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ADVANTAGES OF USING SUBSURFACE FLOW CONSTRUCTED WETLANDS FOR WASTEWATER TREATMENT IN SPACE APPLICATIONS: GROUND-BASED MARS BASE PROTOTYPE

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ABSTRACT

Research and design of subsurface flow wetland wastewater treatment systems for a ground-based experimental prototype Mars Base facility has been carried out, using a subsurface flow approach. These systems have distinct advantages in planetary exploration scenarios: they are odorless, relatively low-labor and low-energy, assist in purification of water and recycling of atmospheric CO2, and will support some food crops. An area of 6-8 m2 may be sufficient for integration of wetland wastewater treatment with a prototype Mars Base supporting 4-5 people. Discharge water from the wetland system will be used as irrigation water for the agricultural crop area, thus ensuring complete recycling and utilization of nutrients. Since the primary requirements for wetland treatment systems are warm temperatures and lighting, such bioregenerative systems may be integrated into early Mars base habitats, since waste heat from the lights may be used for temperature maintenance in the human living environment. "Wastewater gardens™" can be modified for space habitats to lower space and mass requirements. Many of its construction requirements can eventually be met with use of in-situ materials, such as gravel from the Mars surface. Because the technology requires little machinery and no chemicals, and relies more on natural ecological mechanisms (microbial and plant metabolism), maintenance requirements are minimized, and systems can be expected to have long operating lifetimes. Research needs include suitability of Martian soil and gravel for wetland systems, system sealing and liner options in a Mars Base, and wetland water quality efficiency under varying temperature and light regimes. © 2003 COSPAR. Published by Elsevier Science Ltd. All rights reserved.

INTRODUCTION - CONSTRUCTED WETLAND WASTEWATER TREATMENT SYSTEMS

The past several decades has produced new approaches to wastewater treatment and utilization, stemming from a fundamental change of perspective based on a total ecosystem approach. "Wastewater" is in fact a valuable source of nutrients and water, upon which ecologically flourishing wetlands can subsist. Wetland scientists have demonstrated that not only natural but also properly designed and constructed man-made wetland ecosystems are extremely efficient at utilizing and cleaning such nutrient-rich waters (Mitsch and Gosselink, 1993). Constructed wetlands have gained increasing acceptance for many types of bioremediation, including domestic sewage, mining and agribusiness wastewater (Hammer, 1989; EPA, 1993; Reed et al, 1995).

There are three basic types of wetlands for wastewater treatment: surface flow wetlands, subsurface flow wetlands and aquatic plant wetlands. In surface flow wetlands, the wastewater runs through a shallow basin in contact with the underlying sediment. Both emergent (rooted) and floating plants can be used. In subsurface flow wetlands, the wastewater is kept below the surface of the wetland medium, generally gravel. Only emergent wetland vegetation can be used. Aquatic plant treatment systems utilize open bodies of water and can thus support only floating wetland vegetation. However, aquatic plant systems have declined in popularity due to poorer performance and necessity of removing vegetation, which is costly. Surface flow wetlands require substantially more area than subsurface flow wetlands; This is because wastewater flows over and only contacts the top layer of

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the sediment whereas subsurface flow wetlands are designed to make the wastewater flow through the entire volume of their gravel substrate. This allows the surface area of each piece of gravel in a subsurface system to function as a locale for hosting microorganisms and as a site for wastewater filtration, sedimentation and microbial interaction. An engineering rule of thumb is that surface flow wetlands require about 100 hectares (250 acres) for treatment of one million gallons (4 million litres)/day wastewater loading vs. 5-10 hectares (12-25 acres) for subsurface flow wetlands (Kadlec and Knight, 1996). Surface flow wetlands also have the detractions of potential odor, mosquito-breeding and accidental public contact. Therefore, subsurface flow wetlands seem to be the most applicable type of wetland treatment system for wastewater purification and recycling for bioregenerative space life support.

The cost of the medium (generally gravel) and water-sealing liners usually makes the cost per area more for constructing subsurface flow wetlands, but this is offset by heavier loading and thus a smaller area that subsurface flow wetlands require compared to surface flow wetlands. As a consequence, subsurface wetlands are usually a less expensive option than aquatic plant systems or surface flow wetlands (TVA, 1993, Reed et al., 1995).

