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Abstract

Amphibian populations globally are in decline. One important threat is the abstraction of water resources that alter surface-water hydrology. Conservation actions aimed at restoring or manipulating surface-water is frequently employed as a management tool, empirical evidence on the effectiveness of these approaches is scarce. In this systematic review we summarised the global experience of manipulating water for amphibian conservation. We explore examples of manipulating water to conserve amphibian species and communities. Approaches vary in their frequency of implementation and in their success. Extending hydroperiod to match larval requirements shows encouraging results, as does off-season drying to control predators. Spraying water into the environment has several potential applications, but successes are limited. Despite some promising interventions, we identified few (*n* = 17) empirically supported examples of successful water manipulation to benefit amphibians globally. It is unclear if this stems from publication bias or if it is an artefact of language selection. Manipulating water shows great potential in amphibian conservation, particularly at sites with a proximal water source and regions where aridity is increasing due to climate change. Regardless of the scale of the intervention or its perceived probability of success, high-quality reporting of empirical results will progress our understanding of how water manipulations could benefit threatened amphibian populations.

Introduction

The Amphibia (anurans, salamanders, and caecilians) are one of the world's most at-risk vertebrate classes —41% of assessed species are threatened with extinction (IUCN 2019). Amphibians are more susceptible to climate-driven shifts in niche than birds or mammals (Rolland et al. 2019), and changing climate may negatively affect amphibians more strongly than other vertebrates (Lawler et al. 2009). Anthropogenic alteration to natural hydrological regimes (Kupferberg et al. 2012), habitat loss (Cushman 2006; Ferreira & Beja 2013), and exotic species (Pyke & White 2000) rank among the top threatening processes. Such threatening processes can be additive or interactive, with the strongest effects predicted in global regions with highest amphibian richness (Hof et al. 2011). Furthermore, the intensity of these processes will likely increase as the climate changes (Walther et al. 2002).

Changing rainfall volume and pattern is projected to affect amphibians at several points during their lifecycle. Changes in the seasonal onset of rainfall will likely affect the temporal initiation of breeding (Ludovisi et al. 2014), and contraction of annual rainfall patterns could increase interspecific competition by changing the temporal segregation between breeding events (Luna-Gomez et al. 2017). In areas subject to aridification under climate change, reductions hydroperiod will increase the risk of recruitment failure due to pool desiccation (Chandler et al. 2016), while increasing duration and/or severity of droughts would increase the frequency of recruitment failures (Dodd 1994). Drying of landscapes can reduce pool connectivity (Olson & Burton 2019) which may result in increased mortality rates during emigration (Tournier et al. 2017), reducing population connectivity (Peterman et al. 2014) and ultimately, regional species richness (Lescano et al. 2015).

As climate changes and the level of water abstraction increases, the manipulation of hydrological regimes for amphibian conservation may be necessary (Greenwood et al. 2016). Programs focused on the managed release of water for environmental purposes are thus increasing worldwide (Kennen et al. 2018), but most rarely consider amphibians specifically within their mandates. For example, in a review of 30 environmental-flow programmes throughout Europe, amphibians were not mentioned (European Commission

2016). Despite this trend, a range of hydrological manipulations have been implemented specifically for amphibian conservation (see also reviews by Shoo et al. 2011 and Smith et al. 2019), the scope and success of which vary considerably.

Our aim in this systematic review is to synthesise the global body of evidence examining how manipulating water is used to increase amphibian abundance, distribution, and/or recruitment. We address the following questions: (1) What forms of water manipulation have been recommended or implemented to improve amphibian abundance, distribution, and recruitment? (2) What forms of water manipulation have been recommended or implemented to control undesirable (typically, invasive) amphibians? (3) Based on the available evidence, which manipulations are recommended for implementation?

