Ecosystem Services of Constructed Wetlands for Wastewater Treatment

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Constructed wetlands (CWs) are nature-based solutions that utilize natural vegetation, soils, and microbes to treat domestic wastewater and industrial effluents. They are engineered treatment systems that mimic the functions of natural wetlands to capture stormwater, reduce nutrient loads, and create diverse wildlife habitats. As an ecosystem, CWs contribute to human well-being by providing certain ecosystem services that can be classified into four distinct categories, namely: provisioning services, regulating services, supporting services, and cultural services.

Keywords: constructed wetlands ; ecosystem services valuation ; nature-based solution ; wastewater treatment

1. Introduction

Rapid urbanization, population growth, and unsustainable economic development resulted in a significant increase in wastewater generated by humans and industries that are released into the environment. Globally, water discharges from industry, municipalities, and agriculture have doubled compared to the world's population over the last century.[1] In 2020 alone, only 56% of all wastewater flow generated by households globally was collected and safely treated.[2] The world has targets to improve this by reducing water pollution through the elimination of released hazardous chemicals, halving the proportion of untreated wastewater, and increasing the recycling and safe reuse of water by 2030. Following the Sustainable Development Goal (SDG) 6.3.1, the proportion of the total, industrial, and household wastewater flows should be safely treated in compliance with national or local standards.[2]

Several technologies are employed to treat wastewater. These include physical, biological, chemical, and hybrid treatment techniques for the removal of various contaminants from wastewater.[3][4][5] Currently, the best method has not yet been identified as these techniques have their benefits and challenges in terms of technical difficulty, environmental impact, effectiveness, economic feasibility, and cost-efficiency.[3] Yet, these technologies helped improve wastewater management not only for protecting drinking water resources from fecal contamination and waterborne diseases but also for protecting aquatic ecosystems from nutrient input and chemical/plastic pollution and for mitigating and adapting to climate change.[2]

Another alternative is constructed wetlands (CWs), which is a nature-based solution (NBS) to improve the quality of water. Naturally, wetlands are being considered increasingly for wastewater treatment due to the ability of several wetland plants to absorb huge amounts of nutrients and a variety of toxic substances.[6] Major kinds of wetlands include swamps, marshes, and bogs, while these may also refer to peatlands, sloughs, muskegs, fens, potholes, and mires. On the other hand, CWs are engineered treatment systems that have been designed and constructed using natural processes consisting of wetland vegetation, soils, and their associated microbial assemblages to assist in treating wastewater.[7] The performance of CWs depends on the type, vegetation, application by hydraulic load, and media used in the bed.[8] For instance, various types of CWs are free water surface, horizontal flow, vertical flow, hybrid, aerated, and baffled sub-surface flow. These CWs combine the core structural components of natural wetland ecosystems to mimic and perform the selected functions of natural wetlands and, therefore, deliver a range of monetary and non-monetary benefits, including water quality improvement, flood protection, and the promotion of biodiversity.[9][10]

2. Ecosystem Services of Constructed Wetlands

A millennium ecosystem assessment (MEA)[11] defined the different types of benefits that humans could obtain from ecosystems and coined the phrase "ecosystem services" to describe them. In a broader sense, ecosystem services are the advantages that humans obtain from ecosystems that serve as a connection between human societies and the ecosystem. This results in complex ecosystem conditions and mechanisms in which the living and nonliving elements of the ecosystem produce these ecosystem services.

Constructed wetlands (CWs) are designed and built to mimic natural wetlands to treat wastewater. Currently, CWs can be used as NBS to treat water from various sources and applications, including agricultural runoff,[12][13][14] industrial effluents,[15][16][17] stormwater runoff,[18][19][20] and municipal wastewater.[21][22][23] Considering them as an ecosystem, CWs contribute to human well-being by providing certain ecosystem services that can be classified into four distinct categories, namely: provisioning services, regulating services, supporting services, and cultural services.[24][25] The ecosystem services provided by CWs for wastewater treatment are summarized in **Figure 1**.

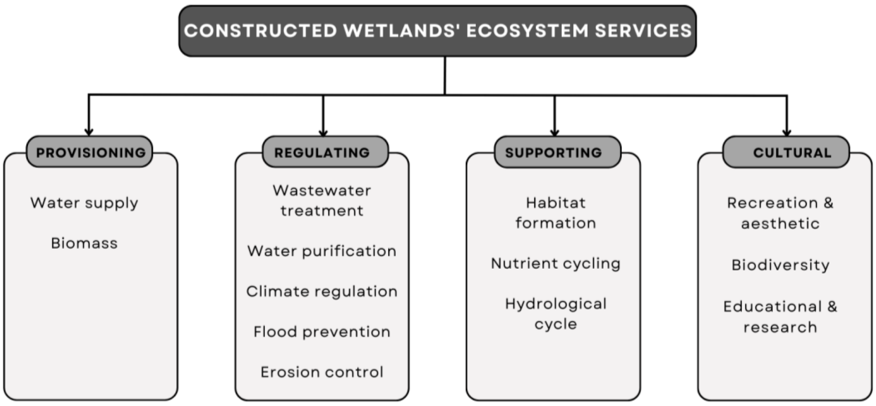

Figure 1. Summary of ecosystem services of constructed wetlands for wastewater treatment.[25]

2.1. Provisioning Services

The tangible resources or material products that humans harvest from ecosystems are referred to as provisioning services. These are limited in quantity but have the potential to be replenished, and are capable of being directly consumed, appropriated, and exchanged.[26] The provisioning services provided by CWs are sources of biomass and water supply.

