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Adaptive Management of Malkumba-Coongie Lakes Ramsar Site in Arid Australia—A Free Flowing River and Wetland System

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Citation: Kingsford, R.T.; McLoughlin, C.A.; Brandle, R.; Bino, G.; Cockayne, B.; Schmarr, D.; Gotch, T.; Norris, V.; McCann, J. Adaptive Management of Malkumba-Coongie Lakes Ramsar Site in Arid Australia—A Free Flowing River and Wetland System. *Sustainability* **2021**, *13*, 3043. https://doi.org/10.3390/su13063043

Academic Editor: Denielle M. Perry

Received: 3 February 2021
Accepted: 28 February 2021
Published: 10 March 2021

Abstract: The Malkumba-Coongie Lakes Ramsar Site has extensive terrestrial and freshwater ecosystems (largest Ramsar Site in Oceania, 2,178,952 ha, designated in 1987), including freshwater and salt lakes, lignum swamps and river channels in central Australia. It is supplied by Cooper Creek, a free-flowing Lake Eyre Basin river system. The area includes pastoral leases (97% of site grazed, including a regional conservation reserve (35%)) and a National Park (3%), with the largest oil and gas production field in Australia. We developed a Strategic Adaptive Management (SAM) Plan, linking science, monitoring and management of this social-ecological system, involving stakeholders and workshops. This involved developing a shared vision and hierarchy of objectives linked to management actions and identified outputs and outcomes. We exemplify this approach with explicit and measurable end-points (thresholds of potential concern) culminating from low level objectives for fish communities, particularly the alien sleepy cod *Oxyeleotris lineolata*. We describe this framework, highlighting the benefits in prioritizing management actions and monitoring in collaboration with a diverse range of stakeholders, driving adaptive feedback for learning. The whole approach is aimed at successfully achieving mutually agreed management objectives and the vision to maintain the ecological character of the Malkumba-Coongie Lakes Ramsar Site.

Keywords: Strategic Adaptive Management; freshwater fish; sleepy cod; thresholds of potential concern; freshwater management; social-ecological system

1. Introduction

The world's biodiversity is in critical decline, particularly freshwater ecosystems, including rivers and wetlands [1]. Like most realms, ecosystem loss comes from habitat loss and degradation, pollution, overharvesting, invasive species, disease and climate change [2–4]. These threats are directly and indirectly also diminishing ecosystem services, including drinking water, fishing, spiritual and cultural values and building resources, tourism and grazing resources for human communities around the world [5]. Pressures to develop the world's rivers are ongoing, given the burgeoning population and our dependence on fresh water, making it among the top five global risks to human well-being [6]. Habitat loss is particularly acute, often mediated through the development of rivers by the widespread building of dams [7], extracting water and the development of floodplains, devastating biodiversity and ecosystem services of many of the world's rivers and wetlands [8]. There is widespread fragmentation and development of rivers [9], leaving relatively few free-flowing rivers around the world [10]. In addition, freshwater ecosystems around the world are seriously threatened by invasive species, particularly fish [11]. Effects of climate change are compounding, altering flow and flooding regimes of rivers and wetlands [12], while increased temperatures are driving higher evaporation rates, affecting freshwater ecosystems and their dependent organisms and processes.

Ongoing and often accelerating degradation reflects the challenges for governments and their communities, often struggling with governance and management frameworks which can adequately deal with uncertainty in the complex management of rivers, usually extending over thousands of kilometers. Effective management of such complex social-ecological systems must integrate social and ecological dimensions, across diverse stakeholders. The management of rivers also has significant legacy challenges, with many dependent communities affected by upstream water resource developments [13], reflecting major power imbalances involved in decision-making. Adding to the complexity, many rivers also extend over political or jurisdictional borders, where issues of sovereignty occur [14,15].

This often produces highly fragmented management, sometimes with competing legislation and policy even within the same jurisdiction. For example, traditionally, water, mining and agricultural legislation, policy and management have a history of driving exploitation of natural resources, including rivers and their fresh water. This contrasts with corresponding conservation and sustainable use interests, broadly focused on the protection and restoration of biodiversity and ecosystems. Further, conservation instruments often focus primarily on particular locations (e.g., protected areas) [16]. They do not adequately deal with highly connected systems or those where the primary natural resources (e.g., water) are provided from a catchment, sometimes thousands of kilometers away [17]. As a result, river management is often a wicked problem where there are competing objectives and many stakeholders producing intractable social-ecological challenges [18].

The integration of different values and uses, within overarching governance and management processes, is needed for effective conservation management of rivers and their dependent ecosystems. Strategic Adaptive Management (SAM) is an approach, explicitly identifying values and key processes which underpin the conservation management system, usually drawn up as a plan [19–21]. It is a version of natural resource management that skillfully links science, monitoring and management within a learning-by-doing approach [22], focusing on stakeholder collaboration and effective knowledge management [21,23], applicable for a range of natural resource applications [24–26]. Importantly, for rivers, such a structured management approach can capture the dependencies of a particular wetland ecosystem on upstream processes, in the attributes, values and engagement of stakeholders. Implementation of SAM involves identifying a shared vision by all stakeholders, reflecting a future 'desired state'. From this, an explicit hierarchy of objectives is developed, increasing in specificity [27]. At the most detailed level, these objectives can be converted into actions and linked to specific indicators, outputs and outcomes for any ecosystem [21,25]. Actions can be triggered when Thresholds of Potential Concern (TPCs) are exceeded [28], or close to being exceeded, informed by targeted monitoring programs [29]. Feedback from this monitoring provides the data and information for learning about the effects of management and for adapting actions [22,30] and ultimately indicate whether the shared vision is being achieved [31].

Wetlands of international importance are listed under the Convention for Wetlands of International Importance, also known as the Ramsar Convention, aimed at maintaining their ecological character [32]. We developed a Strategic Adaptive Management Plan (Ramsar SAM Plan) for the Malkumba-Coongie Lakes Ramsar Site (MCLRS), an extensive wetland ecosystem consisting of lakes, river channels and floodplains as well as a substantial terrestrial area [33] (Figure 1). This system is part of the Lake Eyre Basin, one of the few large river basins in the world with free-flowing rivers, which was awarded the Australian National River Prize in 2014 and the International River Prize in 2015, for protecting this magnificent system [34]. The wetlands of Malkumba-Coongie Lakes in South Australia depend on flows from Cooper Creek, upstream from western Queensland [35] (Figure 1). Flows reach the system via two main channels, diverging from Cooper Creek with the northern channel inundating most of the lakes [36] (Figure 1). The MCLRS incorporates a range of different land uses, including National Park, grazing, mining leases and Traditional Owner areas (Figure 1). Further, Cooper Creek, the wetland's upstream water supply, has a long history of pressure from potential water resource developments, including establishment of cotton farming with irrigation in the 1990s, requiring diversion of water [37,38] and most recently potential mining development on floodplains [39,40]. There is currently a strong commitment by all Governments, including the main 'basin states' of Queensland, South Australia and the Northern Territory and the Australian Government, to protect the Lake Eyre Basin rivers, primarily driven by the crisis of water resource development in the 1990s [34,37,41].

