




Which Natural Wetland Characteristics Could be Used in Creating Temporary Wetlands?

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Abstract

Temporary wetlands have mostly been disregarded in freshwater habitat regulation (with noticeable exceptions such as turloughs) leading to their global degradation despite their high value in terms of diverse ecosystem services. Wetland creation may be used to mitigate this habitat loss. In this review, we compiled information on the ecological features of temporary wetlands based on 45 scientific publications. We identified seven types of natural temporary wetlands to be emulated in wetland construction and their restoration in the Northern Hemisphere, with hydroperiod lengths ranging from less than one month in ephemeral ponds to multi-year floods. We highlight the biodiversity associated with various hydroperiods, and show that different organisms use different temporary wetland types. We give examples of how temporary wetland creation has been used for biodiversity enhancement and list characteristics of created temporary wetlands. Colonization of the newly created temporary wetlands by aquatic macroinvertebrates and amphibians was rapid, but species compositions differed from reference sites. Finally, we provide management recommendations for creating temporary wetlands to support high biodiversity. We highlight the importance of hydroperiod management, creating banks with gradual slopes, enhancing macrophyte vegetation and fish absence to promote biodiversity in created temporary wetlands. Monitoring and ongoing management practices are discussed as tools for ensuring management targets in the long term. For example, performing partial or full drawdowns at temporary wetlands with long multi-year hydroperiods are discussed. On the landscape level, we recommend planning a network of well-connected heterogeneous wetlands with different hydroperiods to enhance colonization and dispersal, and thereby biodiversity.

Keywords Vernal pool · Wetland Creation · Flooding · Invertebrates · Amphibians · Waterbirds

Introduction

Temporary wetlands are typically depressions in the ground characterized by intermittent inundations (Stewart and Kantrud 1971; Colburn 2004; Calhoun and DeMaynadier 2007). They can be of various kinds based on their hydroperiod, timing, water depth and size (Calhoun et al. 2017).

Present classifications of temporary wetlands are mostly based on their hydroperiod gradient including ephemeral, seasonal, temporary, semi-permanent ponds (Stewart and Kantrud 1971), turloughs (Sheehy Skeffington et al. 2006) and multi-year floods (Kivinen et al. 2020; Nummi et al. 2021a; Romansic et al. 2021). They encompass different habitat types such as rock pools (Minissale and Sciandrello 2016), bog pools (Mazerolle et al. 2006), wet meadows (Stewart and Kantrud 1971) and beaver floods (Kivinen et al. 2020). The inundation might be the result of melting snow and rain in spring as in the case of vernal pools (Keeley and Zedler 1998; Schrank et al. 2015), groundwater raising in the case of turloughs (Sheehy Skeffington et al. 2006) or floods as the result of beaver floods, for example. While some temporary wetlands (e.g. vernal pools and turloughs) typically follow a seasonal cycle, others such as boreal beaver ponds may have a flood cycle lasting 3–10 years (Kivinen et al. 2020). Temporary wetlands might not be

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connected to other waterbodies, while beaver floods are usually connected to a stream or pond and will eventually host fishes (Snodgrass and Meffe 1998; Johnston 2017). Flooded areas are usually productive, as floods bring organic matter and nutrients into the water (Kortelainen et al. 1997; De-Campos et al. 2012; Nummi et al. 2018). Carbon cycling is affected by water level movements; the decomposition rate is usually slower with wetter and longer flooding, and net ecosystem productivity (carbon dioxide (CO₂) exchange) is lower (Larmola et al. 2004). Small wetlands can create high β -diversity (Scheffer et al. 2006; Altermatt and Eber 2010; Nummi et al. 2021a): they can be seen as patches that differ in hydroperiod length, water depth, bottom substrates, and surrounding landscape. Thus, each of the patches can have its specific community of organisms (Williams et al. 2004; Williams 2005).

For instance, due to drying, temporary wetlands usually create an environment with reduced fish predation risk, thus providing a safe place for the reproduction of many organisms such as amphibians and invertebrates (Scheffer et al. 2006; Colburn et al. 2008; Evans et al. 2017). However, sometimes small fishes such as sticklebacks (*Gasterosteus aculeatus*, *Pungitius pungitius*) can be present in e.g. turloughs (Williams et al. 2006). The natterjack toad (*Bufo calamita*), for example, specifically needs temporary ponds for breeding (Sanuy et al. 2008). Temporary wetlands such as vernal pools are highly used as foraging habitats by breeding ducks (e.g. *Anas* sp.) (Kantrud and Stewart 1977), and certain waders, e.g. the green sandpiper (*Tringa ochropus*), use flooded areas for brood rearing (Nummi et al. 2021a). Turloughs are important sites for overwintering bird populations (Sheehy Skeffington et al. 2006). Hence, many species use temporary wetlands during some phase of their life cycle and then move elsewhere or enter a dormant state when these wetlands dry out (Colburn et al. 2004).

