

TIDAL WETLAND LIVING MACHINE SYSTEM® SYSTEM DESCRIPTION AND SCIENTIFIC BASIS

The Tidal Wetland Living Machine system is comprised of multiple flood and drain (tidal) wetland cells (Figure 1). Tidal wetland cells flood and drain in a serial fashion. A recycle loop passes water several times through the treatment system. The Tidal Wetland Living Machine system (TW LM) achieves advanced biochemical oxygen demand (BOD), total suspended solids (TSS), and total nitrogen removal at a fraction of the energy cost of conventional technologies. This technology is protected by two US patents with other patents pending.

Simultaneous nitrification and denitrification is a key feature of the TW LM system. Nitrification occurs in drained wetland cells while denitrification occurs in flooded wetland cells. The mechanisms of this process differ from conventional aerated treatment processes and are therefore explained in detail below.

TIDAL OXIDATION PROCESS

The TW LM uses flood and drain methods to transfer oxygen to wastewater (Figure 2). Cation exchange chemistry and thin film aeration are key mechanisms for nitrification and denitrification in tidal wetland cells (Austin 2006, Austin *et al.* 2003, Tanner and McBride 2000, Tanner *et al.* 1999). In the tidal oxidation process, ammonium ions (NH_4^+) in bulk water adsorb to negatively-charged aggregate surfaces. When the tidal cell drains, adsorbed ammonium ions remain in thin biofilms that quickly saturate with oxygen on exposure to air. Nitrifying bacteria in biofilms convert ammonium (NH_4^+) to nitrate (NO_3^-) and nitrate ions desorb into bulk water when the tidal cells flood again. Nitrate is then denitrified by bacteria action in cells with high labile organic carbon (BOD) content.

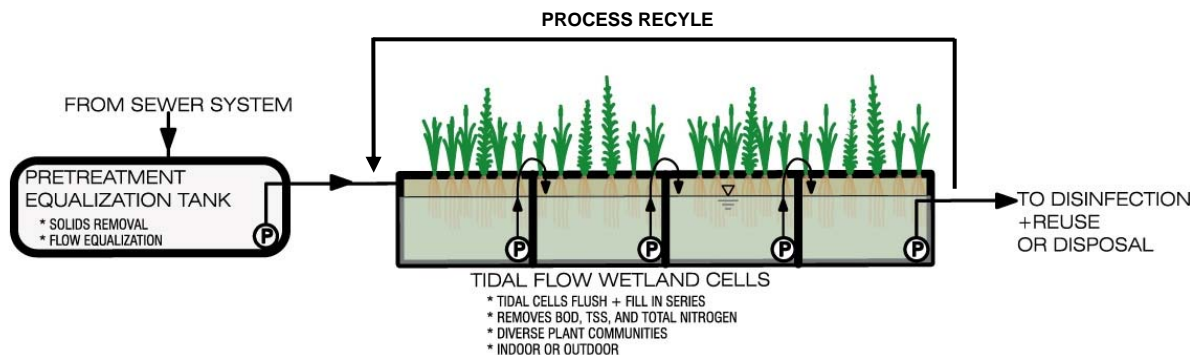


Figure 1. Tidal Wetland Living Machine system schematic. Primary treatment depicted here for small flows may be comprised of a variety of technologies per scaling criteria. Step feed to wetland cells is not depicted.

The effect of this sorption chemistry on oxygen demand is best understood by first considering oxygen transfer to water. Oxygen transfer is limited by the low solubility of oxygen in water. Clean, cold freshwater saturates at 10 to 12 mg/L O_2 . Saturation of oxygen in wastewater is substantially less.