Methods

In this review, we employed the preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) (Moher et al. 2015). We included the *Science Direct*, *Aquatic Sciences and Fisheries Abstracts* (ASFA), and *Web of Science* databases for all searches. We searched *Science Direct* using 'amphibian' OR 'frog' OR 'toad' OR 'salamander' OR 'caecilian' [*present in the title*] AND ('hydro*' OR 'water' OR 'flow') AND ('manipulation' OR 'environmental' OR 'artificial' OR 'pump*' OR 'spray*') [*present in the title, abstract or keywords*]. This search returned 184 results. We searched the *ASFA* database using ti('amphibian' OR 'frog' OR 'toad' OR 'salamander' OR 'caecilian') AND ((ab(('hydro*' OR 'water*' OR 'flow') AND ('manipulation' OR 'environmental' OR 'artificial' OR 'pump*' OR 'spray*'))) OR (ti(('hydro*' OR 'water*' OR 'flow') AND ('manipulation' OR 'environmental' OR 'artificial' OR 'pump* OR 'spray*'))) OR (if(('hydro*' OR 'water*' OR 'flow') AND ('manipulation'

OR ‘environmental’ OR ‘artificial’ OR ‘pump* OR ‘spray*)))). This search returned 461 results. Here, ‘ti’ = ‘title’, ‘ab’ = ‘abstract’, but these abbreviations have subsequently changed in the Web of Knowledge search engine. Finally, we searched *Web of Science* using TI=(‘amphibian’ OR ‘frog’ OR ‘toad’ OR ‘salamander ‘OR ‘caecilian’) AND TS=((‘hydro*’ OR ‘water’ OR ‘flow’) AND (‘manipulation’ OR ‘environmental’ OR ‘artificial’ OR ‘pump*’ OR ‘spray*’)). Here, ‘TI’ = ‘title’, ‘TS’ = ‘topic’. This search returned 783 results. We thus accumulated a total of 1040 documents after removing duplicates. This protocol required an amphibian search term in the title, so we acknowledge that our initial search might have missed records that did not focus specifically on amphibians.

We developed inclusion criteria as follows: we only searched English-language studies but did not restrict the temporal range. We included studies with a purposeful, field-based manipulation of a wetting regime (i.e., with water from any source) that resulted in a change in amphibian abundance, distribution, or recruitment. This included manipulation for a purpose other than conservation (e.g., stormwater treatment, or water storages). The outcomes could have been identified through changes in abundance, calling behaviour, or recruitment, and could have been assessed over any time scale. Full text screening included reviewing the associated reference list for relevant inclusions. When we knew of additional studies that did not emerge from the review protocol, we included these as well.

Results

We summarise our results under two main headings: *Section 1* examines the purposeful manipulation of water resources to benefit amphibians, while *Section 2* reviews the purposeful manipulation of water resources to exclude undesirable amphibian species.

Our review identified 40 papers on amphibian use of created water resources — e.g., sewage and stormwater storage ponds, while not involving a purposeful manipulation of water resources, this information is relevant to the review and included in Appendix S1.

1. Water manipulation to benefit amphibians

Hydroperiod has a strong influence on amphibian ecology. Fully aquatic species require permanent aquatic habitats, while species that breed early or later in the season, or require multiple seasons to complete larval stages, can also benefit from waterbody permanence (Shulse et al. 2010). In Canada, artificial pools are pumped to maintain water permanence to support waterbirds. These pools support lower densities of northern leopard frog *Lithobates pipiens* larvae but protect against larval desiccation and produce larger frogs than vernal pool control sites (Pouliot & Frenette 2010). Longer hydroperiods are also important for larger species that typically require more time to complete their larval development (Patterson & McLachlan 1989). Shorter hydroperiods can stimulate shorter larval periods (Parris 2000), with smaller metamorphs emerging as a result (Johansson et al. 2010; Bekhet et al. 2014; Charbonnier & Vonesh 2015); such hydroperiods have been associated with poor fitness and low lifetime reproductive output (Smith 1987). Hydroperiods shorter than the minimum larval requirement for a given species result in complete reproductive failure, with all larvae drying *in situ*.

Permanent pools may have increased risk of predation, can be more likely to support fish and crustacean predators (Nystrom et al. 2002), and have higher densities of invertebrate predators (Lowe et al. 2015). In fish-free vernal pools, longer hydroperiods can support greater species richness (da Silva et al. 2011), higher abundance of egg masses (Baldwin et al. 2006; Veysey et al. 2011), and more metamorphosing juveniles (Semlitsch & Gibbons 1985; Pechmann et al. 1989).