Of temporary wetlands with longer flooding duration, beaver flowages can be particularly beneficial to species that require waters with longer hydroperiod to complete their development, e.g. Odonata or some amphibians (Hartun 1999; Karraker and Gibbs 2009; Romansic et al. 2021).

In addition to common water quality problems faced by permanent wetlands, such as eutrophication and brownification (Broyer 2009; Dudgeon 2010; Blanchet et al. 2022), temporary wetlands are also in danger of disappearing completely due to climate change and drainage (Curado et al. 2011; Ruhí et al. 2012b; Remm et al. 2015; Death et al. 2016; Evans et al. 2017; Montgomery et al. 2018; James et al. 2019; Mitchell et al. 2022). Their small size and/or temporality render them easily overlooked (Semlitsch and Bodie 1998; Martin et al. 2012; Calhoun 2014, 2017). Until recently, they have hence been globally disregarded in nature conservation regulations (with some exceptions e.g.

turloughs, mediterranean temporary ponds and active raised bogs) (Water Framework Directive (WFD) 2000; The Interpretation manual of European union habitats EUR 28 (EC) 2013; Ramsar Convention on Wetlands 2018). They are also often part of managed (forest and agriculture) lands, where they have been left unnoticed when making management decisions (Evans et al. 2017).

Creating and restoring wetlands is an effective tool for mitigating wetland loss and wetland degradation (Kingsford et al. 2016). Created and restored wetlands can provide habitats for various biota. However, achieving this requires knowing the habitat requirements of the targeted species group(s) and implementing them in wetland construction (Wiegleb et al. 2017; Magnus and Rannap 2019; Rajpar et al. 2022).

Our aims are (i) to review the main characteristics of natural temporary wetlands classified by their hydroperiod that may be emulated for temporary wetland construction and management, (ii) to describe their related biodiversity, (iii) to present case studies of constructed temporary wetlands created to promote biodiversity, and, finally, (iv) to discuss concrete actions to improve the quality of constructed temporary wetlands for the organisms targeted by management actions. This review focuses on the Northern Hemisphere, with special focus on Europe and North America.

Methods

In this review, we will focus on freshwater temporary wetlands experiencing flooding, which may last from a few weeks in small-sized temporary wetlands to a few years in beaver flowages. Temporary wetlands covered by this review are listed in the Table 1. We use the North American classification by Stewart and Kantrud (1971). We extended the classification to include Irish turloughs which are specific by having a hydroperiod from autumn to spring. We also added multi-year floods (e.g. beaver floods) because they are often emulated in temporary wetland construction (Nummi and Holopainen 2020). We did not deal with floodplains because rivers have their own dynamics and management measures. Their creation requires wider scale construction actions. Neither did we focus on man-made temporary wetlands created for other purposes than biodiversity. We focus on the ecological aspect of temporary wetlands. Detailed construction guidelines can be found in technical guides which have been adapted to the local environment (e.g. Alhainen et al. 2015; Kozáková and Rozínek 2021; Sayer et al. 2023). The term “temporary wetlands” is in this study used as a general term encompassing all types of non-permanent wetlands listed in Table 1. When specific typology exists to characterize a temporary wetland, e.g.

Table 1 Types of natural temporary wetlands to be emulated in wetland construction and their restoration with examples of associated flora and fauna. The reference column includes information regarding the study biomes: BF: boreal forest, TF: temperate forest, TG: temperate grassland, MVC: Mediterranean vegetation, chaparral, MZ: multi-zonal

