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Review

Can Constructed Wetlands be Wildlife Refuges? A Review of Their Potential Biodiversity Conservation Value

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Abstract: The degradation of wetland ecosystems is currently recognized as one of the main threats to global biodiversity. As a means of compensation, constructed wetlands (CWs), which are built to treat agricultural runoff and municipal wastewater, have become important for maintaining biodiversity. Here, we review studies on the relationships between CWs and their associated biodiversity published over the past three decades. In doing so, we provide an overview of how wildlife utilizes CWs, and the effects of biodiversity on pollutant transformation and removal. Beyond their primary aim (to purify various kinds of wastewater), CWs provide sub-optimal habitat for many species and, in turn, their purification function can be strongly influenced by the biodiversity that they support. However, there are some difficulties when using CWs to conserve biodiversity because some key characteristics of these engineered ecosystems vary from natural wetlands, including some fundamental ecological processes. Without proper management intervention, these features of CWs can promote biological invasion, as well as form an 'ecological trap' for native species. Management options, such as basin-wide integrative management and building in more natural wetland components, can partially offset these adverse impacts. Overall, the awareness of managers and the public regarding the potential value of CWs in biodiversity conservation remains superficial. More in-depth research, especially on how to balance different stakeholder values between wastewater managers and conservationists, is now required.

Keywords: biodiversity conservation; natural and constructed wetlands; treatment efficiency; sub-optimal habitat; ecological trap

1. Introduction

Wetlands represent one of the world's most important types of ecosystems [1]. They are suitable habitats for many species and are among those ecosystems with the richest biodiversity [2]. Although freshwater wetlands cover only 6–8% of the Earth's surface, these wetlands are home to 20–40% of the world's flora and fauna species [3–6]. Many of these biotas depend on wetland ecosystems to complete their life cycles [7]. Despite the recognized ecological value and services they provide, natural wetlands have been seriously degraded and have declined during the last few decades, either directly or indirectly as a result of human activities, such as land reclamation, hydrological alterations, and over-exploitation [8]. This has changed global ecological processes and led to significant negative impacts on sustainable development goals, especially biodiversity conservation all over the world [2,9–11].

Constructed wetlands (CWs) are artificial ecosystems that simulate biogeochemical processes occurring in natural wetlands to optimize their water purification function. Due to their characteristics of being low-cost, having a low energy consumption, and being relatively easily managed [12], CWs are considered important forms of green infrastructure that are widely used for wastewater treatment, especially for the treatment of agricultural runoff, domestic wastewater, and industrial landfill leachate [13,14]. Although accurate data are not available, it is estimated that CWs have increased 5–50% globally since the 1960s [15]. In China, there were more than 800 CWs in operation by 2016, accounting for about 2% of the country's wastewater treatment facilities [16,17]. The rapid expansion of CWs can, to some degree, compensate the loss and degradation of natural wetlands, which was recognized as one of the key factors contributing to global biodiversity decline [2].

CWs offer potential habitats for wildlife conservation and could potentially mitigate the negative effects of human activities on biodiversity decline, especially when used as wildlife refuges when natural habitats are severely destructed [18]. The role of CWs in biodiversity conservation is increasingly acknowledged by members of the public and resource managers. Some theoretical and empirical studies have confirmed that management of CWs can enhance the biodiversity of different taxonomical or functional groups, such as vegetation, invertebrates, fish, and birds [19–21]. In the meantime, there are studies that demonstrate that rich biodiversity in CWs can improve their treatment efficiency by enhancing their biogeochemical cycling [22–24]. However, research into CWs has mainly focused on their purification function, while less attention has been given to their biodiversity value. As far as we know, there has been no systematic study of the interactions between CWs' primary function of sewage treatment and the biodiversity they can support [25], leading to a lack of biodiversity-oriented management of CWs, which could have a potentially negative impact on global biodiversity.

In this paper, we provide an overview of how a range of wildlife utilizes CWs and the effects of biodiversity within CWs on pollutant transformation and removal. The aim of this review is to create a context regarding the potential value of the use of CWs in biodiversity conservation, emphasizing the opportunities that exist for co-managing CWs for the benefit of both wastewater treatment and biodiversity conservation. Through our review, we provide suggestions for future research and practical guidance on biodiversity maintenance in CWs.