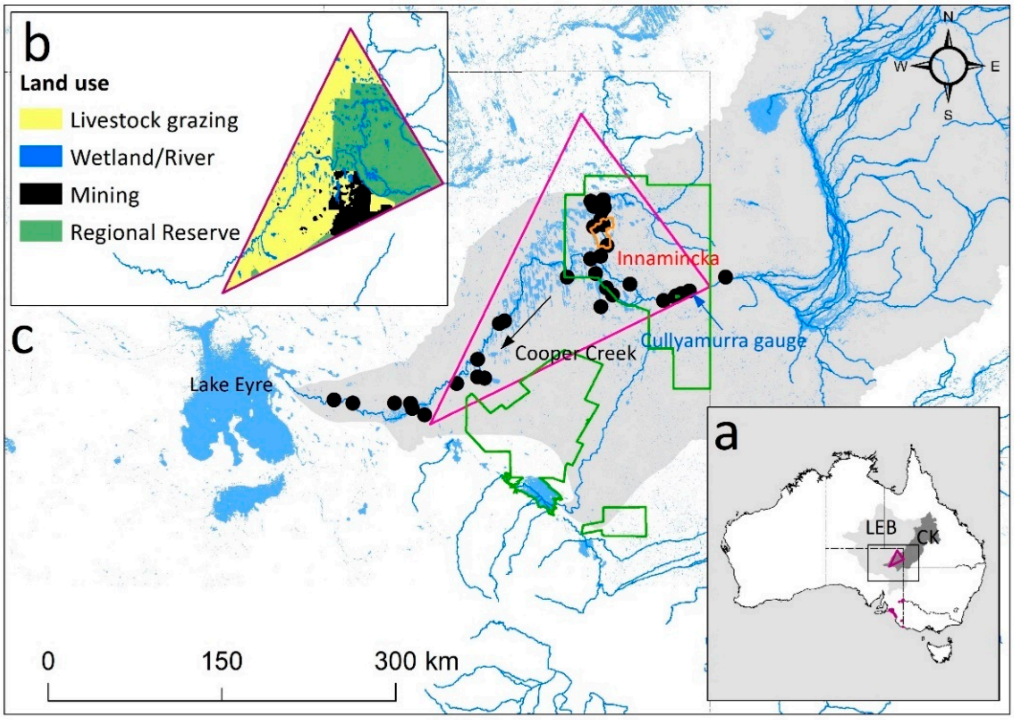

Figure 1. (**a**). Lake Eyre Basin (LEB, light grey) in central Australia, showing Cooper Creek (CK, dark grey) and the Malkumba-Coongie Lakes Ramsar Site (triangle, inset), (**b**). with the area's different land uses (inset) and (**c**). details of reserves (green boundaries), Malkumba-Coongie National Park (orange line within the Ramsar site), inflowing rivers and lakes (blue), Cooper Creek (arrow indicating flow direction) catchment (grey), Innamincka (red), Cullyamurra river gauge (blue arrow) and sites where fish communities were surveyed (filled black circles, 2000–2019).

The aim of this paper was to build a value driven framework for ongoing adaptive management of the extensive MCLRS area (21,790 km^2). We describe the development of the Ramsar SAM Plan, which involved workshopping with all stakeholders, including government, industry and Traditional Owners. The vision and upper hierarchy of objectives for the plan were developed first. Next, we developed the associated lower level objectives related to fish community management, as this is where most data are currently available. The plan allows for conscious links to be made between research, monitoring and management (current and future), as well as identifying priority scientific questions for targeting investments. We highlight key research and adaptive management learning benefits enabled by the Ramsar SAM Plan, for this complex social-ecological system.

2. Methods

2.1. Case Study Site: Malkumba-Coongie Lakes

The MCLRS includes a large part of the free-flowing Cooper Creek catchment (Figure 1). Flows down Cooper Creek to the Ramsar Site are highly variable, often reflecting strong monsoonal or tropical systems, which can drive flows down the river all the way to Lake Eyre during sequences of flooding years, often coinciding with El Nina phases [42–44]. The wetlands include a variety of river channels, many temporary waterholes, a few permanent waterholes, braided swamps, floodplains and terminal freshwater and saline lakes. Intermittent local rainfall events mostly drive the terrestrial ecosystems, which make up most (~87%) of the surface area of the Ramsar Site (Figure 1). The site is well-known for its high biodiversity and cultural values and processes, resulting in its listing as Ramsar Site in 1987. It is a multi-use area, epitomizing some of the challenges for implementation of the Ramsar Convention, focused on wise use of wetlands, under a range of land uses.

The MCLRS has a rich ongoing culture and a connection with the Yandruwandha and Yawarrawarrka, Dieri and Wangkangurru people. Pastoralists arrived in the 1870s and disrupted the Yandruwandha and Yawarrawarrka people, moving many off their land where they had lived for tens of thousands of years around the lakes, rivers and other wetlands [45]. Connection was maintained through stories, language and culture, reflecting the importance of country to all life and being, where all aspects of human society and condition are interrelated with the environment's health and condition [46]. Establishment of the Yandruwandha Yawarrawarrka Parks Advisory Committee provides a mechanism for formal cooperative management of the Ramsar Site, including Malkumba-Coongie Lakes National Park and Innamincka Regional Reserve [45,46].

Malkumba-Coongie Lakes National Park occupies 3% of the Ramsar Site (26,661 ha), with the remaining consisting of either pastoral lease, Innamincka Regional Reserve (35%, 1,354,055 ha) and 15% with the largest mainland oil and gas production field in Australia (Figure 1). Under the South Australian National Parks and Wildlife Act 1972, Innamincka Regional Reserve is protected for its natural values, while allowing access to oil and gas resources, hunting, traditional use, tourism and grazing of livestock (Figure 1) [46]. There are three management zones within the Ramsar Site which relate to mining access to high environmental value areas, created to ensure that oil and gas exploration and production does not impact on sensitive areas in the Ramsar Site. This includes a No Mining Zone created under the National Parks and Wildlife Act 1972 for Malkumba-Coongie Lakes National Park and an area to the east of the National Park, over a major flood-out area with significant natural and cultural values. Additionally, there is a Walk-in Zone of Malkumba-Coongie Lakes National Park and its surrounds and another, a Controlled Access Zone, established under the South Australian Petroleum and Geothermal Energy Act 2000. Subsurface drilling for petroleum may occur under license within the Walk-in Zone but with only walk-in access. Oil and gas extraction, tourism and pastoralism contribute more than $3 billion annually. The population in the region is low with less than 50 residents in the main town of Innamincka (Figure 1) with others comprising itinerant oil and gas industry and seasonal visitors to the National Park. Nature conservation is also a significant land use within the region. The wetland areas within these parks are also the major focus of tourism in the region.

The MCLRS meets seven criteria under the Ramsar Convention, including: unique or rare diversity of wetlands (Criterion 1); supports threatened species or ecological communities (Criterion 2); maintenance of biological diversity (Criterion 3); supports waterbird species at an important stage in their life cycle (Criterion 4); regularly supports 20,000 or more waterbirds (Criterion 5); regularly supports more than one percent of individuals of a species (pink-eared duck *Malacorhynchus membranaceus*, red-necked avocet *Recurvirostra* *novaehollandia*) (Criterion 6) and as an important source of fish (food, spawning, nursery, migration) (Criterion 8) [47]. It is also one of Australia's important bird areas [48].

2.2. Strategic Adaptive Management Context

The Lake Eyre Basin Intergovernmental Agreement brings together the Australian, Queensland, South Australian and Northern Territory Governments to ensure the sustainability of the Lake Eyre Basin river systems, in particular to avoid or eliminate cross-border impacts [49]. The Agreement was signed by Ministers of the Australian, Queensland and South Australian governments in October 2000, and has been enacted in the Australian, Queensland and South Australian Parliaments. The Northern Territory signed in 2004. A secretariat and a senior officers group support the governments and their Ministers. The Lake Eyre Basin Ministerial Forum endorsed the SAM approach associated with the Lake Eyre Basin Rivers Assessment, the 10-yearly assessment of river and catchment health across the whole Lake Eyre Basin.

