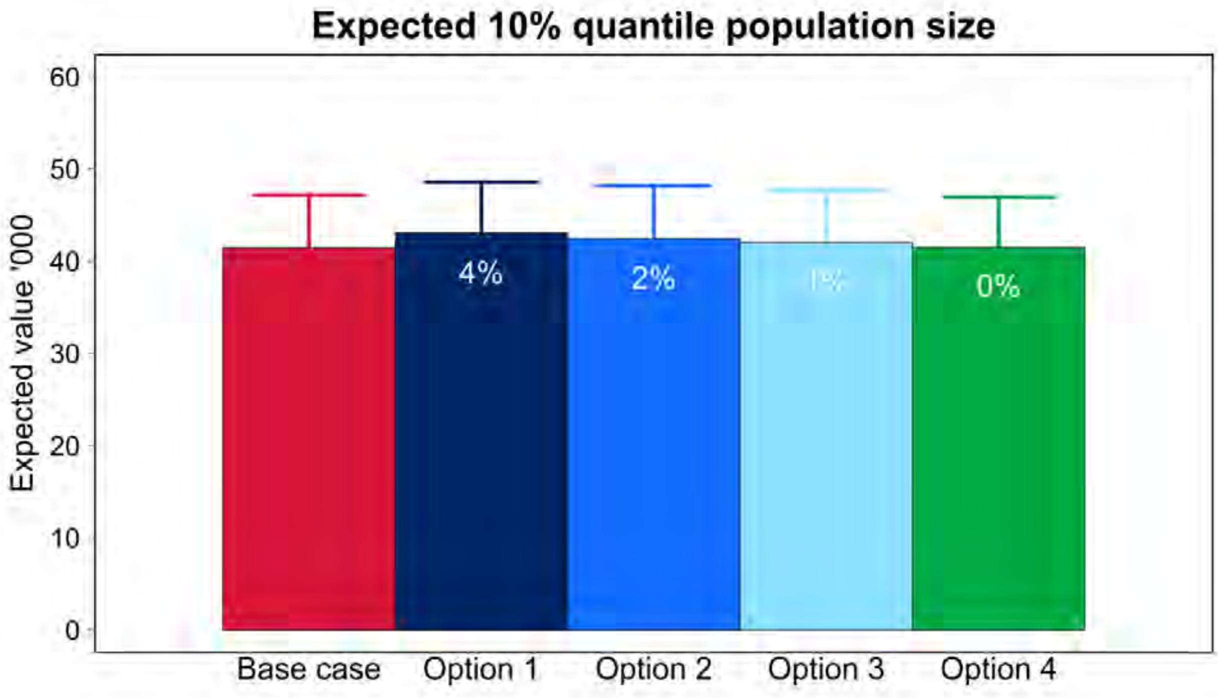


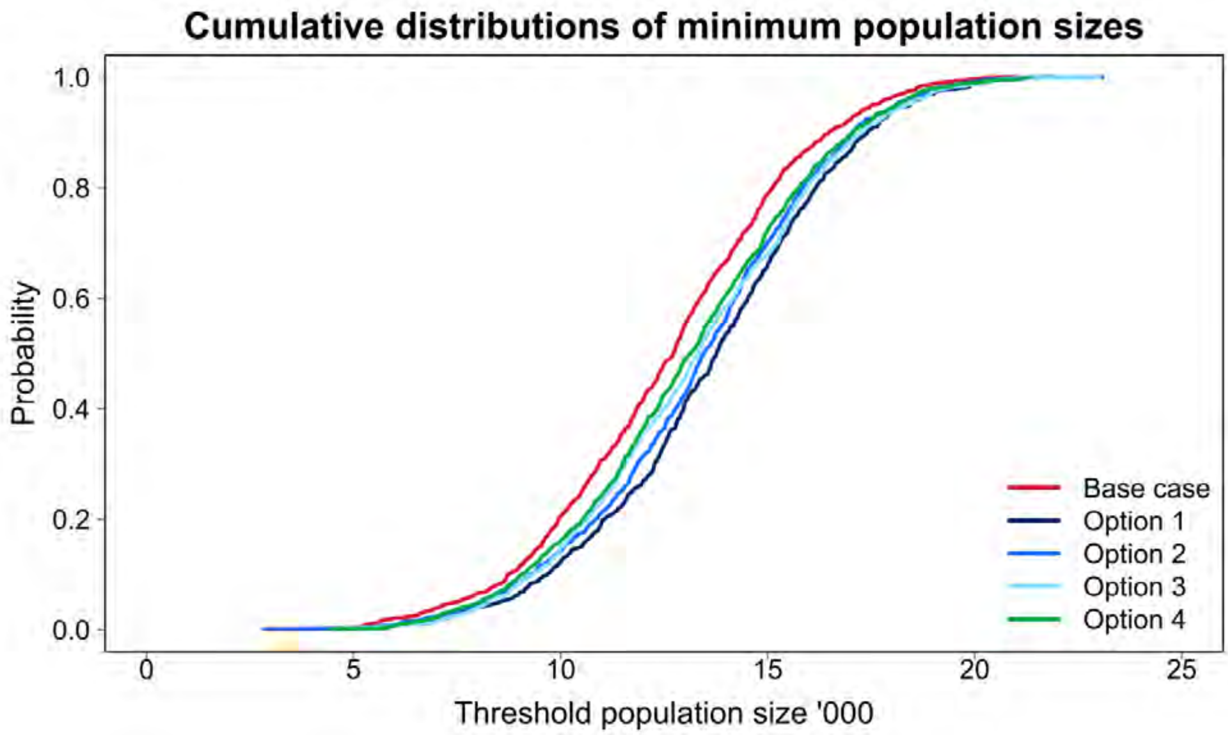


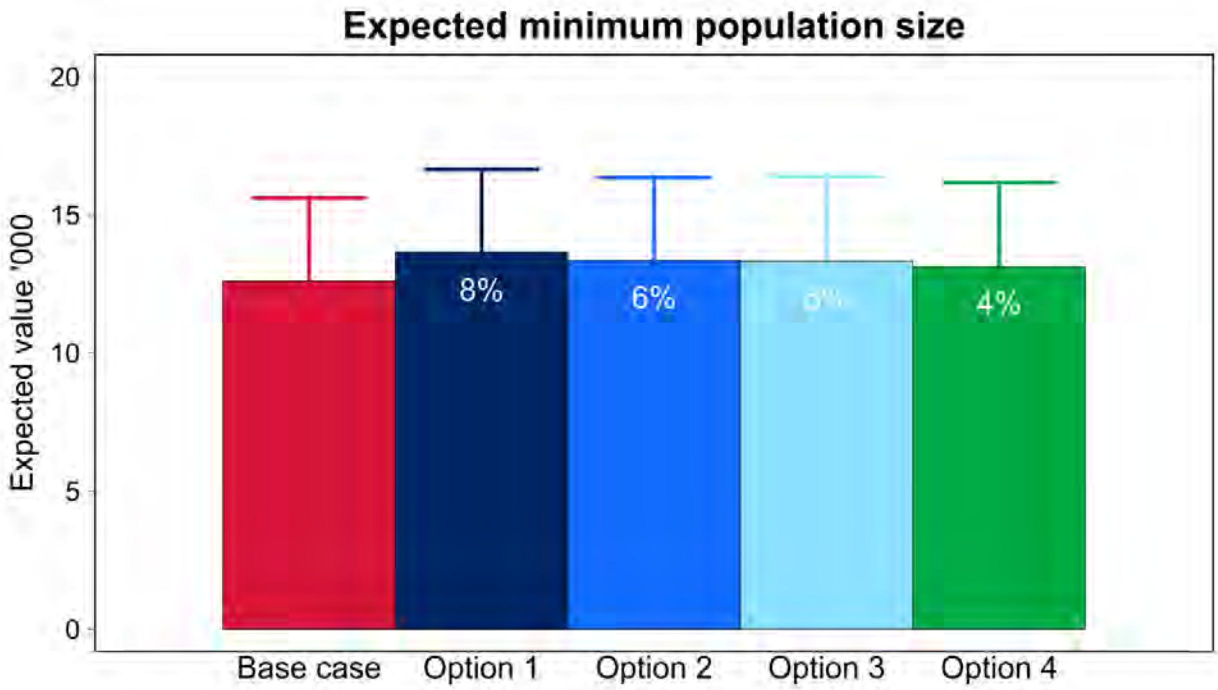

Cumulative distributions of mean population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
45
50
55
60
65
70
75
80
85
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected mean population size
Expected value '000
80
60
40
20
0
2%
1%
1%
1%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of 10% quantile population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
20
30
40
50
60
70
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected 10% quantile population size
Expected value '000
60
50
40
30
20
10
0
4%
2%
1%
0%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected minimum population size
Expected value '000
20
15
10
5
0
8%
6%
4%
Base case
Option 1
Option 2
Option 3
Option 4

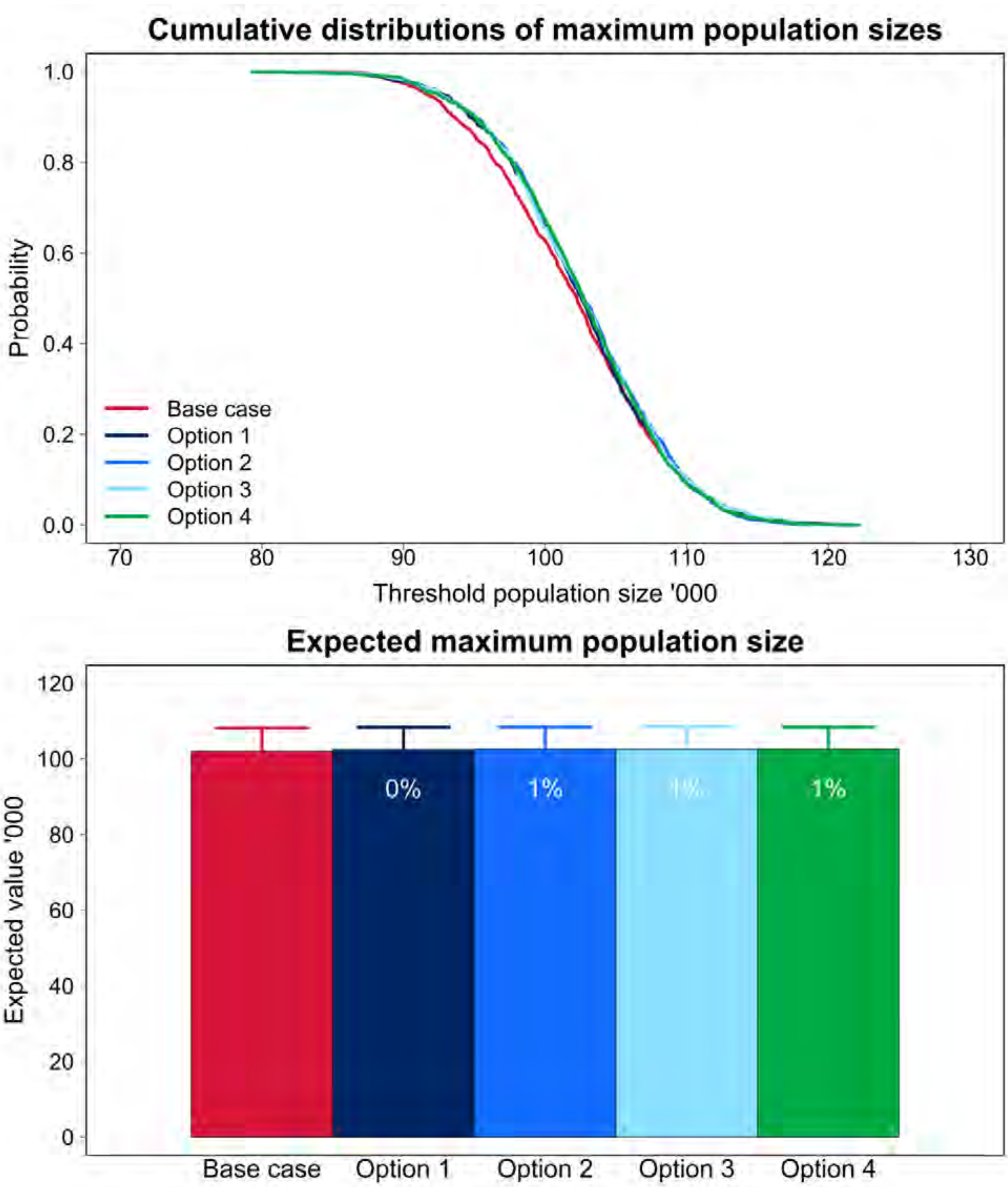
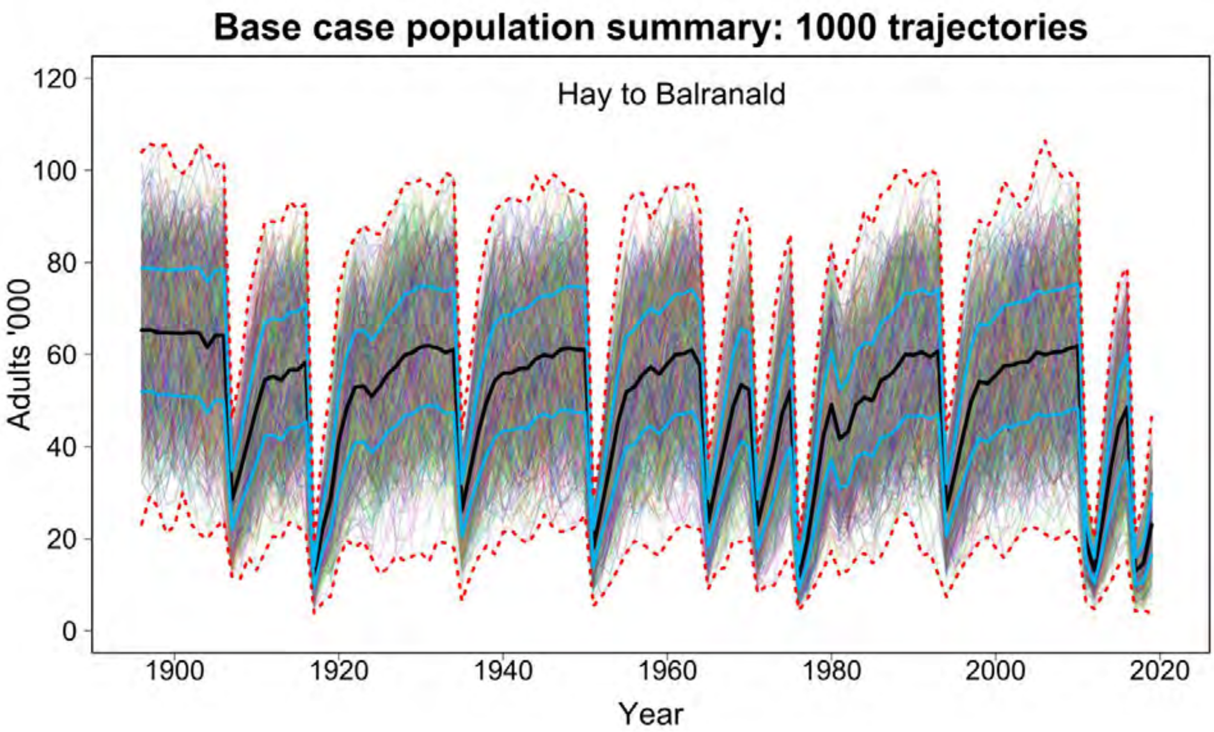
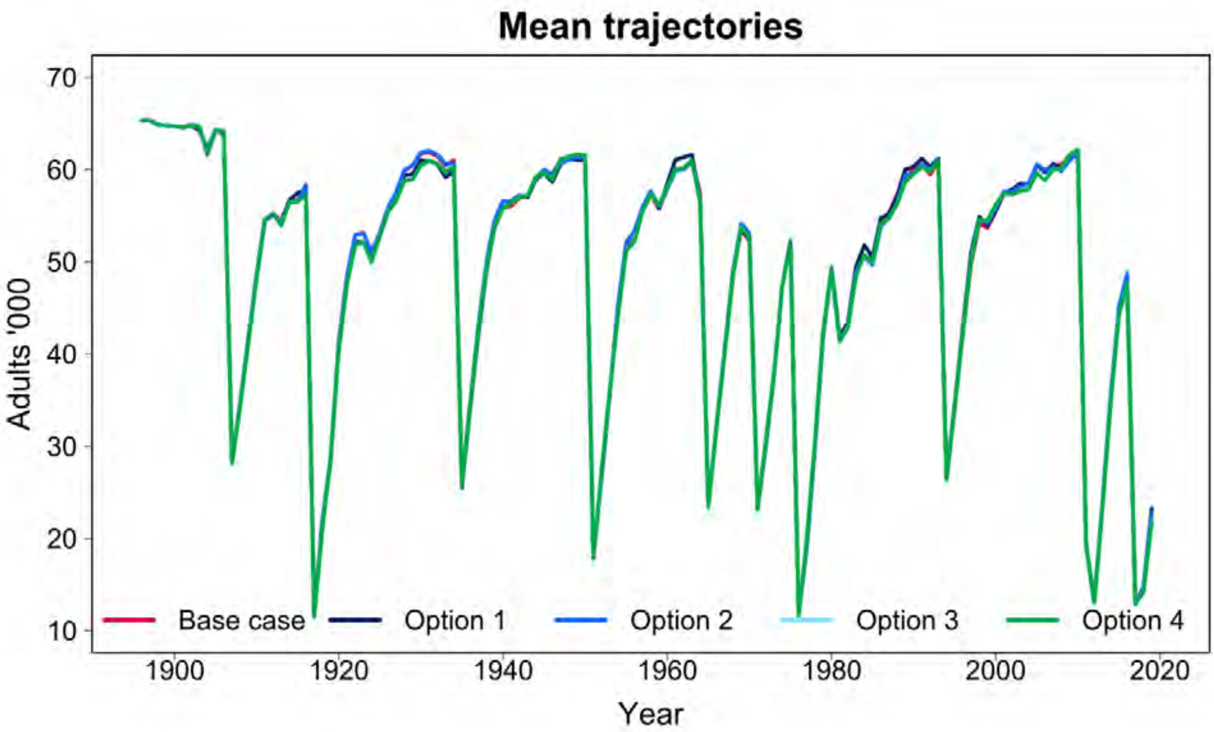
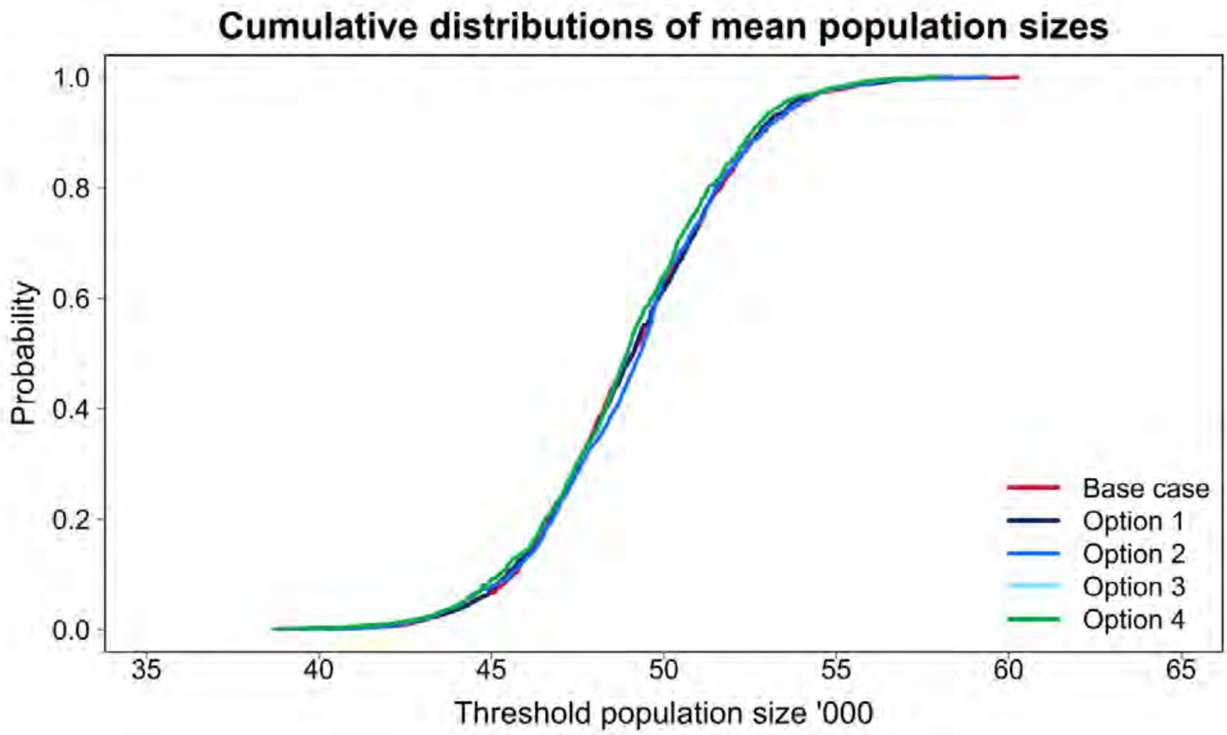


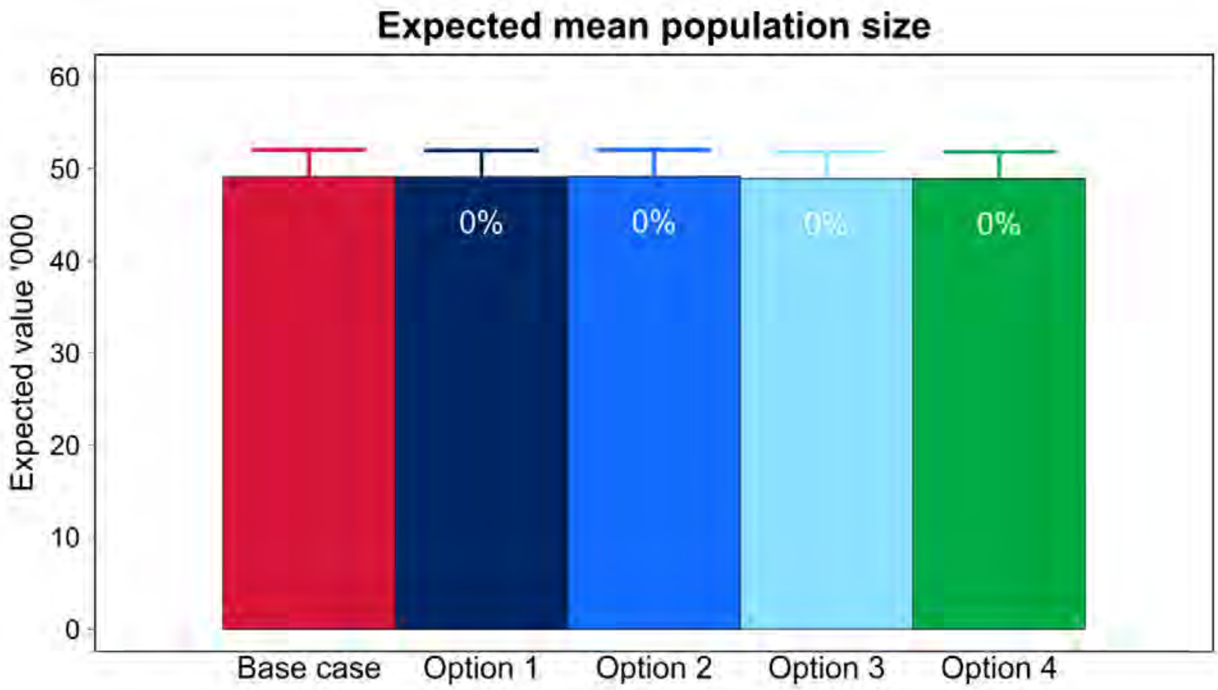
Figure A3.31. Murray Cod adults in the Edward River for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

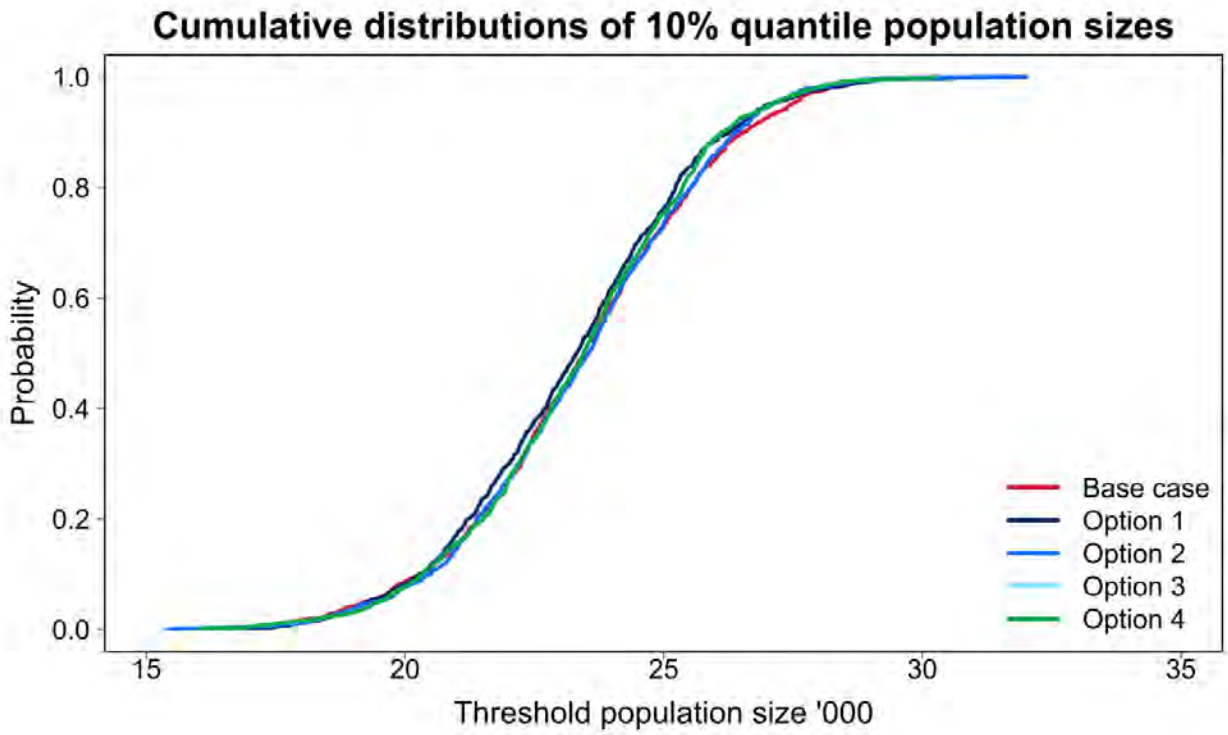
Murray Cod – Hay to Balranald

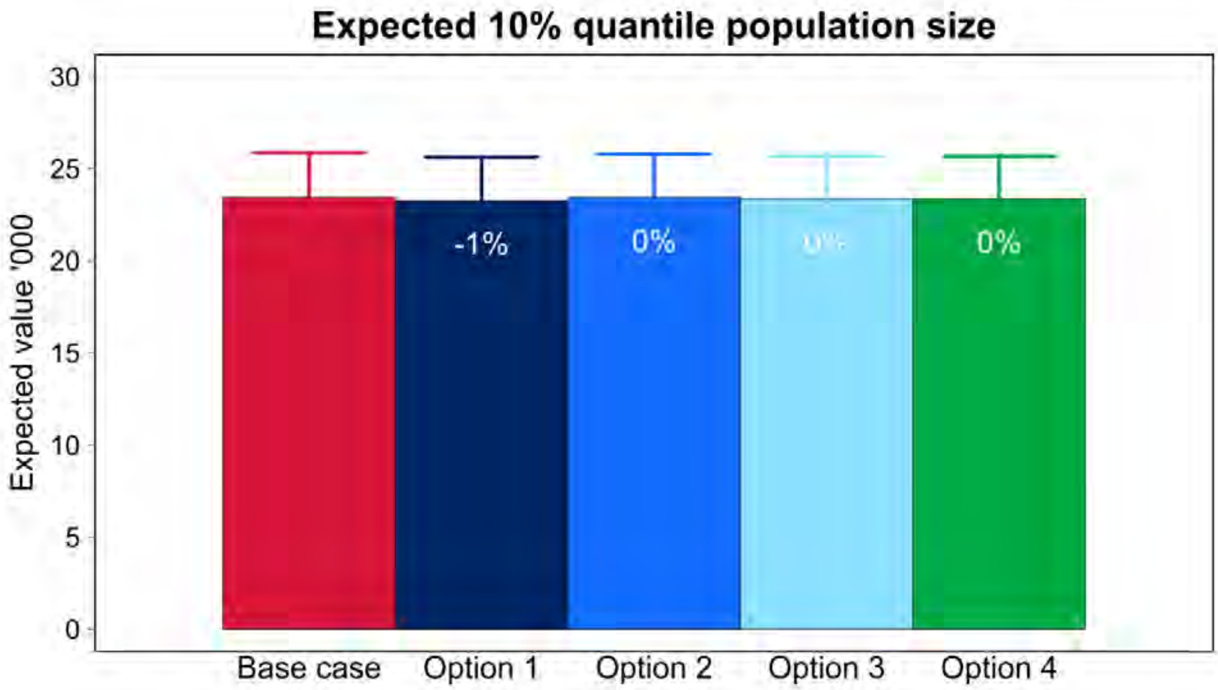


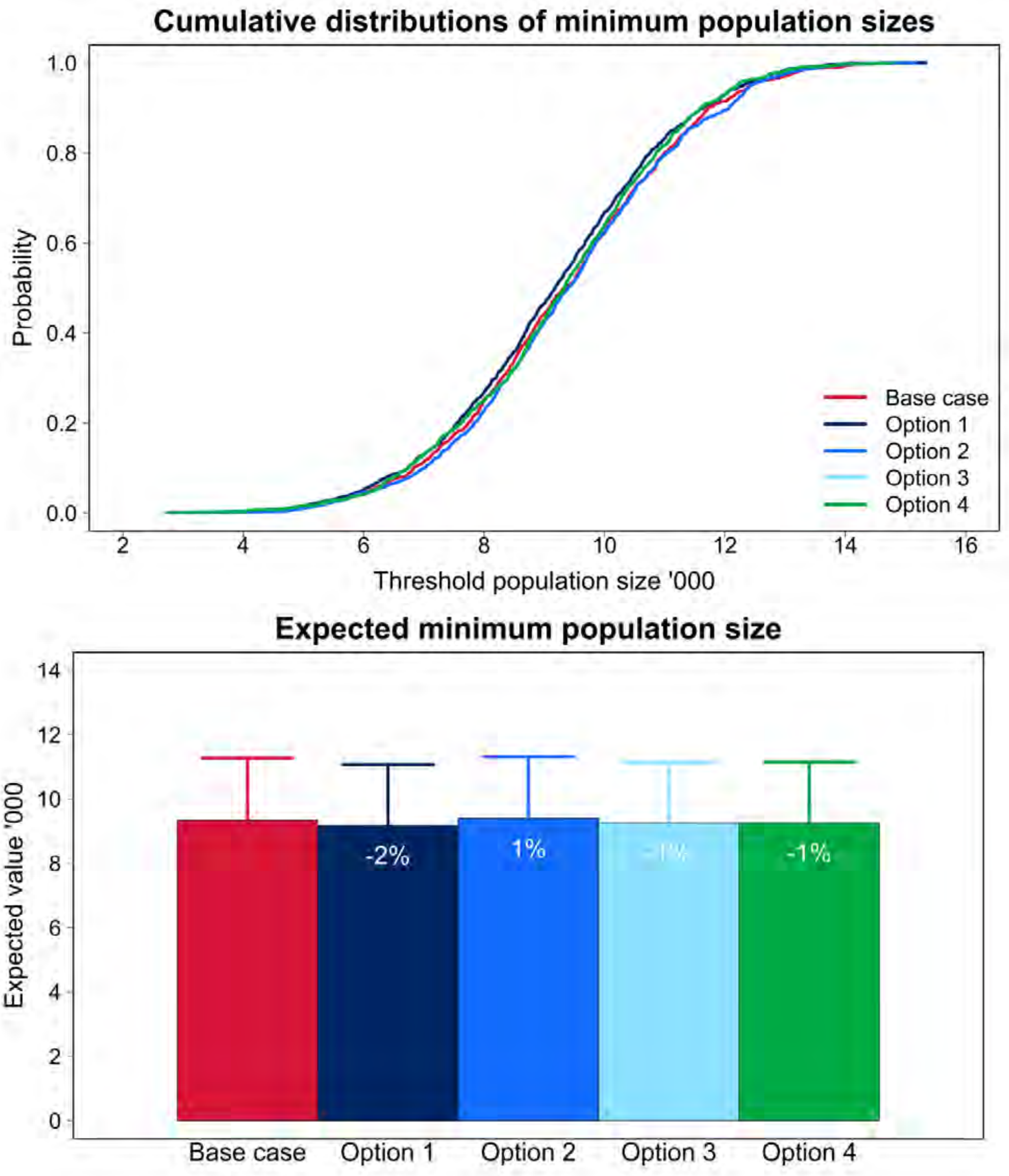



Cumulative distributions of mean population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
35
40
45
50
55
60
65
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected mean population size
Expected value '000
60
50
40
30
20
10
0
0%
0%
0%
0%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of 10% quantile population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
15
20
25
30
35
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected 10% quantile population size
Expected value '000
30
25
20
15
10
5
0
-1%
0%
0%
0%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
2
4
6
8
10
12
14
16
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4
Expected minimum population size
Expected value '000
14
12
10
8
6
4
2
0
-2%
1%
-1%
-1%
Base case
Option 1
Option 2
Option 3
Option 4

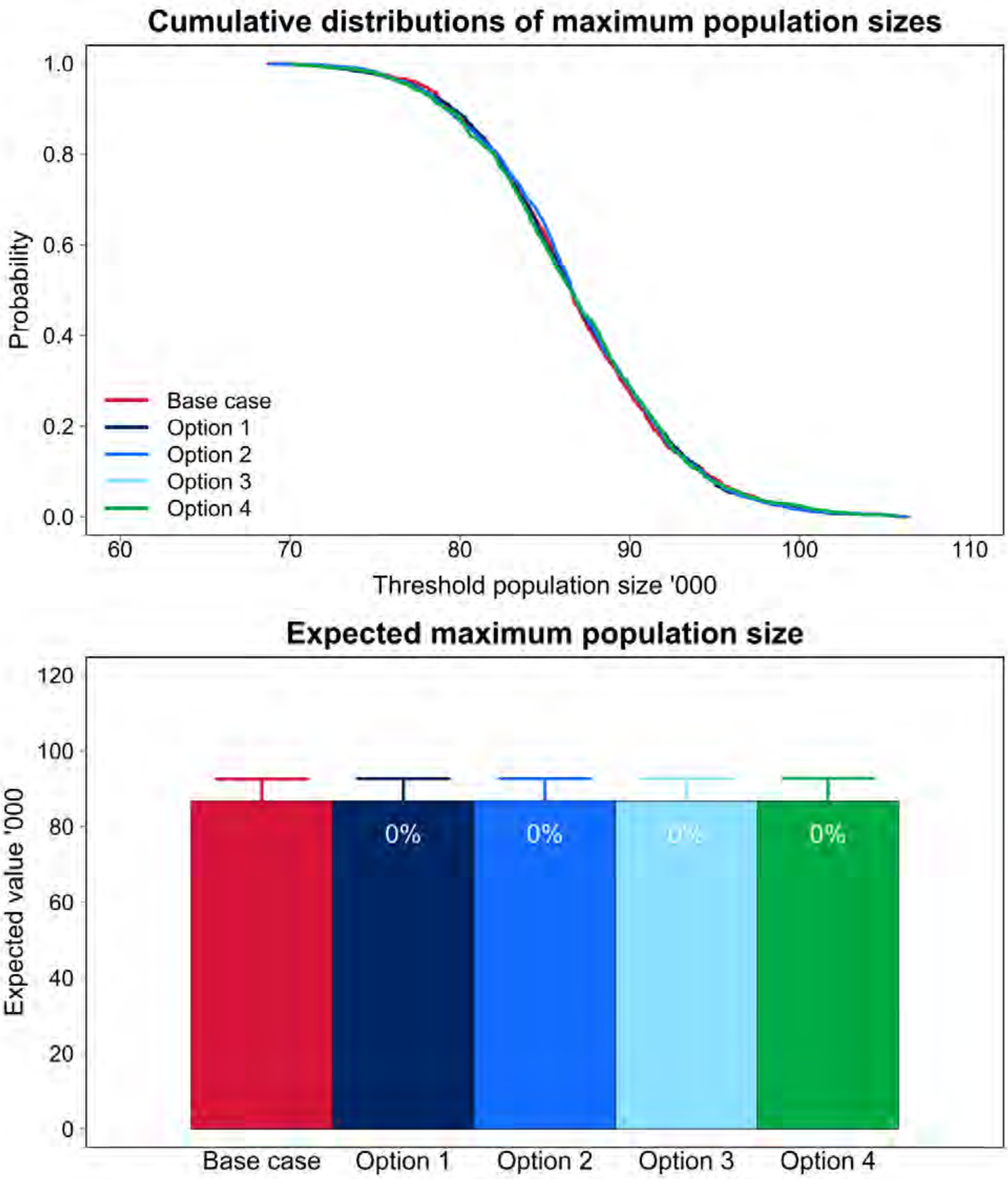
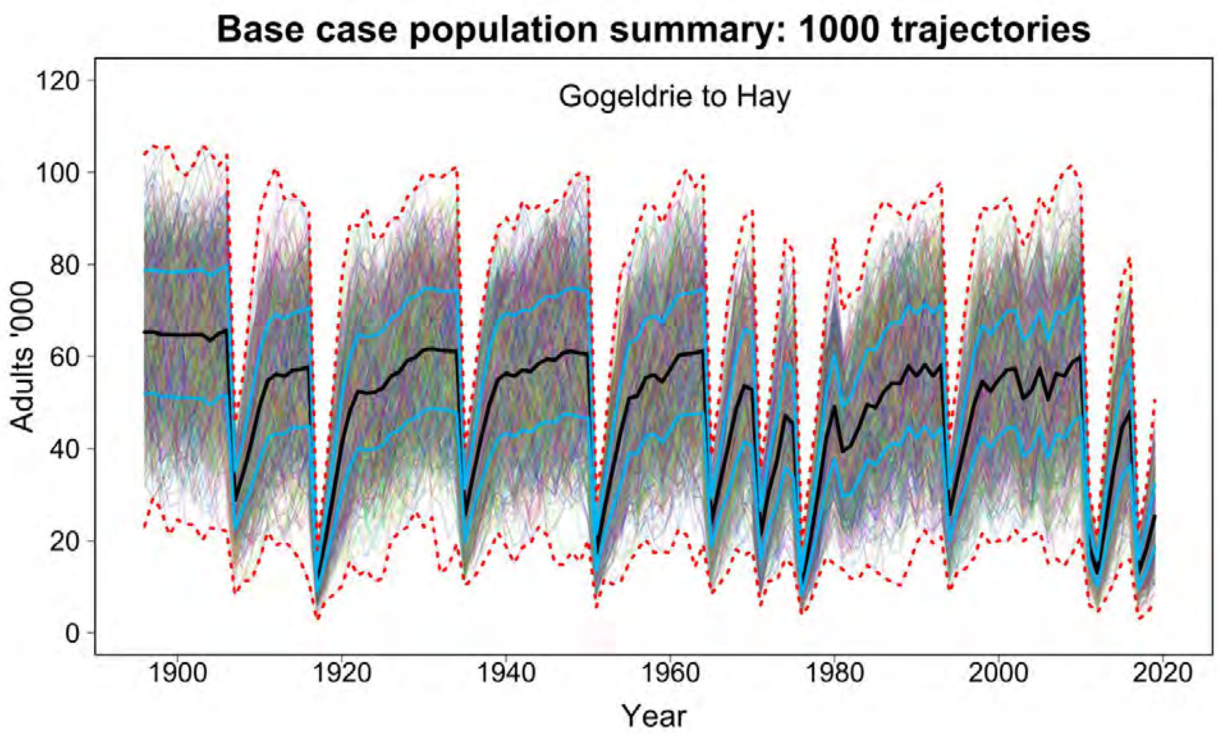
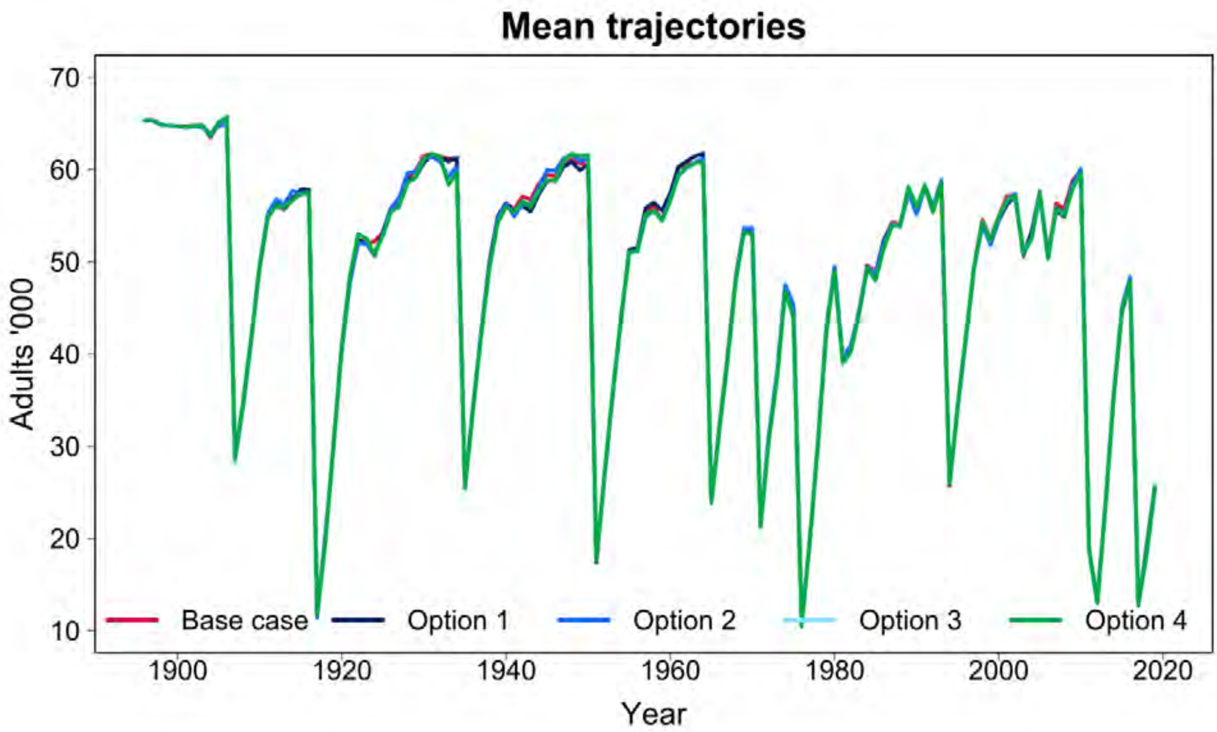
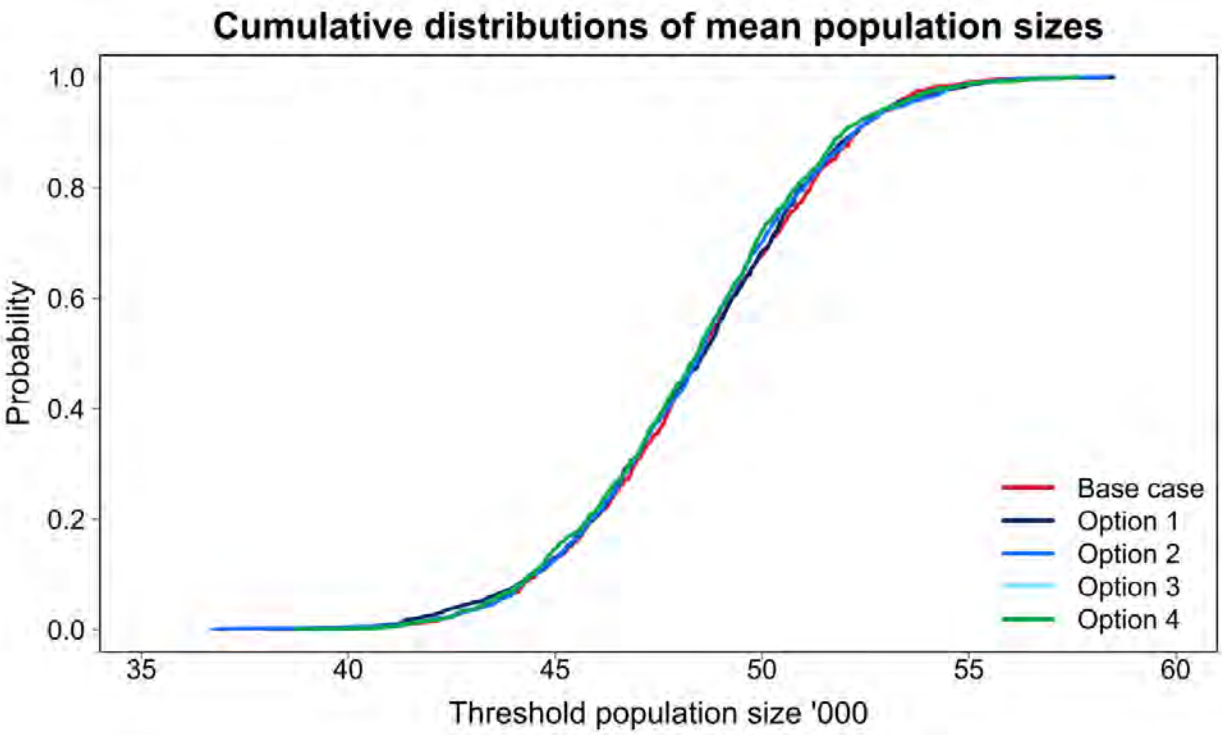


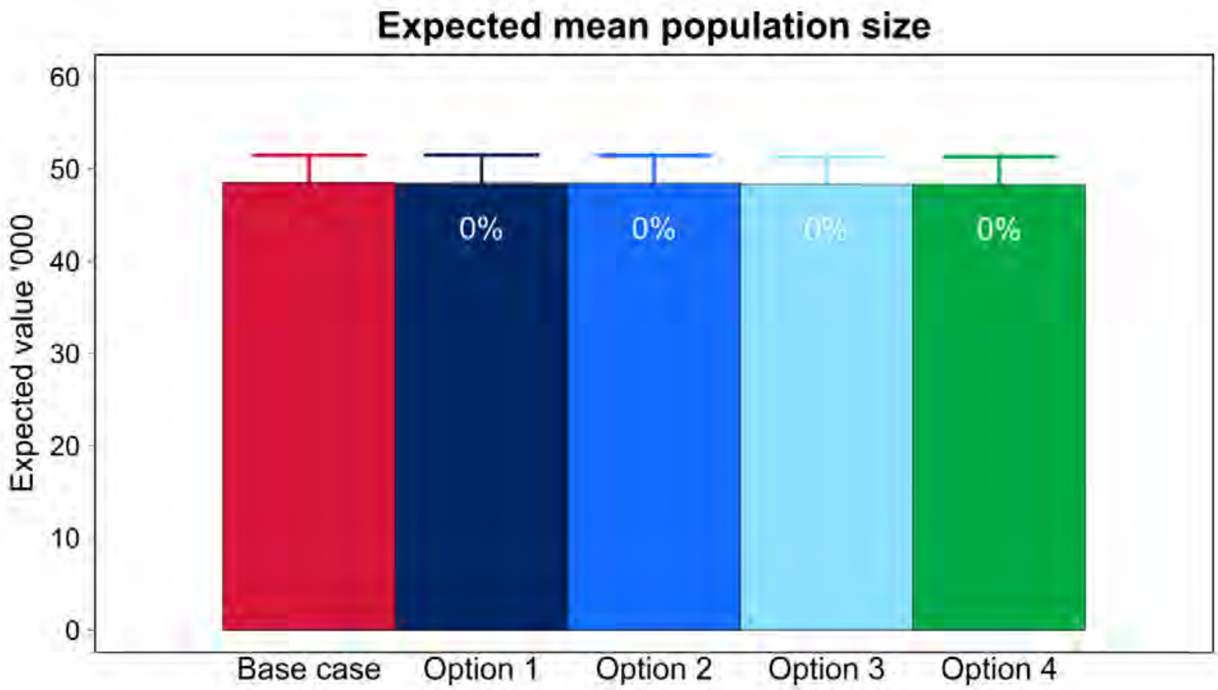
Figure A3.32. Murray Cod adults in the Hay to Balranald reach for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

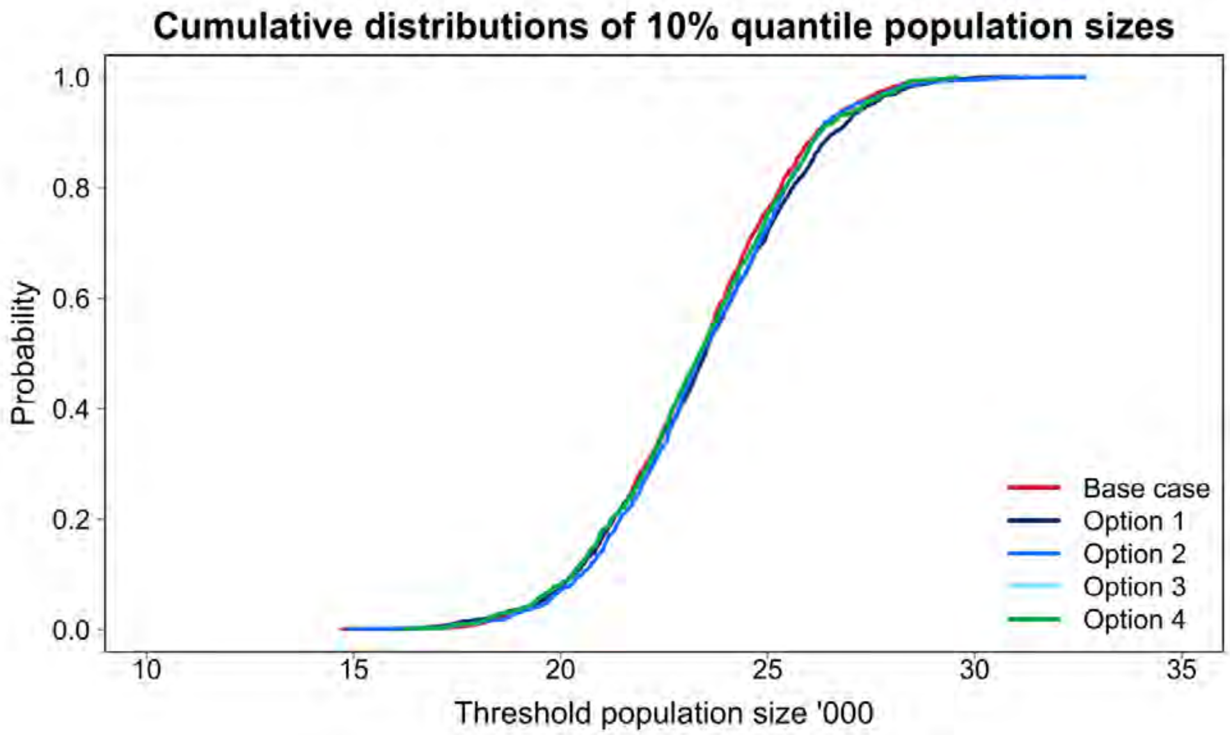
Murray Cod – Gogeldrie to Hay

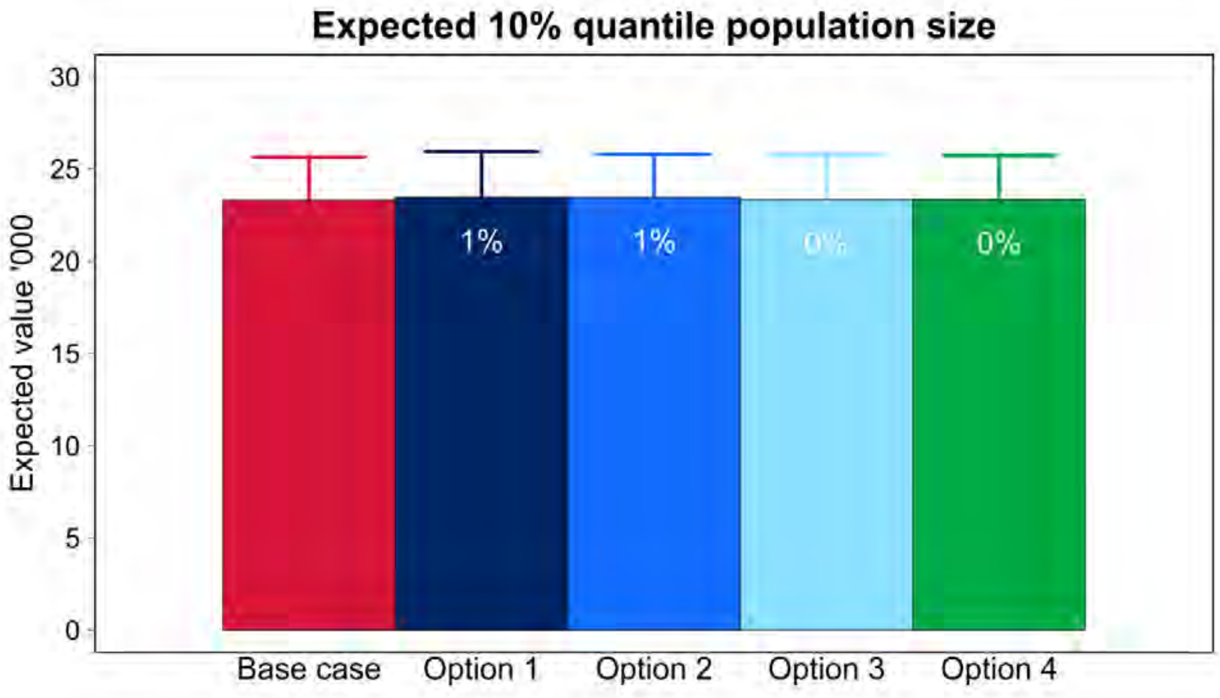


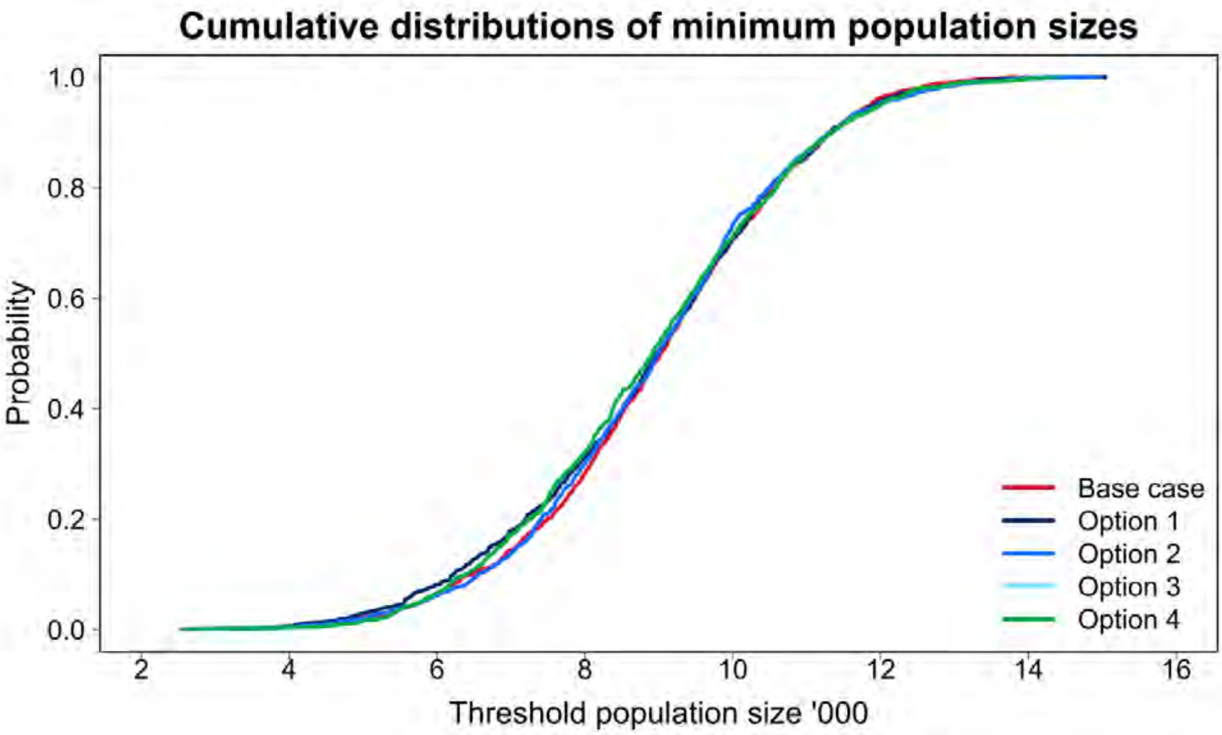


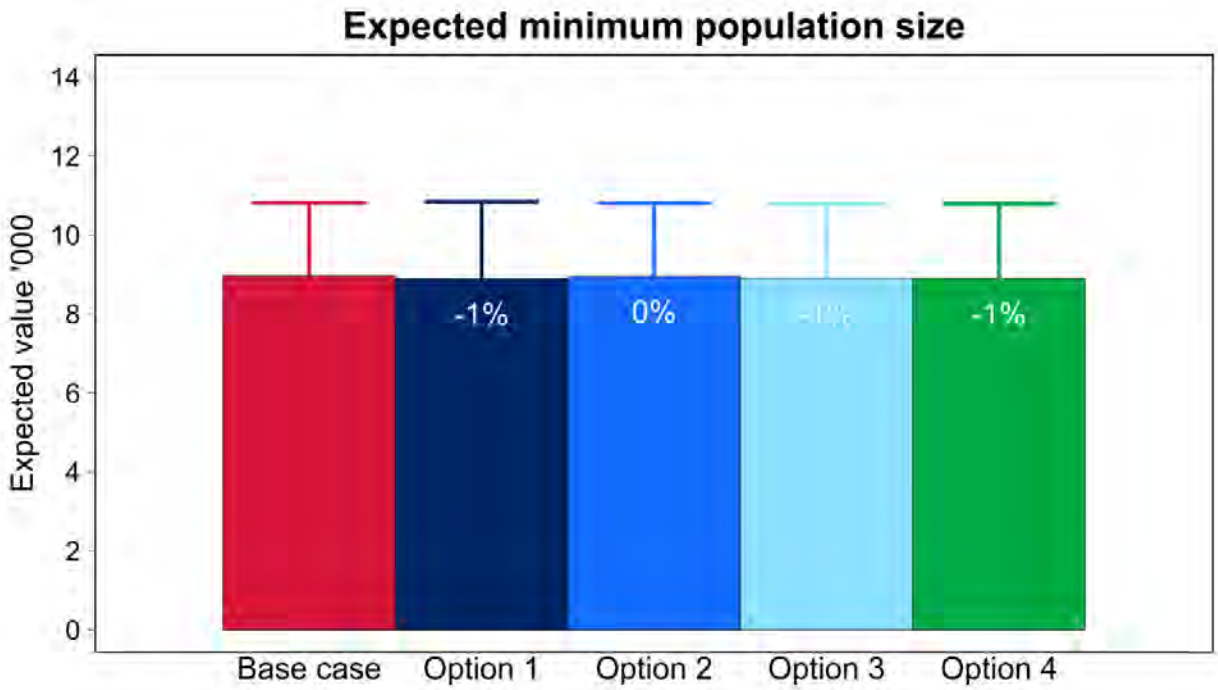

Cumulative distributions of mean population sizes
Probability
0.0
0.2
0.4
0.6
0.8
1.0
35
40
45
50
55
60
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4

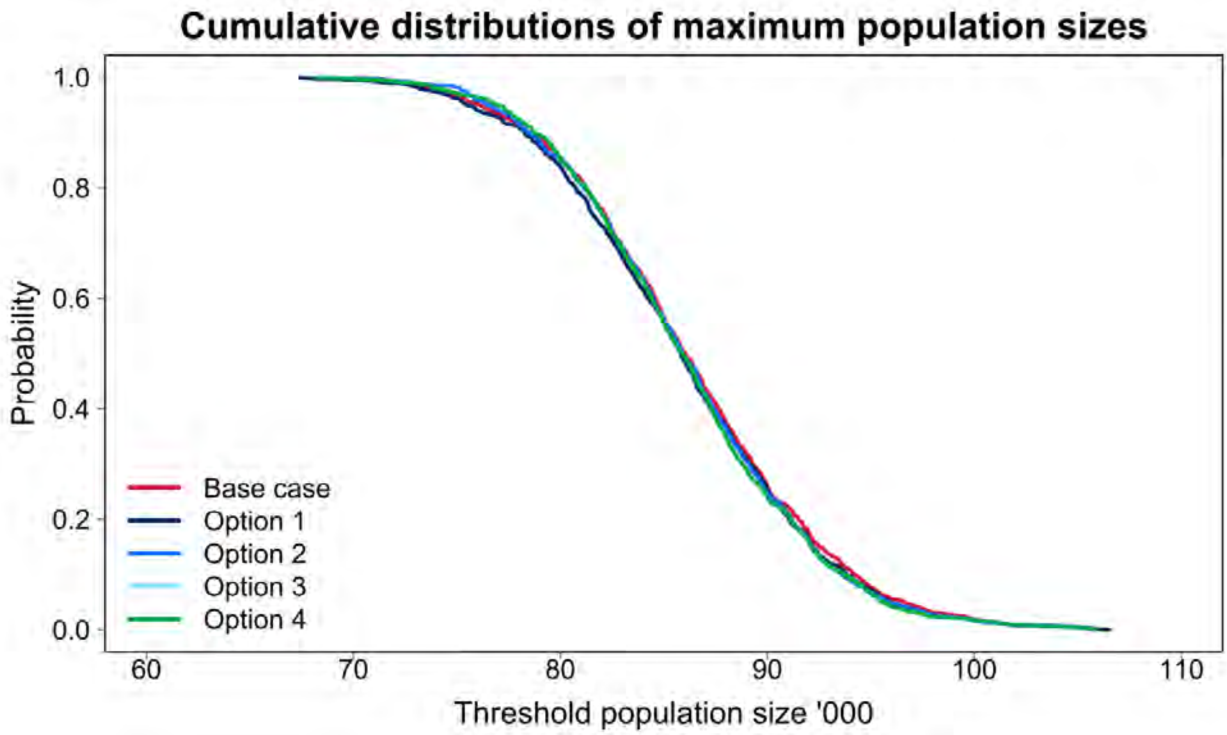

Expected mean population size
Expected value '000
0
10
20
30
40
50
60
0%
0%
0%
0%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of 10% quantile population sizes
Probability
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4
1.0
0.8
0.6
0.4
0.2
0.0
10
15
20
25
30
35


