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Constructed wetlands for water reclamation

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Abstract

Constructed wetlands have been increasingly used throughout the world for secondary and especially for tertiary treatment of wastewater and stormwater. If well designed and maintained, their effluents can meet the high standards required for reclaiming the water. One can also partially reclaim nutrients by harvesting the aquatic vegetation or by combining wastewater treatment with aquaculture. Constructed wetlands further provide certain ancillary benefits such as wildlife habitat function, recreational facilities etc. This paper gives an overview of treatment performances and consequent reuse possibilities, operation and maintenance requirements, costs and constraints interfering with the application of this technology.

Keywords: Ancillary benefits; Polishing; Reuse; Reed beds; Tertiary treatment

1. Introduction

Constructed wetlands (CWs) are man-made copies of natural wetlands that optimally exploit the biogeochemical cycles that normally occur in these systems for the purpose of wastewater treatment. Different types can be distinguished, based on water flow characteristics and plant species. Systems with above-ground flow are referred to as surface-flow CWs (SF), the ones with below-ground flow as subsurface-flow CWs (SSF). The latter ones can be further subdivided according to the water flow direction, i.e. horizontal or vertical flow. Commonly used plants in all types of systems are helophytes like reed and cattails. Some SF systems also make use of free-floating

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macrophytes like duckweed and water hyacinth, floating-leaved bottom-rooted macrophytes like lotus or submersed macrophytes like waterweed but these are less frequently used and therefore not further discussed in this paper. For an extensive overview on system types and pollutant removal mechanisms, one is referred to the standard work of Kadlec et al. [1].

Obviously, different CWs do not necessarily function as stand-alone treatment plants but can be combined with each other or with other low-tech or high-tech wastewater treatment units in order to exploit the specific advantages of the different systems. CWs are indeed increasingly used as tertiary treatment step after activated sludge, rotating biological contactors, UASB etc.

2. Reuse options and ancillary benefits

A literature search through the extensive amount of data available on CWs yielded a number of preliminary conclusions with regard to their use for water reuse purposes:

- Reuse *sensu stricto* of the effluent of CWs is in Europe more popular with small systems than with larger ones. Many examples exist of single-household and on-farm systems where the effluent is reused for flushing the toilet, watering the garden, cleaning the stables etc. Large-scale applications are less common in Europe but wide-spread in Australia and the USA.
- Although the term reuse is often mentioned in title or abstract of scientific papers, most authors only theoretically consider the possibility by comparing the effluent concentrations of the investigated CW with national or international reuse standards. Actual cases where effluent is effectively reused are more commonly found in general literature.
- Reuse by larger CWs is most often considered in the broadest sense: creation of extra habitat for wildlife, recreation, education etc.

2.1. Water reuse

Treated effluent can be reused for restricted or unrestricted irrigation of agricultural crops, depending on its quality. Other applications are watering of gardens, golf courses, public parks, etc. Merz [2] for instance states that irrigation reuse is practised at about 30% of Australian constructed wetlands. Effluent can also be reused for flushing toilets, for cleaning purposes [3], as cooling water [4] and as a reliable water supply for natural wetlands or nature reserve areas [5]. CWs can also serve as infiltration areas for groundwater replenishment [6].

From an ecological point of view, effluent of a SF CW has some added value compared to effluent of conventional technologies as it already sustains a basic food chain of phyto- and zooplankton. Its impact upon discharge in surface water is therefore reduced. This concept is studied at length in the Waterharmonica project [7].

2.2. Nutrient reuse via plant and/or animal biomass production

Certain plant species have commercial value, some as ornamental plants [8] and others as raw material. Mulching and composting of harvested plants can for instance yield soil additives; pulping of plants provides fibres; and silaging produces livestock fodder. As the plants sequester carbon during their growth, they could be used after harvesting for energy production which raises the possibility to obtain carbon credits. Another option is to integrate wastewater reclamation with aquaculture. Nutrients in the wastewater are converted into algal or plant biomass and are then passed on via the food chain to fish or even ducks, which can then be harvested for human consumption [9]. Although nutrient reuse is much more common practice in developing countries, attempts have been made in Europe as well, e.g. Staudenmann and Junge-Berberovic [10].

