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# "LIVING OFF THE LAND": RESOURCE EFFICIENCY OF WETLAND WASTEWATER TREATMENT

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## ABSTRACT

Bioregenerative life support technologies for space application are advantageous if they can be constructed using locally available materials, and rely on renewable energy resources, lessening the need for launch and resupply of materials. These same characteristics are desirable in the global Earth environment because such technologies are more affordable by developing countries, and are more sustainable long-term since they utilize less non-renewable, imported resources. Subsurface flow wetlands (wastewater gardens™) were developed and evaluated for wastewater recycling along the coast of Yucatan. Emergy evaluations, a measure of the environmental and human economic resource utilization, showed that compared to conventional sewage treatment, wetland wastewater treatment systems use far less imported and purchased materials. Wetland systems are also less energy-dependent, lessening dependence on electrical infrastructure, and require simpler maintenance since the system largely relies on the ecological action of microbes and plants for their efficacy.
Detailed emergy evaluations showed that wetland systems use only about 15% the purchased emergy of conventional sewage systems, and that renewable resources contribute 60% of total emergy used (excluding the sewage itself) compared to less than 1% use of renewable resources in the high-tech systems. Applied on a larger scale for development in third world countries, wetland systems would require 1/5 the electrical energy of conventional sewage treatment (package plants), and save 2/3 of total capital and operating expenses over a 20-year timeframe. In addition, there are numerous secondary benefits from wetland systems including fiber/fodder/food from the wetland plants, creation of ecosystems of high biodiversity with animal habitat value, and aesthestic/landscape enhancement of the community. Wetland wastewater treatment is an exemplar of ecological engineering in that it creates an interface ecosystem to handle byproducts of the human economy, maximizing performance of the both the natural economy and natural ecosystems. Wetland systems accomplish this with far greater resource economy than other sewage treatment approaches, and thus offer benefits for both space and Earth applications. 

## INTRODUCTION

Design planning for extended space exploration on planetary surfaces and eventual long-term habitation has increasingly recognized the importance of the use of in-situ materials and locally available energy (e.g. Mckay et al, 1993; Zubrin, 1996). This strategy has multiple benefits. There are savings in mission costs as the mass and volume of materials that must be launched from Earth can be reduced. In addition, utilizing resources available in space opens the possibility of increasing permanent infrastructure on a continuing basis.

To date, there has been little attempt in space missions to recycle human waste products. Even in bioregenerative life support research conducted by the major space agencies, relatively little work has been done (Nelson, 1997). In the most advanced Russian facility, Bios-3 in Krasnoyarsk, Siberia, closed ecological system experiments involving 2-3 crew for closures of 4-6 months only recycled urine which was added to the irrigation supply for crop plants, while solid waste was exported from the system (Terskov et al, 1979). The integration of waste recycling has not yet occurred in NASA CELSS (Controlled Ecological Life Support Systems) human closure and life support research.

Part of the challenge these testbeds have faced is that they use hydroponic systems for plant growth, necessitating the breakdown of waste products into forms that can be integrated into the required nutrient solutions. The more technical approaches frequently advocated among space scientists, such as wet oxidation and supercritical oxidation, in addition to their requirements for sophisticated technology, labor and power, result in the reduction of the wastewater nutrients into simple molecular form, with a consequent loss of chemical bond energy (Schwartzkopf and Cullingford, 1990).

## CONSTRUCTED WETLANDS FOR SEWAGE TREATMENT

An alternative approach has been developed by both environmental and space scientists, utilizing constructed wetlands for wastewater treatment and recycle. NASA scientists, led by Bill Wolverton at Stennis Space Center, experimented with wetland treatment systems but not in the context of human closure and life support experiments (Wolverton, 1990). In the Biosphere 2 project, constructed wetlands were further developed and tested in the Biosphere 2 Test Module for one-person closures of 1-21 days (Alling et al, 1990; Nelson et al, 1994). In the two year closure with eight people in Biosphere 2 from 1991, anaerobic holding tanks accomplished solids separation, and constructed surface-flow wetlands recycled all human, domestic animal and laboratory/workshop wastewater (Nelson et al, 1999).

