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Rethinking refuges: implications of climate change for dam busting

Running head: Dam removal and climate change

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Abstract

Climate change is projected to alter river discharge in every populated basin in the world. In some parts of the world, dam removal now outpaces their construction and the diminishing cost efficiency of dams in drying regions is likely to further increase the rate of removals. However, the potential influence of climate change on the impact of dam removals has received almost no consideration. Most dams have major biological and ecological impacts and their removal would greatly benefit riverine ecosystems. However, using model regions in the Southern Hemisphere, we highlight that artificial lentic habitats created by dams can act as refuges for increasingly imperiled freshwater fishes, and dams may also prevent the upstream spread of invasive alien species in rivers. We argue that, in these and other regions where the major impact of climate change will be to reduce streamflow and aquatic refuge availability, a shifting balance between the negative and positive environmental impacts of dams requires policy makers to include climate change predictions in prioritization processes for dam removal.

1. Introduction

Human infrastructure captures more than 50% of available fresh water runoff (Jackson et al., 2001) with global water withdrawal increasing ~65% 1979-2010 (Wada et al., 2014). Dams, and the impoundments created by them, provide many benefits to humans, including water supply, flood control, irrigation, navigation, recreation and the generation of hydropower. Throughout the world, there are now more than 50,000 dams with a crest height greater than 15 m and an estimated 16.7 million reservoirs >0.01ha (Lehner et al., 2011).

Although they have underpinned the development of human societies, dams also usually have numerous detrimental effects on aquatic biodiversity. Over half of the world's large river systems, including the eight most biogeographically diverse, are now affected by dams

(Nilsson et al., 2005). Through altering natural flow regimes, the abiotic impacts of dams include habitat fragmentation, reductions in habitat quality and complexity, and disruption to processes of erosion, sediment transport, channel scouring and nutrient cycling (e.g., Poff et al., 1997; Arthington, 2012). The biological responses to these impacts can include shifts in community composition, loss of species abundance and diversity, and changes in species distribution (Nilsson et al., 2005). The impacts of dams on fishes can be particularly severe, including the disruption of migratory pathways, creation of unfavorable habitats for native species and loss of riparian habitat (Winemiller et al., 2016).

Between 1979 and 2010, the global abstraction of groundwater has increased proportionally more (an overall increase of ~85%) than the capture of surface water (an increase of ~56%) (Wada et al., 2014). While dam construction continues at pace in many parts of the world, particularly China and India, in contrast in North America and Europe there has been a marked overall slowdown in large dam construction (Chao et al., 2008; Winemiller et al., 2016) and concurrent increases in dam removal (O'Conner et al., 2015). Dam removal now outpaces construction in the USA and is increasing at an exponential rate (American Rivers 2014) (Fig. 1). This surge in dam removals has been driven principally by economic factors with many built in the middle years of the 20th Century reaching the end of their working life, and the costs to repair aging infrastructure greatly outweigh removal costs (Stanley and Doyle, 2003). More recently, the impetus for the removal of many dams has been to mitigate their ecological impacts; usually to reinstate fish migration pathways and restore natural flow regimes (Service, 2011; O'Conner et al., 2015).

How may climate change affect the value of dams into the future? Climate change and water withdrawal is projected to alter river discharge in every major river basin in the world (Palmer et al., 2008). On the one hand, increasing global population growth and per capita income, particularly in the developing world, will increase water demand and the value of surface water (Palmer et al., 2009). On the other hand, the cost efficiency of maintaining storage dams is likely to be reduced in regions where rainfall and surface flows decline, and in regions where increased extreme weather events, such as flooding, will require dams to be reinforced and/or modified to mitigate associated risks such as overflows and structural failure (Pittock and Hartmann, 2011). Therefore, the combined effect of the finite lifespan of dams and their diminishing utility as a reliable water source in regions that are transitioning to a drier climate is likely to increase the rate of dam obsolescence and removal. Certainly, there has been increasing interest in the ecological and social benefits of dam removal even in arid and semi-arid regions such as Australia (e.g. Neave et al, 2009) and South Africa (e.g. Mantel *et al.* 2010). However, we are unaware of inventories of dam removals in the Southern Hemisphere and development of a database would be of great benefit; similar to that maintained in the USA (American Rivers, 2014). While the negative ecological impacts of dams are well recognised, here we argue the influences of climate change on the future impacts and value of dams requires greater consideration in decision making processes to remove them in drying temperate regions.

2. Environmental impacts of dam removal

Although environmental concerns have often not been the principal driver of dam removals, the process of restoring artificial lentic habitats back to their original lotic state usually has profound associated environmental benefits. The restoration of more natural temperature and sediment transport regimes can contribute to increased species richness, abundance, and biomass of fishes at formerly impacted sites. Reinstating longitudinal river connectivity can permit fishes to access habitat beyond former barriers, with evidence of increases in recruitment and productivity of eel, lampreys and salmon within relatively short timeframes (Service, 2011; O'Conner et al., 2015). Dam removal may also improve connectivity between rivers and associated habitats (e.g. floodplains), benefiting aquatic and dependent terrestrial fauna (Shuman, 1995).

Although the removal of a dam usually has overwhelmingly positive outcomes for the river ecosystem, it should be considered an ecological disturbance in its own right (Stanley and Doyle, 2003), and some ecological changes might be environmentally costly rather than beneficial. A major concern with dam removal is the mobilisation of accumulated sediments, as this can impact habitats downstream through sediment deposition (which may contain toxins, heavy metals or nutrients) and erosion (Bednarek, 2001; Stanley and Doyle, 2003). We also need to be aware that once a dam has been constructed, the original aquatic ecosystem has been changed, and although it may be physically altered from its original state, the new lentic ecosystems can support considerable aquatic biodiversity. These potentially positive values need to be considered in proposals for dam removal, because we cannot always assume that an ecosystem will return to its original state following the removal of a barrier. More research is required to assess and quantify the impacts of dam removal over longer spatial and temporal scales (Graf, 2003).