2. Wetland Loss Is a Great Threat to Global Biodiversity

2.1. Accelerating Loss of Natural Wetlands

Several studies indicate that the global-scale destruction and degradation of wetlands has gradually accelerated in the modern era [26,27]. Up to 87% of global wetland resources have been lost since 1700 in places where data exist, with losses of 50% since 1900 and 35% since 1970 [28]. The average annual rate of natural wetland loss between 1990 and 2015 is more than three times faster than that of natural forests (−0.24%) [29].

Across the world, Europe, Asia, and South America are hotspot regions of wetland loss. Europe has the greatest percentage of loss, with 45% of natural wetlands disappearing since the 19th century. The largest wetland losses by area have occurred in Asia, with approximately 265 million ha of natural wetlands being replaced by croplands, hard surfaces, and other types of land cover [30]. In China alone, the area of wetlands decreased by 3.39 million ha between 2003 and 2013, of which the natural wetland area decreased by 3.37 million ha, which is equivalent to a 9.33% loss. Activities associated with economic development, such as land reclamation for agriculture and urban expansion, the overexploitation of water resources, and river regulation, are major threats to natural wetlands [31].

2.2. Ecological Consequences of Wetland Loss

Wetland loss results in a reduction in, or even the disappearance of, many important ecological functions, leading to serious ecological issues all over the world, including water resource shortages, intensified flooding and droughts, escalated soil and coastal erosion, a reduction in climate regulation and pollution purification capabilities, a reduction in biodiversity and the destruction of fisheries and agricultural productivity [9–11].

With respect to biodiversity loss, 21% of extinct or globally threatened birds, 37% of mammals, 20% of freshwater fish, and nearly one third of amphibians are wetland-dependent [32]. Furthermore, data published from the Ramsar Convention suggests that, of the more than 18,000 species surveyed, 25% of inland wetland-dependent species are globally threatened and 6% are critically endangered [15].

3. CWs Have the Potential to Mitigate Global Biodiversity Loss

3.1. CWs Can Play an Important Role in Biodiversity Conservation

The loss and degradation of natural wetlands have forced wetland-dependent species to increasingly use and colonize sub-optimal habitats, including CWs [18]. At the same time, the creation of these artificial ecosystems—originally built to treat agricultural runoff or municipal wastewater—is becoming more and more popular worldwide [33,34]. As a result, CWs offset the ecological consequences of natural wetland loss to some extent [35]. Constructed wetlands can be divided into surface flow CWs (SFCWs), subsurface flow CWs (SSFCWs), and hybrid systems, according to the differences in how water is introduced and distributed within the system [36–38]. Subsurface flow CWs can further be divided into horizontal subsurface flow (HF) and vertical flow (VF) CWs [39]. In recent years, some new types of CWs, such as floating treatment wetlands (FTWs), bio-ecological A2O-wetland systems and microbial fuel cells (MFCs) have been developed to enhance the treatment efficiency of CWs [40–42].

The importance of CWs in biodiversity maintenance is highlighted given their relatively small areas and the high richness and abundance of species that they support [43,44]. Indeed, studies on species–area relationships demonstrate that a collection of small habitat patches contain more species than single, large habitats with the same total area [45]. Low-level management approaches, such as regular dredging or harvesting, are required to maintain the purification function of CWs [46,47]. These actions are considered to cause intermediate disturbances to ecosystems, which could also promote biodiversity through the regulation of the dominant species [48,49].

3.2. Empirical Studies Confirm the Biodiversity Benefits of CWs

Many studies have been undertaken on the biodiversity of existing CWs, including plants, freshwater invertebrates, amphibians, and birds (Table 1). These studies collectively show that CWs can provide significant and biologically valuable habitats for wildlife, promote the dispersal of aquatic biotas, and support higher-level organisms, including fish and migratory birds [19,21].