1.1. Increasing hydroperiod through pumping

In several instances, manipulating water resources to increase hydroperiod in vernal pools has been successfully implemented to support amphibian populations (see also Smith et al. 2019). Increasing hydroperiod can improve population viability through increased recruitment (Hamer et al. 2016). For example, models of the eastern narrow-mouthed toad *Gastrophryne carolinensis* show that reproductive failure and extirpation arise mainly from insufficient hydroperiod (Salice 2012). In North America, solar and wind-powered pumps are used to maintain water level in breeding pools used by the Chiricahua leopard frog *Lithobates chiricahuensis* in conjunction with other conservation actions (McCaffery and Phillips 2012, 2015) contributing to increasing populations and range size, but the role of pumping cannot be disentangled from the other interventions. Similarly, water was pumped into a vernal breeding pool to prevent desiccation prior to metamorphosis resulted in successful recruitment of the critically endangered dusky gopher frog *Rana sevosa* which was at risk of local extinction following repeat recruitment failure (Seigel et al. 2006). In the Sydney Olympic Park, Australia, treated stormwater is pumped into multiple ponds to extend hydroperiod and has contributed to increased recruitment, population size and distribution of green and golden bell frog *Litoria aurea* (Darcovich & O'Meara 2008).

1.2. Physical manipulation of habitats to extend hydroperiod

The creation and physical alteration of habitat for amphibian conservation is a broad field with considerable complexity. Our review specifically considers the alteration of existing habitats to extend hydroperiod. More thorough examinations of habitat creation and alteration can be found in Brown et al. (2012) and Calhoun et al. (2014) (see also Smith et al. 2019).

Physical manipulation of habitat to extend hydroperiod has been implemented at various spatial scales. In Switzerland, the installation of plastic containers that mimic the natural spawning sites of the yellow-bellied toad *Bombina variegate*, created breeding habitats that were more likely to retain water (0.94 probability cf. 0.63 for proximate natural breeding sites), resulting in lower site abandonment and more consistent interannual breeding occurrence (Tournier et al. 2017). To preserve sufficient hydroperiod for the striped newt *Notophthalmus perstriatus*, pond liners were installed in three temporary pools, creating breeding habitats that filled more rapidly during rainfall events and extended hydroperiod by up to three months (Means et al. 2016). Excavation and installation of pond liners has also been used to increase hydroperiod to support the wood frog *Lithobates sylvatica*, maintaining breeding effort and metamorph occupancy rates similar to high-performing natural pools (Green et al. 2013). In Sydney Olympic Park, liners are also used to extend hydroperiod and create productive breeding habitats for *L. aurea* (Darcovich & O'Meara 2008). In the chalk Downs, southern England, restoring dewponds (traditional agricultural ponds lined with clay and straw) increases depth and hydroperiod, maintaining the quality of amphibian habitats in the landscape (Beebee 1997).

Siltation and in-filling can reduce depth and hydroperiod at sites that have previously supported amphibian recruitment. On Prince Edward Island, Canada, accumulated sediments were excavated from 22 small (> 6 ha) ponds to increase depth and hydroperiod (Stevens et al. 2002). All five amphibian resident species occupied the excavated wetlands, with three species calling in higher abundances from excavated ponds compared to reference wetlands. In southern Estonia, 230 ponds were excavated in

27 clusters, increasing the depth of 22 existing ponds and re-excavating 73 historic pond sites (Rannap et al. 2009). This manipulation increased the number of ponds occupied by all seven regional amphibian species, including two species of conservation significance - the crested newt, *Triturus cristatus* and the common spadefoot toad, *Pelobates fuscus*. Excavating pools to increase water depth has been recommended to increase drought resilience of the northern corroboree frog *Pseudophryne pengilleyi*, but has not been implemented (Scheele et al. 2012).

Earthworks have been used at the catchment scale to increase the area and duration of standing water for amphibian conservation. In the Narew River valley Poland, dams were built, channels de-sludged, culverts removed, and flow diversion installed to restore flow dynamics, while stock-watering points were constructed. Amphibian species richness and breeding success increased in pre-existing vernal pools (11 species and 56.9% of observations) compared to new watering points (ten species and 32.5% of observations) or river sites (eight species and 10.6% of observations) (Deoniziak et al. 2017). Likewise, in Montana (USA) the outlet of Dahl Lake was blocked, increasing lake size from 43 to 360 ha. After ten years of monitoring proximate wetlands, only the Columbia spotted frog *Rana luteiventris* increased the number of off-channel pools occupied, while the boreal toad *Anaxyrus boreas* declined rapidly and two other species remained stable (Hossack 2017).