3. Impacts of dams may alter due to climate change

Dams can act as refuges

One potential cost of dam removals that has not been adequately addressed is the potential loss of novel refuges for aquatic organisms under ongoing climate change. To date, most studies that have considered the implications of climate change on fish distributions have had a strong northern-hemisphere bias, and concentrated on rising water temperature as a driver of change in cold-water fish communities (e.g., Comte et al., 2013). Hydrological shifts have rarely been considered, yet, over the last 50 years, streamflow has decreased by more than 30% across large areas of southern Europe, the Middle East, western and southern

Africa, south-east Asia and Australia, and by 10-30% in western North America and much of South America (Milliman et al., 2008), with most of this decrease due to climate forcing (Dai *et al.* 2009). Projections from climate change models suggest decreases in streamflow will continue across these regions in the future (Jiménez Cisneros et al., 2014; Schewe et al., 2014) (Fig. 2a).

These areas of the world all currently have strongly seasonal rainfall and hence streamflow. Freshwater communities in these regions are typically structured by regular patterns of flooding and drying, with isolated pools or waterholes providing ecological refuges between streamflow events (Magoulick and Kobzna, 2003). These refuges are critical to the periodic cycle of retreat and recolonisation that characterises non-perennial river systems. Decreased streamflow (e.g. Fig. 2a) and increasing temperatures as a result of climate change will affect the size, number and connectivity of these refuges, with likely major impacts on freshwater biota, particularly freshwater fishes (Davis et al., 2013; Beatty et al., 2014; Jaeger et al., 2014) (Fig. 2b).

There is an increasing recognition that artificially created waterbodies may have an important role to play in creating refuge habitat for aquatic organisms (e.g. Halliday et al., 2015; Beatty and Morgan, 2016). Such artificial refuges include water storage reservoirs, drainage ditches, irrigation pipes, borrow pits, water transport canals and golf course lakes. Importantly, they have also been identified as refuge habitat for a range of endangered aquatic organisms, including freshwater fishes (Tonkin et al., 2010, 2014; Ebner et al., 2011), molluscs (Clements et al., 2006) and waterbirds (Li et al., 2013).

We contend that the potential loss of natural refuges under reduced rainfall and flow conditions in drying climatic regions may be offset to some extent by maintaining existing dams and their associated impoundments. The value of impoundments as artificial refuges must of course be balanced against the impact of dams on existing natural refuges. Dams can impede the access of fish to natural refuges by physically blocking migratory pathways and increasing the number of no-flow days (Perkins et al., 2015). Dams may also reduce the ability of rivers to maintain natural refuges such as oxbows and scour pools, as they can negatively impact fluvial geomorphic processes and disrupt the dynamics of the habitat mosaic (Hauer and Lorang, 2004). These impacts must therefore be properly evaluated; however in seasonally flowing river systems in arid and semi-arid regions of the world, they may be outweighed by the loss of natural refuge pools in both regulated and unregulated rivers in drying climates. In many of those systems, the ecological and conservation value of at least a proportion of existing reservoirs is likely to increase in the future and this has not been sufficiently appreciated in the dam removal discourse. In addition, it may be possible to at least partially overcome the negative effects of dams on natural refuges, for example by constructing fishways to enhance fish movement (Harris et al., 2016) and by using environmental flows to maintain downstream ecosystems (Arthington, 2012).

Dams as barriers to invasive species

Invasive species and the exotic diseases they introduce represent a considerable threat to aquatic ecosystems throughout the world. There is an increased likelihood of novel invasions by aquatic species that possess physiological thresholds mismatched to current environmental conditions, but matched to conditions likely to prevail under future climatic scenarios (Rahel and Olden, 2008). Warmer water temperatures may also increase the transmission and virulence of exotic parasites and pathogens to native fish species (Marcogliese, 2001). We may therefore expect more invasive aquatic species, and greater impacts from these species, in many regions due to climate change.

While the reservoirs created by dams are often hotspots of alien fish species, particularly predatory sportfish, there are also several examples of dams (both intentionally and unintentionally) limiting the spread of invasive species (McLaughlin et al., 2007; Rahel, 2013; and see case study below). Moreover, while often difficult, eradicating alien species from reservoirs is possible (Meronek et al. 1996) and can directly facilitate their use as refuges by native fishes (Beatty and Morgan 2016).

The relative value of restoring connectivity for native species versus limiting the spread of invasive species requires careful consideration in decisions to remove dams or install fishways. There may be trade-offs between the benefits to lotic ecosystems of removing a dam (such as re-instating migratory pathways for diadromous or potamodromous fishes) against potentially facilitating the spread of invasive species by removing barriers. The dispersal of invasive species following barrier removal is not always predictable (Stanley et al., 2007), highlighting the desirability of a sound biological and ecological understanding of the fauna (both native and alien) that will be impacted. In some cases, retaining or even creating new barriers may help offset the increasing threats that invasive alien species pose to native biodiversity in changing climates (Rahel, 2013).

4. Case studies of the influence of climate change on the value of dams

South-western Australia

South-western Australia is a global biodiversity hotspot due to exceptionally high rates of endemism. The rivers naturally have a highly seasonal flow regime and generally cease to flow during the annual dry season, forming disconnected refuge pools. This region has a depauperate freshwater fish fauna consisting of just 11 native species, however nine of these are regionally endemic, the highest rate (~82%) of endemism of freshwater fishes of any icthyological province in Australia (Morgan et al., 2014). All of the endemic species have suffered range declines (with nearly half being listed as threatened) principally due to secondary (anthropogenic) salinisation of waterways, impacts of introduced species, habitat destruction and climate change (Table S1).