Reliable and inexpensive methods of wastewater treatment are of importance for solving human disease and environmental problems as well as for sustainable long-term space life support. At present, lack of effective and affordable means of sewage disposal is widespread through the tropical, developing world. This leads to chronic disease through human contact with polluted water and environmental damage to sensitive ecosystems. Contamination of water resources is one of the leading causes of disease in tropical countries (UN, 1995) and is destroying marine habitats such as coral reefs (Alling et al, *in press*)

One of the principal advantages of constructed wetlands is that, because they rely on more natural methods, they are less expensive to build and operate than conventional sewage treatment plants (Tchonbanoglous, 1991). Constructed wetlands also can produce a standard of treatment equivalent to tertiary or advanced wastewater treatment. This is far better than a typical "package plant" or municipal sewage plant that produces effluent at secondary sewage standards quality, requires high capital investment and technical expertise and is energy-intensive (Reed et al, 1995). Subsurface wetlands use little or no electricity and technology and require little technical supervision once installed (Green and Upton, 1992; Steiner, 1992, Kadlec and Knight, 1998).

Wetland systems have long hydraulic residence times and through a variety of mechanisms (sedimentation, antibiotics, filtration, natural die-off etc.) have shown promise in achieving large reductions in nutrient levels and 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) and 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.

Conventional sewage treatment plants are very capital-intensive. Three-quarters of overall costs are involved in the pumping required to move raw sewage to the centralized sewage plant (Southwest Wetland Group, 1995). Much of the cost for conventional sewage treatment is for purchased goods, which originates outside the region and frequently is imported in third world countries. Operation and maintenance costs are high, since such facilities require highly trained technicians and engineers.

Electrical costs are high for conventional sewage treatment plants since much of the system process relies on machinery. Maintenance for such systems can be expected to be more expensive in developing countries because of the tropical environment, salt-spray and saline groundwater, and the high cost of importing equipment. Treatment by package plants even in industrialized countries frequently decreases over time with poor maintenance of equipment and inadequate technical supervision (Reed et. al., 1995).

Ecological engineering approaches, of which constructed wetlands for sewage treatment is an exemplar, seeks a symbiotic mix of man-made and ecological self-design that maximizes productive work of the entire system including the human economy and the larger-scale environmental system. Allowing this process to self-organize may develop better adapted ecosystems that prevail because of their greater efficiency and productivity (Odum, 1991). By minimizing human manipulation and management, materials are recycled, efficiency is enhanced, costs are reduced, and ecological processes contribute more. An important application of ecological engineering is the design of interface "buffer" ecosystems to handle byproducts of the human economy, such as waste and wastewater (Mitsch and Jorgensen, 1991).

## RESEARCH IN MEXICO USING SUBSURFACE FLOW WETLANDS

To prevent pollution of groundwater and coral reef on the calcareous east coast of Yucatan, Mexico, a subsurface wetland system (wastewater gardens™) was developed and constructed by the Planetary Coral Reef Foundation in 1996 for treatment and recycle of saline, septic-tank wastewater. High diversity wetland ecosystems were planted in two concrete-lined chambers, using subsurface flow through limestone gravel, arranged in series with discharge to backbeach mangroves. Over the course of a two-year study, the subsurface wetlands recycled nutrients and greatly improved the quality of saline domestic wastewater In addition, they have maintained extremely high levels of biodiversity, with over 60 species of wetland shrub, grass, palm and tree in the 2 system covering 130m2. The wastewater gardens have a Shannon diversity index of 4.95 (base 2), just 5% less than the Yucatan tropical forest biodiversity and three times higher than natural mangrove wetlands along the coast (Nelson, 1998a; Nelson, 1998b). Subsequent and on-going work has adapted the wastewater garden™ approach for sewage treatment for projects in the United States, Belize, Australia and Bali, Indonesia.

## EMERGY EVALUATION FOR COMPARING RESOURCE AND ENERGY USE OF SYSTEMS

As part of the Mexican wetland study, conducted under a joint research program of the Planetary Coral Reef Foundation and the University of Florida Center for Wetlands, economic and emergy evaluations of the wastewater gardens and comparisons with conventional high-tech sewage treatment were conducted.

