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SUBSURFACE FLOW WETLANDS FOR WASTEWATER TREATMENT IN MARS PROTOTYPE TESTBEDS AND MARS SURFACE HABITATS

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ABSTRACT

Wastewater treatment in space, as on Earth, is needed for elimination of health hazards but could also include recycling and utilization of the valuable resources contained in sewage: nutrients and water. Prior to the Biosphere 2 experiment, 1991-94, bioregenerative life support facilities, such as the Russian Bios-3, accomplished only re-use of urine wastewater. Biosphere 2, utilizing a surface-flow wetland treatment system, achieved total recycle of wastewater within the closed ecological system. The wetland system produced fodder for domestic animals and acceptable levels of wastewater purification. Research and development subsequent to the Biosphere 2 experiment, in Mexico and Indonesia, have demonstrated the advantages of subsurface flow wetlands. These advantages include: increased treatment per unit area, lower maintenance and operating time requirements, safer production of food crops, capability of sustaining high biodiversity and elimination of odor and accidental contact. This type of ecological engineering can demonstrate the congruence of solving environmental problems on Earth and advancing space exploration and habitation. “Wastewater gardens” can be modified for space habitats to lower space and mass requirements, and can be a valuable part of overall food production, as well as assisting in air and water purification.

KEYWORDS: wastewater treatment, wetlands, Biosphere 2, closed ecological systems, nutrient recycling

WASTEWATER HEALTH AND ENVIRONMENTAL PROBLEMS – ON EARTH

Pollution of water resources by improperly or inadequately treated domestic wastewater (sewage) contaminates drinking water supplies and so is a leading cause of human disease worldwide (U.N., 1995). Health problems related to sewage are widespread, ranging from children swimming in open sewage treatment ponds, failure of leachfields due to wet season inundation, and sewage effluent pollution of groundwater, rivers and lakes with adverse impact on drinking water quality and recreational use of these resources. Water pollution includes pathogens carried by improperly treated sewage and potentially toxic chemicals. Pathogens include disease-causing bacteria, protozoa, viruses and helminths. Chemical hazards include heavy metals, organic chemicals, and nitrates in sufficient concentrations to cause illness (Krishnan and Smith, 1987).

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Especially for small, rural and isolated communities, there is great expense and difficulty in maintaining the highly technical systems that they are given. It is frequently reported that such systems are poorly maintained, their performance declines with age, and inadequate sewage treatment results. For developing countries, there is great difficulty in the high costs of sewage collection and the centralized conventional (high tech) sewage treatment facility itself (Reed et al, 1995).

In addition to issues of human health, the release of nutrients from wastewater causes eutrophication (nutrient pollution) in the environment, leading to a wide range of environmental problems. These negative impacts from wastewater discharge include coral reef decline, ecological degradation of rivers and lakes including oxygen depletion/fish kill, and giving competitive advantage to weed species over native plants in ecosystems impacted by release of human wastewater.

NEW ECOLOGICAL APPROACHES

But the past several decades has also produced development of new approaches to wastewater 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 exist. 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,).

The new disciplines of “ecological engineering” and ecotechnics seek to utilize predominately natural, ecological mechanisms in integrating human economy with the biospheric ecology. This approach turns out not only to be easy to maintain but highly efficient in turning what was previously “waste” into green plants and reusable water. Wetlands are also lower cost, in that there is far less reliance on complex technology, which is capital and maintenance-intensive, and uses much electricity/fuel. Designing the wetlands to do on-site treatment greatly reduces the costs of sewage collection. The use of ecologically constructed wetlands for human sewage treatment relies on the ability of green plants and non-pathogenic microbes rather than expensive machinery. Designed wetlands create a “buffer” ecosystem between the human economy and the environment to mitigate negative impacts, increasingly illegal as well as unpleasant and unhealthy.

WASTEWATER TREATMENT IN CLOSED ECOLOGICAL LIFE SUPPORT SYSTEMS

Prior to the Biosphere 2 experiment (1991-1994), the most advanced testbed for bioregenerative, closed ecological system space research was the Bios-3 facility operated by the Institute of Biophysics, Siberia. The 3-6 month long 2-person closure experiments in Bios-3 achieved near total air and water purification, some 50% of food production, but only recycled the crew’s urine. Solid metabolic wastes were exported from the facility (Terskov et al, 1979).

NASA scientists, led by Bill Wolverton, at Stennis Space Center experimented with wetland systems and applied them to NASA testbeds in the 1980s, but not in the context of human closure and life support experiments (Wolverton, 1990). The wetland treatment approach was further developed by the creators of Biosphere 2, and tested in a very small system for one-person closure experiments of 1-21 days in the Biosphere 2 Test Module before application for the design crew size of 8-10 people in Biosphere 2 (Alling et al, 1990, Nelson et al, 1994).

