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Review

Manipulating water for amphibian conservation

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Abstract: Amphibian populations globally are in decline. One great threat is the abstraction of water resources that alter surface-water hydrology. Conservation actions aimed at restoring or manipulating surface water are employed as a management tool, but empirical evidence on the effectiveness of these approaches is scarce. In this systematic review, we summarized the global experience of manipulating water for amphibian conservation. We explored examples of manipulating water to conserve amphibian species and communities. Approaches varied in their frequency of implementation and in their success. Extending hydroperiod to match larval requirements showed encouraging results, as did off-season drying to control predators. Spraying water into the environment showed several potential applications, but successes were limited. Despite some promising interventions, we identified few (n = 17) empirically supported examples of successful water manipulation to benefit amphibians. It is unclear whether this stems from publication bias or if it is an artifact of language selection. However, manipulating water shows some potential in amphibian conservation, particularly at sites with a proximal water source and in 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 further understanding of how water manipulations can benefit threatened amphibian populations.

Keywords: amphibian, conservation, environmental, flow, frog, pump, salamander, spray, toad, water

Manipulación del Agua para la Conservación de Anfibios

Resumen: Las poblaciones mundiales de anfibios están en declinación. Una gran amenaza es la extracción de los recursos hídricos que alteran la hidrología superficial. Las acciones de conservación enfocadas en la restauración o manipulación del agua superficial se emplean como herramientas de manejo, pero la evidencia empírica de la efectividad de estas estrategias es escasa. En esta revisión sistemática resumimos la experiencia mundial de la manipulación del agua para la conservación de anfibios. Exploramos ejemplos de la manipulación del agua para conservar especies y comunidades de anfibios. Las estrategias variaron en la frecuencia de implementación y en el éxito que tuvieron. La extensión del periodo hídrico para que cumpla con los requerimientos de las larvas mostró resultados alentadores, así como lo hizo la sequía atemporal para controlar a los depredadores. La aspersión de agua en el ambiente mostró varias aplicaciones potenciales, pero el éxito fue limitado. A pesar de algunas intervenciones prometedoras, identificamos pocos (n = 17) ejemplos con respaldo empírico de la manipulación exitosa del agua para el beneficio de los anfibios. Todavía no está claro si esto proviene de un sesgo en las publicaciones o si es un artificio de la selección del lenguaje. Sin embargo, la manipulación del agua muestra cierto potencial en la conservación de los anfibios, particularmente en sitios próximos a una fuente de agua y en regiones en donde la aridez está incrementando debido al cambio climático. Sin importar la escala de la intervención o la probabilidad de éxito percibida, la comunicación de alta calidad de los resultados empíricos hará crecer el entendimiento de cómo la manipulación del agua puede beneficiar a las poblaciones amenazadas de anfibios.

Palabras Clave: agua, ambiental, anfibio, aspersión, bomba, conservación, flujo, rana, salamandra, sapo

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摘要: 全球两栖动物的数量正在下降。一个巨大的威胁是水资源开发, 这改变了地表水文。旨在恢复或控制地表水的保护行动已被用作一种管理工具, 但是相关方法有效性的经验证据尚且很少。在这篇综述中, 我们总结了全球利用水资源保护两栖动物的经验。我们探索了利用水资源保护两栖动物物种及群落的例子。各种方法的实施频率和成功与否各不相同。延长水文周期以适应幼虫需求的方法, 以及在非生产季节干燥土壤以控制捕食者的方法, 都获得了喜人的成果;向环境中喷水也表现出潜在应用价值, 但成功的例子还很有限。尽管采取了一些有前景的干预措施, 但我们只确定了少数成功控制水资源使两栖动物受益的经验支持的例子 ($n = 17$) 。目前还不清楚这是否源于文献发表偏倚或是对论文语言的选择。不过控制水资源已在两栖动物保护方面展现潜力, 特别是水源附近的地点和因气候变化而愈加干旱的地区。无论干预规模或其预测成功率, 高质量的经验结果报告都将推进人们对于如何利用水资源以造福受威胁两栖动物种群的认识。【**翻译: 胡怡思; 审校: 聂永刚**】

关键词: 两栖类, 青蛙, 蟾蜍, 蝾螈, 环境, 水流, 水, 泵, 喷水, 保护

Introduction

Amphibia (anurans, salamanders, and caecilians) is 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 niche shifts than birds or mammals (Rolland et al. 2018), and changing climate might 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; the strongest effects are predicted in global regions with the highest amphibian richness (Hof et al. 2011). The intensity of these processes will likely increase as the climate changes (Walther et al. 2002).