RESEARCH AND DEVELOPMENT WITH WASTEWATER GARDENS APPROACH

Biosphere 2, utilizing a surface-flow wetland treatment system, was the first closed ecological system to achieve total recycle of wastewater within the life support facility. The wetland system produced fodder for domestic animals and acceptable levels of wastewater purification (Nelson et al., 1999; Nelson et al, 1994). In research subsequent to the Biosphere 2 experiment, the authors working in collaboration with the Planetary Coral Reef Foundation (a division of Biospheres Foundation) and the eminent systems ecologist, Prof. H.T. Odum of the Center for Wetlands at the University of Florida, developed an innovative approach to wastewater treatment using man-made wetlands, employing subsurface flow (Nelson, 1998a; Nelson, 1998b). This basic approach has been extensively tested and successfully applied in the United States and Europe over the past several decades (EPA, 1993). This advanced design, Wastewater Gardens™, which raises artificial subsurface flow wetlands to a complete engineered ecosystem, is now operating in over eighty sites in southern Mexico, Belize, United States, the Bahamas, Poland, France, the Philippines, West Australia and in Bali, Indonesia.

Wastewater gardens™ start with primary treatment, to separate solids, which occurs in a watertight septic tank or settling lagoon of adequate volume. But then instead of passing directly into a leachfield, with its attendant problems of little further treatment, odor, clogging and large size, the nutrient-rich wastewater effluent is fed into a lined, two-cell, subsurface flow wetland. The sewage water is kept 5-10 cm. below the surface of a bed (0.5 - 1 m deep) of gravel. The treatment compartments are planted with a wide variety of wetland plants, specially selected for the locality, into the gravel bed filled with sewage water. The wastewater gardens™ generally operate with gravity flow, and so no machinery or electricity is required, and no chemicals are used. Wastewater is generally held in the wetland systems for 5-7 days.

In detailed research conducted along the coast of the Yucatan, in southeastern Mexico, Wastewater Gardens™ were tested as a means of preventing pollution of groundwater and eutrophication damage to off-shore coral reefs. An area of 3-4 square meters of wetland per full-time resident proved capable of removing 85-90% of BOD (biochemical oxygen demand, a measure of the quantity of organic compounds in the wastewater that tie up oxygen), 75-80% of nitrogen and phosphorus, and fecal coliform bacteria was reduced 99.8+% without use of chemicals. Two Wastewater Gardens™ totaling 130 square meters, served to treat the gray and blackwater of 40 residents, and supported 65-70 varieties of wetland plants. Biodiversity during the first two years of operation was three times greater than in adjoining natural mangrove wetlands, and only 5% less than in the inland tropical forest areas (Nelson, 1998a).

RESPONSE OF WETLANDS TO WARM ENVIRONMENTAL CONDITIONS

Since such natural or constructed wetlands are often limited by solar insolation and show increased rates of uptake in warmer climates, such systems may be expected to operate more efficiently in tropical regions. In addition, it has been theorized that wastewater interface ecosystems may benefit from the high species diversity found in tropical regions since diversity at the biotic and metabolic level increases the efficiency of ecosystems (Jorgensen and Mitsch, 1991).

Nutrient removal of the Mexican constructed wetland systems compares very favorably with those of similar systems previously applied in temperate latitudes. Table 1 compares the tropical climate wastewater garden™ systems with average values for subsurface and surface flow wetlands in North America (Kadlec and Knight, 1996). BOD loading for the wastewater gardens™ is slightly higher than the average subsurface wetland and removal rates are higher (88% vs. 69%). Total phosphorus loading in Mexico was less than 40% that of average North American systems and removal was 76% vs. 32%. Nitrogen loading in the Wastewater Gardens™ was around 4/5 that of typical subsurface flow wetlands, and removal efficiency is 79% vs. 56% for North American systems. Reduction of coliform bacteria is generally 90-99% (EPA, 1993), while the Yucatan systems averaged 99.8% removal (Nelson, 1998a)

Table 1. Comparison of loading rates and removal efficiency of Mexican wastewater garden™ systems with average North American surface and subsurface flow wetlands (Kadlec and Knight, 1996).

Parameter	Wetland system	In mg/l	Out mg/l	Removal %	Loading kg/ha·day
BOD (Biochemical oxygen demand)	Surface flow	30.3	8.0	74	7.2
	Subsurface flow	27.5	8.6	69	29.2
	Wastewater garden™	145	17.6	87.9	32.1
Total Phosphorus	Surface flow	3.78	1.62	57	0.5
	Subsurface flow	4.41	2.97	32	5.14
	Wastewater garden™	8.05	1.9	76.4	1.7
Total Nitrogen	Surface flow	9.03	4.27	53	1.94
	Subsurface flow	18.92	8.41	56	13.19
	Wastewater garden™	47.6	10.0	79	10.3

Many subsurface flow wetlands in temperate climates are started with just a few plant species, often virtually monocultural systems. These systems composed exclusively of *Typha latifolia, Scirpus* spp. or *Phragmites australis* are less attractive and less beneficial for wildlife. However, some large surface flow systems have included natural wetlands and been managed to foster a wider biodiversity of plants and habitats (Kadlec and Knight, 1997; Reed et al, 1995). The research data from the wastewater gardens™ in Mexico suggests that subsurface flow sewage treatment wetlands can support a far higher biodiversity than has been widely assumed previously (Nelson, 1998a).

