United States
Environmental Protection
Agency

Office of Water
Program Operations (WH-547)
Washington DC 20460

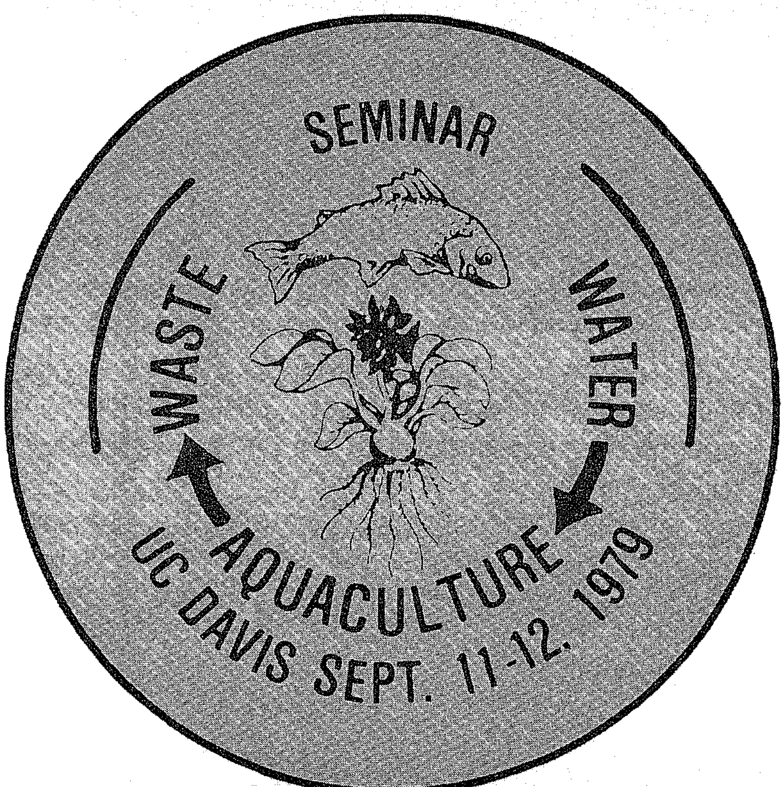
September 1979
430/9-80-006

Water

EPA

Aquaculture Systems for Wastewater Treatment

Seminar Proceedings and Engineering Assessment



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AQUACULTURE SYSTEMS FOR WASTEWATER TREATMENT:

Seminar Proceedings and Engineering Assessment

Robert K. Bastian
Sherwood C. Reed

Project Officers

September 1979

U.S. Environmental Protection Agency
Office of Water Program Operations
Municipal Construction Division
Washington, D.C. 20460

EPA Comment

This report is one of a series planned for publication by the U.S. EPA Office of Water Program Operations to supply detailed information for use in evaluating, selecting, developing, designing, and operating innovative and alternative (I/A) technologies for municipal wastewater treatment. This series will provide indepth presentations of available information on topics of major interest and concern related to I/A technologies. An effort will be made to provide the most current state-of-the-art information available concerning I/A technologies for municipal wastewater treatment.

These reports are being prepared to assist EPA Regional Administrators in evaluating grant applications for construction of publicly owned treatment works under Section 203(a) of the Clean Water Act of 1977. They also will provide state agencies, regulatory officials, designers, consulting engineers, municipal officials, environmentalists and others with detailed information on I/A technologies.

Harold P. Cahill, Jr.

Harold P. Cahill, Jr.
Director
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This publication contains an engineering assessment and the proceedings of a seminar held at the University of California-Davis on September 11-12, 1979, on the use of aquatic systems for the treatment of municipal wastewater. Case studies drawn from throughout the United States are used to illustrate the engineering, design, operation, and management of various wastewater aquaculture systems, including projects involving wetlands processes, aquatic plant processes, and combined aquatic processes. The potential recovery of energy and resources is also considered.