Beaver dams can create lentic habitats suitable for amphibians. In Germany, beaver dams are linked to greater amphibian species richness than unobstructed proximate streams (Lüscher et al. 2007), and in Canada, three species of amphibian bred in beaver dams, but not in nearby free-flowing streams (Stevens at al. 2007). In drier regions like the Adirondack Mountains in North America, beaver dams create a mosaic of heterogeneous hydroperiods including both ephemeral and permanent aquatic habitats, producing between 23 and 69 times more metamorphs than comparable vernal breeding sites (Karraker & Gibbs 2009).

1.3. Dam releases (environmental flows) to increase hydroperiod

River regulation alters hydrological regimes, including timing, frequency, and duration of flow pulses and the extent of inundation (Bunn & Arthington 2002; Eskew et al. 2012). Operational flows released from dams to manage reservoir depth, transfer water between storages and deliver irrigation flows may not be timed to emulate natural flow patterns, and can negatively affect amphibian fauna (Kupferberg et al. 2012). Operational dam releases can disadvantage amphibians in several ways. Flows that remain in-channel encourage the development of a homogenous single channel (Hazell et al. 2003), which could remove microhabitats important for amphibian recruitment (Manenti et al. 2009), and high energy flows might scour eggs and larvae from the reach (Kupferberg 1996). Hypolimnetic flows, where cold water is released from storages, are particularly harmful because they alter thermal regimes and can increase mortality (Bury 2008), delay metamorphosis (Rogell et al. 2011), and reduce body condition at metamorphosis (Wheeler et al. 2015).

Releases aimed at eliciting positive ecological outcomes (often termed ‘environmental flows’) represent a potentially attractive technique for conservation because they can typically be delivered using existing infrastructure and interventions can target multiple taxa simultaneously. Using environmental flows to increase hydrological heterogeneity across the landscape appears more promising. Inundation events tend to enrich local species diversity (Real et al. 1993) and inundation also increases aquatic connectivity. One model suggested that releasing regular flow pulses, timed to emulate seasonal variation, would benefit the California red-legged frog *Rana* *aurora draytonii* and control American bullfrog *Lithobates catesbeianus*, but we could not identify evidence of its implementation (Doubledee et al. 2003).

1.4. Spraying water

Without specific adaptations to minimise cutaneous water loss, most amphibians suffer rapid desiccation out of water. Amphibians display behavioural adaptation to minimise water loss during dry periods (O'Connor & Tracy 1992) and in some instances foraging and courtship behaviour can cease (Feder 1983). In these instances spraying water can increase foraging and reproduction opportunities (see also Shoo et al. 2011). For example, experimental spraying of Bibron's toadlet *Pseudophryne bibroni* (a terrestrial nest breeder) increased substratum water potential, resulting in increased calling behaviour (157 calling nights compared to 48 in unwetted nests), successful mating events (5 cf. 1), and egg survival (95% cf. almost complete mortality) (Mitchell 2001). Spraying has been recommended to protect the microendemic nest breeder, northern corroboree frog *Pseudophryne pengilleyi* from extinction due to climate change, but has not been implemented (Scheele et al. 2012).

Spraying might also be useful to increase dispersal and population connectivity. During periods of drought, the frosted flatwoods salamander *Ambystoma cingulatum* reduces breeding migrations (Palis et al. 2006). High rainfall events increase colonisation between proximate pools (Cayuela et al. 2012) and during torrential rain events, even fully aquatic frogs migrate overland (Lobos & Jaksic 2005). It is possible that landscape spraying could decrease landscape resistance, resulting in increased population resilience (Brown & Kodric-Brown 1977). This approach is especially promising for species that have spatial genetic population structure over as little as tens of metres (Sunny et al. 2014).