In contrast to oxygen, nitrate is highly soluble in water. Organic nitrogen and ammonia (TKN-N) are typically present in wastewater in concentrations from 20 to 85 mg/L (Crites and Tchobanoglous 1998), which is several times that of the saturation value of oxygen in wastewater. On a mass basis, nitrate has the same oxidizing

capacity of 2.86 kilograms of oxygen (US EPA 1993). Oxygen equivalency of nitrate significantly reduces oxygen demand (Equations 1 & 2). In activated sludge systems, formation of nitrate produces a net demand on dissolved oxygen even with denitrification in a process recycle (Equation 1).

Equation 1. **Bulk water oxygen demand for activated sludge (Metcalf and Eddy, 2003)ⁱ.**

$$\text{mg/L O}_2 \text{ demand} = (\text{COD influent} - \text{COD effluent}) + 4.6(\text{NO}_3)_f - 2.86(\text{NO}_3)_u$$

Where: COD = chemical oxygen demand, mg/L

$(\text{NO}_3)_f$ = nitrate formed, mg/L

$(\text{NO}_3)_u$ = amount of nitrate utilized, mg/L.

The nitrification oxygen demand term $(4.6(\text{NO}_3)_f)$ for bulk water oxygen demand drops out in the TW LM system because nitrate is formed in drained wetland cells. Formation of nitrate then becomes a net reduction to dissolved oxygen demand (Equation 2).

Equation 2. **Bulk water oxygen demand for a TW LM system.**

$$\text{mg/L O}_2 \text{ demand} = (\text{COD influent} - \text{COD effluent}) - 2.86(\text{NO}_3)_u$$

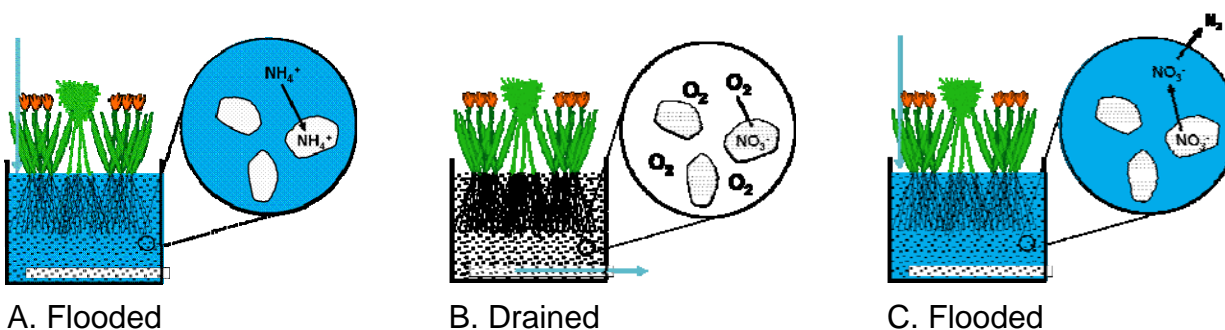


Figure 2. Oxygen transfer by sorption chemistry and thin film diffusion. A. Ammonium ions (NH_4^+) adsorb to aggregate surfaces from bulk water. B. Adsorbed NH_4^+ ions nitrify as oxygen saturates thin biofilms. C. Nitrated ions (NO_3^-) that desorb into bulk water are denitrified by bacterial action.

Table 1. Comparison of theoretical bulk-water oxygen demand between a TW LM system and a Modified Ludzack-Ettinger (MLE) activated sludge system.

System	Influent COD, mg/L	Effluent COD, mg/L	Influent TKN, mg/L	% nitrification	Nitrate formed, mg/L	Effluent nitrate, mg/L	Bulk water oxygen demand, mg/L
MLE	400	10	45	95%	42.75	5.0	479
TW LM	400	10	45	95%	42.75	5.0	282
Equation 1	$\text{mg/L O}_2 = (400-10) \text{ mg/L} + 4.6(42.75) \text{ mg/L} - 2.86(42.75-5.0) \text{ mg/L}$						
Equation 2	$\text{mg/L O}_2 = (400-10) \text{ mg/L} - 2.86(42.75-5.0) \text{ mg/L}$						

The difference in oxygen demand as calculated by the above equations for the treatment of average strength wastewater is 41% (Table 1). Differences in the COD:TKN-N ratio between various wastewaters will alter the reduction in oxygen demand by nitrate. Demonstration systems have established that the remaining oxygen demand can be satisfied by turnover of the water column and diffusion of oxygen into thin films in flood and drain cycles (Austin *et al.* 2003).