Expected 10% quantile population size
Expected value '000
30
25
20
15
10
5
0
1%
1%
0%
0%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
2
4
6
8
10
12
14
16
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected minimum population size
Expected value '000
14
12
10
8
6
4
2
0
-1%
0%
-1%
Base case
Option 1
Option 2
Option 3
Option 4



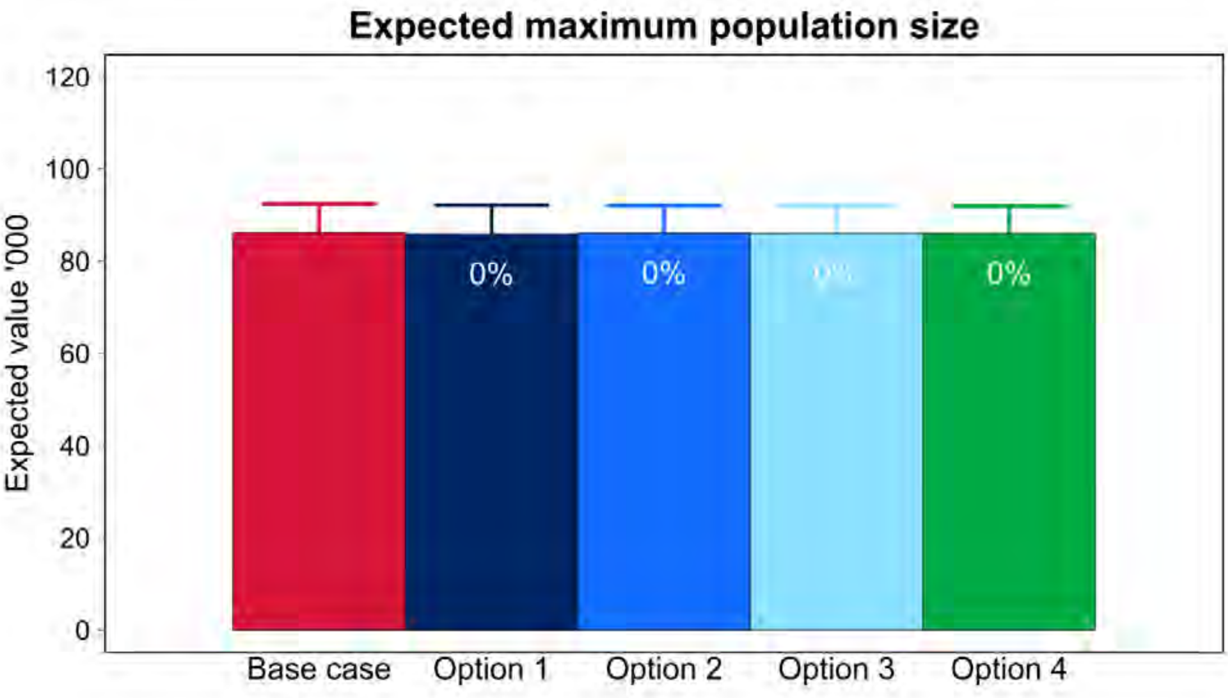
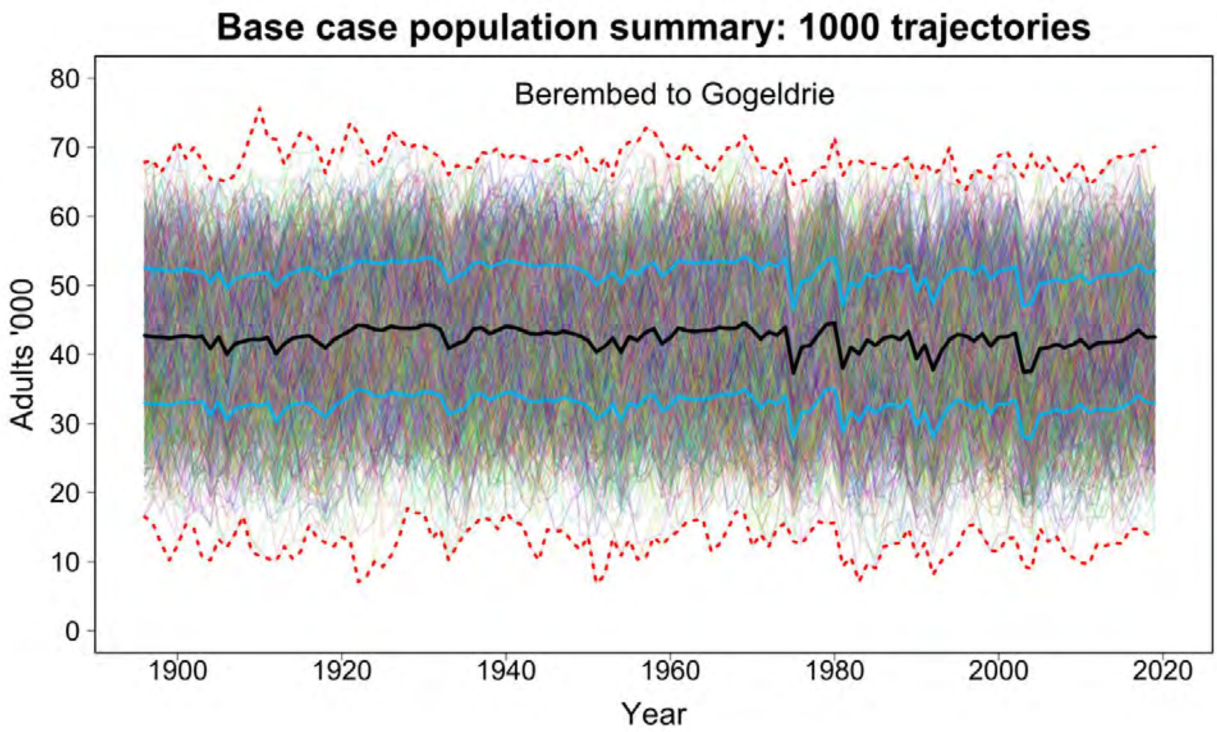
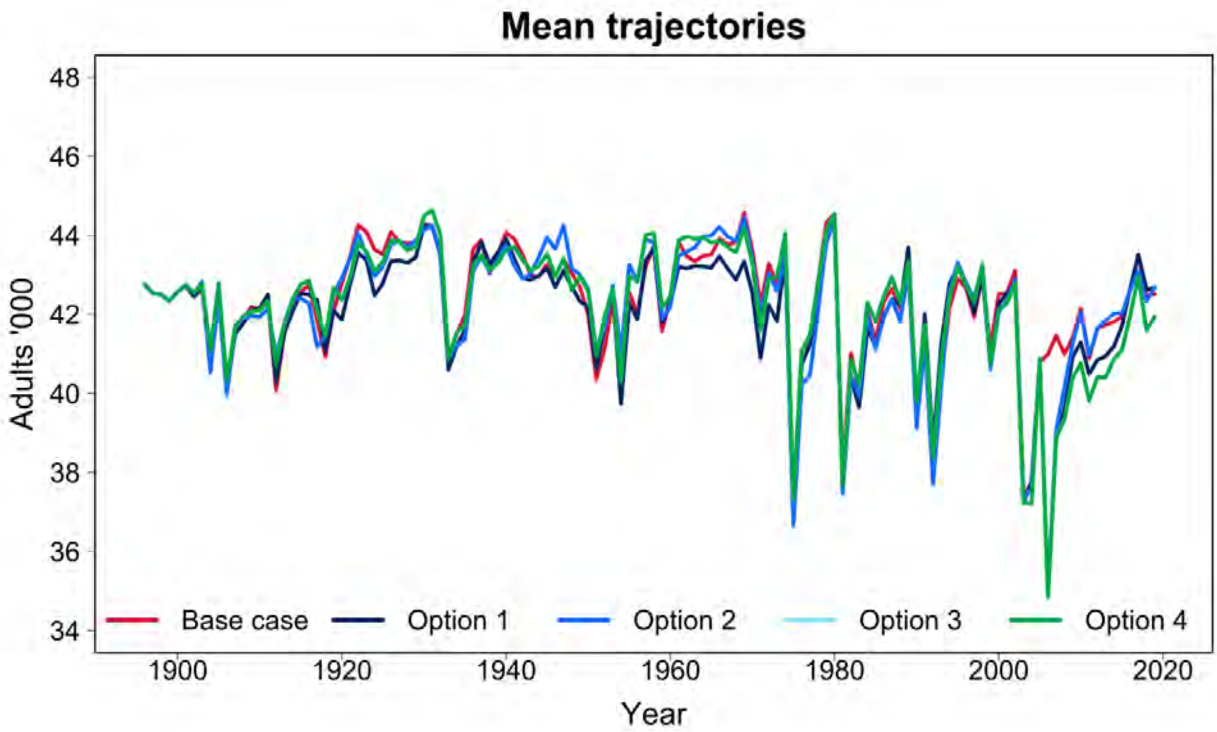
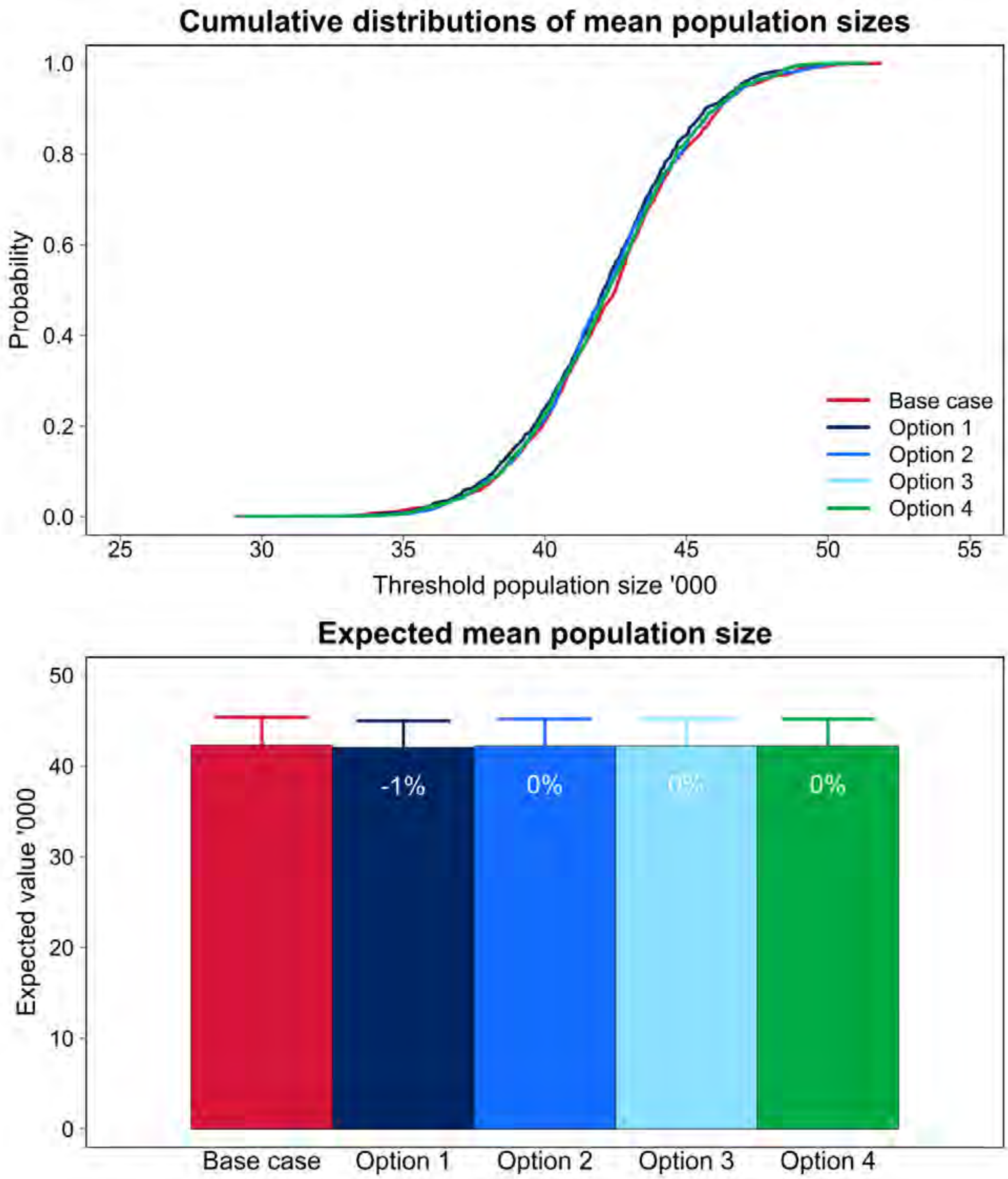


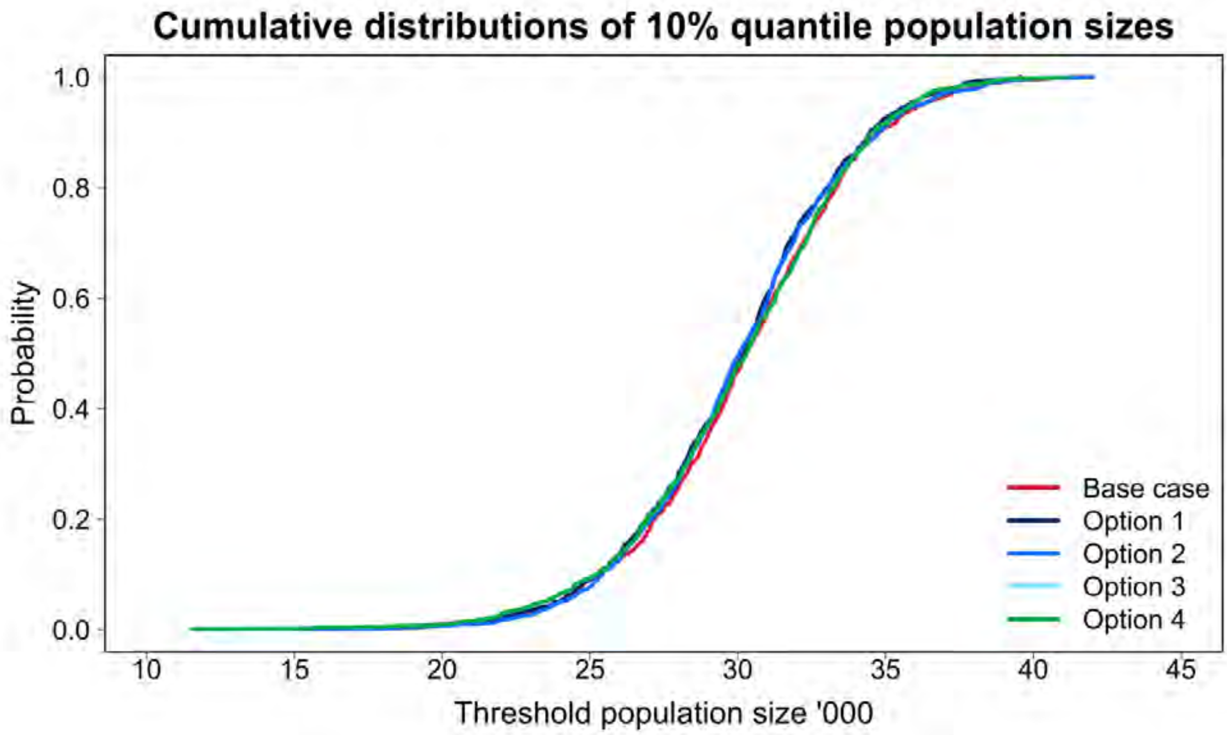
Figure A3.33. Murray Cod adults in the Gogeldrie to Hay reach for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

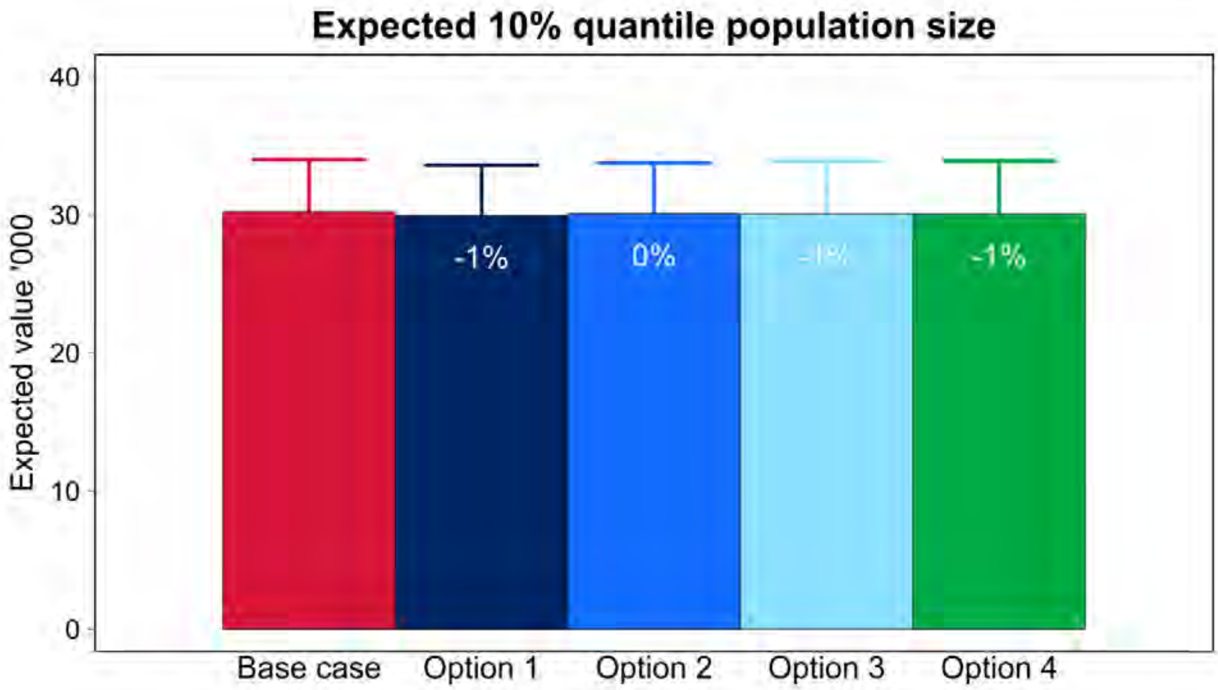
Murray Cod – Berembed to Gogeldrie

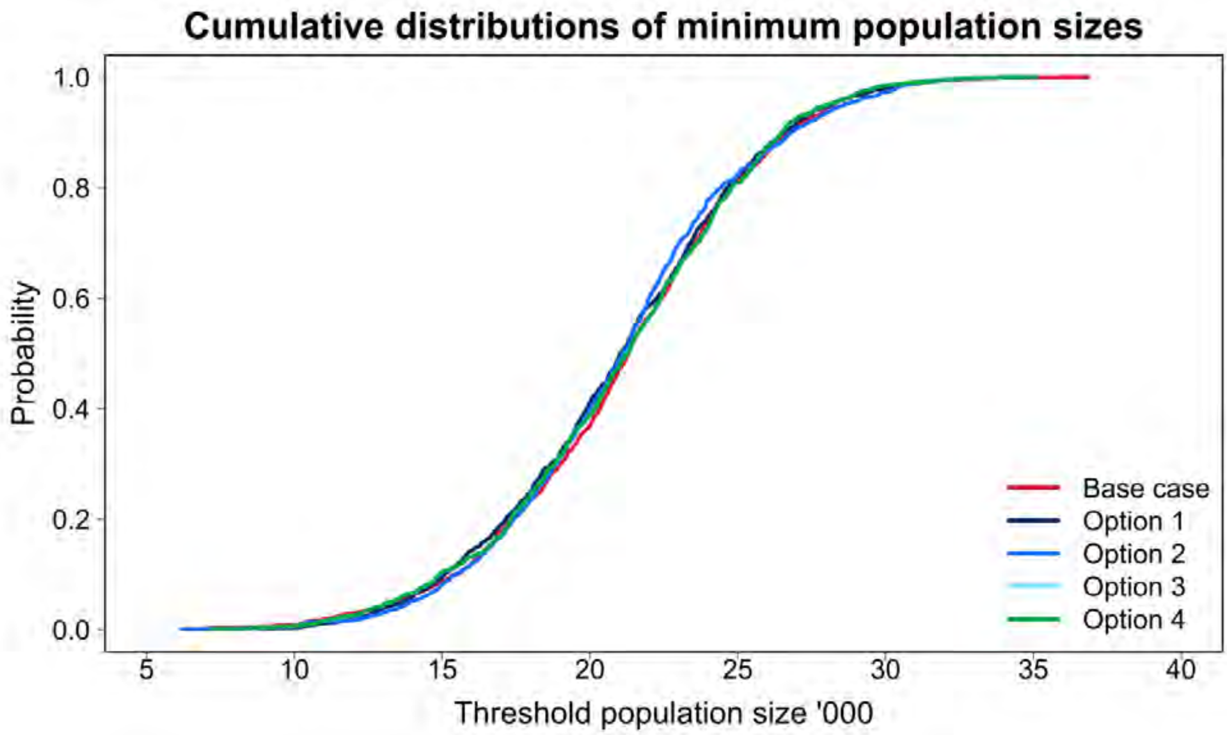


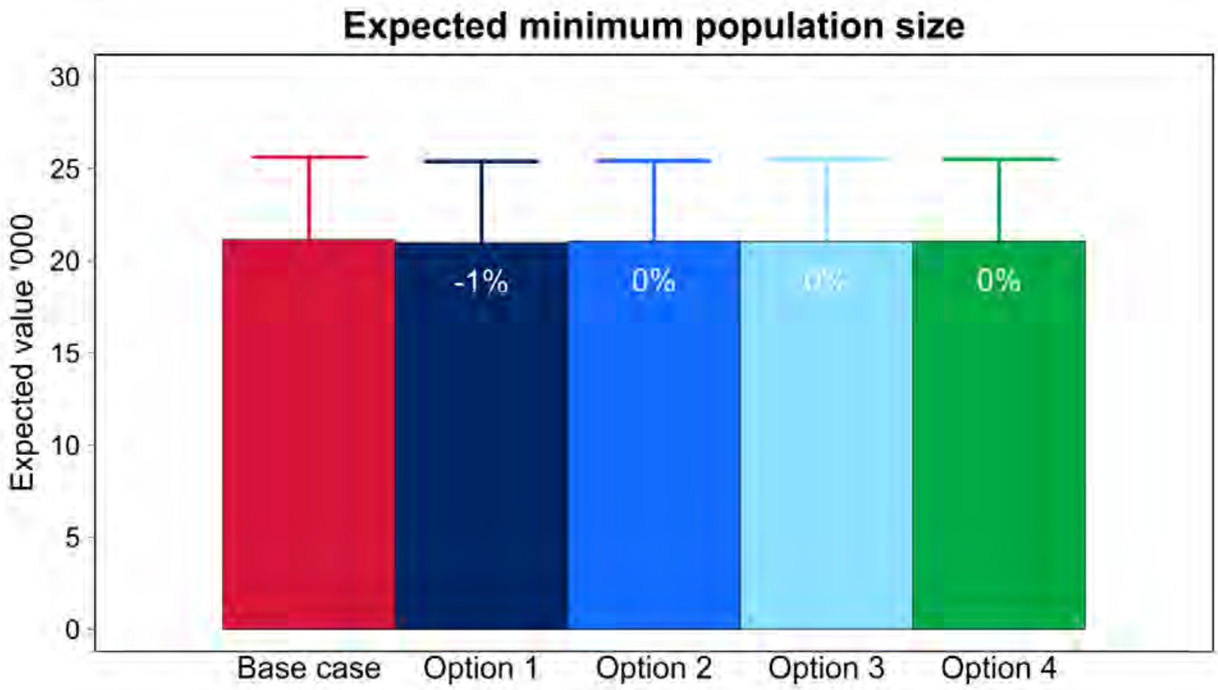



Cumulative distributions of mean population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
25
30
35
40
45
50
55
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4
Expected mean population size
Expected value '000
50
40
30
20
10
0
-1%
0%
0%
0%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of 10% quantile population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
10
15
20
25
30
35
40
45
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected 10% quantile population size
Expected value '000
40
30
20
10
0
-1%
0%
-1%
-1%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
Threshold population size '000
1.0
0.8
0.6
0.4
0.2
0.0
5
10
15
20
25
30
35
40
Base case
Option 1
Option 2
Option 3
Option 4


Expected minimum population size
Expected value '000
30
25
20
15
10
5
0
-1%
0%
0%
0%
Base case
Option 1
Option 2
Option 3
Option 4

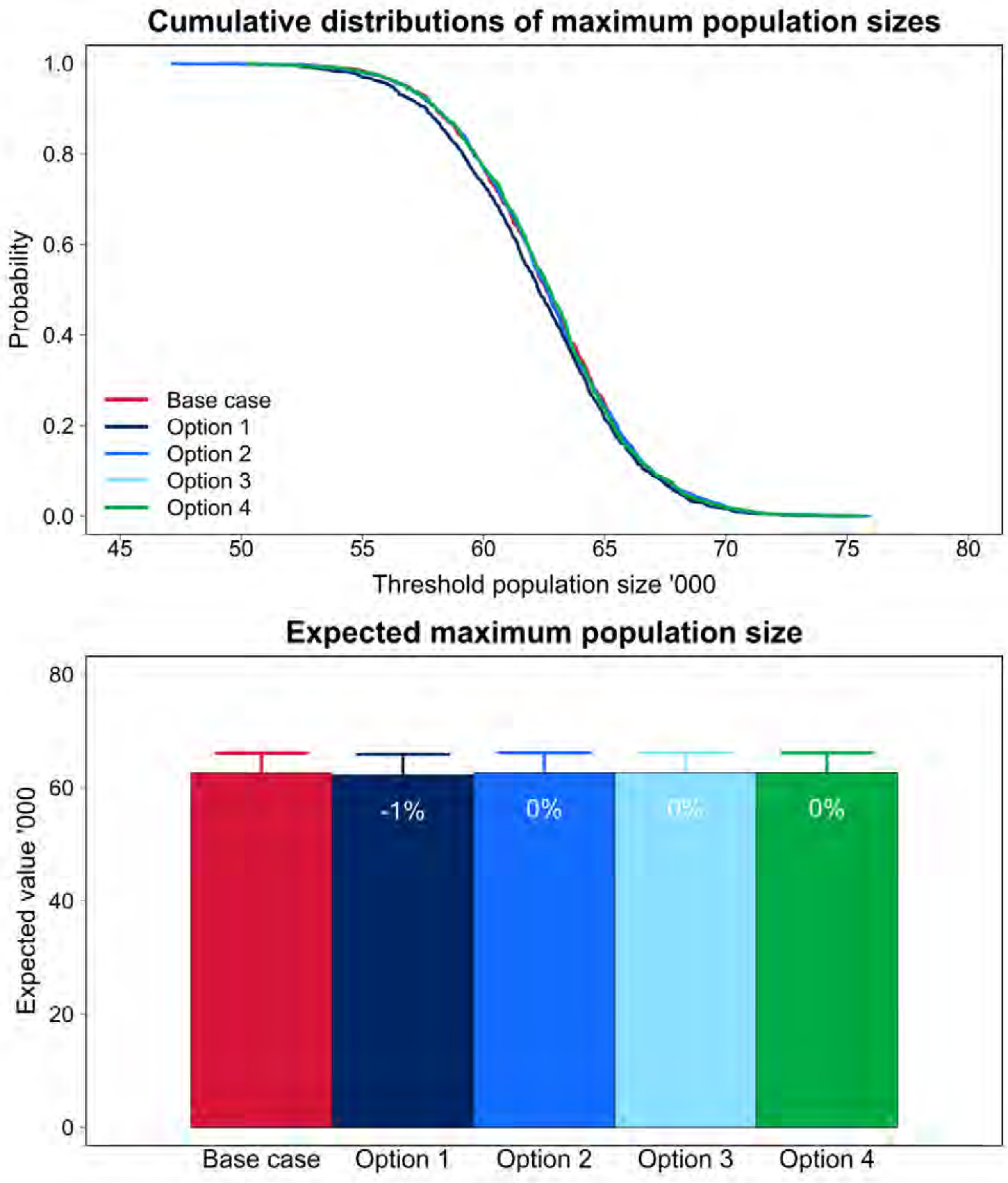
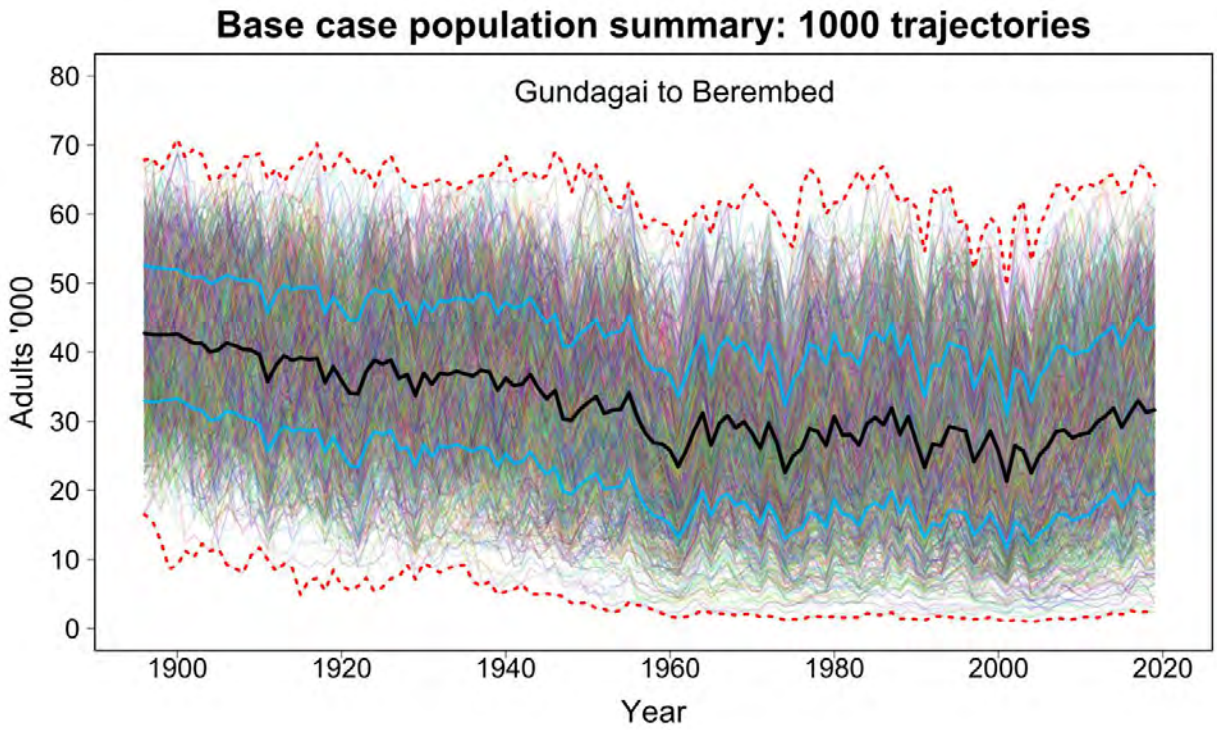
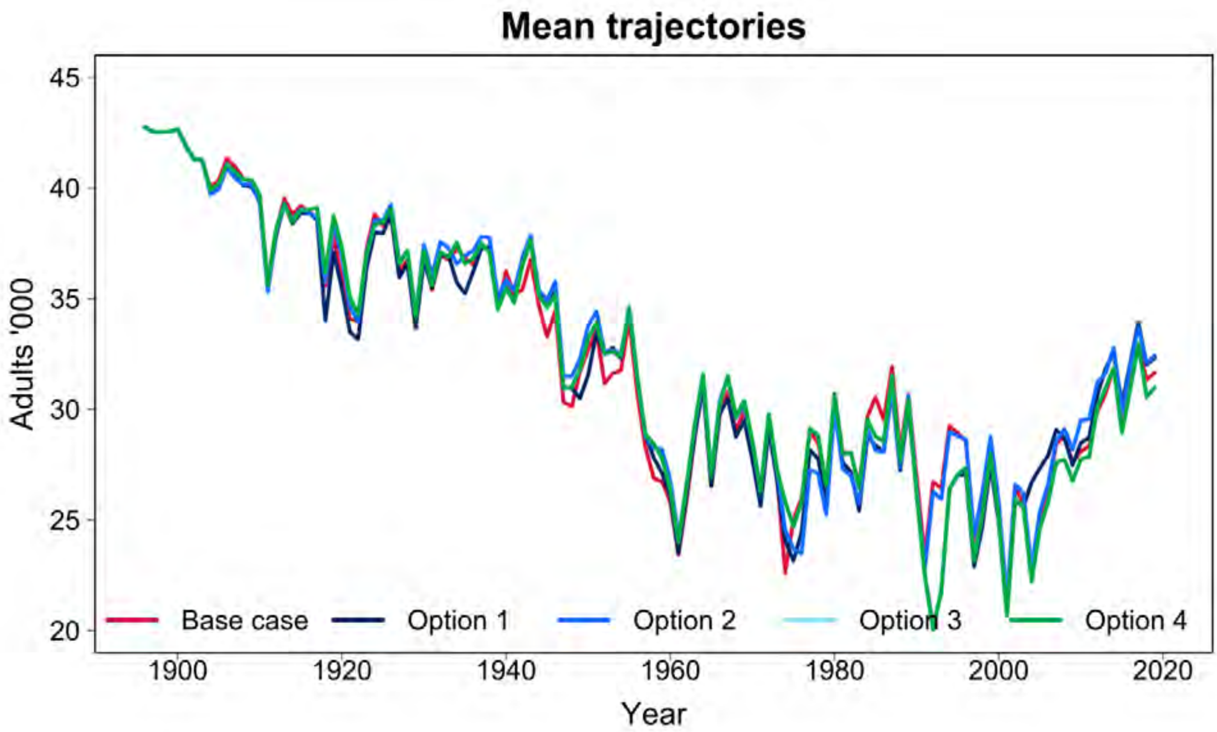
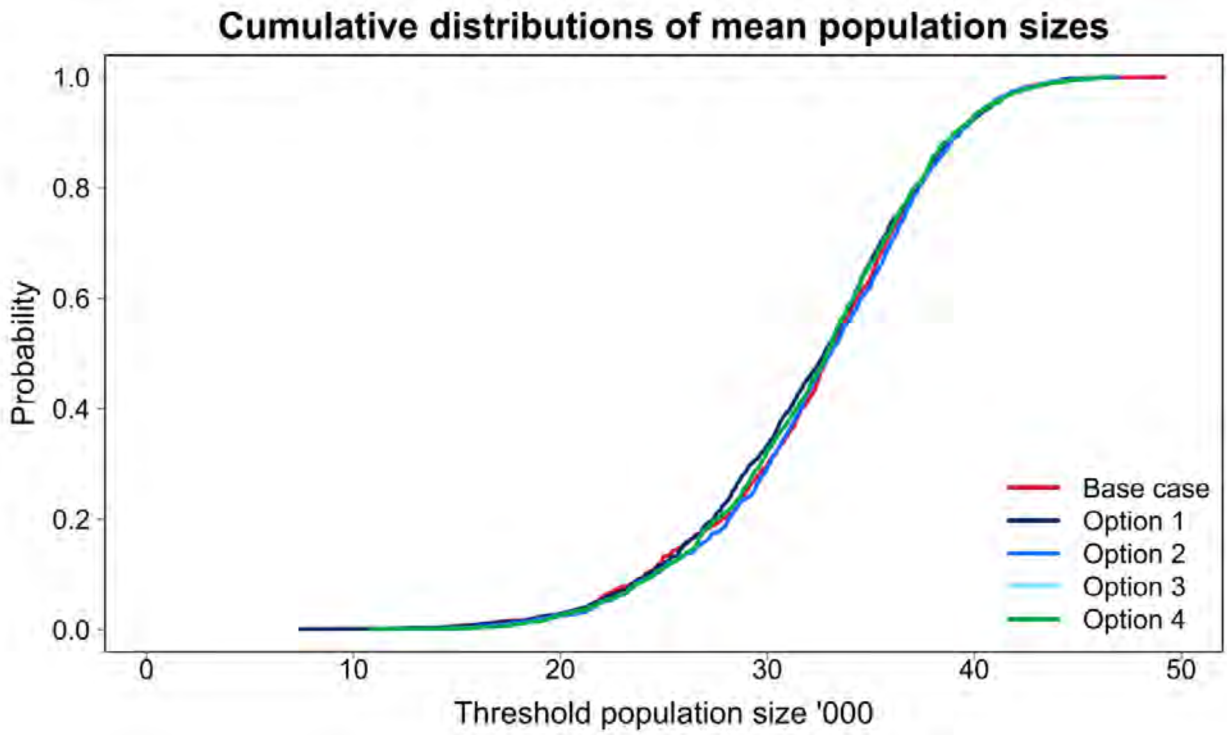


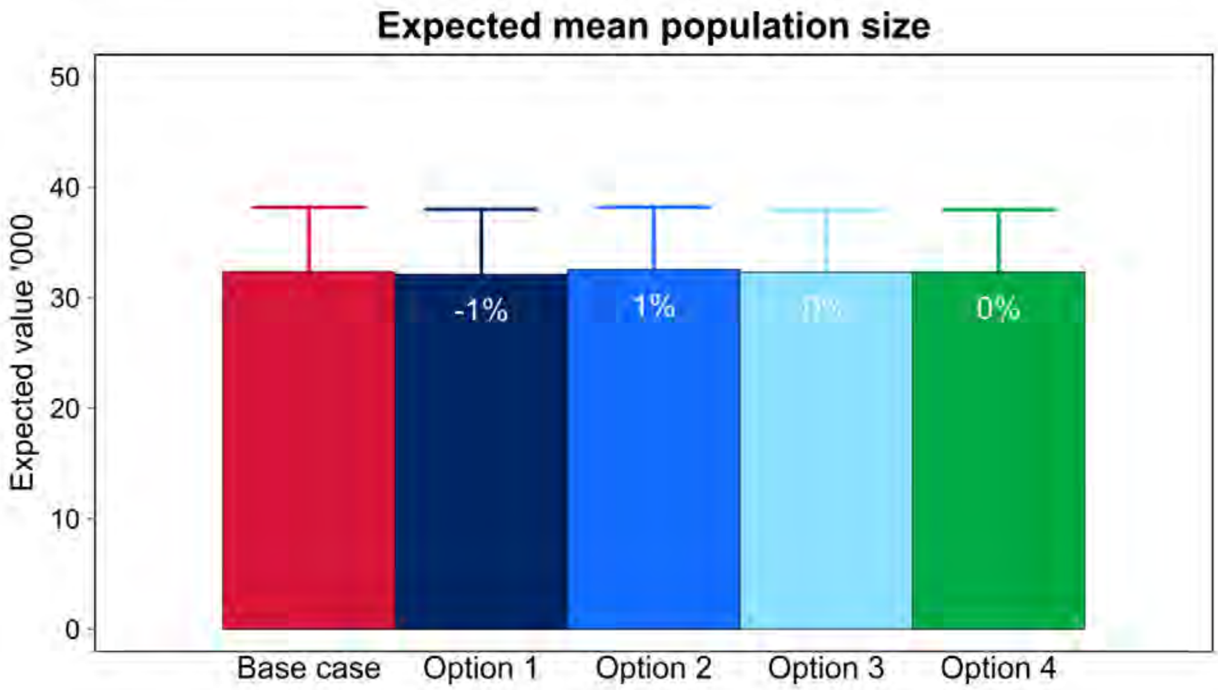
Figure A3.34. Murray Cod adults in the Berembed to Gogeldrie reach for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

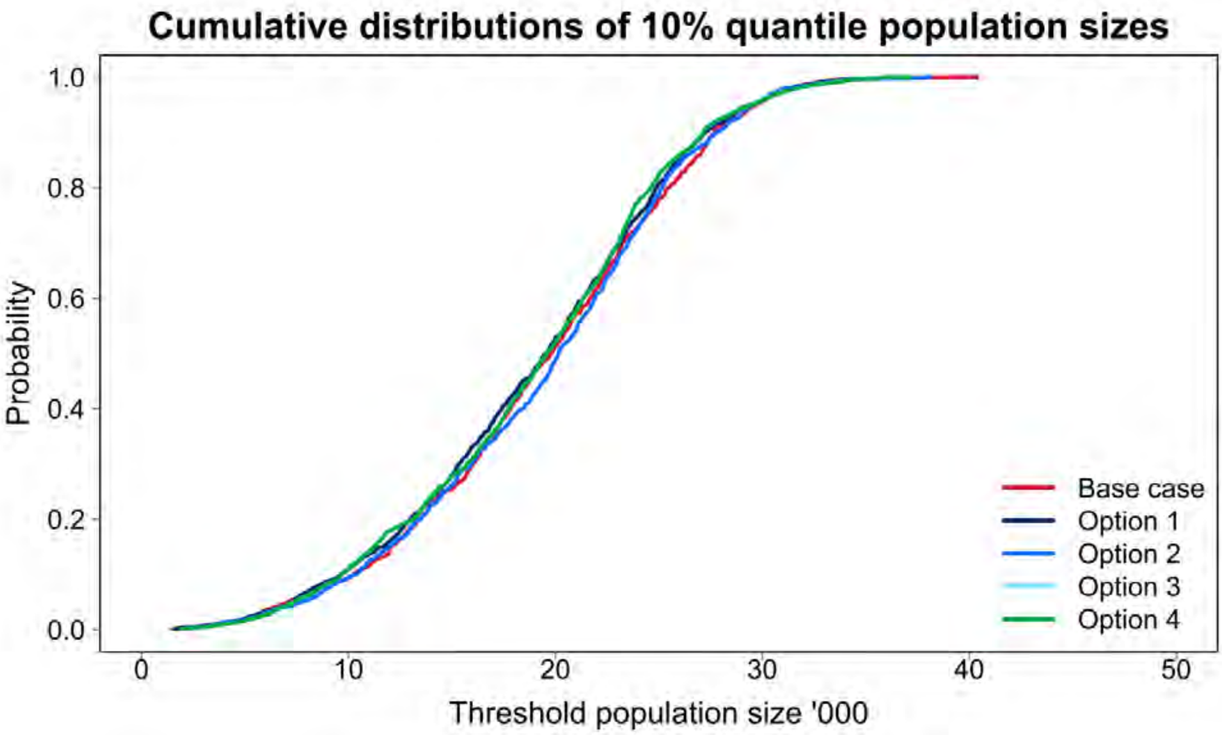
Murray Cod – Gundagai to Berembed

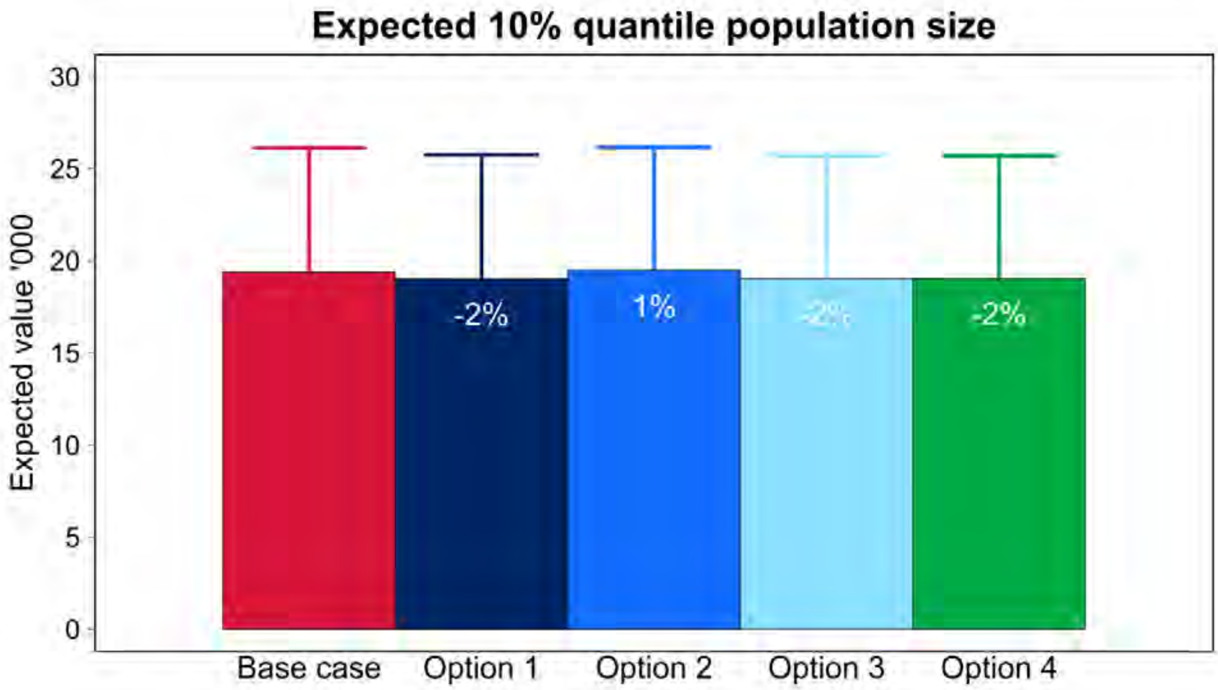


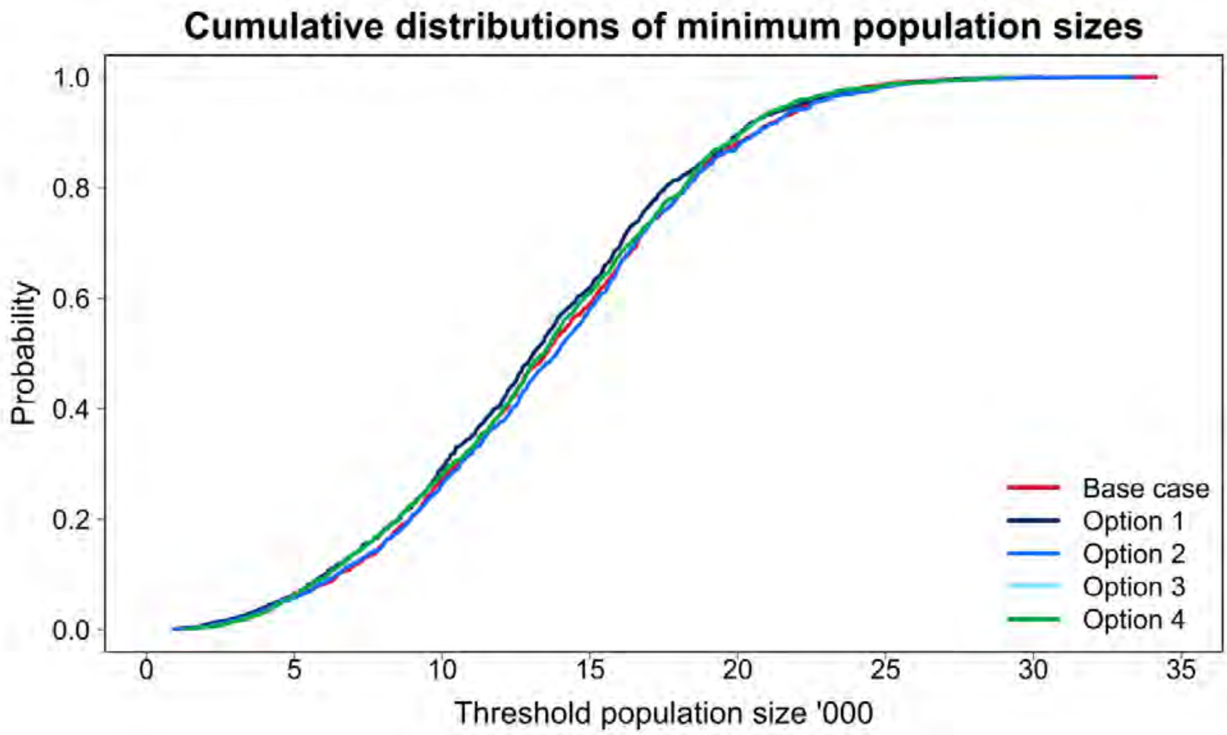



Cumulative distributions of mean population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4

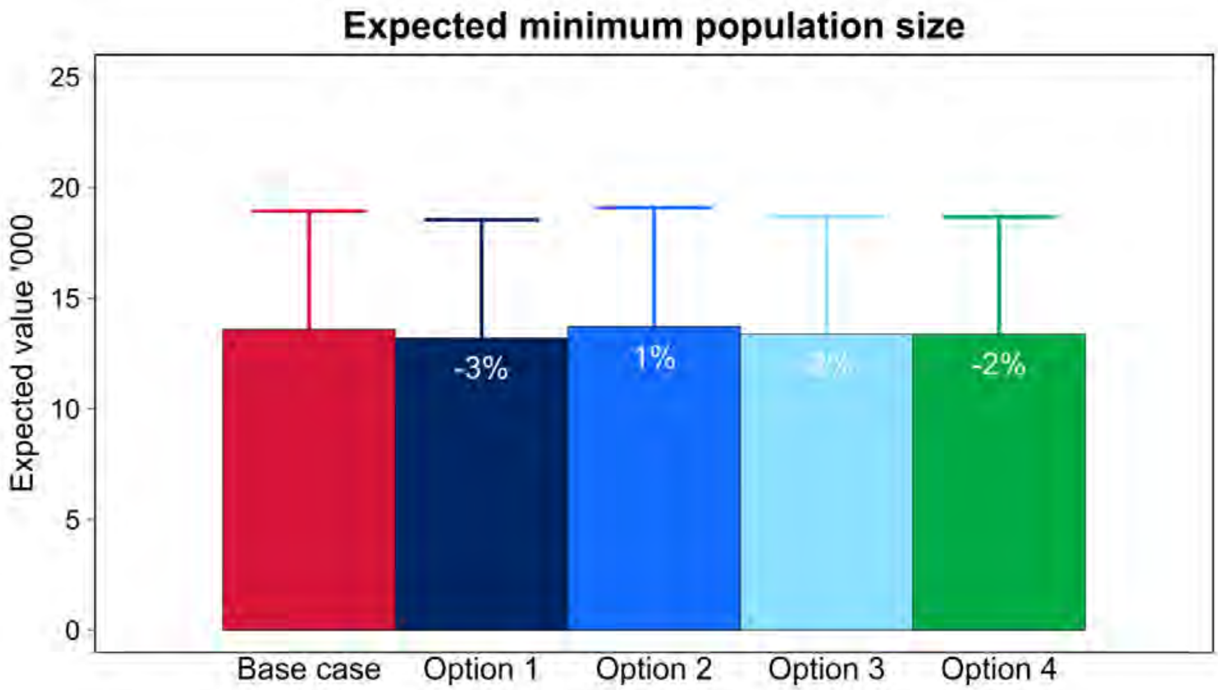

Expected mean population size
Expected value '000
50
40
30
20
10
0
-1%
1%
0%
0%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of 10% quantile population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected 10% quantile population size
Expected value '000
30
25
20
15
10
5
0
-2%
1%
-2%
-2%
Base case
Option 1
Option 2
Option 3
Option 4



Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
35
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4



Expected minimum population size
Expected value '000
25
20
15
10
5
0
-3%
1%
-2%
Base case
Option 1
Option 2
Option 3
Option 4

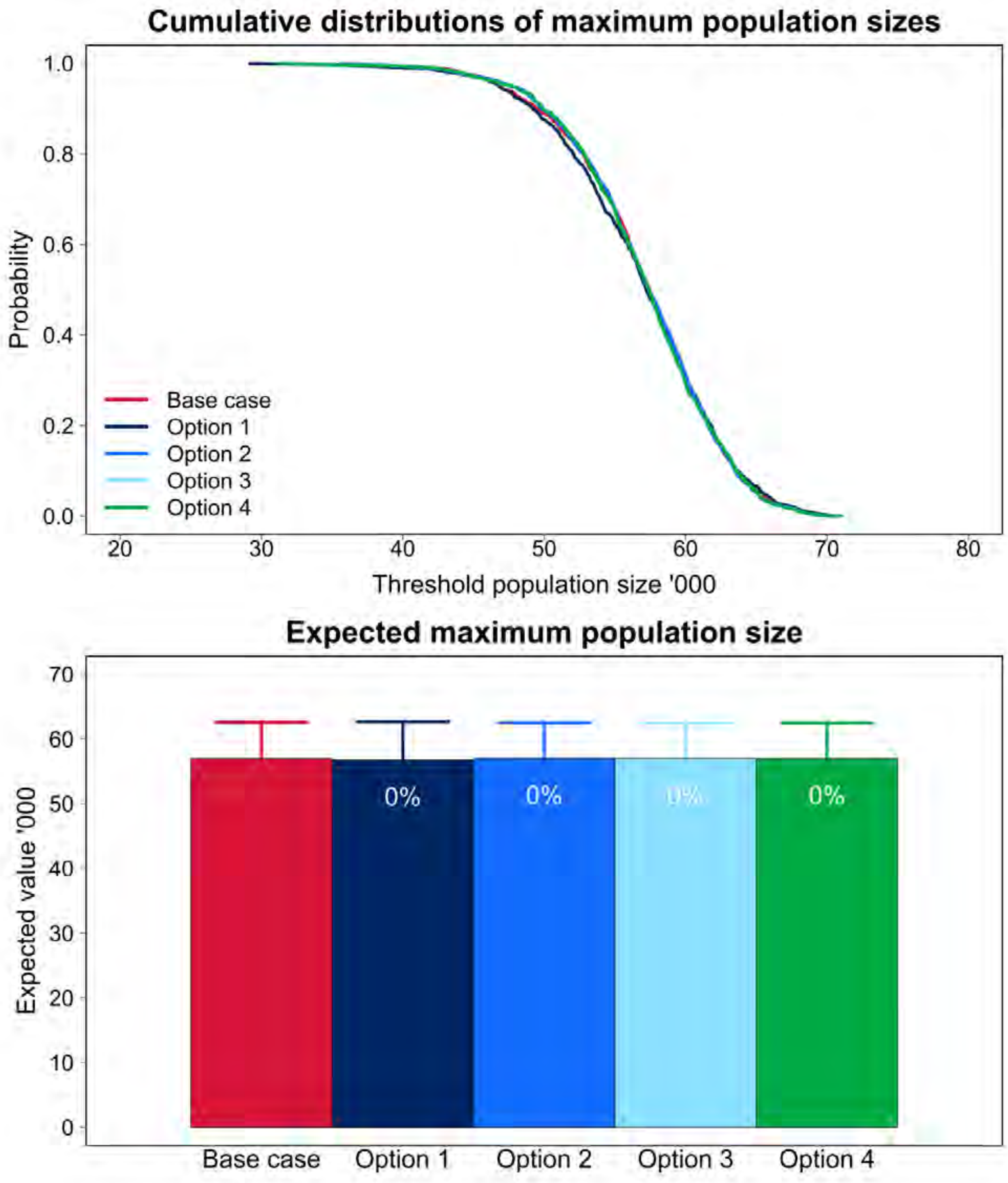
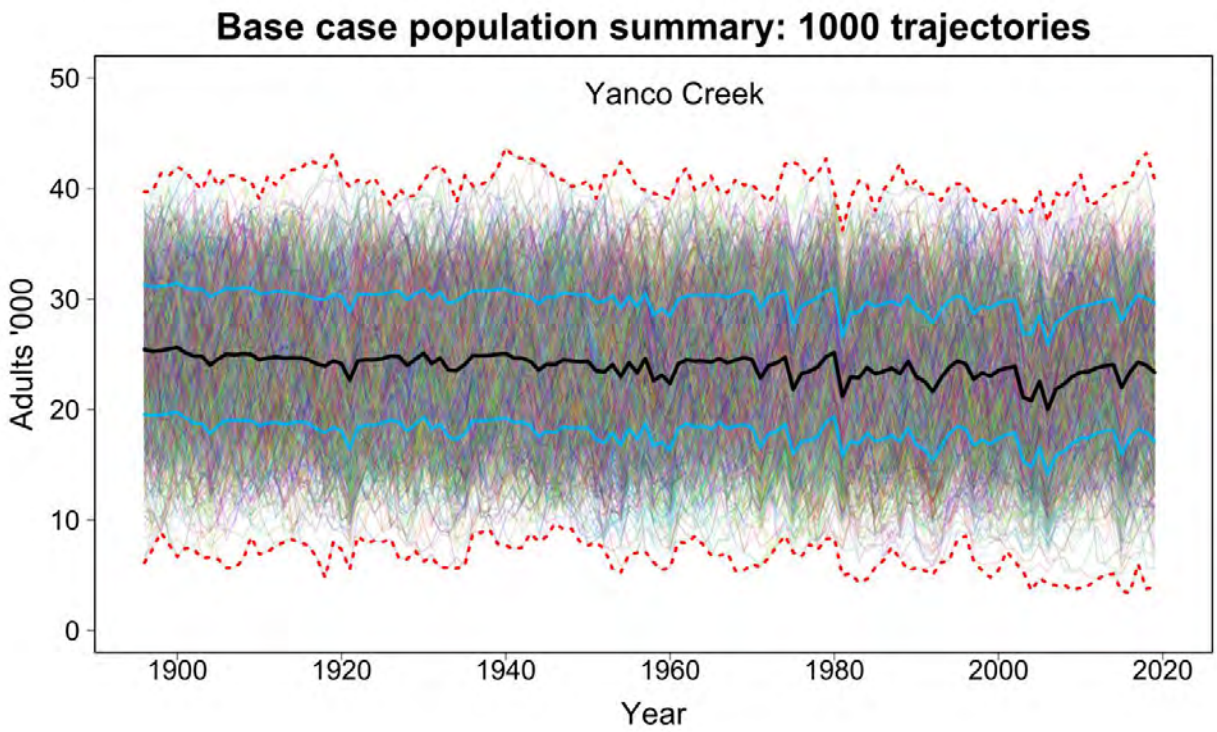
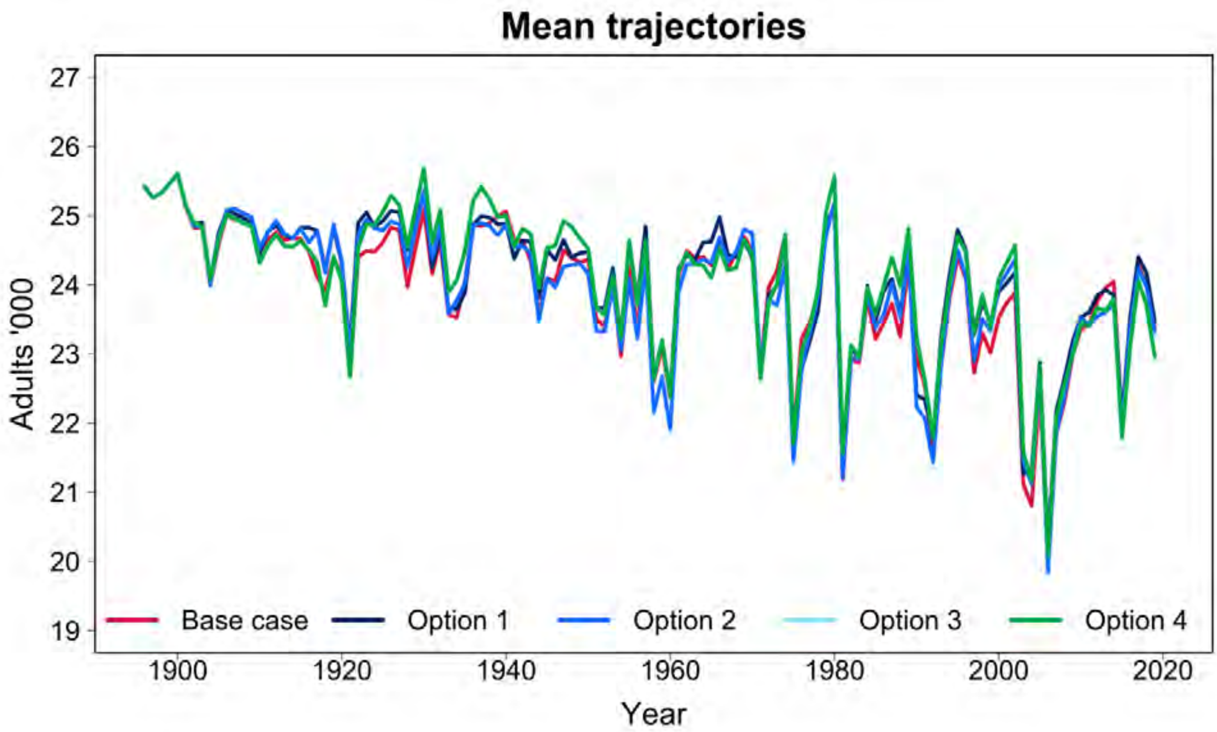
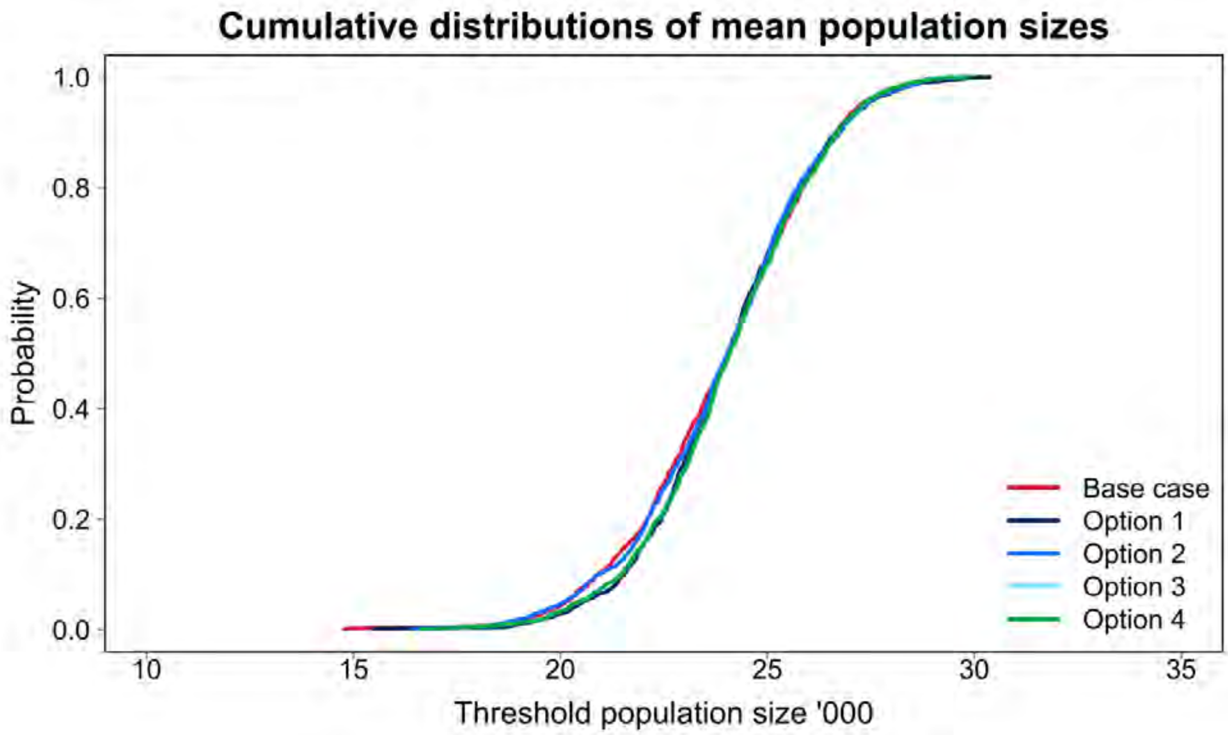