2.3. Workshops—Strategic Adpative Management

We organized three workshops to develop the Ramsar SAM Plan for MCLRS: September of 2017 (14–15th, 38 people) and 2018 (4–5th, 35 people) and May of 2019 (24–25th, 20 people). Stakeholders included representatives of the grazing, petroleum, tourism and fishing industries, Aboriginal Traditional Owners, Regional Natural Resource Management staff, including Natural Resources South Australian Arid Lands, the arid zone science community, the conservation sector, and the South Australian, Queensland and Australian Governments.

These workshops were the foundation for building the Ramsar SAM Plan, which first identifies the values of the site which need to be managed for and then specific information needs, expressed as objectives, some of which can become specific research questions. We went through several steps: identifying values; management concerns; visions for the future and obstacles. These were independently done, individually and within stakeholder groups, to maximize input and then discussed collectively after this input was posted on a wall at workshops. Subsequently, we developed a shared vision, reflecting the future 'desired state'. This can be informed by social, technical, environmental, economic, political values, and constraints (e.g., the area is a Ramsar Site). An important preliminary step was the identification of a set of vital attributes (with their determinants and threats) so that stakeholders could work together to develop a shared vision for the 'desired state' [26]. Vital attributes were characteristics which made the area special or distinctive. They could be scientific, ecological, legal, historic, cultural or socio-economic. They helped to craft the vision, with a focus on social, conservation and ecosystem health.

Subsequently, stakeholders discussed developing their shared vision into a hierarchy of cascading objectives, initially with four hierarchical levels, increasing in focus and rigor. We then focused on two of the agreed Level 4 objectives, related to fish communities (native and alien), developing them into finer level objectives with increased specificity, given this community is currently the most data rich source of information. Importantly, we also provided links back to management with explicit and measurable triggers, and indicators and endpoints or TPCs [50], focusing on the current management concern of alien fish species. Within the context of understanding priority drivers, determinants and threats within the Ramsar Site, we developed the alien fish related TPCs, with a focused stakeholder group comprising scientists, managers and government personnel. We also tackled the associated management actions, linking these to the agreed operational outputs and strategic outcomes. The process is demonstrated using the alien sleepy cod *Oxyeleotris lineolata*. The TPC for this alien fish species does not specifically represent an 'ecosystem' threshold, rather an optimization of an 'ecological' (scientific/model-based) and 'utility' (value/objectives-based) threshold [29,50], applied as a 'decision' threshold [28].

3. Results

3.1. Desired State—Shared Vision

We asked workshop participants to identify vital attributes of the site, separately and then in their respective stakeholder group. This was informed by the context for the Ramsar Site, specifically its cultural, environmental, legal and socio-economic context (Figure 2). The vital attributes were then discussed in plenary to identify overlap and produce largely mutually exclusive set of vital attributes which defined the social-ecological identity of the MCLRS. Consequently, we collectively agreed that eight vital attributes broadly captured the essence of MCLRS, spanning cultural, environmental, legal and socio-economic dimensions (Table 1). These included three vital attributes related to environmental values: international Ramsar obligations, natural systems, and waterbirds. The other vital attributes related to the social dimensions and included cultural heritage; economically productive and permanent communities; collaboration; and health and well-being (Table 1). It was also clear that the wetland ecosystem and its nationally important largely free-flowing river are critically important, supporting high biodiversity of significance and extensive waterbird populations (Table 1).

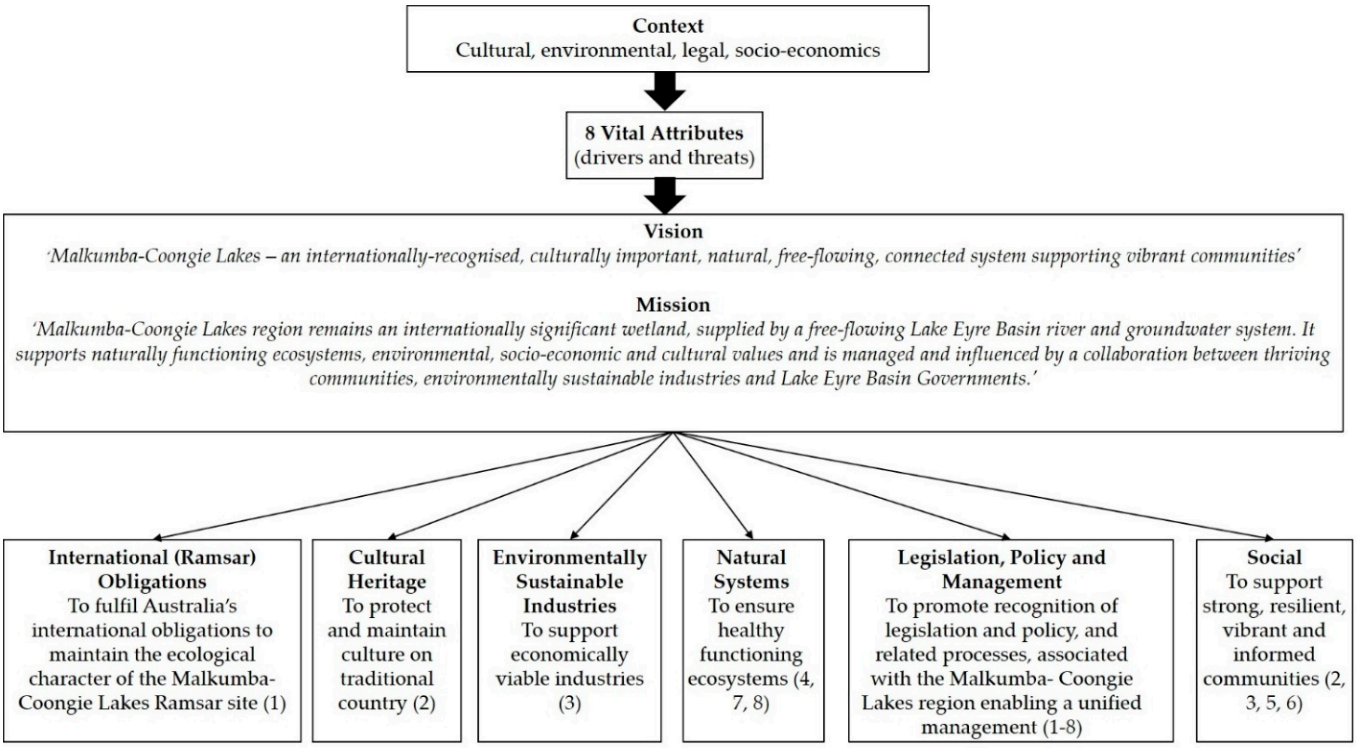

Figure 2. Value driven process, informed by the context (cultural, environmental, legal and socio-economic factors), led to identification of the eight vital attributes (see Table 1) and formulation of the vision and supporting mission for Strategic Adaptive Management of the Malkumba-Coongie Lakes Ramsar Site. Level 1 objectives for six main areas associated with this complex social-ecological system came from the vision and mission linking with relevant vital attributes (represented by numbers in the six bottom boxes, and Table 1).

After establishing the eight vital attributes, there was a facilitated discussion of the threats and socio-economic drivers or determinants affecting these vital attributes. Threats included not only abiotic anthropogenic direct or indirect impacts (e.g., water resource development) but also social threats, such as uncoordinated land and water management, people capacity and funding affecting the different social-ecological dimensions. This was mediated through a dedicated workshop session where drivers and threats were identified for each of the vital attributes. For example, it was clear that the system was highly reliant on a dependable free-flowing river and its water supply for environmental, cultural and socio-economic values. The associated identified threats were the diversion or extraction of water upstream or in the area, reducing the variability and extent of flooding. In this context, the drivers were the flow and flooding regimes. Further, for the cultural heritage attribute, there were other threats including protection of key sites from disturbance with key drivers including tourism and industry damage or destruction of these sites. There were also threats to the viability of human communities, both in terms of economy and well-being, with access to knowledge, legislation, policy and involvement in management identified as key drivers. There were also inherent tensions between different values. For example, the oil and gas and grazing industries were threatened by reduced access to areas, while some of the threats to cultural and environmental values related to industrial practices, including floodplain developments which were inconsistent with the obligations of the Ramsar Convention.