2.3. Habitat function

Another benefit includes the creation of a new habitat for flora and fauna. Knight et al. [11] summarize data from the North American treatment wetlands database concerning sightings of mammals, birds, amphibians, reptiles, fish and invertebrates and vegetation mapping surveys. Initial concern about bioaccumulation of certain pollutants and spreading of diseases via visiting fauna seemed in most cases premature.

Very few CWs have been specifically designed to contribute to wildlife conservation. According to Connor et al. [12] there are indeed many obstacles like a lack of understanding of conservational needs and ecological principles among engineers, the additional costs entailed, lack of comprehensive design manuals and a lack of obviously tangible benefits to local communities. Worrall et al. [5] conclude likewise that CWs can be specifically designed and managed to optimize wildlife potential if approached from an ecological point of view as opposed to a strictly engineering perspective. Constraining factors for wildlife development are mainly (i) the wetland size, (ii) the structural diversity of the wetland as habitat, (iii) biological stresses imposed by the nature of the influent and (iv) design features such as subsurface or surface flow. Several positive examples are summed up by Connor et al. [12] as counterarguments. The Western Treatment Plant of Melbourne for example (10850 ha with lagoons, land infiltration and grass filtration) has been included in the Ramsar convention as a wetland of international importance for bird conservation.

2.4. Other benefits

Knight et al. [11] finally mention education (nature study), exercise activities (walking, jogging), recreational harvest (hunting, trapping), as other positive contributions of constructed wetlands. Gearheart and Higley [13] add picnicking, relaxing and art (photography, painting) to this list.

3. Removal efficiencies and effluent concentrations

Constructed wetlands are known to have a high buffering capacity. Effluent quality is therefore normally quite stable. On the other hand, adverse effects can be expected from low temperatures (especially inhibition of N-removal), peak flows (wash out of solids) and clogging of subsurface-flow systems. Removal percentages are mainly dependent on temperature, hydraulic residence time (HRT) and loading rate, and are highly variable between systems.

Provided the influent is well oxidised, tertiary treatment BOD_5 and SS effluent levels as low as 5–10 mg L^{-1} can be attained with both FWS and SSF CWs [14,15].

Nutrient removal on the contrary is more problematic. For effluent polishing purposes, effluent N of 3 mg L^{-1} or less seems achievable with SF at influent nitrogen concentrations up to 16 mg L^{-1} and hydraulic loading rates up to 300 m^3 ha^{-1} d^{-1} [16]. As aeration is limited especially in horizontal flow SSF, nitrification can be problematic but denitrification can occur at high rates, provided a carbon source is available such as BOD_5 not removed during the secondary treatment or degrading plant biomass.

At low P concentrations, typical removal efficiencies can still amount to 60–90% and yield effluent concentrations of 1.0 mg P L^{-1} or lower. Effluent polishing studies from the USA are reported where influent P of 1–2 mg L^{-1} was reduced to 0.005–0.3 mg L^{-1} at mass loading rates of 3 to 4 g P m^{-2} y^{-1} and mean hydraulic loading rates of 190 m^3 ha^{-1} d^{-1}. Australian experience shows sustained P removal in a free-water-surface constructed wetland of over 60% for more than 3.5 years at loading rates between 3–5 g P m^{-2} d^{-1} [16].

Tertiary treatment wetlands can be rather effective in removing pathogenic organisms. Kamizoulis [17] summarized treatment efficiencies as follows: 0.5–3 $\log_{10}$ units for bacteria, 3 $\log_{10}$ units for helminths, 0.5–2 $\log_{10}$ units for protozoa and 1.5–2 $\log_{10}$ units for viruses. García et al. [18]

found similar removal rates, i.e. 0.1–3.4 $\log_{10}$ units for faecal coliforms and 0.5–2.6 $\log_{10}$ units for somatic coliphages. The latter study also revealed the effect of granular medium size and HRT on pathogen removal: finer gravel and a longer HRT enhance treatment performance.