Severe range contractions have occurred for most species as a result of secondary salinisation, with remnant populations restricted to fresh tributaries and downstream reaches of less salinised catchments (Beatty et al., 2011; Morgan et al., 2014). At least half of the species migrate, however, most undertake short spawning migrations into tributaries during the annual peak flow period before contracting to refuge pools during the dry period (Fig. 2b, Beatty et al., 2014). While instream barriers are known to somewhat restrict the migration of the more common species, their relative impact is minor compared to the other stressors (Table S1).

South-western Australia has undergone a 50% reduction in median streamflow since the 1970's (Fig. 2b). Global Climatic Models all project rainfall declines to continue (Hope et al., 2015), with a further 25% reduction in median surface flows projected to occur by 2030 (Suppiah et al., 2007). This dramatic change will continue to have direct and indirect impacts on freshwater fishes (Morrongiello et al., 2011; Beatty et al., 2014). Reductions in surface flows and increasing temperatures are likely to reduce the abundance, size and quality of natural refuge pools for aquatic fauna (Fig. 2b). Simultaneously, the drying trend will render most water supply dams unviable as reliable water sources by the end of the century, increasing the economic pressure to remove them.

Although reservoirs and other artificial lentic systems in south-western Australia would benefit from habitat rehabilitation to improve their value as aquatic refuges (Fig. 2b), many are free from alien species, have no significant impact to migratory fishes and some already act as important refuges for endemic threatened species. Beatty and Morgan (2016) highlighted that those reservoirs that were free from alien piscivores invariably housed viable populations of endemic fishes. Moreover, the latter study revealed that the eradication of the alien Eurasian Perch *Perca fluviatilis* preceded a rapid proliferation of an endemic galaxiid that was previously undetectable in the impoundment. Ogston et al. (2016) also demonstrated that the region's two species of aestivating fishes had suffered major range declines due to the drying climate, however, they also revealed that artificial lentic habitats would likely hold the key to preventing their extinction in the wild. As natural refuge pools are lost as the climate continues to dry, the potentially ecological value of artificial reservoirs in this region will increase; particularly if actively managed such as eradicating alien fishes, and re-stocking with endemic fishes. Removing them for economic reasons without proper evaluation of their potential ecological value may therefore cause a major loss of vital refuge habitat and result in a net negative impact on native freshwater fishes.

Cape Floristic Region of South Africa

The Cape Floristic Region is a southern African hotspot of fish endemism and diversity. Geographic isolation has resulted in exceptional levels of regional diversity with 18 formally described endemic fish species (and 42 additional recognised taxa with discrete genetic lineages), most of which are narrow range endemics that are either restricted to single river systems or even single tributaries within river systems (Table S1).

Seasonal or episodic flows coupled with high demands for water have resulted in the construction of many dams for water storage and high levels of water abstraction for agriculture. These modifications of the natural flow regime of rivers, coupled with large-scale land transformation, invasion by alien plant species in the catchment, changes to water chemistry, siltation, and introduction of alien fishes, have considerable impacts on native fishes. As a result, main stem populations of many native fishes have been extirpated and most are considered imperilled (Table S1), with remnant populations confined to relatively un-impacted upper reaches of tributaries, usually above barriers that prevent invasion by alien fishes (Weyl et al., 2014; Van der Walt et al., 2016).

Climate change will place further pressure on already stressed natural refuges above physical barriers in streams. It has been predicted by the end of the 21st century the annual rainfall for the Cape Floristic Region (including Cape Town) will decrease by between 10-20%, causing major declines in surface run-off (de Wit and Stankiewicz, 2006). These reductions in surface run-off will intensify competition for water resources between the human population and the ecological reserves legally required for the maintenance of river functioning by the National Water Act of South Africa. Predicted higher temperatures and lower flows associated with decreased rainfall are likely to increase pressure on the already stressed native fishes in the region. This, coupled with increasing water abstraction for agriculture, is likely to result in a loss of critical habitats during the dry summer months.

Impoundments in this region support a variety of freshwater fishes, most of which are alien and extensively utilised for recreational angling. Although small endemic minnows (e.g., *Pseudobarbus phlegethon* and '*Pseudobarbus*' *calidus*) are usually absent from impoundments where predatory alien fishes occur, adults of larger native fishes (such as the Clanwilliam yellowfish *Labeobarbus seeberi*) are able to co-occur with alien fishes in invaded reaches of rivers and in impoundments. As Clanwilliam yellowfish are known to undertake upstream spawning migrations in spring and early summer from deep pools to shallow temporally variable habitats, this large migratory species may benefit from large instream dams for their long term survival by using lentic habitats as refuges during droughts to repopulate rivers when flows resume.

There are also several examples of southern African riverine cyprinids that have been able to establish in impoundments. For example, the Endangered Berg-Breede River whitefish '*Pseudobarbus*' *capensis* exists in several impoundments that are likely to be crucial to its survival. In the Brandvlei Dam, a 2000 ha off-channel water storage reservoir, whitefish are fully established and are the dominant component of the fish community despite the presence of alien predatory fishes in the impoundment. A recent survey of a 10 ha reservoir into which 48 Critically Endangered Twee River redfin '*Pseudobarbus*' *erubescens* were stocked in 1996 demonstrated that these fish had not only established, but also that they were highly abundant (Jordaan et al., in press). Therefore, dam populations might provide important sources for the future re-establishment of native fish if pressures on main stem populations from alien fish can be reduced. Under a drying climate, the value of dams as natural refuges for native fishes will increase as periodic desiccation of riverine habitats becomes more likely.

