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Advanced Treatment Wetlands: A 4th Generation Technology

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Introduction

Constructed wetlands for wastewater treatment have evolved substantially over the last 40 years. Engineered wetlands have become an effective means of advanced water treatment, including nitrogen removal. Integration of hydraulic or aeration machinery into constructed wetlands is responsible for these increased treatment capabilities. Together with improved scientific understanding of wetlands, these developments represent the emergence of a 4th generation of engineered wetlands that not only improve treatment performance, but also can successfully compete with many conventional technologies in the marketplace.

Design History of Treatment Wetlands

The first engineered treatment wetland design is found in a 1901 United States patent. Although the patent is surprisingly sophisticated, no record has been found showing that it was ever built. Other examples of early 20th Century treatment wetlands exist, but Kathe Seidel's pioneering work at the Max Plank Institute in the 1950s and 60s is regarded as the origin of modern treatment wetlands.

Proof of concept characterized 1st generation treatment wetlands. Designs were empirical and intuitive in nature. Early successes, and lessons learned from failures, encouraged further development, often from the pioneering researchers themselves.

The 2nd and 3rd generations evolved along separate paths. Empirical, civil engineering design criteria, such as mass loading rates of X kg BOD per hectare of wetland, characterize 2nd generation efforts. Such design methods are now increasingly regarded as simple "rules of thumb" of limited utility. More rigorous, chemical engineering design criteria characterize 3rd generation designs. The treatment wetland is regarded as a biochemical reactor. Input-output data on mixing and treatment are fitted to model equations. These methods treat the wetland as a "black box" without reference to internal treatment mechanisms. Leading wetland design engineers commonly use 3rd generation methods.

The common element among 1st, 2nd, and 3rd generation wetlands is that they are passive designs, relying on sunlight and atmospheric diffusion to support treatment processes. New "4th generation" wetlands increasingly use hydraulic or aeration equipment to overcome these limitations.

Recent Developments in Engineered Wetlands

Different types of wetlands form a continuum from completely passive designs, which require large land areas to highly engineered wetlands that are very compact (Figure 1). Pond wetlands and free water surface wetlands are typically used in situations where ancillary benefits, such as wildlife habitat, are an important part of the design process.

Subsurface flow (SSF) wetlands have received the most attention from technology developers because of their treatment efficiency. SSF wetland influent is typically raw or primary wastewater. They “work harder” than free water surface or pond wetlands because they have larger surface areas of bacteria biofilms in contact with wastewater. Passive SSF wetlands are proven technology for removal of biochemical oxygen demand (BOD) and total suspended solids. Due to the limited availability of oxygen, the root zone of these SSF wetlands is anaerobic, and processes that require oxygen, such as oxidation of ammonia to nitrite and nitrate (nitrification) occurs very slowly, if at fall.

Aeration and tidal flow are the two methods developed to provide oxygen for nitrification to wetland systems. Other benefits come from these 4th generation methods.

Aerated wetlands

Aerated wetlands use tubing distributed across the bed of the wetland to create multiple coarse bubble curtains through which wastewater must pass (Figure 2). They are effective at nitrification even in cold climates (

Figure 3).

Aerated wetlands use less energy than conventional treatment processes, such as activated sludge. Passive processes remove BOD near the inlet zone, leaving much of the aerated wetland free for nitrification (Figure 2). Recycle of nitrified effluent to the anoxic inlet zone can be implemented to promote denitrification.

Tidal flow wetlands

Tidal flow systems employ two or more flood and drain cycles per day within the wetland bed. The cation exchange capacity of wetland media is important to design. When the wetland floods, ammonium ions (NH_4^+) adsorb to negatively charged surfaces within the aggregate/root matrix (Figure 4). When the wetland drains, the adsorbed ammonium ions remain in thin biofilms exposed to atmospheric oxygen. Rapid oxygen saturation of biofilms induces nitrification.

In the next flood cycle, nitrate ions (NO_3^-) desorb into bulk water. Nitrate is then denitrified by bacteria. Significantly, there is no BOD inhibition of nitrification in the drained phased, but there can be a high BOD *and* nitrate environment in the flooded phase, creating ideal conditions for denitrification.

Advantages of process machinery in treatment wetlands

The 4th generation treatment wetlands embrace the pragmatic integration of machinery into wetland treatment processes. The need to nitrify has been the principal driving force behind this development. The benefits, however, go beyond nitrification.