Sponsored by:

California State Water Resources Control Board
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CONTENTS

ECONOMICS, ENERGY, AND BY-PRODUCT UTILIZATION SESSION

Engineering Assessment Overview

ENGINEERING ASSESSMENT OF AQUACULTURE SYSTEMS FOR WASTEWATER TREATMENT: AN OVERVIEW

Sherwood Reed — USACRREL, Hanover, N.H.
Robert Bastian — US EPA/OWPO, Washington, DC
William Jewell — Cornell University, Ithaca, NY

BACKGROUND

The use of aquaculture concepts for wastewater treatment has received increasing attention in recent years. Systems studied to date have included both natural and constructed wetlands, ponds, raceways and other structures based on various combinations of aquatic plants and animals.

In some cases these systems were not optimized for wastewater treatment since the principal goal was biomass production or the recovery of some other beneficial product. In other cases wastewater treatment has been the primary objective with byproduct recovery of secondary importance. Both types have been studied at the research level, tested at the pilot scale, and in some cases demonstrated as a full scale operational system.

Some of these systems have shown a potential for reducing energy requirements and operation and maintenance costs. The incentives of the Clean Water Act of 1977 provide a strong encouragement for increased use of such "innovative and alternative" technologies for wastewater treatment. However, much of the engineering profession, which is responsible for the design of municipal treatment facilities, is not familiar with these aquaculture concepts or their capabilities and limitations.

The purpose of this assessment was to define the current status of aquaculture technologies and to determine if they are ready for routine use in municipal wastewater treatment. If they are not ready for such use the assessment was to recommend procedures for reaching that goal. This could take the form of further research, demonstration, or construction of full scale "innovative" systems at selected locations.

A team of six internationally recognized engineers was retained to help conduct the engineering assessment. They represented a broad range of expertise and included both practicing consultants and university professors. All were experienced in both research and design and were knowledgeable regarding biological systems and innovative technologies. The team included:

Mr. Gordon Culp
Culp Wesner and Culp.

Dr. E.J. Middlebrooks
Utah State University

Dr. Walter J. O'Brien
Black & Veatch

Dr. Edward Pershe
Whitman & Howard, Inc.

Dr. H.G. Schwartz, Jr.
Sverdrup & Parcel & Assoc. Inc.

Dr. George Tchobanoglous
University of California-Davis

This team was organized and directed by Mr. Sherwood Reed, USACRREL and Mr. Robert Bastian, EPA/OWPO. The basis for the assessment was a multi agency sponsored seminar entitled "Aquaculture Systems for Wastewater Treatment" held at the University of California - Davis, on September 11-13, 1979 (EPA 430/9-80-006). At this meeting research scientists, operating system personnel and others presented papers on various projects and concepts relative to aquaculture systems for wastewater treatment. The final day of the seminar was reserved for direct discussion and interchange between the team of engineers and the seminar speakers. Each member of the engineer team then prepared his assessment based on the seminar presentations, supplemented by other information available with general literature. The areas addressed were organized into three major categories and two team members assigned to each one:

1. Wetland processes - Tchobanoglous & Culp

2. Processes primarily dependent on aquatic plants - Middlebrooks & O'Brien

3. Combined processes where more than one element has a significant role - Schwartz & Pershe

This overview is based on those individual reports plus a review and analysis of the available information by the authors of the overview. This overview is organized in three topical areas with discussion, conclusions and recommendations presented for each.

WETLAND PROCESSES

For purposes of this assessment wetlands are defined as land where the water table is at or above the surface for long enough each year to maintain saturated soil conditions and the growth of related vegetation. These can be either preexisting natural wetlands (eg. marshes, swamps, bogs, cypress domes and strands, etc.) or constructed wetland systems. Constructed systems can range from creation of a marsh in a natural setting where one did not permanently exist before to intensive construction involving earth moving, grading, impermeable barriers or erection of containers such as tanks or trenches. The vegetation that is introduced or emerges from these constructed systems will generally be similar to that found in the natural wetlands.

Studies in the United States have focused on peatlands, bogs, cypress domes and strands, as well as cattails, reeds, rushes, and related plants in wetland settings. A constructed wetland involving bullrushes in gravel filled trenches was developed at the Max Planck Institute in Germany. This patented process has seen limited application to date in the U.S. A number of projects have been developed in the U.S. in recent years for restoration or enhancement of wetlands. These use wastewater but are not necessarily optimized for wastewater treatment.