SPACE APPLICATIONS OF THE TECHNOLOGY

This approach to wastewater seems ideal to support long-term space exploration and habitation where bioregenerative resupply of food is utilized. This is because the wetland treatment system requires the same environmental conditions necessary for crop plant growth: light (sunlight or artificially produced) and warm temperatures. Since the wetland systems rely on green plants and microbes, they perform even better in warm, sunny conditions than the successful wetland systems in cold climates such as Canada, Germany, the United Kingdom, and northern United States. In milder conditions with higher temperatures and increased light, system effectiveness is high year-round. These environmental conditions may well be the case in "space greenhouses" as such conditions optimize crop growth and thus will also minimize greenhouse area requirements.

The low-labor requirements and absence of consumables also makes subsurface flow wetlands advantageous for space application. Once set-up, they will require no resupply from Earth of machinery or chemicals and will make little demand on valuable astronaut time.

It is probable from what we currently know of Mars surface geology that Martian soil and rocks can be mined and screened to supply the gravel substrate of the wetland systems. Mars soil evidently contains many of the micronutrients necessary for life, and what is lacking may be amended by the nutrients contained in human wastewater (Stoker et al, 1993, McKay et al, 1993). For initial wetland systems, one strategy to lower mass requirements would be through the use of lightweight media (e.g. styrofoam or perforated plastic pellets), which would provide the required microbial surface area, but without the weight of conventional rock gravel. Then when the infrastructure and machinery for screening planetary surface material/regolith is available, the fine material may provide a base from which to build the initial soils, while the larger aggregate is separated for use in expansion of the wastewater systems. The high chemical oxidative reactivity of Mars surface materials will, of course, have to be evaluated in its impact on wastewater nutrient recycling mechanisms.

The required wetland treatment area for Mars habitats can be considerably smaller than in most terrestrial applications, if the wetland discharges to the main food-cropping agricultural system. In this case, the holding tanks and small wetland area can serve to separate solids and initiate microbial purification of the wastewater. There would be no need for achieving high nutrient uptake, as the effluent water from the wetlands would carry those nutrients to the soils of the agriculture system, helping to maintain soil fertility.

The plants grown in the wetlands (e.g. rice, banana etc.) would add to overall food production. In Biosphere 2, the wetland treatment system functioned as part of the sustainable food production system through the production of forage for domestic animals, and by the utilization of excess nutrients remaining in the wastewater effluent for crop irrigation (Silverstone and Nelson, 1996). Wetland systems have the advantage of handling a wide variety of potential pollutants because of its multiplicity of treatment mechanisms and diversity of microbiota. The Biosphere 2 treatment wetland handled all wastewater from the human habitat (toilet, kitchen, shower, laundry), domestic animal urine + pen washdown water, and effluent from medical/analytical laboratories and workshops inside the facility (Nelson and Dempster, 1996; Nelson et al, 1999).

There are also synergetic benefits of the use of this wetland treatment system for air purification and potable water production. The wetlands will help recycle and purify the internal air of the space habitat. The high transpiration rates of wetland plants release pure water to the internal habitat atmosphere that can be condensed as a source of potable water (as was successfully done in Biosphere 2).

For use in prototype Mars bases in remote and ecologically sensitive areas such as Antarctic and Arctic, the wetland systems may assist in prevention of contamination of local surface and groundwater resources. Subsurface flow wetlands may be located inside the prototype Mars habitat, since they have no malodor and would give the crew the pleasure of beautiful gardens. Artificial lights would be needed for wetland plant growth but their waste heat might effectively warm the interior. Wetland plants would help prevent "sick building syndrome" by absorbing trace gases that may accumulate in tightly sealed structures.