Table 1. The eight vital attributes, agreed upon by stakeholders of the Malkumba-Coongie Lakes Ramsar Site, informed the vision and its supporting mission as given in the Ramsar Strategic Adaptive Management (SAM) Plan (Figure 2).

Vital Attributes	Description
1. International (Ramsar obligations)	An internationally recognized (world-class) Ramsar wetland, providing a leading model for the sustainable management of wetlands in one of the few remaining large free-flowing river systems in the world.
2. Cultural heritage	Guardians of a strong and ongoing culture—a cultural meeting place, which facilitates Traditional Owner connection to country with its life gaining environment and protection of environmental assets for future generations. Relatively low levels of development, combined with protected Traditional Owner cultural heritage Sites and artefacts, contributes to a unique spiritual experience, with water and wildlife all interlinked.
3. Economically productive and permanent communities	The diverse landscape, with prime natural resources, supports economically productive and permanent communities, contributing significantly towards knowledge, community well-being and local, regional, state and national financial benefit. The natural resources include significant oil and gas reserves currently subject to exploration and production; pastures of native vegetation that provide excellent cattle fattening and breeding resources for a highly productive sustainable pastoral industry; and a growing tourism industry. The Great Artesian Basin groundwater system supports unique environmental assets and industry.
4. 'Near natural' river system, including floodplains	A rare example of a 'near natural' river, floodplains and wetland system in Australia. The intact, healthy functioning aquatic ecosystem exhibits a largely unimpeded flow regime which has near natural flow variability while supporting multiple uses across a diverse landscape.
5. Collaboration	The collaboration and participation of stakeholders involved in the management of the site and its threats with strong relationships, extensive local knowledge and experience, long term commitment and vested interests in shared values is the inclusive approach which underpins our success and ability to adapt and change.
6. Health and wellbeing	The strength and sense of community in the region supports the health and wellbeing of its diverse peoples. A healthy thriving and free-flowing river system empowers the people spiritually, making the country a great place to live in, being clean, quiet, spacious and safe.
7. Biodiversity significance	Conservation significance of the arid region is high, contributing to national and international biodiversity. The region maintains significant populations of aquatic and terrestrial fauna and flora species, including threatened species, dependent on healthy largely intact ecosystems and processes, including refugia.
8. Waterbirds	Supports the maintenance of healthy waterbird populations, on a national and international scale.

This rich documented discussion provided the information relevant for creating a shared vision and its associated mission for the MCLRS, within a plenary session. Importantly, this was done separately by all individuals in the workshops, followed by a facilitated discussion to produce a single shared vision. This was a broad inspirational statement of intent of a future 'desired state' for the MCLRS, which guided the development of the hierarchy of objectives (Figure 2).

3.2. Hierarchy of Objectives

Our Ramsar SAM Plan's hierarchy of objectives begins with the vision and its supporting mission, informed by the eight vital attributes and associated discussions of their threats and determinants or drivers (Figure 2). We then identified six Level 1 objectives (linked to the vital attributes through the vision and mission, Figure 2), expressed to define the broadest level of the main areas of management activity. Importantly, the Level 1 objectives are not mutually exclusive and their inter-relatedness was recognized. Associated with the first Level 1 objective (Figure 2), Ramsar Obligations, the South Australian Government and its agencies (Department of Environment and Water) and affiliated management body (South Australian Arid Lands Board) have a responsibility to manage the MCLRS, as a social-ecological system, with reporting and oversight from the Australian Government. The Cultural Heritage Level 1 objective recognizes the connection to and ownership of the area by Traditional Owners. Given the complexity of different land uses in the area, there was clearly a need for a third Level 1 objective, Environmentally Sustainable Industries. The fourth Level 1 objective relates to the free-flowing status of the MCLRS (Figure 2), while the final two Level 1 objectives are focused on the challenges and opportunities for improving Legislation, Policy and Management, and the importance of a cohesive and collaborative community via a Social Objective (Figure 2).

For each of the six Level 1 objectives, we developed objectives with increasing focus and rigor at Levels 2–4, with stakeholders (Figure 3, Supplementary Figure S1a–e). Stakeholders broke out into small groups with an interest in a particular area (e.g., Cultural Heritage with Traditional Owners) but reporting back, so links to other objectives could be discussed. As an example, three identified Level 2 objectives (Flow Regime, Biodiversity and Waterbirds), formulated under the Natural Systems Level 1 objective (Figure 3), are developed into a series of Level 3 and Level 4 objectives (Figure 3). For the remaining five Level 1 objectives, we developed similar hierarchies, which represented the stakeholders' needs and requirements for effectively managing this complex social-ecological system (see Supplementary Figure S1a–e). Inevitably, there was some overlap in objectives, given similarities (e.g., International Ramsar and Natural Systems Level 1 objectives, Figure 3 and Supplementary Figure S1a). Such potential redundancy was considered important as social dimensions of particular objectives may be as important as environmental dimensions for effective management. Ultimately, the approach is evolving, lower level objectives can be achieved and more objectives can be developed, continuing a process of ongoing learning. All stakeholders were subsequently provided with the final list of objectives for further revisions.

3.3. Malkumba-Coongie Lakes Fish Communities

We illustrate the implementation of Strategic Adaptive Management approach using the fish community, as this is the most progressed, with other objectives and analyses a work in progress. Thirteen native fish species were recorded during long-term fish surveys in the MCLRS and adjacent areas along Cooper Creek, 2000–2019 across 39 Sites (annual average 7.44 $\pm$ 5.37 sd, Figures 1 and 4a) using different survey methods (fyke, bait traps, drum and gill nets). These included Australian smelt (*Retropinna semoni*), Barcoo grunter (*Scortum barcoo*), bony herring (*Nematalosa erebi*), carp gudgeon (*Hypseleotris klunzingeri*), Cooper Creek catfish (*Neosiluroides cooperensis*), desert glassfish (*Ambassis agassizii*), desert rainbowfish (*Melanotaenia splendida*), golden perch (*Macquaria ambigua*), Hyrtl's catfish (*Neosilurus hyrtlii*), Lake Eyre hardyhead (*Craterocephalus eyresii*), silver tandan (*Porochilus argenteus*), spangled grunter (*Leiopotherapon unicolor*) and, Welch's grunter (*Bidyanus welchi*) (Figure 4b). Number of fish species recorded each year ranged between 8 and 13 (10.88 ± 1.36sd), peaking during large flows, 2010–2012 (Figure 4a), but this coincided with extensive field survey effort, suggestive of adequate monitoring. Two alien fish species, gambusia (*Gambusia holbrooki*) and goldfish, were recorded after 2000, responding favorably to high flows (Figure 4b). The alien sleepy cod was a more recent invader, recorded after 2016 (Figure 4b), steadily increasing in numbers and extent from the northern parts of the Cooper Creek catchment (Figure 1).