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The role of sorption chemistry in the tidal oxidation process underscores the importance of the surface charge to design. The cation exchange capacity (CEC) of aggregate measures the effect of surface charge on the adsorption of cations, such as ammonium. Because adsorption of ammonium ions is the principle mechanism for nitrification, a wetland media or aggregate without a substantial CEC severely impairs nitrification even after accumulation of organic material (Austin 2006). The TW LM aggregate specification is therefore restricted to expanded shale, clay, or slate that meet ASTM C-330-04. This standard is used to specify aggregate for the manufacture of lightweight concrete. Surface charge is not a specification of this standard. Rather, certain manufactured aggregates meeting this standard have both the desired surface and physical properties that make them ideal for this application.

PROCESS MICROBIOLOGY

Current WWT research suggests that process microbiology for the TW LM system operates in a significantly different manner than the conventional wetland treatment processes. Heterotrophic nitrification and associated aerobic denitrification plays an important role in nitrogen removal. In the tidal oxidation process wetland biofilms oscillate between states of high dissolved oxygen and anoxia as long as the wastewater exerts significant oxygen demand. These conditions favor heterotrophic nitrification with associated aerobic denitrification rather than facultative denitrification. Similar community development has been found in activated sludge systems subject to alternating anaerobic/aerobic conditions (Frette et al. 1997).

Facultative denitrifiers mobilize membrane-bound nitrate reductase (NAR) under anoxic conditions over a 4 to 8 hour period (Robertson and Keunen 1990) and any dissolved oxygen suppresses NAR. Repeated exposure to oxygen in drained phases within periods of less than 4 to 8 hours is likely to interfere with NAR mobilization. In contrast, aerobic denitrification is constitutive by means of periplasmic nitrate reductase (NAP), which is not suppressed by the presence of oxygen (Richardson 2000). In the tidal oxidation process, producing both nitrate and oxygen reductases provides a competitive advantage over facultative denitrifiers. Moreover, denitrification is not inhibited by high oxygen concentrations. High rates of denitrification occur in cells that are frequently exposed to atmospheric oxygen. Exhaust gas analyses of wetland cells confirm denitrification in the presence of high concentrations of oxygen (Austin *et al.* 2003).

Biomolecular probes have confirmed that 17% of all system bacteria are comprised of the aerobic denitrifier (and heterotrophic nitrifier) *Paracoccus denitrificans*. A small population of aerobic ammonia oxidizers such as *Nitrosomonas sp.* was found as well, comprising approximately 5% of system bacteria. Common nitrite oxidizing bacteria such as *Nitrobacter sp.* were not found and facultative denitrifiers accounted for no more than 5% of all bacteria. These results confirm the importance of heterotrophic nitrification and aerobic denitrification that is seen experimentally (Austin *et al.* 2006).

SYSTEM DESIGN

As with any wastewater treatment system, the principle elements of system design are hydraulics and mass loading rates. The TW LM system hydraulic design is based primarily on recycling rate capacity. Process recycle rates will vary by wastewater characteristics from three to twelve times forward flow. Mass loading rates are based on BOD and TKN-N. The sustainable volumetric BOD loading rate is set at $r_{XBOD} = 0.11 \text{ kg/m}^3 \text{ aggregate day}$ based on empirical data. A safety factor is then applied to this loading rate to ensure maintenance of long-term aggregate hydraulic conductivity. Nitrification capacity is currently set by mass loading criteria as well. Current research has established that a tidal cell with a CEC of approximately 4 meq/100 grams aggregate and operated at six flood and drain cycles per day will have a nitrification rate of approximately $r_{XNH4} = 45 \text{ g NH}_4^+ \text{-N/m}^3 \text{ aggregate} \cdot \text{day}$.