Wetland type	Hydroperiod	Range of max depth (cm)	Surface area (ha)	Flora	Fauna		References
					Invertebrates	Vertebrates	
Ephemeral pond (I)	< 1 month	20–80	< 0.01–1	Low grassland vegetation (e.g. <i>Poa pratensis</i> , <i>Solidago altissima</i>)	Culicidae, Anostraca, Dytiscidae	Ducks	BF: Nilsson and Svensson 1994; TG: Stewart and Kantrud 1971; Kantrud and Stewart 1977; Gleason and Rooney 2018; Montgomery et al. 2018; MVC: Serrano and Fahd 2005
Temporary pond (II)	1–2 months	20–100	< 0.01–1	Wet-meadow vegetation (e.g. <i>Poa palustris</i> , <i>Boltonia latiquana</i> , <i>Hordeum jubatum</i> , <i>Calamagrostis inexpansa</i>)	Anostraca, Culicidae, Notostraca, Chironomidae, Dytiscidae	Waders, frogs	BF: Nilsson and Svensson 1995; TG: Stewart and Kantrud 1971; Mauser et al. 1994; Gleason and Rooney 2018; Montgomery et al. 2018; MVC: Serrano and Fahd 2005; MZ: Dodd 2010
Seasonal pond (III)	3–4 months	48–144	0.02–4	Shallow-marsh vegetation (e.g. <i>Carex ath-erodes</i> , <i>Glyceria grandis</i> , <i>Scolochloa festucacea</i> , <i>Eleocharis palustris</i> , <i>Alisma gramineum</i> , <i>Beckmannia syzigachne</i>)	Crustacea, Rotifera, Nematoda, Chironomidae, Dytiscidae	Waders, ducks, frogs, newts	BF: Nilsson and Svensson 1995; TG: Stewart and Kantrud 1971; Kantrud and Stewart 1977; Talent et al. 1982; Gleason and Rooney 2018; Montgomery et al. 2018; MVC: Serrano and Fahd 2005; MZ: Dodd 2010
Semi-permanent pond (IV)	> 5 months	70–285	3–30	Deep-marsh vegetation (<i>Scirpus heterochateum</i> , <i>Typha</i> spp., <i>Scirpus acutus</i> , <i>Scirpus paludosus</i>)	Crustacea (e.g. <i>Daphnia magna</i>), Rotifera, Tipulidae, Nematoda	Ducks, newts	TG: Stewart and Kantrud 1971; Gleason and Rooney 2018; Montgomery et al. 2018; MVC: Serrano and Fahd 2005; MZ: Dodd 2010
Turlough “seasonal ground-water-dependent winter lake”	Usually 3–6 months (but can be < 3 months and > 6 months)	50–600	2–267	Small sedge vegetation (e.g. <i>Carex panicea</i> , <i>C. nigra</i> , <i>C. flacca</i>), grass/forb vegetation (<i>Plantago major</i> , <i>Ranunculus repens</i> , <i>Trifolium repens</i> , <i>Lolium perenne</i>)	Gastropoda, Cladocera, Copepoda, Ostracoda, Crustacea (<i>Asellus</i> , <i>Gammarus</i>), Ephemeroptera, Dytiscidae	Waders, ducks, swans, newts, frogs	TF: Regan et al. 2007; Sheehy Skeffington et al. 2006
Multi-year flood, early succession (e.g. new beaver flood)	1–2 years	100–250	1–15	<i>Alnus</i> sp., <i>Salix</i> sp., <i>Sphagnum</i> sp., duckweed (<i>Lemna</i> spp., <i>Spirodela</i> spp.)	Cladocera, Crustacea (<i>Asellus</i>), Dytiscidae, Amphipoda,	Waders, ducks, frogs	BF: Nummi 1989; Nummi and Hahtola 2008; Hood and Larson 2014; Nummi et al. 2021a; Romansic et al. 2021; TF: Dalbeck et al. 2007
Multi-year flood, late succession (e.g. old beaver flood)	> 2 years	25–200	1–20	Pondweeds (<i>Potamogeton</i> spp.), hornwort (<i>Ceratophyllum demersum</i>), water lily (<i>Nymphaea</i> spp., yellow water lily (<i>Nymphaea lutea</i>), old wood, wood-rotting fungi	Chironomidae, Gastropoda	Bats, fishes	BF: Schlosser and Kallemeyn 2000; Nummi et al. 2011; MZ: Rosell et al. 2005; Larsen et al. 2021

vernal pool or seasonal pond (see Table 1), then this specific term is used accordingly.

We collected international literature using Web of Science. Our search (see supplementary material S.1) resulted in 361 hits, 45 of which were relevant to our study. In the collected literature, we perused the reference lists, which navigated us to other relevant resources. We also paid

attention to “gray literature.” We used Google Scholar to search for methodological handbooks for nature management. Many conservation and management practices are only published in handbooks, such as descriptions of appropriate frog pool structure (e.g. Kozáková and Rozínek 2021) and how to perform drawdowns (e.g. Fredrickson and Reid 1988; Fredrickson 1991).

Natural Temporary Wetland Types

The terminology of temporary wetlands varies between areas. In Table 1, we present the classification of temporary wetlands used in this article. We use the classification by Stewart and Kantrud (1971) for prairie temporary wetlands and potholes (wetland type I–IV in Table 1). In Europe, the temporary wetland biota has not been classified along the hydroperiod gradient as opposed to North America, thus we mainly present examples from the latter. The term “vernal pool” is not used in Stewart and Kantrud’s (1971) classification. Vernal pools would most likely encompass the first three categories in Table 1 according to their hydroperiod length. In addition to the four categories defined by Stewart and Kantrud (1971), we also include turloughs that are specific by having wet phase mostly during winter and multi-year floods for their important role in terms of biodiversity.