WETLAND TREATMENT SYSTEMS FOR THE MARS MODULAR BIOSPHERES PROJECT

Global Ecotechnics Corp. has been developing a prototype Mars Base Modular Biosphere to simulate a four person manned Mars mission utilizing a biospheric closed life support system. The base would be composed of four to six modular units, each 110 m^2 (1,200 ft^2) that will be linked via airlock tunnels. This test bed will determine the feasibility of maintaining humans in a self-sustaining system on a remote planet and will be used for development of systems for Martian exploration such as robotics. Each modular biosphere will be atmospherically closed to permit detailed study of biogeochemical cycles, but open to information, energy and certain material exchanges. Material exchange will include imports or exports that facilitate the experimental objectives for developing a biospheric long-term closed system on Mars. Initial research will focus on agricultural systems including cultivar selection, soil composition and nutrient cycling (Silverstone et al., 2002).

The overall design will address not only the functional requirements for maintaining a long term human habitation in an artificial environment, but the aesthetic need for beauty and diversity of foods which has been noticeably lacking in most space settlement designs. A soil-based system with field crops, horticulture garden, and ecological waste recycling system will be designed to accomplish air, water and food regeneration. Initial research is scheduled to begin in facilities at the headquarters of Global Ecotechnics Corp. south of Santa Fe, New Mexico in the U.S. Once this biospheric life support system is developed, the second phase of the project is to build and operate a Mars Base Modular Biosphere in the Great Sand Sea region of Egypt, which is the a geologically similar Earth desert region to Mars, or in other regions offering useful corollaries as extreme cold (polar regions) or reduced air pressure (high mountain areas).

The wastewater treatment for such a 4-person Mars habitation can be accomplished in 4-6 m2 of wastewater garden™ wetlands. Given reasonable wastewater loading per person (100-200 litres/day) this area should prove sufficient to give adequate reduction of BOD and suspended solids to permit integration of the discharge water with irrigation supply for the other field and horticultural crops. There is no need for maximal uptake and recycling of nutrients contained in the wastewater, as they will be used maintaining soil fertility levels. Solids (sludge) from the initial anaerobic tanks are low nutrient and may be composted and used to add organics/minerals to the Martian soils used at the base. It is likely that for at least initial planetary bases, the health of the crew will be excellent, and disinfection for control of infectious diseases will probably not be required.

Incident sunlight may be used in opaque structures on Mars with fiber optics to collect and deliver the light inside. If no incident sunlight is utilized, and all lighting for the wetland green plants are done using conventional high intensity discharge lamps, a wetland of 4-6 m^2 would require about 36-54 kwh/day electrical energy to receive 30 $mol•m^{-2}•d^{-1}$; or 60-90 kwh/day for 50 $mol•m^{-2}•d^{-1}$. This is regardless of the period (hours/day) in which the total light energy is delivered. Virtually all of this energy ultimately becomes heat within the enclosure. Some 70% - 80% is "waste" heat and most of the remaining 20% - 30% actual light energy becomes heat upon striking a surface. Even the small fraction that is photosynthetically converted to plant growth is later released as heat when the plant matter is metabolized. In the extreme cold of a Mars base there will be a great need for heat to keep the interior at habitable temperatures, and therefore there is a synergetic use for the plant growth lighting energy.

FURTHER RESEARCH NEEDS

Wetlands for wastewater treatment are deceptively simple. They have the complexity that all ecological systems possess, and being a relatively new technology further research and development studies need to be conducted. For example, there is conflicting data on the impact on system efficiency of high biodiversity of wetland plants. Research on the metabolic capacity of wetland plant species for specific pollutants is only available for a limited number of plants. The impact of temperature and light regime is not well understood, and wetland designers and engineers have developed a number of conflicting formulas for determining size and hydraulics of constructed wetlands in different climatic regimes. The Biosphere 2 wetlands were clearly light limited, producing twice as much biomass in the higher light seasons (Nelson et al, 1999) and higher productivity will clearly be obtained with enhanced light levels. The tradeoffs between the energy cost and the performance yield at differing light levels and lighting cycles need to be quantified. Advanced lighting systems such as LED lights, direct sunlight or sunlight through optical fibers may substantially reduce electrical energy demands. A practical system to deliver plant growth lighting for a Mars base is an important research objective. More research is required to determine the range of useful plants for food, fiber, and fodder that may be used. There is insufficient information on the longevity of subsurface flow wetlands (although several decades seem reasonable). Will there be gradual loss of hydraulic conductivity, and at what rates, through deposition of secondary minerals, suspended solids or filling of void spaces by deposition of peat from anaerobic carbon reduction? Strategies and experiments are needed for minimization of initial weight and volume of wetland treatment systems' liner and substrate media for space application. The feasibility and technologies for using in-situ planetary resources need to be developed. There needs to be extensive ground-based testing of candidate system configurations so that actual space application has a solid backing of both theory and experimental performance data.

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