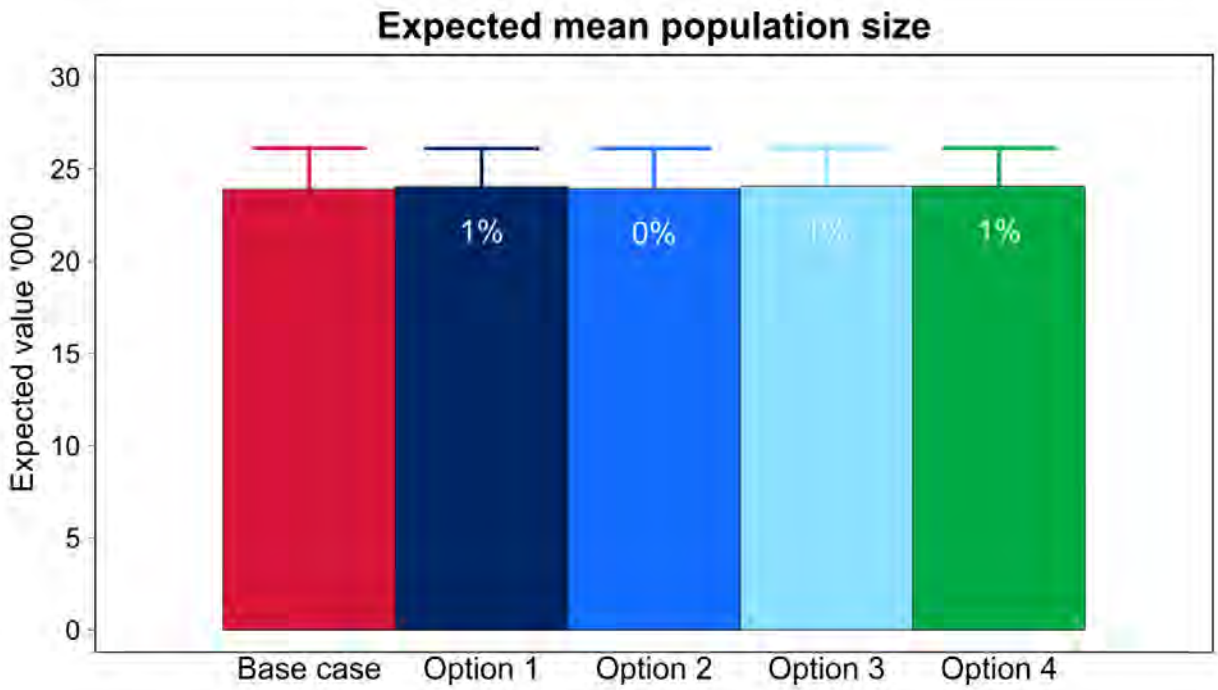
Figure A3.35. Murray Cod adults in the Gundagai to Berembed reach for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

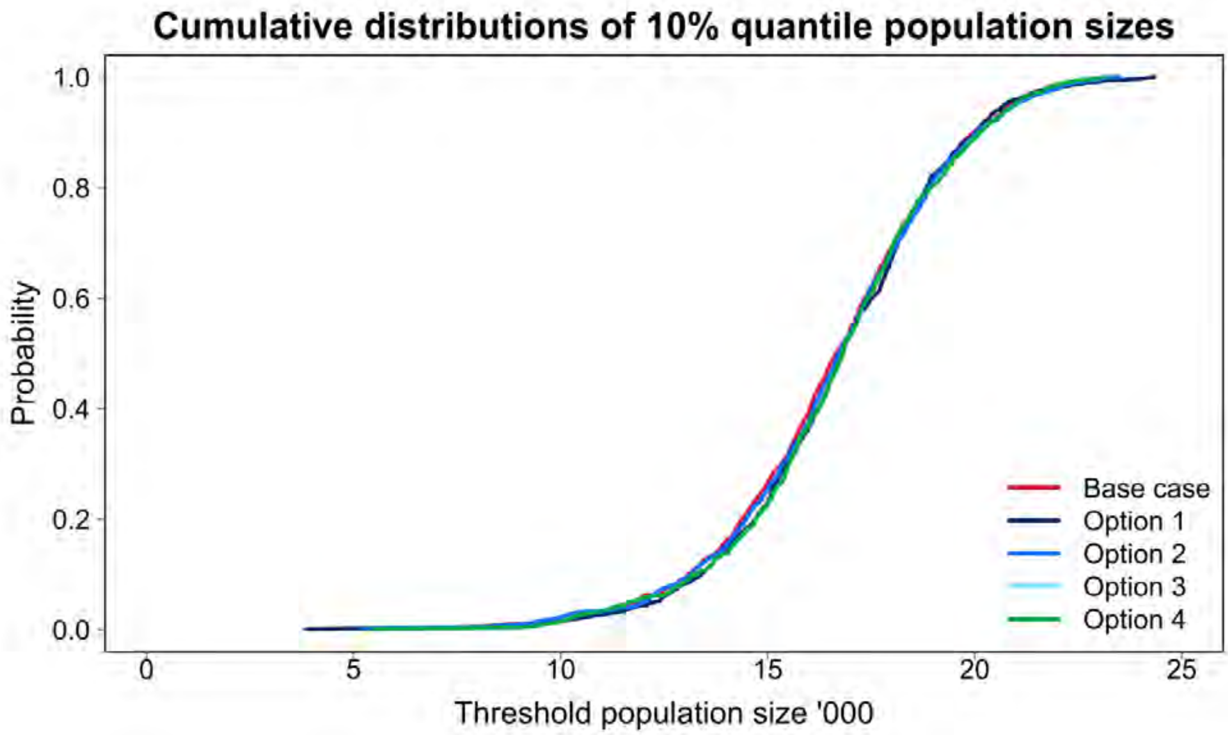
Murray Cod – Yanco Creek



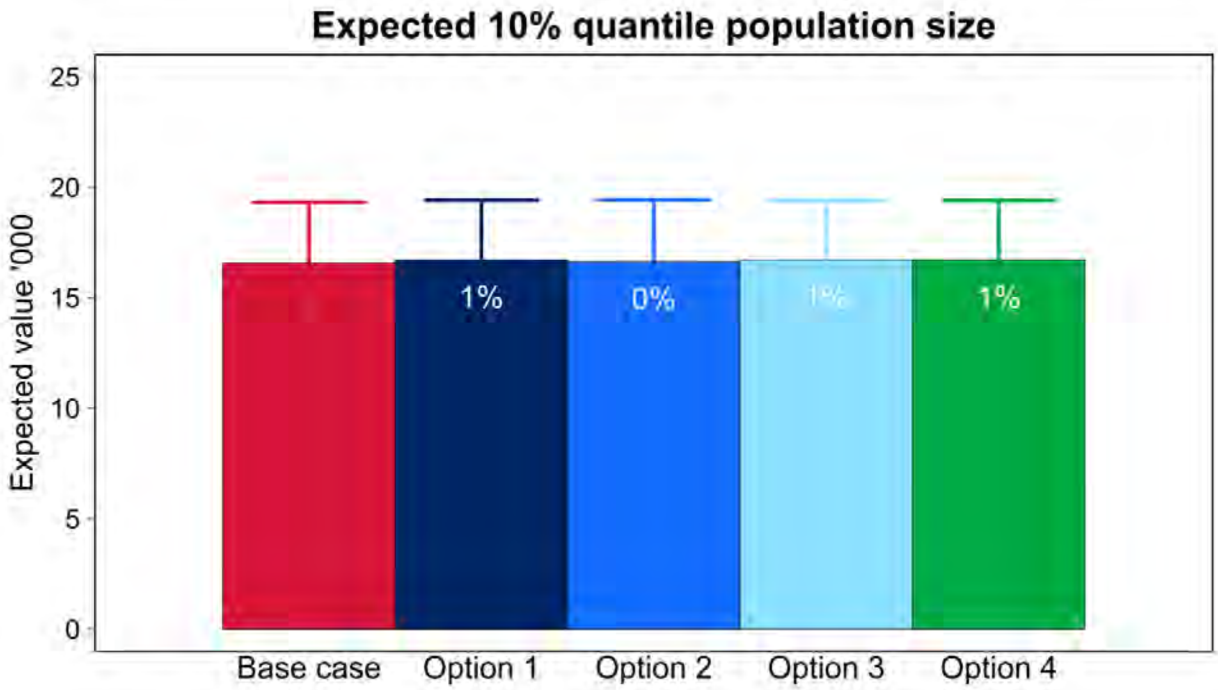



Cumulative distributions of mean population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
10
15
20
25
30
35
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4

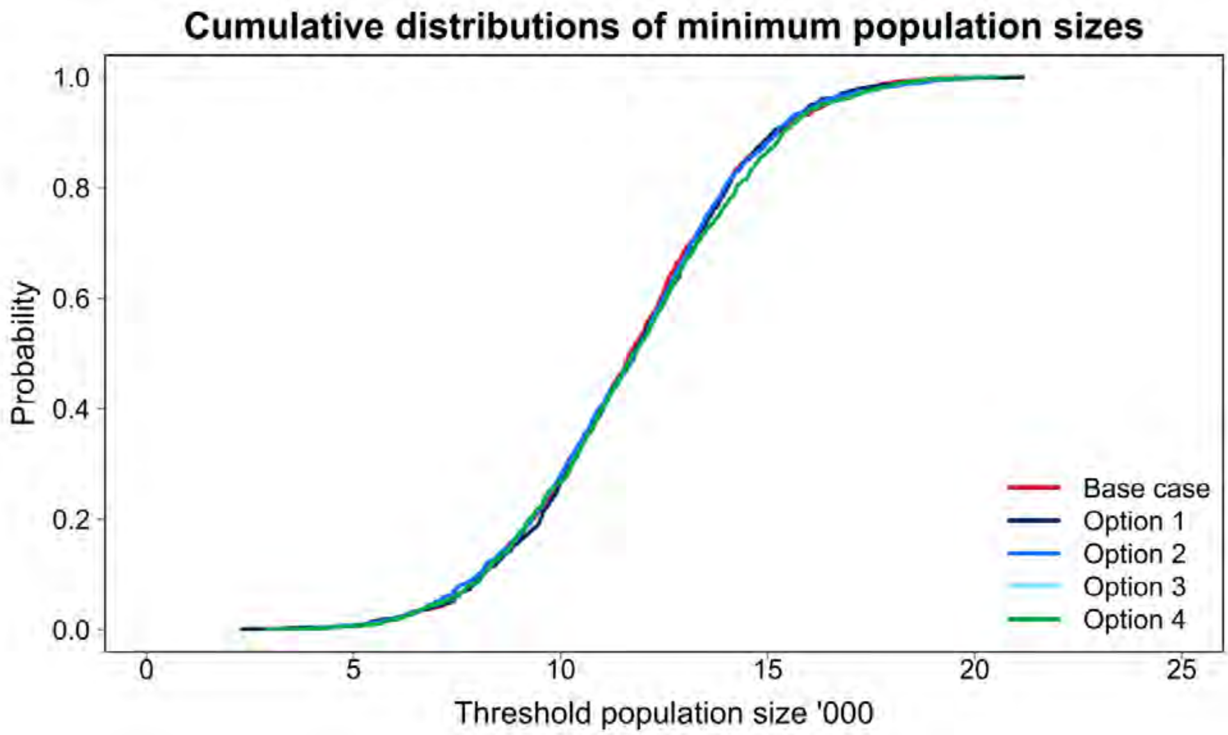

Expected mean population size
Expected value '000
30
25
20
15
10
5
0
1%
0%
1%
1%
Base case
Option 1
Option 2
Option 3
Option 4

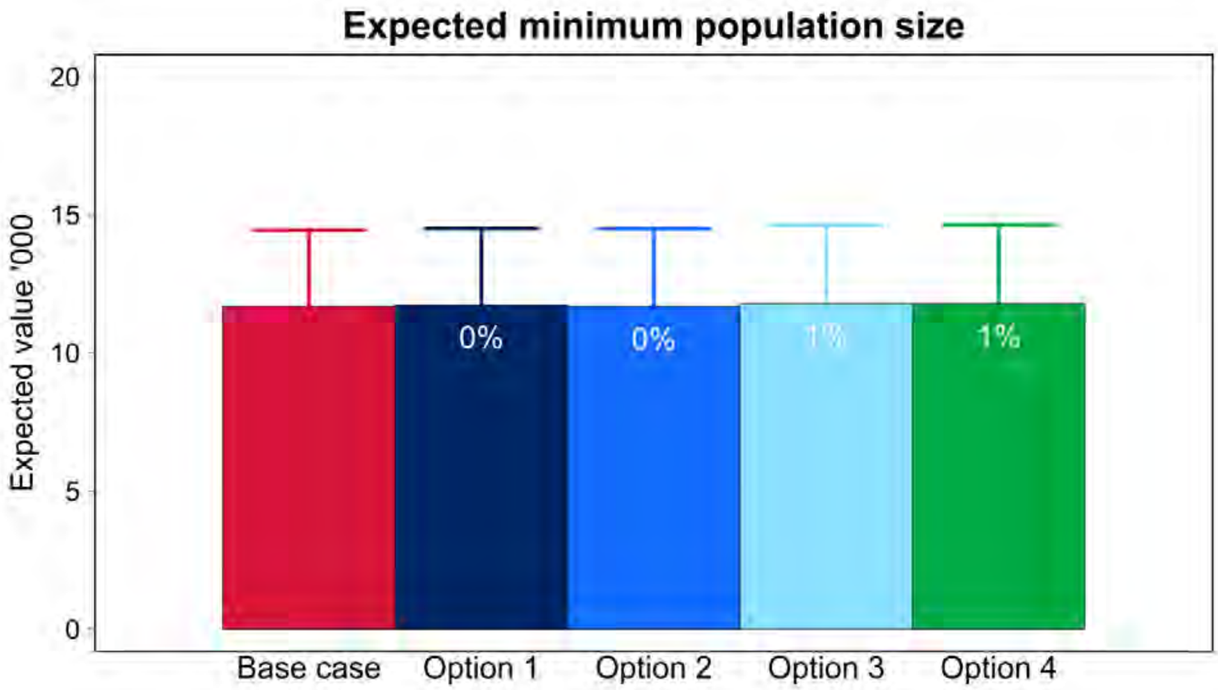


Cumulative distributions of 10% quantile population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4



Expected 10% quantile population size
Expected value '000
25
20
15
10
5
0
1%
0%
1%
1%
Base case
Option 1
Option 2
Option 3
Option 4


Cumulative distributions of minimum population sizes
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
Threshold population size '000
Base case
Option 1
Option 2
Option 3
Option 4


Expected minimum population size
Expected value '000
20
15
10
5
0
0%
0%
1%
1%
Base case
Option 1
Option 2
Option 3
Option 4

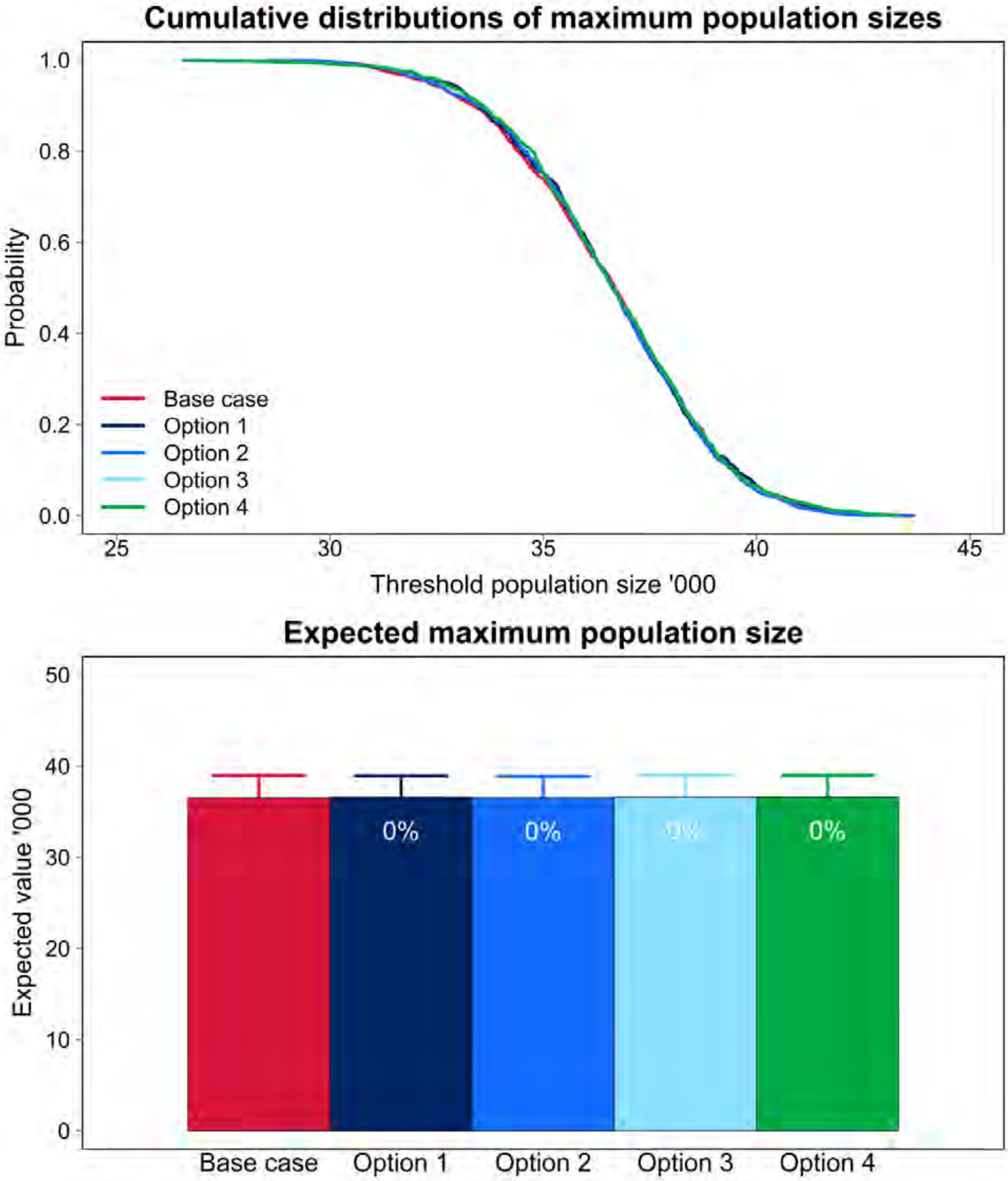


Figure A3.36. Murray Cod adults in Yanco Creek for the RRCP flow scenarios Base case – Option 4. Top panel: summary of 1000 adult trajectories for the Base case scenario; second panel: the mean adult population size; third panel: associated distributions of mean population sizes; fourth panel: expected mean population sizes, with the percentage change from Base case shown in each Option bar; fifth panel: associated distributions of 10% quantile population sizes; sixth panel: expected 10% quantile population size; seventh panel: associated distributions of minimum population sizes; eighth panel: expected minimum population size; ninth panel: associated distributions of maximum population sizes; tenth panel: expected maximum population size.

Murray Cod Recruits

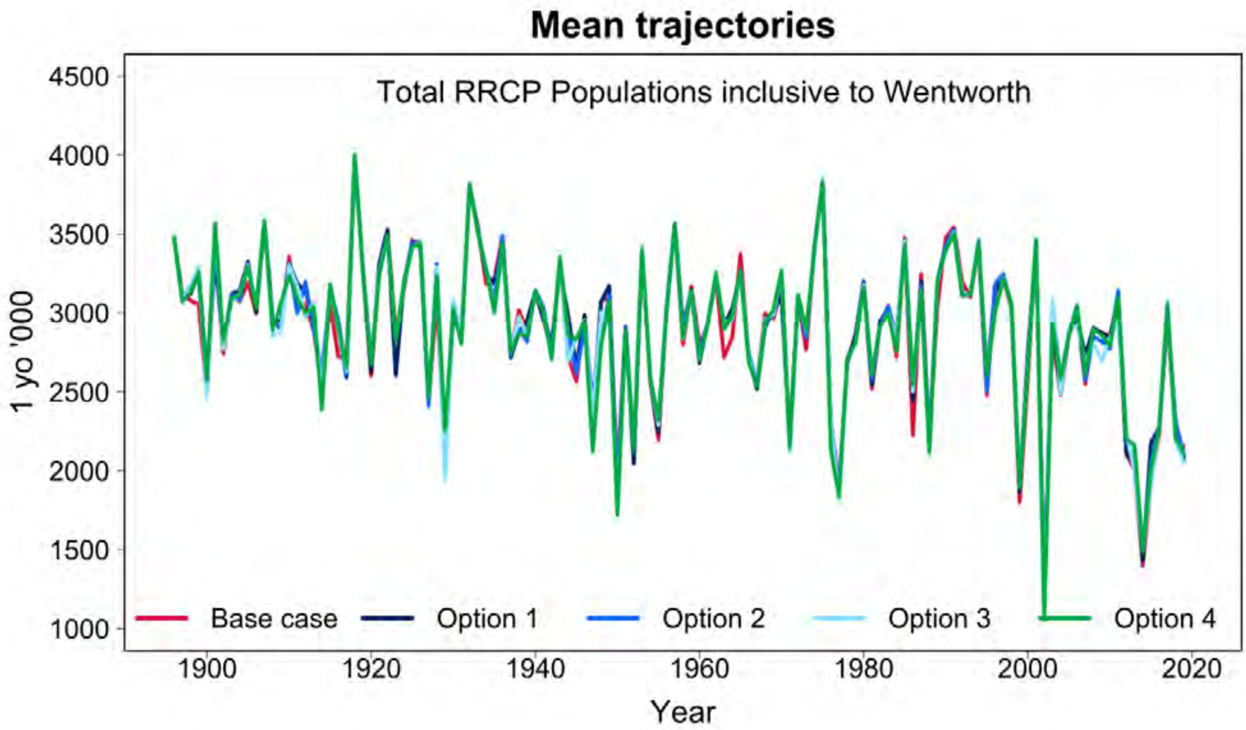


Figure A3.37. Murray Cod recruits mean population size aggregated across all modelled RRCP focal zones, together with the Wakool Junction to Wentworth reach, for the RRCP flow scenarios Base case – Option 4.

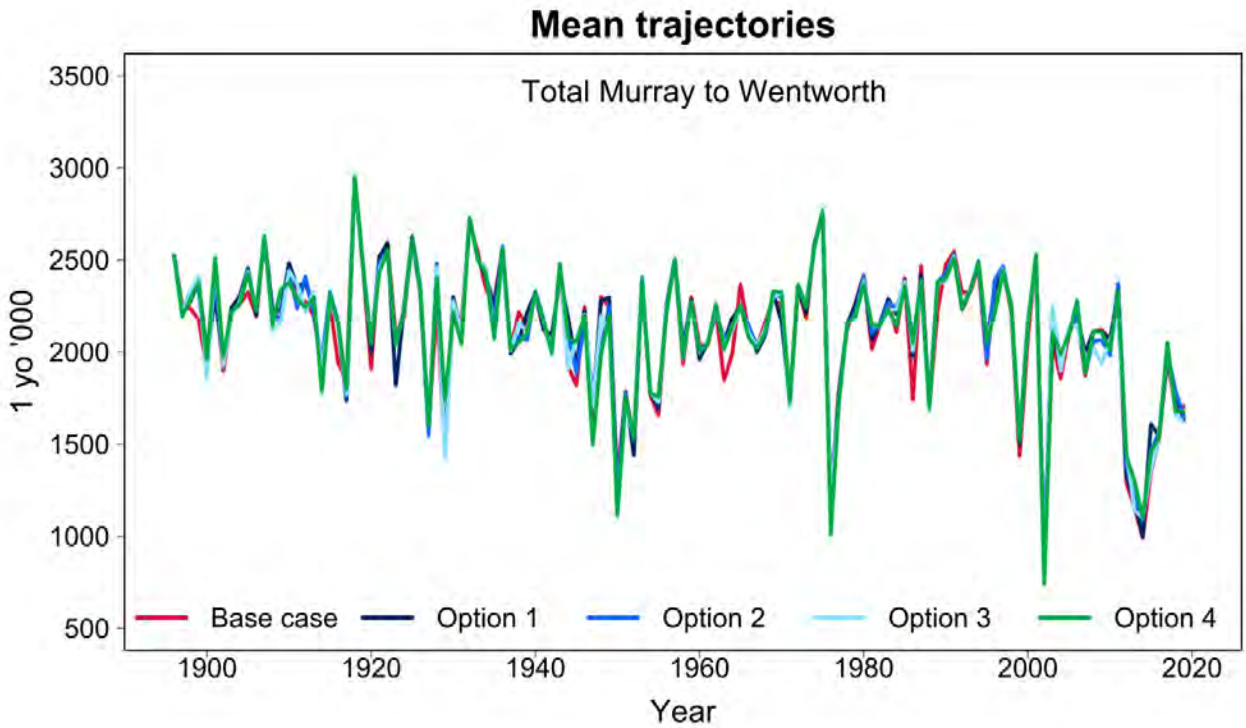


Figure A3.38. Murray Cod recruits mean population size aggregated across the Murray River RRCP focal zones (including the Edward River), together with the Wakool Junction to Wentworth reach, for the RRCP flow scenarios Base case – Option 4.

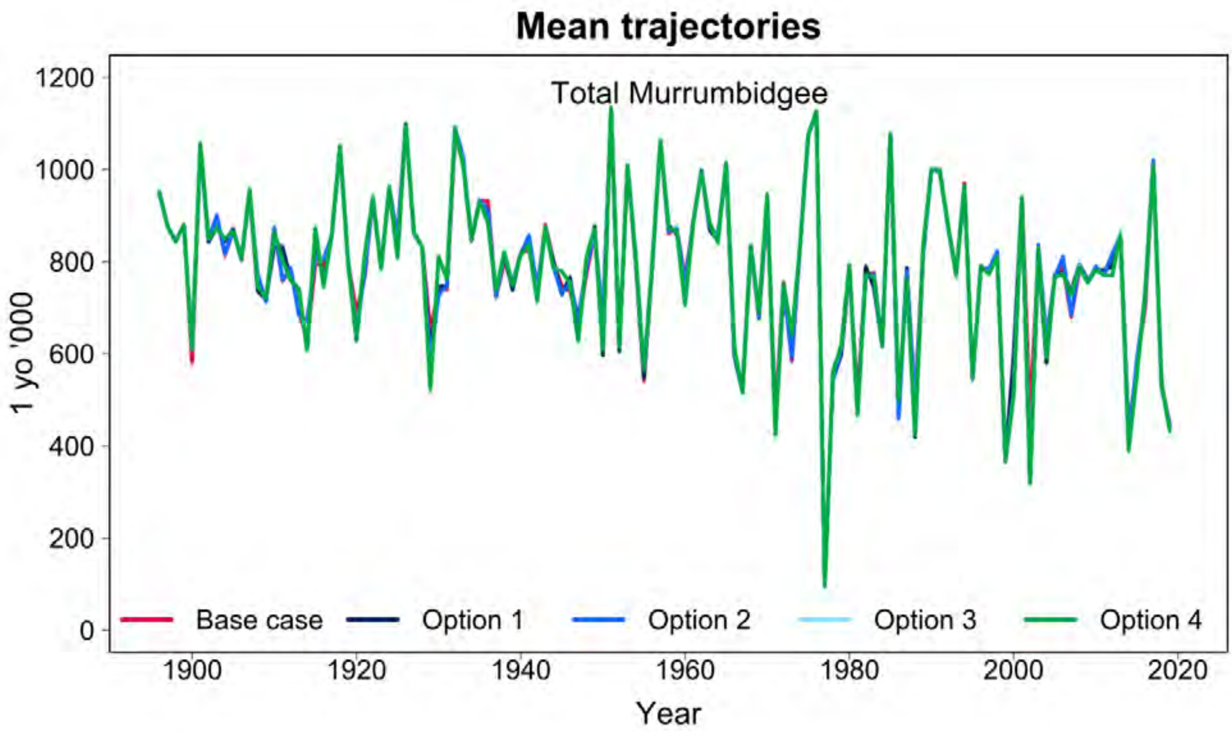


Figure A3.39. Murray Cod recruits mean population size aggregated across the Murrumbidgee River RRCP focal zone for the RRCP flow scenarios Base case – Option 4.

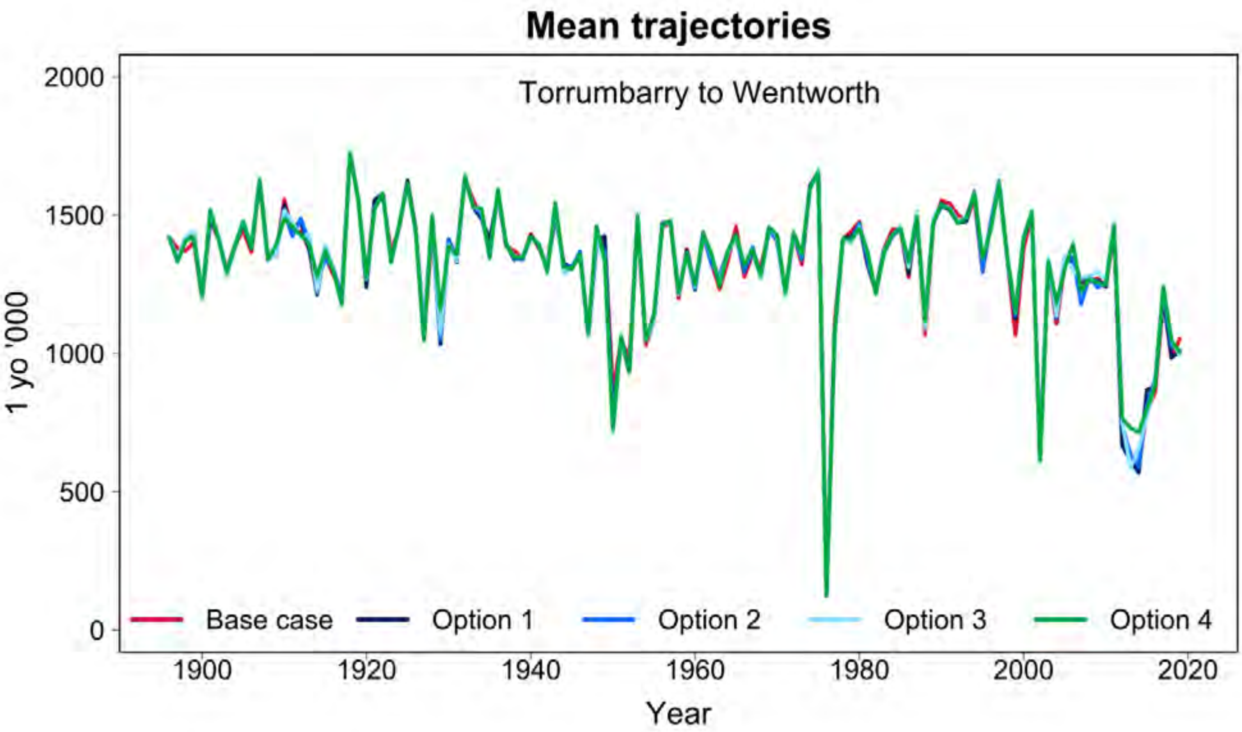


Figure A3.40. Murray Cod recruits mean population size in the Torrumbarry to Wentworth reach for the RRCP flow scenarios Base case – Option 4.

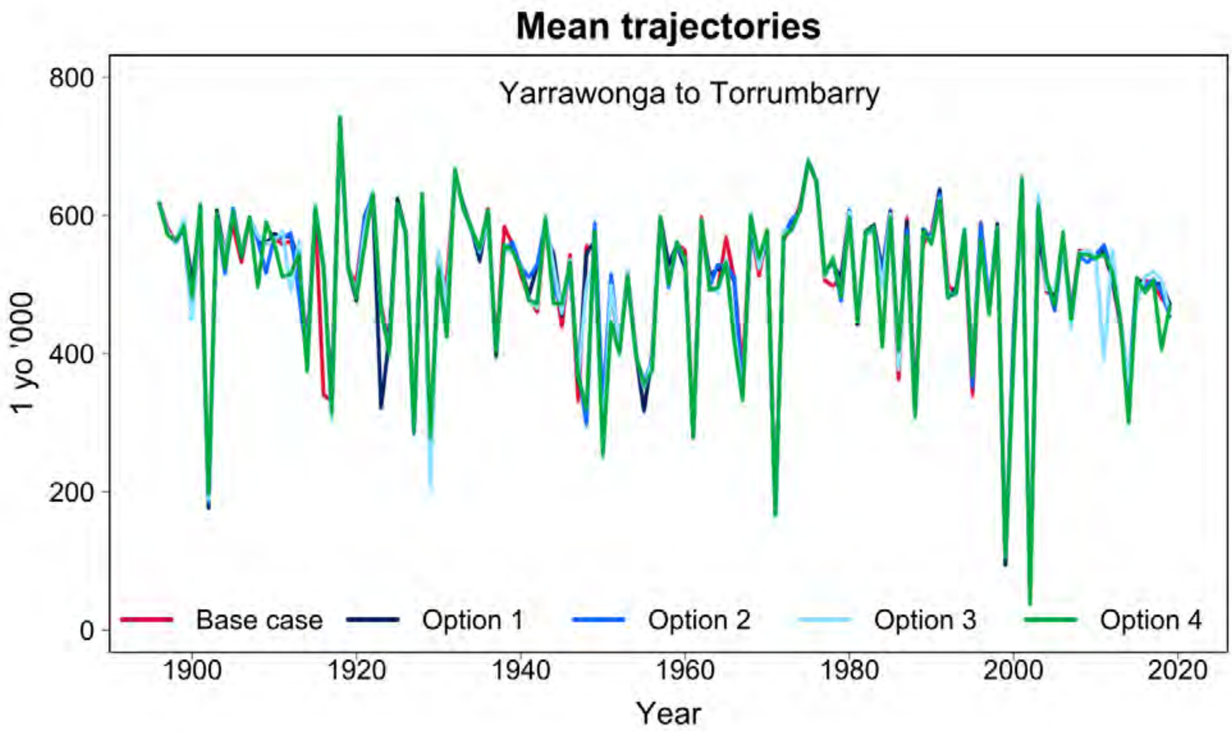


Figure A3.41. Murray Cod recruits mean population size in the Yarrawonga to Torrumbarry reach for the RRCP flow scenarios Base case – Option 4.

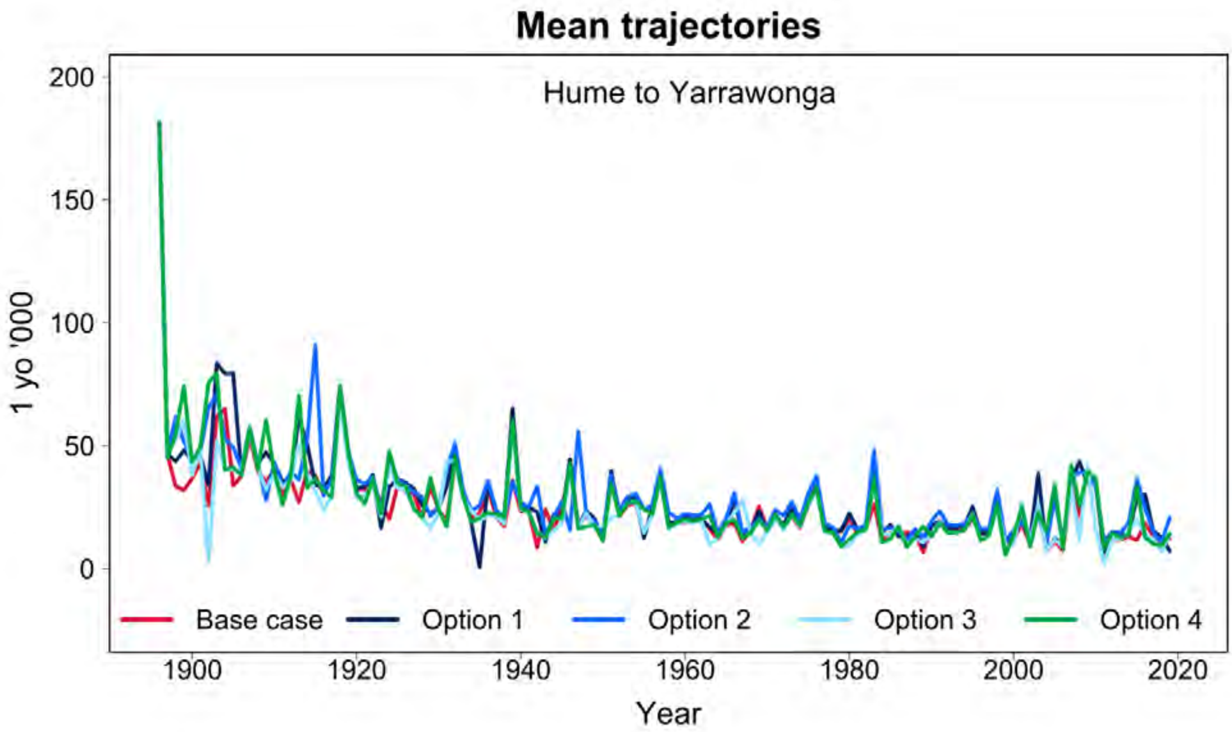


Figure A3.42. Murray Cod recruits mean population size in the Hume to Yarrawonga reach for the RRCP flow scenarios Base case – Option 4.

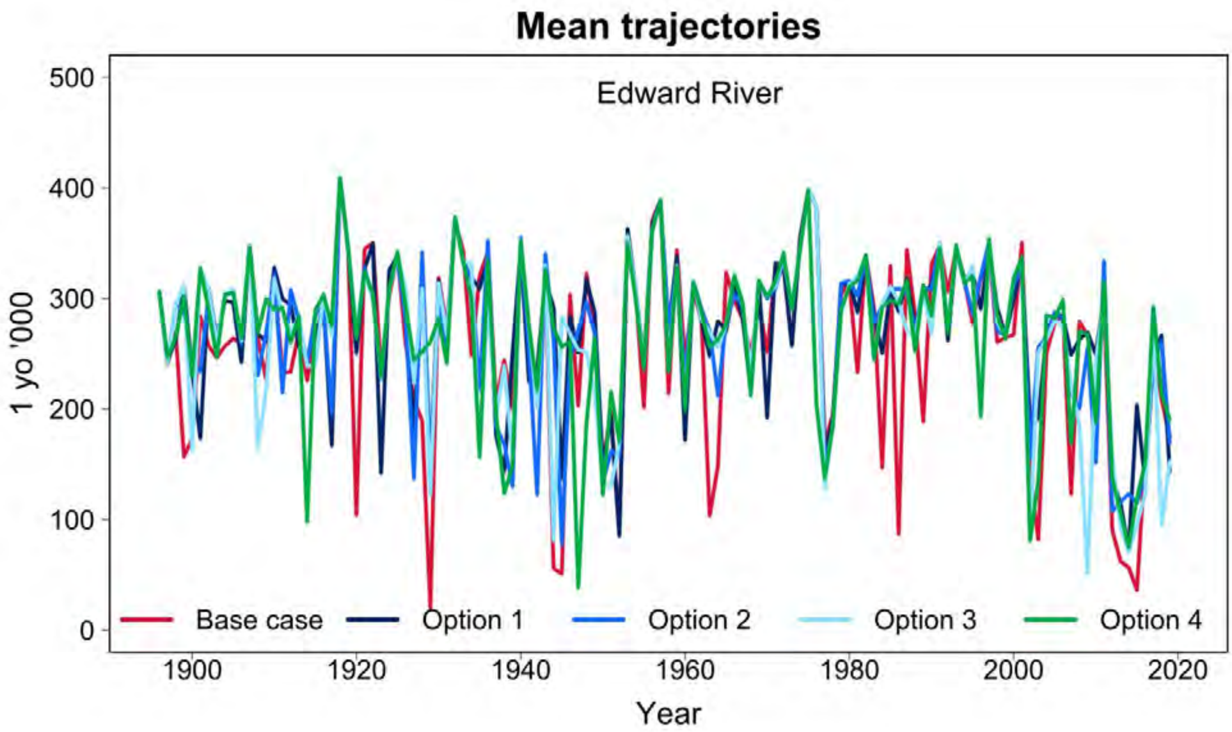


Figure A3.43. Murray Cod recruits mean population size in the Edward River for the RRCP flow scenarios Base case – Option 4.

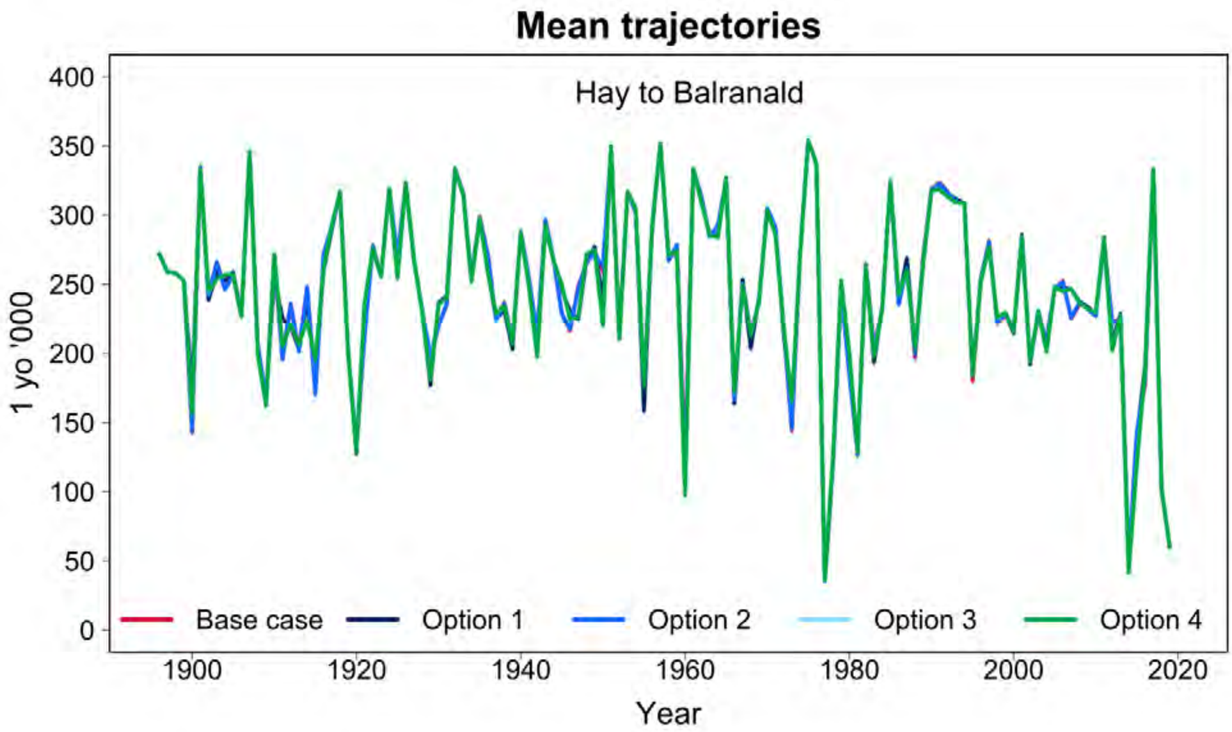


Figure A3.44. Murray Cod recruits mean population size in the Hay to Balranald reach for the RRCP flow scenarios Base case – Option 4.

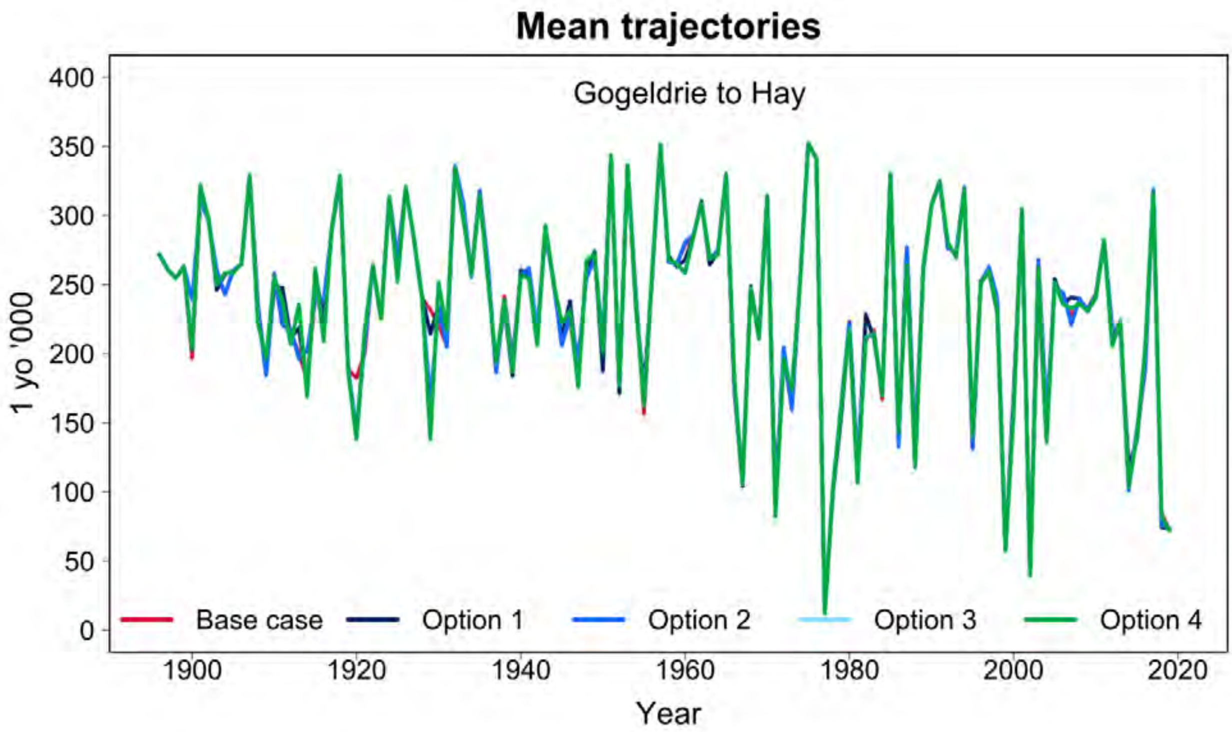


Figure A3.45. Murray Cod recruits mean population size in the Gogeldrie to Hay reach for the RRCP flow scenarios Base case – Option 4.

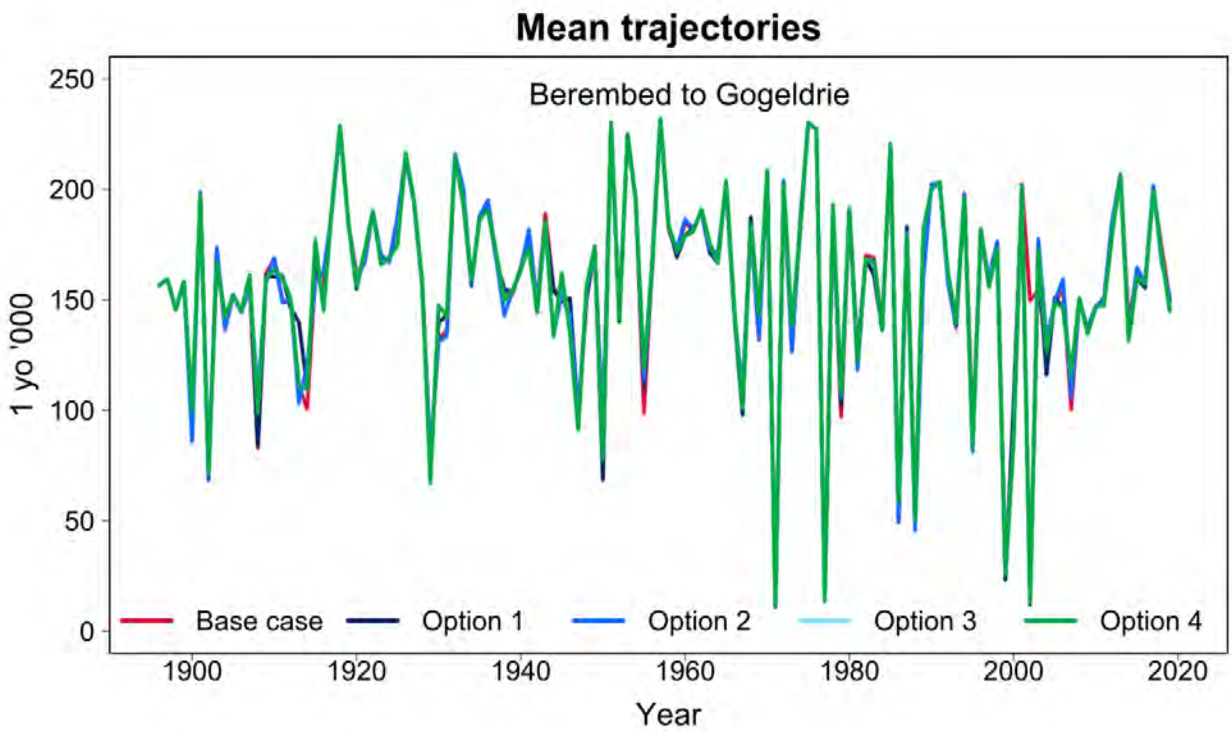


Figure A3.46. Murray Cod recruits mean population size in the Berembed to Gogeldrie reach for the RRCP flow scenarios Base case – Option 4.

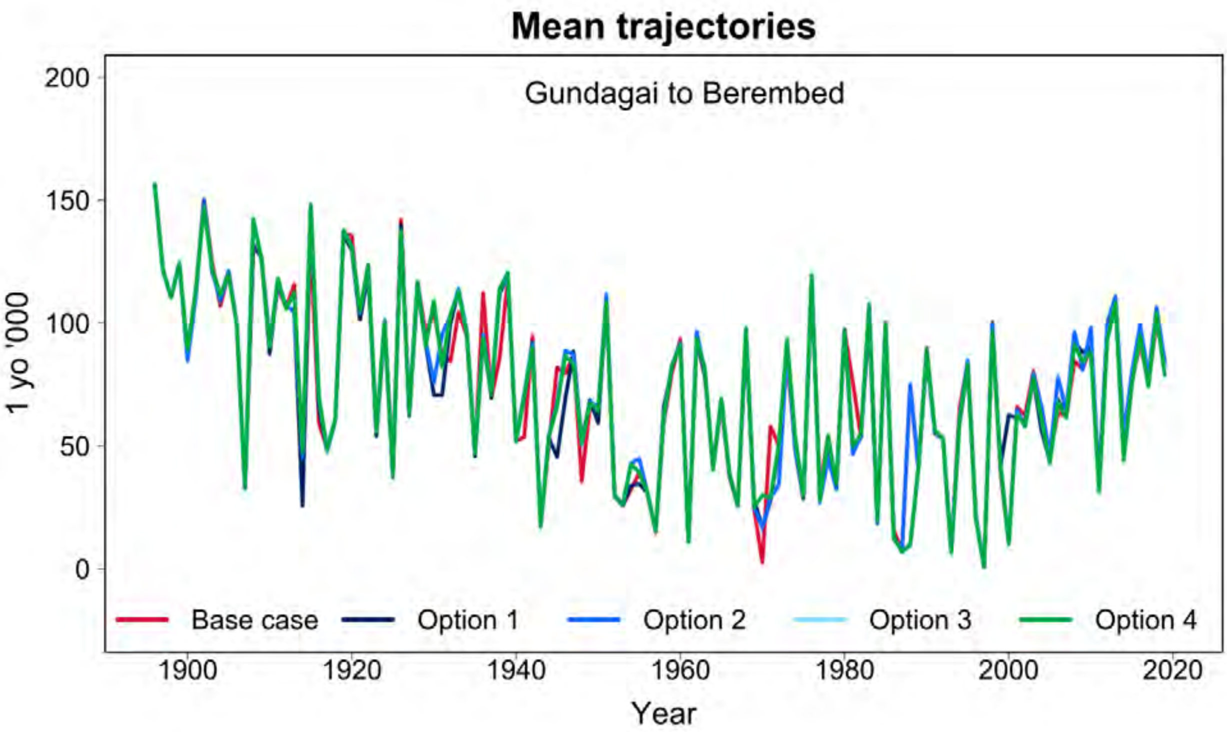


Figure A3.47. Murray Cod recruits mean population size in the Gundagai to Berembed reach for the RRCP flow scenarios Base case – Option 4.

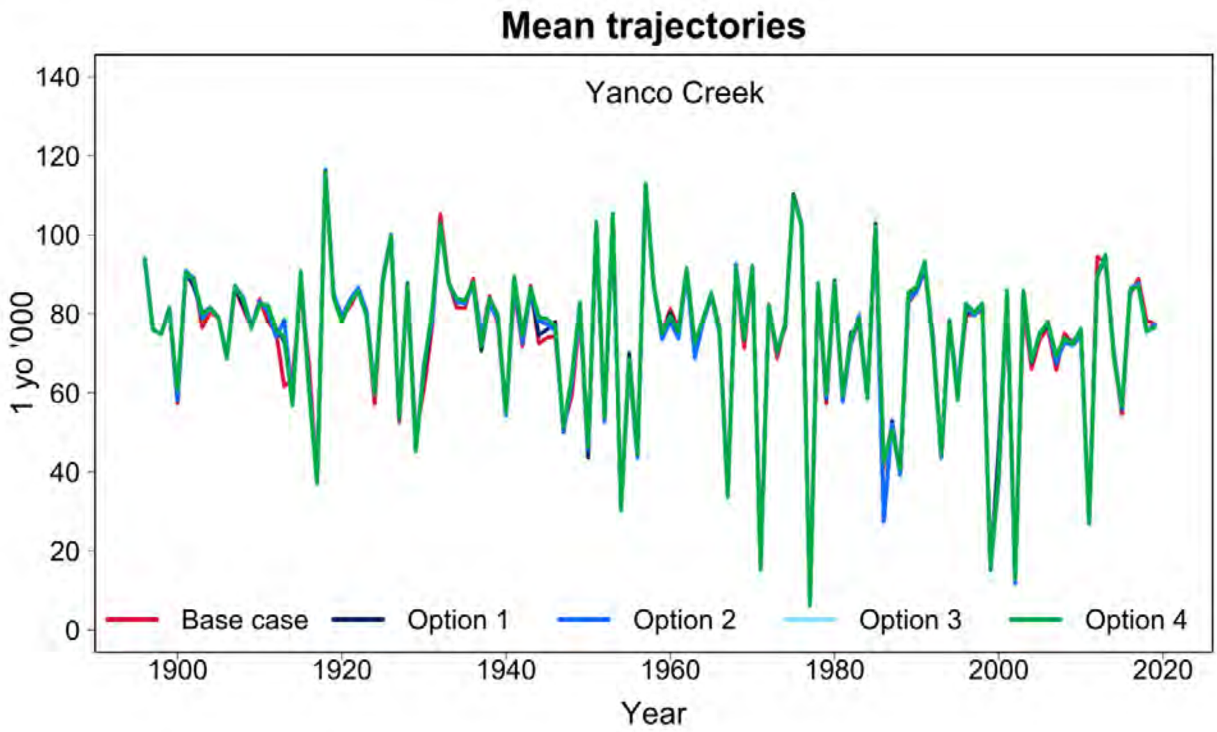


Figure A3.48. Murray Cod recruits mean population size in Yanco Creek for the RRCP flow scenarios Base case – Option 4.

Appendix 4: Sensitivity of the Golden Perch metapopulation model

The purpose of the sensitivity analysis was to ensure that the outcomes presented, and conclusions drawn, are robust in the assessment of the relaxed-flow-constraints scenarios. This involves sensitivity analysis of the key assumptions of the Golden Perch metapopulation model and their influence on model outcomes. Sensitivity analyses were undertaken of variables for which there were known uncertainties, to explore their effects on the Golden Perch model outputs and to assess the robustness of the model outcomes (to determine whether the outcomes from the sensitivity analysis alter the interpretation of the RRCP flow scenarios results). The changes considered were: changes in movement rates (gross and nuanced); altered initial population sizes; and altered immigration from the MDB. The sensitivity analysis performed was not a full exploration of all RRCP flow scenarios: Base case and Option 4, the lowest and highest flow scenarios, were considered sufficient for this analysis. As numerous scenarios were explored in this analysis, only 100 iterations were undertaken for each scenario. The first approach in undertaking the sensitivity analysis was to adjust the gross movement rates and compare the results with the default parameterisation (sensitivity 1: Table A4.1; Figure A4.1 to Figure A4.36). The second approach in undertaking the sensitivity analysis was to make targeted adjustments to movement from the Lower Murray, changing the initial population size, changing the immigration level from the Northern MDB and combining altered movement and altered immigration to assess whether any of these changes would alter the interpretation of the results (sensitivity 2: Table A4.2).

Table A4.1. Sensitivity 1: gross changes to movement in the metapopulation model for Golden Perch

Scenario name	Description
Default	Base rules
P1 = 0	Movement from the Lower Murray below Wentworth reach set to zero[A]
P2 = 0	Movement from the Torrumbarry to Wentworth reach set to zero
P3 = 0	Movement from the Yarrawonga to Torrumbarry reach set to zero
P5 = 0	Movement from the Lower Darling set to zero
P6 = 0	Movement from the Lower Murrumbidgee River set to zero
P7 = 0	Movement from the Edward River set to zero

A: All movement of adults and juveniles set to 0, larval drift continues.

Table A4.2. Sensitivity 2: gross changes to movement in the metapopulation model for Golden Perch

Scenario name	Description
Default	Base rules
+P1P2	Movement from the Lower Murray-below-Wentworth reach upstream to the Torrumbarry to Wentworth reach was increased: adult movement ×2 and juvenile movement ×5
AP1P2	Adult movement rate from the Lower Murray-below-Wentworth reach upstream to the Torrumbarry to Wentworth reach was decreased to the same level as juveniles
IP	The adult initial population size was set to half the adult carrying capacity of each reach
M2	Increased immigration from the Northern MDB
AP1P2+M2	Decreased adult movement from P1 to P2 and increased immigrations from the Northern MDB

The third approach was to use different time frames over which to generate expected mean population sizes. The time period that the model was run over to generate the expected values in the above results was equivalent to 124 years. As an alternative, different time periods were explored, and periods of divergence and convergence were highlighted, again, to assess the robustness of the model outcomes.

First sensitivity analysis

The first approach in undertaking the sensitivity analysis was to adjust the gross movement rates and to compare the results with those of the default parameterisation, to understand the impacts on the population modelling outcomes.

Movement from:

(1) the Lower Murray below Wentworth reach was set to zero, i.e. no movement to any other reach in the metapopulation (P1 = 0);
(2) the Torrumbarry to Wentworth reach was set to zero (P2 = 0);
(3) the Yarrawonga to Torrumbarry reach was set to zero (P3 = 0);
(4) the Lower Darling was set to zero (P5 = 0);
(5) the Hay to Balranald reach was set to zero (P6 = 0); and
(6) the Edward River was set to zero (P7 = 0).

The upper Murrumbidgee (Gundagai to Hay) and upper Murray (Hume to Yarrawonga) reaches were not included in the sensitivity analysis as they only had one connection.

Figure A4.4 and Figure A4.5 show the model behaviour to be dependent upon the movement rates specified in the model. Specifying no movement from the Lower Murray had a negative impact on the Total RRCP Populations due to the lack of contribution of migrating fish from the Lower Murray to the rest of the metapopulation. While there was a decline in the Total RRCP Populations in this scenario compared with the default, there was an increase in the Total Population, as the Golden Perch population in the Lower Murray increased in size but was not accounted for in the Total RRCP Populations. Setting no movement from the Torrumbarry to Wentworth reach, and separately setting no movement from the Lower Darling, had similar effects on the Total RRCP Populations, causing large declines in comparison with the default (Figure A4.4 and Figure A4.5). The Torrumbarry to Wentworth reach is an important connecting reach—it is connected to five other populations, and stopping movement from this population negatively affects the whole metapopulation. The Lower Darling is an important migratory pathway connecting the Northern Murray–Darling Basin with the Southern MDB, and when this connection is removed, the Total RRCP Populations decline. The other three populations assessed by removing their connections to the metapopulation showed little effect. The mean trajectories and expected mean population size bar charts presented above (Figure A4.4 and Figure A4.5) were comparable, i.e. the Base case results were comparable with the default Base Case results. However, when the Base case was compared with Option 4, it was observed that in all circumstances Option 4 generated a higher expected mean population size for the Total RRCP Populations (Figure A4.6). This was the case for all sensitivity scenarios except for P1 = 0, which was only slightly higher (Figure A4.6).

