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LIMESTONE WETLAND MESOCOSM FOR RECYCLING SALINE WASTEWATER IN COASTAL YUCATAN, MEXICO

By

MARK NELSON

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE
OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

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By

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

H T Odum

Howard T. Odum, Chairman
Graduate Research Professor
of Environmental Engineering Sciences

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MT Brown

Mark T. Brown, Co-chairman
Assistant Professor
of Environmental Engineering Sciences

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Clay L. Montague

Clay L. Montague
Associate Professor
of Environmental Engineering Sciences

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Konda R. Reddy
Graduate Research Professor
of Soil and Water Science

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Daniel P. Spangler

Daniel P. Spangler
Associate Professor of Geology

This dissertation was submitted to the Graduate Faculty of the College of Engineering and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

December 1998

Winfred M. Phillips
Dean, College of Engineering

Richard J.
M.J. Ohanian
Dean, Graduate School

ACKNOWLEDGMENTS

I would like to thank my dissertation committee and especially its chair, Howard T. Odum, who was an invaluable friend, critic, catalyst and inspiration for my work in ecological engineering. I was fortunate to have a committee of gifted teachers and scientists whose professional fields spanned the topics covered in the research. Mark Brown, my co-chair, gave freely of his knowledge of emergy analysis, wetland ecology and restoration. K.R. Reddy is a master of wetland biogeochemistry and generously made his laboratory available. Daniel Spangler is a gifted theoretical and field hydrogeologist who helped design much of the mangrove research. Clay Montague shared his expertise in estuarine dynamics and ecological modeling. I owe a debt to all of them for their support, guidance and patience.

The present study would not have been possible without the generous support of the Planetary Coral Reef Foundation, Bonsall, CA and Akumal, Q.R., Mexico. The wetland systems have been recipients of the hard work, intelligence and care of Abigail Alling, Gonzalo Arcila, John Allen, Mark van Thillo, Ingrid Datica and Klaus Eiberle, who share the vision of coral reef protection and bringing appropriate new technology to the tropical world.

I am indebted to Richard Smith, laboratory manager, and the Water Reclamation Facility of the University of Florida for making possible most of the water quality analyses. Yu Wang, manager of the Biogeochemistry Laboratory, Soil & Water Sciences,

conducted the limestone/phosphorus analyses, and Biol. Edgar F. Cabrera contributed his extensive knowledge of the plants of the Yucatan.

The Center for Wetlands supported my work with a research assistantship and by providing a stimulating environment of creative staff and students. The Centro Ecologico Akumal (CEA) contributed the land for the research wetland units and financially assisted in their construction costs. Charles Shaw, staff geologist for CEA, greatly assisted by sharing his research on the hydrogeology of the region.

Finally, I would like to thank my colleagues in the Institute of Ecotechnics for allowing me the time to pursue this research, and for all the camaraderie and challenge during more than two decades of wonderful ecological work. "Friendship, honor, discipline and beauty."

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LIMESTONE WETLAND MESOCOSM FOR RECYCLING SALINE WASTEWATER IN COASTAL YUCATAN, MEXICO

By

Mark Nelson

December 1998

Chairman: Howard T. Odum
Major Department: Environmental Engineering Sciences

To understand wetland self-organization and to prevent pollution of groundwater and coral reef on the calcareous east coast of Yucatan, Mexico, a wetland mesocosm system was developed for treatment and recycle of saline, septic-tank wastewater. High diversity wetland ecosystems were developed in two concrete-lined chambers, using subsurface flow through limestone gravel, arranged in series with discharge to backbeach mangroves.

Evapotranspiration in the wetlands averaged 35% of design influent during summer months and 20% during winter months. Tall wetland vegetation developed with 66 plant species in 131 m^2. Shannon diversity of vegetation was 5.01 (logarithm base 2), far greater than that of the mangrove wetland (1.49), but less than the inland Yucatan forest (5.35). Leaf area index increased over 13 months from 3.96 ± 0.28 to 6.05 ± 0.49.

In wastewater passing through the systems, biochemical oxygen demand was reduced 85%, suspended solids 40%, phosphorus 78% and nitrogen 75%. Coliform bacteria were reduced 99.8+%. Limestone gravel in the treatment system removed 5.75 ± 1.68 mg/kg phosphorus per year. Nutrients in mangrove water and soil sediments increased 5-10% from discharge of treated wastewater. Water budgets in treatment system and mangrove were studied with simulation model.

On a per-capita basis, the wetland systems for 40 people cost approximately $160 per person to construct, vs. over $400 for alternative treatment technologies. Operation and maintenance costs were 10% that of conventional treatment. Emergy in purchased inputs for construction were less than 1/3 of free environmental inputs; empower density was 2.5 E19 sej/ha/yr (one third that of conventional treatment).

The potential for economic development using the new treatment systems was evaluated. Treatment systems would require 0.3% of the annual monetary flow (vs. 1.1% for conventional sewage treatment) and 2.4% of total emergy while contributing 71,000 emdollars (the monetary equivalent of useful work contributed by nature and by humans). The new systems conserve mangroves, reduce eutrophication, prevent pollution of groundwater, protect marine resources, and contribute aesthetic values.

Research results indicate high biodiversity can be achieved in sewage treatment wetlands, use of limestone gravel augments phosphorus uptake and such systems can be integrated into the larger environmental setting.

CHAPTER 1
INTRODUCTION 1

A central question in ecological engineering is how to organize the hydrological cycle of the human economy symbiotically with that of the supporting ecosystems and geological substrate so as to maximize their joint performance. This dissertation reports the development and evaluation of an ecologically engineered wastewater interface between saline municipal wastewater and a tropical coastal zone with limestone substrate, mangrove wetlands, tourist beaches and coral reefs. Potential for this wetland system was evaluated by estimating its role in the water, nutrient, and emergy budgets of the emerging coastal economy.

To achieve the performance observed in ecosystems in nature, an ecologically engineered system may need to be coupled to the geological setting and cycles as organized with groundwater. This project uses a human-assisted self-organization and structure to innovate a union of wastewater treatment with the larger ecosystem context.

Ecological engineering 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 empower (Odum, 1991). By such minimal 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 ecosystems to handle byproducts of the human economy and to maximize the performance of both the human economy and natural ecosystems (Mitsch and Jorgensen, 1991).

Scientific Questions in Ecological Engineering of Wastewater

Treatment and release of wastewater from coastal development in Quintana Roo, in the Yucatan Peninsula of Mexico, involve new scientific questions..

Wastewater Interface Ecosystems in the Tropics

Tropical coastlines have dry and wet season properties, frequent hurricanes and high temperatures year-round. There has been increasing interest in using wetlands as interface ecosystems for wastewater treatment since early studies demonstrated their effectiveness at removal of nutrients and suspended solids. These included use of cypress swamps in Florida (Odum et al., 1977; Ewel and Odum, 1984) and peatlands in northern Michigan (Kadlec, 1979).

Constructed wetlands using surface-flow or subsurface flow emergent vegetation or aquatic plant systems have gained increasing acceptance (Hammer, 1989; Mitsch and Gosselink, 1993; Reed et al, 1995). 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 even more efficiently 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 efficiency of ecosystems (Jorgensen and Mitsch, 1991). Plant diversity may benefit wastewater treatment by providing 1/ greater variety of root systems, allowing for greater penetration of the limestone gravel and supporting a wider range of associated microorganisms; 2/differing metabolic needs (e.g. nutrient uptake) may lead to greater capacity for absorbing wastewater constituents; 3/differing seasonal cycles of activity which may increase plant productivity year-round; 4/ greater ability to utilize the full spectrum of incident solar radiation by the inclusion of shade-tolerant as well as top canopy species and 5/ differing "specialist" capabilities (e.g. C_3 and C_4 photosynthetic pathways, or quantity of aerenchyma tissue in saturated conditions) allowing for greater system response to changing environmental conditions such as light, heat, and nutrient levels. Greater diversity also buffers against system failure should disease or herbivory decimate selected plant species in the constructed wetland. There is evidence that allowing self-organization to develop cooperative mechanisms enhances the ability of adapted ecosystems to handle pollution and toxicity (Odum, 1991).

Wastewater Interactions in Landscapes with Soil Substrate of Limestone

Landscapes on limestone platforms offer special challenges and opportunities for ecologically engineered wastewater treatment. Calcium carbonate, the predominant mineral compound, has the ability to react with phosphorus and thus offers the potential for enhanced nutrient retention. On the other hand, such karstic landscapes are characterized frequently by relatively poor or shallow soil depth. In addition, the presence of rock such as limestone, which is dissolved by water, at ground surface permits rapid infiltration and lateral movement of wastewater (Bogli, 1980; Milanovic, 1981).

Studies in similar subtropical and tropical limestone coastlines (e.g. the Florida Keys and Caribbean islands such as Jamaica) have indicated that they are especially susceptible to eutrophication through flow of septic tank effluent through porous calcareous strata since retention time does not allow for sufficient plant uptake or microbial decomposition (Bright et al, 1981; Pastorok and Bilyard, 1985).

Salty Wastewater

Wastewater with appreciable salt content has only rarely been studied in sewage treatment. It is an especially important vector in ecologically engineered wetland treatment systems as salinity is frequently a controlling factor in determining the types of organisms that will best self-organize such systems. In addition, salinity is important in coastal regions as groundwater salinity varies depending on factors such as tidal interchange, rainfall and evapotranspiration. Saltwater ecosystems such as estuaries, mangrove and salt marsh are amongst the world's most productive (Day *et al*, 1989). Previous work with mangroves (Sell, 1977) and with marine ponds receiving treated sewage have demonstrated their treatment effectiveness and capacity to self-organize to the input of eutrophic wastewater (Odum, 1985).

Using Small-Scale Mesocosm Tests to Evaluate Regional Potentials

The two small constructed wetlands (total area 130 m^2) evaluated in this research may be viewed as a mesocosm study of the impact of such interface ecosystems if more widely applied to the coastal regions of karstic tropical countries. A growing body of literature has demonstrated the applicability of such mesocosm studies to evaluate processes and potentials at higher spatial and energetic levels (Beyers and Odum, 1993). Frequently distinctive patterns of self-organization result from interface mesocosms exposed to extreme forcing functions such as high nutrient and hydrological subsidies (Odum, 1991) that can then be evaluated for scaling-up and application at regional levels.

Problems of Fitting Water Systems to the Landscape

Unique Characteristics of Tropical Coastal Development

Over half the world's population live along coasts and adjoining rivers, and the rate of population increase in coastal areas exceeds those of inland regions (NRC, 1995). Especially in tropical developing countries, such issues have gained increasing attention due to recent accelerated growth of tourism and land development, exploitation of natural resources and the vulnerability of marine ecosystems, such as coral reefs, and coastal ecosystems, such as mangrove wetlands, to the effects of pollution and eutrophication (U.N., 1995).

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. Coastal tourist development has been pursued by some developing tropical countries as a method of economic progress, utilizing their resources of warm climates, beautiful beaches and eco-tourism if they have attractive marine or terrestrial ecosystems. All too frequently, this tourist development exacerbates the problems of water contamination by placing large demands on available freshwater, adding new permanent and transient populations to an area, and converting land from natural ecosystems.

Tropical areas are frequently characterized by extremely high biological diversity. The Yucatan, because of its tropical climate and isolation, has been able to sustain to date some of the most widespread and undamaged stands of tropical forest. The coastline around Akumal and this portion of the eastern Yucatan coast is an important breeding ground for loggerhead and green sea turtles, which come ashore annually to lay their eggs.

In areas like the eastern Yucatan, the environmental hazard is especially great because of the highly permeable karstic geology and the presence of coral reefs offshore that are particularly sensitive to eutrophication. It is critical to not only evaluate current development, but to develop ecologically engineered solutions. The subsurface flow constructed wetlands, constructed as part of the present research effort in Akumal, will be evaluated as one strategy for sustaining water quality both for people and for environmental preservation in tropical coastal regions.

Eutrophication Impacts on Coral Reefs

Economic development results in the release of nutrients in coastal waters causing replacement of ecosystems such as coral reefs important to tourism. The impact of nutrients in coastal regions is greater than that of deeper waters because of the interplay between sediments and the water column, due to the strong vertical mixing by tidal currents and wind in the shallow water depths (Nixon and Pilson, 1983). Thus coastal regions are unlike deeper oceanic areas where deposited materials are "lost" to surface ecosystems. Thus coral reef ecosystems and other mature ecosystems are dependent on internal nutrient recycling for a large portion of their gross productivity (Laws, 1983), new growth requiring added nutrients. Nitrogen is sometimes a limiting factor for coral reefs (D'Elia and Wiebe, 1990), normally supplied by zooplankton captured by coral polyps. Excessive nutrients displace mature ecosystems with low diversity growths.

Thus nutrient retention by the interface ecologically engineered wastewater wetland is an important criterion for maintenance of optimal environmental health at the higher level.

A growing body of research indicates that coral reefs and other marine ecosystems such as seagrass can be rapidly degraded due to pollution from inadequately treated sewage. Seagrass ecosystems are normally mesotrophic and are vulnerable to shading, disease, and excessive epiphytic growth in eutrophied waters (Pastorok and Bilyard, 1985). Caribbean coral reefs, despite their high gross productivity, are adapted to oligotrophic waters where they maintain themselves using high nutrient retention and recycling. Corals are vulnerable to sewage pollution due to the following causes: 1/ stress; 2/ decrease of available light and dissolved oxygen due to higher rates of sedimentation and enhanced growth of phytoplantkon and other microorganisms in the water column; 3/ overgrowth and bio-erosion of corals by fleshy macro-algae and benthic filter-feeding invertebrates that outcompete corals in high-nutrient waters; 4/ diseases resulting from bacterial growth stimulated by mucus-production by eutrophied corals; and 5/ direct chemical toxic effects (Hallock and Schlager, 1986; Pastorok and Bilyard, 1985; Lapointe and Clark, 1992; and Hughes, 1994).

Issues of Human Health

Contamination of water resources is one of the leading causes of disease in tropical countries (U.N., 1995). Coastal areas with their shallower water tables are especially vulnerable to groundwater pollution. 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).

Previous Studies

Coral reef deterioration caused by eutrophication was studied in Kaneohe Bay, Oahu, Hawaii, which received sewage effluent from a treatment plant. In parts of the bay, coral loss stemmed from a buildup of organic matter, causing anaerobic conditions that released hydrogen sulfide, overgrowth from the explosive growth of "green bubbly algae" (*Dictosphaeria cavernosa*), sedimentation, and loss of light and competition by filter-feeders in increasingly turbid waters (DiSalvo, 1969; Laws, 1983; Grigg and Dollar; 1990). There was a proliferation of filter-feeders that bore into the corals. Benthic organisms outcompete water column plankton and filter-feeders in oligotrophic waters, but the reverse is true in nutrient-rich conditions (Laws, 1983).

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, or in situations where avoidance of malodor and mosquito-breeding are important (Kadlec and Knight, 1996). These are all the case in Akumal because of the high visibility of the treatment site, the need to create a nuisance-free and aesthetically attractive system, and the potential of a well-designed subsurface flow wetland of providing an inexpensive but highly effective degree of 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 (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 (Cooper, 1992, Steiner and Freeman, 1989; Green and Upton, 1992; Steiner, 1992). However, there is little prior research with these systems in tropical, karstic, coastal conditions.

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 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).

The dynamics of limestone in subsurface flow wetlands is also largely unknown. Theory suggests that limestone should increase phosphorus retention since calcium and magnesium are the primary agents of phosphorus fixation in alkaline conditions (Reddy, 1997). A previous study with subsurface flow wetlands in Canada examined the efficacy of dolomite [$CaMg(CO_3)_2$] substrate containing 55% $CaCO_3$. The substrate was found to be effective at removal of P in influent wastewater handling secondary wastewater, but when primary wastewater with higher P levels were used, P retention capacity proved inadequate, and P-retention capacity decreased by 77% over 45 months of operation (Reddy, 1997).

Study Sites in the Yucatan

Regional Study Area: Akumal Coastline

The research site is the coastal region around Akumal, Quintana Roo, Mexico (Figure 1-1), about 90 kilometers south of Cancun on the eastern coast of the Yucatan Peninsula, and 10 km north of the town and Mayan ruins at Tulum. Like many tropical coastlines, the eastern Yucatan is underlain by permeable limestone that, in a kilometer-wide area adjacent to the coast, is believed to be the remains of Pleistocene coral reef communities (Shaw, *in press*). The hydrogeology of the coastal region around our study site in Mexico was studied during the 1960s and 1970s (Ward and Weidie, 1976; Ward et al, 1985), and water budgets for the region were developed by Lesser (1976).

In the northern third of the Yucatan (which includes the study site at Akumal), maximum elevation is about 40 m though most of the land surface is in a very flat plain of rough, pitted terrain, caused by weathering of the very permeable limestone, which is exposed over most of the surface. Because of the general absence of other sediments or soil, no surface drainage system exists. Cenotes (sinkholes) are the main bodies of fresh water, and almost all water movement is subsurface through the fractured limestone.

Shaw (*in press*) has described the area's geologic profile and how the modern topographic features have been derived from their Pleistocene predecessors (Figure 1-2). About one kilometer inland is an Upper Pleistocene (Sangamon) beach ridge, with a maximum elevation of 8 m, which is segmented by triangular spits that extend up to 750 m towards the sea. Modern, sandy, rounded bays have been formed by Holocene flooding

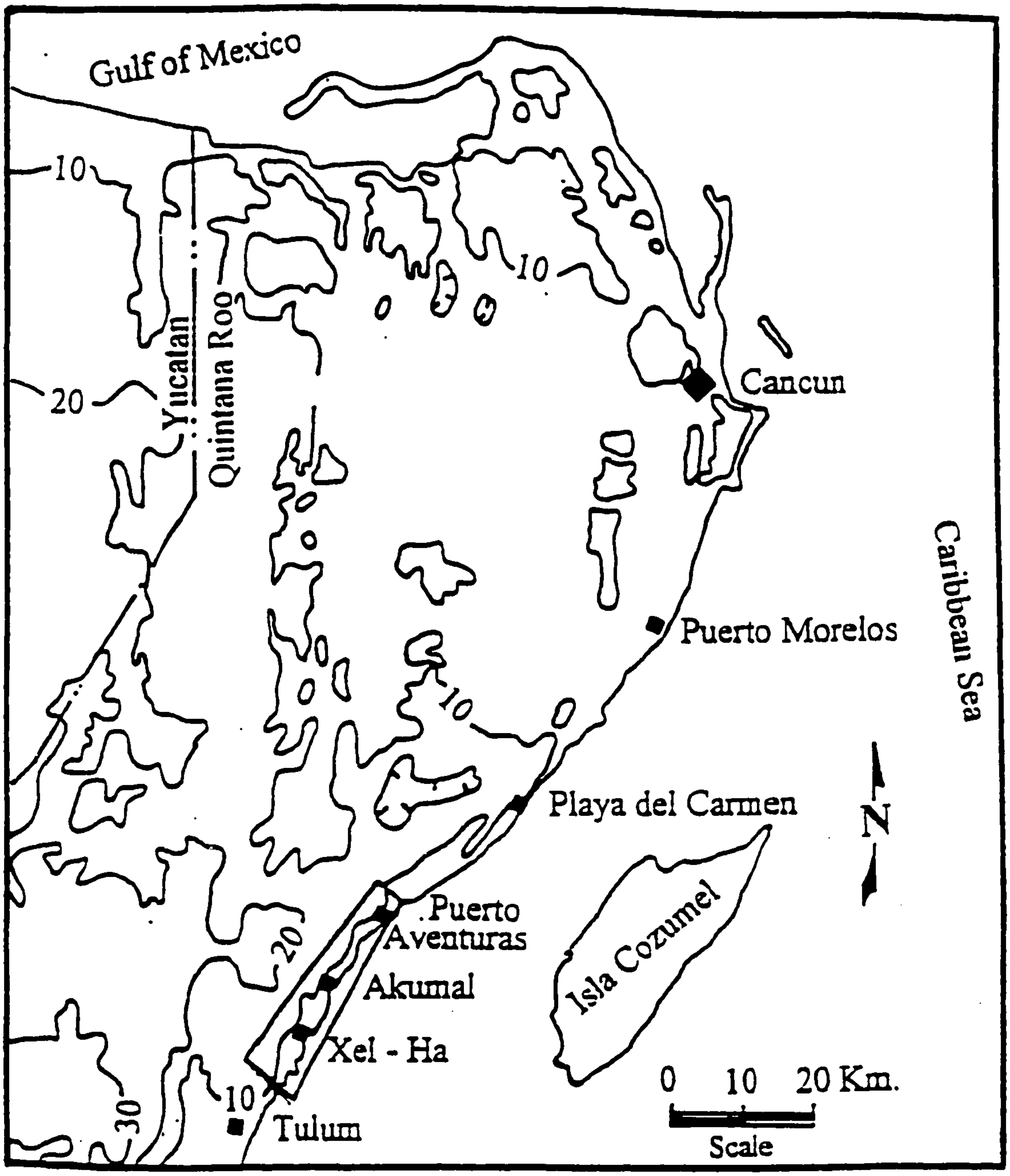


Figure 1-1 Map of eastern Yucatan Peninsula of Mexico showing coastal area of study around Akumal, Quintana Roo, north of Tulum.

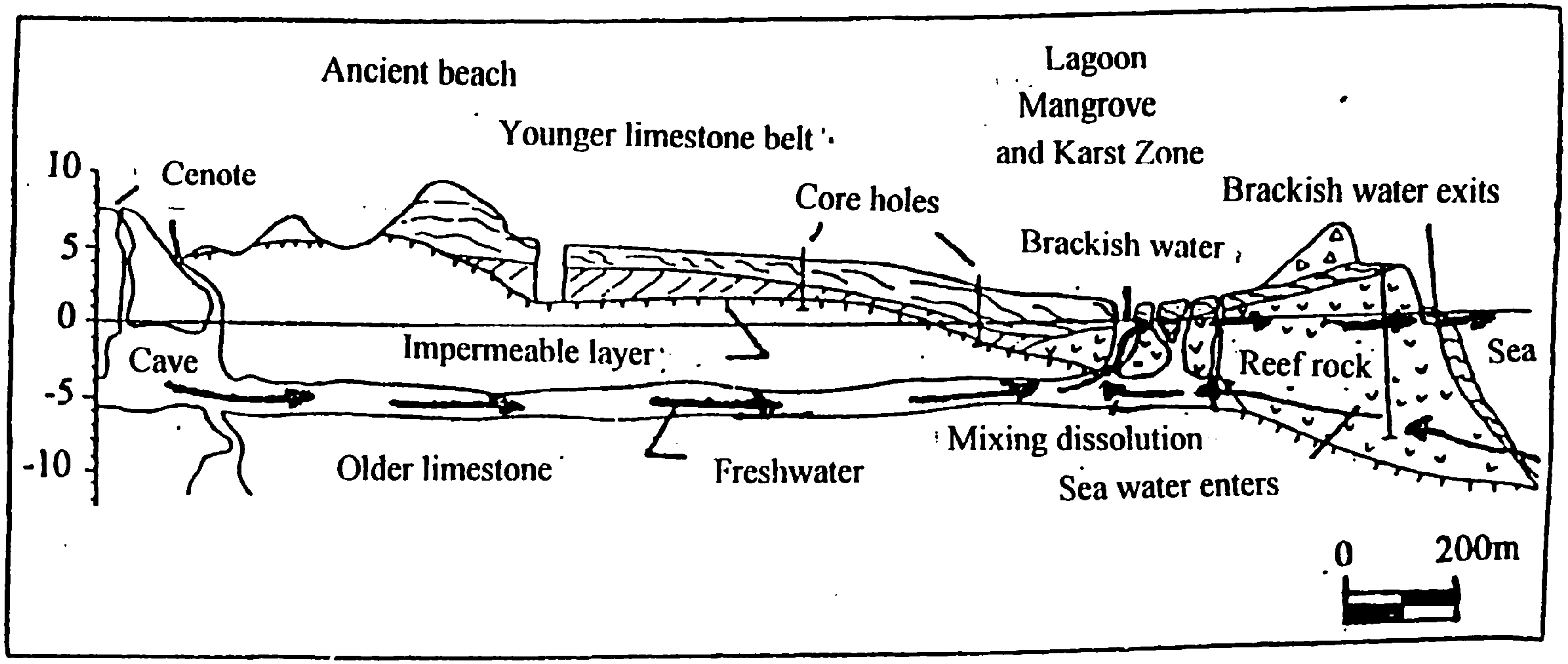


Figure 1-2 Geological cross-section in study area showing flow and mixing of fresh groundwater and seawater (Shaw, *in press)*

of the Pleistocene ones. Behind the headlands several hundred meters is a mixing zone where the mix of fresh and saltwater have led to dissolution of limestone, the collapse creating lagoons such as Yal-Ku in Akumal (Figure 1-3). While this collapse has been attributed solely to the $CaCO_3$ solution kinetics in the mixing zone (Back *et al*, 1979), this area is associated with mangrove wetlands and biological activity may have been at least partly responsible for the limestone dissolution (Odum, *pers. comm.*).

Akumal, which attracts tourists for its beaches, diving and snorkeling, has experienced growth, from dozens of permanent residents in 1970 to around 500 currently, with yearly tourist stays in the tens of thousands of days. There is evidence, from water quality monitoring done by the Centro Ecologico Akumal (CEA), that there is growing pollution of the terrestrial and marine environments. Shaw (1997) has documented a pollution plume in Akumal as high as 2000 coliform colonies/100 ml in groundwater. The finding of pollution correlates with the movement of this water through reef rock of high porosity and permeability (Figures 1-4, 1-5, 1-6).

This pollution poses dangers both for people, due to contamination of groundwater supplies and recreational contact with improperly treated sewage, and for natural ecosystems such as the coral reef system offshore. Pollution and beach development also are of concern in the study area because the coastline around Akumal is an important breeding ground for leatherback and green sea turtles, which come ashore annually to lay their eggs.

Growth and Development in the Yucatan

The rapid growth of the Yucatan Peninsula as an international and Mexican tourist destination followed the selection of the area by the national government because

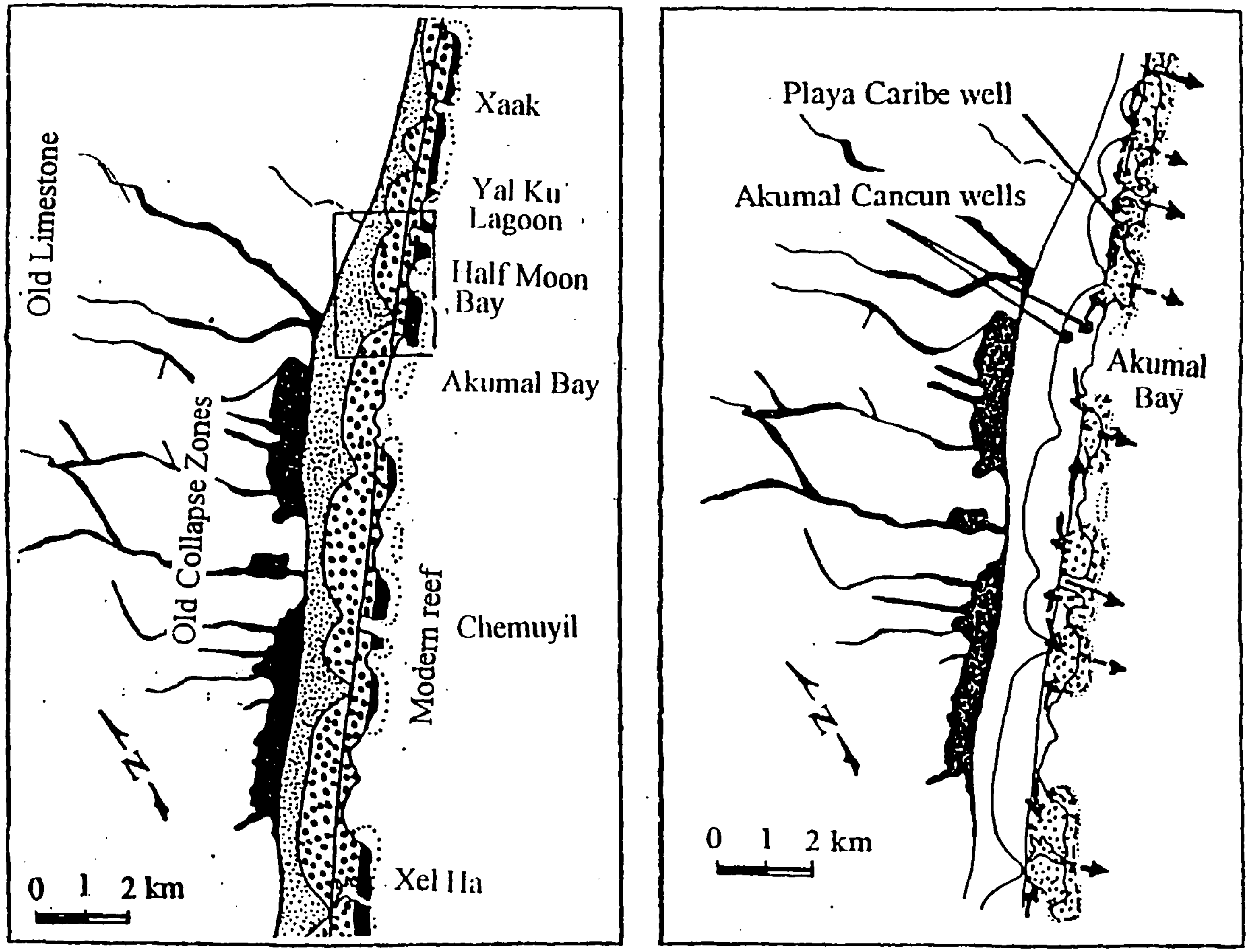


Figure 1-3 Map of study area a) shows collapse zones and areas of ancient bays (larger black dots) b) shows areas of groundwater discharge along the coast and sampling points. In both diagrams modern reef is indicated by light dots offshore (Shaw, 1997)

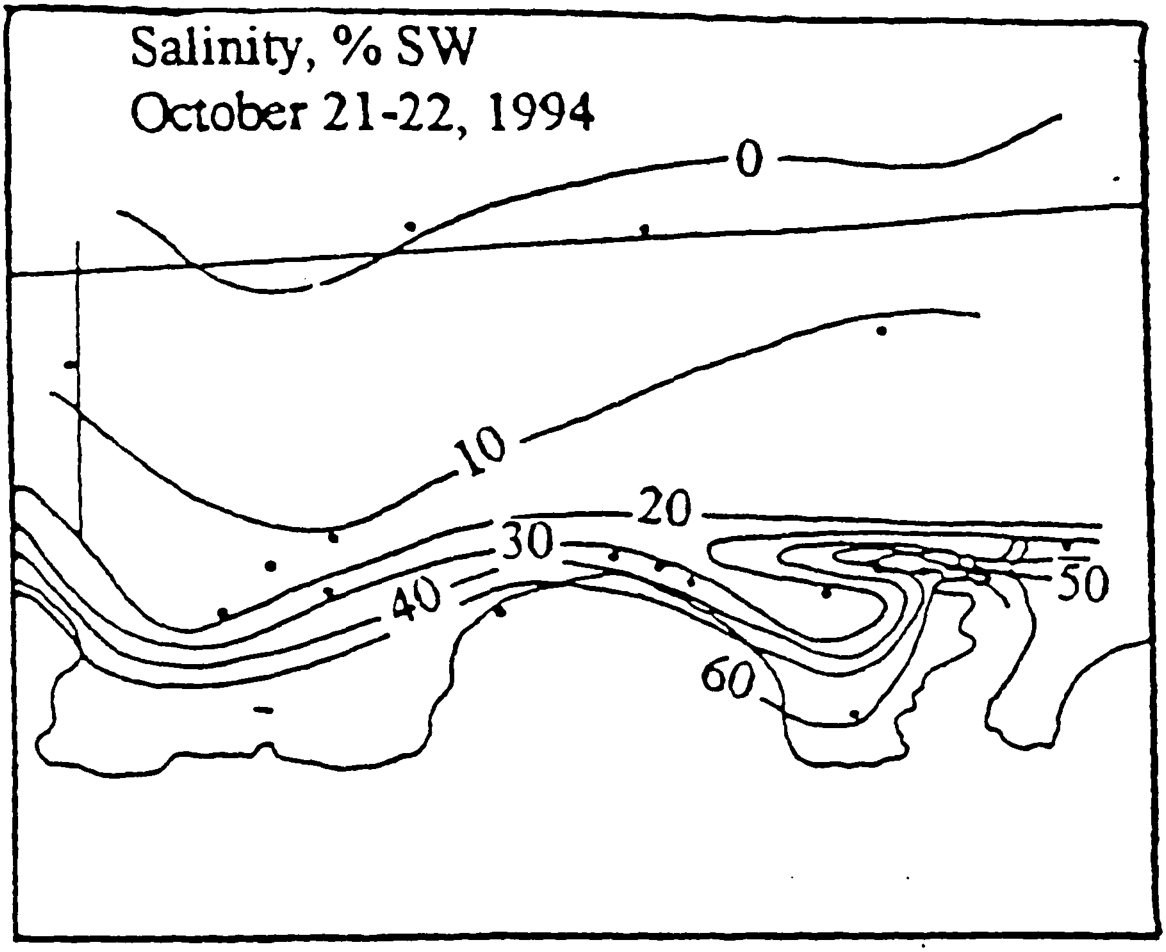


Figure 1-4 Salinity contours in Akumal during a period of no rain. Contours are compressed on the highly porous and permeable limestone. At the 20% contour, mixing of saltwater and freshwater below ground surface makes the gradients steeper (Shaw, 1997).

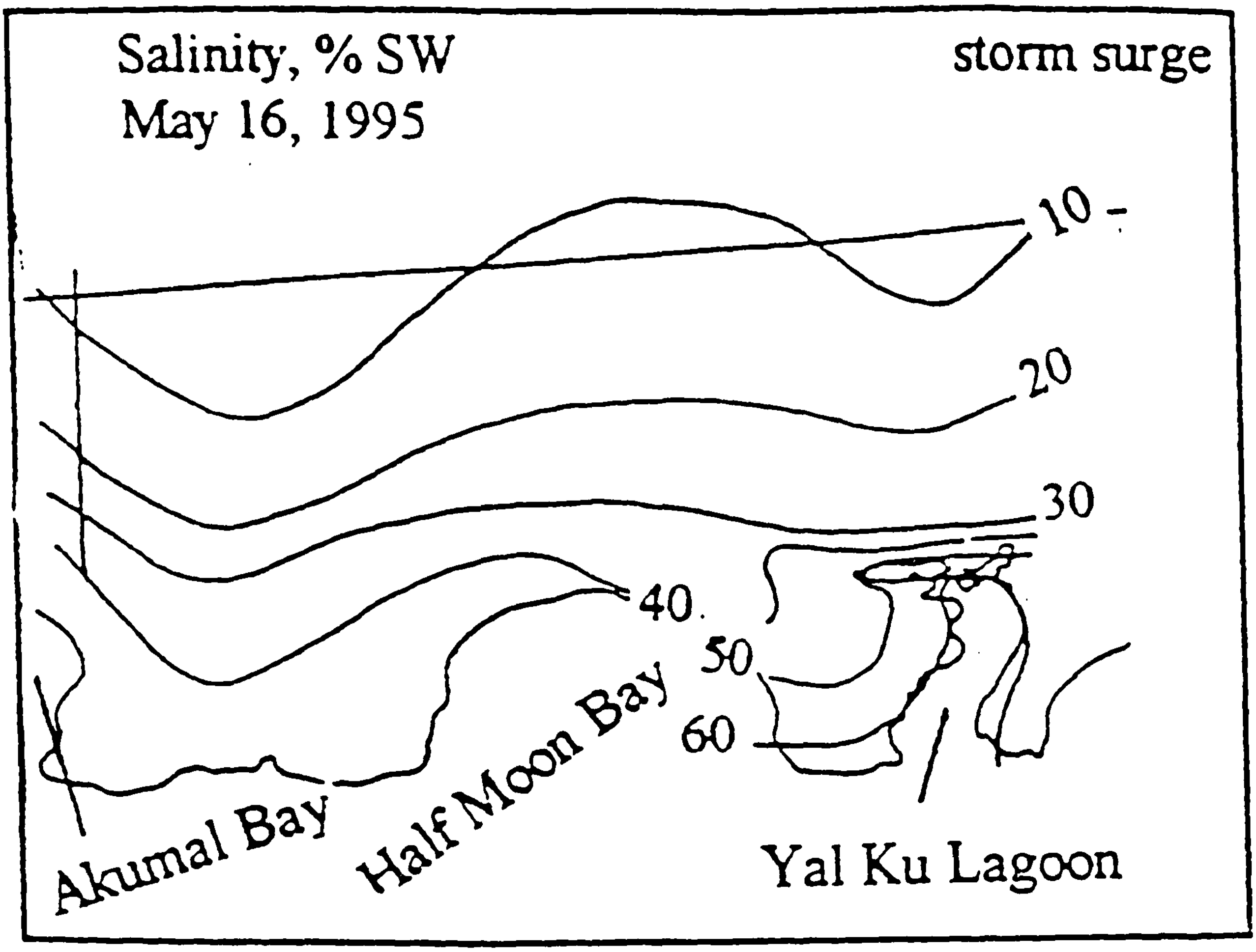


Figure 1-5 Salinity contours in Akumal area after a heavy rain. Compared to Figure 1-4, salinity gradient is displaced inland due to dilution by rain and groundwater flow (Shaw, 1997)

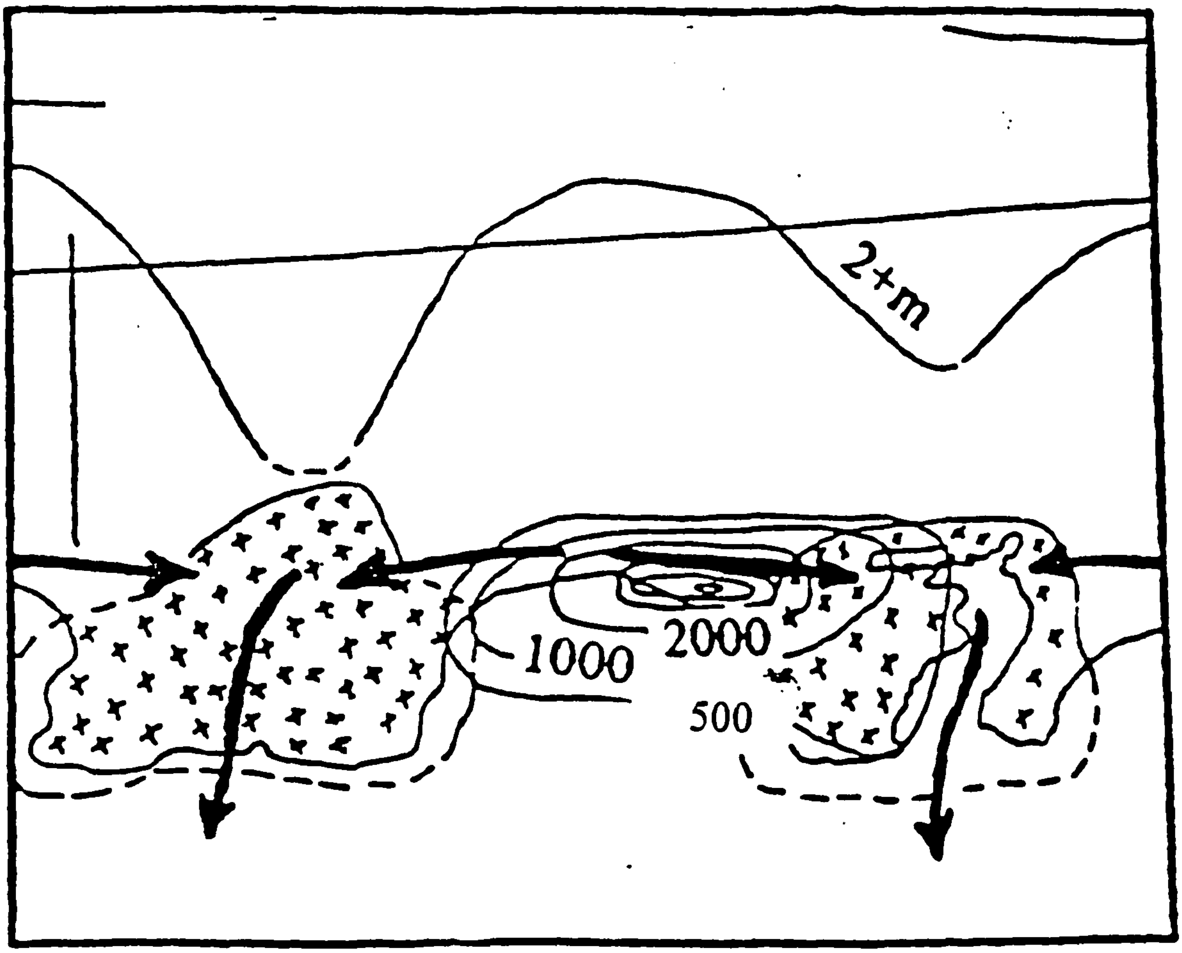


Figure 1-6 Map of study area showing groundwater flow in relation to porous limestone rock (indicated by crosses) and coliform contours from studies conducted in May-August 1997 (Shaw, 1997).

of its excellent beaches, beautiful off-shore coral reefs, and Mayan ruins. Cancun now receives over two million visitors per year and Quintana Roo close to three million annually. The entire population of the state of Quintana Roo was less than 25,000 in 1950, but grew to around 200,000 by 1980 (Edwards, 1986). Evidence from tourism development in other countries indicates that intensity of negative environmental and cultural impact are related to scale (Jenkins, 1982, Rodenburg, 1980).

The geology of the coastal area of the eastern Yucatan is one of extreme topographic flatness, underlain with carbonate rocks, predominantly limestone, of Tertiary age. The soil is generally shallow (0-20 cm deep), which, coupled with high permeability of the limestone, results in rapid infiltration of rain and high lateral movement. The result is a thin lens of groundwater (less than 70 m thick) overlying deeper groundwater that is close to the salinity of ocean water (Hanshaw and Back, 1980).

The Yucatan region is freshwater limited despite the ample rainfall (around 1100 mm of annual rainfall) and humid climate, and strategies for effective water utilization have characterized human settlement in the region since the time of the Mayan civilization (Back, 1995). These water limitations result from the nature of its almost pure limestone karstic geology without appreciable other sediments. When the limestone dissolves, forming solution depressions, these channels are not filled, so retain high permeability and porosity. This geology produces low hydraulic head, which results in restricted freshwater aquifers since the freshwater/saltwater interface is quite close to the ground surface near to the coast. The Yucatan also lacks rivers, except in its southern portions, because with the nearly flat topography of a coastal plain, and absence of sediments, infiltration of rain to the water table is extremely rapid (Espejel, 1987). Seasonal variability of rainfall is considerable, which also limits freshwater availability. The region's high permeability not only decreases the amount of freshwater available, but also makes the water supply very vulnerable to contamination by sewage effluent, agricultural runoff, and the products of litterfall decomposition from the inland forests. The resulting pollution, exacerbated by tropical climate, which favors the growth of disease bacteria, is widespread in the Yucatan (Back, 1995).

Sites of Mesocosm Tests

Two subsurface flow wetlands for sewage treatment were constructed off the "main street" in Akumal to serve residences, offices and public toilets. These constructed wetlands are located about 250 m inland from Akumal Bay, and in close proximity (5-50 m) to a natural mangrove wetland as can be seen in an aerial photo of Akumal (Figure 1-7), a topographic map of the study area (Figure 1-8) and sketch of treatment wetland units and mangrove areas of the study (Figure 1-9). Groundwater was encountered at less than 1 m below ground surface during construction in August 1996. There is a thin layer of sandy soil (6-10 inches) below which limestone rock is encountered.

Receiving Wetland

The mangrove wetlands around Akumal are unusual in that most have a groundwater connection to seawater rather than having surface tidal channels. But like all mangrove ecosystems, their hydrologic and salinity environments are highly dependent on the relative and shifting predominance of freshwater and seawater that they receive. Productivity in mangroves typically increases as one moves from mangrove areas

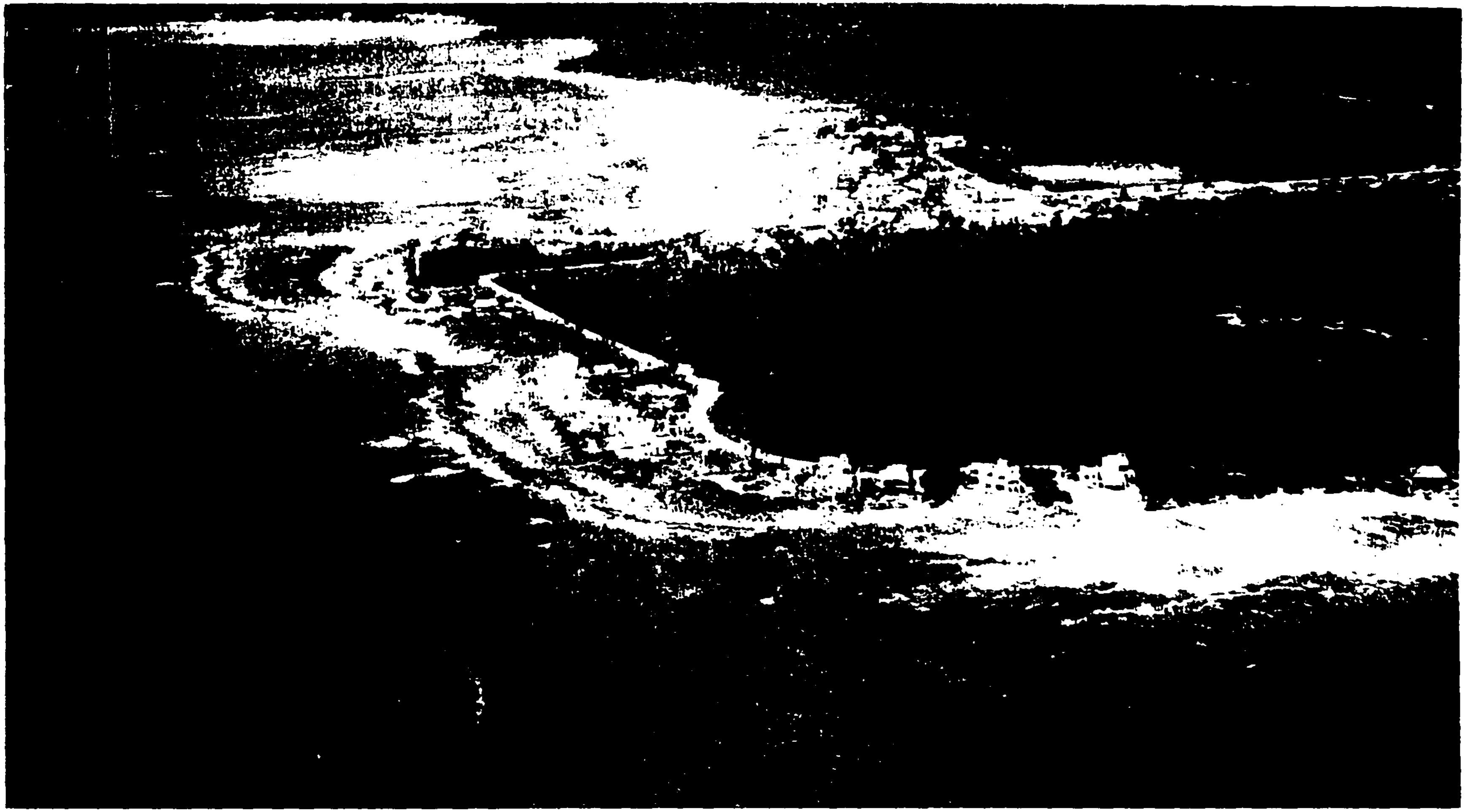


Figure 1-7 Aerial photograph of study area, Akumal, Quintana Roo, Mexico.

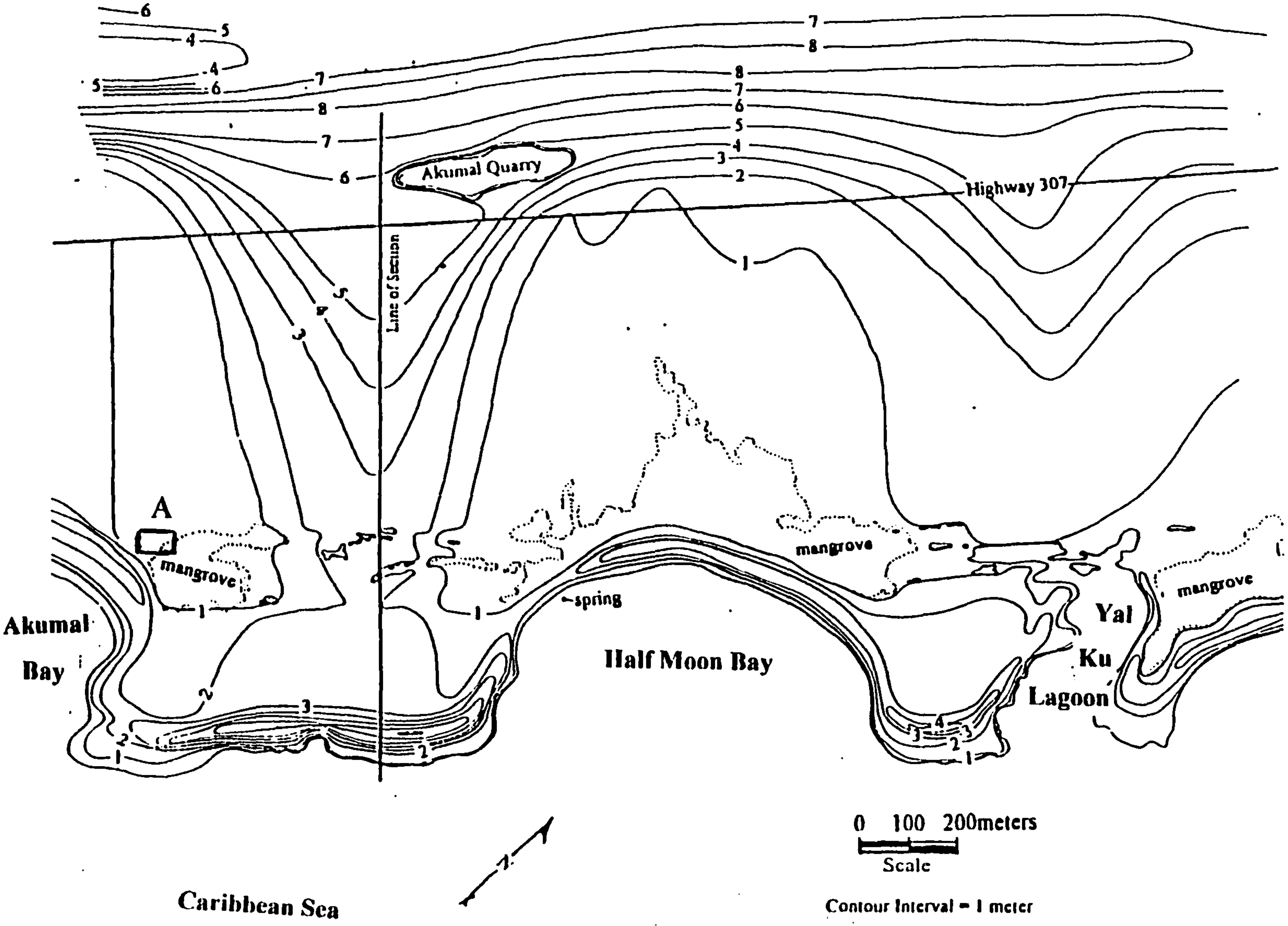
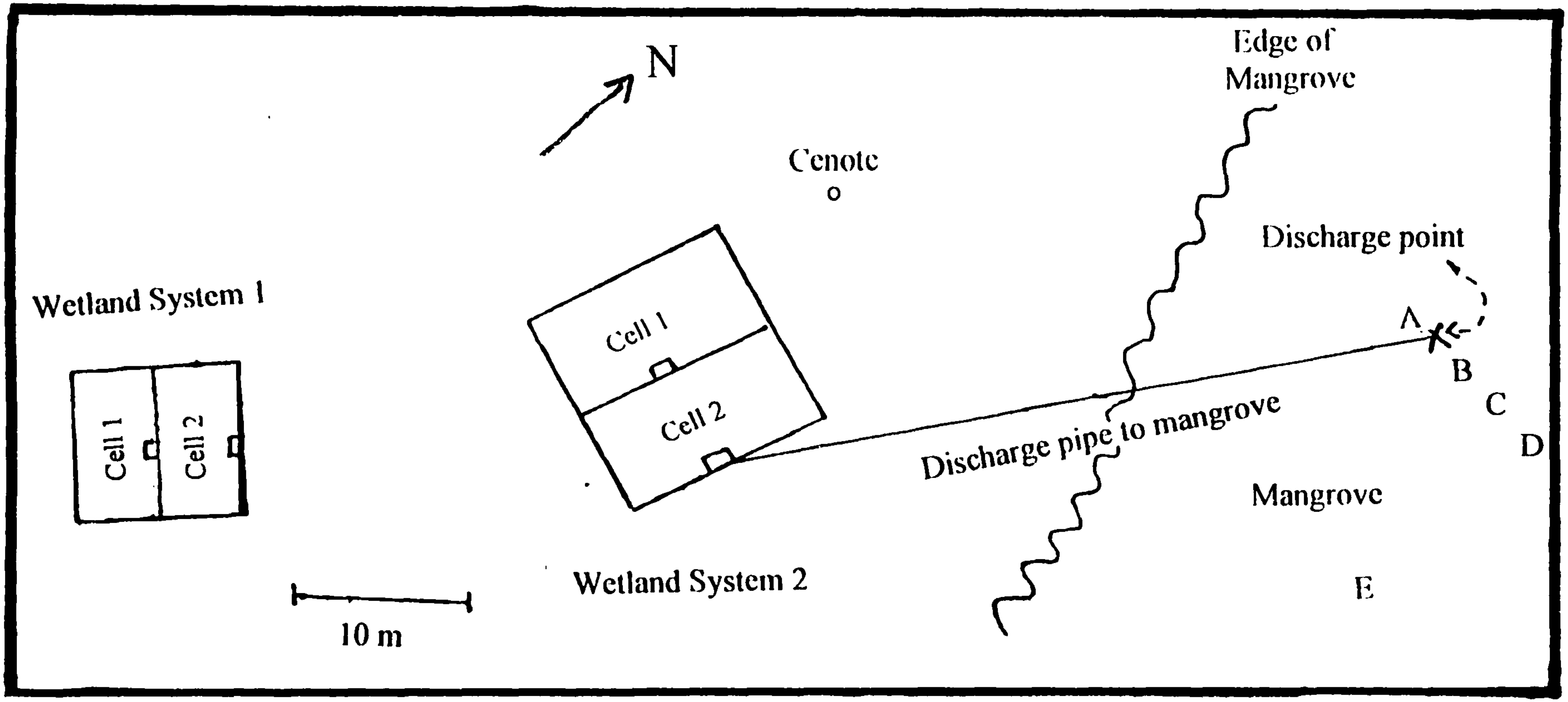


Figure 1-8 Study area around Akumal, Mexico showing location of the wetland systems at "A", enlarged in Figure 1-9. Contour lines in meters. (Shaw, *in press*).



Sampling points A,B,C, D and E

Figure 1-9 Enlarged sketch of area "A" in Figure 1-8 showing location of wetland treatment areasmangrove where treated effluent was discharged. Points labeled A to E are mangrove sampling stations.

dominated by low-nutrient and high salinity seawater to ones enriched by freshwater nutrient inputs and with decreased salinity (Day et al., 1989).

Mangroves have been shown to be effective in treating secondary wastewater. Sell (1977) studied two South Florida tidal mangrove ecosystems enriched by effluent from a sewage treatment plant. Mangrove growth was enhanced and there were no significant differences in species composition, seedling survival or litterfall between mangroves areas receiving enriched nutrient waters and control mangrove ecosystems.

Soils in the Akumal region are characterized by low nutrient status. Noguez-Galvez (1991) studied nutrient levels near Carillo Puerto (19deg 16'N., 88 deg. 07' W) about 50 km inland from the coast and 75 km south of Akumal after differing ages of fallow following slash-and-burn shifting agricultural use. Total N in the 0-5 cm layer was 0.437 ± 0.022% at 1 year fallow rising to 0.619 ± 0.095% after 20 years fallow. In the 6-11cm layer, the total nitrogen data were 0.316% ± 0.044% after 1 year, and 0.478 ± 0.076% after 20 years. Phosphate levels were 12.16 ± 1.75 mg/kg after 1 year in the 0-5 cm level, rising to 16.72 ± 4.61 mg/kg after 10 yrs, and 6.35 ± 2.35 mg/kg in the 6-11 cm level after 1 year, and 11.33 ± 7.7 mg/kg after 10 years of fallow.

At Puerto Moreles, Mexico, about 70 km north of the study site, Feller (1998) found autochtonous mangroves without external source of sediment, creating a highly organic peat substrate in the saturated subsurface. These soils are classified as solonchaks and histosols in view of their high organic content and salinity (McKee, 1998). The overall environment is oligotrophic and dominated by calcium carbonate limestone. Human impacts include road-making, clearing, diking, filling, and garbage dumping associated with tourist development. Road impoundments have not severed hydrological connections since drainage is predominantly through groundwater connection with both fresh and saltwater. Trejo-Torres et al (1993) found that Yucatan coastal mangroves export freshwater during the rainy season and receive considerable seawater during drier periods. In Belize, south of the study site, mangroves were primarily phosphorus limited, and fertilization with phosphorus or a combination of nitrogen, phosphorus and potassium (but not with nitrogen alone) produced sizeable increase of growth in mangrove species (Feller, 1995).

Mangroves were found in five zones along the Yucatan coast depending on distance from the coast. Highest biomass and basal areas were found in the mangrove zone closest to the coast (Feller, 1998), which is the zone receiving the experimental discharge of treated sewage effluent at Akumal.

Concepts

Aggregated Conceptual Model

Figure 1-10 is an aggregated systems diagram of the treatment unit within the context of the coastal economy and environment. The sources of natural energy include sun, wind, rain, inland groundwater flow, and wave and tidal activity of the sea. Primary producing ecosystems are the inland forest, the mixed wetlands shaped by both freshwater and saltwater near the coast, and the marine ecosystems (seagrass, coral reef etc.). The human economy is supported by these natural ecosystems, local resources (limestone, forest products), and imported goods and services. Tourism is the principal source of monetary flow in the area; it pays for goods and services. The treatment wetland units make an interface between the wastewater produced by the human

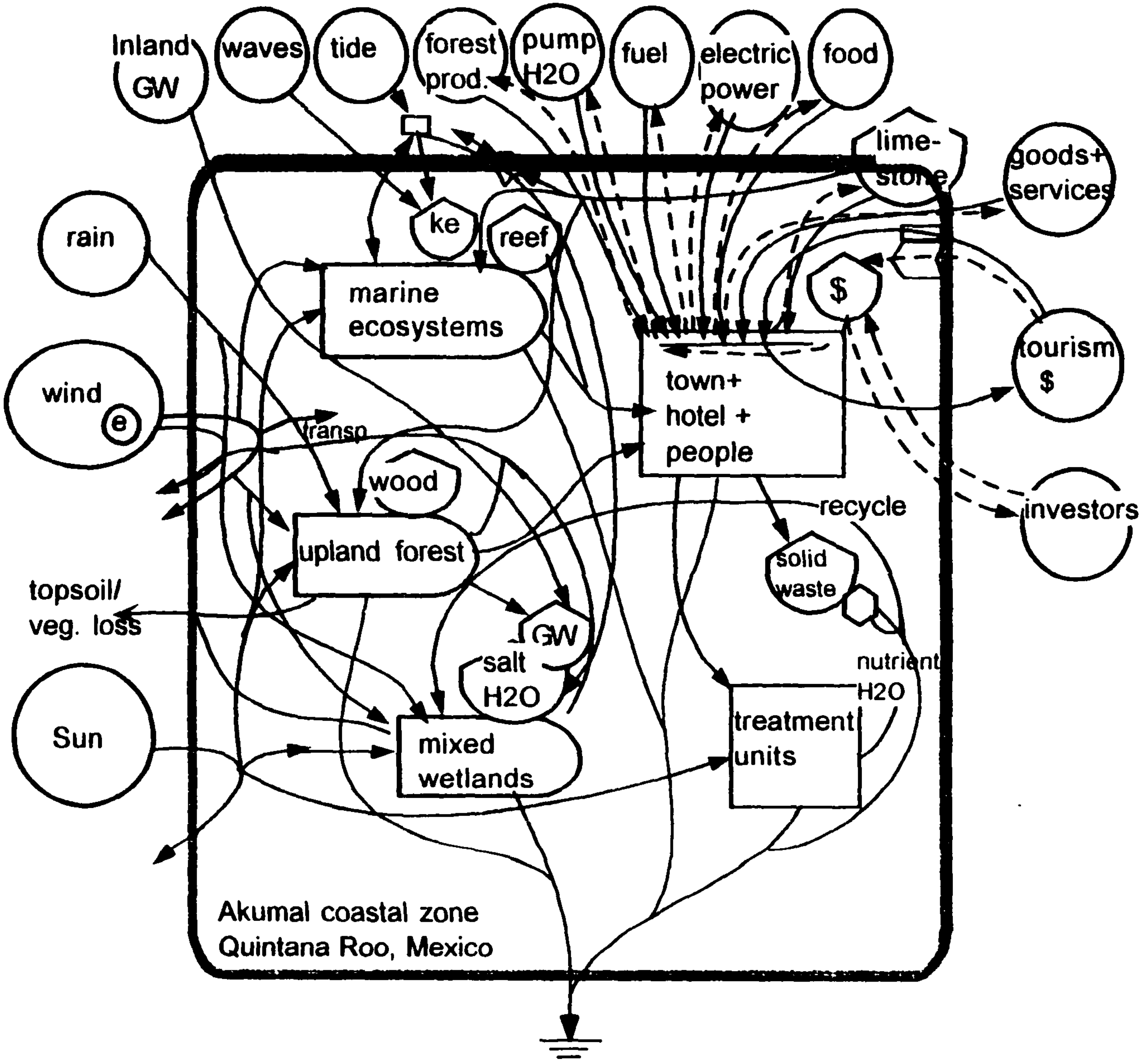


Figure 1-10 Systems diagram showing the wetland treatment unit within the context of the coastal zone economy and ecology.

economy before discharging treated water and nutrients to be recycled back into the mixed wetlands.

Diversity vs. Trophic Conditions in the Interface Treatment System

These ecologically engineered systems provided an opportunity to investigate issues of diversity vs. trophic state. Constructed wetlands have generally failed to maintain high species numbers and diversity. This failure has been attributed to high nutrient waters favoring the growth of species (such as *Typha* spp. or *Phragmites* spp.) that out-compete other, less aggressive species. In the United States and Europe, many constructed wetlands have not attempted to provide ecosystem attributes. They were designed as monocultures or planted with only 2-3 species, but have nevertheless provided satisfactory water treatment (Reed et al, 1995).

The relationship between nutrient status and species diversity is far from well understood. Yount (1956 cited in Odum, 1996) correlated pulses of nutrient enrichment with increased dominance, variation, competitive exclusion and loss or masking of rarer species. However, natural conditions of steady-state, high eutrophication have also promoted high diversity as contrasted to sudden conditions of eutrophication caused by anthropogenic pollution (Odum, 1996). Some types of human disturbance (e.g. fire, grazing and cutting in Mediterranean-climate Israel) enhance numbers of species (Naveh and Whittaker, 1979 cited in Mooney, 1986).

Similarly, while the prevalent tendency is to regard high species diversification as a sign of ecosystem development toward maturity (Margalef, 1968), there are other circumstances in which high initial nutrient levels and species numbers are reduced as storages are consumed (Odum, 1968), leading to suggestions that maximum species numbers may be maintained at intermediate successional stages (E.P. Odum, 1993).

Ecological Succession in the Treatment System

The research presented an opportunity to study ecological succession in the wetland mesocosms and to investigate some of the theoretical relationships posited for such self-organization.

Odum (1994) noted that succession is the process by which structure and processes are developed by ecosystems from available energies and resources. These progressions often include system adaptation to physiological challenges, the building of storages, development of diversity and interchange with the larger, external environmental setting.

Ecological succession typically includes a period of rapid initial growth dominated by aggressive, short-lived, pioneer species, giving way over time to species with high biomass and gross productivity but less net production.

Among the characteristic patterns observed after system biomass and non-living organic matter have been increased and as primary succession gives way to a more mature, or equilibrium, stage are a greater balance between primary productivity and respiration. As succession proceeds, the more mature ecosystem tends to display greater internal cycling and retention of nutrients, increased specialization and mutualism, and increase of efficiency of use of input energy (E.P. Odum, 1971).

The Akumal research offered an opportunity to track ecological succession and self-organization from an initial state of virtually lifeless quarried limestone gravel and to track ecosystem changes that resulted from the input of domestic wastewater to an initial planting of wetland species.

Major Objectives of the Research

The major objectives of the present research were to develop a new, ecologically engineered wastewater treatment system and to evaluate its effectiveness and integration into the Yucatan coastal environment and human economy. Among the new elements under investigation were the efficacy of utilizing limestone gravel as the primary substrate for the constructed wetland, the ability of constructed wetlands with high-nutrient inputs to sustain a high level of biodiversity and devising an integration with the natural mangrove wetlands. In addition, evaluating whether the new treatment system was economically cost-effective compared to other approaches and whether its use of local resources (evaluated through emergy comparisons with other alternatives) would make it more sustainable for a tropical developing country than conventional sewage treatment options. Finally, if applied on a regional scale, to what extent would such a system retain the anthropogenically-produced nutrients which pollute groundwater and threaten the health of off-shore ecosystems such as coral reef?

Plan of Study

1. Two pilot sewage treatment systems were constructed using saline influent wastewater, limestone gravel and multiple seeding of species on the eastern coast of the Yucatan.
2. The living ecosystem was evaluated as it developed tracking species, diversity indices, percent cover, leaf area index, and transpiration estimated indirectly.

3. The water and nutrient budgets were evaluated by analysis of inflow waters and outflow waters, and a budget and simulation model that represents the seasonal cycle and role of the ecosystem were developed.

4. After defining a representative square kilometer of coastal zone including tourist developments and their wastewater flows, the coastal water budget was evaluated. The role the new wastewater systems can have in the coastal water budget if expanded to service a kilometer of coastline was examined.

5. The share of the system contributed by the environment and the economy was evaluated using emergy, transformity, empower and empower densities of the principal features of the wastewater unit and the main parts of the coastal area (hotels, people, substrate limestone, dollar circulation and exchange).

Sampling and Measurement

Periodic sampling of water quality was conducted for the septic tanks, wetland treatment compartments, groundwater and mangrove receiving wetland. Analysis was done in local Mexican laboratories (Alquimia, Cancun and Centro Ecologico Akumal) for parameters such as coliform bacteria and biochemical oxygen demand (BOD_5), which require immediate testing. Other parameters, such as phosphorus, nitrogen, suspended solids, and alkalinity, were tested in laboratories at the Water Reclamation Facility, University of Florida, Gainesville by Richard Smith, the laboratory manager.

Bulk density and water-holding capacity for soils from the mangrove receiving wetland were conducted in the laboratory of the Centro Ecologico Akumal. Soil samples from the mangrove receiving wetland were analyzed for organic matter content and phosphorus and nitrogen content at the at the Institute of Food and Agricultural Sciences

(IFAS) Soil Testing Laboratory, Gainesville. Analysis for mineral composition of the soil was conducted using X-ray diffraction techniques by Dr. Willie Harris at the Pedology Laboratory of the University of Florida, Gainesville.

Field measurements for ecological characteristics such as species number, cover and frequency were conducted during research visits to the study site. Identification of species were made with Edgar F. Cabrera, a biologist from Chetumal, Quintana Roo.

Limestone from the system was collected before treatment began and after 11 months of system operation. Analysis of the limestone for elemental composition was done at the IFAS Soils Laboratory, with the help of Dr. James Bartos. Analysis of limestone gravel for phosphorus was done at the University of Florida Wetland Biogeochemistry Laboratory with the help of its manager, Ms. Yu Wang. Experiments on limestone uptake of phosphorus were conducted at the same laboratory.

Outline of the Research Report

The research was reported in the following manner. Chapter 2 gives the methodology followed in all the components of the research. Chapter 3 presents results from the following areas

a/ Ecological characterization of the limestone wetland ecosystem, including species number, biodiversity, frequency, cover, leaf area index, leaf holes, interception of sunlight, canopy closure and surface organic matter.

b/ Wastewater treatment including total phosphorus, total nitrogen, biochemical oxygen demand, total suspended solids, salinity, alkalinity and uptake of phosphorus by limestone gravel, and water budget.

c/ Economic and emergy evaluation of the wetland treatment system and in comparison with an alternative conventional treatment approach.

d/ Impact on the mangrove wetland including characterization of the hydrology and soil sediments of the ecosystem; and nutrient status of the soils and water before and after discharge of treated wastewater effluent from the limestone wetland unit.

d/ Simulation of the water budget of wetland treatment system and mangrove.

e/ Regional evaluation of application of the treatment wetlands. This was done by first assessing the emergy and monetary flows in a square kilometer of developed coastline, then evaluating the impact on this larger system's water and nutrient budgets with and without the use of the wetland treatment systems.

Chapter 4 presents a discussion of the major findings of the present study, and commentary on important vectors in the new wetland system for treating domestic wastewater along the Yucatan coast. Observations are presented on the pattern of ecological succession, the role of limestone, and a simulation model is developed for the interaction of the environment and the tourist economy of the area. Finally, potential for future application of the system in the region is discussed and remaining questions for future research are listed.

Appendix A contains water levels measured for the tide at Akumal, in the mangrove and in nearby cenote (groundwater well). Appendix B presents literature data used in the model. Appendix C contains the emergy evaluation of the University of Florida sewage treatment facility that is used for comparison to the limestone wetland system.

CHAPTER 2
METHODS

Treatment Systems

Ecological Engineering Design

A constructed wetland for sewage treatment was developed meshing with the environmental/geological context of the Akumal coastline. Following the concept of ecological engineering, maximizing the work of natural elements, minimizing the use of machinery and reducing cost. A system of contained wetlands was used to treat septic tank discharge using gravity-flow, eliminating the need for electrical pumps (Figure 2-1).

Because of the thin soil layer, high porosity of underlying limestone and high water table of the coastal settlements, an impermeable concrete liner prevented discharge of wastewater before adequate treatment could be accomplished. A two-celled system was used so that there was capacity to absorb torrential rains.

Limestone gravel with 1/4 - 3/8 inch diameter was used in the system. The advantage of using smaller size gravel is that surface area and porosity is increased. However, the trade-off is that smaller limestone gravel may undergo greater danger of compaction and dissolution over time (Steiner and Freeman, 1989). Larger limestone rock (2-4 inch diameter) was used in the first and last meter of each treatment cell to minimize the danger of clogging near inlet and collector pipes.

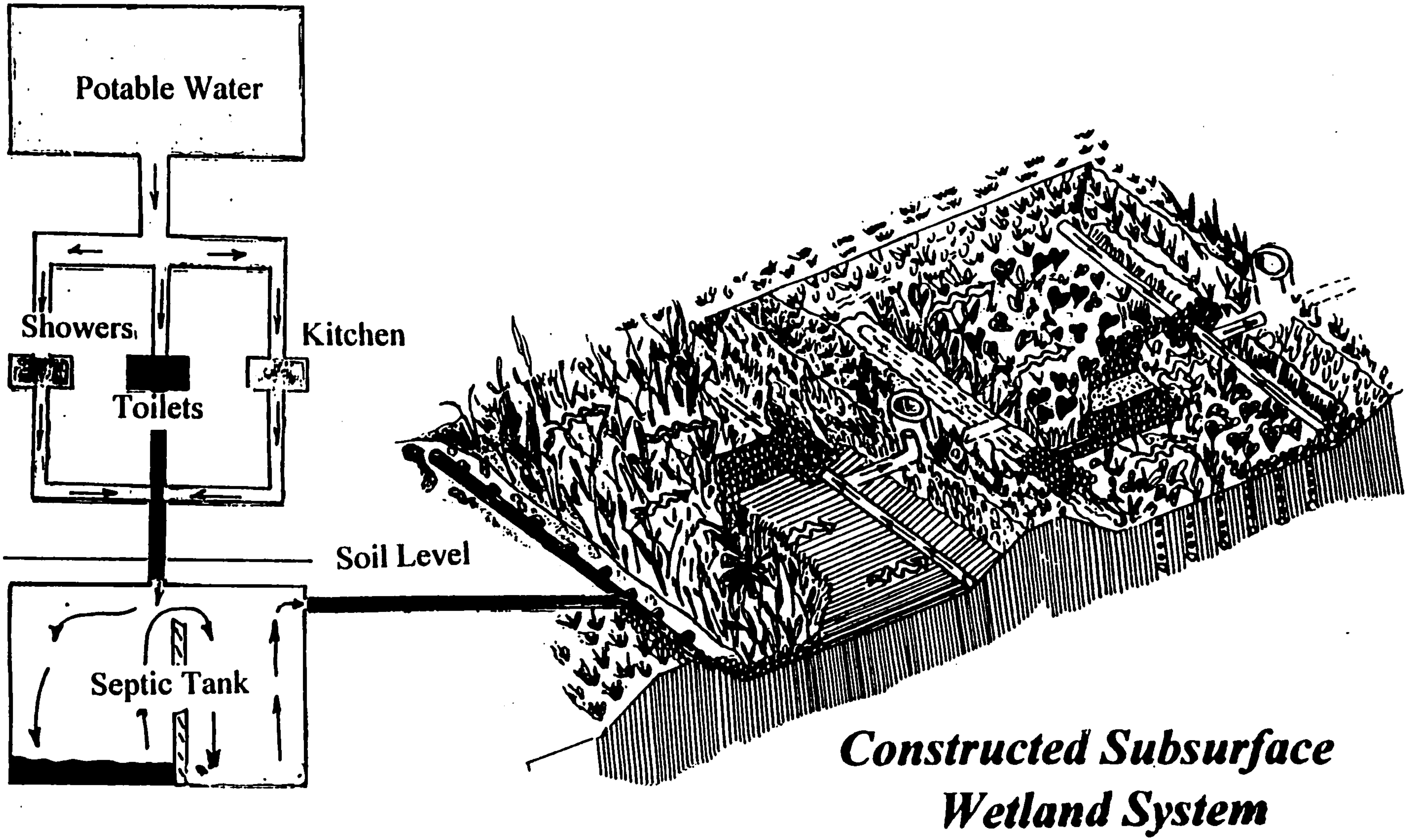


Figure 2-1 Schematic of wetland treatment system showing flow from houses to septic tanks to wetlands.

Outflows from the treatment wetlands were discharged into natural groundwater mangrove wetlands where there was natural filtering capacity of rich, organic soils and root uptake.

The treatment wetland systems were built with financing and support from Planetary Coral Reef Foundation and the Centro Ecologico Akumal. Local Mayan contractors and laborers did the construction work. Local sources of limestone and sand were used. Public meetings in Akumal explained the planned research and provided updates on research findings to government, business and local residents.

Procedures for Start-up and Management

An initial layer of sawdust mulch was applied to the system over the limestone, establishing an aerobic layer for plants that could be sustained later by leaf litter drop.

Maintenance guidelines called for minimal interference without pruning vegetation or eliminating species. Disease or pest pulses would be allowed, since these form a part of nature's diversity mechanisms. Monitoring allowed tracking of natural self-organization of introduced and volunteer plant species.

Seeding with Biota

The wetlands were planted with a wide variety of wetland plants, some transplanted from local wetland areas, some from local commercial plant nurseries, others from the botanical garden at Puerto Moreles and local gardens in Akumal. Some species entered the system as seeds carried in by wind or animals from nearby wetlands, as seeds or seedlings in the soil of plants transplanted from the wild, or during the construction process.

There was no attempt to limit species. None were removed manually as unwanted (‘weeds”). Trees and large palm species were planted at least 2 m away from the system piping to minimize maintenance problems with roots. Multiple rounds of seeding were arranged following experience with promoting self-organization in mesocosms (Beyers and Odum, 1993).

Field Measurements

Biodiversity

Plant species richness was determined by identification of plant species in the wetlands with the assistance of Edgar Cabrera, Chetumal, Q.R., a botanist from the region. Transects of approximately 250 observations were conducted in each of the two treatment cells of the two wetland systems, giving a total of about 1000 observations. These observations were made in May 1997, December 1997 and July 1998. Comparisons with biodiversity of natural ecosystems in the region (mangrove and tropical inland forest) were done by conducting transects with 1000 individual plants, identifying each to species in December 1997.

Biodiversity was calculated using the Shannon diversity index (Shannon and Weaver, 1949; Brower *et al*, 1991):

$H' = -\Sigma\ p_i \log p_i$

where $p_i = n_i/N$

“p_i” is the proportion of species “I” in the total number of individuals in the population (N). The Shannon biodiversity index was calculated using the above formulas for log 2 and log 10.

Frequency

Frequency is a measure of the probability of finding an individual species with the overall population sample (Brower *et al*, 1991). Plant species' frequency in the wetlands was determined by analysis of the transects. Each individual plant stem was counted as an observation in the transect. Data was tabulated for each treatment cell and cumulative data were tabulated for each wetland system, and data for the combined two wetland systems were analyzed.

Cover

Plant cover for each species was determined by 1/ use of 0.25 m^2 quadrats in each treatment cell and estimating percent cover of each species present, as well as percent of bare ground; 2/ measuring canopy cover of the most prevalent species (15-20) in each treatment cell (May 1997) and 3/estimating canopy coverage of all wetland species in each treatment cell (December 1997 and July 1998).

Importance values

Importance values (IV) were calculated combining frequency and cover data and dividing by two, so that the sum of all IV values for each system equaled one. These calculations were made using the May 1997, December 1997 and July 1998 field data. The graph of these data, called a dominance-density curve or species importance curve, was plotted on a log/arithmetic scale against rank order (Brower *et al*, 1991).

Leaf area index

Leaf area index was determined by the point-intercept method. Approximately 50 measurements were made in each treatment cell of the wetland systems in May, 1997, December 1997 and July 1998. Using a tall piece of steel rebar moved a set distance along pre-assigned transect lines, the number of leaves touching the pole were recorded. Each treatment cell had approximately 50 observations at each round of study.

Leaf holes

Holes in leaves due to herbivory, decomposition and other causes were measured in December 1997 and July 1998 by estimating percent leaf damage and loss on 5 randomly selected leaves of each of the species present in the wetland. Then these data were multiplied by the relative frequency of each species to give an overall measure of leaf holes in the wetland systems.

Surface organic matter

Surface organic matter was determined by collecting surface litter from four 0.1 m^2 quadrats within each cell of the two wetland systems in July 1998. Four samples of the original woodchip/sawdust mulch from 0.1 m^2 quadrats from a similarly constructed wetland system in Akumal were collected to provide a measure of the starting surface organic matter of the wetlands. The surface litter was dried at 70°C and weighed, then combusted at 450°C in a muffle furnace of the Water Reclamation Laboratory of the University of Florida and reweighed. Organic matter content of samples was determined as the difference between starting and final weights.

Solar insolation

Solar insolation and light interception in the wetland systems was measured using a LI-COR LI-189 Quantum/Radiometer/Photometer equipped with a LI-COR Terrestrial Radiation Sensor, Type SA (LI-200SA) pyranometer sensor. The pyranometer was factory calibrated against an Eppley Precision Spectral Pyranometer under natural daylight conditions, giving an absolute error of ± 5% maximum, typically ± 3%. Quantum light measurement results were in μmol s^{-1} m^{-2} (1 μmol s^{-1} m^{-2} is equivalent to 1 μEinstein s^{-1} m^{-2}).

Light measurements were conducted on 28 July 28 1998, a cloudless day, from 1050 to 1145 AM. Measurements were made of ambient solar insolation outside the wetland systems before and after measurements of each wetland cell. Approximately 30 measurements were made in each of the 2 wetland cells of wetland system 1 and 50 measurements in each cell of wetland system 2. Measurements were made 0.5 m in from the edge of each cell and then every 1 m across the cells.

Canopy closure

Canopy closure in the wetland systems was evaluated in July 1998 using analysis of hemispheric canopy photography (Rich, 1989). Photographic images of the wetland canopies were made using a 180° fish-eye lens adapter on a Nikon camera. Nine photos were taken at predetermined and equivalent locations in each of the wetland cells, and in the discharge area of the mangrove ecosystem, then digitized and converted to a gray scale using Photoshop 2.0. Analysis for amount of canopy and light penetration was done with MapFactory software.

Analytic Measurements

Total nitrogen and total phosphorus

To determine nutrient treatment in the wetlands of phosphorus and nitrogen, laboratory tests for total phosphorus and total nitrogen were conducted on wastewater samples from the wetland treatment systems.

Phosphorus was determined using persulfate digestion followed by the ascorbic acid method, SM 4500-P (APHA, 1995). Tests were conducted at the University of Florida Water Reclamation Laboratory. Total nitrogen was determined using the persulfate method, SM 4500-N (APHA, 1995).

Samples were collected from the septic tank, from the standpipe at the end of cell 1 and cell 2 in each wetland treatment system. A sample was collected from a cenote (shallow groundwater well) with water accessible a few feet below ground level located just a few meters from the wetland treatment system. This cenote is located on the inland side of the wetland systems, and is presumed to give some indication of local groundwater background levels. After collection in a 10 ml sample bottle, 1-2 drops of concentrated sulfuric acid was added to preserve the samples until shipping to the laboratory.

To determine variability in the total P and total N laboratory test, two samples were run three times in August and September, 1997 so that standard deviation and standard error of the mean could be determined.

Biochemical oxygen demand (BOD)

Biochemical oxygen demand (BOD) was determined using EPA method 405.1 (EPA, 1993). This is a five day test with sample kept at 20°C. Samples (250 ml) were collected as described above and kept cool during transport to the laboratory. The materials were tested in laboratories in Cancun. The tests from January to April 1997 were conducted at Laboratorio Alquimia, Cancun and those from May 1997 were conducted at the laboratory of Jose Castro in Cancun. Both are certified laboratories for water analysis.

Chemical oxygen demand (COD)

Chemical oxygen demand in the water of the mangroves was determined using the closed reflux, colorimetric method, APHA 5220D (APHA, 1995). The sample was digested using $K_2Cr_2O_7$, H_2SO_4, and $HgSO_4$. Tests were conducted using Hach prepared reagants, and analyzed on a Hach DR-3000 colorimetric instrument at the laboratory of the University of Florida Water Reclamation Facility.

Total suspended solids

Total suspended solids (TSS) in the wastewater were determined using the filterable residue, a gravimetric method with the material dried at 180°C, EPA method 160.1 (EPA, 1993), method 2540DSM (APHA, 1995). 250 ml. samples were collected from the seven points described above and stored for shipment to the Water Reclamation Laboratory, University of Florida, where the tests were conducted.

Fecal coliform bacteria

Fecal coliform in the wastewater was determined using membrane filtration and most probable number (MPN) of colonies per 100 ml of sample. This is method 9222DSM (APHA, 1995). Samples (175 ml) were collected from the seven points described above and transported to the laboratory in Cancun for analysis within hours of collection. The same laboratories that conducted the BOD-5 tests conducted the analyses for fecal coliform until May 1998, when analysis was conducted in the water laboratory of the Centro Ecologico Akumal.

