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WETLAND SYSTEMS FOR BIOREGENERATIVE RECLAMATION OF WASTEWATER: FROM CLOSED SYSTEMS TO DEVELOPING COUNTRIES

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ABSTRACT

Results are presented from constructed wetland systems designed to treat wastewater in Akumal, Quintana Roo, Mexico, which was, developed after prior experience with the Biosphere 2 closed ecological system wetland systems. These systems illustrate the congruity of needs in advanced life support systems and in solving social and environmental problems in developing countries. For sustainable food production for life support, closed ecological systems need to bioregenerate and recycle nutrient-rich wastewater. Developing countries need low-tech ecologically engineered systems that minimize requirements for capital, non-renewable energy, and technical expertise. Biosphere 2's surface flow wetlands covered 41 m^2 and treated the wastewater from eight inhabitants, laboratories, and domestic animals during the 1991-1993 closure experiment. The Mexican wetlands are subsurface flow wetlands using limestone gravel as substrate. Two wetland systems treat sewage from 40 people and cover 131 m^2. During the initial year of operation, the wetlands in Akumal reduced BOD 86%, TSS 39%, total P 80%, total N 75%, and coliform bacteria 99.85%. Phosphorus uptake in the limestone gravel was around 6 mg/kg. High biodiversity, with 70 plant species, was maintained in the Akumal constructed wetlands 1.5 years after planting. The Shannon diversity index was 4.7 (base 2). Plant diversity was slightly less than tropical forest ecosystems of the region, but far greater than biodiversity in natural mangrove wetlands.

Key words: constructed wetlands, ecological engineering, sewage treatment, closed ecological systems, eutrophication, recycling, wastewater, subsurface flow, Mexico, Biosphere 2.

Introduction

The recycling of nutrients is fundamental to achieving ecological sustainability. in space-based life support systems where volume, weight and energy constraints dictate the necessity of rapid recycling in systems with small reservoirs and acceptable buffering capacity. However, nutrient recycling is just as central to the challenge of transforming human economic activities in Earth's vaster biospheric life support system to a sustainable basis. Sewage treatment should do far more than simply preventing pollution and the degradation of natural ecosystems occasioned by the incomplete treatment and discharge of wastewater. Wastewater treatment should also accomplish the return of nutrients and water to productive use. An important development of the past few decades has been the use of natural and constructed wetlands for the treatment of domestic sewage and industrial wastewater (16). Constructed wetlands illustrates the parallel problems and solutions common to space life support systems and those which can contribute to solving environmental problems.

This paper presents a brief overview and comparison of the methods and research results of two wastewater recycling experiments. These are the wastewater recycling wetlands of the Biosphere 2 closed ecological system in Arizona, and sewage treatment wetlands along a tropical karstic coastline in the Yucatan peninsula of Mexico which were designed to set-up and test inexpensive "field" wetlands based on the Biosphere 2 experience.

Biosphere II Westland Treatment System

Wetland sewage treatment systems have been developed by NASA scientists at Stennis Space Center and later applied in NASA test beds (22, 23, 24), and further developed by the creators of Biosphere 2 (11). Biosphere 2 was the first closed ecological system that was designed for recycling of all human waste products. 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 (17).

The Biosphere 2 wastewater recycling system employed a two-stage process that began with anaerobic digestion in sealed holding tanks. Next the wastewater was passed for final treatment to a surface flow wetland (marsh) system (Figure 1). Two separate wetland systems were created so that laboratory or mechanical workshop water could be isolated if necessary due to chemical or oil/grease spills. This was not the case during the two-year closure experiment, and the two wetland subsystems were utilized interchangeably as required for maximizing hydraulic residence time.

Daily wastewater input was around 1 m^3 (260 gallons) per day. Around 750 m^3 (1.95 E5 gallons) of wastewater were treated over the course of the two year closure experiment, 1991-1993. The created wetland totaled 41 m^2 of surface area with emergent and floating plants and produced a total of 720 kg, dry weight, of emergent vegetation and 493 kg, dry weight, of floating vegetation during the two-year experiment. Plant productivity was limited by available sunlight as winter daylength was shorter than summer daylength and the glass and spaceframe shading reduced light levels by 50-60%. Analysis for BOD indicated reduction was >75% with hydraulic retention times of around four days in the holding tanks and three days in the wetland treatment system (12). High intensity UV lights were available as a method of final disinfection, but weren't used during the two year closure since the health status of the eight crew members was closely monitored, and they carried no infectious diseases prior to closure.