Emergy is an analysis tool to measure the work previously required to produce a product or service. The analysis reveals the "embedded energy", or energy memory contained in the production process. Odum, his long-term co-worker Brown and their associates developed the emergy evaluation system over the past several decades. One of the unique values of emergy analysis is that it measures both the human economy and the environmental "services" provided by nature, and puts both type of inputs into common units, solar emjoules, sej (see Odum, 1996 for a handbook of the methodology; Brown, 1981; Odum, 1994; Odum et al, 2000). Emergy analysis thus has great value as a comparative tool for evaluating the amount of environmental services (in the forms of natural resources and renewable energy) and products of the human economy (labor, manufactured goods, capital). Emergy analysis reveals how much renewable and non-renewable resources are being utilized, what contributions derive from within the region and what is imported from elsewhere. It has great value, along with economic analysis, for determining how much a given technology "lives off the land" whether the land is a region of Earth or in space.

The systems that were compared are 1/two wastewater garden subsurface flow wetlands built for 40 residents in Akumal, Quintana Roo, Mexico. These wetlands included primary treatment in septic tanks, and used gravity flow for all movement of wastewater into and out of the system. 2/a "package plant" sewage treatment system built for 40 residents of the same town. The package plant includes blowers, grinders, pumps and a final chlorination for disinfection. In addition, to see the effect of scale on conventional sewage treatment: 3/the University of Florida sewage treatment system for approximately 40,000 people. The University of Florida Water Reclamation Facility is an activated sludge wastewater plant similar to those used in many cities in the United States and Europe. It includes primary treatment with screens and grit chambers for removal of large particles, followed by alternating treatment in anaerobic and aerobic basins. Clarification, settling tanks allow sludge to settle and be removed. Effluent water is filtered and treated with chlorine for sterilization.

## ECONOMIC EVALUATION

Economic evaluations of the constructed wetlands vs. a "package plant" sewage treatment system built for a comparable number of residents show that capital costs of package plants are more than twice that of the wetlands ($15,400 vs. $6,650) and maintenance costs are about ten times as great ($1,130 $yr^{-1}$ vs. $120 $yr^{-1}$) (Nelson, 1998a). The wetlands are also expected to last longer, as machinery, especially in tropical conditions, has a far shorter replacement time. On an amortized basis, the capital costs per year are even more divergent: over $2000 yr-1 for the package plant vs. $330 yr-1 for the wetland (even with the conservative assumption that the wetland only lasts 20 ears).

Dependence on infrastructure is also greater for the package plant for since the system will not work without electricity to run grinders, pumps and blowers. The wetlands, relying on gravity flow for all movement of the sewage, and on filtration by the limestone and bacterial and higher plant metabolic activity for treatment of the sewage, have mainly the requirement that filters be cleaned so that pipes do not clog. The package plant also requires a supply of chlorine for disinfection, since its hydraulic residence time (2-4 hours) is insufficient to achieve significant coliform bacteria reduction.

The University of Florida wastewater treatment facility has capital costs over three times higher per person than the Mexican wetlands, and operating costs at $27/person/year are nine times higher (Nelson, 1998a).

### Regional Analysis: Percent of Economy and Electrical Usage Required for Sewage Treatment

An evaluation of the implications of development using wetland sewage treatment vs. conventional sewage treatment plants (STP), such as package plants was conducted for the coastal region of eastern Yucatan.

Economic comparisons of the Yucatan wastewater garden wetlands confirms previous studies which show that constructed wetlands are usually some 50% less expensive than conventional STP in capital costs. Operational and maintenance costs are even lower, averaging 10% (Kadlec and Knight, 1996. However, this varies considerably, depending on such factors as labor and land costs. The economic advantages of the Mexican wetland treatment include capital costs for the limestone wetlands totaling around $165/person compared to $385/person for a package treatment plant; and maintenance costs for the wetland at $3/person compared to $27/person for the package plant. On a regional basis, the constructed wetlands would require 0.3% of yearly monetary flows along a square kilometer of developed coastline, vs. 1.1% for the package plant assuming 250 residents $km^{-1}$.