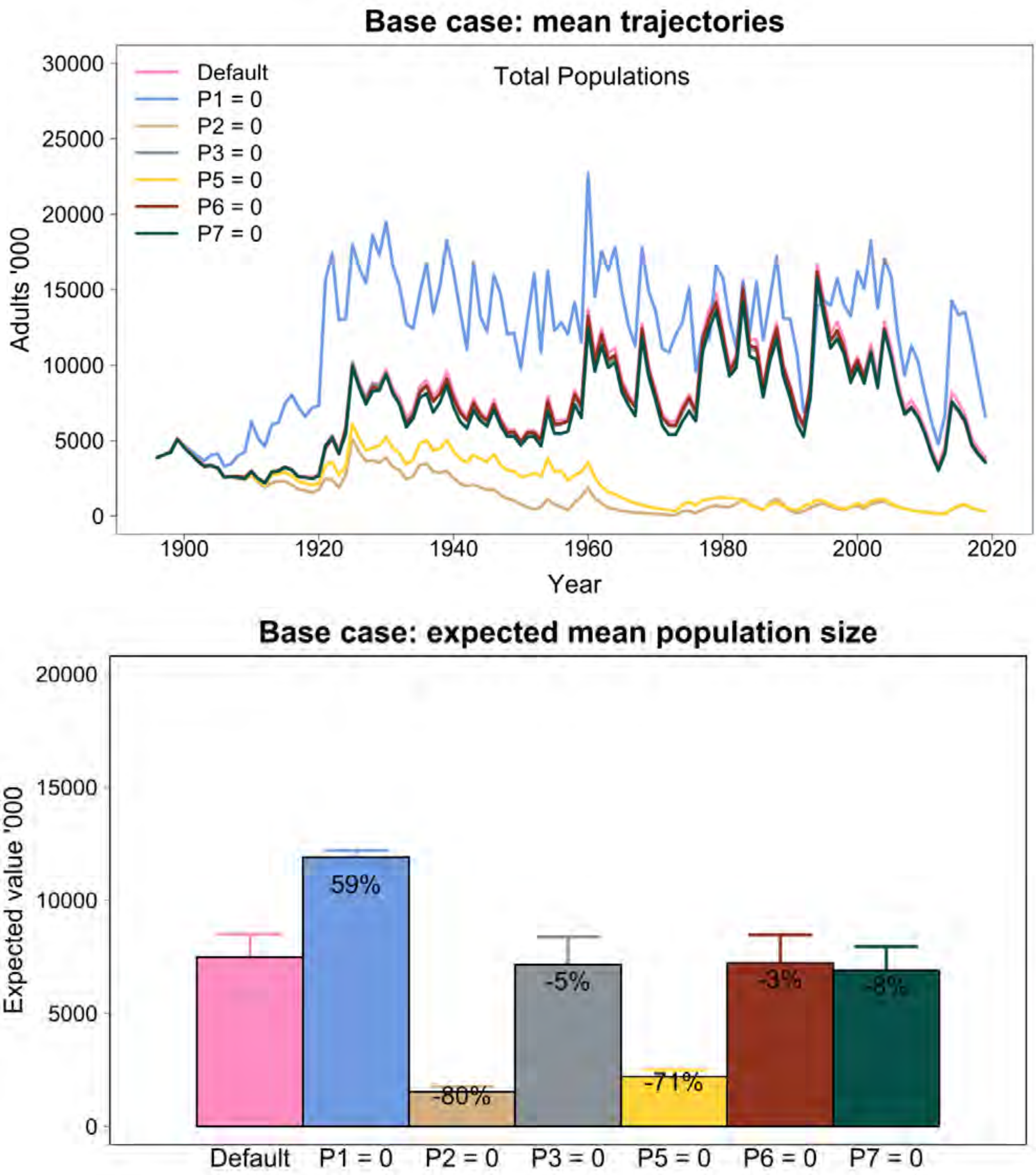


Figure A4.1. The Base case sensitivity analysis 1 scenarios modelled for Golden Perch adult populations aggregated across all reaches in this study in the southern MDB. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean adult population sizes, with the percentage change from the default shown in each bar.

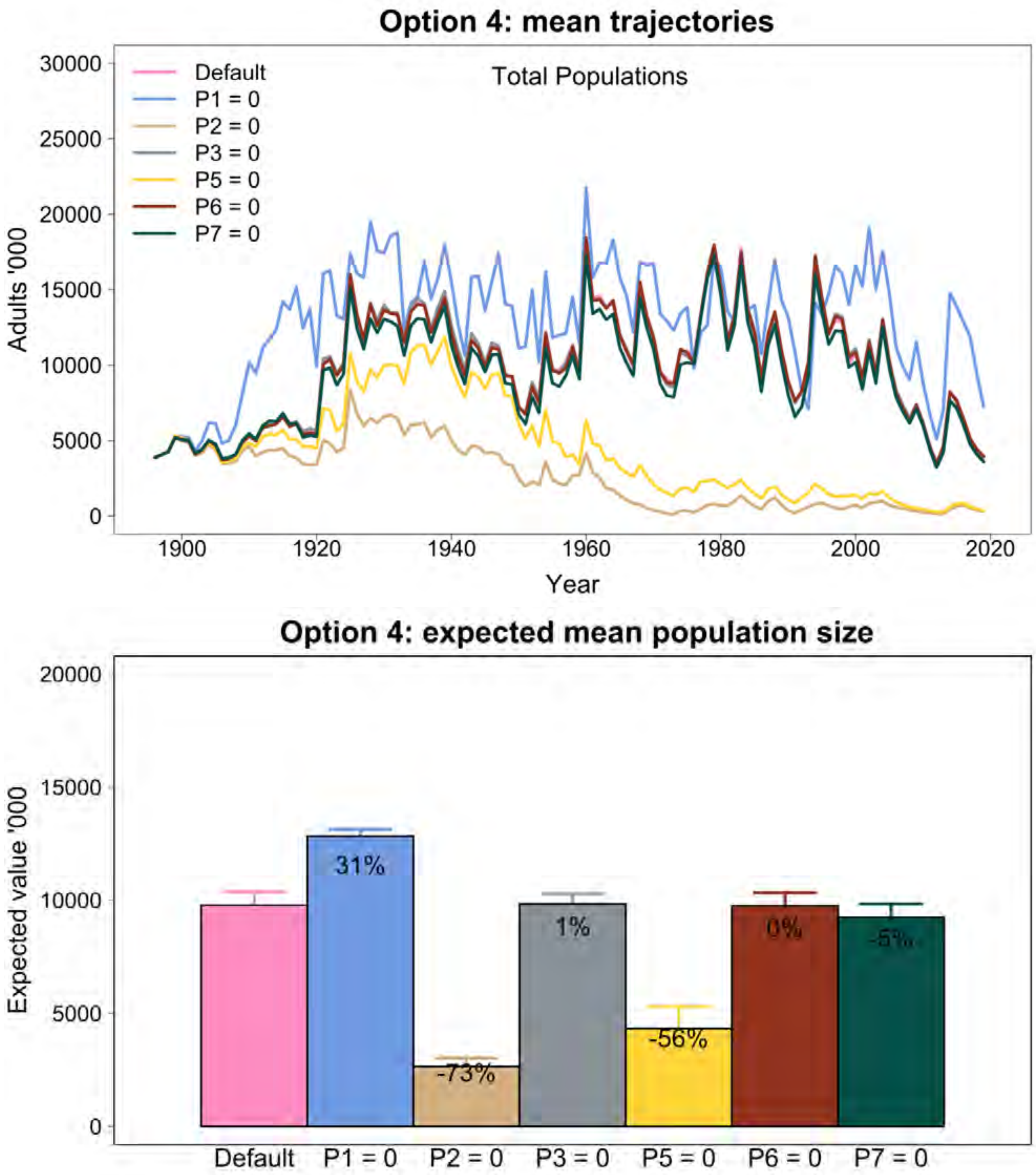


Figure A4.2. Option 4 sensitivity 1 scenarios modelled for Golden Perch adult populations aggregated across all reaches in this study in the southern MDB. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

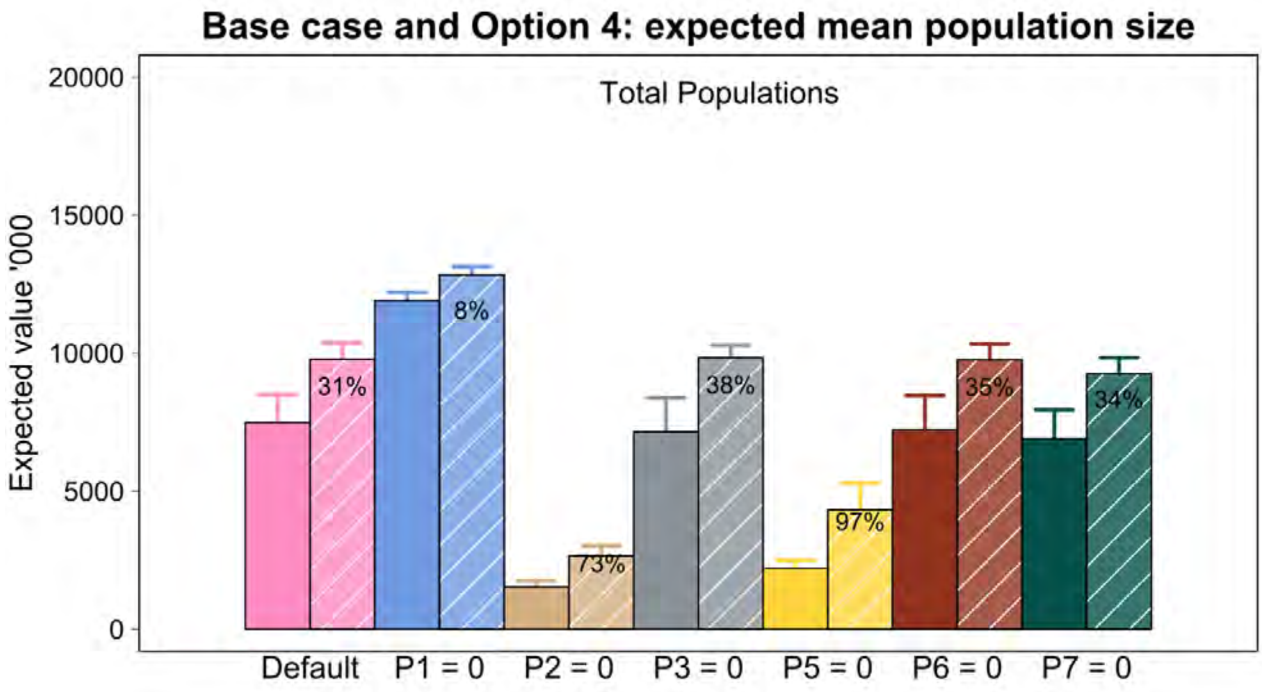


Figure A4.3. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis aggregated across all reaches in this study in the southern MDB.

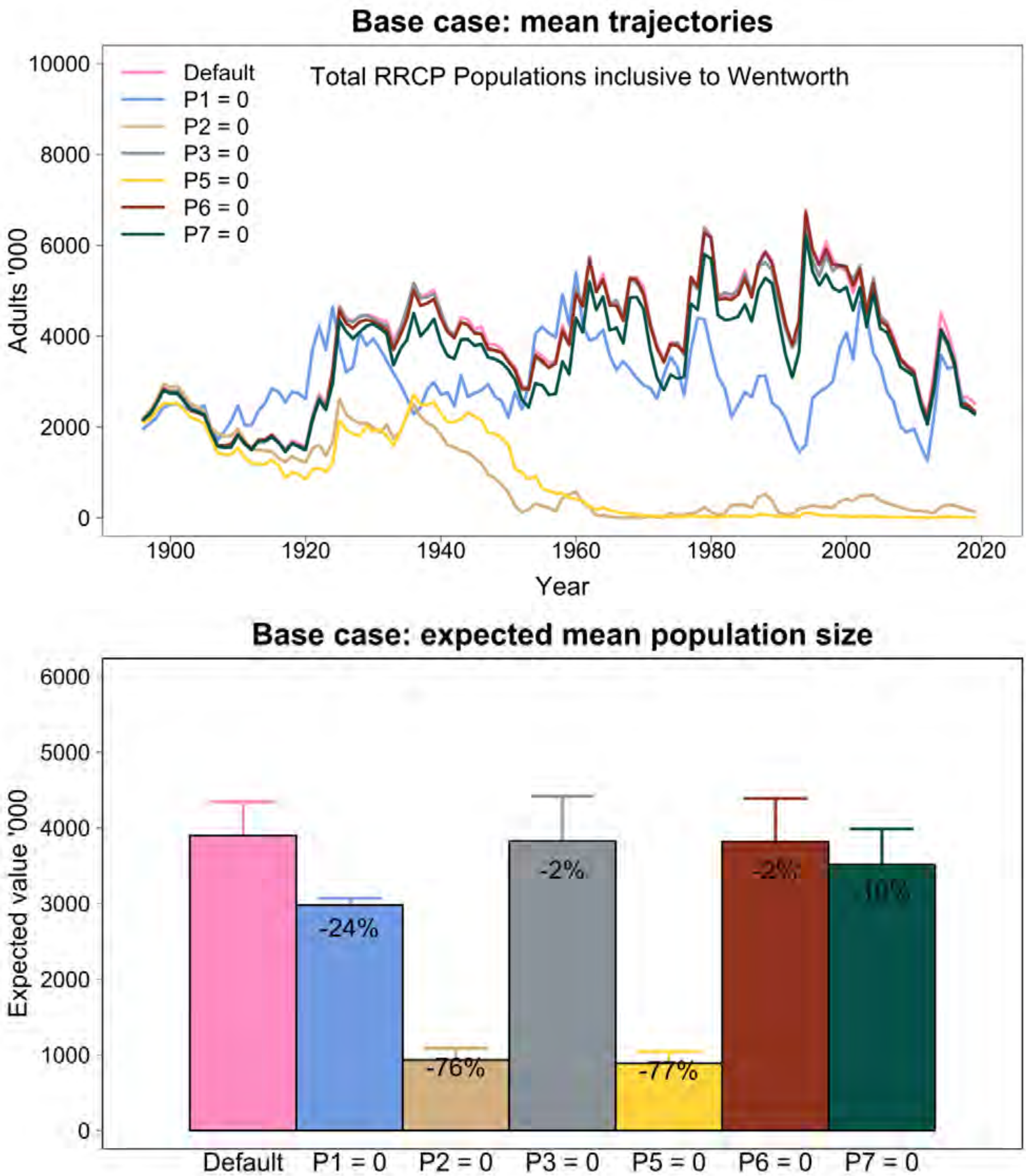


Figure A4.4. The Base case sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis cross all RRCP focal zones, together with the Wakool Junction to Wentworth reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

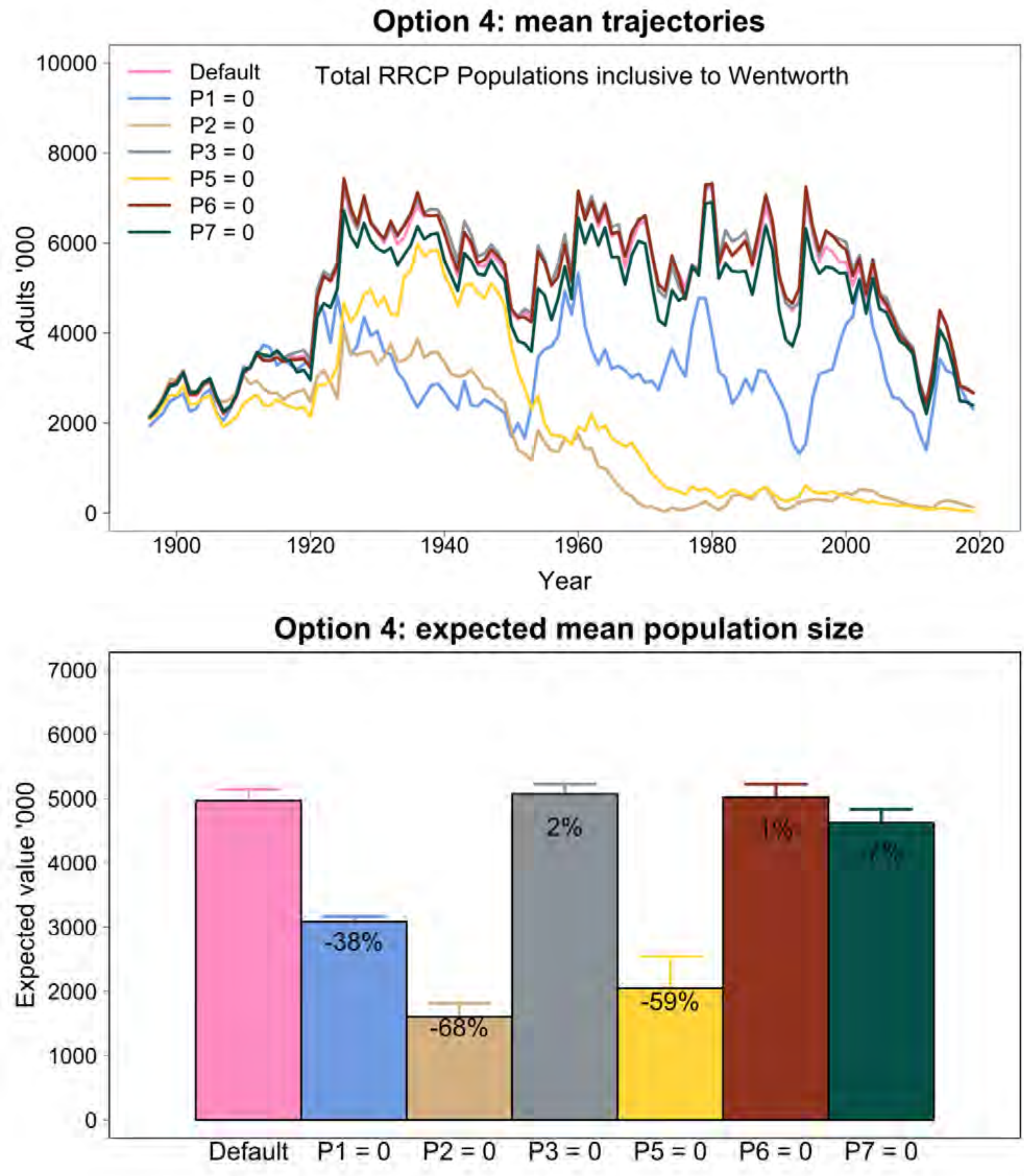


Figure A4.5. Option 4 sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis cross all RRCP focal zones, together with the Wakool Junction to Wentworth reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

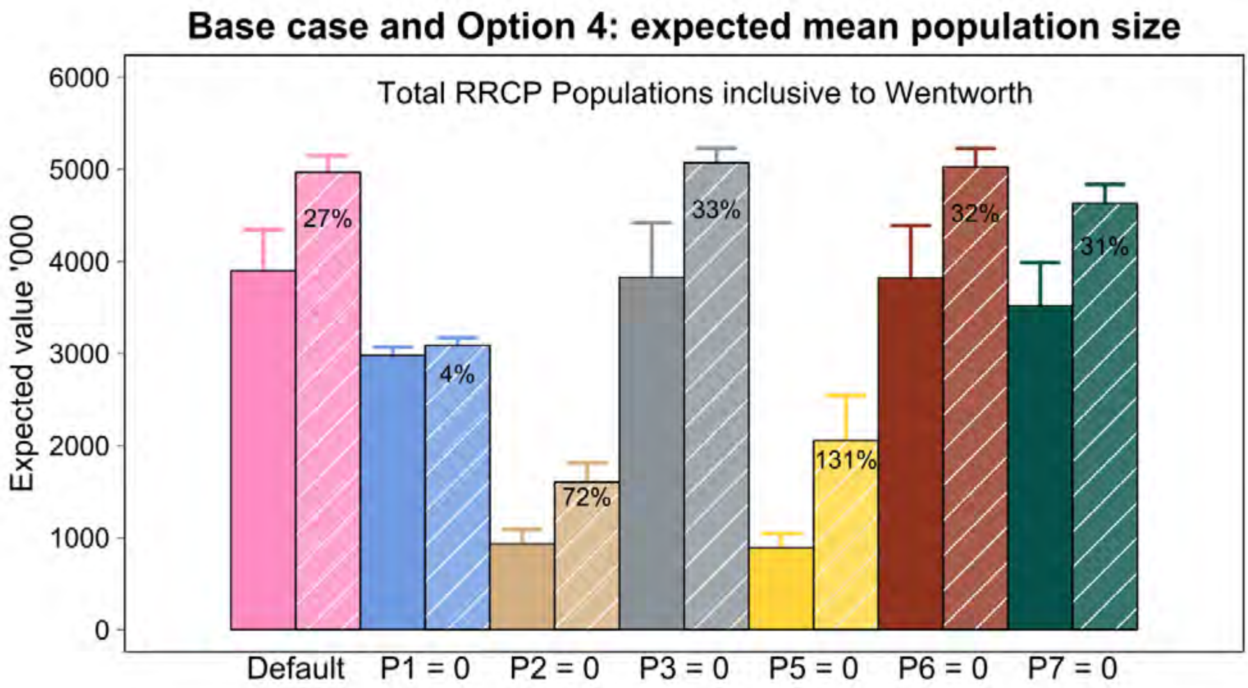


Figure A4.6. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis across all RRCP focal zones, together with the Wakool Junction to Wentworth reach.

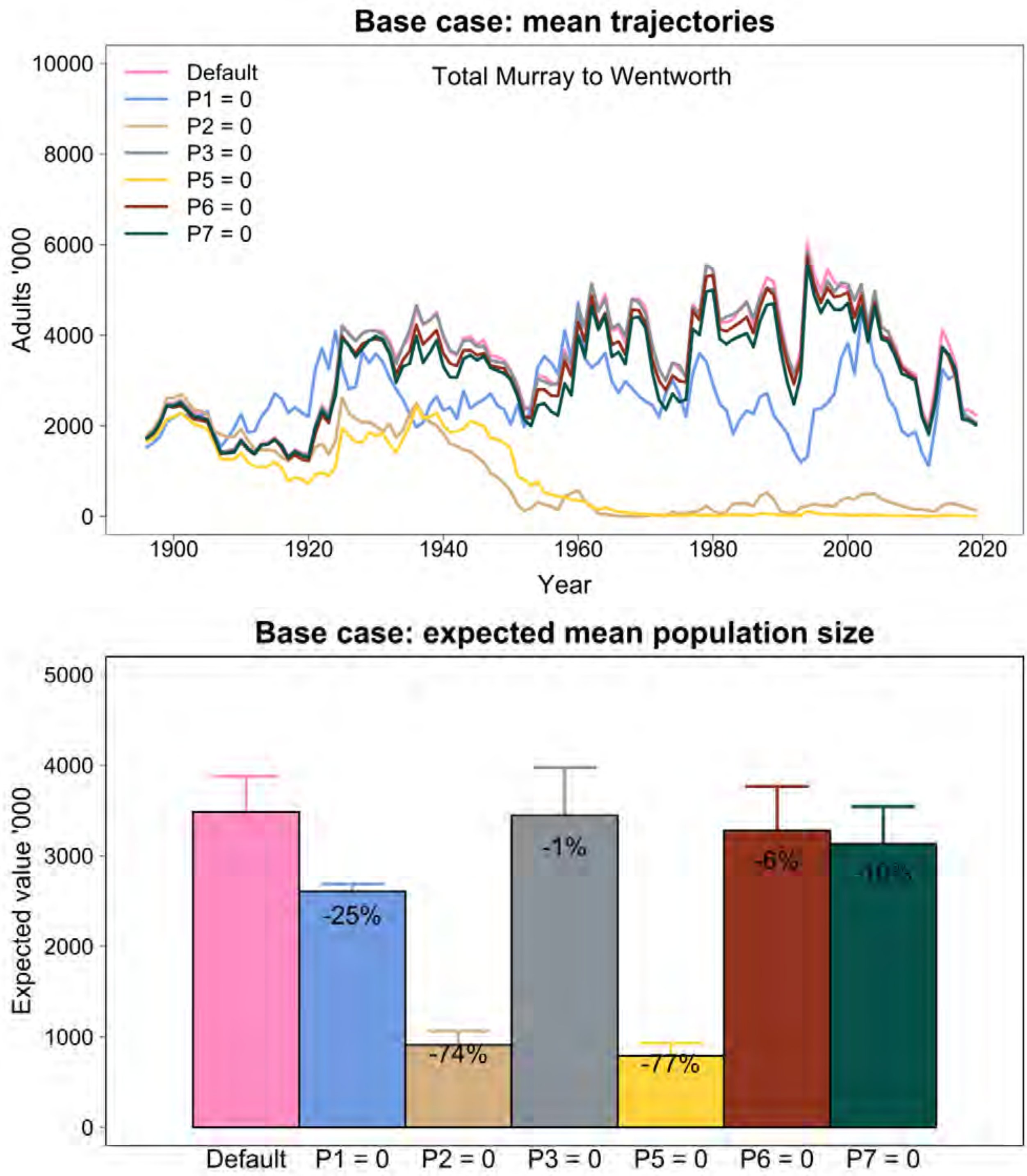


Figure A4.7. The Base case sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis aggregated across the Murray River RRCP focal zones (including the Edward River), together with the Wakool Junction to Wentworth reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

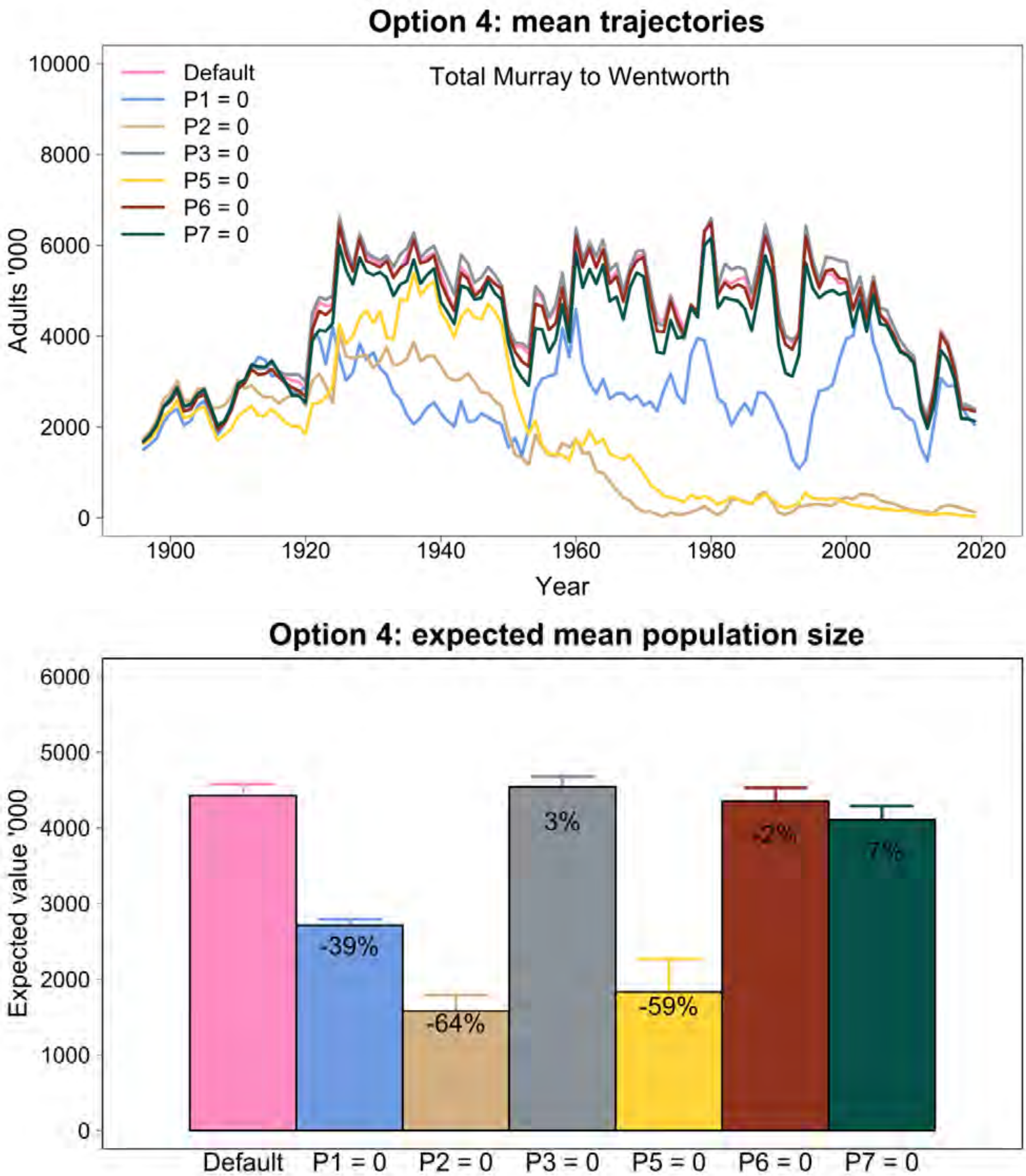


Figure A4.8. Option 4 sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis aggregated across the Murray River RRCP focal zones (including the Edward River), together with the Wakool Junction to Wentworth reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

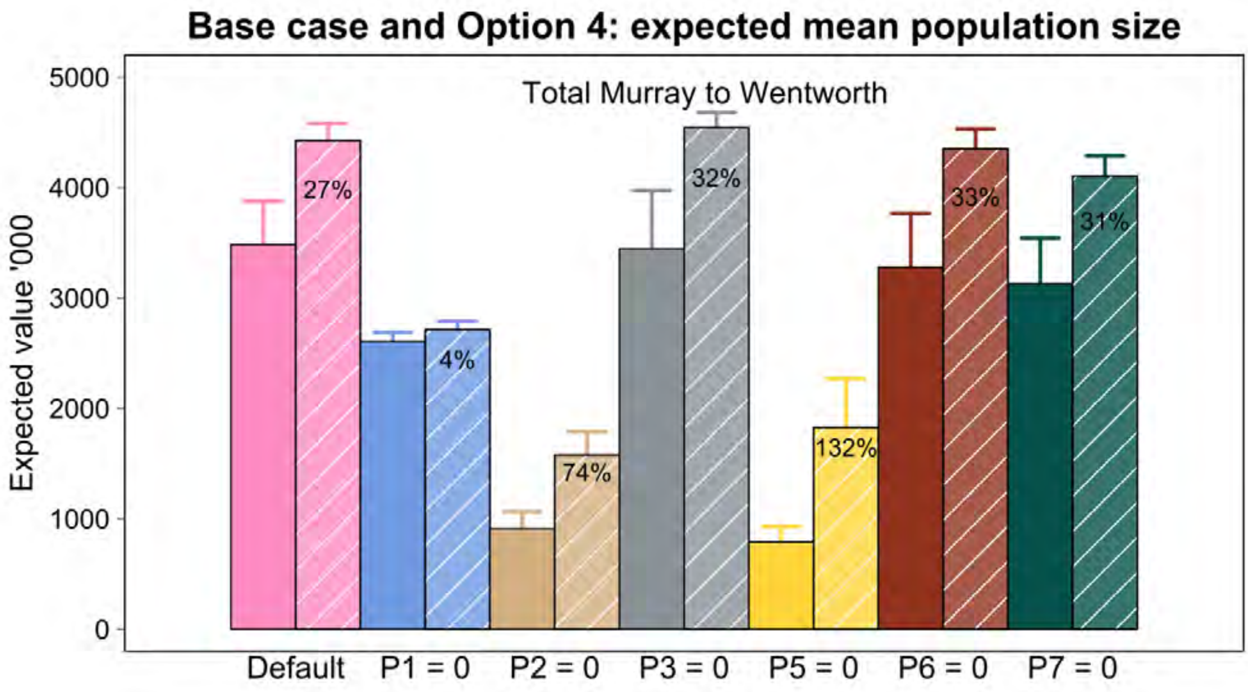


Figure A4.9. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis aggregated across the Murray River RRCP focal zones (including the Edward River), together with the Wakool Junction to Wentworth reach.

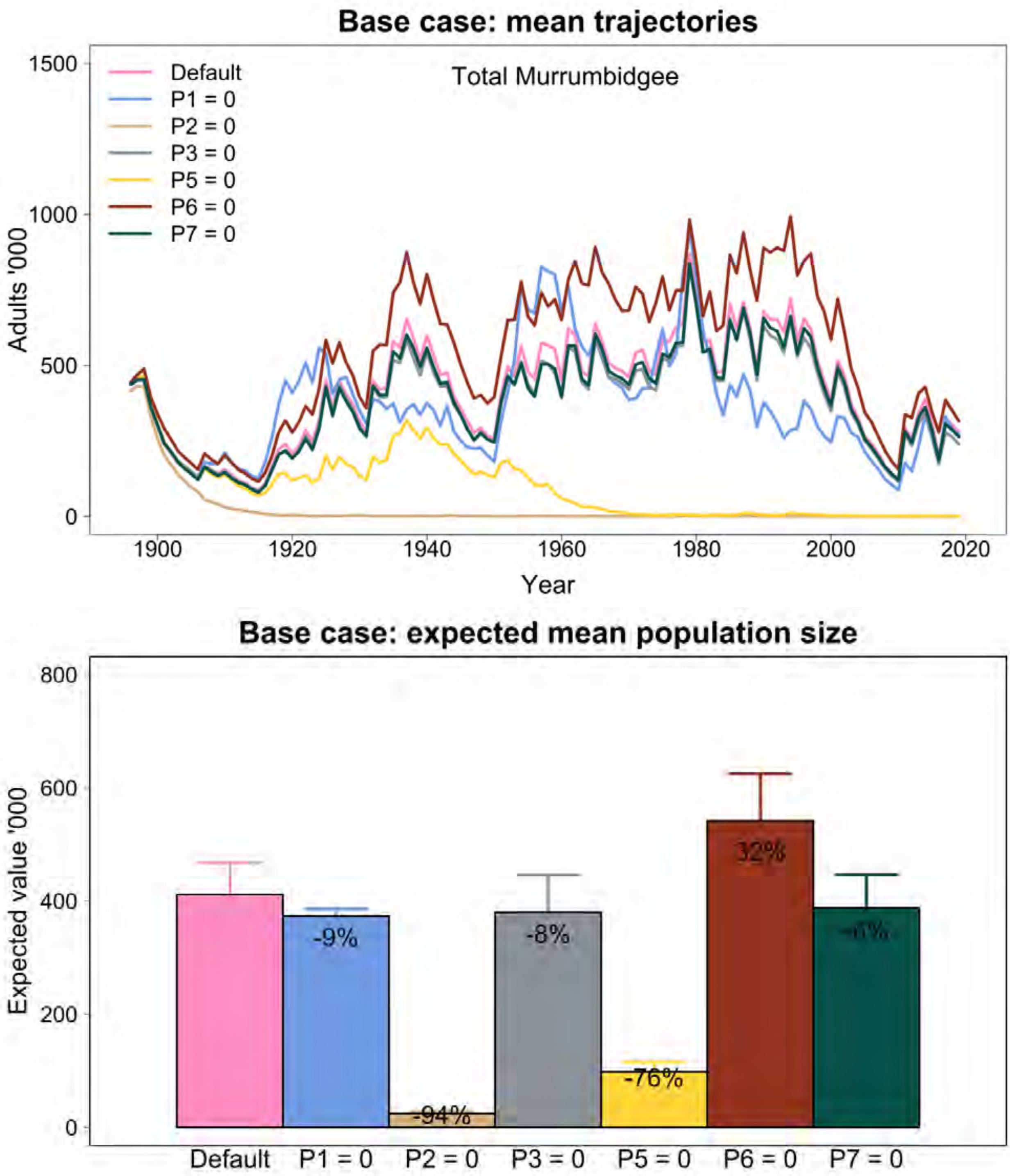


Figure A4.10. The Base case sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis aggregated across the Murrumbidgee River RRCP focal zone. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

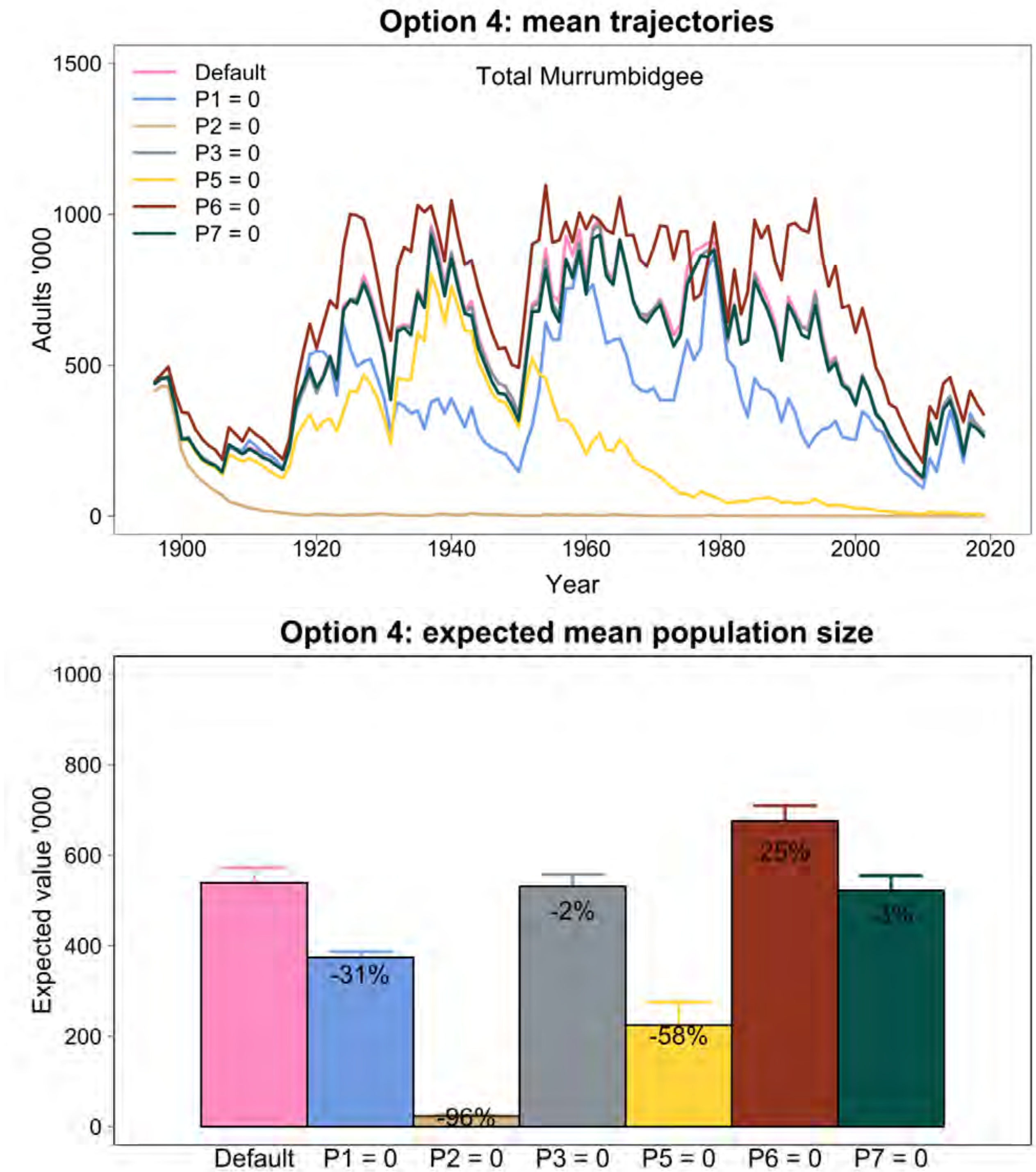


Figure A4.11. Option 4 sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis aggregated across the Murrumbidgee River RRCP focal zone. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

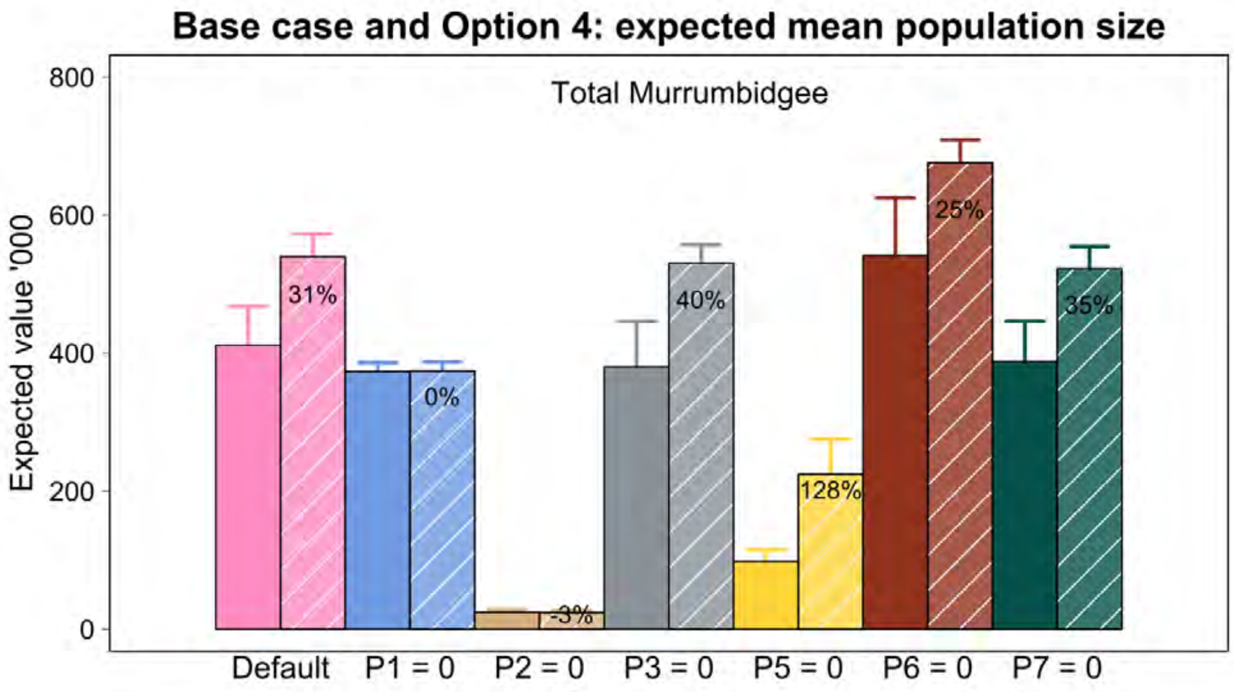


Figure A4.12. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis aggregated across the Murrumbidgee River RRCP focal zone.

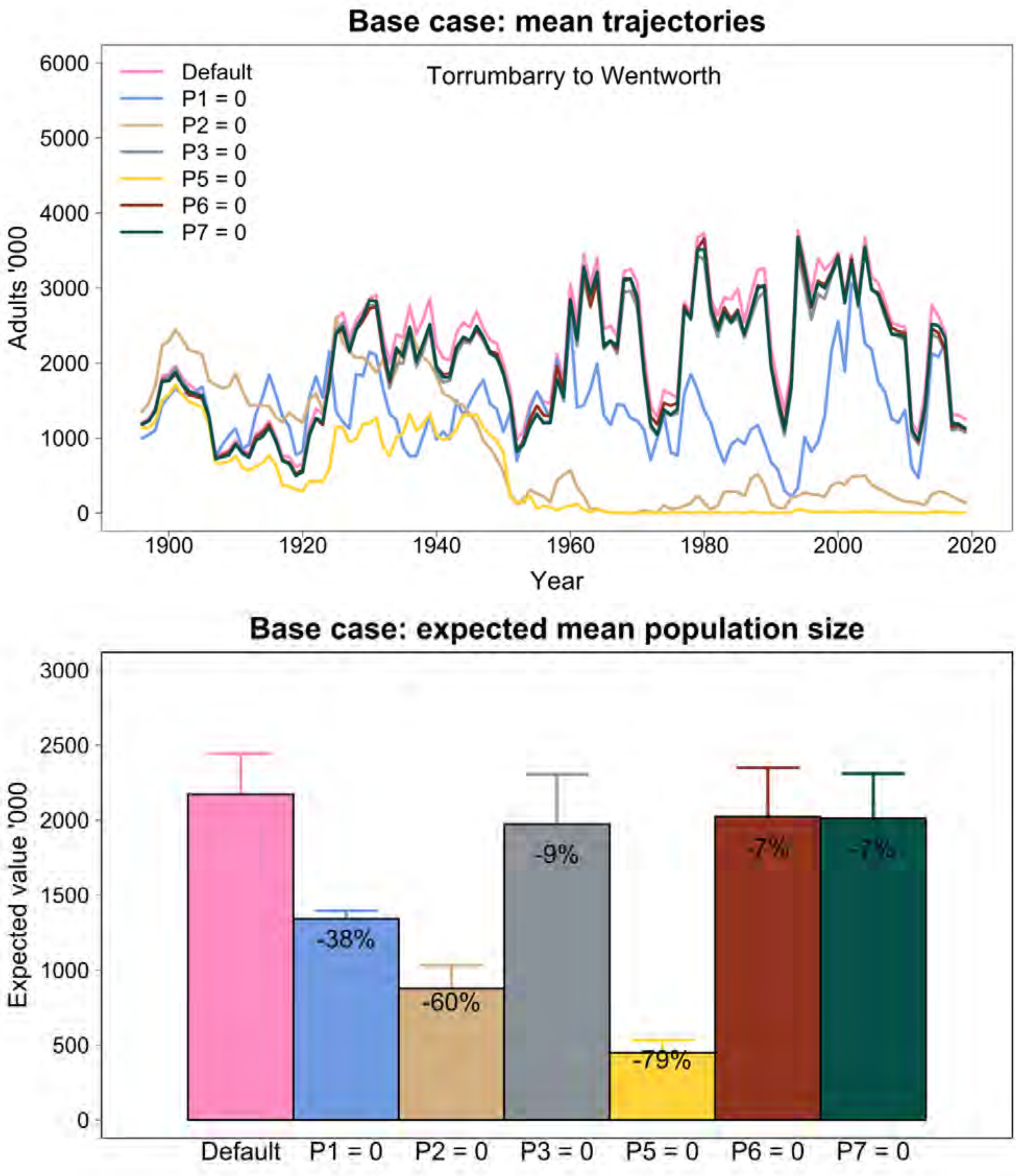


Figure A4.13. The Base case sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis in the Torrumbarry to Wentworth reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

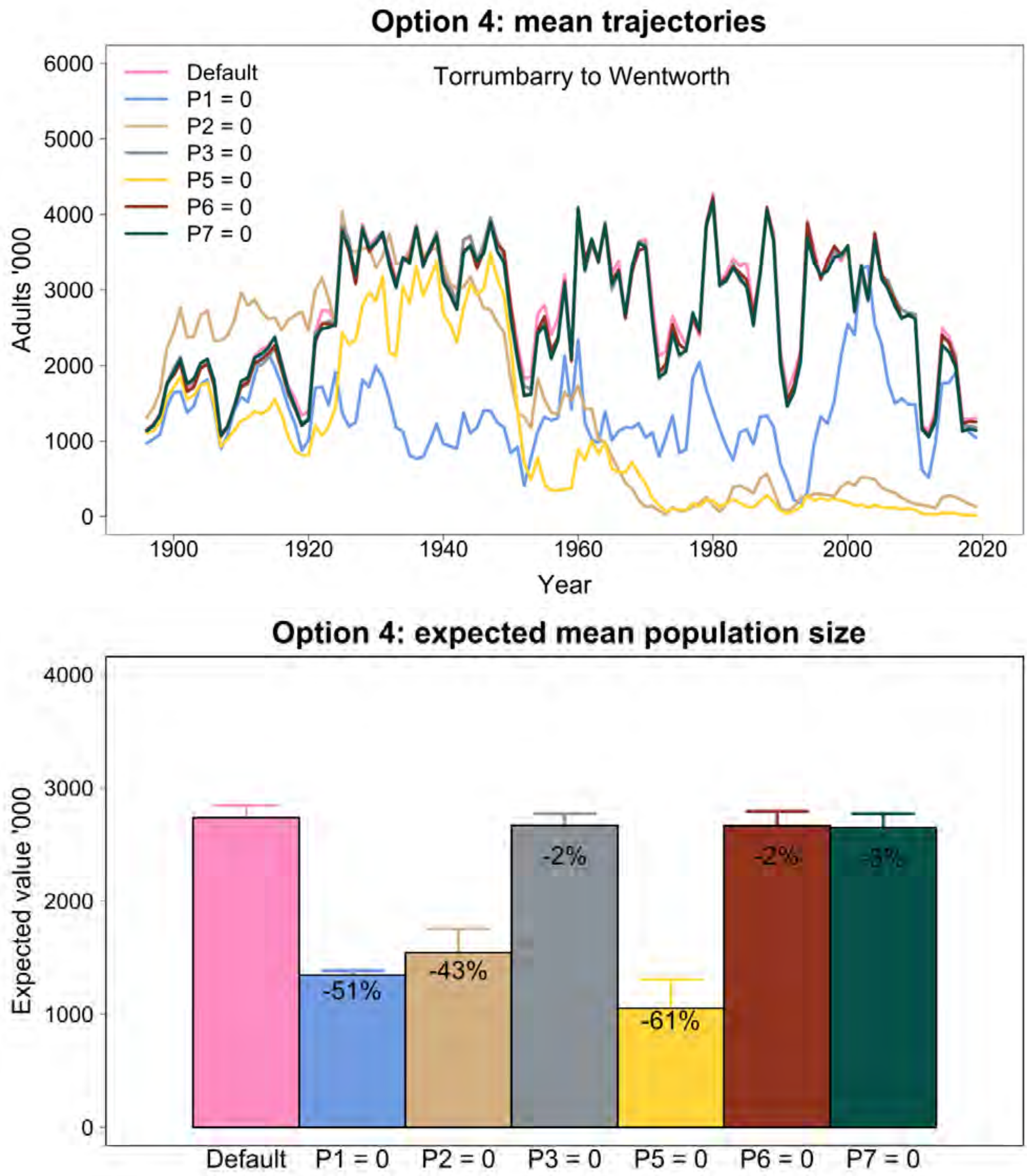


Figure A4.14. Option 4 sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis in the Torrumbarry to Wentworth reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

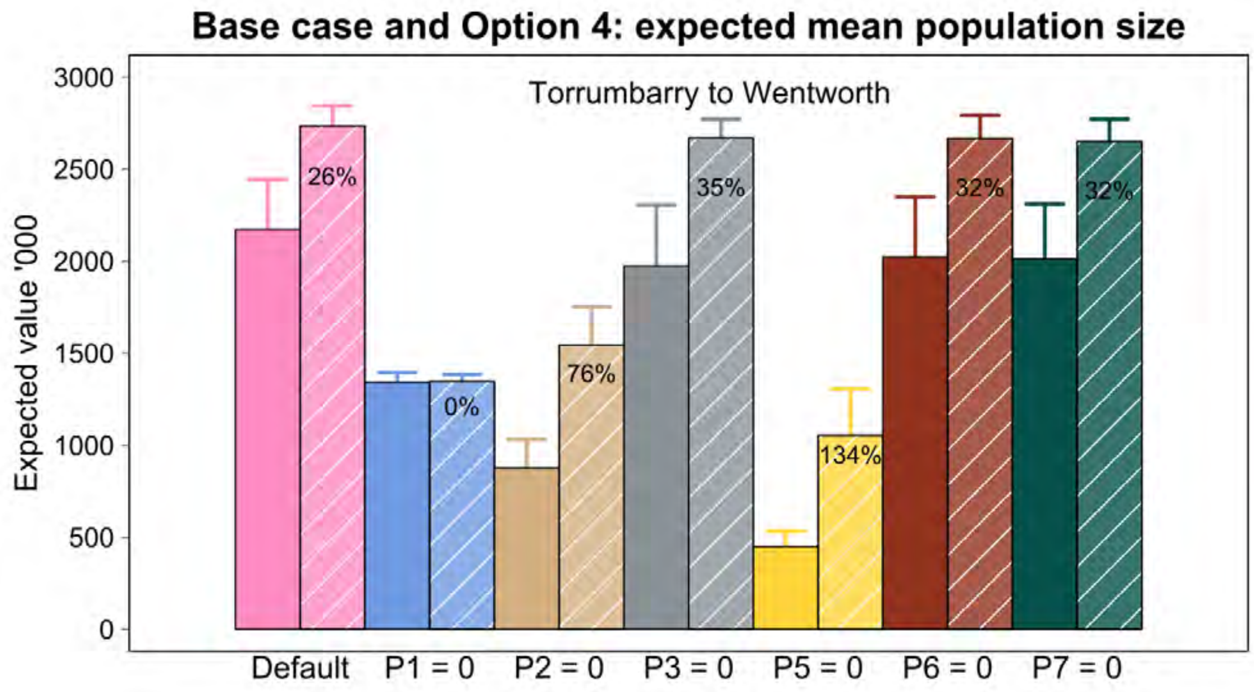


Figure A4.15. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 1 scenarios modelled for Golden Perch sensitivity in the Torrumbarry to Wentworth reach.

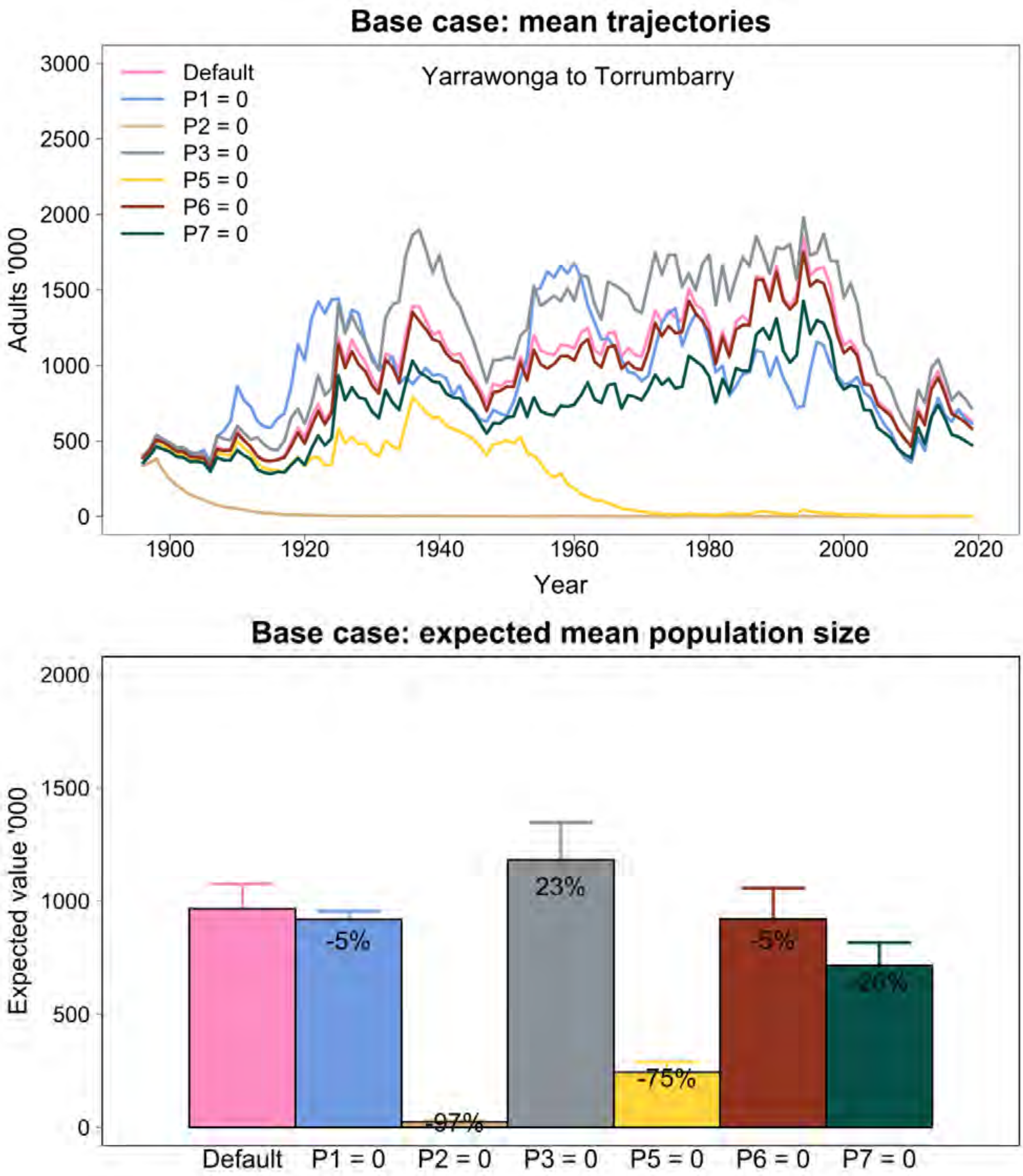


Figure A4.16. The Base case sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis in the Yarrawonga to Torrumbarry reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

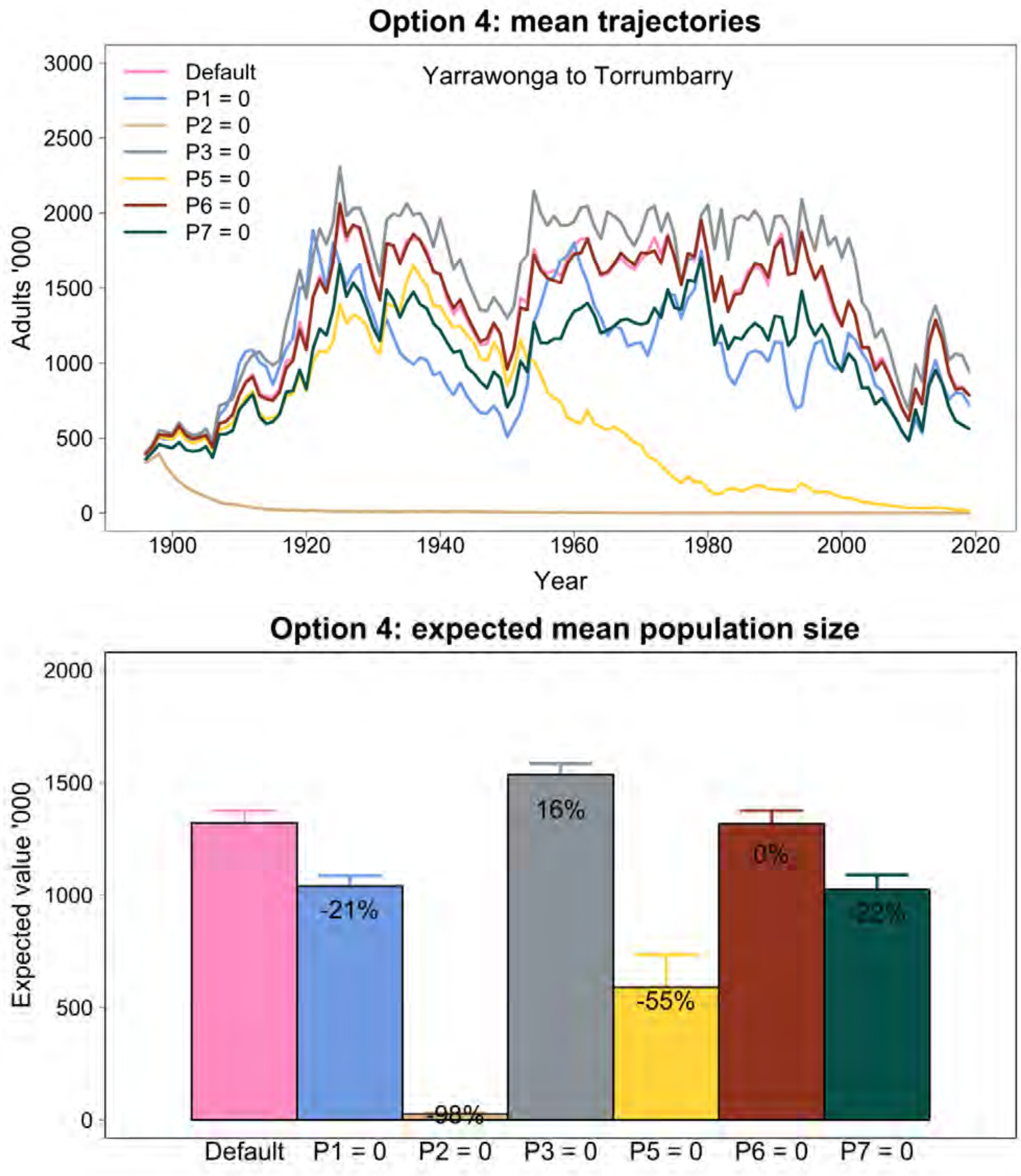


Figure A4.17. Option 4 sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis for the Yarrawonga to Torrumbarry reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

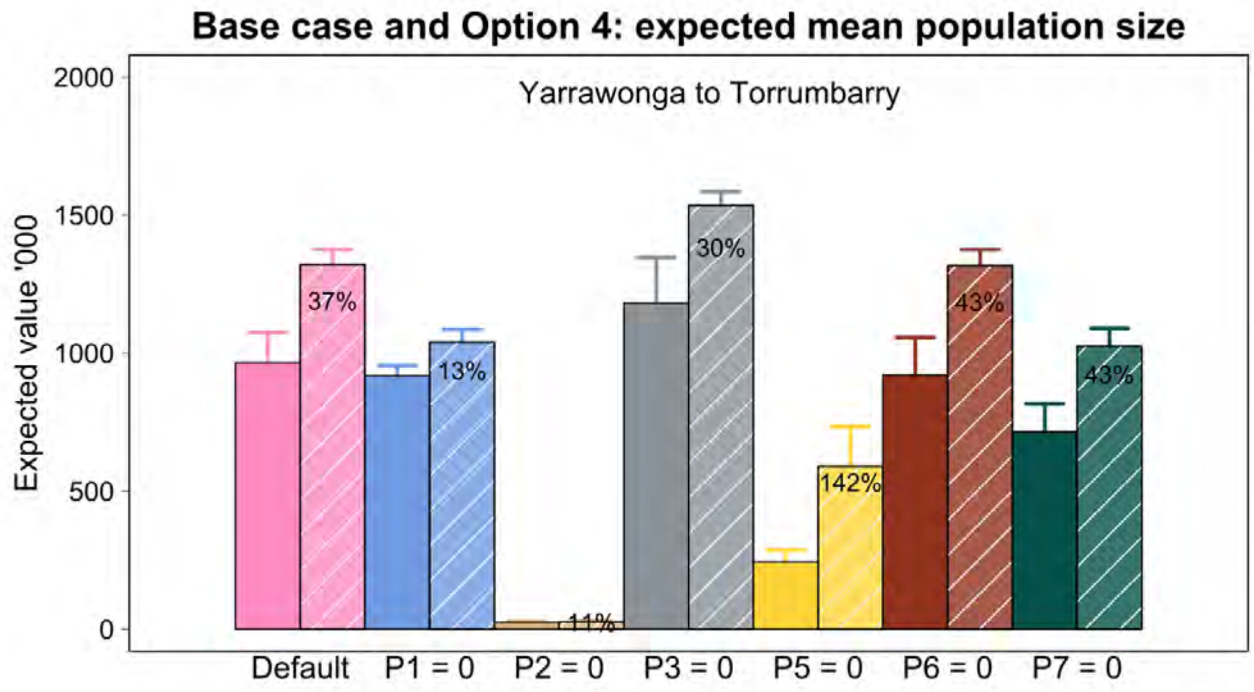


Figure A4.18. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 1 scenarios modelled for Golden Perch sensitivity in the Yarrawonga to Torrumbarry reach.