Fourteen plant species composed the primary autotrophic level in the wetland system (Table 1). The constructed wetland system supported floating (aquatic) and emergent (rooted) wetland species. The aquatic plants colonized open-water channels and the emergents utilized upland soil areas in the wetland. The wetland system was housed in several fiberglass tanks and submersible pumps maintained water recirculation between tanks. Loading to the system was on a batch basis after the primary settling tanks became full. The system served as habitat for insects (e.g. lady bugs) and animals (such as the Colorado cane toad) within the Biosphere 2 agricultural biome. Production of floating vegetation declined during the two year closure as shading from robust emergent vegetation increased. Occasional outbreaks of powdery mildew on *Canna* sp. were controlled by water spray and pruning of affected vegetation. The system operated with few problems, but technical changes after the two-year experiment were instituted to make water sampling easier, to prevent overfilling of tanks and lower labor requirements. Little malodor was reported by the Biosphere 2 crew, and the constructed wetlands added to the diversity of attractive foliage within the facility.

Yucatan Coastal Sewage Treatment Wetlands

In 1996, subsurface flow wetland systems were designed and installed along the calcareous coastline (21) of the eastern Yucatan peninsula, in Akumal, Quintana Roo, Mexico Akumal is approximately 100 kilometers south of Cancun and fronts extensive coral reefs offshore. Its sandy beaches serve as important nesting areas for sea turtles. The challenge at Akumal was to develop appropriate ecological interface systems to prevent human sewage from damaging coral reefs through eutrophication and improve public health by preventing contamination of groundwater supplies, a leading cause of ill-health in developing countries (20). Studies in geologically similar limestone coastlines (e.g., the Florida Keys and Caribbean islands such as Jamaica) have indicated that they are especially susceptible to eutrophication (9). Septic tank effluent flows rapidly through porous calcareous strata and does not allow sufficient retention time nor provide adequate soil sediments for microbial decomposition and plant uptake (3,15,9).

Sewage treatment systems must be low-tech, low maintenance and minimal in their energy requirements to be affordable and practicable in developing countries, attributes which wetland systems exemplify. Natural and constructed wetlands rely on solar insolation as a main driving energy, and warmer climates improve treatment rates (8). Therefore, wetland treatment systems may be expected to operate more effectively in tropical regions. In addition, wastewater interface ecosystems may benefit from the high species diversity found in tropical regions since diversity at the biotic and metabolic level increases the buffering capacity of ecosystems (10). Allowing self-organization of plant, animal and microbial biota to develop cooperative mechanisms may develop better adapted ecosystems to handle pollution and toxicity (13).

Previous studies of subsurface flow wetlands for sewage treatment have demonstrated their advantages in situations of small on-site sewage loading, in areas where land is scarce, and in situations where avoidance of malodor and mosquito-breeding are important. In Akumal the high visibility of the treatment site, in the center of the commercial district, dictated the necessity for a nuisance-free and aesthetically attractive system. A well-designed subsurface flow wetland also can provide inexpensive but highly effective sewage treatment. As is the case in the U.S. and Europe where this approach is rapidly spreading, the advantages of constructed wetlands are that because they rely on more natural methods, they are less expensive to build and operate than conventional sewage treatment plants. They can also produce a standard of treatment comparable to tertiary or advanced wastewater treatment (16). This is far better than a typical "package plant" or municipal sewage plant that produces effluent of secondary sewage standards and requires high capital investment, technical expertise and which are energy-intensive to operate. Subsurface wetlands use little or no electricity and technology and require little technical supervision once installed (4,18,6,19). However, there is little research with these systems in tropical karstic coastal conditions.

Materials and Methods

Design of the Yucatan Wetlands. In August 1996, the two wetland sewage treatment systems were constructed in Akumal by Planetary Coral Reef Foundation following the author's design. One treatment system was designed to treat the wastewater of 16 people, 2 m^3/day (520 gal./day), and required 50.6 m^2 of wetland area. The second wetland was designed to handle the sewage of 24 people, 3m^3 (780 gal/day) and required a wetland area of 81.2 m^2.