Alkalinity

Alkalinity of the water samples was determined by titration (buret), method 2320B (APHA, 1995). Samples weighed 50 ml and the method used .02 N sulfuric acid.

Salinity

Salinity of water samples from the septic tank and wetlands was determined with use of a hand-held refractometer accurate to +/- 0.5 parts salt per thousand.

Phosphorus Uptake by Limestone

Initial P content and uptake in wetlands

Samples of limestone were analyzed for initial phosphorus content and phosphorus content after exposure to sewage in the treatment wetlands. Pre-exposure limestone was collected during construction and bagged for later analysis. In December 1997 after one year of sewage treatment had occurred, composite limestone samples were collected from each of the treatment cells of systems 1 and 2. These were divided into limestone from the layer above the sewage line, and those at 0-10 cm depth, 10-20 cm depth, 20-30 cm depth, 30-40 cm depth and 40-50 cm depth. These limestone samples were roughly pulverized mechanically then ground in a ball grinder.

Inorganic P analysis, conducted in the Wetland Biogeochemistry Laboratory at the University of Florida, was determined as follows. Following grinding, the limestone samples were dried in an oven at 70 deg.C. for 48 hours. Then a subsample (0.5 g) of the ground limestone was extracted with 25 ml of 1M HCl for 3 hours, then filtered through a 0.45 micrometer pore size membrane filter. The HCl extract was stored at 4°C in a 20 ml polyethylene vial. The HCl extract was analyzed for inorganic P using an automated ascorbic acid method (Method 365.1, EPA, 1995).

Calcium/magnesium composition of Yucatan limestone

The limestone was analyzed for calcium and magnesium content at the Soils Laboratory of the Institute of Food and Agricultural Sciences (IFAS), University of Florida.

The procedure was to grind and dry samples of limestone in a 120°C oven for 4 hours. Then 5 x 1.0 gram dried sample was placed in a 1000 ml graduated beaker, and. 125 ml of 1N HCl solution was added to dissolve the limestone. The solution was diluted to 250 ml of 0.25M hydrochloric acid. The beaker was covered with a watch glass and boiled gently on hot-plate for 10-15 minutes. Condensate was washed into beaker with de-ionized filtered (D.I.) water and cooled to room temperature. The solution was brought to approximate volume of 1000 ml. with D.I water. Analysis for calcium/magnesium was by inductive coupled plasma spectroscopy.

Experiments on phosphorus uptake by limestone

To determine reaction kinetic rates of the Yucatan limestone with respect to phosphorus, a series of lab and field experiments were designed. The experimental procedure to determine phosphorus uptake by limestone was to combine limestone gravel samples from the wetlands. Five hundred ml plastic bottles were filled with approximately 250 grams of limestone gravel. Bottles were then filled with 450 ml of phosphorus solution. This left some airspace below the neck of the bottles.

For the laboratory experiment, there were 5 experimental treatments x 3 replicates for a total of 15 bottles. The initial phosphorus concentrations were 5.6 mg P/liter, 11mg P/liter, 22 mg P/liter, 56 mg P/liter, and 111 mg P/liter. After addition of phosphorus solution, bottles were maintained with caps only loosely on, allowing air exchange. Bottles were shaken once a day. After 10 days, 10 ml. samples were taken and filtered through a 0.45 μm membrane filter at 1,2,4,6 and 10 days. Separate syringes and filter cases were used for each of the six treatments. Samples were stored in a freezer until analysis for soluble reactive phosphorus.

For the field experiment, 3 x 500 ml. bottles with 250 grams of limestone gravel prepared at the same time as the laboratory ones, were loaded with 450 ml of actual wastewater from the septic tanks in Akumal, Mexico. Three bottles with 250 grams of limestone were filled with 175 ml of actual wastewater (to approximate the condition in the wetland treatment system that the sewage water covers the limestone). The bottles had 10 ml. samples taken and filtered through a 0.45 micrometer membrane filter at 1,2,4,6, 10 and 30 days after loading. The samples were kept in a freezer until shipment to the University of Florida Water Reclamation Laboratory for soluble reactive phosphorus analysis. Analysis for soluble reactive phosphorus used EPA Method 365.1 (EPA, 1995)

Water Budget of the Wetland Systems

In May 1997 and December 1997 the water budget of the wetland systems were determined by measuring inputs and outputs from the system. The only water inputs to the systems are effluent from the septic tanks and direct rain, as no surface runoff or groundwater enters the constructed wetlands. By draining the system 1 and system 2 septic tanks, and then measuring rate of re-fill, it was possible to estimate hydraulic loading.

System evapotranspiration was calculated by measuring the decline over time in the water levels of the standpipes in the control box at the end of each cell of the wetland systems (see Figure 2-3 of the construction blueprints). Water-holding capacity of the gravel used in the wetland was estimated by filling a known quantity (20 liter bucket) with the limestone gravel and then measuring the amount of water that the volume holds.

The only outputs from the system are evapotranspiration and discharge from the outlet in the control box of cell 2. Thus, once the average daily evapotranspiration is calculated, the average discharge from the system may be estimated by difference from average input from the septic tanks.

Economic Evaluation

Data on construction and maintenance costs of the wetland and package plant sewage treatment systems were collected. Annual costs were estimated using expected lifetimes of system components.

Emergy Evaluation

Comparative evaluations of the emergy involved in the wetland sewage treatment system and a conventional "package plant" sewage system were carried out using survey data on materials, labor, equipment used in constructing and operating the systems, plus data on natural resource flow in the area. From these, emergy evaluation tables were developed and emergy indices used to compare the sewage treatment systems.

Receiving Wetland

Biodiversity

Biodiversity of the mangrove area receiving discharge from Wetland system 2 was monitored for biodiversity before effluent began in December 1997. Biodiversity was determined by ten transects of 100 individual plants identified to species. Shannon diversity was then calculated from these data (see previous section).

Mangrove Soils

Depth of the mangrove soils in the vicinity of the wetland discharge was determined in December 1997 by driving a piece of 1/8 inch steel rebar into the soil until it struck rock. This was done in four directions, each 90 deg. from the next, from the center of the discharge, with 20 total observations, each made at 3 m intervals. An isopach map was generated from these data.

Wet/dry weight of the mangrove soils was determined in December 1997 by drying five sample bags of 30 cm. deep soil cores at 70°C until no further weight loss was observed. Bulk density was calculated by taking five soil cores to a 30 cm depth and then determining wet weight and dry weight after drying in an oven at 70 °C until there was no further weight loss. Five soil samples collected in December 1997 were analyzed by the Soil Laboratory of the Institute for Food and Agricultural Sciences (IFAS), University of Florida for total phosphorus and total nitrogen (using Kjeldahl method for N and the dry ash method for P) and total organic content (by loss on ignition method). These latter tests are described below:

Loss on ignition test for soil organic matter determination (Magdoff *et al*, 1996) was used for soils with organic content greater than 6%. Five gram soil samples were placed in a pre-heated oven at 120°C for 6 hours. After cooling for 30 minutes, a weighed subsample of soil was placed in a beaker and placed in a muffle furnace set to 450 °C. for at least 5 hours. For this study, samples were left for 14 hours. After cooling to room temperature, final weight was recorded. Percent organic matter was determined by comparing final weight with initial weight of the soil samples.

Total Kjeldahl Nitrogen (TKN) and dry ash method for phosphorus (Hanlon *et al*, 1998) were used by the IFAS Soil Laboratory in nutrient analysis of the mangrove soils. In the TKN procedure, 0.5 g of soil is digested with 2.0 g of Kjeldahl mixture in a digestion tube. The mixture is wet with pure water and 0.5 ml of concentrated sulfuric acid is added. The tubes are placed on a preheated aluminum block digester at 150 deg C. for 0.5 hours then the temperature is increased to 250°C for 2 hours. One ml. of hydrogen peroxide is added by pipette in two steps of 0.5 ml. A glass funnel is placed over the tube and digestion continues for 2.5-3 hours. The tubes are removed from the digester and cooled, then the sides of the tubes are washed with 5-10 ml of pure water. After mixing with a vortex shaker, the digestate is moved to a 100 ml volumetric flask. Approximately 20 ml of solution is filtered through a Roger's Custom Lab 720 into a 90 ml. plastic cup.

A filtered subsample is transferred to a 20 ml. plastic scintillation vial and refrigerated until analysis on the RFA (air-segmented, continuous-flow, automated spectrophotometer). Final step is analysis on the RFA calibrated with digested standards for total nitrogen.

In the dry ash P analysis, 1 g of oven-dry soil is combusted in a 500°C muffle furnace to ash for a minimum of 5 hours. The ash is then moistened with 5 drops of distilled water and dissolved with 5 ml of 6.0M hydrochloric acid. After 30 minutes, the solution containing the ash is transferred to a 50 ml volumetric flask and brought to volume with pure water. A filtered subsample is transferred to a 20 ml. plastic scintillation vial and refrigerated until analysis on the RFA (air-segmented, continuous-flow, automated spectrophotometer). Final step is analysis on the RFA calibrated with digested standards for total phosphorus.

Micro-analysis for soil composition

The mineral portion of the mangrove soils was assessed using X-ray diffraction at the Soil Pedology Laboratory of the University of Florida.

After soil samples were mixed, organic materials were digested by addition of sodium hypochlorite, 5.25% by weight, to cover the sample. After digestion for 20 hours, each sample was put through a 15 micrometer sieve into distilled water. The soil sample was centrifuged at 2500 RPM for 3 minutes and the supernatant liquid poured off. Then a 1 M solution of sodium chloride was added, and the solution again centrifuged at 2500 RPM and the supernatant poured off. Then de-ionized water was added to the solid materials, and centrifuged at 3000 RPM for 5 minutes. Some of the liquid was poured off, and oriented mounts were prepared for X-ray diffraction analysis by depositing suspended materials onto porous ceramic tiles under suction. One of the tile mounts was treated with potassium chloride, and two with magnesium chloride. The KCl and $MgCl_2$ were added four times, and pulled through the ceramic tiles by a suction device. Then each ceramic tile soil mount was rinsed with de-ionized water four times. To one of the $MgCl_2$ treated tiles, 30% glycerol was added. The clay tiles were then analyzed by X-ray diffraction. Samples were scanned from 2 to 60 degrees 2θ using a computer-controlled x-ray diffraction system equipped with stepping motor and graphite crystal monochromator. Power was 35 kV and scanning rate was $2° \, 2\theta$ per minute.

Nutrients

Mangrove soil samples collected before and after discharge commenced, at the beginning of May 1998 and monthly from June to August 1998, were analyzed using the Total Kjeldahl Nitrogen and Dry Ash Phosphorus methods described above in the section entitled Mangrove Soil. Soil samples were collected at 1, 3, 5 and 10 meters east, west, north and south of the discharge point. Mangrove water samples collected in December 1997 and April 1998 were analyzed for biochemical oxygen demand, fecal coliform, suspended solids, total nitrogen, total phosphorus, salinity and alkalinity using methods described in the section on Analytic Measurements. These tests were repeated after discharge commenced in May, and monthly samples were collected June, July, and August 1998 to ascertain changes in the nutrient and water quality status of the mangrove groundwater.

Hydrogeology

Water in the mangrove site at Akumal exchanged through groundwater channels from below. There was no surface connection to the sea. Hydrologeological studies of the fluxes with the receiving area were made by comparing surface water levels with those of a nearby cenote (well) and the sea. This was done with a water level chart recorder of surface water height during May 1997, December 1997 and July 1998

Direction of water flow in the area was determined from the heights of water in three polyvinyl chloride (PVC) pipes, 10 cm in diameter, placed 60 cm deep in the mangrove soils, which served as piezometers. Elevations were determined by use of manual water-tube levels. Location and directional orientation of the piezometers was determined with a surveying level. Water levels in the piezometers are equal to the elevation of the hydraulic head (Fetter, 1994). Flow lines were determined by triangulation of these data on a map of the potentiometric surface in the vicinity of the discharge outfall. A series of 5 PVC monitoring pipes were installed in December 1997. One pipe was installed 1 meter upstream from outfall of the discharge pipe from the wetland, and three other pipes were installed 1, 3 and 6 meters in the direction of water flowlines in the mangrove. The fifth monitoring pipe was installed 12 meters southeast of the discharge pipe, in the direction of the edge of the mangrove.

Simulation Model of the Water Budgets

Simulation models were developed for the treatment units and their discharge into the receiving wetland. This model followed the methodology outlined in Odum (1994) and Odum and Odum (1996). After selecting a system boundary, outside sources were listed, from the environment and from the human economy. Relationships and pathways between system components were identified including exports from the system. Relationships were translated into energy language symbols and then into rate equations. After average values were put on the pathways and in storage symbols, coefficients were calculated with spreadsheet. A simulation program was written in BASIC and sensitivity studied with scenarios. Simulation runs were compared with field and literature data.

Evaluating Potential of Wastewater System for the Coastal Zone

Potential significance of the treatment system was studied by considering a square kilometer of developed coastal area operating the treatment system. Evaluations were done on two scales: the treatment systems and the square kilometer.

Emergy Evaluation

An emergy evaluation of the square kilometer area was made using data from published sources, data on use of natural resources and human services obtained from hotel owners, homeowners and residents, and from town maps showing density and layout of properties in the area.

Emergy analyses followed methods developed by Odum and Brown (Odum, 1996; Doherty and Brown, 1993; Brown and Ulgiati, in press). This was done by developing systems diagrams showing energy sources, system components, pathways of energy and material flow in the system, system outputs and depreciation/heat sinks. These systems diagrams were developed in three forms: detailed, aggregated and three arm diagrams. Then data was collected, using published and new data, on material and energy flows.

Transformities

Emergy tables were compiled, using transformities for the items. Table 2-1 presents the transformity values used in all the emergy evaluations of the present study. With these system relationships and data, indices to compare emergy flows of the environment with those of the natural environment are evaluated. Among the indices evaluated were the investment ratio, emergy yield ratio, ratio of nonrenewable to renewable resources and empower density. These emergy indices characterize the intensity and balance of environmental vs. developed resources (Odum, 1996).

Economic Evaluation

Economic impact on the square kilometer coastal area were compared for the use of treatment wetlands or conventional package plant treatment systems. These data were evaluated as a percentage of overall capital investment and yearly monetary flow.

Regional Water Budget

A regional water budget for a square kilometer of coastline in the study area was developed including precipitation, inflow of groundwater from inland, tidal exchange, evapotranspiration, pumped water and sewage. Budgets were compared for development with no sewage treatment and development with treatment by constructed wetlands.

Regional Nutrient Budget

Regional nutrient budgets were developed for the same scenarios - that of development of a square kilometer of the Akumal coastal region. Nutrient budgets for nitrogen and phosphorus were examined for the scenarios of full development without sewage treatment and with treatment by constructed wetlands.

Table 2-1 Transformities and emergy per mass used in this study.

Item	Transformity Sej/J solar emjoule/joule	Emergy per mass Sej/gram solar emjoule/gram	Reference
Sunlight	1 (by definition)		a
Wind, kinetic	6.63 E2		a
Rain, geopotential	8.888 E3		a
Rain, chemical potential energy	1.5444 E4		a
Tide	2.3564 E4		a
Waves	2.5889 E4		a
Earth cycle	2.9 E4		a
Wood	3.49 E4		c
Groundwater	4.8 E4		a
Gas	4.8 E4		a
Motor fuel (liquid)	6.6 E4		a
Primitive labor	8.1 E4		b
Food	8.5 E4		c
Hurricanes	9.579 E4		d
Electricity (global average)	1.736 E5		a
Agricultural and forest products	2 E5		c
Untreated wastewater	5.54 E5		f
Concrete		7.0 E7	h
Plastic products		9.26 E7	c
Pulp wood		2.75 E8	e
Sand		1.0 E9	a
Limestone		1.0 E9	a
Steel + iron products		1.78 E9	a
Potassium chloride		1.1 E9	a
Machinery		1.25 E10	g

a Odum, 1996
b Odum and Odum, 1983
c Brown et al., 1992
d Scatena et al., in press
e Christiansen, 1984
f Green, 1992
g Odum et al., 1983
h Brown and McClanahan, 1992

CHAPTER 3

RESULTS

Treatment Mesocosms

Design and Operation of the Wetland Units

In August 1996, the two wetland sewage treatment systems were constructed. One, henceforth referred to as “wetland system 1” was designed to treat the wastewater of 16 people and covers an area of 50.6 m^2. The second, “wetland system 2”, designed to handle the sewage of 24 people, has an area of 81.2 m^2.

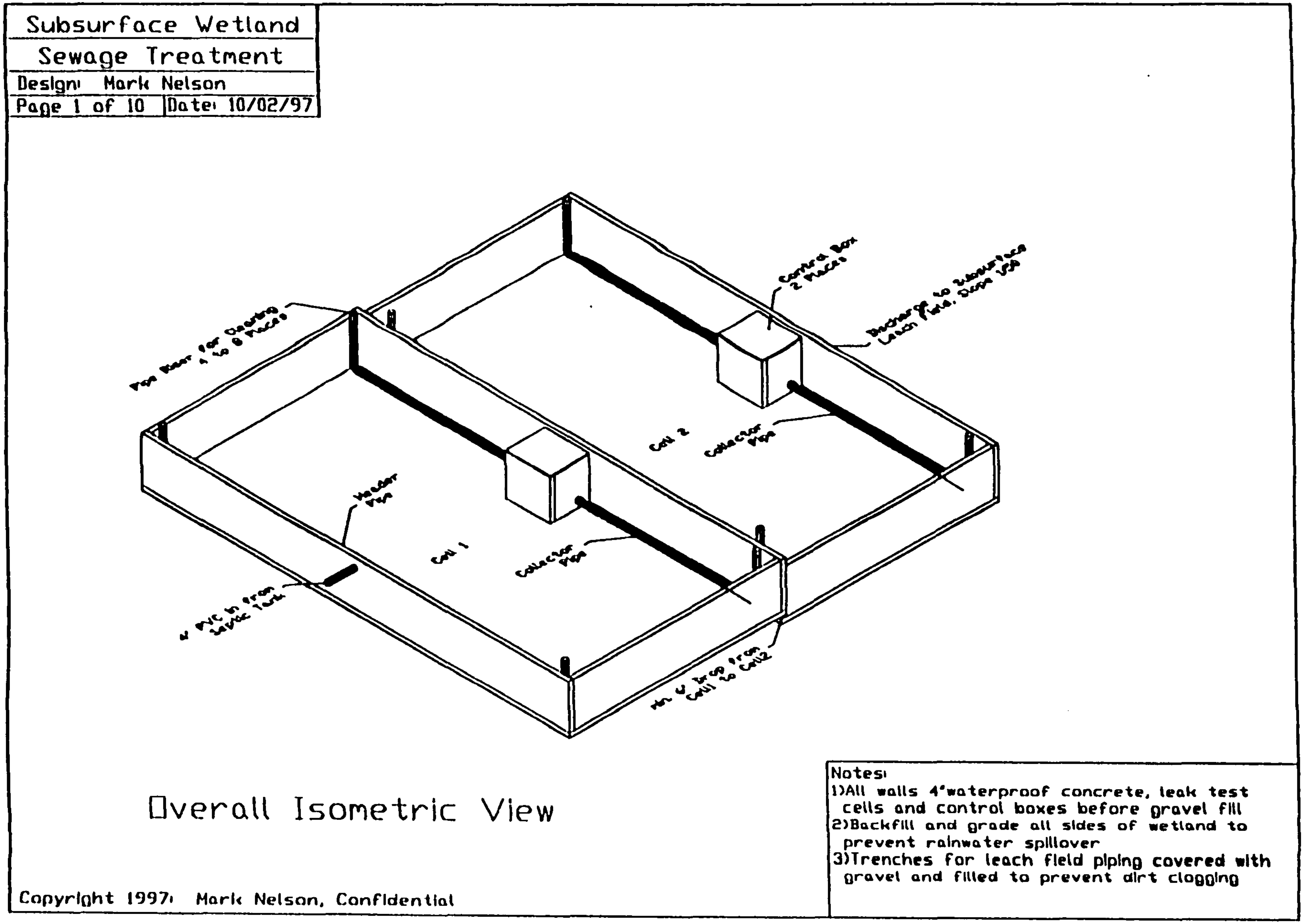
The treatment process for each wetland begins with a well-sealed two-chamber septic tank that receives wastewater from the residences and offices by gravity flow. Solids settle out in the septic tank that serves as primary treatment, and the commencement of microbial treatment of the sewage. A filter at the discharge pipe from the septic tank ensures that no solids larger than 1/64 inch can enter the wetland. Effluent from the septic tank overflows by gravity feed into a header pipe which distributes the sewage along the total width of the first of two treatment cells (compartments) of the constructed wetland.

These wetlands were designed as subsurface flow systems, and have a cement liner and sides to prevent movement of untreated sewage into the groundwater. They were filled with limestone gravel to a depth of 0.6 m. Each cell of the wetland has a collector, perforated 4 inch PVC pipe at the end which direct wastewater into the centrally-located control box. Inside the control box, an adjustable standpipe determines the level at which wastewater is maintained in the wetland, as wastewater overflows its open end either from Cell 1 into the header pipe for Cell 2, or from Cell 2 to final discharge. Normally, the standpipe is fully vertical at a height of 55 cm. The wastewater is kept 5 cm below the level of the gravel. The sides of the system are 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 preclude surface water runoff inflow into the wetland systems. Hydraulic residence with design loading is 5-6 days depending on seasonal evapotranspiration.

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 dangers of clogging. After the addition of the gravel, the systems were filled with tapwater and planted with wetland plants gathered from nearby wetlands, or purchased from botanical gardens or commercial plant nurseries in the area. 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 sawdust.

After discharge from Cell 2 of the wetland, the wastewater from System 1 enters perforated drainage pipes that slope away from the wetland. The trenches in which these pipes were laid were back-filled with limestone gravel to prevent clogging by dirt. System 2 effluent is sent to the nearby mangrove wetland and discharged near soil surface.

The blueprint drawings (Figures 3-1 to 3-10) show additional details of the construction. Limestone gravel depths were increased for wetlands built subsequently to this research in the area were done to a design specification of 80 cm to increase hydraulic



Subsurface Wetland
Sewage Treatment
Design: Mark Nelson
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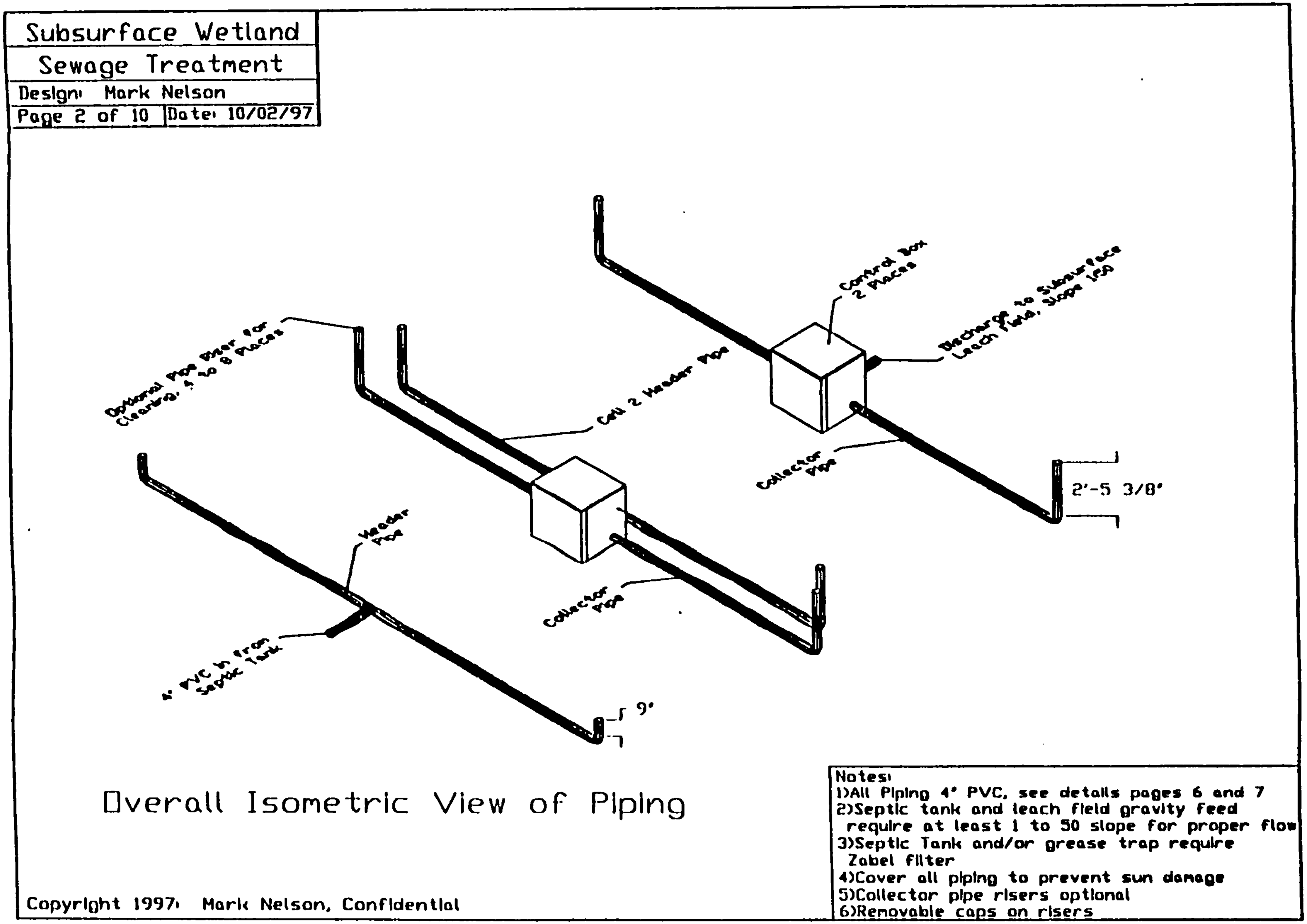
Overall Isometric View

Notes:
1)All walls 4"waterproof concrete, leak test cells and control boxes before gravel fill
2)Backfill and grade all sides of wetland to prevent rainwater spillover
3)Trenches for leach field piping covered with gravel and filled to prevent dirt clogging

Figure 3-1 Construction blueprint: isometric view of the wetland treatment system.



Subsurface Wetland
Sewage Treatment
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Overall Isometric View of Piping

Notes:
1)All Piping 4" PVC, see details pages 6 and 7
2)Septic tank and leach field gravity feed require at least 1 to 50 slope for proper flow
3)Septic Tank and/or grease trap require Zabel filter
4)Cover all piping to prevent sun damage
5)Collector pipe risers optional
6)Removable caps on risers

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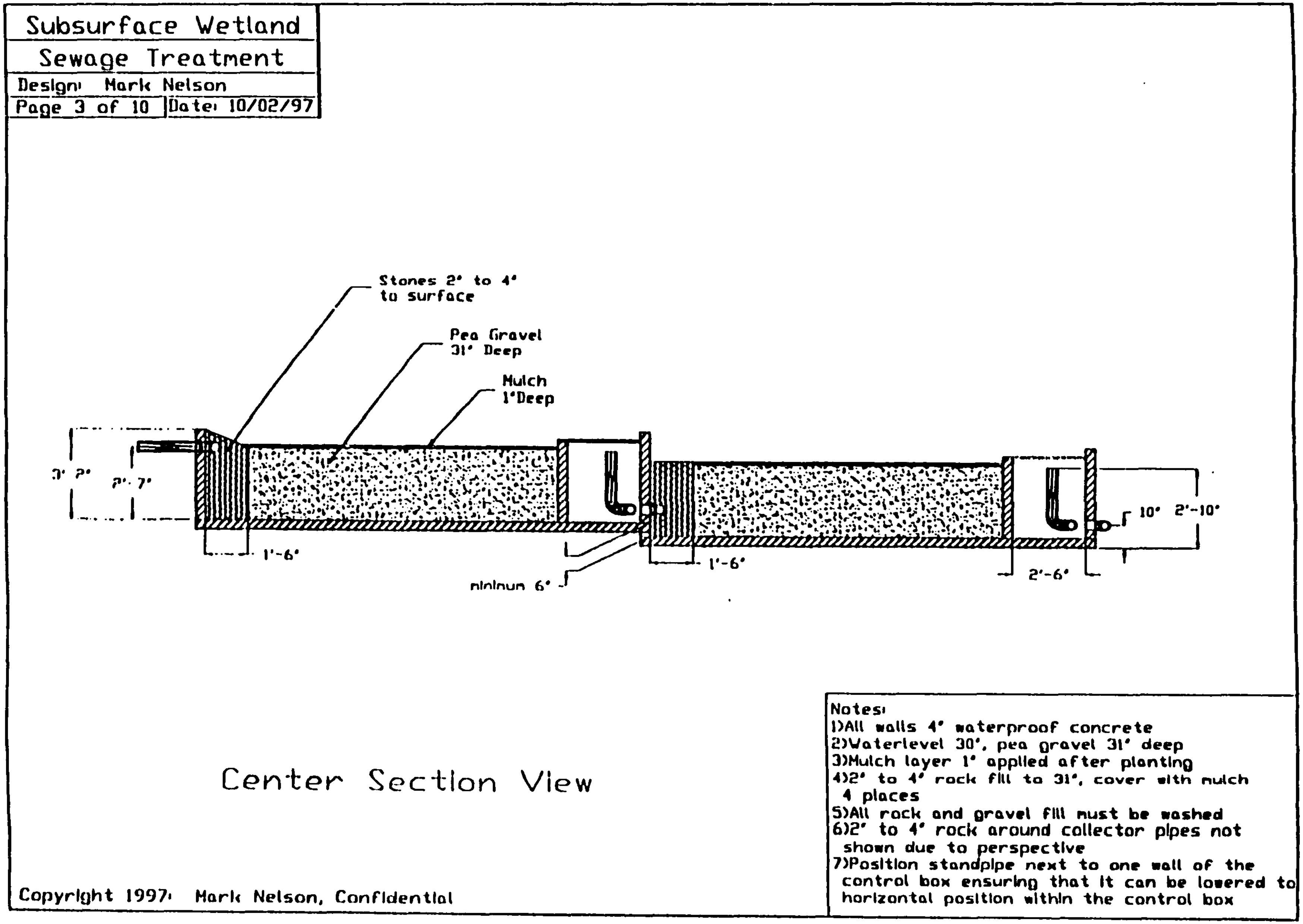
Figure 3-2 Construction blueprint: isometric view of piping in the wetland system.



Subsurface Wetland

Sewage Treatment

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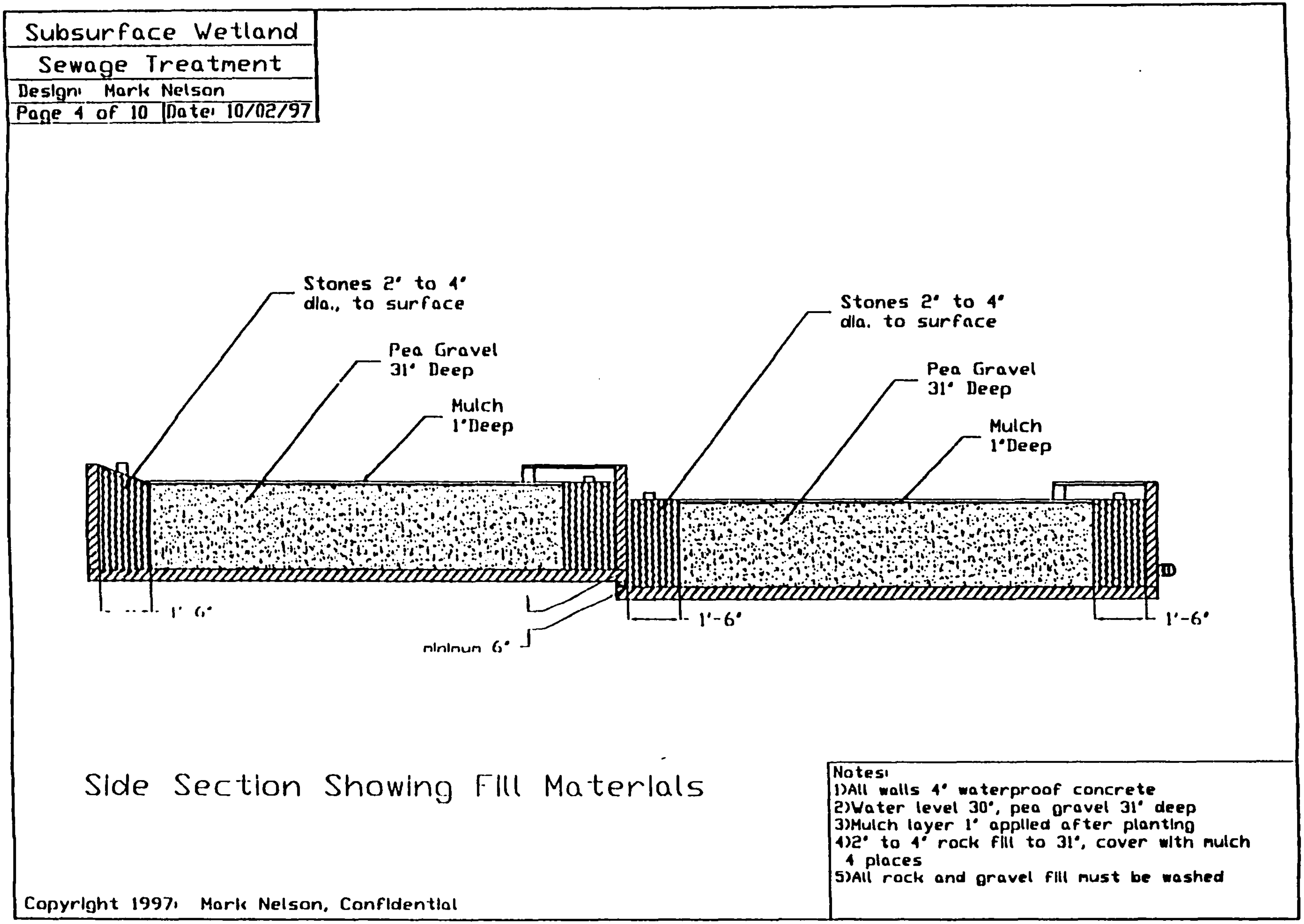
Center Section View

Notes:
1)All walls 4' waterproof concrete
2)Waterlevel 30', pea gravel 31' deep
3)Mulch layer 1' applied after planting
4)2' to 4' rock fill to 31', cover with mulch
4 places
5)All rock and gravel fill must be washed
6)2' to 4' rock around collector pipes not
shown due to perspective
7)Position standpipe next to one wall of the
control box ensuring that it can be lowered to
horizontal position within the control box

Figure 3-3 Construction blueprint: center section view of the wetland system.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Side Section Showing Fill Materials

Notes:
1)All walls 4' waterproof concrete
2)Water level 30', pea gravel 31' deep
3)Mulch layer 1' applied after planting
4)2' to 4' rock fill to 31', cover with mulch
 4 places
5)All rock and gravel fill must be washed

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Figure 3-4 Construction blueprint: side section showing fill materials in the wetland system.

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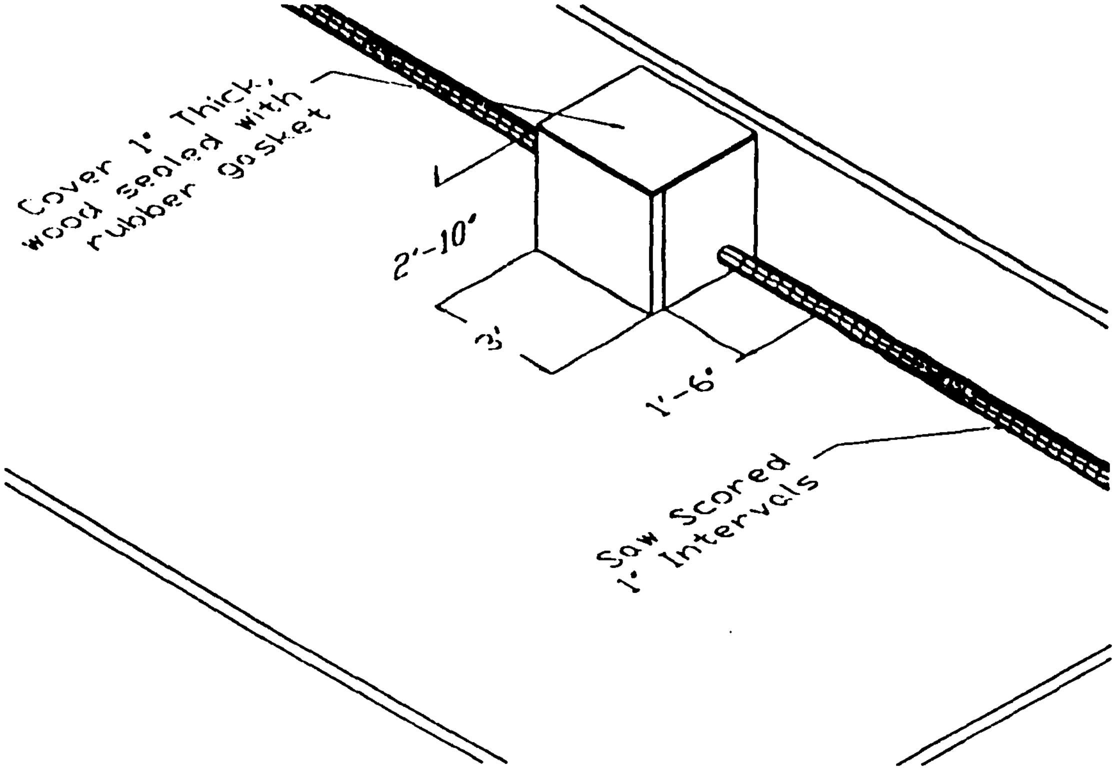
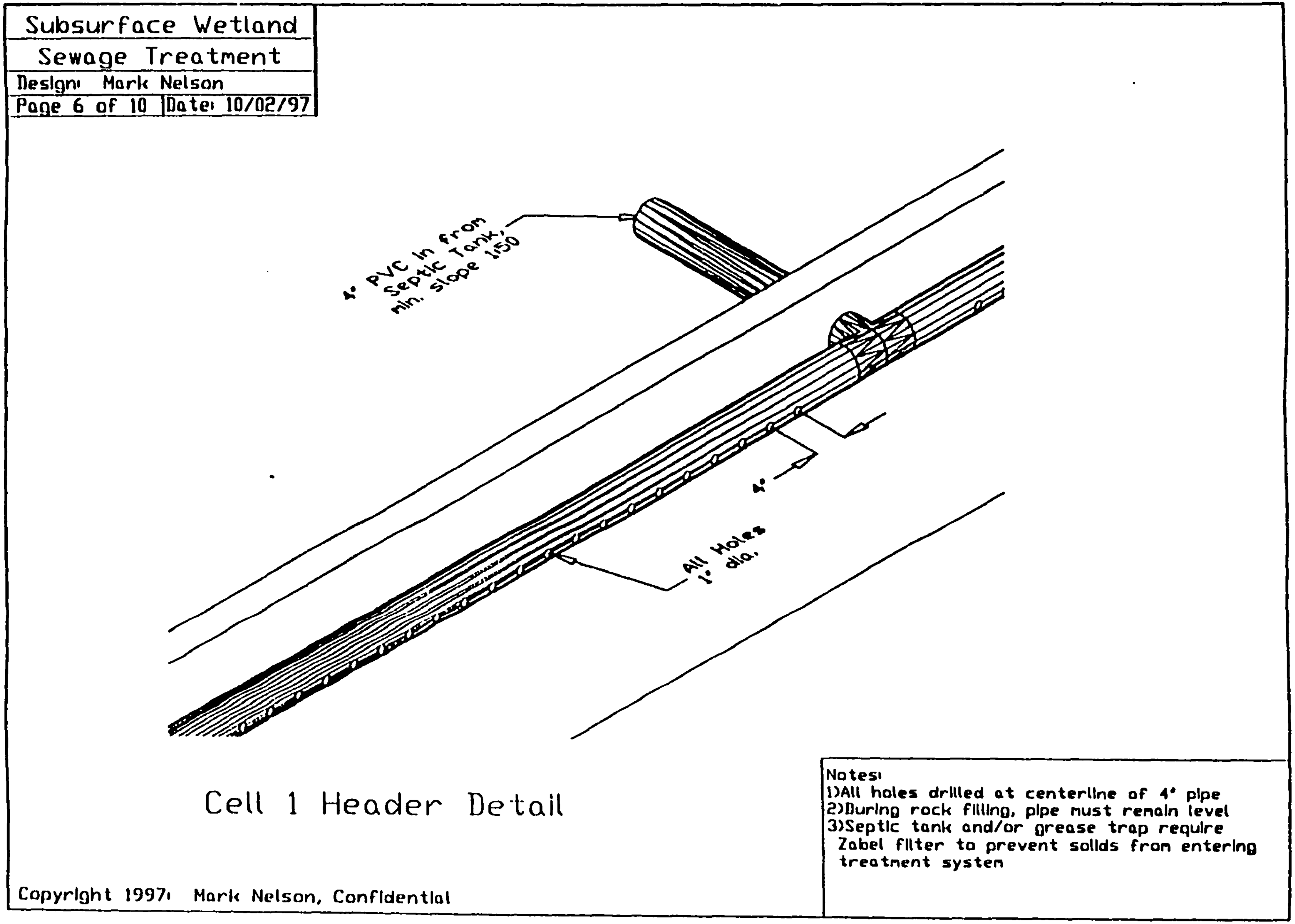


Box Detail with Dimensions

Notes:
1)1" thick wood control box cover, sealed with rubber gasket to prevent odor and mosquito breeding
2)4" waterproof concrete walls
3)Position standpipe next to one wall of the control box ensuring that it can be lowered to horizontal position within the control box

Figure 3-5 Construction blueprint: control box with dimensions of the wetland treatment cells.



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Cell 1 Header Detail

Notes:
1)All holes drilled at centerline of 4" pipe
2)During rock filling, pipe must remain level
3)Septic tank and/or grease trap require Zabel filter to prevent solids from entering treatment system

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Figure 3-6 Construction blueprint: treatment cell 1 header detail of the wetlands.

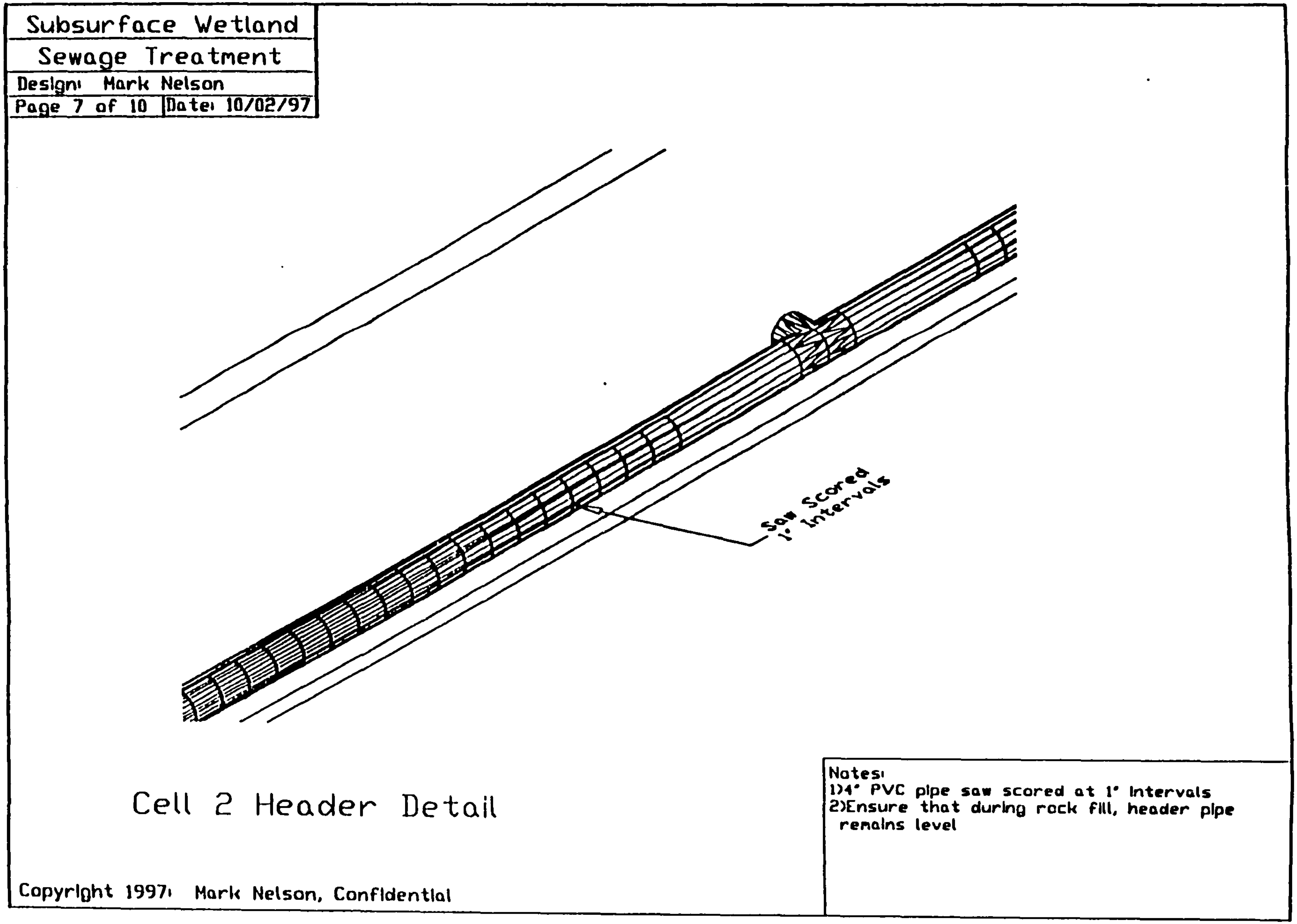

Figure 3-7 Construction blueprint: treatment cell 2 header detail of the wetlands.

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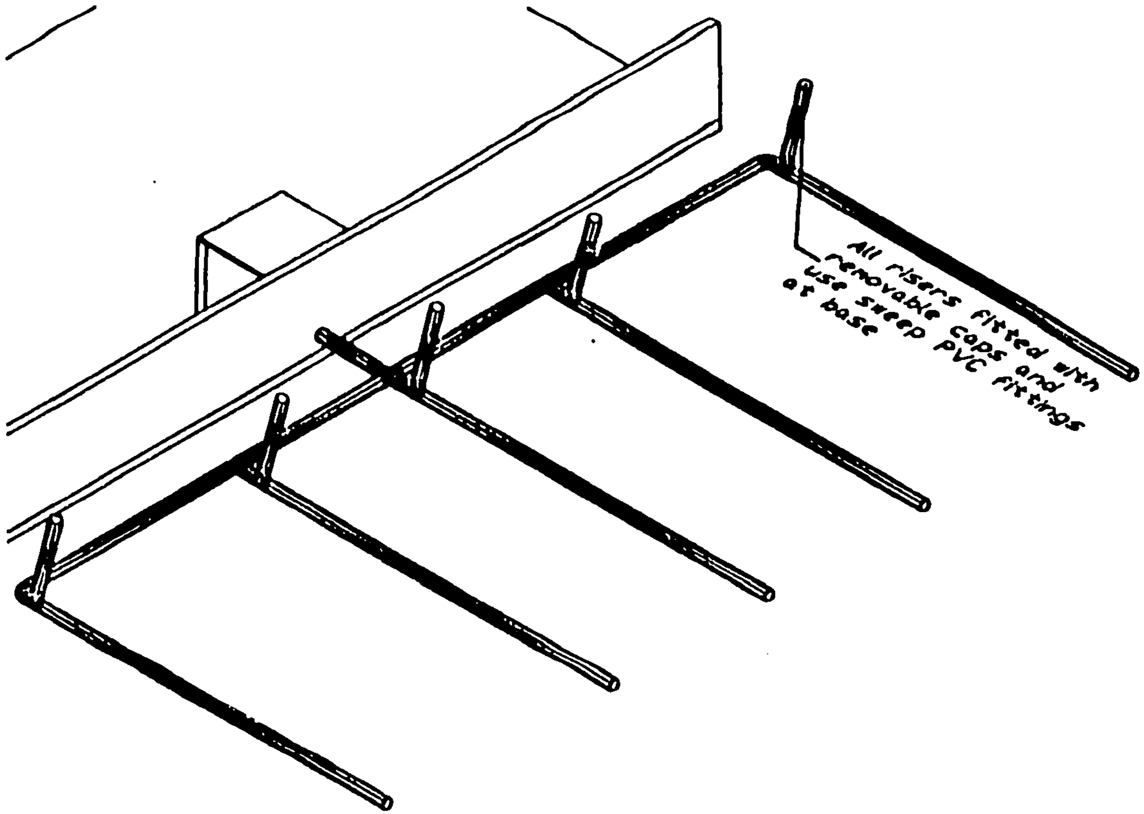
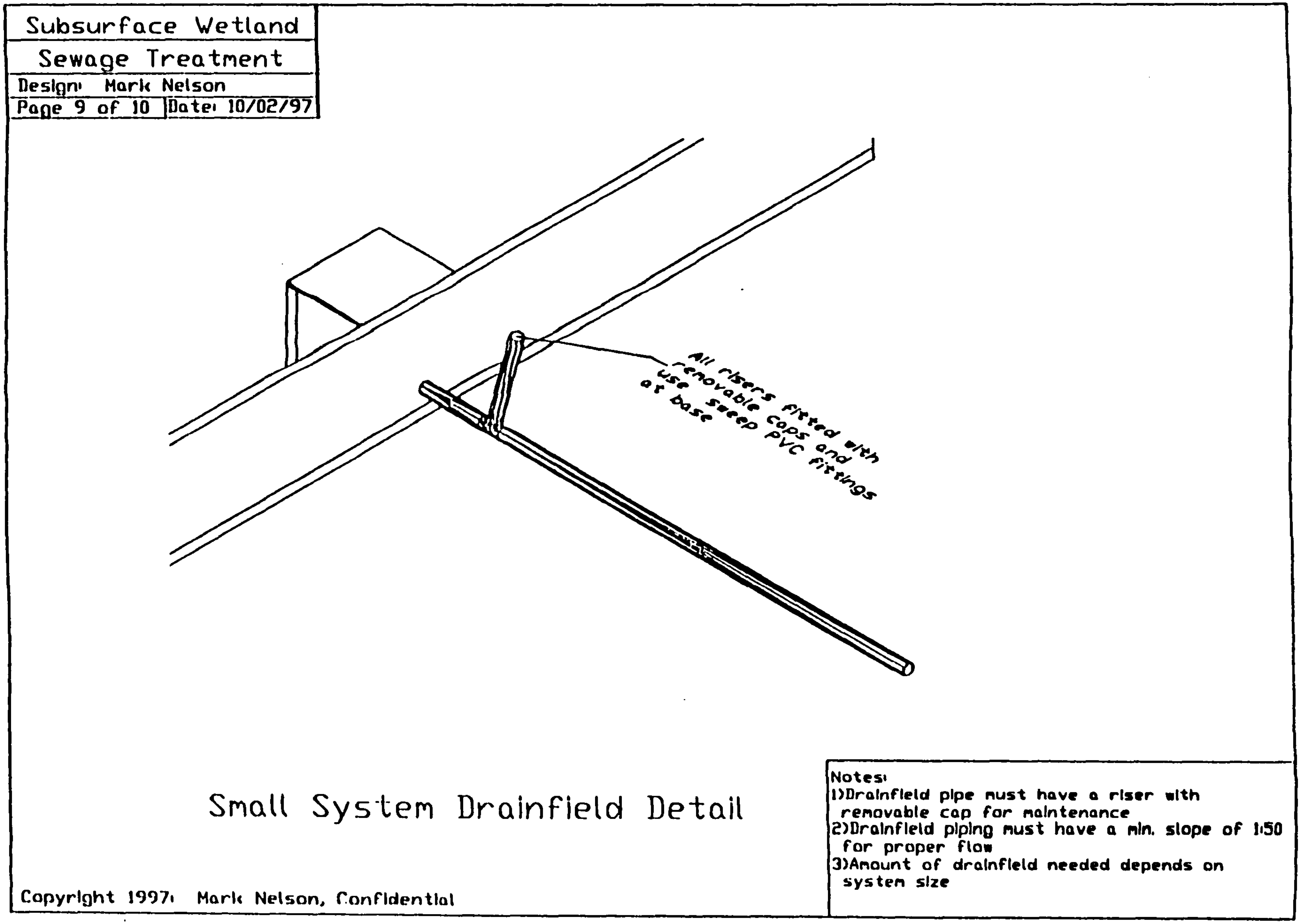


Large System Drainfield Detail

Notes:
1)Each drainfield pipe must have a riser with removable cap for maintenance
2)Drainfield piping must have a min. slope of 1:50 for proper flow
3)Amount of drainfield needed depends on system size

Figure 3-8 Construction blueprint: schematic showing drainfield detail for large wetland systems.



Subsurface Wetland
Sewage Treatment
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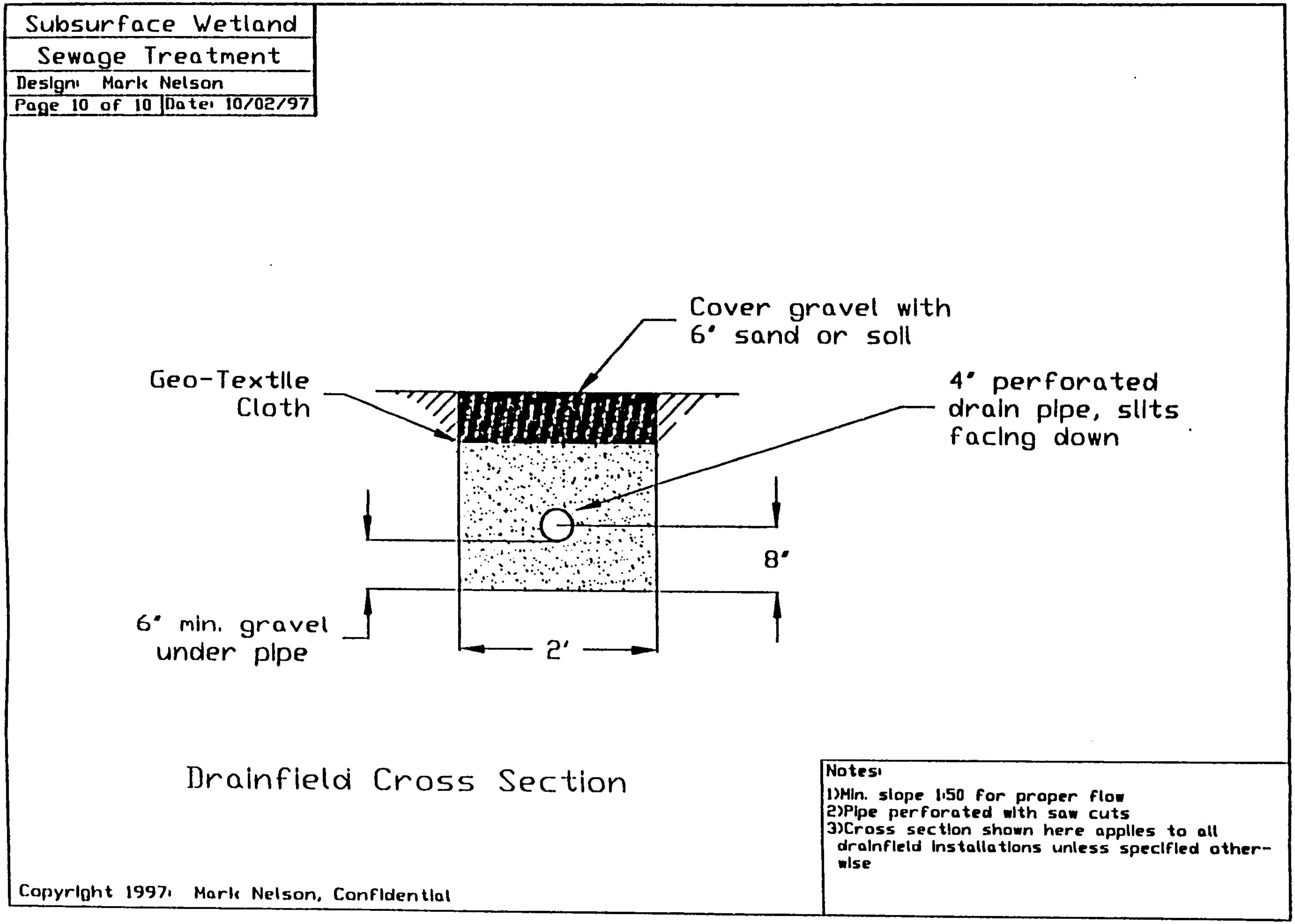
All risers fitted with renovable caps and use sweep PVC fittings at base

Small System Drainfield Detail

Notes:
1)Drainfield pipe must have a riser with removable cap for maintenance
2)Drainfield piping must have a min. slope of 1:50 for proper flow
3)Amount of drainfield needed depends on system size

Figure 3-9 Construction blueprint: schematic showing drainfield detail for small wetland systems.



Notes:

1) Min. slope 1:50 for proper flow
2) Pipe perforated with saw cuts
3) Cross section shown here applies to all drainfield installations unless specified otherwise

Figure 3-10 Construction blueprint: drainfield cross-section drawing of wetland system.

retention time, rather than the 60 cm of limestone used in the two research wetlands of this study.

Ecological Characteristics

Patterns of biodiversity and dominance

In May 1997, December 1997 and July 1998 (nine, fifteen and twenty-three months after planting, respectively) examinations of the wetland systems for species diversity was conducted with the assistance of Edgar Cabrera, a botanist from Chetumal, Quintana Roo. A total of 68 species were identified in May 1997, 70 species in December 1997 and 66 species in July 1998 (Table 3-1). Species native to the Yucatan constituted 47 of the 66-68 species present in May, 1997 and December 1997, with the remainder being cultivated and introduced species.

Plant species richness (total number of species present) in each treatment cell decreased slightly over the course of the study as shown in Figures 3-11, 3-12 and 3-13. For example System 1 Cell 1 had 41 species in May 1997, 37 species in December 1997 and 35 species in July 1998; while System 1 Cell 2 had 37 species in May 1997, 35 species in December 1997 and 36 species in July 1998. In May 1997, wetland System 1 averaged 39 plant species per cell, in December 1997 and July 1998, the average was 36 species. Wetland System 2 averaged 47 species per cell in May 1997, 45 species in December 1997 and July 1998.

Considering the systems as a whole, in May 1997 there were 63 species in System 2 (with 482 observations), 17% higher than in wetland System 1 with 54 species (from 482 observations) (Figure 3-14). By December 1997, plant species had declined by about 10% in

Table 3-1. Plant species in the treatment wetlands from surveys of May, 1997, December, 1997 and July, 1998. Total number of species as of May, 1997: 68 species; as of December, 1997: 70 species, as of July, 1998: 66 species.

	Scientific Name	Common Name	**Notes: N = Native, I = Introduced; C= Cultivated**
D2	*Acalypha hispida*	Cola de gato; cat's tail	C; red cattail flowers
	Acrostichum danaefolium	Helecho	N; wetland fern, to 3 m
	Ageratum littorale		N: blue-flowering little shrub (purplish flowers); annual
	Alocasia macrorhiza	Mafota; elephant ears, taro	I; starchy root, very shiny Large leaves; leaf is straighter and flatter than Xanthosema
N2	*Aloe vera*	Sabila	C;
N2	*Alternanthera ramossissima*		N
D1	*Angelonia angustifolia*		N; delicate shrub, purple flowers
	Anthurium Schlechtendalii	Moco de povo	N; epiphyte
N1	*Anthurium sp.*		N
	Asclepias curassavica		N; orange and yellow flowers
D1	*Bambusa* sp.	Bambu; bamboo	I;
	Bidens pilosa	Margarita	N; yellow or white flowers (like daisy)
	Bravaisia tubiflora	Sulub	N; pink flowers like bells
	Caladium bicolor	Bandera	C; decorative taro
	Canna edulis	Platonillo; canna lilly	I; yellow flowers
N2	*Capraria biflora*	Claudiosa	N
	Carica Papaya	Papaya	N; edible fruit
D1	*Cestrum diurnum*	Galon de noche	I; shrub/tree CEA Cell 2, long thin leaves
	Chamaedorea Seifrizii	Palma camedor	N; palm
	Chamaesyce hypericifolia		N; delicate shrub with tiny white flowers
	Chrysobalanus icaco	Icaco	N; woody, sturdy shrub with thick leaves
N1	*Cissus sicyoides*		N;
	Cissus trifoliata		N; vine, elongated, ovate leaves
	Citrus Aurantium	Naranja agria; orange tree	C; edible fruit

	Scientific Name	Common Name	**Notes: N = Native, I = Introduced; C=Cultivated**
	Coccoloba uvifera	Uva de mer; sea grape	N; beach tree, prostrate or upright
	Conocarpus erecta	Botoncillo; buttonwood tree	N; mangrove area tree
	Corchorus siliquosus		N; woody shrub, long-hard seed pods (tree)
	Cordia sebestena	Siricote	N; tree with large leaves, (next to Eleocharis CEA Cell 2)
N2	*Crinum amabile*	Lidio reina	C
D1	*Cucumis melo*	Melo; melon	I; melon vine
D2	*Cyperus ligularis*	Zacate cortadera	N;
N1	*Delonix regia*	Poinsettia	C;
N1; D2	*Desmodium incanum*		N; 3-leaved leguminous vine
N2	*Desmodium tortuosum*		N
	Distichlis spicata.		N; grass
D1	*Eclipta alba*		N; like botoncillo with dots on leaves;
	Eleocharis cellulosa	Spike reed grass	N; short wetland reed
D1	*Eleusine indica*		N;
	Eupatorium albicaule		N: 2 notches on leaves nearer base
D1	*Euphorbia cyathophora*		N;
D1	*Eutachys petraea*		N; grass with "feathers" on ends
	Flaveria linearis		N; yellow flowers
	Hymenocallis littoralis	Lirio/Spider lilly	N; white flowers;
N1	*Ipomoea indica*	morning glory	N; vine with heart-shaped leaves
	Ipomoea Pes-caprae	rinonina	N;vine, morning glory family
N1; D2	*Iresine celosioides*		N; flowers are scales
	Ixora coccinea	Ixora	I; yellow or orange flowers, low shrub
	Kalanchoe pinnata		I;
D1	*Lactuca intybacea*	Milk weed	N; CEA Cell 1
D2	*Lantana involucrata*	oregano xiru	N; small flowering shrub, woody shrub; small serrations on leaves; succulent; fragrant leaves
N2	*Leucaena glauca*		C

	Scientific Name	Common Name	**Notes: N = Native, I = Introduced; C=Cultivated**
N1; D2	*Lochnera rosea*	Teresita	C; lavender flowers
D1	*Ludwigia octavalis*		N; yellow flowers
D1	*Lycopersicum esculenta*	Tomate; tomato	I; tomato plant
D2	*Melanthera nivea*		N; small button-white flowers on sprawling shrub; 3-lobed leaves
N2	*Mimosa* sp.		N
	Malvaviscus arboreus	tulipancillo	N; red flowers, tree
	Musa sp.	Platano; banana	C; edible fruit
	Nerium oleander	Oleonder; oleander	I; pink flowers, small tree
N1	*Nopalea cochinillifera*	Napolito	C; cactus; used as food
	Paspalum virgatum	Sacate	N; sharp-leaved clump grass
	Pedilanthus tithymaloides		I;
N1; D2	*Pelliciera alliacea*		N; long stalk, delicate flower
	Philodendron sp		N;
	Phyla nodiflora		N: red stems, white flowers, sprawling shrub with sharp notches near tip of leaves, deep-grooved veins
N2	*Phyllanthus niruri*		N
	Pluchea odorata	Santa Maria	N; purple flowering shrub
D1	*Porophyllum punctatum*		N; decorative black dots on leaves, shrub, small leaf
D1	*Portulaca oleracea*	Verdolaga; moss rose	N; various colors
	Psychotria nervosa		N;
	Rabdadenia biflora		N; "mangrove-like" vine CEA Cell 2
N2	*Rhizophora mangle*	Red mangrove	N
	Rhoeo discolor	Platonillo morado;	N; purple and green leaves, roseatte form
	Sansevieria triasiate	Lengue de suegra	C; small agave-like
	Scindapsus aureus	Telefono	C; variegated leaves
N1; D2	*Selenicereus Donkelaarii*		N: viney, thin cactus
	Senna biflora	Modrecacao	N; tree with rounded leaves; with a bunch of small, varied colored flowers
D1	*Sesbania emerus*		N; tree with leguminous leaves

	Scientific Name	Common Name	**Notes: N = Native, I = Introduced; C=Cultivated**
	Sesuvium portulacastrum	Verdolaga de playa; succulenta	N; beach succulent
D1	*Solanum erianthum*		N;
	Solanum Schlechtendalii		N; red berries like small tomatoes
N1; D2	*Syngonium* sp.		N; palmate leaves, 5-folias
	Terminalia Catappa	Almendro	C; corner PCRF Cell 1 nr septic tank; tree
	Thrinax radiata	Chit	N; palm, used for thatching
	Typha domingensis	Tule; cattail	N; to 3-4 m
N1: D2	*Vigna elegans*		N; vine, 3-leaves, purple flowers
N1	*Vigna luteola*		N; yellow flower otherwise similar to V. elegans (77)
N1; D2	*Viguiera dentata*		N
	Washingtonii robusta	Washingtonii palm	C: palm tree; sharp thorns on fronds
N1	*Wedelia trilobata*		N; vine, yellow flowers
	Xanthosoma roseum	mafata; taro, elephant ears	N; starchy root; soft-leaved and more curved leaf form of taro
	Zamia purpuraceus		C; purple flowering shrub
N1	*Zephyranthes Lindleyana*		C; thin, short blades, grass-like with pink flower

Plant species identified by Edgar F. Cabrera, Chetumal, Q.R. on surveys in May and December 1997, and July 1998.Code for column 2, D1 = dead or not found in December 1997 survey but present in May, 1997 survey; N1 = new in December 1997 survey; D2 = dead or not found in July, 1998 survey, N2 = new in July 1998 survey.

Botanic names: Cabrera, Martinez (1987), UNAM (1994), Brummitt (1992).

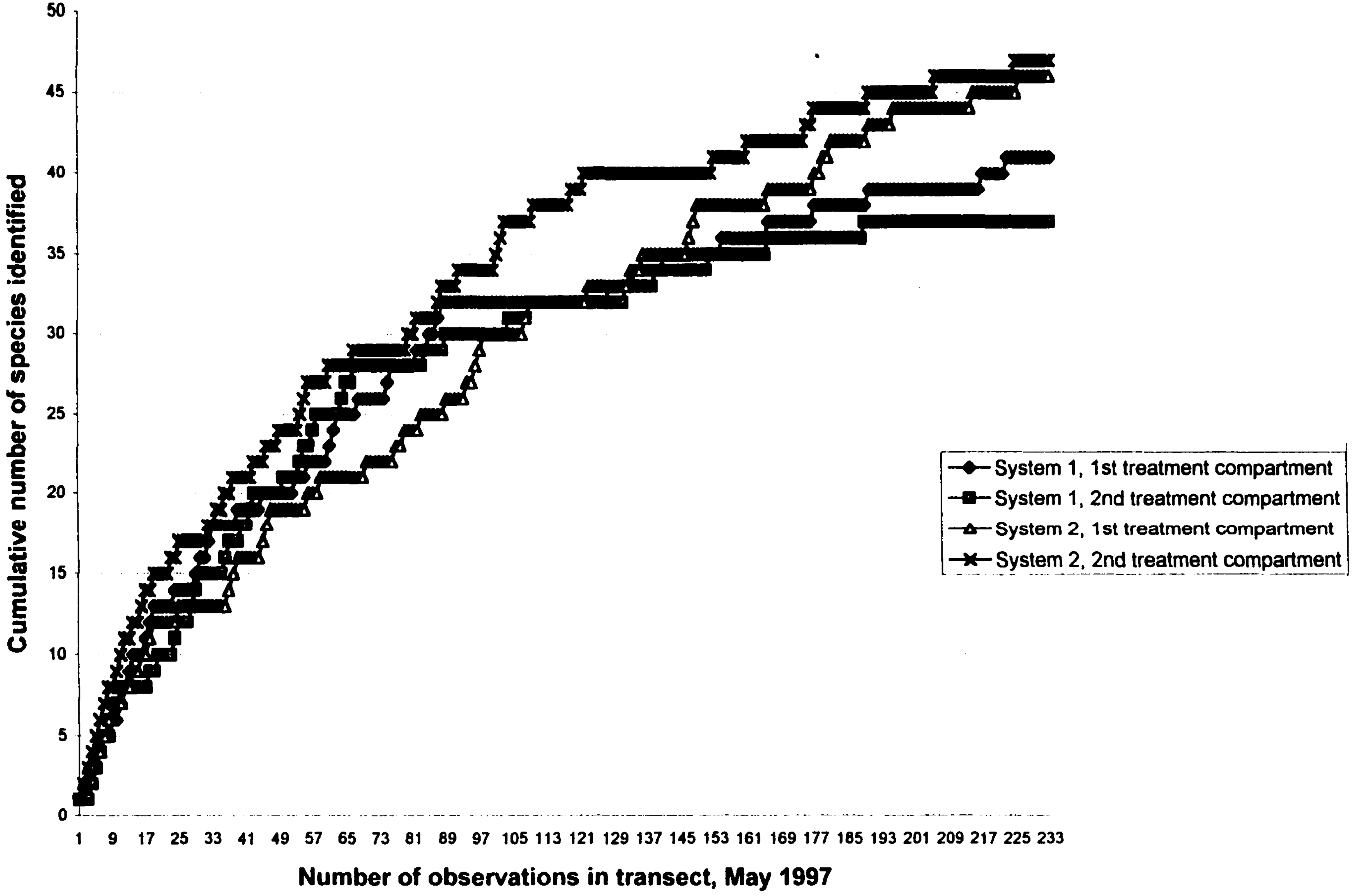


Figure 3-11 Species-area curves for each of the four wetland treatment cells, May 1997 data.

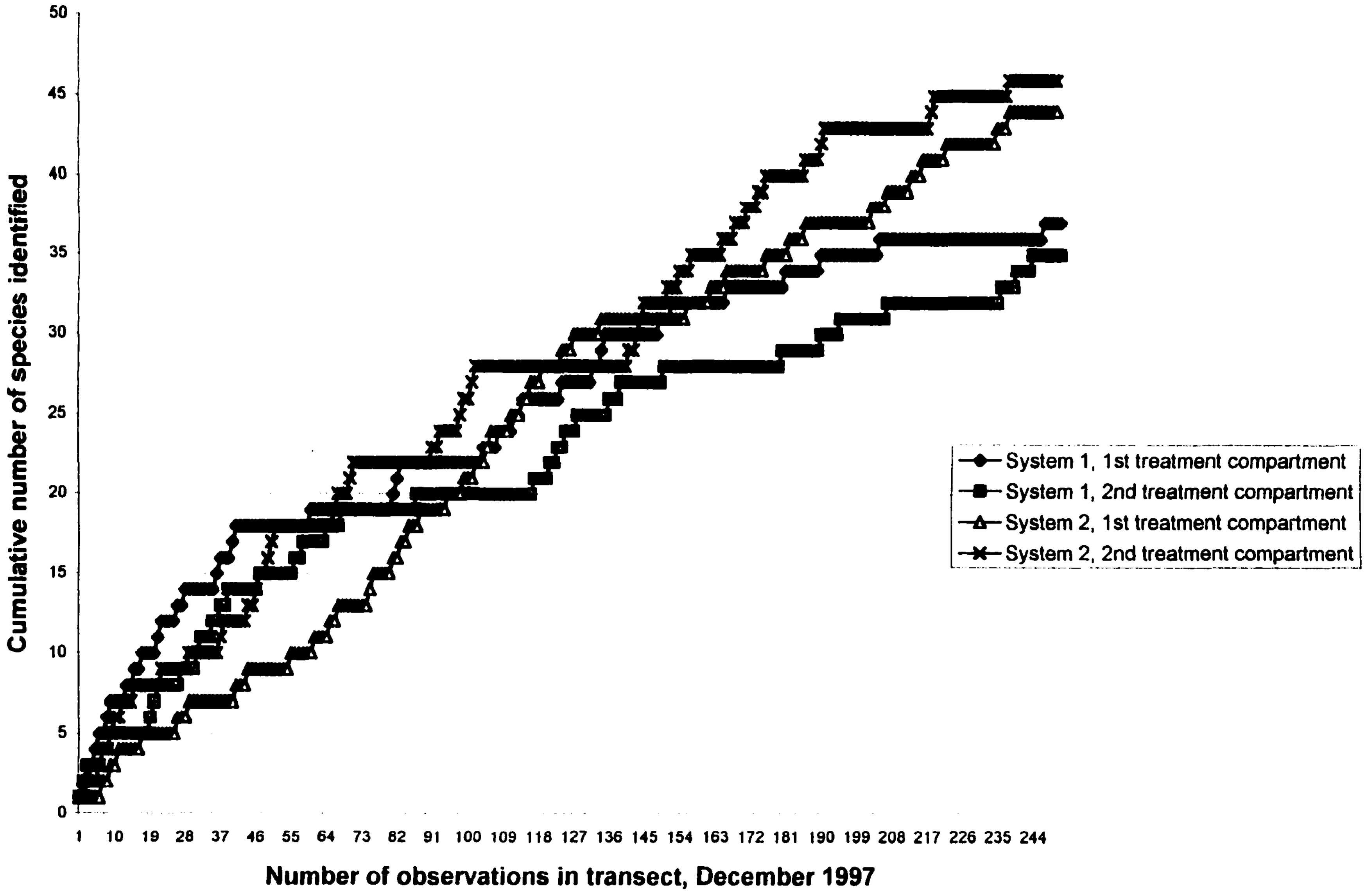


Figure 3-12 Species-area curves for each of the four wetland treatment cells, December, 1997 data.

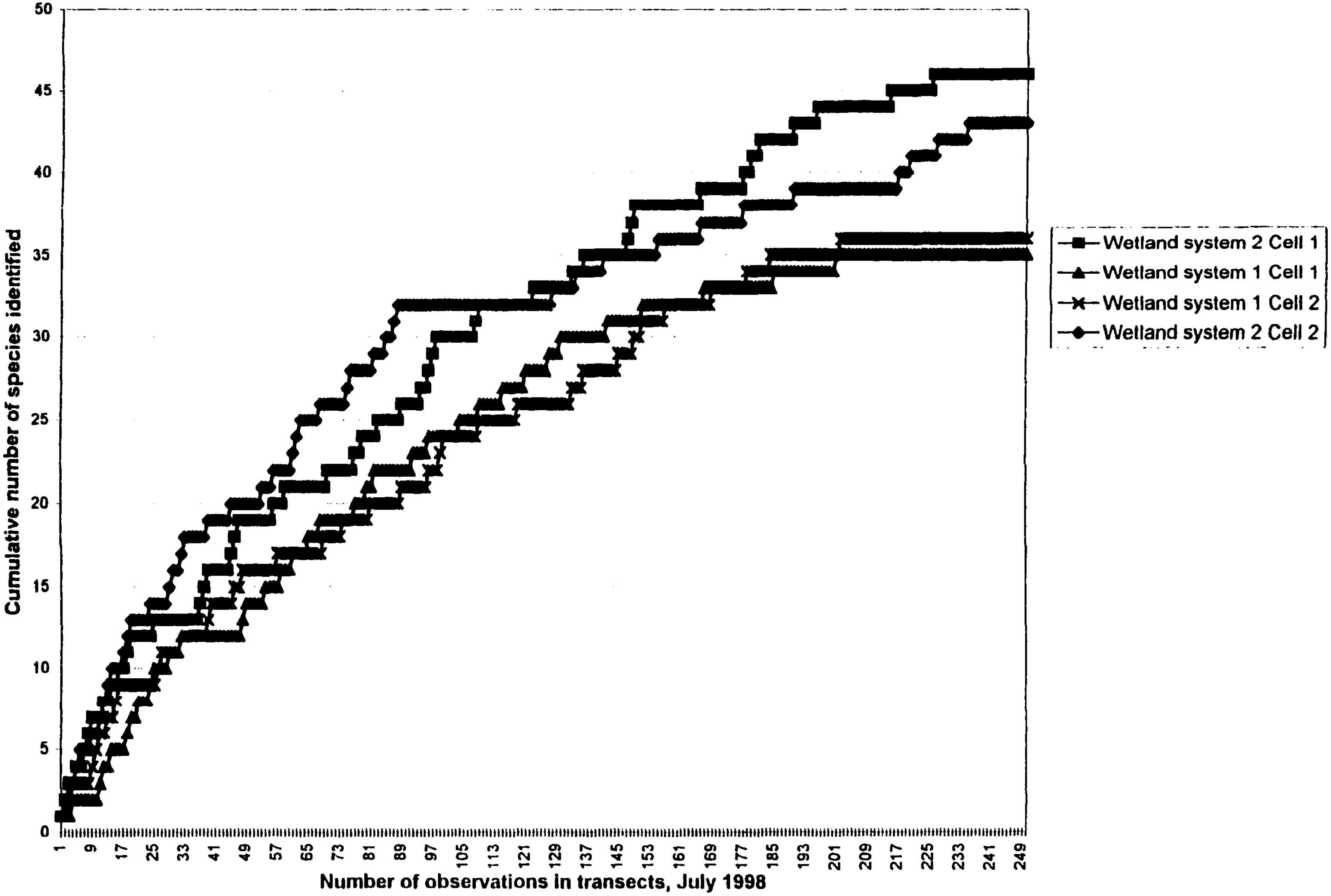


Figure 3-13 Species-area curves for each of the four wetland treatment cells, July , 1998 data.

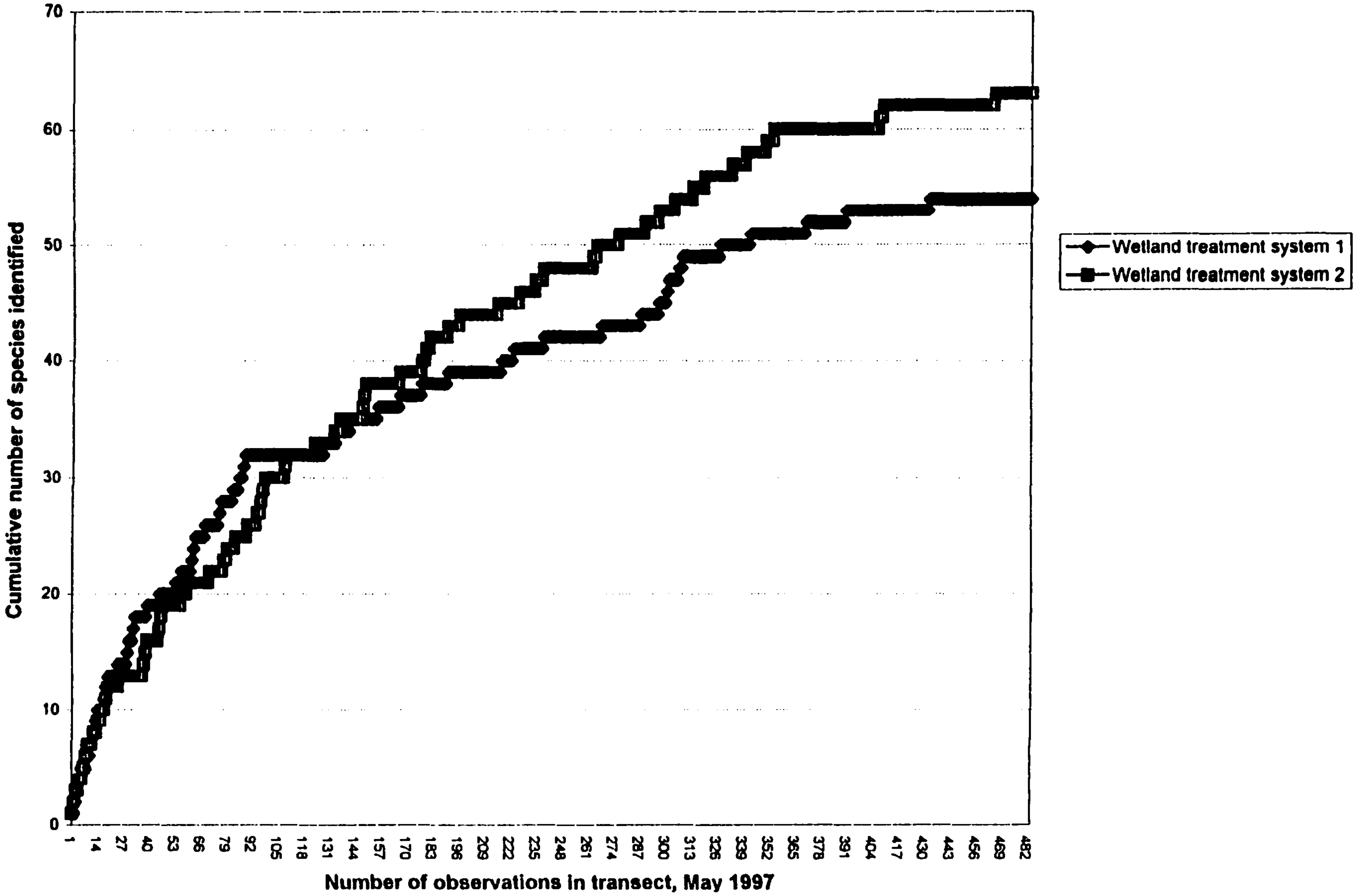


Figure 3-14 Species-area curves for the 50.6 m^2 wetland unit (system 1) and the 81.2 m^2 wetland (system 2), May, 1997. Transects counted 482 individuals in each system.

the individual wetlands (Figure 3-15) although overall number of species present in both wetlands increased slightly (from 68 to 70 species). Many of the species no longer present were low, understory shrubs, while almost half the newly present species were native vines.

In July 1998, System 1 lost an additional 10% of species, with a total of 44 species, while System 2 remained constant at 57 (Figure 3-16), although again both numbers included a loss of some previously present species and establishment of new species (Table 3-1).

Comparison with natural ecosystems

In December 1997, transects with 1000 observations showed 73 species present in the inland tropical forest ecosystem, and 17 species in the natural mangrove wetlands, compared with the 70 species found in the constructed wetland treatment systems (Figure 3-17). Table 3-2 lists the species found in the mangrove and Table 3-3 presents the species found in the forest ecosystem. Figure 3-18 compares number of species in treatment wetland systems 1 and 2 with number of species found in the transects through forest and mangrove ecosystems. The wetlands had diversity of plant species comparable to that found in nearby forest ecosystems and a much greater number of species than were found in the adjacent mangrove wetlands.

Dominance

Dominance was assessed through species relative frequency, Shannon diversity index, percent cover, estimate of areal coverage and importance value.