- Biomass—Constructed wetlands provide biomass, which may be collected, dried, and utilized in the food and energy industries. Humans may utilize biomass as food for direct consumption, fodder for livestock, and semi-woody biomass for fueling purposes, such as directly for heating and cooking or the creation of biogas and/or biofuel.[27] In the case of CW in Costa Rica, the absence of wastewater treatment ecosystem services had biomass production costs ranging from 243 to 1287 USD dry Mg-1, depending on model assumptions.[28] Considering the ecosystem services, the costs of biomass production range from 38 to −290 USD dry Mg-1, in which the negative costs indicate income, suggesting that the value of water treatment services is large enough to pay for wetland operations and that biomass can be provisioned for free while still maintaining system profitability.[28]

- Water supply—Constructed wetlands can treat several types of water, including agricultural wastewater, industrial wastewater, municipal wastewater, stormwater runoff, landfill leachate, and mining water. Treated wastewater is expected to be appropriate for reuse in a variety of settings, including construction and agricultural irrigation. A study revealed that the practice of using untreated or treated wastewater for agricultural irrigation, particularly in the least developing countries, poses a significant risk to human health due to the presence of pathogens in the water.[29] Building a constructed wetland is one of several methods for purifying wastewater with higher enteric pathogen removal efficiency and converting it into a resource that can be used for agricultural irrigation. Consequently, additional agricultural benefits might come from the potential reuse of wastewater from CWs, considering it as an ‘extra’ income for avoided losses on production due to drought events equal to 20% of gross saleable production.[12]

2.2. Regulating Services

Regulating services are the result of various ecological processes that contribute to the operation of an ecosystem, particularly the regulation of the environment in which humans live and work. In addition, they regulate the amount, timing, and quality of water supplies, as well as the impact of extreme weather on ecosystems and people [30] As an NBS, regulating services of CW maintains nature’s ability to provide material contributions that are usually in indirect ways. Among the regulating services of CWs are wastewater treatment, water purification, climate regulation, flood prevention, and erosion control.

- Wastewater treatment—In the last five decades, CWs have developed into dependable wastewater treatment technologies. It becomes a solution for treating various forms of wastewater, such as sewage, industrial and agricultural wastewater, landfill leachate, and stormwater runoff.[31] For instance, the CW in Beijing is dominated by the ecosystem service of waste treatment, with a fraction of 63.82% corresponding to the amount of 1.31 million USD/ha/yr.[32]

Pollution is cleaned in natural wetland ecosystems by mechanisms that are also present in constructed wetland ecosystems, although equivalent processes occur under more closely regulated settings in CWs.[31]

- Water purification—Water purification is the process of eliminating potentially harmful impurities from water. The objective is to produce water that can be utilized for human consumption for other reasons. A study identified the factors affecting the purification effect of CWs including zeolite characteristics, isothermal adsorption modeling, adsorption kinetics simulation, and pollutant purification.[33] The findings demonstrate that zeolite's adsorption is greater than that of the total phosphorus suggesting that the purification process of CWs with compound substrates has increased. Additionally, CWs provide a strategy to improve water quality via the removal of phosphorus, which may lead to an excessive algal bloom that decreases lake clarity, quality, functionality, and recreation value.[34]

- Climate regulation—Constructed free-water surface (FWS) wetlands and constructed riverine wetlands (CRWs) are also useful in climate regulation.[35] The relationship between greenhouse gas (GHG) emissions, methane emissions, and nitrous oxide (N2O) emissions and the biophysical and design factors of the systems was studied, and it was found that the current global warming potential (GWP) of FWS, CW, and CRWs was generally small, but their rapidly increasing number should alert wetland designers and stakeholders to improve the design and management of these systems. Meanwhile, On the contrary, GHG regulation from the CW in Beijing resulted in negative ecosystem services values of −238 USD/ha/yr due to the vast GHG emission from the treated wastewater, in contrast to the positive values associated with the Sanyang and mean.[32]

- Flood prevention—CWs are cost-effective treatment systems that can be used to treat urban stormwater runoff. As CWs are generally controlled by a pit and a piped outlet, they act under the same principle as a retarding basin by discharging flood flows at a controlled rate; hence, they can be utilized to assist in flood protection in urban areas.[36] For instance, there has been a rising interest in constructed wetland projects in Korea, both as a flood control tool and for ecological reasons. Hydraulic and hydrologic analyses were conducted on a wetland development plan for use as an alternative sustainable flood defense during the flood season and a wetland that could maintain the environment during non-flood seasons.[37] Analyses found that the CWs potentially served as an alternative instrument for flood prevention and a refuge for biodiversity. Meanwhile, in agriculture, surrounding sugarcane farms benefited from the reduced flooding of cropland and the elevation of low-lying croplands with deposited spoil excavated from CWs' construction.[38] Improved drainage and flow regulation increased the sugarcane yield, while elevated land increased gross margins by extending the length of the cane production cycle or enabling a switch from cattle grazing to cane production.[38]