The treatment process for each wetland begins with a well-sealed two-chamber septic tank that receives wastewater from the residences and offices by gravity flow.
Solids settle out in the septic tank that serves as primary treatment, and the commencement of microbial treatment of the sewage. Effluent from the septic tank overflows by gravity feed into a header pipe that distributes the sewage along the total width of the first of two treatment cells (compartments) of the constructed wetland.

The Akumal wetlands were designed as subsurface flow systems, and have a cement liner to prevent movement of untreated sewage into the groundwater. The constructed wetland tanks were filled with limestone gravel to a depth of 0.55 m. A collector pipe (perforated 10 mm PVC) located at the end of each cell of the wetland directs wastewater into the centrally located control box (Figure 2). Inside the control box, an adjustable standpipe determined the level at which wastewater was maintained in the wetland. Wastewater overflowed the open top end of the standpipes from cell 1 into the header pipe for cell 2, or from cell 2 to final discharge (Figure 2). Normally, the standpipe was set fully vertical at a height of 0.50 m. Thus, the wastewater was kept 5 cm below the level of the gravel. The sides of the system were at least 15 cm above the top of the gravel to allow for natural litter buildup and to prevent overflow in heavy rains. The terrain was graded to prevent surface runoff water inflow into the wetland systems.

After the cement liner was completed, the system was filled with water and leak-tested. Then the gravel was added and leveled. Larger limestone rock (5-10 cm) was used in the first and last meter of each cell (around the header and collection pipes) to minimize the potential for clogging. After the addition of the gravel, the systems were filled with tapwater and planted with wetland plants from nearby wetlands, botanical gardens and commercial plant nurseries. Soil was not introduced into the system, except for rootballs of the plants. The plants were planted with at least 2-5 cm contact with the water. After planting, the two wetlands were mulched with 2-4 cm of sawdust. After discharge from cell 2 of the wetlands, the wastewater entered perforated drainage pipes that sloped away from the wetland. The trenches in which these effluent pipes were laid were back-filled with limestone gravel to prevent clogging by dirt.

Characterization of Wetland Efficiency. Studies were initiated to examine the performance of the Akumal subsurface flow wetlands beginning in December, 1996 when the systems were connected to household sewage flow. Water quality analyses done in water laboratories in Cancun and at the University of Florida have included Biochemical oxygen demand (BOD) using EPA method 405.1 (5), keeping the sample at 20 deg. C. for five days. Total suspended solids (TSS) in the wastewater were determined using the filterable residue (EPA method 160.1 (5)), a gravimetric procedure with the material dried at 180 deg. C. Total phosphorus was determined using persulfate digestion followed by the ascorbic acid method, SM 4500-P (1). Total nitrogen was determined using the persulfate method, SM4500-N (1). Fecal coliform bacteria in the wastewater was determined using method 9222DSM (1), membrane filtration and most probable number (MPN) of colonies per 100 ml of sample. Phosphorus uptake in limestone gravel was studied by analysis for inorganic P using an automated ascorbic acid method (EPA Method 365.1 (5)) which involves the initial steps of grinding, drying at 70 deg. C., extraction with 1M HCl and filtration through a 0.45 micrometer pore size membrane filter.

Ecological field methods included measurement of Leaf Area Index (LAI) using the point intercept method with 200 measurements at each sampling date (2). Plant species diversity was measured using the1000 observation transect procedure (2), and biodiversity computed for base 2 and base 10 using the Shannon-Weaver index (14). Relative frequency (RF) was computed from the results of transects (482 - 500 observations in each wetland). Relative cover was calculated using 66 1/4 m^2 quadrants and visual estimation of plant canopy cover. Importance Value rankings of the species present was done by adding relative frequency and relative cover data and dividing by two (2).

Results

Patterns of biodiversity, dominance and ecological development in the wetlands. Biodiversity was high in the Yucatan constructed wetlands, nearly equalling natural tropical forest ecosystems of the region and much higher than nearby mangrove wetlands. Seventy vascular plant species were identified in the 131 m^2 of constructed wetlands (Table 2). Both systems increased in biodiversity since planting, probably as a result of seeds germinating from soil brought in with natural wetland plants, and seed dispersal by wildlife from wetlands near the constructed systems. Overall number of plant species was maintained for seven months between surveys conducted in May, 1997 when 68 species were found and December, 1997 when there were 70. Nine species were lost and eleven new species were present (Table 2).