Creation and Restoration of Temporary Wetlands

On the landscape scale, restoration and wetland creation may work together. Under the label of “restoration”, management practices can involve both creating new wetlands in novel places and restoring existing ones (see Coccia et al. 2016). Here, restoration is defined as returning the habitat that formerly existed to its original state (Callaway 2004), while creation is establishing the habitat where it did not exist previously. Constructed and restored wetlands may have different targets and functions depending e.g. on how natural the end results should be. Timetables may also differ; a constructed wetland for waterbirds may hit its target of high bird diversity within a few years (Kačergytė et al. 2021; Čehovská et al. 2022). For some restored wetlands (e.g. peatlands), a much longer time may be required for reaching the target and attaining natural biodiversity (Alsila et al. 2021). We must also be mindful that certain biotopes are very difficult to emulate, such as bog pools with long-term peat accumulation (see Neustupa et al. 2023).

Creating wetlands without prior consideration regarding the ecological requirements of the targeted organisms may lead to unsuccessful management actions (Wheeler et al. 2002; Piczak et al. 2023). A detailed beforehand study of the entire area, including the historical and current state of vernal pools, is necessary when planning mitigation projects (Calhoun et al. 2017). One challenging task is the ability to create/recreate the hydrology of temporary wetlands. For example, 20% of the restored wetlands in the Prairie Pothole Region failed hydrologically; sometimes there were structural problems, sometimes the ephemeral and temporary ponds did not fill with water for unknown

reasons. (Galatowitsch and van der Valk 1996). Predicting how the created vernal pools succeed locally may also be challenging because the environmental conditions affecting their hydrology vary between areas (Calhoun et al. 2014). An additional aspect to consider in temporary wetland creation/restoration is environmental pollution, e.g. pesticides, which affect water quality in agricultural lands (Hildebrandt et al. 2008).

For wetlands to effectively improve biodiversity, it is advantageous if they are designed for this purpose (Mulkeen et al. 2017, 2024). Even many wetlands constructed for biodiversity fail if they lack important features such as gradual slopes and the absence of fish predators (e.g. Drayer and Richter 2016). Studies show that wetlands constructed for other purposes than biodiversity can contribute to mitigation of the current wetland loss. But without following the wetland design recommendations for the targeted species, they will host only a part of local populations, and will not match natural wetlands in the long term (Mulkeen et al. 2017, 2024; Rooney et al. 2015; Semeraro et al. 2015; Li et al. 2021). Interestingly, there is a lack of studies evaluating how effectively wetlands constructed for biodiversity can perform other functions such as water retention and/or purification. In Table 2, we present examples of temporary wetlands that were constructed and restored to promote biodiversity and to mitigate habitat loss. The table shows that creating and restoring temporary wetlands can enhance biodiversity, although some species may colonize new sites more rapidly than others and the species composition between natural and created temporary wetlands may differ (see Table 2). Despite the hydroperiod being a crucial factor affecting species communities, several studies on constructed temporary wetlands in Table 2 did not report it; whereas water depth, also an important factor is more commonly reported.

Management Implications

Based on the existing literature, we summarize attributes that make constructed temporary wetlands favorable for biodiversity enhancement.

Flooding and the Detritivore-Based Food Chain

Flooding is an effective tool to promote biodiversity, whether done by man or beaver (Čehovská et al. 2022; Nummi and Holopainen 2020). During flooding, a high invertebrate biomass is rapidly created in both man-made (Danell and Sjöberg 1982; Ruhí et al. 2009; Coccia et al. 2016) and beaver-created wetlands (Nummi and Hahtola 2008); this consequently attracts invertivores that feed on the invertebrates

Table 2 Examples of created, restored, and managed flooded temporary wetland characteristics promoting different species group. Column “Locality” includes information of the study biomes: BF: boreal forest, TG: temperate grassland, MVC: Mediterranean vegetation, chaparral