Aerated and tidal flow wetlands are hydraulically efficient because they resist formation of preferential flow paths that commonly short-circuit passive SSF wetlands. Aerated wetlands do so by mixing perpendicular to the flow, tidal systems by complete flooding and draining of the wetland. As a result, aerated and tidal flow wetlands can be twice as deep (about 1.2 m) as passive horizontal SSF wetlands without losing hydraulic efficiency. Deeper systems occupy less area, thereby broadening the number of potential wetland treatment sites.

The higher oxidation reduction potential of aerated or tidal flow wetland systems (> -200 mV) suppresses hydrogen sulfide (H_2S) formation. Hydrogen sulfide is toxic to plants, and high concentrations of H_2S in the root zone forces plants to grow “on tiptoe” in highly reduced wetland environments. When H_2S formation is eliminated through aeration or tidal flow, plant roots have no problem growing deep into the wetland bed.

The energy efficiency of aerated and tidal flow systems is higher than equivalent activated sludge nitrogen removal systems. Passive BOD removal mechanisms, low yield with *in situ* degradation of biosolids, and the absence of mixing requirements require substantially less energy than conventional activated sludge systems; however, wetland systems have larger area requirements than conventional treatment processes. Tidal flow systems may use up to 70% less energy for nitrogen removal because of the use of efficient pumps and the occurrence of nitrification during the drained phase. Similarly, aerated wetlands use much less energy than activated sludge systems. More operational experience is needed to rigorously assess the energy efficiency of these technologies.

Future Outlook

Future developments in wetland technology will depend on improved scientific knowledge of internal treatment mechanisms. Designers need to be able to understand which wetland technologies best fit targeted wastewater parameters. There are markets that offer excellent opportunities for increased expansion of wetland treatment technology.

There is an increasing need worldwide to treat and reuse wastewater locally for irrigation. Nitrogen demand is both seasonal and varies with crop maturity. Control of both nitrification and denitrification is operationally possible to meet irrigation needs with 4th generation wetland technologies. Recent demonstration of helminth egg removal in SSF wetlands indicates that these technologies may be effective means to meet World Health Organization treatment criteria for agricultural wastewater reuse in developing countries.

Groundwater remediation is one area in which 4th generation wetlands have distinct advantages. At the site of a former oil refinery in the State of Wyoming, U.S.A, an 11,000 m^3/d aerated wetland treats benzene contaminated groundwater to non-detect standards. Aeration provides a kinetic advantage for treatment of benzene and related compounds (

Figure 6). Full remediation of the site will take 50 - 100 years of continuous pumping and treatment. Thousands of legacy contamination sites around the world will require similar treatment timelines.

The low operational and capital cost of aerated wetlands gives them a competitive advantage over more complicated technologies. As a “green” technology, wetlands can be integrated into much-coveted public open space (Figure 5). Advanced wetland technologies are likely to be the remediation treatment technology of choice in the 21st Century.

Science has recently provided wetland engineers with biomolecular probes to decrypt the microbial basis of treatment processes. Recent wetland research (Figure 7) and the unfolding revolution in molecular and environmental microbiology suggest that these techniques will powerfully inform wetland engineering designs in the future.

Future generations of treatment wetland will be based on a comprehensive knowledge of internal wetland treatment mechanisms. Advances in environmental microbiology and knowledge imported from other environmental fields will result in a wide variety of systems descended from 3rd and 4th generation designs. Passive methods will remain important, but as an informed design choice, not a technology limitation. The contribution of 4th generation designs will be a menu of mechanical methods design engineers use to maintain internal conditions favorable to the biochemical mechanisms essential to achieve treatment goals.

Conclusions

A 4th generation of treatment wetland technologies is emerging to build upon the successes of earlier wetland technologies. These new 4th generation wetlands can address current market needs or open new market niches, while addressing the limitations of earlier wetland systems. The judicious integration of machinery into heretofore passive wetland processes is a distinguishing characteristic of these emerging technologies. Moreover, increasing scientific sophistication of treatment wetland designers is likely only the beginning of a more profound understanding in the near future of how these complex bioreactors function at a molecular level. Better knowledge is already leading to new applications for engineered wetlands. This trend shows every sign of continuing into the foreseeable future.

Figure 1. Treatment efficiency and size by wetland type. Engineered wetlands are taken here as having some kind of process machinery. Figure courtesy of Jim Higgins.