As mentioned earlier, CWs can also efficiently remove low-concentration compounds such as pharmaceuticals and personal care products [19] and heavy metals [14,20]. Long-term accumulation of heavy metals may render a CW into a black point, but in the current case of tertiary CWs for domestic wastewater, few adverse effects can be expected.

4. Process operation, maintenance and monitoring

Maintenance and operation of CWs are fairly easy due to the virtual absence of mechanical and/or electrical parts [21]. It is nevertheless being recommended to check larger systems (>500 PE) on a daily basis. In practice however, insufficient maintenance is often observed, resulting in uneven flow distribution and consequently local overloading. Initially, treatment efficiency seems to be unaffected, but progressive deterioration of the system can irreversibly reduce the performance in the long term.

Kadlec and Knight [22] more or less concur and indicate that adjustment of flows and water levels and monitoring of water quality and biological parameters are the only day-to-day activities required to achieve successful performance in CWs. Other operations and maintenance activities in CWs such as repair of pumps, dikes and control structures; vegetation management; and removal of accumulated mineral solids must be carried out at much less frequent intervals. Kadlec et al. [1] also recommend including cover estimates and observations concerning plant health as a routine part of operational monitoring. Because plants grow slowly and are important for maintaining the performance of CWs, problems must be anticipated or prevented before they have caused irreversible damage.

One of the continuing debates in CW management is whether or not the plants should be harvested. Main advantages of harvesting are: (i) nutrient export and (ii) prevention of thick layers of dead material with stagnant water in SF which are ideal pest breeding places [23]. Main advantages of leaving the plants on the wetlands are: (i) creation of an isolating layer of dead plant material on top of SSF, (ii) provision of a bottom detritus layer in SF that can adsorb trace metals, (iii) provision of a carbon source for denitrification. Kadlec and Knight [22] nevertheless advise against harvesting as it may alter the ecological functioning of wetlands.

5. Operational problems and constraints

5.1. Build-and-forget solution

Vymazal [21] separates operational problems into two categories: those resulting from poor maintenance and those associated with parts of the system that were not properly designed or built. Natural treatment systems are too often considered to be a ‘build-and-forget’ solution not needing any attention at all. When denied the minimal amount of maintenance that even natural systems need, failing treatment systems are often reported [24].

Severn Trent Water Ltd, one of the larger water utilities in the UK, operates more than 300 tertiary treatment CWs, most of which are of the horizontal subsurface-flow type. Although none of these sites has any intentional reuse purposes (P. Griffin, Severn Trent Water Ltd, personal communication), some important lessons can nevertheless be learnt from their operation. Cooper et al. [25] surveyed more than 120 of these CWs and noted in many cases problems with sludge deposition, inlet flow distributor problems, outlet collector problems, weed infestation, tree growth and above-ground flow. Especially sludge deposition is important for polishing wetlands, since in most cases it seemed to be caused by wash-out of solids from the preceding secondary treatment step. Despite these problems, all effluents were still compliant with the regulatory consents. The authors therefore call CWs "very forgiving and abuse tolerant".

5.2. Mosquito nuisance and muskrat problem

CWs are possible breeding spots for mosquitoes. Greenway et al. [23] state that a wetland with a high biodiversity (no monospecific stands) and an extensive food web will cause low mosquito nuisance. As mosquitoes preferably deposit their eggs in small, stagnant waters, the problem will be less persistent or even absent in SSF where water flows belowground. For an elaborate number of design and management strategies to minimize this nuisance, the reader is referred to Knight et al. [26].

Another major threat to the wetland as a whole and the vegetation in particular are muskrats. Especially systems planted with *Scirpus* or *Typha* are vulnerable since the animals use the plants both as a food source and for nesting material [27]. *Phragmites* does not seem to serve as a food source and is therefore less vulnerable.

5.3. Odour nuisance

Odour nuisance may occur in high-loaded systems when anaerobic conditions prevail. For low-loaded tertiary treatment CWs odour nuisance therefore tends to be limited. When needed, Kadlec and Knight [22] suggest (i) to further reduce BOD and NH_4 loading rates and (ii) to create aerobic environments by means of shallow basins or by implementation of cascading outfall structures.