An environmental enclosure is not needed for the TW LM system if planted with native wetland vegetation and located in a suitable environment. Thermal simulation models have been developed in conjunction with Thermal Energy System Specialists, Madison, WI to quickly evaluate climate and site conditions.

The overall treatment system consists of four or six tidal wetland cells. Each cell is a lined excavation with a highly porous traffic rated HDPE under drain system. Influent and recycle (Cell 1 only) is distributed to the

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cells through a sump hydraulically connected to the under drain system or for the final cell through a surface distribution system. Each cell is connected to a pump sump that lifts water from one cell to the next, thereby draining one cell and filling the next.

Pumps are controlled by a programmable logic controller (PLC) with inputs from level sensors in each wetland cell. Cells fill and drain in a serial fashion. The even number of cells facilitates system controls. Overflow is prevented first by program logic, then by overflow structures from cell to cell. Effluent flows from the TW LM system via an overflow drain from the final cell. Pumped discharge from the final cell is available to drain or for other site considerations. Prior to discharge, effluent is disinfected to design standards.

The TW LM system may be designed with or without intermittent free water surfaces. Free water surfaces allow for a larger working volume, passive surge control, and a more diverse community of detritivores. In some locations, free water surfaces may present issues of public exposure to wastewater and can be designed out. Intermittent free water surfaces are unlikely to create conditions favorable for the breeding of disease vectors or nuisance organisms.

The areal requirements of the TW LM system are less than those of conventional vegetated submerged bed (VSB). Hydraulic areal loading rates should be considered cautiously because mass loading rates that actually determine wetland sizing vary widely with wastewater characteristics. Nevertheless, hydraulic loading rates do provide convenient comparisons with average strength effluents. It is safe to say that a TW LM system is less than one quarter to one eighth the size of a VSB system. There are two reasons why it can be smaller. One reason is that the TW LM system can have much greater media depth than a VSB system because of vertical flow. Also, plant roots penetrate much two to three times deeper than in a VSB system. The second reason is that reaction rates are higher in an anoxic/aerobic treatment system than in an anaerobic treatment system. High reaction rates translate into lower hydraulic retention time (HRT) and thus less area. Demonstration systems have revealed that a 24-hour retention time is sufficient to achieve full treatment in a TW LM.

Primary treatment is an important design consideration. The TW LM system is essentially a series of packed bed filters. Preliminary treatment must remove grit and other inorganic material first to avoid clogging. In small systems, an interceptor tank will serve this function. In larger systems, grit must be removed by other means. Pressure washed, advanced screening will serve to remove other inorganic material. Collection systems that employ interceptor tanks, such as STEP or STEG¹ systems, will perform all of these functions adequately.

ENERGY REQUIREMENTS

As a point of comparison, electrical power requirements for the TW LM were compared with a conventional activated sludge treatment system using a modified Ludzack-Ettinger (MLE) process. Design influent and effluent characteristics are detailed in Table 2. Electrical requirements for the MLE and TW LM system are detailed in Tables 3 and 4 respectively.

Table 2. Design Influent and Effluent Characteristics

System	Flow m³/d	COD_{in}(a) mg/L	COD_{out} mg/L	TN_{in}(c) mg/L	TN_{out} mg/L
MLE ^(b)	1000	300	10	60	10
TW LM	1000	300	10	60	10

(a) COD is assumed to be completely labile.

(b) Aerobic digestion and local land application of biosolids.

(c) Influent total nitrogen (TN) is assumed to be all TKN.

¹ STEP – septic tank effluent pump. STEG – septic tank effluent gravity.

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The computed electrical power requirement for the TW LM system is 20%-30% of that of MLE system. This low energy requirement is due to reduced oxygen requirements, better electromechanical efficiency of pumps compared to diffused air supplied by blowers and process simplicity. There are further energy savings in the TW LM as no waste biosolids are produced.