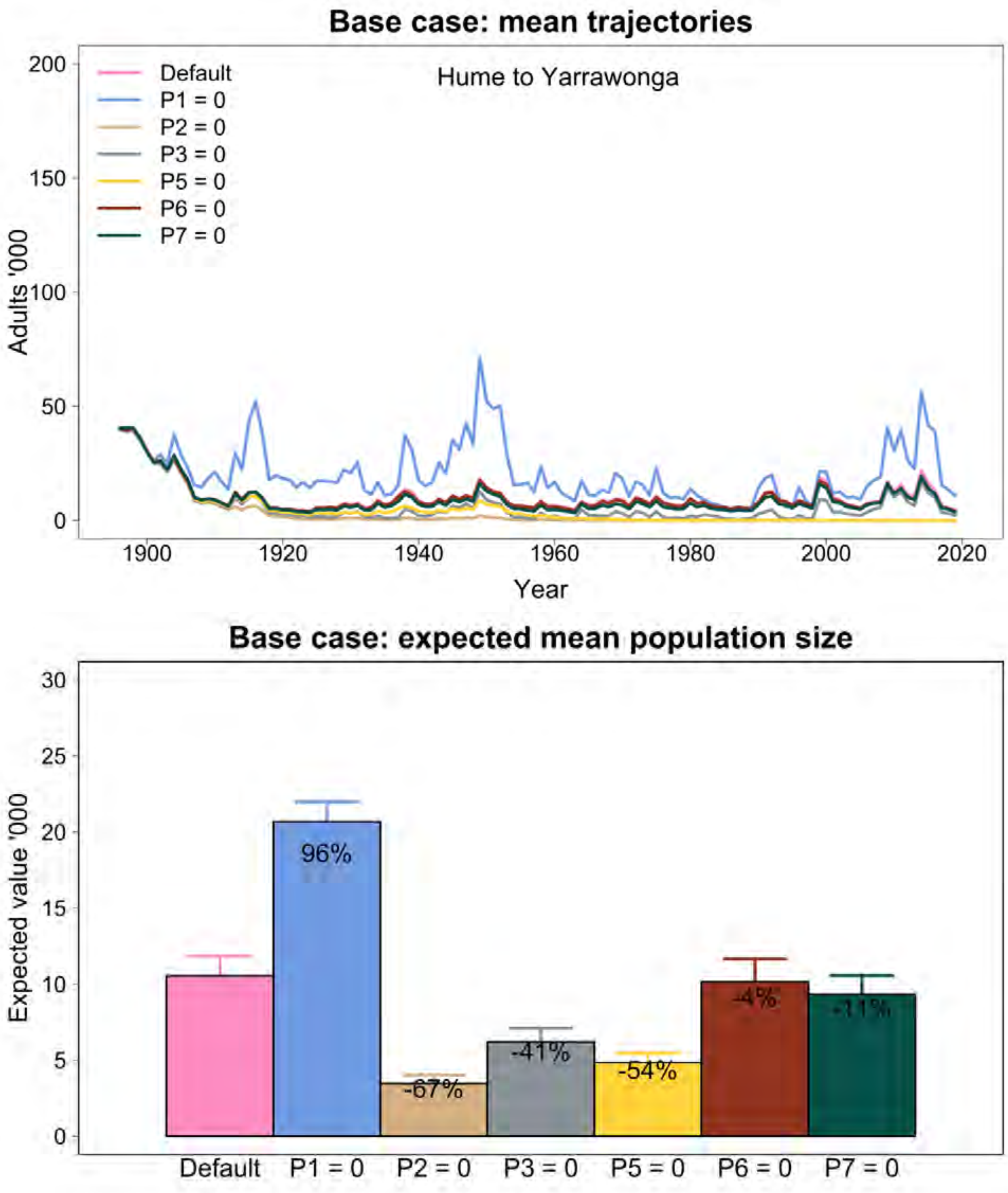


Figure A4.19. The Base case sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis for the Hume to Yarrawonga reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

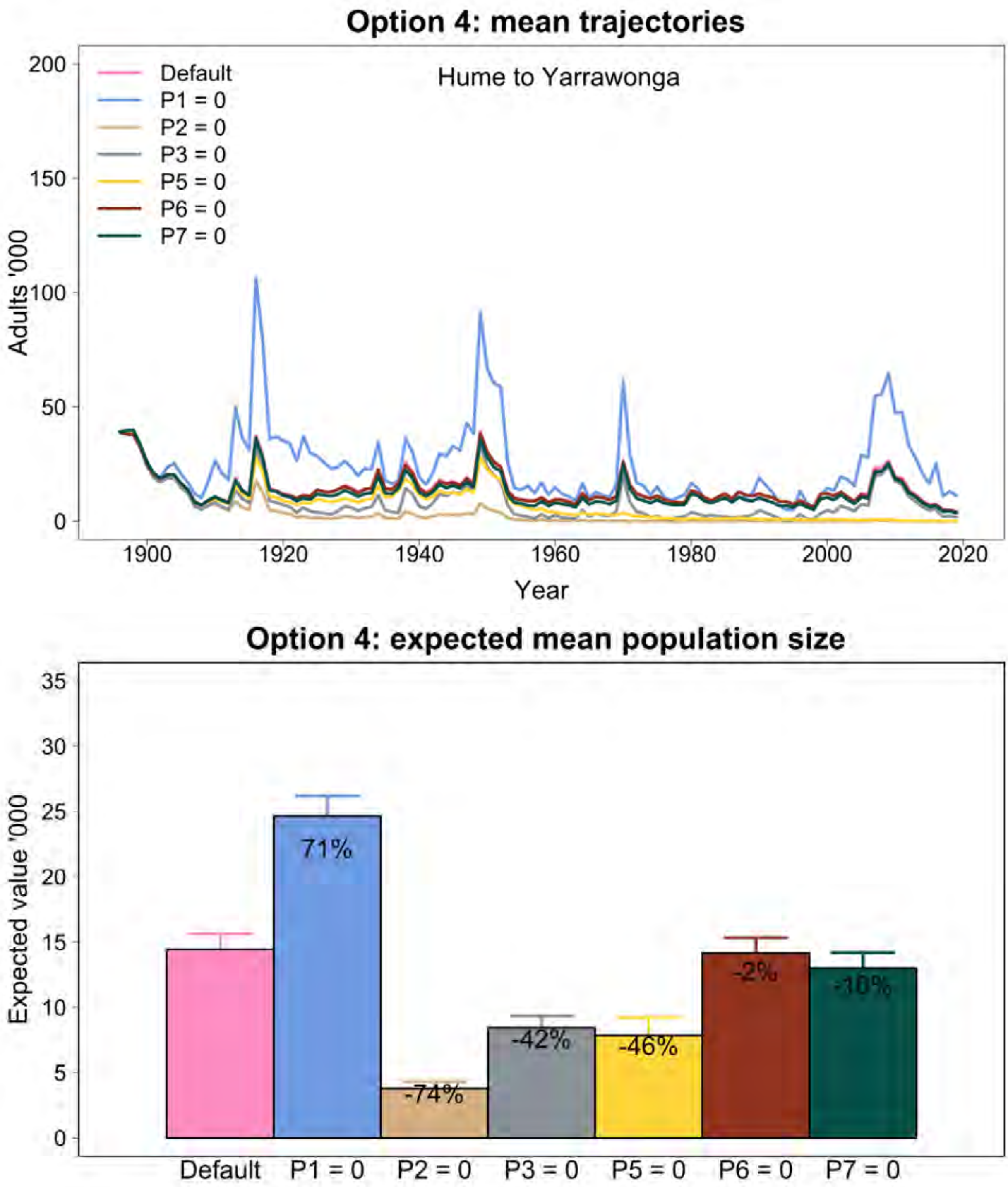


Figure A4.20. Option 4 sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis for the Hume to Yarrawonga reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

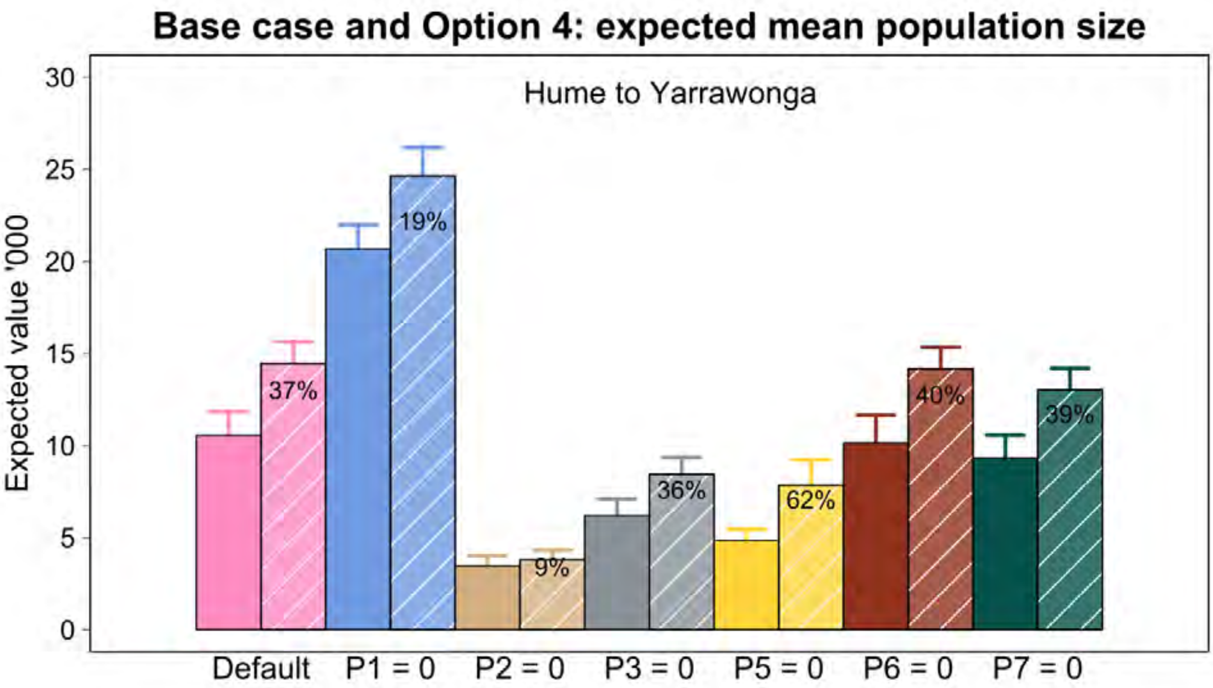


Figure A4.21. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 1 scenarios modelled for Golden Perch sensitivity in the Hume to Yarrawonga reach.

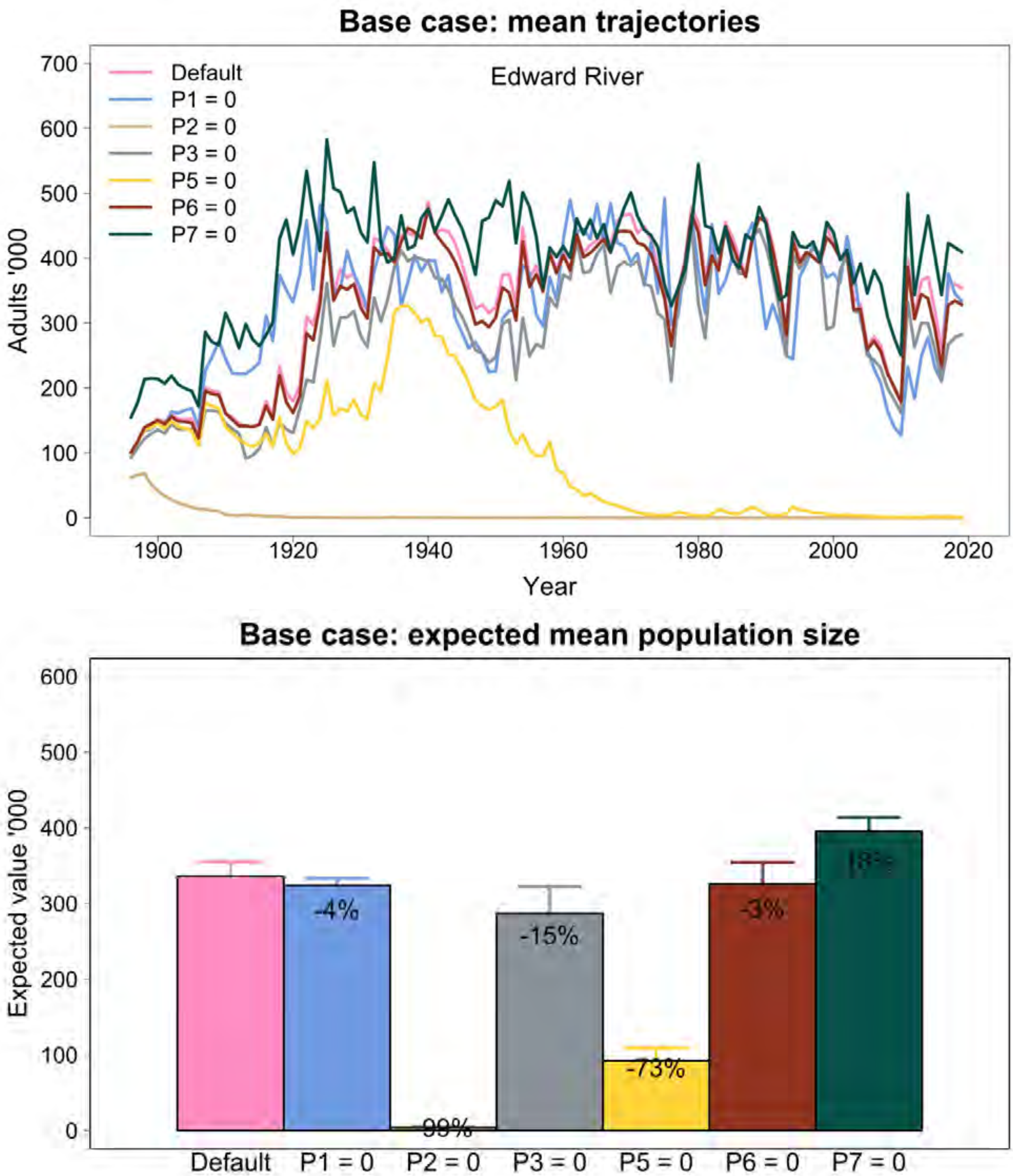


Figure A4.22. The Base case sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis for the Edward River. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

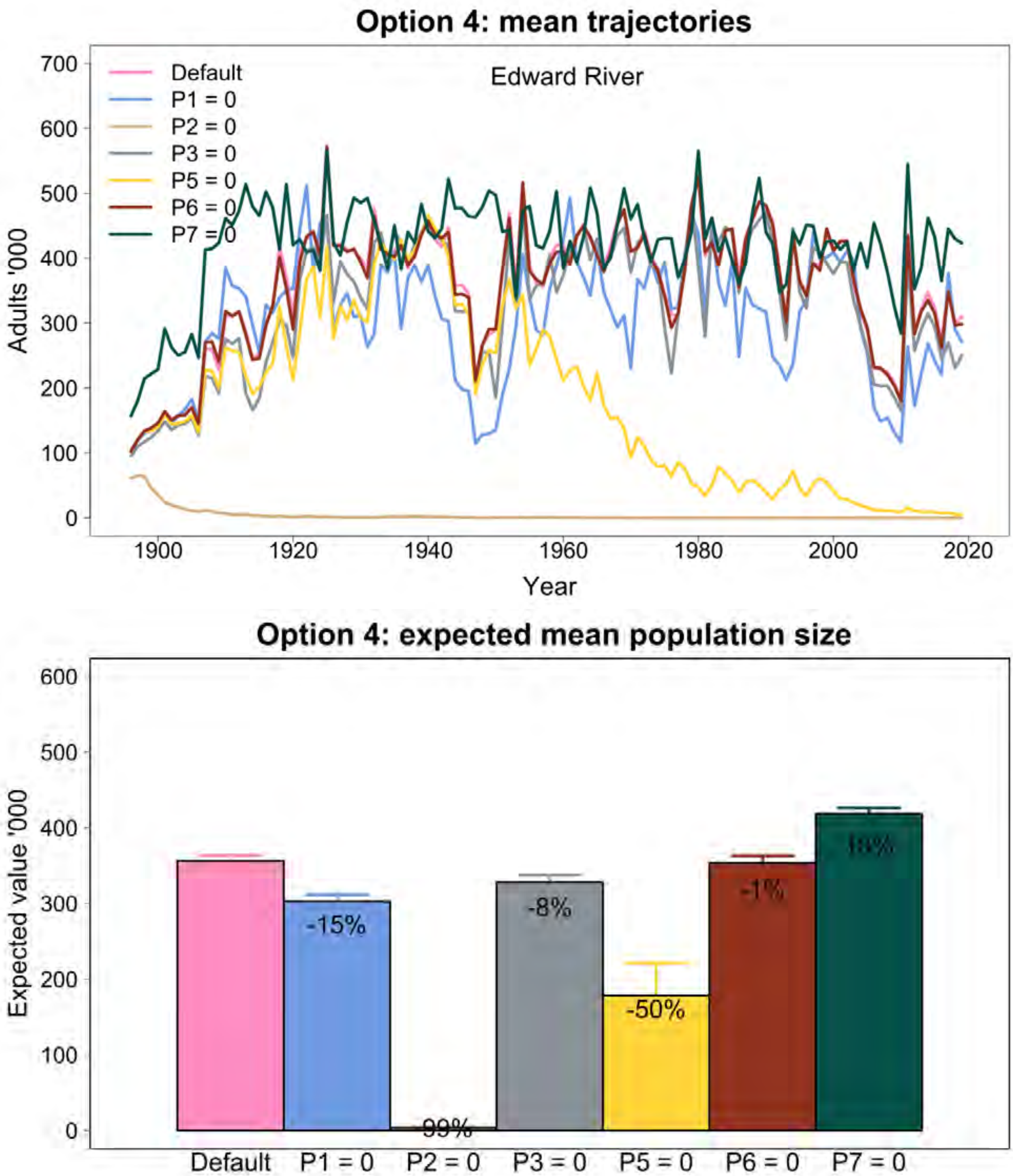


Figure A4.23. Option 4 sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis for the Edward River. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

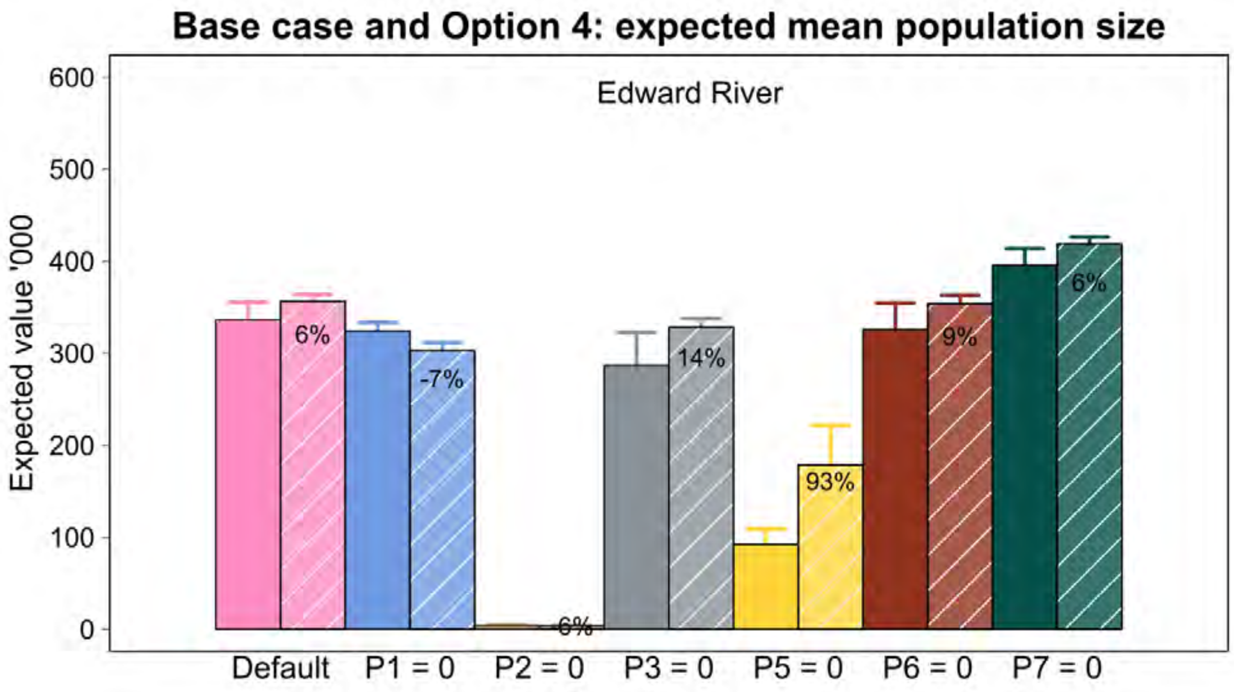


Figure A4.24. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 1 scenarios modelled for Golden Perch sensitivity in the Edward River.

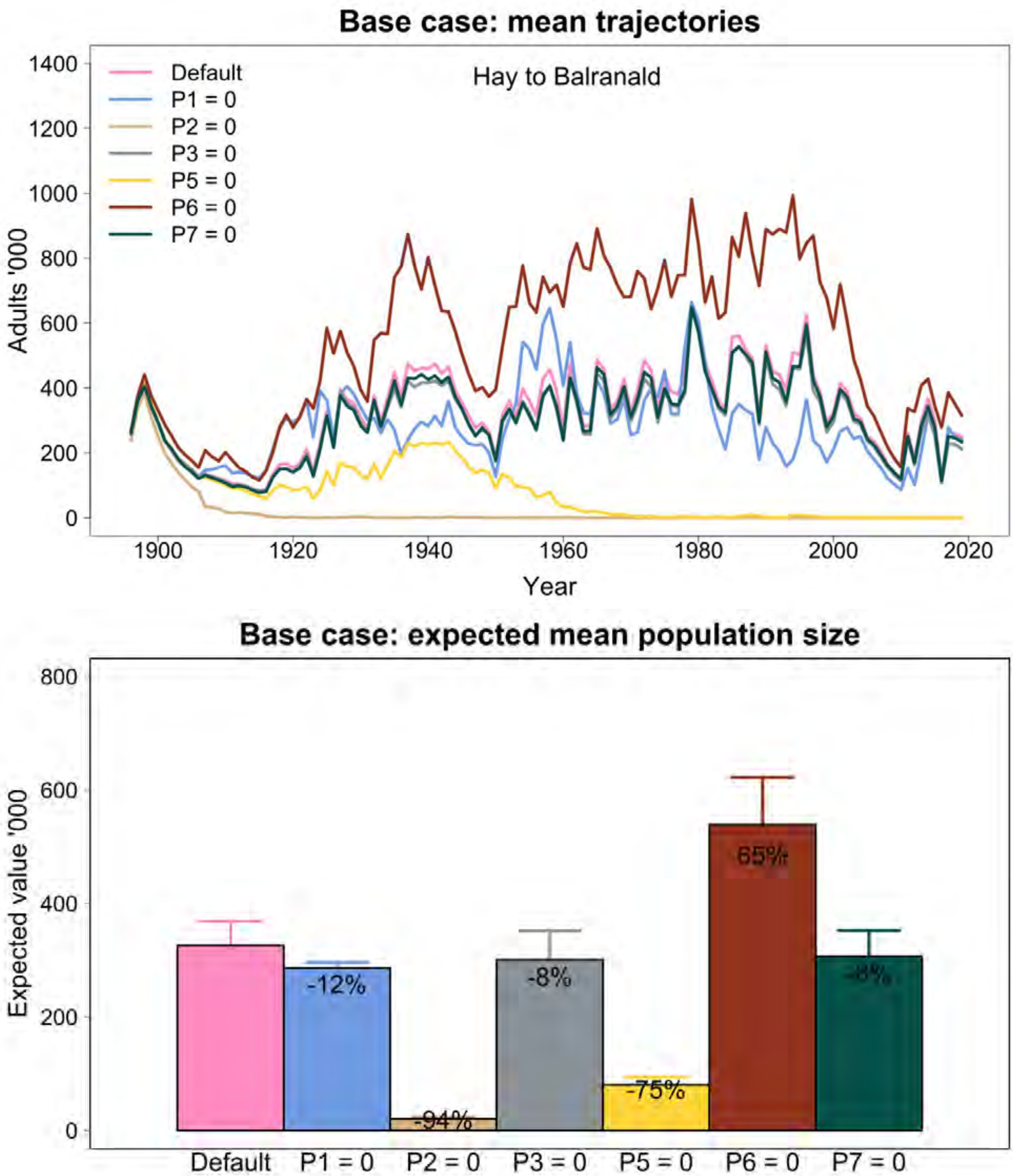


Figure A4.25. The Base case sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis for the Hay to Balranald reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

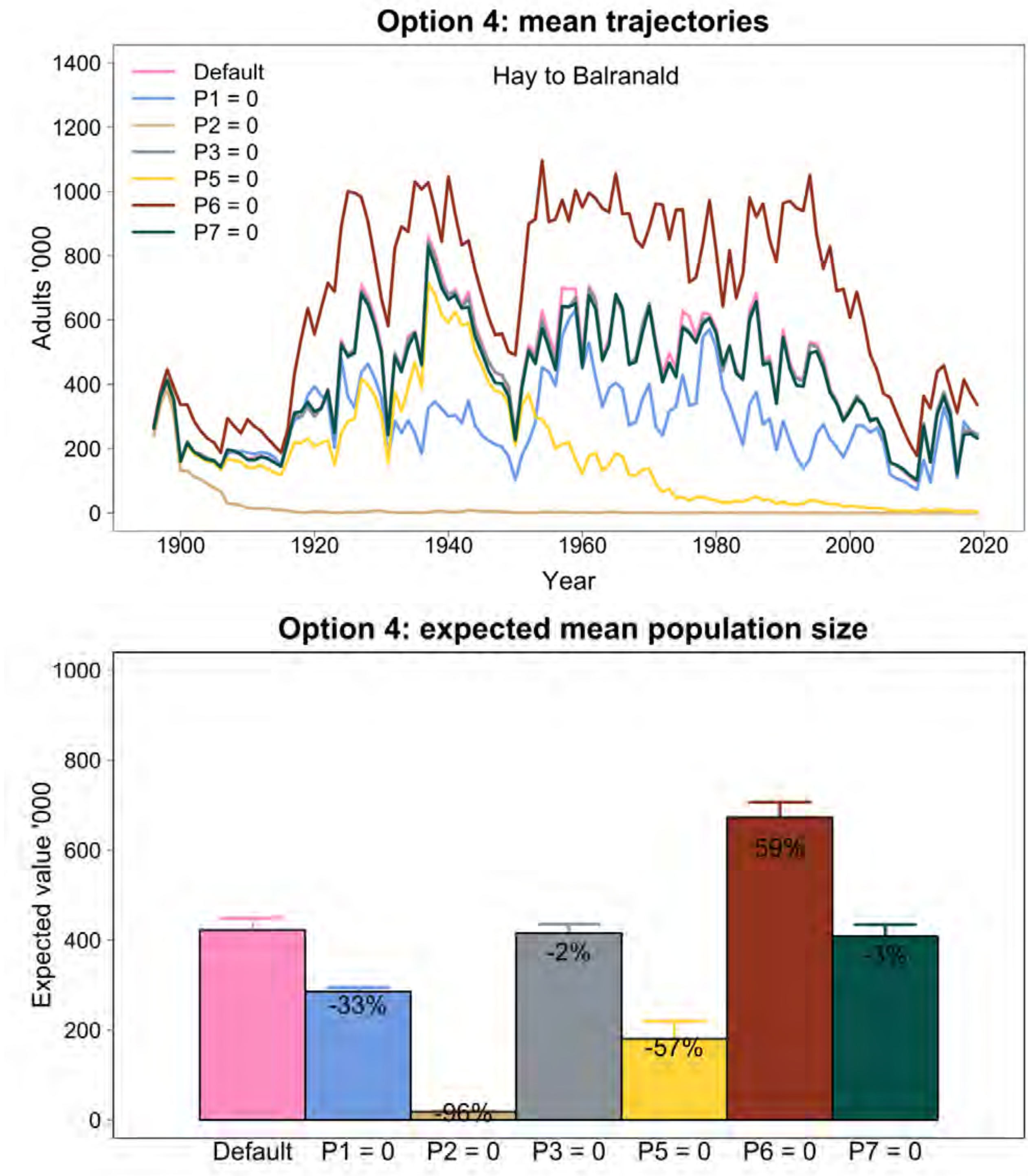


Figure A4.26. Option 4 sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis for the Hay to Balranald reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

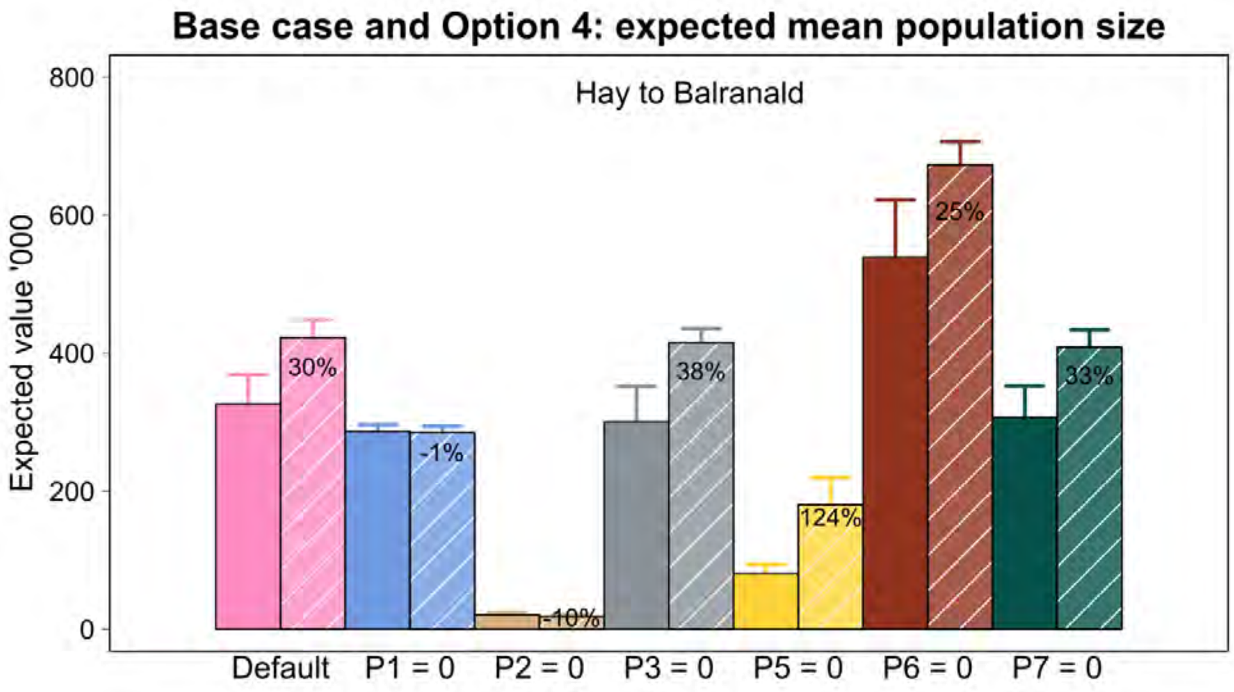


Figure A4.27. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 1 scenarios modelled for Golden Perch sensitivity in the Hay to Balranald reach.

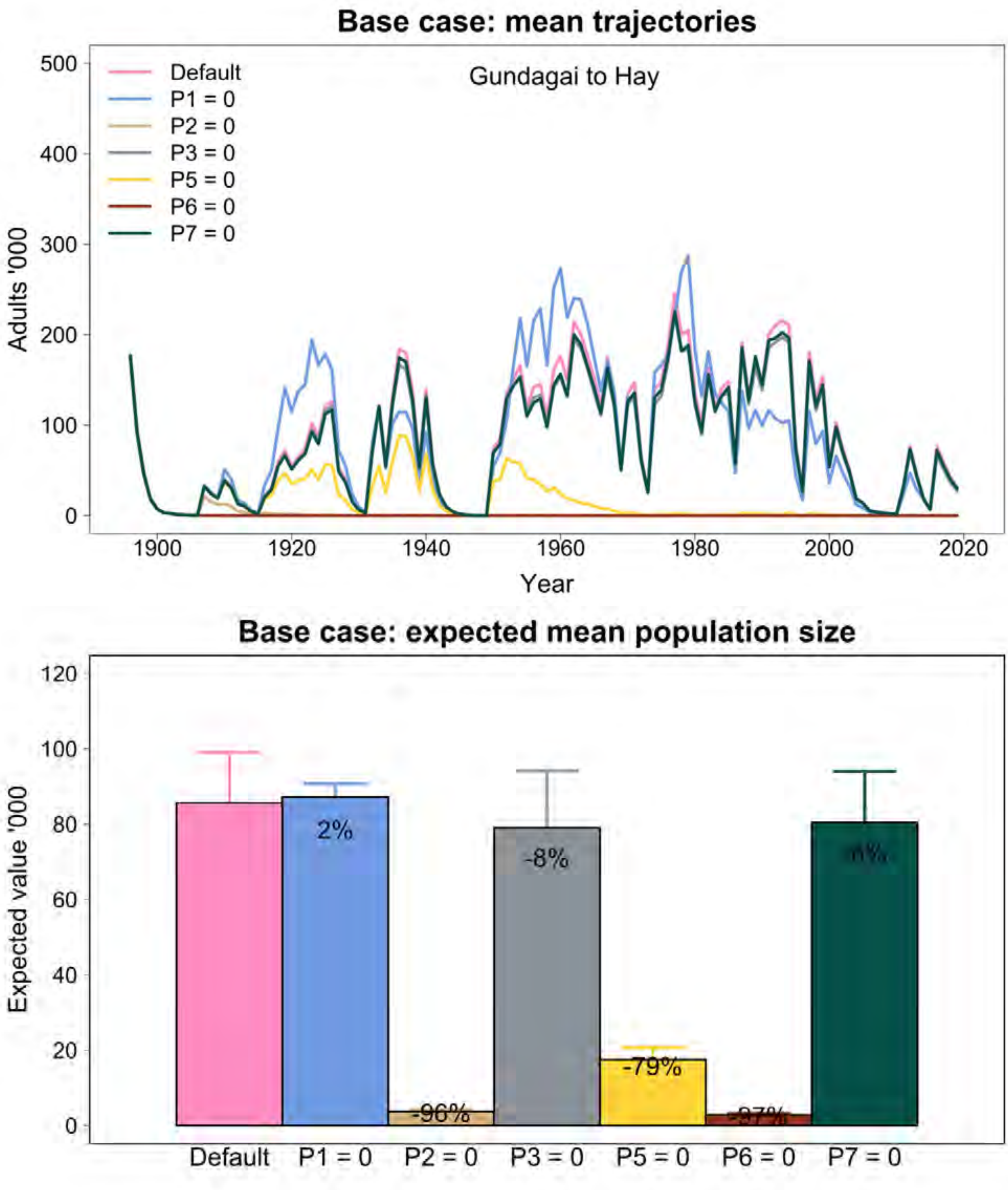


Figure A4.28. The Base case sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis for the Gundagai to Hay reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

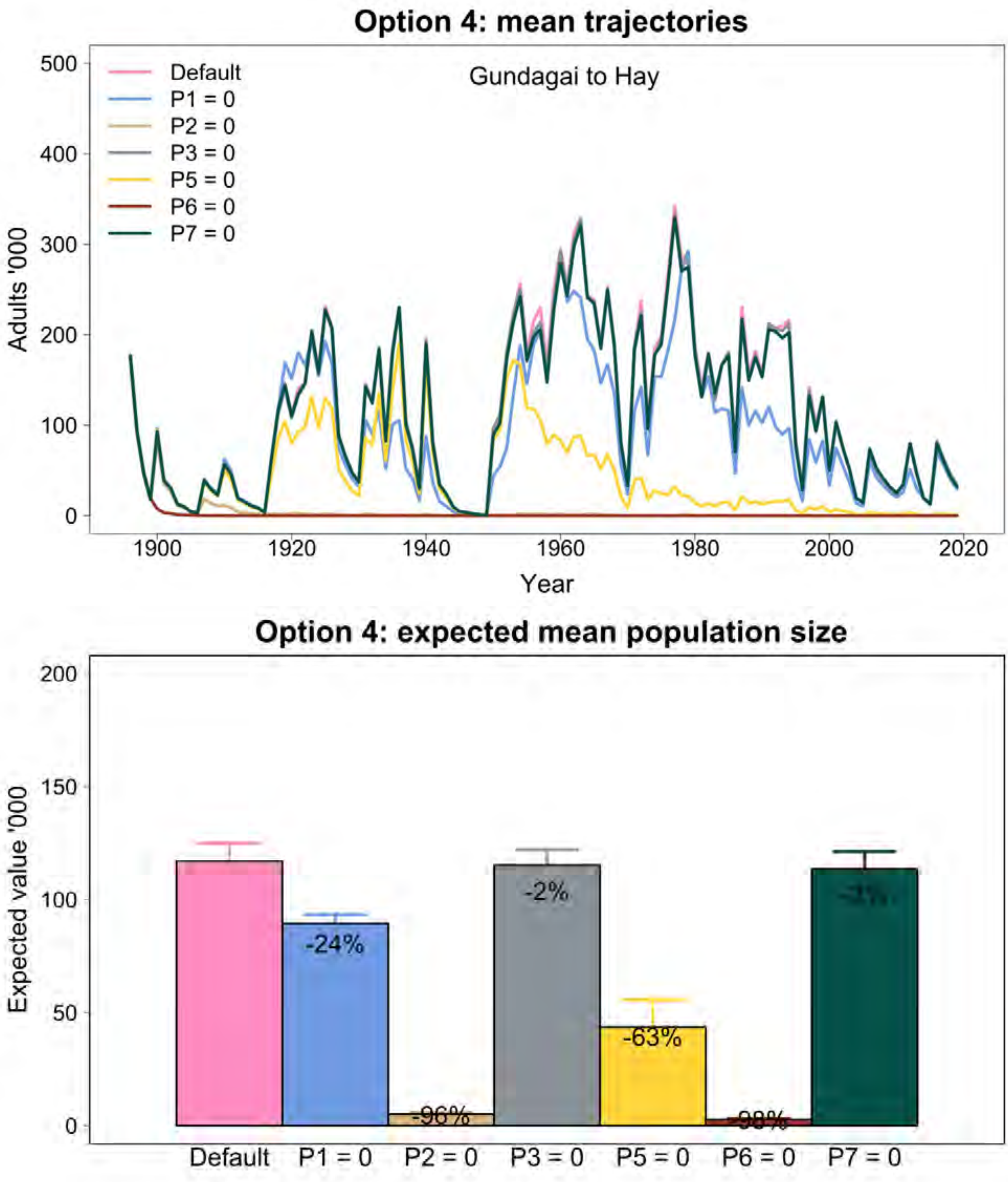


Figure A4.29. Option 4 sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis for the Gundagai to Hay reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

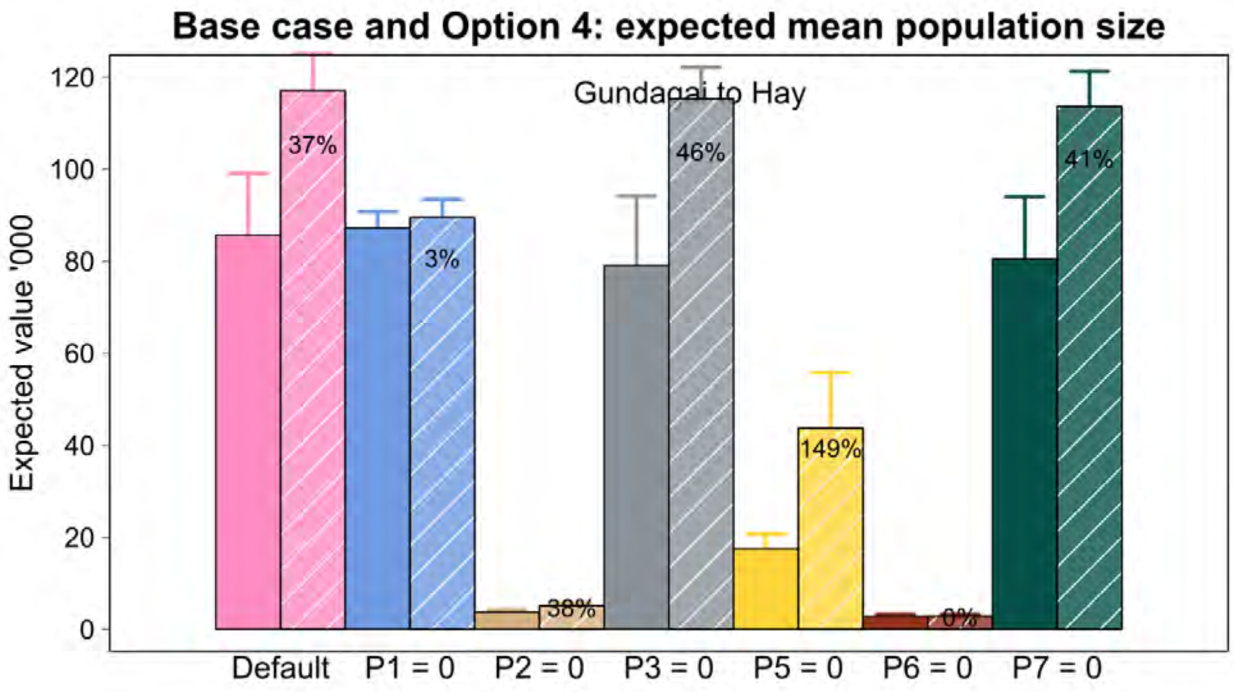
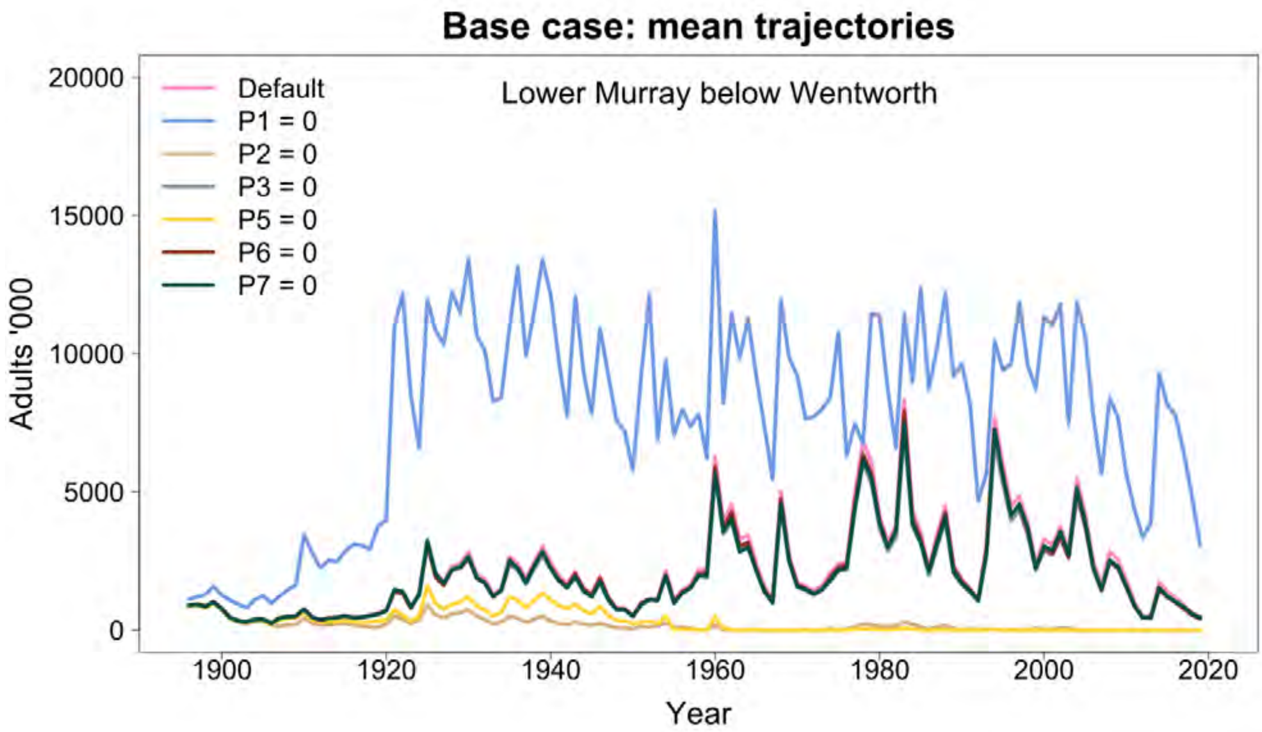


Figure A4.30. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 1 scenarios modelled for Golden Perch sensitivity in the Gundagai to Hay reach.



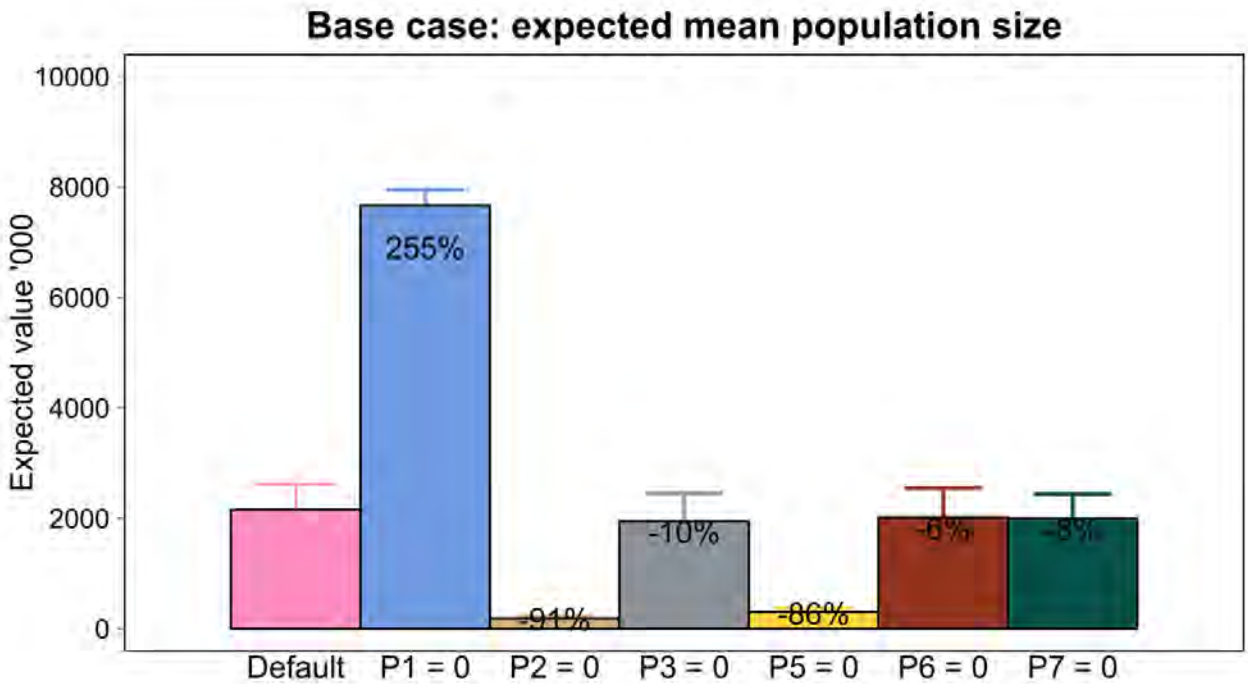


Figure A4.31. The Base case sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis for the Lower Murray below Wentworth reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

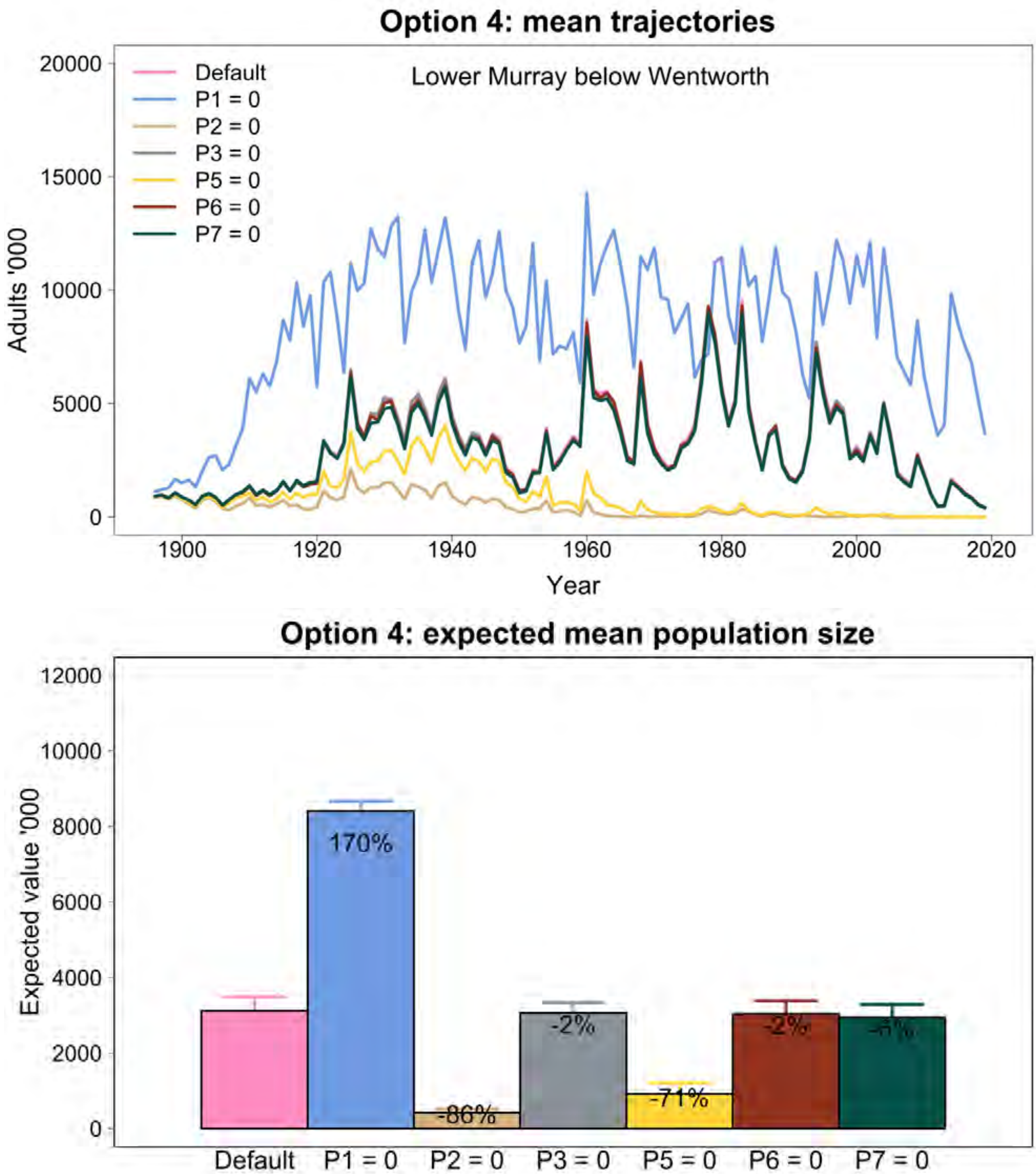


Figure A4.32. Option 4 sensitivity 1 scenarios modelled in the Golden Perch sensitivity analysis for the Lower Murray below Wentworth reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

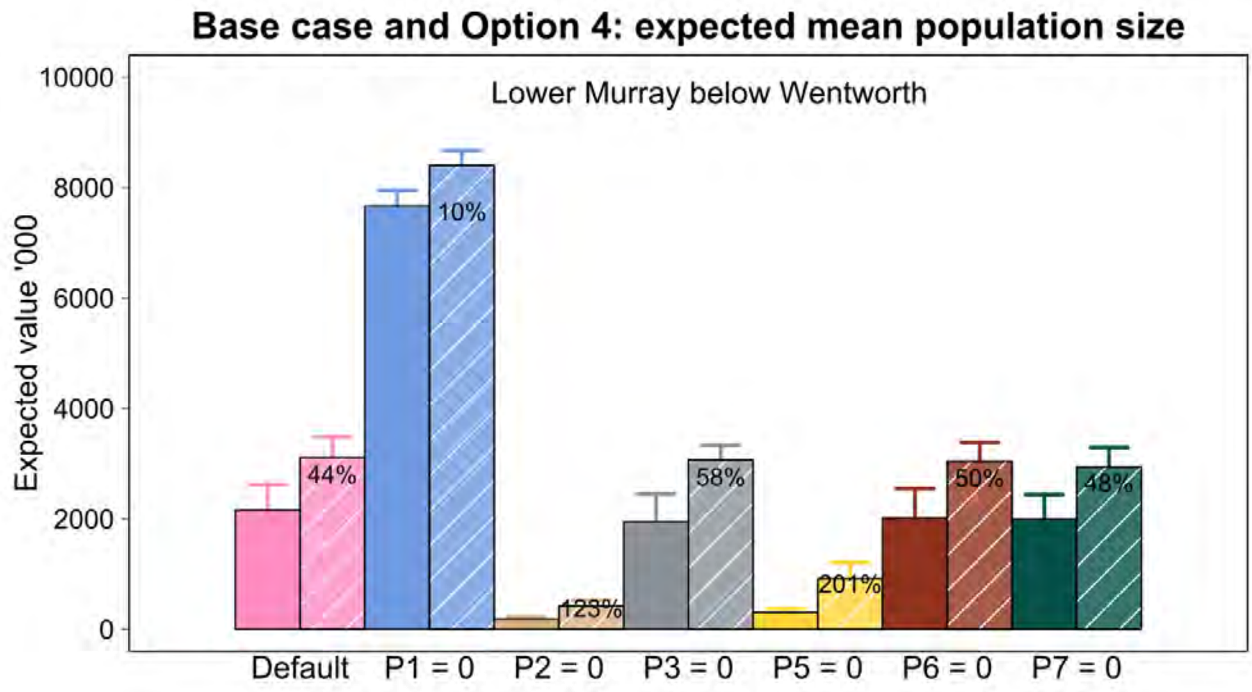


Figure A4.33. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 1 scenarios modelled for Golden Perch sensitivity in the Lower Murray below Wentworth reach.

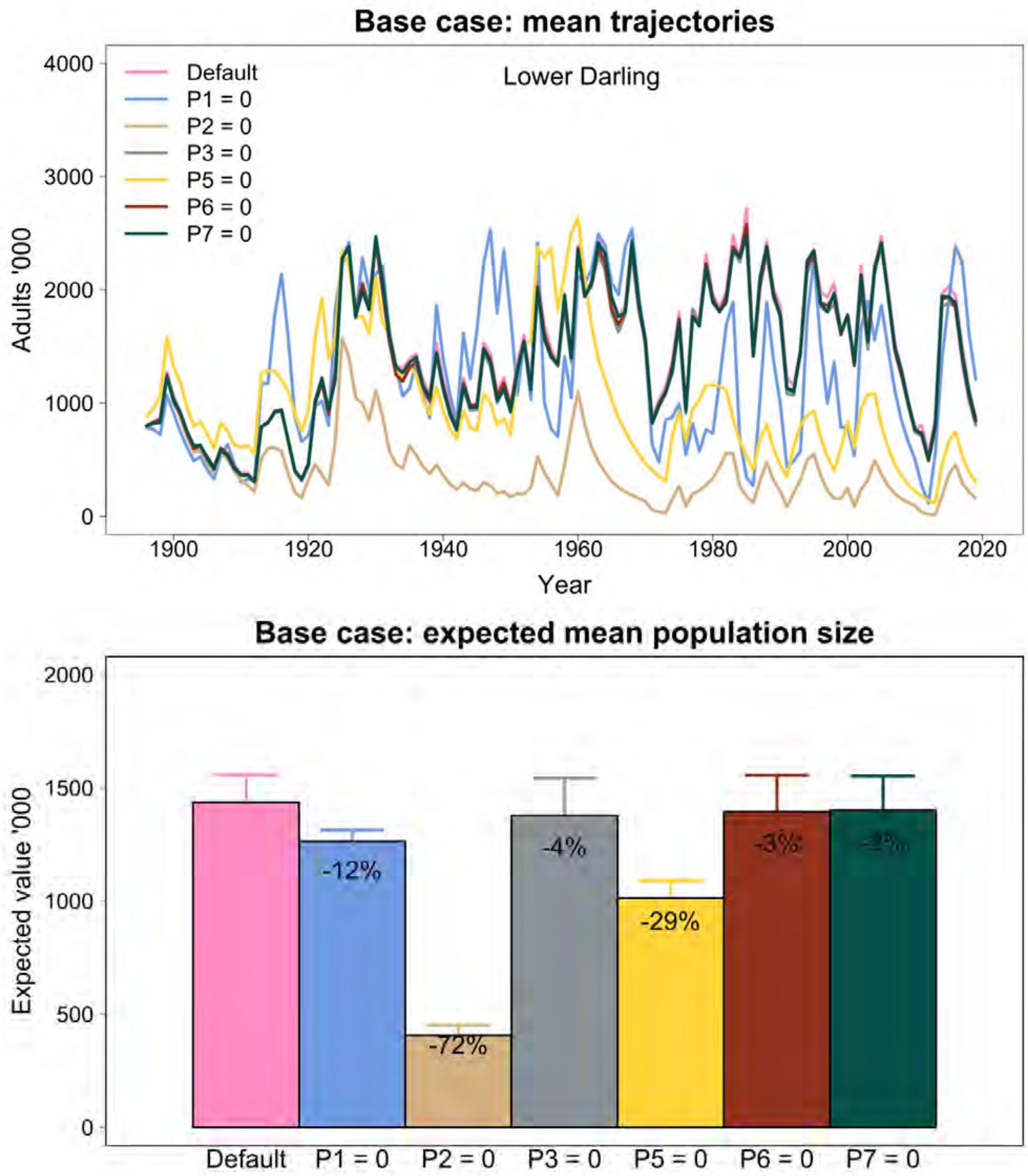


Figure A4.34. The Base case sensitivity 1 scenarios modelled for Golden Perch sensitivity analysis in the Lower Darling reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

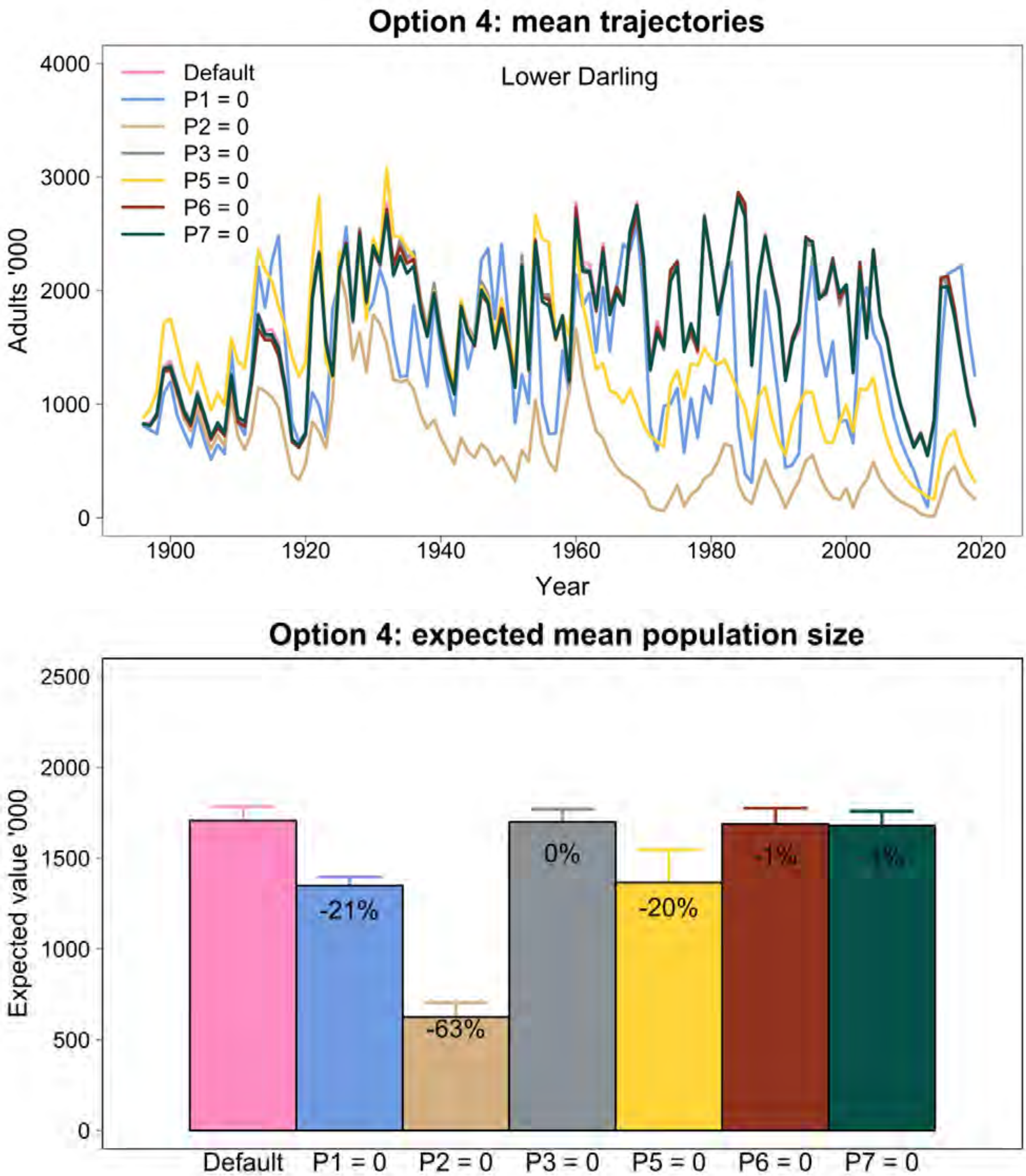


Figure A4.35. Option 4 sensitivity 1 scenarios modelled for Golden Perch sensitivity analysis in the Lower Darling. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

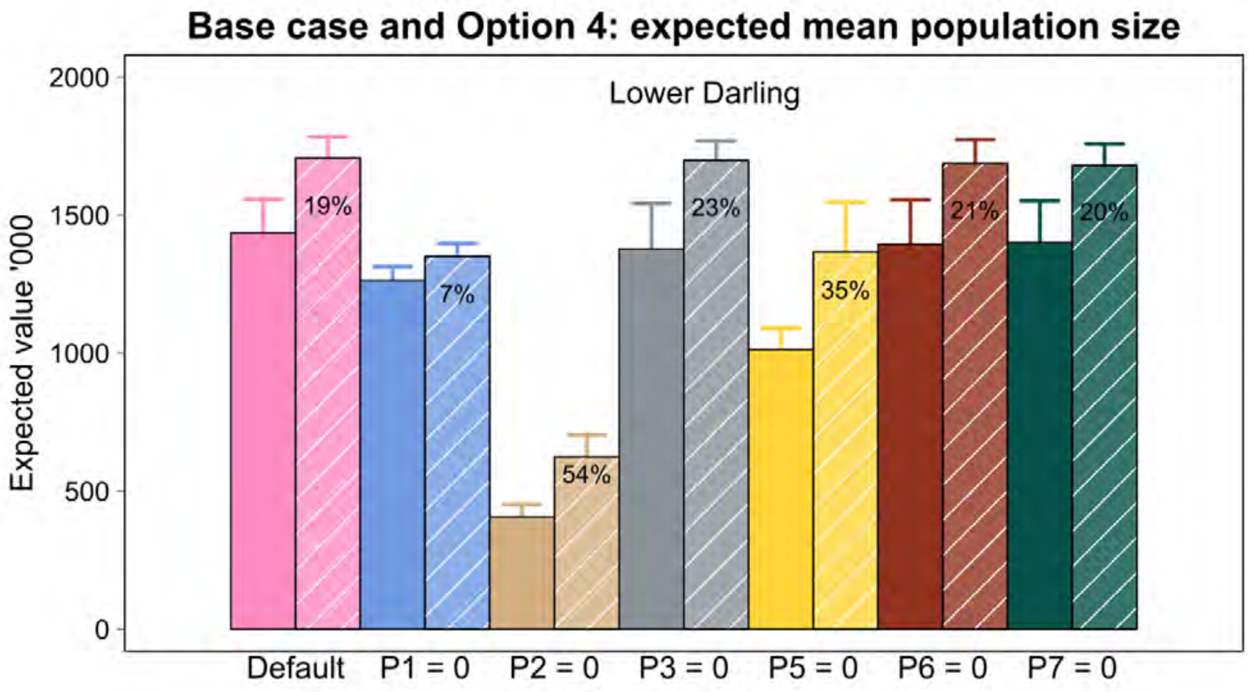


Figure A4.36. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 1 scenarios modelled for Golden Perch sensitivity in the Lower Darling.