In Biosphere 2, the wastewater 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 (Nelson, in press). The system 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. The system used anaerobic holding tanks (which functioned in a similar fashion to septic tanks) as a first step, then circulated the wastewater between three interconnected fiberglass tanks which contained the wetland system. The system contained soil-rooted emergent wetland vegetation and floating aquatic plants in the water channels. Wastewater input averaged around 260 gallons/day (1 m3/day) into a total wetland area of 41 m2 and produced 1213 kg of vegetation during the 2-year experiment that was periodically cut for fodder to feed domestic animals. Available sunlight was a limiting factor for plant growth, as only 40-50% of outside sunlight was received inside Biosphere 2. Biochemical oxygen demand (BOD), a measure of total organics in the water, was reduced by 75% from influent levels from the holding tanks. Final disinfection (if needed) was with high intensity UV lights (Nelson et al, 1998b). Since the health status of the crew was known, and no infectious diseases were present, the disinfection was not used during the two-year closure.

The 2-year closure of Biosphere 2 (1991-3) marked the first time that all wastewater was successfully recycled within a closed ecological life support system for people. The wetland treatment system continued to be used during the seven month second closure experiment with a 7-person crew (March-September 1994). The system included 15 species of vascular wetland plants, and provided additional wildlife habitat (Nelson, 1998b).

RESEARCH AND DEVELOPMENT WITH WASTEWATER GARDENS (APPROACH)

In research subsequent to the Biosphere 2 experiment, the author 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). This basic approach, which the Institute of Ecotechnics has refined, has been extensively tested and successfully applied in the United States and Europe over the past several decades (EPA, 1993). The Institute's advanced design, Wastewater Gardens, which raises artificial wetlands to a complete system, is now operating in over forty sites in southern Mexico, Belize and in Bali, Indonesia.

The Ecotechnics' system uses simple but very effective design principles. Primary treatment, to separate solids, occurs in a conventional, watertight septic tank or settling lagoon. But then instead of passing directly into a leachfield, with its attendant problems of little further treatment, smell, clogging and large size, the nutrient-rich wastewater effluent is fed into a lined, two-cell, subsurface flow wetland. In this type of 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. As entering effluent overflows the first stage cell, it passes to the second, and then to a comparatively small subsurface discharge or the treated water can be recycled for further irrigation of lawns, shrubs, flowers or trees. Wastewater is generally held in the wetland systems for 5-7 days.

Subsurface flow systems have long hydraulic residence times and through a variety of mechanisms (Table 1) have achieved large reductions in coliform bacteria without the use of disinfectants like chlorine used in conventional sewage treatment (Reed et al., 1995). Chlorine has the potential to form toxic byproducts, such as chloramine, when released into marine environments (Berg, 1975). Bacteria can break down chlorinated hydrocarbons into compounds that may be far more dangerous than the original ones (Gunnerson, 1988), and sometimes de-chlorination has been required by regulatory agencies, further adding to the expense of such approaches (Kott, 1975). Subsurface wetlands use little or no electricity and technology and require little technical supervision once installed (Cooper, 1992, Steiner and Freeman, 1989; Green and Upton, 1992; Steiner et al, 1992).

WASTEWATER GARDEN™ SYSTEM ADVANTAGES

Advantages of the ecological subsurface flow wetland approach include:

1) Fecal coliform bacteria are reduced more than 99% in the wetlands, without the use of expensive, environmentally harmful chemicals like chlorine. Biochemical oxygen demand (BOD) reduced 85-90% from influent levels, and removal of nitrogen and phosphorus is substantial.

2) The wetlands are low-cost, low-tech and long-lived. Maintenance requirements are simple. These systems require only 5-10% of the labor and expense of more technical wastewater treatment systems.

3) There is no malodor as the sewage is kept from contact with the air.

4) There are no mosquito-breeding or other nuisances associated with open wastewater (e.g. sewage lagoons or surface-flow wetlands).

5) The possibility of accidental public contact with the sewage is virtually eliminated as the sewage is kept below the surface of the gravel bed.

6) Subsurface flow wetland systems are capable of extremely high rates of wastewater cleaning. In research over the past several decades, this type of wetland, even in its earlier design forms,

has a well-documented track record of consistently cleaning water to levels better than municipal standards for wastewater treatment.

7) The intensity of treatment is such that only 1/2 - 1/5 the area is required compared to a surface-flow wetland (Kadlec and Knight, 1996). Every particle of gravel becomes colonized by the natural variety of microbes that are effective in utilizing and treating wastewater, and the root systems and water/nutrient uptake of the plants increase treatment efficiency.

8) Where higher treatment than normal municipal standards is required for special purposes, an increase in wetland area can provide the equivalent of advanced water treatment.

9) Significantly less wastewater (35-70% depending on design) is discharged from these special wetlands, because the plants use large quantities of water in their transpiration.

10) Subsurface wetlands can be exactly sized from small units for a single residence to larger areas for small city/town systems. On the other hand, new demands can easily be met by simple unit expansion.

11) The wetland systems add considerably to the landscape beauty in communities where they are used, and can also include plants to be harvested for useful or saleable products.