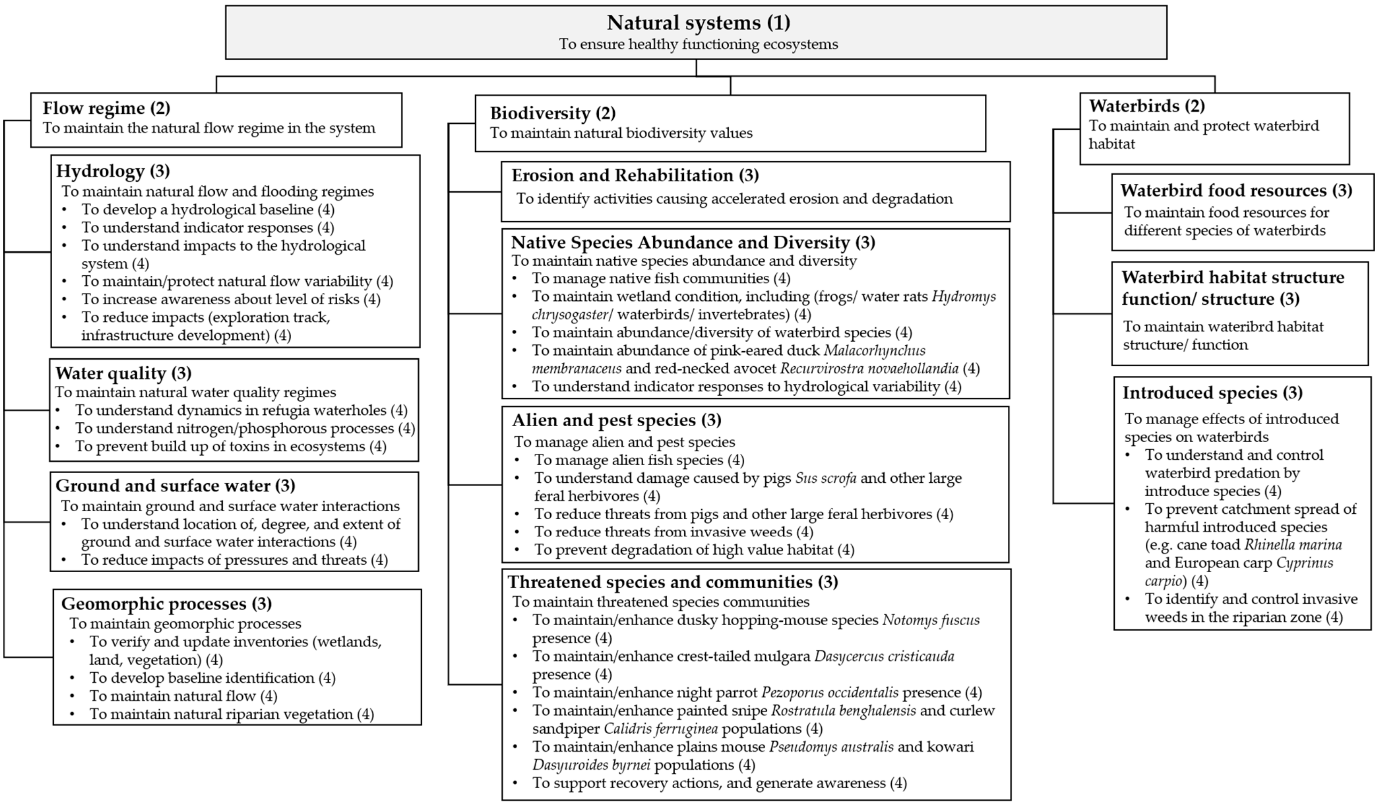

Figure 3. Hierarchical objective structure associated with the Natural Systems Level 1 objective (see Figure 2), leading into finer level objectives at Levels 2 to 4 (numbers in parentheses indicate levels).

3.4. Objectives, Triggers/Thresholds of Potential Concern, Management Actions, Outputs and Outcomes

As further demonstration of the objectives' hierarchy development within our Ramsar SAM Plan, the Biodiversity Level 2 objective breaks down into four Level 3 objectives, two of which are the Native Species Abundance and Diversity objective, and the Alien and Pest Species objective (Figure 3). These two Level 3 objectives are each associated with several lower Level 4 objectives, two of which correspond with concerns related to native and alien fish species management, respectively (Figure 3, Table 2). These two particular Level 4 objectives break down further into lower objectives at Levels 5 and 6 (Table 2). Explicit detail at Level 6 provides the necessary focus for constructing triggers and TPCs for targeted management actions and monitoring (Table 2). Additional information, in relation to expected achievement timelines for objectives and reasons for delay, are also important and can be added.

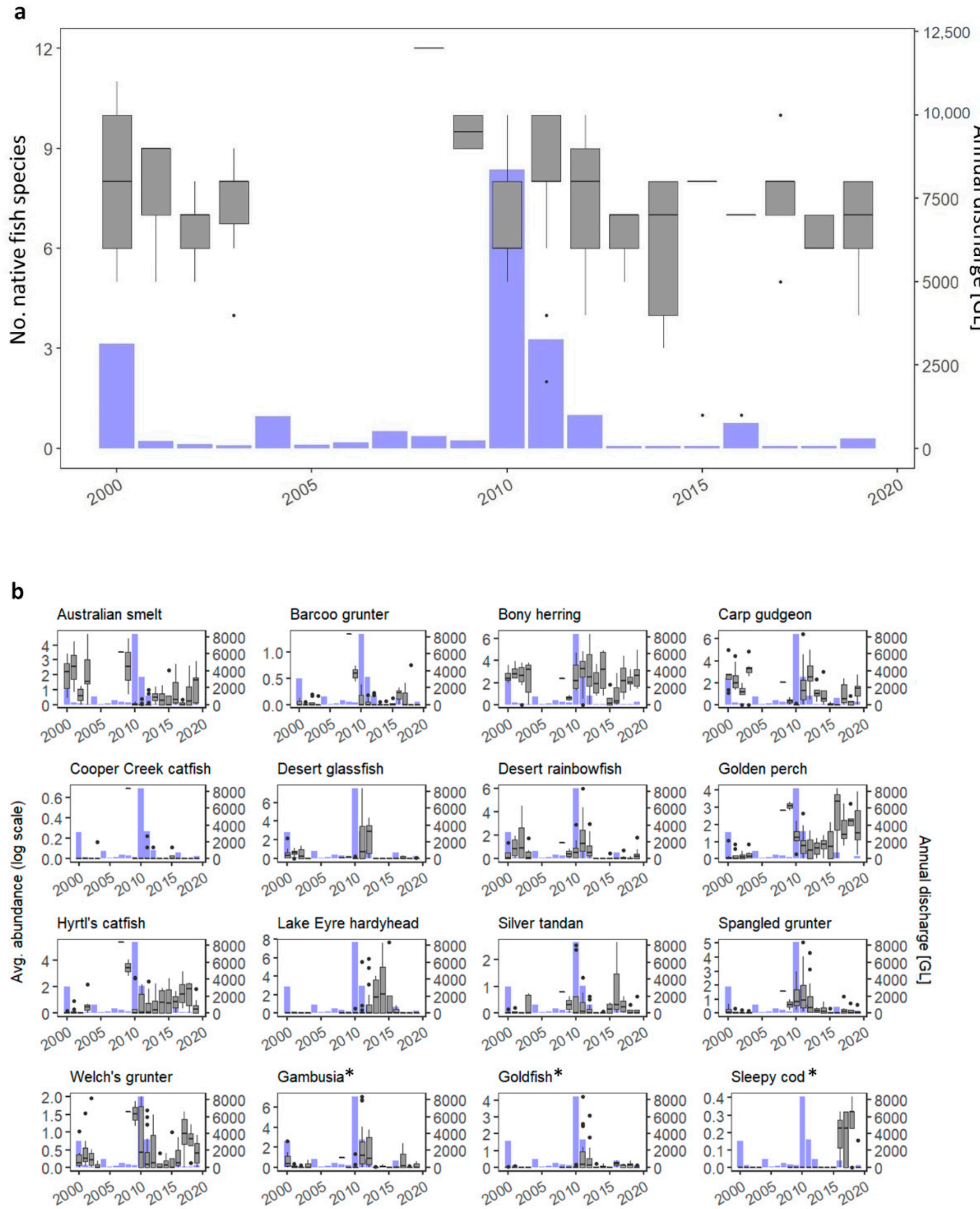

Figure 4. (**a**). Average number of native fish species (box plot) from surveys of abundance of the fish community sampled at 39 locations, within or proximate to the Malkumba-Coongie Lakes Ramsar Site (Figure 1, 2000–2019, not every year surveyed). This is in relation to total annual flow (blue) in Cooper Creek measured at Cullyamurra (see Figure 1) and (**b**). box and whiskers plots (25, 50 and 75 percentiles) of Catch Per Unit Effort (log(CPUE + 1)) for 13 native and three alien fish species (marked *), in relation to annual flow (blue).