Current experience with wetland systems is generally limited to the further treatment of secondary effluents. In a few cases primary effluent has been applied in constructed systems. The removal efficiency of typical pollutants are reported as:

	% Removal	
	Natural Wetland (Sec. Effluent)	Constructed Wetland (Pri. Effluent)
BOD_5	70-96	50-90
SS	60-90	-
N	40-90	30-98
P	10-50	20-90

It is assumed that bacteria attached to plant stems and the humic deposits are the major factor for BOD and for nitrogen removal when plant harvest is not practiced. Plant production can play a more significant role in nutrient removal when harvesting is included. With respect to phosphorus removal the contact opportunities with the soil are limited in most natural wetland systems (an exception might be peat bogs) and a release of phosphorus has been observed during the winter in some cases. Based on current experience the land area being used for natural wetland systems ranges from 30 to over 60 acres per million gallons of wastewater applied. The surface area for constructed marshes range from 23 to 37 acres per million gallons of wastewater applied.

The major costs and energy requirements for natural wetlands are the preapplication treatment, pumping and transmission to the site, distribution at the site, minor earthwork, and land costs. In addition to these factors a constructed system may require the installation of a barrier layer and additional containment structures.

Other factors to be considered are potential disruption of the existing wildlife habitat and ecosystems in a natural wetland, loss of water via evapotranspiration for all wetlands in arid climates, the potential for increased breeding of mosquitoes or flies, and the development of odor. The major benefits that can be realized from use of wetlands include preservation of open space, wildlife habitat enhancement, increased recreation potential, streamflow stabilization and augmentation in addition to wastewater treatment.

Conclusions

1. Wetland systems can achieve high removal efficiencies for BOD, SS, trace organics and heavy metals. Their potential may exceed that achieved in mechanical treatment systems. The specific factors responsible for these high treatment levels are not clearly understood at this time.

2. Optimum, cost effective criteria are not yet available for routine design of wetland type municipal wastewater treatment systems throughout the U.S. The concept has been shown to be viable and should certainly qualify under current EPA definitions as an innovative technology.

3. The use of constructed wetlands has a greater promise of more general application. These have potential for better reliability and process control with a lesser risk of adverse environmental impact.

4. The use of natural wetlands offers a lesser opportunity for process control due to natural variability within the system. They do however have considerable potential as a low cost, low-energy technique for upgrading wastewater effluents, especially for smaller communities located in areas of abundant wetlands. The prevention of adverse impacts on the existing, sensitive wetland ecosystem will require adequate monitoring and appropriate management practices.

5. Optimization of criteria for constructed wetlands should result in much lower land and preapplication treatment requirements as compared to the use of natural systems.

6. Health risks for wetland systems are probably not higher than for conventional treatments assuming that insect vectors are controlled and that harvested materials are not used for direct human consumption.

7. The potential for general, routine use of wetland systems, particularly the constructed type, seems high as soon as reliable, cost effective engineering criteria are available.

Recommendations

1. Development of reliable engineering criteria will require additional research and study. These efforts should focus on constructed wetlands or on large scale carefully controlled plots in natural wetlands.

2. Several large scale natural systems should be installed in different geographical locations, representing the major types of wetland systems, with a range of design loadings. These should be

extensively monitored to obtain "real world" operating information and to serve as the data base for development of design criteria. This development should be an interdisciplinary effort involving engineers, scientists and regulatory agencies.

3. A number of constructed wetland systems should be established concurrently in a variety of geographical settings with other variables held to the minimum. This should allow development of regionally applicable criteria and eventually of generalized relationships for universal application.

4. Studies of constructed systems should be directed towards minimizing cost and energy inputs. Therefore, tests with very dilute or highly treated effluents should be avoided. The focus should be on untreated wastewaters, primary effluents, and on nutrient removal mechanisms.

AQUATIC PLANT SYSTEMS

This assessment is based primarily on those systems that use free floating aquatic plants (macrophytes) for the treatment or polishing of wastewater. Most of the information that is available is limited to the use of either water hyacinths or duckweeds and most of these data are from water hyacinth systems in warm climates. These systems are all constructed and are generally similar in concept to wastewater treatment pond technology.