The limestone wetlands cost approximately $450 per year (over its 20 year anticipated operation) to treat 3000 gallons (11.4 m3) per day, which is $0.15 per gallon (3.8 litres) of wastewater. This is considerably lower than the $0.62 per gallon reported in a survey of subsurface flow wetlands in the United States (EPA, 1993b). This may reflect lower labor and construction costs in Mexico, as well as the fact that the research wetlands entailed no land costs, as they were built on land already allocated for landscaping purposes. Package plant costs would average $0.66 per gallon (3.8 litres) to treat wastewater.

Far less treated wastewater is discharged from the constructed wetland, since more wastewater is utilized within the system. Such use of emergy within the system rather than passing it out helps produce a high quality ecosystem, which adds to the landscape and biodiversity values of the region. Though the

Mexican wetlands use a far greater proportion of locally available resources, and little purchased goods, such systems require more land area per person and time (hydraulic residence time) than conventional STP.

Electricity required for the package plants are estimated at 250 Kilowatt-hours (kWh)/month/system or 18,750 kWh/year for the 6.25 package plants in the coastal area to serve 250 residents. This is 2.8% of the estimated total electrical usage of the developed kilometer of coastline. Should half the wetland treatment systems require use of a submersible lift-pump, rather than gravity flow (either because slopes do not permit gravity flow, or to get treated effluent to the receiving wetland), electrical usage for each wetland treatment systems will be around 35 kWh/month or 420 kWh/yr, so 10 pumps will use 4,200 kWh, or 0.6% of total electrical usage of the developed square kilometer (Nelson, 1998a). Thus electrical usage for constructed wetlands is estimated to be less than 22% of the electrical usage of development using conventional STP.

## EMERGY EVALUATIONS

Emergy evaluations of the wastewater gardens, small package plant and large sewage treatment plant (STP) are presented in Tables 1-3. The largest emergy contribution is from the wastewater itself, reflecting its high value as a by-product of the sustenance of the human population. Wastewater share of total emergy is 97.6% for the wetland treatment system, 97% for the small package plant, and 99.4% for the large STP. This fact reinforces the authors' assertion that "wastewater" is in fact a potentially valuable renewable natural resource, containing as it does valuable nutrients and water which can be used to construct and support productive wetland ecosystems. It also underscores that sewage is virtually self-cleansing if well engineered, as at the heart of even conventional sewage treatment is natural bacterial reactions (anaerobic and/or aerobic depending on the type of treatment system).

For the wetland treatment system, renewable resources such as rain, wind and sunlight are a small emergy input (<1%) and those, like local limestone, which require service to access constitute 1.6% of emergy used in the wetland treatment process and are the predominant source of system emergy use apart from the wastewater (Table 1). The emergy contained in service are 0.6% of emergy, and imported goods are less than 0.001%. Emergy from local materials (Yucatan limestone, vegetation, and mulch) constitute over 60% of total emergy used for construction of the wetland treatment units. Operational costs total less than 3% of total construction emergy.

By contrast, emergy analysis of a "package plant" sewage treatment system (Table 2) built for a comparable number of residents shows the far higher use of purchased services and imported resources that
such highly technical systems use. There was very little use of renewable resources. The largest emergy flows (apart from wastewater) are that of imported goods and services, mainly representing the costs of imported machinery and high maintenance labor costs by technical personnel. Imported resources are also sizable (and more than 100 times higher than those of the constructed wetland) as might be expected as equipment and technical processing is substituted for the large buffering and retention the use of limestone gravel permits in the wetland systems.

Operational costs of the package plant are around ten times higher than the wetland system ($1100 vs. $117) and emergy in services are eighteen times higher (3.7E15 sej/yr vs. 0.2E15 sej/yr) in the package plant compared to the wetland treatment system.

For the Yucatan treatment wetland units, the majority of emergy apart from sewage was from local sources. These inputs include wind energy, limestone gravel, limestone rock, and wetland plants. Purchased, imported goods are less than one-third of the total emergy (excluding that of the sewage itself) in the systems. Since the construction was labor-intensive, requiring local workers for excavation, construction of the concrete liners and placement of the gravel, the system to a large extent draws on and keeps both monetary transactions and emergy within the area. By contrast the University of Florida system (Table 3) derives most of its non-sewage emergy from purchased goods and services, as does the small package plant STP.