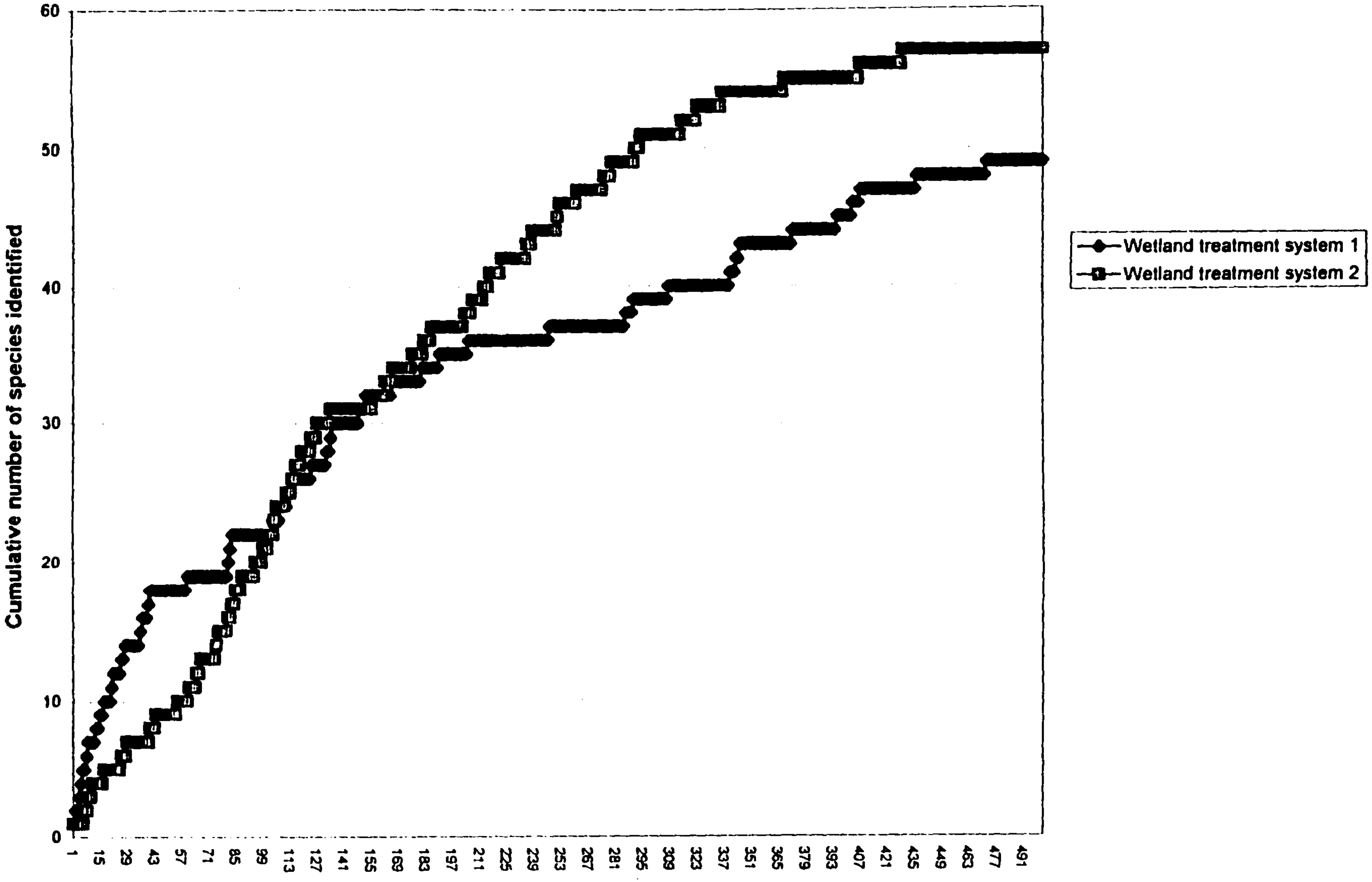


Figure 3-15 Species-area curves for the 50.6 m^2 Yucatan wetland (system 1) and the 81.2 m^2 wetland (system 2), December, 1997. Transects counted 500 individuals in each system.

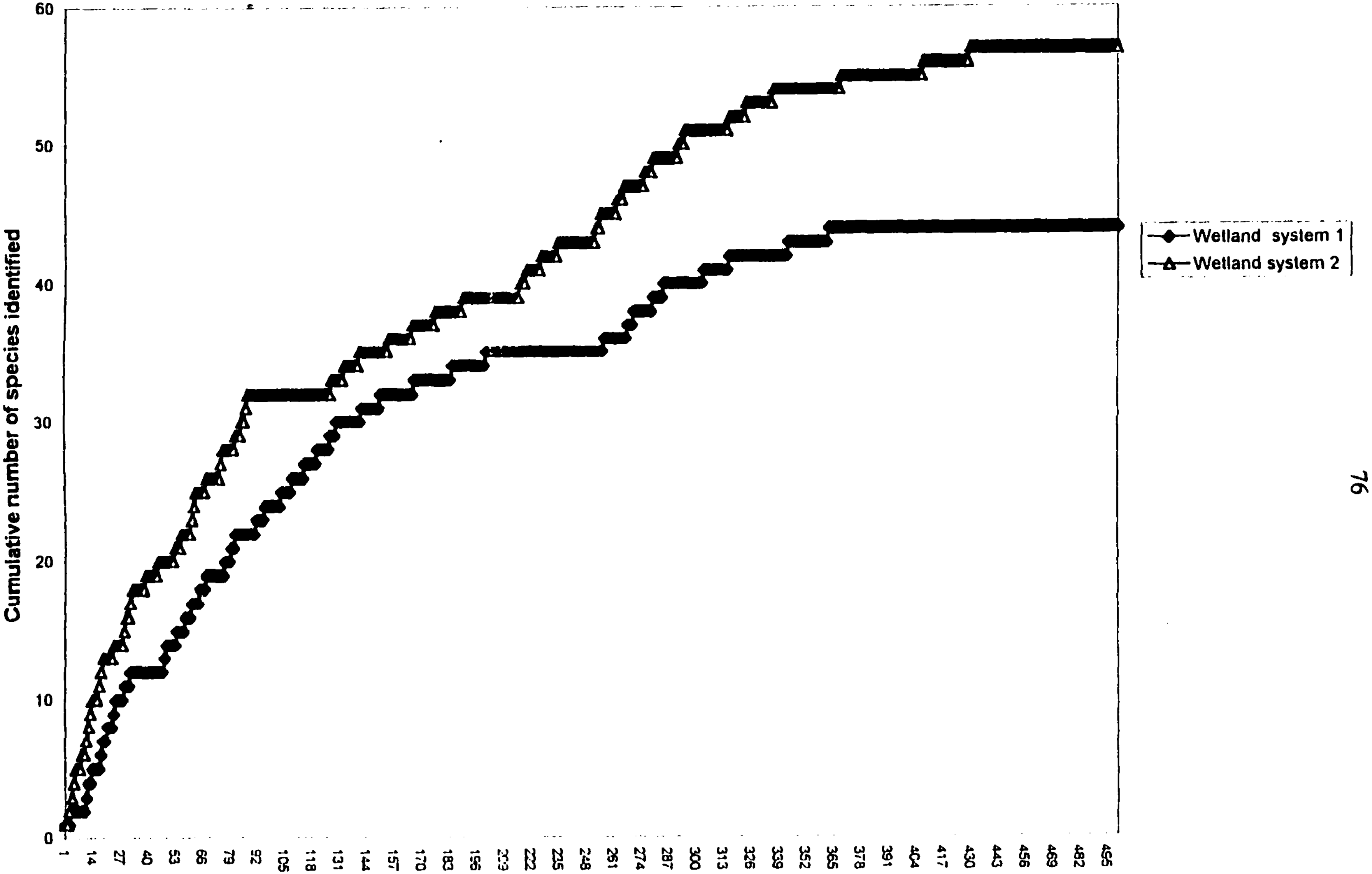


Figure 3-16 Species-area curves for the 50.6 m^2 Yucatan wetland (system 1) and the 81.2 m^2 wetland (system 2), July, 1998. Transects counted 500 individuals in each system.

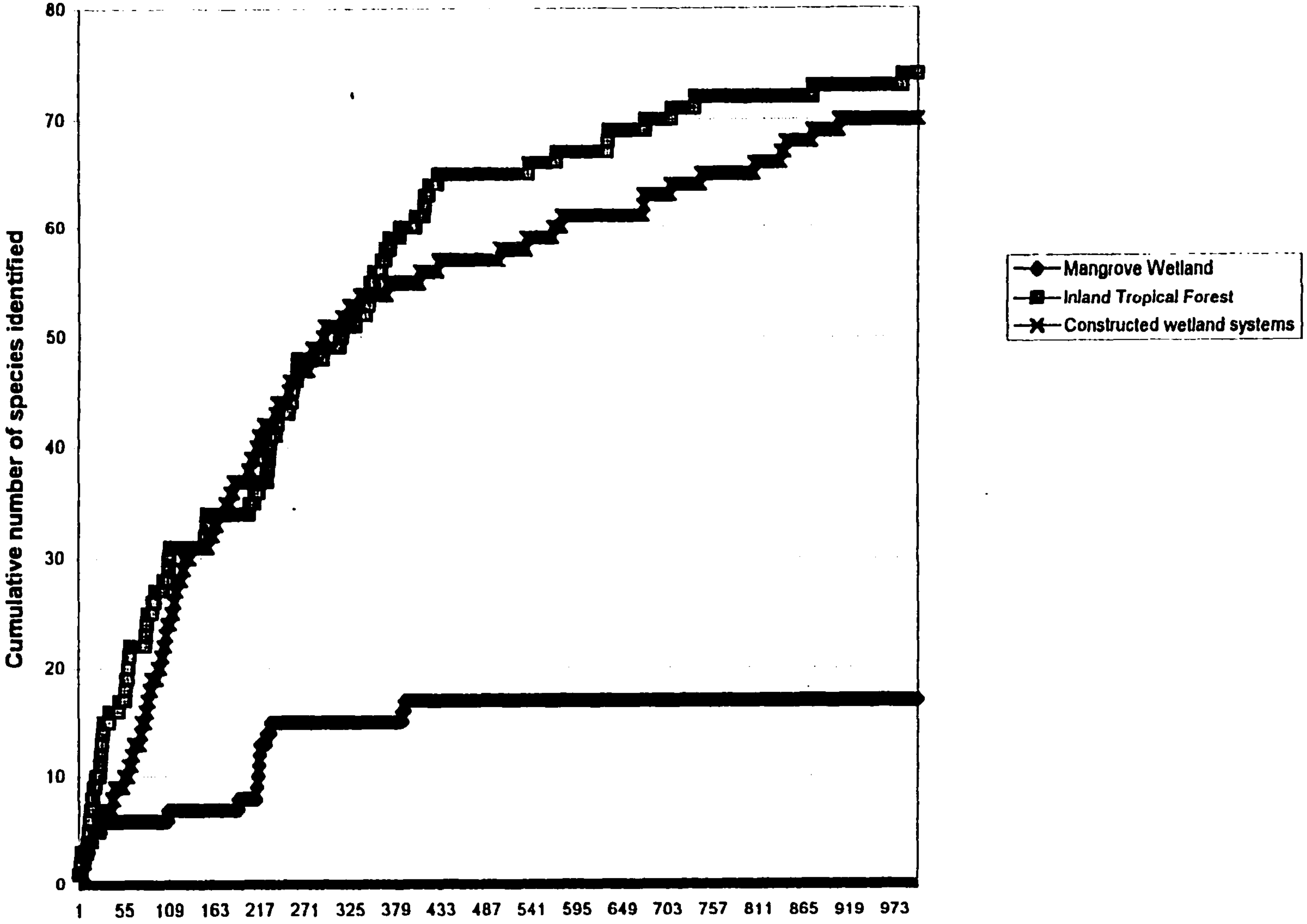


Figure 3-17 Comparison of species richness between treatment wetlands, mangrove wetland and forest ecosystems, December 1997. Transects were 1000 individuals from each system.

Table 3-2 Species list: mangrove wetland ecosystem, 8 December 1997. Species identified by Edgar Cabrera, Chetumal, Q.R.

Name of Species
Acrostichum danaefolium
Anthrurium Schlectendalii
Chlorophora tinctoria
Conocarpus erecta
Cyperus ligularis
Diospyros cuniata
Enriquebeltrania cientifola
Ipomoea indica
Laguncularia racemosa
Piendia aculeata
Rhabdadenia biflora
Rhizophora mangle
Selenicereus Donkelaarii
Selenicereus testudo
Solanum Schlechtendalii
Thrinax radiata
Yithecellobium dolle

Botanic names: Cabrera, Martinez (1987), UNAM (1994), Brummitt (1992).

Table 3-3 Species list of inland forest near Akumal, Q.R., 9 December 1997. Species identified by Edgar Cabrera, Chetumal, Q.R.

Species Name	Species Name
Acacia Collinsii	*Karwinskyia Humboldtiana*
Acacia dolycostachia	*Lantana camara*
Acacia Gaumeri	*Lesaea divericata*
Acacia pennatula	*Malpighia amarginata*
Amyris elemfera	*Malvaviscus arboreus*
Anthurium Schlechtendalii	*Manilkara zapodilla*
Astronium graveoleus	*Melanthera nivea*
Ayenia pusilla	*Melochia tomentosa*
Bauhinia divaricata	*Microgramma nitida*
Beaucarnea ameliae	*Neea tenuis*
Bromelia alsodeii	*Ocimum micranthum*
Brosimum Alicastrum	*Olira yucatana*
Bursera Simaruba	*Oncidium* sp.
Caesalpinia Gauneri	*Otopappus guatemalensis*
Calocarpum acuminata	*Parthenium hysterophorus*
Cenchrus ciliaris	*Paullinia pinnata*
Chamaedorea Seifrizii	*Petrea volubilis*
Coccoloba acapulcensis	*Phyllanthus macriorus*
Coccoloba diversifolia	*Piendia acileata*
Coccoloba spicata	*Piscidia piscipula*
Coccothrinax readea	*Plumeria obtusa*
Dactyloctenium aegypticum	*Priva lapulacea*
Desmodium inconun	*Psychotria nervosa*
Digitaria decumbens	*Sebastiania adenophora*
Diospyros veracruzensis	*Selenicereus testuda*
Drypetes lateriflora	*Senna racemosa*
Eleusine indica	*Sida acuta*
Esenbeckia Berlandieri	*Spermacoce tetracera*
Galactia striata	*Talisia olivaeformis*
Gouania lupuloides	*Themeda microntha*
Grass sp.	*Thevetia Gaumeri*
Gymnopodium floribundun	*Thouinia paucidentata*
Helicteris baruensis	*Thrinax radiata*
Hevea obovata	*Unknown vine*
Hompea trilobata	*Veronia cinerea*
Ichnanthus lanceolatus	*Vitex Gaumeri*
Jacquemontia nodiflora	

Botanic names: Cabrera, Martinez (1987), UNAM (1994), Brummitt (1992).

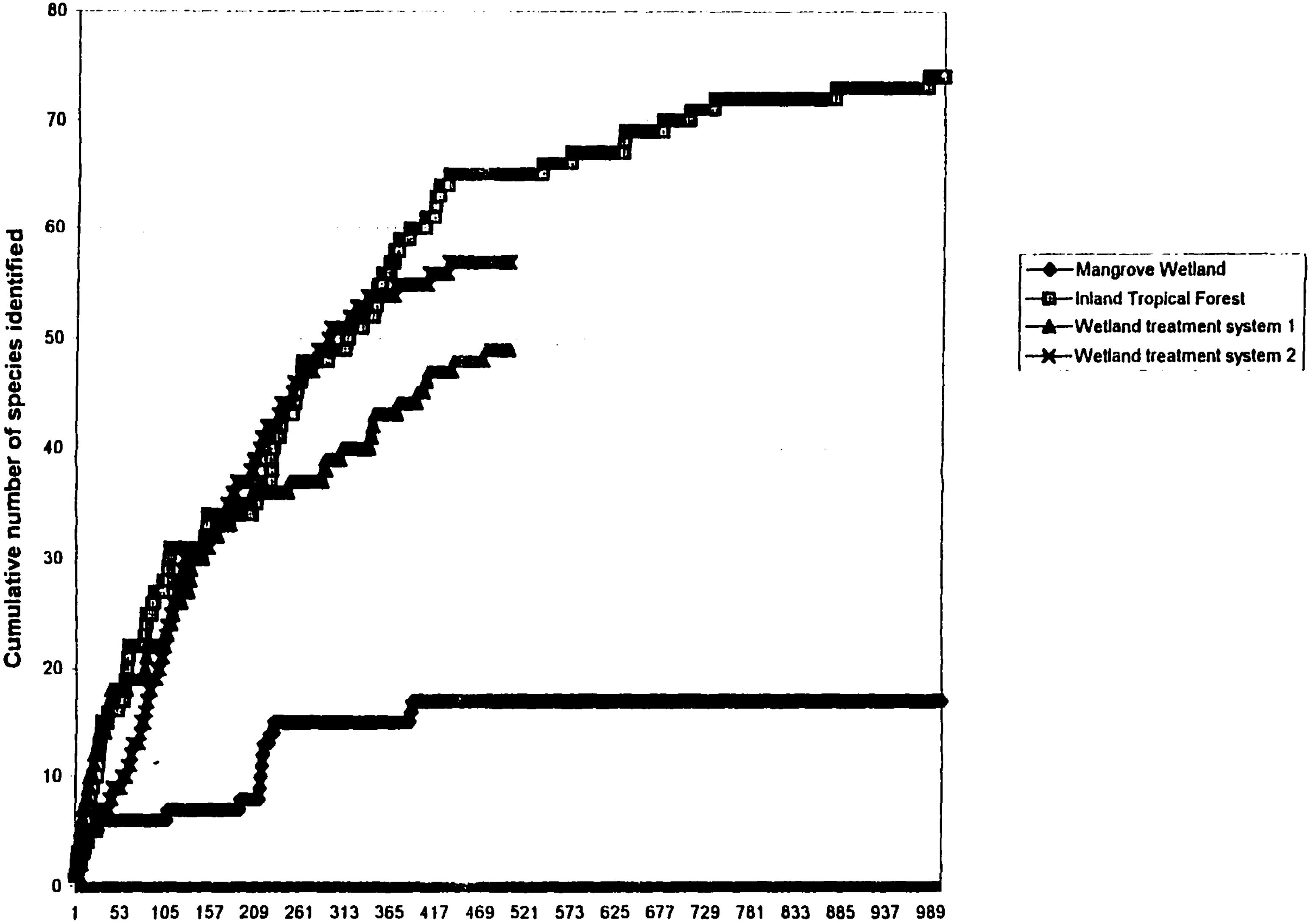


Figure 3-18 Comparison of species richness between mangrove, forest and each treatment wetland. Transects counted 1000 individuals in mangrove and forest, and 500 each in wetland systems 1 and 2.

Shannon diversity index

Shannon diversity indices for the wetlands (Table 3-4) confirmed that there was relatively high diversity in both constructed wetlands. In May 1997, wetland System 2 with a with a Shannon diversity of 4.59 (base 2), 1.38 (base 10) was higher than wetland System 1, whose diversity was 4.17 (base 2), 1.25 (base 10). However, by December 1997, their indices were far closer, with System 1 at 4.52 (base 2) and 1.36 (base 10) and System 2 at 4.49 (base 2) and 1.35 (base 10). In July 1998, Shannon diversity had increased and remained very similar between the two wetland systems. Wetland System 1 had an index of 4.81 (base 2) and 1.45 (base 10), while wetland System 2 had a diversity index of 4.85 (base 2) and 1.46 (base 10).

Comparing the treatment wetlands with the nearby natural ecosystems (Table 3-5) shows that the tropical forest ecosystem was about 7% more diverse since it had a Shannon diversity index of 5.35 (base 2) and 1.61 (base 10). On the other hand, the constructed wetlands were far more diverse than the natural mangrove wetlands, which had a Shannon diversity of 1.49 (base 2) and 0.45 (base 10), only about 30% that of the treatment wetlands.

Plant cover

Calculation of species cover in each wetland treatment cell is shown in Table 3-6, Table 3-7 and Table 3-8. These observations demonstrate that overall plant coverage was higher in the first treatment cells of both wetland systems in May 1997. Plant cover in wetland System 1, Cell 1 averaged 85% compared to 74% in Cell 2, and in wetland System 2, Cell 1 plant cover averaged 91%, while in Cell 2, plant cover was 48% of ground surface in the quadrats. By December 1997, coverage was equal between cells 1 and 2 of wetland

Table 3-4 Shannon diversity indices for constructed wetland systems based on May 1997, December 1997 and July 1998 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
	July 1998	1.36	4.52
System 1, Cell 2	May 1997	1.29	4.27
	December 1997	1.32	4.39
	July 1998	1.42	4.71
System 2, Cell 1	May 1997	1.42	4.72
	December 1997	1.26	4.19
	July 1998	1.43	4.74
System 2, Cell 2	May 1997	1.35	4.47
	December 1997	1.29	4.27
	July 1998	1.36	4.52
System 1 (whole)	May 1997	1.25	4.13
	December 1997	1.36	4.52
	July 1998	1.45	4.81
System 2 (whole)	May 1997	1.38	4.58
	December 1997	1.35	4.49
	July 1998	1.46	4.85

Table 3-5 Comparison of Shannon diversity indices for constructed wetlands vs. natural mangrove and tropical forest ecosystems of the study area, based on December 1997 and July 1998 survey data.

Ecosystem	Shannon diversity, base 10	Shannon diversity, base 2
Constructed wetland System 1	1.45	4.81
Constructed wetland System 2	1.46	4.85
Both constructed wetlands	1.51	5.01
Mangrove ecosystem	0.45	1.49
Tropical forest ecosystem	1.61	5.35

Table 3-6 Relative cover in the wetland system cells, based on 0.25 sq m quadrat analysis, May 1997.

Wetland system and cell	Plant species	Relative cover by species	Rank
System 1 Cell 1	*Canna edulis*	37.3%	1
	Sesuvium portulacastrum	12.6%	2
	Typha domingensis	11%	3
	Alocasia macrorhiza	9.5%	4
	Paspalum virgatum	8.7%	5
	Solanum erianthum	8.2%	6
	Nerium oleander	6.5%	7
System 1 Cell 2	*Canna edulis*	25.2%	1
	Melanthera nivea	12.2%	2
	Hymenocallis littoralis	9%	3
	Sesuvium portulacastrum	8.4%	4
	Washingtonii robusta	8%	5
	Chrysobalanus icaco	5.5%	6
	Cyperus ligularis	4.6%	7
System 2 Cell 1	*Canna edulis*	13.8%	1
	Typha domingensis	13.1%	2
	Pluchea odorata	9.7%	3
	Sesuvium portulacastrum.	9%	4
	Ipomoea Pes-caprae	6.6%	5
	Ageratum littorale	6.2%	6
	Eleocharis cellulosa	5.9%	7
System 2 Cell 2	*Canna edulis*	28.7%	1
	Typha domingensis	17%	2
	Nerium oleander	12.9%	3
	Sesbania emerus	8.8%	4
	Solanus erianthum	7%	5
	Eleocharis cellulosa	6.4%	6
	Paspalum virgatum	4.7%	7 (tie)
	Alocasia macrorhiza	4.7%	

Table 3-7 Estimates of area coverage, including canopy, of dominant plants in the wetland treatment cells, May 1997. Total area of each cell in System 1 is 25.3 square meters, and area of each cell in System 2 is 40.6 square meters.

Wetland system and cell	Plant species	Total coverage (m2)	Percentage of total area	Rank
System 1, Cell 1	*Canna edulis*	5.35	20.9%	1
	Typha domingensis	2.95	11.7%	2
	Alocasia macrorhiza	1.58	6.2%	3
	Solanum erianthum	1.1	4.3%	4
	Xanthosema roseum	0.8	3.2%	5 (tie)
	Musa sp.	0.8	3.2%	
	Phyla nodiflora	0.6	2.4%	7
	Pluchea odorata	0.5	2%	8 (tie)
	Conocarpus erecta	0.5	2%	
System 1, Cell 2	*Canna edulis*	3.95	15.6%	1
	Washingtonii robusta	3.15	12.5%	2
	Cyperus ligularis	2.2	8.7%	3
	Hymenocallis littoralis	2.1	8.1%	4
	Typha domingensis	1.9	7.5%	5
	Acrostichum danaefolium	0.9	3.6%	6
	Ipomoea Pes-caprae	0.8	3.2%	7
	Sesuvium portulacastrum	0.7	2.8%	8
System 2, Cell 1	*Typha domingensis*	4.85	11.9%	1
	Canna edulis	3.73	9.2%	2
	Sesuvium portulacastrum	2.5	6.2%	3
	Nerium oleander	2.45	6.1%	4
	Washingtonii robusta	1.9	4.7%	5
	Pluchea odorata	1.75	4.3%	6
	Ageratum littorale	1.6	3.9%	7
	Phyla nodiflora	1.4	3.4%	8
System 2, Cell 2	*Typha domingensis*	8.25	20.3%	1
	Canna edulis	3.75	9.2%	2
	Solanum erianthum	3.0	7.4%	3
	Eleocharis cellulosa	1.5	3.7%	4
	Sesbania emerus	1.15	2.8%	5
	Sesuvium portulacastrum	1.0	2.5%	6
	Nerium oleander	0.95	2.3%	7
	Alocasia macrorhiza	0.5	1.2%	8 (tie)
	Musa sp.	0.5	1.2%	

Table 3-8 Estimates of area coverage, including canopy, of dominant plants in the wetland treatment cells, December 1997 and July 1998. Total area of each cell in System 1 is 25.3 square meters, and area of each cell in System 2 is 40.6 square meters.

Wetland system and cell	Plant species	Total coverage (m2)	Percentage of total area	Rank
System 1, Cell 1				
December 1997	*Washingtonii robusta*	3.1	12.3%	1
	Typha domingensis	2.6	10.4%	2
	Conocarpus erecta	2.4	9.5%	3
	Nerium oleander	1.6	5.9%	4 (tie)
	Musa sp.	1.6	5.9%	
	Alocasia macrorhiza	0.9	3.6%	6
	Pluchea odorata	0.8	3.2%	7 (tie)
	Sesuvium portulacastrum	0.8		
	Xanthoseum roseum	0.8		
July 1998	*Conocarpus erecta*	7.0	28%	1
	Washingtonii robusta	6.0	24%	2
	Alocasia macrorhiza	4.8	19.2%	3
	Musa sp.	4.2	16.8%	4
	Typha domingensis	2.8	11.2%	5
	Nerium oleander	2.0	8%	6
	Coccoloba uvifera	1.8	7.2%	7
	Xanthosema roseum	1.3	5.2%	8
System 1, Cell 2				
December 1997	*Washingtonii robusta*	3.3	13%	1
	Canna edulis	2.0	7.9%	2
	Hymenocallis littoralis	1.7	6.7%	3
	Musa sp.	1.6	6.3%	4
	Typha domingensis	1.3	5.1%	5
	Oleander nerium	0.9	3.6%	6
	Acrostichum danaefolium	0.8	3.2%	7 (tie)
	Cyperus ligularis	0.8		
	Chrysobalanus icaco	0.8		
July 1998	*Washingtonii robusta*	14.4	57.6%	1
	Hymenocallis littoralis	3.9	15.6%	2
	Nerium oleander	2.4	9.6%	3
	Ipomoea Pes-caprae	1.9	7.6%	4
	Typha domingensis	1.4	5.6%	5
	Terminalia Catappa	0.7	2.6%	6
	Pedilanthus tithymaloides	0.6	2.2%	7
	Coccoloba uvifera	0.4	1.4%	8
System 2, Cell 1				
December 1997	*Washingtonii robusta*	5.6	13.9%	1
	Musa sp.	2.4	5.9%	2 (tie)

Wetland system and cell	Plant species	Total coverage (m2)	Percentage of total area	Rank	
	Typha domingensis	2.4			
	Alocasia macrorhiza	1.9	4.7%	4	
	Nerium oleander	1.4	3.5%	5 (tie)	
	Sesuvium portulacastrum	1.4			
	Acalypha hispida	1.3	3.2%	7	
	Cissus erosus	1.2	2.9%	8	
July 1998	*Washingtonii robusta*	9.4	23.2%	1	
	Typha domingensis	4.4	10.8%	2 (tie)	
	Nerium oleander	4.4	10.8%		
	Cissus erosus	3.6	8.9%	4	
	Musa sp.	3.2	7.9%	5	
	Xanthoseum roseum	3.0	7.4%	6	
	Alocasia macrorhiza	1.3	3.2%	7	
	Cissus trilofolia	1.2	3.0%	8	
System 2, Cell 2					
December 1997	*Typha domingensis*	3.9	9.6%	1	
	Alocasia macrorhiza	2.3	5.7%	2	
	Canna edulis	2.1	5.2%	3	
	Xanthoseum roseum	1.7	4.2%	4	
	Musa sp.	1.6	3.9%	5 (tie)	
	Washingtonii robusta	1.6			
	Vigna elegans	1.1	2.7%	7 (tie)	
	Nerium oleander	1.1	0.9	2.2%	9
July 1998	*Nerium oleander*	4.9	12.1%	1	
	Washingtonii robusta	4.8	11.8%	2	
	Typha domingensis	3.6	8.9%	3	
	Xanthoseum roseum	3.5	8.6%	4	
	Alocasia macrorhiza	3.1	7.6%	5	
	Solanum Schlechtendalii	2.0	4.9%	6	
	Carica Papaya	1.8	4.4%	7	
	Acrostichum danaefolium	1.7	4.2%	8	

System 2 (both around 70%) while Cell 1 of System 1 at 94% cover was still far ahead of Cell 2 with 76%.

Estimates of area covered by dominant species in each wetland treatment cell were also done by visual inspection and estimation of cover by each species in May 1997, December 1997 and July 1998. These results (Tables 3-7 and Table 3-8) show that dominance decreased between May and December 1997. In May 1997, the top 4 species covered 38%, 47%, 37% and 37% in individual treatment cells, while in December 1997, the top four species covered 32%, 28%, 24% and 21% of the wetlands. For the top 8 species, combined coverage in May 1997 was 54%, 56%, 50%, and 49% while in December 1997, coverage had fallen to 54%, 49%, 38% and 38%. By July 1998, the top four species in each treatment cell had greater canopy cover, (71%, 83%, 45% and 33%). This reflected the growth and increased canopy of trees and large palms, such as *Washingtonii robusta*, *Conocarpus erecta*, and *Musa* sp.

Plant frequency

The frequency of species in the treatment wetlands was evaluated in May 1997, December 1997 and July 1998 (Table 3-9).

The 8 plant species with highest relative frequency in the treatment cells of each wetland system in May and December 1997 are shown in Table 3-9. These results show that *Canna edulis* and *Typha domingensis* were the two most frequently observed plant species overall in May 1997, but that some differences are seen in the wetland cells. In wetland System 2, Cell 1, *Hymenocallis littoralis* is the second most frequent species, and a number of different species appear in the top seven species depending on the wetland area. By December 1997, the pattern had changed somewhat with *Canna edulis* coverage

Table 3-9 Frequency rankings of dominant plants in constructed wetlands in May 1997, December 1997 and July 1998 transects.

Wetland location	Date	Most frequent species	Percent frequency	Date	Most frequent species	Percent frequency
System1 Cell 1	May 1997	*Canna edulis*	25.4	Dec. 1997	*Typha domingensis*	20.3
		Typha domingensis	12.5		*Alocasia macrorhiza*	11.4
		Alocasia macrorhiza	9.1		*Sesuvium portulacastrum*	9.6
		Sesuvium portulacastrum	8.2		*Hymenocallis littoralis*	8.0
		Hymenocallis littoralis	5.6		*Canna edulis*	7.1
		Solanum erianthum	3.9		*Nerium oleander*	3.8
		Paspalum virgatum	3.4		*Conocarpus erecta*	2.6
		Nerium oleander	2.6		*Melanthera nivea*	2.6
	July 1998	*Typha domingensis*	16.8			
		Alocasia macrorhiza	6.4			
		Hymenocallis littoralis	5.6			
		Canna edulis	5.2			
		Solanum Schlechtendalii	4.8			
		Scindapsus aureus	4.4			
		Washingtonii robusta	3.6			
		Pluchea odorata	3.6			
System 1 Cell 2	May 1997	*Canna edulis*	25.2	Dec. 1997	*Canna edulis*	17.5
		Hymenocallis littoralis	14.0		*Typha domingensis*	10.8
		Typha domingensis	8.8		*Hymenocallis littoralis*	7.6
		Acrostichum danaefolium	4.4		*Acalypha hispida*	7.2
		Sessuvium portulastrum	4.4		*Washingtonii robusta*	4.4
		Cyperus ligularis	3.6		*Melanthera nivea*	4.0

Wetland location	Date	Most frequent species	Percent frequency	Date	Most frequent species	Percent frequency
		Chrysobalanus icaco	3.2		*Alocasia macrorhiza*	4.0
		Chamaesyce hypericifolia	2.4		*Cyperus ligularis*	4.0
	July 1998	*Hymenocallis littoralis*	9.2			
		Canna edulis	8.4			
		Typha domingensis	8.0			
		Ipomoea Pes-caprae	8.0			
		Washingtonii robusta	6.4			
		Alocasia macrorhiza	4.4			
		Nerium oleander	4.4			
		Phyla nodiflora	4.0			
System 2 Cell 1	May 1997	*Typha domingensis*	19.4	Dec. 1997	*Typha domingensis*	29.7
		Canna edulis	15.1		*Canna edulis*	12.7
		Nerium oleander	5.2		*Nerium oleander*	6.6
		Ageratum littorale	3.9		*Xanthoseum roseum*	3.4
		Sessuvium portulastrum	3.4		*Sessuvium portulastrum*	3.1
		Phyla nodiflora	3.4		*Ipomoea Pes-caprae*	3.1
		Ludwigia octavalis	3.0		*Cissus erosus*	2.2
		Pluchea odorata	3.0		*Acalypha hispida*	2.2
					Ageratum littorale	2.2
	July 1998	*Typha domingensis*	17.6			
		Cissus erosus	8.4			
		Alocasia macrorhiza	6.4			
		Nerium oleander	5.2			
		Washingtonii robusta	4.8			
		Sesuvium portulacastrum	2.8			
Wetland	Date	Most frequent	Percent	Date	Most frequent	Percent

location		species	frequency		species	frequency
		Bravaisia tubiflora	2.4			
		Ipomea indica	2.4			
System 2 Cell 2	May 1997	*Typha domingensis*	21.6	Dec. 1997	*Typha domingensis*	28.6
		Canna edulis	19.2		*Canna edulis*	12.1
		Solanum erosanthum	7.0		*Nerium oleander*	7.1
		Eleocharis cellulosa	6.4		*Alocasia macrorhiza*	3.8
		Alocasia macrorhiza	4.7		*Vigna elegans*	2.9
		Paspalum virgatum	4.7		*Sessuvium portulastrum*	2.9
		Hymenocallis littoralis	4.1		*Eleocharis cellulosa*	2.9
		Phyla nodiflora	4.1		*Hymenocallis littoralis*	2.9
		Washingtonii robusta	4.1		*Acalypha hispida*	2.0
		Cestrum diurnum	4.1			
	July 1998	*Typha domingensis*	20.8			
		Nerium oleander	8.4			
		Xanthoseum roseum	4.8			
		Alocasia macrorhiza	4.8			
		Canna edulis	4.4			
		Pluchea odorata	4.4			
		Scindapsus aureus	4.3			
		Hymenocallis littoralis	3.6			
		Rhabdadenia biflora	3.3			

declining (from 17% overall to 12%), *Typha domingensis increasing* (from 15% to 22%) and other cells showing changes in species and their frequency. The cover by vines was greater in System 2, with *Ipomoea Pes-caprae, Cissus erosus* and *Vigna elegans* among the most frequently observed species. By July 1998, the decline of *Canna edulis* accelerated, both in frequency and in size of individual plants, as it became overtopped by a taller canopy.

Along with greater species richness, System 2 was less heavily dominated by its most frequently observed plant species in May 1997. In System 2, Cell 1, the five most frequent species constitute 47% of total observations and in System 2, Cell 2, the top five are 52%. By contrast in System 1, Cell 1, the top 5 are 60%, and in System 1, Cell 2, are 56% of total observations in May 1997. When considered as a whole, in System 1 the top 5 species are 58.3% of observations, while in System 2, the top 5 are 47.7%. By December 1997, the situation had changed, and the two wetlands were more comparable. In System 2's cells 1 and 2, the top 5 species constituted 56% and 55% of observations, while in wetland System 1, the top five species represented 60% and 48% of observations. In July 1998, the decrease in dominance continued, with the top 5 species constitute 42.4% of observations in System 2, and 37.2% in System 1 (Table 3-9).

Rarely observed species are found in all cells of both systems, but more are found in wetland System 2. In May 1997, in System 1, Cell 1, there were 10 species with only 2 observations and 9 with only 1; in System 1, Cell 2, there were 5 species with only 2 observations, and 8 with only 1; in System 2, Cell 1, there were 11 species with only 2 observations, and 9 with only 1; and in System 2, Cell 2, there were 12 species with only 2 observations and also 12 species with only 1 observation. In December 1997, System 1, Cell

1 had 9 species with 2 observations, 5 species with 1; System 1, Cell 2 had 6 species with 2 observations, 8 species with 1; while System 2, Cell 1 had 13 species with 2 observations, 10 species with 1; and System 2, Cell 2, had 12 species with 2 observations and 16 with 1. In July 1998, System 1 Cell 1 had 4 species with 2 observations and 6 with one; System 1 Cell 2 had 4 species with 2 observations and 3 with one. System 2 Cell 1 had 12 species with 2 observations and 10 with one; System 2 Cell 2 had 5 species with two observations, and 14 with one.

Importance values

Importance values for the plant species in the wetland systems were calculated combining their relative frequency (from transect studies) and their relative cover (from quadrat analysis) and dividing by two (Brower *et al.*, 1991). Table 3-10 presents the Importance Value results which show that in May 1997, *Canna edulis* and *Typha domingensis* were the two most important plant species overall as they occupied all but one of top two rankings in the four treatment cells. In December 1997, *Typha* remained the highest ranking species, but now *Washingtonii robusta* was second overall. Below that level, there was some variability in which plants ranked highest in importance in each treatment cell. In July 1998, *Typha* remained the top species in the two system cells of System 2, but *Washingtonii robusta* and *Conocarpus erecta* were the top plants in each of System 1's cells (Table 3-10).

Graphing the rank sequence of species from each system cell is a method of comparing dominance vs. evenness of systems (Brower et al, 1991). Figure 3-19, Figure 3-20, and Figure 3-21 show that there was great similarity in the pattern of dominance/evenness for all four of the wetland treatment cells in May 1997, December

Table 3-10 Importance value ranking of top eight species in each wetland treatment cell, May 1997, December 1997 and July 1998 surveys. Values were computed by adding relative species frequency and relative species cover and dividing by 2. Maximum value is therefore 1.0, and total is 1.0 summing all species found in the treatment cell

Wetland system and cell	Survey date	Plant species	Importance value	Rank
System 1, Cell 1	May1997	*Canna edulis*	0.31	1
		Typha domingensis	0.12	2
		Sesuvium portulacastrum	0.10	3
		Alocasia macrorhiza	0.09	4
		Paspalum virgatum	0.06	5
		Solanum erianthum	0.06	6
		Hymenocallis littoralis	0.05	7
		Nerium oleander	0.04	8
	Dec.1997	*Typha domingensis*	0.15	1
		Alocasia macrorhiza	0.08	2
		Washingtonii robusta	0.08	3
		Sesuvium portulacastrum	0.07	4
		Conocarpus erecta	0.06	5
		Nerium oleander	0.05	6
		Hymenocallis littoralis	0.05	7
		Canna edulis	0.05	8
	July 1998	*Conocarpus erecta*	0.13	1
		Typha domingensis	0.12	2
		Washingtonii robusta	0.10	3
		Alocasia macrorhiza	0.10	4
		Musa sp.	0.07	5
		Nerium oleander	0.06	6
		Solanum Schlechtendalii	0.04	7
		Hymenocallis littoralis	0.04	8
System 1, Cell 2	May 1997	*Canna edulis*	0.25	1
		Hymenocallis littoralis	0.11	2
		Melanthera nivea	0.07	3
		Sesuvium portulacastrum	0.06	4
		Typha domingensis	0.06	5
		Acoelorhaphe wrightii	0.05	6
		Chrysobalanus icaco	0.04	7
		Acrostichum danaefolium	0.04	8
	Dec.1997	*Canna edulis*	0.14	1
		Washingtonii robusta	0.11	2
		Typha domingensis	0.09	3

Wetland system and cell	Survey date	Plant species	Importance value	Rank
		Hymenocallis littoralis	0.08	4
		Acalypha hispida	0.05	5
		Musa sp.	0.05	6
		Cyperus ligularis	0.04	7
		Acrostichum danaefolium	0.04	8
	July 1998	*Washingtonii robusta*	0.25	1
		Hymenocallis littoralis	0.11	2
		Ipomoea Pes-caprae	0.07	3
		Typha domingensis	0.06	4
		Nerium oleander	0.06	5
		Canna edulis	0.04	6
		Alocasia macrorhiza	0.03	7
		Solanum Schlechtendalii	0.03	8
System 2, Cell 1	May 1997	*Typha domingensis*	0.16	1
		Canna edulis	0.14	2
		Pluchea odorata	0.06	3
		Sesuvium portulacastrum	0.06	4
		Nerium oleander	0.05	5
		Ageratum littorale	0.05	6
		Ipomoea Pes-caprae	0.05	7
		Eleocharis cellulosa	0.04	8
	Dec. 1997	*Typha domingensis*	0.19	1
		Washingtonii robusta	0.11	2
		Canna edulis	0.08	3
		Nerium oleander	0.06	4
		Musa sp.	0.05	5
		Sesuvium portulacastrum	0.04	6
		Alocasia macrorhiza	0.04	7
		Acalypha hispida	0.03	8
	July 1998	*Typha domingensis*	0.14	1
		Washingtonii robusta	0.14	2
		Cissus erosus	0.09	3
		Nerium oleander	0.08	4
		Musa sp.	0.05	5
		Alocasia macrorhiza	0.05	6
		Xanthoseum roseum	0.05	7
		Hymenocallis littoralis	0.04	8
System 2, Cell 2	May 1997	*Canna edulis*	0.24	1
		Typha domingensis	0.19	2
		Nerium oleander	0.08	3
		Sesbania emerus	0.06	4

Wetland system and cell	Survey date	Plant species	Importance value	Rank
		Alocasia macrorhiza	0.05	5
		Eleocharis cellulosa	0.04	6
		Paspalum virgatum	0.04	7
		Solanum erianthum	0.04	8
	Dec. 1997	*Typha domingensis*	0.21	1
		Canna edulis	0.10	2
		Alocasia macrorhiza	0.06	3
		Nerium oleander	0.06	4
		Vigna elegans	0.04	5
		Xanthoseum roseum	0.03	6
		Washingtonii robusta	0.03	7
		Musa sp.	0.03	8
	July 1998	*Typha domingensis*	0.15	1
		Nerium oleander	0.10	2
		Washingtonii robusta	0.07	3
		Xanthoseum roseum	0.07	4
		Alocasia macrorhiza	0.06	5
		Solanum Schlechtendalii	0.06	6
		Acrostichum danaefolium	0.04	7
		Canna edulis	0.03	8

(Brower et al, 1991).

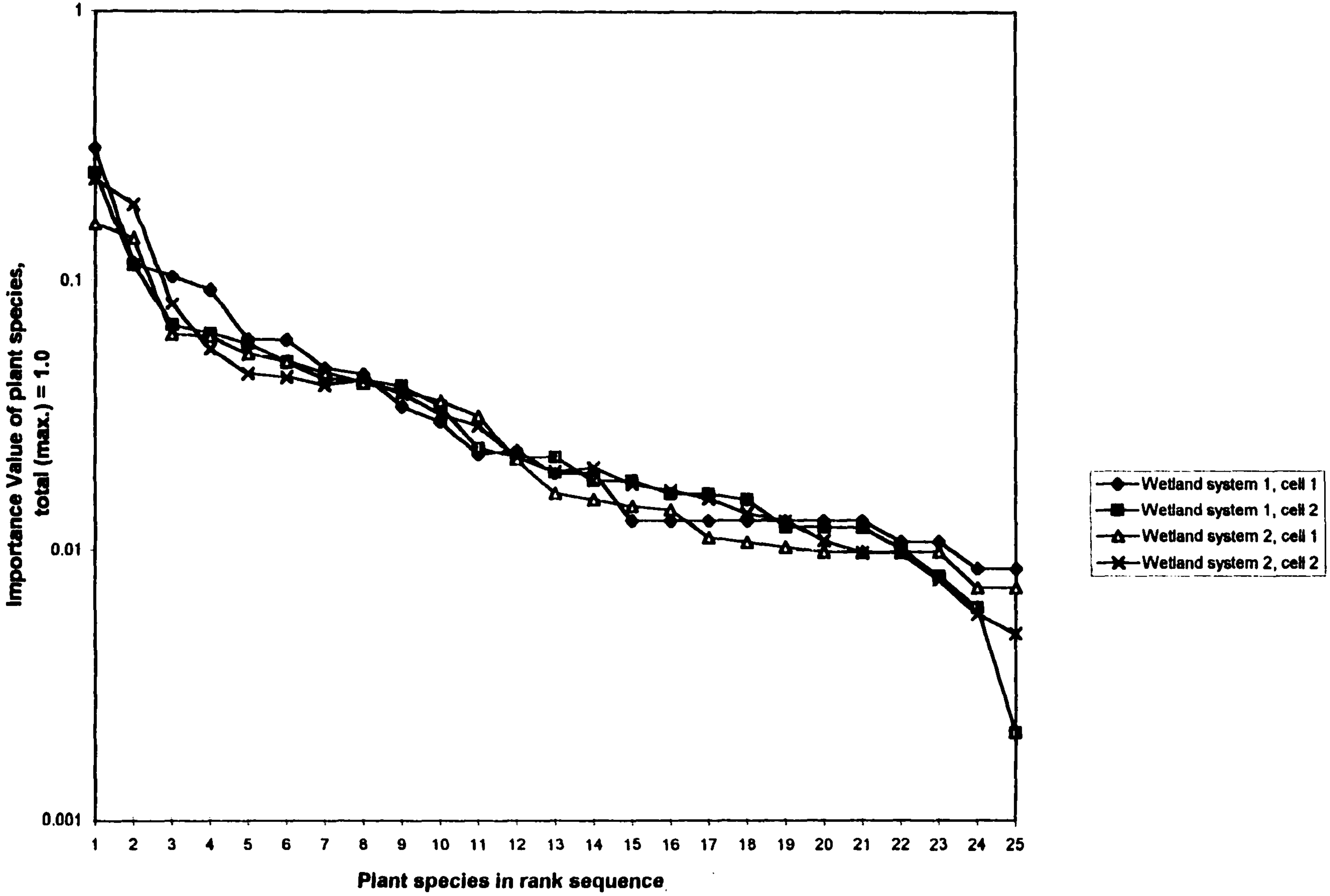


Figure 3-19 Plant species in rank sequence of Importance Value (IV) in the four wetland treatment cells, May, 1997 data. Importance Value = (Frequency + Cover)/2.

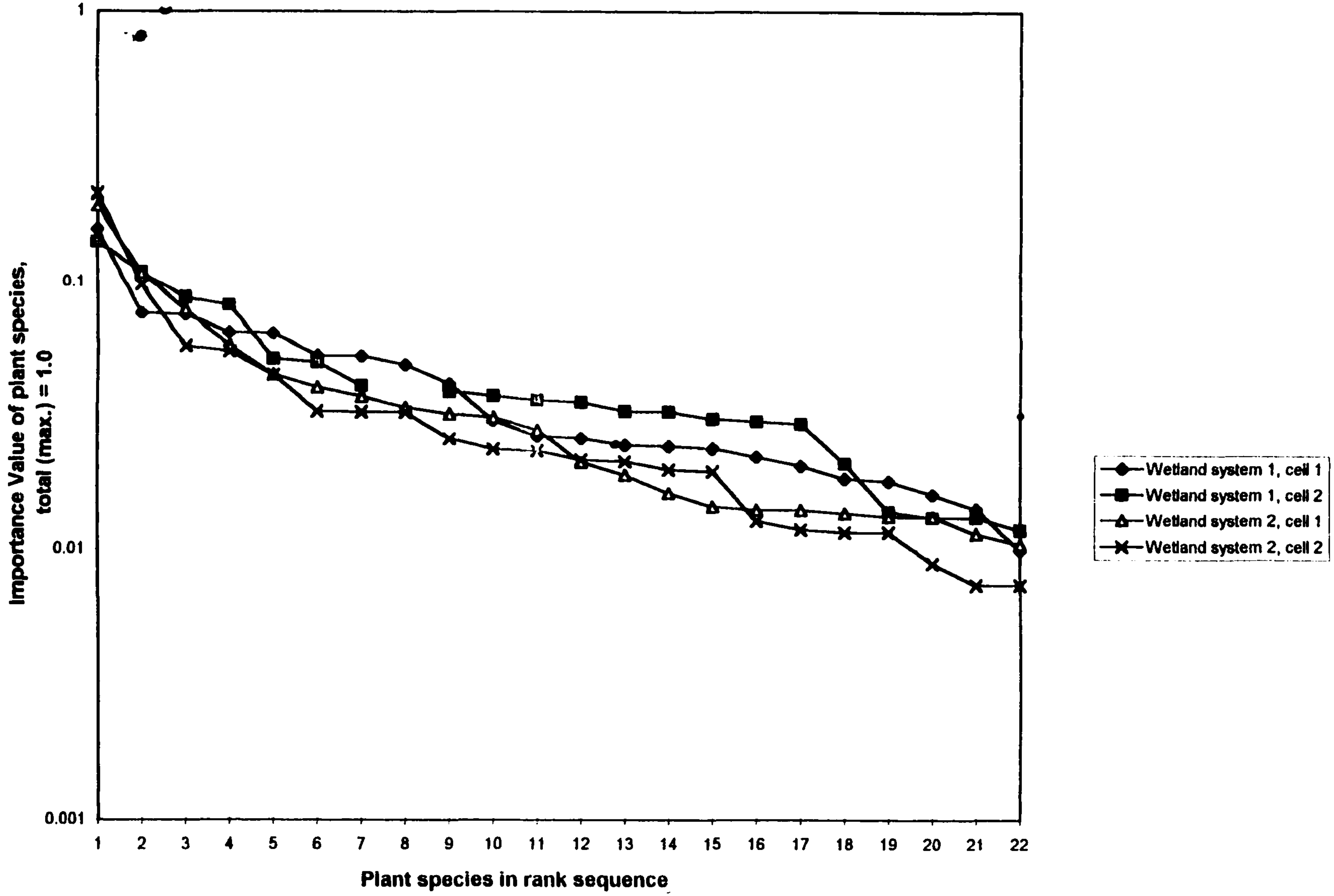


Figure 3-20 Plant species in rank sequence of Importance Value (IV) in the four wetland treatment cells, December, 1997 data. Importance Value = (Frequency + Cover)/2.

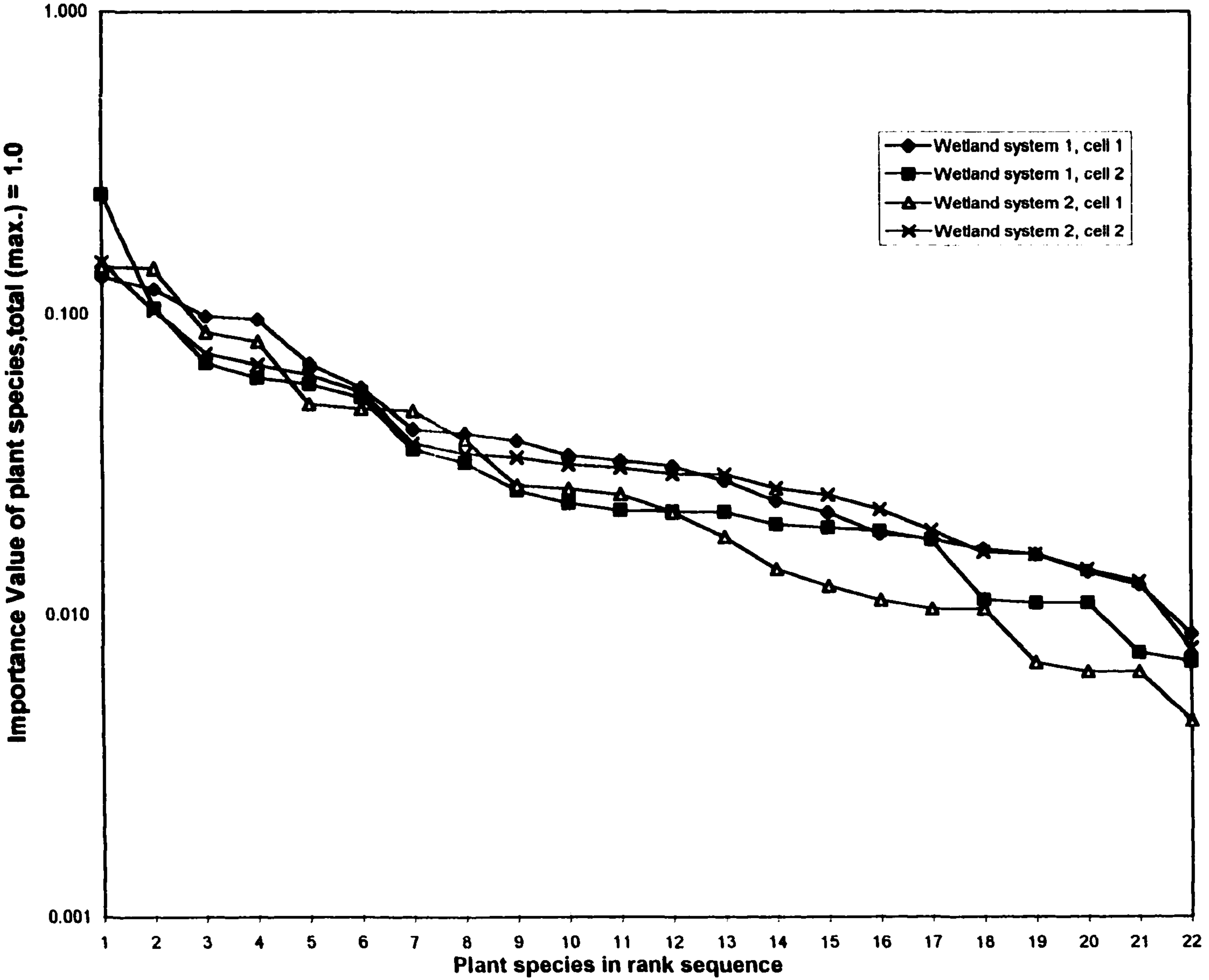


Figure 3-21 Plant species in rank sequence of Importance Value (IV) in the four wetland treatment cells, July, 1998 data. Importance Value = (Frequency + Cover)/2.

1997 and July 1998. Distribution is somewhat more even in December 1997, as evidenced by a flatter shape to the graph lines than in the earlier and later measurements.

Leaf area index

Data on the structure of vegetation in the wetlands monitored with leaf area index (LAI) are summarized in Table 3-11. Photographs of the wetlands illustrating canopy development are presented in Figures 3-22 to 3-25.

The initial development of the canopy in the two wetlands was similar. The overall LAI for the System 1 and System 2 wetlands were 4.04 ±0.28 and 3.89 ±0.29 in May 1997. However, leaf area indexes were markedly different between the first and second treatment cells. The first cells of the two wetland systems averaged 5.56 ± 0.27. By contrast, the second cells were substantially lower, averaging 2.33 ± 0.19 (Table 3-11).

By November 1997, after an additional six months growth, and July 1998, with an additional 14 months growth, all cells had increased in LAI. The difference between first and second cells had considerably narrowed in System 1 and was no longer evident in System 2. Average LAI for System 1 had increased to 5.73 ± 0.48 and System 2 was 6.38 ± 0.51 (Table 3-11).

Leaf holes

Leaf holes due to herbivory and other causes were measured in December 1997 and July 1998 (Table 3-12, Table 3-13).

Overall estimates for the ecosystem were determined by multiplying leaf holes per species by species frequency. The result was 4.7% of leaf material in the wetlands in December 1997 and 2.1% in July 1998 (Table3-12, Table 3-13).

Table 3-11 Measurements of leaf area index in the treatment cells of the wetland systems, May 1997, December 1997 and July 1998. Values are given with standard error of the mean.

May, 1997

Wetland Unit	No. of observations	First Cell	Second Cell	Overall Wetland
System 1	93	5.51 +/- 0.40	2.54 +/- 0.23	4.04 +/- 0.28
System 2	105	5.60 +/- 0.36	2.33 +/- 0.19	3.89 +/- 0.29

November 1997

Wetland Unit	No. of observations	First Cell	Second Cell	Overall wetland
System 1	109	6.22 +/- 0.4	4.24 +/- 0.43	5.23 +/- 0.31
System 2	109	5.76 +/- 0.36	4.9 +/- 0.31	5.33 +/- 0.26

July 1998

Wetland Unit	No. of observations	First Cell	Second Cell	Overall wetland
System 1	66	6.68 ± 0.46	4.77 ± 0.55	5.73 +/- 0.48
System 2	71	6.38 ± 0.48	6.39 ± 0.54	6.38 +/- 0.51

Figue 3-22 Photogrpah of wetland systems in Akumal shortly after planting, August 1996. System 1 is in foreground and System 2 in background, in front of edge of mangrove wetland.

Figure 3-23 Photograph of vegetation in wetland system 1, May, 1997.

Figure 3-24 Photograph of vegetation in wetland system 1, December, 1997.

Figure 3-25 Photograph of vegetation in wetland system 1, July 1998.

Table 3-12 Leaf holes in the wetland treatment units, December 1997.

Name of Species	Percent Holes[a]	Leaf Frequency[b]	Species Contribution[c]
Canna edulis	0.15	0.123	0.018
Acalypha hispida	0.1	0.036	0.004
Hymenocallis littoralis	0.04	0.052	0.002
Lantana involucrata	0.16	0.015	0.002
Melanthera nivea	0.074	0.029	0.002
Solanum Schlechtendalii	0.11	0.016	0.002
Alocasia macrorhiza	0.026	0.047	0.001
Cissus erosus	0.11	0.006	0.001
Cissus sicyoides	0.26	0.002	0.001
Cyperus ligularis	0.05	0.017	0.001
Eupatorium albicaule	0.19	0.006	0.001
Ipomea indica	0.15	0.005	0.001
Ipomoea Pes-caprae	0.042	0.024	0.001
Phyla nodiflora	0.15	0.005	0.001
Sesuvium portulacastrum	0.014	0.046	0.001
Terminalia Catappa	0.058	0.009	0.001
Vigna elegans	0.1	0.013	0.001
Washingtonii robusta	0.03	0.022	0.001
Acrostichum danaefolium	0.014	0.014	0.000
Ageratum littorale	0.04	0.008	0.000
Anthurium schlechtendallii	0.012	0.005	0.000
Anthurium sp.	0.03	0.005	0.000
Asclepias curossavica	0.01	0.001	0.000
Bidens pilosa	0.018	0.003	0.000
Bravaisia tubiflora	0.07	0.005	0.000
Caesalpinia pulcherrima	0.014	0.003	0.000
Caladium bicolor	0.02	0.007	0.000
Carica Papaya	0.05	0.001	0.000
Chamaedorea Seifrizii	0.012	0.001	0.000
Chamaesyce hypericifolia	0.038	0.004	0.000
Chrysobalonus icaco	0.002	0.013	0.000
Citrus aurianthum	0.014	0.001	0.000
Coccoloba uvifera	0.048	0.008	0.000
Conocarpus erecta	0.02	0.007	0.000
Corchorus siliquosus	0.07	0.005	0.000

Name of Species	Percent Holes[a]	Leaf Frequency[b]	Species Contribution[c]
Desmodium incanum	0.12	0.002	0.000
Distichlis spicata	0	0.006	0.000
Eleocharis cellulosa	0.01	0.006	0.000
Flaveria linearis	0.05	0.004	0.000
Iresine celosioides	0.03	0.002	0.000
Ixora coccinea	0	0.007	0.000
Kalanchoe pinnata	0.008	0.003	0.000
Lochnera rosea	0.09	0.001	0.000
Malvaviscus arboreus	0.022	0.003	0.000
Nerium oleander	0	0.052	0.000
Nopalea cochinillifera	0.008	0.001	0.000
Paspalum virgatum	0.014	0.018	0.000
Pedilanthus tithymaloides	0.03	0.011	0.000
Pelliciera alliacea	0.09	0.002	0.000
Philodendron sp	0.004	0.001	0.000
Pluchea odorata	0.046	0.009	0.000
Psychotria nervosa	0.02	0.001	0.000
Rabdadenia biflora	0.08	0.003	0.000
Rhoeo discolor	0.02	0.009	0.000
Sansevieria triasiate	0.01	0.010	0.000
Scindapsus aureus	0.03	0.008	0.000
Selenicereus dontielarii	0	0.001	0.000
Senna biflora	0.004	0.001	0.000
Syngonium sp.	0.07	0.002	0.000
Thrinax radiata	0	0.004	0.000
Typha domingensis	0.002	0.220	0.000
Vigna luteola	0.07	0.001	0.000
Viguiera dentata	0.06	0.001	0.000
Wedelia trilobata	0.1	0.001	0.000
Xanthosoma roseum	0.014	0.026	0.000
Zamia purpuraceus	0	0.005	0.000
Zephranthes Lindleyana	0.014	0.005	0.000
Total		1.000	0.047

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[a] Portion of measured leaves of one species which showed holes

[b] Frequency is based on the frequency of the species in the wetlands

[c] Product of percent holes and species frequency.

Table 3-13 Leaf holes in the wetland treatment units, July 1998 data.

Name of Species	Percent Holes[a]	Leaf Frequency[b]	Species Contribution[c]
Solanum Schlechtendalii	0.11	0.038	0.004
Alocasia macrorhiza	0.028	0.055	0.002
Nerium oleander	0.028	0.060	0.002
Sesuvium portulacastrum	0.054	0.030	0.002
Bidens pilosa	0.06	0.012	0.001
Canna edulis	0.022	0.055	0.001
Hymenocallis littoralis	0.01	0.062	0.001
Phyla nodiflora	0.06	0.017	0.001
Pluchea odorata	0.034	0.028	0.001
Scindapsus aureus	0.018	0.036	0.001
Typha domingensis	0.004	0.158	0.001
Xanthosoma roseum	0.05	0.028	0.001
Acrostichum danaefolium	0.02	0.018	0.000
Ageratum littorale	0.04	0.010	0.000
Aloe vera	0.028	0.003	0.000
Alternanthera ramossissima	0.014	0.002	0.000
Anthurium schlechtendallii	0.014	0.006	0.000
Anthurium sp.	0.018	0.003	0.000
Bravaisia tubiflora	0.014	0.023	0.000
Caesalpinia pulcherrima	0	0.001	0.000
Caladium bicolor	0	0.007	0.000
Capraria biflora	0.04	0.003	0.000
Carica Papaya	0.024	0.001	0.000
Chamaedorea Seifrizii	0.002	0.002	0.000
Chamaesyce hypericifolia	0	0.007	0.000
Chrysobalonus icaco	0.01	0.006	0.000
Cissus erosus	0	0.029	0.000
Cissus sicyoides	0.004	0.006	0.000
Citrus aurianthum	0.004	0.003	0.000
Coccoloba uvifera	0.034	0.013	0.000
Conocarpus erecta	0.018	0.020	0.000
Corchorus siliquosus	0.05	0.004	0.000
Cordia sebestena	0.004	0.001	0.000
Crinum amabile	0.004	0.002	0.000
Desmodium tortuosum	0.014	0.006	0.000
Distichlis spicata	0	0.005	0.000

Name of Species	Percent Holes[a]	Leaf Frequency[b]	Species Contribution[c]
Eupatorium albicaule	0.018	0.007	0.000
Flaveria linearis	0	0.001	0.000
Ipomea indica	0.004	0.006	0.000
Ipomoea Pes-caprae	0.014	0.033	0.000
Ixora coccinea	0.034	0.009	0.000
Kalanchoe pinnata	0.04	0.002	0.000
Leucaena glauca	0	0.002	0.000
Mimosa sp.	0.01	0.003	0.000
Malvaviscus arboreus	0	0.004	0.000
Musa sp.	0.004	0.015	0.000
Nopalea cochinillifera	0.03	0.001	0.000
Paspalum virgatum	0.02	0.003	0.000
Pedilanthus tithymaloides	0.004	0.014	0.000
Philodendron sp.	0.025	0.001	0.000
Phylanthus niruri	0.03	0.001	0.000
Psychotria nervosa	0.014	0.003	0.000
Rabdadenia biflora	0	0.008	0.000
Rhizophora mangle	0	0.003	0.000
Rhoeo discolor	0.01	0.017	0.000
Sansevieria triasiate	0.008	0.009	0.000
Senna biflora	0.004	0.003	0.000
Terminalia Catappa	0.004	0.017	0.000
Thrinax radiata	0.07	0.006	0.000
Vigna luteola	0	0.003	0.000
Washingtonii robusta	0.004	0.044	0.000
Wedelia trilobata	0.004	0.008	0.000
Zamia purpuraceus	0	0.004	0.000
Zephranthes Lindleyana	0.05	0.007	0.000
Total		1.00	0.021

[a] Portion of measured leaves of one species which showed holes
[b] Frequency is based on the frequency of the species in the wetlands
[c] Product of percent holes and species frequency.

More holes were found in *Cissus sicyoides* (26%), *Eupatorium albicaule* (19%), *Lantana involucrata* (16%), Canna edulis (15%), *Ipomea indica* (15%), *Phyla nodiflora* (15%), *Solanum schlectendalionum* (11%) and *Cissus erosus* (11%). Because of its abundance *Canna edulis* (1.8%) was responsible for over one-third of the total. Eighteen species accounted for 89% of total herbivory in the wetlands in December 1997 (Table 3-12).

By July 1998, when average leaf holes were 1.8%, the leading species were *Thrinax radiata* (7%), *Bidens pilosa* (6%), *Phyla nodiflora* (6%), *Sesuvium portulacastrum* (5.4%), *Xanthoseum roseum* (5%) and *Corchorus siliquosus* (5%). Leaf holes were more evenly divided among species than in December 1997, with *Solanum Schlechtendalii* contributing the highest individual amount (4%), while *Alocasia macrorhiza*, *Sesuvium portulacastrum*, and *Nerium oleander* each contributed 2% (Table 3-13).

Surface organic matter

Results of analysis of organic matter on the gravel surface of treatment systems are presented in Figure 3-26.

Average organic matter surface material was initially 1582 ± 242 g m^{-2} (dry weight). In July, 1998, after twenty three months of wetland operation since planting, surface organic matter averaged 1458 ± 254 g m^{-2} in System 1 Cell 1, 1515 ± 373 g m^{-2} in System 1 Cell 2, 1210 ± 81 g m^{-2} in System 2 Cell 1, and 1610 ± 242 g m^{-2} in System 2 Cell 2. The overlap of the standard error bars shows that these values are not statistically different from the starting value. T-tests for samples of unequal variance show their probabilities to be $p<0.73$, $p<0.96$, $p<0.36$ and $p<0.20$ respectively indicating that statistically there was no significant change.

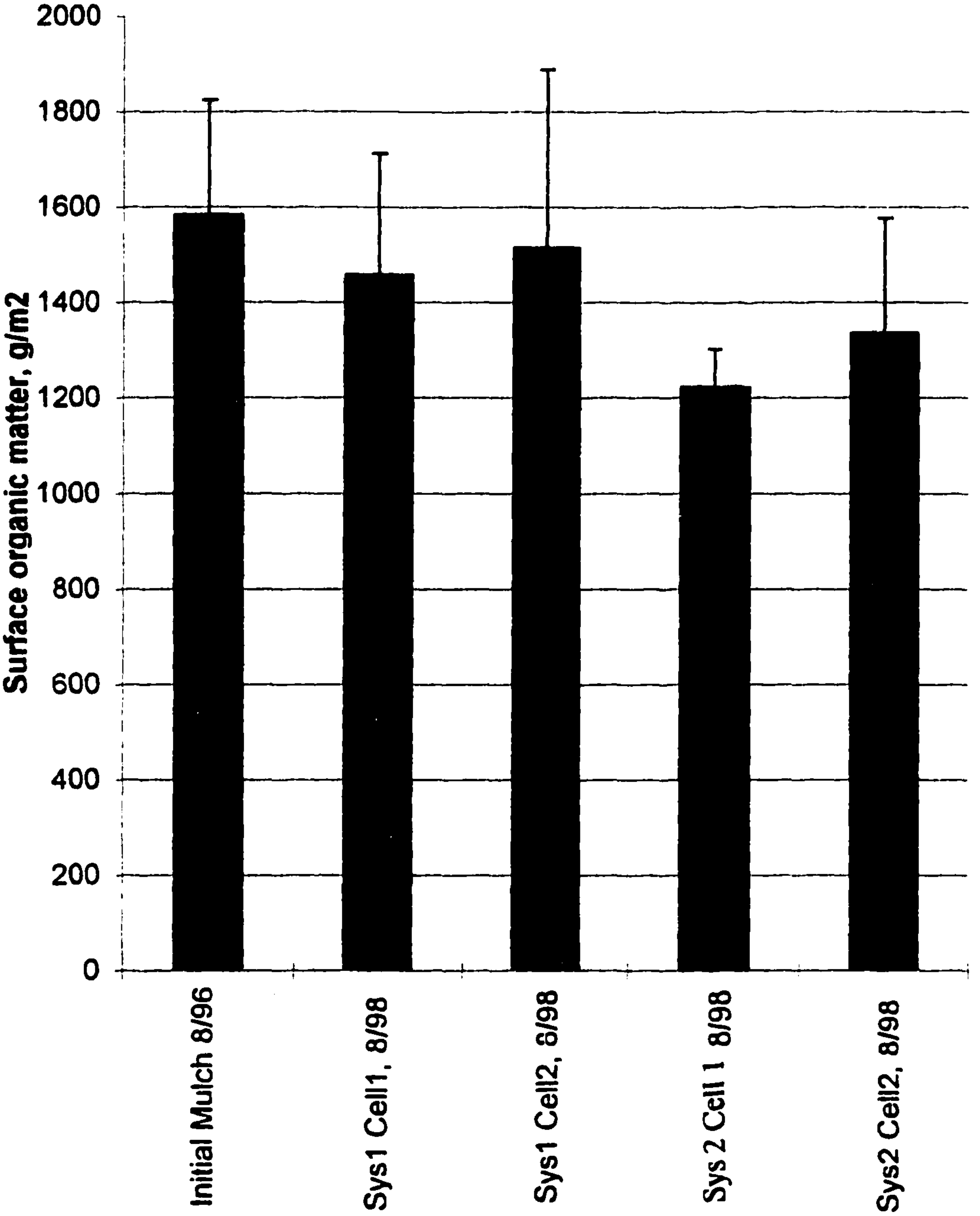


Figure 3-26 Surface organic matter in the wetland treatment cells. Data presented are those of initial mulching (August 1996) and surface organic matter (July 1998), after 23 months of operation. Bars are ± standard errors.

Solar insolation

Data on solar insolation and canopy interception in the wetland systems are presented in Table 3-14. Part of the canopy of wetland System 2 in July 1998 is shown in Figure 3 –27.

On a summer, cloudless day, near mid-day when outside ambient solar insolation levels averaged 7464 ± 25 μmoles m^{-2}, solar insolation reaching ground level in the wetland systems averaged 373 ± 20 μmoles m^{-2} in System 1 Cell 1, 367 ± 32 μmoles m^{-2} in System 1 Cell 2, 563 ± 51 μmoles m^{-2} in System 2, Cell 1, and 504 ± 61 μmoles m^{-2} in System 2, Cell 2 (Table 3-14). These data represent canopy interception reductions of 95% in System 1 Cell 1, 93% in System 1 Cell 2, 82% in System 2 Cell 1 and 90% in System 2 Cell 2.

Measurements of solar insolation reaching the perimeters of the wetland treatment cells (the outer 0.5 m), show that in System 1 Cells 1 and 2, the light levels are slightly lower than but comparable to average light levels for the whole treatment cell (4.9% on the perimeter vs. 5% for Cell 1, and 6.8% on the perimeter vs. 7.5% for Cell 2).

Perimeter light levels are considerably higher, however, for wetland System 2, with Cell 1 perimeter light averaging 33% of ambient vs. 18.1% for the whole cell, and in Cell 2 perimeter light averaging 12.1% of ambient compared to 9.8% for the whole cell. The statistical significance of these differences (by t-test for two samples of unequal variance) are $p<0.12$ for System 2 Cell 1 and $p<0.19$ for System 2 Cell 2.

Canopy closure

Canopy closure of the wetland treatment cells was analyzed with hemispheric canopy photographs 23 months after planting (Table 3-15, Figure 3 -28).

Table 3-14 Insolation levels and their reduction in the constructed wetlands, 28 July 1998 between 1050 and 1145 AM. Perimeter light levels are the measured insolation at locations 0.5 m inside the wetland systems along their outside edges.

Location	Solar insolation µmol	Percent of ambient light
Ambient	7464 ± 25	------------
System 1 Cell 1	373 ± 20	5.0%
System 1 Cell 1 Perimeter	367 ± 32	4.9%
System 1 Cell 2	563 ± 51	7.5%
System 1 Cell 2 Perimeter	504 ± 61	6.8%
System 2 Cell 1	1350 ± 225	18.1%
System 2 Cell 1 Perimeter	2460 ± 641	33.0%
System 2 Cell 2	722 ± 64	9.8%
System 2 Cell 2 Perimeter	902 ± 112	12.1%

Figure 3-27 Photohraph showing dense canopy cover intrecepting solar insolation, wetland system 2, July, 1998.

Table 3-15 Light penetration and canopy closure in the wetland systems and adjoining mangrove wetland, 29 July 1998. Data presented ± standard error of the mean.

Location	Number of Photographs	Light through canopy (percent)	Canopy closure (percent)
System 1 Cell 1	9	12.5 ± 1.4	87.5 ± 1.4
System 1 Cell 2	9	16.1 ± 2.9	83.9 ± 2.9
System 2 Cell 1	9	15.2 ± 2.6	84.8 ± 2.6
System 2 Cell 2	8	13.1 ± 1.8	86.9 ± 1.8
Mangrove wetland	9	14.8 ± 1.8	85.2 ± 1.8

Figure 3-28. An example of canopy cover photograph using fish-eye lens, 2 July 1998.

Canopy closures were greater than 80% in all the treatment cells. The largest closure in System 1 Cell1 (87.5 ± 1.4%) was slightly greater than in the least, System 1 Cell 2 (83.9 ± 2.9%). The significance of this difference by t-test for two samples of unequal variance is $p<0.27$. Canopy closures in System 1 (85.7%), System 2 (85.8%) and the mangrove receiving wetland in the vicinity of the discharge (85.2 ± 1.8%) were similar.

Chemical Characteristics and Uptake

Phosphorus

Data on total phosphorus from the two wetland systems are presented in Figure 3-29 and Figure 3-30. The influent concentrations and reduction of phosphorus in the wastewater varied seasonally in both systems, as they did for all other wastewater constituents as a result of large seasonal changes in numbers of residents and tourists in the buildings connected to the wetland units. System 1 had average discharge of 1.1 ± 0.2 mg/liter phosphorus, compared to the background levels in the cenote of 0.46 ± 0.17 mg/liter (Table 3-16). In wetland System 2 discharge water contained 2.7 ± 0.4 mg/liter P. Overall reduction in phosphorous between initial levels in the septic tank and discharge from wetland Cell 2 was greater in System 1 which averaged 84% while System 2 had a P reduction of 71% on average (Table 3-17)

Tests to determine the variability in analysis of total P at the University of Florida Water Reclamation Laboratory were conducted with the samples of 31 August 1997 and 27 September 1997. Results in Table 3-18 show that the largest standard error of the mean was less than 6% of the determination.

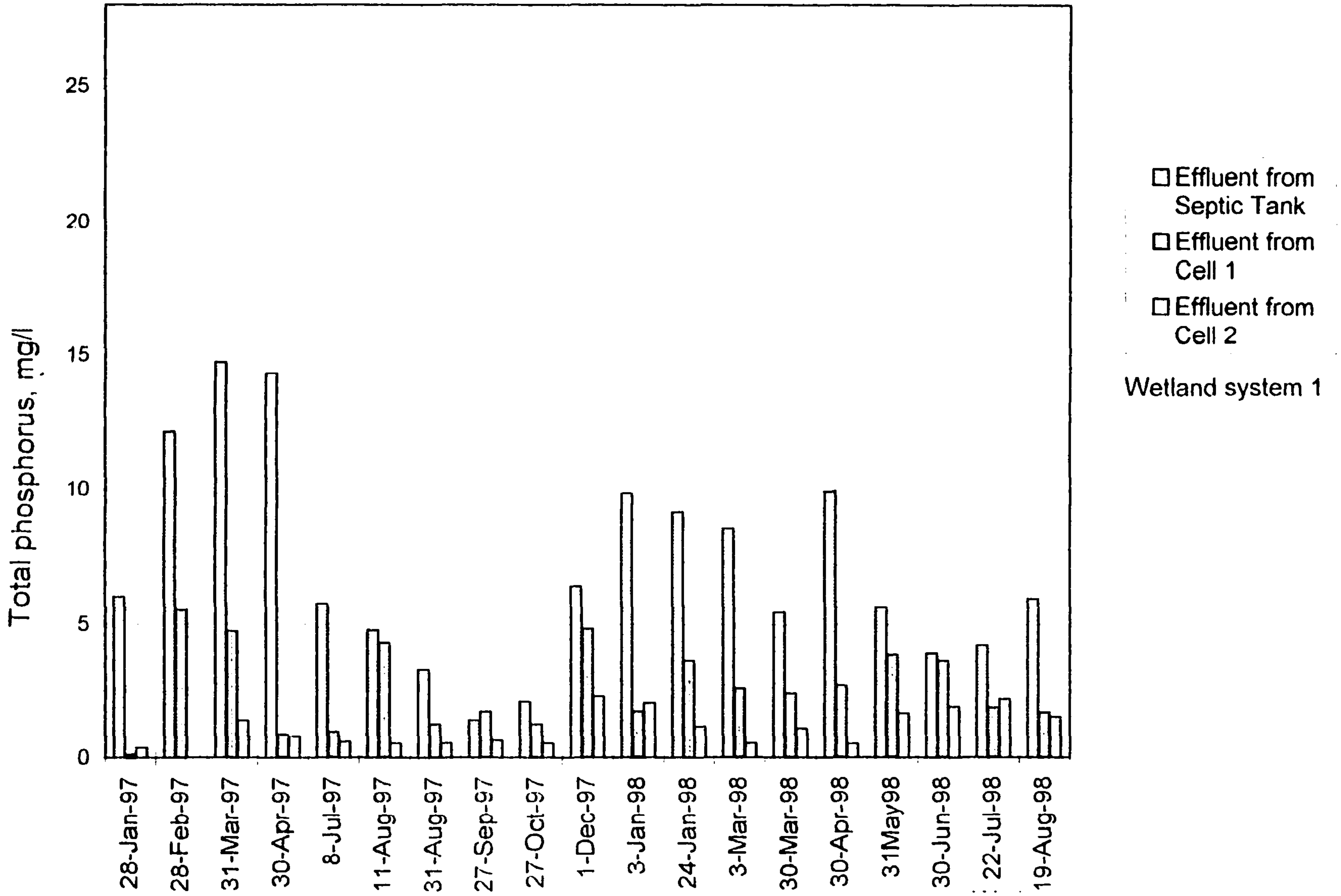


Figure 3-29 Total phosphorus (TP) analyses of water samples from wetland treatment system 1.

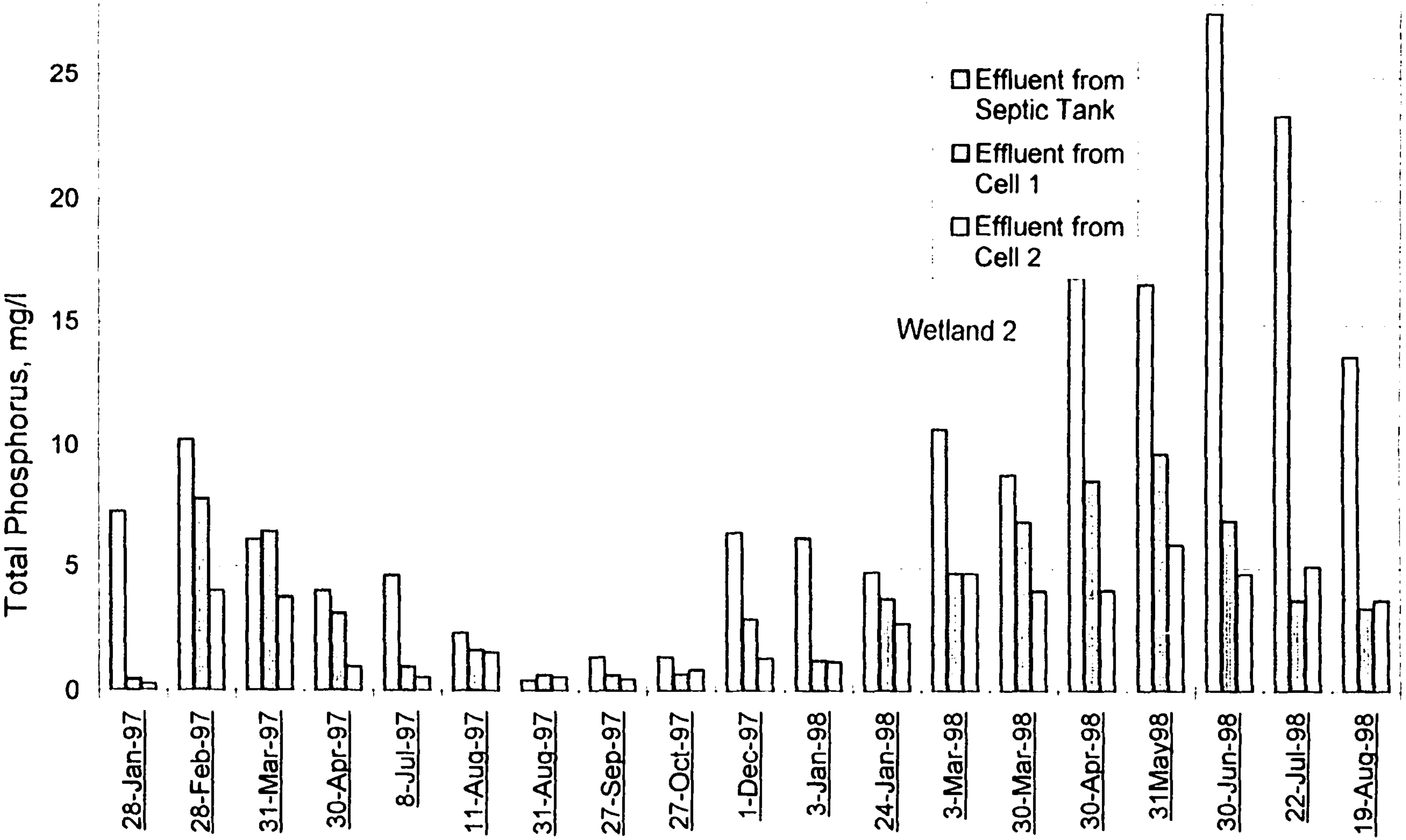


Figure 3-30 Total phosphorus (TP) analyses of water samples from wetland treatment system 2.

Table 3-16 Total phosphorus content of water samples from cenote (groundwater well) near wetland treatment systems.