5.4. Clogging

Clogging of SSF is a tangible risk and is principally influenced by loading rates of BOD and/or SS, the hydraulic loading rate and the particle size and distribution of the matrix material as well as the wastewater particles. Clogging can be counteracted by lowering loading rates or by leaving one or more beds to rest. During this resting period, organic material that blocks the pores can be composted and the hydraulic conductivity thus restored. When most pores are filled with inorganic material and the hydraulic conductivity is too low, the only solution is to excavate the bed and either refill it wit new matrix material or refill it with the same matrix material after rinsing.

5.5. Evapotranspiration and salinisation

Cadelli et al. [28] investigated the suitability of their 'Mosaïque Hiérarchisée d'Ecosystèmes Artificiels' (MHEA®) system under the Mediterranean conditions of Morocco. MHEA® combines different artificial ecosystems that can typically be found along a land-water gradient, i.e. from drier to wetter conditions, and is used for secondary and tertiary treatment. The MHEA® provides extremely efficient removal rates for SS, COD, BOD_5 and disinfection. Introduction of certain plant species also allowed high N and P removal. However, volumes of evapotranspiration are extremely large and zero outflow can occur in summer which makes these treatment systems less adapted for water reuse purposes. Green et al. [29] have additional concerns that extensive evapotranspiration could cause too high salinities and therefore render the effluent unsuitable for irrigation. They provided advanced secondary treatment in an upflow anaerobic sludge blanket reactor and passively aerated vertical beds while HSSF reed beds were only used as a polishing step. This reduced land requirement and ETP losses, but logically increased O&M costs.

6. Capital costs and maintenance costs

6.1. Capital costs

Major costs usually are land acquisition, earth moving, plastic liners to prevent groundwater contamination or infiltration and the matrix material (sand or gravel) in case of SSF. However, after its functional life, the land can be readily made available for other purposes and therefore certain authors exclude this cost from the balance. Capital costs are highly dependent on the local situation, i.e. soil type, groundwater table height, terrain slope, distance from settlement, discharge criteria, climate etc. Another important factor usually is the economy of scale: larger wetlands tend to be relatively cheaper per PE or per m^3 of wastewater treated. Economic analyses of CWs specifically applied for reuse purposes are rather rare but there seems to be no reason why unit investment costs would diverge significantly from those of secondary CW. Of course, total costs could be lower because the lower loading rates can be treated with smaller systems. One uncertain cost is the 'removal' cost of the system after its functional life, now estimated at around 20 years. Especially dumping or cleaning of saturated filter materials of SSF could result in high extra costs.

One other uncertainty concerns the design of CW. Kadlec and Knight [22], Rousseau et al. [30] and many others have reviewed model-based design of treatment wetlands. State-of-the-art nowadays is still a first-order plug-flow model that assumes an exponential decrease of pollutant concentrations to a background value. However, this black-box model is based on only two parameters, the first-order decay rate k and the background concentration C^*, which is an obvious oversimplification of the complex wetland processes. Moreover, this model can only be used to predict average behaviour over at least several hydraulic residence times. Predictive models of hourly or even daily variations are still in a premature stage. CWs are therefore frequently oversized to ensure regulatory compliance, entailing excessive costs.

Due to the reasons summed up above, the range of capital costs reported by Kadlec and Knight [22] is quite large: 25,000–250,000 \$ ha^{-1} or 500–1,000 \$ m^{-3}. Also, one should be cautious when comparing costs given in literature. Firstly, it is not always clear from the original sources which components are included, i.e. the wetland costs *sensu stricto* or also the costs for sewer construction, fencing, buildings etc. Secondly, many authors do not mention if taxes/VAT are included and at what rate. Finally, inflation and fluctuating exchange rates can give a wrong idea about current costs. Rousseau et al. [24] reviewed CWs in Flanders (Belgium) and found average capital costs for SF of € 392 PE^{-1} and for SSF of € 1,258 PE^{-1}. The latter value was however biased as it was based on only two systems of which one served educational purposes and therefore had some extra features.