Dams can also be used as barriers to invasions and as mechanisms for rehabilitating native fish populations in this region. In the Cape Floristic Ecoregion, invasions by black bass *Micropterus* spp. have resulted in the extirpation of native fishes from invaded river reaches (Van der Walt et al., 2016). In some cases, such as the in the Rondegat River (Fig. 2c), the construction of weirs facilitated alien smallmouth bass *Micropterus dolomieu* removals by preventing re-invasion from downstream source populations after their eradication using the piscicide rotenone. Native fishes begun to colonise the rehabilitated section of river almost immediately (Weyl et al., 2014) and two years after the removal of smallmouth bass, their abundance and diversity was similar to that in the non-invaded reaches of the river. Similar use of instream barriers in alien species eradication and native fish recovery has been employed in Australia (Lintermans 2000; Lintermans and Raadik 2003). Therefore, with active management, many dams and strategic instream barriers could be used to offset the impact of climate change and other stressors, particularly invasive fish species.

5. Management and policy challenges

River basins impacted by dams require a greater level of proactive management than those that are free-flowing, in order to mitigate the ecological and human impacts of climate change (Palmer et al., 2009). Figure 3 outlines the criteria that should be considered when assessing the impacts of dams and prioritising their removal, and we specifically identify those criteria upon which climate change may have a direct or indirect influence. In order to determine whether the removal of a particular dam will result in a net ecological benefit, there is clearly a need to understand the hydrology and ecology of both the artificial water body and the watershed in which it is situated, as well as the probable impacts of projected climatic change and water withdrawals on fluvial systems in the region.

Prioritisation processes have been increasingly developed to rank dams and other instream barriers for mitigation and removal. Historically, the majority of barrier prioritisation methods used score and rank techniques, where barriers within a given spatial range are scored based on ecological, physical and financial impacts and ranked for mitigation under given budgetary constraints (Kemp and O'Hanley, 2010). The speed and simplicity of score and rank prioritisation systems come at the cost of efficiency and effectiveness primarily due to insufficient consideration of multiple barriers within catchments, which can result in minimal habitat gains for migratory species, and this can be a major shortcoming of these methods (O'Hanley and Tomberlin 2005). To enhance cost-effectiveness, Kemp and O'Hanley (2010) argued strongly for the use of more robust optimisation-based models that consider the cumulative effects of multiple barrier networks on habitat connectivity and fish passage within catchments, rather than considering each barrier independently.

Both score and rank systems and optimisation approaches are intrinsically designed to incorporate additional variables and we propose that including projections of altered streamflow, natural refuge availability and likely spread of invasive species in those processes should greatly enhance the robustness of decisions to remove dams on a longer temporal scale. Null et al. (2014) included future climatic conditions when modelling economic losses (reduced water supply and hydropower) and environmental gains (gains in anadromous fish habitat quantified as river length gained between dams) for optimising dam removals. While they did not consider any potential negative environmental impacts of dam removal, they found considerable variability existed between dams in terms of future economic benefit and environmental impacts. Peterson et al. (2013) incorporated climate change projections into a Bayesian network approach to predict that barrier removal decisions, previously made assuming a stationary climate, were robust in a climate change scenario.

Such approaches are the way forward and we propose that these should routinely incorporate robust assessments of both positive and negative ecological impacts of dam removal under projected climate scenarios. Crucially, these assessments need to be underpinned by regionally specific data. For example, Perkin et al. (2015) provide an example of a comprehensive modelling exercise leading to predictions of which dams if removed are likely to yield optimal environmental gains, in particular the expansion or recovery of populations of small, pelagic-spawning fishes in large and historically perennial streams in the central USA. By contrast, in the current study, we draw on examples from South Africa and south-western Australia, which are dry temperate regions, characterised by smaller, non-perennial streams. In the South African- Australian scenarios, habitat alteration, water extraction and alien fishes (particularly large-predatory alien species) are decimating small-bodied native fishes. Under these circumstances, natural upland headwaters, aquifer springs and designed habitats (cf. designed ecosystems, Higgs 2016), namely water reservoirs, provide important refuges for small-bodied native fishes, including threatened species. Furthermore, control of alien fish species is often feasible owing to the small scale of these systems and in the case of designed habitats there are opportunities afforded by infrastructure (e.g. draw down) that facilitate alien fish control (Beatty and Morgan, 2016). Therefore, although the optimisation approach provided by Perkin et al. (2015) represents a very useful template for progress, the focus in temperate dryland streams may shift from main channel specialists that have evolved in perennial streams (e.g. pelagic spawners) to threatened species/guilds that have adapted to regular cycles of drying and flooding.

Utilising reservoirs as ecological refuges also has a distinct set of management challenges, given they have invariably been designed for other purposes. Their physical characteristics and location in the landscape can lead to water quality issues such as depleted oxygen owing to stratification, and contamination of water and sediments from industrial and agricultural pollutants, particularly during periods of drought (Mosley, 2015). However, these challenges, while they may be more severe in reservoirs, are not qualitatively different to those existing in natural riverine refuges. There are few river systems in the world that are truly undisturbed (Vörösmarty et al., 2010) and as reservoirs are often located in (and contribute to the creation of) novel ecosystems, harnessing them as tools for ecological restoration rather than their original purpose is a management challenge that climate change may force us to meet.

6. Conclusion

Both the construction and removal of dams are often highly controversial and have divided communities throughout the world (Sarakinos and Johnson 2003; Lejon et al., 2009). Finding a balance between competing socioeconomic interests and environmental impacts has proved challenging for policy makers (e.g. Williams et al. 1999). Therefore, the need to include climate change as a key consideration in dam removal, as we propose here, will add another potentially contentious aspect; particularly in situations where climate change increases both the environmental value, as well as the economic value of stored surface water.

Given the overwhelming negative biological and ecological impacts that dams have had globally, their removal, in the great majority of cases, would have a significant net positive impact on riverine ecosystems and aquatic biodiversity (Williams et al. 1999, Perkin et al. 2015). Nevertheless, more research is required to quantify the existing ecological values of artificial impoundments and to predict how these values may change in the future. Most notably, in drying temperature streams where natural surface water refuges will be lost, the implication of climate projections on the value of dams and the impacts of their removal need much greater consideration by researchers and policy makers.