Many factors, both environmental and biotic, govern biodiversity in CWs [50]. Environmental factors directly determine the occurrence and survival of organisms in these habitats and indirectly influence the biotic interactions (i.e., competition and predation) that determine population sizes and, therefore, the structure of biodiversity in CWs. Because of their relatively shallow depth, large surface area, and high shoreline complexity, wetlands are likely to support a high diversity of birds, benthic invertebrates, and macrophytes [51]. Fish diversity, however, is generally lower in smaller, more isolated patches due to their limited colonizing ability [52]. Although not consistent across studies, the biodiversity and community structure of animals in CWs can be comparable to natural wetlands under certain circumstances [53].

Table 1. Key studies demonstrating the biodiversity benefits of constructed wetlands (CWs).

Country/Region	Biota Studied	Wastewater Treated	Main Findings	Reference
USA	Invertebrates	Secondarily treated domestic wastewater and low-nutrient river water	A total of 36 and 39 macroinvertebrate taxa were collected in the wastewater wetland and river wetland, respectively. Average diel dissolved oxygen and specific conductivity were the best environmental predictors of invertebrate community metrics.	[58]
Ireland	Macroinvertebrates	Agricultural runoff	The last ponds in the chain of these integrated constructed wetland (ICW) systems are capable of supporting a similar number of taxa as natural ponds.	[59]
USA	Amphibians	Surface run-off and groundwater	The created pools exhibited higher taxa diversity than natural pools due to a more even distribution of organisms between the three families.	[60]
USA	Birds	Municipal wastewater	A total of 63, 48, and 68 species were noted during the 1995– 96, 1998, and 2000–2001 monitoring periods, respectively.	[61]
USA (California)	Birds	Surface run-off and groundwater	Average avian species richness was high, ranging between 65 and 76 species month^{-1}, while average relative abundance was moderate, at 65–83 birds ha^{-1} month^{-1}. Birds observed included both common and rare species.	[62]
USA	Amphibians, aquatic reptiles, aquatic insects, mollusks, and crayfish	Urban stormwater	Urban wetlands supported a 60% lower richness of amphibians and aquatic reptiles and a 33% lower richness of aquatic insects, mollusks, and crayfish.	[21]
Sweden	Vegetation and benthic invertebrates	Stormwater	There was a tendency for common species to be dominant and for less common species to be rare.	[19]
Australia	Macroinvertebrates	Urban stormwater	There was a significant negative relationship between total imperviousness (TI) and the abundance of aquatic invertebrates in western sites but not in south-eastern sites.	[63]
China	Birds, fish, and macroinvertebrate	Surface run-off and groundwater	A total of 58 bird species, 7 fish species, and 34 aquatic macroinvertebrate taxa were recorded in the two wetlands. Variations in the community structures of birds, fish, and aquatic macroinvertebrates were best explained by water temperature, wetland area, and the species richness of fish.	[50]
Denmark	Invertebrates	Stormwater	Stormwater wet detention ponds (SWDP) become aquatic environments that play a local role for biodiversity in a similar way to natural small and shallow lakes.	[53]
USA	Macroinvertebrates	Stormwater	Constructed stormwater ponds and constructed stormwater wetlands supported similar levels of macroinvertebrate diversity, although community composition was variable.	[54]
Italy	Vegetation	Surface run-off and groundwater	The flora of the EcoSistema Filtro (ESF) accounted for 54% of Regional Park’s flora. This these species, 12% were alien and 6% of the taxa are of conservation concern.	[55]
Italy	Vegetation, amphibians, reptiles, birds, mammals	Effluent water from a sewage treatment plant	An increase in the number of plants was observed compared to the start-up phase of the constructed treatment wetland (CTW). A greater abundance of birds (73 species) than mammals (6 species), reptiles (3 species), and amphibians (4 species) was highlighted.	[56]