Species group	Findings	Wetland characteristics	Locality	Reference
Macroinvertebrates	<ul style="list-style-type: none"> Newly created temporary ponds had the same level of diversity and species richness as reference sites had. Invertebrate biomass higher in newly created ponds. Community composition between newly created ponds and reference sites diverged. 	<ul style="list-style-type: none"> 32 temporary ponds were constructed during a restoration project. Three sizes (length 60, 125, and 250 m). Two excavation depths (30 and 60 cm). 6-month hydroperiod. 	<ul style="list-style-type: none"> Doñana, Spain Biom: MVC 	Coccia et al. (2016)
Macroinvertebrates	<ul style="list-style-type: none"> Colonization of newly created ponds by macroinvertebrates was rapid. No change in macroinvertebrate assemblage during the first year, indicating that succession requires more time. Macroinvertebrate biomass increased with time. 	<ul style="list-style-type: none"> 9 created ponds in 3 areas to mitigate habitat loss. Depth < 2 m. Different hydroperiod lengths (< 12 months and 6–9 months). 	<ul style="list-style-type: none"> Northeastern Iberian Peninsula, Spain Biom: MVC 	Ruhí et al. (2009)
Amphibians	<ul style="list-style-type: none"> In the first year, man-made ponds became habitats for regional amphibians. Species such as the natterjack toad (<i>Bufo calamita</i>) can profit from creating temporary ponds. 	<ul style="list-style-type: none"> 2 temporary man-made wetlands. Size < 0.5 ha. Depth < 1 m. 	<ul style="list-style-type: none"> Northeastern Iberian Peninsula: Baix Ter and Plana de la Selva, Spain Biom: MVC 	Ruhí et al. (2012b)
Arthropods, amphibians	<ul style="list-style-type: none"> Amphibians of various development stages occurred more in man-made pools than in natural bog pools, probably because of higher water pH. Species composition of amphibians differed between man-made and natural wetlands. Arthropods (water beetles) were less abundant (2–26 times less) in man-made pools than in natural bog pools. The colonization of many arthropods was rapid. 	<ul style="list-style-type: none"> Man-made bog pools created during a restoration project. Max. depth 1.2 m. 	<ul style="list-style-type: none"> Eastern New Brunswick, eastern Québec, Canada Biom: BF 	Maze-rolle et al. (2006)
Macroinvertebrates, ducks	<ul style="list-style-type: none"> Chironomids and <i>Asellus</i> abundant in the littoral. <i>Pisidium</i> and Chironomids abundant in the creek bed. <i>Eurycercus</i> the most abundant in the nekton during the first year of flooding. Creek use by ducks (teal, mallard, goldeneye) increased in the flooded part. 	<ul style="list-style-type: none"> Wetland created by damming creek, e.g. simulating beaver effect. Mean depth 55 cm. 	<ul style="list-style-type: none"> Evo, southern Finland Biom: BF 	Nummi (1989)
Aquatic vegetation	<ul style="list-style-type: none"> Only a few restored temporary wetlands developed a sedge meadow zone typical for the area. Most of the wetlands had emergent vegetation and submerged aquatic vegetation. 	<ul style="list-style-type: none"> 62 restored ephemeral/temporary ponds. Morphological parameters of the restored wetlands copied those of natural ones. 	<ul style="list-style-type: none"> Southern Prairie Pothole Region, Iowa, southwestern Minnesota and northeastern South Dakota Biom: TG 	Gala-towitsch and van der Valk (1996)

(e.g. breeding ducks; Väänänen et al. 2012; Nummi et al. 2013; Holopainen et al. 2014, 2024), waders (Nummi et al. 2022), and bats (Park and Cristinacce 2006; Nummi et al. 2011; Stahlschmidt et al. 2012). Organic matter from decomposing flooded plants leads to high productivity with high aquatic invertebrate biomass, such as Branchiopods, *Daphnia*, Chironomids, and Dytiscidae (Fredrickson and Reid 1988; Nummi 1989; Coccia et al. 2016; Nummi et al. 2021b). Invertebrate biomass and diversity can decrease with time as detritus levels decline (Murkin 1989) and predators colonize the area (Schneider and Frost 1996; Williams 1997; Wellborn et al. 1996; Lahr et al. 1999). However, this decrease can be counterbalanced with the development of

more diverse macrophyte vegetation which may increase the invertebrate diversity by providing structural heterogeneity (Downing 1991; Bazzanti et al. 2008).

In temporary wetlands, conditions with abundant resources for the detritivore-based food chain are restored with the new wet phase when vegetation that grew during the dry phase is flooded (Merendino et al. 1991). In addition, the drought phase generates fishless conditions that result in an increase of invertebrate abundance during reflooding (Dorn 2008). Having temporary wetlands in a landscape increases the landscape-level heterogeneity of wetlands. Hence, aquatic invertebrate communities differ in wetlands with different hydroperiods (Leeper and Taylor 1998; Tarr

et al. 2005). Wetlands with various hydroperiods in a landscape (see Fig. 1) are also important for the life cycle of many organisms that have aquatic and terrestrial phases such as amphibians, e.g. most salamanders and the wood frog (*Rana sylvatica*) breed in seasonal ponds and winter on land (Semlitsch and Skelly 2008).