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Figure Captions

Fig. 1 Annual and cumulative number of dams removed in the U.S. between 1912-2014 (Data source American Rivers 2014).

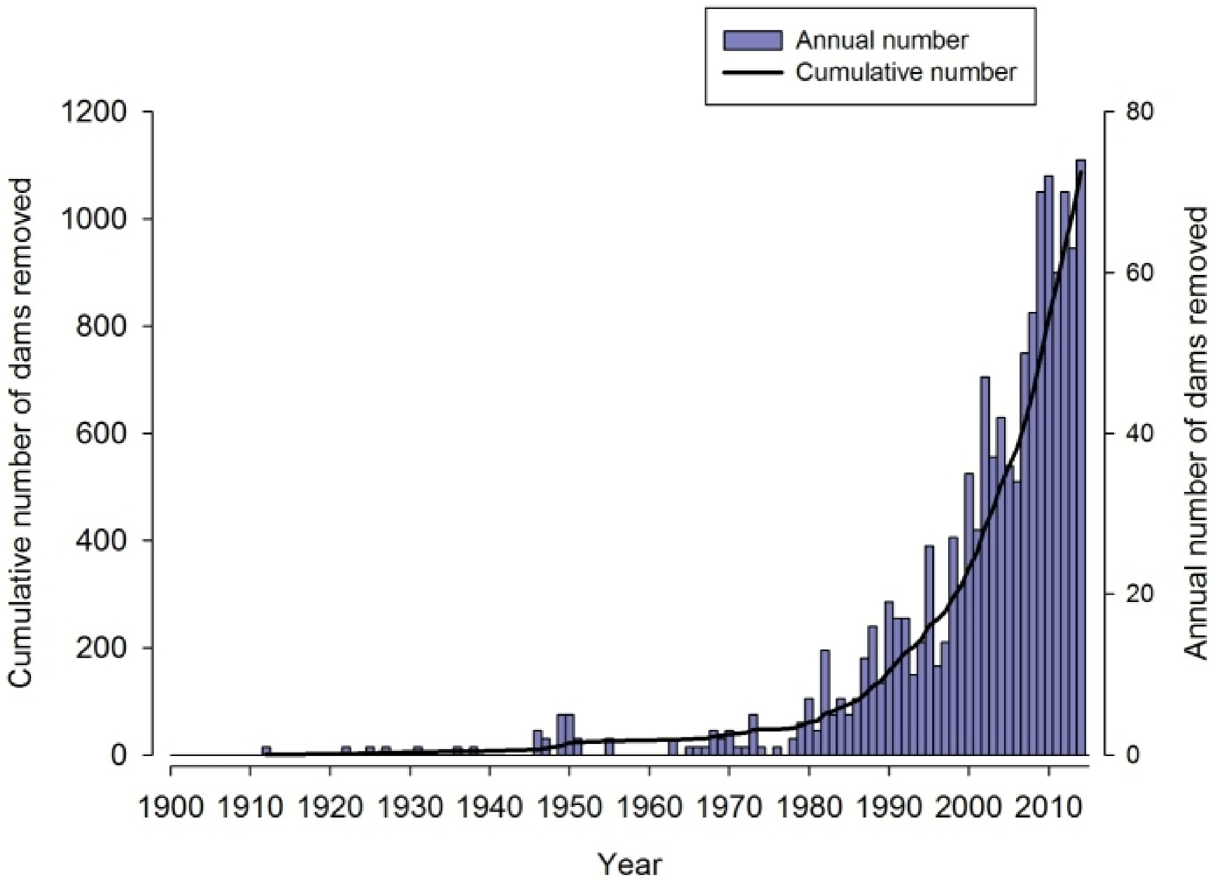
Fig. 2 (a) Percentage change of mean annual streamflow for a global mean temperature rise of 2°C above 1980–2010 (2.7°C above pre-industrial). Color hues show the multi-model mean change across five General Circulation Models (GCMs) and 11 Global Hydrological Models (GHMs), and saturation shows the agreement on the sign of change across all 55 GHM–GCM combinations (percentage of model runs agreeing on the sign of change). Reproduced with permission from Jiménez Cisneros et al. (2014).

(b) (top to bottom) Annual surface flow into dams that supply Perth (the capital of Western Australia) has declined markedly since 1975 with further decline since 2001 (data source Water Corporation, Western Australia); Natural lentic refuge in south-western Australia (e.g., Lake Quitjup, middle right) are crucial refuges for threatened endemic freshwater fishes; water supply reservoirs (e.g., bottom right) will be increasingly valuable as natural refuges are lost due to climate change.

(c) In South Africa's Rondegat River alien smallmouth bass penetrated 5 km upstream from Clanwilliam Dam to a natural waterfall below which they extirpated native minnows and co-occurred only with large Clanwilliam yellowfish. The subsequent construction of a small 2-m high weir 4 km downstream of the waterfall, effectively isolated a portion of the smallmouth bass population in this stretch of river. In 2012, this isolated section of river was treated using the piscicide rotenone to remove smallmouth bass. Within a year following smallmouth bass removal, threatened redfin minnows had begun to utilise the rehabilitated section of river and native fish abundance and diversity had increased significantly (data source Weyl et al. 2014).