Water hyacinths have been studied in systems treating primary effluents, as the final treatment cells in multiple cell ponds, and as an advanced waste treatment step after conventional secondary treatment. A field scale system for treating industrial wastewaters is in operation at the NASA facilities in Bay St. Louis, MS and pilot scale systems are under study at a refinery in Baytown, TX. A field scale system incorporating duckweed is located in N. Biloxi, MS. Effluent from this two cell pond system is much better than secondary quality.

Water hyacinth systems are capable of removing high levels of BOD, SS, metals, and nitrogen, and significant removal of refractory trace organics. Removal of phosphorus is limited to the plant needs and probably will not exceed 50 to 70% of the phosphorus present in the wastewater. Phosphorus removal will not even approach that range unless there is a very careful management program with regular harvests. In addition to plant uptake the root system of the water hyacinth supports a very active mass of organisms which assist in the treatment. The plant leaves also shade the water surface and limit algae growth by restricting light penetration.

Multiple cell pond systems where water hyacinths are used on one or more of the ponds are the most common system design. Based on current experience a pond surface area of approximately 15 acres per million gallons seems reasonable for treating primary effluent to secondary or better quality. For systems designed to polish secondary effluent to achieve higher levels of BOD and SS removal an area of about 5 acres per million gallons should be suitable. For enhanced nutrient removal from secondary effluent an area of approximately 12 acres per million gallons seems reasonable. Effluent quality from such a system might achieve: less than 10 mg/L for BOD and SS, less than 5 mg/L for N, and approximately 60% P removal. This level of nutrient removal can only be obtained with careful management and harvest to yield 50 dry tons or more, per acre per year.

The organic loading rates and detention times used for water hyacinth systems are similar to those used for conventional stabilization ponds that treat raw sewage. However, the effluent from the water hyacinth system can be much better in quality than from a conventional stabilization pond, particularly with respect to: SS (algae), metals, trace organics, and nutrients.

Harvest of the water hyacinth or duckweed plants may be essential to maintain high levels of system performance. It is essential for high levels of nutrient removal. Equipment and procedures have been demonstrated for accomplishing these tasks. Disposal and/or reuse of the harvested materials is an important consideration. The water hyacinth plants have a moisture content similar to that of primary sludges. The amount of plant biomass produced (dry basis) in a water hyacinth pond system is about 4 times the quantity of waste sludge produced in conventional activated sludge secondary wastewater treatment. Composting, anaerobic digestion with methane production, and processing for animal feed are all technically feasible. However, the economics of these reuse and recovery operations do not seem favorable at this time. Therefore only a portion of the solids disposal costs will be recovered unless the economics can be improved.

The major cost and energy factors for water hyacinth systems are construction of the pond system, water hyacinth harvesting and disposal operations, aeration if provided, and greenhouse covers where utilized. Evapotranspiration in arid climates can be a critical factor. The water loss from a water hyacinth system will exceed the evaporation from a comparable sized pond with open water. Greenhouse structures may be necessary where such water loss and related increase in effluent TDS are a concern. Mosquito control is essential for water hyacinth systems and can usually be effectively handled with Gambusia or other mosquito fish. Legal aspects are also a concern. The transport or sale of water hyacinth plants is prohibited by federal and state law in many situations. The inadvertant release of the plants from a system to local waterways is a potential concern to a number of different agencies. Water hyacinth plants cannot survive or reproduce in cool waters so the concept will be limited to "warm" areas unless climate control is provided. Other floating plants such as duckweed, alligator weed, and water primrose have a more extensive natural range but limited data as their performance in wastewater treatment is available.

Conclusions

1. Aquatic plant systems using water hyacinths can achieve high removal efficiencies for BOD, SS, trace organics, heavy metals and nitrogen. The potential can equal, and may exceed that achieved in mechanical treatment systems.

2. Water hyacinth systems are ready for routine use in municipal wastewater treatment, at least within the geographical range where such plants grow naturally. Reliable engineering criteria are available for the design of systems for treating primary effluent, for upgrading existing systems, for advanced secondary treatment and for full AWT.

3. It is unlikely at this time that the costs of plant harvest and processing will be completely offset by the value of useful products (eg: animal feeds, compost, biogas, etc.).