Table 2. Lower level objectives at Levels 4, 5 and 6 for management of the Malkumba-Coongie Lakes Ramsar Site fish community, related to the Level 1 Natural Systems objective (Figures 2 and 3); the associated Level 2 Biodiversity objective; and the two Level 3 objectives: Native Species Abundance and Diversity, and Alien and Pest Species (Figure 3). Level 6 objectives culminate explicitly into the thresholds of potential concern (or triggers) and their indicators, management actions, outcomes and outputs.

Level 4 Objective	Level 5 Objective	Level 6 Objective	Thresholds of Potential Concern/Triggers	Management Action	Outputs	Outcomes
To manage native fish communities	To maintain natural levels of abundance, diversity, condition, reproduction and disease levels for native species	To monitor fish assemblages each year at identified sites	Identified time of year/season, with accessible river and wetland conditions and sufficient resources	Sample at long-term monitoring sites across the Ramsar Site Figure 1), including recording abundance of species, condition (weight, length), disease prevalence and other threats (e.g., recreational fishing, pollution)	Analyses of abundance, diversity, reproductive and disease data	Regular tracking of populations over time to ensure long-term viability
		To develop a TPC plan, promoting awareness to mitigate threats	Approval of the Strategic Adaptive Management Plan, with identified resources and responsibilities and development of TPC	Organize relevant TPC meetings and draft the TPC plan for assessment	Published TPC plan for native fish, to mitigate threats	Approved TPC with related processes and stakeholder understanding and consensus on indicators and thresholds, logistics and responsibilities
		To ensure natural levels of diversity, abundance, condition, reproduction and disease levels of native fish	Developed thresholds of potential concern, for TPC plan, used to monitor changes in diversity, abundance, condition, reproduction and disease, within natural bounds	Meetings and/or workshop/s to identify potential causes and mitigation opportunities and refinement of TPCs	Annual TPC audit reporting, with tracking of indicators	Maintenance of native fish communities including abundance, diversity, condition, reproduction and disease levels
		To identify potential causes to changes in native fish communities	Identify and develop thresholds of potential concern for possible drivers affecting diversity, abundance, condition, reproduction and disease	Meetings and/or workshop/s to identify potential causes and mitigation opportunities	Analysis of abundance, diversity, condition, reproduction and disease levels for native species to identify links to potential causes of decline	Stable or improved native fish communities

Table 2. *Cont.*

Level 4 Objective	Level 5 Objective	Level 6 Objective	Thresholds of Potential Concern/Triggers	Management Action	Outputs	Outcomes
To manage alien fish species	To minimize the impacts of alien aquatic fish species on native fish	To develop a TPC plan for promoting awareness, and mitigating threats	Approval of the Strategic Adaptive Management Plan, with identified resources and responsibilities and development of TPC	Organize relevant TPC meetings and draft the TPC plan for assessment	TPC plan for alien fish, mitigating threat to native fish	Approved TPC related processes with stakeholder understanding and consensus on indicators and thresholds, logistics and responsibilities
		To reduce abundances of alien species	At least one young -of-year alien fish individual, caught within two consecutive years at the same site. (1) biomass of sleepy cod does not exceed 30% of the total number of fish caught and (2) The proportion of all alien fish is less than 5% of the total number of fish	Meeting/s and/or workshop/s to discuss risk mitigation opportunities (further monitoring, and/or research, and/or awareness campaigning), and management intervention/s. Option to reassess/refine the TPCs	Annual TPC audit reporting and tabling	Improved native fish communities in the rivers and wetlands, in relation to invasive species. Ensuring adaptive feedback loops for evaluation, learning and adapting management
		To identify potential causes for increasing numbers of alien fish	Identify and develop thresholds of potential concern for possible drivers affecting increases in alien fish species	Meeting/s and/or workshop/s to discuss mitigation opportunities (further monitoring, and/or research, and/or awareness campaigning, and/or other management intervention/s). Option to reassess/refine the TPCs	Analysis of abundance, diversity, condition, reproduction and disease levels of alien fish species and relationships to drivers	Reductions in abundance of alien fish

Monitoring is essential within SAM for assessment and audit of the status of TPCs: determining whether any indicators of change are exceeded or nearing exceedance [21]. These indicators and related TPCs represent a way of organizing information in adaptive management. The TPCs were established collaboratively among scientists, managers and government personnel using a range of information sources including available rudimentary understanding of data (Figure 4) and expert opinion. There are future opportunities to prioritize research needs associated with developing quantitative measures for indicators and their acceptable boundaries. In these early stages, we also observed requisite simplicity principles [51], where simplification of ideas helps increase management functional utility enabling future knowledge growth. Thus, promoting understanding about complex cause-and-effect relationships helping to identify specific TPCs (e.g., fish composition, natural flow variability) with high efficacy for management, while remaining simple enough for implementation.

If or when TPCs become exceeded, or close to being exceeded, identifying the causes is important, with informed decisions made to develop, adjust or refine management actions within a stakeholder-driven process (Table 2). After completed outputs (e.g., monitoring, TPC audit reporting; Table 2), managers reflect on achievement of the agreed strategic outcomes (e.g., improved native fish communities, communication, feedbacks; Table 2) identified, linked to associated levels of objectives, ultimately supporting the vision (Figures 2 and 3). The Malkumba-Coongie Lakes SAM process is ongoing and evolving, with indicators/TPCs (and triggers) currently only developed for Level 6 objectives related to fish communities.

3.5. Strategic Adaptive Management of Sleepy Cod, an Invasive Alien Species

Sleepy cod were deliberately translocated in about 2008 into the Cooper Creek catchment from adjacent coastal catchments of the Gulf of Carpentaria and are now widespread throughout the Lake Eyre Basin [52], including since 2016 in the MCLRS (Figure 4b). It is a piscivorous fish potentially affecting prey populations and other species occupying a similar niche [53]. Governments and communities remain concerned about the impact of the species on the ecosystem and its values, although relatively little is known of the extent of its impact in the MCLRS. It was identified as a key management concern for governments and communities. A first step to devising management actions is understanding the life history of the species, captured by a conceptual model (Figure 5). This can assist in identifying key opportunities for management, vulnerabilities, as well as assessing the level of impacts (Figure 5), linked to a range of priority scientific questions.

Sleepy cod have life history traits which make them an extremely successful high-level predator in fish communities of the Lake Eyre Basin. Their numbers are usually at their highest during dry periods when there are concentrations of fish in waterholes, which remain the only permanent habitat in the rivers. During high levels of freshwater connectivity, they can disperse hundreds of kilometers along the rivers (Figure 5). They are generalists and capable of surviving in a range of different water quality conditions, exhibiting high fecundity when they breed in the summer (Figure 5). They are a likely added threat to native fish populations, exacerbating effects of climate change, other pest species and recreational fishing (Figure 5). Further, this can guide management. For example, it can be used to track the invasion front up and down rivers (Figure 5) and identify potential management measures (such as trapping and removal). Abundances (biomass) are highest during dry periods (discharge, Figure 5) which may result in concentrations allowing targeted removal. High survival and reproduction also mean that one management strategy is awareness to avoid spread of this alien fish into other rivers. The conceptual model can also be used to identify ecological effects to be measured to determine the full scope of impact (Figure 5).