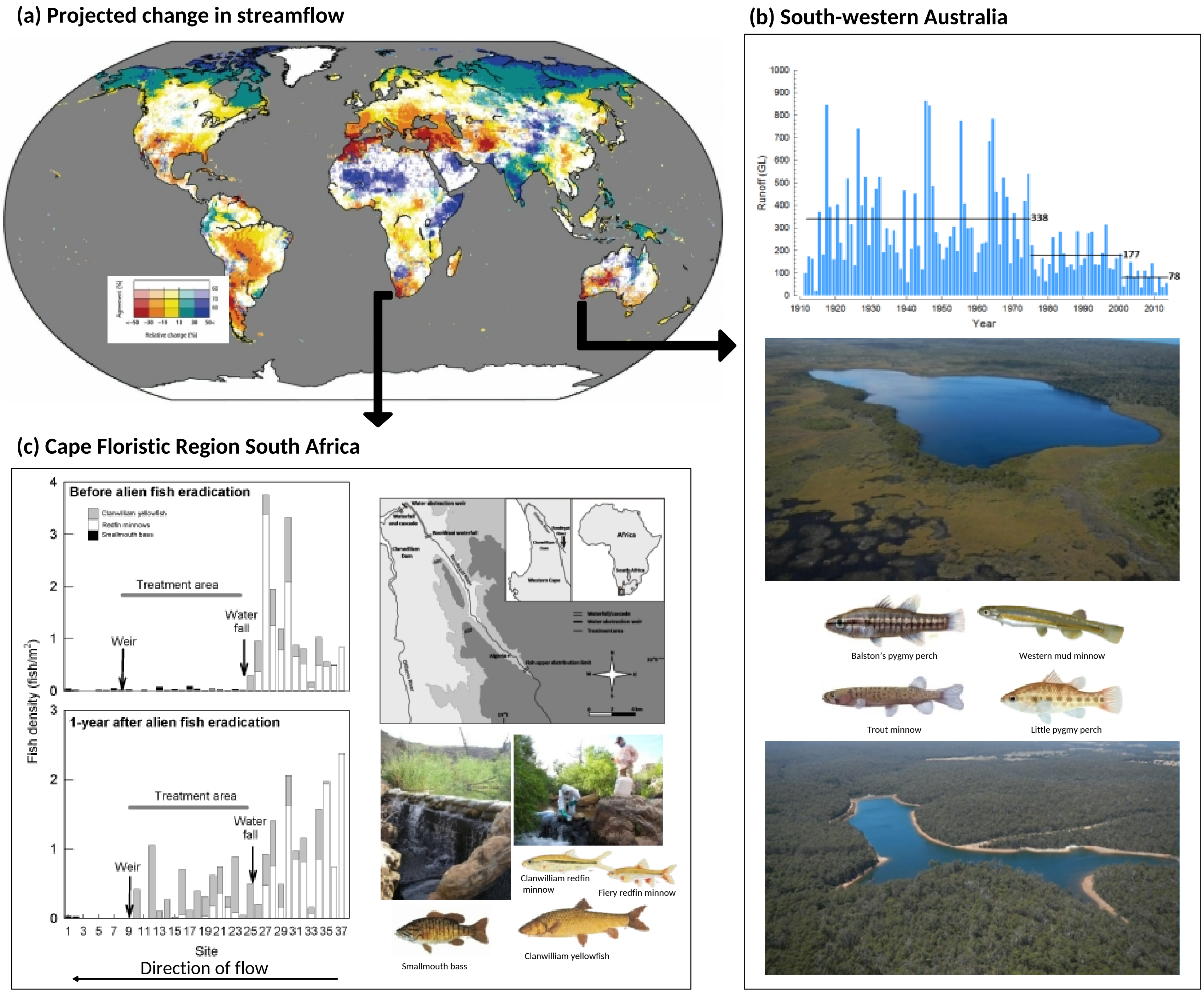
Fig. 3 (Left to right) Summary of the criteria commonly considered during decision processes for dam removal, how climate change may influence and interact with those criteria, and (right-hand panels) details on how the specific criteria may be impacted by climate change.

Fig. 1



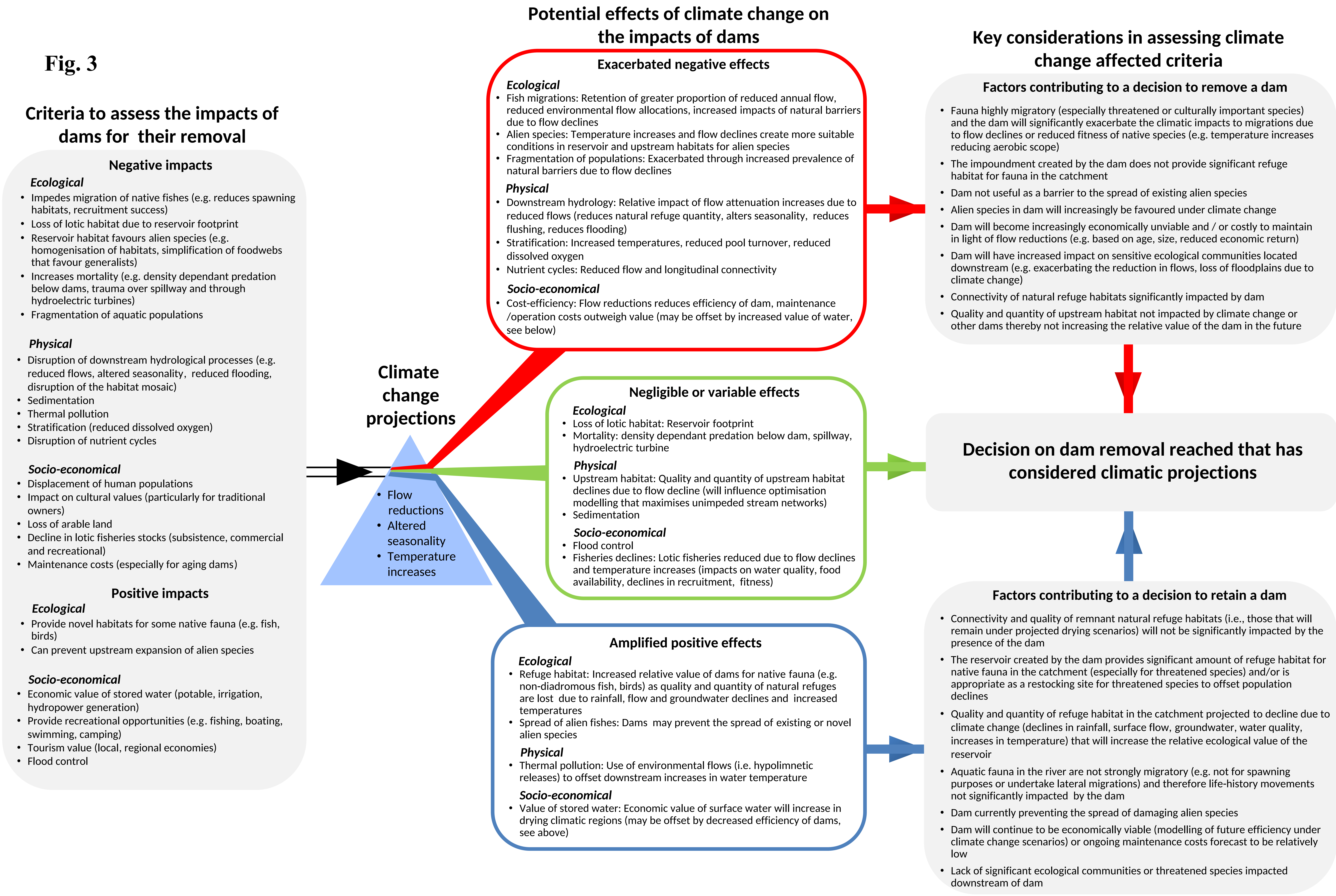
Annual number
Cumulative number
Cumulative number of dams removed
Annual number of dams removed
Year
0
200
400
600
800
1000
1200
0
20
40
60
80
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010