Table 1. *Cont.*

Country/Region	Biota Studied	Wastewater Treated	Main Findings	Reference
Spain	Birds	Surface run-off and groundwater	Almost 50% of the waterfowl species visiting the zone were of special conservation concern. Differences in vegetation structure between subunits drove the selection of stopover sites for migratory species.	[57]
Sweden	benthic invertebrates, aquatic plants and birds	Urban stormwater	CWs are shown to favour the biodiversity of benthic invertebrates, aquatic plants and birds, although biodiversity trends to decline some years after the initial colonization period	[64]
Sweden	benthic invertebrates, birds, vegetation, amphibians and fish	Agricultural runoff	Species richness varied among the wetlands, with a mean of 34 species of benthic invertebrates, 34 species of macrophytes, 5 species of bird per wetland	[51]
Sweden	wetland birds and amphibians	Agricultural runoff	Wetland birds and amphibians colonized constructed wetlands irrespective of the original objective of the wetland. The mean maximum breeding bird species number in the wetlands occurred after 3.8 years.	[65]
Italy	Macroinvertebrates	wastewater from the mixed sewer system of a hamlet	Although differences in the composition of macroinvertebrate assemblages, the overall level of biodiversity was comparable between CWs and natural ponds	[66]
USA	Benthic invertebrates	Surface run-off and groundwater	Taxa richness, evenness, and community similarity were comparable between CWs and adjacent natural ponds	[67]

Constructed wetlands with emergent vegetation show a greater potential for maintaining vegetation diversity and increase the likelihood of colonization by a more diverse assemblage of macroinvertebrates [54]. One CW in the Regional Natural Park, Italy, was found to maintain a vegetation community consisting of 54% of the floral species pool of the whole park, despite covering just 2.52% of the total park area [55]. The development of a diverse vegetation community is also attributed to the presence of visiting and nesting birds [20]. In southern Italy, 73 species of birds were identified in an 8 ha free-water surface CW, of which 13 species are listed on the International Union for Conservation of Nature (IUCN) Red List and the Italian Red List [56]. Similarly, a free-water surface CW in eastern Spain, planted with a range of macrophytes, was shown to attract 38 waterfowl species during the breeding period, 16 of which are of conservation concern, as listed in Annex I of the Birds Directive [57].

3.3. Spatial-Temporal Characteristics of the Biodiversity Benefits of CWs

Constructed wetlands are generally very efficient at removing contaminants, although this can vary between types of CWs, wastewater sources, and operational conditions [68–70]. As a result of their contaminant removal effects, CWs can reduce the concentration of pollutants in the surrounding environment, thus reducing the negative effects of environmental pollution on wildlife and providing a relatively suitable habitat for wildlife [71]. At the same time, CWs increase landscape heterogeneity and ecological diversity within river basins. Eutrophic CWs, along with oligotrophic downstream environments, contribute to the maintenance of regional biodiversity [72]. Moreover, the unequal purification effect of CWs, with respect to different contaminants, can change regional stoichiometric characteristics, thus having potential impacts on regional biodiversity [73,74].

With high concentrations of pollutants, CW plant communities are often dominated by a small number of tolerant species, which means an inevitable reduction in plant biodiversity over time, despite having initially high biodiversity [75,76]. For example, Saggaï et al. (2017) reports that 72% of the plant species initially used in a CW were lost after eight years of operation because of environmental constraints and pressure from interspecific competition [77]. The surviving plants in this community were predominantly monocot species with C_4 or C_4-like photosynthetic pathways. Research in wetlands in Ohio, USA, also shows that the integrity of vegetation communities based on floristic quality is lower in wetlands with higher concentrations of plant-available phosphorus [78].

4. Biodiversity Enhances the Treatment Efficiency of CWs

4.1. Microorganisms Dominate Contaminant Removal

The efficiency of wastewater purification in CWs depends on a variety of processes, such as precipitation, abiotic adsorption by sediments and other substrates, biotic uptake by plants and microorganisms, nitrification and denitrification, and biodegradation and photodegradation (in the case of polymeric pollutants). Wetland organisms, especially microorganisms, have significant impacts on the purification function of CWs because they are the main participants in many contaminant-removal processes, such as nitrification and denitrification, and organic pollutant degradation. They can also promote phosphorus removal processes by forming biofilms that enhance the phosphorus adsorption capacity of the substrate. Furthermore, microbial communities are highly efficient in the transformation of complex contaminants [79].