Date	Total phosphorus mg/liter
28 Jan 97	0.52
28 Feb 97	0.37
31 Mar 97	0.33
30 Apr 97	0.17
8 Jul 97	0.75
11 Aug 97	0.5
31 Aug 97	0.35
27 Sep 97	0.9
27 Oct 97	0.4
1 Dec 97	0.3
Mean ± standard error	0.46 ± 0.07

Table 3-17 Total phosphorus in effluent from septic tank and discharge effluent from wetland treatment systems and percent reduction of phosphorus levels.

Date of Test	System 1 Septic tank mg P/liter	Discharge from System 1 mg P/liter	Percent Reduction	System 2 Septic tank mg P/liter	Discharge from System 2 mg P/liter	Percent Reduction
28 Jan 97	6.0	0.4	93.7	7.3	0.28	96.1
28 Feb 97	12.2	N/A	------	10.3	4	61.0
31 Mar 97	14.8	1.4	90.5	6.1	3.75	38.5
30 Apr 97	14.3	0.8	94.4	4.0	0.95	76.3
8 Jul 97	5.8	0.6	89.6	4.7	0.55	88.3
11 Aug 97	4.8	0.55	88.5	2.3	1.55	32.6
31 Aug 97	3.3	0.55	83.3	0.4	0.55	-37.5
27 Sep 97	1.4	0.65	53.6	1.4	0.45	66.7
27 Oct 97	2.1	0.55	73.8	1.4	0.85	37.0
1 Dec 97	6.4	2.3	64.1	6.4	1.3	79.7
3 Mar 98	8.55	0.54	93.7	10.75	4.77	55.6
30 Mar 98	5.45	1.07	80.4	8.84	4.05	54.2
30 Apr 98	9.93	0.52	94.8	17.43	4.07	76.6
31 May 98	5.64	1.67	70.4	16.59	5.96	64.1
30 June 98	3.93	1.91	51.4	27.59	4.72	82.9
22 Jul 98	4.22	2.2	47.9	23.39	5.1	78.2
19 Aug 98	5.95	1.52	74.5	13.71	3.71	72.9
Mean ± standard error	7.0 ± 1.0	1.1 ± 0.2		9.1 ± 1.7	2.7 ± 0.4	
Overall reduction			83.9			70.9

Table 3-18 Total phosphorus content of water samples from the treatment wetlands.

Wetland treatment area	Date of sample	Average result from 3 tests mg P/liter	Standard error of the mean mg P/liter
Wetland System 1, septic tank	31 August 1997	3.38	± 0.044
Cell 1	31 August 1997	1.35	± 0.05
Cell 2	31 August 1997	0.58	± 0.017
Wetland System 2, septic tank	31 August 1997	0.42	± 0.017
Cell 1	31 August 1997	0.58	± 0.033
Cell 2	31 August 1997	0.53	± 0.017
Wetland System 1, septic tank	27 September 1997	1.47	± 0.033
Cell 1	27 September 1997	1.72	± 0.017
Cell 2	27 September 1997	0.6	±0.029
Wetland System 2, septic tank	27 September 1997	1.42	± 0.033
Cell 1	27 September 1997	0.62	± 0.033
Cell 2	27 September 1997	0.45	0

Nitrogen

Figures 3-31 and 3-32 present results of total nitrogen water quality tests from the wetland systems. Final effluent reduction of initial nitrogen tended to become more efficient as the wetland systems developed. In the more heavily nutrient-loaded wetland System 2, which had final effluent N concentrations in the septic tank ranging from 38 mg N/liter (28 February 1997 to 6 mg N/liter (30 April 1997, 8 July 97 and 11 August 1997) to 1-2 mg/liter (31 August 1997 and 29 September 1997). There was considerable variability, septic tank N concentrations ranging from a high of 117 mg N/liter to a low of 6 mg N/liter (Table 3-19).

Ammonia (NH_3) analysis was conducted, when the plants were still very undeveloped, on 12 January 1997 (Table 3-19). Wetland System 1 had only a 30% reduction (from 17.2 mg N/liter in the septic tank to 12 mg N/liter in discharge water from Cell 2). Wetland System 2 had a 46% reduction (from 32 mg N/liter in the septic tank to 17.2 mg N/liter in wetland Cell 2). The rest of the nitrogen analyses were for total N.

The nearby cenote had an average concentration of 7.6 ± 1.8 mg N/liter from laboratory analyses conducted concurrently with those for the constructed wetlands (Table 3-20). Discharge water from Wetland System 1 had an average N concentration of 6.1 ± 1.1 mg N/liter, statistically not significantly different than the cenote. Discharge water from Wetland System 2 averaged 13.9 ± 3.5 mg N/liter.

During the course of the study, total nitrogen levels in the wetland system discharge effluent were reduced from initial septic tank levels by an average of 86.0% in wetland System 1 and 73.1% in wetland System 2 (Table 3-19).

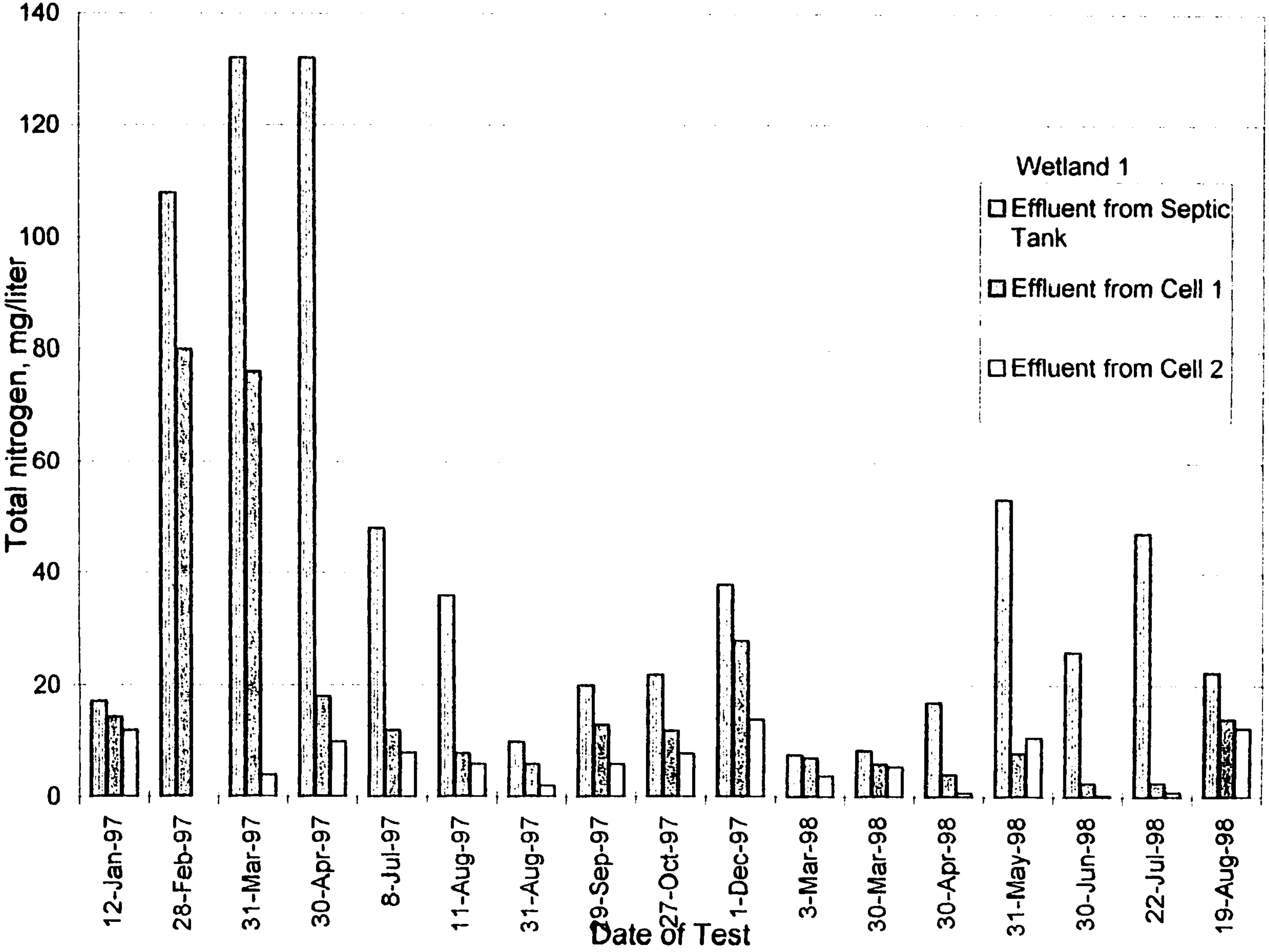


Figure 3-31 Total nitrogen (TN) analyses of water samples from wetland treatment system 1.

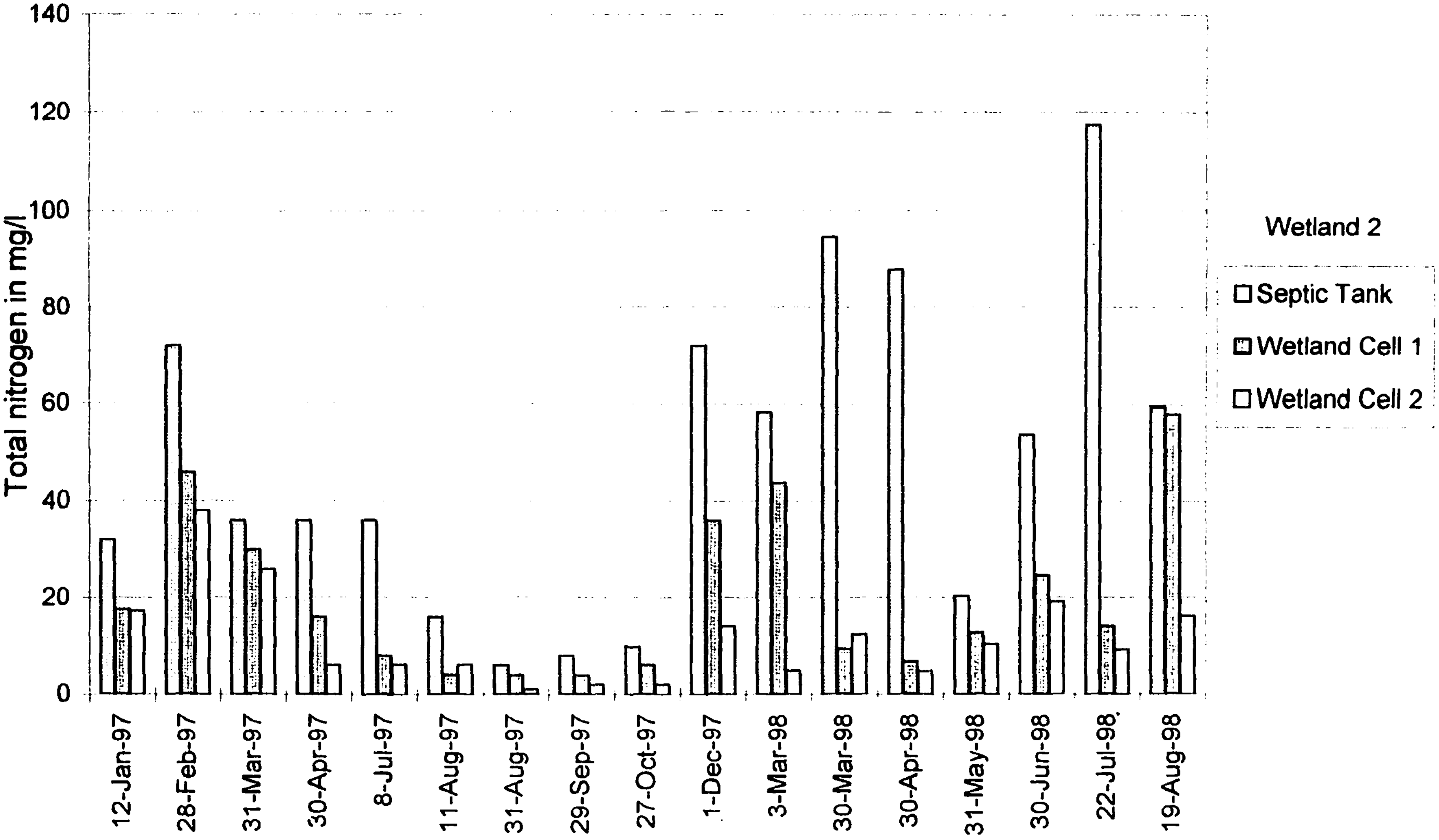


Figure 3-32 Total nitrogen (TN) analyses of water samples from wetland treatment system 2.

Table 3-19 Total nitrogen in effluent from septic tank and discharge effluent from wetland treatment systems and percent reduction of nitrogen levels.

Date of Test	System 1 Septic tank mg N/liter	Discharge from System 1 mg N/liter	Percent Reduction	System 2 Septic tank mg N/liter	Discharge from System 2 mg N/liter	Percent Reduction
28 Jan 97	17.2	12	30.2	32	17.2	46.3
28 Feb 97	108	N/A	----	72	38	47.2
31 Mar 97	132	4	97.0	36	26	27.8
30 Apr 97	132	10	92.4	36	6	83.3
8 Jul 97	48	8	83.3	36	6	83.3
11 Aug 97	36	6	83.3	16	6	62.5
31 Aug 97	10	2	80.0	6	1	83.3
27 Sep 97	20	6	70.0	8	2	75.0
27 Oct 97	22	8	63.6	10	2	80.0
1 Dec 97	38	14	63.2	72	14	80.6
3 Mar 98	7.6	3.82	49.7	58.4	4.86	91.7
30 Mar 98	8.44	5.51	34.7	94.45	12.5	86.8
30 Apr 98	16.99	0.7	95.9	87.8	4.82	94.5
31 May 98	53.36	10.74	79.8.	20.38	10.64	47.8
30 Jun 98	25.88	0.28	98.9	53.96	19.1	64.6
22 Jul 98	47.22	0.86	98.2	117.5	9.32	92.1
19 Aug 98	22.34	12.48	44.1	59.6	16.2	72.8
Mean +/- standard error	43.8 ± 9.9	6.1 ± 1.1		51.5 ± 9.0	13.9 ± 3.5	
Overall reduction			86.0			73.1

Table 3-20 Total nitrogen content of water samples from cenote (groundwater well) near wetland treatment systems.

Date	Total nitrogen mg N/liter
28 Jan 97	19.6
28 Feb 97	10
31 Mar 97	8
30 Apr 97	4
8 Jul 97	8
11 Aug 97	10
31 Aug 97	1
27 Sep 97	4
27 Oct 97	10
1 Dec 97	1
Mean ± standard error	7.6 ± 1.8

Biochemical oxygen demand

BOD-5 (biochemical oxygen demand, 5 day test) analyses are presented in Figure 3-33 and Figure 3-34. Reduction of BOD improved after the initial analyses in January 1997 shortly after the wetlands were first connected to sewage inputs

Table 3-21 presents septic tank effluent and final discharge levels of BOD from the wetlands. Wetland System 1 had average discharge concentration of 12.4 ± 1.7 mg BOD/liter over the course of study. Wetland System 2 had an average discharge of 23.4 ± 6.6 mg BOD/liter.

Wetland System 2, which received sewage from a higher percentage of its design population, showed higher levels of influent BOD, with septic tank analyses averaging 161.7 mg/l compared to 129 mg/l in System 1's septic tank effluent (Table 3-21). BOD reduction was comparable in the two wetlands, with wetland System 1 averaging a 87.7% reduction compared to 83.5% in wetland System 2.

Final effluent BOD from the wetland System 1 was around 40% lower than the nearby cenote whose BOD averaged 20.7 +/- 3.9 mg/liter (Table 3-22), while discharge effluent from wetland System 2 was about 15% higher.

Total suspended solids

Results of total suspended solids (TSS) analyses in effluents from septic tanks and treatment systems are presented in Table 3-23 and Table 3-24 and in Figure 3-35 and Figure 3-36.

During the study, TSS averaged around 70 mg/liter in the two septic tanks' effluent and was reduced 41% on average. Suspended solids were consistently higher in wetland

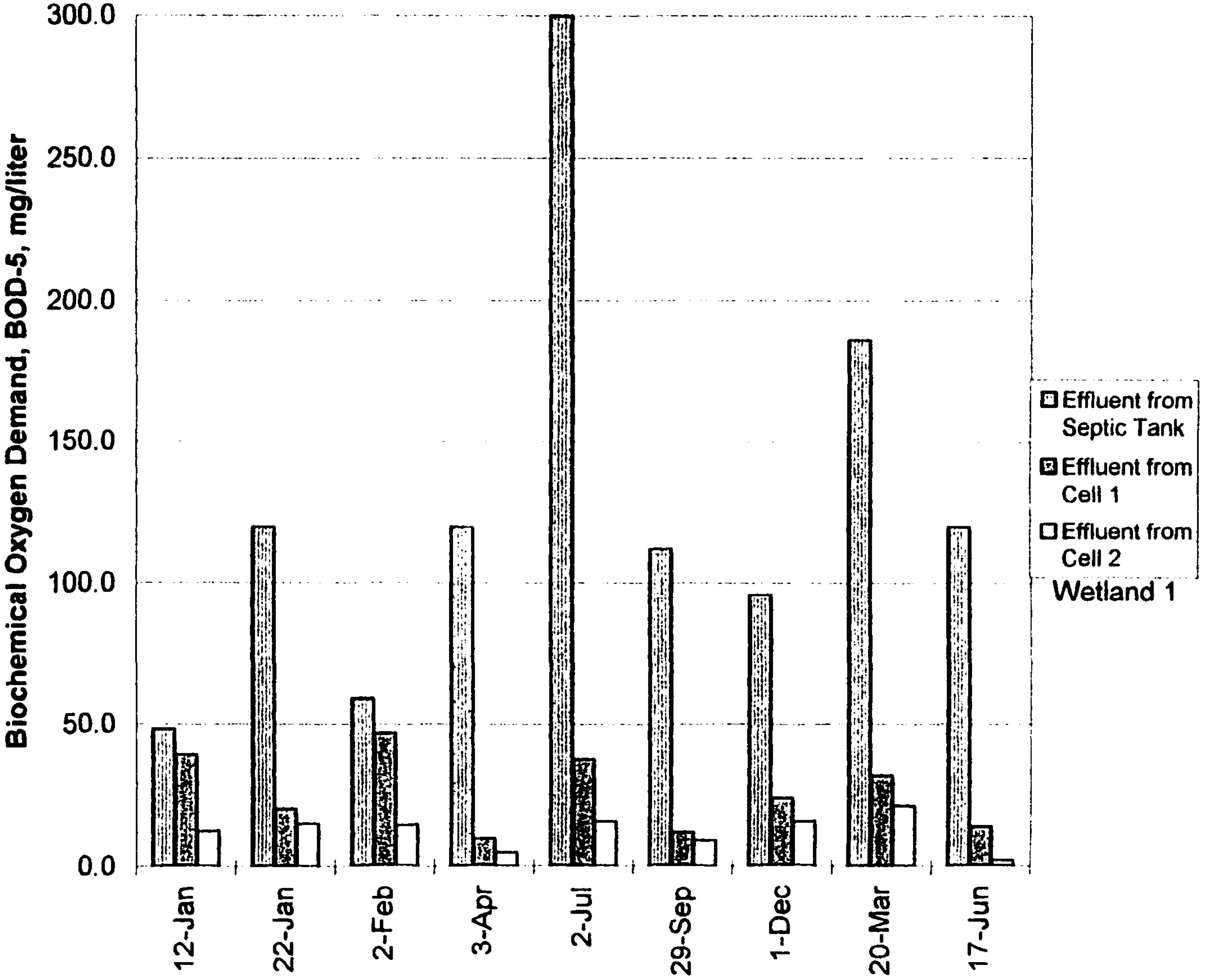


Figure 3-33 Biochemical oxygen demand (BOD_5) in wetland system 1 water samples.

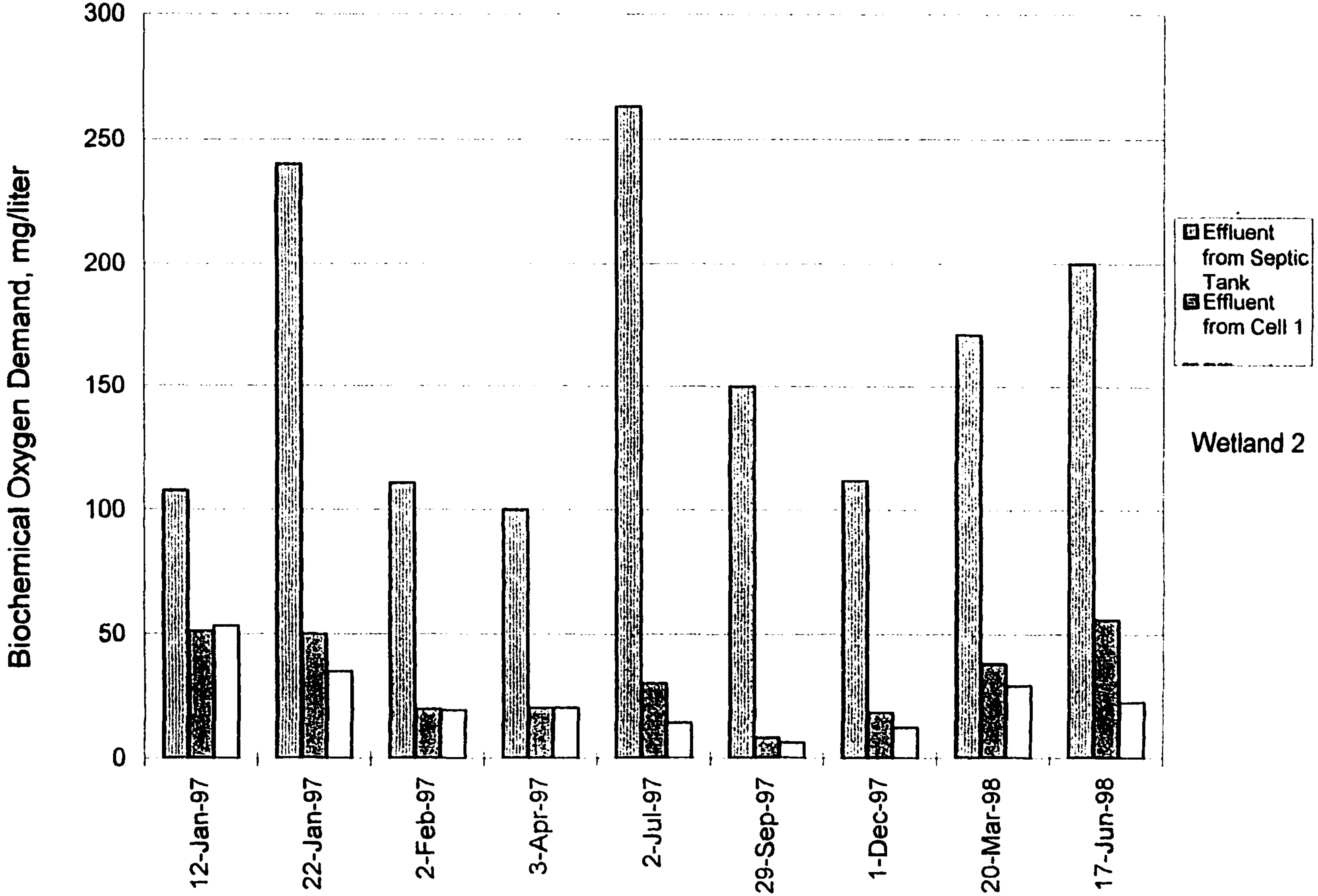


Figure 3-34 Biochemical oxygen demand (BOD_5) in wetland system 2 water samples.

Table 3-21 Biochemical oxygen demand (BOD-5) in effluent from septic tank and discharge effluent from wetland treatment systems and percent reduction.

Date of Test	System 1 Septic tank mg BOD/l	Discharge from System 1 mg BOD/l	Percent Reduction	System 2 Septic tank mg BOD/l	Discharge from System 2 mg BOD/l	Percent Reduction
12 Jan 97	48.3	12.6	73.9	108.3	53.4	50.7
22 Jan 97	120	15	87.5	240	35.0	85.4
2 Feb 97	59.1	14.7	75.1	111	18.9	83.0
3 Apr 97	120	5	95.8	100	20.0	80.0
2 Jul 97	300	16	94.7	263	14.0	94.7
29 Sep 97	112	9	92.0	150	6.0	96.0
1 Dec 97	96	16	83.3	112	12.0	89.3
20 Mar 98	186	21	88.7	171	29	83.0
17 Jun 98	120	2	98.3	161.7	23.4	83.5
Mean ± standard error	129 ± 34.1	12.4 ± 1.7		161.7 ± 27.8	22.8 ± 6.6	
Overall reduction			87.7			83.5

Table 3-22 Biochemical oxygen demand (BOD-5) content of water samples from cenote (groundwater well) near wetland treatment systems.

Date	BOD-5 mg BOD/liter
12 Jan 97	29.7
28 Jan 97	15.0
2 Feb 97	16.0
3 Apr 97	25.0
2 Jul 97	32.0
29 Sep 97	6.5
1 Dec 97	12.0
Mean ± standard error	20.7 ± 3.9

Table 3-23 Total suspended solids (TSS) concentrations and reduction in septic tank and discharge water from the Akumal wetland treatment systems.

Date of Test	System 1 Septic tank mg TSS/l	Discharge from System 1 mg TSS/l	Percent Reduction (Increase)	System 2 Septic tank mg TSS/l	Discharge from System 2 mg TSS/l	Percent Reduction (Increase)
12 Jan 97	17.2	12.0	30	32	17.4	46
28 Feb 97	57.6	29.2	49	59.2	33.2	44
31 Mar 97	46	27.2	41	45.2	36.8	19
30 Apr 97	56	41.6	26	34.4	27.2	21
8 Jul 97	31	18	42	37	9	76
11 Aug 97	42.5	22.5	47	33.5	25.5	24
27 Sep 97	8	16	(+100)	23.2	16	31
29 Oct 97	2	32.8	(+1540)	37.6	35.6	5
3 Jan 98	31.6	20	37	53.2	16	70
24 Jan 98	40	16.8	58	48	27.2	43
3 Mar 98	100	56	44	77	64	17
30 Mar 98	80	55	31	85	48	44
30 Apr 98	79	65	18	106	97	8
31 May 98	64	79	(+23)	227	66	71
30 Jun 98	65	58	11	238	60	75
22 Jul 98	62	76	(+23)	209	67	68
19 Aug 98	131	23	82	118	26	78
Mean ± standard error	53.7 ± 8.0	38.2 ± 5.4		86.1 ± 17.3	39.5 ± 5.8	
Overall reduction			29.0			54.1

Table 3-24 Total suspended solids (TSS) content of water samples from cenote (groundwater well) near wetland treatment systems.

Date	Total suspended solids mg TSS/liter
12 Jan 97	19.6
28 Feb 97	20.4
31 Mar 97	34.4
30 Apr 97	24.4
8 Jul 97	20
11 Aug 97	26.5
27 Sep 97	28.4
29 Oct 97	10.4
Mean ± standard error	23.0 ± 2.5

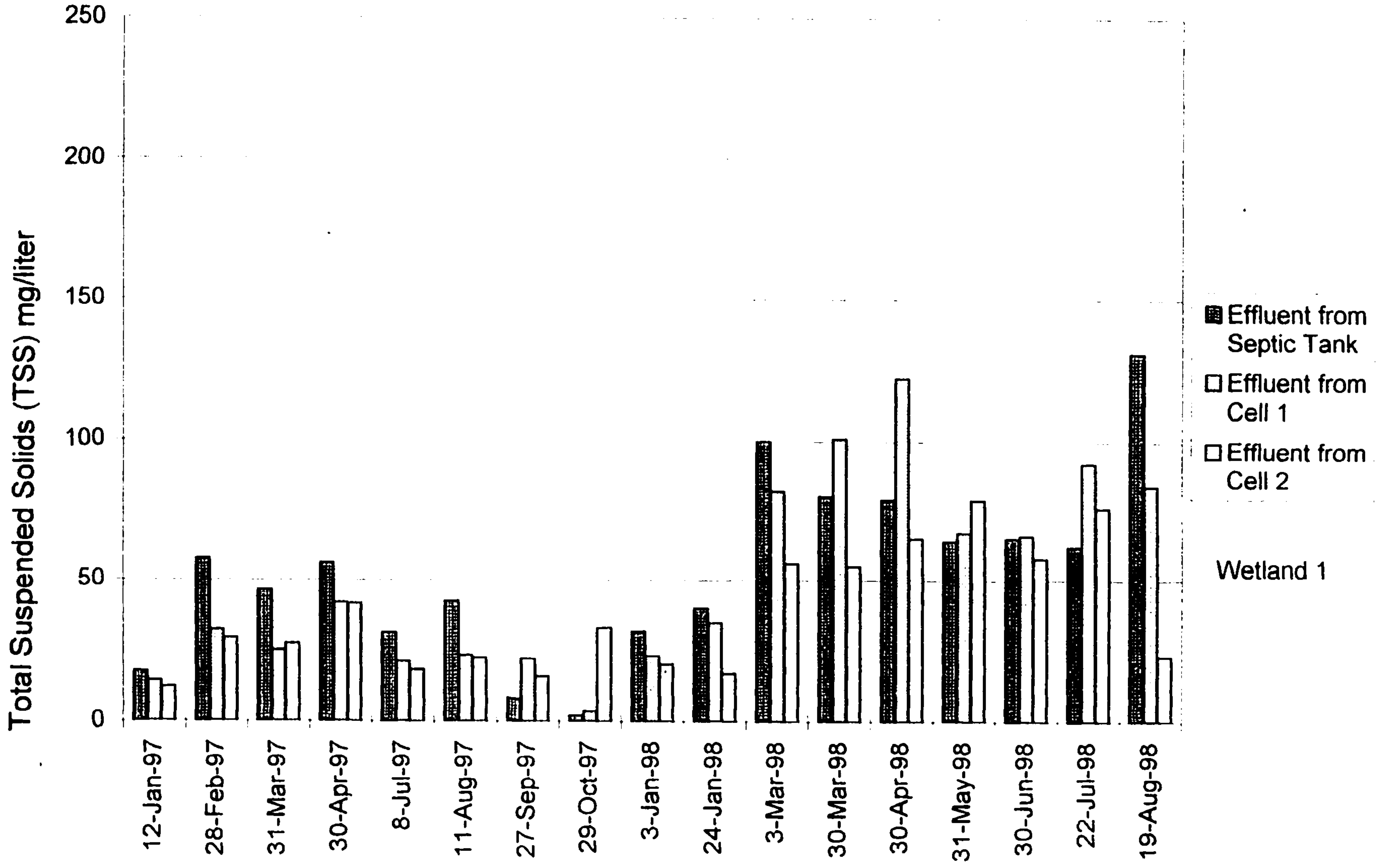


Figure 3-35 Total suspended solids (TSS) in water samples from wetland system 1.

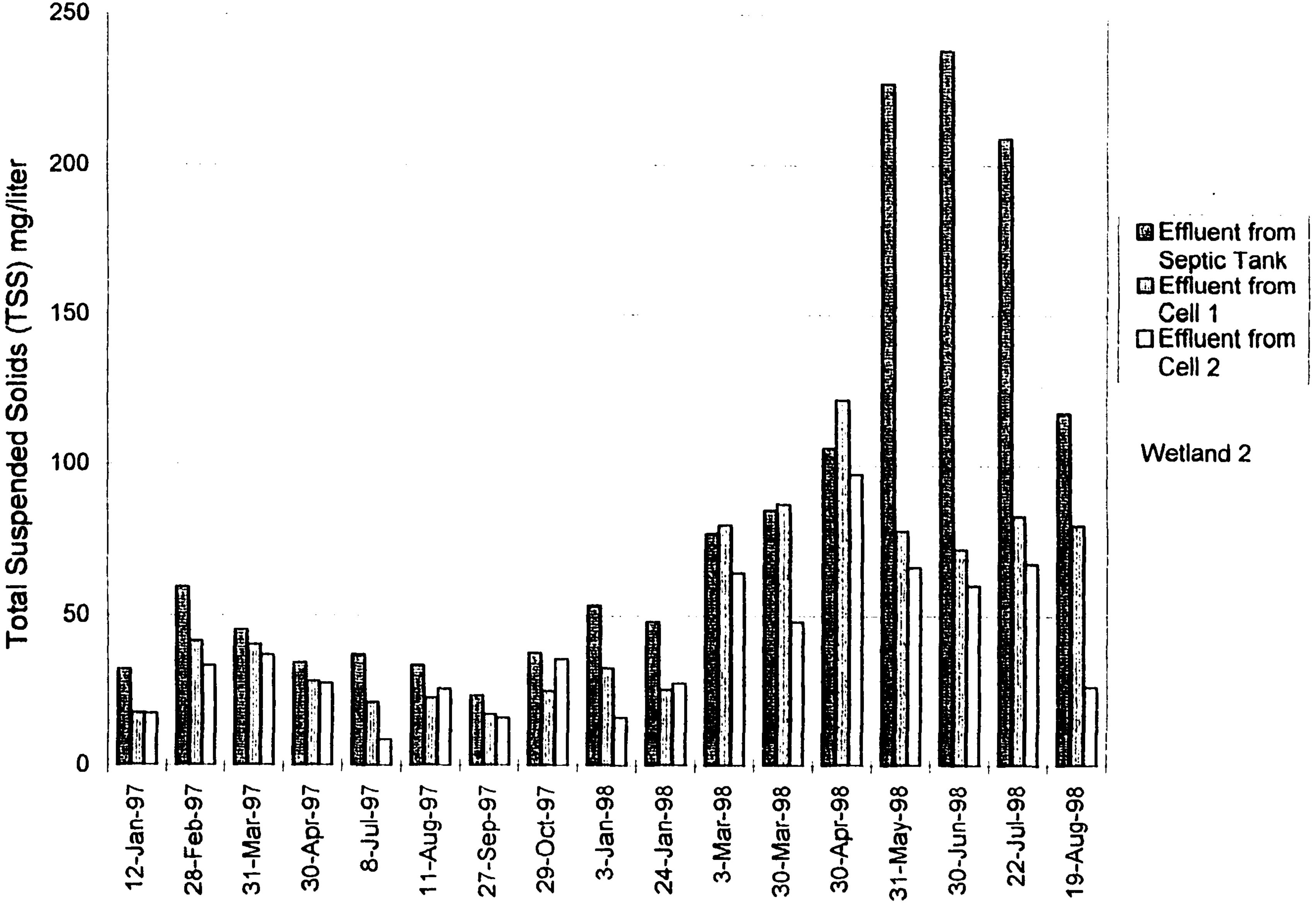


Figure 3-36 Total suspended solids (TSS) in water samples from wetland system 2.

System 2 and were reduced more (54%) than in System 1 (29% reduction). On average both systems reduced TSS to around 39 mg/liter but discharge varied from under 20 mg/l to over 90 mg/l (Table 3-23). TSS in the nearby cenote averaged 23.0 ± 2.5 mg/liter (Table 3-24).

TSS reduction varied widely, both on a percentage basis, and in concentrations in effluent water. For example, several times wetland System 1 showed higher discharge TSS than influent TSS, and suspended solid concentrations were higher during March – August 1998 than they had been earlier in the study (Table 3-23). This may reflect release of materials from biota or gravel of the wetlands themselves.

Alkalinity

Data on alkalinity is presented in Table 3-25. Alkalinity in the septic tanks was far lower (155 mg/l) than in either wetland System 1 or wetland System 2. These systems averaged 308 mg/l and 344 mg/l alkalinity respectively. Alkalinity in the cenote was lower than in the wetlands, averaging 252 mg/l.

Salinity

Salinity observations are presented in Table 3-26. Salinity decreased as the sewage effluent passed from septic tank through Cell1 and Cell 2 of the wetland systems. Average salinity was 4.1 ± 0.2 ppt (parts per thousand salt) in System 1 septic tank but decreased to 3.3 ± 0.3 ppt salt in Cell 2 effluent. In System 2 variability was greater, and salinity differences were not statistically significant. In System 2 septic tank effluent averaged 3.6 ± 0.2 ppt salt, while in Cell 2 it was 2.6 ± 0.8. Salinity in the cenote averaged 2.6 ± 0.2 ppt.

Table 3-25 Alkalinity in septic tanks, wetland systems and cenote.

Location	27 Sep 97	29 Oct 97	Average
Septic tank System 1	72	32	52
Wetland 1 Cell 1	248	414	331
Wetland 1 Cell 2	266	304	285
Septic tank System 2	214	300	257
Wetland 2 Cell 1	320	344	332
Wetland 2 Cell 2	360	350	355
Cenote	224	280	252

Table 3-26 Salinity in septic tanks, wetland system and cenote. Salinity expressed as parts per thousand salt (ppt).

Date	System 1 Septic tank ppt	Cell1 ppt	Cell 2 ppt	System 2 Septic tank ppt	Cell 1 Ppt	Cell 2 ppt	Cenote Ppt
12 Jan 97	3.5	2.5	2.5	4	3	2	2
2 Feb 97	4.5	4	3	3	1	0.5	2
28 Feb 97	4	4	4	4	5	5	3
14 Apr 97	4	3.5	3.5	3	2	2	3
21Dec 97	4.5	4	3.5	4	3	3.5	3
Mean ± std. error	4.1 ± 0.2	3.6 ± 0.3	3.3 ± 0.3	3.6 ± 0.2	2.8 ± 0.7	2.6 ± 0.8	2.6 ± 0.2

Reduction in Coliform Bacteria

Figure 3-37 and Figure 3-38 are graphs of coliform bacteria concentrations in the septic tanks and treatment cells of the wetlands. These data show levels of the bacteria were reduced by 99.87% on average after treatment in the wetlands (Table 3-27).

Final effluent coliform bacteria levels were fairly uniform for the two wetland systems, averaging 1580 ± 810 colonies (MPN)/100 ml in wetland System 1 and 2850 ± 1160 (MPN)/100 ml in wetland System 2 (Table 3-27).

Consistent reduction of fecal coliform bacteria was achieved as the wetlands developed, although the absolute numbers varied widely between tests. Even initial tests in January 1997 showed 99% reduction (wetland System 1) and 99.8% reduction (wetland System 2). Subsequent tests generally showed reductions of 99.9+% in both wetlands (Table 3-27).

Concentrations of coliform bacteria in the final discharge into the mangroves, although numerically lower, were not statistically significant from coliform bacteria concentrations in the cenote, which averaged 3,339 ± 2,267 (Table 3-28).

Phosphorus Uptake by Limestone

Ca/Mg analysis of limestone

Table 3-29 presents results of analysis of the Yucatan limestone gravel used in the wetland treatment units for calcium and magnesium content. Calcium constitutes 26.6 ± 0.6 percent of the gravel material and magnesium is 11.9 ± 0.2 percent by weight. If both occur primarily as carbonate minerals (e.g. calcite, Mg-calcite, aragonite, and dolomite), we can calculate their overall molecular weight as 100.1 for CaCO3 and 84.3 for $MgCO_3$. Thus,

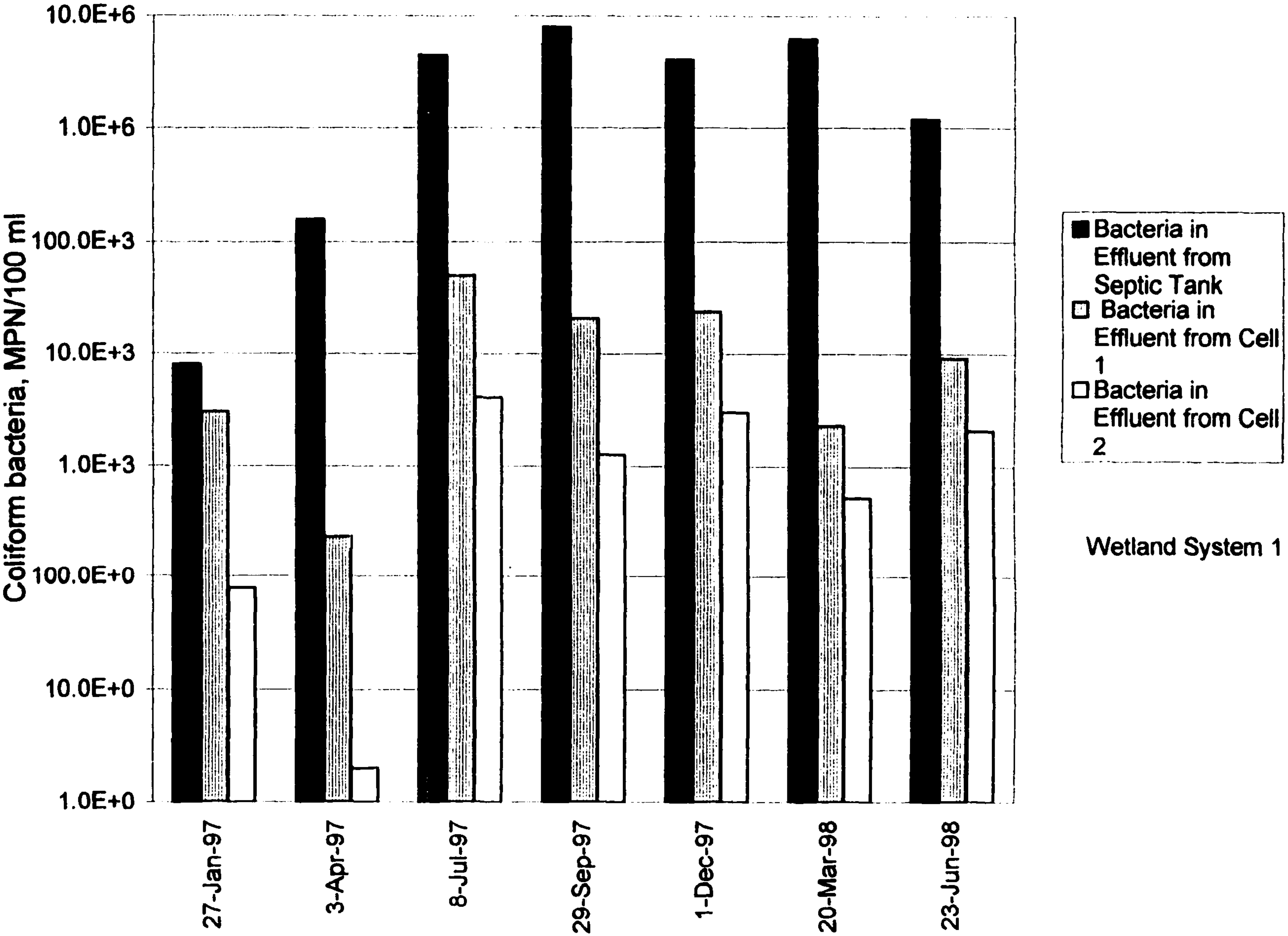


Figure 3-37 Fecal coliform bacteria in water samples from wetland system 1. Data plotted on log scale, and units are Most Probable Number (MPN) of bacterial colonies per 100 ml.

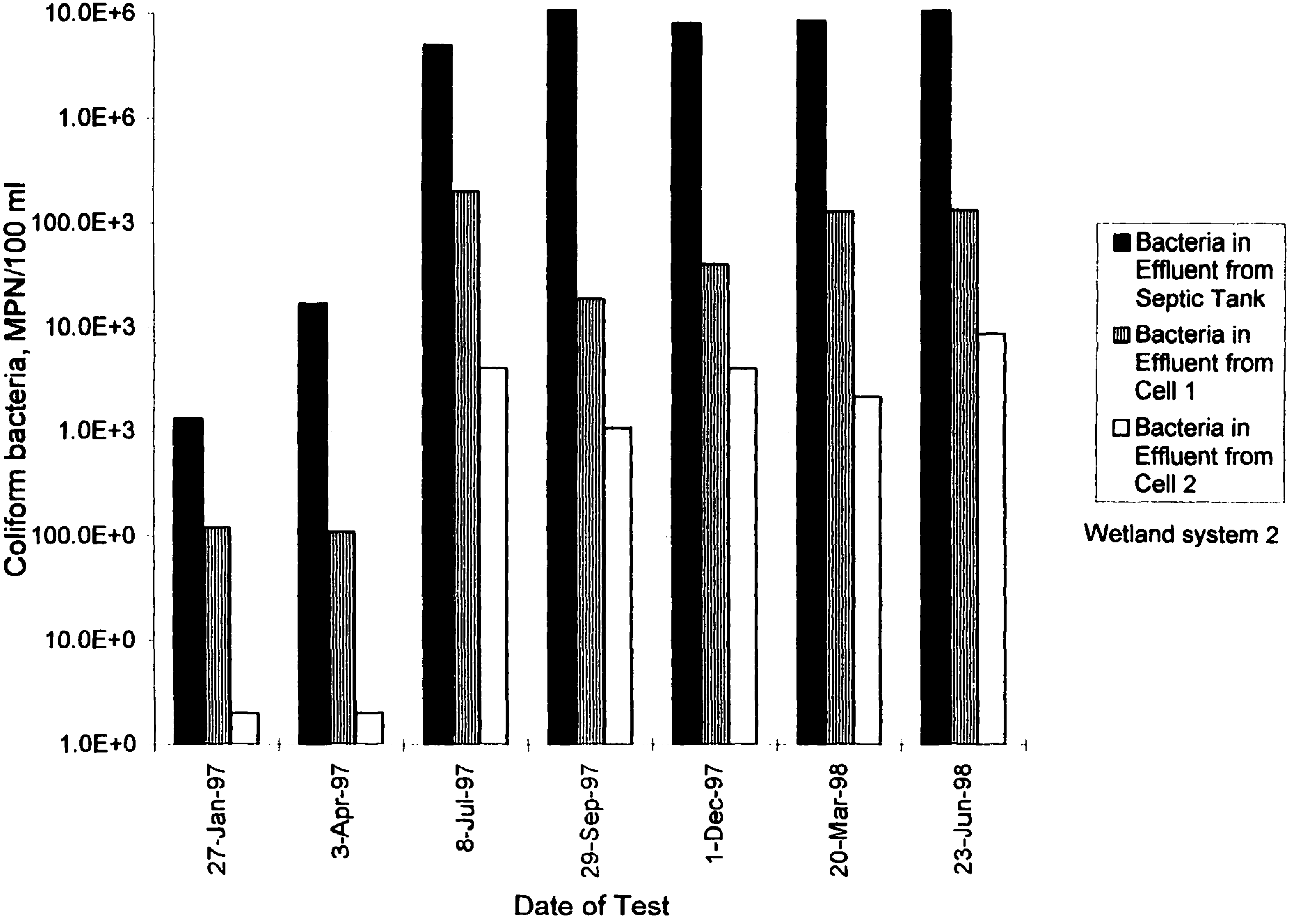


Figure 3-38 Fecal coliform in water samples from wetland system 2. Data plotted on log scale, and units are Most Probable Number (MPN) of bacterial colonies per 100 ml.

Table 3-27 Coliform bacteria concentrations in effluent from septic tank and discharge effluent from wetland treatment systems and percent reduction. Data is in units of most probable number of colonies per 100 ml (MPN/100 ml).

Date of Test	System 1 Septic tank MPN/100 ml	Discharge from System 1 MPN/100 ml	Percent Reduction	System 2 Septic tank MPN/100 ml	Discharge from System 2 MPN/100 ml	Percent Reduction
27 Jan 97	8,000	80	99.0	1,300	2	99.85
3 Apr 97	160,000	2	99.99	17,000	2	99.99
8 July 97	4,400,000	4,100	99.91	5,000,000	4,000	99.92
29 Sep 97	8,000,000	1,280	99.98	12,000,000	1,100	99.99
1 Dec 97	4,000,000	3,000	99.93	8,000,000	4,000	99.95
20 Mar 98	6,200,000	520	99.97	8,600,000	2,180	99.97
23 June 98	1,200,000	2,100	99.82	11,200,000	8,700	99.92
Mean +/- standard error	3,424,000 ± 1,167,000	1,580 ± 590		6,403,000 ± 1,861,000	2,850 ± 1,160	
Overall % reduction			99.80			99.94

Table 3-28 Coliform bacteria concentrations in water samples from cenote (groundwater well) near wetland treatment systems. Data is in units of MPN/100 ml (most probable number of colonies per 100 ml).

Date	Coliform bacteria MPN/100 ml
27 Jan 97	1,100
3 Apr 97	1,100
8 July 97	1014
29 Sep 97	10.140
Mean +/- standard error	3,339 ± 2,267

Table 3-29 Calcium/magnesium content of Yucatan limestone gravel as analyzed by inductive coupled plasma spectroscopy.

Sample	Percent calcium	Percent magnesium
1	25.6	12.5
2	26.3	12.1
3	28.2	11.7
4	25.4	12.1
5	27.7	11.2
Average ± standard error of the mean	26.64 ± 0.56	11.92 ± 0.22

carbonate minerals constitute over 95% of the material. This compares with published estimates, for example, of Pleistocene dune rocks of northeastern Quintana Roo being totally carbonate, dominated by aragonite with 20-40% mg-calcite and small amounts of calcite, and dolomite comprising 25-68% of supratidal sediments in lagoons studied near Akumal (Ward, 1975 cited in Weide, 1985).

Initial and uptake phosphorus levels

To determine the rate at which phosphorus was being absorbed by the limestone gravel, samples of 1/limestone gravel not exposed to the sewage 2/limestone above the sewage water level of the wetlands and 3/limestone below the water level and thus exposed to the sewage for eleven months of system operation were analyzed for inorganic phosphorus content (Table 3-30). These results indicate that phosphorus enrichment has averaged some 6 mg/kg (ppm) per year in the limestone exposed to sewage. Limestone prior to placement and limestone above the sewage level average 38.0 ± 2.9 mg/kg while limestone below the sewage level averaged 43.8 ± 1.7 mg/kg.

Limestone in the first treatment cells of both wetland systems were marginally higher in phosphorus content than the limestone of the second cells, but the results are not statistically significant. In System 1, first cell limestone totaled 43.5 ± 3.7 mg P/kg while in the second cell, phosphorus content totaled 39.9 ± 3.7 mg P/kg. In wetland System 2, first cell limestone totaled 48.1 ± 2.5 mg P/kg while that of the second cell was 43.6 ± 3.4 mg P/kg (Table 3-30).

Figure 3-39 presents the phosphorus starting value and uptake by limestone in the wetland systems during their first year of operation. Since limestone gravel averages 1350 kg/m3, and there are 25 m^3 of limestone in System 1 and 41m^3 in System 2, we can

Table 3-30 Inorganic phosphorus content of limestone samples.

Date collected	Description	# of samples	Mean phosphorus mg/kg	Standard error of the mean
Aug 96	Limestone gravel not used in wetlands	3	40.3	± 4.2
Dec 97	Limestone above the sewage line	4	36.3	± 4.35
Aug 96 + Dec 97	All limestone not exposed to sewage (total of above 2 categories)	7	38.0	± 2.9
Dec 97	All limestone exposed to sewage (composite of samples from all cells and systems)	20	43.75	±1.68
Dec 97	System 1, Cell 1 below sewage level	5	43.5	± 3.7
Dec 97	System 1, Cell 2 below sewage level	5	39.9	± 3.7
Dec 97	System 2, Cell 1 below sewage level	5	48.1	± 2.5
Dec 97	System 2, Cell 2 below sewage level	5	43.6	± 3.4

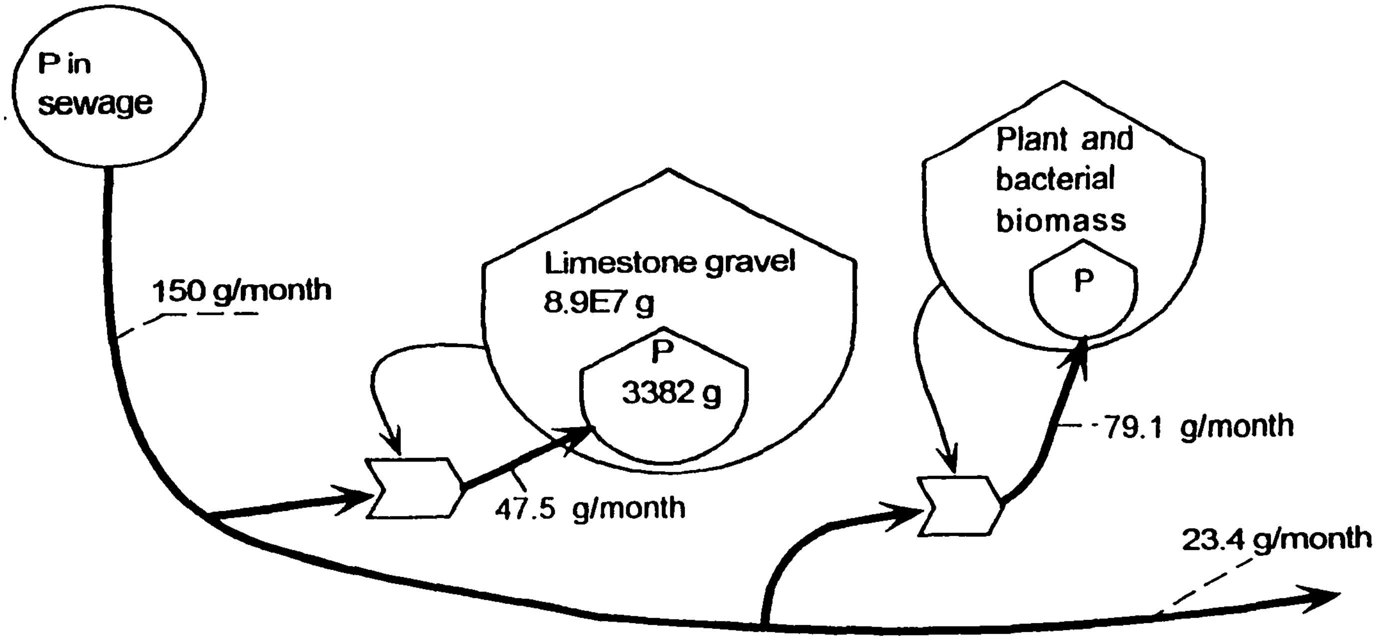


Figure 3-39 Estimates of monthly flows of phosphorus during first year of wetland treatment system operations (1997). Data from both wetland systems are combined.

calculate that System 1 limestone totaled 33,750 kg and System 2 limestone totaled 55,350 kg, for a combined weight of around 89,000 kg (8.9E7 g). Average enrichment in System 1 limestone was 3.8 mg P /kg. Enrichment in System 2 limestone averaged 7.8 mg P/kg, for a total uptake of 570 g P/yr, or 47.5 g P/month. This is equivalent to 40 kg P ha^{-1} yr^{-1} uptake by the limestone in the wetlands on an areal basis.

Phosphorus levels in influent water averaged 6.25 mg/l and was 1.3 mg/l in effluent water. So with 800 litters/day entering the system, phosphorus into the system was 150 g/month, and after ET losses, discharge was 600 litters/day, phosphorus in discharge water totaled 23.4 g/month. The unaccounted for phosphorus, totaling 79.1 g/month was likely taken up by bacterial and plant biomass.

Experiments on limestone P uptake

In Table 3-31 and Figure 3-40 the reduction in phosphorus is reported from laboratory experiments where phosphorus solutions were mixed with Yucatan limestone in bottles. After ten days, phosphorus was reduced 28-63% when initial conditions were 5.6-111 mg P/liter.

Field experiments where actual septic tank effluent was employed, showed 56.9% reduction with a starting concentration of 5.11 mg P/l. In samples where the ratio of limestone gravel and effluent were kept nearly equal (comparable to conditions in the wetland units) reduction of phosphorus increased to 85.6% after 10 days (Table 3-31).

Table 3-31. Results from experiments on limestone uptake of phosphorus.

Laboratory:

Sample number	Initial loading mg/l P	One day after loading mg/l P	Two days Mg/l P	Four days mg/l P	Six days mg/l P	Ten days mg/l P
2-1	5.6	4.35	4.35	4	3.65	3.19
2-2	5.6	4.35	4.23	4.12	3.42	2.9
2-3	5.6	4.23	4.29	3.71	3.31	2.67
Average	5.6	4.31± 0.04	4.29± 0.03	3.94±0.12	3.46± 0.1	2.92± 0.15
Percent Reduction		23.0	23.4	29.6	38.2	47.9
3-1	11.1	8.1	8.16	7.52	7.23	6.25
3-2	11.1	8.62	8.85	7.75	7.75	6.66
3-3	11.1	8.62	8.85	8.21	8.25	6.77
Average	11.1	8.45± 0.17	8.62± 0.23	7.83± 0.2	7.74± 0.29	6.56 ± 0.16
Percent Reduction		23.9	22.3	29.5	30.2	40.9
4-1	22.2	18.6	19.3	19.3	17.5	16.2
4-2	22.2	18.6	19.5	19.1	17.7	15.5
4-3	22.2	18.6	19.8	23.1	16.7	16.5
Average	22.2	18.6 ± 0.0	19.5± 0.15	20.5±1.3	17.3±0.32	16.0±0.31
Percent Reduction		16.3	12.1	7.7	22.0	27.7
5-1	55.6	46.9	56.8	46.4	33.4	29.8
5-2	55.6	52.1	53.7	50.0	63.0	37.6
5-3	55.6	53.7	45.4	53.7	35.0	33.9
Average	55.6	51.0±2.04	51.9±3.41	50.0±2.1	43.8 ±9.62	33.8±2.25

Sample number	Initial loading mg/l P	One day after loading mg/l P	Two days Mg/l P	Four days mg/l P	Six days mg/l P	Ten days mg/l P
6-1	111.1	106.2	91.6	103.0	79.6	37.7
6-2	111.1	101.1	108.7	101.8	83.4	42.7
6-3	111.1	101.8	97.3	85.9	77.6	42.7
Average	111.1	103.0±1.61	99.2±5.04	96.9±5.51	80.2±1.68	41.1±1.69
Percent Reduction		7.3	10.7	12.8	27.8	63.1

Field studies:

Sample number	Initial loading mg/l P	One day after loading mg/l P	Two days mg/l P	Four days mg/l P	Six days mg/l P	Ten days mg/l P	30 days mg/l P
7-1	5.11	3.3	2.65	3.1	2.1	1.55	0.85
7-2	5.11	3.9	3.75	3.6	3.3	2.8	1.95
7-3	5.11	4	4	3.55	3.15	2.25	1
avg	5.11	3.7± 0.2	3.47± 0.41	3.42± 0.16	2.85± 0.38	2.2±0.36	1.27± 0.34
Percent Reduction		27.3	32.2	33.1	44.2	56.9	75.2
7-4	5.11	1.45	0.8	0.95	0.75	0.85	0.45
7-5	5.11	3.05	1.1	0.7	0.85	0.7	0.45
7-6	5.11	1.15	1.1	0.95	0.75	0.65	0.4
avg	5.11	1.88± 0.59	1.0± 0.1	0.87± 0.08	0.78± 0.03	0.73± 0.06	0.43± 0.02
Percent reduction		63.1	80.4	83.0	84.7	85.6	91.5

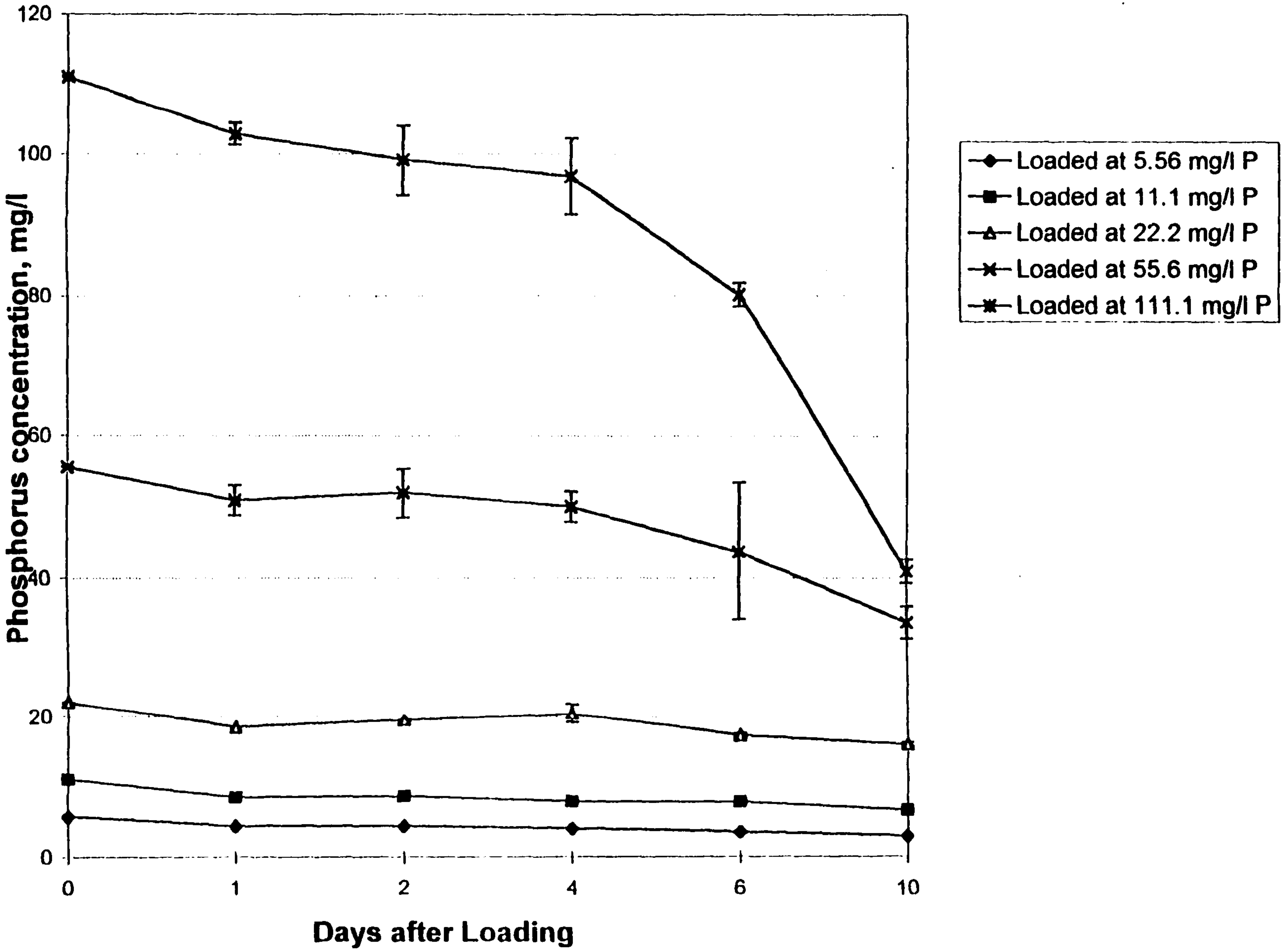


Figure 3-40 Graphs with results of experiments on limestone uptake of P

Water Budget

Estimates of the water budget of the wetland treatment systems are given in Table 3-32 and Table 3-33.

The results from the May 1997 study indicated that evapotranspiration rates are similar in wetland systems 1 and 2, since total evapotranspiration is 58% greater in System 2 than System 1, and System 2 is 60% larger. With the system loading occurring in May 1997, on average 0.05 m^3 (9 gal.) [equivalent to 0.99 mm over the area] was discharged per day from wetland System 1 and 0.33 m^3 (85 gal.) [4.1 mm] were discharged per day (Table 3-32).

The data from the December 1997 measurements show that overall evapotranspiration was only 50% that of the summertime for wetland System 1 and 39% in wetland System 2. Discharge in December 1997 was 0.16 m^3 (42 gal.) [3.2 mm] per day from wetland System 1 and 0.3 m^3 (79 gal) [3.7 mm] from wetland System 2 (Table 3-33).

Hydraulic loading of the wetland systems in May 1997 was equivalent to about 1.9 inches/week for wetland System 1, and 2.8 inches of wastewater/week for wetland System 2.

Under these conditions, ET losses were 90% of influent in wetland System 1 and 59% in wetland System 2. Estimated hydraulic residence time in May 1997 was about 28.8 days for wetland System 1 and 19.8 days for wetland System 2. The data indicate that hydraulic loading in December 1997 was similar in wetland System 1, but had dropped in wetland System 2 to 1.7 inches/week. Evapotranspiration losses were 41% in wetland System 1 and 38% in wetland System 2.

Economic Evaluation

Economic evaluations of the constructed wetlands vs. a "package plant" sewage treatment system built for a comparable number of residents in Akumal show that capital

Table 3-32 Daily water budget of wetland treatment systems, May 1997.

Date	Wetland system	Input from septic tank m^3/day (gal/day)	Evapotranspiration loss m^3/day(gal/day)	System discharge m^3/day (gal/day)
May 1997	System 1	0.34 (88)	0.29 (79)	0.05 (9.)
May 1997	System 2	0.79 (205)	0.46 (120)	0.33 (85)

See notes below Table 3-33.

Table 3-33 Daily water budget of wetland treatment systems, December 1997.

Date	Wetland system	Input from septic tank m^3/day (gal/day)	Evapotranspiration loss m^3/day(gal/day)	System discharge m^3/day (gal/day)
December 1997	System 1	0.3 (87)	0.14 (361.)	0.16 (42)
December 1997	System 2	0.48 (127)	0.18 (48)	0.3 (79)

Notes on Table 3-32 and Table 3-33

1. Water input from septic tanks

Effluent from the septic tanks was estimated from their volume and measured inflow after they were pumped out.

Wetland System 1 septic tank is 2.5 m wide x 4 m long x 1 m deep (to the discharge pipe), with a capacity of 10 m^3 (2600 gallons). Over the course of 9.5 days In May 1997, septic tank filled 0.32 m, or 3.2m^3 (832 gallons). This is a daily input of 0.34 m^3 (87.6 gallons).There were 3 people resident in buildings serviced by the septic tank, plus 3 people working in shops whose bathrooms are connected to the septic tank. These daytime workers are counted as 0.33 people, so a total of 4 people were serviced by the septic tank. Their daily wastewater production was 0.085 m^3 (22.1 gallons/day).

In December 1997, septic tank of wetland System 1 filled 0.28 m, so inflow was 2.8 m^3 (739 gallons) over the course of 9.4 days. This is a daily input of 0.3 m^3 (78.6 gal). There were 3.5 people using the system (computed as above), so daily wastewater production was 0.086 m^3 (22.5 gal) per person.

Table 3-33 continued

The wetland System 2 septic tank is 2.3 m wide x 4.5 m long x 1.15 m deep (to discharge pipe), a volume of 11.9 m^3 (3095 gallons). In 10 days of refill in May 1997, 7.87 m^3 (2046 gallons) of water entered the septic tank of wetland System 2. This is equivalent to 0.787m^3 or 204.6 gallons/day. During this period there were 7 people living in housing which the septic tank served. On average, wastewater production during this period was 29.2 gallons/person/day for wetland System 2.

In December 1997, this septic tank filled 4.51m^3 (1191 gal.) over 9.4 days so daily inflow was 0.48m^3 (127 gal.). With 5 people on average using the system, this equals a daily wastewater production of 0.096 m^3 (25.4 gal) per person per day.

2. System evapotranspiration

Evapotranspiration (ET) was estimated from decreases in standpipe water levels during periods without discharge, input from septic tank. Inputs from direct rain were measured and this addition was factored into calculations of system ET.

Porosity of limestone gravel in the wetlands was determined to be 35% through successive measuring of water required to fill a 20 liter bucket filled with the same grade of limestone used in the wetland. Since wetland System 1 is 50.6 m2 with a normal wastewater level of 0.55 m (with standpipe vertical) and a porosity of 0.35, total water capacity of wetland System 1 is 9.74 m^3 or 2,533 gallons. Wetland System 2 is 81.2 m^2, with wastewater depth of 55 cm, porosity 0.35, giving a total system capacity of 15.6 m^3 (4,064 gallons).

Standpipe water declines in May 1997 in wetland System 1 totaled 7.4 cm (0.074 m) over 4.5 days and in wetland System 2, standpipe water decline totaled 8.9 cm (0.089 m) over 5.5 days. Since there was no input into the wetlands during this period, and no discharge from standpipe overflow, this loss is equivalent to evapotranspiration in the system. Evapotranspiration in wetland System 1 was thus calculated to equal 1.31 m^3 (340.7 gallons) over 4.5 days, or 0.29 m^3 (75.7 gallons) per day. Evapotranspiration in wetland System 2 was 2.52 m^3 (657.6 gallons) over 5.5 days, or 0.46 m^3 (119.6 gallons/day) in May 1997. Standpipe water declines in December 1997 averaged 5.7 cm in wetland System 1 and 5.17 cm over 9.4 days in wetland System 2. There were three rains totaling 1.8 cm over this period. Total evapotranspiration in wetland System 1 was thus 1.29 m^3 (340.6 gal) over 9.4 days, or 0.137 m^3 (36.2 gal) per day. Evapotranspiration in wetland System 2 was 1.7 m^3 (449 gal) over 9.4 days or 0.18 m^3 (47.8 gal) per day.

3. Discharge of wastewater from the wetland treatment systems

Average discharge of wastewater from the wetland systems was estimated from the difference between hydraulic inputs to the system and evapotranspiration losses from the system from wetland System 2. The data from the December 1997 measurements show that

Table 3-33 continued

overall evapotranspiration was only 50% that of the summertime for wetland System 1 and 39% in wetland System 2. Discharge in December 1997 was 0.16 m^3 (42 gal.) [3.2 mm] per day from wetland System 1 and 0.3 m^3 (79 gal) [3.7 mm] from wetland System 2.

Hydraulic loading of the wetland systems in May, 1997 was equivalent to about 1.9 inches/week for wetland System 1, and 2.8 inches of wastewater/week for wetland System 2. Under these conditions, ET losses were 90% of influent in wetland System 1 and 59% in wetland System 2. Estimated hydraulic residence time in May, 1997 was about 28.8 days for wetland System 1 and 19.8 days for wetland System 2. The data indicate that hydraulic loading in December 1997 was similar in wetland System 1, but had dropped in wetland System 2 to 1.7 inches/week. Evapotranspiration losses were 41% in wetland System 1 and 38% in wetland System 2.

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}) (Table 3-34 and Table 3-35). The wetlands are also expected to last longer, as machinery, especially in tropical conditions, has a far shorter replacement time. So on an amortized basis, the costs per year are even more divergent: over $2000 for the package plant vs. $330 for the wetland (even if the wetland only lasts 20 years as was assumed).

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/vegetative action 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.

Emergy Evaluation

Emergy evaluations of the limestone constructed wetland system are calculated in Table 3-36 and summarized in Figure 3-41 a summary diagram of emergy flows in the wetlands. Wind is the largest environmental resource, but environmental inputs constitute a small flow (<1%) of total system emergy. Local materials, primarily Yucatan limestone, contribute some 2% of emergy used in the wetland treatment process and are the predominant source of system emergy use apart from the wastewater. The emergy contained in service and imported goods are less than 1% of total emergy.

Emergy from local materials (Yucatan limestone, vegetation, mulch) constitute over 60% of total emergy used for construction of the wetland treatment units. Operational costs

Table 3-34 Purchased materials and services used in construction of wetland systems, Akumal, Mexico. Costs are expressed in Mexican pesos (1996) and converted to U.S. dollars at the rate of 7.8 peso/$, which was the exchange rate in 1996 when systems were built.

Item	Quantity	Cost per unit	Cost (pesos)	Cost (U.S. $)
Native Materials:				
Limestone gravel	72 m3	1460 peso/12 m3	8760	$1123
Limestone rock	12 m3	1460 peso/12 m3	1460	$ 187
Sand	21 m3	800 peso / 7 m3	2400	$ 308
Plants	327	variable, some free	2200	$ 282
Imported Materials:				
Cement	105 50-kg bags	50 peso / bag	5250	$ 673
Lime	40 25-kg bags	15 peso / bag	600	$ 77
Steel rebar	15 x 12-m	48 pesos / piece	720	$ 92
PVC pipe	8 x 6-m, 10 cm dia.	550 peso / piece	4400	$ 564
Steel wire mesh	131 m2, 3 mm dia.	----	750	$ 96
Labor and Services:				
Backhoe rental	20 m3 excavated	450 peso / m3	9000	$1154
Jackhammer rental	25 m3 excavated	450 peso / m3	11250	$1442
Construction laborers	3 people x 15 days	70 peso / day	3150	$ 404
Plumber, labor	1 person x 1 week	1500 peso / week	1500	$ 192
Fuel and Power:				
Gasoline	60 liters	8 peso / liter	480	$ 62
Total Construction Cost			51,920	$6,656
Maintenance costs:				
Labor and Services:				
Labor	104 hours/yr	70 pesos/8 hrs	910	$117
Annual Maintenance Cost			910	$117

Table 3-35 Purchased materials and services used in construction and annual maintenance of package plant sewage treatment system, Akumal, Mexico. Costs are expressed in Mexican pesos (1996) and converted to U.S. dollars at the rate of 7.8 peso/$, which was the exchange rate in 1996 when system was built.

Item	Quantity	Cost per unit	Cost (pesos)	Cost (U.S. $)
<u>Native Materials:</u>				
Sand	7 m3	800 peso / 7 m3	800	$102.30
<u>Imported Materials:</u>				
Concrete blocks	125 blocks	2.9 peso	362	$46.50
Cement	35 50-kg bags	50 peso / bag	1,750	$224.40
Rebar Steel	7.5 pcs x 12 m	48 pesos	360	$46
PVC Pipe	32 x 6m	550 pesos	17,600	$2256
Jet system	includes blowers, grinders, motors		70,200	$9000
<u>Labor and Services:</u>				
Construction labor	80 people/days	70 pesos	5,600	$718
Excavation of injection well	includes steel pipe liner		23,400	$3000
<u>Fuel and Power:</u>				
Gasoline	30 l	8 pesos	240	$31
Total - Construction Cost			120,312	$15,425
Maintenance costs:				
<u>Imported materials</u>				
Chlorine	10 kg	40 pesos	400	$51.30
<u>Labor and Services:</u>				
Labor	150 hrs/yr	50 pesos	7500	$961.50
<u>Fuel and Power:</u>				
Electricity	250 kWh/month	79 pesos	948	$121.50
Annual Maintenance Costs			8,848	$1,134

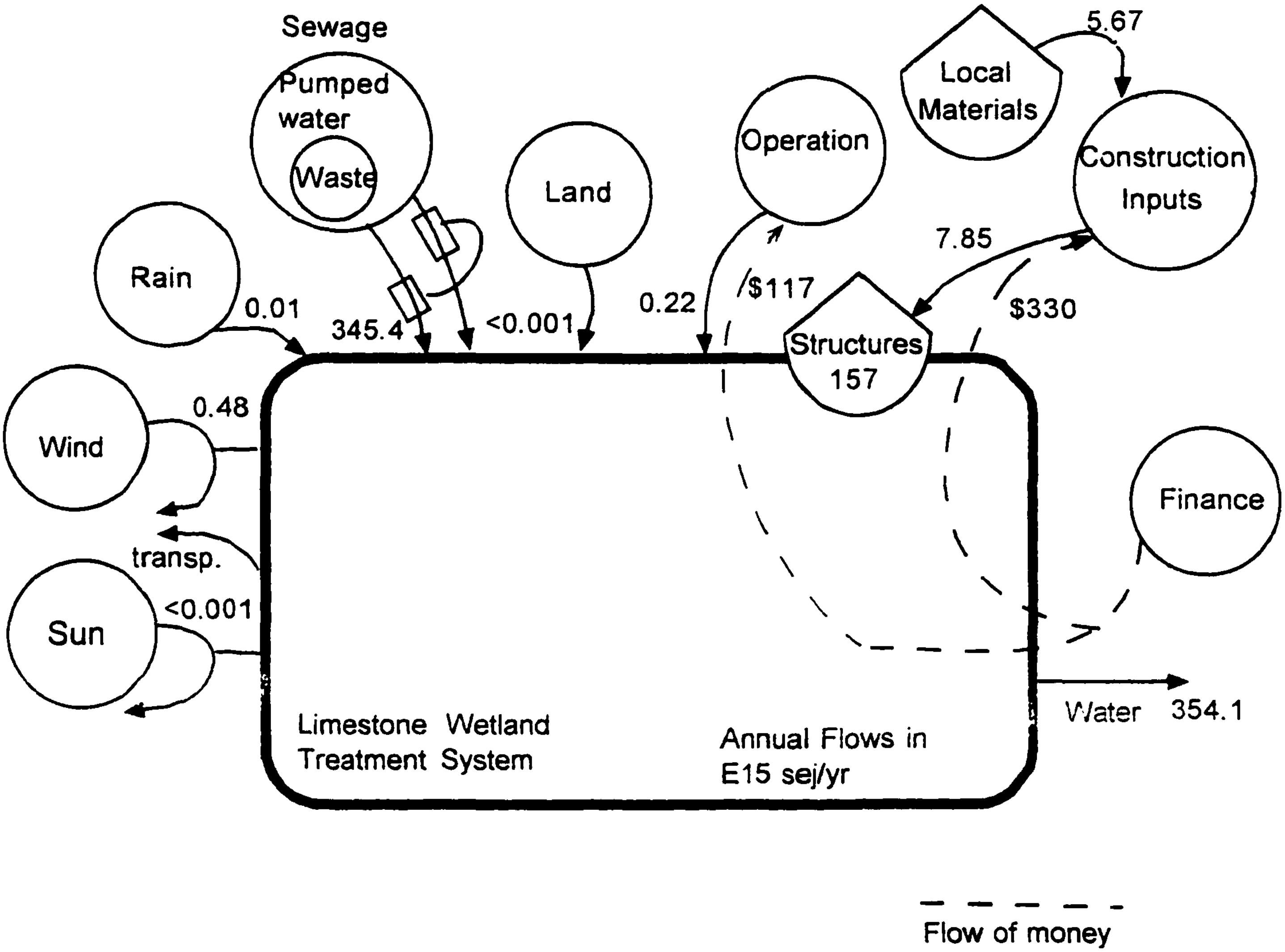


Figure 3-41 Diagram of emergy and money flows in wetland treatment systems, Akumal, Mexico. Units of diagram are E15 sej/yr.