Fig. 2



(a) Projected change in streamflow
(b) South-western Australia
Runoff (GL)
Year
1000
900
800
700
600
500
400
300
200
100
0
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
338
177
78
Balston's pygmy perch
Western mud minnow
Trout minnow
Little pygmy perch
(c) Cape Floristic Region South Africa
Before alien fish eradication
Clanwilliam yellowfish
Redfin minnows
Smallmouth bass
Treatment area
Water fall
Weir
1-year after alien fish eradication
Treatment area
Water fall
Weir
Fish density (fish/m²)
4
3
2
1
0
3
2
1
0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37
Site
Direction of flow
Africa
Clanwilliam redfin minnow
Fiery redfin minnow
Smallmouth bass
Clanwilliam yellowfish

Fig. 3



Criteria to assess the impacts of dams for their removal
Negative impacts
Ecological
• Impedes migration of native fishes (e.g. reduces spawning habitats, recruitment success)
• Loss of lotic habitat due to reservoir footprint
• Reservoir habitat favours alien species (e.g. homogenisation of habitats, simplification of foodwebs that favour generalists)
• Increases mortality (e.g. density dependant predation below dams, trauma over spillway and through hydroelectric turbines)
• Fragmentation of aquatic populations
Physical
• Disruption of downstream hydrological processes (e.g. reduced flows, altered seasonality, reduced flooding, disruption of the habitat mosaic)
• Sedimentation
• Thermal pollution
• Stratification (reduced dissolved oxygen)
• Disruption of nutrient cycles
Socio-economical
• Displacement of human populations
• Impact on cultural values (particularly for traditional owners)
• Loss of arable land
• Decline in lotic fisheries stocks (subsistence, commercial and recreational)
• Maintenance costs (especially for aging dams)
Positive impacts
Ecological
• Provide novel habitats for some native fauna (e.g. fish, birds)
• Can prevent upstream expansion of alien species
Socio-economical
• Economic value of stored water (potable, irrigation, hydropower generation)
• Provide recreational opportunities (e.g. fishing, boating, swimming, camping)
• Tourism value (local, regional economies)
• Flood control
Climate change projections
• Flow reductions
• Altered seasonality
• Temperature increases
Potential effects of climate change on the impacts of dams
Exacerbated negative effects
Ecological
• Fish migrations: Retention of greater proportion of reduced annual flow, reduced environmental flow allocations, increased impacts of natural barriers due to flow declines
• Alien species: Temperature increases and flow declines create more suitable conditions in reservoir and upstream habitats for alien species
• Fragmentation of populations: Exacerbated through increased prevalence of natural barriers due to flow declines
Physical
• Downstream hydrology: Relative impact of flow attenuation increases due to reduced flows (reduces natural refuge quantity, alters seasonality, reduces flushing, reduces flooding)
• Stratification: Increased temperatures, reduced pool turnover, reduced dissolved oxygen
• Nutrient cycles: Reduced flow and longitudinal connectivity
Socio-economical
• Cost-efficiency: Flow reductions reduces efficiency of dam, maintenance /operation costs outweigh value (may be offset by increased value of water, see below)
Negligible or variable effects
Ecological
• Loss of lotic habitat: Reservoir footprint
• Mortality: density dependant predation below dam, spillway, hydroelectric turbine
Physical
• Upstream habitat: Quality and quantity of upstream habitat declines due to flow decline (will influence optimisation modelling that maximises unimpeded stream networks)
• Sedimentation
Socio-economical
• Flood control
• Fisheries declines: Lotic fisheries reduced due to flow declines and temperature increases (impacts on water quality, food availability, declines in recruitment, fitness)
Amplified positive effects
Ecological
• Refuge habitat: Increased relative value of dams for native fauna (e.g. non-diadromous fish, birds) as quality and quantity of natural refuges are lost due to rainfall, flow and groundwater declines and increased temperatures
• Spread of alien fishes: Dams may prevent the spread of existing or novel alien species
Physical
• Thermal pollution: Use of environmental flows (i.e. hypolimnetic releases) to offset downstream increases in water temperature
Socio-economical
• Value of stored water: Economic value of surface water will increase in drying climatic regions (may be offset by decreased efficiency of dams, see above)
Key considerations in assessing climate change affected criteria
Factors contributing to a decision to remove a dam
• Fauna highly migratory (especially threatened or culturally important species) and the dam will significantly exacerbate the climatic impacts to migrations due to flow declines or reduced fitness of native species (e.g. temperature increases reducing aerobic scope)
• The impoundment created by the dam does not provide significant refuge habitat for fauna in the catchment
• Dam not useful as a barrier to the spread of existing alien species
• Alien species in dam will increasingly be favoured under climate change
• Dam will become increasingly economically unviable and / or costly to maintain in light of flow reductions (e.g. based on age, size, reduced economic return)
• Dam will have increased impact on sensitive ecological communities located downstream (e.g. exacerbating the reduction in flows, loss of floodplains due to climate change)
• Connectivity of natural refuge habitats significantly impacted by dam
• Quality and quantity of upstream habitat not impacted by climate change or other dams thereby not increasing the relative value of the dam in the future
Decision on dam removal reached that has considered climatic projections
Factors contributing to a decision to retain a dam
• Connectivity and quality of remnant natural refuge habitats (i.e., those that will remain under projected drying scenarios) will not be significantly impacted by the presence of the dam
• The reservoir created by the dam provides significant amount of refuge habitat for native fauna in the catchment (especially for threatened species) and/or is appropriate as a restocking site for threatened species to offset population declines
• Quality and quantity of refuge habitat in the catchment projected to decline due to climate change (declines in rainfall, surface flow, groundwater, water quality, increases in temperature) that will increase the relative ecological value of the reservoir
• Aquatic fauna in the river are not strongly migratory (e.g. not for spawning purposes or undertake lateral migrations) and therefore life-history movements not significantly impacted by the dam
• Dam currently preventing the spread of damaging alien species
• Dam will continue to be economically viable (modelling of future efficiency under climate change scenarios) or ongoing maintenance costs forecast to be relatively low
• Lack of significant ecological communities or threatened species impacted downstream of dam