Comparison was made with nearby natural ecosystems by conducting 1000 observation transects (Figure 3). The mangrove wetlands contained 17 species of plants, while the inland tropical forest contained 73 species. Shannon diversity index in the constructed wetlands was 4.71 (base 2) and 1.42 (base 10). The tropical forest ecosystem was about 13% more diverse since it had a Shannon diversity index of 5.35 (base 2) and 1.61 (base 10). The constructed wetlands had higher biodiversity than the natural mangrove wetlands, which had a Shannon diversity of 1.49 (base 2) and 0.45 (base 10), only about 33% that of the treatment wetlands.

The larger treatment wetland initially maintained a larger number of species than the smaller one (62 vs 54 species in May, 1997 and 57 vs 49 in December, 1997). Shannon Weaver diversity indices for the two wetlands are becoming closer as the systems matured (Table 3). Patterns of dominance are similar throughout the four cells of the two wetlands (Figure 4). Although the smaller treatment system was initially somewhat more heavily dominated by its most frequently observed plant species, this difference was lessening. In May, 1997, in the smaller wetland system, five species constituted 58% of observations in transects, while in the larger system, the top five were 49% of observations. But in December, 1997, the top 5 species were 55% of observations in the larger system and 54% in the smaller wetland. Importance Value graphs show high similarities in patterns of dominance/evenness for all four treatment cells in May and December 1997 (Figure 4).

Leaf Area Index values show similar trends. Plant development was at first stronger in the first treatment cells of both systems, which had access to higher nutrient levels in the wastewater. In May, 1997, first cells' Leaf Area Index averaged 5.56 +/- 0.27 vs 2.33 +/- 0.19 for

the second cells. At the same time, 88% surface cover in the first cells exceeded the 61% cover of the second cells. But by December, 1997,
although both systems continued to grow vigorously, differences between the two cells were lower. Leaf Area Index averaged 5.99 for the first cells, and 4.57 for the second cells. Overall, LAI for the wetland treatment systems increased from 3.96 to 5.28 from May to December 1997.

Water quality results from the wetland systems. Biochemical oxygen demand (BOD) has been reduced 86% in the smaller wetland and 89% in the larger wetland during the first year of system operation, and BOD levels in discharge water have averaged 12.6 mg/l and 22.8 mg/l respectively (Figure 5). Suspended solids reduction was lower, with 40% reduction in the smaller wetland and 38% in the larger wetland. Discharge levels of suspended solids average around 25 mg/l.

Nutrient reduction, especially nitrogen and phosphorus, is of greatest importance for protection of the coral reef. Phosphorus, which reacts with limestone, as well as being taken up by plants and bacteria, showed high reduction from the beginning and over the course of the first nine months had discharge effluent concentrations of 0.8 mg/l and 1.8 mg/l in the smaller and larger wetland systems respectively. Phosphorus levels in discharge effluent were 91% and 67% reduced compared with levels of P in septic tank water, or a combined average of 80% reduction (Figure 6).

Average P levels increased from 38.0 +/- 2.9 mg/kg P to 43.8 +/- 1.7 mg/kg P in the wetland's limestone gravel, a statistically insignficant increase. However, because of the large mass of limestone in the wetlands (some 85,000 kg), this P increase represents an uptake of around 500g/yr of phosphorus by the gravel. Limestone from both wetland's first cells show higher levels (by 3-5 mg/kg) than their second cells, but the highest levels are just 48.1 +/- 2.5 mg/kg in the first cell of the larger wetland.

Nitrogen reduction has increased as the wetland plants developed. Two of the primary mechanisms for nitrogen treatment in wetlands depend on plant activity. The primary mechanism is nitrification followed by denitrification that releases influent N as N_2 gas. Nitrification is dependent upon aerobic conditions, which in wetlands is produced in the microenvironments of plant roots that act as "oxygen pumps" through aerenchyma tissue in wetland plants' stems and roots. A secondary mechanism is uptake by wetland plants either through nitrogen fixation or direct nitrogen uptake (7).