**Table 1. Emergy Analysis of the Wastewater Garden Wetlands**

| Note | Item | Raw Units | Emergy per Unit sej/unit | Solar Emergy E15 sej/yr | EmDollars Thousands |
|---|---|---|---|---|---|
| ENVIRONMENT | | | | | |
| 1 | Sunlight | 7.12E7 J/yr | 1 | <0.001 | |
| 2 | Rain, chemical | 5.85 E8 J/yr | 1.82E4 | 0.01 | 0.01 |
| 3 | Rain, geopotential | 2.58 E5 J/yr | 1.05E4 | <0.001 | |
| Total (renewable resources) | | | | 0.01 | 0.01 |
| CONSTRUCTION INPUTS Local materials: | | (divided by 20 year lifetime) | | | |
| 4 | Gravel | 4.9E6 g/yr | 1.0 E9 sej/g | 4.9 | 3.577 |
| 5 | Rock | 7.35E5 g/yr | 1.0 E9 sej/g | 0.74 | 0.54 |
| 6 | Vegetation | $14.1/yr | 1.9 E12 sej/$ | 0.03 | 0.0058 |
| 7 | Mulch | 4.5 E3 g/yr | 2.75 E8 sej/g | <0.001 | 0.00007 |
| Subtotal (Local Renewable resources requiring service) | Items 5-7 | | | 5.67 | 4.14 |
| Imported goods and services | | | | | |
| 8 | Cement | 0.3 ton/yr | 6.4 E13 sej/ton | 0.02 | 0.0015 |
| 9 | Lime | 5E4 g/yr | 1.0E9 sej/g | 0.05 | <0.001 |
| 10 | Concrete brick | 0.5 ton/yr | 6.4 E13 sej/ton | 0.03 | 0.0022 |
| 11 | Sand | 1.48E6 g/yr | 1.0 E9 sej/g | 1.48 | 1.08 |
| 12 | Rebar steel | 15 lbs/yr | 8.9 E11 sej/lb | 0.003 | 0.0022 |
| 13 | PVC pipe | 5.6E3 g/yr | 9.26E7 sej/g | <0.001 | <0.001 |
| 14 | Wire mesh | 12.5 lb/yr | 8.9 E11 sej/lb | 0.001 | <0.001 |
| 15 | Gasoline | 1.2 E8 J/yr | 6.6E4 sej/J | 0.008 | 0.0058 |
| 17 | Backhoe | $57.7/yr | 1.9E12 sej/$ | 0.11 | 0.08 |
| 18 | Jackhammer | $72.1 /yr | 1.9E12 sej/$ | 0.14 | 0.1 |
| 19 | Labor | 2.4 E7 J/yr | 8.1 E4 sej/J | 0.002 | <0.001 |
| 20 | Plumber | $9.6/yr | 1.9 E12 sej/$ | 0.02 | 0.01 |
| 21 | Purchased goods | $169/yr | 1.9E12 sej/$ | 0.32 | 0.23 |
| Subtotal imported goods and services | | | | 2.18 | 1.59 |
| Total inputs for construction | | | | 7.85 | 5.73 |
| HUMAN WASTE | | | | | |
| 22 | Raw sewage | 3.94 E5 gallons/yr | 8.767 E11 sej/gallon | 345.4 | 252.13 |
| OPERATION | | | | | |
| 23 | Maintenance | $117/yr | 1.9 E12 sej/$ | 0.22 | 0.16 |
| Total emergy | | | | 353.6 | 258.1 |
| OUTPUT (yield) | | | | | |
| 24 | Treated wastewater | 5.17 E10 J/yr | 6.84 E6 sej/J | 353.6 | 258.1 |

* Column 6 (EmDollars) based on 1.37E12 sej/$, U.S. dollar/emergy ratio for 1996 (Odum, 1996) For complete emergy analysis and notes on calculations see Nelson, 1998a