Table 3-36 Emergy analysis of the constructed limestone sewage 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	
4	Wind	7.4E11 J/yr	663 sej/J	0.49	
5	Land	1.3 E8 J/yr	2.9 E4	<0.001	
Total (renewable resources)				0.48	0.35
CONSTRUCTION INPUTS	(divided by 20 years)				
Local materials:					
6	Gravel, limestone	4.9E6 g/yr	1.0 E9 sej/g	4.9	3.577
7	Rock, limestone	7.35E5 g/yr	1.0 E9 sej/g	0.74	0.54
8	Vegetation	$14.1/yr	1.9 E12 sej/$	0.03	0.0058
9	Mulch	4.5 E3 g/yr	2.75 E8 sej/g	<0.001	0.00007
Subtotal (local construction inputs)	items 6-9			5.67	4.14
Imported goods and services					
10	Cement	0.3 ton/yr	6.4 E13 sej/ton	0.02	0.0015
11	Lime	5E4 g/yr	1.0E9 sej/g	0.05	<0.001
12	Concrete block	0.5 ton/yr	6.4 E13 sej/ton	0.03	0.0022
13	Sand	1.48E6 g/yr	1.0 E9 sej/g	1.48	1.08
14	Rebar steel	15 lbs/yr	8.9 E11 sej/lb	0.003	0.0022
15	PVC pipe	5.6E3 g/yr	9.26E7 sej/g	<0.001	<0.001
16	Wire mesh	12.5 lb/yr	8.9 E11 sej/lb	0.001	<0.001
17	Gasoline	1.2 E8 J/yr	6.6E4 sej/J	0.008	0.0058
18	Rental of backhoe	$57.7/yr	1.9E12 sej/$	0.11	0.08
19	Jackhammer rental	$72.1 /yr	1.9E12 sej/$	0.14	0.1
20	General labor	2.4 E7 J/yr	8.1 E4 sej/J	0.002	<0.001
21	Plumber	$9.6/yr	1.9 E12 sej/$	0.02	0.01
22	Payment for Goods	$169/yr	1.9E12 sej/$	0.32	0.23

Note	Item	Raw Units	Transformity Sej/unit	Solar Emergy E15 sej/yr	EmDollars (Thousands)
Subtotal imported goods and services	Items 10-22			2.18	1.59
Total inputs for construction				7.85	5.73
HUMAN WASTE					
23	Raw sewage	3.94 E5 gallons/yr	8.767 E11 sej/gallon	345.4	252.13
OPERATION					
24	Maintenance	$117/yr	1.9 E12 sej/$	0.22	0.16
Total emergy				354.1	258.5
OUTPUT (yield)					
25	Treated wastewater	5.17 E10 J/yr	6.84 E6 sej/J	354.1	258.5

* Column 6 (EmDollars) based on 1.37E12 sej/$, U.S. dollar/emergy ratio for 1996 (Odum, 1996)

Notes:

1. SOLAR ENERGY

Land area: 131.8 m2
Insolation: 1.8 E2 Kcal/cm2/yr (World Energy Data Sheet)
Albedo: 0.30

Energy (J) = (area) (avg insolation) (albedo)
= (131.8m2) (1.8E2Kcal/cm2/yr) (E4 cm2/m2) (0.3)
= 7.12 E7

2. RAIN, CHEMICAL POTENTIAL ENERGY
Land area = 131.8 m2
Rain = 9.44E-1 m/yr (IAM, U of Ga., 1988)
ET = .9 (Lessing, 1975)
Energy (J) = (area) (ET) (rain density) (Gibbs #)

=131.8m2 * (.9) * (1000 kg/m3) * (4.94 E3 J/kg)
=5.85E8 J/yr

Table 3-36 continued

3. RAIN, GEOPOTENTIAL

Area = 131.8 m2
Rainfall = 1.050 (Lessing, 1975)
Avg Elev = 2 m
Runoff rate = .1 (1 - ET)

Energy (J) = (area) * (%runoff) * (rain density) * (avg elevation) * (gravity)
= 131.8m2 * 0.1 * 1000 kg/m3 * 2 * 9.8 m/s2
= 2.58E5

4. WIND

Based on method given in Odum, 1996, p. 294, with values of eddy diffusion and vertical gradient from Tampa, Florida and using wind of 10 m height
(10 m)(I. 23 kg/cu m) (2. 8 cu m/m/sec) (3.154E7 sec/yr) (2.3 m/sec/m)(130 sq m)
= 7.4 E11 J/yr
Transformity for wind from Odum, 1996 p. 186
All of purchased goods and services (except annual maintenance) are divided by 20 (anticipated life of wetland) to give emergy/yr

5. LAND (EARTH CYCLE)

Transformity = 2.9E4 sej/J (Odum, 1996, p. 186)
Energy = (land area) (heat flow per area)
heat flows for old stable areas is 1E6 J/m2/yr (Odum, 1996, p. 296)
Energy = 130 m2 * 1E6 J/m2 = 1.3 E8 J/m2

6. GRAVEL, LIMESTONE

72 m3 at cost of 1460 pesos/12 m3 = 8760 pesos / (7.8 peso/U.S.$) = $1123
Transformity of limestone from Odum (1996, p. 310), emergy/gram: 1E9 sej/g
Weight of limestone from Limestone Products, Newberry, FL (pers. comm.): 3000 lbs/m3
72 m3 * 3000 lbs/m3 * 454 g/lb =9.8E7 g / 20 yrs = 4.9E6 g
emergy in limestone gravel: 4.9E6 * 1E9 = 4.9E15

7. ROCK, LIMESTONE:

12 m3 of 5-10 cm rock at 1460 pesos/7.8 peso/$ = $187
Transformity of limestone from Odum (1996, p. 310) emergy/gram: 1E9 sej/g
Weight of limestone, 5-10 cm. rock, from Limestone Products, Newberry, FL (pers. comm.): 2700 lbs/m3
12 m3 * 2700 lbs/m3 * 454 g/lb =1.47E7 g / 20 yrs = 7.35 E5 g

Table 3-36 continued
emergy in limestone gravel: 7.35E5 * 1E9 = 7.35E14

8. VEGETATION

approx. 2.5 plants per m2 planted, or 325 plants total; purchased plants for total of 2200 peso * $/7.8 peso = $282 /20 yrs = $14.1/yr * 5.2E12 sej/$ (emergy/dollar ratio from this study, see Table 3-64) = 7.33 E13 sej

9. MULCH

2.5 cm of sawdust and woodchip mulch (local and free) over 131 m2 = 3.28 m3
transformity based on that for pulp wood 2.75E8 sej/g (Christensen, 1984)
est. wt of mulch: 200 lbs * 454 g/lb = 9.1E4g / 20 yrs = 4.5E3 g/yr
4.5E3 * 2.75E8 = 1.2E12

10. CEMENT (LOCAL MANUFACTURE):

105 bags @ 50 kg/bag = 5250 kg; price 50 peso/bag * 105 = 5250 peso
5250 peso * $/7.8 peso = $673
Transformity of concrete from Brown and McClanahan (1992, p. 27): 7E7 sej/g * 454 g/lb * 2000 lb/ton = 6.356E13 sej/ton
Concrete in wetland in cu yds: perimeter = 70 yds x 4"(.11 yd) = 7.8 cu yd + bottom: 145 yd2 * 4" (0.11 yd) = 16 cu yd;
23.8 cu yd * 500 lb/cu yd (est. from concrete company) * ton/2000 lbs = 5.95 tons concrete
5.95 tons / 20 yr lifetime = 0.3 tons/yr

11. LIME (LOCAL):

40 bags @ 25 kg/bag = 1000 kg; price 15 pesos/bag * 40 bags = 600 peso * $/7.8 peso = $77
1000 kg/20 yr = 50 kg/yr
using same transformity as for limestone: 1E9 sej/g * 50 kg * 1000 g/kg = 1E13 sej

12. CONCRETE BLOCK (LOCAL)

250 blocks (40 cm x 20 cm x 15 cm) @ 2.9 peso/block = 725 peso * $/7.8 peso = $93

using transformity of concrete from Brown and McClanahan (1992, p. 27): 7E7 sej/g * 454 g/lb * 2000 lb/ton = 6.356E13 sej/ton
est. wt of each concrete block = 20 lbs, total wt 20,000 lb * ton/2000 lb = 10 ton / 20 yrs = .5 ton/yr
.5 ton * 6.356E13 sej/ton = 3.2E13 sej

Table 3-36 continued

13. SAND (LOCAL)

21 m3 for 2400 peso total; 2400 peso * \$/7.8 peso = \$308
est. wt of sand from Florida Rock Mines, Grandin, FL plant (pers. comm.): 3100 lbs/m3
transformity of sand using Odum (1996, p. 310) for other Earth products: 1E9 sej/g
21m3 * 3100 lbs/m3 * 454 g/lb = 2.96E7 g /20 yrs = 1.48E6 g
1.48E6 g * 1E9 sej/g = 1.48E15 sej

14. REBAR STEEL

15 pcs, 12 m length = 180 m; price 48 pesos/pc * 15 = 720 peso * \$/7.8 = \$92
transformity of steel and iron products from Odum (1996, p. 193): 1.78E15 sej/ton * ton/2000 lb = 8.9E11sej/lb
est. wt of rebar: 15 pcs * 20 lb/piece = 300 lbs / 20 yr lifetime = 15 lbs/yr
15 lb * 8.9E11 = 1.34E13 sej/yr

15. PVC PIPE

transformity for plastic from Brown et al, 1992, p. 27: 9.26E7 sej/g
weight of PVC pipe (est.) 14 kg / 6 m piece * 8 pc = 112 kg * 1000 g/kg = 1.12E5 /20 yr = 5.6E3 g/yr
5.6E3 g/yr * 9.26E7 sej/g = 5.2 E11 sej

16. WIRE MESH:
3 mm diameter, 131 m2; total price = 750 pesos * \$/7.8 = \$96
transformity of steel and iron products from Odum (1996, p. 193): 1.78E15 sej/ton * ton/2000 lb = 8.9E11 sej/lb
est. wt of wire mesh: 250 lbs / 20 yr lifetime = 12.5 lbs/yr
12.5 lb * 8.9E11 = 1.34E13 sej/yr

17. GASOLINE

gasoline for concrete mixer: 60 liter @ 8 peso/liter (est.) = 480 pesos * \$/7.8 peso = \$62

Transformity for motor fuel from Odum (1996, p. 308): 6.6E4 sej/J
60 liter = 15 gal; bbl of oil = 42 gal;
barrel of oil = 6.28E9 J/bbl * 15 gal/42 gal/bbl = 2.35E9 J / 20 = 1.2E8 J/yr
1.2E8 J/yr * 6.6E4 sej/J = 7.9E12 sej

**18. BACKHOE RENTAL

450 peso per 1 m3 of excavation: approx. 20 m3 excavated = 9000 peso * \$/7.8 peso = \$1154
\$1154 /20 yr = \$57.7/yr * 1.9E12 sej/\$ (Trujillo, 1998)

Table 3-36 continued

**19. JACKHAMMER RENTAL

450 pesos per 1 m3 of excavation: approx. 25 m3 excavated = 11250 pesos * $/7.8 peso = $1442

$1442 / 20 yr = $72.1 /yr * * 1.9E12 sej/$ (Trujillo, 1998)

20. LABOR

Workers (general excavation and construction): 15 days * 3 people * 70 peso/day = 3150 peso * $/7.8 peso = $404
transformity for primitive (uneducated labor) from Odum and Odum, 1983: 8.1E4 sej/J
energy per person: 2500 Kcal/day * 4186 Kcal/J * 45 days = 4.7E8 J/20 yrs = 2.4E7 J/yr
2.4E7 J * 8.1E4 sej/J = 1.9E12

21. PLUMBER LABOR

7 days * 1 person = 1500 pesos * $/7.8 peso =$192 / 20 yrs = $9.6/yr * 1.9E12 sej/$(Trujillo, 1998)

22. PAYMENT FOR GOODS

Monetary expenditures included limestone gravel: 8760 pesos, limestone rock: 1460 pesos, cement: 5250 pesos, lime: 600 pesos, sand: 2400 pesos, PVC pipe: 4400 pesos, steel rebar:720 pesos, wire mesh: 750 pesos, vegetation: 2200 pesos, and gasoline:480 pesos, for a total of 27,020 pesos / 7.8 pesos per dollar = $3464 U.S. dollars / 20 yrs = $173 per year

1.9E12 sej/$(Trujillo, 1998)

23 HUMAN WASTE
:
Yearly sewage = 36 people * 30 gal/day * 365 days/yr = 3.94 E5 gallons/yr

Transformity based on emergy per person

Since emergy per person in U.S. = 32 E15 sej/yr and that for Mexico = 8 E15 sej/yr (Odum et al, 1998), we will use an in-between average emergy since Akumal system is unlike typical Mexican one because of tourist economy: 16 E15 sej/yr
Total wastewater per person = 50 gal/day * 365 days = 18250 gallons

Transformity : 16 E15 sej / 1.825 E4 gallons = 8.767 E11 sej/gallon

Table 3-36 continued

24. OPERATION

(est.) 2 hours/week * 52 weeks = 104 hr. for gardener/handyman @ 70 peso/8 hours = 910 peso * $/7.8 peso = $117
$117 * 1.9E12 sej/$(Trujillo, 1998)

25. OUTPUT (yield): TREATED WASTEWATER

Chemical potential of yearly inputs of raw sewage:
Yearly treated wastewater = 1493.2 m3/yr - (1493.2m3 * .3 (evapotranspiration loss)) = 1045.2m3

Water: (1045.2 m3/yr) * (10E6 g/m3) * (4.94 J/g) = 5.17E10 J

Transformity: 354.1 E15 sej / 5.17 E10 J = 6.85 E6 sej/J

** in systems which don't have hard limestone excavation (e.g. beach sand sites) excavation costs are 6400 peso or 14,000 pesos less expensive; 14000 * $/7.8 peso = $1794 less expensive total less than 3% of total construction emergy.

The wetland system discharges less treated wastewater than it receives, since about 30% are used in transpiration by the vegetation.

By contrast, emergy analysis of a "package plant" sewage treatment system (Table 3-37 and Figure 3-42) built for a comparable number of residents in Akumal 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 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 (3.7 E15 sej/yr vs. 0.2 E15 sej/yr).

The transformity of treated water from the package plant is 4.83 E6 sej/J, which is about 30% lower than the transformity for the wetland system (6.85 E6 sej/J), reflecting the greater quantity of discharged water in the package plant, since virtually all input water to the system is discharged.

The empower density of the package plant is about three times higher than that of the wetland system (7.1 E19 sej/ha vs. 2.5 E19 sej/ha) since such a highly technical system occupies requires less land area.

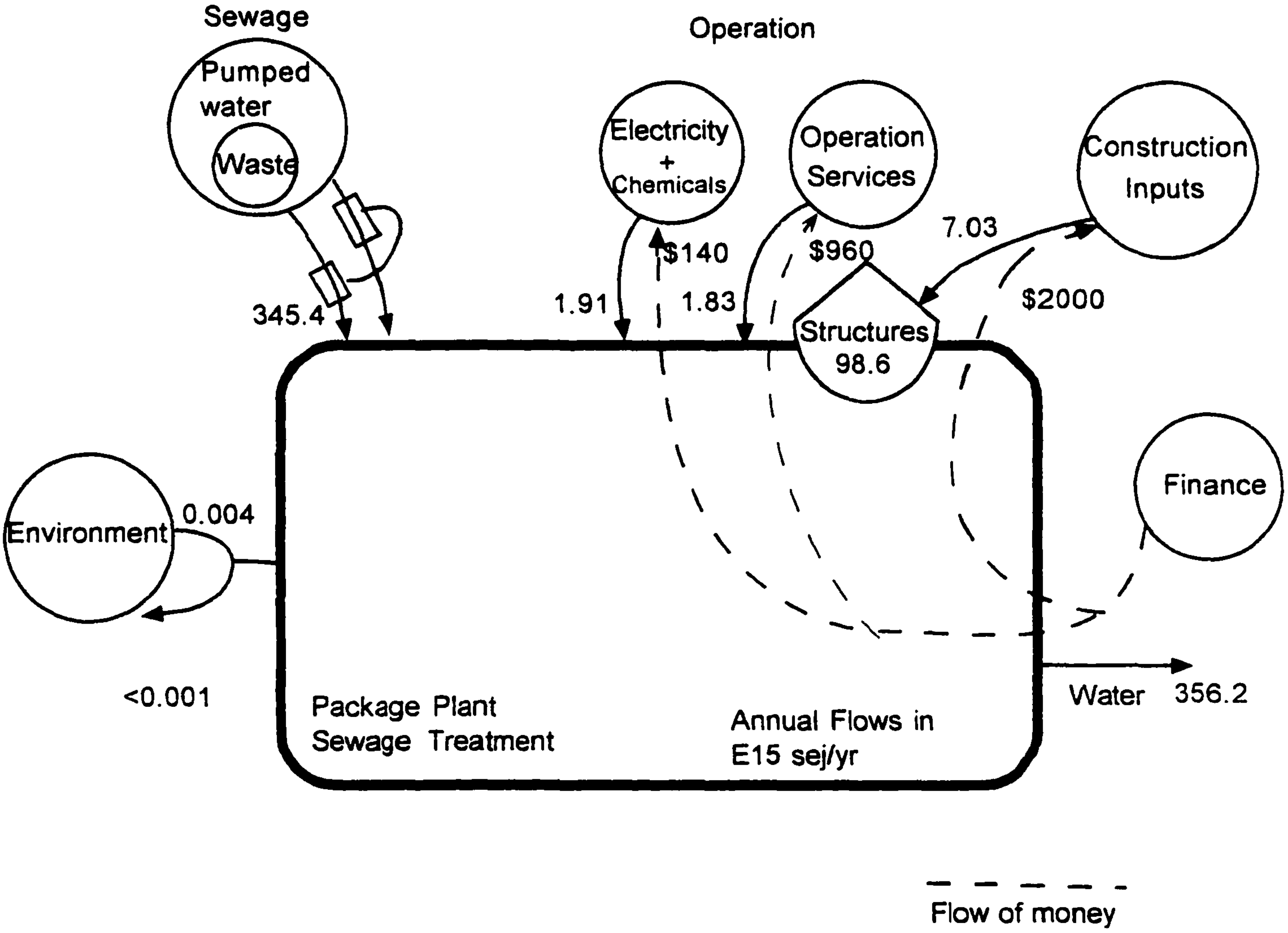


Figure 3-42 Diagram of emergy and money flows in package plant sewage treatment systems, Akumal, Mexico. Units of diagram are E15 sej/yr.

Table 3-37 Emergy analysis of package plant sewage treatment system

Note	Item	Raw Units	Emergy per Unit sej/unit	Emergy E15 sej/yr	EmDollars Thousands
ENVIRONMENT					
1	Sunlight	2.75 E7 J/yr	1	<0.001	<0.001
2	Rain, chemical	2.2 E8 J/yr	1.82E4 sej/J	0.004	0.002
3	Rain, geopotential	9.8 E4 J/yr	1.05E4 sej/J	<0.001	<0.001
4	Land	5 E7 J/yr	2.9 E4 sej/J	<0.001	
Total (Environment)				0.004	0.002
CONSTRUCTION INPUTS	Divided by 20 years except machinery divided by 5 years				
Imported goods and services					
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
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	Excavation of injection well	$150/yr	1.9 E12 sej/$	0.29	0.2
13	"Jet system" cost	$1800/yr	1.9 E12 sej/$	3.42	2.5
14	General labor	4.2E7 J/yr	8.1 E4 sej/J	0.003	.002
Total construction inputs				7.03	5.13
HUMAN WASTE					
15	Raw sewage	3.94 E5 gallons/yr	8.767 E11 sej/gallon	345.4	252.13

Note	Item	Raw Units	Emergy per Unit sej/unit	Emergy E15 sej/yr	EmDollars Thousands
OPERATION					
16	Electricity	1.1E10 j/yr	1.74E5 sej/J	1.9	1.4
17	Maintenance	$961.5/yr	1.9 E12 sej/$	1.83	1.34
18	Chlorine	1E4 g/yr	1.1E9 sej/g	0.01	.008
Total Operation				3.74	2.73
Total emergy				356.2	260
OUTPUT (yield)					
19	Treated wastewater	7.38 E10 J	4.95 E6 sej/J	356.2	260

* Column 6 (EmDollars) based on 1.37E12 sej/$, U.S. dollar/emergy ratio for 1996 (Odum, 1996)

Notes:

1. SOLAR ENERGY

Land area: 50 m2
Insolation: 1.8 E2 Kcal/cm2/yr (World Energy Data Sheet)
Albedo: 0.30

Energy (J) = (area) (avg insolation) (albedo)
= (50m2) (1.8E2Kcal/cm2/yr) (E4 cm2/m2) (0.3)
= 2.75 E7

2. RAIN, CHEMICAL POTENTIAL ENERGY

Land area = 50 m2
Rain = 9.44E-1 m/yr (IAM, U of Ga., 1988)
ET = .9 (Lessing, 1975)
Energy (J) = (area) (ET) (rain density) (Gibbs #)
=50m2 * (.9) * (1000 kg/m3) * (4.94 E3 J/kg) =2.2 E8 J/yr

3. RAIN, GEOPOTENTIAL

Area = 50 m2
Rainfall = 1.050 (Lessing, 1975)
Avg Elev = 2 m

Table 3-37 continued
Runoff rate = .1 (1 - ET)

Energy (J) = (area) * (%runoff) * (rain density) * (avg elevation) * (gravity)
= 50 m2 * 0.1 * 1000 kg/m3 * 2 * 9.8 m/s2
= 9.8 E4

4. LAND (EARTH CYCLE)

Transformity = 2.9E4 sej/J (Odum, 1996, p. 186)
Energy = (land area) (heat flow per area)
heat flows for old stable areas is 1E6 J/m2/yr (Odum, 1996, p. 296)
Energy = 50 m2 * 1E6 J/m2 = 5 E7 J/m2

5. CEMENT

35 bags @ 50 kg/bag = 1750 kg; price 50 peso/bag * 35 = 1750 peso
1750 peso * $/7.8 peso = $224.40
Transformity of concrete from Brown and McClanahan (1992, p. 27): 7E7 sej/g * 454 g/lb * 2000 lb/ton = 6.356E13 sej/ton
Concrete in system in cu yds: 6 cu yd;
6 cu yd * 500 lb/cu yd (est. from concrete company) * ton/2000 lbs = 1.5 tons concrete
1.5 tons / 20 yr lifetime = 0.75 tons/yr

6. CONCRETE BLOCK

125 blocks (40 cm x 20 cm x 15 cm) @ 2.9 peso/block = 362 peso * $/7.8 peso = $46.50
using transformity of concrete from Brown and McClanahan (1992, p. 27): 7E7 sej/g * 454 g/lb * 2000 lb/ton = 6.356E13 sej/ton
est. wt of each concrete block = 20 lbs, total wt 2500 lb * ton/2000 lb = 1.25 ton / 20 yrs = .0625 ton/yr
.0625 ton * 6.356E13 sej/ton = 3.97E12 sej

7. SAND

7 m3 for 800 peso total; 800 peso * $/7.8 peso = $102
est. wt of sand from Florida Rock Mines, Grandin, FL plant (pers. comm.): 3100 lbs/m3
transformity of sand using Odum (1996, p. 310) for other Earth products: 1E9 sej/g
7m3 * 3100 lbs/m3 * 454 g/lb = 0.98E7 g /20 yrs = 5E5 g
5E5 g * 1E9 sej/g = 5E14 sej

8. REBAR STEEL

7.5 pcs, 12 m length = 90 m; price 48 pesos/pc * 15 = 360 peso * $/7.8 = $46

Table 3-37 continued

transformity of steel and iron products from Odum (1996, p. 193): 1.78E15 sej/ton * ton/2000 lb = 8.9E11sej/lb
est. wt of rebar: 7.5 pcs * 20 lb/piece = 150 lbs / 20 yr lifetime = 7.5 lbs/yr
7.5 lb * 8.9E11 = 6.7E12 sej/yr

9. PVC PIPE

10 cm diameter, 32 pc x 6 m = 192 m; price 17,600 pesos * $/7.8 = $2256
transformity for finished product, use average emergy/dollar ratio for Mexico: 5.5E12 sej/$ (source?)
$2256/20 yr = $113 /yr * 5.5 E12 sej/$ = 6.2E14
transformity for plastic from Brown et al, 1992, p. 27: 9.26E7 sej/g
weight of PVC pipe (est.) 14 kg / 6 m piece * 32 pc =448 kg * 1000 g/kg = 4.48E5 /20 yr = 2.24E4 g/yr
2.24E4 g/yr * 9.26E7 sej/g = 5.2 E11 sej

10. GASOLINE

gasoline for concrete mixer: 30 liter @ 8 peso/liter (est.) = 240 pesos * $/7.8 peso = $31
Transformity for motor fuel from Odum (1996, p. 308): 6.6E4 sej/J
30 liter = 7.5 gal; bbl of oil = 42 gal;
barrel of oil = 6.28E9 J/bbl * 7.5 gal/42 gal/bbl =1.175E9 J / 20 = 6E7 J/yr
6E7 J/yr * 6.6E4 sej/J = 4E12 sej

11. MACHINERY

2 blowers, 2 HP engine, grinder, 2 check valves, 2 u-joints
estimated weight: 1500 lbs; divided by 3 years (expected life) = 500 lb * 454g/lb = 2.27E5 g
Transformity = 1.25E10 sej/g (Odum et al, 1983, p. 432)

12. EXCAVATION OF INJECTION WELL

$3000/20 yrs = $150

13. JET SYSTEM

Jet system costs: including machinery, parts, bacterial media, filters: $9000 / 5 yr life = $1800
* 1.9E12 sej/$(Trujillo, 1998)

Table 3-37 continued

14. LABOR

Workers (general excavation and construction): 20days *4 people * 70 peso/day = 5600 peso * $/7.8 peso =$718
transformity for primitive (uneducated labor) from Odum and Odum, 1983: 8.1E4 sej/J
energy per person: 2500 Kcal/day * 4186 Kcal/J * 80 days = 8.37E8 J/20 yrs = 4.2E7 J/yr
4.2E7 J * 8.1E4 sej/J = 3.4E12

15. RAW WASTEWATER

Yearly sewage = 36 people * 30 gal/day * 365 days/yr = 3.94 E5 gallons/yr
Transformity based on emergy per person
Since emergy per person in U.S. = 32 E15 sej/yr and that for Mexico = 8 E15 sej/yr (Odum et al, 1998), we will use an in-between average emergy since Akumal system is unlike typical Mexican one because of tourist economy: 16 E15 sej/yr
Total wastewater per person = 50 gal/day * 365 days = 18250 gallons
Transformity: 16 E15 sej / 1.825 E4 gallons = 8.767 E11 sej/gallon

16. ELECTRICITY

estimate for operating system: 250 kWh/month = 3000 kWh/yr
Transformity for electricity taken as mean global value = 173,681 sej/J (Odum, 1996, p. 305)
Electrical energy = (3000 kWh) * (3.606E6 j/kWh) = 1.1E10 J

17.. MAINTENANCE LABOR:

estimated at 3 hrs/week of "technician" = 150 hrs/yr @ 50 pesos/hr = 7500 pesos *$ /7.8 pesos = $961.50
* 1.9E12 sej/$(Trujillo, 1998)

18. CHLORINE

10 kg used per year; 400 pesos cost;
transformity - taken as equiv. to potassium chloride = 1.1E9 sej/g (Odum, 1996, p. 310)
10 kg * 1000g/kg = 1E4 g/yr

19. OUTPUT (yield): TREATED WASTEWATER

Chemical potential of yearly inputs of raw sewage:
Yearly treated wastewater = 1493.2 m3/yr
Water: (1493.2 m3/yr) * (10E6 g/m3) * (4.94 J/g) = 7.38 E10 J
Transformity: 356.2 E15 sej / 7.38 E10 J = 4.83 E6 sej/J

Receiving Wetland -- Groundwater Mangroves

Biodiversity

Biodiversity in the mangroves near the discharge was determined by transects of 1000 observations, made in December 1997 before effluent was released to the system. Total number of plant species was 17 (Table 3-2). The Shannon Diversity Index was 1.49 (base 2) and 0.45 (base 10) in December 1997 (Table 3-5).

White mangrove (*Laguncularia racemosa*) is the most dominant plant in the wetland, accounting for some 84% of observations in the December 1997 transect and over 75% of tree stems in the discharge area.

Mangrove Soils

The mangrove soils had an average water content of 72% and dry weight averaged 27.4% ± 1.7% in six soil samples taken in December 1997 (Table 3-38). Bulk density in five samples taken to 31-35 cm depth with a 2.1 cm diameter soil corer, showed that bulk density averaged 0.060 ± 0.003 g/cm^3 (Table 3-39).

Organic matter averaged 76.5 ± 0.8% in five soil samples (x 3 replicates) collected in December 1997 (Table 3-40). Variability amongst the five soil samples ranged from one sample with a mean of 79.4 ± 0.3% and the lowest organic matter content in a sample with a mean of 72.5 ± 0.1%.

X-ray diffraction and scanning electron microscope analysis of the mineral portion of mangrove soil samples revealed the presence of calcite, amorphous silica, and the aragonite form of limestone. All the peaks on the X-ray diffraction analysis were small, with calcite being the most abundant mineral. Some slight presence of weddelite (calcium oxalate

Table 3-38 Wet weight/dry weight of soils in mangrove receiving wetland, December, 1997.

Sample No.	Wet Weight kg	Dry weight kg	Percent dry weight/wet weight
1	0.634	0.129	20.3
2	0.099	0.029	29.3
3	0.079	0.024	30.4
4	0.094	0.029	30.9
5	0.099	0.029	29.3
6	0.099	0.024	24.2
Average ± standard error of the mean			27.4% ± 1.7%

Table 3-39 Bulk density of soils in mangrove receiving wetland, December, 1997.

Sample	Volume cm^3	Dry weight grams	Bulk density grams/ cm^3
1	473	29	0.061
2	468	24	0.051
3	439	29	0.066
4	443	29	0.065
5	439	24	0.055
Average ± standard error of the mean			0.060 ± 0.003

Table 3-40 Organic matter content of soils in mangrove receiving wetland estimated from loss on ignition and mean values of the five soil samples, December 1997.

Soil Sample	Number of samples	Mean percentage loss on ignition ± standard deviation of the mean
1-1	3	73.2 ± 0.1
1-2	3	79.1 ± 0.1
1-3	3	79.4 ± 0.3
1-4	3	78.4 ± 0.1
1-5	3	72.5 ± 0.1
Mean ± Standard error of the mean		76.5 ± 0.8

hydrite, $C_2CaO_4 \cdot 2H_2O$) detected by the X-ray diffraction may have been a secondary product resulting from the preparation procedure (Dr. W. Harris, *pers. comm.*)

Ash remaining after combustion for determination of organic matter was analyzed by inductive coupled plasma spectroscopy for calcium and magnesium content (Table 3-41).

These results indicate that 41.9 +/- 1.3 percent is calcium and 3.2 +/- 0.1 is magnesium. Calcium thus constitutes a sizeable portion of the 23.5% non-organic portion of the mangrove soils, and if present as calcium carbonate would account for virtually all of the inorganic material.

Depths of the mangrove wetland's organic soil were measured (Figure 3-43) to ascertain if there were limestone outcrops or cenotes in the vicinity of the outfall location which might prevent sufficient residence time to permit filtration and uptake of nutrients in the effluent. The results were mapped (Figure 3-44), showing that within a 15 meter radius of the outfall, soil depths varied from 33 to 55 cm before limestone rock was encountered. Average depth was 41.6 cm. No consistent pattern emerged, so an isopach could not be generated from the data, although many of the deepest soil depths were found close to the outfall site, and to its south (where soils averaged 48 cm deep along an axis 15 m long).

Nutrients

Sampling tubes were installed in the mangrove receiving wetland to determine water nutrient content before and after discharge. Sample point A was 1.1 m upstream from the point of outfall, B was 1.1 m downstream, C was 3.25 m downstream, D was 6.1 m downstream, and sample point E was 12 m southeast of discharge and closer to the edge of the wetland area.

Before treated effluent discharge began nitrogen content of the mangrove soils

Table 3-41 Calcium and magnesium content of mangrove soil ash after combustion for organic content. Results determined by inductive coupled plasma spectroscopy.

Sample	Calcium %	Magnesium %
1	40.1	3.38
2	42.8	3.46
3	39.1	3.15
4	41.3	3.15
5	46.4	3.07
Average ± standard error of the mean	41.9 ± 1.27	3.24 ± 0.08

Figure 3-44 Howard T. Odum inspecting root penetration and peat depth in mangroves, Akumal, December 1997.

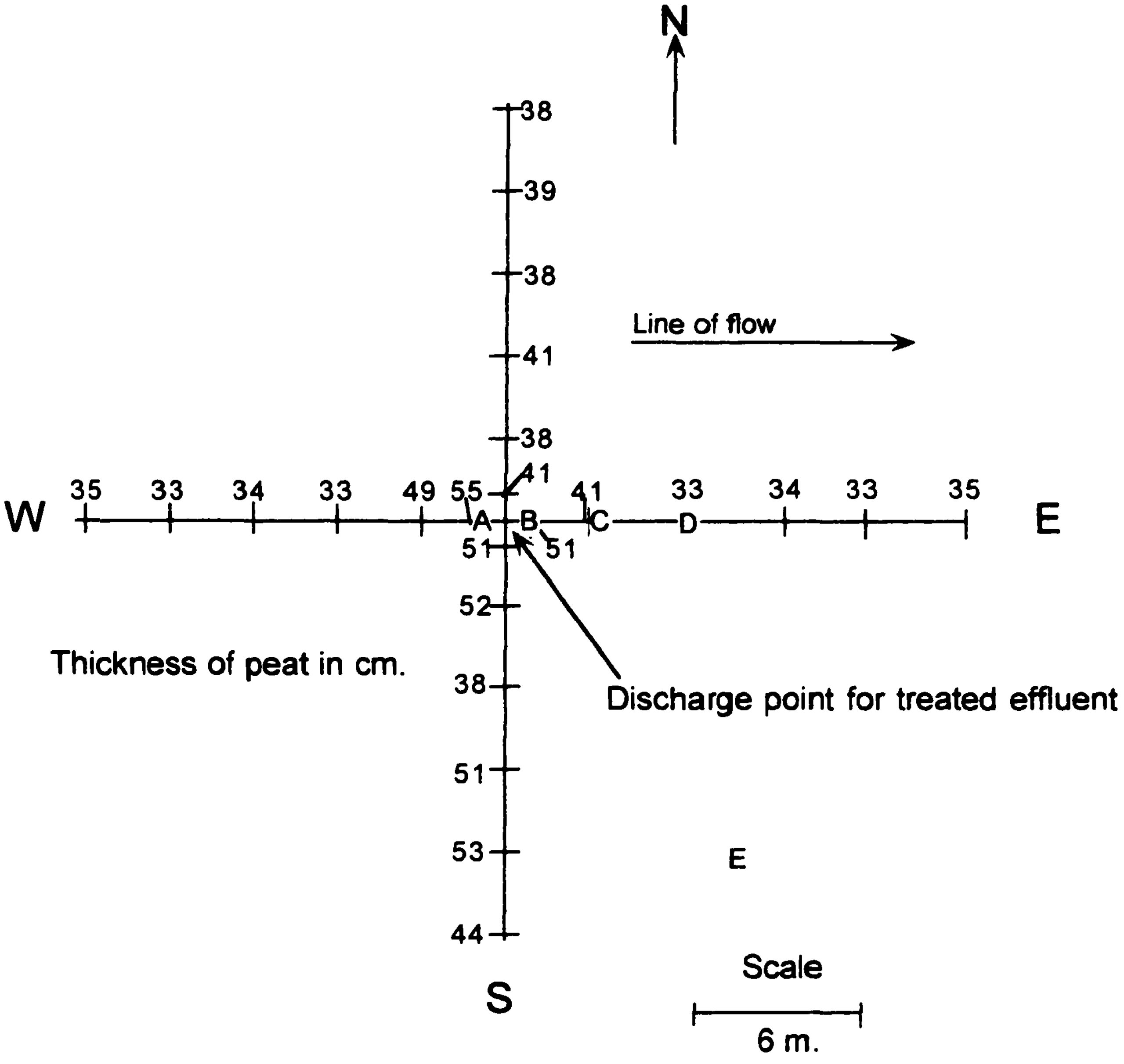


Figure 3-44 Thickness of mangrove peat in the receiving wetland around the outfall pipe discharging effluent, December 1997. See Figures 1-8 for location of mangrove discharge point in Akumal. Mangrove soil samples were collected 1,3,5 and 10 m from discharge point in N,S, E and W directions (Tables 3-43 and 3-45). Water samples were collected at 1 m upstream (A), 1m (B), 3m (C) and 6 m (D) downstream and 15 m (E) SE of discharge point (see Figure 1-9).

was 1.58% +/- .02% (Table 3-42), with a range from a low value of 1.44% N to a high of 1.74% N. Table 3-43 presents nitrogen levels measured at specific distances from outfall in the mangrove wetland prior to and after discharge of treated effluent.

Nitrogen levels measured 1m from discharge point of the effluent showed about a 7% increase after 4 months of receiving the treated sewage (from 1.68% to 1.79% nitrogen). However, this increase may be due to other factors as the increase at 3m from discharge was 11%, at 5m was 9% and 10m was 9% (Table 3-43). Nitrogen increase over pre-discharge levels totaled 18% for the South 1-10m samples, 6% for the East 1-10m, and 5% for both North and West 1-10m.

In December 1997, phosphorus levels in the mangrove soils averaged 0.32% +/- 0.006% (Table 3-44). These nutrient concentrations may have been caused by anthropogenic additions to the site, as construction workers during this period used the wetland as an outdoor bathroom. In the mangrove soil samples from April – August 1997, phosphorus was measured at lower levels, ranging from 0.065% to 0.115% (Table 3-47).

Table 3-47 shows analyses of mangrove soil from just before to four months after discharge commenced, which reveal increases in phosphorus levels of 5-10%.. At 1m distance from outfall, P levels were 7% above those pre-discharge, and at 3m were unchanged, at 5m were +7%, and –9% at 10 m. Only in the South (+14%) and West (+3%) direction samples were phosphorus levels higher than pre-discharge. East and West direction soils samples were 5-6% lower (Table 3-47).

Table 3-42 Total Kjeldahl nitrogen content of soils in mangrove receiving wetland on 12 December 1997 before discharge of treated effluent.

December 1997 mangrove soil samples	Total Kjeldahl nitrogen g/kg
1	14.4
2	14.4
3	14.2
4	16.2
5	16.4
6	15.8
7	16.4
8	15.2
9	16.8
10	16.6
11	17.4
12	16.0
13	16.6
14	15.6
15	15.8
mean ± standard error of the mean	15.9 ± 2.5

Laboratory accuracy with nitrogen standard +3.1%

Table 3-43 Total Kjeldahl nitrogen content of soils in mangrove receiving wetland before discharge (30 April 1998) and 2 months (3 July 1998), 3 months (3 August 1998) and 4 months (2 September 1998) after discharge of treated effluent began 3 May 1998.

Sample Location (Distance from discharge)	# of Samples n	30 Apr 1998 Total Kjeldahl Nitrogen g/kg	3 Jul 1998 Total Kjeldahl Nitrogen g/kg	3 August 1998 Total Kjeldahl Nitrogen g/kg	2 Sep 1998 Total Kjeldahl Nitrogen g/kg	Percent change from 30 Apr 1998 to 2 Sep 1998 data
East 1m	3	17.7 ± 0.2	18.2 ± 0.6	19.0 ± 0.4	17.3 ± 0.3	-2%
East 3m	3	15.4 ± 0.4	16.6 ± 04	16.8 ± 0.3	17.6 ± 0.3	+14%
East 5m	3	16.2 ± 0.5	17.7 ± 0.2	18.7 ± 0.4	16.8 ± 0.3	+4%
East 10m	3	15.1 ± 0.6	16.8 ± 0.2	18.0 ± 0.3	16.3 ± 0.5	+8%
West 1m	3	16.6 ± 0.2	17.8 ± 0.3	15.9 ± 0.6	18.1 ± 0.4	+9%
West 3m	3	17.9 ± 0.6	17.8 ± 0.2	18.6 ± 0.8	18.6 ± 0.1	+4%
West 5m	3	16.3 ± 0.7	18.0 ± 0.3	19.6 ± 0.4	18.1 ± 0.6	+11%
West 10m	3	17.5 ± 0.4	16.3 ± 0.3	16.8 ± 0.6	17.0 ± 0.3	-3%
North 1m	3	16.8 ± 0.7	15.9 ± 0.2	17.0 ± 0.6	18.5 ± 0.3	+10%
North 3m	3	16.3 ± 0.3	19.3 ± 0.1	18.5 ± 0.3	17.5 ± 0.2	+8%
North 5m	3	17.4 ± 0.3	18.2 ± 0.5	20.1 ± 0.3	17.7 ± 0.2	+2%
North 10m	3	18.0 ± 0.2	18.4 ± 0.3	19.5 ± 0.6	18.0 ± 0.3	No change
South 1m	3	16.1 ± 0.1	17.4 ± 0.4	18.9 ± 0.4	17.8 ± 0.4	+11%
South 3m	3	14.7 ± 0.3	17.6 ± 0.6	19.6 ± 0.8	17.6 ± 0.5	+19%
South 5m	3	14.8 ± 0.8	16.9 ± 0.4	17.3 ± 0.2	17.5 ± 0.3	+19%
South 10m	3	13.5 ± 0.8	16.7 ± 0.3	17.4 ± 0.6	16.7 ± 0.2	+24%
Average1m	12	16.8	17.3	17.7	17.9	+7%
Average3m	12	16.1	17.8	18.4	17.8	+11%
Average5m	12	16.2	17.7	18.9	17.6	+9%
Average10m	12	16.0	17.1	17.9	17.0	+7%
Average East	12	16.1	17.3	18.1	17.0	+6%
Average West	12	17.1	17.5	17.7	18.0	+5%
Average North	12	17.1	17.9	18.8	17.9	+5%
Average South	12	14.8	17.2	18.3	17.4	+18%

Laboratory accuracy with nitrogen standard - 4.2% (April & August 1998), -3.1% (July and September 1998)

Table 3-44 Phosphorus content of soils in mangrove receiving wetland on 12 December 1997 before discharge of treated effluent.

December 1997 mangrove soil samples	Total phosphorus g/kg
1	3.7
2	3.3
3	3.5
4	3.2
5	3.3
6	3.1
7	2.9
8	3.0
9	3.1
10	2.9
11	3.1
12	3.3
13	3.3
14	3.4
15	3.5
Average ± standard error of the mean	3.2 ± 0.1

Laboratory accuracy with phosphorus standard +2.4%.

Table 3-45 Phosphorus content of soils in mangrove receiving wetland before and after discharge began May 3, 1998.

Sample Location (Distance from discharge)	# of samples n	30 Apr 1998 Total Phosphorus g/kg	3 Jul 1998 Total Phosphorus g/kg	3 Aug 1998 Total Phosphorus g/kg	2 Sep 1998 Total Phosphorus g/kg	Percent change from 30 Apr 1998 to 2 Sep 1998 data
East 1m	3	0.88 ± 0.03	1.08 ± 0.03	0.65 ± 0.01	0.90 ± 0.03	+2%
East 3m	3	0.86 ± 0.02	1.06 ± 0.03	0.87 ± 0.07	0.84 ± 0.07	-2%
East 5m	3	0.90 ± 0.02	0.94 ± 0.06	1.04 ± 0.04	0.93 ± 0.05	+3%
East 10m	3	0.99 ± 0.03	1.04 ± 0.03	0.91 ± 0.07	0.69 ± 0.03	-30%
West 1m	3	0.88 ± 0.06	0.91 ±0.05	0.99 ± 0.01	1.00 ± 0.03	+12%
West 3m	3	0.90 ± 0.07	0.90 ± 0.05	0.81 ± 0.04	0.96 ± 0.02	+6%
West 5m	3	0.89 ± 0.01	0.81 ± 0.04	0.98 ± 0.13	0.98 ± 0.09	+10%
West 10m	3	1.13 ± 0.09	1.15 ± 0.02	0.87 ± 0.06	0.92 ± 0.05	-18%
North 1m	3	0.76 ± 0.03	1.03 ± 0.01	0.97 ± 0.04	0.77 ± 0.03	+1%
North 3m	3	0.90 ± 0.04	0.93 ± 0.04	0.85 ± 0.09	0.71 ± 0.04	-21%
North 5m	3	0.84 ± 0.07	0.79 ± 0.05	0.85 ± 0.09	0.81 ± 0.03	-3%
North 10m	3	0.76 ± 0.04	0.72 ± 0.04	0.90 ± 0.09	0.78 ± 0.03	+3%
South 1m	3	0.99 ± 0.06	1.03 ± 0.07	0.79 ± 0.04	1.10 ± 0.09	+11%
South 3m	3	0.86 ± 0.03	1.00 ± 0.07	1.16 ± 0.06	1.00 ± 014	+16%
South 5m	3	0.92 ± 0.03	1.08 ± 0.07	1.05 ± 0.08	1.11 ± 0.08	+20%
South 10m	3	0.98 ± 0.05	1.04 ± 0.04	1.15 ± 0.06	1.05 ± 0.05	+8%
Average1m	12	0.88	1.01	0.85	0.94	+7%
Average3m	12	0.88	0.97	0.92	0.88	No change
Average5m	12	0.89	0.91	0.98	0.96	+7%
Average10m	12	0.96	0.96	0.96	0.86	-9%
Average East	12	0.91	0.87	0.87	0.84	-6%
Average West	12	0.95	0.91	0.91	0.97	+3%
Average North	12	0.81	0.89	0.89	0.77	-5%
Average South	12	0.84	1.04	0.94	1.06	+14%

Laboratory accuracy with phosphorus standard +5.3% (April and August 1998), .-6.5% (July and September 1998).

Hydrogeology of Coastal Zone

Cross Section

Figure 3-45 presents a systems diagram of the effluent-receiving salt-fresh wetland in the treatment system. The driving energy sources are sun and wind, while rain, tidal exchange, inland freshwater groundwater inflow and wastewater effluent contribute to the hydrology of the ecosystem.

A geological cross-section of the coastal area (Figure 1-3) shows that the natural wetlands along the coast are located in the collapse karst zone where seawater and freshwater mix leading to dissolution of limestone. These wetlands are dominated primarily by mangrove-type vegetation except where limestone rocks provide elevated hammocks. Figure 1-9 presents a map showing the relationship of the wetland treatment units and the mangrove discharge and sampling areas in Akumal.

Ground Water

Measurements of water levels in three piezometer tubes in the mangrove receiving wetland enabled calculation of water flowlines. The difference between the three piezometers was slight, only 3/8 inch (0.95 cm) although they were separated by 10-14 meters (Figure 3-46). Directions to the three piezometers were established from a reference point by surveyor transit level. These calculations showed that line of groundwater flow was approximately in an easterly direction. Changes in tidal range may be expected to change the gradient of flow but not its direction.

Chart recorder data tracking changes in water levels in the mangrove wetland, in a nearby cenote (near to the edge but outside the wetland), and at the seaside at Yal-Kul lagoon in Akumal, showed that the mangrove soils had a large impact in lessening tidal fluctuations,

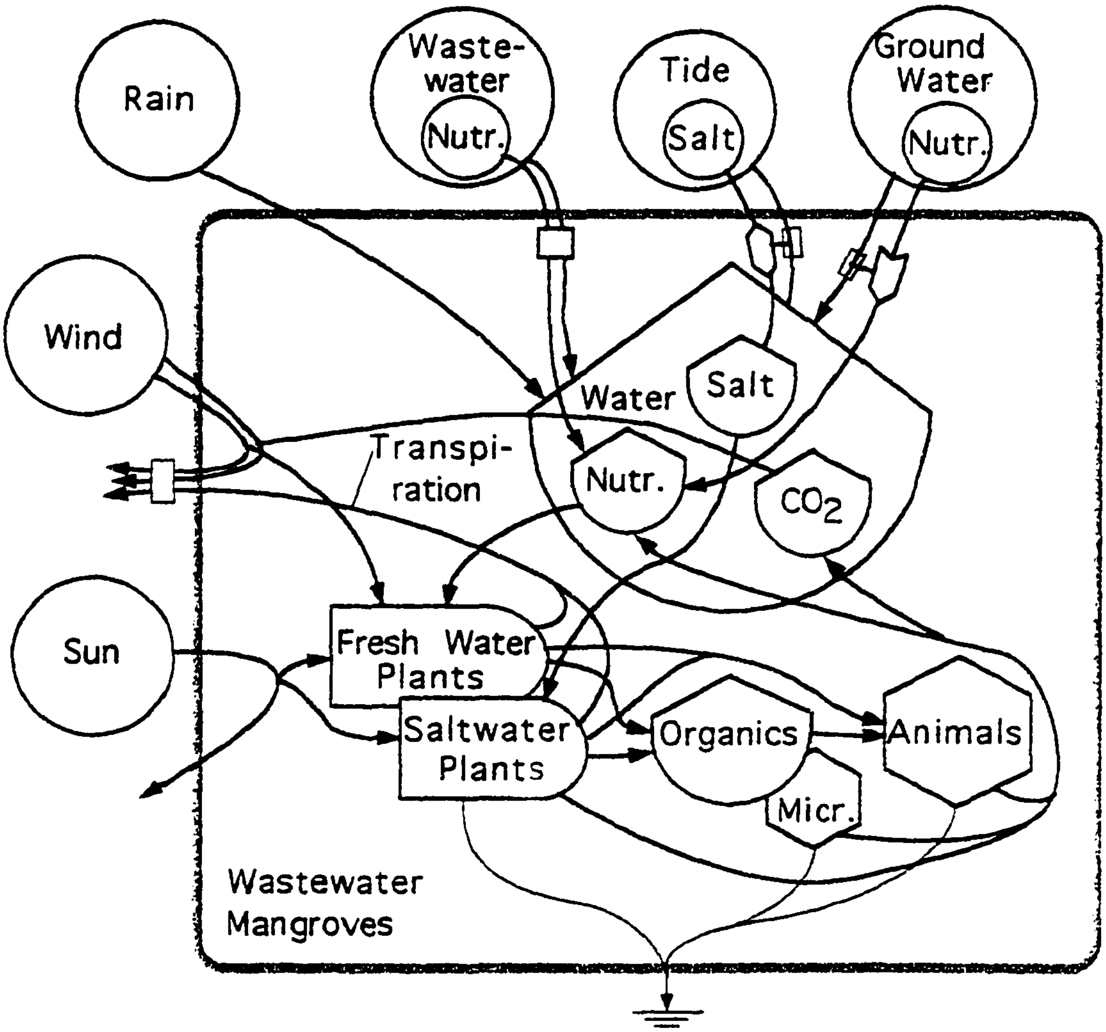


Figure 3-45 Systems diagram of the mangrove wetland receiving treated effluent.

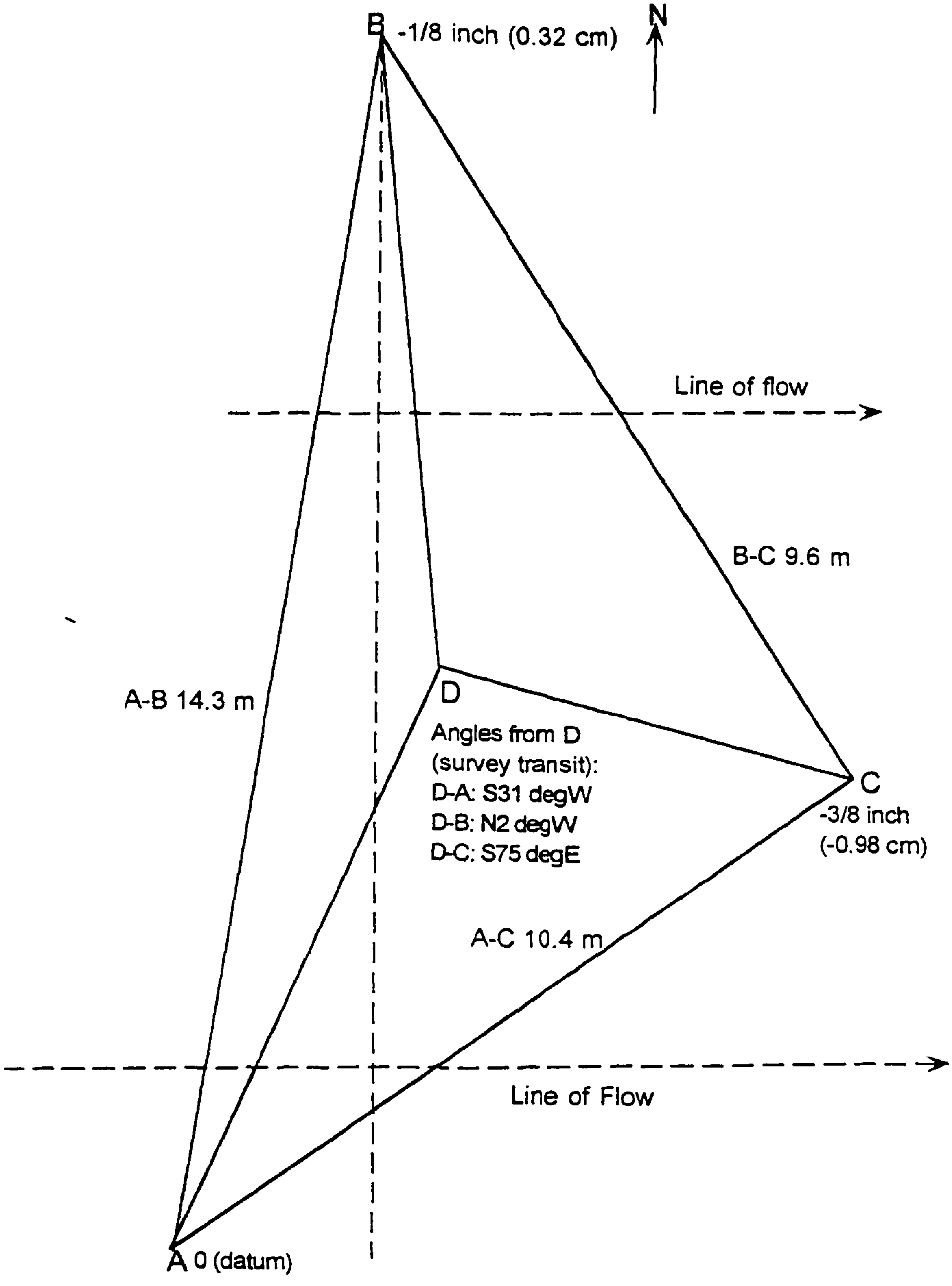


Figure 3-46 Potentiometric measurements of groundwater level in mangroves, December, 1997. Piezometers were located at A,B, and C. Survey transit level was located at point D. Flowlines calculated from data are approximately in easterly direction.

larger than would be expected by mere distance from the ocean. For example, chart recording data from May 27-28, 1997 (Figures 3-47 and Figure 3-48) showed that the cenote near the mangrove had total water level changes less than half as great as the ocean. Water level changes totaled 22.5 cm in the cenote while tidal flux at Yal-Ku totaled 48.5 cm. Also, the amplitude of the tides were less: 26 cm at Yal-Ku and 16.5 cm in the cenote.

The mangrove wetland had considerably less water level changes than the cenote, despite the fact that both are nearly equidistant from the ocean (and in fact, the mangrove wetland where the chart recorder was placed is some 5-10 meters closer to the sea). For example, during December 10-14, 1997, total water level change in the mangrove was some 17 cm as contrasted with 119 cm in the cenote, and 246 cm in tidal changes at Yal-Ku Lagoon (Figure 3-49, Figure 3-50, Figure 3-51). The greatest amplitude change in the mangroves was 7 cm while the shorter, sharper tidal fluxes in the cenote was as high as 21 cm, and the tidal range at Yal-Ku reached 28 cm.

Water Quality in Mangroves

Total nitrogen

Table 3-46 presents results of nitrogen analyses of water in the mangroves before and after discharge of treated effluent.

Pre-discharge total nitrogen concentrations average around 4 mg/l in the discharge area of the mangroves. After 3.5 months of receiving treated effluent, nitrogen concentrations in mangrove water were increased to 9-12 mg/l in sites close to the discharge location. Increases of total nitrogen were 5-7 mg/liter in sampling sites 1-3 m from the discharge, but returned to background levels by 6 m distance (Table 3-46).

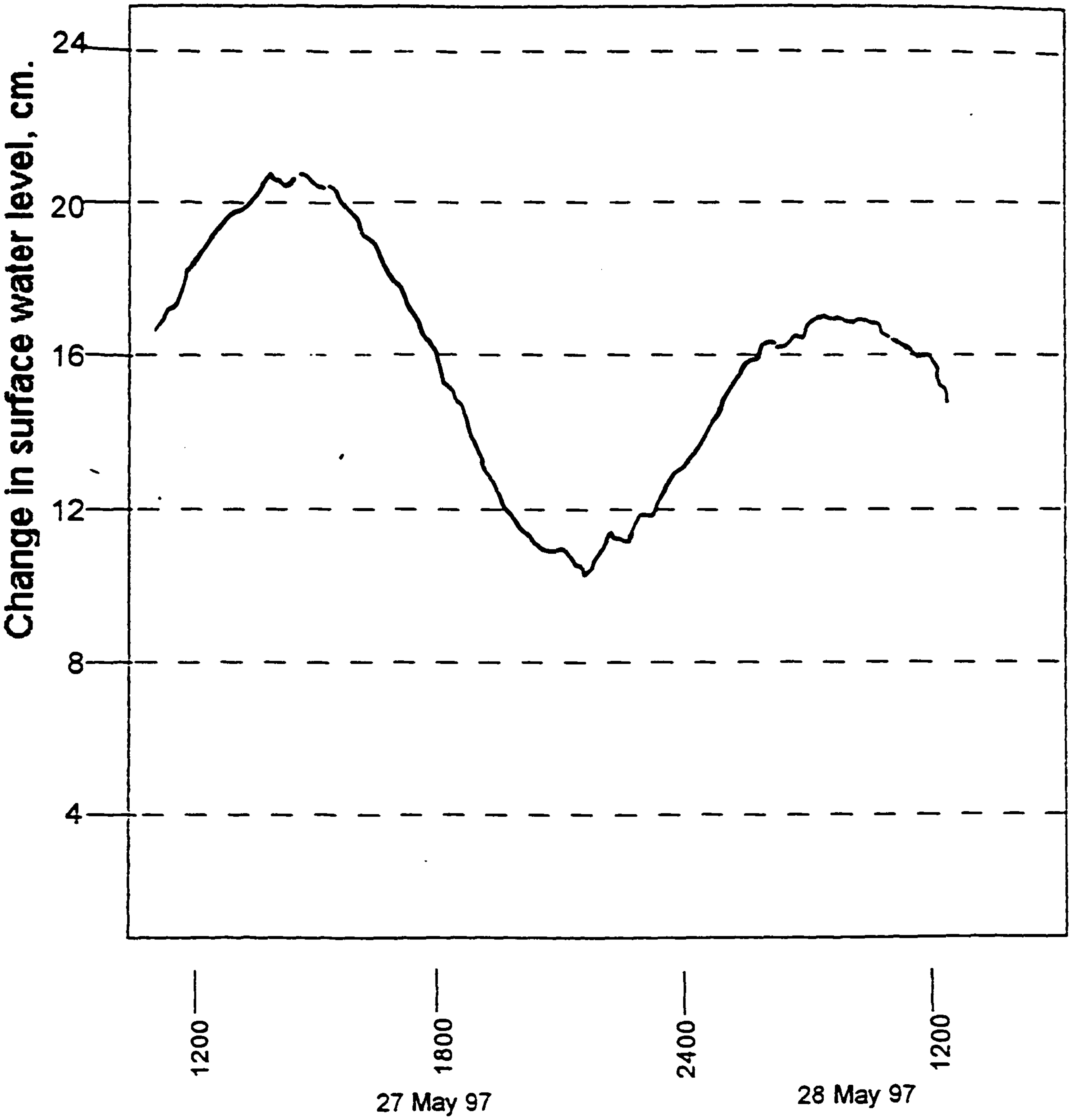


Figure 3-47 Chart recorder water levels in cenote near wetland systems, 27-28 May 1997.

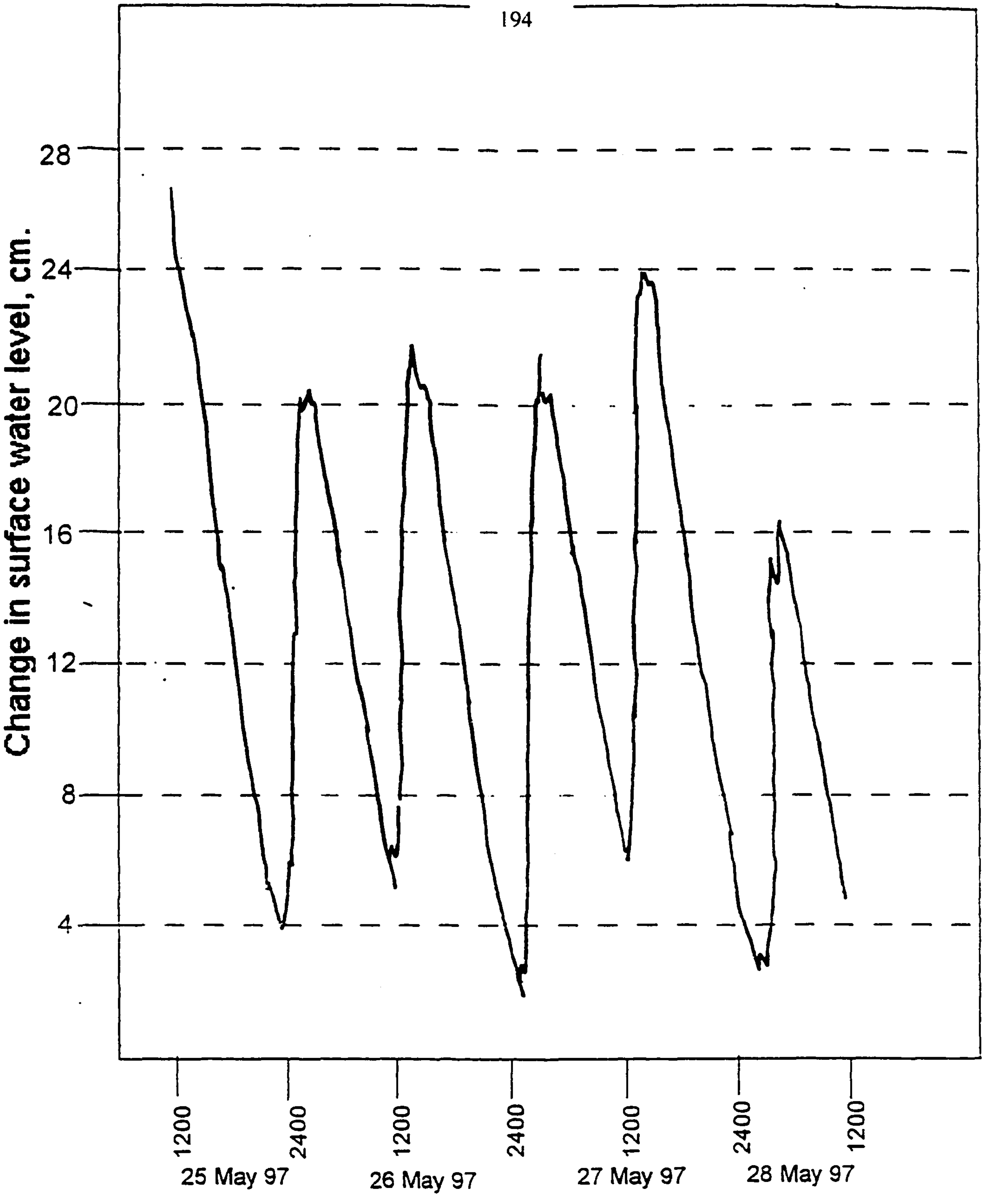


Figure 3-48 Chart recorder water levels at Yal-ku lagoon, showing tidal record, 27-28 May 1997.

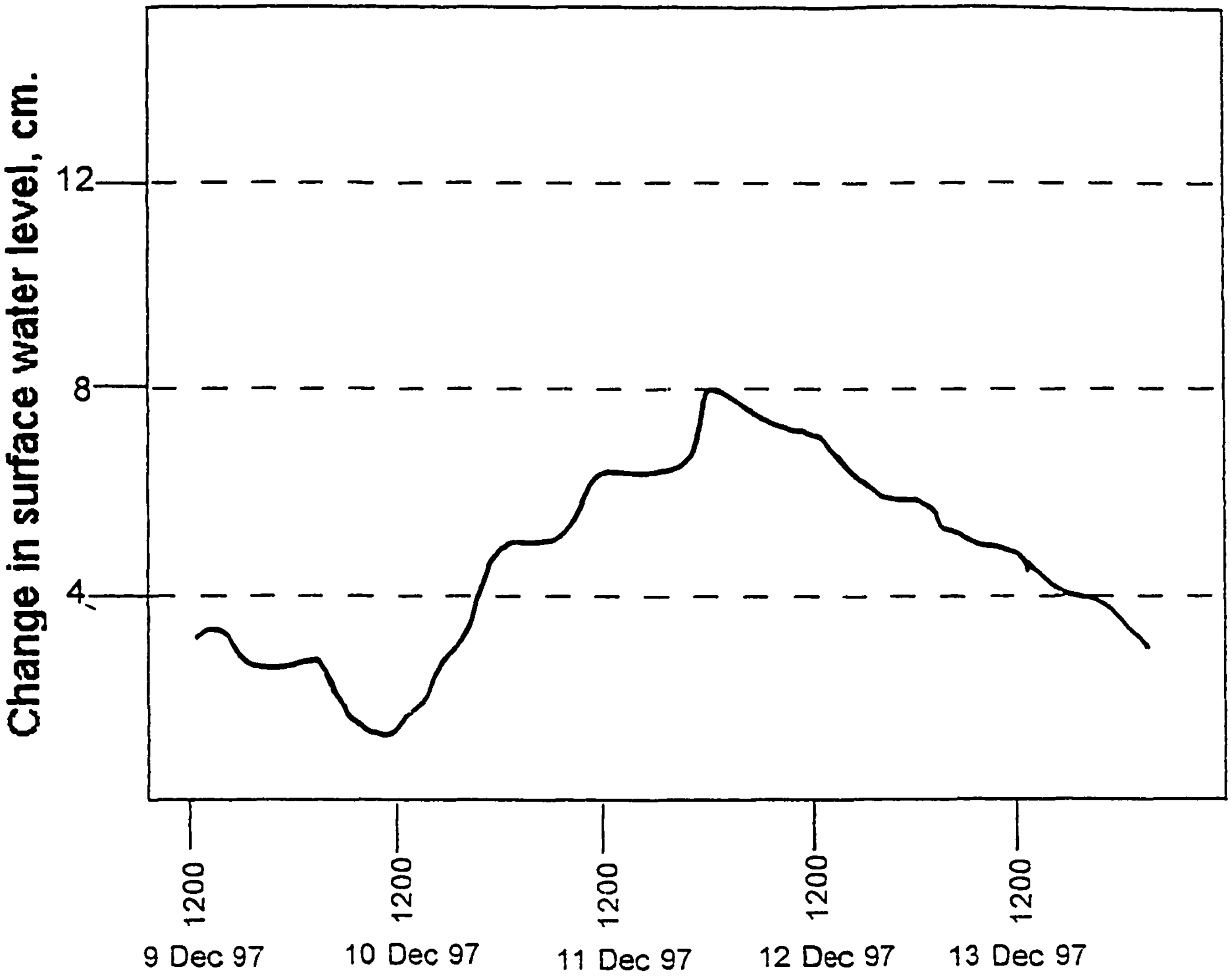


Figure 3-49 Chart recorder water levels in mangrove receiving wetland, 9-14 December 1997.

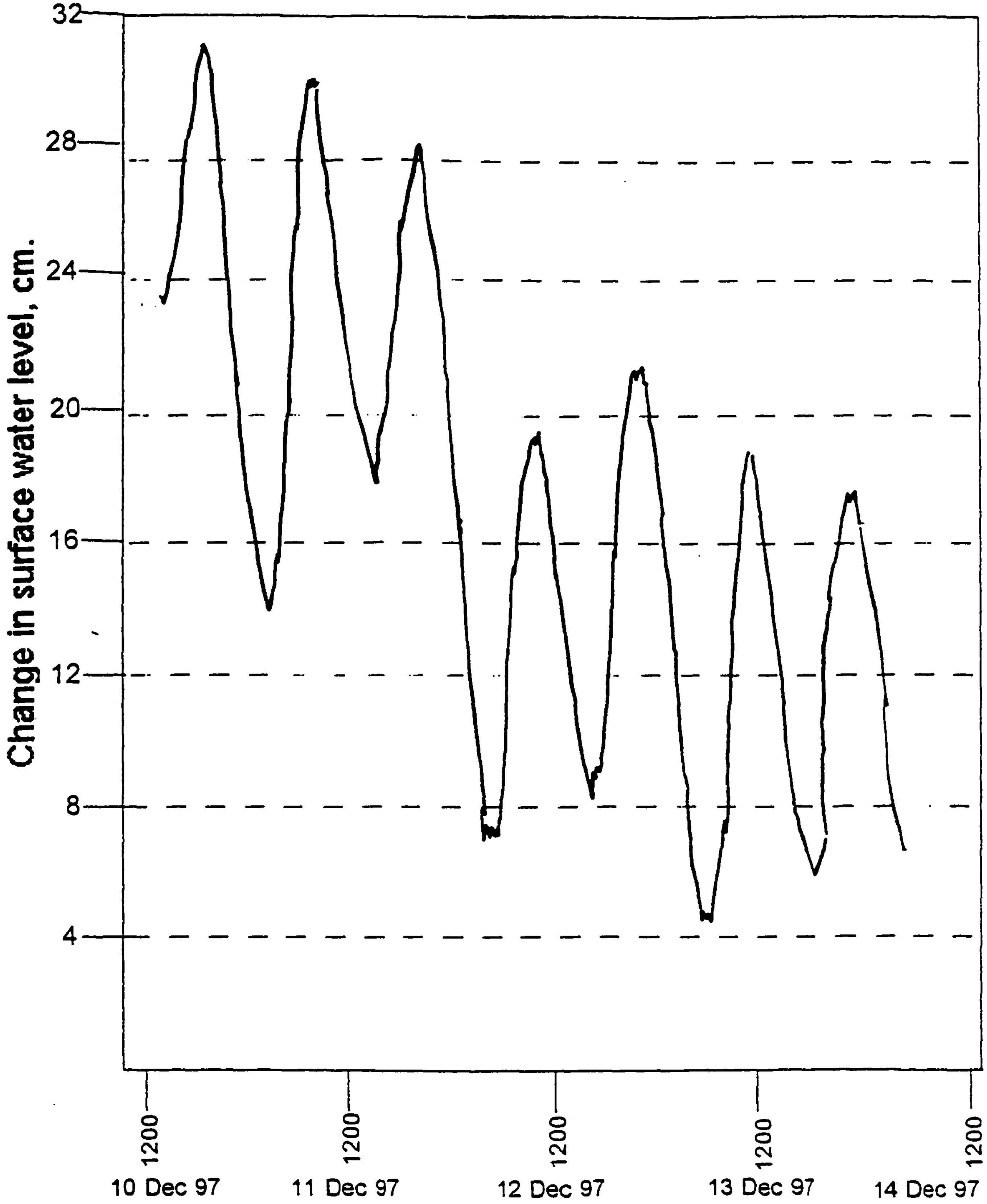


Figure 3-50 Chart recorder water levels in cenote near wetland systems, 10-14 December 1997.

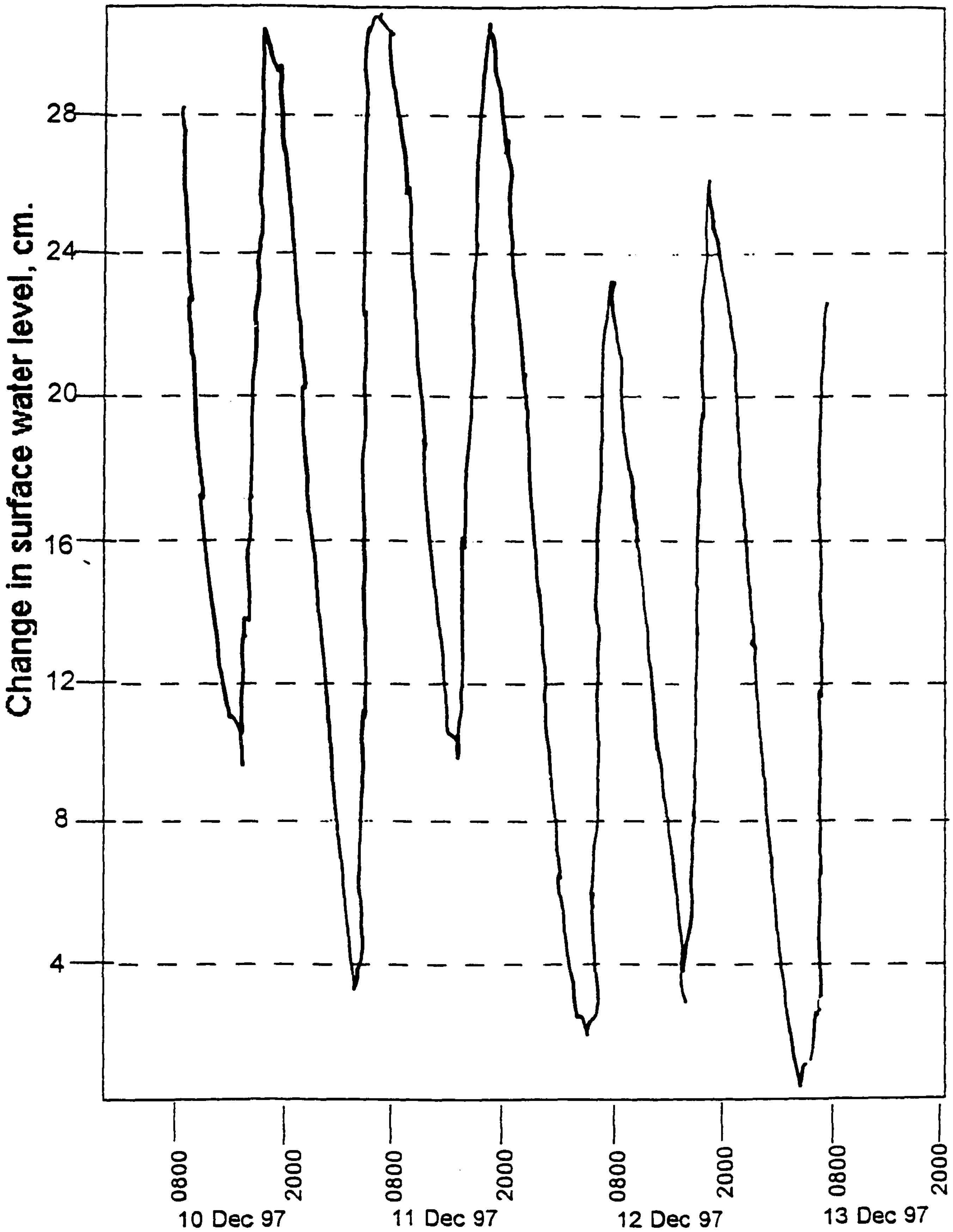


Figure 3-51 Chart recorder water levels at Yal-ku lagoon, showing tidal record, 10-14 December 1997.

Table 3-46 Total nitrogen in water of mangroves before and after discharge of treated wastewater.

Before discharge:

Sample Location	12 Dec 1997 Total nitrogen mg/l	3 Mar 1998 Total nitrogen mg/l	30 Mar 1998 Total nitrogen mg/l	30 Apr 1998 Total nitrogen mg/l	Average ± standard error of mean Total nitrogen mg/l
A, 1 m upstream	8.2	1.1	1.6	5.5	4.1 ± 1.7
B, 1 m downstream	7.7	0.2	2	5.1	3.8 ±1.7
C, 3 m downstream	10.3	2.4	2.8	3.6	4.8 ±1.9
D, 6 m downstream	5.9	2.2	3.1	4.3	3.9 ±0.8
E, 12 m SE	9.7	2.3	4.9	9.2	6.5 ±1.8

After discharge:

Sample Location	31 May 1998 Total nitrogen mg/l	30 Jun 1998 Total nitrogen mg/l	1 Aug 1998 Total nitrogen mg/l	19 Aug 1998 Total nitrogen mg/l	Average ± standard error of mean Total nitrogen mg/l
A, 1 m upstream	7.6	7.3	14.8	13.5	10.8 ± 2.0
B, 1 m downstream	2.9	1.7	20.2	10.1	8.7 ± 4.3
C, 3 m downstream	1.3	9.8	21.5	15.7	12.1 ± 4.3
D, 6 m downstream	0.9	3.5	3.1	3.0	2.6 ± 0.6
E, 12 m SE	4.9	0.2	3.2	2.2	2.6 ± 1.0

Soluble reactive phosphorus

Analyses of soluble reactive phosphorus in the mangrove water before and after discharge of treated effluent are presented in Table 3-47.

Before discharge, soluble reactive phosphorus varied from 0.9 – 1.2 mg P/liter on average in mangrove water. After 3.5 months of discharge, locations 1 m distant had increased phosphorus levels by 2-3 mg/liter, but showed less increase at 3m from the discharge point. The sampling location 6m distant showed similar phosphorus concentrations to background levels in the mangrove (Table 3-47).

Chemical oxygen demand

Analyses of chemical oxygen demand (COD) in mangrove water are presented in Table 3-48.

Mangrove water prior to discharge ranged from 60-160 COD mg/l. After 3.5 months of receiving treated effluent, sampling sites 1m from discharge location had COD concentrations around 150 mg/l, and showed a decline in COD with distance from the discharge. By 6m distance, COD concentration was below that shown pre-discharge for that sampling location, and was below background levels of COD in the mangrove (Table 3-48).

Total suspended solids

Total suspended solids (TSS) were examined in the mangrove before and after the discharge of treated effluent (Table 3-49). Pre-discharge levels ranged from an average of 280-360 with high variability (over 25% in some cases). After 3.5 months of receiving treated effluent, there was on average significant decline in suspended solids in the mangrove water. Sampling locations 1-3m from the discharge had TSS levels 30-50% lower than they

Table 3-47 Soluble reactive phosphorus (SRP) in water of mangrove before and after discharge of treated wastewater.

Before discharge:

Sample location	12 Dec 1998 Total SRP Mg/l	3 Jan 1998 Total SRP mg/l	24 Jan 1998 Total SRP mg/l	3 Mar 1998 Total SRP mg/l	30 Mar 1998 Total SRP mg/l	30 Apr 1998 Total SRP mg/l	Average ± standard error of mean Total SRP mg/l
A, 1 m upstream	1.65	1.75	0.7	0.95	1.1	1.16	1.22 + 0.17
B, 1 m downstream	1.55	1.05	1.35	1.05	0.88	1.4	1.21 + 0.11
C, 3 m downstream	1.35	0.95	0.7	0.8	0.84	0.67	0.89 + 0.1
D, 6 m downstream	1.05	1.8	0.6	1.15	0.66	1.16	1.07 + 0.18
E, 12 m SE	2.1	0.85	0.95	0.6	0.65	0.54	0.95 + 0.24

After discharge:

Sample location	31 May 1998 Total SRP mg/l	30 June 1998 Total SRP mg/l	1 Aug 1998 Total SRP mg/l	19 Aug 1998 Total SRP mg/l	Average ± standard error of mean Total SRP mg/l
A, 1 m upstream	3.54	4.1	3.69	3.63	3.74 ± 0.12
B, 1 m downstream	2.3	6.54	4.76	3.44	4.26 ± 0.91
C, 3 m downstream	0.34	1.67	4.03	3.44	2.37 ± 0.84
D, 6 m downstream	0.37	1.3	1.74	2.45	1.47 ± 0.44
E, 12 m SE	0.56	0.44	1.03	2.17	1.05 ± 0.39

Table 3-48 Chemical oxygen demand (COD) in water of mangrove receiving wetland. before and after discharge of treated wastewater

Before discharge:

Sample location	3 Mar 1998 COD mg/l	30 Mar 1998 COD mg/l	30 Apr 1998 COD mg/l	Average ± standard error of mean COD mg/l
A, 1 m upstream	54	70	69	64 ± 5
B, 1 m downstream	48	65	144	86 ± 30
C, 3 m downstream	54	76	106	79 ± 15
D, 6 m downstream	129	129	203	154 ± 25
E, 12 m SE	189	202	93	161 ± 34

After discharge:

Sample location	31 May 1998 COD mg/l	1 Aug 1998 COD mg/l	19 Aug 1998 COD mg/l	Average ± standard error of mean COD mg/l
A, 1 m upstream	102	204	150	152 ± 29
B, 1 m downstream	112	203	129	148 ± 28
C, 3 m downstream	67	211	123	134 ± 42
D, 6 m downstream	55	199	76	110 ± 45
E, 12 m SE	82	203	133	139 ± 35

Table 3-49 Total suspended solids (TSS) in water of mangrove receiving wetland before and after discharge of treated wastewater

Before discharge:

Sample location	3 Mar 1998 TSS mg/l	30 Mar 1998 TSS mg/l	30 Apr 1998 TSS mg/l	Average ± standard error of mean TSS mg/l
A, 1 m upstream	275	277	330	294 ± 18
B, 1 m downstream	218	400	282	300 ± 53
C, 3 m downstream	139	378	424	314 ± 88
D, 6 m downstream	157	371	312	280 ± 64
E, 12 m SE	209	435	435	360 ± 75

After discharge:

Sample location	31 May 1998 TSS mg/l	30 Jun 1998 TSS mg/l	1 Aug 1998 TSS mg/l	19 Aug 1998 TSS mg/l	Average ± standard error of mean TSS mg/l
A, 1 m upstream	74	112	328	145	195 ± 58
B, 1 m downstream	55	151	176	173	167 ± 7
C, 3 m downstream	73	194	162	208	188 ± 12
D, 6 m downstream	49	248	198	228	225 ± 13
E, 12 m SE	52	104	164	326	198 ± 57

had been pre-discharge. This was also true for the more distant sampling points (6m downstream and 12 m SE) and thus may reflect a general lowering in suspended solid content on the mangrove during this period of the year. There is, in any case, no increase in suspended solids content of the waters, as the locations closest to the discharge point are lower than other locations in the mangrove (Table 3-49).

Coliform bacteria

Coliform bacteria were measured in mangrove surface water before and after discharge (Table 3-50).

In December 1997 and March 1998, coliform bacteria levels were 30,000 colonies/100 ml. After discharge began on 3 May 1998, coliform levels close to the outfall were influenced by coliform concentration in the discharge effluent. When 700 colonies/100 ml were counted in discharge water on 15 May 1998, only location A, 1 m upstream of the discharge showed elevated bacteria count (3500 colonies/100 ml). On 20 June 1998, when 8700 colonies/100 ml were counted in discharge water, and on 3 August 1998 when 87,000 colonies/100 ml were counted, elevated coliform levels were found in the monitoring locations 1-3 m from outfall, but point D, 6m downstream, was at or below background levels (Table 3-50).

Salinity

Salinity in the surface water of the mangrove measured December 21-22, 1997 (Table 3-51) showed considerable variability, ranging from 7 - 15 parts per thousand (ppt).

Over the course of a two day study, a smaller range was found in individual monitoring pipes, 1-2.5 ppt. At this time, the pumped tapwater in Akumal was 4.5 ppt, and salinity in the two wetland treatment systems varied from 3 to 4.5 ppt.

Table 3-50 Coliform bacteria in water of mangroves in 1998 after discharge of treated effluent.

Sample location or type	15 May Coliform MPN/100 ml	20 June Coliform MPN/100 ml	3 August Coliform MPN/100 ml	Mean Coliform MPN/100 ml
Discharge Effluent	700	8700	83,000	30,800
Station A, 1 m upstream	3500	4000	5300	4267
Station B, 1 m downstream	120	9000	46000	18373
Stn. C, 3 m downstream	0	3000	6800	3267
Stn D., 6 m downstream	820	520	40	460
Stn.E, 12 m SE	19400	510	3060	7657

* measurements of mangrove water before discharge began:
1 December 1997, 30,000 MPN/100 ml; 20 March 1997, 30,000 MPN/100 ml.

Table 3-51 Salinity in mangroves in 1997 before discharge of sewage effluent.

Location	21 Dec 0900 hr ppt	21 Dec 1530 hr ppt	22 Dec 97 1000 hr ppt	22 Dec 97 1230 hr ppt
A, 1 m upstream	13	13	14	14
B, 1 m downstream	7	8	9.5	9.5
C, 3 m downstream	9	9.5	10	10
D, 6 m downstream	9	9	10	10
E, 12 m SE	13	14	14.5	15

Salinity was measured at these locations monthly from March, 1998 through August 1998 (Table 3-52).

After discharge began in early May 1998, salinity was around 2 ppt at locations A - D which were within 6 meters of the treated effluent. However, on 31 May 1998 when salinity was low (<0.5 ppt at station E), effluent with 2 ppt increased salinity (which averaged 1.8 ppt at stations A-C).

These data suggest that salinity was mostly lowered by the discharge of treated effluent. However, in periods of very low salinity in the mangrove (e.g. after heavy rains or during periods of high input of inland fresh groundwater) the treated effluent may be expected to raise salinity in the discharge area.

Simulation of Water in Treatment Units and Mangroves

A computer simulation model was developed to increase understanding of factors affecting water inputs and outflows in the wetland treatment units and mangroves. Figure 3-52 presents systems diagrams of water in the treatment wetland units and the water in the mangrove receiving wetland with equations used in the simulation model. Figure 3-53 shows the systems diagram with calibration values for storages and for flows along pathways. Table 3-53 gives the computer program for the simulation and Table 3-54 is the spreadsheet with calibration values for storages and flows used to calculate coefficients of the model.

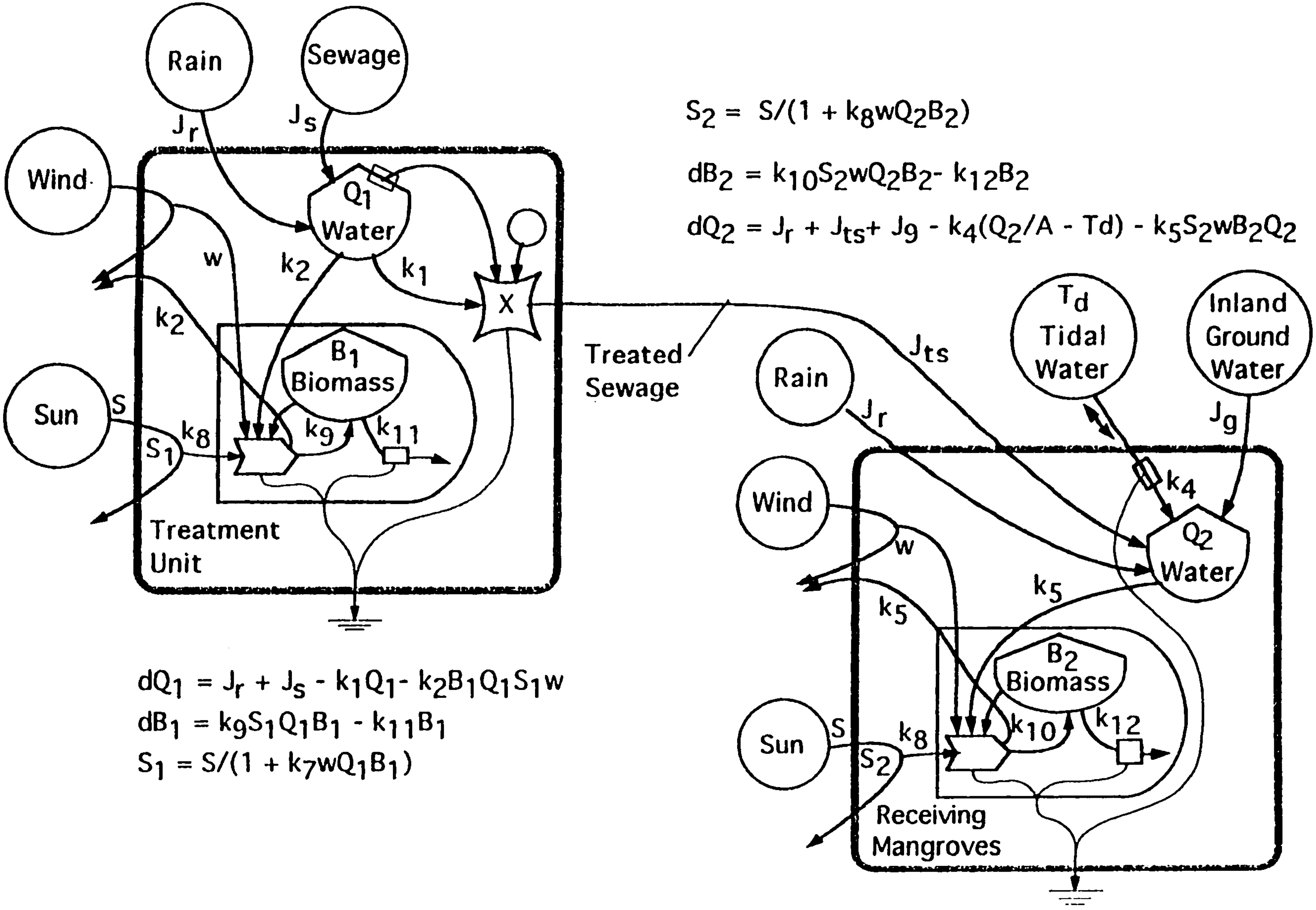
The treatment wetland units receives inputs of water from incident rainfall (J_r) that falls directly on the wetlands and sewage (J_s). Transpiration (k_2) is controlled by amount of water in the wetland (Q_1) and its interaction with sunlight (S_1), wetland biomass (B_1), and the wind (w). Wetland biomass increase (k_8) is autocatalytic, driven by

Table 3-52 Salinity in mangroves in 1998. Discharge of treated effluent began May, 1998.