- Erosion control—Sediment stabilization is one of the many advantages of using CWs for stormwater management.[39] The major feature of stormwater wetlands (similar to other CWs) is the presence of vegetation, which plays an important part in the system's processes. They act as a protective ground cover and aid in preventing soil erosion. Its roots prevent soil from being blown or washed away by wind and water. Hence, they have the potential to slow the flow of water over land, which allows the soil to absorb a greater proportion of precipitation. Additionally, the vegetation absorbs nutrients and stabilizes the currently exposed banks of the wetlands, thus reducing the risk of erosion while also increasing resistance to water flow, thus reducing kinetic energy and promoting increased sedimentation.[40]

2.3. Supporting Services

Supporting services are indirect benefits since they are ecological activities that benefit communities indirectly by maintaining one of the other three types of services.[30] As a result, supporting services constitute a subset of indirect services. They include processes and functions that provide the basis for appropriate provisioning, regulatory, and cultural services. The supporting services from CWs include habitat formation, nutrient cycling, and hydrological cycle.

- Habitat formation—The benefits of CW habitats extend beyond their initial design and construction standards. CWs that are utilized for wastewater treatment provide extra benefits such as habitats for local species. The habitat and refugia provision services represent the environment provided by CWs for biodiversity.[32] Scientists in several European countries as well as New Zealand, have calculated monetary estimates for the benefits gained from wetland ecosystems, including those altered by humans.[41] The conservation and restoration of natural habitats was the most highly valued ecosystem function at these locations, with monetary estimates ranging from 197 USD/ha/year in Whangamarino, New Zealand[42] to 27,678 USD/ha/year in Cheimaditida and Zazari, Greece.[43]

- Nutrient cycling—Through the movement of nutrients, nutrient cycles provide a connection between living species and non-living organisms. Vegetation can minimize the quantities of elements in CWs that would otherwise be deemed pollutants because they make use of nutrients such as nitrogen and phosphorus. Additionally, they can store phytotoxic substances, such as heavy metals, in vacuolar or granular compartments of their tissues. As a result, phytoremediation might be a significant part of the plants' roles in CWs.[44] Further, the presence of biochar (from sewage sludge and cattail plants) in CWs not only kills pathogenic bacteria in the sludge but also promotes carbon release and nutrient cycling (P, K, Ca, Mg, etc.).[45]

- Hydrological cycle—According to the "Sponge City" concept,[46] CWs are recognized for their ability to connect the water cycle with urban development while also contributing to meeting the ongoing issues of climate change and increasing urban growth. This concept incorporates drainage, penetration, detention, storage, and purification, which make CWs an important technological answer for water purification. Within the urban hydrologic cycle, CWs may contribute to integrated urban water management by recycling the stored water volume.[17]

2.4. Cultural Services

Cultural services refer to the contribution of ecosystems to the intangible benefits resulting from interactions between humans and ecosystems. One example of a cultural ecosystem function is the cultural sense of place or identity linked with the management of a particular environment.[26]

- Recreation and Aesthetics—The term "recreational ecosystem services" refers to all of the benefits that humans derive from landscapes and the natural environment.[47] People benefit from an ecosystem's aesthetic and recreational components, which include physical, mental, and emotional well-being benefits.[48] Leisure activities also serve as a basis for the local economy and directly related enterprises in several cases. In 2015, there were already 166 identified CWs that support public recreational and educational activities worldwide.[49] Along with the calculation of the economic value of a CWs, societal, cultural, and recreational components should be accounted for as well.[50] Since every year, primary and middle schools organize field trips to the CWs in China for their students, the CW is vital to the local community in terms of both educational and recreational purposes.[50]

- Biodiversity—While CWs have shown efficiency as NBS for water treatment, their ability to enhance biodiversity in various agricultural landscapes by providing suitable breeding habitats for various animal species was also reported.[51] In subtropical Taiwan, the biodiversity of two free-water-surface integrated constructed wetlands was also investigated by examining the water quality, habitat characteristics, and biotic communities of algae, macrophytes, birds, fish, and aquatic macroinvertebrates in treatment cells.[52] The two wetlands were home to 58 birds, seven fish, and 34 aquatic macroinvertebrate species. As the most important factors impacting diversity in CWs, community structures within taxonomic groups change based on the wetland acreage, aquatic macrophyte coverage, and water quality. According to the findings of this research, well-planned and managed wetland treatment facilities can improve water quality and biodiversity.[52]

- Educational and Research—The provision of educational opportunities is one of the many benefits to human societies that ecosystems and landscapes offer. The numerous techniques for quantifying ecosystem services hardly ever take into consideration the significance of this factor, albeit those that are important to both formal and informal learning, as well as nature-based cognitive tourism.[53] For instance, the primary and middle schools in Hangzhou organize students to visit the CW each year, creating an important role in local education and recreation.[50]

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