**Table 2. Emergy Analysis of Package Plant Sewage Treatment System**

| Note | Item | Raw Units | Transformity sej/unit | Emergy E15 sej/yr | EmDollars Thousands |
|---|---|---|---|---|---|
| RENEWABLE | RESOURCES: | | | | |
| 1 | Sunlight | 2.75 E7 J/yr | 1 | <0.001 | <0.001 |
| 2 | Rain, chemical | 2.2 E8 J/yr | 1.82E4 | 0.004 | 0.002 |
| 3 | Rain, geopotential | 9.8 E4 | 1.05E4 | <0.001 | <0.001 |
| Total (renewable resources) | | | | 0.004 | 0.002 |
| LOCAL NONRENEWABLE | RESOURCES | | | | |
| 4 | Raw sewage | 3.94 E5 gallons/yr | 8.767 E11 sej/gallon | 345.4 | 252.13 |
| 5 | Cement | 0.3 ton/yr | 6.4 E13 sej/ton | 0.002 | .001 |
| 6 | Concrete block | 0.0625 ton/yr | 6.4 E13 sej/ton | 0.004 | .002 |
| 7 | Sand | 5E5 g/yr | 1.0 E9 sej/g | 0.5 | 0.4 |
| Total (Local non-renewable resources) | | | | 345.9 | 252.53 |
| IMPORTED GOODS | | | | | |
| 8 | Rebar steel | 7.5 lbs/yr | 8.9 E11 sej/lb | 0.007 | .005 |
| 9 | PVC pipe | 2.24E4 g/yr | 9.26E7 sej/g | 0.002 | .001 |
| 10 | Gas for concrete mixer | 6 E7 J/yr | 6.6E4 sej/J | 0.004 | .002 |
| 11 | Machinery | 2.27E5 g/yr | 1.25E10sej/g | 2.8 | 2.0 |
| 12 | Electricity | 1.1E10 j/yr | 1.74E5 sej/J | 1.9 | 1.4 |
| 13 | Chlorine | 1E4 g/yr | 1.1E9 sej/g | 0.01 | .008 |
| Subtotal (imported resources) | sum of items 8-13 | | | 4.72 | 3.4 |
| SERVICES | | | | | |
| 14 | Excavation of injection well | $150/yr | 1.9 E12 sej/$ | 0.29 | 0.2 |
| 15 | "Jet system" cost | $1800/yr | 1.9 E12 sej/$ | 3.42 | 2.5 |
| 16 | General labor | 4.2E7 J/yr | 8.1 E4 sej/J | 0.003 | .002 |
| 17 | Maintenance | $961.5/yr | 1.9 E12 sej/$ | 1.83 | 1.34 |
| Total (services) | sum of items 14-17 | | | 5.54 | 4.0 |
| Total emergy | | | | 356.2 | 259.9 |
| OUTPUT (yield) | | | | | |
| 18 | Treated wastewater | 7.38 E10 J | 4.83. E6 sej/J | 356.2 | 259.9 |

* Column 6 (EmDollars) based on 1.37E12 sej/$, U.S. dollar/emergy ratio for 1996 (Odum, 1996)
For complete emergy analysis and notes on calculations see Nelson, 1998a

**Table 3. Emergy Analysis of the University Of Florida Sewage Treatment Facility**

| Note | Item | Data | EMERGY/unit (sej/unit) | SOLAR EMERGY (x E17 sej) | Em$ * |
|---|---|---|---|---|---|
| Renewable Resources | | | | | |
| 1 | Sunlight | 2.6 E13 J/yr | 1 | <0.001 | 19 |
| 2 | Wind | 2.53 E13 J/yr | 663 sej/J | 0.18 | 12,244 |
| Subtotal | | | | 0.18 | 12,244 |
| Non-renewable resources | | | | | |
| 3 | Raw sewage | 714.1 E6 gallons/yr | 8.76 E11 sej/gallon | 6256 | 456,644,230 |
| Purchased Goods | | | | | |
| 4 | Electricity | 1.18 E13 J/yr | 173681 sej/J | 20.49 | 1,825,552 |
| 5 | Fuel | 1.52 E11 J/yr | 6.6 E4 sej/J | 0.11 | 7,308 |
| 6 | Water | 1.36 E11 J/yr | 665714 sej/J | 0.91 | 66,085 |
| 7 | Chlorine | 6.37 E11 J/yr | 39800 sej/J | 0.25 | 18,514 |
| 8 | Capital Costs | $546,750 | 1.37 E12 sej/$ | 7.49 | 546,750 |
| 9 | Maintenance (Goods) | $365,000 | 1.37 E12 sej/$ | 5.00 | 365,000 |
| Subtotal Purchased Goods | | | | 34.34 | 2,829,209 |
| 10 Services | Operating and Maintenance | $385,118 | 1.37 E12 sej/$ | 5.28 | 385,118 |
| Total Emergy | | | | 6295.8 | 124,174,853 |
| 11 Yield | Treated sewage | 13.36 E13 J/yr | 4.71 E6 sej/J | 6295.8 | 124,174,853 |