In detailed research conducted along the coast of the Yucatan, in southeastern Mexico, and critically checked by University of Florida scientists, Wastewater Gardens™ were tested as a means of preventing pollution 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, 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 was three times greater than in adjoining natural mangrove wetlands, and only 5% less than in the inland tropical forest areas (Nelson, 1998a).

Table 2 compares the prototype Wastewater Gardens researched in the Yucatan, Mexico with average values for subsurface and surface flow wetlands in North America (Kadlec and Knight, 1996, Nelson, 1998a). BOD loading for the Yucatan wetlands is slightly higher than the average subsurface wetland and removal rates are higher (88% vs. 69%). Total phosphorus loading in the Yucatan was less than 40% that of average North American systems and removal is 76% vs. 32%. Nitrogen loading in the Yucatan is around 4/5 that of typical subsurface flow wetlands, and removal efficiency is 79% vs. 56% for North American systems. 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 plants, specially selected for ecosystem fit and productivity, used in the Wastewater Garden systems are key to their performance. In addition to direct uptake of the nutrients contained in the sewage water, wetland plants act like oxygen-pumps, supplying their root systems with the aeration required for growth. In the process, the plants create micro-zones for aerobic bacteria to flourish. Thus, the wetland has both anaerobic and aerobic biochemical reactions, which aids in recycling of nutrients and treatment of the wastewater.

The opportunities for beneficial and productive use of the wetland plants give a great range of choice. The wetlands can be used for creating beautiful gardens and landscape diversity of home, business, hotel or town. The gardens can also feature productive plants, such as flowers for sale, fiber/fodder plants and timber trees. Plants harvested above the dry surface of the gravel pose no danger of wastewater contamination, and so food crops can be grown. Other opportunities include botanic garden displays, and for creating additional areas of wetland ecosystems, with rich biodiversity, wildlife and bird habitat, to compensate for wetland loss elsewhere.

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 micro-nutrients 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 is by using lightweight plastic (e.g. Styrofoam) which would provide the required microbial surface area, but without the weight of conventional rock gravels.

A further consideration favoring bioregenerative approaches to wastewater treatment for space habitats is that many of the more technical approaches previously advocated, such as wet oxidation and supercritical oxidation, in addition to requiring more technical maintenance, labor and power, result in the reduction of the wastewater nutrients to simple molecular form, with a consequent loss of chemical bond energy (Swartzkopf and Cullingford, 1990). This is not true of wetland systems that recycle the valuable nutrients in forms available for bacteria, algae and higher plants.

The required wetland treatment area for Mars habitats can be considerably smaller than in most terrestrial applications, if the wetland is connected 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. 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 (such as the Arctic base currently envisaged by the Mars Society for Devon Island in the Canadian 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 accumulate in tightly sealed buildings. In addition, developing wetland systems for use in the outside Arctic environment could be useful in preventing water pollution from the other members of the scientific research teams. Such specially developed wetland systems, using plants native to the region, might elicit interest for use in indigenous communities, National Park facilities and mining towns in the north of Canada.

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TABLES

Table 1. Contaminant removal mechanisms in subsurface flow wetlands.

Mechanism	**Contaminant Affected**	**Description**
Physical Sedimentation	Settleable solids, colloidal solids, BOD, nitrogen, phosphorus, organics, bacteria and virus	Gravity settling solids
Filtration	Settleable solids, colloidal solids	Particulates filtered mechanically As water passes through substrate and plant roots
Absorption	Colloidal solids	Interparticle attraction force
Chemical precipitation	Phosphorus, heavy metals	Formation of co-precipitation products with insoluble compounds
Adsorption	Phosphorus, heavy metals, refractory organics	Adsorption on substrate and plant surfaces
Decomposition	Refractory organics	Decomposition or alteration of less stable compounds by oxidation/reduction
Biological Microbial Metabolism	Colloidal solids, BOD, nitrogen, refractory organics, heavy metals	Removal of colloidal solids by bacteria. Bacterial nitrification and denitrification, microbially mediated oxidation of metals
Plant metabolism	Refractory organics, bacteria and virus	Uptake and metabolism of organics by plants
Plant absorption	Nitrogen, phosphorus, heavy metals, refractory organics	Uptake by plants
Natural die-off	Bacteria and virus	Natural decay of organisms in unfavorable environments

(after Watson et al., 1989)

Table 2. Comparison of loading rates and removal efficiency of Yucatan, Mexico Wastewater Gardens(with average North American surface and subsurface flow wetlands (Nelson, 1998a, Kadlec and Knight, 1996).

Parameter	Wetland system	In Mg/l	Out Mg/l	Removal %	Loading kg/ha/d
BOD (Biochemical oxygen demand)	Surface flow	30.3	8.0	74	7.2
	Subsurface flow	27.5	8.6	69	29.2
	Tropical 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
	Tropical 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
	Tropical Wastewater Garden	47.6	10.0	79	10.3