Location	3 Mar	30 Mar	30 Apr	31 May	30 Jun	1 Aug	19 Aug
	ppt	ppt	ppt	ppt	ppt	ppt	ppt
A, 1 m upstream	9	11	12	1.5	2	2	2
B, 1 m downstream	7	9	10.5	2	2	1.5	2
C, 3 m downstream	5	12	14	1.5	2	2	1.5
D, 6 m downstream	5.5	8	10	< 0.5	4	2	2
E, 12 m SE	5.5	12.5	13.5	< 0.5	3	5	4

Table 3-53 Salinity in mangroves in 1997 before discharge of sewage effluent.

Location	21 Dec	21 Dec	22 Dec 97	22 Dec 97
	0900 hr	1530 hr	1000 hr	1230 hr
	ppt	ppt	ppt	ppt
A, 1 m upstream	13	13	14	14
B, 1 m downstream	7	8	9.5	9.5
C, 3 m downstream	9	9.5	10	10
D, 6 m downstream	9	9	10	10
E, 12 m SE	13	14	14.5	15



$$S_2 = S/(1 + k_8wQ_2B_2)$$

$$dB_2 = k_{10}S_2wQ_2B_2 - k_{12}B_2$$

$$dQ_2 = J_r + J_{ts} + J_g - k_4(Q_2/A - Td) - k_5S_2wB_2Q_2$$

$$dQ_1 = J_r + J_s - k_1Q_1 - k_2B_1Q_1S_1w$$

$$dB_1 = k_9S_1Q_1B_1 - k_{11}B_1$$

$$S_1 = S/(1 + k_7wQ_1B_1)$$

Figure 3-52 Systems diagram for simulation model of water budgets of treatment unit and receiving wetland showing difference equations.

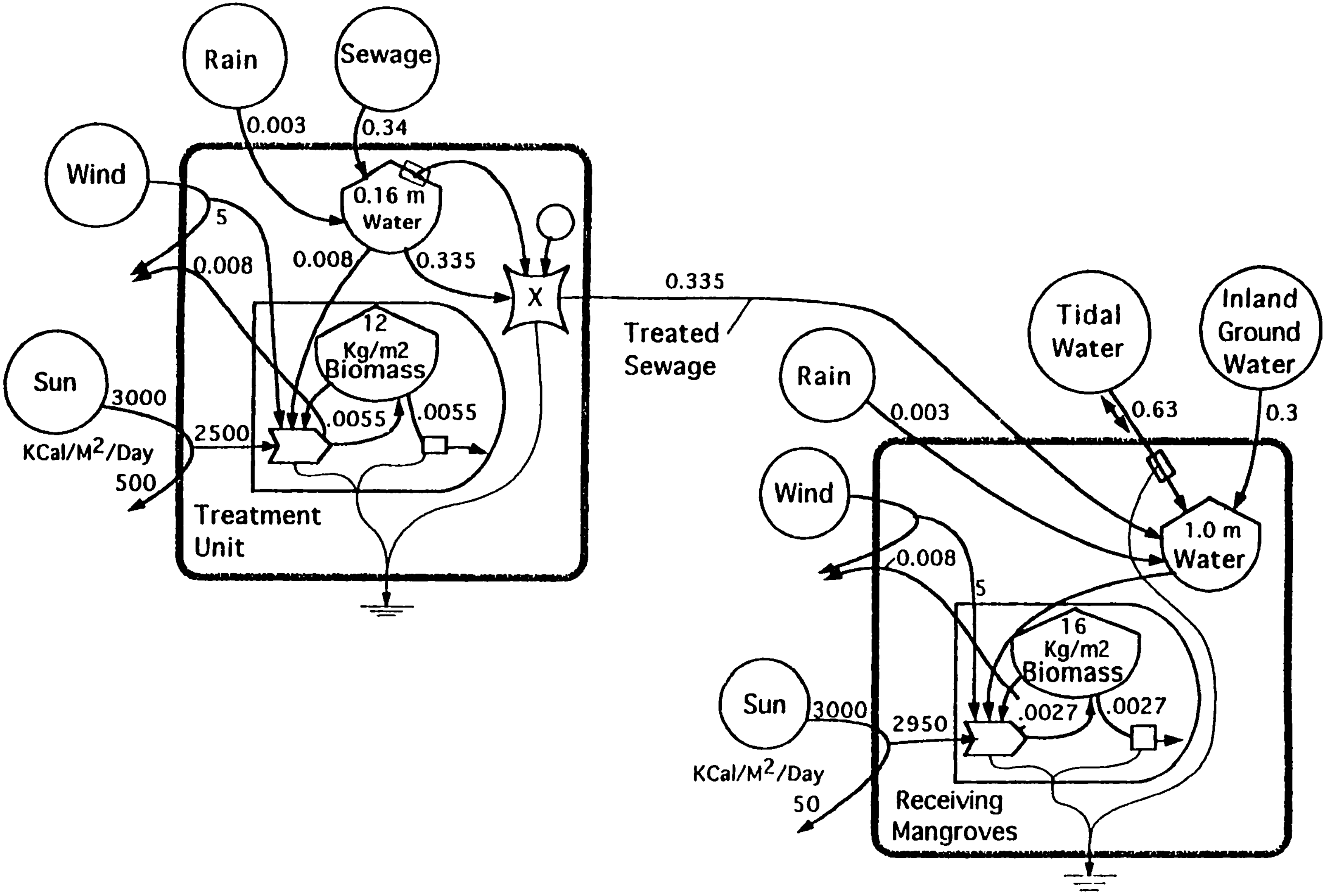


Figure 3-53 Systems diagram showing steady state storages and pathway flows for water budget simulation model of treatment units and mangroves.

Table 3-53 Computer program in BASIC for simulation model of water budget in treatment wetland unit.

```
'Water budget simulation model for
treatment system
4 CLS
5 SCREEN 1, 0
6 COLOR 15, 1
10 LINE (0, 0)-(400, 300), 15, B
15 LINE (0, 60)-(400, 60)
20 LINE (0, 120)-(400, 120)
25 LINE (0, 180)-(400, 180)
30 LINE (0, 240)-(400, 240)
35 LINE (0, 300)-(400, 300)
50 dT = 1
55 t0 = 1 ' make equal to yr #
60 Td0 = .6
65 S0 = 90
70 Q20 = .1
75 Q10 = .1
80 B10 = .2
85 B20 = .1
86 Jr0 = .01
87 Jg0 = .1
95 S = 3000
110 Td = .68
155 Jr = 0!
180 B1 = 2
185 B2 = 9
190 Q1 = .16
195 Q2 = 1
196 A = 1
205 DIM w(12), Jg(12), Js(12)
223 FOR I = 1 TO 12
224   READ w(I)
225   NEXT I
226   DATA
5,6.6,4.3,4.4,5.6,5.4,4.5,3.6,4.1,4.4,5.9,6.7
230 FOR I = 1 TO 12
232   READ Jg(I)
234   NEXT I
236   DATA
0.254,0.2,0.2,0.2,0.6,0.47,0.29,0.33,0.47,0.4
4,0.22,0.21
238 FOR I = 1 TO 12
240   READ Js(I)
242   NEXT I
244 Data
.034,0.034,0.034,0.034,0.022,0.022,0.022,0.
022,0.022,0.034,0.034,0.034
275 K2 = .0000016666#
282 k4 = 1.012625#
285 K5 = .000002#
290 K7 = .520833
292 K8 = .7375#
294 K9 = .00000114#
295 k10 = .000000675#
300 K11 = .000457
305 K12 = .000169#
306 k1 = .02902#
309 I = 1
320 PSET ((t + y * 365) / 10 * t0, 60 - S /
S0), 2
325 PSET ((t + y * 365) / 10 * t0, 160 - Q1 /
Q10), 1
330 PSET ((t + y * 365) / 10 * t0, 120 - Q2 /
Q20), 2
335 PSET ((t + y * 365) / 10 * t0, 160 - B1 /
B10), 4
340 PSET ((t + y * 365) / 10 * t0, 180 - B2 /
B20), 3
350 PSET ((t + y * 365) / 10 * t0, 60 - Jr /
Jr0), 2
360 PSET ((t + y * 365) / 10 * t0, 180 - Jg(I)
/ Jg0), 4
380 S = 3000 + 1500 * SIN(t * .0193 - 90) '
ANNUAL SINE WAVE SUNLIGHT
385 IF S < 0 THEN S = 0
390 S1 = S / (1 + K7 * Q1 * B1 * w(I))
395 S2 = S / (1 + K8 * Q2 * B2 * w(I))
400  Jts = Q1 - .16
403 IF Q1 < .16 THEN x = 0
405 IF Q1 > .16 THEN x = 1
415 dQ1 = Js(I) + Jr - Jts - (K2 * S1 * B1 *
Q1 * w(I))
418 dQ2 = Jr + (x * k1 * Q1) + Jg(I) - (k4 *
(Q2 / A - Td)) - (K5 * S2 * B2 * w(I) * Q2)
425 dB1 = (K9 * S1 * Q1 * B1 * w(I)) -
(K11 * B1)
```

Table 3-53 continued

```
428 dB2 = (k10 * S2 * Q2 * B2 * w(I)) - (K12 * B2)
430 ET1 = (K2 * S1 * B1 * w(I) * Q1)
431 ET2 = (K5 * S2 * B2 * w(I) * Q2)
440 B1 = B1 + dB1 * dT
442 Q1 = dQ1 * dT + Q1
444 Q2 = dQ2 * dT + Q2
446 B2 = dB2 * dT + B2
450 TJr = TJr + Jr * dT
454 TJs = TJs + Js(I) * dT
456 TET1 = TET1 + ET1 * dT
458 TJts = TJts + Jts * dT
460 TET2 = TET2 + ET2 * dT
560 prob = RND
562 Jr = 0
570 IF t <= 30.42 AND prob < .164 THEN Jr = .0156
580 IF (t > 30.42 AND t <= 60.84) AND prob < .131 THEN Jr = .0103
590 IF (t > 60.84 AND t <= 91.26) AND prob < .072 THEN Jr = .0192
600 IF (t > 91.26 AND t <= 121.68) AND prob < .059 THEN Jr = .0229
610 IF (t > 121.68 AND t <= 152.1) AND prob < .158 THEN Jr = .0348
620 IF (t > 152.1 AND t <= 182.52) AND prob < .26 THEN Jr = .0182
630 IF (t > 182.52 AND t <= 212.94) AND prob < .224 THEN Jr = .0129
640 IF (t > 212.94 AND t <= 243.46) AND prob < .256 THEN Jr = .0129
650 IF (t > 243.46 AND t <= 273.78) AND prob < .322 THEN Jr = .0153
660 IF (t > 273.78 AND t <= 304.2) AND prob < .312 THEN Jr = .0148
670 IF (t > 304.2 AND t <= 334.62) AND prob < .253 THEN Jr = .0097
680 IF (t > 334.62 AND t <= 365) AND prob < .22 THEN Jr = .0085
690 IF (y > 5 AND y < 10) THEN Jr = Jr * .5
700 IF t <= 30.42 THEN I = 1
702 IF (t > 30.42 AND t <= 60.84) THEN I = 2
704 IF (t > 60.84 AND t <= 91.26) THEN I = 3
706 IF (t > 91.26 AND t <= 121.68) THEN I = 4
708 IF (t > 121.68 AND t <= 152.1) THEN I = 5
710 IF (t > 152.1 AND t <= 182.52) THEN I = 6
712 IF (t > 182.52 AND t <= 212.94) THEN I = 7
714 IF (t > 212.94 AND t <= 243.46) THEN I = 8
716 IF (t > 243.46 AND t <= 273.78) THEN I = 9
718 IF (t > 273.78 AND t <= 304.2) THEN I = 10
720 IF (t > 304.2 AND t <= 334.62) THEN I = 11
722 IF (t > 334.62 AND t <= 365) THEN I = 12
1000 t = t + dT
1010 IF t < 365 GOTO 320
1020 y = y + 1
1030 t = 1
1040 IF y <= 10 GOTO 320
```

Table 3-54 Spreadsheet for calculation of coefficients in water bydget simulation model of treatment units and mangroves.

Sources:

Sunlight S= 3000 kcal/m2/day

Calibration States:

Unused sunlight, treatment wetland

S1= 500 kcal/m2/day

Unused sunlight, mangrove wetland

S2= 50 kcal/m2/day

Tide level Td= 0.68 m3/m2

Sewage input

Js= 0.034 m/m2/day

Rain Jr= 0.00302 m/m2/day

Inland GW Jg= 0.3 m/m2/day

Wind w= 5 m/sec

Depth of water in treatment wetland

Q1= 0.16 m

Depth of water in mangrove wetland

Q2= 1 m

Biomass, treatment wetland

B1= 12 kg/m2

Biomass,mangrove wetland

B2= 16 kg/m2

Flows per day:

Calculations of coefficients	flow (qty)		
Outflow from treatment wetland			
k1 * (Q1 - Qthreshold) =		k1=	0.02902
transpiration in treatment wetland			
k2*B1*Q1*S1*w =	0.008	k2=	1.67E-06
Exchange between mangrove surface water and groundwater			
k4*((Q2/A) -Td) = ((Jr + Jts + Jg - (k5*B2*S2*W*Q2))		k4=	1.012625
k4*((Q2/A) -Td) =	0.32404		
transpiration in mangrove wetland			
k5*B2*Q2*S2*w =	0.008	k5=	0.000002
Unused sunlight, treatment wetland			
k7*Q1*B1*w = 500	500	k7=	0.520833
Unused sunlight,mangrove wetland			
k8*Q2*B2*w =	50	k8=	0.7375
Biomass increase, treatment wetland			
k9*S1*Q1*B1*w =	5.48E-03	k9=	1.14E-06
Biomass increase,mangrove wetland			
k10*S2*Q2*B2*w =	2.70E-03	k10=	6.75E-07
Respiratory losses, treatment wetland			
k11*B1 =	5.48E-03	k11=	0.000457
Respiratory losses, mangrove wetland			
k12 * B2 = .0027	2.70E-03	k12=	0.000169

sunlight, wind, water levels, and the quantity of existing wetland biomass. Respiratory losses (k_{11}) are a function of quantity of the biomass. Water exits the system by two methods: from transpiration from the wetland plants, and by outflow of treated wastewater (k_1). Because of the density of plants, evaporation and plant uptake are minimal and have been omitted from this aggregated model. Treated sewage (k_1) overflows out drainage pipe and leaves the wetland for the mangrove when the holding capacity of the treatment unit is exceeded (X in switch =1).

The water inputs to the mangroves are direct incident rainfall (J_r), treated wastewater outflow from the treatment wetland units (J_{ts}), and groundwater input (J_g) and tidal inflow (k_4) when the water level of the mangrove (Q_2) is lower than that of the tides (Td). Water outputs are from transpiration (k_5) by the mangrove vegetation and tidal exchange (k_4) when mangrove water level exceeds sea level. Mangrove biomass grows (k_{10}) by an autocatalytic process, the energy drivers being sunlight (S_2), wind (w), available fresh water (Q_2) and its own biomass state (B_2). Mangrove biomass losses through plant respiration and animal consumption (k_{12}) are a function of the quantity of biomass.

The model was calibrated and its sources programmed with seasonally varying data from available literature on climatic factors (temperature, humidity, rainfall, tidal range, wind, evapotranspiration, groundwater flow) in the Yucatan (Appendix B). Groundwater discharge becomes more important in months with heavy rain, and treated effluent decreases at the same time of year (the off-peak tourist summer season). In the dry season, sewage inputs are greater and rainfall is decreased.

Simulation of the model under normal anticipated conditions (Figure 3-54) shows that treatment wetland biomass increases more rapidly than the mangrove biomass, though the constructed wetland reaches equilibrium (when rate of primary productivity equals respiration) at a lower value than the mangroves. Water levels remain fairly constant in the treatment wetlands since effluent discharge to mangroves occurs when the limestone is saturated, however there is a small annual elevation due to peak tourist season loading. Sewage inputs are an order of magnitude greater than rainfall inputs. Mangrove water levels reflect the influence of the large inland groundwater discharge during the summer/fall and inputs of treated sewage effluent are of the same order of importance as groundwater from inland sources.

Simulation runs were conducted for extreme conditions (Appendix B). If sewage loading is increased ten-fold due to increased population use of the treatment system, there is rapid growth of wetland biomass and the mangroves show higher standing water levels (Figure 3-55). If inland development has eliminated groundwater flow to the mangroves, this results in lowering mangrove water levels, and decreasing mangrove growth (Figure 3-56). Hurricane events bring high rain, wind, and tidal levels, resulting in loss of half of both treatment wetland and mangrove biomass. Wetland vegetation recovery is more rapid than mangrove, but that overall both ecosystems may take 5-10 years to fully restore biomass after a large hurricane (Figure 3-57).

Notes on literature values used to estimate storage values and pathway flows in the water budget simulation model are given in Appendix B.

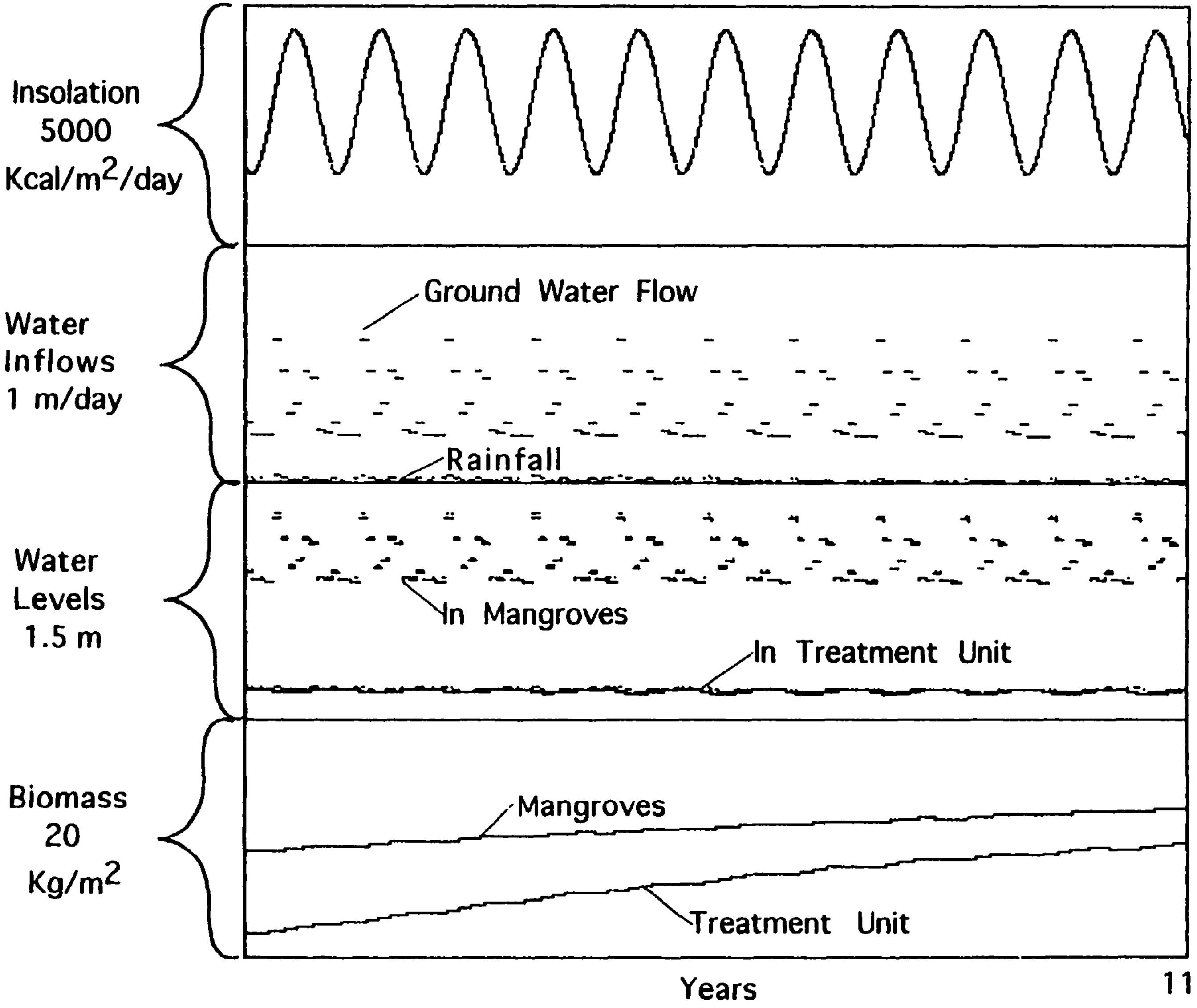


Figure 3-54 Computer simulation of the water budgets of treatment units and mangroves.

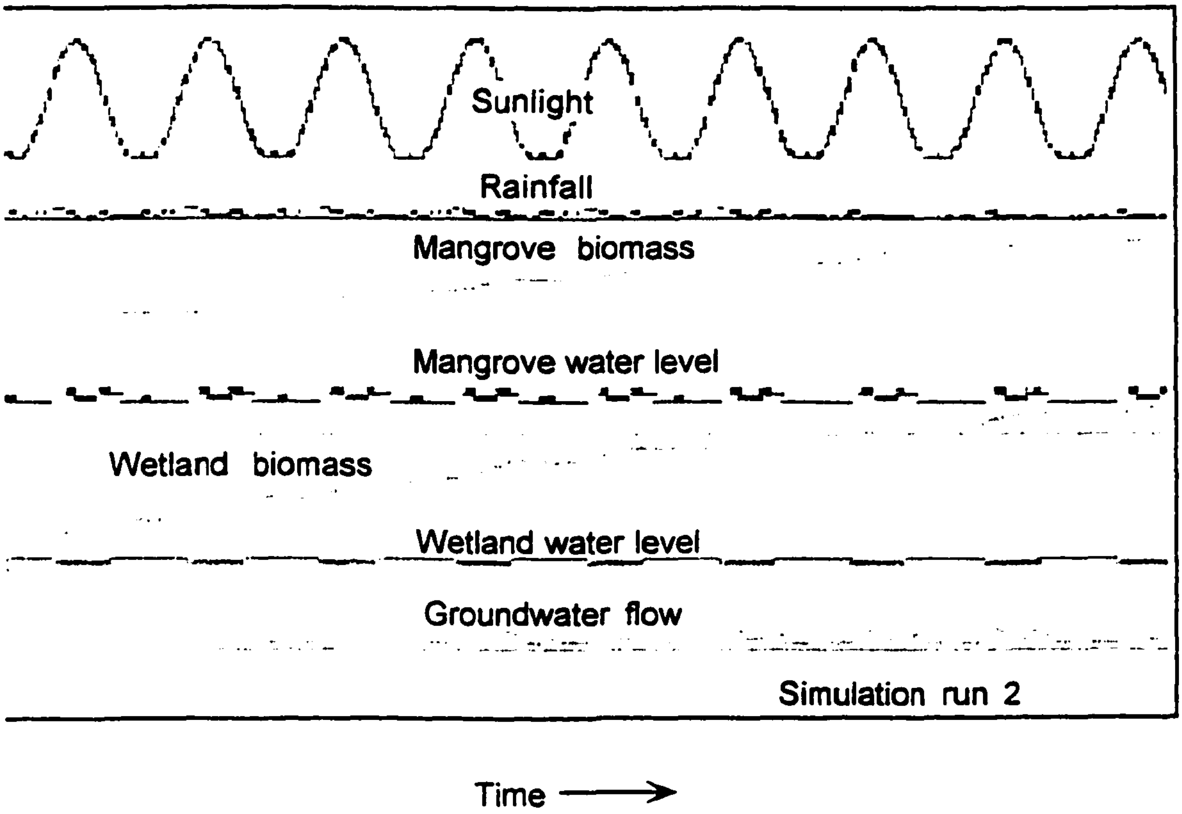


Figure 3-55 Simulation of water budget for wetland treatment unit and mangroves with increase of wastewater loading (10 times higher). Scale: sunlight 5000 Kcal/m^2/day, biomass 20 kg/m2, water levels 1.5 m, water inflows 1 m/day.

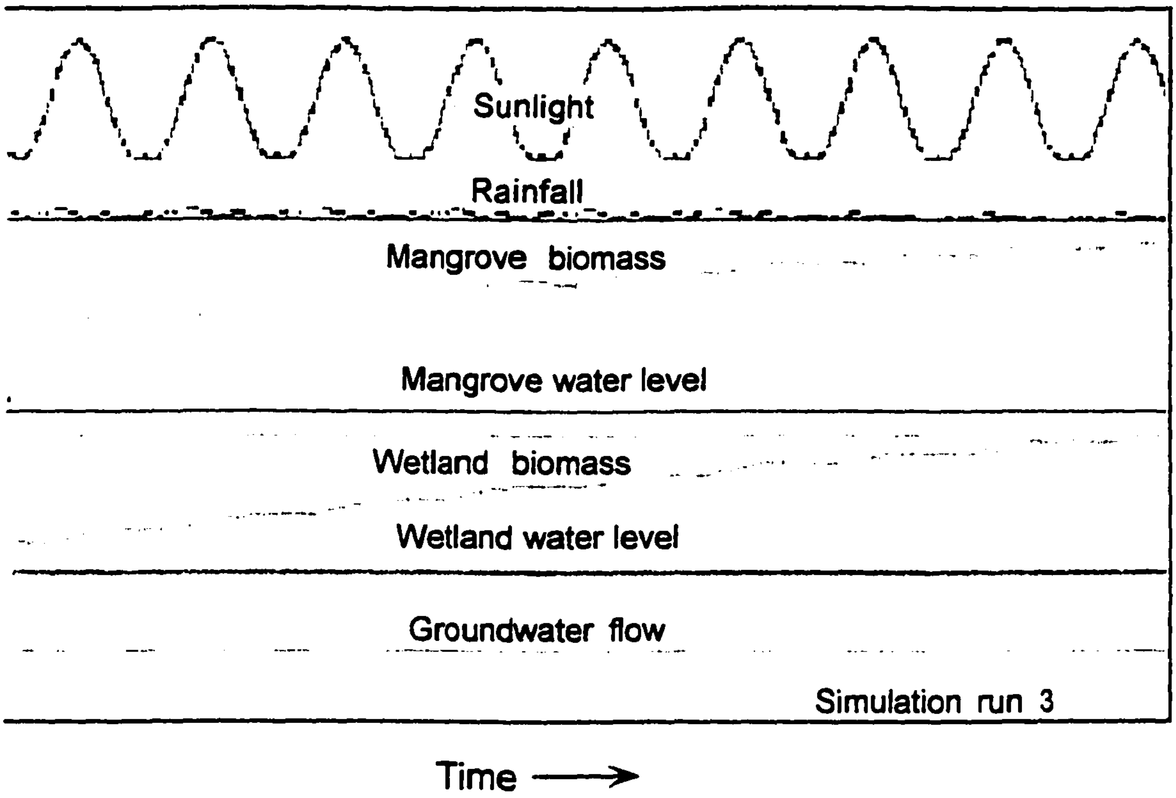


Figure 3-56 Simulation of water budget for wetland treatment unit and mangroves with loss of groundwater inflow. Scale: sunlight 5000 Kcal/m^2/day, biomass 20 kg/m2, water levels 1.5 m, water inflows 1m/day.

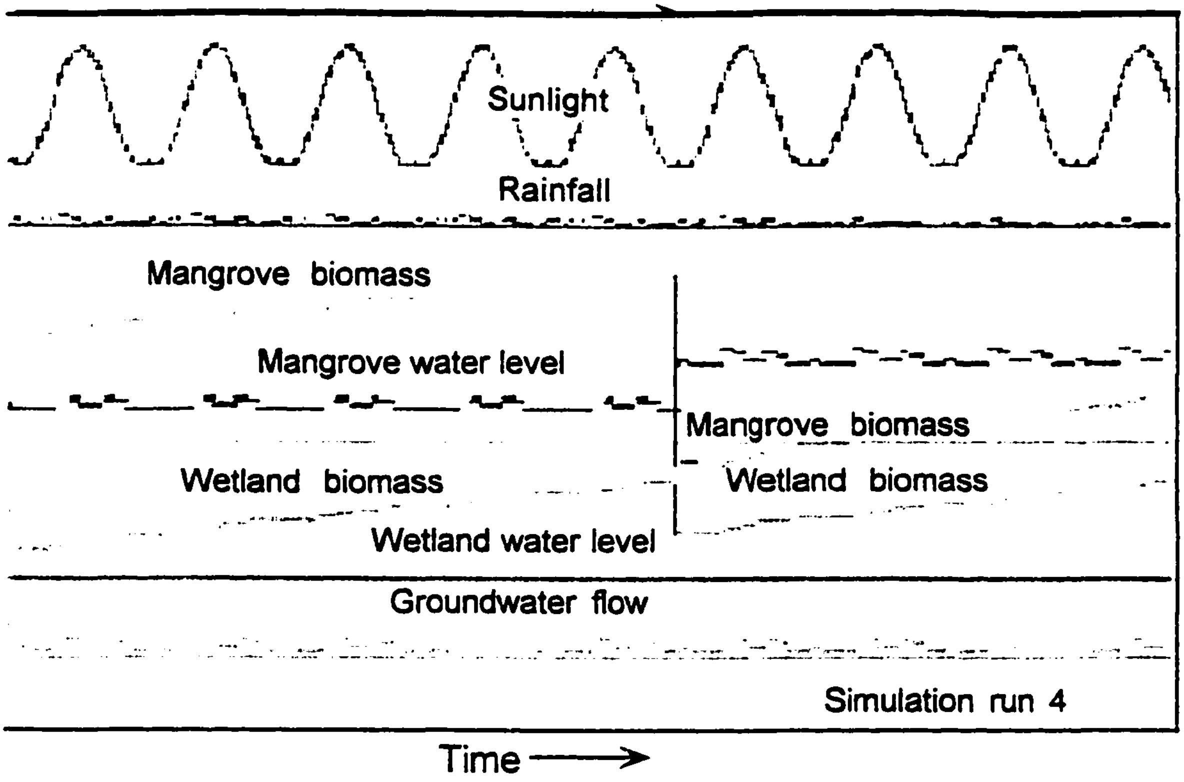


Figure 3-57 Simulation of water budget for wetland treatment unit and mangroves with hurricane event at year 5. Scale: sunlight 5000 Kcal/m^2/day, biomass 20 kg/m2, water levels 1.5 m, water inflows 1m/day.

Regional Potential of Wastewater Treatment System

Definition of Coastal System

For purposes of estimating the regional role of the new wastewater treatment systems, a square kilometer area around Akumal was defined (Figure 3-58). Data collected from the homeowner's association in Akumal combined with interviews permitted an assessment of the environmental flows and support systems for this area. Judging from the pattern of current development, this area may contain 15 private houses and four hotels/condominium complexes, with a total resident population of 225-250 (permanent residents plus tourists).

Emergy Evaluation

For this scenario, inputs to this area are diagrammed in Figure 3-59 and evaluated in Table 3-55. With the use of transformities from Table 2-1, emergy and emdollars were calculated in the last two columns.

The largest renewable source emergy flows are those of inland groundwater and hurricanes. Tourism revenues (income) are the largest imported emergy flow, followed by imported goods, petroleum products and building materials (limestone, sand, concrete). Local services are about 25% of tourist revenues (Table 3-55). In aggregate, natural emergy from renewable natural resources is about 39% of total emergy flows.

Inflows are grouped in categories in Figure 3-60 and used to calculate the indices shown in Table 3-56. Empower density is 1.2 E16 sej /ha /yr. Service emergy compared to free energy is 0.32. Imported emergy flows are somewhat greater than local ones as the nonrenewable / renewable resource ratio is 1.22. The investment ratio of 1.49 is far lower than the United States, where it averages 7 (Odum, 1996). The sej / money flow ratio is

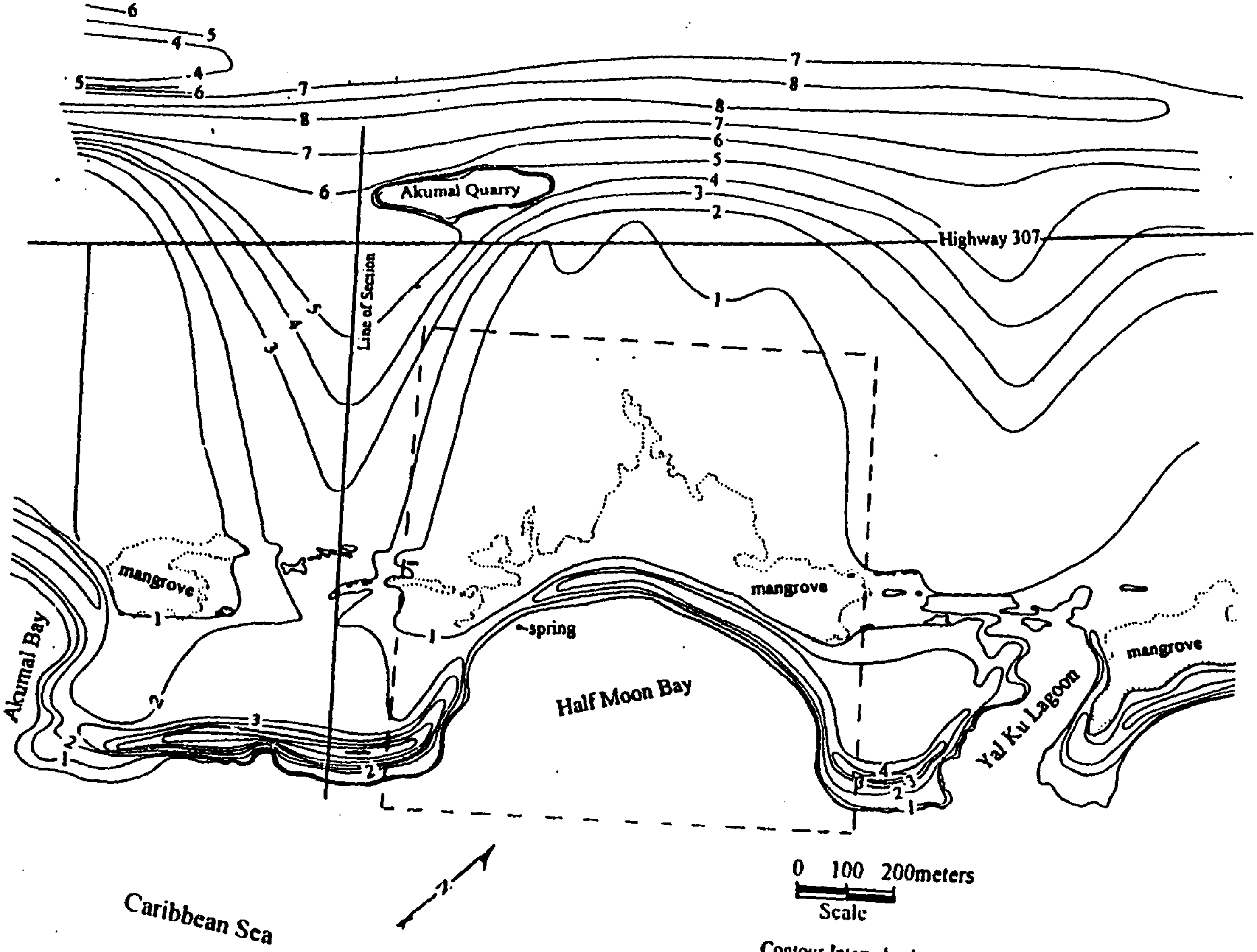


Figure 3-58 Map of Akumal, Mexico showing the one square kilometer coastal study area.

Table 3-55 Emergy evaluation table of 1-square-kilometer of developed coastline, Akumal, Mexico (see Figure 3-58).

Note	Item	Raw Units	Transformity (sej/unit)	Solar emergy E18 sej	EmDollars
	RENEWABLE RESOURCES:				
1	Sunlight	4.54 E13 J	1	<0.001	<0.001
2	Rain	5.5 E12	1.544 E4	0.09	62.0
3	Rain transpired	4.46 E12 J	1.544 E4	0.07	51.1
4	Rain, geopotential	2.65 E11	8.88 E3	<0.001	<0.001
5	Wind, kinetic	2.7 E9	6.63 E2	<0.001	<0.001
6	Hurricanes	1.14 E13	9.579 E4	1.09	796
7	Waves	7.88 E6	2.59 E4	<0.001	<0.001
8	Tide	7.53 E5	2.36 E4	<0.001	<0.001
9	Earth cycle	1 E12	2.9 E4	0.03	21.2
10	Inland water flow	7.41 E13	4.8 E4	3.54	2,584
11	Pumped groundwater	4.28 E11	4.8 E4	0.02	15.0
	Subtotal (items 2 + 6 + 9 + 10)			4.77	3,482
	NON-RENEWABLE RESOURCES				
12	Loss of soil due to development	4.24 E11	7.37 E4	0.031	22.6
13	Loss of vegetation due to development	4.7 E11	2 E5	0.094	68.6
	Subtotal (items 12+13)			0.13	95
	LOCAL SERVICES				
14	Local labor and services	7.68 E5$	1.88 E12	1.44	1,146
	+ ½ of item 22			0.13	
	Subtotal			1.57	
	IMPORTED GOODS AND SERVICES				
15	Forest products	5.09 E12	3.49 E4	0.2	146
16	Limestone, gravel, sand	1.53 E11	8.98 E6	1.4	1,022
17	Food	8.6 E11	8.5 E4	.007	51
18	Gas	6.96 E4	4.8 E4	<0.001	<0.001
19	Petroleum products	1.84 E13	6.6 E4	1.21	880
20	Electricity	2.37 E12	1.74 E5	0.4	292
21	Imported Goods	7.02 E5$	1.88 E12	1.32	885.4
22	Capital investments	1.375 E5$	1.88 E12	0.25	183.5
23	Tourism	4.9 E5$	1.88 E12	0.92	2,476.7
	Subtotal (items 15-23)			5.71	4,168
	Total			12.05	8,891

* Column 6 (EmDollars) based on 1.37E12 sej/$, U.S. dollar/emergy ratio for 1996

Table 3-55 continued

Notes:

1 SUN
Solar exposure of 2381 hours/year (Viguera et al, 1994)
area = 1E6 m2
avg insolation: 1.55 E2 kcal/cm2/yr (Brown et al, 1992) [taken as equal to that of Nayarit, Mexico]
albedo = .3
Energy = area * avg insolation * (1 - albedo) = 1E6 m2 * 1.55E2 kcal/cm2 * E4 cm2/m2 *.7 * 4186 J/kcal
= 4.54 E13 J

2 RAIN, TOTAL
Average rainfall at Puerto Moreles is 1123 mm ((Ibarra and Davalos, 1991) for Puerto Moreles, Q.R.
and at Tulum is 1104 mm (Viguera et al, 1994). Therefore, a value of 1114 mm was used
transformity = 15,444 sej/J (Odum, 1996 p. 186)
land area = 1E6 m2
rainfall = 1.114 m
Rain, total = area * rainfall * Gibbs # = (1E6 m2) * (1.114 m) * 1000 kg/m3 * 4.94E3 J/kg = 5.5E12

3 RAIN, TRANSPIRED
land area = 1E8 m2
rainfall = 1.114 m
ET = 0.9 (Viguera et al, 1994), given as % of rainfall = .81
Rain, transpired = area * ET * rainfall * Gibbs #
=1E6m2 * 1.114m * .81 * 1000 kg/m3 * 4.94E3 J/kg = 4.46E12
transformity (Odum, 1996 p. 186): 15,444/J

4 RAIN, GEOPOTENTIAL
Transformity = 8.888E3 (Odum, 1996, p. 186)
Energy = area * %runoff * rainfall * average elevation * gravity
= 1E6 m2 * [(1-ET)= .81]* 1.114 m * 1000 kg/m3* 3 m * 9.8 m/s = 2.65 E11

5 WIND
Average wind velocity of 5.0 m/s (Ibarra and Davalos, 1991) for Puerto Moreles, Q.R.
Wind transformity = 663 sej/J (Odum, 1996, p. 186)
Diffusion coefficient - taken as similar to Tampa, Fl = 2.2 m3/m/sec (Odum, 1996, p.295)
Vertical gradient - taken as similar to Tampa, Fl =1.9E-3 m/sec/m
Kinetic energy of wind = (height) (density) (diffusion coefficient) (wind gradient) (area)
energy at 1000 m = (1000 m) (1.23 kg/m3) (2.2 m3/m/sec) (5m/s/m) (1E6m2)
energy = 1.35E12 J
energy available at ground level = 20% (H.T. Odum, pers. comm.) = .2 * 1.35E10 J = 2.7E9 J

6 HURRICANES
Transformity = 9.579E4 sej/J (Scatena et al, in press)
Method following that of Scatena et al.:
average hurricane has kinetic energy of wind of 1.3E18 j/day (Riehl, 1979)
assume has overall diameter of 500 km but hurricane winds in two 50 km zones around center,
and strip 1 km wide passes over Akumal location; assume 10% of wind energy does work at surface
assume area on average has major hurricane event every 50 years

Table 3-55 continued

hurricane wind energy = (0.10)*(1.3 E18 J/day)* (0.25 days)* (1 km * (50+50 km)) / [(3.14*250*250 km)* (50 yr) = 1.14 E13 J/yr

7 WAVES
Average wave height is given as 0.8 m for the coast at Puerto Moreles (Ibarra and Davalos, 1991)
Energy of waves absorbed at shore = shore length*1/8*density*gravity*height squared * velocity (Odum, 1996, p. 298)
velocity is: square root of gravity * depth at gauge (taken as 3 m for Akumal coastline)= 9.8m/sec2 * m^.5= 5.4m/sec
energy = 1000 m * 1/8 * 1.025E3 kg/m3*9.8m/sec2 *.64 * 5.4m/sec = 4.34E6
Transformity for wave energy = 25,889 sej/J (Odum, 1996)

8 TIDE
average tidal height of 18.1 cm (Ibarra and Davalos, 1991) for Puerto Moreles, Q.R.
transformity for tidal energy = 23,564 sej/J (Odum, 1996, p. 186)
Energy = shelf area * (0.5) * tides/yr * (height squared) * (density) * gravity (Odum, 1996, p.298)
=5E4m2 * 0.5 * 730 * 3E-2m2 * 1025 kg/m3 * 9.8 m/sec2 = 7.53 E5

9. EARTH CYCLE
Transformity = 29,000 sej/J (Odum, 1996, p. 186)
Energy = (land area) (heat flow per area)
heat flows for old stable areas is 1E6 j/m2/yr (Odum, 1996, p. 296)
Energy = 1E6 m2 * 1E6 j/m2 = 1E12

10 INLAND GROUNDWATER FLOW
following methodology of Back, 1985:
average rainfall = 1.05 m - .9 m evapotranspiration = .15 m mean annual recharge to groundwater
area including inland drainage basin = 65,500 km2; total recharge = 9,800E6 m3 per yr. groundwater consumption (Lesser, 1976) is 350E6 m3/yr. Assuming this water is lost, total discharge along the approximately 1,100 km of coastline = 9450E6 m3/ 1100 km = 8.6E6 m3/yr for each km of coastline
the amount of groundwater underlying the coastal area can be estimated as around 3 m (Back, 1985)
thus total groundwater in the study area is about 50% of this depth, or 1.5 m * 10E6 m2 = 1.5E7m3
1.5E7 * 1000 kg/m3 * 4.94E3 J/kg = 7.41E13

11 PUMPED GROUNDWATER
calculated at 100 gallons/person/day
Energy: 225 people *100gal/day * 1m3/260 gallons * 365 days * 1000 kg/m3 * 4.94E3 J/kg
Energy = 4.28E11
Transformity = 4.8E4 (Odum, 1996, p. 120)

12. LOSS OF SOIL (due to development)
estimate loss of 20m2 of mangrove wetland per hotel * 4 = 80 m2 and 5 m2 per house * 15 = 60m2
total 140 m2; depth of organic soil @ 0.3m * .06 g/cm3 (bulk density mangrove soil from this study)
soil lost = 140 m2 * 0.3m * 1 E6cm3/m3 * .06g/cm3 = 2.52 E6 g in mangrove
loss of soil of beach/sand dune ecosystems: 4 E3 m2 x 0.15m = 6 E2m3 * 1.0 g/cm3 (bulk density)
soil lost = 6.2 E2m2 * 1 E6 cm3/m3 * 1.0 g/cm3 = 6.2 E8g
Energy = (2.52 E6g)*(0.76organic)*(5.4Kcal/g)*(4186J/Kcal) + (6.2 E8g)*(0.03organic)*(5.4Kcal/g)*(4186J/Kcal) = 4.33 E9 J + 4.2E11 =4.24 E11J
Transformity = 7.37 E4 sej/J (Brown et al, 1992)

Table 3-55 continued

13. LOSS OF VEGETATION (due to development)
average biomass for mangrove = 15 kg/m2 (Mitsch and Gosselink, 1993); sand dune est. at 0.5 = 7.5 kg/m2
lost vegetation: 140m2 * 15 kg + 4 E3m2 * 7.5 kg = 3.21 E4 kg
Energy = 3.21 E4kg * 1 E3 g/kg * 3.5 Kcal/g * 4186J/Kcal = 4.7 E11 J
Transformity = 2E5 (Brown et al, 1992 for agricultural. + forest products)

14 LOCAL SERVICES
estimated from revenues of local labor and businesses (e.g. diving shops, travel agency etc.)
125 local workers @ $35 week * 52 weeks = $227,500
15 higher paid labor (dive instructors, drivers etc.) @ $3,000/month * 12 = $540,000
Total $7.68E5
Mexican national sej/$ = 1.88 E12 (Trujillo, 1998)

15 WOOD
wood products harvested locally for construction, repairs + palm frond for roofing
estimated at 500 m3/yr
Energy = 500m3 * 1E6cm3/m3 * 10176J/cm3 = 5.09E12
transformity = 3.49E4 (Brown et al, 1992)

16 LIMESTONE, GRAVEL, SAND
limestone (+ local sand and gravel): used in construction and repair.
from survey data: 120 m3/yr sand; 120 m3 gravel; 60 m3 limestone rock

Transformity of limestone gravel and rock =1.62E6 sej/J from Odum (1996, p. 310)
Weight of limestone from Limestone Products, Newberry, FL (pers. comm.): 3000 lbs/m3
Energy (gravel) = 120 m3 * 3000 lbs/m3 * 454 g/lb *611 J/g = 9.99E10
limestone rock, 5-10 cm. rock, from Limestone Products, Newberry, FL (pers. comm.): 2700 lbs/m3
Energy (rock)= 60 m3 * 2700 lbs/m3 * 454 g/lb * 611J/g = 4.49E10
est. wt of sand from Florida Rock Mines, Grandin, FL plant (pers. comm.): 3100 lbs/m3
transformity of sand using Odum (1996, p. 310) for sandstone: 2E7 sej/J
Energy (sand) = 120m3 * 3100 lbs/m3 * 454 g/lb * 50J/g = 8.44E9
total energy (gravel, rock and sand) = 1.53E11
Composite transformity calculated by combining those for gravel, rock and sand in proportions of materials used

17 FOOD
Based on 2500 Kcal/person/day (10.47E6 J/day) and population on average of 225
Transformity: 8.5E4 (Brown et al, 1992)
Energy = 225 * 365 * 10.47E6J = 8.60E11

18 GAS
Hotel usage = 30,200 litters butane gas (survey data) * 6 = 181,200 l butane/yr
transformity = (Odum,. 1996, p. 187)
Energy = 1.81E5 litters * 1 ft3/28.3 litters * 1031 BTU/ft3 * 1055 J/BTU = 6.96E4 J

19 FUEL (Petroleum products)
Fuel usage by hotels (from survey data): 8500 litters gasoline/yr + 650 litters diesel
if we combine gasoline+diesel, we can estimate that owner use of oil products is 9000 l *6 = 54,000 l

Table 3-55 continued

and adding 10 l/day *365 * 150 tourists = 547,500 litters/yr; total = 601,500 litters = 150,400 gal = 54,000 gallons = 3008 barrels
Oil products energy = 3008 barrels * 5.8E6 BTU/barrel * 1055 J/BTU = 1.84E13
Transformity of petroleum products = 66,000 sej/J (Odum, 1996, p. 186)

20 ELECTRICITY
Transformity for electricity taken as mean global value = 173,681 sej/J (Odum, 1996, p. 305)
Electrical usage: avg for hotels: 144,000 kWh/yr * 4 = 576,000 (from survey data)
avg for homes: 5500 kWh/yr * 15 = 82,500 (from survey data)
Energy = (658,500 kWh) * (3.606E6 j/kWh) = 2.37E12 J

21 IMPORTED GOODS
estimated as tourist revenues - local services - 25% profit on investment =
1.96 E6$ - 7.68 E5$ - 4.9 E5$ = 7.02 E5$
Mexican national sej/$ = 1.88 E12 (Trujillo, 1998)

22 CAPITAL INVESTMENT
capital investment: figured as $50,000 per house x 15 = $750,000 and $500,000 per hotel x4 = $2,000,000.
Total $2,750,000 divided by lifetime of 20 years = $137,500
Mexican national sej/$ = 1.88 E12 (Trujillo, 1998)

23 TOURISM (Income)
from survey data, $490,000/yr per hotel * 4 = $1,960,000

To avoid double counting in table: tourist revenues – service – imported goods:
1.96 E6 – 7.02E5 – 7.68E5 = 4.9 E5$
Mexican national sej/$ = 1.88 E12 (Trujillo, 1998)

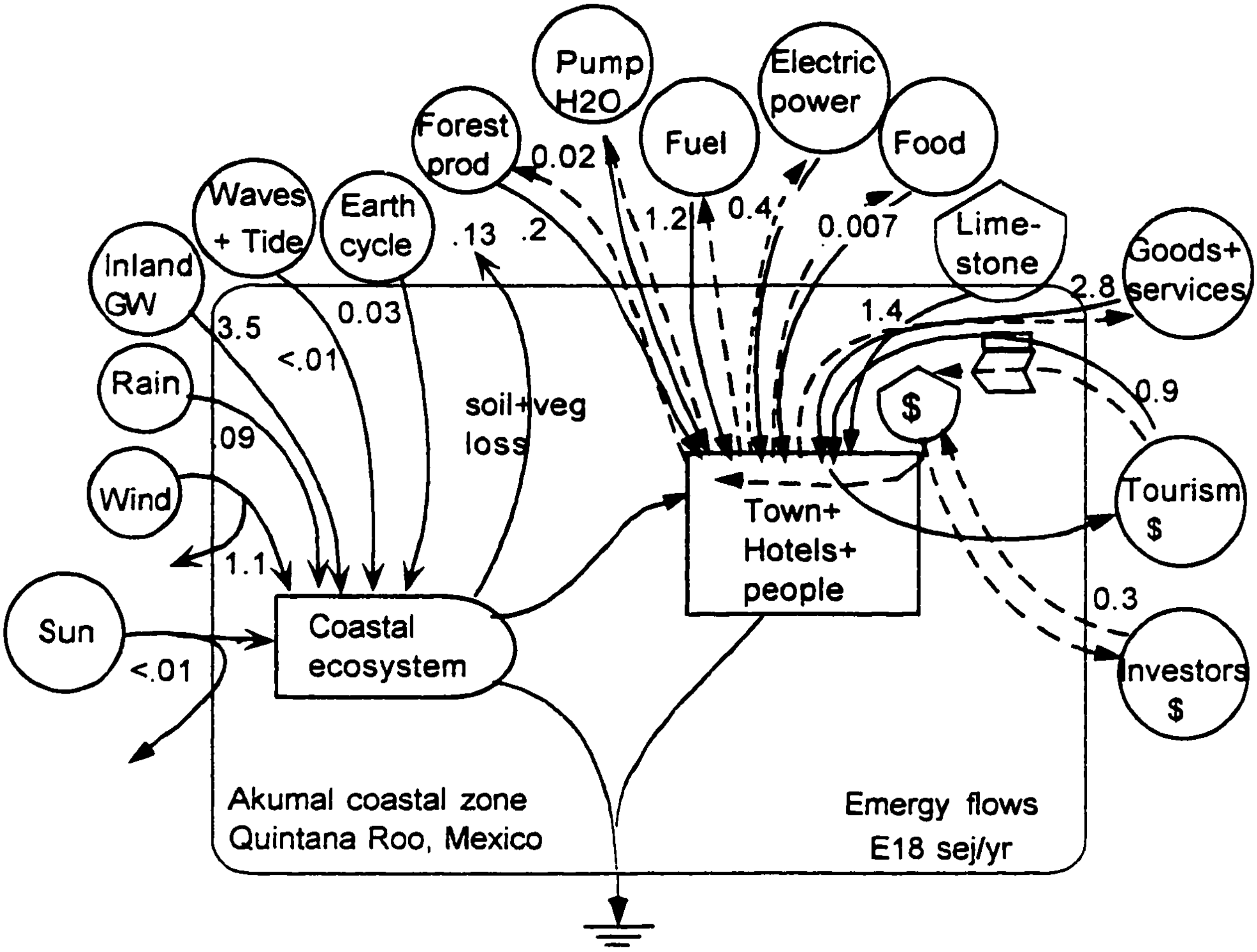


Figure 3-59. Systems diagram of the square kilometer coastal economy and environment, labelled with emergy flows from Table 3-57.

Table 3-56 Emergy indices for evaluating one square kilometer of developed coastline, Akumal, Mexico.

Name of Index	Definition	One km^2 of developed coastline, Akumal, Mexico
Nonrenewable/renewable	F +N / R	1.22
Service / free	S / N + R	0.32
Empower density	Emergy / area / time	1.2 E 16 sej / ha / yr
Emergy/$ ratio	Emergy / money flow	5.7 E12 sej/$
Investment ratio	(F + S) / (R+ N)	1.49

R = 4.77 E18 sej/yr (Table 3-57, subtotal after line 11)

N = 0.13 E18 sej/yr (Table 3-57, subtotal after line 13)

S = 1.57 E18 sej/yr (Table 3-57, lines 14 + 1/2 of line 22)

F = 5.71 E18 sej/yr (Table 3-57, lines 15-23 - 1/2 of line 22)

Empower density = 12.05 E18 sej/yr / 100 ha = 1.2 E16 sej/ha/yr

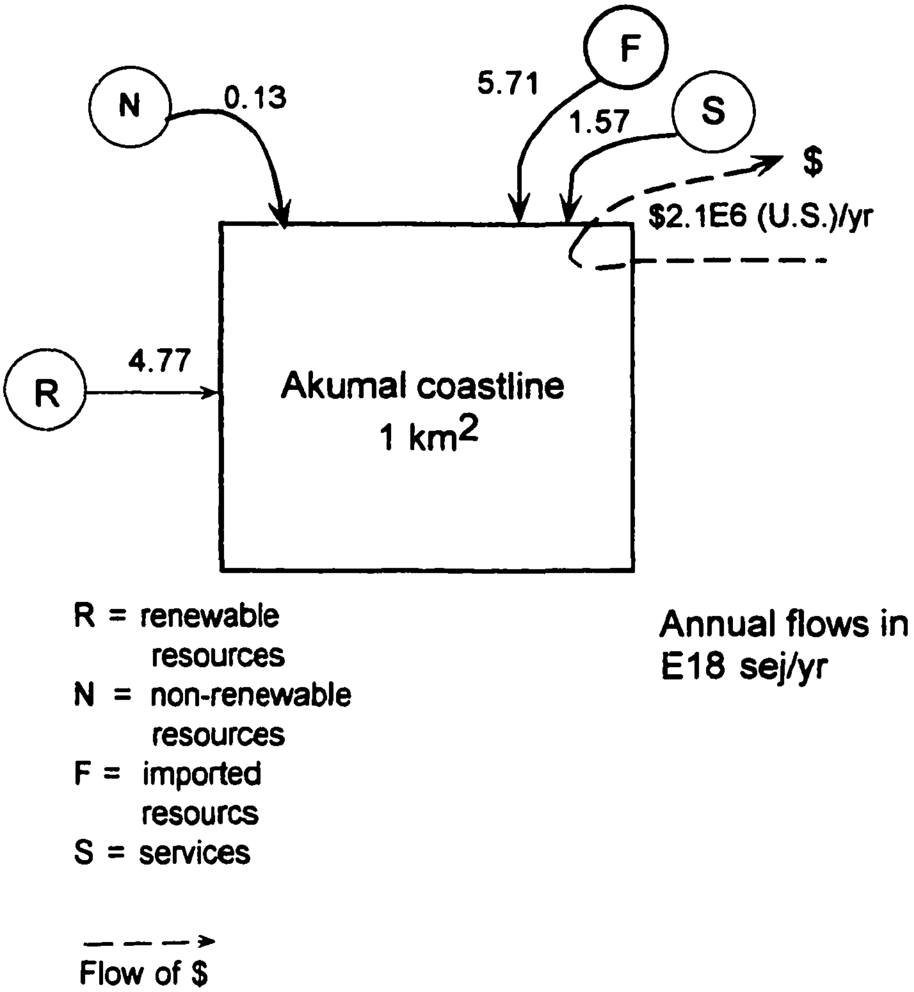


Figure 3-60 Diagram of emergy and money flows in the 1-square-kilometer coastal area, Akumal, Mexico. Units of diagram are expressed in E18 sej (solar emergy joules)/yr.

5.7 E12 sej / $, four times greater than the U.S. and three times that of the national Mexican average (Trujillo, 1998), showing the dominance of environmental emergy flow vs. monetary flow in the region.

Economic Evaluation

The application of wetland treatment systems to the developed square kilometer will require the construction of wetlands to treat the hotels and houses. Construction costs vary depending on size of the wetland, with individual house systems being smaller and therefore more expensive than the research wetlands, and the hotel systems being larger and costing less.

The two wetlands in our study averaged $165/person to construct. If we estimate the individual house systems as $250/person and hotels at $150/person, the costs for 15 houses of 6 people each = $22,500 plus 4 hotels with 160 people = $24,000 for a total capital expenditure of $46,500. If lift pumps are required on half the systems (either because slopes do not permit gravity flow, or to get treated effluent to the receiving wetland), costs will be increased by around $3,000. Averaged over 20-year lifetime (and 5 years for pumps), this equals $2,925/yr. Maintenance costs are estimated at $100 per house system, $500 per hotel system, for a total of $3500/yr. Total yearly expenditures are thus $6,425 for the wetland treatment units to serve the developed square kilometer.

Package plants would cost $15,600 for each of the hotels and if the houses send their sewage to a common collection point, the equivalent of 2.25 additional package plants will be required. Additional pumping/piping to centralize the house sewage will add an additional $10,000. The overall capital cost will be $107,500, and with an average lifetime of 7.5 years (averaging machinery and other components) is $14,330/yr. Maintenance costs at $1100/system will be $6,875, so total costs are $21,205/yr.

Given a yearly money flow of about $1,950,000 for the developed kilometer in Akumal, capital and operating/maintenance (O/M) costs of the wetland treatment systems equals 0.3% of this economic activity, and capital and O/M costs of the package plants would account for 1.1% of overall monetary flows.

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. This is 2.8% of the total electrical usage of the developed kilometer. Should half the wetland treatment systems require use of a submersible lift-pump, electrical usage 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.

Water Budget

Water budgets for a square kilometer of coastline were prepared for the square kilometer development scenario with no sewage treatment and the changes to the water budget assuming that all human wastewater is treated by the installation of wetland systems (Table 3-57, Figure 3-61).

These regional water budgets show that the largest water inputs are from tidal exchange (36.5E6 m3/yr) and secondly from inland groundwater (8.6E6 m3/yr). These quantities of water far exceed that of pumped groundwater used by the area's population (1.7E4 m3/yr). However, pumped groundwater is far larger than the quantity of water deriving from precipitation that directly falls on the square kilometer (1.05E3 m3/yr).

Table 3-57 Water budget of a square kilometer of coastline around research site without use of wetland treatment systems. Changes with use of wetland treatment units are shown in parentheses.

	Item	Quantity of water m^3/yr E5 m^3/yr
	Water in:	
1	Direct precipitation	0.01
2	Pumped groundwater used by people	0.17
3	Inland groundwater flow	86
4	Tidal inputs	365
	Total water in	451.2
	Water out:	
5	ET	8.59 (+0.02)
6	Subsurface groundwater discharge to sea (includes tidal return + discharge of input precipitation, domestic sewage + inland groundwater)	442.6 (-0.02)
	Total water out	451.2

Notes:

1 Precipitation
Based on average precipitation of 1050 mm for Yucatan (Lesser, 1976).
$1.05 * 1000\ m^2 = 1050\ m^3$

2 Pumped groundwater use
based on estimated population of 250 people x 50 gallons/person/day
$250 * 50$ gallons $* 365 = 4.56E6$ gal/yr $* m^3/264$ gal $= 17{,}280\ m^3$

3 Inland groundwater flow
based on estimate (Back, 1985) on average discharge of groundwater per km of coastline in northeastern Yucatan

Table 3-57 continued

4 Tidal exchange

-- estimated on basis that 1 m of saltwater underlies and mixes with freshwater: 1000m * 1000m * 1 m = 1E6m^3 and that turnover is every 10 days

365/10 = 36.5/yr * 1E6m^3 = 36.5E6m^3/yr

5 Evapotranspiration

sum of

a. estimates by Lesser (1976) that .9 m on average of 1.05 of precipitation was evapotranspired in the Yucatan

.9m * 1000m^2 = 900 m^3

b. plus 690 m^3 from ET of water used for watering gardens etc.
(based on estimates that average per capita production of wastewater is 30 gal/person/day in the Yucatan. 20 gal/person/day is the difference between water consumption and wastewater production rates, usually largely accounted for by watering of gardens etc.
assume that this water has same characteristics as GW pumped
20 gal/person/day * 250 people * 365 * m^3/264 gal = 6,910 m^3
further assume that 10% of this water is lost to ET before infiltrating
therefore, ET is increased by 690 m^3)

c. plus water evapotranspired by mangrove wetlands of area
based on water budget for southern Florida mangrove swamp (Twilley, 1982) = 108 cm/yr, so if mangrove + other natural wetland vegetation covers 50 ha (half) of area = 50*10,000 m^2 * 1.08m = 5.4E5 m^3.

Total ET = 9 E2 + 6.9 E2 + 8.57 E5 = 8.59 E5 m^3

Impact of wetland based on wastewater discharge of 30 gal/person/day estimate.
30 gal/per person/day * 250 people * 365 day/yr * m^3/264 gal = 10,370 m^3
However, with use of wetlands, estimated ET losses of wastewater
are 20% (from research for this study)
therefore ET is increased by 2, 070 or 0.02E5 m^3

6 Subsurface discharge is based then on difference between inputs and ET since there is no surface water discharge.

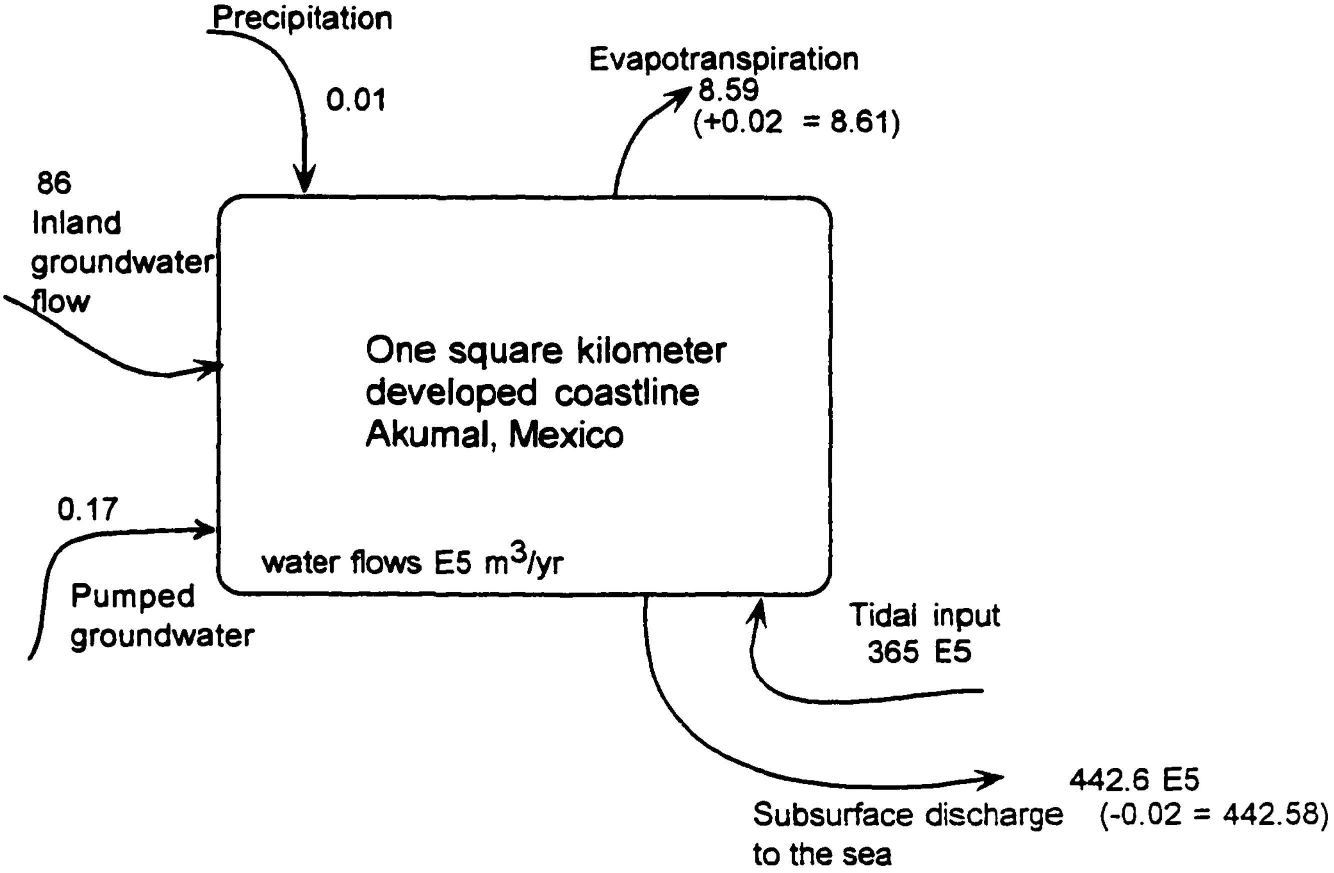


Figure 3-61 Diagram of water budget of one square kilometer of developed coastline, Akumal, Mexico. Figures in parentheses show changes in budget if all sewage is treated by constructed limestone wetlands.

The regional water budget with installation of wetlands for treatment of all wastewater shows a higher percentage of water going to ET, as occurs currently as the ET is greatly increased by the estimated 20% evapotranspiration of sewage influent to the wetlands (Table 3-57). .

Nutrient Budget

Table 3-58 shows the quantities of nitrogen, phosphorus, organic compounds (BOD) and coliform bacteria added to the groundwater of the square kilometer if development occurs without sewage treatment and if wetland systems are used. Use of the wetland treatment systems for the 250 people living in the square kilometer area results in reductions of 76% for N added to the groundwater, 85% less P being added, 88% less BOD (organic compounds) and 99.97% less fecal coliform bacteria being added (Table 3-58). These reductions amount to 75 kg less P, 425 kg less N, and 1430 kg less BOD in the groundwater on an annual basis. When the further uptake and retention in the receiving mangrove wetlands are included, discharge of N,P, BOD and coliform are further reduced.

It is more difficult to estimate what levels of nutrients and coliform bacteria will be discharged to the sea from our study area. Some nutrients are undoubtedly utilized by soil bacteria and vegetation in the coastal wetlands and beach zone, and some nitrogen are volatilized due to oxidative/reductive biochemical reactions in wetland zones. Some phosphorus may be absorbed in limestone in the subsurface zone. Coliform bacteria have an extinction rate in inhospitable environments, apart from other processes such as plant and bacterial antibiotics which lower their number. The budgets for phosphorus,

Table 3-58 Comparative additions to groundwater (GW) of nitrogen, phosphorus, BOD (organic compounds) and fecal coliform from domestic sewage in a 1-square-kilometer area of study site with and without the use of wetland treatment systems.

Item	Addition to GW without use of wetlands	Addition to GW with use of wetlands	Reduction in kg (or number of bacteria)	Percent reduction by use of wetlands + mangroves
Nitrogen	466.7	41.5	425.2 kg	91%
Phosphorus	83 kg	8.3 kg	74.7 kg	90%
BOD	1504 kg	75 kg	1429 kg	95%
Fecal coliform	1.04 E14 bacteria	0.001 E14 bacteria	1.039 E14 bacteria	99.99+%

Notes:

wastewater infiltration based on 30 gal/person/day estimate.
30 gal/per pers./day * 250 people * 365 day/yr * m^3/264 gal = 10,370 m^3
With use of wetlands, estimated ET losses of wastewater are 20% (from research for this study) therefore ET is increased by 2, 070 m^3 and wastewater infiltration is 8,300 m^3

N based on average input levels of 45 mg/l and discharge levels of 10 mg/l in wetland system effluent (from this research study)
45 mg/l * 1000 l/m^3 * 10,370 m^3 * kg/E6 mg = 466.7 kg
10 mg/l * 1000 l/m^3 * 8,300 m^3 * kg/E6 mg = 83 kg – 50% reduction in mangroves = 41.5 kg

P based on average input levels of 8 mg/l and discharge of 1.6 mg/l in wetland system effluent (from this research study)

8 mg/l * * 1000 l/m^3 * 10,370 m^3 * kg/E6 mg = 83 kg
80% reduction in wetlands + 50% in mangroves = discharge of 8.3 kg P (reduction of 74.7 kg P)

BOD based on average input of 145 mg BOD/kg and discharge of 18 mg/l in wetland system effluent (from this research study)
145 mg/l * 1000 l/m^3 * 10,370 m^3 * kg/E6 mg = 1504 kg BOD
18 mg/l * 1000 l/m^3 * 8,300 m^3 * kg/1000 mg = 149 kg + 50% reduction in mangroves = 75 kg

Coliform numbers based on influent of 1E6 per 100 ml (1E7 per liter) and discharge of 2000 per 100 ml (2E4 per liter) in wetland system effluent (from this research study)
1E7/liter * 1000 l/m^3 * 10,370 m^3= 1.04 E14 coliform
2E4/liter * 1000 l/m^3 * 8,300 m^3 = 1.66E11 coliform (0.001 E14)

nitrogen, organic materials (BOD) and coliform inputs, are shown in Tables 3-59, 3-60, 3-61 and 3-62 and are diagrammed in Figures 3-62, 3-63, 3-64 and 3-65. These regional budgets indicate that for a population of 250 people along 1 square kilometer of developed Yucatan coastlines, the use of the wetland treatment units will reduce yearly discharge to the sea of around 680 kg of organic matter (BOD), 190 kg of nitrogen, 50 kg of phosphorus and reduce total coliform discharge by over 1E13 coliform bacteria.

Table 3-59 Phosphorus budget of a developed square kilometer of coastline, Akumal, Mexico with no sewage treatment and changes if wetland systems are installed.

	Item	Quantity of water m^3/yr	Quantity of P kg P/yr	Change if wetland treatment systems used kg P /yr
	Inputs to system:			
	In water:			
1	precipitation	1.05 E3	neg.	
2	pumped GW used by people	1.728 E4	0.5	
3	Inland groundwater flow	8.6E6	258	
4	Tidal exchange	36.5E6	3.7	
	In solids:			
5	Food	----------	83.0	
	Total in	45.123 E6	345.2	
	Inside system:			
6	Addition to groundwater from domestic sewage	1.037 E4	83.0	8.3 (difference is −74.7)
7	Increase in storage: limestone + vegetative/bacteria biomass		86.3	140.3 (difference is +54)
	Outputs from system:			
8	ET	8.59 E5	Negligible.	Negligible.
9	Subsurface groundwater discharge to sea	44.26441 E6	258.9	204.9 (difference = -54)

Notes:
(see also notes to Table 3-50 and 3-52)

2
based on estimated population of 250 people x 50 gallons/person/day
250 * 50 gallons * 365 = 4.56 E6 gal/yr * m^3/264 gal = 17,280 m^3
P content based on average of 15 groundwater samples collected by C. Shaw and M. Nelson 12 Jan 97 and analyzed at the labs of the Soils Dept. Univ. of Florida, which

Table 3-59 continued
had avg P of 0.03 mg/l.
P = 0.03 mg/l * 1000 l/m^3 * 1.728 E4 m^3 * kg/1 E6 mg = 0.52 kg P

3
based on estimate (Back, 1985) on average discharge of groundwater per km of coastline in northeastern Yucatan
P = 0.03 mg/l * 1000 l/m3 * 8.6 E6m3 * kg/1 E6 mg = 258 kg P

4
tidal exchange -- estimated on basis that 1 m of saltwater underlies and mixes with freshwater: 1000m * 1000m * 1 m = 1E6m3 and that turnover is every 10 days
365/10 = 36.5/yr * 1E6m3 = 36.5E6m3/yr
P concentration in seawater (Drever, 1988) averages 0.001 mg/kg
total P = 36.5E6m3 * 0.001 mg/kg * kg/1E6mg * 1.025E3kg/m3 = 3.7 kg

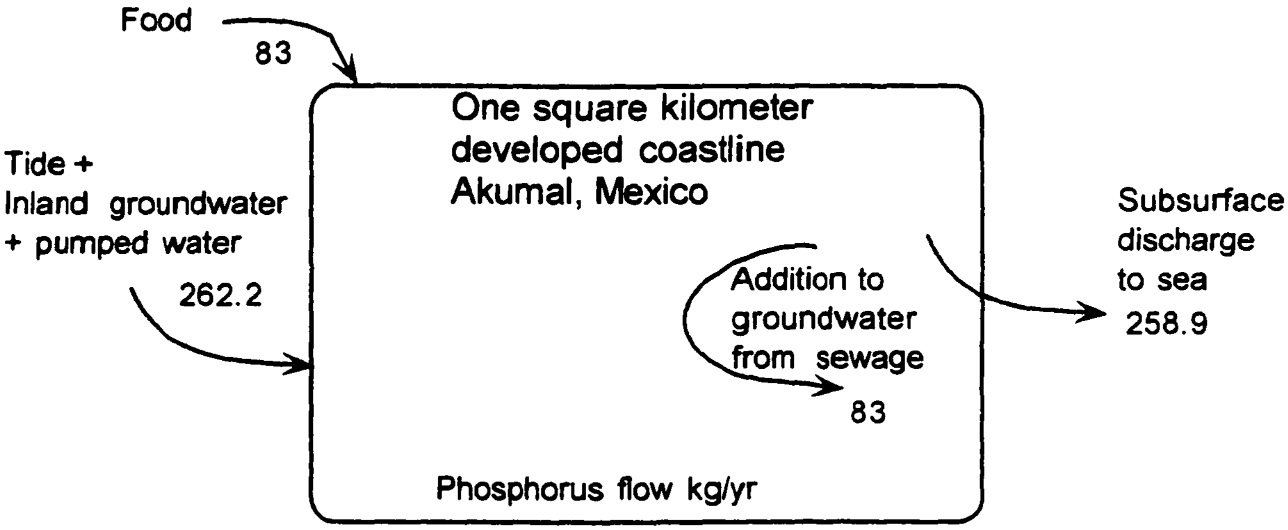
5
food P matches approx. discharged P in sewage (see note 6)

6
wastewater infiltration based on 30 gal/person/day estimate.
30 gal/per pers./day * 250 people * 365 day/yr * m^3/264 gal = 10,370 m^3
P based on average levels of 8 mg/l in septic tank effluent (from this research study)
8 mg/l * 1000 l/m^3 * 10,370 m^3 * kg/E6 mg = 83 kg
addition to groundwater = 75% x 83 = 62.3 (w/o wetland sewage treatment)
Reduction in wetland treatment systems: 80% in wetlands (from this study) + 50% in mangrove (est.)
83 * .2 = 16.6 * .5 = 8.3 kg P added to groundwater with sewage treatment (a reduction of 74.3 kg)

7
if no sewage treatment, estimate storage in limestone + vegetative/bacterial biomass = 25% of P in groundwater from sewage additions and natural inputs) 345.2 * 0.25 = 86.3
wetland + mangrove sewage treatment removes 74.7 kg P of wastewater P, and natural removal
is 25% of 262.2 kg P (other inputs of P) = 65.55; total storage = 56.1 + 65.55 =140.3 kg P

9
if assume in scenario of development without sewage treatment that uptake of P by limestone and bacteria/vegetation is 25%, P is reduced from (6.222 E4 + 5.24 E2 = 6.274 E4)/4 = 4.71 E4

in scenario of wetland treatment systems, P is further reduced by mangrove receiving wetlands (data forthcoming from ongoing research). If reduction is 90%, then P reduces from (9.13 E3 + 5.24 E2 = 9.654 E3) * (0.1) = 9.65 E2 a/ Phosphorus budget without sewage treatment



b/ Phosphorus budget with constructed limestone wetland treatment systems + receiving wetlands

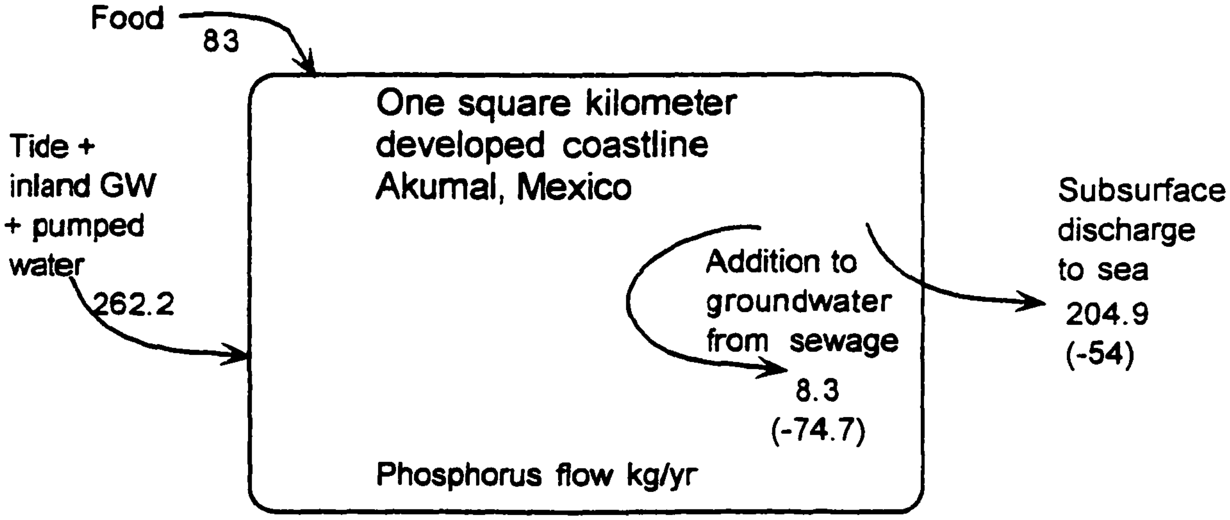


Figure 3-62 Diagram of phosphorus budget of one square kilometer of developed coastline, Akumal, Mexico. Figures in parentheses show changes in budget if all sewage is treated by constructed limestone wetlands and receiving wetlands.

Table 3-60 Nitrogen budget of a developed square kilometer of coastline, Akumal, Mexico with no sewage treatment and changes if wetland systems are installed.

	Item	Quantity of water m^3/yr	Quantity of N kg N/yr	Change if wetland treatment systems used kg N/yr
	Inputs to system:			
	In water:			
1	Precipitation	1.05 E3	786	
2	Pumped GW Used by people	1.728 E4	19.5	
3	Inland groundwater flow	8.6 E6	9720	
4	Tidal exchange	36.5 E6	18.7	
	Subtotal (water inputs)	45.123 E6	10,526	
5	In solids:			
	Food	----------	467	
	Total In		10,993	
	Inside system:			
6	Addition to groundwater from domestic sewage	1.037 E4	467	41.5 (difference = -425.5)
7	Increase in storage within system		2748	3045 (difference = +297)
	Outputs from system:			
8	ET	8.5859 E5	Neg.	Neg.
9	Subsurface groundwater discharge to sea	44.26441 E6	5,492	5,305 (difference = - 187)

Notes:

(see also notes to Table 3-65 and Table 3-67)

1 Based on average precipitation of 1050 mm for Yucatan (Lesser, 1976).
$1.05 * 1000\ m^2 = 1050\ m^3$

Table 3-60 continued

N-content of precipitation based on Valiela and Teal (1979) in their N budget for a Cape Cod salt marsh concluded rainfall contributed 0.786 gN/m^2/yr or 7.86 kg N/ha/yr. There are 100 hectares in 1 km^2, hence: 7.86 kg * 100 = 786 kg

2 based on estimated population of 250 people x 50 gallons/person/day
250 * 50 gallons * 365 = 4.56E6 gal/yr * m^3/264 gal = 17,280 m^3
N content based on average of 15 groundwater samples collected by C. Shaw and M. Nelson 12 Jan 97 and analyzed at the labs of the Soils Dept. Univ. of Florida, which had avg N of 1.13 mg/l.