Reductions in the levels of total nitrogen in the wetlands averaged 75% in the two systems during the first year of system operation. Average discharge effluent from the smaller wetland system was 7.0 mg/liter and from the larger wetland was 11.3 mg/liter. After six months of operation, N reduction increased, with average effluent from July to October, 1997 averaging 6 mg/l in the smaller and 3.4 in the larger wetlands respectively (Figure 7).

Levels of coliform bacteria were reduced, without use of chemicals, by 99.85% on average after treatment in the wetlands during the first year of operation. Final effluent coliform levels were fairly uniform for the two wetland systems, averaging 1690 colonies (MPN)/100 ml in the smaller wetland system and 1820 colonies (MPN)/100 ml in the larger wetland system. Average starting levels of coliform in the septic tanks were 3.3 E6 and 5.0 E6 in the smaller and larger system's septic tanks (Figure 8). Coliform levels are expected to continue to decline as the discharge effluent passes through the mangrove soil or passes through the groundwater system. Use of chlorine as a final disinfectant was avoided since chlorinated chemicals can have adverse impacts in the environment.

When considered on a mass basis, the reduction efficiency of wetland treatment systems for potential pollutants is greater than water analyses show. This is because evapotranspiration (ET) losses result in less water being discharged than are received by the wetlands. Preliminary data from Akumal suggest that ET losses will account for at least 15-20% of influent water, even when systems are receiving all the hydraulic loading for which they were designed.

Discussion

Comparison of the Biosphere 2 and Yucatan wetland sewage treatment systems. Although both the Biosphere 2 and Akumal systems are types of constructed wetlands, they vary considerably in design and operation. Biosphere 2's wetlands were surface flow systems, while the Yucatan wetlands were subsurface flow. Biosphere 2's wetland had areas of open water, and areas of saturated soil. The Yucatan wetlands used limestone gravel as the sole substrate.

Consequently, Biosphere 2's system supported both emergent and aquatic plant species, while only emergent plants are present in the Mexican wetlands. However, plant species number was much higher in the Yucatan subsurface flow wetlands because a larger number of species and variety of wetland species was planted (e.g., wetland vines, shrubs, grasses, reeds, palms and trees) as a means of allowing the greatest possible self-organization to occur over time. The Yucatan wetlands are also open to natural enrichment by recruitment from natural wetlands as contrasted with the Biosphere 2 system isolated from other wetlands.

Both wetlands used anaerobic settling tanks as primary treatment stages, and for separation of large solids. However, input to the wetlands in Biosphere 2 was by batch flow, while the Yucatan wetlands have continuous input as septic tanks overflow. Biosphere 2's wetland used submersible pumps for internal recirculation and discharge, while the Yucatan wetlands used no pumps, designed so that water movement was accomplished using only gravity feed to and from the septic tank, and through the wetland cells. Biosphere 2's wetlands were freshwater systems while the Akumal wetlands received the somewhat brackish groundwater (2-7 ppt salt) from the town's water supply.

Effluent discharged from Biosphere 2's wastewater wetland was used in rice paddies and other irrigation water for crops in its agricultural system. The Yucatan wastewater is discharged subsurface after leaving the system, with one wetland's outfall utilizing the nearby mangrove wetland organic soils for final filtration and nutrient uptake. Plant material in the Biosphere 2 wetlands were cut frequently for fodder for domestic animals. Some food crops are being tested in the Yucatan wetland (e.g., *Musa* sp.) but system operation does not depend nor call for biomass harvesting. It is optional and may be done for improving the appearance of the wetland (increasing flower production or trimming unsightly dead leaves). However, the potential exists for such constructed wetlands to produce usable products such as food, fiber and fodder especially in tropical countries where plant productivity is high year-round. Labor requirements for operation of the Mexican wetlands are far lower than of those for the Biosphere 2 system that required frequent manual batch releases and maintenance of equipment.

Because nutrient treatment is a high priority in the Yucatan system, for protection of coral reef ecosystems, design hydraulic retention times are longer (7-10 days) than in the Biosphere 2 wetland (3 days). Both wetlands are hydrologically isolated to prevent discharge of wastewater before treatment. The Biosphere 2 system was constructed in a series of fiberglass tanks, the Yucatan system is separated from groundwater by a concrete liner.