Changing rainfall volume and patterns are 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 in hydroperiod will increase the risk of recruitment failure due to pool desiccation (Chandler et al. 2016), and increasing duration or severity of droughts will increase the frequency of recruitment failure (Dodd 1994). Drying of landscapes can reduce pool connectivity (Olson & Burton 2019), population connectivity (Peterman et al. 2014), and ultimately regional species richness (Lescano et al. 2015).

As the climate changes and the degree of water abstraction increases, the manipulation of hydrological regimes for amphibian conservation might be necessary (Greenwood et al. 2016). Programs focused on the managed release of water for environmental purposes are increasing worldwide (Kennen et al. 2018), but few consider amphibians specifically within their mandates. For example, in a review of 30 environmental-flow programs throughout Europe, amphibians were not mentioned (European Commission 2016). Despite this trend, a range of hydrological manipulations have been implemented specifically for amphibian conservation (reviews by Shoo et al. [2011] and Smith et al. [2019]), the scope and success of which vary considerably.

Our aim was to synthesize the global body of evidence examining how manipulating water is used to increase amphibian abundance, distribution, and recruitment. We addressed the following questions: what forms of water manipulation have been recommended or implemented to improve amphibian abundance, distribution, and recruitment; what forms of water manipulation have been recommended or implemented to control undesirable (typically, invasive) amphibians, and based on available evidence, which manipulations are recommended for implementation?

Methods

We employed the preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) (Moher et al. 2015). We used ScienceDirect, Aquatic Sciences and Fisheries Abstracts, and Web of Science. In ScienceDirect, we searched for the terms "*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 for the following terms in the Aquatic Sciences and Fisheries Abstracts (ASFA) database: 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* is title and *ab* is abstract, but these abbreviations subsequently changed in the Web of Knowledge search engine. Finally, we searched Web of Science for 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* is title and *TS* is 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 our initial search could have missed records that did not focus specifically on amphibians.

We developed inclusion criteria as follows. We searched only English language studies. Temporal range was not restricted. 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 behavior, or recruitment and could have been assessed over any period. Full-text screening included reviewing the associated reference list for additional inclusions. When we knew of additional studies that did not emerge from the review protocol, we included them.

Results

In addition to the following results, we identified 40 papers that explored amphibian use of created water resources (e.g., sewage and stormwater storage ponds). Although not involving a purposeful manipulation of water resources, this information is relevant to the review and is included in Supporting Information.

Water Manipulation to Benefit Amphibians

Hydroperiod has a strong influence on amphibian ecology. Fully aquatic species require permanent aquatic habitats, and 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 large species that typically require more time to complete their larval development than small species (Patterson & McLachlan 1989). Short hydroperiods can stimulate short larval periods (Parris 2000) in which small metamorphs emerge (Johansson et al. 2010; Bekhet et al. 2014; Charbonnier & Vonesh 2015); such hydroperiods are 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, in which all larvae dry in situ.

Permanent pools can have a higher risk of predation, can be more likely to support fish and crustacean predators (Nystrom et al. 2002), and can have higher densities of invertebrate predators (Lowe et al. 2015) than vernal pools. Fish-free vernal pools with long 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) than short-hydroperiod pools that contain fish.

Increasing Hydroperiod through Pumping

In several instances, manipulating water resources to increase hydroperiod in vernal pools has successfully supported amphibian populations (Smith et al. 2019). Increasing hydroperiod can improve population viability by increasing 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, among other actions, are used to maintain water level in breeding pools used by the Chiricahua leopard frog (*Lithobates chiricahuensis*) (McCaffery & Phillips 2012, 2015). This work has increased populations and range size, but the role of pumping cannot be disentangled from the other interventions. Similarly, water pumped into a vernal breeding pool to prevent desiccation prior to metamorphosis resulted in successful recruitment of the critically endangered dusky gopher frog (*Rana sevos*a), which was at risk of extirpation following repeated recruitment failure (Seigel et al. 2006). In 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).