Second sensitivity analysis

The purpose of this second analysis was to make subtle changes to movement from the Lower Murray below Wentworth reach, as it was expected that this reach contributes significantly to Golden Perch dynamics, and then to assess other elements of the model that were considered likely to influence the population modelling outcomes. The second approach in undertaking the sensitivity analysis was to make targeted adjustments to movement from the Lower Murray, changing the initial population size, changing the immigration level from the Northern MDB and combining altered movement and altered immigration to assess whether any of these changes would alter the interpretation of the results.

The following changes were made:

(1) movement from the Lower Murray below Wentworth reach upstream to the Torrumbarry to Wentworth reach was increased: adult movement ×2 and juvenile movement ×5 (+P1P2)
(2) the adult movement rate from the Lower Murray below Wentworth reach upstream to the Torrumbarry to Wentworth reach was decreased to the same level as that of juveniles (AP1P2)
(3) the adult initial population size was set to half the adult carrying capacity of each reach (IP)
(4) increased immigration from the Northern MDB (M2)
(5) combined changes (2) and (4) (AP1P2+M2).

The second sensitivity analysis for the Total RRCP Populations indicated that the outcomes were highly sensitive to the initial population size (Figure A4.40 and Figure A4.41). Increasing movement from the Lower Murray to the Torrumbarry to Wentworth reach had a markedly negative impact in comparison with the default parameterisation for the Total RRCP populations. This was due to too many Golden Perch migrating from the Lower Murray, resulting in an insufficient breeding population remaining and causing the population dynamics to decline overall (see the mean adult trajectories in each figure). For most renditions of the model, the mean trajectories remained low for the first 25 years; however, increasing the initial population size caused the modelled outcomes in the first 25 years to be higher, hence increasing the expected mean population size. The initial populations were set at the default levels due to the first modelled year being 1896, which was impacted by the

'Federation Drought' (Verdon-Kidd and Kiem 2009); thus, it was appropriate to set the initial population sizes at a lower level. The tested scenarios had higher expected mean population sizes for the Base case in comparison with Option 4 (compare Figure A4.40 and Figure A4.41). As was the case in the first sensitivity analysis, when comparing the Base case with Option 4 for each scenario, Option 4 generated a higher expected mean population size for the Total RRCP Populations for all sensitivity scenarios (Figure A4.42).

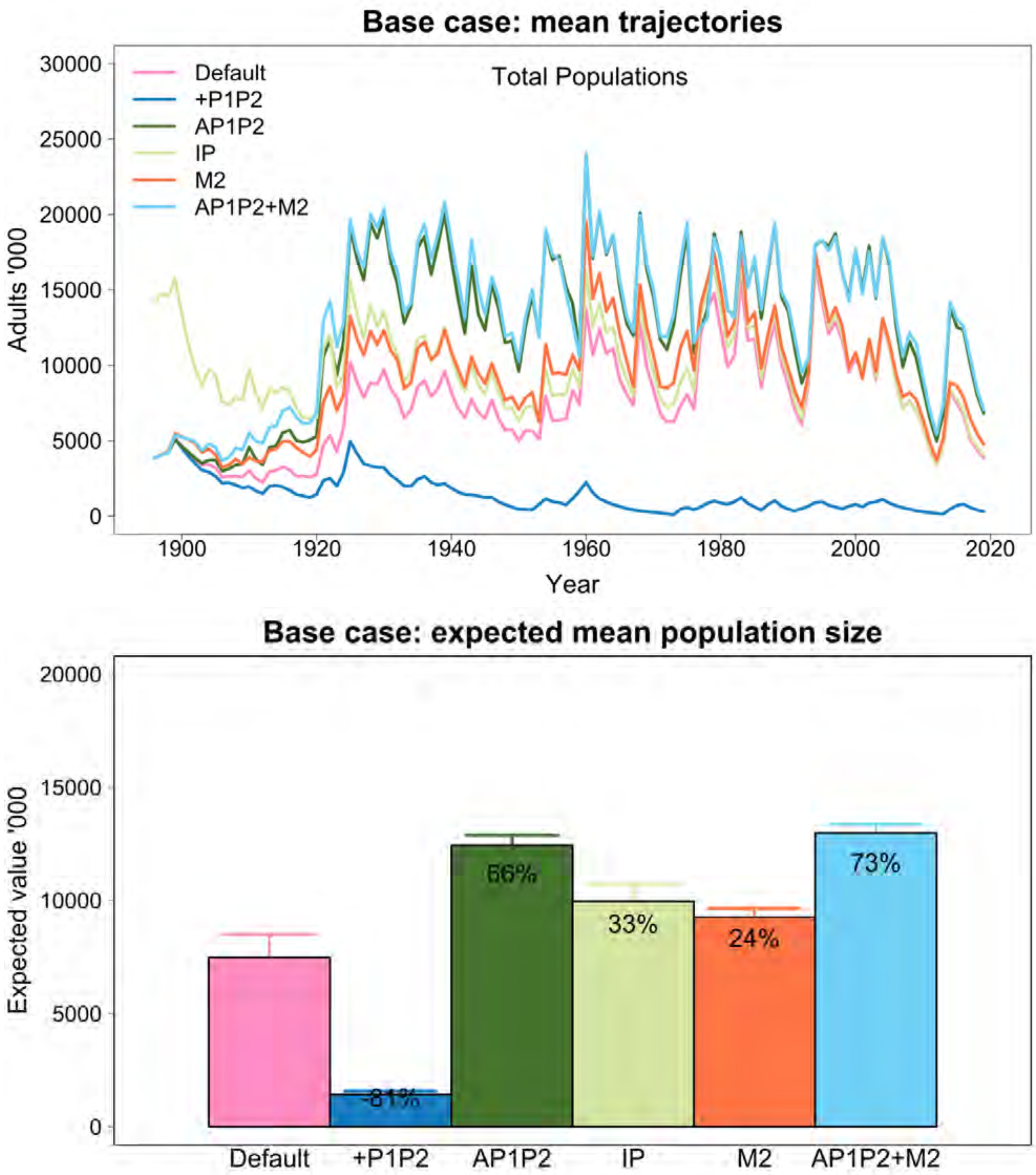


Figure A4.37. The Base case sensitivity 2 scenarios modelled for Golden Perch sensitivity analysis aggregated across all reaches in this study in the southern MDB. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

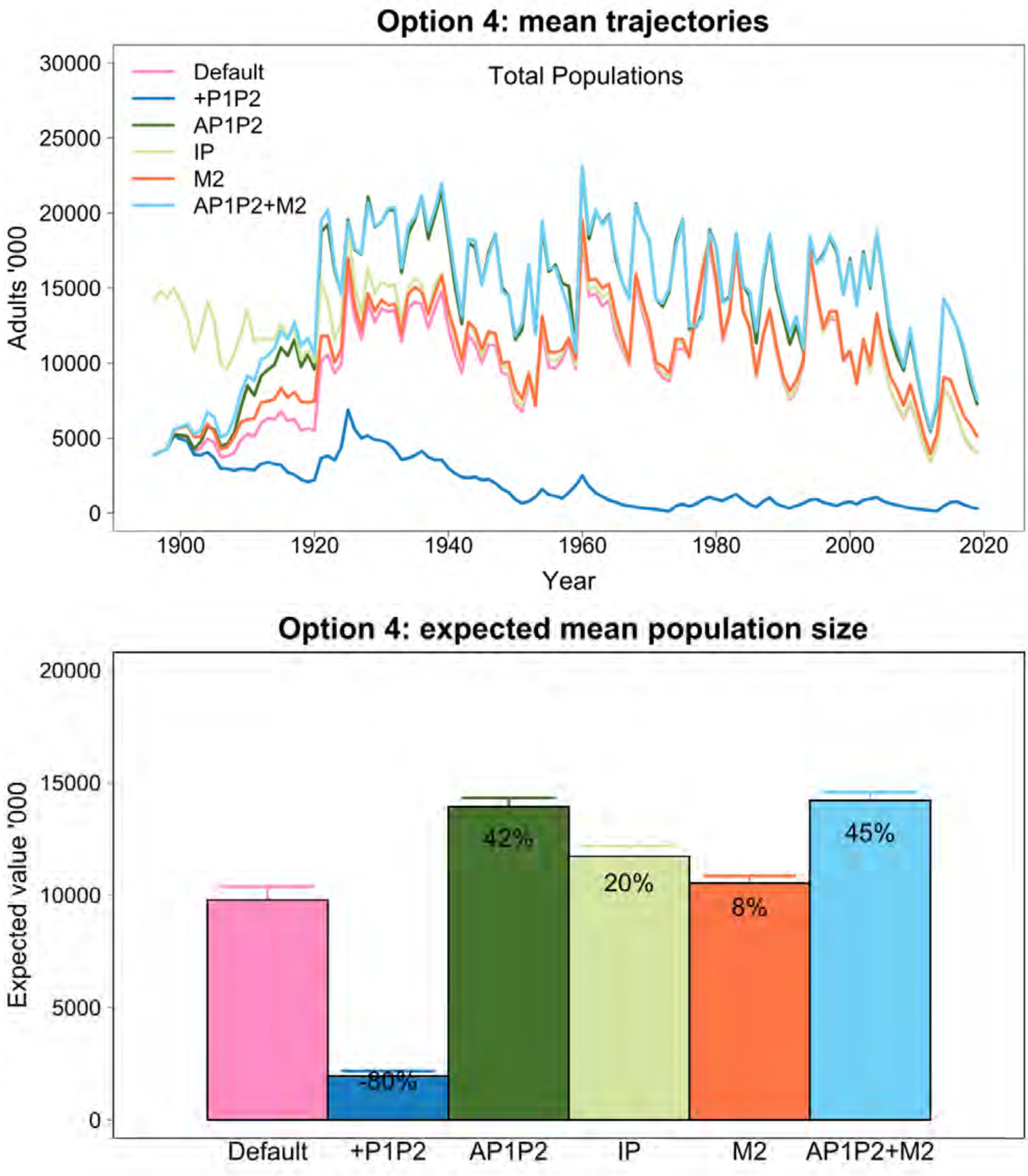


Figure A4.38. Option 4 sensitivity 2 scenarios modelled for Golden Perch sensitivity analysis aggregated across all reaches in this study in the southern MDB. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

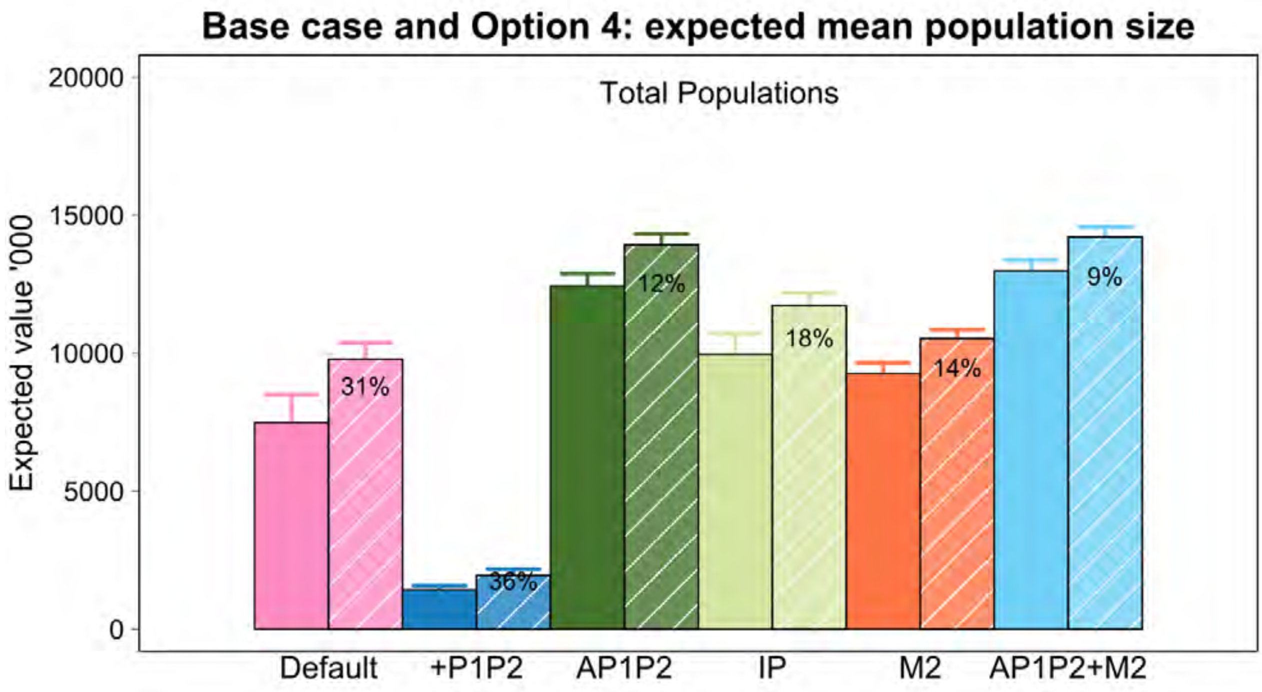


Figure A4.39. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 2 scenarios modelled for Golden Perch sensitivity analysis aggregated across all reaches in this study in the southern MDB.

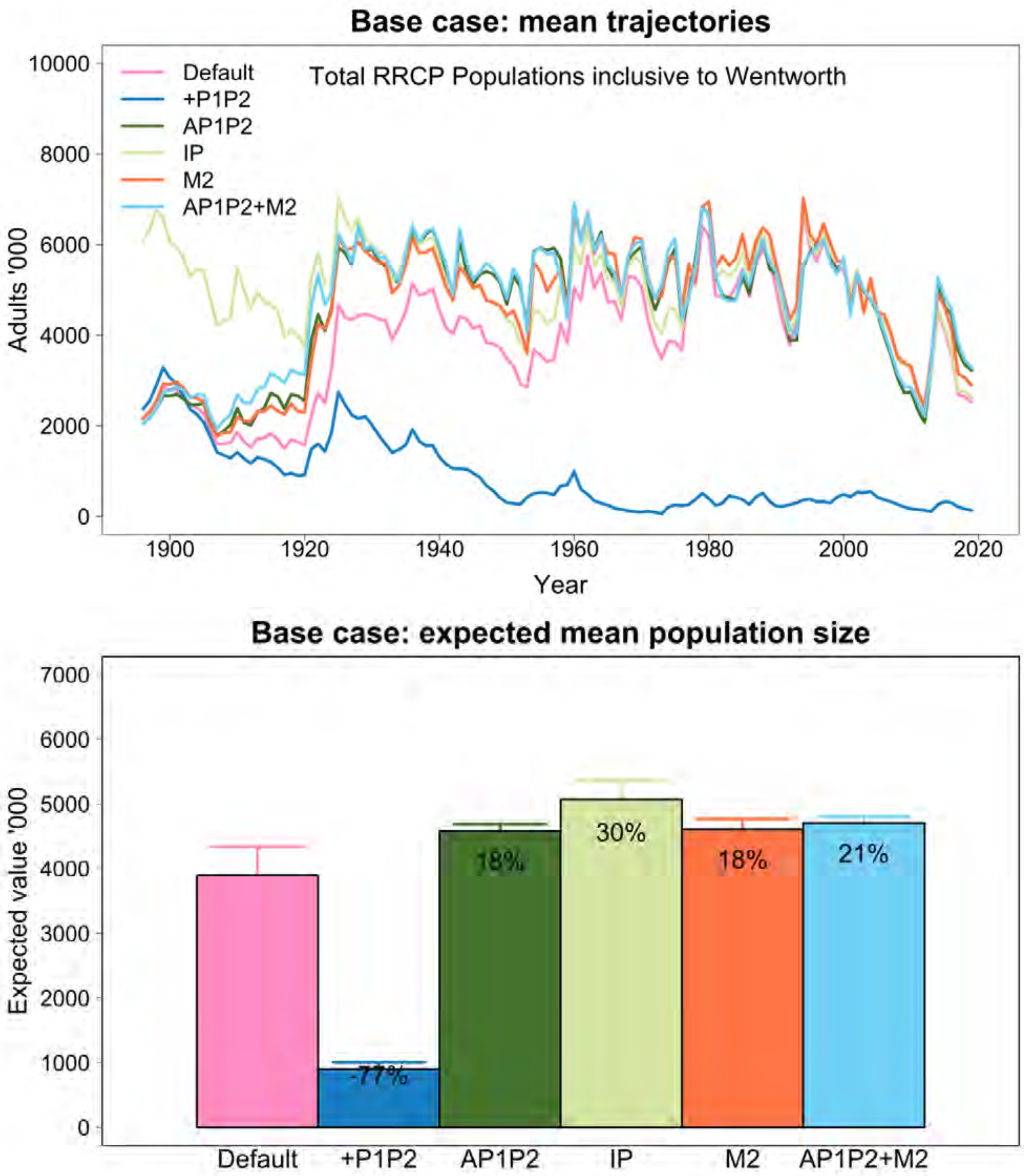


Figure A4.40. The Base case sensitivity 2 scenarios modelled for Golden Perch sensitivity analysis aggregated across all modelled RRCP focal zones, together with the Wakool Junction to Wentworth reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

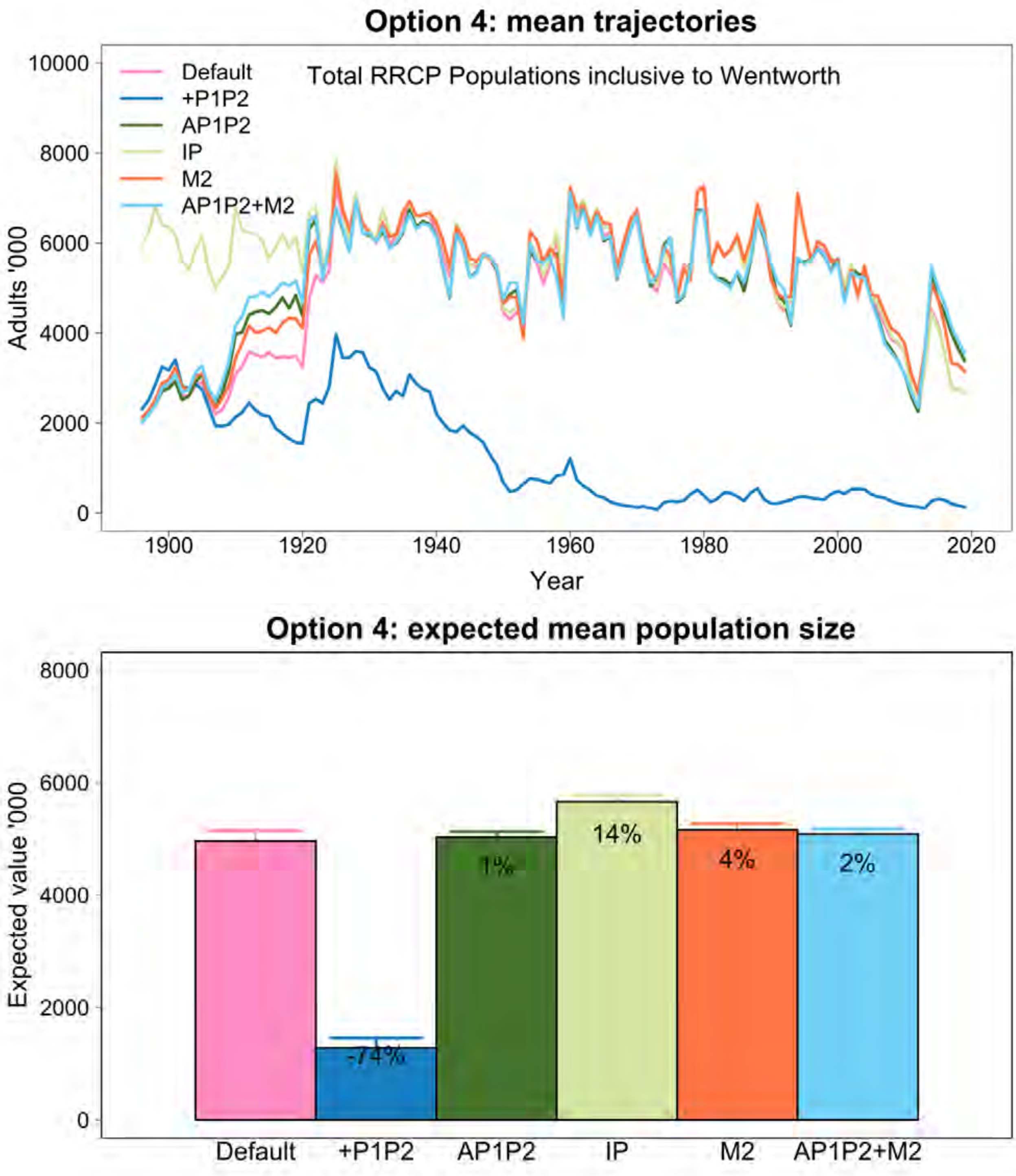


Figure A4.41. Option 4 sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis aggregated across all modelled RRCP focal zones, together with the Wakool Junction to Wentworth reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

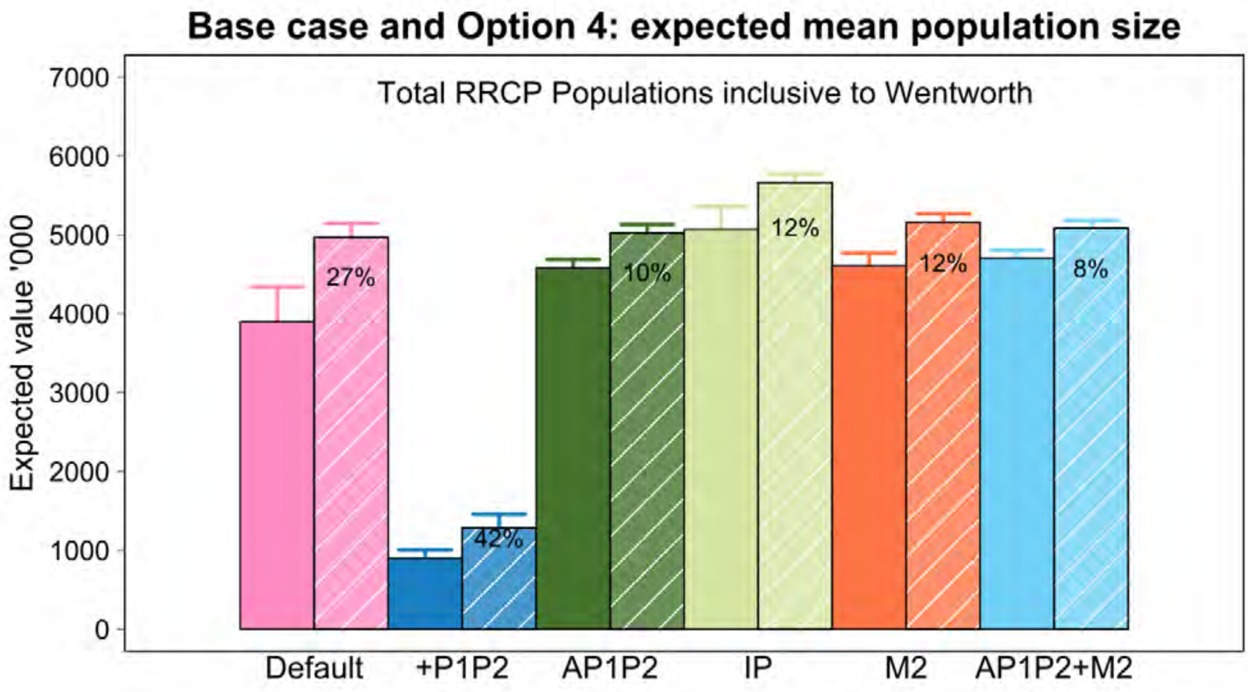


Figure A4.42. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis aggregated across all modelled RRCP focal zones, together with the Wakool Junction to Wentworth reach.

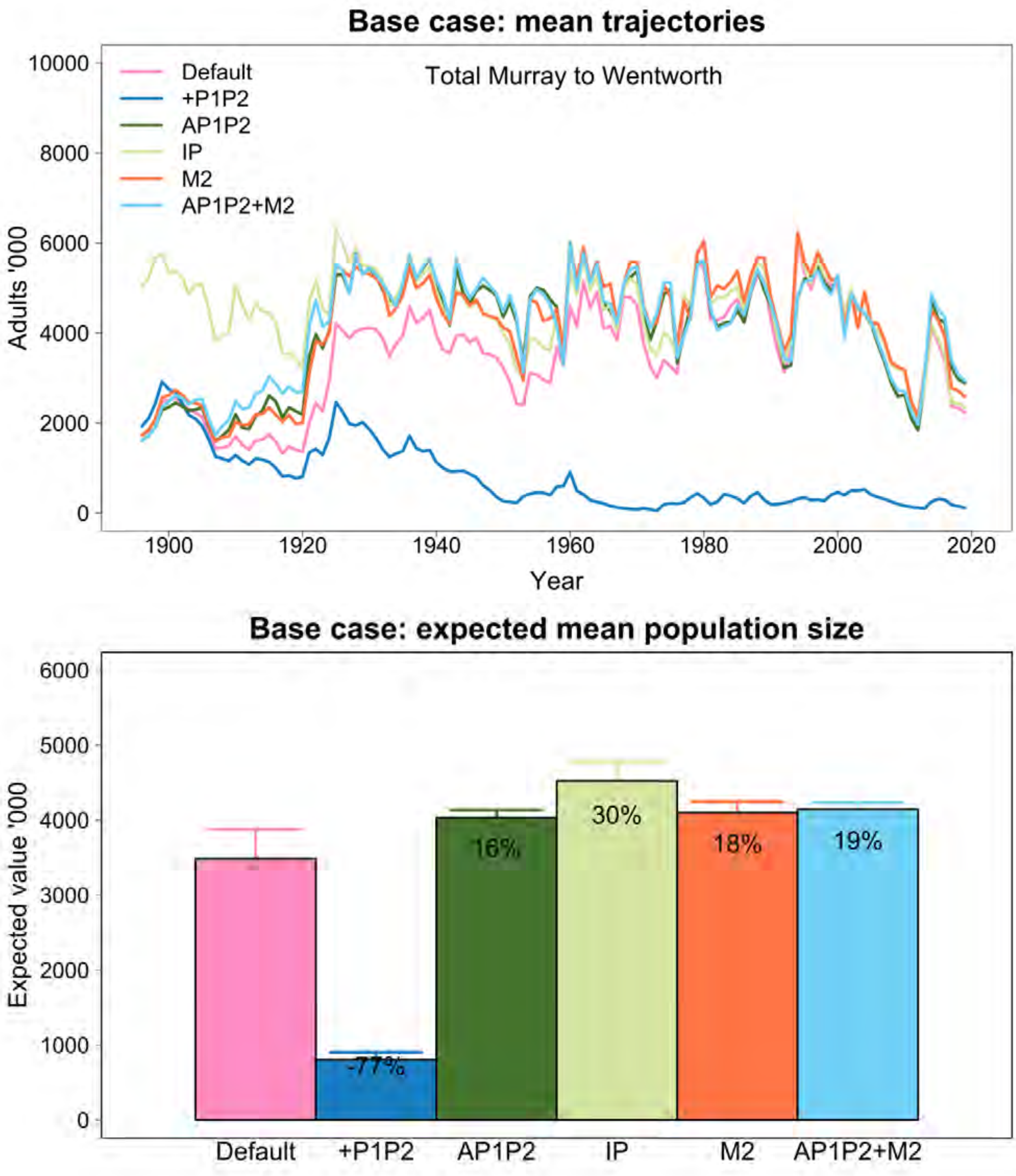


Figure A4.43. The Base case sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis aggregated across the Murray River RRCP focal zones (including the Edward River), together with the Wakool Junction to Wentworth reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

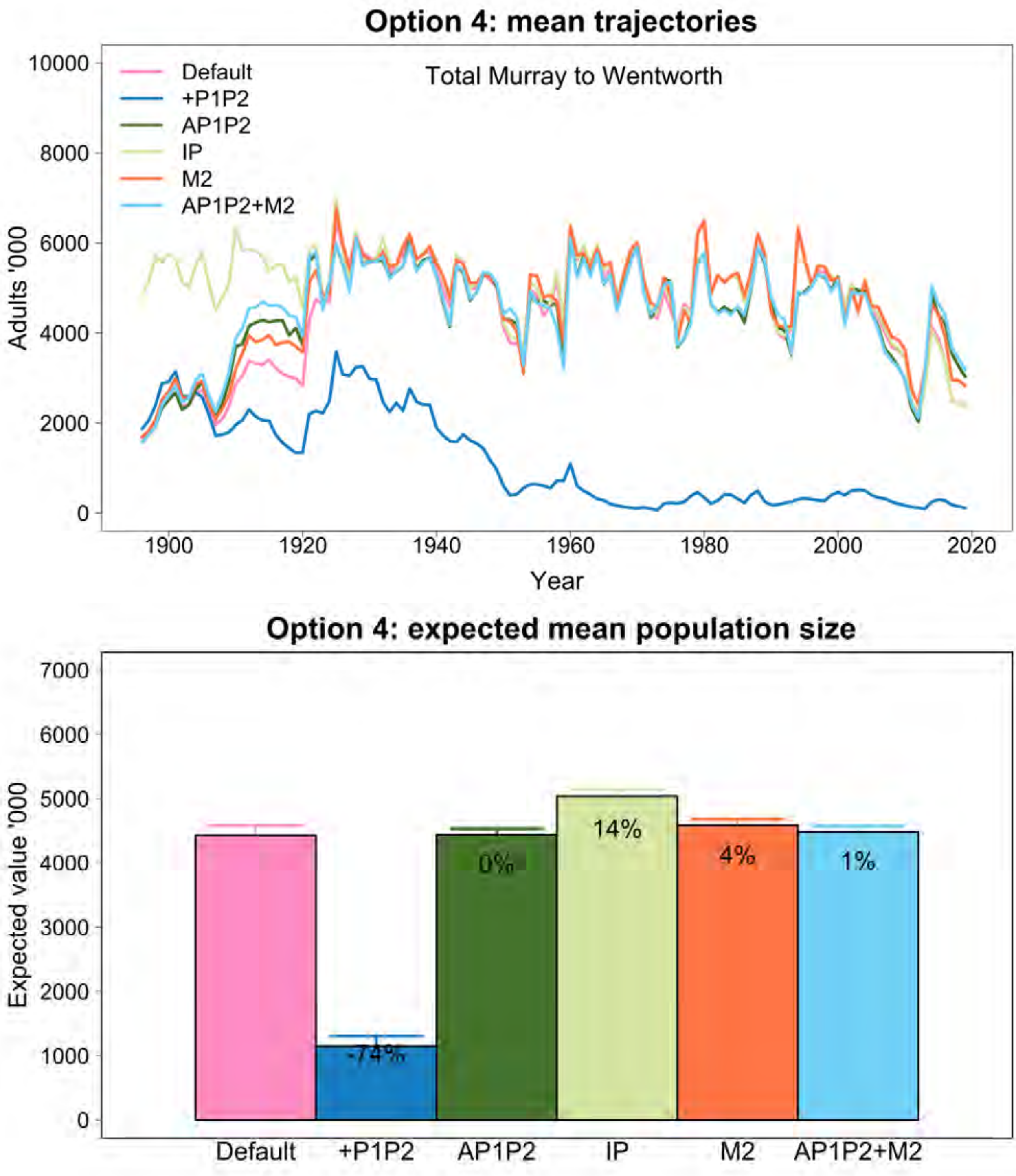


Figure A4.44. Option 4 sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis aggregated across the Murray River RRCP focal zones (including the Edward River), together with the Wakool Junction to Wentworth reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

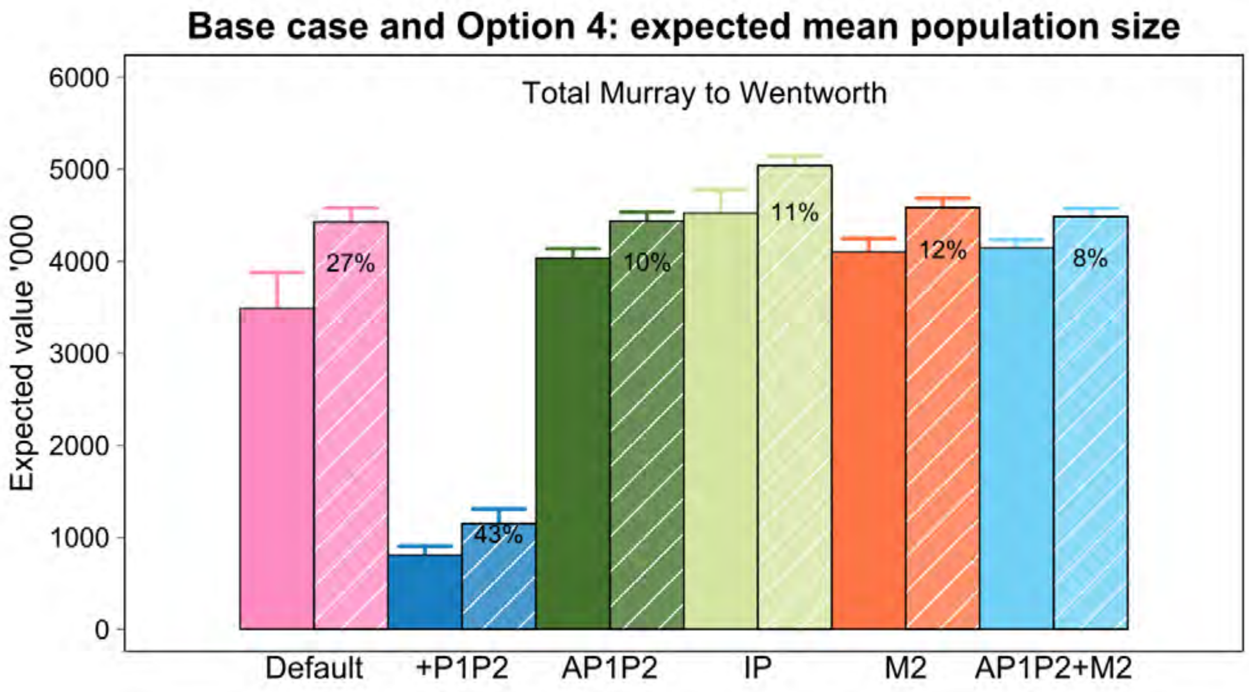


Figure A4.45. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis aggregated across the Murray River RRCP focal zones (including the Edward River), together with the Wakool Junction to Wentworth reach.

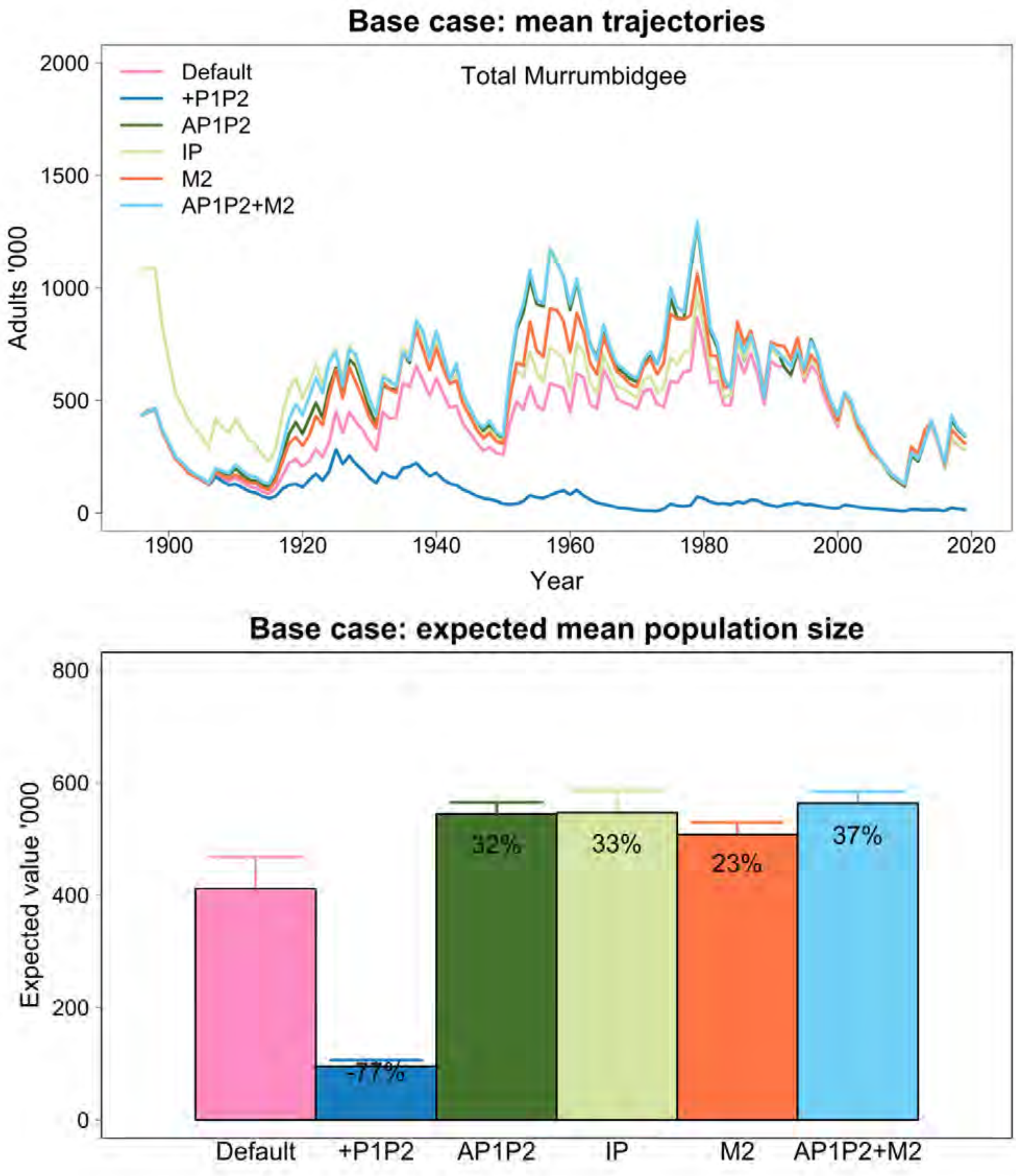


Figure A4.46. The Base case sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis aggregated across the Murrumbidgee River RRCP focal zone. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

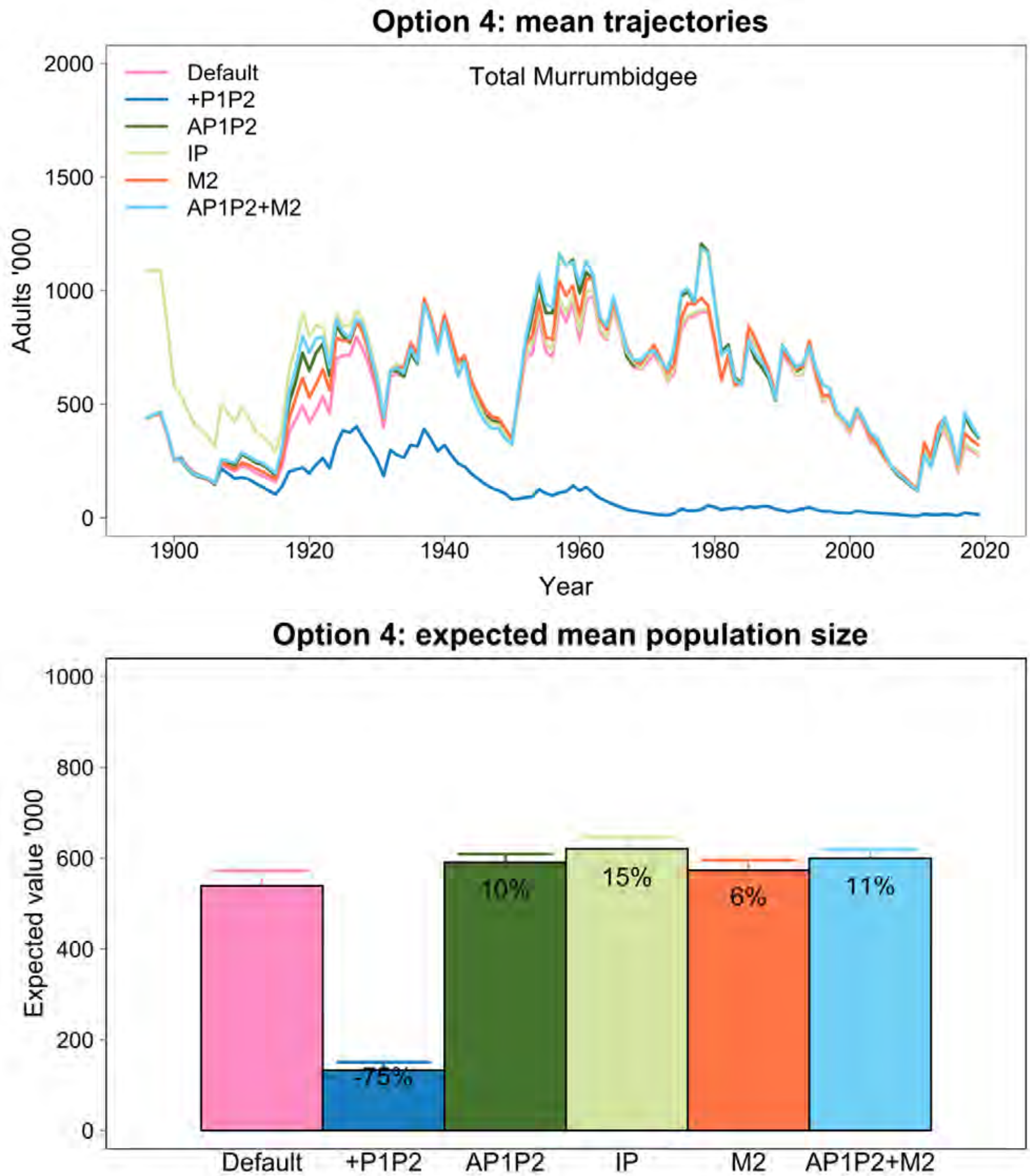


Figure A4.47. Option 4 sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis aggregated across the Murrumbidgee River RRCP focal zone. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

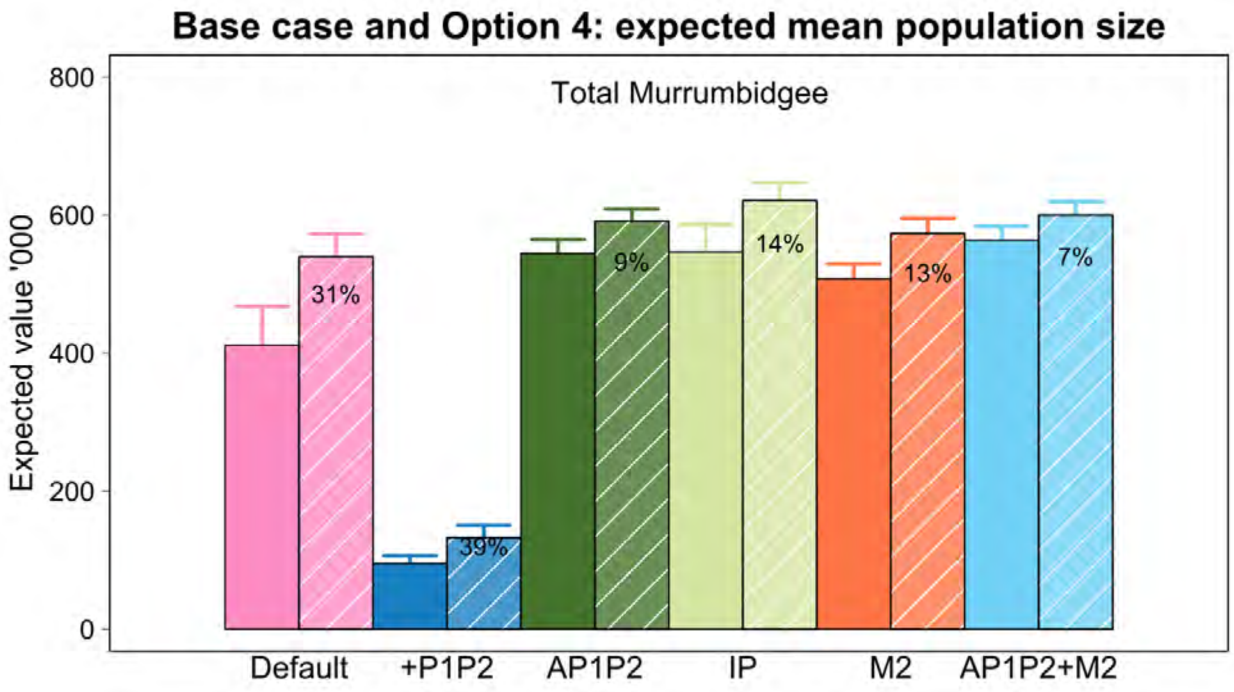


Figure A4.48. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis aggregated across the Murrumbidgee River RRCP focal zone.

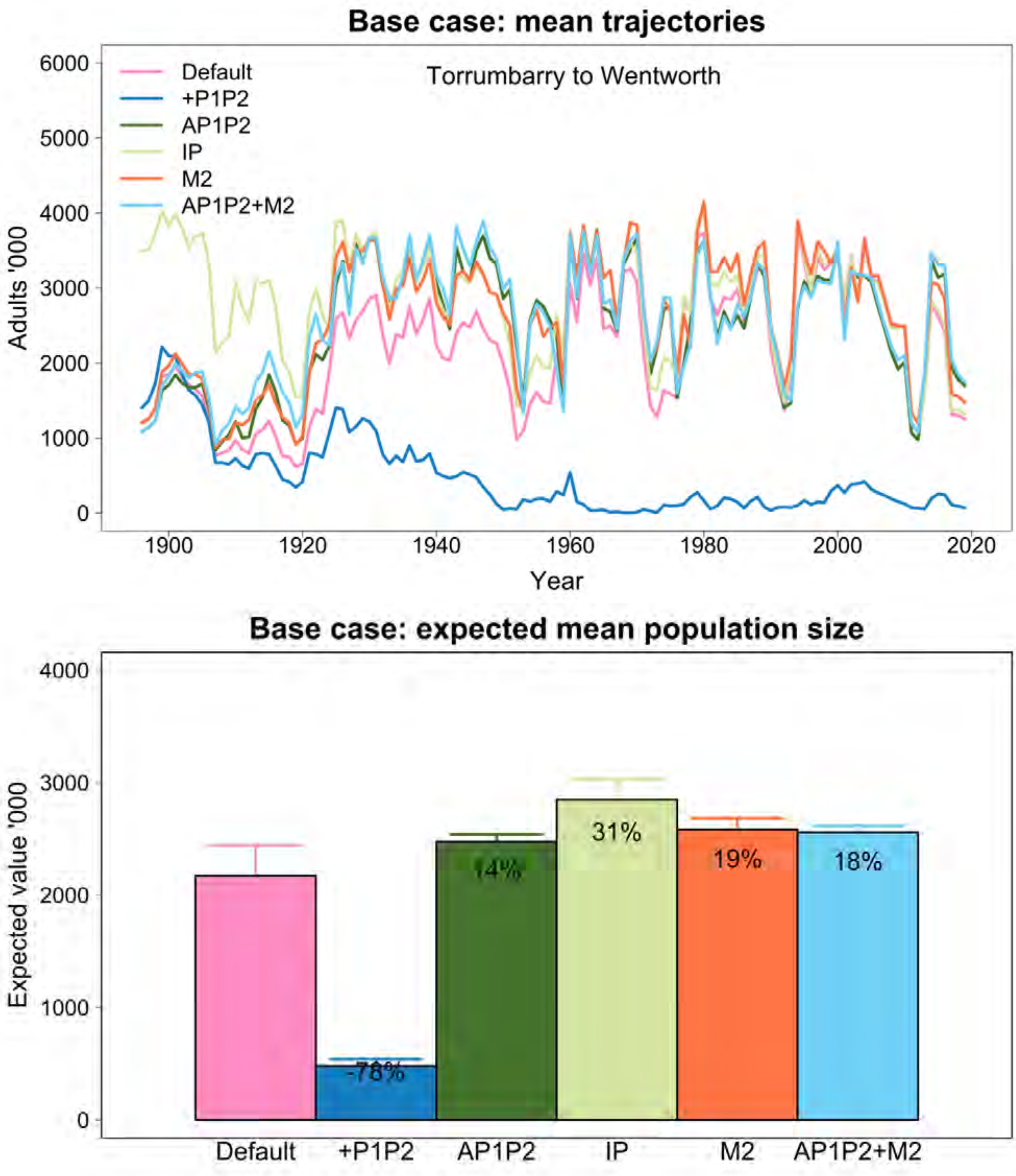


Figure A4.49. The Base case sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis for the Torrumbarry to Wentworth reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

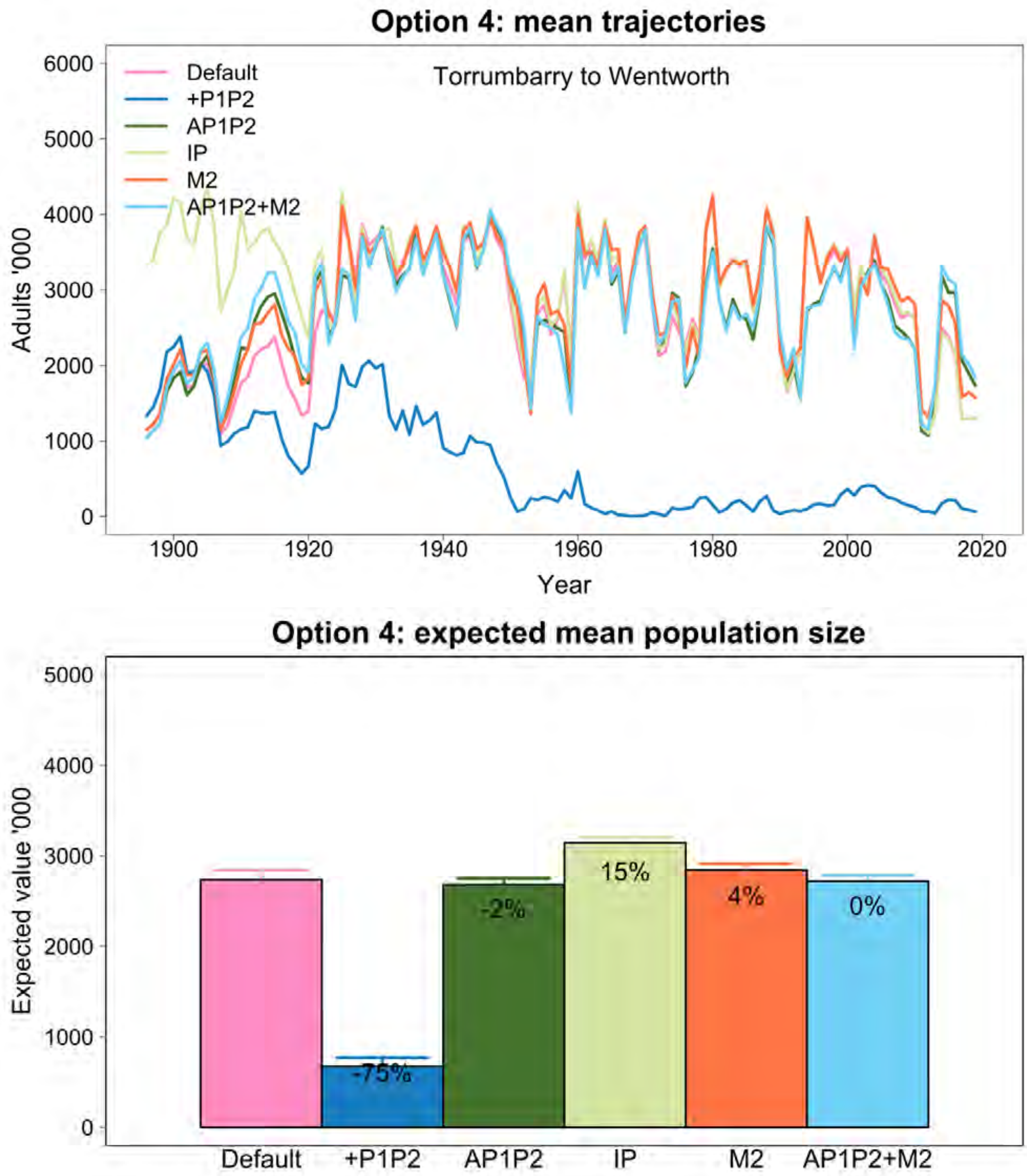


Figure A4.50. Option 4 sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis for the Torrumbarry to Wentworth reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

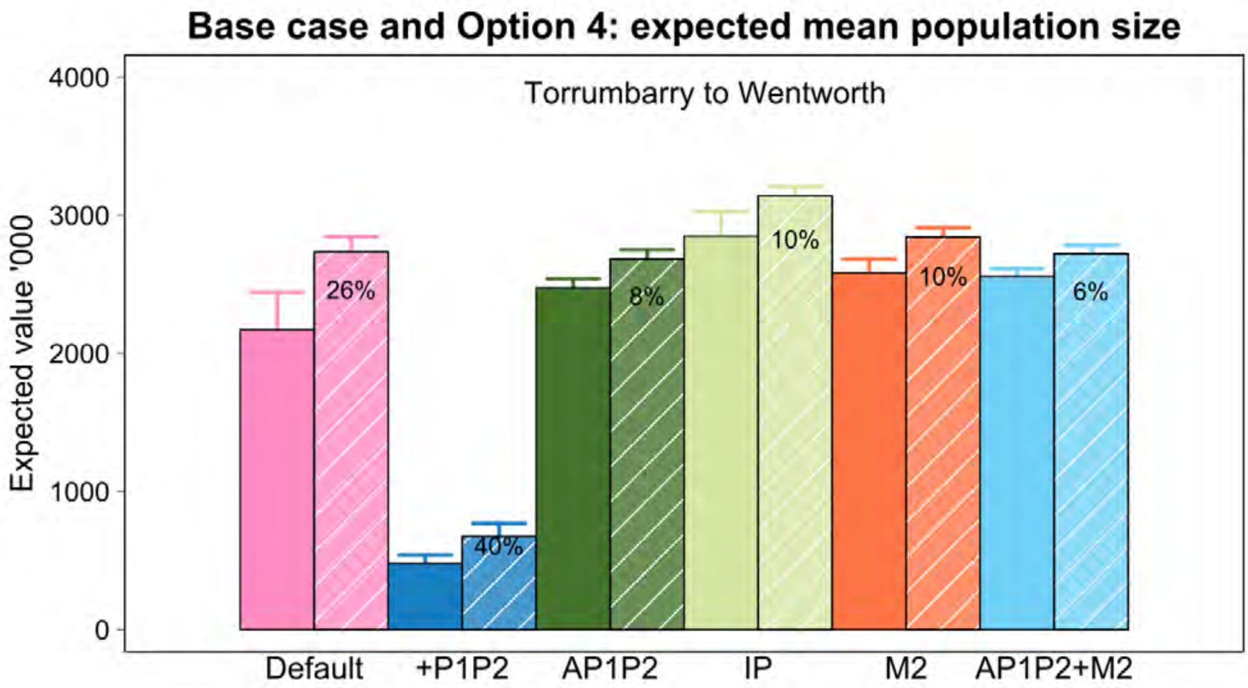


Figure A4.51. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 2 scenarios modelled for Golden Perch sensitivity in the Torrumbarry to Wentworth reach.

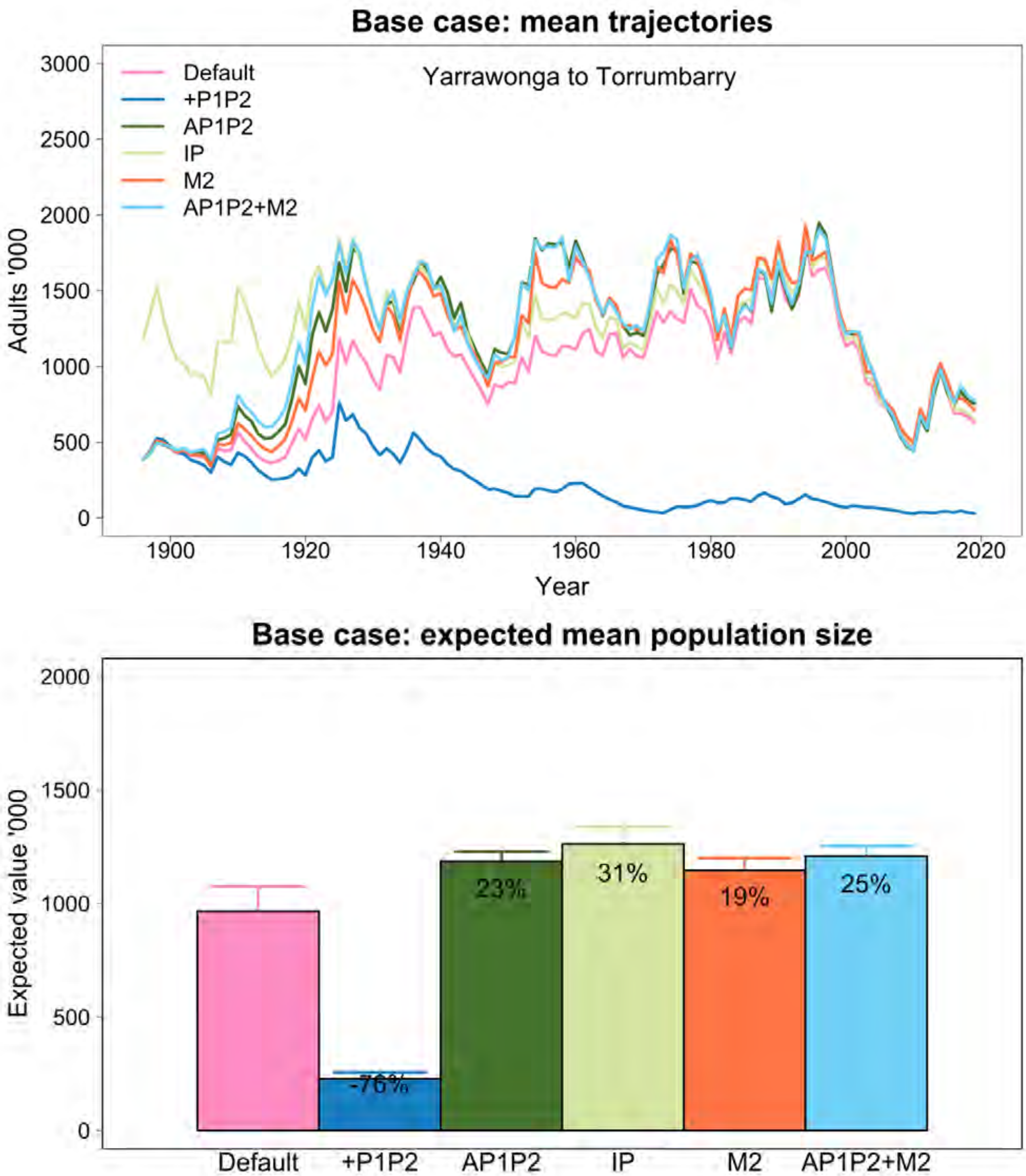


Figure A4.52. The Base case sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis for the Yarrawonga to Torrumbarry reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

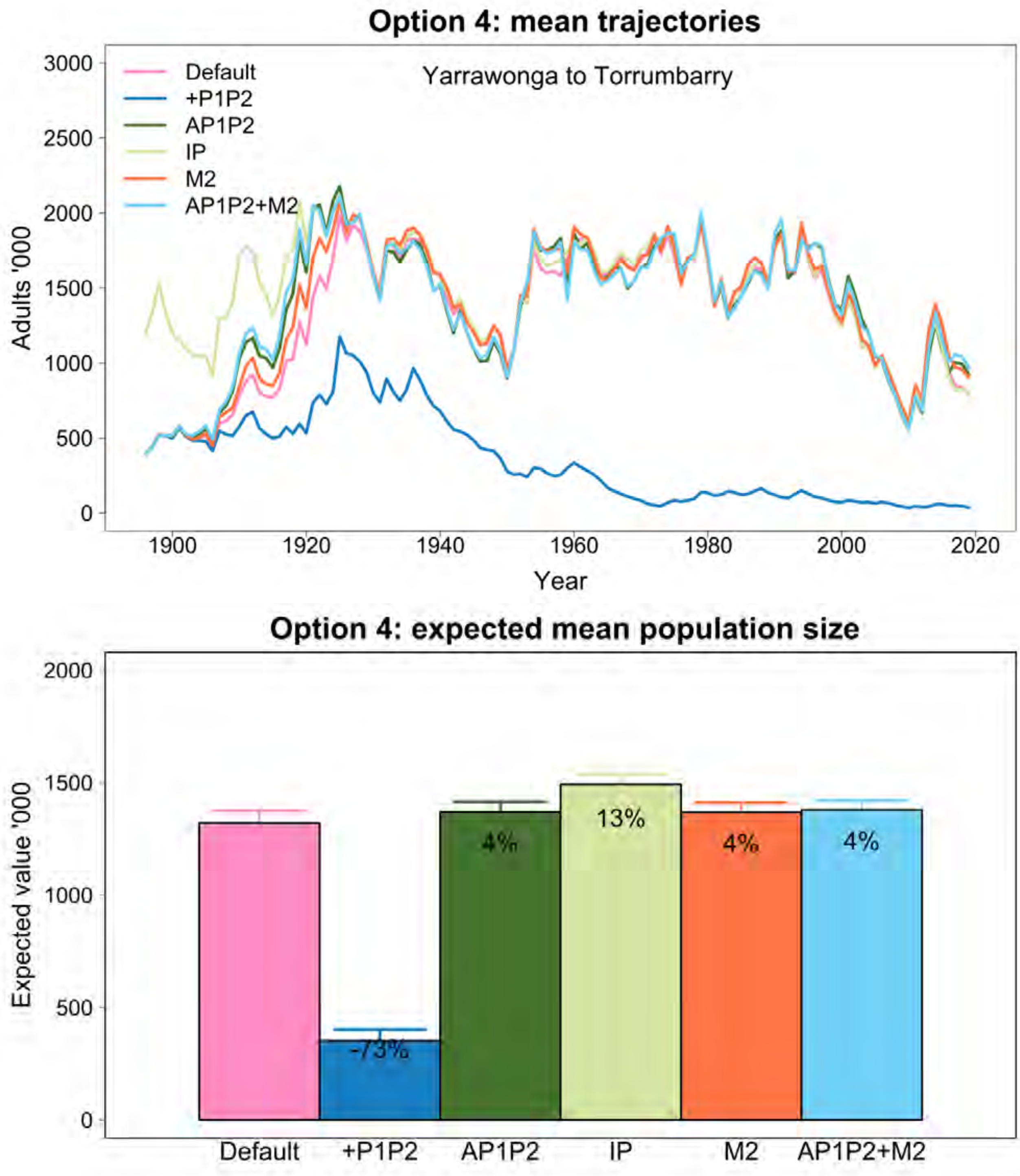


Figure A4.53. Option 4 sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis for the Yarrawonga to Torrumbarry reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

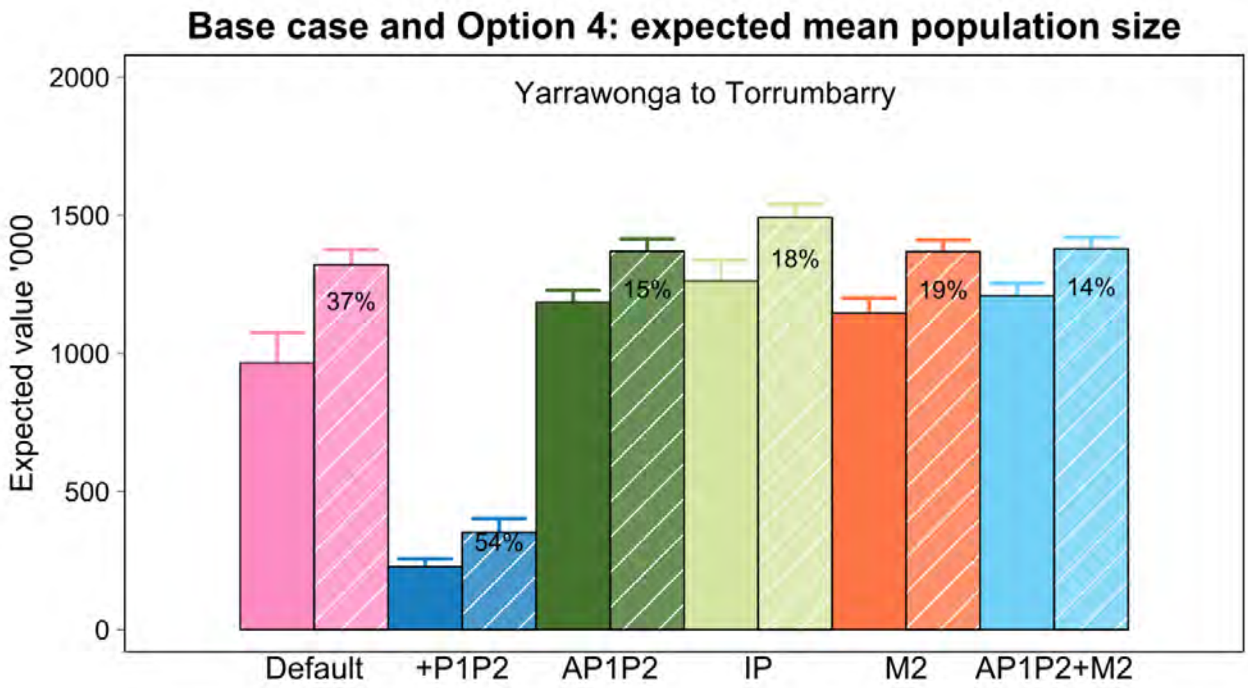


Figure A4.54. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 2 scenarios modelled for Golden Perch sensitivity in the Yarrawonga to Torrumbarry reach.