N = 1.13 mg/l * 1000 l/m^3 * 1.728E4 m^3 * kg/1E6 mg = 19.5 kg N

3 based on estimate (Back, 1985) on average discharge of groundwater per km of coastline in northeastern Yucatan
N= 1.13 mg/l * 1000 l/m3 * 8.6E6m3 * kg/1E6 mg = 9,720 kg N

4 tidal exchange -- estimated on basis that 1 m of saltwater underlies and mixes with freshwater: 1000m * 1000m * 1 m = 1E6m3 and that turnover is every 10 days
365/10 = 36.5/yr * 1E6m3 = 36.5E6m3/yr
N concentration in seawater (Drever, 1988) averages 0.005 mg/kg
total N = 36.5E6m3 * 0.005 mg/kg * kg/1E6mg * 1.025E3kg/m3 = 18.7 kg

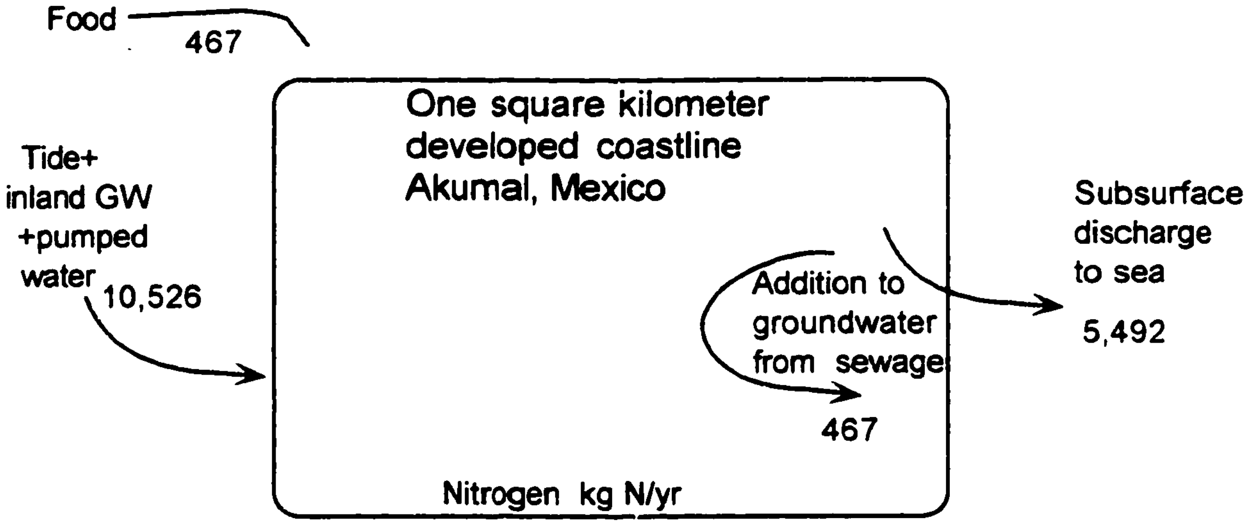
5 Food inputs of N taken to be equal to sewage-content of N

6 wastewater infiltration based on 30 gal/person/day estimate.
30 gal/per pers./day * 250 people * 365 day/yr * m^3/264 gal = 10,370 m^3
N based on average levels of 45 mg/l in septic tank effluent (from this research study)
45 mg/l * 1000 l/m^3 * 10,370 m^3 * kg/E6 mg = 466.7 kg
with wetland treatment: 10 mg N/l * 1000 l/m^3 * 8300 m^3 * kg/E6 mg = 83 kg * 50% reduction in mangrove: 41.5 kg

7 storage w/o treatment based on 25% uptake of N (see note 9): 2748 kg
storage with treatment: 25% of 10526 kg N = 2631.5 + 50% of 425.5 kg N reduction of sewage: 413 = 3045 kg N

9 without sewage treatment: if 50% of input N (10,993) is either volatilized as N2 gas or taken up by sediments, bacteria and vegetation in the coastal zone, then 5,492 kg will be released to the sea in subsurface flow

wetland systems with further treatment in receiving wetland: discharge = .5 x 10,526 = 5263 + 41.5 from sewage = 5,305 kg a/ Nitrogen budget without sewage treatment



b/ Nitrogen budget with constructed limestone wetland treatment systems + receiving wetlands

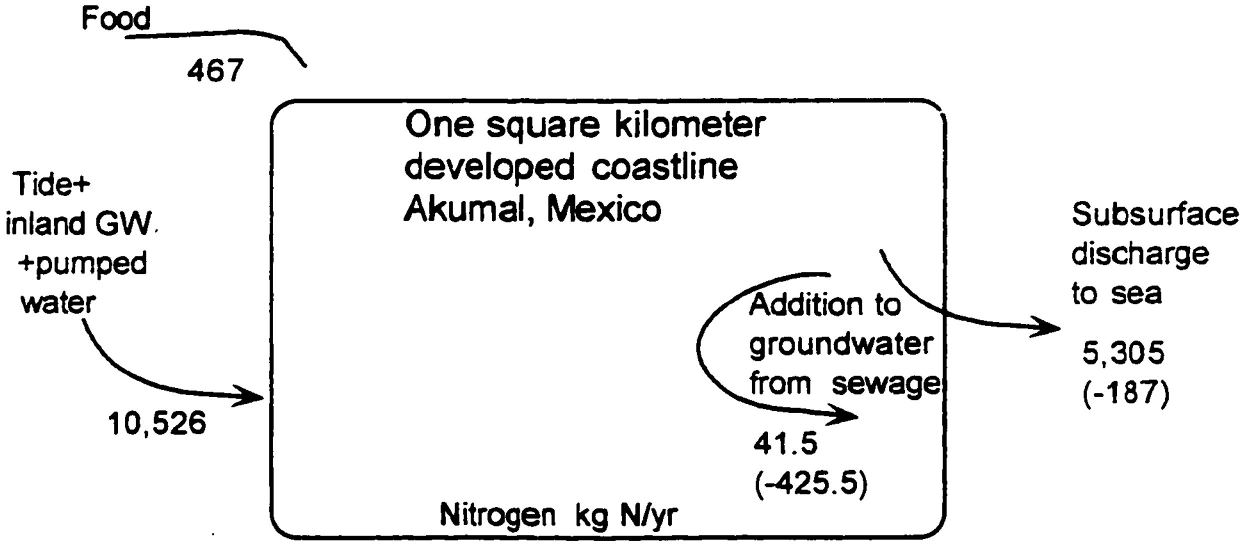


Figure 3-63 Diagram of nitrogen budget of one square kilometer of developed coastline, Akumal, Mexico. Figures in parentheses show changes in budget if all sewage is treated by constructed limestone wetlands and receiving wetlands.

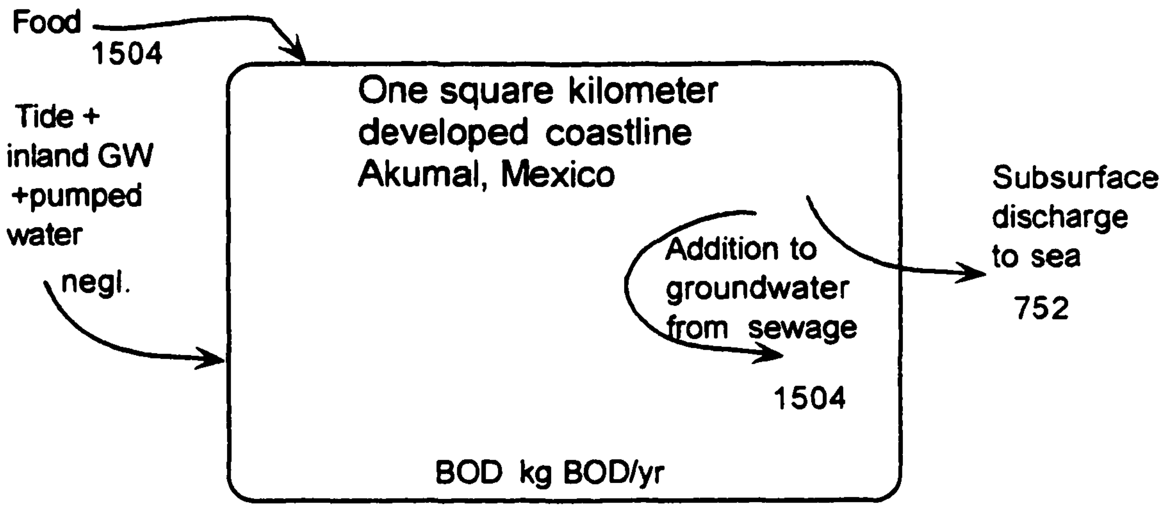
Table 3-61 Organic compounds (BOD) budget of a developed square kilometer of coastline, Akumal, Mexico, with no sewage treatment and changes if wetland systems are installed.

	Item	Quantity of water m^3/yr	BOD kg/yr	Changes if wetland systems are used kg BOD/yr
	Inputs to system:			
	In water:			
1	Precipitation	1.05 E3	neg.	
2	pumped GW used by people	1.728 E4	neg.	
3	Inland groundwater flow	8.6 E6	neg.	
4	Tidal exchange	36.5 E6	neg.	
	Subtotal in (water inputs)	45.123 E6	neg.	
	In solids:			
5	Food	-------------	1504	
	Total in		1504	
	Inside system:			
6	Addition to groundwater from domestic sewage	1.037 E4	1504	75 (difference is 1429 kg BOD)
7	Increases in storage in the system	-------------	752	1429
	Outputs from system:			
8	ET	8.5859 E5	----	-----
9	Subsurface groundwater discharge to sea	44.26441 E6	752	75 (difference is 677 kg BOD)

Notes:
(see also notes to Table 3-65 and Table 3-67)
6
wastewater infiltration based on 30 gal/person/day estimate.
30 gal/per pers./day * 250 people * 365 day/yr * m^3/264 gal = 10,370 m^3
BOD based on average input of 145 mg BOD/kg and discharge of 18 mg/l in wetland system effluent (from this research study)
145 mg/l * 1000 l/m^3 * 10,370 m^3 * kg/E6 mg = 1504 kg BOD
18 mg/l * 1000 l/m^3 * 8,300 m^3 * kg/1000 mg = 149 kg + 50% reduction in mangroves = 75 kg

9 discharge to sea:
if 50% of BOD is removed in groundwater: 752 stored in biota

a/ Organic matter (BOD) budget without sewage treatment



b/ Organic matter (BOD) budget with constructed limestone wetland treatment systems + receiving wetlands

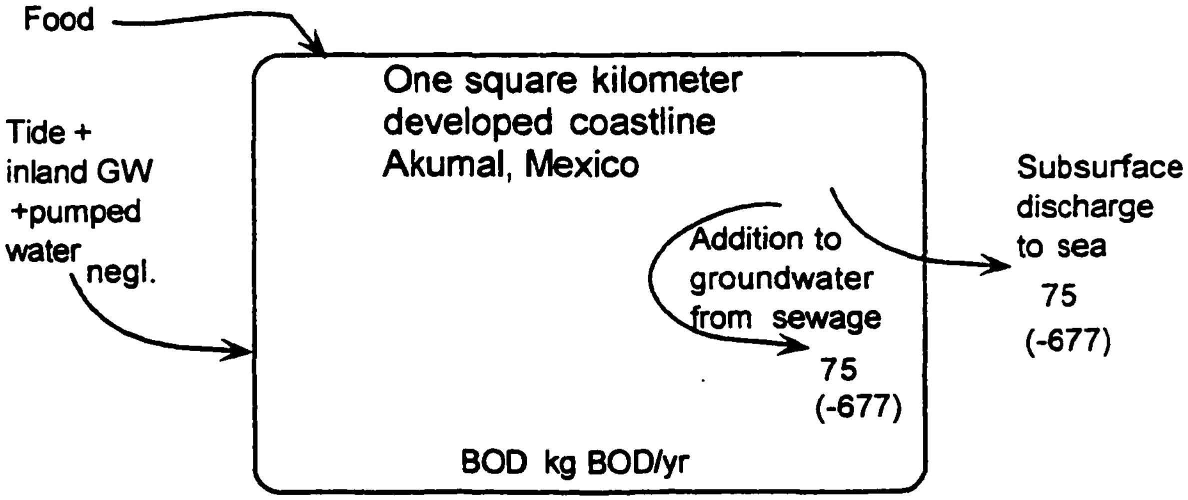


Figure 3-64 Diagram of organic matter (BOD) budget of one square kilometer of developed coastline, Akumal, Mexico. Figures in parentheses show changes in budget if all sewage is treated by constructed limestone wetlands and receiving wetlands.

Table 3-62 Coliform bacteria budget of a developed square kilometer of coastline, Akumal, Mexico, with no sewage treatment and changes if wetland systems are installed.

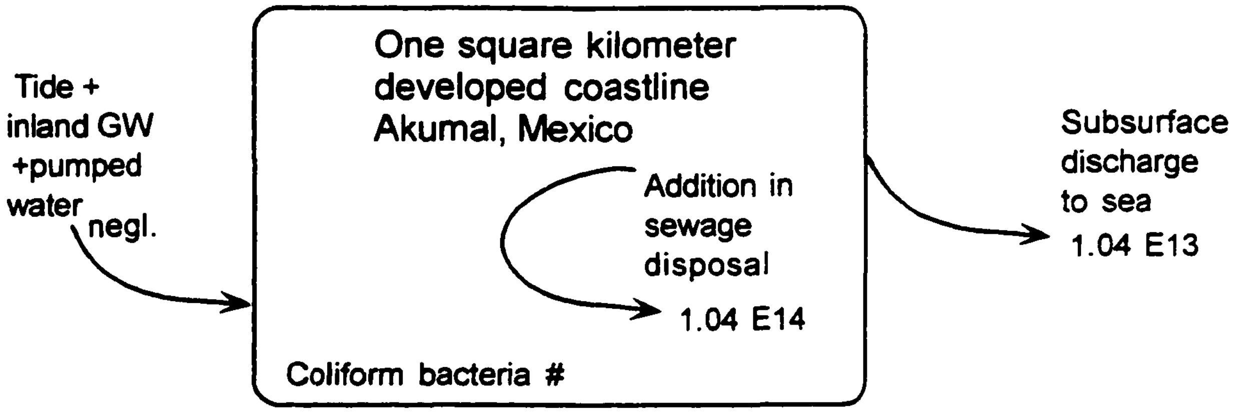
	Item	Quantity of water m^3/yr	# of fecal coliform	Changes if wetland systems are used # of fecal coliform
	Inputs to system:			
1	Precipitation	1.05 E3	neg.	
2	Pumped GW used by people	1.728 E4	neg.	
3	Inland groundwater flow	8.6 E6	neg.	
4	Tidal exchange	36.5 E6	neg.	
	Total in	45.123 E6	neg.	
	Inside system:			
5	Addition to groundwater from domestic sewage	1.037 E4	1.04 E14	0.001 E14 (difference = -1.039 E14)
	Outputs from system:			
6	ET	8.5859 E5	----	
7	Subsurface groundwater discharge to sea	44.26441 E6	1.04 E13	0.005 E13 (difference = - 1.035 E13 coliform)

Notes:
(see also notes to Table 3-50 and Table 3-52)

5
wastewater infiltration based on 30 gal/person/day estimate.
30 gal/per pers./day * 250 people * 365 day/yr * m^3/264 gal = 10,370 m^3
Coliform numbers based on influent of 1E6 per 100 ml (1E7 per liter) and discharge of 2000 per 100 ml (2E4 per liter) in wetland system effluent (from this research study)
1E7/liter * 1000 l/m^3 * 10,370 m^3= 1.04 E14 coliform
2E4/liter * 1000 l/m^3 * 8,300 m^3 = 1.66E11 coliform (0.001 E14)

7
without sewage treatment: if coliform are reduced 90% before discharge to sea:
= 1.04 E14 * .1 = 1.04 E13
with wetland treatment systems: if receiving wetlands further reduce coliform by 50%, then discharge water will contain 0.01E13 * .5 = 0.005E13

a/ Coliform bacteria budget without sewage treatment



b/ Coliform bacteria budget with constructed limestone wetland treatment systems + receiving wetlands

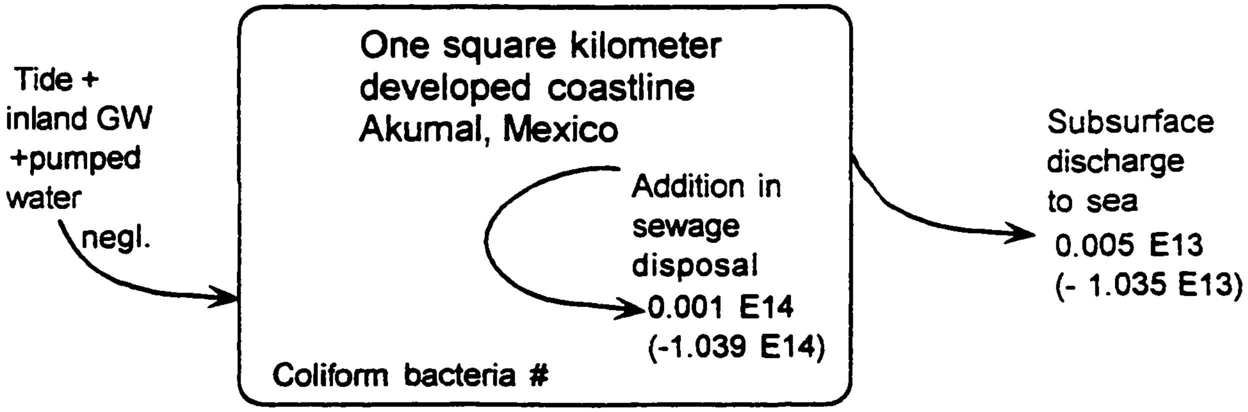


Figure 3-65 Diagram of coliform bacteria budget of one square kilometer of developed coastline, Akumal, Mexico. Figures in parentheses show changes in budget if all sewage is treated by constructed limestone wetlands and receiving wetlands.

CHAPTER 4

DISCUSSION

Contribution of Research to Science of Ecological Engineering

The principal contributions of the present research to the science of ecological engineering are in its use of local limestone gravel as substrate for the wetland, the demonstration that high species diversity can be maintained from the outset in a constructed wetland, and its successful integration in the regional environment by the use of mangrove wetlands as the final bio-filter for the treated wastewater.

Limestone proved to be effective in improving phosphorus treatment by the wetlands (Figure 3-39 and Figure 3-40). Since limestone is a local Yucatan material, it also was important in lowering cost of construction and increasing the use of regional natural resources compared to alternative, conventional sewage treatment systems.

Although the research aimed at high diversity, it was unexpected that the wetlands would substantially increase and sustain plant species beyond the 35 planted (Table 3-1), demonstrating that species from the local environment were able to successfully invade and contribute to the ecosystem. This runs counter to current practice in constructed wetlands for sewage treatment where few species are planted, and almost all of which tend to be dominated by aggressive pioneer species of wetland bulrush, reed and cattail.

The use of mangroves as a final bio-filter and recipient of the effluent from the limestone wetlands may be an important advance in ecologically engineering, for usually constructed wetlands are placed into environmental contexts with little regard for their integration in the larger ecological system. In coastal Yucatan, the mangroves are the natural interface between the human economy and the beach/marine zone and offer great advantages in that they have an organic sediment which can function as a biotic filter for groundwater flow of nutrients. This type of mangrove use should increase awareness of the importance of the mangroves in maintaining environmental health in the region and offer cogent reasons to prevent their continued destruction for tourist development.

The wetlands have also been shown to be less costly in construction and operation than conventional sewage treatment (Tables 3-34 and 3-35). The limestone wetlands also use far more local resources and less imported goods and services (Tables 3-36 and 3-37). Both these factors facilitate their practical application for third world tropical countries where capital and technical expertise is limited.

Analysis of the regional nutrient budgets show that the wetlands would prevent virtually all anthropogenic nutrients from entering the groundwater and impacting coastal ecosystems (Tables 3-59 to 3-62). This type of ecologically engineered system may help ensure the health of regional ecosystems normally put at risk by tourist development.

Ecological Succession in the Limestone Wetland Units

The Akumal limestone wetlands have demonstrated a rapid pattern of ecological succession. In August 1996 the wetlands were first planted, and initially had only partial cover of the ground, little canopy structure, and an average height of 0.5 m. The wetlands were not connected to sewage flow until December, 1996, and during that period demonstrated little growth. Once sewage flow commenced, plant growth and canopy development were quite rapid as ecological succession theory would suggest. By May 1997 when the first extensive surveys were conducted, the dominant plants were *Canna edulis*, *Nerium oleander*, *Typha domingensis* and *Alocasia esculenta*, and average height had increased to 1m. By December 1997 and July 1998, the increasing prominence of upper canopy trees and palms was evident. Lower canopy vegetation remained, but the system now favored shade-tolerant species. Lower canopy and annual species were the most likely species to be lost from the system. By July 1998, canopy closure averaged 85% in the wetlands (Table 3-15), light interception was around 90% (Table 3-14), and average plant height was around 2 m (with some of the top canopy reaching 4-5 m).

It appears that the wetlands are still in early succession. On each of the last two surveys (December 1997 and July 1998), about 20% of previous species were lost, and were replaced by new species. Some of the differences in development may be the result of stochastic processes, and even from the random choice of which plants were placed in the different cells. While the striking difference in plant development and leaf area index between first and second cells has been eliminated in Wetland System 2, there is still a marked difference in Wetland System 1 (Table 3-11).

Odum (1994) notes that the equalization of productivity and respiration seen in the later stages of many successions may not apply in situation where ecosystems receive a continued input of nutrients and convert it into organic storage, as in a sewage treatment wetland. Detritus flushed into mangroves is likely to be beneficial. Currently, plant growth and canopy development still continues, and may be expected to do so until trees and palms attain their full height.

Succession theory predicts that organic matter will build in the ecosystem (Odum, 1971), a result not seen in the two years since construction (Figure 3-26). However, the original sawdust mulch has been replaced by litterfall, and as biomass continues to increase, one would expect the quantity of litterfall will increase.

Animal usage of the wetlands was not monitored in this research, but it was noted that frogs invaded the wetlands within months of its creation. Snake skins have been found in the system and birds have been observed in the system. Dozens of insects were observed during the studies of leaf holes (Tables 3-12 and 3-13) on the plants, evidence of active herbivory.

Figure 3-45 summarizes the main processes in the ecosystem during its first two years including the inputs and transpiration of water, the production and deposition of organic matter, the absorption of nutrients and possible role of salt in maintaining biodiversity.

Comparison of the Akumal Systems with other Treatment Approaches

The Akumal wetlands are low in cost, and low in requirements for imported goods and electricity as are other low-tech approaches such as use of surface flow wetlands and aerated lagoons. However, aerated lagoons and surface flow wetlands may not be suitable for use in the Yucatan unless built with impermeable liners, as otherwise wastewater will be lost to the permeable limestone before adequate treatment is effected.

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. For example, the University of Florida wastewater treatment facility has capital costs over three times higher per person than the Akumal wetlands, and operating costs at $27/person/year are nine times higher (Appendix D, Table 3-36)

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 the Yucatan because of the tropical environment, salt-spray and saline groundwater, and the high cost of importing equipment from elsewhere in Mexico or the United States. Treatment by package plants decreases over time with poor maintenance of equipment and inadequate technical supervision (Reed et. al., 1995).

In addition, conventional treatment systems and package plants are designed to achieve secondary treatment standards (<30 mg/l of biochemical oxygen demand and total suspended solids) which may be inadequate for preventing eutrophication of marine and terrestrial environments. Large amounts of sludge are produced, which are difficult in an environment like the Yucatan to dispose/use in a responsible manner. For example, the sewage treatment system for the city of Cancun, Quintana Roo has contributed to pollution of the Cancun lagoon.

Shallow-well injection following septic tank residence is low cost, but not very effective in reduction of organic compounds, nutrients or coliform bacteria or in preventing their impact on sensitive coastal marine ecosystems. Septic tank residence, with adequate holding time, only reduces influent BOD <50% (TVA, 1993). Wastes in partially treated wastewater are likely to accumulate in the groundwater and coastal waters of the Yucatan. In similar geological setting, in the Florida Keys, sewage injected into shallow wells on land was found less than one mile away in off-shore waters (Shinn et al, 1992).

Aquatic plant treatment systems (Wolverton, 1987) and surface flow wetlands have the advantages of being low cost to build and operate, and have been applied in many ecosystems and climatic zones, using locally available wetland species. They often are designed for secondary/tertiary wastewater treatment, with lagoons or other settling devices accomplishing primary treatment before release of the wastewater.

However, surface flow wetlands require more area than subsurface wetlands. This is because subsurface flow wetlands are designed to make the wastewater flow through the entire volume of their gravel substrate, as contrasted with surface flow wetlands where wastewater flows over the top of the soil bed. Thus the surface area of each piece of gravel in a subsurface system can function as a locale for hosting microorganisms and as a site for wastewater filtration, sedimentation and microbial interaction. A rule of thumb is that surface flow wetlands require about 100 hectares (250 acres) for treatment of 1-million gallons/day wastewater loading vs. 5-10 hectares (12-25 acres) for subsurface flow wetlands, such as were used in Akumal (Kadlec and Knight, 1996).

The cost of the medium (generally gravel) and liners usually makes the cost per area more for constructing subsurface flow wetlands, but this is offset by the smaller area and heavier loading that such systems receive. Thus subsurface wetlands are usually less expensive than aquatic plant systems or surface flow wetlands (TVA, 1993, Reed et al., 1995). For these reasons, and because such systems would need to be lined if applied in the Yucatan, there is probably limited scope for the use of surface flow wetlands for wastewater treatment in the region. Aquatic plant constructed wetlands may also generally require biomass harvesting (Bagnall et al, 1993), which requires additional labor and is seldom cost-effective (Reed et al, 1995).

There may be applications where use of several approaches can be usefully combined. For example, in some constructed wetland systems, ponds have been used rather than septic tanks as the primary treatment stage to reduce construction costs. Wetlands have also been used following conventional treatment or package plants to increase nutrient recycling and produce higher quality effluent water.

There are numerous natural freshwater and saltwater wetlands that occur in the coastal zone of the Yucatan. Environmental protection regulations in the U.S. have made it more difficult to obtain permits for the use of natural wetlands for sewage treatment or disposal, despite the fact that there are numerous examples of successful historical and recent use of natural wetlands for this purpose.

In the Yucatan the relatively open hydrology of wetlands, due to the limestone geology and rapid movement of water into and through the underlying limestone, cautions against the use of natural wetlands as a primary mechanism of sewage treatment. However, these wetlands are the only coastal ecosystems with a substantial organic soil component, and as such they function as natural bio-filters. Perhaps the most appropriate use of such wetlands is as a final step in sewage treatment, following primary and secondary treatment, such as was done in Akumal.

Comparisons with Temperate Latitude Interface Systems

Nutrient removal of the Mexican constructed wetland systems compares very favorably with those of similar systems previously applied in temperate latitudes. The 85% BOD removal achieved in the Mexican wetlands (Table 3-21) is in the range of 80-90% reduction reported for most wetland systems (EPA, 1992). However, temperate latitude wetlands are reported to achieve nitrogen reduction of <30% and phosphorus reduction of <15% (EPA, 1992), compared with the Akumal data which indicate reductions of 79% for nitrogen and 77% for phosphorus (Tables 3-19, 3-17) respectively. Reduction of coliform bacteria is generally 90-99% (EPA, 1993b), while the Yucatan wetlands have averaged over 99.8% removal over the course of this study (Table 3-27).

Table 4-1 compares the Akumal wetland units with average values for subsurface and surface flow wetlands in North America (Kadlec and Knight, 1996). BOD loading for the Akumal wetlands is slightly higher than the average subsurface wetland and removal rates are higher (88% vs. 69%). Total phosphorus loading in Akumal is less than 40% that of average North American systems and removal is 76% vs. 32%. Nitrogen loading in Akumal 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

Table 4-1 Comparison of loading rates and removal efficiency of Akumal treatment wetland units 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/d
BOD (Biochemical oxygen demand)	Akumal wetlands	145	17.6	87.9	32.1
	Average temperate surface flow wetlands	30.3	8.0	74	7.2
	Average temperate subsurface flow wetlands	27.5	8.6	69	29.2
TP (Total phosphorus)	Akumal wetlands	8.05	1.9	76.4	1.7
	Average temperate surface flow wetlands	3.78	1.62	57	0.5
	Average temperate subsurface flow wetlands	4.41	2.97	32	5.14
TN (Total nitrogen)	Akumal wetlands	47.6	10.0	79	10.3
	Average temperate surface flow wetlands	9.03	4.27	53	1.94
	Average temperate subsurface flow wetlands	18.9	8.41	56	13.19

Note: Akumal wetland data based on loading of 2.7 m3 wastewater per day on area of 130 m2, using average wastewater data from this study. As designed, full loading would be over twice as much.

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).

Comparison of Emergy Indices of Akumal Units

Table 4-2 summarizes the emergy evaluation of the treatment system as compared with a package plant treatment and a larger conventional treatment system at the University of Florida (see Appendix C). Figure 4-1 presents an aggregated systems diagram of the Akumal treatment units and mangroves with flows of emdollars.

For the Akumal 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 derives over 220 times more emergy from purchased goods and services than from free environmental resources (excluding the wastewater) and the package plant derives over 2600 times as much emergy from purchased goods and services rather than from free environmental resources.

The transformity of the output (treated effluent) (6.85 E6 sej/J) from the wetland system is higher than that of the Akumal package plant (4.83 E6 sej/J) reflecting the fact

Table 4-2 Comparison of emergy indices for Akumal treatment units, package plant at Akumal and the University of Florida wastewater treatment system (Appendix C).

a/ Based on transformity for wastewater calculated as co-product of total emergy required to support people

Emergy index	Akumal wetland units	Package plant at Akumal	University of Florida conventional treatment system
Purchased / Free (excluding sewage)	0.39	2,693	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	1.0 E14 sej

b/ Based on transformity of wastewater of 1.0 E6 sej/J (food/services/water used)

Emergy index	Akumal wetland units	Package plant at Akumal	University of Florida treatment system
Purchased / free (excluding sewage)	0.39	2,693	220
Empower density (emergy/area/time)	6.2 E18 sej/ha/yr	1.95 E19 sej/ha/yr	3.3 E20 sej/ha/yr
Purchased emergy per person	0.3 E14 sej	2.3 E14 sej	1.0 E14 sej
Emergy per person	2.4 E14 sej	2.5 E14 sej	72.8 E14 sej

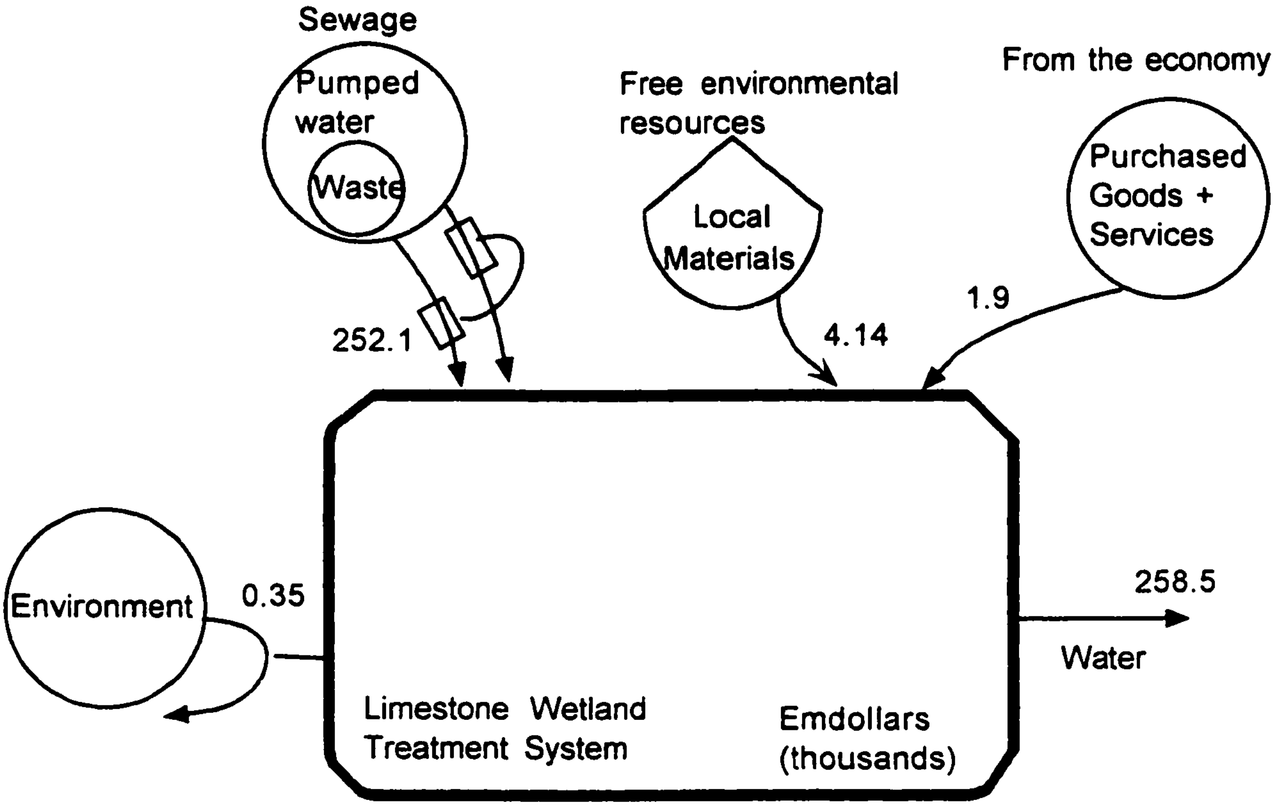


Figure 4-1 Diagram showing annual emdollar contributions in the constructed wetland system in Akumal, Mexico.

that 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. The wetland transformity for treated wastewater is also higher than the University of Florida system (4.71 E6 sej/J) perhaps reflects the economy of scale of a large wastewater plant and its very large throughput of wastewater.

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

The Akumal 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). The wetlands have the lowest empower density, with the package plant almost three times greater, and the University of Florida system being the highest (Table 4-2).

Table 4-2 also presents the results of emergy comparisons if the treated sewage is treated as a product of the food, water and services supporting their population, rather than as a co-product of the total emergy support. Green (1992) calculated the transformity of raw domestic wastewater to be 5.54 E5 sej/J for Nayarit, Mexico. Bjorklund et al (1998) calculate a transformity of 5.46 E6 sej/J for Sweden. Using a transformity in-between these values (1 E6 sej/J) since Akumal has many of the characteristics of a developed economy in its reliance on imported foods. Using this transformity for wastewater has the consequence of reducing emergy flows by around 4.5. However, the main relationships observed between the limestone wetland units, package plant at Akumal and the University of Florida system persist. The purchased to free environmental ratio is unchanged, and the wetland systems still have the lowest empower density and the lowest emergy use per person (Table 4-2).

Role of Limestone Substrate

Unlike unreactive gravel (igneous and metamorphic rock) that has been predominantly used in subsurface flow wetlands, the use of local limestone as the primary substrate in the Mexican wetland units was important in controlling and stabilizing its biogeochemistry and treatment efficiency.

Limestone is predominately calcium/magnesium carbonate and its chemistry is dominated by the common ion effect which carbonate dissociation shares with the hydration of carbon dioxide (to form carbonic acid). The pH of the water determines which form, H_2CO_3, HCO_3^{-1} or CO_3^{-2}, will predominate in the system.

In subsurface wetland units, where water level is kept below ground, algae and aquatic plants are absent. Photosynthesis occurs above the limestone/wastewater level. Thus photosynthesis had little impact on carbon dioxide levels in the underground. Instead, respiration by roots and bacteria increased carbon dioxide concentrations in the water column.

Limestone also aided phosphorus removal because of the reaction of calcium with phosphate, as was illustrated in the laboratory experiments conducted during this study (Table 3-31). This is especially the case in these alkaline conditions, where reactions with calcium and magnesium are the main determinants controlling phosphorus fixation (Reddy and D'Angelo, 1994).

The addition of organic materials with the wastewater probably increased microbial respiration and CO_2 production. However, increase in carbon dioxide was buffered by reacting with the limestone to form bicarbonates. In contrast, anaerobic decay reactions, which predominate in a subsurface flow wetland using wastewater high in sulfates, tend to increase carbonate saturation and deposition (Drever, 1988).

Just as the dissolution of limestone is the controlling geochemical reaction in the Yucatan region, we can also anticipate the slow dissolution of the large quantity of limestone initially placed in the Mexican wetland units. Indeed, observations of discharge water from the treatment cells reveals a whitish color, indicative of carbonate dissolution materials.

Seasonal Changes and Effect of the Dry Season

Although the climate of the Yucatan has a sharp dry season, the coastal microclimate is moderated by steady flows of maritime tropical air from the east augmented by the sea breezes. Annual temperatures do not show great variability in the Yucatan, with the hottest average monthly temperature (26.2 deg. C.) occurring in June, and the lowest 23.1 deg. C. in December (Viquiera et al., 1994). Average relative humidity is even more constant, with a high of 88% in September and the low in March/April with 81% (Ibarra and Davalos, 1991). As a consequence, potential evapotranspiration is high year-round, averaging 4-5 mm/day in the rainy season yet still

3 mm/day in the dry season. (SARH, 1997). Conditions were uniform enough for vegetation to flourish through wet and dry seasons.

The Yucatan is a region with a marked period of higher monthly rainfall, May through October when over 70% of the 1100 mm annual rainfall occurs, and a drier season, November through April (Viquiera et al., 1994).

During the warmer, rainy months, direct rainfall and freshwater subsurface inflow from inland result in larger groundwater prominence of the freshwater, and in a net freshwater discharge to the sea. Consequently, there is a seasonal variation in salinity in the water supply of the treatment units and in the mangroves which receive their discharge effluent.

Average phosphorus and nitrogen reductions were slightly greater in the dry, cooler months with 79% and 81% reductions compared to 74% and 68% reductions, respectively, in the warmer, rainy season. But biochemical oxygen demand reduction was greater in the warmer, rainy months with 94% reduction vs. 86% in the dry cool season. (Tables 3-17. 3-19 and 3-21).

The two-year data suggest that constructed wetlands for sewage treatment in the Yucatan can remain quite effective in its treatment results year-round. Even in the drier winter months, solar insolation and warm temperatures permit active growth of vegetation and high metabolic functioning of microbes, since adequate water and nutrients are maintained though sewage inputs to the system. Hydraulic residence is longer, since rain dilution of the wetlands is less. Treatment efficiency in the wet season is assisted by higher average air temperatures, but diminished by loss of insolation through cloud cover and dilution by rainwater.

Treatment of Wastewater Containing Sea Salt

The wastewaters at Akumal are salty because the town water supply is pumped from groundwater where there is mixing of seawater with freshwater. The high biological diversity maintained by the Akumal systems showed that the regional vegetation was adapted to salinity in this range. These biodiversity results were in contrast to the lower diversity saltwater wastewater mesocosms studied in North Carolina (Odum, 1985).

The salt content of the wastewater may be a contributing factor in the establishment and maintenance of high plant biodiversity. Species tolerant of high salt content, such as occur nearby in the mangrove wetlands, have been able to survive in the system, as have many non-halophytic plants that are able to withstand the moderate salinity of the wastewater and salt aerosols carried from the sea. Indeed, having an intermediate salinity may have been a factor holding in check species capable of aggressive dominance (e.g. *Typha* spp.).

The wastewater being treated in Akumal is saline, generally averaging 3-5 ppt salt. This is in marked contrast to most wastewater treatment facilities that handle fresh, originally potable water. The presence of seawater means that in addition to NaCl, there is a strong presence of sulfates, since seawater contains 2700 mg SO_4/l on average (Day et al, 1989). In the anaerobic conditions of wetlands containing saltwater, sulfate reduction usually dominates rather than the methanogenesis that often prevails in freshwater conditions. This is attributed to the competition for electron donors, the larger thermodynamic yield and higher affinity of sulfate reducers to utilize compounds potentially usable by methanogenic bacteria (Capone and Kiene, 1988; Achtnich et al, 1995).

Simulation of Hydrological Extremes

Simulations of the water budget model for the wetland treatment unit and mangroves indicate water flows and turnover times that help understand the processing of the various inputs. "What if?" experiments with the model suggest the range of water volumes that may develop with extreme events. Simulations were conducted examining the impacts of hurricane events, increased population and sewage loading, and decrease of inland groundwater due to interior development.

Increasing population so that wastewater inputs are ten times greater results in increased water levels in the mangrove, and increases biomass especially in the treatment wetlands (Figure 3-57). Development inland reducing groundwater discharge to the mangroves, has the effect of lowering groundwater levels in the mangrove, results in diminished water level (Figure 3-58). A hurricane producing heavy rainfall, high tides and winds that reduce vegetation by half in the wetlands and mangroves leads to increased flow of treated effluent into and out of the mangroves. Recovery of vegetative biomass to previous levels requires years. The high tides are quickly flushed, so that the flooding of the mangroves is a transient event (Figure 3-59).

Transpiration of Treatment Systems

Because vegetation productivity has been related to transpiration, an estimate of transpiration of the Akumal treatment systems is a productivity index as well as a major component of the hydrological budget. Evaporative water loss was limited since wastewater was maintained below the surface of the wetland, air exchange was reduced by the dense plant canopy (Table 3-14 and Table 3-15) and because the ground was mulched and shaded.

Loss of water through transpiration increases total treatment efficiency of the Akumal wetland compared with conventional sewage treatment facilities. The residence time in conventional treatment sewage facilities is 2-4 hours, allowing for little loss from evaporation, so that virtually all the influent water leaves the system. However, in the wetlands, the loss of 20-30% of water through transpiration means that total pollutant removal on a mass balance basis is greater than is indicated by discharge water analysis alone. For example, if P levels in the discharge water are 75% lower than those in the septic tank in the wetlands, and transpiration removes 20% of the wastewater, actual phosphorus reduction totals 80%. If transpiration is 30% of wastewater, then phosphorus removal increases to 82.5%.

Transpiration of freshwater tends to increase salinity of the wastewater in the treatment units, since relatively freshwater is lost through plant leaves. However, the measured salinity in the treatment cells over the course of this study showed predominantly a slight decrease in salinity (Table 3-26), presumably because of dilution by rainfall on the wetlands.

Maintaining Vegetative Biodiversity

In the two-year study, survival of planted species and environmental seeding produced a dense, high diversity ecosystem. Maintenance of high biodiversity long-term will require successful re-establishment of seedlings of the wetland plants. Some of the loss of species already seen may have resulted from the death of annuals, and the suppression of lower canopy plants and seedlings due to shading (Table 3-1).

The maintenance of high species diversity is of theoretical interest. Some of the factors which may have helped maintain diversity and prevented a few species from dominating the system are

1. the use of slightly saline which allows a range of both freshwater and salt-tolerant plants (as noted above).
2. continued inputs of nutrients which may act as a stress keeping the ecosystem in a productive, intermediate stage between primary succession and maturity (Odum, 1994).
3. nearly constant water temperature (27 ± 0.5 °C year-round)
4. the pulses of nutrient input which low and high tourist season occupancy produce.

Impacts of Effluent Disposal on the Mangroves

Results from the present study have shown that there has been an only moderate increases in nutrient levels in mangrove groundwater (Table 3-46, Table 3-47) and soil sediments (Table 3-43, Table 3-45). Longer-term effects on the mangroves need to be assessed.

Feller (1995), Lugo et al (1976), and Sell (1975) indicated that mangroves typically are nutrient limited, both for nitrogen and phosphorus and can increase productivity with added nutrient inputs. Walsh (1967 cited in W.E, Odum et al, 1982) found mangroves were net sinks for nitrogen and phosphorus. Nutrients are removed in mangrove ecosystems by prop root periphyton, the fine root system, organic sediments, algae and bacteria/fungi. Thus, there is a good likelihood that mangroves will continue to be effective at nutrient removal from wastewater discharge.

Clough et al (1983) expressed concerns that the addition of water containing organic carbon compounds will lead to increased anaerobic conditions in the sediments, further lowering redox potentials. However, W.E. Odum et al. (1982) note that the sediments underlying many mangroves tend to be very anaerobic, with redox values of -100 to -400 mv, due to their high organic matter content. The 75-80% organic matter content in the Akumal mangroves before wastewater discharge exceeds the 10-20% considered more typical of mangrove soils and is indicative of isolation from tidal erosion (W.E. Odum et al, 1982).

After discharge of treated sewage, salinity levels were reduced (Table 3-52), and the small extent of phosphorus increase in soil sediments indicate phosphorus use by the mangroves (Table 3-45).

Carrying Capacity for People - Coastal Development Potential

To anticipate the potential value of these wetland treatment units in preventing pollution caused by tourist development, an emergy evaluation was made of a developed square kilometer of coastline around the Akumal study site, supporting 225 people and employing 125 people (Table 3-55).

Without a good treatment / recycle system large amounts of anthropogenic organics, nutrients, and coliform bacteria will be released into the coastal and marine environment (Table 3-58) with impact on coral reefs, beaches, health and tourist economy. In addition, if development results in further loss of the mangrove areas, nutrients flowing subsurface from inland sources that are currently intercepted will also be discharged to the marine environment. Thus, future planning should ensure adequate area is left in all developments for installation of adequate wetland treatment areas to absorb the additional nutrient loading tourist development brings. Needed for one kilometer of coastal development supporting around 250 people are some 900 square meters of constructed wetland, plus 1-2000 square meters of mangroves.

Currently development is concentrated on the coastal zone itself, but the location of more human population and/or industry in inland areas will impact sustainability of coastal resources by diverting groundwater and increasing nutrient loading of remaining groundwater.

Percent of Economy Required for Wastewater Processing

Kadlec and Knight (1996) indicated that constructed wetlands are at least 50% less expensive than conventional sewage treatment in capital costs. Operational and maintenance costs are even lower, averaging 10%. However, this varies considerably, depending on land costs.

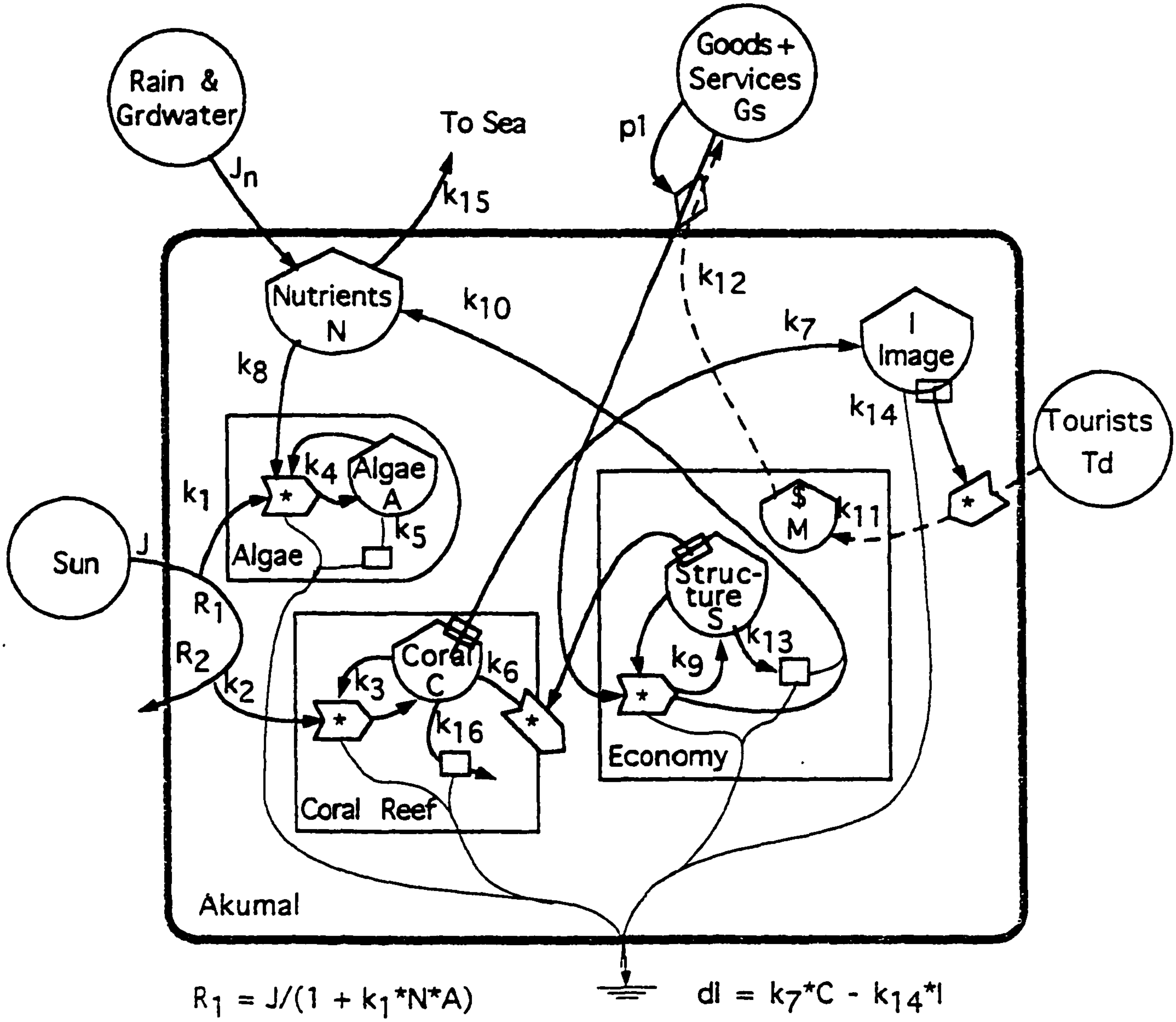
Tables 3-34 and 3-35 show the economic advantages of the Akumal wetland treatment. Capital costs for the limestone wetlands were around $165/person compared to $385/person for a package treatment plant; and maintenance costs for the wetland were $3/person compared to $27/person for the package plant. 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 (Table 3-34, Table 3-35 and Table 3-55).

The limestone wetlands cost approximately \$450 per year (over its 20 year anticipated operation) to treat 3000 gallons per day, which is \$0.15 per gallon 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.

Perspectives from Regional Simulation Model

A regional simulation model was developed in order to elucidate a few of the important interactions between the natural environment and the human economy including tourism in the Yucatan. Figure 4-2 shows the systems diagram with equations, Figure 4-3 shows calibration storages and flows and Figure 4-4 shows a simulation run of the model showing changing levels of assets, coral, algae, nitrogen and image as development proceeds. Table 4-3 presents the program in BASIC for the simulation model.

In the systems diagram, algae (A) and Coral (C) compete for sunlight energy (J), with some sunlight (R_1) going to the algae and a portion of the remainder (R_2) to the corals. Algal growth (k_4) is autocatalytic, using sunlight, nutrients (N), and algal standing biomass for increase, and declining through respiration/death (k_5). Coral growth is also autocatalytic, depending on the interaction of sunlight and coral biomass. Natural coral losses (k_{13}) are augmented by anthropogenic damage linked to increased development (k_{16}). Coral presence adds to the regions image (I), which in turn helps attract income



$$R_1 = J/(1 + k_1*N*A)$$

$$R_2 = R_1/(1 + k_2*C)$$

$$dA = k_4*R_1*N*A - k_5*A$$

$$dI = k_7*C - k_{14}*I$$

$$dS = k_9*S*M/P_1 - k_{13}*S$$

$$dM = k_{11}*I*Td - k_{12}*M$$

$$dC = k_3*R_2*C - k_6*C*S - k_{16}*C$$

$$dN = Jn + k_{10}*S*(M/P1) - k_8*N*R_1*A - k_{15}*N$$

Figure 4-2. Systems diagram and difference equations used for simulation model of the interactions between the natural environment and the human economy along the Yucatan coastline.

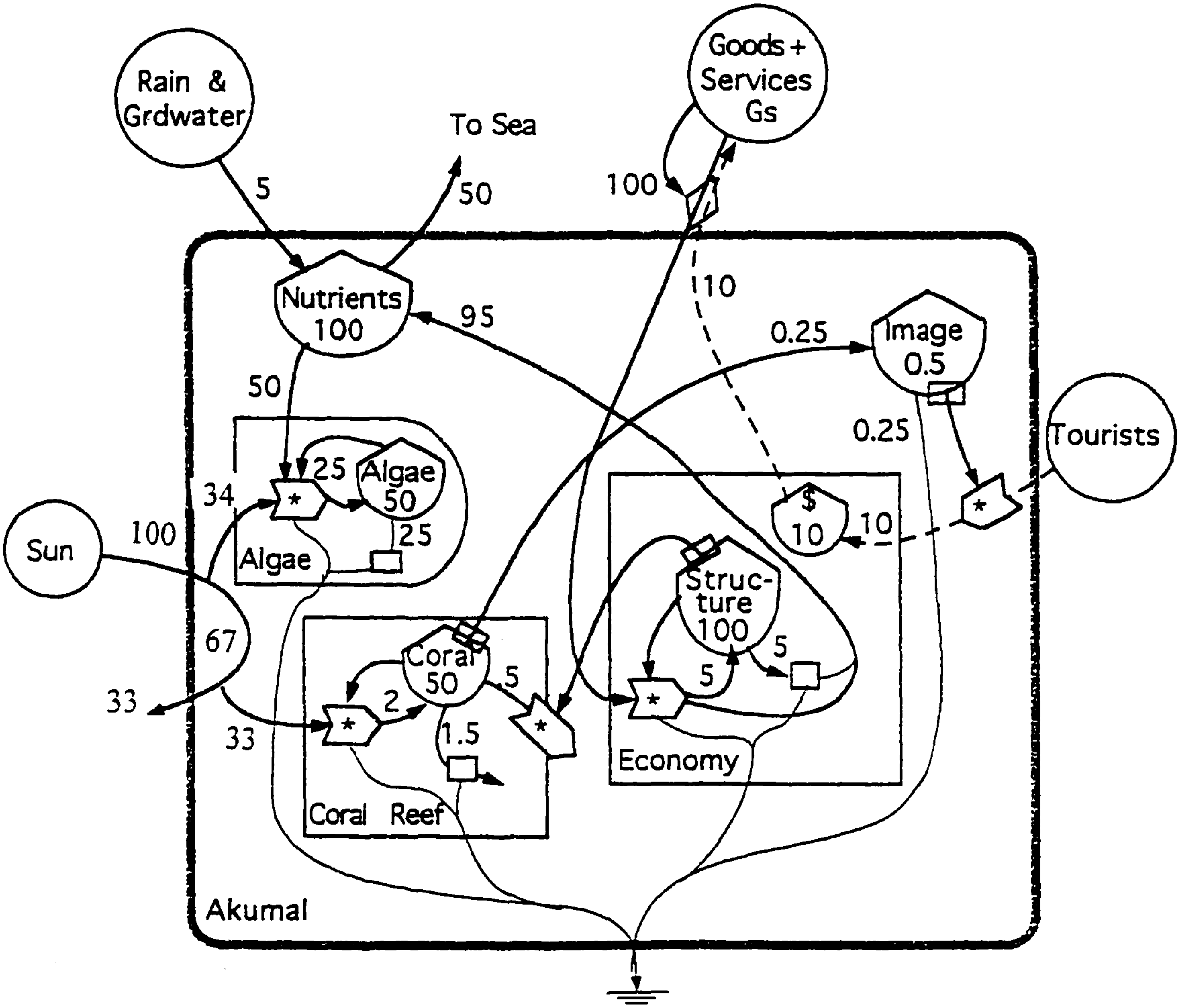


Figure 4-3. Systems diagram for Yucatan coastal model. Values shown are steady-state storages and flows between components.

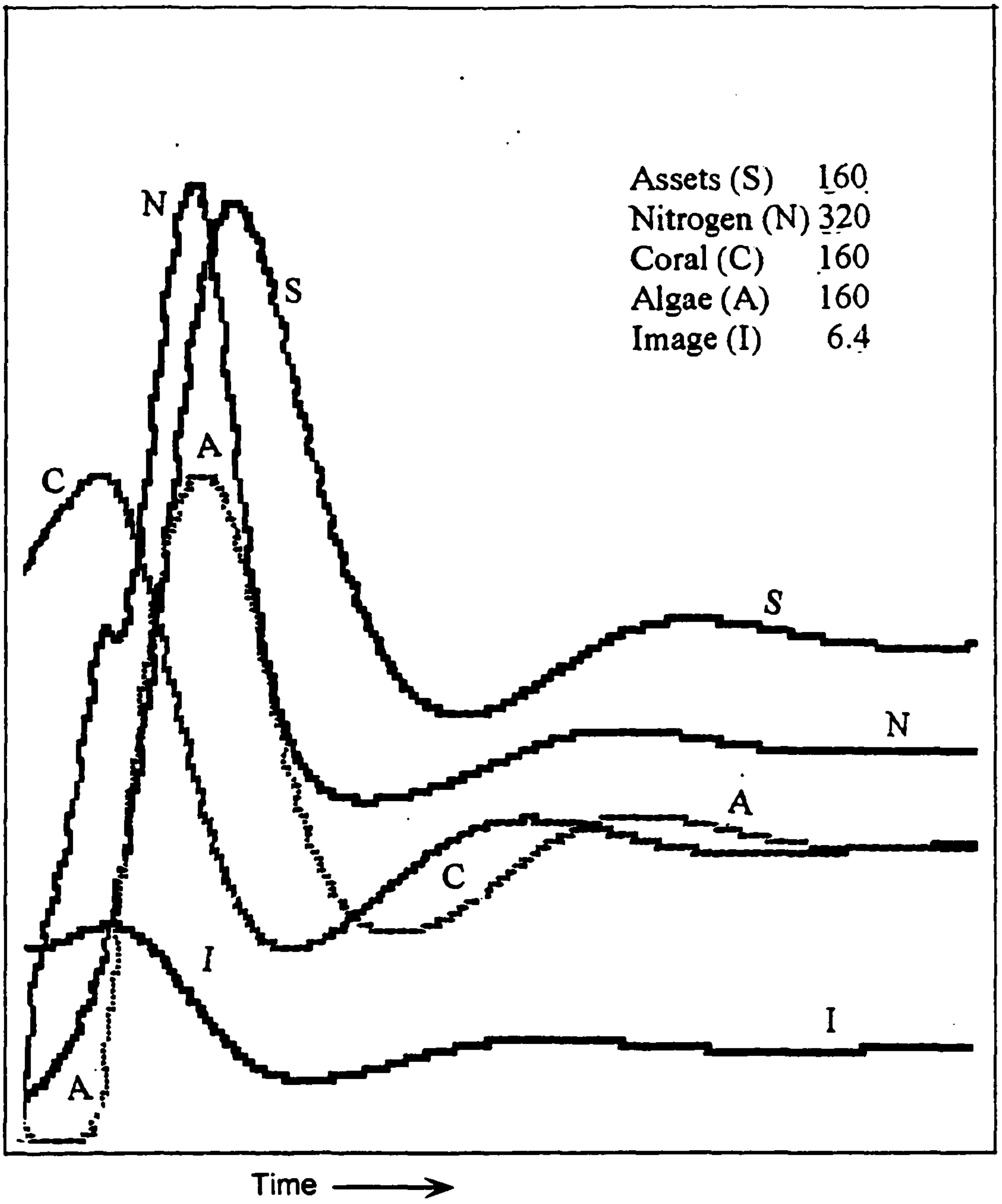


Figure 4-4 Computer simulation of the Yucatan coastal model. The legend gives the full scale values of the ordinate for each quantity.

Table 4.3 Program in BASIC for simulation model of interactions between natural environment and human economy along the Yucatan coast.

```
10 CLS
20 Screen 0,1
30 Color 0,1
40 Line (0,0)-(320,180), 1, B

60 A = 5
70 C = 95
80 N = 10
90 I= 1
110 S = 10
120 M = 1
150 Td = 50
160 J= 100
165 No = 5
170 Rem Coefficient values
172 P1 = 100
175 T = 1
178 dt = 0.1
180 k1 = 0.0000958
190 k2 = 0.020606
200 k3 = 1.212121 E-3
210 k4 = 7.492537 E-4
220 k5 = 0.5
230 k6 = 0.0001
240 k7 = 0.002
250 k8 = 1.492537 E-4
260 k9 = 0.5
270 k10 = 9.5
280 k11 = 0.4
290 k12 = 1
300 k13 = 0.05
310 k14 = 0.2
320 k15 0.5
330 k16 = 0.03
Rem Scaling factors
350 A0 = 2
360 T0 = 1
370 C0 = 2
380 N0 = 1
390 S0 = 2
400 M0 = 2
410 I0 = 50
```

```
440 PSET (T, 180 - I / I0), 3
420 PSET (T, 180 - A / A0), 1
430 PSET (T, 180 - C/C0),2
440 PSET (T, 180 - I / I0), 3
480 PSET (T, 180 - S / S0), 4
490 PSET (T, 180 - M / M0), 5
500 PSET (T, 180 - N / N0), 6
505 PSET (T, 180 - A / A0), 1
510 PSET (T, 180 - C/C0),2
540 R1 = J / (1 + k1*N*A)
550 R2 = R1 / (1 + k2 * C)
560 dA = (k4*R1*N*A) - (K5*A)
570 dC = (k3*R2*C) - (K6*C*S) - (K16*C)
580 dS = (k9*S*M / P1) - (K13*S)
590 dM = (k11*I*Td) - (K12*M)
600 dN = No + (K10*S*(M/P1)) - (K8*N*R1*A)
      - (K15*N)
610 dI = (K7*C) - (K14*I)
620 A = A + dA*dt
640 N = N + dN*dt
660 T = T + dt
700 If N < 0 then N = 0
710 If A > 100 then A = 100
720 If C > 100 then C = 100
730 If A < 0 then A = 0
740 If C < 0 then C = 0
750 If M < 0 then M = 0
760 If T < 640 goto 540
770 Print “A=”, A; “C=”, C, “N=”, N. “S=”, S
```

(k_{11}) from tourism (Td). This income adds to the region's money (M) and is used (k_{12}) to purchase goods and services (Gs). The growth of development structure (S) is autocatalytic (k_{15}) from the interaction of goods and services (Mk_{12}/P_1) and existing structure. The increased development process both increases coral loss and adds (k_{10}) to the quantity of nutrients (N) which can impact the natural environment. Nutrients receive a flow from the natural environment (J_n) as well as from economic development (k_{10}), while some of the nutrient outflow is taken by algae (k_8) and the rest goes to the deeper ocean (k_{17}).

The coral reef plays a major role in sustaining the positive image of the region, which helps attract investment and tourist flow to the region. Decreased coral cover resulting from development without adequate sewage treatment increases algal domination, which acts to lower the image, thus dampening tourist development. Over time, these balance, and the overall system adjusts to a level of development far below the early "boom". Coral cover at first rapidly decreases, then recovers as development tapers down (Figure 4-4).

Simulation results are sensitive to starting conditions. If nitrogen begins at much higher levels, tourist development peaks at far lower levels, and the system regains a steady state earlier (Figure 4-5a). If coral begins at zero, the system crashes since there is no pull for continued investment and tourist development (Figure 4-5b). If assets and money begin at much lower levels, the process of boom takes longer to develop, but rises to a greater peak, and steady state conditions at the end have less coral cover than under the model's standard run (Figure 4-5c).

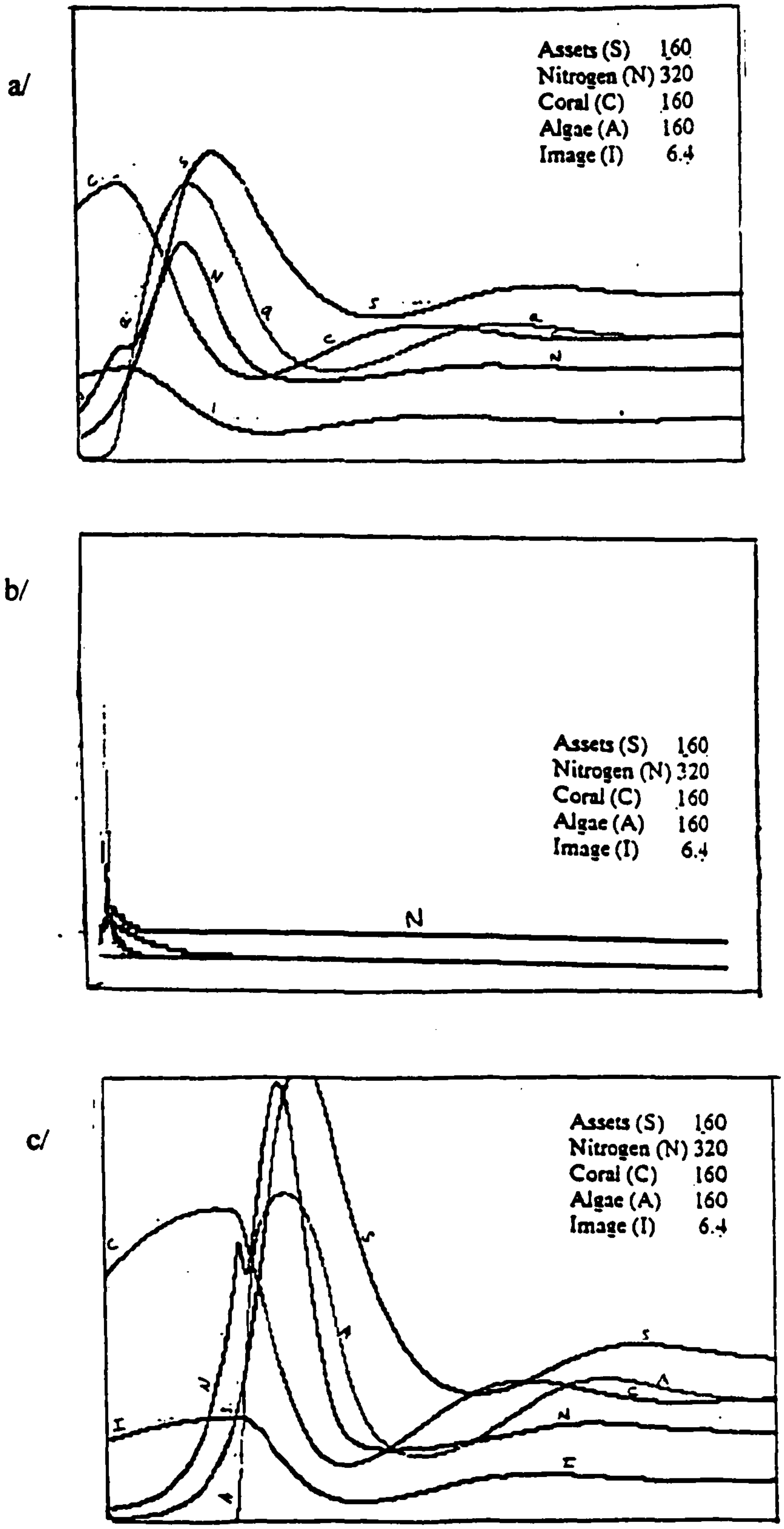


Figure 4-5 Simulation runs of the interaction of the environment and human economy in the Yucatan. a/ Impact of starting with nitrogen at ten times higher value b/ Impact of starting with coral at zero c/ Impact of starting with money and assets at 1/10 value.

The model simulates some components of the present situation in the Yucatan, since diving, snorkeling and fishing are a significant part of the tourist appeal of the area. Most of the hotels offering coral reef exploration now have inadequate sewage treatment, and much current development is threatening other parts of the environment, such as mangroves, which help protect the marine environment. If the coral reef suffers great degradation (as occurred in Jamaica), it seems clear that tourist revenues will decline as a result.

Future Potentials of the Designed Treatment System

The scope for application of the wetland treatment system along the Yucatan coast is great. Already, interest in such systems from those who have seen the prototype systems at Akumal has led to some fifteen additional systems being built from Tulum to Playa del Carmen.. The scale thus far has been from individual house systems, hotels/condominiums of up to 50 people, and a theme park with 1500 visitors per day. In the Cancun area, the government has decided that no new connections will be made to the existing municipal sewage treatment plant, which is already over-loaded, obliging new businesses and homeowners to do on-site treatment. The principal advantages that have attracted new applications are the low-cost and low-maintenance of the wetlands, plus their attractiveness.

To lower costs of larger systems, it is anticipated that rubber or polyethylene liners will be used instead of concrete. Each new system has served as a testing ground for planting new plant species, and an additional 10-15 palm, tree and shrub varieties show promise of doing well in the wetland systems. The search for suitable wetland plants that have economic potential continues. Already, bananas in several systems have successfully produced fruit. Several of the palms in the Akumal systems have value as thatching material. In order to develop systems which will be inexpensive enough to be used by local Mayan families and communities, construction costs need to be lowered and more useful products produced. Ideally, it may be possible for a local family or community to build such systems themselves (thus lowering construction costs) and to, contract with local farmers to maintain the system in return for harvesting rights.

Long-Term System Prospects

It is unknown how long the wetland system will remain effective at sewage treatment. A number of subsurface flow wetlands have been operating successfully for over 10-20 years (Kadlec and Knight, 1996; EPA, 1992). While BOD reduction tends to be adequate, phosphorus and nitrogen removal have sometimes been inadequate in wetlands constructed in temperate latitudes (EPA, 1992).

The limestone may remain effective at phosphorus uptake for a considerable time, as its starting concentration was quite low (40 mg/kg). The 6 mg P/kg uptake of the limestone during the first year of operation may reflect the rapid increase in plant and microbial biomass during early succession in the wetlands. It is to be expected that biotic primary productivity will decline or stabilize as time goes on, thus placing increasing importance on the limestone to act as a sink for influent phosphorus.

The phosphate mining district of Florida demonstrates that phosphate substitution for carbonate in limestone (over geologic periods) can continue indefinitely, producing minerals that are 5-20% phosphorus (Gilliland, 1973: Odum et al, 1998). At the rate of 50-100 mg/kg of phosphorus enrichment, it would take some 100-200 years before the wetland limestone gravel reaches 1% phosphorus content. While occupation of surface area may be a limiting factor in such uptake, bioturbation and the high porosity/permeability of limestone may continue to ensure continued uptake.

Nitrogen removal by the wetlands increased over the first two years of operation, as plant productivity and root penetration of the subsurface zone increased. From half to two-thirds of nitrogen removal in constructed wetlands comes from gaseous release of the nitrogen after nitrification/denitrification processes (EPA, 1992). Therefore, oxygenation of the rhizosphere by plant roots is an important factor, for otherwise only a reducing environment might prevail under the surface of the limestone. The inclusion of wetland species able to deeply penetrate, and the inclusion of a diversity of plant species with varying rooting patterns, may help to maintain adequate oxygenation

For the Akumal system, the inclusion of the mangrove as a final treatment step gives a safety factor for ensuring continued effective wastewater treatment. Should additional nutrients be discharged from the constructed wetlands, the mangroves may help prevent additional nutrients from reaching marine ecosystems. This may be especially true for phosphorus which is the most limiting nutrient for mangroves along this coastal zone (Feller, 1995).

The diversity of the wetland vegetation may also offer long-term performance benefits, as it will tend to make the system less prone to system failure due to disease or other plant failure than if the system was dominated by several plant species.

Hurricane events, which are a periodic event along the Yucatan coastline, may act to "reset the successional clock", dramatically decreasing canopy cover and system biomass in both constructed wetlands and mangrove ecosystems.

In the event of long-term decrease of limestone uptake of P below acceptable levels, or to decrease of system performance because of clogging through deposition of sewage solids or organic material, the system may be regenerated by installation of fresh limestone. The old limestone may be used as a slow-release fertilizer for area gardens or farms. Since the limestone accounts for less than 20% of original construction costs, it will be cost-effective to replace the limestone on this periodic basis if necessary.

Authorization Meeting in Mexico

On August 18, 1998, representatives of Planetary Coral Reef Foundation, Mexico were invited to the University of Quintana Roo at the state capital of Chetumal in order to present the limestone wetland systems to the faculty and federal and state government agencies. Those present included the Commission National de Agua (CNA) and Recursos Naturales y Pesco de Quintana Roo.

Results from the present research study were presented, as well as many of the additional systems that have been built along the Yucatan coast to date. Questions raised following the presentation covered the economics of wetland treatment compared to other alternatives, the impact of catastrophic events such as hurricanes, the mechanisms responsible for nutrient uptake and coliform reduction, and the methods by which larger cities might benefit from such approaches.

Many of those present indicated that there is growing concern in the government and university that the development in the northern portion of the state, and particularly Cancun, was allowed to proceed too rapidly. Thus, there was inadequate regard for issues such as preservation of key ecosystems, such as the mangrove and other wetlands, and before adequate sewage treatment systems were available. The southern portion of the state (from the Sian K'an Biosphere Reserve to the Belize border), is still in very early stages of tourist and other development, and could still put in place better measures for integration of the human and natural environment.

At the conclusion of the three hour meeting, the head of the University of Quintana Roo, Rector Efrain Villaneuva Arco, announced support of the installation of a demonstration limestone wetland to treat the sewage of 200 people at the University as a facility for on-going research and education. The author was invited to design the wetland, working with faculty of the University who are developing improved designs for septic tanks which will serve as the primary treatment of the system.

Questions for Research

Important topics that need future research are the following:

Biodiversity

What impact does the presence of high biodiversity have on system performance in treating wastewater? Will anaerobic conditions in the subsurface rhizosphere limit the variety of plants? Can such high biodiversity be maintained long-term? Which factors are responsible for the maintenance of high biodiversity (salt, nutrient inputs, original planting, proximity to seed sources, wind or animal seed dispersal)? With increasing scale of such wetland systems, will biodiversity patterns be different?

Mangrove Change

Will the mangrove ecosystem be fundamentally altered by the addition of treated effluent? What impact will be seen on growth rates of different mangrove species, and on other system parameters such as canopy closure, soil depth, hydrological regime, species abundances? What impact will wastewater effluents have on permanent and migratory fauna that utilize the mangroves? What loading ratios will sustain mangroves?

Useful Life of the Wetland System

What is the likely longevity of the wetland treatment units? 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? Will the limestone continue to play a role in the retention of phosphorus, or will this be diminished over time as gravel surface area is occupied? Will bioturbation ensure continuous availability of limestone substrate for phosphorus reactions?

Acceptability and Affordability by Local People

What modifications, such as using geomembrane liners rather than concrete, can be made to further lower construction costs? Can the systems be made profit creating rather than simply low-cost by concentrating on the inclusion of usable products (timber, fuel, food, and fiber) which can be harvested from the wetland units? Which products are most desired by and acceptable to the Mayans living in the area?

Summary

Over the course of a two year study, a new system of limestone subsurface flow wetlands was developed and coupled to final treatment in mangrove wetlands. The units recycled nutrients and improved the quality of saline domestic wastewater. The system has maintained a high level of biodiversity of wetland plant species. After two years, the upper canopy of wetland palms and trees is 4-5m (13-16 feet) tall with dense canopy closure. Canopy closure and Interception of light after just two years is already similar to that of natural Yucatan wetlands.

This system is inexpensive and with advantages over alternative sewage treatment approaches in using a preponderance of local resources, few imports, and little use of machinery and electricity. Its two stages were adapted to the hydrogeological setting of the Yucatan coast; limestone gravel helped ensure adequate treatment before release, and natural mangrove wetlands were utilized as the most appropriate biofilter for nutrients remaining in the effluent from the constructed wetlands.

Emergy evaluations show the ratio of imported inputs to free, environmental inputs is small. Economically, the system compares favorably in having low capital and operating costs. In addition, there are aesthetic benefits, habitat protection for wildlife, and producing useful products such as fruit, fiber, building materials, etc.

Yucatan limestone used in the system contains very little phosphorus, and the rate of increase during operation was small, suggesting the substrate may remain effective in phosphorus uptake long-term. Nitrogen and phosphorus increase in the mangrove soils was small (<15%). Coliform bacteria concentrations and chemical oxygen demand were at background levels within 6 m of discharge.

The eastern Yucatan is in the midst of extremely rapid tourist development. The present work demonstrates the feasibility of designing and implementing ecological engineering solutions that can help integrate the human economy with the natural environment. This wastewater treatment system has potential for more widespread application in tropical coastlines and countries that are in great need of low-cost, low-tech solutions that employ natural systems to solve environmental challenges.

APPENDIX A

CHART RECORDER DATA FOR AKUMAL

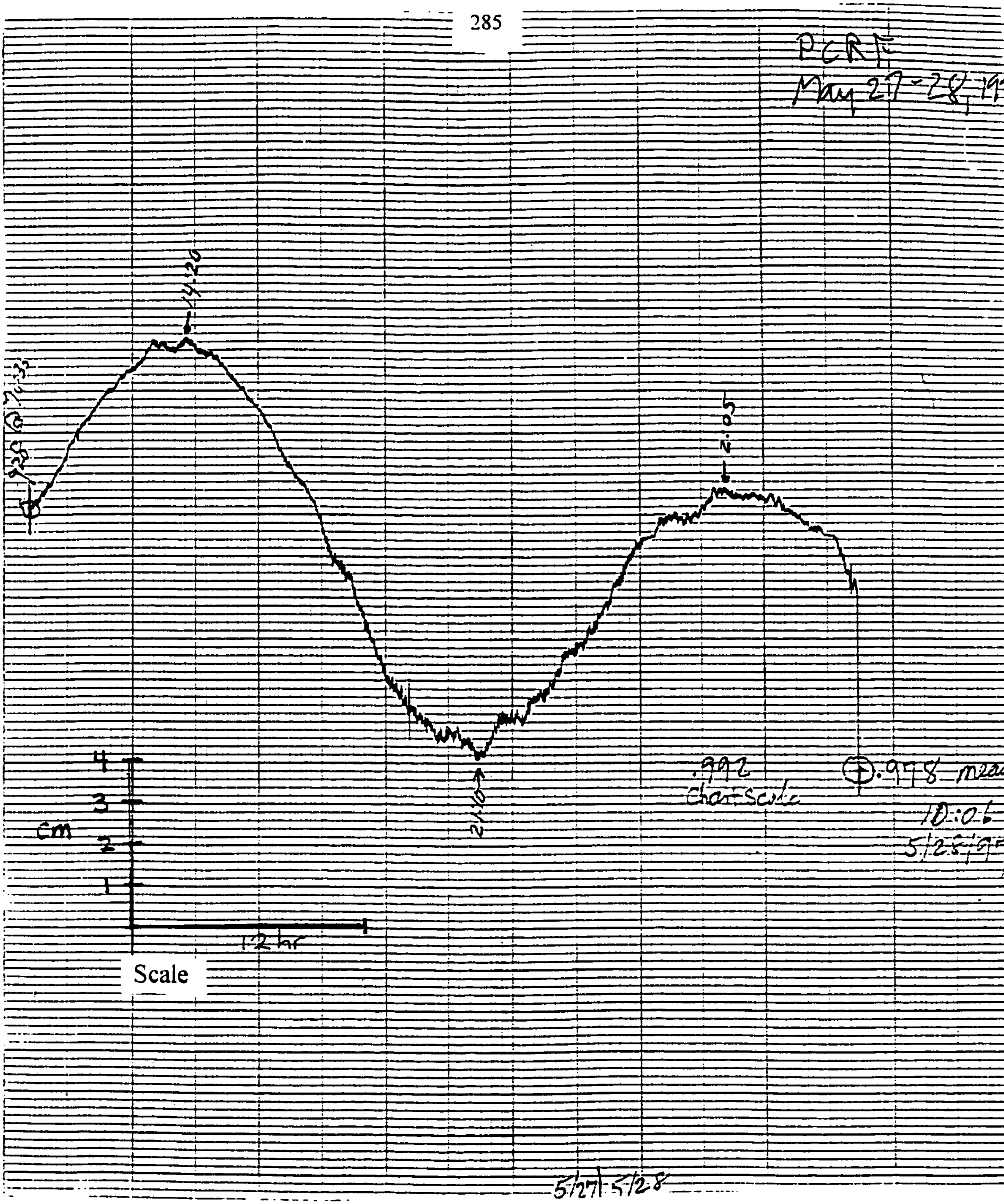


Figure A-1 Water level record for cenote near wetland treatment unit, 27-28 May 1997.

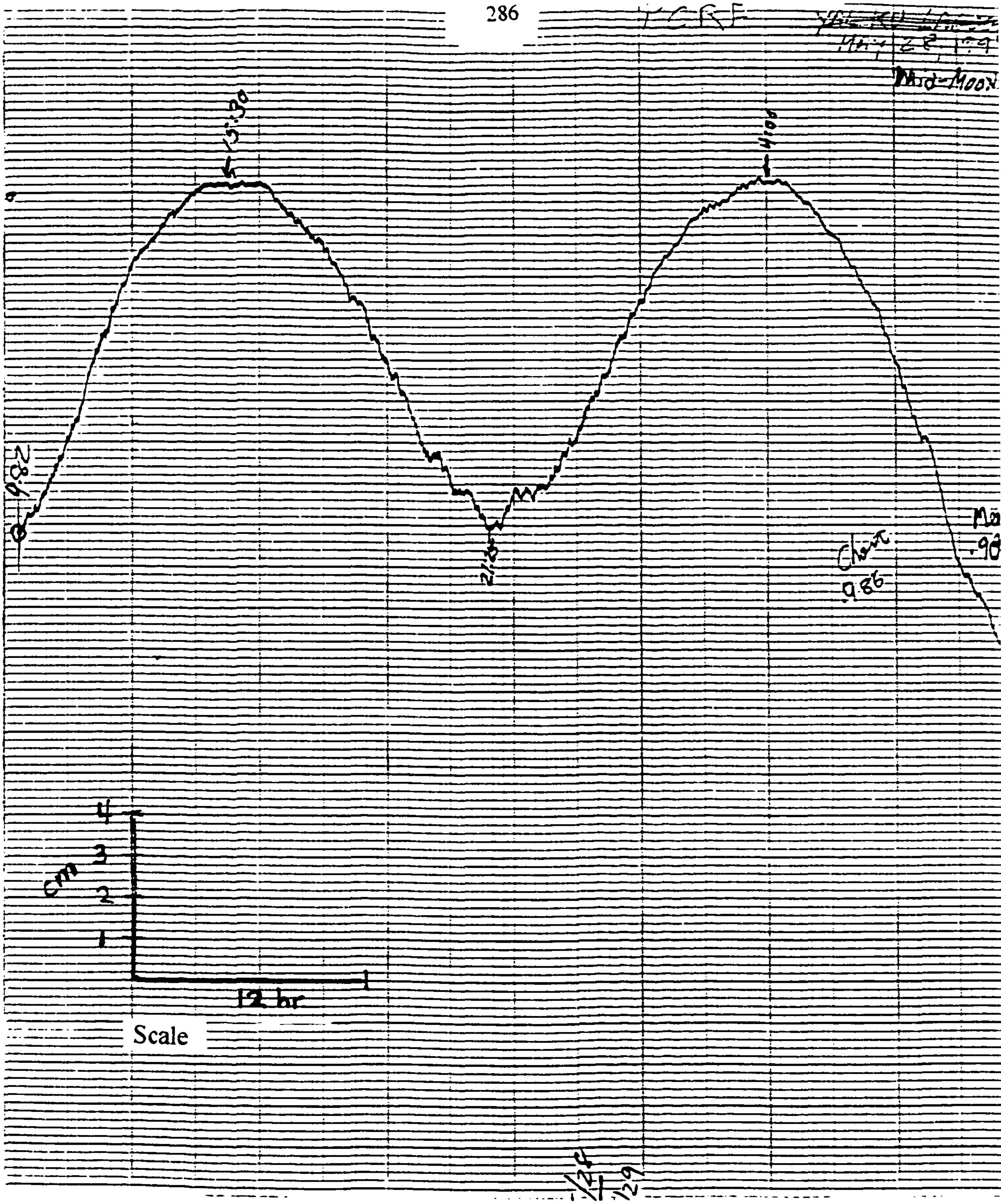


Figure A-2 Water level record for cenote near wetland treatment unit, 28-29 May 1997.