These contrasts underline the flexibility of the constructed wetlands approach. Wetland treatment systems can be ecologically engineered to meet widely varying environmental, geological, and cultural/economic contexts. Such reclamation of "waste" nutrients is key to achieving sustainability in the small systems that characterize space life support closed systems, and in integrating the human economy more harmoniously with the natural environment in Earth's biosphere.

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Captions for Tables and Figures

Table 1. Vascular plants in the Biosphere 2 wetland wastewater recycling system during the two year closure experiment, 1991-1993.

Table 2. Plant species in the treatment wetlands, Akumal, Mexico, December 2, 1997. Total number of species as of May, 1997: 68 species; as of December 1997: 70 species. N= not found in May, 1997 survey; D = not found in December, 1997 survey.

Table 3.a Comparison of Shannon diversity indices for constructed wetlands vs. natural mangrove and tropical forest ecosystems of the study area, based on December 1997 survey data.

Table 3.b Shannon diversity indices for constructed wetlands based on May and December 1997 surveys.

Figure 1. Schematic of the water systems of Biosphere 2 during the two year closure, 1991-1993.

Figure 2. Schematic of the subsurface flow constructed wetlands for sewage treatment in Akumal, Quintana Roo, Mexico.

Figure 3. Species/area curves for the Yucatan constructed wetlands, the natural mangrove wetland and tropical forest ecosystems of the region. Data based on 1000 observation transects conducted in December, 1997.

Figure 4. Graphs of Importance Value (IV) rankings of wetlands from December, 1997 data. IV rank based on (frequency + cover)/2, total = 1.0 (2).

Figure 5. Biochemical oxygen demand (BOD-5) measured in water samples in the wetland treatment systems, Akumal, Mexico. Data presented is average of both systems, showing reduction from septic tank water through treatment cells 1 and 2. Average reduction was 87% during twelve months of system operation.

Figure 6. Total phosphorus levels in water samples from the Yucatan wetlands. Data presented is average of both systems. Reduction of initial P levels in the septic tank averaged 80% and final discharge water from the wetland averaged 1.3 mg P/liter.

Figure 7. Total nitrogen levels in water samples from the Yucatan wetlands. Data presented is average of both systems. Reduction of influent N averaged 75% in the two wetlands, and final effluent averaged 11.3 mg/l. The first analysis presented (12 January 1997) was for ammonia, the rest are for total nitrogen.

Figure 8. Coliform bacteria in water samples from the Yucatan wetlands. Coliform bacteria was reduced 99.85% on average during wastewater residence in the wetlands.

Table 1.
Vascular plants in the Biosphere 2 wetland wastewater recycling system during the two year closure experiment, 1991-1993.

Scientific Name	Common Name
Azolla caroliniana	Mosquito fern
Canna edulis	Canna
Canna flacida	Golden canna
Canna indica	Indian shot
Eichornia crassipes	Water hyacinth
Ipomea aquatica	Water spinach
Lemna minor	Duckweed
Pistia stratoites	Water lettuce
Phragmites australis	Common reed
Sagittaria falcata	Wapato
Sagittaria montevidensis	Giant arrowhead
Scirpus californicus	Bullrush
Spirodela polyrhiza	Duckweed
Wolffia sp.	Water meal

Table 2. (1/2)
Plant species in the treatment wetlands, Akumal, Mexico, December 2, 1997.
Total number of species as of May, 1997: 68 species; as of December 1997: 70 species.
N= not found in May, 1997 survey; D = not found in December, 1997 survey.