Perhaps the best-documented example of spraying for amphibian conservation is the Kihansi spray toad *Nectophrynoides asperginis*. This microendemic is restricted to 40,000 m^2 of spray zone at the base of the Kihansi Falls in Tanzania. The activation of a hydroelectric plant in 2000 reduced or removed spray, prompting the installation of gravity-fed sprinkler system to recreate the microhabitat (paired with captive breeding and reintroduction). In the first two years of operation the wild population grew from 11,385 to 20,989 (Channing et al. 2006); thereafter the populations dwindled (Nahonyo et al. 2017) and it is now considered extinct in the wild (IUCN 2019). Failure of the interventions to stabilise the population was likely due to a combination of effects, including a reduction in the intensity and area of sprayed habitat, invasion of safari ants (*Dorylus* sp.) into the drier habitats (Channing et al. 2006), chytridiomycosis *Batrachochytrium dendrobatidis* (Makange et al. 2014), and trophic shifts within the spray zone which reduced arthropod availability (Zilihona et al. 1998).

1.5. Spraying repurposed water

In Pennsylvania (USA), sprinklers that applied secondarily treated, chlorinated wastewater effluent to 150 ha of forested land increased surface water area by 252%, doubling the number of ponds. Ponds receiving wastewater were characterised by thick blankets of duckweed (*Lemna* sp.), had poorer water quality, fewer egg masses, lower hatching success and larval survival compared to control ponds (Laposata & Dunson 2000). In planning for treated sewage delivery, the authors recommend spraying over the target area and allowing infiltration through the soil to reduce nutrients, pH, and toxin concentrations rather than spraying directly into the target pools or allowing overland flow.

1.6. Drying to control predators

Permanent pools tend to contain the highest predator densities (Wellborn et al. 1996) and intermittent drying can reduce densities of obligate aquatic predators such as fish or crustaceans (see also Smith et al. 2019). The presence of fish is widely associated with amphibian absence (Julian et al. 2006; Arkle & Pilliod 2015) and reduced species richness (Amburgey et al. 2013; Jeliazkov et al. 2014). For example, the introduction of mosquitofish *Gambusia holbrooki* resulted in complete larval mortality for the fire salamander *Salamandra salamandra* (Segev et al. 2009). Similarly, although the Columbia spotted frog laid more eggs in permanent pools, survival to metamorphosis was three times higher in semi-permanent pools because fish were absent (McCaffery et al. 2014). Not all amphibian species are impacted by fish, for example, salmonid predators inhibited breeding in three species of frog but not European toad *Bufo bufo*, which are less palatable (Manenti & Pennati 2016).

Observational and modelling studies suggest drying is an effective tool for controlling introduced fish, especially when native amphibians are not present (Maret et al. 2006). In Michigan (USA), natural drying removes predatory fish, reducing predation and increasing amphibian species richness (Werner et al. 2007). Likewise, natural drying in streamside pools in Kentucky (USA) removes green sunfish *Lepomis cyanellus* resulting in higher rates of streamside salamander *Amystoma barbouri* oviposition (136.6 eggs/m^2 compared to 32.6 eggs/m^2 in pools with fish) (Kats & Sih 1992). In England, drying an urban pool successfully removed fish and improved recruitment in crested newt (from 76 larvae to 396 in the year following drying) (Cooke 1997). In Sydney (Australia), draining to remove mosquitofish prior to the breeding season increased occupancy by *L. aurea* larvae (O'Meara & Darcovich 2008).

Laboratory studies show that desiccation can control some amphibian pathogens (e.g., chytridiomycosis) (Johnson et al. 2003), but not others (e.g., ranavirus FV3) (Nazir et al. 2012); however, field-based studies are required to confirm and quantify the viability of drying to manage amphibian diseases.

2. Manipulating water to control undesirable amphibians

Water infrastructure can provide refuge, transport corridors and stepping stones that facilitate movement and occupancy of exotic amphibians (Brainwood & Burgin 2009; Chester & Robson 2013; Davies et al. 2013; Shine 2014). In these systems, the strategic drying of aquatic resources can be used to restrict the spread of exotic amphibians (see also Smith et al. 2019). Population models provide support for pool drying as an effective technique for population control of the American bullfrog (Maret et al. 2006), and to reduce the ability of invasive cane toads *Rhinella marina* to cross inhospitable habitat patches in arid parts of Australia (Tingley et al. 2013). This approach is most promising during dry seasons or in regions where access to water is limited (Child et al. 2009). Altering the design of farming infrastructure from bore-fed, earthen dams to tanks or troughs (Feit et al. 2015) and targeting dry-season aggregations at pools (Reynolds & Christian 2009) could also supplement this approach.