Beaver (genus *Castor*) 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, 3 species of amphibian bred in beaver dams, but not in nearby free-flowing streams (Stevens et al. 2007). In drier regions, such as the Adirondack Mountains (U.S.A.), beaver dams create a mosaic of heterogeneous hydroperiods, including both ephemeral and permanent aquatic habitats, and produce 23–69 times more metamorphs than comparable vernal breeding sites (Karraker & Gibbs 2009).

Dam Releases 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 are released from dams to manage reservoir depth, transfer water between storage areas, and deliver irrigation flows, but might not be timed to emulate natural flow patterns and can negatively affect amphibians (Kupferberg et al. 2012). Operational 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 can scour eggs and larvae from the reach (Kupferberg 1996). Hypolimnetic flows, where deep, cold water is released, 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 than channel flows. Inundation events tend to enrich local species diversity (Real et al. 1993) and increase aquatic connectivity. One model suggests 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*),(Doubledee et al. 2003), but we found no evidence of its implementation.

Spraying Water

Without specific adaptations to minimize cutaneous water loss, most amphibians suffer rapid desiccation in dry conditions. Amphibians display behavioral adaptation to minimize water loss during dry periods (O'Connor & Tracy 1992), and in some instances foraging and courtship behavior can cease (Feder 1983). In these instances, spraying water can increase foraging and reproduction opportunities (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 behavior (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 can 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 colonization 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 meters (Sunny et al. 2014).

Perhaps the best-documented example of spraying for amphibian conservation is the Kihansi spray toad (*Nectophrynoides asperginis*). This microendemic species was 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 2 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 the species is now considered extinct in the wild (IUCN 2019). Failure of the interventions to stabilize the population was likely due to a combination of effects, including a reduction in the intensity and area of sprayed habitat, movement of safari ants (*Dorylus* sp.) into the drier areas (Channing et al. 2006), chytridiomycosis (*Batrachochytrium dendrobatidis*) (Makange et al. 2014), and trophic shifts within the spray zone that reduced arthropod prey availability (Zilihona et al. 1998).

Spraying Repurposed Water

In Pennsylvania (U.S.A.), 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 had thick blankets of duckweed (*Lemna* sp.), poorer water quality, fewer egg masses, and lower hatching success and larval survival than 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.

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 (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 of fire salamanders (*Salamandra salamandra*) (Segev et al. 2009). Similarly, although the Columbia spotted frog laid more eggs in permanent pools, survival to metamorphosis was 3 times higher in semipermanent pools than in permanent pools because fish were absent in the former (McCaffery et al. 2014). Not all amphibian species are affected by fish. For example, in Italy salmonid predators inhibited breeding in 3 species of frog, but not the European toad (*Bufo bufo*), which is less palatable (Manenti & Pennati 2016).

Observational and modeling studies suggest drying is an effective tool for controlling introduced fish, especially when native amphibians are not present (Maret et al. 2006). In Michigan (U.S.A.), natural drying removes predatory fish, reducing predation and increasing amphibian species richness (Werner et al. 2007). Likewise, natural drying in streamside pools in Kentucky (U.S.A.) removes green sunfish (*Lepomis cyanellus*), resulting in higher rates of streamside salamander (*Ambystoma barbouri*) oviposition (136.6 eggs/m^2 compared with 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 the 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 green and golden bell frog larvae (O'Meara & Darcovich 2008).

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

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 (Smith et al. 2019). Population models provide support for pool drying as an effective technique to control populations of American bullfrog (Maret et al. 2006) and to reduce the ability of invasive cane toads (*Rhinella marina*) to cross inhospitable habitat patches in arid regions 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 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 in which selected pools 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 reinvasion pathways are present (Louette 2012). Lobos and Jaksic (2005) hypothesized that pond drying stimulated 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 (Table 1). It is unlikely that the modest number of studies identified accurately reflects the extent or range of interventions deployed.