Environmental factors, such as temperature, pH, and dissolved oxygen concentration, have significant impacts on the abundance, diversity, and community structure of microorganism communities, which, in turn, dramatically affect pollutant removal processes. For example, ammonia-oxidizing bacteria prefer aerobic environments, while denitrifying bacteria are favored under anaerobic conditions [25]. A large number of studies show that appropriate management approaches (e.g., the addition of external carbon sources and intermittent aeration) can enhance contaminant removal efficiency by promoting microbial growth and reproduction, and by increasing the microbial community diversity and richness of CWs [12,46].

4.2. Vegetation Has Multiple Effects on Treatment Efficiency of CWs

Plants are the most commonly used biological elements in the construction and management of CWs, and play important roles in pollutant removal, both directly and indirectly, through stimulating microbial growth. Numerous studies have shown that the indirect roles of plants (e.g., increases in hydraulic retention time, creation of aerobic–anaerobic micro-zones, decreases in the resuspension of contaminants in sediments) are substantial, while their direct role is usually limited [80–84]. In particular, effective plant–bacteria relationships can successfully remove a large number of contaminants in wastewater, including a variety of biotoxic substances (e.g., heavy metals and antibiotics). [85–90].

Studies about the relationships between biodiversity and ecosystem function (BEF) generally focus on the primary productivity of grasslands and forests [91]. Both experimental studies and field research have demonstrated the tendency of ecosystem functions to be enhanced as biodiversity increases [92,93]. Furthermore, the effect of biodiversity on ecological function is strengthened over time relative to other abiotic factors [94]. Some mechanisms have been hypothesized to explain the positive effects of increasing species richness on ecosystem functions, including complementarity effects (i.e., the synergistic effects of biodiversity through resource partitioning or facilitation) and selection effects (i.e., the chance that one dominant and highly productive species increases with increasing species richness) [95–97].

Less attention has been paid to the relationship between the plant biodiversity of CWs and their purification function and relevant research is generally carried out at the lab scale or pilot scale [23,98]. Furthermore, these studies reported inconsistent results. For example, a study reported that experimental wetland mesocosms with a mixture of macrophyte species could retain up to 30% more polluting nutrients than those with monocultures [22]. In contrast, Han et al. (2019) found there was no significant relationship between species' richness and nitrogen treatment efficiency, while systems with the presence of *Rumex japonicus* L. significantly enhanced nitrogen treatment efficiency when compared to systems without this species in a microcosm experiment [24]. Geng et al. (2017) showed that higher plant species richness led to more effective purification of phosphorus (P) due to the higher biomass production and a larger plant P pool in hydroponic microcosms, and that species composition exerted a stronger effect than richness on P removal from wastewater [99]. For full-scale CW studies, Zhu et al. (2012) reported that the efficiency of nitrogen removal was enhanced as plant species richness increased [100]. However, biodiversity in treatment wetlands would decrease with aging due to interspecific competition induced by nutrient enrichment and this diminishment in biodiversity has only negligible impacts on the treatment efficiency of CWs [77].

4.3. Effects of Aquatic Animals on Purification in CWs are Understudied

In recent years, ecologists' attentions regarding BEF relationships have extended to biodiversity through different trophic levels, particularly the influences of herbivory and cascade effects resulting from predation [101]. Studies have shown that the diversity of higher trophic-level species may have an even stronger effect on ecosystem function than plant diversity [102–104]. For CWs, many aquatic animals, including sludge worms (*Tubifex tubifex*), fish, oysters, and mussels are considered bio-remediators [105–107]. For example, mussels have an excellent ammonia removal capacity, and they also increase the N and P uptake by wetland plants and their adsorption by the substrate [106]. On the other hand, macrofaunal bioturbation can promote the suspension of contaminants in sediments, thus increasing endogenous pollution within CWs [108].