Managing an area by flooding is an effective way to provide suitable habitats for waterbirds. These temporary floods, usually on agricultural lands, can be used along flyways as stopover sites (Golet et al. 2018) and for overwintering (Davis et al. 2014) and breeding (Czech and Parsons 2002). Agricultural floods, made to enhance crops, such as rice, are known to be used for nesting by many waterbirds, e.g. ducks and shorebirds (Czech and Parsons 2002; Pierluissi 2010). This has led to the idea of extending flooding duration in places where flooding is a part of the crop management or to intentionally create these floods as compensation habitat for waterbirds (Golet et al. 2018). Incentives, such as subsidies, are well-established methods for achieving management actions, e.g. in England, where landowners are granted subsidies to raise or maintain water levels for breeding wading birds (Ausden and Hirons 2002). Also, landowners and stakeholders in Sweden, Finland, and North America who create and maintain a wetland on their land are granted subsidies to cover their expenses (George 2002; Hansson et al. 2012; Nummi and Holopainen 2020). As migratory species are highly threatened by habitat loss (Runge et al. 2014), conservation practices should identify

suitable areas and the timing of flooding based on waterbird flyway data (Reynolds et al. 2017).

Absence of Fish: A Key Feature for Temporary Wetland Biodiversity

Temporary wetlands can be good habitats for many species, as they are usually fishless because fish die naturally during the dry period (Calhoun and DeMaynadier 2007). Fishes can reduce amphibian populations by competition for food resources and/or predation (Semlitsch 1988; Knapp 2005; Orizaola and Brana 2006; Boone et al. 2007; Hartel et al. 2007). Fish introductions are one of the main factors responsible for the worldwide decrease of amphibians (Kats and Ferrer 2003). Furthermore, fish compete with breeding ducks for aquatic invertebrates (Hill et al. 1987; Musil et al. 1997; Nummi et al. 2016). Specifically, ducklings mainly feed on aquatic invertebrates during their first weeks (Chura 1961; Reinecke 1979; Nummi 1985; Winfield and Winfield 1994). Competition between ducks and fish for invertebrates as a source of food can influence the breeding habitat choice of ducks and consequently their breeding densities (Anderson 1981; Nummi et al. 2012).

Vegetation Associated with Temporary Wetlands

Macrophyte vegetation enhances wetland heterogeneity and complexity and is important for invertebrates, amphibians,



Fig. 1 Example of a cluster of wetlands with various water depths fulfilling the habitat requirements of many organisms

and waterbirds (Scheffer et al. 2006; Hansson et al. 2010; Thomaz and Cunha 2010). The effect of macrophyte structures has not been studied specifically in man-made wetlands, but the discovered positive effect of macrophyte vegetation on fauna most likely also applies to temporary wetlands. Macrophyte vegetation provides both shelter against predators and foraging habitats for aquatic invertebrates (Jeppesen et al. 1988; Streever et al. 1995; Bazzanti and Della Bella 2004). Vegetated areas can contain higher invertebrate levels, thus positively affecting waterfowl for which invertebrates are an important source of protein (Krull 1970). Moreover, many waterbirds use macrophyte vegetation for nesting, e.g. ducks, swans (*Cygnus* sp.), coots (*Fulica* sp.), and moorhens (*Gallinula* sp.), and it is also part of the diets of Eurasian wigeons (*Mareca penelope*), gadwalls (*Mareca strepera*), geese (*Anser* sp.), and swans (Batt 1992; Keller et al. 2020). For example, duckling plant food consists of pondweed (*Potamogeton* sp.), duckweed (*Lemna* sp.), and seeds (e.g. *Carex* spp., *Scirpus* spp.) (Chura 1961; Collias and Collias 1963; Sugden 1973).

There are two approaches to introduce macrophyte vegetation to a created wetland site: leaving the introduction to natural succession processes, such as dispersion and the seed bank (Meeks 1969; Danell and Sjöberg 1982), or by facilitating the process by initially planting macrophytes that occur in the area (Chovanec 1994; Solimi et al. 2003; Ruhí et al. 2012a). In restoration projects of temporary wetlands aiming to recover wetland vegetation, sediment transfer with a seed bank can be more effective than natural colonization (Nishihiro et al. 2006; Muller et al. 2013; Rodrigo 2021). In the Prairie Pothole Region, most restored temporary ponds were colonized by submerged and emergent aquatic plants, but a sedge meadow zone typical for the area was not established (Galatowitsch and van der Valk 1996).

Breeding ducks can benefit from minimizing the presence of trees and shrubs in wetland surroundings (Kačergytė et al. 2021). Regarding amphibians, some species, such as the spring peeper (*Pseudacris crucifer*) and dusky gopher frog (*Rana sevosia*), specifically require open tree canopy wetlands. A few species can occur in both closed and open canopy cover habitats, e.g. the wood frog and the southern leopard frog (*Rana sphenoccephala*) (Skelly et al. 2002; Thurgate and Pechmann 2007).