Although models support strategic drying to disrupt invasive amphibians, there are several factors that influence successful implementation. In Belgium, experiments aimed at controlling the abundance of the American bullfrog included a selective, dry-down treatment where pools within the matrix were drained and seined to remove vertebrate life. Draining alone had no impact on larval densities in subsequent years, indicating that this process is unlikely to produce positive results when re-invasion pathways are present

(Louette 2012). Lobos and Jaksic (2005) hypothesised that pond drying stimulates mass migration events in African clawed frog *Xenopus laevis* in Chile.

Discussion

There are various management techniques available to manipulate water resources to influence amphibian reproduction, recruitment, movement, and survival. Despite an increasing need for effective amphibian conservation interventions, we detected only 17 published, field-based interventions of this type in our systematic review (Table 1). It is unlikely that the modest number of studies identified accurately reflects the extent or range of interventions deployed,

This systematic review protocol targeted only English-language publications, potentially creating an *a priori* language bias in our results. This hypothesis is supported by examining a global distribution of study sites. If language bias were not relevant, we might expect a somewhat scattered distribution of relevant studies across the globe but instead, the studies are almost exclusively in countries where English is an official language. Furthermore, these results likely reflect a publication bias on several fronts: (1) flow manipulation may be implicit but not presented as the main aim of the study or within the publication title or abstract (2) interventions are probably deployed by organisations that do not prioritise primary publication (3) budget and logistical constraints could preclude sufficient replication or monitoring to infer a strong relationship resulting in low publication rates, (4) there could be a reluctance to publish null results due to a perceived failure of the intervention (Fanelli 2012). Regardless of the mechanism, we are concerned by the obfuscation of these interventions. We strongly advocate for increased peer-reviewed publication of hydrological manipulations, regardless of the outcome. We similarly advocate for improved labelling and division of grey literature to help distinguish innovative approaches and notable outcomes from more routine monitoring reports.

Given the few published studies, attempts to assess the strength of different approaches objectively, through meta-analysis is not possible. This is further complicated because seven of the 17 studies combined hydrological manipulations with other conservations techniques (e.g., revegetation, fencing, *ex situ* breeding, and reintroduction). As such, isolating the effect size of hydrological manipulations is not yet possible. Instead, we summarise our main findings without quantitative analysis.

The most broadly implemented conservation technique we discovered was altering existing habitats to increase hydroperiod. This was successfully implemented across a range of spatial scales. Techniques included creating habitats (Rannp et al. 2009; Tournier et al. 2017), excavating to increase pool depth (Cooke 1997; Rannap et al. 2009), lining ponds with an impervious liner (Green et al. 2013; Means et al. 2016; O'Meara & Darcovich 2008), and installing dams or regulators (Pouliot & Frenette 2010; Deoniziak et al. 2017; Hossack 2017). Amphibian responses to these alterations were generally positive, although they were often spatially and temporally variable. For example, Green et al. (2013) detected production of post metamorphic frogs in only one of the four treatments, and Deoniziak et al. (2017) detected improved breeding response only in natural vernal habitats proximate to the intervention sites. In several studies experimental results were explained by proximity to existing populations (e.g., Stevens et al. 2002) and the dispersal capacity of each species (e.g., Beebee 1997). The most successful conservation outcomes incorporated dispersal pathways in the design (e.g., Darcovich & O'Meara 2008; Rannap et al. 2007). Thus, we recommend site alteration to increase hydroperiod as a management strategy, although factors like proximity to source populations, landscape resistance, and dispersal capacity of the target population will affect the amphibian response.

Four studies pumped water to create breeding habitats free from predators or to prolong hydroperiod to allow for completion of metamorphosis. Amphibian response to pumping was consistently positive, with expansion in both range and abundance (Darcovich & O'Meara 2008; McCaffery et al. 2014) and increased recruitment success (Seigel et al. 2006). We therefore recommend this intervention, particularly in discrete, vernal pools.