Our 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 is not relevant, one might expect a somewhat scattered distribution of relevant studies across the globe. Instead, the studies were almost exclusively in countries where English is an official language. Furthermore, these results likely reflect a publication bias on several fronts: flow manipulation could be implicit but not presented as the main aim of the study or within the publication title or abstract; interventions are probably deployed by organizations that do not prioritize publication in the peer-reviewed literature; budget and logistical constraints could preclude sufficient replication or monitoring to infer a strong relationship resulting in low publication rates; and there could be a reluctance

Table 1. Examples of hydrological manipulation to benefit amphibians that ranged from small manipulated experiments to large, ecosystem-level rehabilitation.

Reference	*Location*	*Target fauna*	*Intervention*	*Outcome*	*Concurrent interventions*
Beebee 1997	chalk downs, England	5 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 stabilized initially but then dwindled and 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 decreased 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	some species increased, others decreased	observational amphibian study
Laposata & Dunson 2000	Centre County, Pennsylvania, U.S.A.	sewage treatment	secondarily treated, chlorinated wastewater effluent sprayed across 150 ha	three species bred in irrigated ponds, but breeding responses were higher in natural pools	observational amphibian study
McCaffery & Phillips 2012, 2015	Ladder Ranch, New Mexico, U.S.A.	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. 2016	Apalachicola National Forest, Florida, U.S.A.	striped newt (*Notophthalmus perstriatus*)	installation of EPDM pond liners	hydroperiod extended by up to 6 weeks; improved frog breeding; newt response unclear	ex situ breeding and reintroduction

Continued

Table 1. Continued.

Reference	*Location*	*Target fauna*	*Intervention*	*Outcome*	*Concurrent interventions*
Mitchell 2001	Watts Gully Reserve, South Australia, Australia	Bibron's toadlet (*Pseudophryne bibroni*)	sprinklers installed to manipulate water potential at breeding sites	calling males attracted to wetted areas; 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 observed only in ponds that 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 in natural sites but emerged larger in 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 7 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 were 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 3 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

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 labeling and division of gray literature to help distinguish innovative approaches and notable outcomes from more routine monitoring reports.

Given the few published studies, attempt to assess the strength of different approaches objectively through meta-analysis is not possible. This is further complicated because 7 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 summarize 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 (Rannap et al. 2009; Tournier et al. 2017), excavating to increase pool depth (Cooke 1997; Rannap et al. 2009), lining ponds with an impervious liner (O'Meara & Darcovich 2008; Green et al. 2013; Means et al. 2016), 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 postmetamorphic frogs in only one of the 4 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., Rannap et al. 2009; Darcovich & O'Meara 2008). Thus, we recommend site alteration to increase hydroperiod as a management strategy, although factors such as 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; both range and abundance expanded (Darcovich & O'Meara 2008; McCaffery et al. 2014) and recruitment success increased (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 program with conservation targets specific to amphibians, but we identified potential aspects of flow delivery (for operational or environmental purposes) that might 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 modeled examination of this question (Doubledee et al. 2003).

Spraying water into the landscape can reduce evaporative water loss in amphibians. There is some evidence spraying increases breeding success for terrestrial nest breeders, and it could increase opportunities for foraging and reduce landscape resistance. However, increasing soil moisture could also increase the likelihood of disease transmission (Beyer et al. 2015) and enhance dispersal of non-native amphibians (Cohen & Alford 1996; Child et al. 2009). There is little empirical evidence to support spraying to reconstruct habitats. Poor water quality can influence outcomes for amphibians, and there was little evidence of 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.

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 5-fold increase in crested newt recruitment in the season following intervention, recruitment was lower during the final 3 years of monitoring than before the intervention. 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 spreads the risk relative 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 problem we found was the lack of sufficient empirical evidence to evaluate the success of these approaches confidently. Nonetheless, 2 approaches warrant recommendation. First, the extension of hydroperiod in vernal pools is the most supported approach and has been implemented successfully to achieve amphibian conservation targets. Second, 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 be sufficiently funded to include the monitoring and assessment of the intervention and that the results be reported in a discoverable manner regardless of format or perceived success of the intervention.

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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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