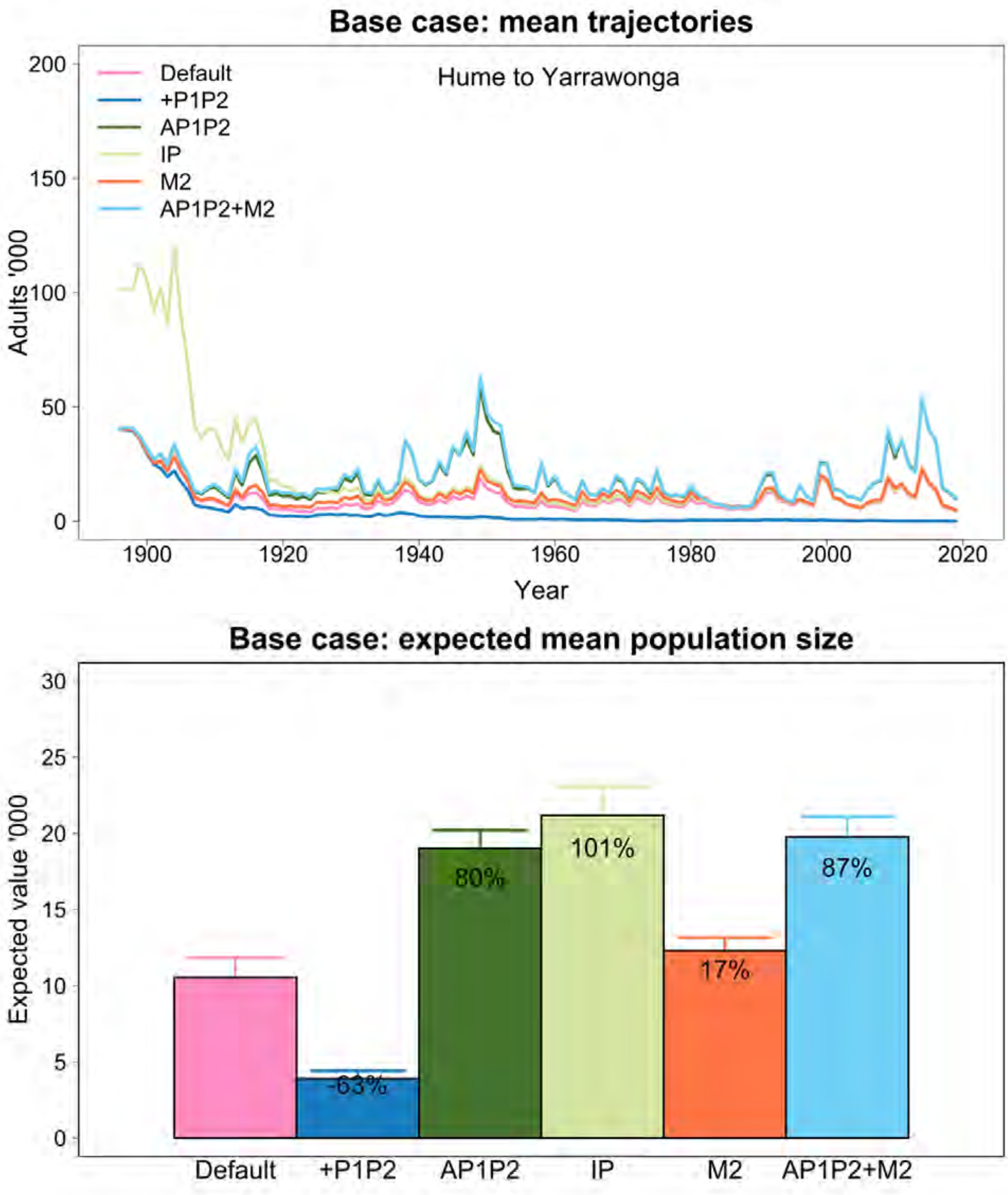


Figure A4.55. The Base case sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis for the Hume to Yarrawonga reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

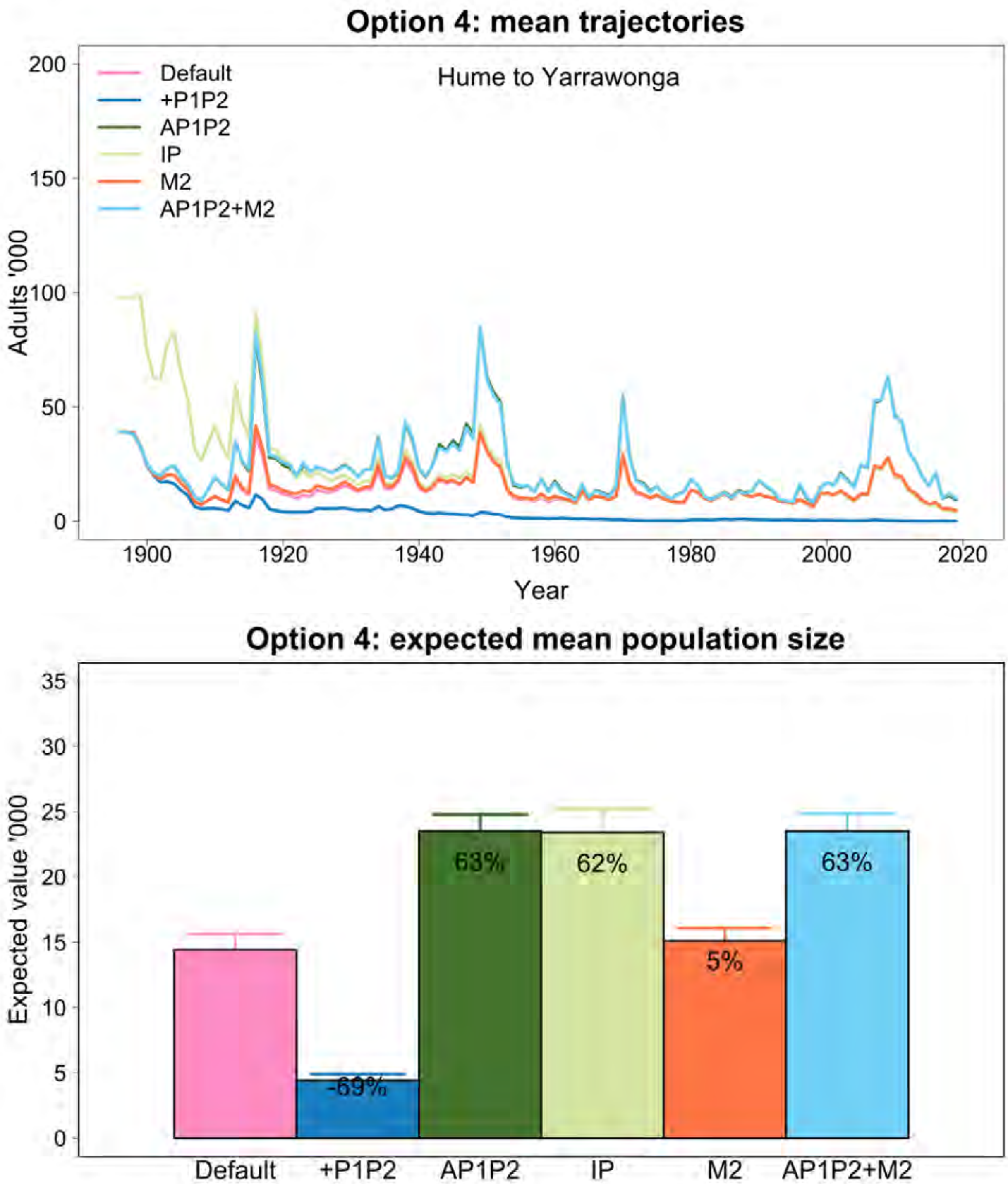


Figure A4.56. Option 4 sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis for the Hume to Yarrawonga reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

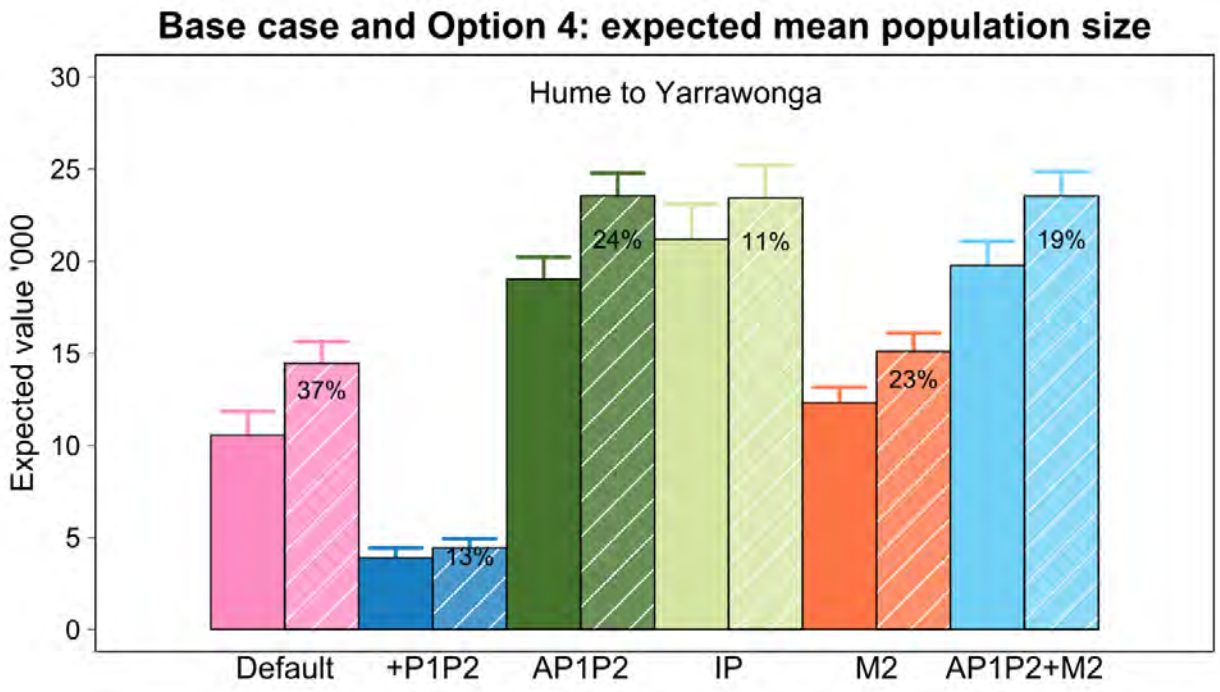


Figure A4.57. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 2 scenarios modelled for Golden Perch sensitivity in the Hume to Yarrawonga reach.

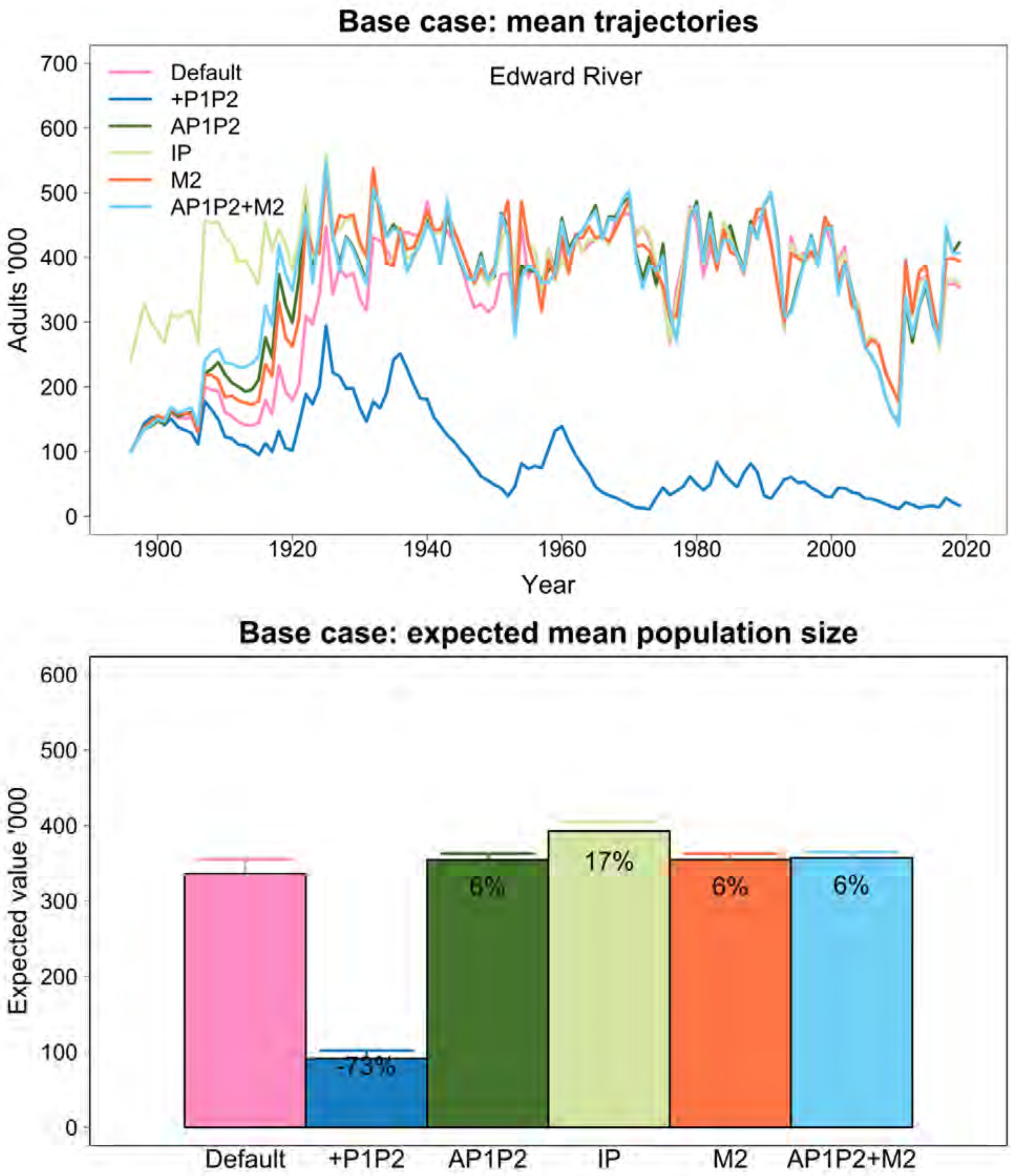


Figure A4.58. The Base case sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis for the Edward River. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

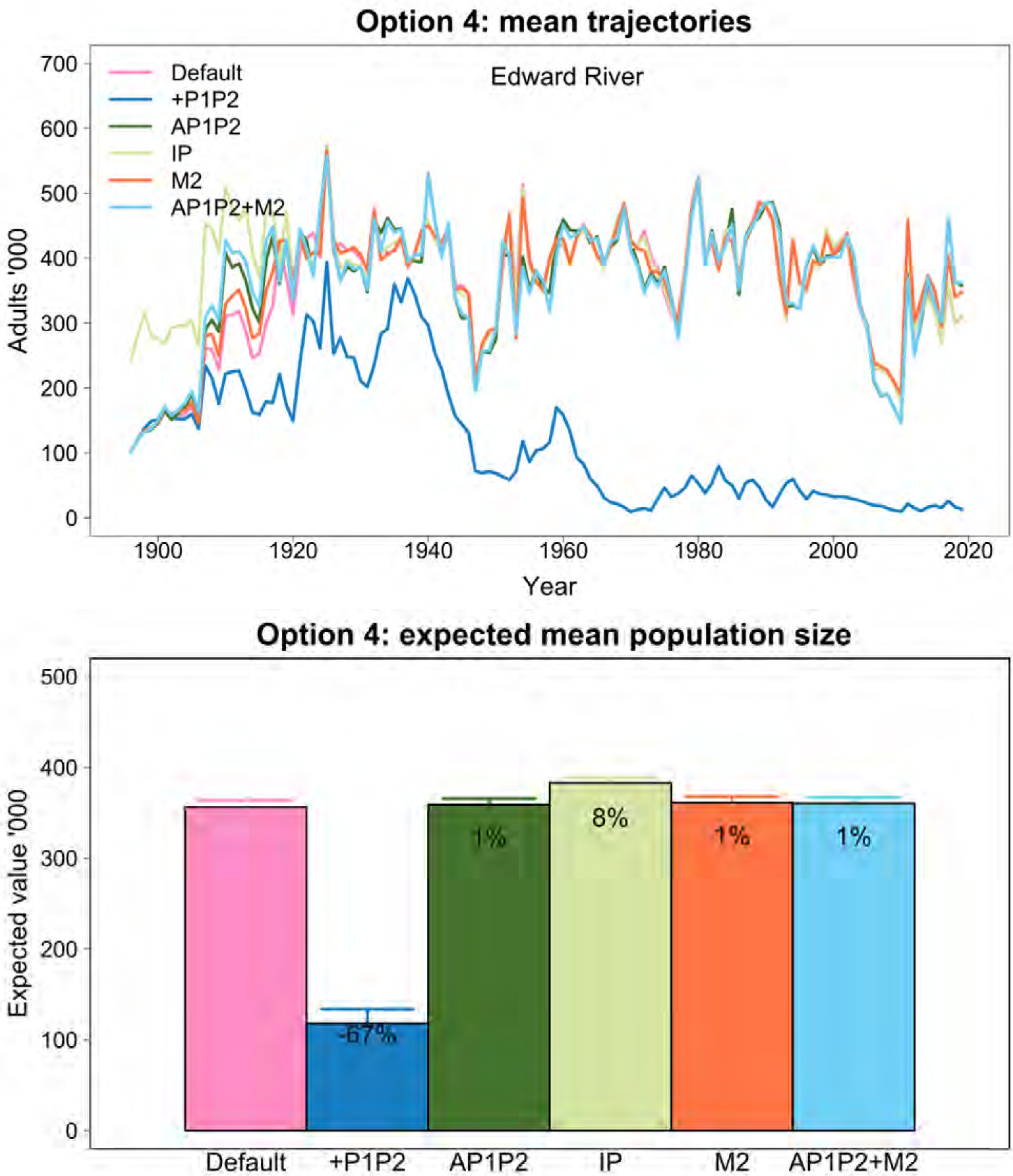


Figure A4.59. Option 4 sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis for the Edward River. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

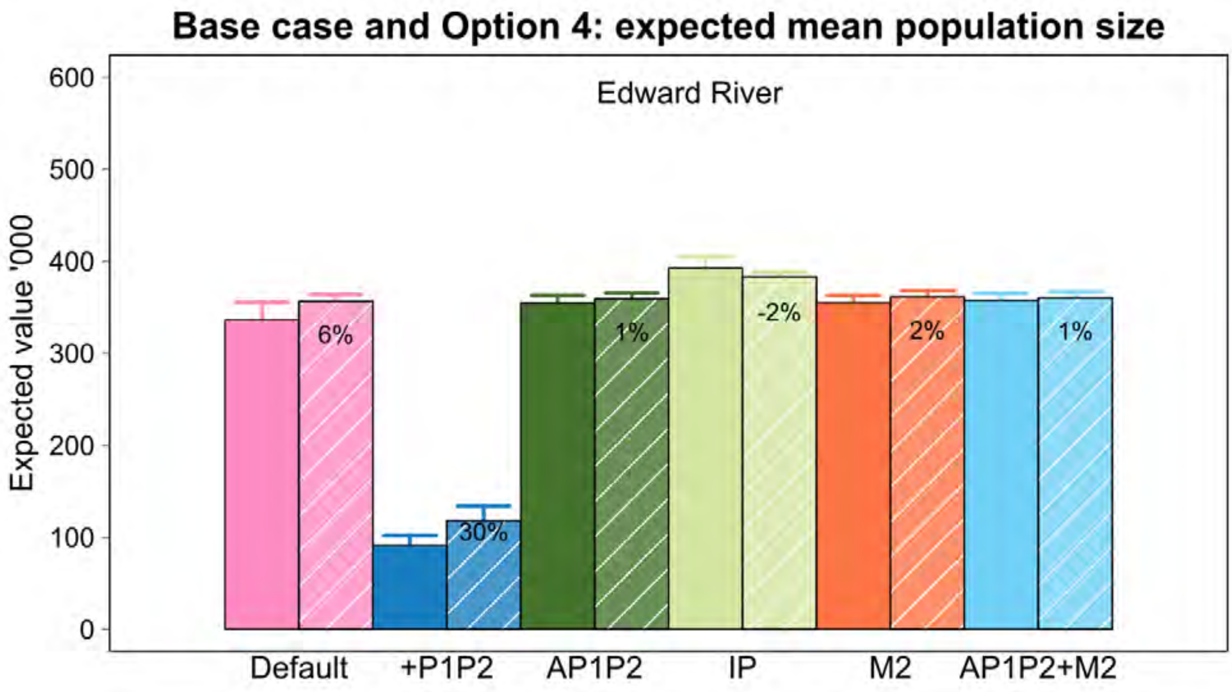


Figure A4.60. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 2 scenarios modelled for Golden Perch sensitivity in the Edward River.

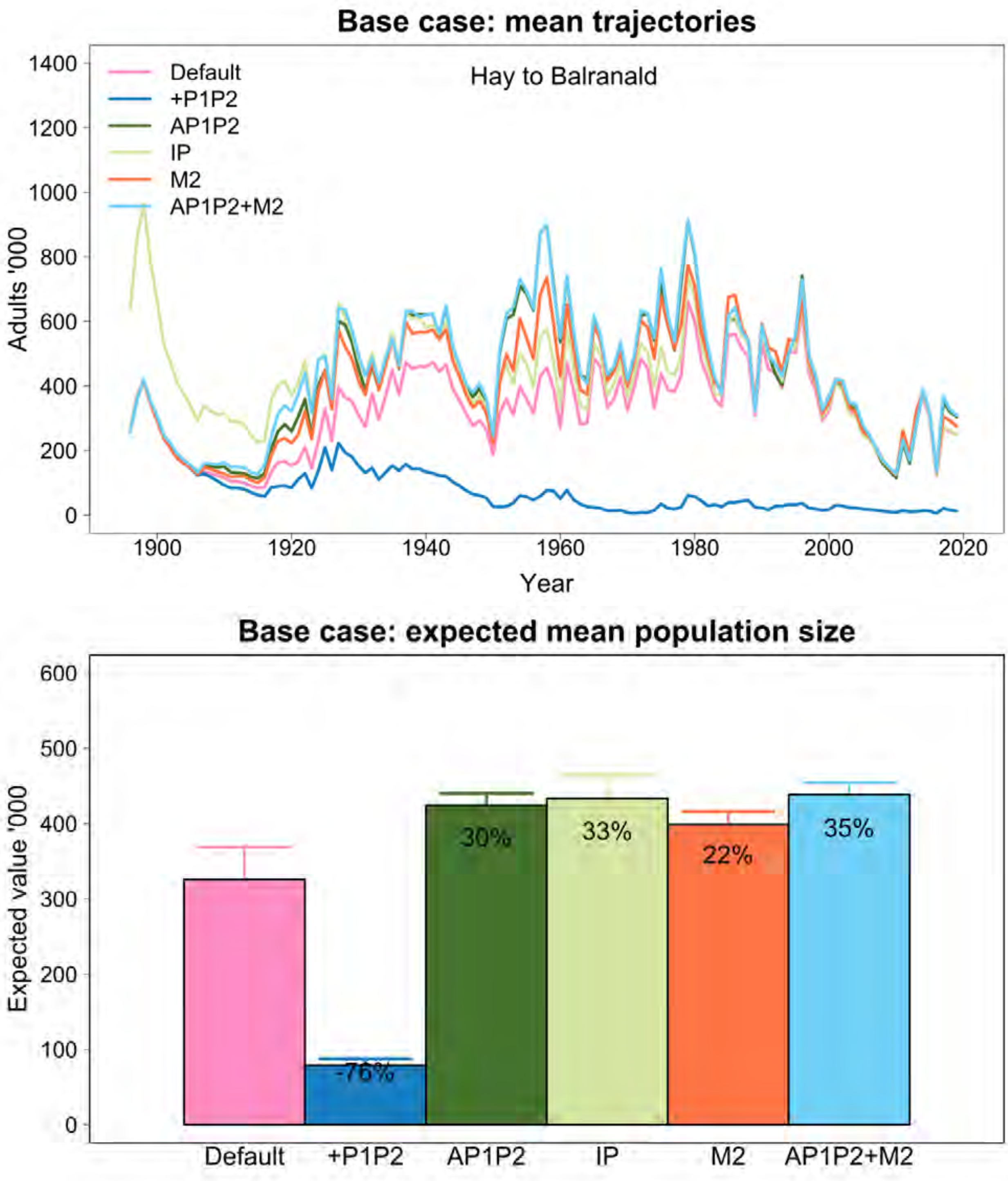


Figure A4.61. The Base case sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis for the Hay to Balranald reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

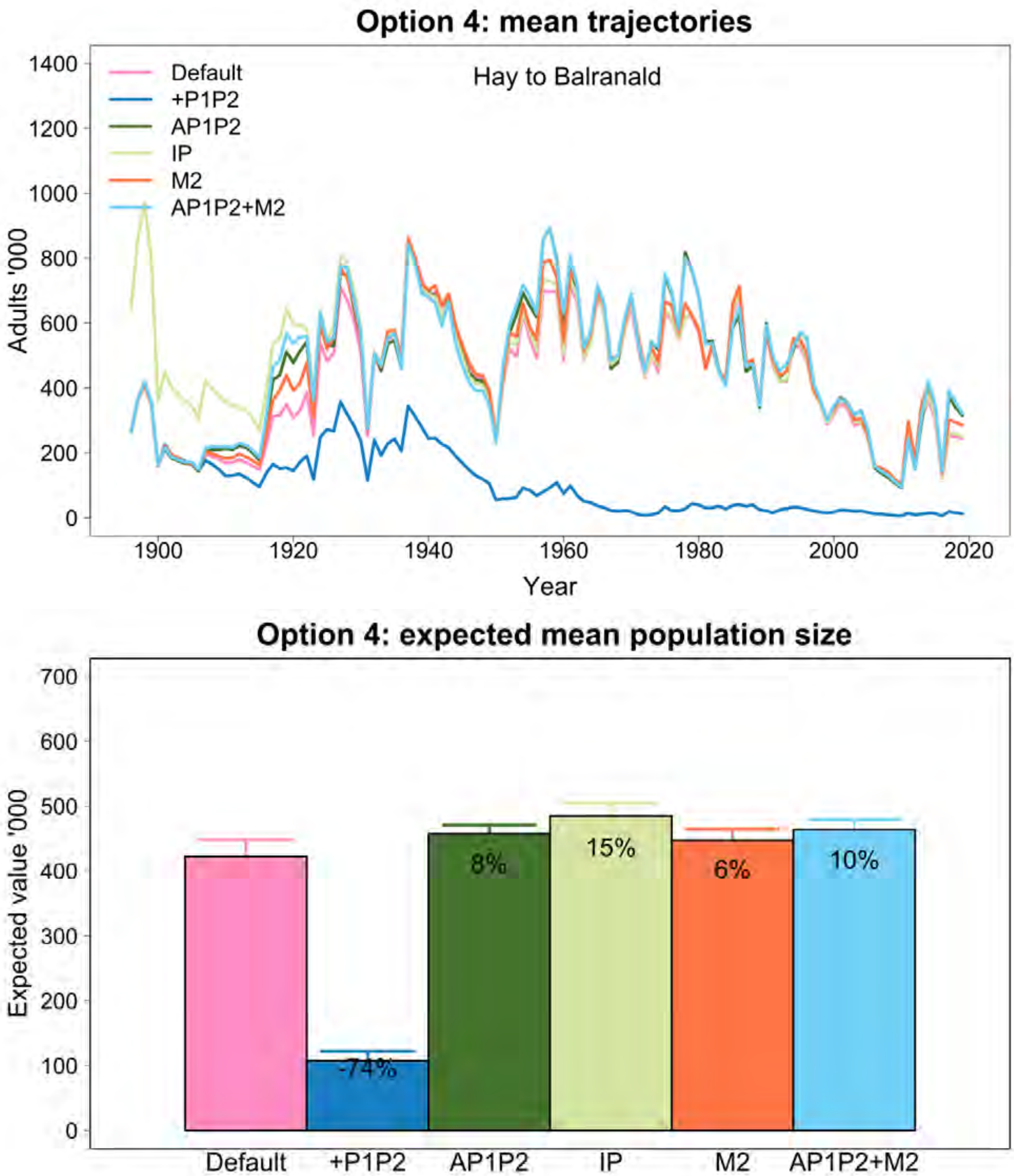


Figure A4.62. Option 4 sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis for the Hay to Balranald reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

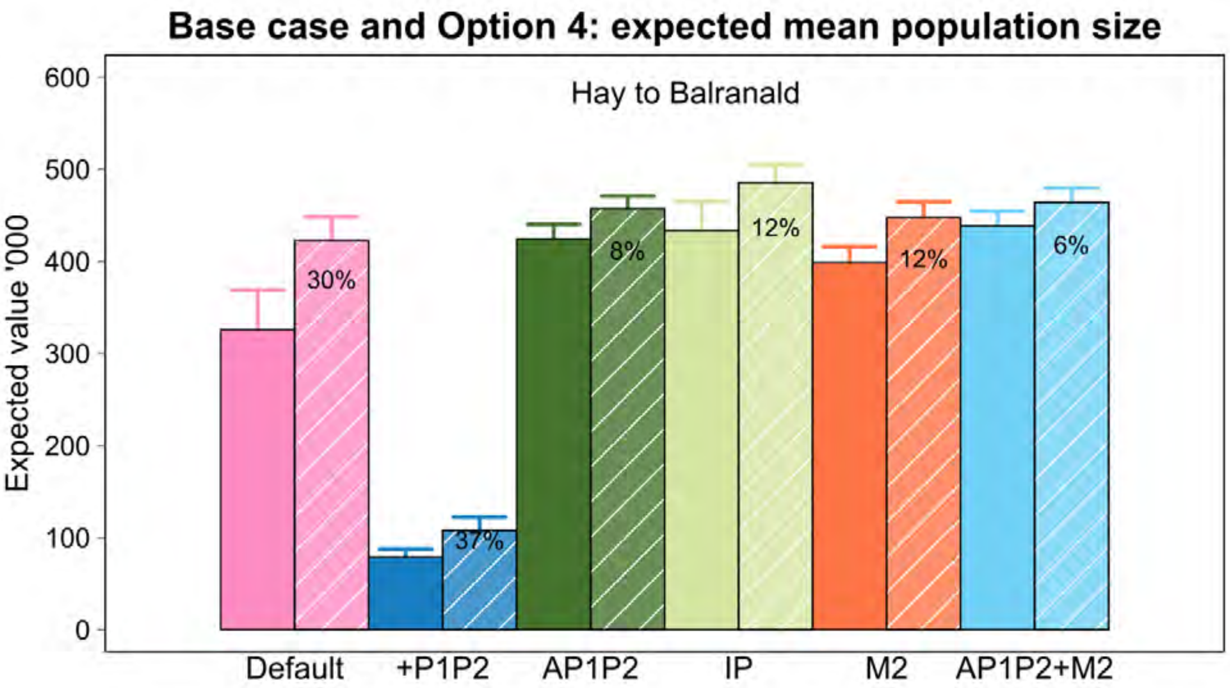


Figure A4.63. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 2 scenarios modelled for Golden Perch sensitivity in the Hay to Balranald reach.

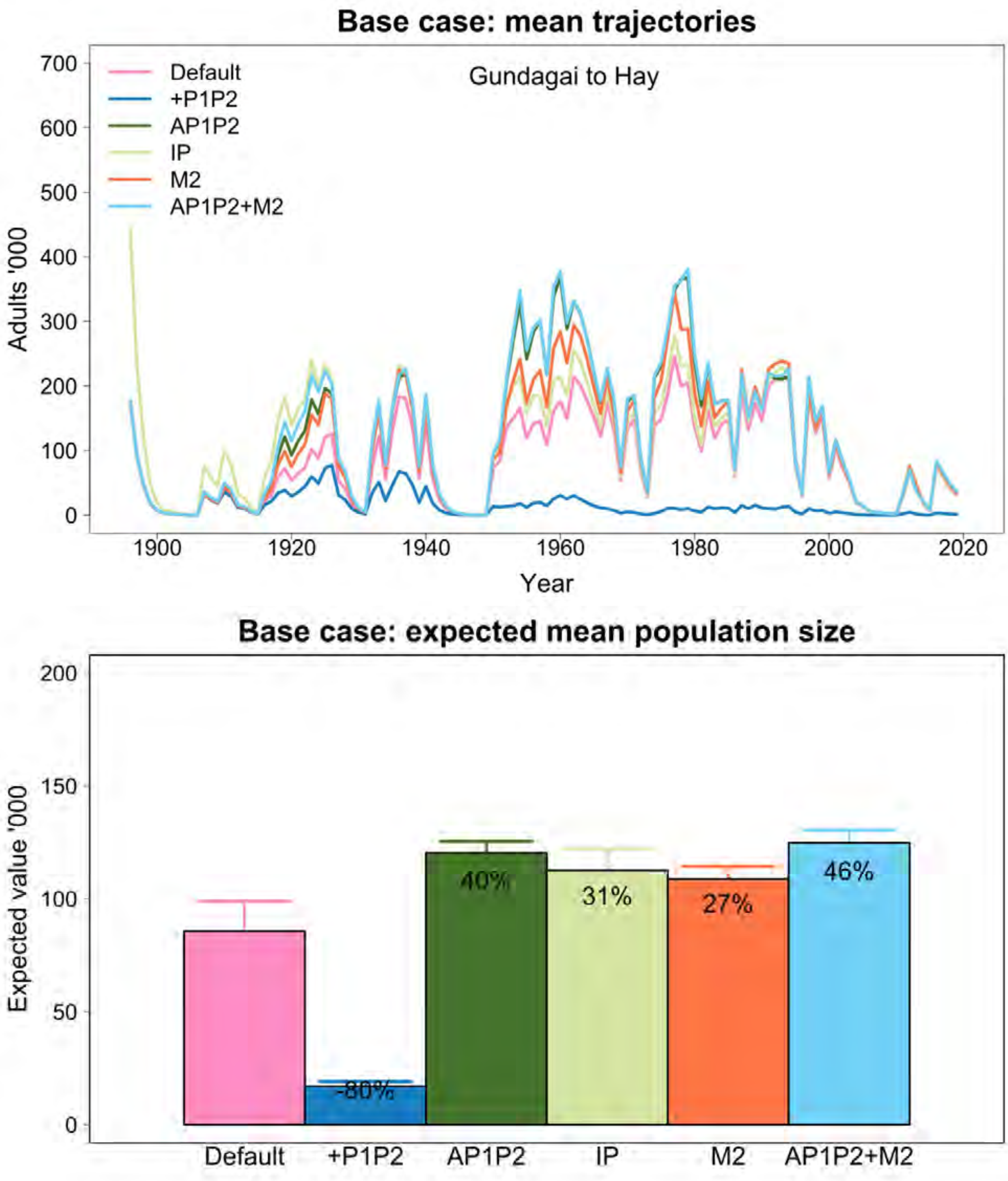


Figure A4.64. The Base case sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis for the Gundagai to Hay reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

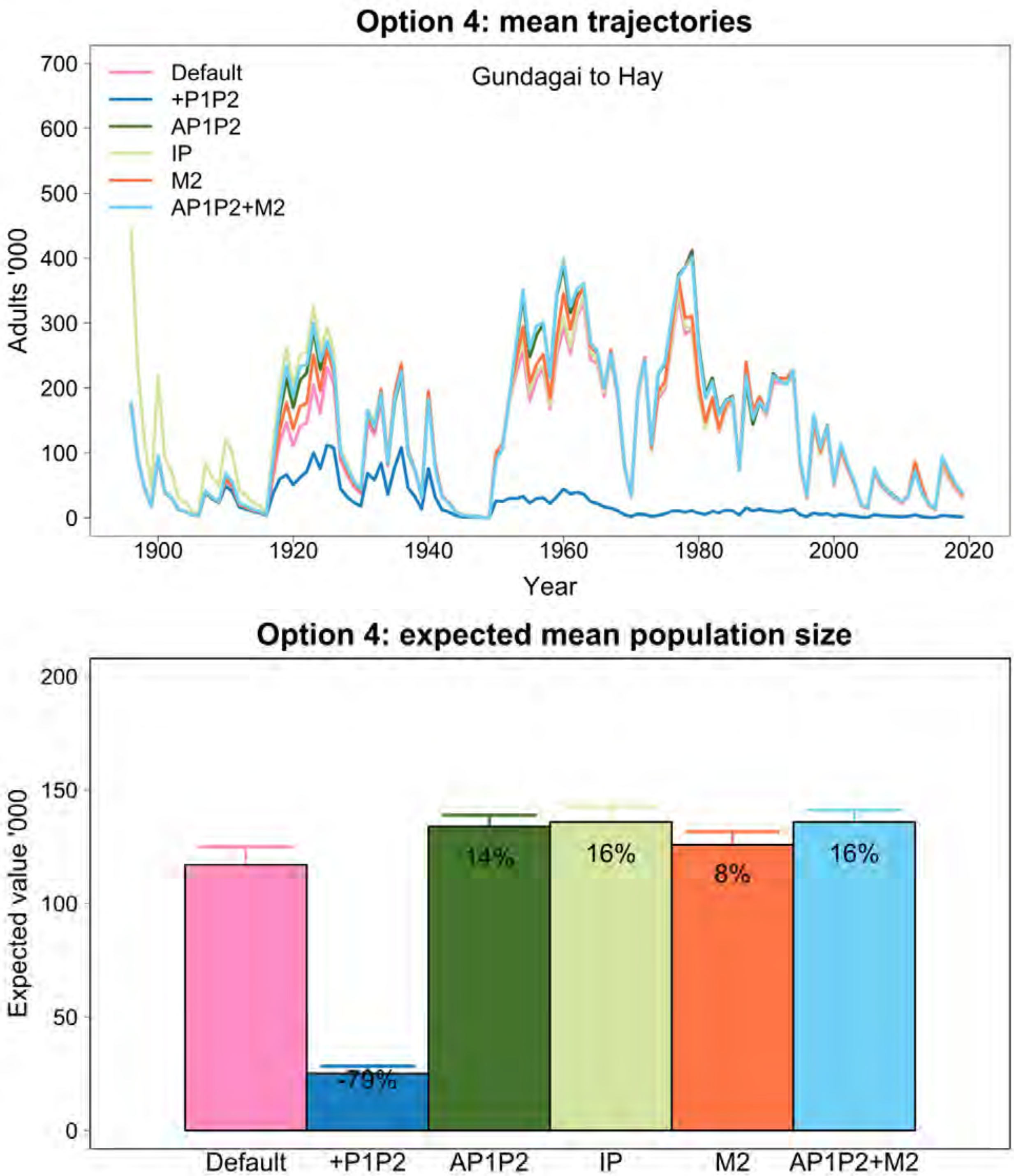


Figure A4.65. Option 4 sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis for the Gundagai to Hay reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

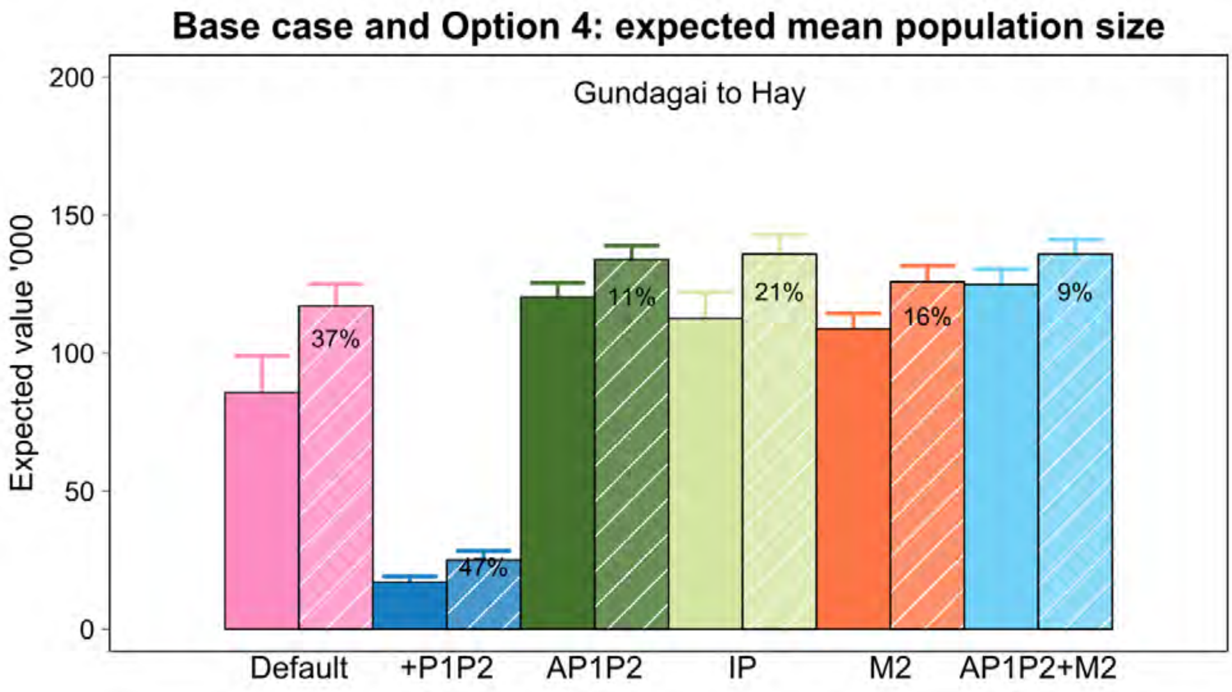


Figure A4.66. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 2 scenarios modelled for Golden Perch sensitivity in the Gundagai to Hay reach.

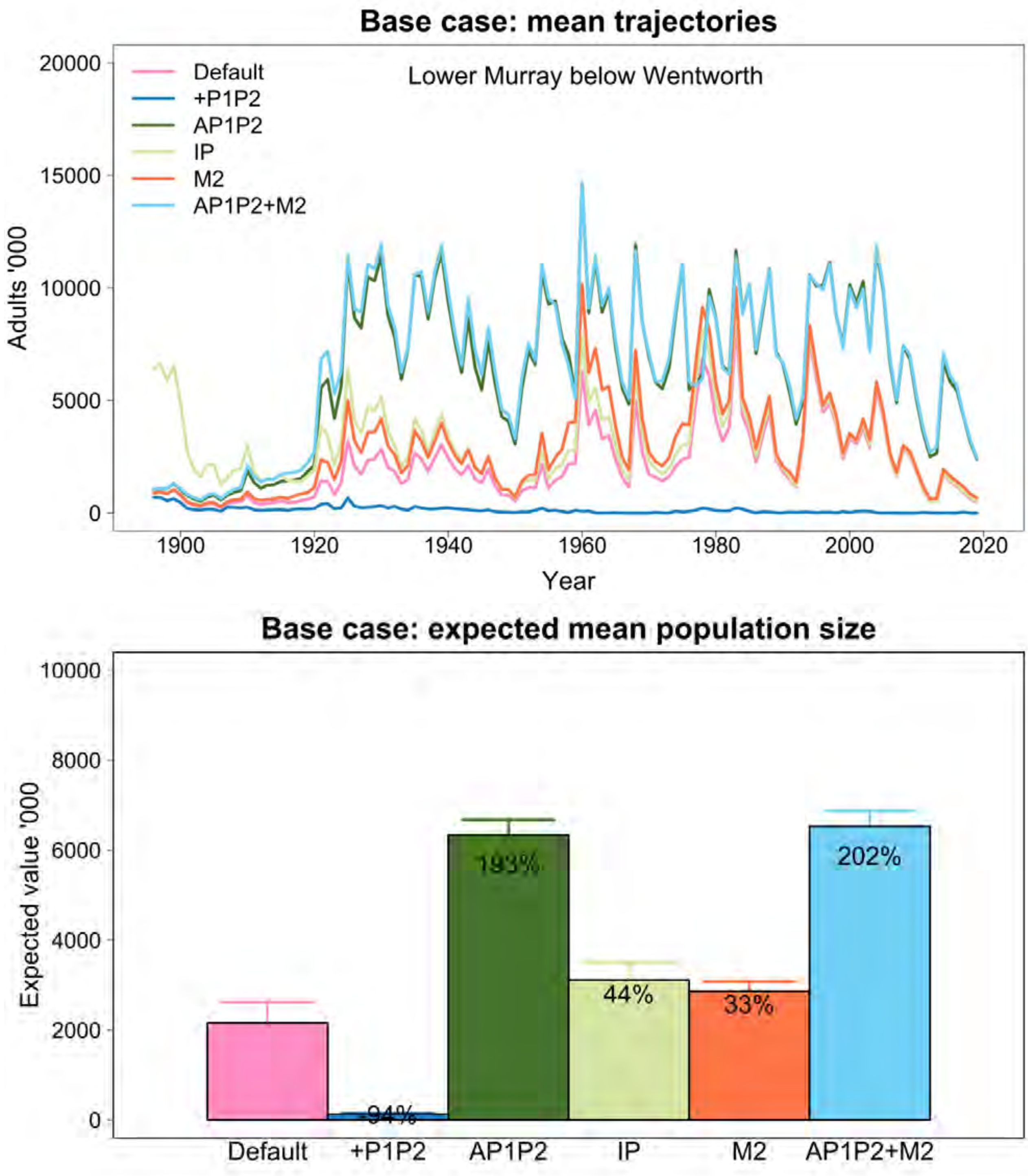


Figure A4.67. The Base case sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis for the Lower Murray below Wentworth reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

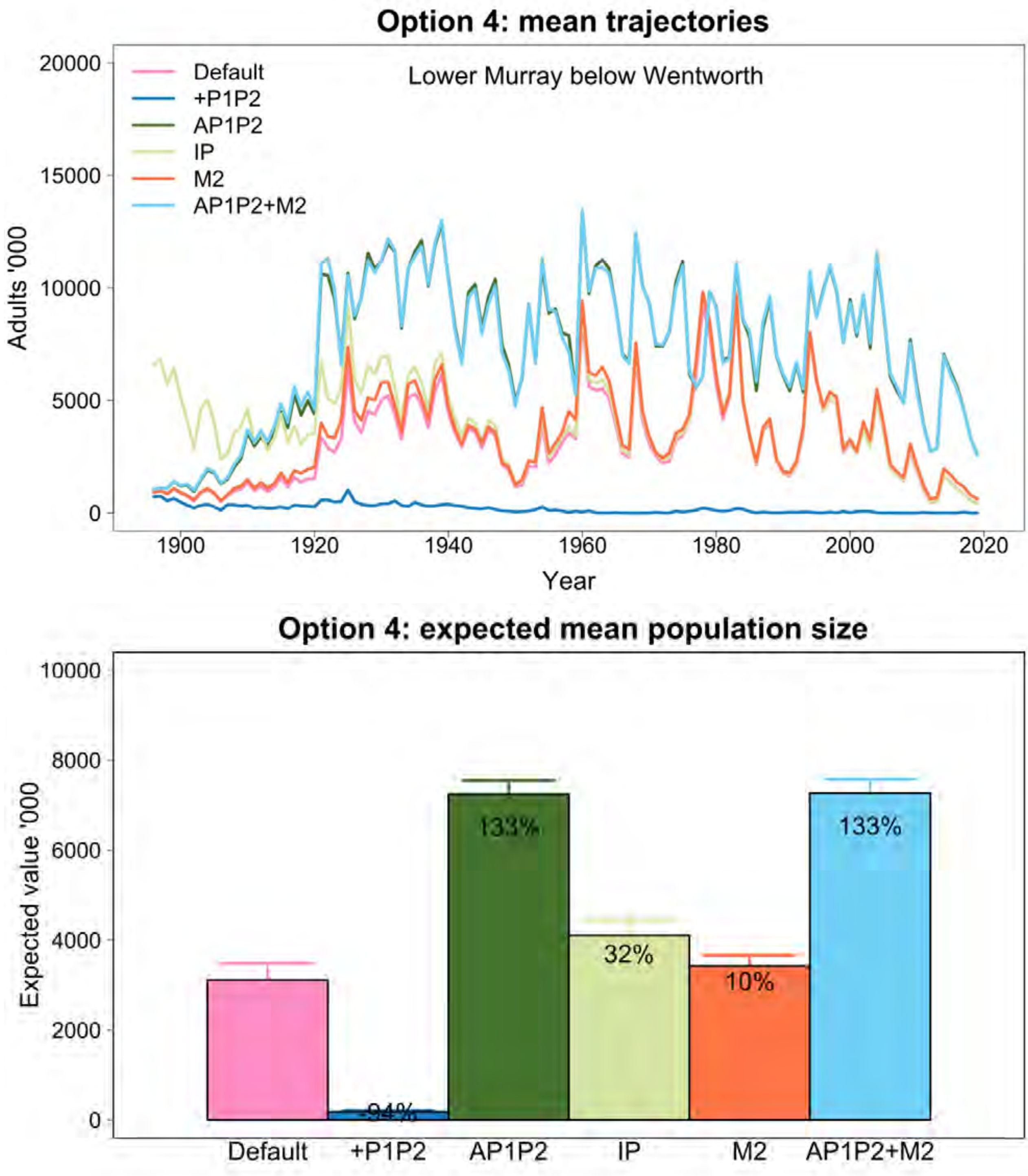


Figure A4.68. Option 4 sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis for the Lower Murray below Wentworth reach. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

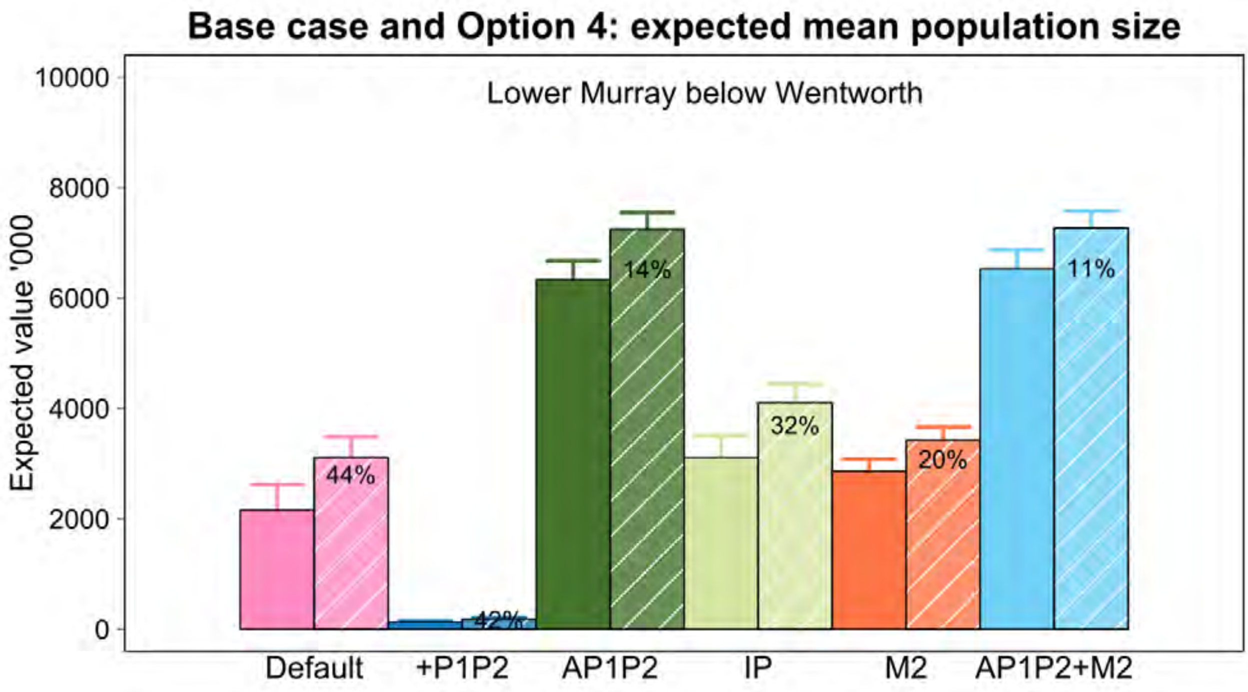


Figure A4.69. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 2 scenarios modelled for Golden Perch sensitivity in the Lower Murray below Wentworth reach.

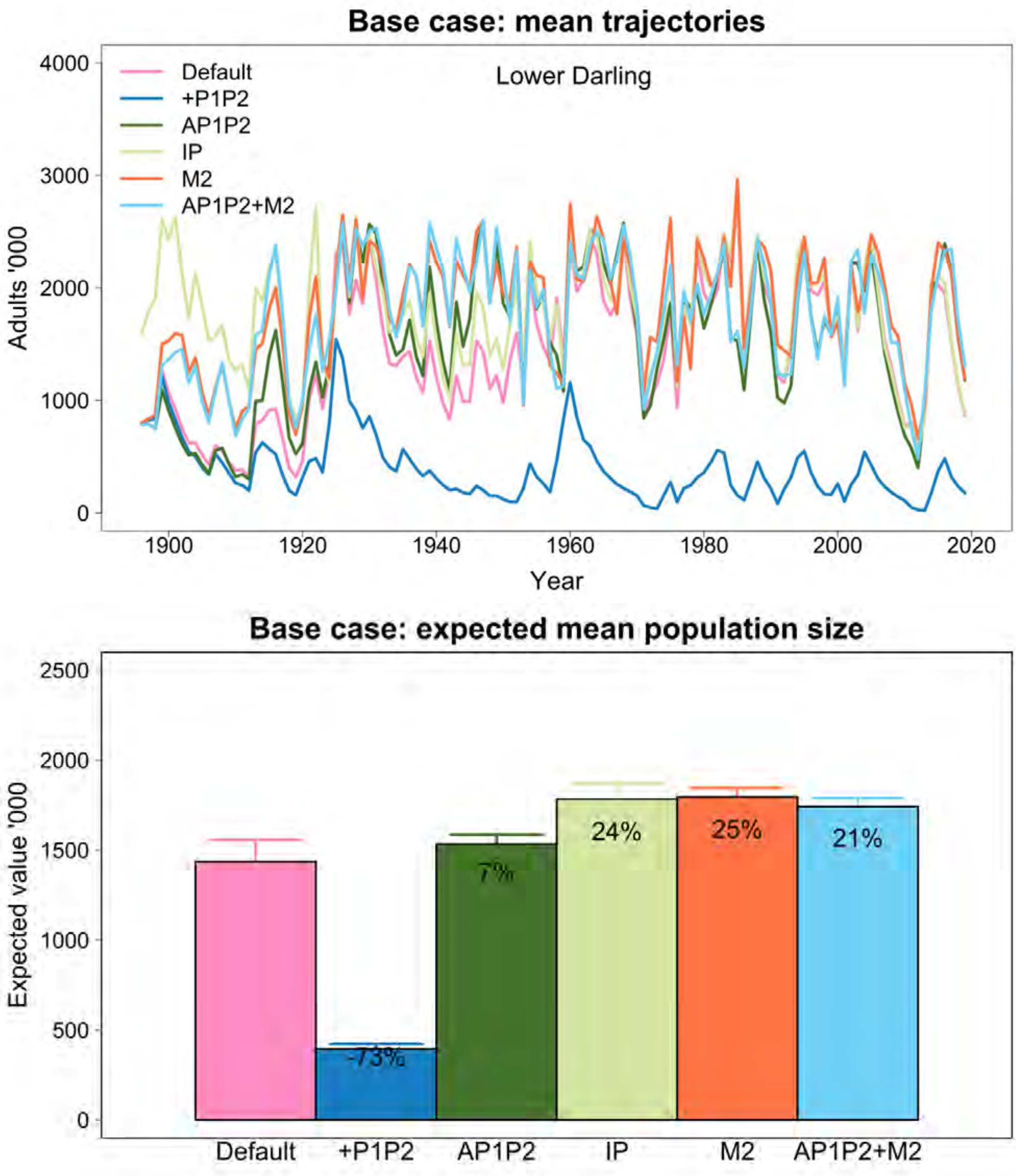


Figure A4.70. The Base case sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis for the Lower Darling. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean population sizes, with the percentage change from the default shown in each bar.

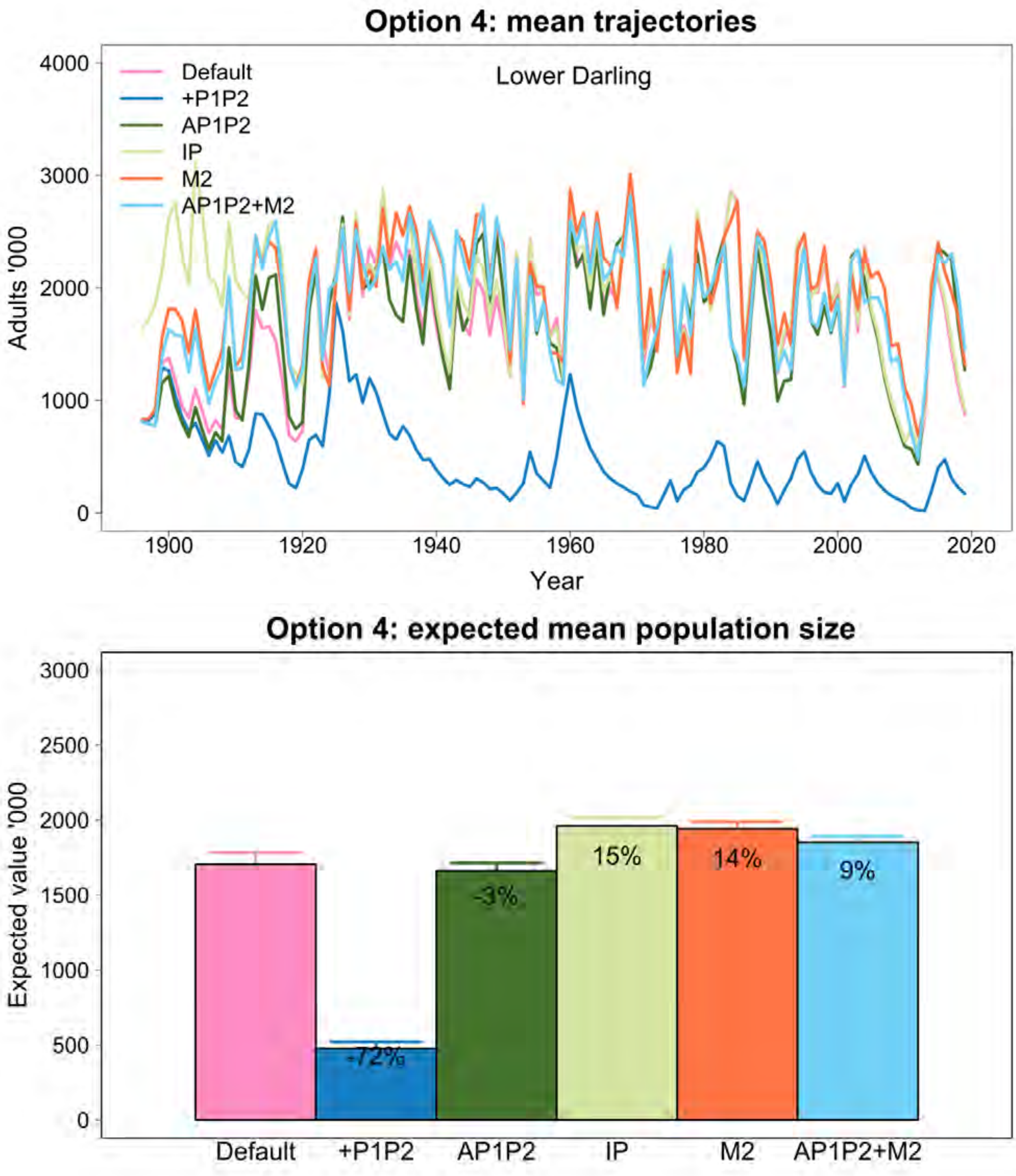


Figure A4.71. Option 4 sensitivity 2 scenarios modelled in the Golden Perch sensitivity analysis for the Lower Darling. Top panel: the mean adult population size trajectories. Bottom panel: the expected mean adult population sizes, with the percentage change from the default shown in each bar.