Herbivorous animals have been found to have contrasting effects on the purification function of CWs. They can, for example, increase plant damage by destructing the tissue and thereby lower the purification efficiency of CWs. However, moderate herbivory can enhance plant tolerance to eutrophication, meaning an enhanced purification function [109]. Constructed wetlands with combined macrophytes and macrofauna tend to show greater efficiency in removing organic waste [110]. Overall, the potential mechanisms through which a diversity of heterotrophs can promote nutrient cycling have not been widely implemented in CW management.

5. Challenges in Using CWs to Conserve Biodiversity

5.1. CWs are Simplified Replications of Natural Wetlands

Natural wetlands have been described as 'transitional environments' occurring between terrestrial and aquatic systems, which create diverse habitats for wildlife. The environmental gradients that occur from the terrestrial to the aquatic realms can be crucial for maintaining regional biodiversity [111]. However, such habitat heterogeneity is usually ignored in the design and construction of CWs. This often results in the creation of relatively simple and uniform habitat conditions for wildlife [112]. For example, a recent comparative assessment of habitat suitability in CWs and natural wetlands for the smooth newt (*Lissotriton vulgaris*) in Ireland found that natural wetlands had significantly more terrestrial habitat types than CWs [113].

As more attention has been paid to the wastewater treatment capabilities of CWs, the enhancement of the biogeochemical processes has increasingly become a primary design objective. In contrast, hydrological processes are largely overlooked, despite their important role in sustaining wetland biodiversity [114]. Indeed, hydrological regimes (i.e., temporal and spatial variations in water levels), which are considered the main driver of vegetation zonation in natural wetlands, are broadly homogenized in CWs [115].

Water level fluctuations can maintain species-rich wet meadows, fens, and wet prairies. Periodic flooding discourages the succession of wetland shoreline vegetation communities to woody plants and supports the full array of wetland communities and their associated wildlife [116]. In comparison, relatively stable water levels can lead to the development of vegetation communities dominated by a few species, thus reducing the biodiversity function of CWs [117].

5.2. Simple Species Composition Increases the Risk of Invasion

Although CWs are widely considered an 'eco-friendly' approach to wastewater treatment, they have some disadvantages that reduce their operability and affordability. Compared with conventional sewage treatment plants, CWs require a much larger area of land [118]. The purification function of CWs also inevitably leads to the clogging of filtration media and substrate pores [38,119]. In addition, the treatment efficacy of CWs is significantly influenced by the plant species used and environmental factors [120,121]. For example, using plants with high biomass and evapotranspiration rates, strong resistance to pollution stress and low temperatures, fast growth and colonization rates, can alleviate some of these disadvantages to some extent. Therefore, the utilization of single or alien plant species with such favorable traits is widely practiced [122].

The introduction of alien species increases the risk of further species invasion [123,124] and threatens native species through mechanisms such as predation, competition for resources, the release of toxins, disease transmission, and hybridization [125,126]. For example, the invasive bluespotted cornetfish (*Fistularia commersonii*) and silver-cheeked toadfish (*Lagocephalus sceleratus*) predate upon various other fish species and invertebrates and could potentially affect their stocks [127]. Although there are no reports on invasive plants that "escaped" from constructed wetlands published so far, this ecological risk still should not be ignored.

5.3. CWs May Become an 'Ecological Trap'

Ecological traps, which occur when animals mistakenly prefer habitats in which their fitness (i.e., growth, survival, and reproduction) is lower than in other available habitats. This can result from rapid environmental change and has important conservation and management implications. A number of studies (Table 2) have identified CWs as potential ecological traps through the accumulation of pollutants that are difficult to decompose (e.g., heavy metals and polymer compounds) [128].

Animals use environmental cues (e.g., vegetation, temperature, and pH) to select habitats that maximize their fitness [129]. Constructed wetlands can provide such cues, while at the same time being unrepresentative of habitat quality, and wrongly attracting animals to these engineered systems [130,131]. High concentrations of several pollutants have been identified as an ecological trap for some species of fish and frogs in CWs, reducing their survival and impairing their growth [132,133]. A recent global assessment indicated that the fitness of animals in CWs is lower than in natural wetlands, even though the abundance and richness of species can be similar [134]. This suggests that CWs can have negative impacts on biodiversity in the long term. Furthermore, CWs may increase the risk of regional extinction by attracting migration from nearby native habitats.