Highlights

- Dams often have severe ecological impacts and are increasingly being removed in some regions.
- Influence of climate change on the impacts of dam removal has not been addressed.
- The net ecological value of artificial refuges such as dams may increase in drying regions.
- Climate change may profoundly influence the value and impacts of dams in the future.
- Climate change needs greater consideration within prioritisation processes for dam removal.

SUPPORTING INFORMATION

Table 1 Formally described endemic freshwater fishes of south-western Australia and the Cape Floristic Region of South Africa including a summary of threats (Table adapted from Morgan *et al*. 2014; Weyl *et al.* 2014). Key: CR = Critically Endangered, EN = Endangered, VU = Vulnerable, NT = Near Threatened, LC = Least Concern, DD = Data Deficient, NE = Not Evaluated. Main threats in south-western Australia (after Morgan *et al*. 2014; Beatty *et al*. 2014) and in the CFR, South Africa [adapted from www.iucnredlist.org and CapeNature unpublished data]. *valid species names for former *Barbus* species as listed in the California Academy of Sciences- Catalog of Fishes http://researcharchive.calacademy.org/research/ichthyology/catalog/fishcatmain.asp).

Region and species	**IUCN Redlist (National Listing)**	**Main threats**							
		Alien fish	Habitat destruction	Pollution	Human utilisation	Genetic integrity	Instream barriers	Climate change	Water abstraction
South-western Australia									
Freshwater cobbler (*Tandanus bostocki*)	NE		■	■				■	■
Salamanderfish (*Lepidogalaxias salamandroides*)	NT (EN)		■					■	■
Western minnow (*Galaxias occidentalis*)	NE	■	■	■			■	■	■
Western Mud minnow (*Galaxiella munda*)	NT	■	■	■				■	■
Black-stripe minnow (*Galaxiella nigrostriata*)	NT (EN)	■						■	■
Nightfish (*Bostockia porosa*)	NE	■	■	■			■	■	■
Western pygmy perch (*Nannoperca vittata*)	NE	■	■	■			■	■	■
Little pygmy perch (*Nannoperca pygmaea*	NE (EN)	■	■	■				■	
Balston's pygmy perch (*Nannatherina balstoni*)	DD (VU)	■	■					■	■
Cape Floristic Region, South Africa									
Barnard's rock catfish (*Austroglanis barnardi*)	EN	■	■					■	■
Clanwilliam rock catfish (*Austroglanis gilli*)	VU	■	■					■	■
Berg-Breede River whitefish ('*Pseudobarbus*' *capensis*)*	EN	■	■	■	■	■		■	■
Clanwilliam redfin ('*Pseudobarbus*' *calidus*)*	VU	■	■					■	■
Twee River redfin ('*Pseudobarbus*' *erubescens*)*	CR	■	■	■					■
Sawfin ('*Pseudobarbus*' *serra*)*	EN	■	■		■		■	■	
Eastern Cape redfin (*Pseudobarbus afer*)	EN	■						■	
Smallscale redfin (*Pseudobarbus asper*)	EN	■	■	■			■	■	■
Burchell's redfin (*Pseudobarbus burchelli*)	CE	■	■					■	■
Berg River redfin (*Pseudobarbus burgi*)	CR	■	■			■		■	■
Fiery redfin (*Pseudobarbus phlegethon*)	EN	■	■					■	■
Giant redfin (*Pseudobarbus skeltoni*)	NE	■						■	
Slender redfin (*Pseudobarbus tenuis*)	NT	■	■					■	■
Verlorenvlei *redfin (Pseudobarbus verloreni*)	NE	■	■					■	■
Clanwilliam sandfish (*Labeo seeberi*)	CR	■	■				■	■	■
Clanwilliam yellowfish (*Labeobarbus seeberi*)*	VU	■	■	■	■		■	■	■
Cape galaxias (*Galaxias zebratus*)	DD	■	■	■		■		■	■
Cape kurper (*Sandelia capensis*)	DD	■	■	■		■		■	■