4. Water hyacinth systems may be technially feasible even in northern climates if operated in a protected environment or run as a seasonal activity. However, this has yet to be shown to be cost effective for climatic zones where the plants cannot exist naturally.

5. Nutrient removal in water hyacinth systems is more complex than uptake by the plant alone, but the responsible mechanisms are not yet clearly defined.

6. Duckweeds are a more cold tolerant plant than the water hyacinth. Wastewater treatment experience with these plants is limited and engineering criteria for routine design are not yet available.

7. Many other cold tolerant aquatic plants exist but their potential for wastewater treatment has not been evaluated.

Recommendations

1. Further optimization of water hyacinth system design is possible. This should include: tracer studies of existing systems to determine actual detention time, the full range of organic and hydraulic loadings that may be possible, and on mass balances of water and pollutant materials.

2. Additional study is needed to establish optimum plant harvesting and utilization techniques and to evaluate alternative methods for removing additional phosphorus with water hyacinth systems.

3. A study should be undertaken to evaluate the potential for water hyacinth systems in cooler climates. This should include energy requirements and overall cost effectiveness. If results of the paper study are favorable a pilot testing/demonstration program might be considered.

4. Research and demonstration projects should focus on the use of duckweed and other plants (especially the more cold tolerant types) for wastewater treatment. These efforts should include: removal kinetics for pollutants as a function of detention time, temperature, plant type, etc.; and the effect of system configuration, season, benthic materials, and plant harvest on degree of treatment.

COMBINED SYSTEMS

For purposes of this assessment, combined systems are defined as treatment systems derived from aquaculture concepts that either contain more than one active aquaculture component in a single unit or that are combined with other aquaculture or conventional units to form a process. An example of the former are the experiments at Woods Hole Oceanographic Institute involving a number of different marine organisms. Examples of the latter are the Solar Aquacell System at Hercules CA, the marsh/pond systems studied at Brookhaven National Laboratories, LI, and the use of fish in the final cells of wastewater stabilization ponds in Arkansas.

Based upon the results of experimental and pilot testing work to date, it is clear that both agricultural and municipal wastewater in treated or partially treated forms can be used in fish culture and other aquatic protein or biomass production systems. Fin fish such as Tilapia, carp, gamefish and bait minnows have been very successfully raised in and harvested from wastewater stabilization pond systems. Daphnia, shellfish, vascular plants, algae, and other aquatic organisms have also been successfully produced and harvested. However, it is not clear that such systems can be optimized for both waste treatment and protein production purposes at the same time.

Since each concept is unique it is not possible to present a general summary of performance for "combined systems". The potential for routine use must also be discussed on an individual basis. For that reason, the examples cited above are discussed individually below. Discussion of this limited number of projects is not intended to imply that there are not other viable systems or combinations, but space limitations have precluded an exhaustive presentation. It is hoped that the assessment of these few projects will provide some general indications or trends regarding combined systems.

Marine Polyculture
Woods Hole Oceanographic Institute, MA

This pilot scale, continuous flow system was designed to remove nitrogen from secondary effluents and at the same time culture marine organisms that have commercial value. The secondary effluent was diluted with seawater and introduced to a system that consisted of shallow algae ponds, followed by aerated raceways containing stacked trays of shellfish and then into a final unit for seaweed production.

The algae ponds were designed as the initial nitrogen removal step. The projected area requirement for this step was comparable to that required for conventional facultative stabilization ponds. Problems encountered at this step included inhibition of algae production by particulate matter in the secondary effluent, seasonal variation of algae species and protozoan predation. Some algae species proved detrimental to shellfish culture and the problem of algae species control was not resolved. The shellfish experiments with the American oyster and hard clams indicated slow growth rates and high mortality. The last unit contained seaweeds for final nutrient removal with vigorous circulation to keep the seaweed in suspension. Overall nitrogen removal was 89% with all components functioning but the overall cost effectiveness was questionable since the shellfish production unit was not successful. It appears that nitrogen removal could be achieved by just a seaweed unit without the preliminary algae and shellfish steps.