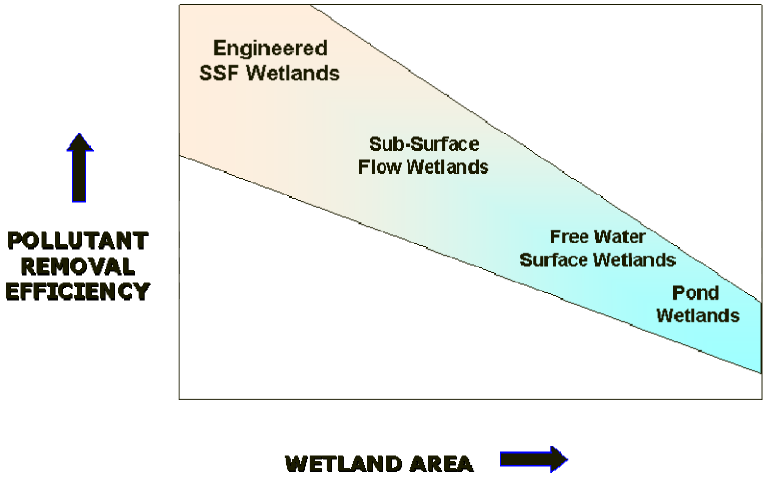

Figure 2. Aerated wetland schematic (Forced Bed Aeration™, North American Wetland Engineering). This process is patented in the United States and Canada.

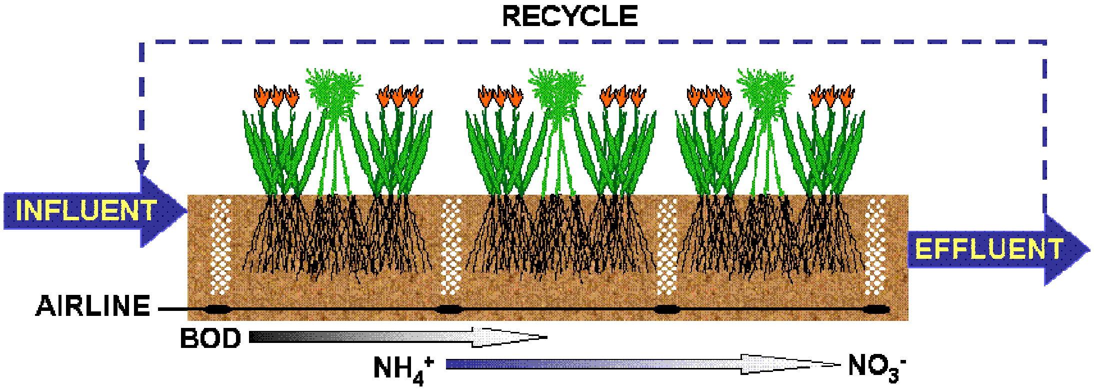

Figure 3. Total nitrogen removal with an aerated wetland system in Minnesota, northern United States. Mulch insulation of the wetland prevents freezing. Nitrification continues well below 10° C. Figure, North American Wetland Engineering.

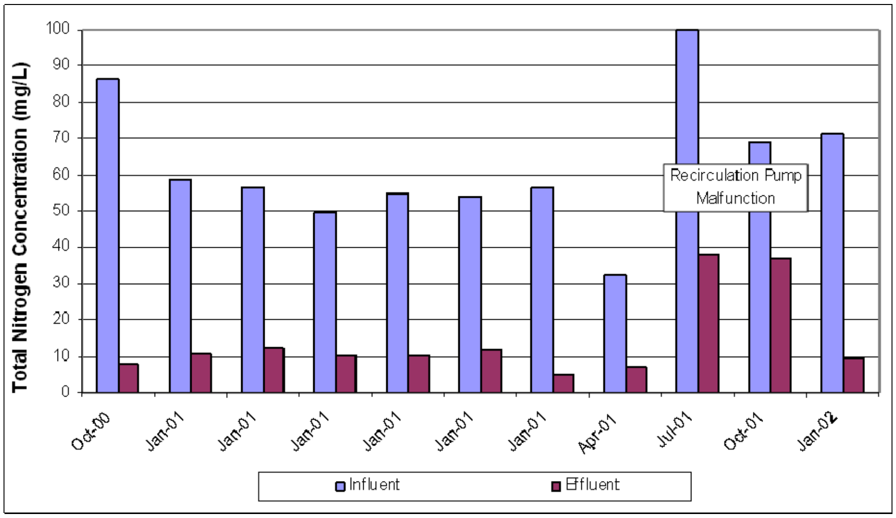

Figure 4. Nitrification and denitrification in tidal flow systems. Tidal flow configurations are covered by several United States and international patents. There are also public domain configurations in all countries. Figure courtesy of DLS, Inc.