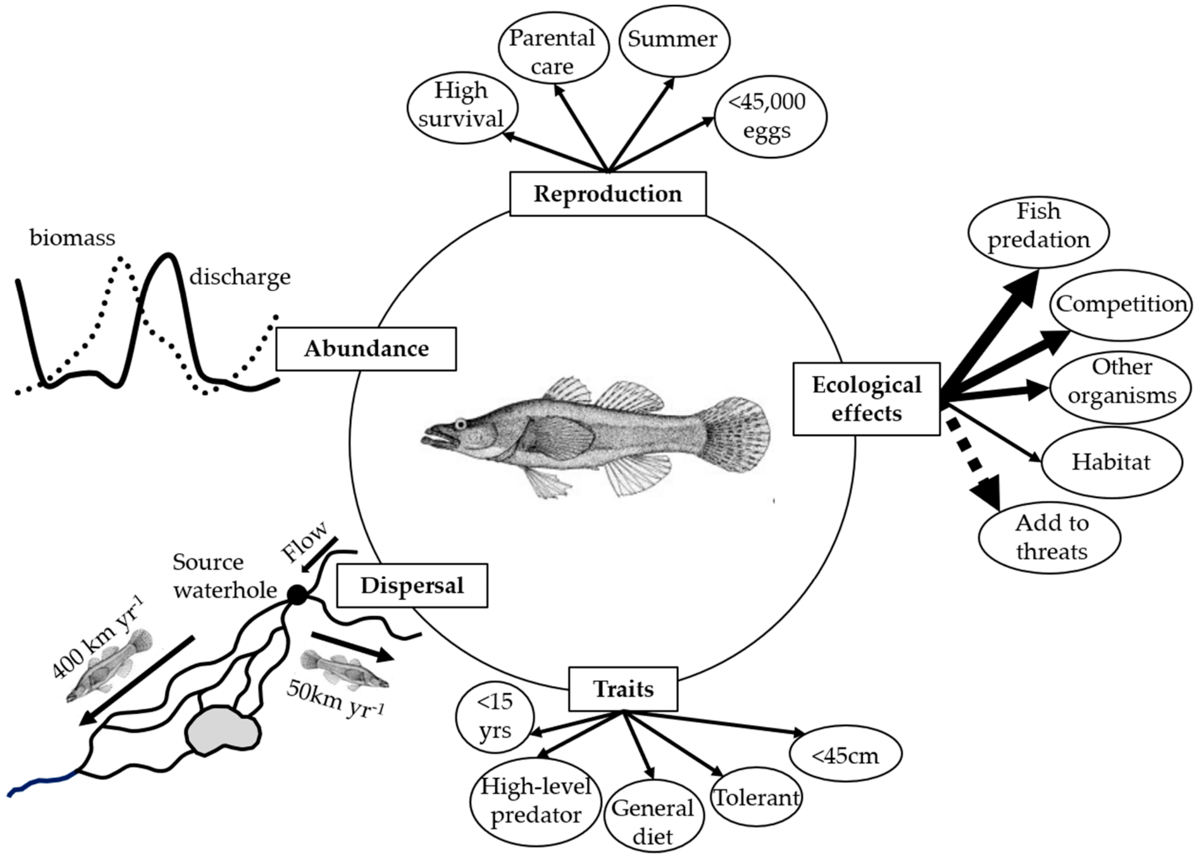

Figure 5. Conceptual model of the alien fish species sleepy cod (from northern Australia), showing life history and impacts on native fish species in the Malkumba-Coongie Lakes Ramsar Site, a key current focus within the Ramsar Strategic Adaptive Management Plan.

We used management of alien fish species to illustrate the operation of SAM and the central role played by the objectives' hierarchy in guiding management and research—albeit with understanding that managers were at a starting point, primarily problem definition. One of our more detailed Level 6 objectives focuses on reducing the abundances of alien fish species and uses sleepy cod as one key indicator species for aiding ongoing decision-making whilst managing fish (Table 2). Since first detected in the MCLRS in 2016, sleepy cod numbers have increased with detection in seven surveyed sites (Figure 1). In addition, young-of-year were recorded over two consecutive years, suggesting establishment, thus crossing of a TPC and triggering a management action to discuss mitigation opportunities (Table 2). The crossed TPC for sleepy cod represents current understanding of how this response indicator behaves in the MCLRS. Even during the early evolution of this Ramsar SAM Plan, the TPC process is assisting management in identifying when there may be concern about alien species, that is impacting native fish species to such an extent to warrant active intervention. Further, this process allows identification of key analyses required in relation to relative impact of drivers on native fish species as well as potential management actions, such as an education campaign about the impacts of sleepy cod.

4. Discussion

Management of complex social-ecological systems is difficult because there are so many different aspects that demand management attention, often with few resources. Traditionally, natural resource management is siloed, with different management objectives reflecting the values and operational environments of stakeholders, including different government agencies, industries and other stakeholders. The Malkumba-Coongie Lakes Ramsar Site is an extremely large and complex social-ecological system, with many different management challenges and stakeholders. As a freshwater ecosystem dependent on maintaining natural river flows from upstream, it also has significant spatial dimensions linked to upstream flows in the catchment with all the pressures for development of water resources or interruptions of flows [54,55].

We have outlined our Ramsar Strategic Adaptive Management Plan for the MCLRS. This is a long journey which we have only just begun but this overarching plan with its vision, hierarchy of objectives and end-points provide the architecture for a clear focus on what needs to be done to focus on the issues that matter for protecting and managing this amazing wetland ecosystem. The MCLRS hierarchy of objectives (Figure 2, Supplementary Figure S1) is central to SAM, focusing research and management, thus supporting agreed stakeholder objectives [56]. It should drive monitoring and investment in targeted management.

SAM implementation has several key components: (i) scoping of management options to meet objectives; (ii) planning and operationalization of selected options; and (iii) developing and implementing monitoring to generate the information vital for evaluation and learning [22,23]. Eventually objectives are sufficiently defined to have utility as specific actions, supported by triggers and thresholds of potential concern (TPCs), which guide the timing and nature of the actions if required. We have tried to illustrate this by documenting how broad objectives become increasingly focused for the MCLRS, until they identify and prioritize specific management requiring action/s. An emerging list of TPCs in SAM allows monitoring to be prioritized, identifying which indicators are important and when, where and how often they should be measured. Monitoring must be practicable, fast, and cost effective for timely and useful feedback that is actually used in decision-making [29]. The TPC process is intended as a warning signal, alerting managers, scientists and stakeholders to investigate the cause of any TPC exceedance, and decide on suitable management actions (Table 2) or a recalibration of the TPC [19]. For sleepy cod, it can identify when actual abundance, or modelled abundance, or impact of sleepy cod jeopardizes the vision, via the TPC endpoint. Over time, management and monitoring, along with independent research, enables updating of the knowledge on which any indicators and TPCs are based. The timing and nature of actions hinges on the development, refinement, feedbacks and ongoing learning associated with application of thresholds of change or TPCs.