Solar Aquacell System
Hercules, CA

This system was developed through bench and pilot scale testing of combined aquaculture and conventional technologies. A full scale system has been recently constructed at Hercules, CA. The system consists of a two cell anerobic unit, followed by an aerated cell followed by a final aerated cell covered with water hyacinths and some duckweeds. An internal feature of all cells are buoyant plastic strips to serve as a substrate for the growth of attached organisms. The entire system is covered by a (double layer polyethylene, air inflated roof) greenhouse structure. Aeration is provided by submerged tubing and is low to moderate in intensity.

Performance results are not yet available from the Hercules system. Based upon pilot units, tested elsewhere, it was predicted that final effluent quality would be 5 mg/L or less for BOD and SS if 5 days detention time is provided in the final water hyacinth cell. The buoyant plastic webbing, with its attached growth is credited with 80% or more of the removal achieved in this cell. Removal of total nitrogen was about 50% in the same 5 day detention pilot tests and the water hyacinth plants accounted for only 10% of that removal. Phosphorus removal was relatively low (1-2 mg/L removed in 5 days) since the aquatic plants and organisms are the only pathways available.

The Solar Aquacell concept requires a regular schedule of water hyacinth harvest, processing and disposal. The Hercules, CA system also includes ozone disinfection and a sand filter for final polishing to maximize reuse potential for the effluent. A functional analysis of the various elements and components in the system seems to indicate that the major portion of BOD, SS, and nitrogen removal is provided by the anaerobic cells and by the attached biomass on the plastic webs in the aerated cells. The major function of the water hyacinths and duckweeds may be in shading the water surface to prevent algae growth. The use of the buoyant plastic web in an aerated pond is a novel and innovative application. The system can then benefit from both suspended and attached organisms and the presence of the webs should reduce or eliminate short circuiting of flow in the system.

Marsh-Pond System
Brookhaven National Laboratory, NY

This 20,000 gpd, pilot unit included an aerated holding cell with 2 1/2 days detention time followed by a 0.2 acre constructed marsh followed by a 0.2 acre unaerated pond with a partial cover of floating duckweeds. Effluent from the pond was then applied to the land at a forested site in a groundwater recharge experiment. This assessment is not concerned with the land application step or a parallel experiment involving overland flow ahead of another marsh/pond combination.

The system was studied for several years (1975-1978) and received a wide variation of flow and pollutant loadings. Effluent recycle from the pond to the head end of the marsh was conducted frequently to maintain flow in the system. However, neither this recirculation or the preaeration were controlled in a regular manner. The system was operated on a year-round basis in the relatively temperate winter climate on Long Island (average air temperature below freezing 5 months of the year and the water temperature in the system was 2°C or less 4 months of the year). Reported effluent characteristics averaged for the period 1975-1977 were:

	mg/L	% Removal
BOD	21	89
SS	42	91
TKN	11	63
Total P	2	66

The parallel overland flow marsh/pond produced slightly better results in all categories. Neither system during the period under discussion could consistantly meet secondary treatment standards for suspended solids. Both however, provided an excellent, and probably cost effective preapplication treatment for the groundwater recharge operation. It is not possible from the published data on the Brookhaven studies to develop optimum engineering criteria for rational design since detention times, mass balances, effect of configuration, season, plant type, etc. were not quantified.

Fin Fish in Stabilization Ponds
Benton, Ark.

There are numerous examples of successful fish culture operations, with a variety of species, in cooling ponds and wastewater stabilization ponds. This assessment will focus on studies in Arkansas where the effect of fin fish on water quality improvement was evaluated in controlled experiments.

The preliminary experiments compared parallel 3 cell stabilization ponds receiving equal volumes of the same wastewater (BOD 260 mg/L, SS 140 mg/L). The cells in one set were stocked with silver, grass, and bighead carp while the other set received no fish and was operated as a conventional stabilization pond. The comparitive study continued for a full annual cycle. Results indicated generally similar performance of the two systems but the fish culture units consistantly performed somewhat better than the conventional pond. For example, the effluent BOD from the fish system ranged from about 7 to 45 mg/L with values less than 15 mg/L obtained more than 50% of the time. The conventional pond system had effluent BOD ranging from 12 to 52 mg/L with values less than 23 mg/L about 50% of the time. Suspended solids were very similar in the effluents for both systems except in July when the concentration was about 110 mg/L for the conventional pond and 60 mg/L for the fish system.