6.2. Operation and maintenance costs

Operation and maintenance (O&M) costs of tertiary treatment CWs with reuse purposes will be lower than those of secondary treatment ones, not only because of the lower intensity of processes (lower loading rates) but also because of certain investment returns such as plant harvesting, aquaculture etc. O&M costs are rarely given in literature, but Kadlec and Knight [22] mention median costs for SF of about \$1000 ha^{-1} y^{-1} whereas O&M costs for SSF are estimated between \$2500 and \$5000 ha^{-1} y^{-1}. The complexity of CWs is quite low and maintenance therefore requires few specialised skills. Energy consumption, if any, is usually limited to pumping and represents only a minor cost since most wetlands are designed to function gravitationally. Chemicals are rather rarely applied. Exceptions are the addition of materials with a high P-sorption capacity in SSF and the use of pesticides to eliminate plant pests such as lice or mosquitoes. A possible by-product is harvested biomass which in some cases can be reused as fodder or as fertilizer. Sludge production tends to be minimal in tertiary systems when pre-treatment is adequate. Maintenance costs are therefore mainly labour costs: site inspection, effluent sampling and control, cleaning of distribution systems and pumps, weed control, plant harvesting etc.

A pond-wetland system in Thailand is reported to have a unit cost (per m^3 d^{-1}) for its operation of US$ 12/y compared to US$ 33–98/y for conventional systems [8]. Extra benefits include selling of ornamental plants (golden torch and bird of paradise — *Heliconia* spp.) at about US$ 0.2 per flower. El Hafiane et al. [31] describe the use of *Arundo donax* for tomato crop production and for artisanal objects, generating an annual income of US$ 1750–2900 ha^{-1} y^{-1} (one plant about US$ 0.007).

Additional benefits such as nature education, walking, bird watching etc. have seldom been economically valued. Knight et al. [11] only mention for a number of wetlands the ‘human use days’, expressing the total amount of time spent by humans for the above-mentioned activities. The 60 ha large Arcata wetland facility in California has 8 km of foot trails and attracts more than 130,000 visitors each year [13]. Carlsson et al. [32] conducted a choice experiment among citizens of southern Sweden and found that biodiversity and walking facilities are the two greatest contributors to welfare, while a fenced waterline and introduction of crayfish decrease welfare.

6.3. Costs from selected case studies

Tsihrintzis et al. [33] compared capital and O&M costs of a SF and a SSF for secondary treatment. The SF treats wastewater of 1200 PE by means of a septic tank and 2 wetland basins with a total area of 6,500 m^2. The SSF treats 1000 PE by means of a settling tank and 3 wetlands with a total area of 1,800 m^2 and also comprises a sludge drying bed. Annotated capital costs (excluding land cost; economical life of 30 years and opportunity cost of 2%) were 12.82 resp. €18.34 PE^{-1} y^{-1}. Costs for roads, buildings, sewers, fencing etc. accounted for 25–33 % of the total investment cost. Annual average O&M costs were 1.20 resp. €6.96 PE^{-1} or 0.32 resp. €0.39/m^3 per year, of which at least 77% were labour costs.

Platzer et al. [34] describe a wastewater treatment system in Nicaragua of 1,000 PE, consisting of screens, an Imhoff tank and 4 parallel horizontal subsurface flow constructed wetlands with a total area of 1,300 m^2. Total investment costs were US$42,000 or US$42/PE. Similar systems in other Central American countries are reported to have investment costs ranging between US$ 34 and US$275/PE, again very much dependent on the scale. Annual O&M costs of the above-mentioned system amount to US$ 4,769 of which an estimated US$ 1950 are labour costs. Since the effluent coliform concentrations (7.5×10^4 MPN $(100\ ml)^{-1}$) do not comply with Nicaraguan reuse standards (1×10^3 MPN $(100\ ml)^{-1}$), it is reused for gravity irrigation which avoids direct contact between the effluent and the crops. This causes however major losses by infiltration and evaporation. A positive conclusion was however that yields from this plot were not very different from an adjacent plot where chemical fertiliser was applied.

7. Conclusions

When carefully designed and maintained, constructed wetlands can yield, at relatively low costs, an effluent suitable for reuse and concurrently provide some opportunities to recycle nutrients and to accommodate wildlife.

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