Releasing water from impoundments into rivers (environmental flow) is an attractive approach to conservation. It requires little additional infrastructure, can be designed to mimic natural climatic cycles, and can be deployed to benefit several taxa simultaneously. We could not identify an environmental-flow programme with conservation targets specific to amphibians during our review, but identified potential aspects of flow delivery (for operational or environmental purposes) that may have negative impacts on stream dwelling amphibians via high-energy flows that disrupt habitat and juvenile life stages. Theoretically, release schedules could be designed to recreate timely inundation, but we identified only one, modelled examination of this question (Doubledee et al. 2003).

Spraying water into the landscape can reduce evaporative water loss in amphibians, there is some evidence of spraying increasing breeding success for terrestrial nest breeders and it may increase opportunities for foraging and reduce landscape resistance. However, increasing soil moisture could increase the likelihood of disease transmission (Beyer et al. 2015) and enhance dispersal of exotic amphibians (Cohen & Alford 1996; Child et al. 2009). There is little empirical evidence to support spraying to reconstruct habitats, but targeted support of terrestrial breeders and to aid foraging appears sound.

Poor water quality can influence outcomes for amphibians, and there was little evidence of a positive amphibian responses following spraying with treated sewage (Laposata & Dunson 2000).

Targeted drying has been successfully implemented on several occasions to remove predators (especially fish). We recommend this approach, especially where existing infrastructure exists to allow draining and refilling of the site. Models support the removal of dry-season aquatic refugia as a control measure for exotic amphibian dispersal. Although theoretically valuable, this approach has not been implemented, and there is little empirical evidence to support its use at the current time.

Despite the promising nature of hydrological manipulation as a conservation tool, unexpected negative outcomes have also been reported and we urge caution during planning. For example, although Cooke (1997) observed a fivefold increase in crested newt recruitment in the season following intervention, recruitment was lower during the final three years of monitoring than the pre-intervention baseline. Similarly, although Hossack (2017) observed an increase in Colombia spotted frog, there was also a rapid reduction in arboreal toad numbers. In theory, negative outcomes are reduced by carefully matching interventions to the biological requirements of the target species and the landscape context of the intervention site. Robust approaches have generally applied interventions in a mosaic pattern (e.g., Rannap et al. 2009) which spread the risk when compared to a single site (e.g., Cooke 1997). Unexpected outcomes should be fully and accurately reported.

Overall, we conclude that manipulating water is a promising management tool in amphibian conservation, particularly where aridity increases due to climate change. The main issue arising from our review is the lack of sufficient empirical evidence to evaluate the success of these approaches confidently. Nonetheless, two approaches warrant recommendation. Firstly, the extension of hydroperiod in vernal pools is the most supported approach and has been successfully implemented to achieved amphibian conservation targets. Secondarily, implementing drying to control aquatic predators is reasonably well-supported by the available evidence. Regardless of the approach taken, interventions must be tailored to meet the ecological needs of the target species. Our strongest recommendation is that future interventions are sufficiently funded to include the monitoring and assessment of the intervention and that the results are reported in a discoverable manner regardless of their format or the perceived success of the intervention.

Supporting Information: A synthesis of amphibian use of anthropogenic water resources (Appendix S1) is available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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Table 1 This systematic review detected 14 examples of hydrological manipulation to benefit amphibians which ranged from small manipulated experiments to larger, whole-of-ecosystem rehabilitation.