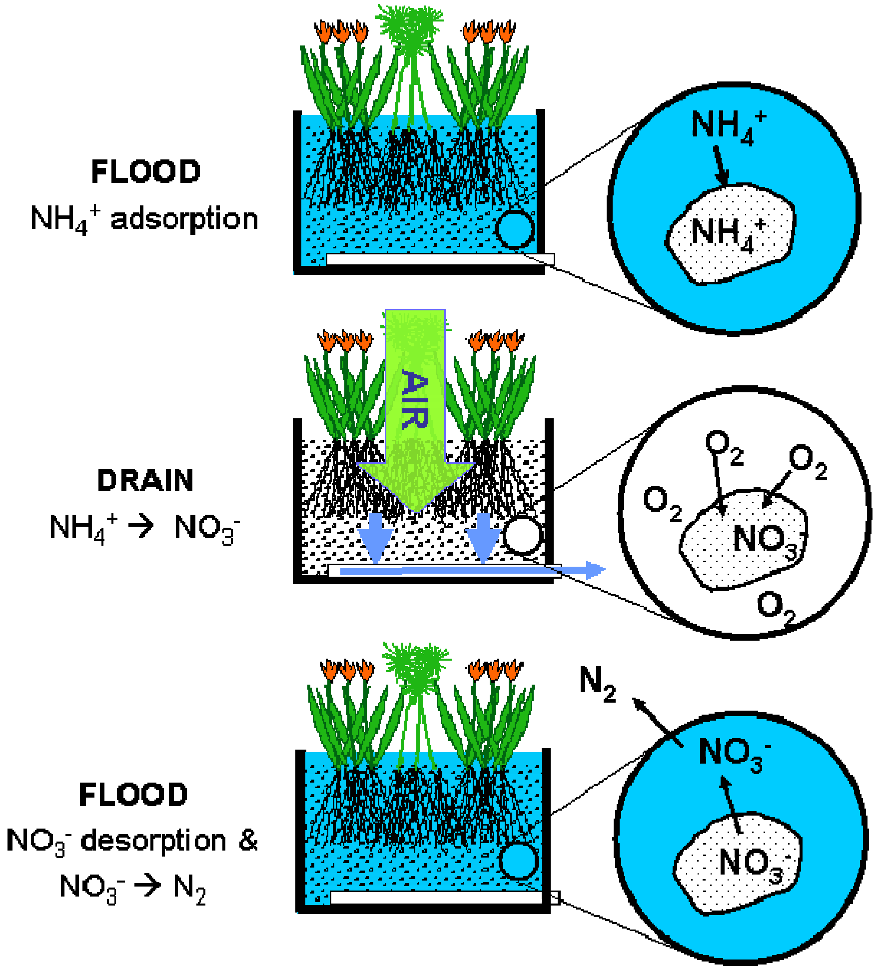

Figure 5. Aerated wetland for groundwater remediation in Casper, Wyoming U.S.A. Photo taken post-construction 2003, North American Wetland Engineering.

Figure 6. Improved reaction rate of benzene. Figure North American Wetland Engineering.

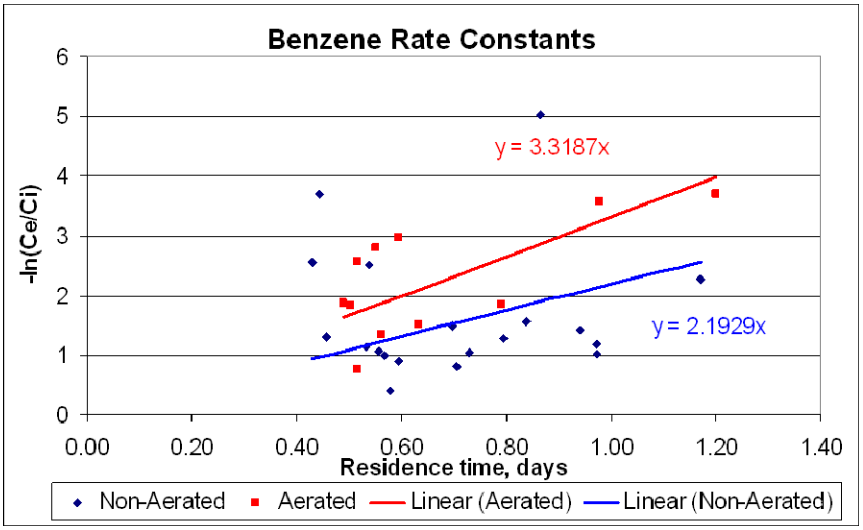

Figure 7. Functional grouping of bacteria from quantitative biomolecular probes (FISH) in a tidal flow wetland. Each category is percent of all bacteria. By tracking functional bacterial consortia, a mechanistic understanding of treatment mechanisms can be obtained. Figure courtesy of Living Machines, Inc.