Table 3. Power requirements for Model MLE system.

Component	Power Draw, kW	Number of Units Operating	Operational Time hr/d	Power Consumed kWh/d
Anoxic Mixers ^(a)	3.7	2	24	178
Aeration Blowers	22.4	1	24	487
Clarifier Drive	2.2	2	24	108
Process Recycle Pump ^(b)	4.2	1	24	75
RAS pump ^(c)	2.1	1	24	36
TOTAL				884

(a) Anoxic mixer design: Impeller diameter 1 m, 1 rpm and k value of 4.8.

(b) Process Recycle flow is 4,000 m³/d, total dynamic head 5 m, 80% pump efficiency and 90% motor efficiency

(c) Based on QRAS (return activated sludge flow) of 500 m³/d, total dynamic head 5 m, 80% pump efficiency and 90% motor efficiency

Table 4. Power requirements for Model TW LM system.

Component	Power Draw kW	Number of Units Operating	Operational Time hr/d	Power Consumed kWh/d
Process Pumps ^(a)	3.7	6	8 each, 48 total	178
TOTAL				178

(a) Six process pumps move cell pore volume to next cell and recycle from cell 6 to cell 1.

Nitrification in the MLE system is a major fraction of the energy demand due to the inefficiencies of meeting dissolved oxygen demands. Recycle of nitrified process water to an anoxic first-stage recovers some of the oxygen used for nitrification but requires pumping and mixing energy. From Equation 1, it is apparent that the theoretical DO demand due to nitrification alone is approximately 276 kg/d for the MLE system. This is 60% of total DO demand of 460 kg/d for the MLE system. In contrast, there is no nitrification component to DO demand of the TW LM which automatically results in TW LM DO demand that is 40% of MLE system.

Because oxygen is sparingly soluble in water, especially warm wastewater, significant energy is required to overcome the thermodynamically unfavorable process of meeting the dissolved oxygen demand with diffused air. Field oxygen transfer efficiencies can be increased but significant increases usually involve sophisticated or expensive equipment with inherent operation and maintenance problems.

Low head pumps can achieve hydraulic efficiencies up to 80%. Assuming a hydraulic efficiency of 70% and a motor efficiency of 90%, the overall energy-to-water efficiency is 63%. The TW LM system harnesses this efficiency by moving water to create a vast surface area of thin films to provide oxygen rather than force the oxygen into bulk water. This is highly efficient compared to a FOTE of 11% for the diffused air system.

EFFLUENT QUALITY AND BENEFITS

The TW LM system achieves reliable tertiary treatment performance. Design effluent BOD and TSS are less than or equal to 10 mg/L. Design effluent ammonia is less than or equal to 1.0 mg/L. Design effluent total nitrogen (TN) depends on influent BOD (or COD):TKN-N ratios but effluent TN will be less than or equal to 10 mg/L. Modifications to the treatment system, such as a recycle to an anaerobic pretreatment system, can be used to further reduce TN <5 mg/l.

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The principal benefits of the TW LM system include:

- Advanced tertiary treatment suitable for reuse systems.
- Operational attention is significantly reduced with no biosolids management. The combination of low energy, no biosolids removal/treatment costs, and less operator hours translates into substantially lower operations costs than activated sludge systems without sacrificing performance.
- The treatment system is covered with beautiful wetland plants. As such, it offers aesthetic enhancement of its location. Beauty and wastewater treatment are seldom associated, but here they are inseparable.

CONCLUSIONS

The Tidal Flow Living Machine is a tertiary treatment system that efficiently removes nitrogen. In comparison to activated sludge, it is a low energy treatment system that does not sacrifice performance. In comparison to conventional wetland treatment technology, it is substantially more compact. This innovative treatment technology is both aesthetically pleasing and simpler to operate than comparable activated sludge systems.

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