TPCs are fundamental to management of Ramsar Sites, particularly in relation to the complexity inherent within the system, whilst needing to maintain ecological character. Management and reporting on the ecological status of Ramsar Sites, their wise-use and maintenance of ecological character is the main driver for reporting, influencing subsequent management. In Australia, the concept of Limits of Acceptable Change (LACs; [57]), is linked to specific indicators of a Ramsar Site's ecological character, captured by its Ecological Character Description (see [47] for MCLRS). By definition, indicators that move outside their defined LAC indicate significant change in ecological character, possibly leading to reduction or loss of the values for which the site was Ramsar listed [57]. TPCs and LACs are similar conceptually in that both allow for refinement of any indicator and its accepted variation over time, with new knowledge, but there are significant differences. LACs represent specific ecological thresholds, whereas TPCs may include overlapping ecological and social values. LACs represent an actual threshold or system tipping-point, while TPCs act as a warning ('red-flag'), before a potential (often hypothetical) ecological tipping-point. LAC exceedance automatically prompts feedback communication to high ministerial levels for mitigation actions. There is natural hesitation if such exceedance occurs, given fear of uncertainty, low confidence, false alarms and unnecessary waste of time and resources. We advocate operational use of TPCs because they implicitly recognize and incorporate uncertainty, using best available information, prompting informal reflection among diverse stakeholders about effects on collaboratively identified objectives. This is before mutually agreed mitigation action is taken [58]. Overall, monitoring and auditing against TPCs in SAM is a learning-by-doing process in complex and uncertain contexts and it determines the extent to which management interventions have succeeded over time and whether they are consistent with the objectives and, ultimately, the vision [56].

TPCs reflect different degrees of uncertainty in social-ecological systems [28], though they must remain tangible to managers and other stakeholders to avoid a crisis of non-implementation of adaptive management [59]. Consequently, assumptions behind TPC construction should always be made explicit, because then confidence in each TPC can be identified and acknowledged. There are benefits to explicitly documenting uncertainty, before applying TPCs: scientists feel more comfortable about the process if there is opportunity to prioritize those TPCs requiring additional hard data to increase scientific rigor. Meanwhile, managers and other stakeholders get a chance to implement the TPCs, improving their confidence in SAM and this inductive approach to management [59].

We illustrated this process by examining the fish communities for which we had reasonably sufficient data to develop the TPCs with acceptable confidence (Figure 3) and specifically the management of sleepy cod, an alien fish species in the MCLRS. Critically, learning and adapting management will be ongoing as part of implementing this Ramsar SAM Plan, via feedback loops [22] supported by the indicators and TPC process [28,29]. Adaptive reflection opportunities must be instigated to evaluate [60] how well the ecological character of the MCLRS links to the objectives, via the explicit measurable end-points or TPCs (Table 2). Here, the natural variability (resilience) of the response indicators is recognized by incorporating upper and/or lower levels (thresholds) of acceptable change where appropriate [19]. The context of understanding threats and priority drivers within MCLRS is important, and the measurable response indicators of change (e.g., sleepy cod), related to these drivers/threats, must be sensitive enough for management interventions to be effective. Once appropriate TPCs are constructed, collectively they define the measurable component (or 'tent-boundary', [28]) of the Ramsar Site's 'desired state', and management aims to keep the system within this boundary (or if the system is outside, the boundary becomes a 'target' for rehabilitation). In doing so, these feedbacks help determine if and when management intervention/s are necessary, in working toward achievement of the objectives and ultimately the vision [56].

Currently, the South Australian Arid Landscape Board is responsible for natural resource management in the region but the South Australian Department of Environment and Water is required to manage the regional reserve and conservation areas and has responsibility to report to the Australian Government on the status of MCLRS. The current overarching Ramsar SAM Plan, described here, provides the first step in the development of a comprehensive plan. It requires ownership by the South Australian Government and carriage by the South Australian Arid Landscape Board. Further, there are opportunities to integrate responsibilities and requirements of other state agencies', providing potential regulatory control. There is also a need to liaise with the Australian Government to ensure that it adequately meets the requirements of the national government to report to the Ramsar Secretariat. This requires more engagement with other managers in the area and identification of their responsibilities for management and monitoring (e.g., mining, conservation, industry, pastoralism). All should be consistent with meeting the vision. More detailed objectives, indicators and TPCs are required for hydrology, surface water, groundwater and biodiversity. In addition, there are also more detailed objectives required for environmentally sustainable industries, cultural heritage, social objectives and legislation, policy and management. Thus, there is a need to develop the range of other high level objectives to provide the requisite representation of values, linked to actions which can continue to drive this planning and management process.

There is increasing effort to better document management and planning for natural resource management, through various planning and management approaches [20–22,25,61,62]. These efforts predominantly focus on increased specificity and linking of high level objectives to management actions, providing clear timelines and triggers and/or TPC's to guide monitoring and management. Learning-by-doing is fundamental to these approaches as well as incorporating the full scope of social as well as ecological values and their objectives.

Strategic Adaptive Management is well established in South Africa and has the necessary rigor to incorporate all these key elements. It was established to deal with river management, where outside pressures of water quality and development were difficult to control [21,27], and is increasingly applicable to freshwater ecosystems around the world [20,26] and other conservation management issues [22,25,56]. There is considerable opportunity to use this framework for the management of Ramsar Sites around the world, allowing for the effective tracking of ecological character.

5. Conclusions

We developed a Ramsar Strategic Adaptive Management Plan for the Malkumba-Coongie Lakes Ramsar Site, an extensive terrestrial and freshwater ecosystem in arid Australia, supplied by a free-flowing river, Cooper Creek in the Lake Eyre Basin. This plan is still at its early stages, representing the start of a long but rigorous process, guided by the value and context driven development of a hierarchy of social-ecological objectives. As we continue to develop fine level objectives, they become management actions which can be progressed, monitored, evaluated and clearly linked to the overall vision. Some of these management actions may require more detailed understanding, informed by management implementation and research. For example, the control of invasive fish species, particularly sleepy cod, requires monitoring of impacts on different parts of the ecosystem to determine the extent of the impact, exploration of opportunities for targeted removal (potentially when concentrated) and also raising of awareness to avoid invasion into other Lake Eyre Basin rivers. Other social objectives require further refinement and development with the key foundations now in place. These include further collaboration with Traditional Owners and industry to identify management actions that reflect accordance with the vision. Our Ramsar SAM Plan provides a clear and transparent management planning approach for this Ramsar Site, enabling identification and mitigation against unacceptable changes in ecological character. The Ramsar SAM Plan is applicable to any wetland, river or other natural resource management related programs. Certainly, a more focused strategic adaptive management approach, building ownership and buy-in among all stakeholders involved, is applicable to all Ramsar Sites worldwide. It could significantly improve management in the achievement of positive ecological, social and economic outcomes.

Supplementary Materials: The following are available online at https://www.mdpi.com/2071-1050/13/6/3043/s1, Figure S1a–e: title Supplementary Figure S1. They provide Levels 2–4 objectives for all other Level 1 objectives, apart from Natural systems (see Figure 3), including International (Ramsar) Obligations; Cultural Heritage; Environmentally Sustainable Industries, Legislation; Policy and Management and Social (see Figure 2) for Malkumba-Coongie Lakes Ramsar Site.

Author Contributions: Conceptualisation and methodology, R.T.K., C.A.M., R.B., G.B.; writing original draft preparation, R.T.K., C.A.M., G.B., R.B.; figures, G.B., B.C.; workshop contribution, R.T.K., C.A.M., R.B., G.B., B.C., D.S., V.N., T.G., J.M.; writing—review and editing, R.B., B.C., D.S., T.G., V.N., J.M. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Lake Eyre Basin Partnership and funding from the National and International River Prizes, the South Australian Arid Lands Board and The Australian Research Council Linkage Grant (LP180100159), identifying a standard for reporting on ecological character of Ramsar Sites.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained in the article or supplementary material.

Acknowledgments: We thank the Malkumba-Coongie Lakes community, the South Australian and Australian Governments and especially Heather Miller for a work in coordinating the workshops.

Conflicts of Interest: The authors declare no conflict of interest.

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