Morphologic Parameters

Substrate provides important feeding opportunities and shelter for aquatic invertebrates (de Necker et al. 2023). Little is known about the effect of substrate on invertebrates in constructed temporary wetlands. One study from New Zealand, conducted in constructed temporary wetlands, found

that invertebrate species compositions differed among wetlands with various substrates, thus raising the need for further studies (Sanders 2000). In general, the increasing size of substratum particles also increased the number of macroinvertebrate species in natural wetlands in the boreal zone (Heino 2000).

When creating wetlands for amphibians, pool sizes of less than 300 m² are usually recommended in management handbooks (Kozáková and Rozínek 2021). Designed pools should have gradual shore slopes and enough shallow flats for amphibian breeding and larval development (Porej and Hetherington 2005; Drayer and Richter 2016; Kozáková and Rozínek 2021). Bank slopes should be less than 15:1 (Porej and Hetherington 2005). For amphibians, the water depth should be less than 20 cm (Drayer and Richter 2016), but there should be deeper part because usually the water column decreases over summer (Colburn 2004). At least one pond for wintering, with a water depth of more than 1 m, should be present in the area (Kozáková and Rozínek 2021).

Temporary wetlands can be good foraging habitats for breeding waterbirds, as shown for beaver ponds (Nummi and Hahtola 2008), when they meet species foraging habitat requirements. For dabbling ducks, such as mallards (*Anas platyrhynchos*), the optimal water depth for feeding is less than 50 cm (Behney 2014). Also, Pöysä (1983) states that dabbling ducks and coots mainly use shallow habitat edges, with depths from 20 cm to 40 cm, for foraging, while diving ducks (e.g. *Aythya* sp.) and grebes (e.g. *Podiceps* sp.) prefer central parts of the habitat with open and deep water, with depths around 70 cm. Thus, varying the depth is important because it attracts different species groups (Sebastián-González and Green 2014). Moreover, deeper wetlands can create suitable conditions for Amphipods and if they have multi-year hydroperiod, also for water lilies (*Nymphaea* sp., *Nuphar* sp.). Water lilies provide habitats for many aquatic invertebrates, so ducklings find good foraging patches with shelter (Fast et al. 2004). However, these features have not been specifically studied for constructed temporary wetlands.

Constructed wetlands for improving waterbird breeding success should ideally include islands, as these can attract ground-nesting birds such as ducks and geese (Lokemoen 1993). The nest survival of ground-breeding ducks is often higher on islands than inlands because there are less or no mammalian predators (Hill 1984; Holopainen et al. 2015).

Landscape Connectivity

Many studies have shown that connectivity between wetlands is important. Connectivity reduces mortality during movements and enhances the colonization of many

animal groups such as invertebrates (Cottenie 2005; Van De Meutter et al. 2007), amphibians (Hecnar and M'Closkey 1996; Rothermel and Semlitsch 2002), and ducks (Pöysä and Paasivaara 2006). The ecological network of wetlands should be optimized to enhance migration and dispersion, which can be achieved by creating/restoring corridors and stepping-stone sites (Ma et al. 2022). Landscape connectivity often has a major effect on the viability of amphibian populations (Cushman 2006), and wet breeding sites for amphibians should therefore be connected to good terrestrial frog habitats (Rothermel 2004). Connecting habitat should have protective vegetation cover and should not have barriers such as wide roads (Cushman 2006). Moreover, the combination of temporary and permanent waterbodies at the landscape level may be essential for fulfilling the ecological requirements of various species, e.g. green frogs (*Lithobates clamitans*), bullfrogs (*Lithobates catesbeianus*), and leopard frogs (*Lithobates blairi/sphenocephalus* complex) require aquatic environment for wintering, and thus the area should also include permanent ponds (Shulze et al. 2012).

Breeding ducks, again, use the environment based on both landscape complementation and landscape supplementation. In landscape complementation, patches provide different resources needed for successful nesting and brood rearing, whereas in landscape supplementation broods move to the next patch with similar resources if the current one is depleted (see Dunning et al. 1992; Nummi and Pöysä 1998; Paasivaara and Pöysä 2008; Sundell et al. 2023). Corridors, such as riparian areas and forestry ditches, leading for example from a nesting pond to a brood-rearing temporary wetland, are considered important features for the safe movements of ducklings (Hepp and Hair 1977; Pöysä and Paasivaara 2006; Dyson et al. 2018).