Table 2. Studies identifying constructed wetlands as ecological traps.

Study Focus	Country	Ecosystem	Biota Studied	Contaminants	Main Findings	Reference
Habitat selection	Australia	Urban stormwater treatment wetlands	Native frogs and fish		Macrophyte cover, zooplankton densities, the occurrence of the invasive eastern mosquitofish (*Gambusia holbrooki*), and the fitness and survival of *G. pusilla* tadpoles were lower at more polluted sites.	[18]
	Australia	Urban wetland	Frogs	Heavy metals and pesticides	Frogs inhabited wetlands with abundant vegetation, regardless of their pollution status.	[130]
	Australia	Stormwater wetland	Frogs (*Litoria raniformis*)	Heavy metals and pesticides	Breeding adults laid comparable numbers of eggs across wetlands with high and low contaminant levels. Tadpoles had lower survival rates and were less responsive to predator olfactory cues when raised in more polluted stormwater wetlands, but also reached metamorphosis earlier and reached a larger size.	[131]
	Australia	Stormwater and non-stormwater wetlands	Dwarf galaxias (*Galaxiella pusilla*)		Fish did not avoid stormwater wetlands that reduce their survival and delay their ovarian maturation.	[135]
	USA	21 wetlands on the Kenai National Wildlife Refuge	Wood frogs (*Rana sylvatica*)		Both predators and contaminants altered ecosystem dynamics to increase the frequency of amphibian abnormalities in contaminated habitats.	[136]
	USA	Stormwater ponds	Amphibians	Trace metals in sediment and Cl concentrations in surface waters	Pollutants appear to limit stormwater pond use by *R. sylvatica* but not by American toads (*Anaxyrus americanus*).	[133]
	USA (California)	Wetlands	Green frog larvae (*Lithobates clamitans*)	Glyphosate-based herbicide, Roundup WeatherMax™ and nutrient enrichment	The abundance of green frog larvae (*Lithobates clamitans*) was higher in the wetlands treated with herbicide and nutrients.	[137]
Effects of contaminants on wildlife	Australia		Dwarf galaxias (*G. pusilla*)	Invasive *G. holbrooki*	The invasive species reduced reproduction rates and consumed the larvae of *G. pusilla*.	[138]
	Australia		Spotted marsh frogs (*Limnodynastes tasmaniensis*) tadpoles	Copper and the insecticide imidacloprid	The swimming speed, distance, and escape response of *L. tasmaniensis* were reduced while erratic swimming behavior increased.	[139]
	USA	Stormwater pond	Amphibians	Metals in sediment and chloride in water	Intolerant *R. sylvatica* embryos showed a 100% mortality rate. Tolerant *B. americanus* embryos and larvae experienced sub-lethal effects.	[132]
	USA		Juvenile coho salmon (*Oncorhynchus kisutch*)	Ethoprop and malathion	Brain acetylcholinesterase activity and liver carboxylesterase were inhabited.	[140]
	USA		Spotted salamanders (*Ambystoma maculatum*)	Chloride	Osmoregulation of egg clutches was disrupted and lost 33% mass under high concentrations.	[141]
	Hungary		Common toads (*Bufo bufo*)	Pesticides	Tadpoles exposed to herbicides developed slower.	[142]
	Hungary		Agile frogs (*R. dalmatina*)	Herbicides	Tadpoles decreased their activity and remaining closer to the water surface.	[143]
	Belgium		Common frogs (*R. temporaria*)	Endosulfan	Contaminated tadpoles traveled shorter distances, swam less often and at a lower mean speed, and occupied a less peripherical positions.	[144]
	UK		Common starlings (*Sturnus vulgaris*	Fluoxetine	Exposure reduced female attractiveness.	[145]
	USA (California)		Wood frogs (*R. sylvatica*)	Roundup™	Tadpoles had reduced basal movement rates.	[146]