Author	Location	Target fauna	Intervention	Outcome	Concurrent interventions
Beebee (1997)	chalk Downs, England	five endemic amphibian species	Ponds relined with clay and straw.	Depth and hydroperiod restored, but net loss of dewponds observed.	Observational amphibian study.
Channing et al. (2006)	Kihansi Falls, Tanzania	Kihansi spray toad (*Nectophrynoides asperginis*)	Gravity fed sprinkler system installed to recreate spray zone.	Population stabilised initially but then dwindled. Now considered extinct in the wild.	Captive breeding and reintroduction.
Cooke (1997)	Peterborough, United Kingdom	crested newts (*Triturus cristatus*)	Pond pumped dry to remove predatory fish.	Fish had not returned to the dried site after 7 years. Increased newt recruitment, but the magnitude of this effect reduced in subsequent years.	Excavation to increase depth.
Darcovich & O'Meara (2008)	Sydney, Australia	green and golden bell frog (*Litoria aurea*)	Treated stormwater pumped to 140 natural and artificial habitats.	Increased in abundance and range.	Revegetation, fencing, habitat construction, selective draining.
Deoniziak et al. (2017)	Narew River Valley, Poland	braided channel marsh ecosystem	Extensive earthworks to increase volume and residence time.	Increased species richness and breeding. Response concentrated in natural, off-channel, vernal ponds.	Observational amphibian study.
Green et al. (2013)	Patuxent Research Refuge, Maryland U.S.A.	wood frog (*Lithobates sylvatica*)	Installation of EPDM pond liners.	Increased breeding effort and production of metamorphs in 1 of 4 pools	Manipulated field experiment.
Hossack (2017)	Dahl Lake, Montana, U.S.A.	wetland ecosystem	Lake outlet dammed increasing lake size from 43 to 360 ha.	Response varied by species. Some increased, others decreased.	Observational amphibian study.
Laposata & Dunson (2000)	Centre County, Pennsylvania, USA	sewage treatment	Secondarily treated, chlorinated wastewater	3 species of amphibian bred in irrigated ponds but	Observational amphibian study.

			effluent sprayed across 150 ha.	breeding responses were higher in natural pools.	
McCaffery & Phillips (2012, 2015)	Ladder Ranch, New Mexico, USA	Chiricahua leopard frog (*Lithobates chiricahuensis*)	Installation of solar and wind powered pumps to increase hydroperiod.	Increased population size and range expansion.	*Ex situ* breeding and reintroduction, fencing, revegetation, damming.
Means et al. (2012)	Apalachicola National Forest, Florida, USA	striped newt (*Notophthalmus perstriatus*)	Installation of EPDM pond liners.	Hydroperiod extended by up to 6 weeks. Improved frog breeding but newt response unclear.	*Ex situ* breeding and reintroduction.
Mitchell (2001)	Watts Gully Reserve, South Australia, Australia	Bibron's toadlet (*Pseudophryne bibroni*)	Sprinklers installed to manipulate water potential at breeding sites.	Calling males were attracted to wetted areas with increased hatch rates.	Manipulated field experiment.
O'Meara & Darcovich (2008)	Sydney, Australia	green and golden bell frog (*Litoria aurea*)	Ponds drained and refilled to remove predatory fish prior to breeding season.	Larvae were only observed in ponds which had been drained to remove predators.	Revegetation, fencing, artificial habitat construction, pumping.
Pouliot & Frenette (2010)	Lac Saint-Pierre, Québec, Canada	waterfowl	Dikes installed to create an artificial wetland. River water pumped to maintain permanence.	Northern leopard frog (*Lithobates pipiens*) were present in lower densities than natural sites but emerged at larger size.	Observational amphibian study.
Rannap et al. (2009)	southern Estonia	crested newt (*Triturus cristatus*) and common spadefoot toad (*Pelobates fuscus*)	22 existing ponds excavated to extend hydroperiod.	Increased number of ponds occupied by all seven species of amphibian, including target taxa.	Excavated 73 historic pond sites and created 130 new ponds. Ponds created in clusters and designed for target taxa.
Seigel et al. (2006)	Desoto National Forest, Mississippi, U.S.A.	dusky gopher frog (*Rana sevosa*)	366,000 L well water pumped to maintain temporary ponds until natural rainfall.	Metamorphs observed for the first time in 3 years.	Manipulated field experiment.

Stevens et al. (2002)	Prince Edward Island, Canada	waterfowl	22 ponds dredged to increase open water and extend hydroperiod.	Increased abundance of three species at restored ponds.	Observational amphibian study.
Tournier et al. (2017)	Geneva, Switzerland	yellow-bellied toad (*Bombina variegata*)	Installation of 169 plastic containers (40 cm depth, circular or rectangular).	Lower rate of site abandonment and more consistent breeding effort at artificial sites.	Manipulated field experiment.