Additional Structural Elements

The biodiversity of constructed temporary wetlands can be supported by creating small elements that facilitate breeding and wintering and provide shelter etc. for the animal groups or species of interest. Aquatic invertebrates can profit from dead wood placed in the water. It serves as a shelter, and the invertebrates can also feed on biofilms growing on the dead wood surface (Hax and Golladay 1993). Concerning amphibians, artificial hibernacula enhance amphibian overwintering (Latham and Knowles 2008). Nesting boxes or tubes enhance duck nesting at sites where suitable nesting opportunities are limited (Dennis and Dow 1984; Pöysä and Pöysä 2002). Vertical sandy banks can be created to support the nesting of colonial sand martins (*Riparia riparia*), or building artificial concrete block walls with pipes is also possible (Hopkins and Officer 2001). Nevertheless, the design and use of these structures must be carefully

considered because artificial materials, e.g. plastics and concrete components, are pollutants for the environment and can negatively affect bird health (Townsend and Barker 2014; Wang et al. 2021). Additionally, artificial structures can be ecological traps, as they can attract more predators to the site, facilitate access to invasive species, or encourage birds to nest in habitats with poor food resources, for example (Watchorn et al. 2022).

Monitoring and Management

Monitoring constructed temporary wetlands allows evaluating their success and, when necessary, taking steps to improve their effectiveness (Ausden and Hirons 2002). Vernal pool monitoring should last at least five years after creation to evaluate their success in the longer run (Calhoun et al. 2014).

Ongoing monitoring of wetland conditions also helps to identify when site management is needed. Continuous management is often necessary to maintain the long-term functionality of constructed wetlands. When wetlands are eutrophic, they tend to overgrow with vegetation and accumulate sediment, which can gradually decrease their size; thus, these wetlands can be restored by cutting overgrown vegetation and removing sediment (Burrow and Lance 2022). For example, excavator work is needed every five years in Central Europe (Kozáková and Rozínek 2021). If fish appear, they should be caught or — if possible — the wetland should be drawn down and emptied (Aitto-Oja et al. 2010). Small-sized temporary wetlands dry out naturally (Keeley and Zedler 1998), but temporary wetlands with long multi-year hydroperiods may need artificial drawdown. Hydroperiod and water level management in these wetlands can help to restore habitat quality for invertebrates by adding organic matter into the water (Fredrickson 1991; Kelley et al. 1993). Alternatively, partial drawdown and shore flooding can be performed periodically or when the organic litter is exploited (Fredrickson and Reid 1988; Gathman and Burton 2011). Moreover, the exposed wet substrate provides feeding opportunities for waders (Sanders 2000).

It is possible to apply adaptive management and adjust management actions according to learning through time and environmental responses. However, this involves challenges, so its efficiency has been discussed (Williams 2011). Ideally, collaboration should occur between nature managers and scientists to evaluate the monitoring outcome and to subsequently configure optimal management (Galatowitsch and Bohnen 2021).

Conclusions

Temporary wetland construction, restoration, and management should be clarified before taking any action, as appropriate actions will differ depending on the target organisms. However, our findings show that an array of habitat characteristics are commonly beneficial for invertebrates, amphibians, and ducks. All these species groups profit from habitats that are established by flooding, have luxuriant heterogeneous macrophyte vegetation, and are fishless. It is essential to ensure a sufficient food supply for each animal group: organic matter for invertebrates and invertebrates for amphibians and breeding waterbirds. Constructed temporary wetlands should have gradual shore slopes along with sufficient shallow patches and macrophyte vegetation for invertebrates, amphibians, and waterbirds. Constructed temporary wetlands with long hydroperiod (emulating beaver floods) should preferably incorporate a deeper part for diving ducks. The ideal would be to create at the landscape scale a network of wetlands of different hydroperiods and sizes to provide diverse living spaces for various organisms and their requirements. A permanent wetland in the area is also important for overwintering invertebrates and amphibians. Ideally, the newly created temporary wetlands could be connected to the existing network of wetlands.

A limiting factor for species occurrence in constructed habitats may be that they lack important structures for breeding and structures that provide shelter for organisms. For example, adding dead wood to wetlands is beneficial, as it provides shelter to invertebrates and amphibians, and nesting boxes can be installed for cavity-nesting birds.

Based on our review, we found that studies on constructed temporary wetlands have clear knowledge gaps. In particular, many studies do not provide the hydroperiod length of the studied temporary wetlands despite its importance in understanding species composition. Furthermore, at present, a large fraction of management practices is only mentioned in the “gray literature”. Specifically, very little is scientifically published about the optimal substrate, macrophyte vegetation, and water depth of constructed temporary wetlands. Moreover, there are studies evaluating how wetlands constructed for other purposes than biodiversity can resemble natural wetlands in species composition. But there is a lack of research on how constructed temporary wetlands for biodiversity can perform other functions.

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Declarations

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