*Based on 1.37 El2 sej/$, 1993 values (Odum, 1996, p. 314). For complete emergy analysis and notes on calculations see Nelson, 1998a

## EMERGY INDICES

Emergy indices (Table 4) show that the ratio, excluding wastewater itself, of purchased goods to renewable resources (purchased inputs as renewable resource emergy inputs) for the wastewater garden™ wetlands are 0.39, the large University of Florida system is 220, and for the small package plant is 2530. This shows that conventional sewage treatment uses few renewable resources. Empower density (emergy flow per area per time) for the large conventional system is 57 times as great as the wetland and the package plant is three times larger than that of the wetland system. This reflects both the higher use of purchased inputs and the far smaller land area of conventional STP.

The transformity of the output (treated effluent) (6.85 E6 sej/J) from the wetland system is higher than the package plant (4.83 E6 sej/J) and the University of Florida STP (4.71 E6 sej/J) reflecting that far less water is discharged as it is used to support the wetland ecosystem.

Output in the treated wastewater from the package plant are 30% higher from the package plant than in the wetland treatment system, indicative that input emergy has been more thoroughly utilized by the wetland ecosystem (e.g. through loss of water to evapotranspiration supporting the vegetation of the wetland ecosystem). Transformity (a measure of the amount of emergy per energy of the product of a system) of the output is 41% higher in the wetland treatment than in the package plant treatment system, and 45% higher than the University of Florida STP as a result of the wetland discharging less effluent water.

Table 4. Comparison Of Emergy Indices for Akumal, Mexico Wastewater Gardens, Package Plant At Akumal, Mexico and the University of Florida Wastewater Treatment System

| Emergy index | Yucatan wetland system | Yucatan package sewage treatment plant | University of Florida sewage treatment system |
|---|---|---|---|
| Purchased / Free (excluding sewage) | 0.39 | 2,530 | 220 |
| Transformity of output | 6.85 E6 sej/J | 4. 83 E6 sej/J | 4.71 E6 sej/J |
| Empower density (emergy/area/time) | 2.5 E19 sej/ha/yr | 7.4 E19 sej/ha/yr | 14.3 E20 sej/ha/yr |
| Purchased emergy per Person | 0.3 E14 sej | 2.3 E14 sej | E14 sej |

The Yucatan constructed wetlands use less than 15% the purchased emergy per person compared to the package plant (0.3 E14 sej vs. 2.3 E 14 sej) while the University of Florida facility uses three times as much purchased emergy per person (1.0 E14 sej/person).

## CONCLUSION

Emergy analysis is an important new tool in doing comprehensive environmental accounting. Its usefulness in comparing on a system level, alternative technologies for life support on Earth and in space lies in its ability to integrate both human economic valuations and those resulting from renewable environmental energy and material resource. Thus, an integrated comparison of the sustainability of different approaches may be readily obtained. This can be coupled with economic and other measures of system performance.

Wastewater gardens, a new ecologically engineered development of the constructed subsurface flow wetland approach, were found to utilize far more local and renewable resources than conventional sewage treatment plants by emergy analysis, and had clear economic and electrical usage advantages as well. This may account for the increasing use of constructed wetlands for solving environmental pollution and health problems caused by improper sewage treatment in many countries of the world. Their lower cost and higher use of local resources make them attractive solutions especially for developing countries that have not invested in expensive centralized sewage infrastructure. Constructed wetlands for sewage treatment applied to long-term space exploration and habitation may well increase our ability to live outside the Earth's biosphere in a resource efficient manner.

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