No.		**Scientific Name**	**No.**		**Scientific Name**
1		*Hymenocalyx littoralis*	43		*Paspalum virgatum*
2	D	*Portulaca oleracea*	44		*Philodendron* sp.
3		*Alocasia macrorhiza*	45		*Caladium bicolor*
4		*Ixora coccinea*	46	D	*Porophyllum punctatum*
5		*Sessuvium portulastrum*	47		*Corchorus siliquosus*
6		*Chamaesyce hypericifolia*	48		*Citrus aurianthum*
7		*Canna edulis*	49	D	*Ludwigia octavalis*
8		*Anthurium schlechtendallii*	50		*Molvariscus arboreus*
9		*Cyperus ligularis*	51		*Cissus erosus*
10		*Pedilanthus tythimaloides*	52		*Bidens pilosa*
11		*Acrostichum danaefolium*	53		*Eleocharis cellulosa*
12		*Ageratum littorale*	54	D	*Sesbania emerus*
13		*Typha dominguensis*	55	D	*Cucumis melo*
14		*Nerium oleander*	56		*Senna biflora*
15		*Washingtonii robusta*	57		*Cordia sebestena*
16		*Ipomea pes-caprae*	58		*Carica papaya*
17		*Lantana involucrata*	59	D	*Bambusa* sp.
18		*Melanthera nivea*	60		*Rabdadenia biflora*
19	D	*Angelonia ongustifolia*	61	D	*Euphorbia cyathophora*
20		unknown vine “Telefono” common name	62	D	*Cestrum diurnum*

Table 2. (2/2)

Plant species in the treatment wetlands, Akumal, Mexico, December 2, 1997.
Total number of species as of May, 1997: 68 species; as of December 1997: 70 species.
N= not found in May, 1997 survey; D = not found in December, 1997 survey.

21		*Chrysobalonus icaco*	63	D	*Lactuca intybacea*
22		*Solanum schlechtendalionum*	64	D	*Eleusine indica*
23		*Cocoloba uvifera*	65		*Kalanchoe pinnata*
24		*Sanseviera triasiate*	66		*Asclepias curossavica*
25		*Rhoeo discolor*	67	D	*Lycopersicum esculenta*
26		*Eupatorium albicaule*	68		*Graminacae sp.*
27		*Phyla nodiflora*	69	N	*Lachnera rosea*
28		*Psychotria nervosa*	70	N	Unk. (*Aracae* family)
29		*Acalypho hispida*	71	N	*Nopalea cochellinifera*
30		*Plucheo odorata*	72	N	*Desmodium incanum*
31		*Flaveria linearis*	73	N	*Wedelia trilobata*
32		*Chamaedorea seifrizii*	74	N	*Iresine celosia*
33		*Zomia purpuraceus*	75	N	*Cissus syciordes*
34		*Terminalia catappa*	76	N	*Syngonium sp.*
35		*Thrinax radiata*	77	N	*Vigna elegans*
36		*Conocarpus erectus*	78	N	*Peliveria alliacea*
37		*Musa* sp.	79	N	*Zephronthes lindeniana*
38	D	*Solanum ersonthum*	80	N	*Caesalpinia pulcherrima*
39		*Bravaisia tubiflora*	81	N	*Ipomea indica*
40	D	*Eclipta alba*	82	N	*Vigna luteola*
41	D	*Eutachys petraea*	83	N	*Selenicereus dontielarii*
42		*Xanthosoma roseum*	84	N	*Viguiera dentata*

Plant species identified by Edgar F. Cabrera, Chetumal, Q.R.

Table 3.a

Comparison of Shannon diversity indices for constructed wetlands vs. natural mangrove and tropical forest ecosystems of the study area, based on December 1997 survey data.

Ecosystem	Shannon diversity, base 10	Shannon diversity, base 2
Constructed wetland system 1	1.36	4.52
Constructed wetland system 2	1.35	4.49
Both constructed wetlands	1.42	4.71
Mangrove ecosystem	0.45	1.49
Tropical forest ecosystem	1.61	5.35

Table 3.b
Shannon diversity indices for constructed wetlands based on May and December 1997 surveys.

Wetland location	Date	Shannon diversity index, base 10	Shannon diversity index, base 2
System 1, cell 1	May 1997	1.22	4.06
	December 1997	1.26	4.19
System 1, cell 2	May 1997	1.29	4.27
	December 1997	1.32	4.39
System 2, cell 1	May 1997	1.42	4.72
	December 1997	1.26	4.19
System 2, cell 2	May 1997	1.35	4.47
	December 1997	1.29	4.27
System 1 (whole)	May 1997	1.25	4.13
	December 1997	1.36	4.52
System 2 (whole)	May 1997	1.38	4.58
	December 1997	1.35	4.49

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