6. Going Forwards: Recommendations for Future Research Priorities

6.1. Multi-Objective Management of CWs

Currently, the design and management of CWs tend to target one—or, at most, two—aspects of their multiple functions [147]. As the biological, biochemical, and hydrological characteristics of CWs are spatially and temporally complicated, the lack of an integrative approach may lead to conflicts between different stakeholders. One key conflict is between pollution control managers and biodiversity conservation practitioners. For example, Hansson et al. (2005) showed that CWs with shallow depths, large surface areas and high shoreline complexities can maintain the high biodiversity of birds, benthic invertebrates, and macrophytes, but have lower phosphorus removal rates in comparison with small, deep CWs [51]. The multi-objective management of CWs, integrating their multiple ecological functions (e.g., wastewater treatment, biodiversity maintenance, climate regulation and flood mitigation) is necessary to balance different stakeholder values and this must be implemented from the initial design stage. Instead of the traditional 'cost-efficiency' approach, a multi-criteria decision analysis based on the full understanding of regional ecological issues and needs is necessary for CW management. Such a multi-criteria decision analysis approach can reflect the whole spectrum of opinions of all stakeholders who may express a preference for the co-benefits of management options and helps decision-makers identify key areas of disagreement [148].

6.2. Integrated Watershed Management

Wetlands are sinks of non-point source pollutants in watersheds and, as such, the necessity, position, and scale of CWs should be determined by the pollution loading patterns and land use within a watershed [149]. To balance the benefits of contaminant purification and biodiversity maintenance, it is necessary to treat terrestrial and aquatic ecosystems as a unified whole (within an integrated watershed management strategy) when deciding where CWs should be constructed [150]. Ecosystem management at the watershed scale would be more effective than at the site level for biodiversity conservation, because watershed-scale approaches may help attract organisms' high-quality natural habitats instead of CWs, thus addressing the 'ecological trap'. Furthermore, network approaches, such as enhancing the connections between CWs and adjacent natural ecosystems, especially through establishing a relatively complete food web, could alleviate the biotoxicity effects of CWs on wildlife through biodilution [151].

6.3. Accurate Simulation of Natural Wetlands

As our understanding of the structure and processes of natural wetland ecosystems continues to increase, CWs with more natural wetland characteristics and those encourage biodiversity conservation should become more feasible. Integrated constructed wetlands, characterized by complex habitat mosaics, can maximize the potential for enhancing macroinvertebrate diversity [152]. Quasi-natural riparian zones that have a high species richness and abundance could be built through hydrological regime regulation and elevation modification. The utilization of indigenous plant species in CWs (based on baseline surveys before they are built) is also an effective option to maintain local biodiversity, and can reduce the risk of exotic species invasion. The value of long-term observation and comparative studies on the multiple ecological functions of CWs and natural wetlands cannot be underestimated, especially given that vegetation succession in CWs and the associated faunal turnover can be rapid. Indeed, the temporal dynamics of biological communities in CWs can have complicated implications for both pollutant removal and biodiversity conservation [153,154].

7. Conclusions

As a promising green engineering technique, CWs are being increasingly implemented across the globe for their wastewater treatment capacity. The rapid increase in CWs creates new opportunities for global biodiversity conservation. These artificial systems can provide alternative sub-optimal habitats for wildlife as compensation for the widespread loss and degradation of natural wetlands, as well as creating heterogeneous habitat conditions for wetland-dependent wildlife. High biodiversity in CWs can also enhance their primary function (water and sewage treatment) via multiple mechanisms, such as biotic uptake, enhanced biodegradation and photodegradation, thus providing opportunities for the multi-objective management of CWs. However, knowledge gaps concerning the ecological processes and mechanisms that sustain biodiversity in CWs could lead to failures in reproducing the critical habitat components of natural wetlands, such as hydrological regimes and topographic complexity. In order to address the challenges in using these engineered systems to conserve biodiversity, more in-depth research into CWs and the biodiversity they support, including the integrated constructed wetland concept, and especially the treatment of terrestrial and aquatic ecosystems as a unified whole (within an integrated watershed management strategy) when deciding where CWs should be constructed, is necessary to maximize the biodiversity of CWs as well as their purification functions.

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