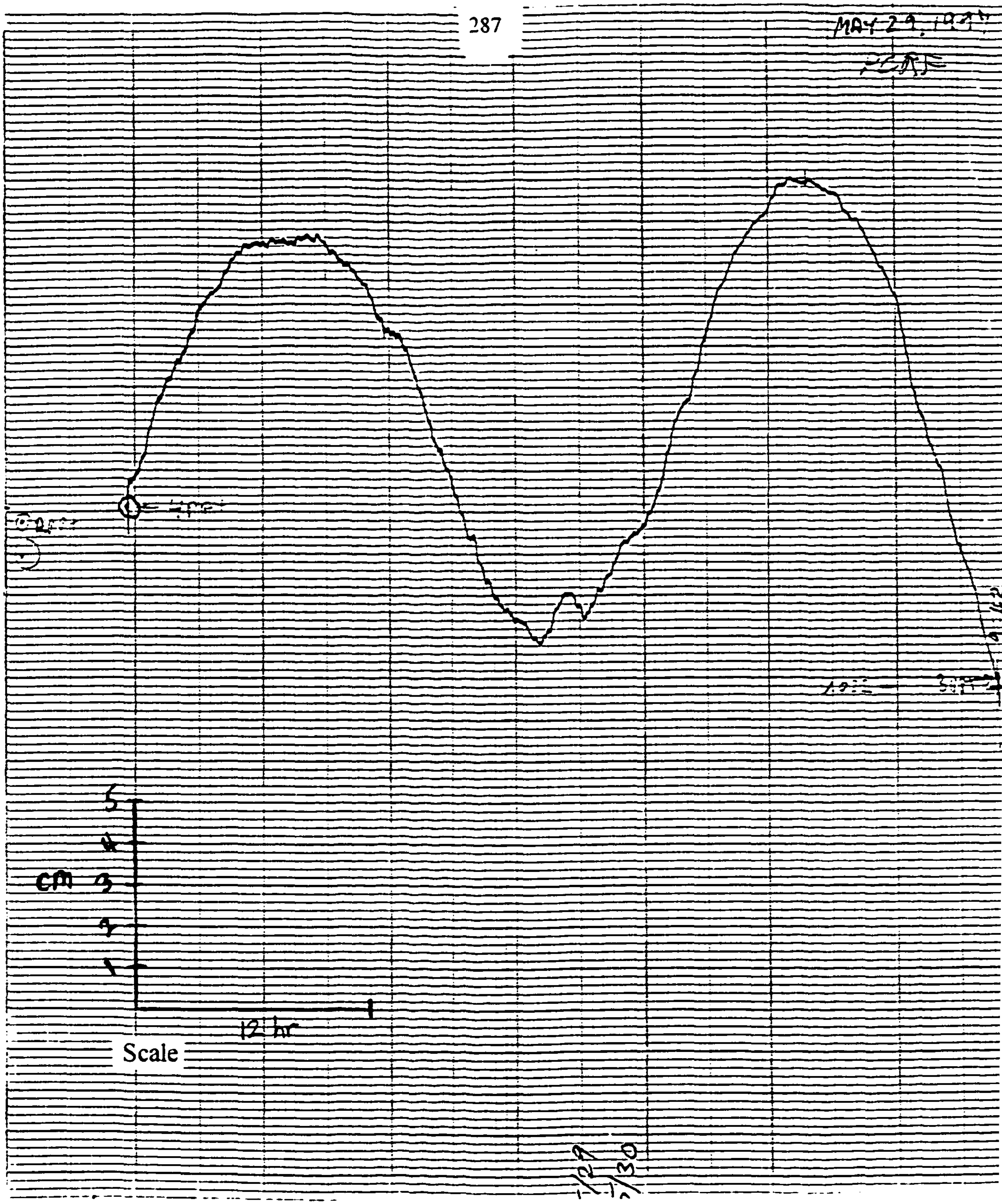


Figure A-3 Water level record for cenote near wetland treatment unit, 29-30 May 1997.

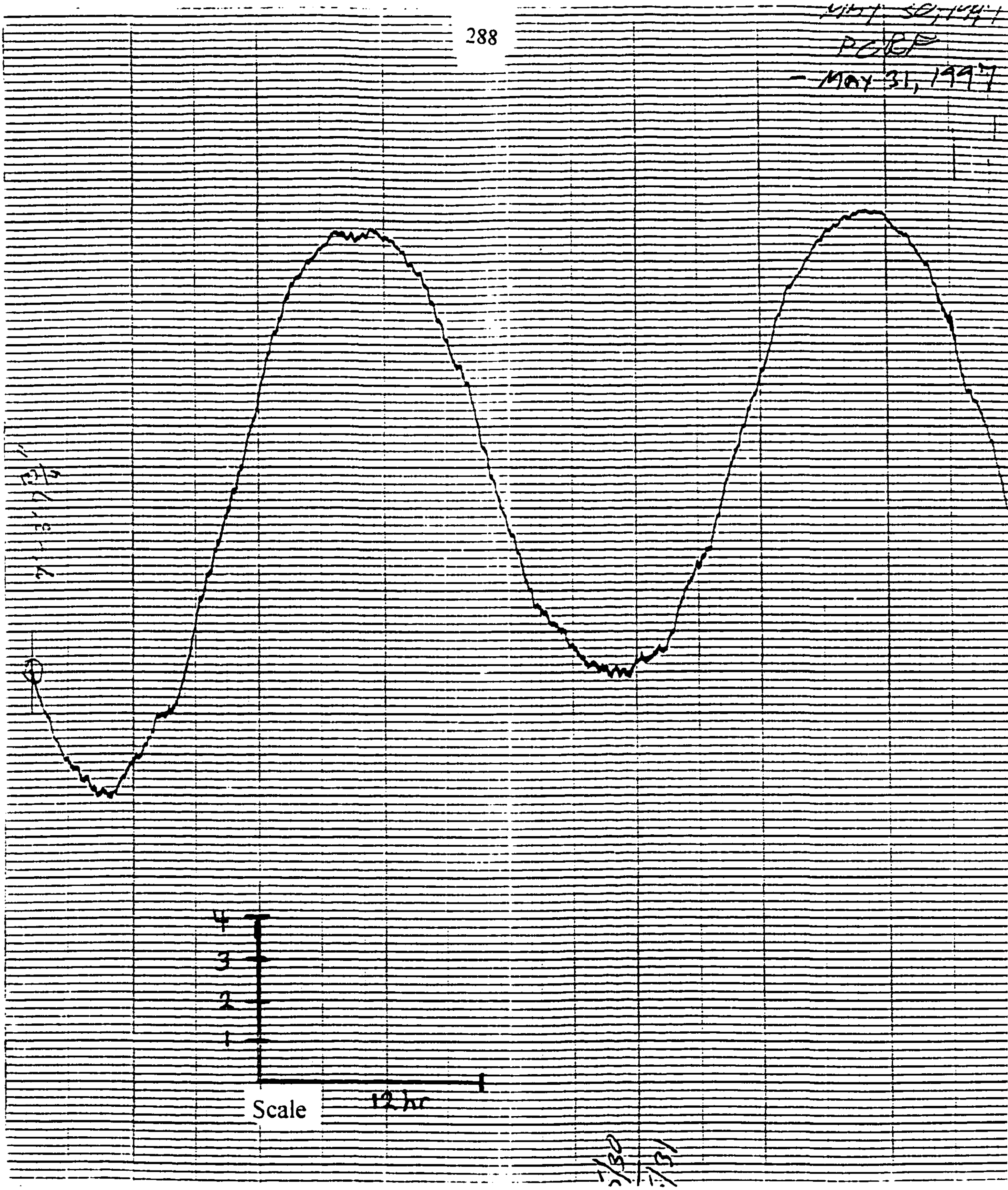


Figure A-4 Water level record for cenote near wetland treatment unit, 30-31 May 1997.

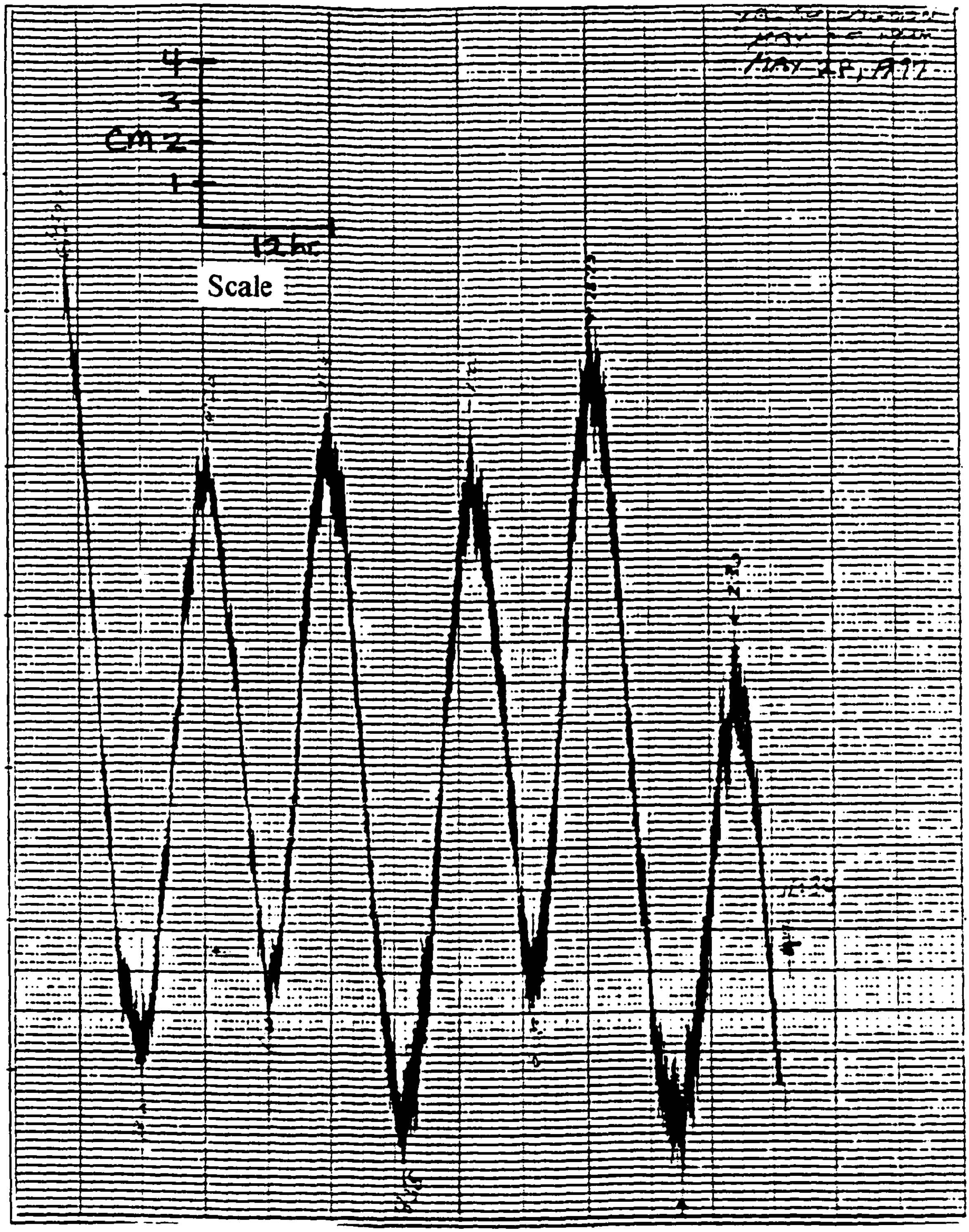


Figure A-5 Water level record of tidal heights at Yal-Ku Lagoon, 27-28 May 1997.

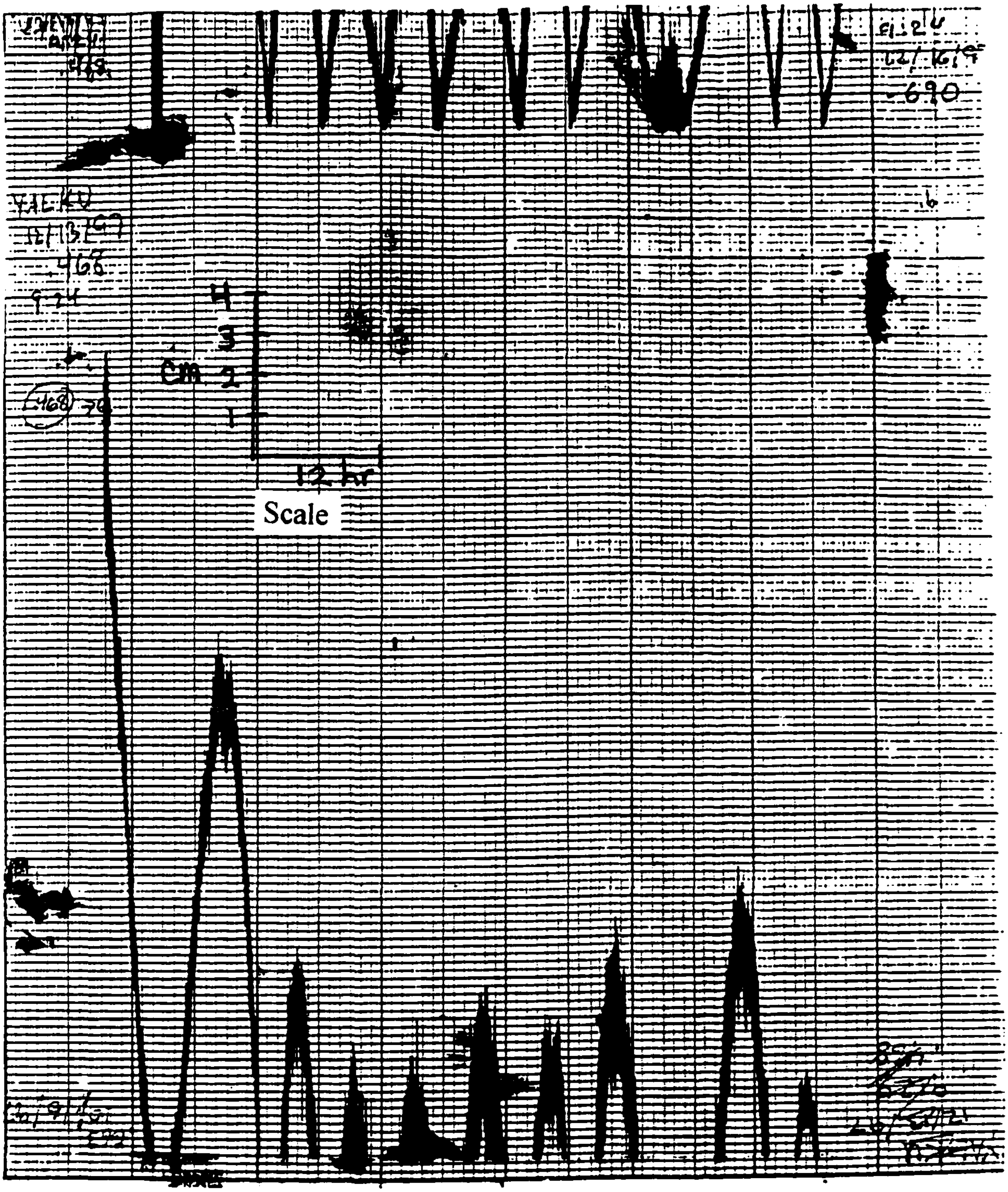


Figure A-6 Water level record of tidal heights at Yal-Ku Lagoon, 13-16 December 1997.

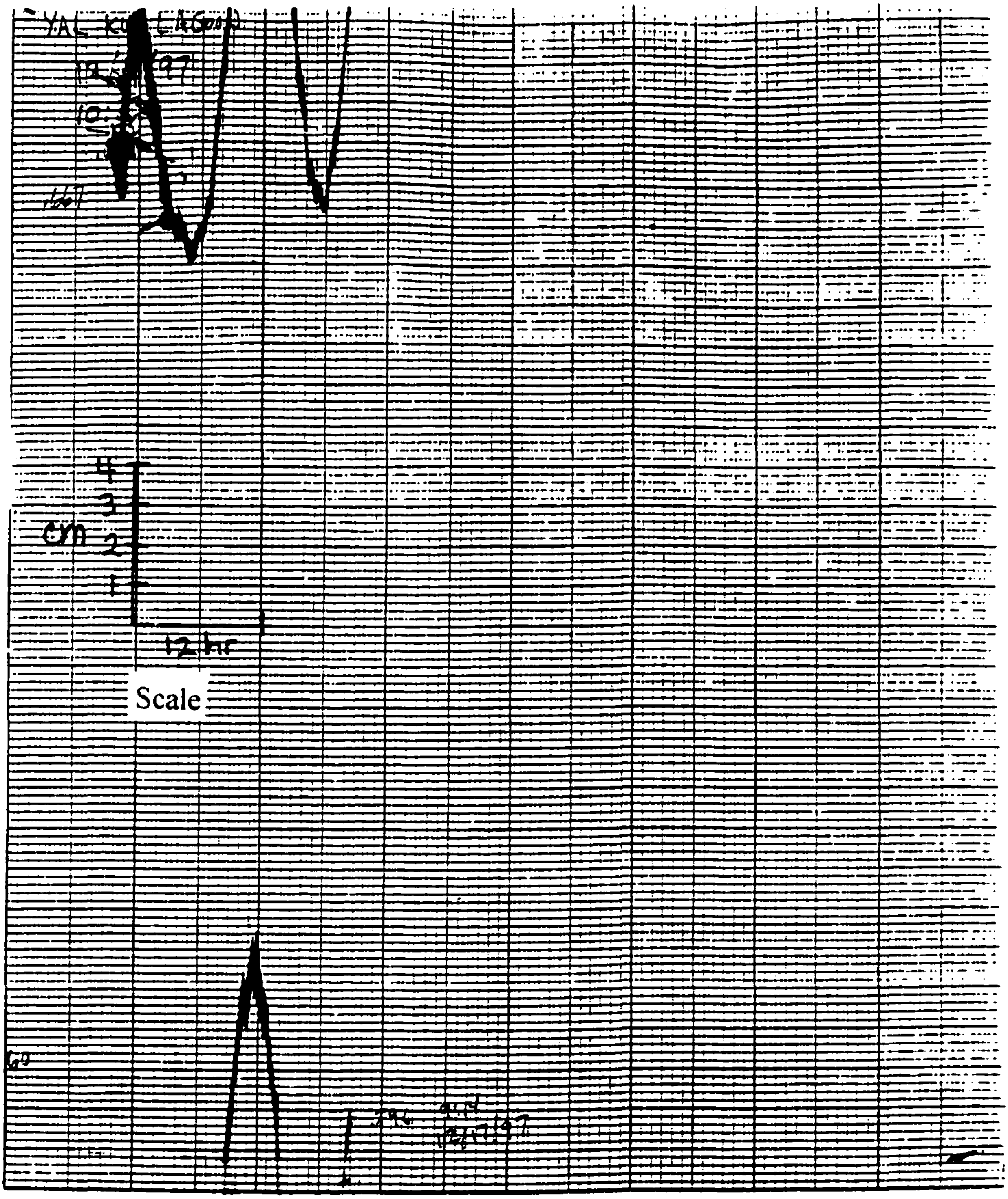


Figure A-7 Water level record of tidal heights at Yal-Ku Lagoon, 16-17 December 1997.

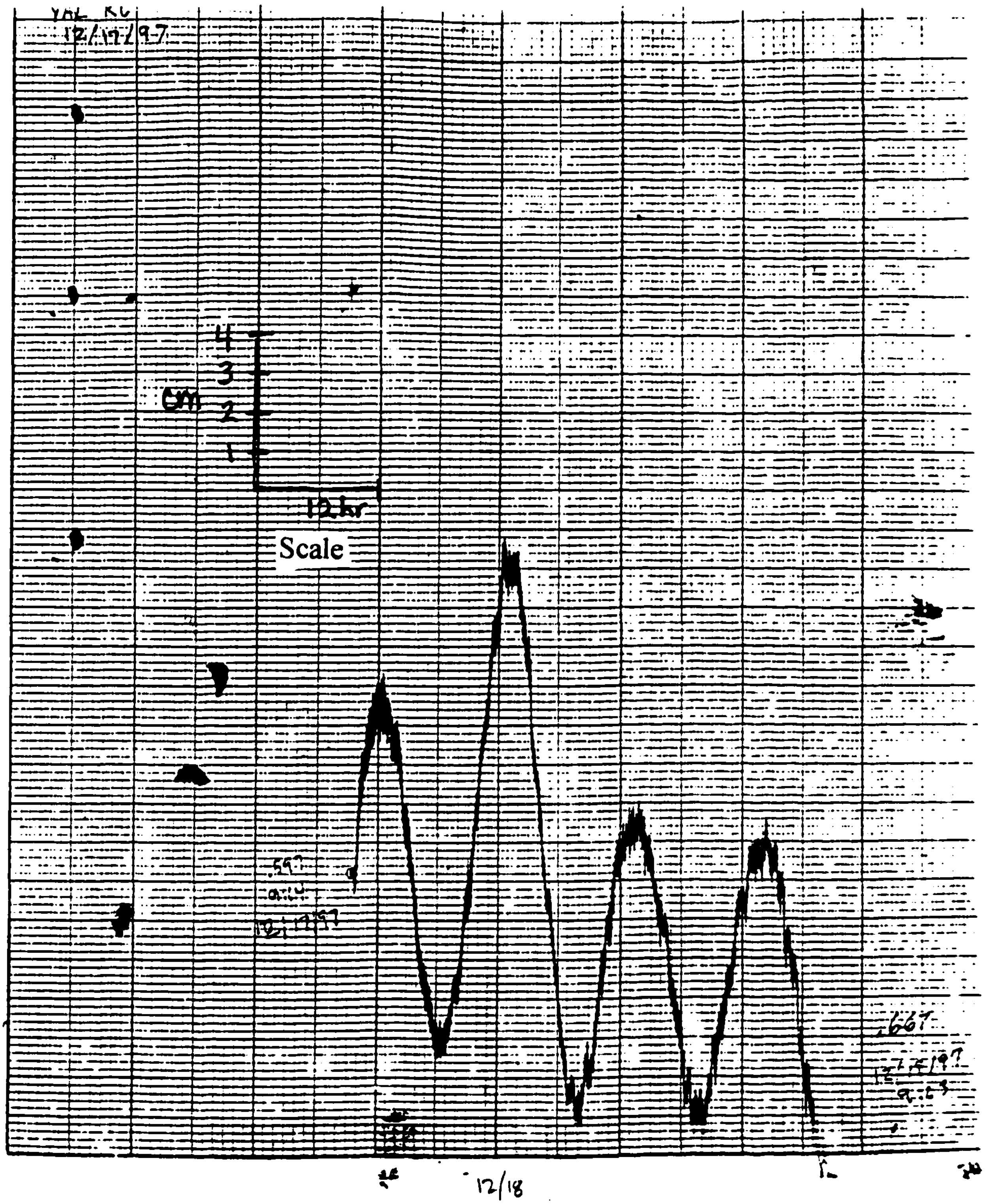


Figure A-8 Water level record of tidal heights at Yal-Ku Lagoon, 17-19 December 1997.

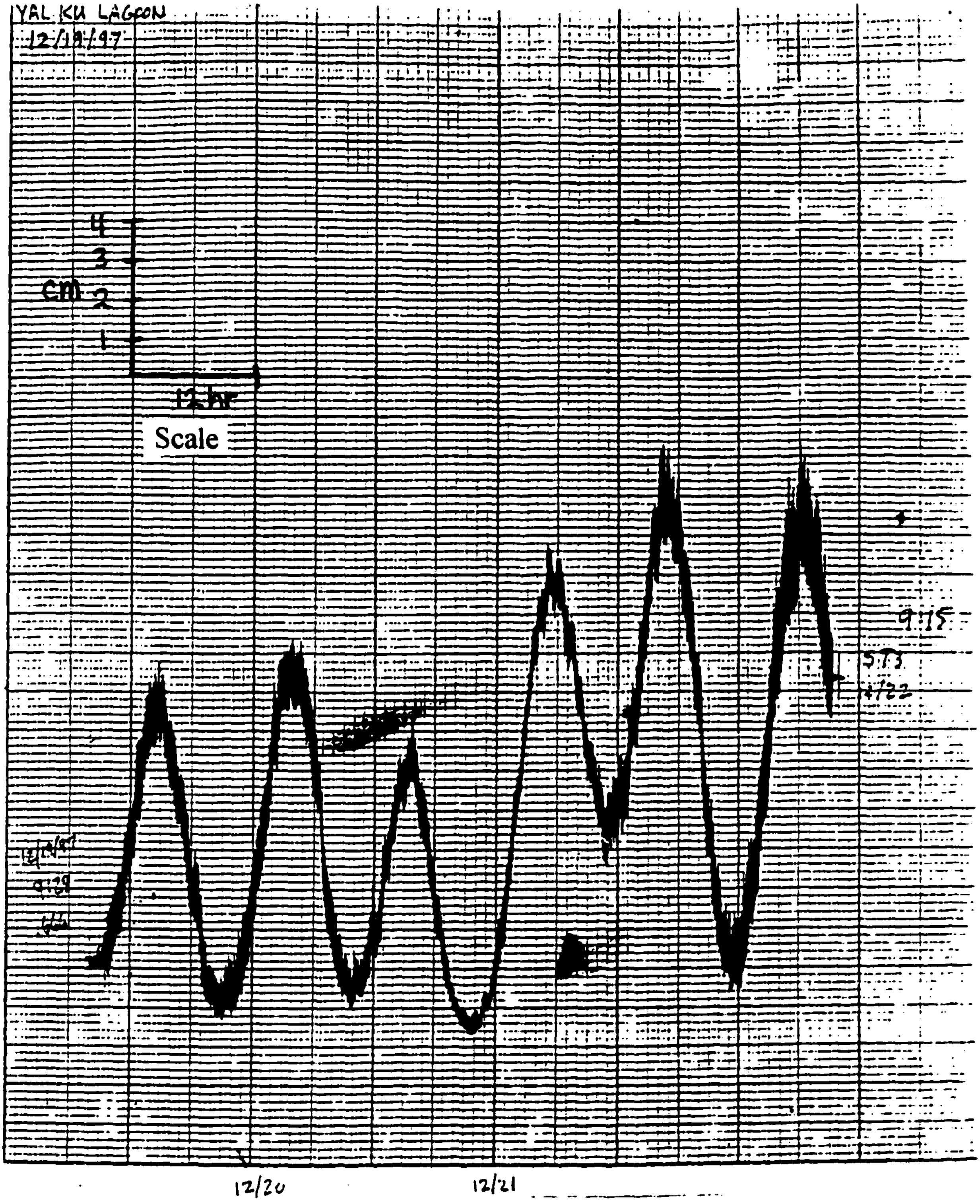


Figure A-9 Water level record of tidal heights at Yal-Ku Lagoon, 19-22 December 1997.

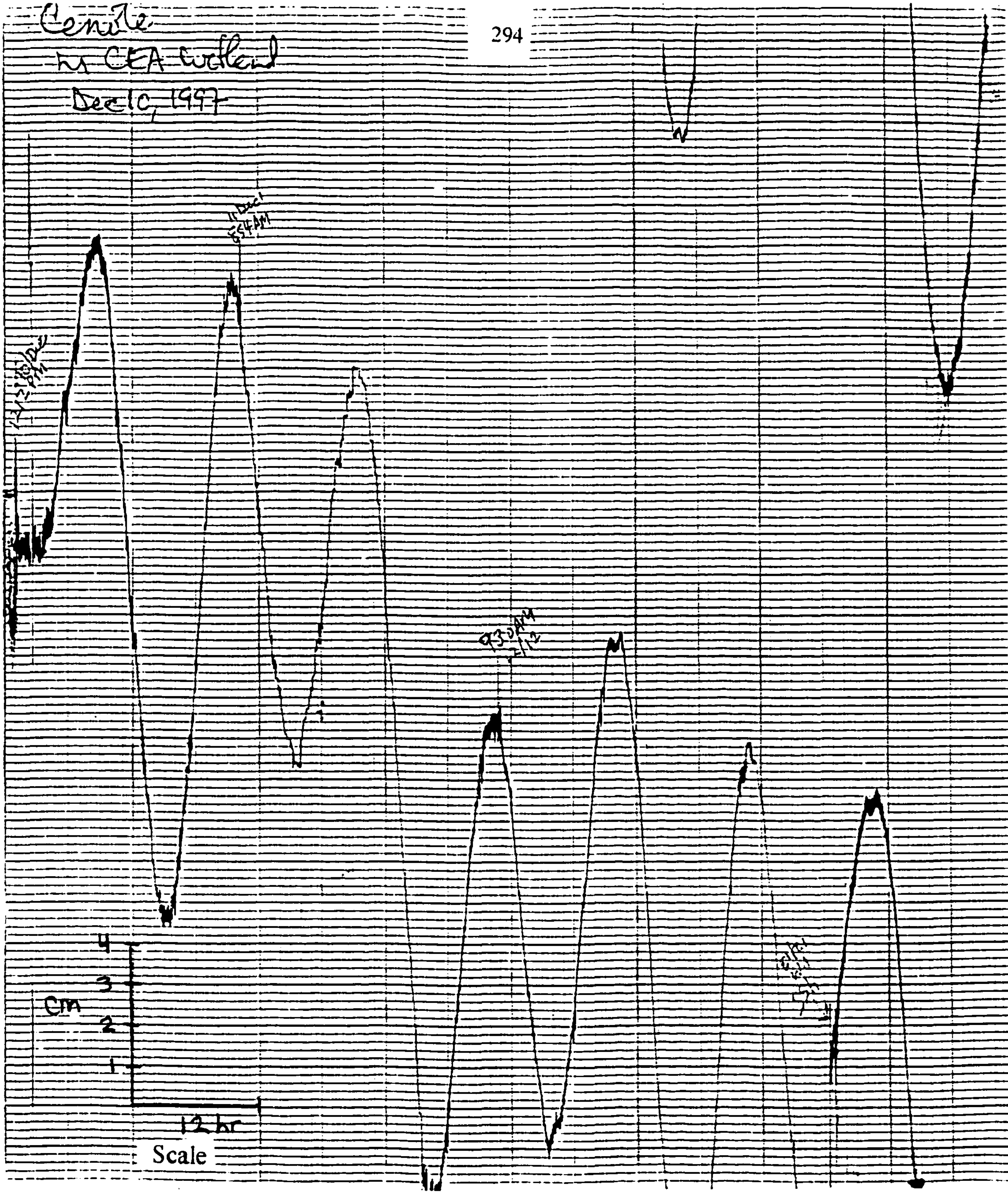


Figure A-10 Water level record for cenote near wetland treatment unit, 10-14 December 1997.

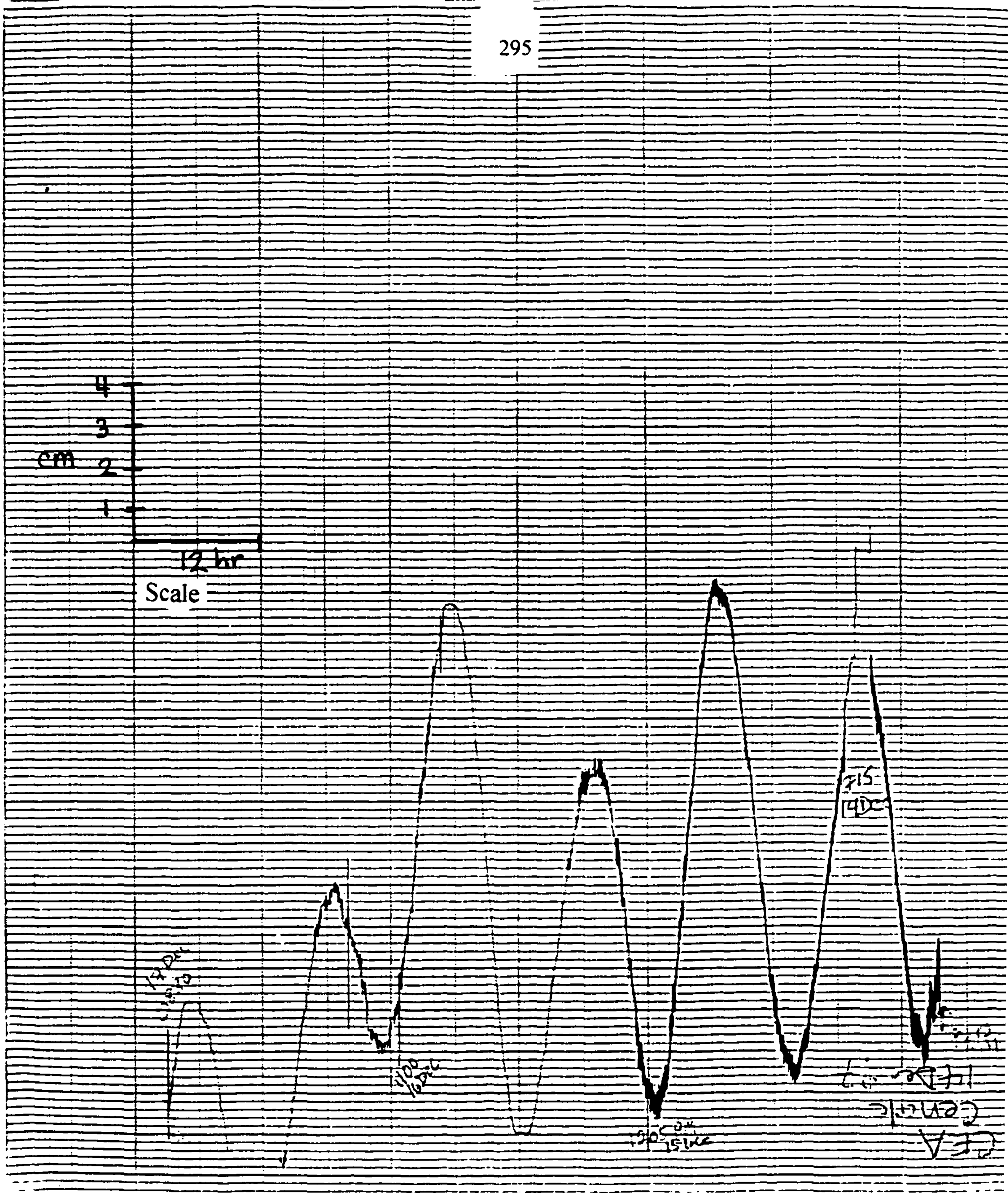


Figure A-11 Water level record for cenote near wetland treatment unit, 14-17 December 1997.

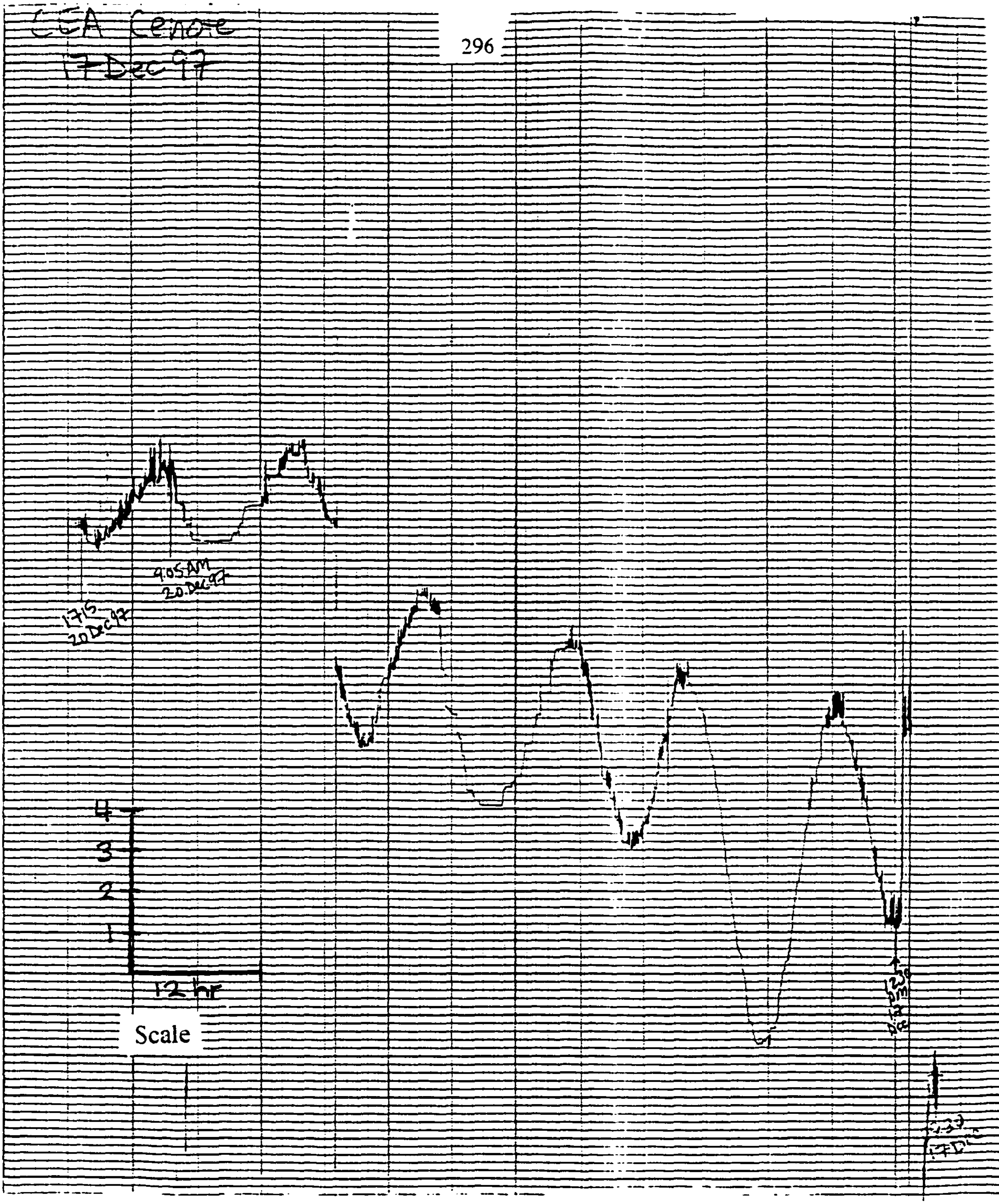


Figure A-12 Water level record for cenote near wetland treatment unit, 17-20 December 1997

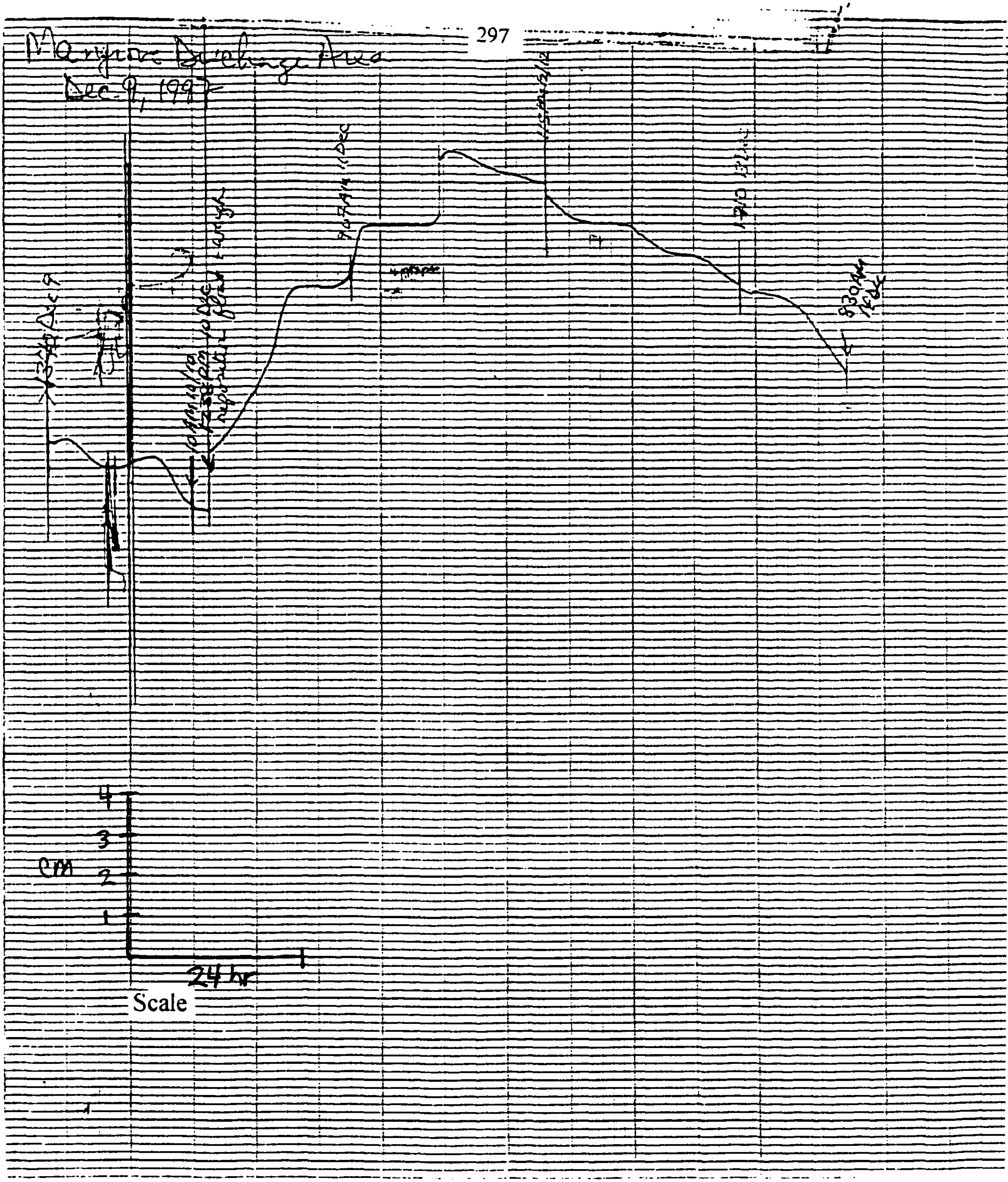


Figure A-13 Water level record for mangrove near wetland treatment unit, 9-14 December 1997.

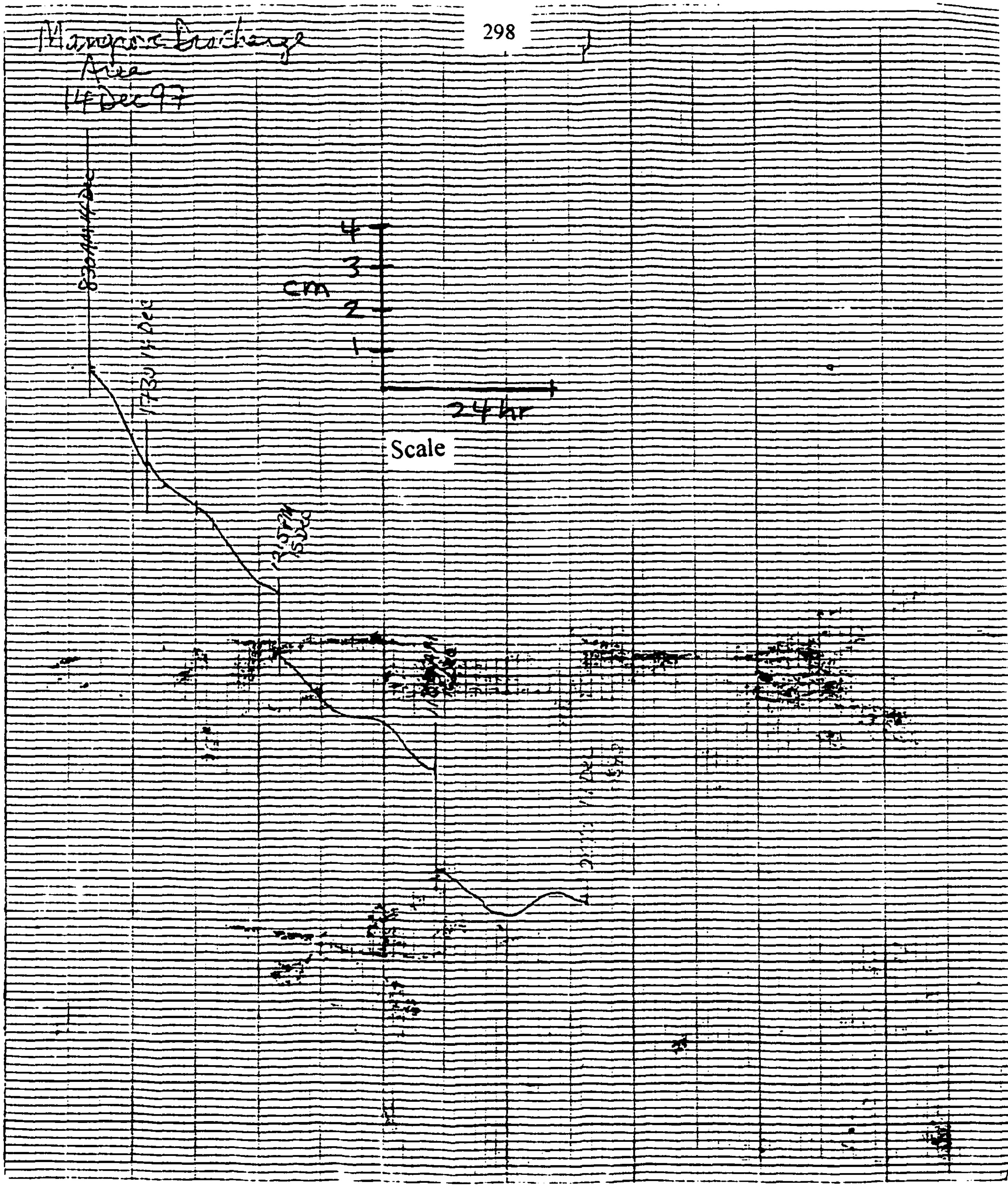


Figure A-14 Water level record for mangrove near wetland treatment unit, 14-17 December 1997.

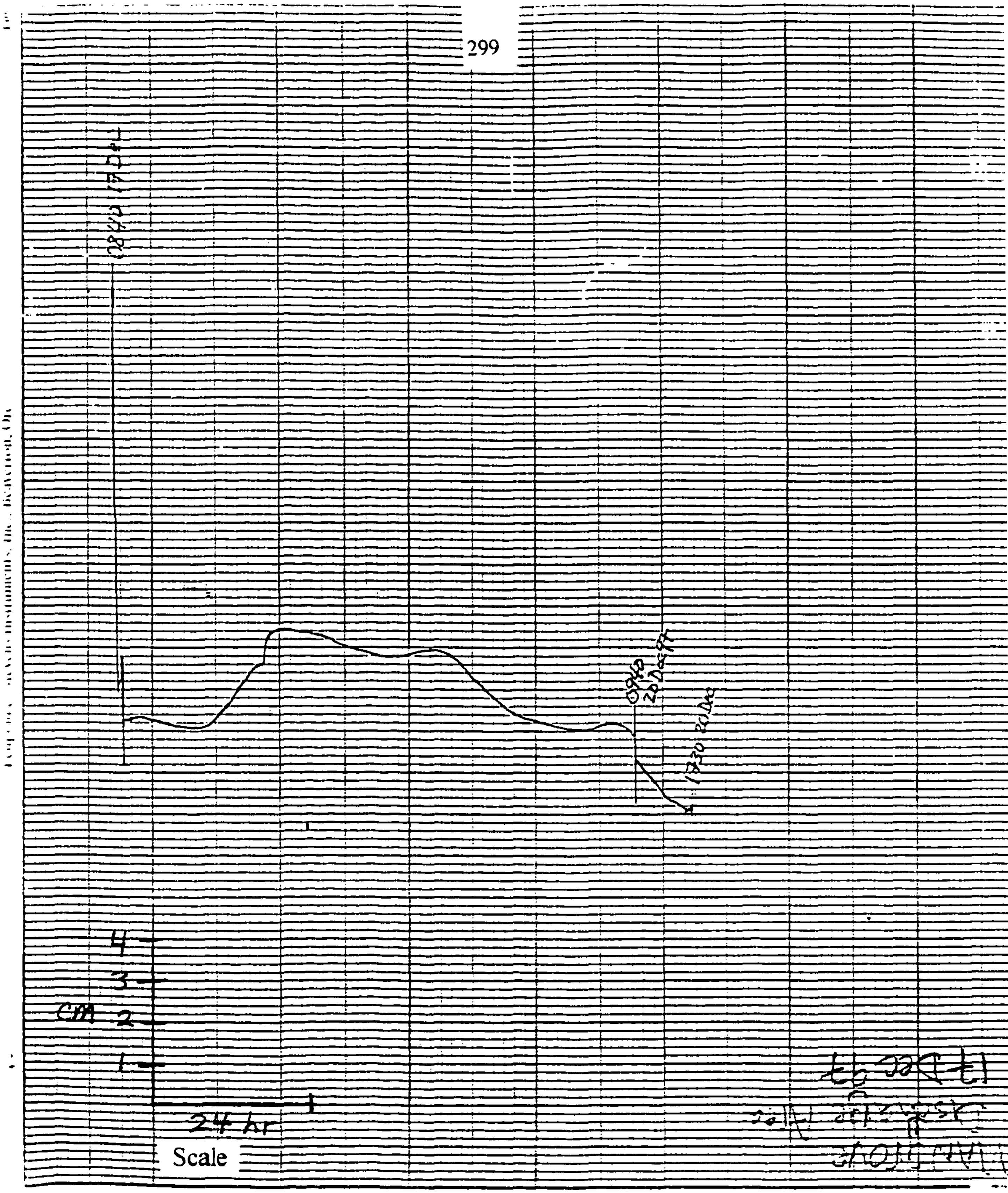


Figure A-15 Water level record for mangrove near wetland treatment unit, 17-20 December 1997.

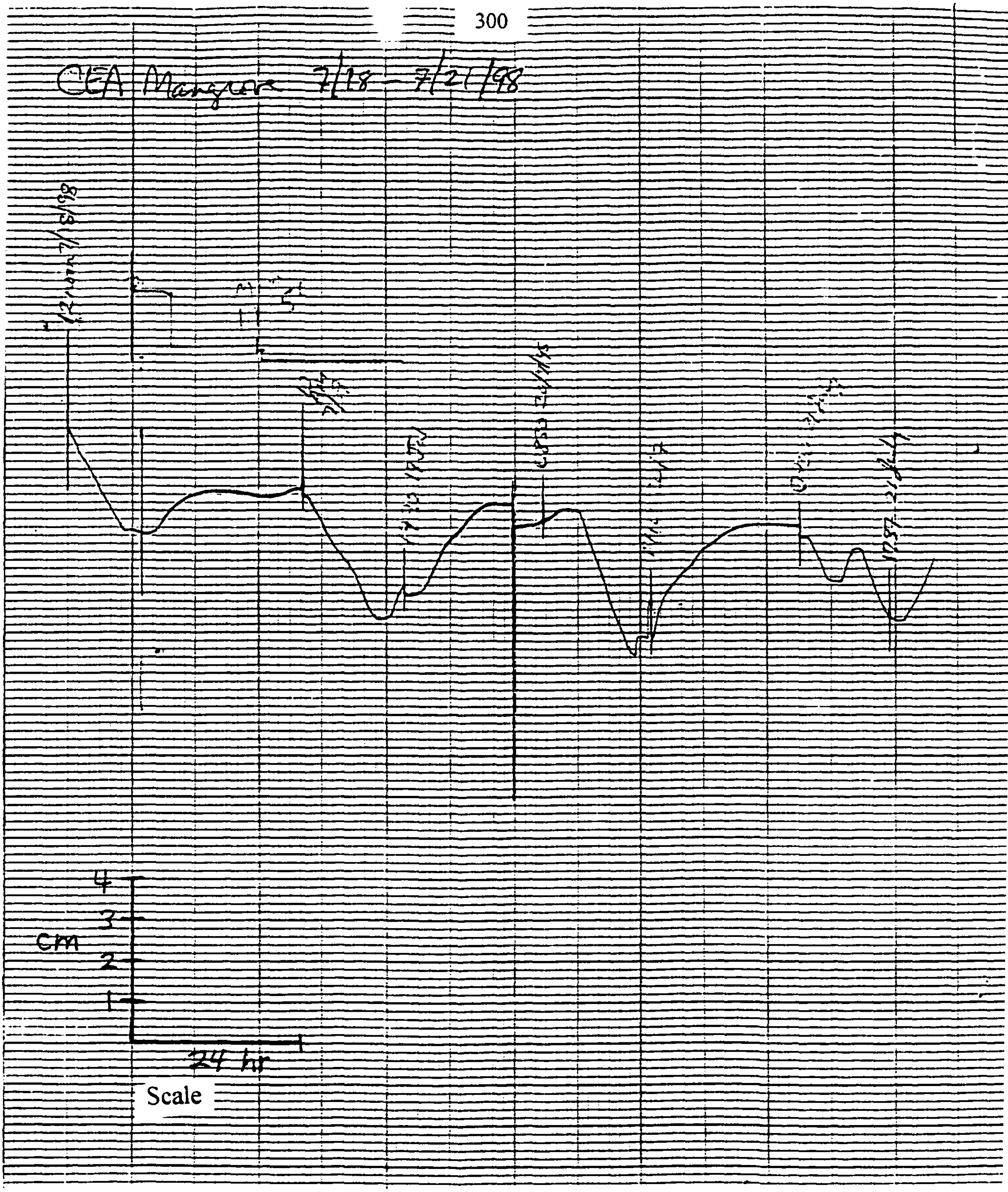


Figure A-16 Water level record for mangrove near wetland treatment unit, 18-21 July 1997.

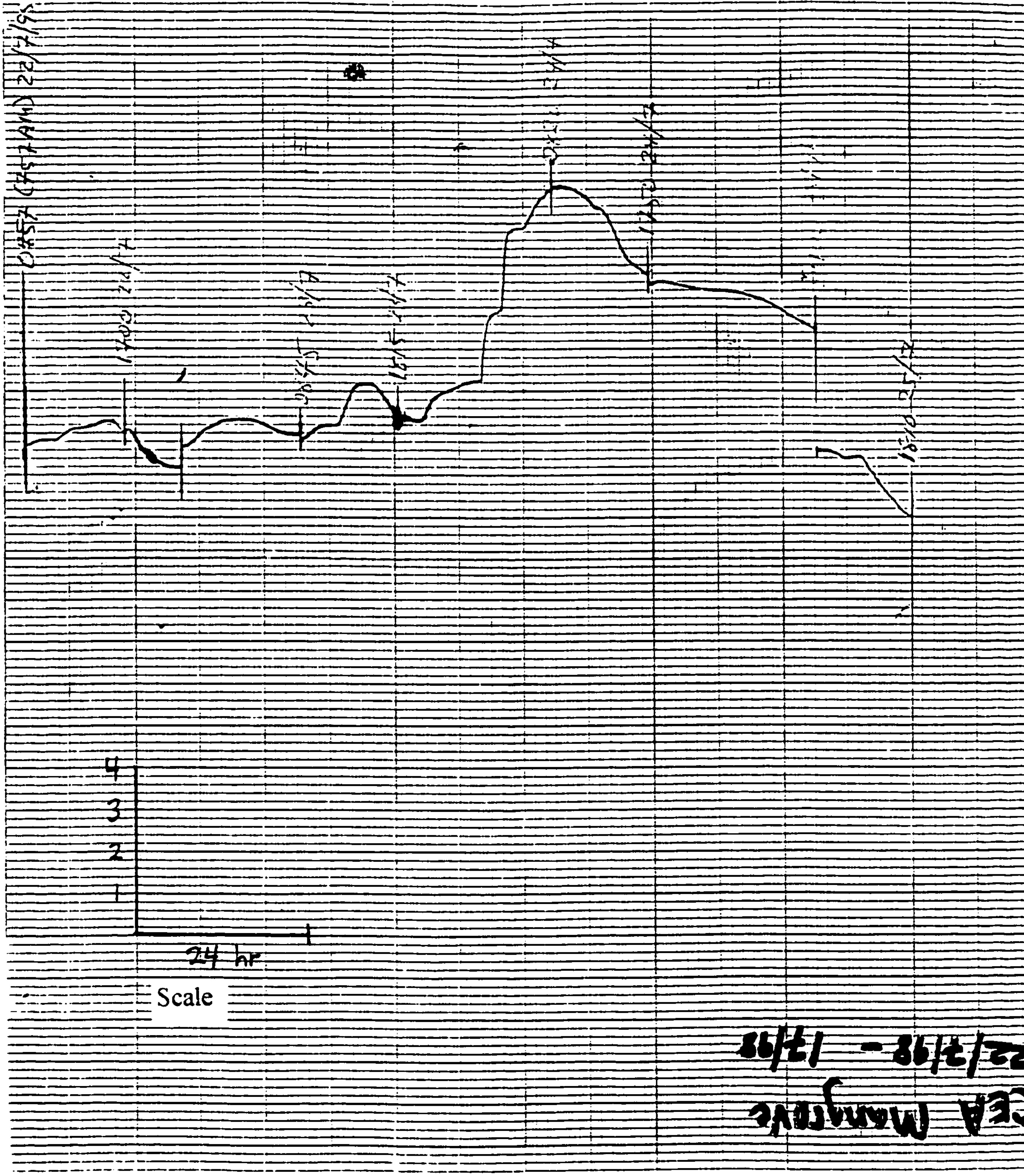


Figure A-17 Water level record for mangrove near wetland treatment unit, 22-25 July 1997.

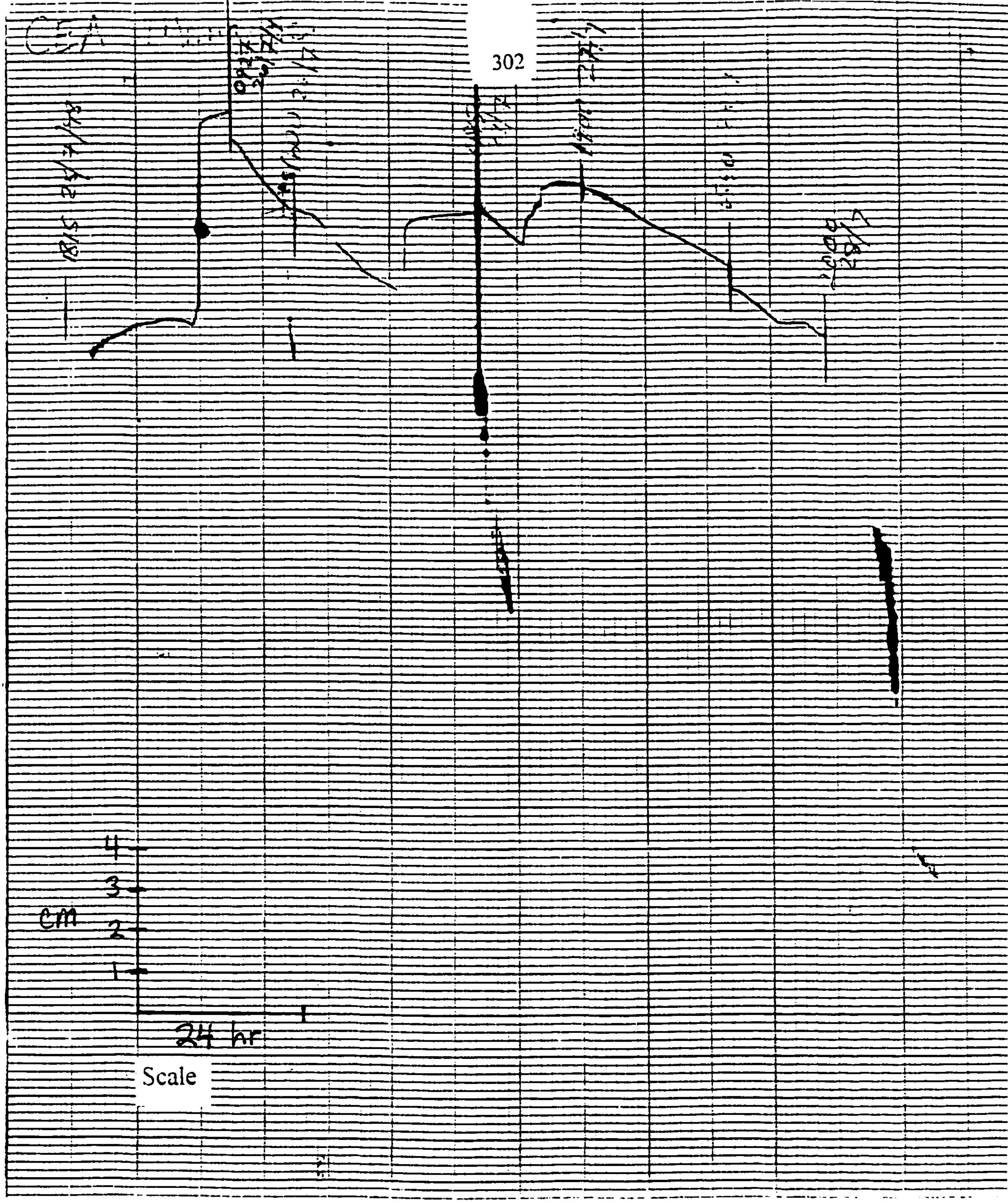


Figure A-18 Water level record for mangrove near wetland treatment unit,.25-28 July 1997.

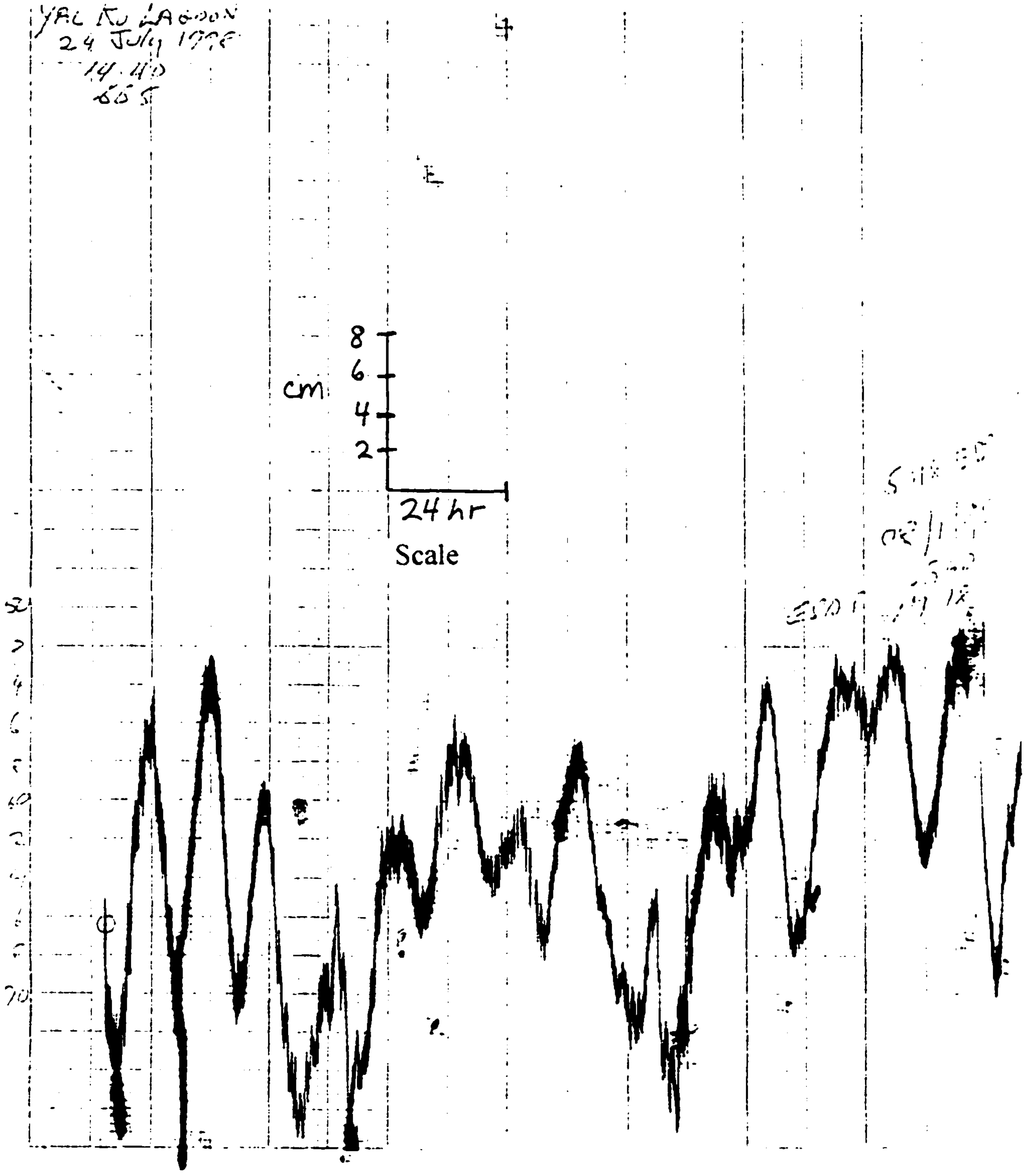


Figure A-19 Water level record of tidal heights at Yal-Ku Lagoon, 24 July – 1 August 1997.

APPENDIX B

NOTES AND TABLES FOR WATER BUDGET SIMULATION MODEL

Notes on literature values used to estimate storage values and pathway flows in the water budget simulation model:

1. Tides. Tidal range is typically 15-20 cm during full moons with a high of 40 cm and a low of 6 cm observed in the last two years (Shaw, pers. comm.) For Puerto Moreles, 80 km further north up the coast, average tidal height is 18.1 cm (Ibarra and Davalos, 1991).
2. Rainfall. Average monthly rainfall at Tulum, a coastal town 20 km further south of Akumal (Viquiera et al, 1994) is presented in Table B-1. Average rain per day is 3.02 mm.
3. Potential evapotranspiration (PET). Potential evapotranspiration (PET) measured at Tulum between 1983-1996 (SARH, 1997) totals 1450 mm and is shown in Table B-2. Average yearly evapotranspiration has been estimated to total 900 mm. Average daily PET is 3.99 mm and average daily evapotranspiration = 900/365 = 2.47 mm.
4. Relative humidity/temperature/saturated and air vapor pressure. Table B-3 shows relative humidity, temperature data for the Yucatan coast. Average monthly relative humidity for the area according to governmental meteorological data from 1958-1980 (cited in Ibarra and Davalos, 1991) shows little variance with March at 81% the

5. lowest and September at 88% being highest. Temperature is from Viquiera et al, 1994 for Tulum. Saturated vapor pressure is from temperature tables contained in Lee, 1978 and air vapor pressure is calculated from relative humidity and temperature monthly averages.
6. Wind. Average wind velocity for the area is 5 m/sec. Table B-4 presents average monthly wind velocity (Ibarra and Davalos, 1991).
7. Inland freshwater groundwater flow. Average groundwater flow was calculated (Back, 1985) by dividing drainage area of 65,500 km^2 by coastal length of 1,100 km. Of the 8.6 E3 m^3/yr through each meter of the receiving wetland, Table B-5 presents estimates of monthly flow by correlation with monthly share of annual rainfall (see note 2). Average daily groundwater flow = 8630/365 = 23.64 m^3 and average monthly groundwater flow is 8630 /12 = 719.16 m^3. In the simulation model, average monthly groundwater flow is taken as 0.30 above datum (1 meter below surface of mangrove, 0.32 m below mean sealevel). The low months (February-April) were taken as 0.2 m height of water in mangrove, and top month (May) as 0.6.Therefore, following gives monthly values, expressed in height (m) of water in mangrove m2: January 0.254, February 0.2, March 0.2, April 0.2, May 0.6, June 0.47, July 0.29, August 0.33, September 0.47, October 0.44, November 0.22 and December 0.21.
8. Solar insolation. The value for solar insolation used by Odum et al (1986) for the Amazon is 140 Kcal/cm^2/yr or 3835 Kcal/m^2/day, with presumably higher cloud interference with solar radiation. Brown et al (1992) use 180 Kcal/cm2/yr for Nayarit (World Energy Data Sheet), or 4932 Kcal/m^2/yr. From Sellers' (1965) diagram

relating latitude to average yearly solar radiation at 20 deg. N latitude gives 110 kilo-langley/cm^2/yr = 110 Kcal/cm^2/yr = 3013 Kcal/m^2/day

9. Mangrove primary productivity and biomass. Productivity in mangrove swamps varies greatly and several characteristic ecosystem types have been traditionally identified. Riverine mangroves are the most productive, followed by fringing mangrove areas and basin mangroves (Table B-6). Less productive are hummock mangroves growing in unfavorable locations. Lugo and Brinson (1979), reviewed the literature and gave data on net primary productivity (NPP) of these mangrove types in Florida. Using an average value of 1.5% N for mangrove plant tissue, we have translated their numbers into average annual N assimilation by mangroves, which shows that Nedwell et al's productivity calculation places their mangrove system as intermediate between riverine and fringing in N-uptake. Cintron et al (1985) (cited in Mitsch and Gosselinke, 1993) give a range of biomass of 0.8 - 15.9 kg/m^2 for fringe mangroves and 1.6 - 28.7 kg/m^2 for basin mangroves. We can use an average figure of 16 kg/m^2 for this model.

10. Primary productivity and biomass of treatment wetland unit. Richardson (1979) estimates net primary productivity in freshwater marshes as follows: *Typha* wetlands: 2740 ± 670 grams of organic matter (m$^{2)-1}$ yr^{-2}; reed wetlands (*Phragmites communis*, *Scirpus* spp., *Juncus effusus*, *Cyperus papyrus*) 2100 ± 580 grams of organic matter (m2)-1 yr-2 and freshwater tidal marshes (*Peltandra virginica*, *Acorus calamus*, *Zizania aquatica*): 1600 ± 200 grams of organic matter (m^2)$^{-1}$ yr^{-2}. These three data average 2154 grams of organic matter (m^2)$^{-1}$ yr^{-2}, or 5.9 g (m^2)$^{-1}$ day^{-2}. Total biomass estimates for tidal marshes range from 0.145 - 0.725 kg/m^2 for a freshwater tidal

marsh (Simpson et al, 1983, cited in Mitsch and Gosselink, 1994), to estimates for peak standing crop of the salt marsh species *Spurtina alterniflora* of 0.754 -0.903 kg/m^2 (Hopkinson et al, 1980 and Kaswadji et al, 1990 cited in Mitsch and Gosselink, 1994), which probably comprise 20-30% of total biomass, and 6.55 kg/m^2 for total above and belowground biomass in a Louisiana salt marsh (Buresh et al., 1980 cited in Day et al, 1989). We can use 6 kg/m^2 as an estimate for the treatment wetland unit's biomass since they include larger tree and palm species as well as wetland grasses and shrubs.

11. Wastewater inputs. At design loading, for the 81.6 m^2 wetland, inputs are 24 people x 0.115 cu m/day = 2.76 m^3/day / 81.2 m^2, or 0.034 m/day. Our model will use 0.34 m/day wastewater input for October - April, and in the off-tourist months of May - September, a loading of 0.22 m/day.

Table B-1 Average monthly rainfall at Tulum, 20 km south of study site

Month	Rainfall, mm.
January	77.9
February	41.3
March	42.3
April	41.2
May	166.6
June	143.3
July	88.1
August	101.1
September	149.7
October	140.9
November	74.7
December	57.0
	Total: 1,104.1

(Viquiera et al, 1994).

Table B-2 Measured evaporation at Tulum, 20 km south of study site along the Yucatan coast. Actual evapotranspiration is estimated at 900 mm for the Yucatan. The last column is a calculation of evapotranspiration based on the percentage of yearly evaporation that occurs in each month..

Month	Average monthly potential evapotranspiration, mm.	Percentage of Yearly ET, %	Monthly evapotranspiration if year total is 900 mm
January	89.2	6.1	54.9
February	102.5	7.0	63.0
March	129.9	8.9	80.1
April	148.1	10.2	91.8
May	142.1	9.8	88.2
June	141.9	9.8	88.2
July	150.8	10.4	93.6
August	144.1	9.9	89.1
September	125.9	8.7	78.3
October	101.8	7.0	63.0
November	94.5	6.5	58.5
December	83.8	5.7	51.3
	1454.6 (Total)	100	900.0

(SARH, 1997).

Table B-3 Average monthly relative humidity, temperature and air vapor pressure calculated for the given temperature and relative humidity for the Yucatan coast.

Month	Average relative humidity, percent	Temperature degrees C.	Saturated vapor pressure at monthly average temp., mb	Air vapor pressure at average relative humidity and temp. for month, mb
January	84	23.3	28.61	24.03
February	83	23.5	28.96	24.04
March	81	24.7	31.12	25.21
April	81	25.5	32.64	26.44
May	82	25.8	33.22	27.24
June	85	26.2	34.02	28.92
July	86	26.0	33.61	28.90
August	86	26.0	33.61	28.90
September	88	25.0	31.67	27.87
October	87	24.9	31.49	27.39
November	84	24.8	31.31	26.30
December	85	23.1	28.26	24.02
Average	84	24.9	31.49	26.45

(Ibarra and Davalos, 1991, Viquiera et al, 1994, Less, 1978)

Table B-4. Average wind velocity, measured at Puerto Moreles, Mexico, 80 km north of study site.

Month	Average wind velocity meters/second
January	5.0
February	6.6
March	4.3
April	4.4
May	5.6
June	5.4
July	4.5
August	3.6
September	4.1
October	4.4
November	5.9
December	6.7
Average	5.0

(Ibarra and Davalos, 1991).

Table B-5 Estimates of monthly groundwater flow based on data and average monthly rainfall in the Yucatan.

Month	Share of annual rainfall, Decimal	Groundwater flow, per square meter of mangrove wetland, $m^3/m/yr$
January	0.07	604.1
February	0.04	345.2
March	0.04	345.2
April	0.04	345.2
May	0.15	1294.5
June	0.13	1121.9
July	0.08	690.4
August	0.09	776.7
September	0.13	1121.9
October	0.12	103 5.6
November	0.06	517.8
December	0.05	431.5
Total	100	8630

Back (1985)

Table B-6 Net primary productivity (NPP) in mangrove ecosystems.

Mangrove System	NPP grams organic matter/m^2/day	NPP per yr ($gOM/m^2/yr$)
Riverine	12.6	4600
Basin	5.6	2044
Fringe	2.9	1059
Hummock	2.6	949
Average	5.85	2163

(Lugo and Brinson, 1979).

APPENDIX C

COMPARISON WITH UNIVERSITY OF FLORIDA SEWAGE TREATMENT FACILITY

Table D-1 presents an emergy evaluation of the University of Florida Water Reclamation Facility. 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. Disposal is via groundwater injection (84%), use in air-conditioner cooling towers (8%) and use in campus irrigation (4%).

Wastewater flow totals about 2 million gallons per day for a population of about 40,000. This amounts to 50 gallons per person, however, since most of the population do not live on-campus, wastewater generation is even higher. If assumed to be equivalent to a full-time residence for 20,000 people, wastewater flow is around 100 gallons/person. Capital investment for the University of Florida treatment plant was around $11.2 million

The University of Florida system is dependent on the use of much electricity (even ignoring electricity used to pump to the facility) and uses 4.1 E6 kilowatt-hours annually to operate the mechanical aerators, grinders, and pumps. Chemicals are also used: alum for coagulation, chlorine for disinfection. Freshwater totaling 7.3 million gallons/year is used at the University of Florida facility for disinfection and general plant operations.

Emergy analysis of the University of Florida treatment plant (Table 5-1) shows that >99% of resources are non-renewable (raw wastewater), and purchased goods are 0.5% and services 0.1%. Renewable resources contribute less than 0.001% of emergy inputs. The purchased / renewable ratio is 220 for the University of Florida facility (220 times as much purchased inputs as renewable resource emergy inputs). Emergy required per person is 314 E14/person. Empower density (energy per area per time) is 14.3 E20 sej/ha/yr. for the University of Florida system.

Table C-1 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				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 E12 sej/$, 1993 values (Odum, 1996, p. 314)

Sunlight received in Gainesville, Florida with albedo estimated at 10% x .44 ha (size of sewage facility): (1.58 x 1 OE6 kcal/sq m/yr) (.90)(1 x 10 E4 sq m/ha) (4186 J/kcal) (0.44ha) = 2.62E 13 or 0.262E 14 J/yr (Odum, 1996, p. 114)

2
Based on method given in Odum, 1996, p. 294, with values of eddy diffusion and vertical gradient from Tampa, Florida and using wind of 10 m height as relevant for re

Table C-1 continued

aeration of microbial reactor tanks of facility: (10 m)(I. 23 kg/cu m) (2. 8 cu m/m/sec)
(3.154E7 sec/yr) (2.3 m/sec/m)E2 (4400 sq m) = 2.53 EI3 J/yr
Transformity for wind from Odum, 1996 p. 186

3
Yearly inputs of raw sewage: 714.1 E6 gallons

Transformity based on emergy needed to sustain people in Florida: 32 E15 sej/yr (Odum et al, 1998)

divided by yearly outputs of wastewater per person = 100 gallons/day *365 days =
(3.65E4 gallons)
32 E15 sej/yr / 3.65 E4 gallons = 8.76 E11 sej/gallon

4
Electricity chemical potential: (3,291,300)60 kWh/yr) (3.6E6 J/kWh) = 1. 1 8EI3 J/yr
(Odum, 1996, p.300)

Mean transformity for electricity (Odum, 1996, p. 305)

5
Fuel chemical potential based on P. Green, 1992, p. 27: (1000 gal/yr) (3.7 L/gal) (41E6 J/L) = 1. 5 2E11 J/yr

Fuel transformity based on calculation of Slesser, 1978 cited in Odum, 1996, p. '308

6
Water, Chemical Potential Energy:

4940 J/kg given in Odum, 1996, p. 120, density of water at 20 deg C = 998.2 kg/ cu m (Kraut, Fluid Mechanics for Technicians, 1992, p. 365; (7,296,700 gal/yr) (I cu in/ 264 gal) (4940 J/kg) (998.2 kg/cu m) = 1.36EI I J/yr

Transformity of water from Brown and Arding, 1991, Transformity Working Paper

7
Chlorine: (7E6 kcal/ton) (4186 J/kcal) (21.75 tons/yr) = 6.37EI 1 J/yr and the transformity of coal (Odum, 1996, p. 194)

8
Capital Costs: Facility excluding the sludge drying component

$10,935,000/20 yrs lifetime = $546,750 x 1.37EI2 sej/$ = 749.05EI7

Table C-1 continued

9
Maintenance (goods) $365,000 * 1.37 E12 sej/$ = 749.05 E17

10
Operation: labor costs: $385,118/yr x 1.37E12 sej/$ = 527.61 E 17 sej

11
Discharge of treated wastewater: 714.1 E6 gallons/yr
Chemical potential of wastewater: 714.1E6 gal * 1 cu m/264 gal * 10E6 g/cu m * 4.94 J/g = 13.36 E13 J

Transformity of treated wastewater: 6295.8 E17 sej / 13.36 E13 J = 4.71 E6 sej/J

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BIOGRAPHICAL SKETCH

Mark Nelson was born 29 May 1947, in Brooklyn, New York, and was educated at Dartmouth College, where he graduated Summa Cum Laude in 1968, with high honors in philosophy and was elected a member of Phi Beta Kappa. His M.S. degree (1995) is from the University of Arizona's School of Renewable Natural Resources, Tucson.

A founding director and currently Chairman and C.E.O. of the Institute of Ecotechnics, London, Mark has worked in demonstration ecological projects in the United States and Australia for over two decades. His research interests includes pasture improvement and regeneration of tropical savannah ecology, high desert orchardry and silvicultural systems, ecological engineering and closed ecological systems. Mark served as director of Environmental and Space Applications for the Biosphere 2 project in Oracle, AZ from 1985-1994. He was a member of the eight-person biospherian crew that operated and researched Biosphere 2 during its first two year closure experiment, 1991-1993. He is currently a Contributing Editor for the journal, *Life Support and Biosphere Science.*

As Vice President for Wastewater Recycling Systems for Planetary Coral Reef Foundation, he has designed and implemented constructed wetland systems in Mexico, Bali and the United States. He is also a director of Eco-Frontiers, Inc., which owns and manages projects in a number of challenging environments around the world.

IMAGE EVALUATION
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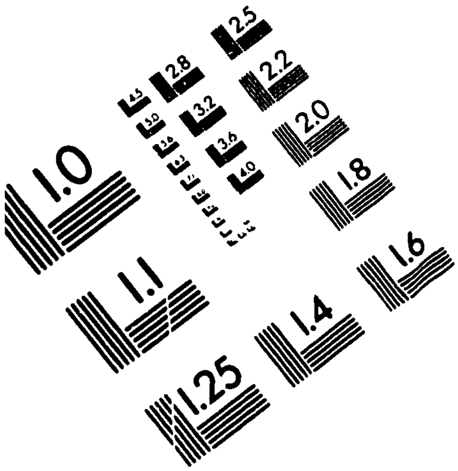

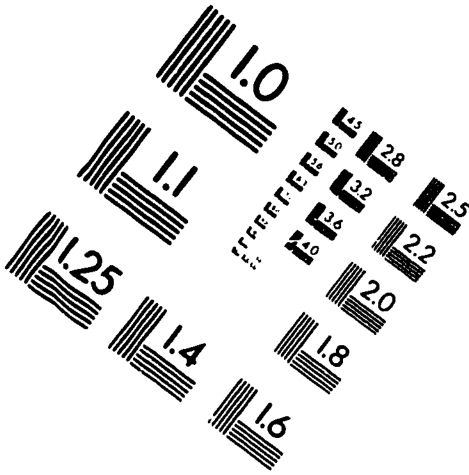

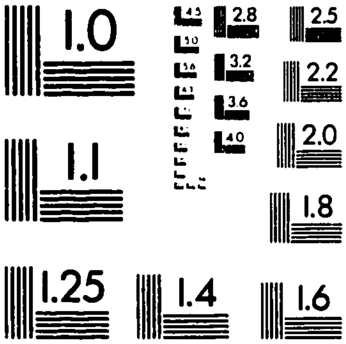

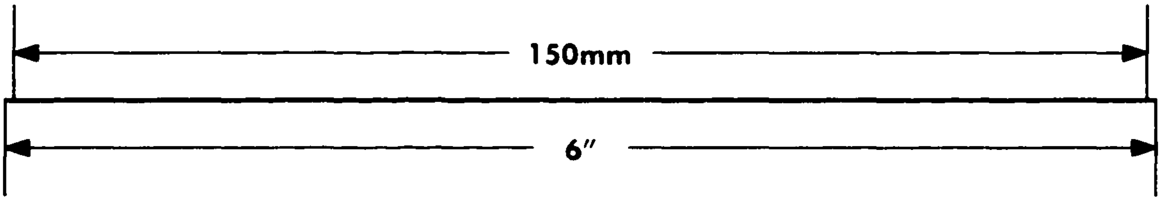

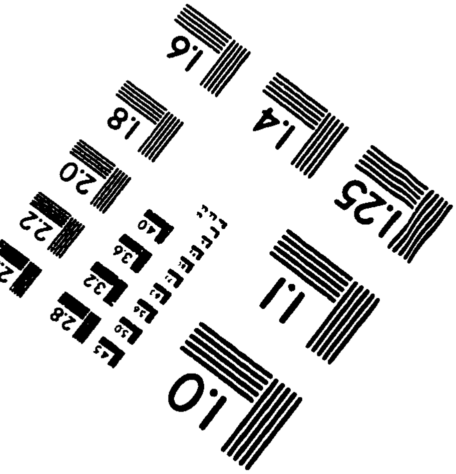

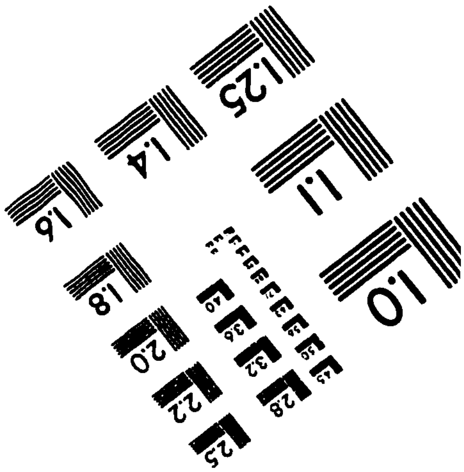

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