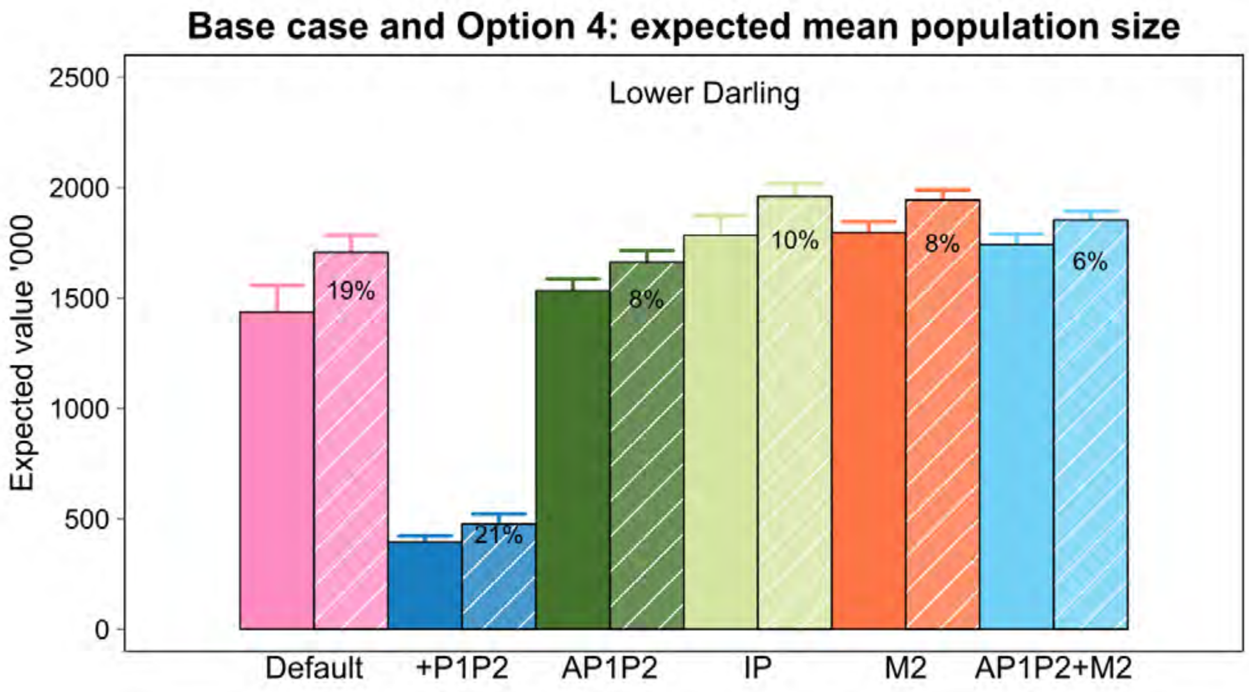


Figure A4.72. Comparisons between Base case (solid colour) and Option 4 (striped colour) for the sensitivity 2 scenarios modelled for Golden Perch sensitivity in the Lower Darling.

Third sensitivity analysis

The third approach changed the period over which the expected mean population size was generated. Flow and temperature data were generated for the five scenarios examined in this study, Base case – Option 4, over 124 years at the various gauges that underpin the Golden Perch metapopulation model construct, with the results for the Total RRCP Populations shown in Figure 18 and reproduced in Figure A4.73. The expected mean adult population size was calculated from the distribution of mean population sizes across the whole 124-year data time frame. When the time frame is altered, the associated expected mean would differ from the expected mean calculated for the 124-year data time frame. Convergence was observed to occur among the five scenarios in the period from the early 1980s to the end of the dataset, 2019, see Figure A4.73 (see Appendix 5 for an investigation of this convergence). Selecting the time frame for collecting the distribution of the mean population sizes to 1980–2019, 40 years, and then calculating the associated expected mean population size, it can be seen that the population size benefits of the relaxed-flow-constraints scenarios decrease in comparison with the overall expected mean population size (compare the bottom panel of Figure 36 with the top panel of Figure A4.74). Alternatively, selecting the time frame for collecting the distribution of mean population sizes to 1910–1949 increases the population size benefits of the relaxed-flow-constraints scenarios in comparison with the overall expected mean population size (compare the bottom panel of Figure A4.73 with the bottom panel of Figure A4.74). While the expected mean population size was sensitive to the time frame in which the statistic was calculated, Option 4 generated a higher expected mean population size for the Total RRCP Populations across different time frames.

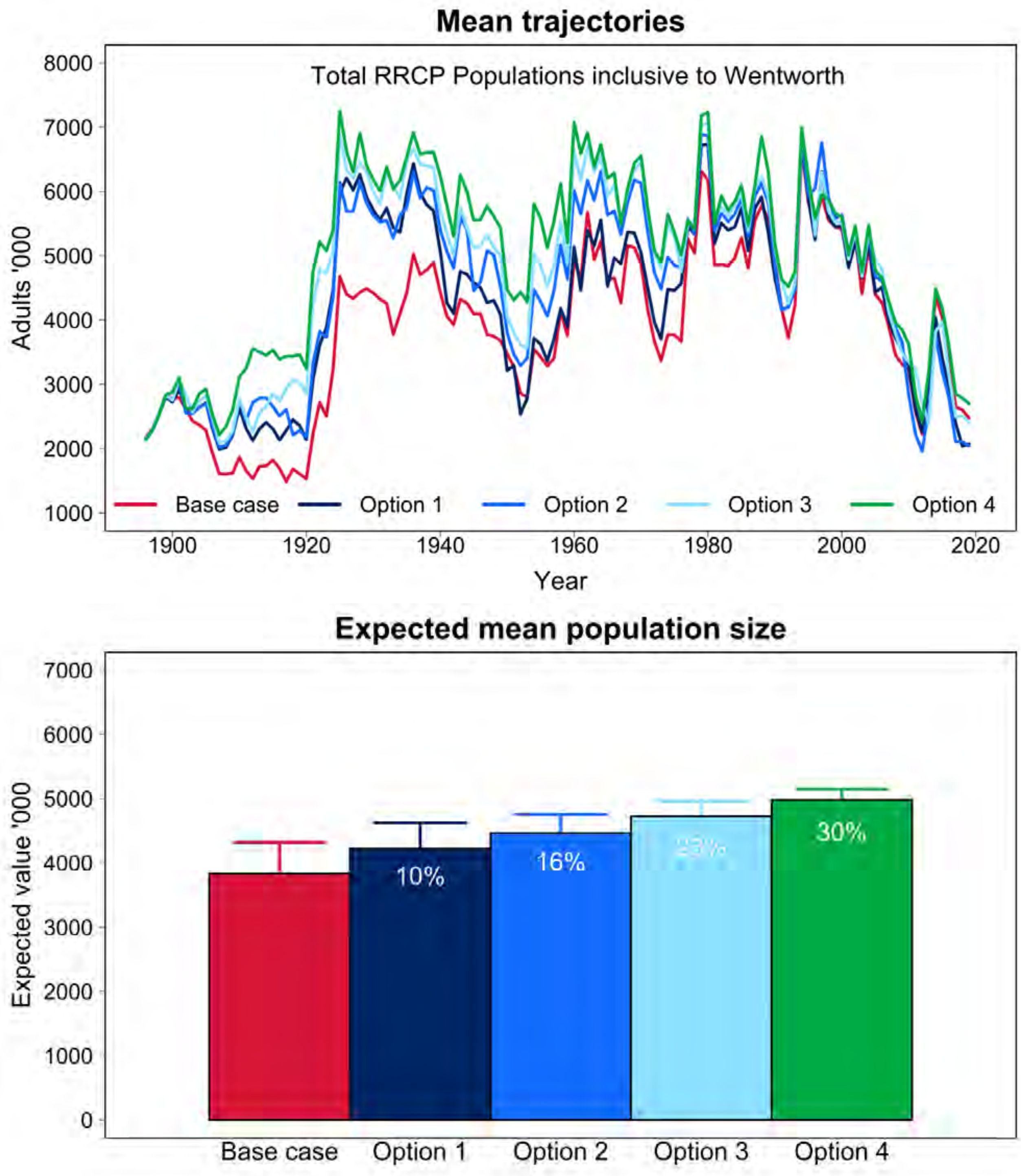


Figure A4.73. Modelled Golden Perch Total RRCP Populations reproduced from Figure 18 for the RRCP flow scenarios Base case – Option 4. Top panel: mean adult population size through time. Bottom panel: expected mean adult population size with the percentage change from Base case shown in each bar.

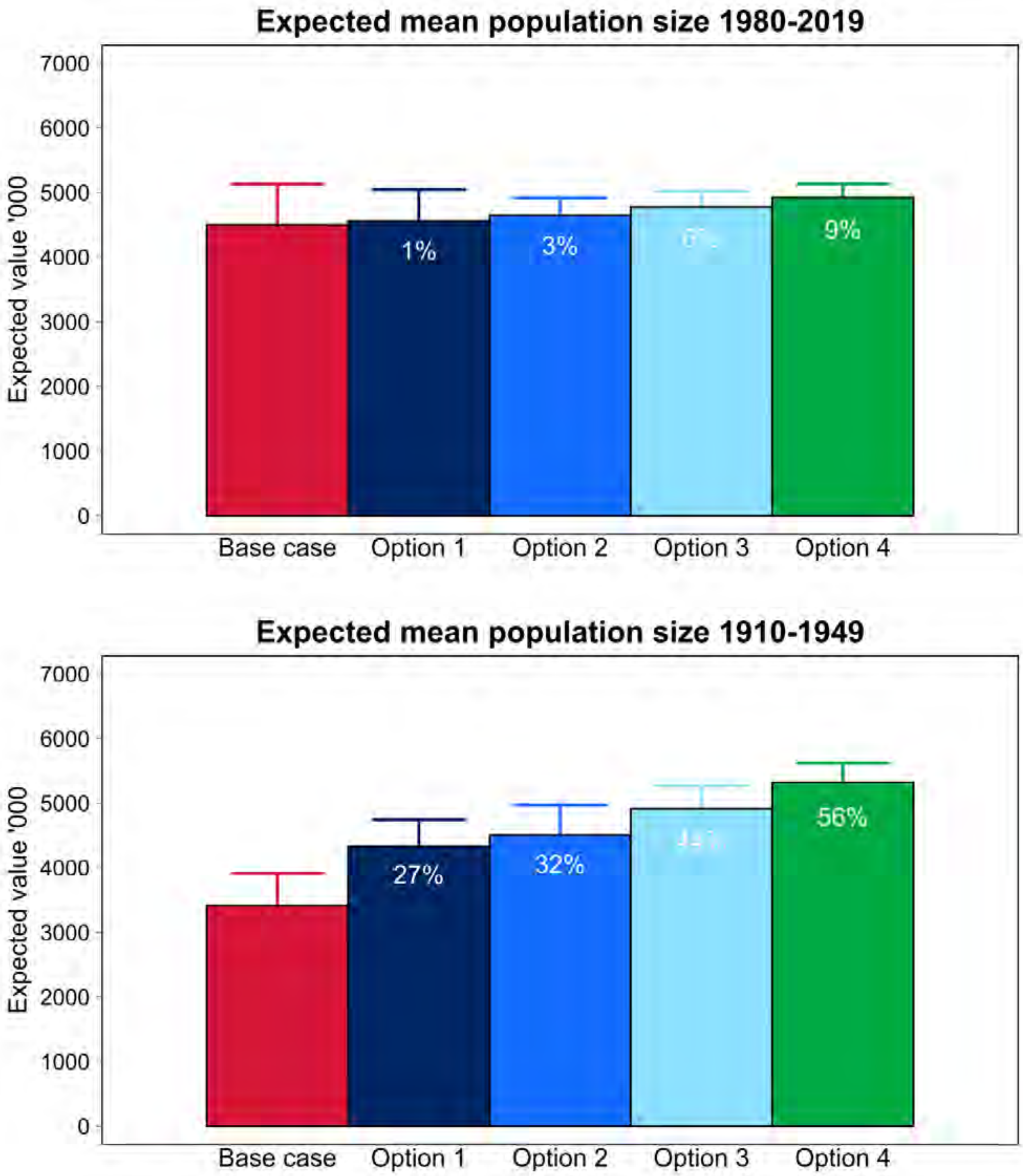


Figure A4.74. Modelled Golden Perch Total RRCP Populations expected mean adult population size for the 40-year period 1980–2019 (top panel) and the expected mean adult population size for the 40-year period 1910–2049 (bottom panel) for the RRCP flow scenarios Base case – Option 4.

Appendix 5: Golden Perch model convergence investigation

The purpose of the convergence testing was to ensure that the outcomes presented and conclusions drawn are robust in the assessment of the relaxed-flow-constraints scenarios. Model outputs displayed a convergence (i.e. congruence) among the relaxed-flow-constraints scenarios across time for Golden Perch (for examples, see the top panel of Figure 18, 1980 onwards). There is an apparent divergence of responses to the relaxed-flow-constraints scenarios that then later converge to very similar outcomes from around 1980 onwards (Figure 18: top panel). To assess the convergence of model response to the relaxed-flow-constraints scenarios, two analyses were undertaken to understand why it occurs and whether it is an artifact of the model or the input data.

First investigation

The first method was to examine the model input data (life-history responses to flow and temperature data) for time series correlation. A Rolling Pearson Correlation (Kirch 2008) demonstrates the correlation between two data series over the course of a time series, thus allowing for the investigation of correlation through time. Rolling Pearson Correlations were calculated across 10-year windows of flow inputs, Golden Perch population model inputs and Golden Perch population model outputs. For simplicity, only correlations between the Base case time series and the Option 4 time series were assessed. They generated statistics split into 10-year windows, and Pearson Correlations were calculated for each window and stitched together across the time series window index. Note that these windows overlap with one another, rather than being discreet from one another.

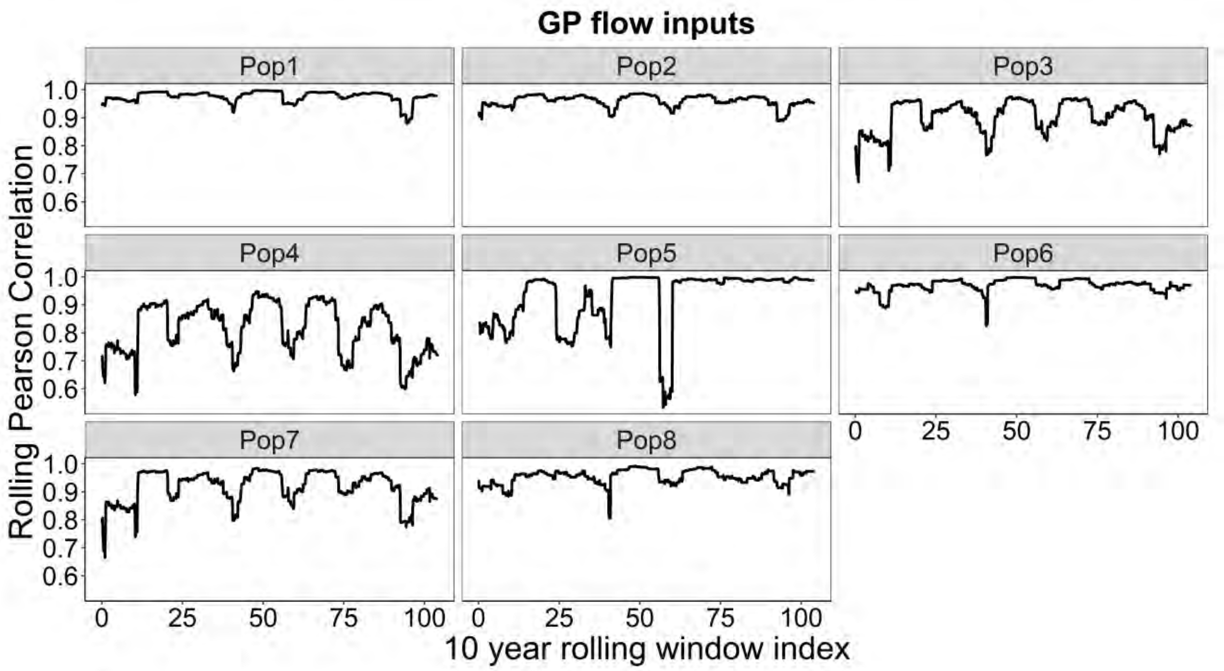


Figure A5.1. Rolling Pearson Correlations between the Base case and Option 4 generated across 10-year windows demonstrates serial correlation of the flows in each location. Pop1: Lower Murray below Wentworth; Pop2: Torrumbarry to Wentworth; Pop3: Yarrawonga to Torrumbarry; Pop4: Hume to Yarrawonga; Pop5: Lower Darling; Pop6: Hay to Balranald; Pop7: Edward River; and Pop8: Gundagai to Hay.

The correlation analysis demonstrated the flow inputs to be highly correlated for some of the populations. The reaches of the Lower Murray below Wentworth, Torrumbarry to Wentworth, Hay to Balranald and Gundagai to Hay (Pop1, Pop2, Pop6 and Pop8 – Figure A5.1) are highly correlated, and all populations exhibit positive correlation, are dynamic and shift through time, as indicated by the repetitive patterns in all populations (Figure A5.1). The high correlation indicates that there is little difference between the Base case and Option 4 in behaviour through time (i.e. if the Base case changes, then Option 4 changes in a similar manner, and this is consistent through the time series) (Figure A5.1). This would be expected, given that the environmental water delivery under relaxed flow constraints provides only modest changes to flows overall, for example, extending the duration of natural flow events in the Base case, raising the peak of an existing event in the Base case, or in some years creating a new flow peak in winter–spring. However, the broad pattern of flows (dominated by higher winter–spring flows and lower summer–autumn flows) is largely consistent between the Base case and the RRCP flow scenarios. Generally, the Lower Murray below Wentworth population drives the Golden Perch population in the Southern (connected) MDB; the Lower Darling and Torrumbarry to Wentworth are very important as well, but it is the Lower Murray below Wentworth where there is high correlation between the Base case and Option 4, and there is high correlation in the latter part of the time series between the Base case and Option 4 in spawning (Figure A5.2). We conclude that the correlation in flow in the Lower Murray below Wentworth, combined with correlation in spawning leads to correlation in the Golden Perch population trajectories (Figure A5.3). In addition, the Lower Murray below Wentworth strongly influences the dynamics of the Golden Perch population in the Southern (connected) MDB correlation in the population trajectories in the Lower Murray below Wentworth (Figure A5.4), which leads to correlation in the rest of the populations (Figure A5.3) and hence the convergence that is observed in the model outcomes (Figure 18: top panel).

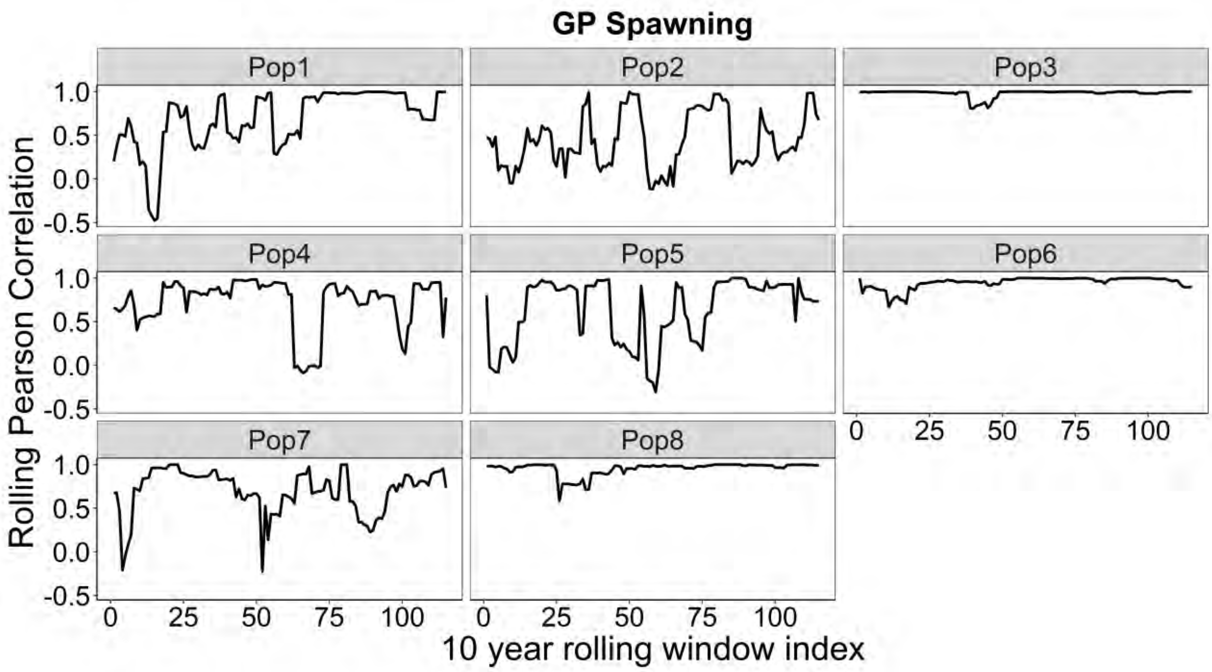


Figure A5.2. Rolling Pearson Correlations between Base case and Option 4 generated across 10-year windows demonstrate serial correlation of spawning in each location. Pop1: Lower Murray below Wentworth; Pop2: Torrumbarry to Wentworth; Pop3: Yarrawonga to Torrumbarry; Pop4: Hume to Yarrawonga; Pop5: Lower Darling; Pop6: Hay to Balranald; Pop7: Edward River; and Pop8: Gundagai to Hay.

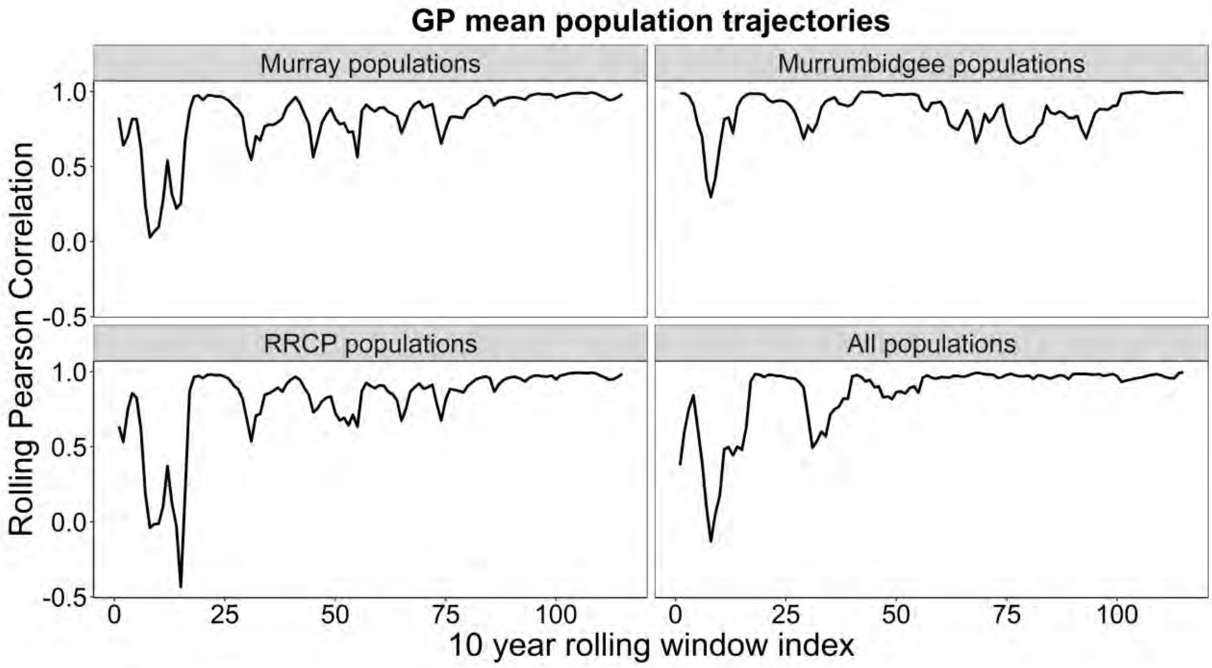


Figure A5.3. Rolling Pearson Correlations of population trajectories between Base case and Option 4 generated across 10 year windows demonstrate serial correlation at the broad-scale population level.

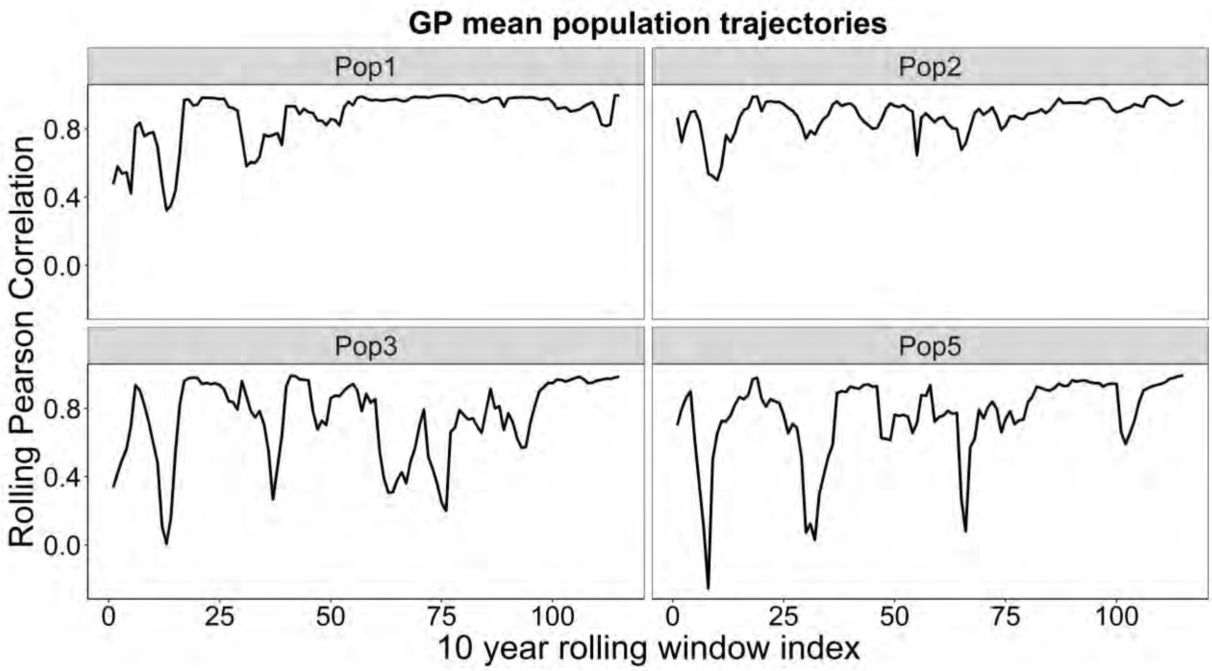


Figure A5.4. Rolling Pearson Correlations of population trajectories between Base case and Option 4 generated across 10-year windows demonstrate serial correlation for the major Golden Perch populations. Pop1: Lower Murray below Wentworth; Pop2: Torrumbarry to Wentworth; Pop3: Yarrawonga to Torrumbarry; and Pop5: Lower Darling.

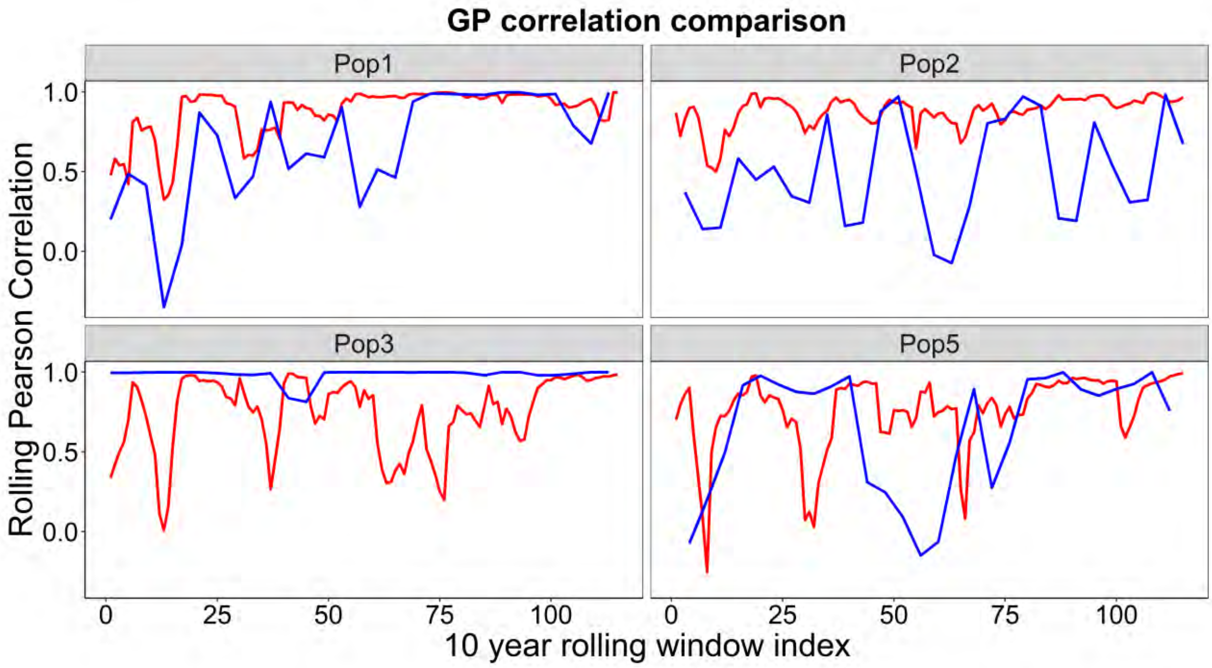
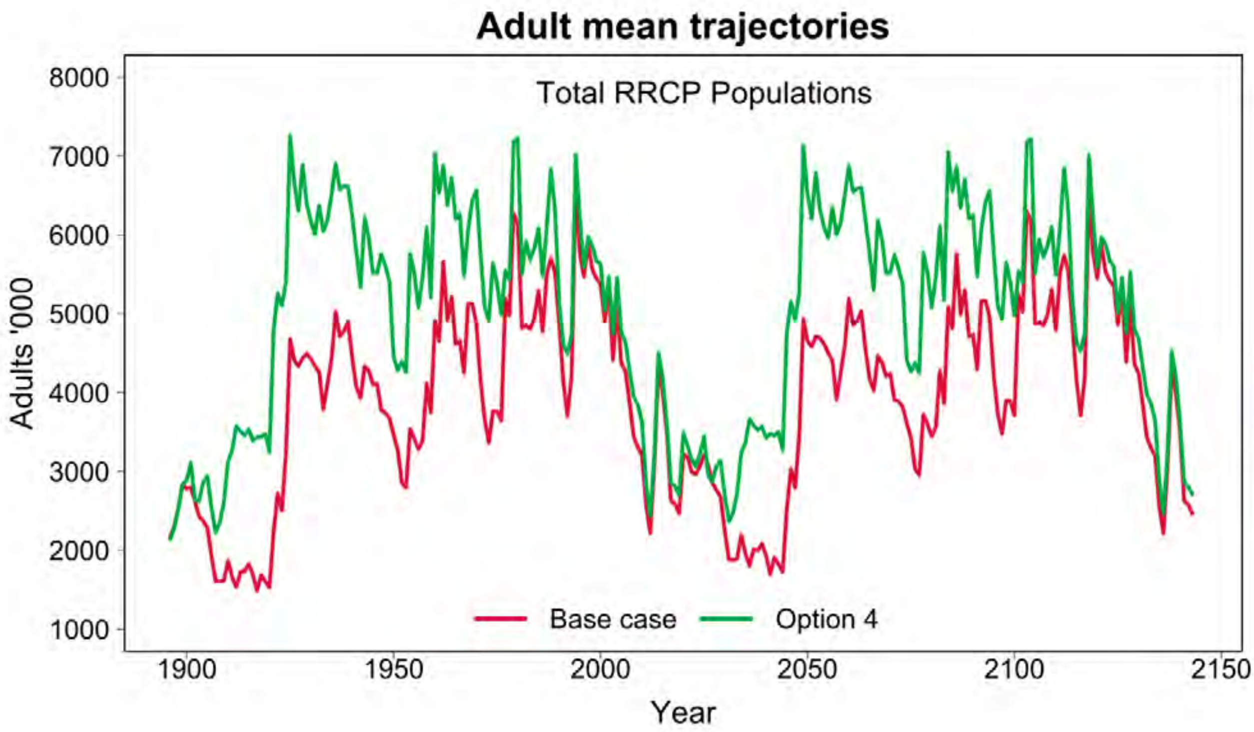


Figure A5.5. Rolling Pearson Correlations between Base case and Option 4 generated across 10-year windows demonstrate serial correlation for the major Golden Perch populations: red lines represent population trajectory correlations, and blue lines spawning correlations. Pop1: Lower Murray below Wentworth; Pop2: Torrumbarry to Wentworth; Pop3: Yarrawonga to Torrumbarry; Pop4: Hume to Yarrawonga; Pop5: Lower Darling; Pop6: Hay to Balranald; Pop7: Edward River; and Pop8: Gundagai to Hay.

Second investigation

The second method of examining population trajectory convergence was to repeat the input data time series in two ways: (1) simply add a repeat of the time series, i.e. run the model for 248 years; and (2) the section of input data that corresponded to the period of high correlation between scenarios (years 1963 to 2019: Pop1; Figure A5.1; Figure A5.2 and Figure A5.5) was copied and attached to the end of the original input data time series for both the Base case and Option 4 time series. This gave a total of 182 years of input data. These time series were then run through the population model as described in section 2 (except that each model contained 248 and 182 time steps, respectively).



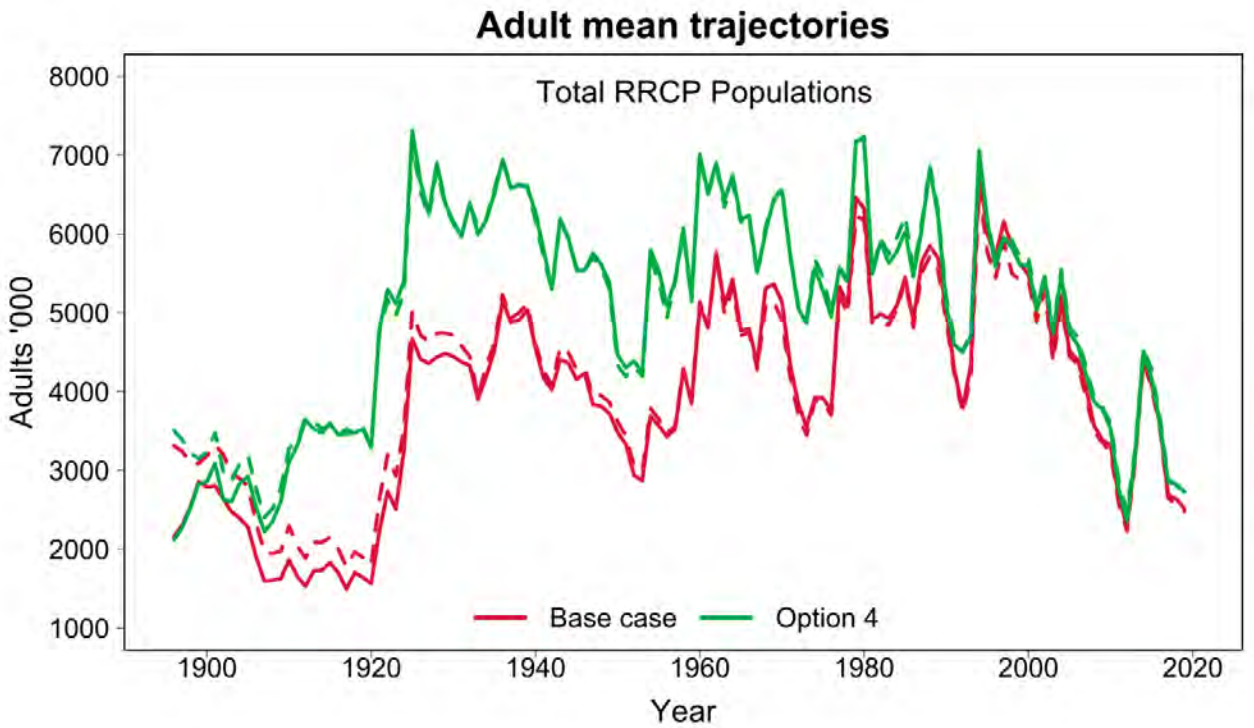


Figure A5.6. Modelled Golden Perch population across all RRCP reaches reproduced for the model run of 248 years, for the RRCP flow scenarios Base case and Option 4. Top panel: mean adult population size over the 248-year time series. Bottom panel: mean adult population size over the first 124 years in the solid lines and the second 124 years in the dashed lines.

In doubling of the time series, the pattern of initial divergence and then convergence repeats (Figure A5.6: compare top and bottom panels). The bottom panel of Figure A5.6 clearly shows that doubling the time series produces an almost exact replica of the first 124-year time series.

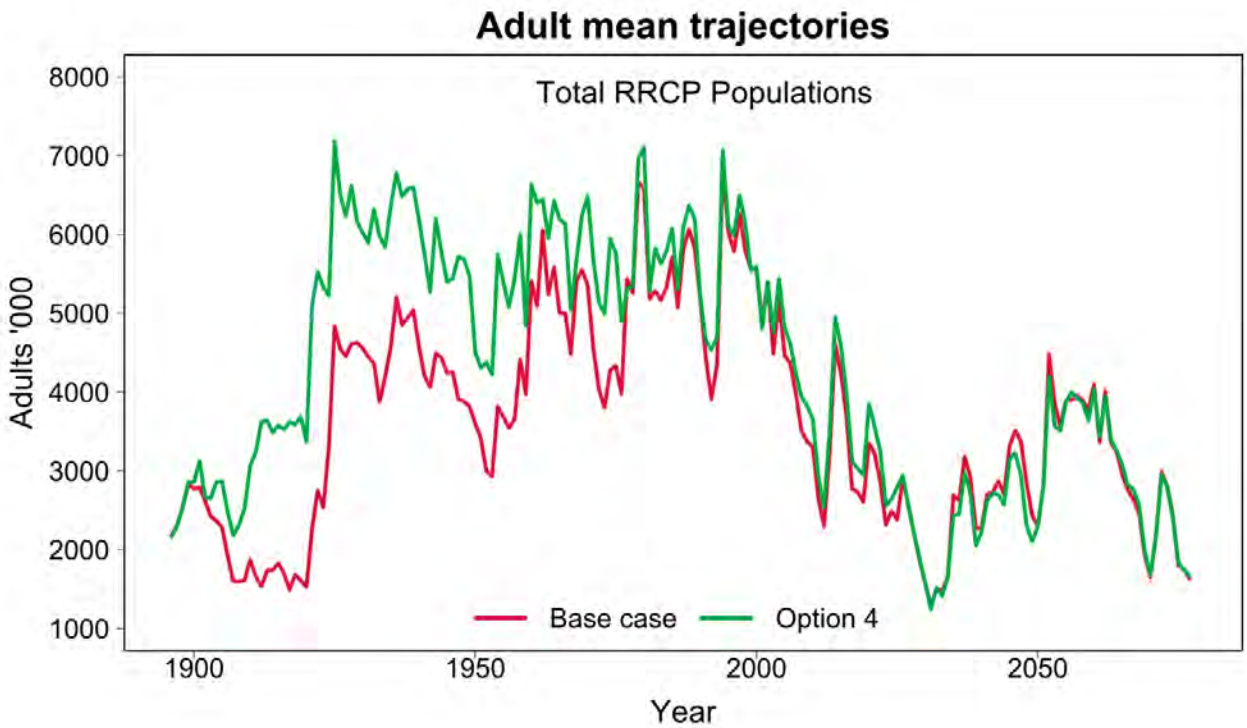


Figure A5.7. The mean adult population size of Golden Perch over the 182-year time series across all RRCP reaches, for the RRCP flow scenarios Base case and Option 4.

In repeating the data time series that showed high spawning correlation, the pattern of convergence remained in the modelled output (Figure A5.7), extending beyond 2019 to the end of the modelled period.

Figure A5.6 and Figure A5.7 demonstrate that model behaviour is not likely to be driven by the model construct, and that the observed convergence seen in the original model outputs (Figure 18) is due to inherent drivers within the input data.

Appendix 6: Validation

Data preparation

Temporal alignment of datasets

We needed to ensure that the MODEL, ARI, and NSW datasets had similar sampling periods. For the MODEL outputs, fish age was defined at the end of the fish year (June), at which point population numbers were tabulated. The ARI study sampling occurred in late Autumn (May). The NSW data sampling period spanned a wide range of months. To better align with the MODEL estimates, we retained only the samples obtained between March and August (using this wider range to increase the sample size). Throughout this study, a year was defined by the sampling date (the 'end' of a fish year).

Alignment of fish ages between MODEL and NSW/ARI outputs

It was important to ensure that we were comparing the same age classes between the MODEL and NSW/ARI outputs. Specifically, we needed to ensure that we were comparing the same age classes comprising the population size estimates.

For the ARI data, 220+-mm fish were tagged. For both Golden Perch and Murray Cod, the 220-mm mark is coarsely the cut-off for 2+-year-old fish (Anderson et al. 1992; Wright et al. 2020).

For the NSW data, we examined the distribution of lengths for each species, coarsely grouped into age classes: 0+ (<100 mm), 1+ (100–220 mm), 2+ (>220 mm but ≤340 mm), 3+ (>340 mm) (Figure A6.1). For both species, the NSW electrofishing data included a substantial proportion of fish of <220 mm, down to ~40 mm. For the NSW data, we applied the 220-mm cut-off. To adjust the number of fish caught so that it only represented the 2+ fish in the NSW samples, we calculated the percentage of fish caught that were >220 mm and then adjusted the number caught by this proportion. Adjustments were only necessary in large samples in which not all fish were measured.

For the population models, the adult Golden Perch and Murray Cod population sizes were defined as including fish ≥4 years old ($N_{t,adult} = \sum_{i=4}^{I} N_{t,i}$) and ≥5 years old ($N_{t,adult} = \sum_{i=5}^{I} N_{t,i}$), respectively. However, as the ARI data tagged fish down to 220 mm (2+) for both species, we needed to recalculate the adult population size in the MODEL for both species. As the sampling surveys for all datasets were aligned to late autumn/early winter, most 1+ fish would have been excluded from the fish counts used in the NSW and ARI datasets. Therefore, it is likely that the surveys are missing most of the $N_{t-1,1}$ class represented in the MODEL data (which later becomes the $N_{t,2}$). Therefore for validation purposes, we re-defined MODEL the 'adult' population size as 3 year and older: $N_{t,adult} = \sum_{i=3}^{I} N_{t,i}$.

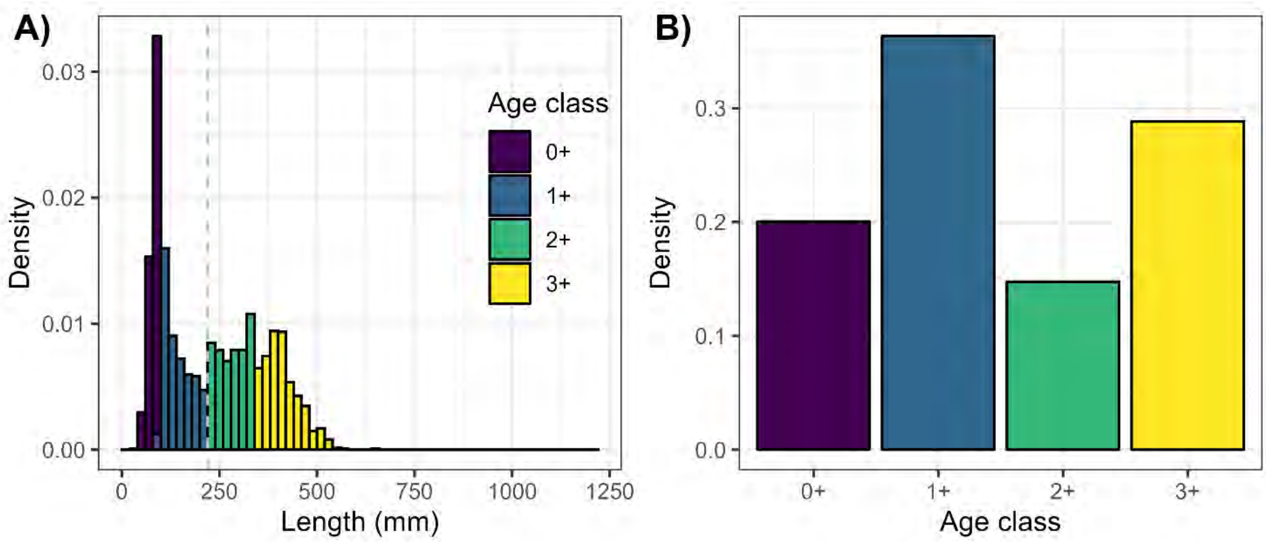


Figure A6.1. A) Fish length distributions for Golden Perch from the NSW electrofishing data. The vertical dotted line shows the 220-mm threshold used in the ARI data. Nominal age class categories based on length are provided. B) Age distribution (based on nominal age categories) for Golden Perch.

Collection and preparation of the NSW datasets

Datasets were provided by NSW Fisheries, and were collected as part of the Murray–Darling Basin Commission Sustainable Rivers Audit program (SRA) and Long-Term Intervention Monitoring project (LTIM). Sampling for the SRA project involved 12 replicate 90-s boat electrofishing operations (7.5 kW Smith-Root model GPP 7.5 H/L boat mounted), and sampling for the LTIM project involved boat-electrofishing (*n* = 32 operations, each consisting of 90 seconds 'on-time').

Before analysis, we prepared the NSW data through a series of steps:

(1) We assigned sampling sites to their population area and omitted any sites not within a population boundary.
(2) We only kept river sites, because these sites were the majority of the sites sampled and hence provided a more comparable dataset.
(3) We only kept sampling dates between March and August, to better align the population dynamics with those of the population model (see section previous section for more on sampling alignment).

(4) We only kept sites for which there were ≥5 years of repeated sampling, to provide a population trajectory more comparable with that of the model.
(5) We kept years in which we had ≥2 sites and ≥2 consecutive years (to allow estimation of the annual growth rate).
(6) We omitted any sites in which fewer than 10 fish were caught over the 5+ years.
(7) Finally, having identified the focal years, we added in any sites that had 3+ years of consecutive data in the focal years.

The final dataset is summarized in Table A6.1.

Table A6.1. Summary of NSW data kept for Golden Perch and Murray Cod for the analyses. Note, the number of sites and years can differ between species due to sites being dropped due to insufficient catches (e.g. at some sites Golden Perch were caught, but not Murray Cod).

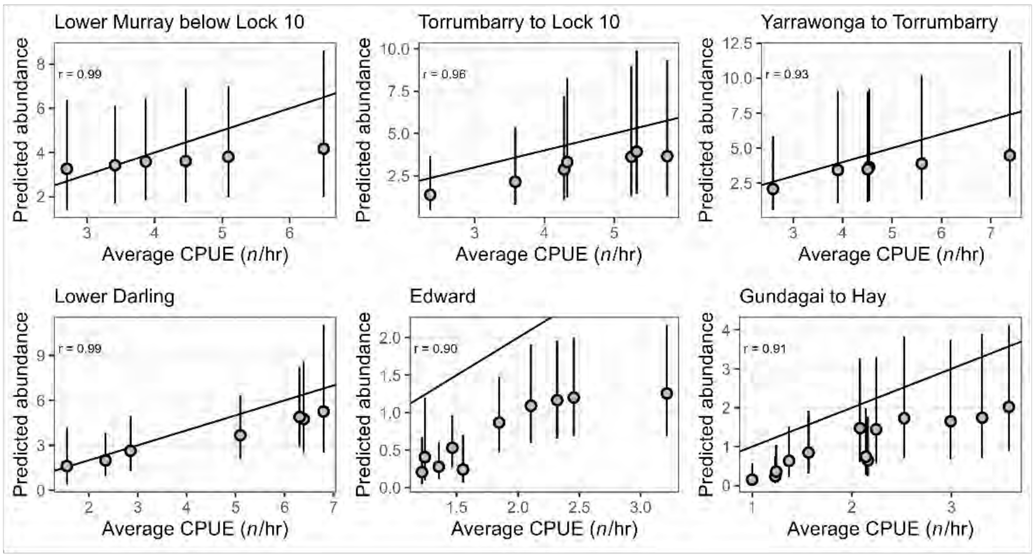
Population name	Species	Year range	No. sites	No. years	Total fish
Lower Murray below Wentworth	MACAMB	2006–2012	7	6	344
Torrumbarry to Wentworth	MACAMB	2004–2012	8	7	320
	MACPEE	2006–2012	7	6	78
Yarrawonga to Torrumbarry	MACAMB	2011–2018	3	6	65
	MACPEE	2011–2018	3	6	93
Lower Darling	MACAMB	2006–2012	7	7	1,377
Edward	MACAMB	2010–2019	30	10	305
	MACPEE	2010–2019	19	10	503
Gundagai to Hay	MACAMB	2006–2019	9	13	120

MACAMB – Golden Perch (*Macquaria ambigua*).

MACPEE – Murray Cod (*Maccullochella peelii*)

Data analysis

Golden Perch



Murray Cod

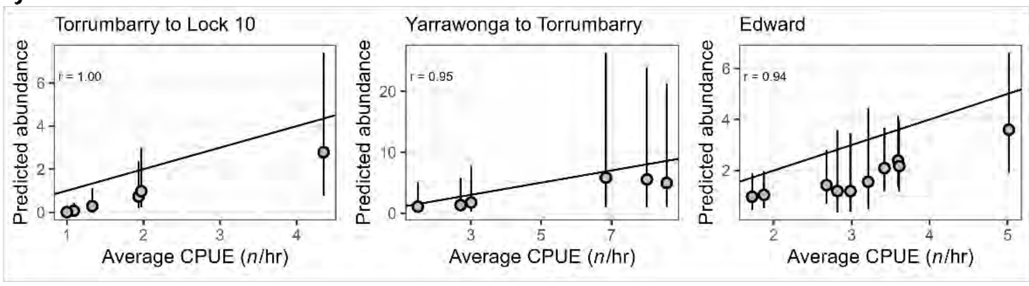


Figure A6.2. Plot of predicted abundance vs average CPUE with 95%CI error bars. Every model had high r values, indicating a good fit. The bias in the model estimates underpredicting is twofold: (1) the CPUE is partly an artefact of averaging the CPUE on a raw scale rather than a log scale (due to zero catches), and (2) the random-effects component of the model restricts higher growth rates. CPUE: catch-per-unit-effort. Solid black line shows 1:1 relationship.

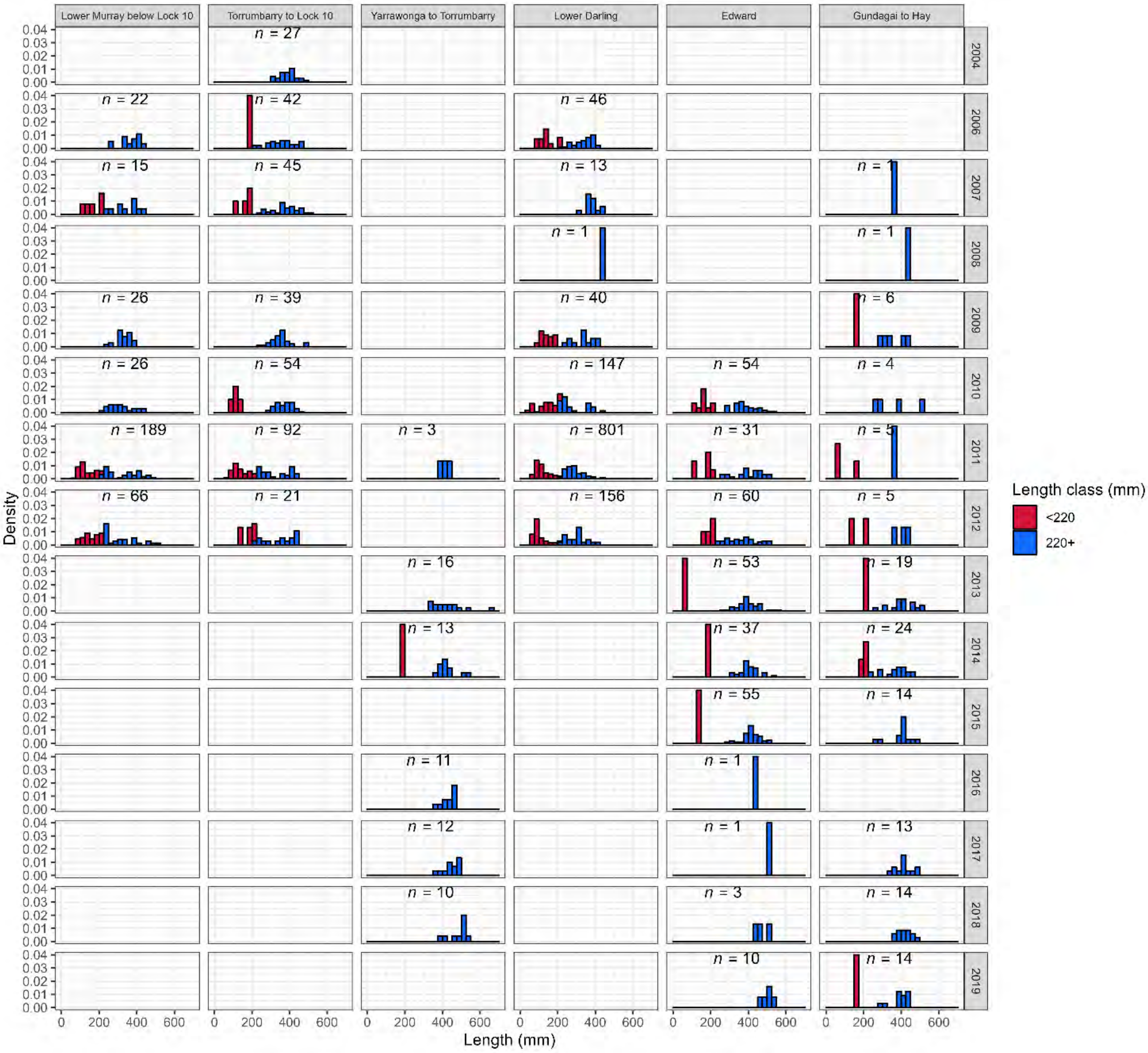


Figure A6.3. Length distributions of selected data for each population area for Golden Perch.

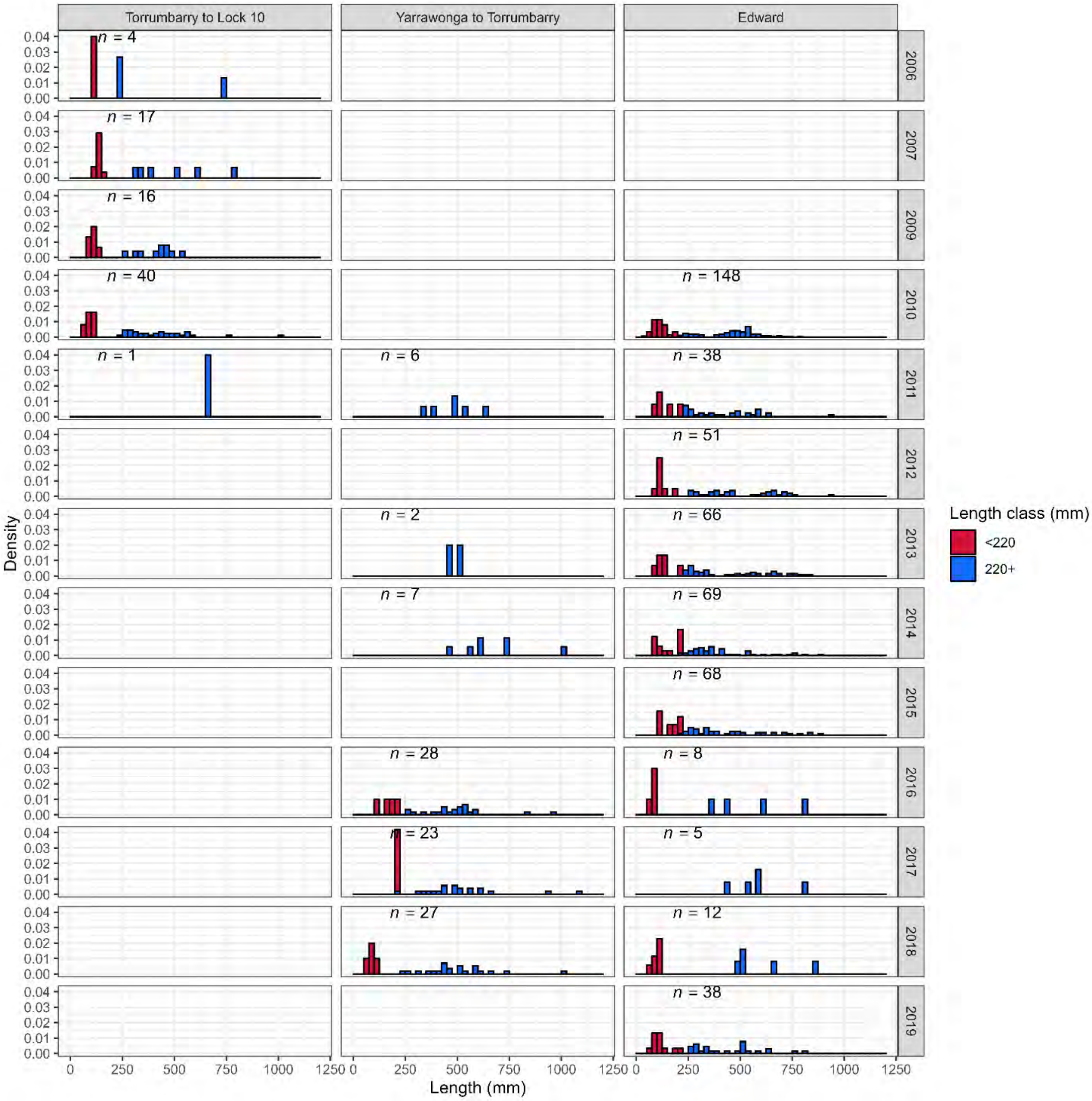


Figure A6.4. Length distributions of selected data for each population area for Murray Cod.

Summary of validation results

Table A6.2. Summary of the validation results, possible explanations for mismatches, future work to improve MODEL/DATA correlation, and implications of the validation work for confidence in using the MODEL predictions.

	Summary of comparison of population model predictions (MODEL) and empirical data (DATA)	Possible explanations for mismatches	Future work to improve MODEL/DATA correlation	Relative confidence for using MODEL predictions in RRCP project
Golden Perch				
Yarrawonga to Torrumbarry	• Similar trends in MODEL and DATA • Some temporal misalignment (MODEL lagged cf. DATA) • Weaker correlation between MODEL and DATA at extremes of observed hydrology • Excellent alignment in MODEL and DATA estimates of immigration	• Lagged MODEL prediction to 2010–2010 floods could be due to size of flooding leading to a redistribution of fish throughout the system • MODEL only allows fish to move between adjoining populations in each year, but flood may have led to more extensive movement • ARI Jolly–Seber modelling used for DATA may be overcompensating for changes in detection during flood • Possibility of overestimated movement from upstream	• MODEL has a 'reset' rule for after large floods—consider if this needs to be larger • Explore movement into reach from upstream (Hume to Yarrawonga), and revisit movement rules	• Very high
Lower Darling	• Similar trends in MODEL and DATA • Some temporal misalignment (MODEL lagged cf. DATA)	N/A	N/A	• Very high
Yarrawonga to Torrumbarry	• MODEL and DATA broadly consistent • DATA temporally limited (2005–2010)	No mismatches	• Confidence of alignment between MODEL and DATA would be stronger with more extensive empirical datasets	• Medium

	Summary of comparison of population model predictions (MODEL) and empirical data (DATA)	Possible explanations for mismatches	Future work to improve MODEL/DATA correlation	Relative confidence for using MODEL predictions in RRCP project
Edward River	• Low correlation. DATA shows decrease in 2015–2016 and small populations thereafter	• Blackwater events occurred in 2015/2016 and blackwater was not included in MODEL	• Include blackwater impacts in MODEL	• Low
Gundagai to Hay	• Low correlation. DATA shows gradual increase. MODEL shows decrease in 2000–2010, than an increase post 2010	• DATA likely reflects maintenance of this population from stocking • MODEL shows increase in 2010 due to movement from downstream population due to flow. This is likely unrealistic given the barriers	• Include stocking in model • Revisit movement rules to more accurately model movement past barriers	• Low
Lower Murray	• Low correlation but DATA limited • DATA also only from NSW, but population for MODEL extends to Lower Murray in South Australia	N/A	• Extend validation, if possible using datasets from South Australia	• DATA too spatially/temporally limited to say
Murray Cod				

	Summary of comparison of population model predictions (MODEL) and empirical data (DATA)	Possible explanations for mismatches	Future work to improve MODEL/DATA correlation	Relative confidence for using MODEL predictions in RRCP project
Yarrawonga to Torrumbarry	• MODEL predicts relatively stable population, whereas ARI DATA shows decrease until 2010, large increase in 2015. NSW data shows increase in 2015	• Possible that decrease in size until 2010 is a negative response to drought, and increase 2014–2015 is a delayed response to 2010–2011 floods	• Additional empirical studies under high- and low-flow conditions to determine effects of detectability on population abundances estimated from DATA. • Revisit effects of temperature, dissolved oxygen, and productivity in MODEL, particularly under low-flow conditions	• Low
Torrumbarry to Wentworth	• MODEL predicts and DATA shows decrease in 2010	• Decreases in MODEL and DATA likely due to blackwater, but MODEL may be underestimating magnitude of response	• Revisit blackwater inputs for MODEL	• Medium/Low
Edward River	• MODEL and DATA both show decrease in 2010 • MODEL low variability 2011 onwards • DATA shows increase until 2015, then decrease	• MODEL not capturing 2015–2016 blackwater events	• Revisit blackwater inputs for MODEL	• Low

N/A: not applicable.

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