The second phase of the study was conducted at the same location with the same wastewater. The six pond cells were all connected in series and a baffle constructed in each to reduce short circuiting. Silver carp and bighead carp were stocked in the last four cells and additional grass carp, buffalofish and channel catfish in the final cell. No supplemental feed or nutrients were added to the fish culture cells. Estimated fish production after 8 months was over 3000 pounds per acre.

Effluent quality steadily improved during passage through the six cell system. The BOD removal for the entire system averaged 96% for the 12 month study period. About 89% of that removal was achieved in the first two conventional stabilization cells. Removal of suspended solids averaged 88% in the entire system with 73% of the removal occurring in the first two conventional stabilization cells. It is not clear wether the fish or the additional detention time or some combination is responsible for the additional 7% BOD removal in the final 4 fish culture cells. The final average effluent concentration of about 9 mg/L is typical for six cell conventional stabilization ponds of comparable detention time. It seems very likely that the fish contributed significantly to the low suspended solids value in the final effluent (17 mg/L) via algal predation. A value two or three times that high might be expected for conventional stabilization ponds.

Conclusions

1. Finfish were effective in providing further treatment in wastewater treatment ponds. Their major role seems to be suspended solids control for final polishing.
2. It does not appear that aquaculture components in "combined systems" can be optimized for both protein or biomass production and waste treatment in the same unit.
3. Systems involving higher forms of animals seem to be less efficient (at waste treatment), require more land area, or are more difficult to control than systems primarily based on plants.
4. There is sufficient information available to install fish culture units in the final cells of stabilization ponds. There is not enough information available to permit routine design of such units for wastewater treatment. Specific removal rates and growth rates and O&M requirements under different environmental and wastewater conditions need further definition.
5. Most of the other combined systems discussed here are either in the exploratory or developmental stage and rational criteria for their routine design are not available at this time.

Recommendations

1. Development of new concepts in the use of polyculture or combined systems for wastewater treatment should be strongly encouraged. The focus should be on high rate, low energy combinations involving plants and possibly animals or mechanical elements.
2. Further study and evaluation of combined systems is necessary. This should focus on identifying critical components and on the development of engineering design criteria.
3. The most promising concepts should be tested in a variety of geographical settings to define removal kinetics and develop criteria for a range of wastewaters and environmental conditions. This would include the degree of thermal protection and energy required for operation in cooler climates.
4. Studies should focus on the health effects of the direct use of animal protein harvested from these systems in human foods. Studies

should also consider development of alternative products from the animal protein.

REFERENCES

References are not included in this Overview since it was drawn from the six engineering assessments published elsewhere ("Aquaculture Systems for Wastewater Treatment: An Engineering Assessment"; EPA 430/9-80-007; June, 1980) and from presentations at the Davis, CA aquaculture seminar.

Introduction and Overview Session

AQUACULTURE SYSTEMS FOR WASTEWATER TREATMENT: SEMINAR OVERVIEW

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Our real interest in wastewater aquaculture started about three years ago when a number of requests were received asking the California State Water Resources Control Board to fund aquaculture type treatment facilities under the Federal Water Pollution Control Act (PL 92-500). The Clean Water Act of 1977 (PL 92-217) also encourages an examination of aquaculture treatment as a facet of innovative and alternative (I/A) technology. The California State Water Resources Control Board (State Board) staff was requested to evaluate the state-of-the-art and to advise the State and its Regional Boards on a course of action that should be taken that would be in the best interests of the people of the State in regards to the utilization of aquaculture technologies as well as the expenditure of the grant funds.

In our discussion with the federal EPA and others, we discovered that a similar need existed for the entire United States. As a result this seminar was born. It was sponsored by the State of California and a number of interested federal agencies. It brings together current projects and workers in the field of wastewater aquaculture. These proceedings in effect represent the current state-of-the-art on the topic as presented by the various authors and speakers. A unique feature of the seminar was the development of an independent engineering assessment of the material presented. The assessment can be found elsewhere in this document. The reader is encouraged to read the original papers, correspond directly with the authors, and develop a personal assessment as to the status of wastewater aquaculture technology.

Technical sessions at the seminar were organized in four major categories: Wetland Processes, Aquatic Plant Processes, Polyculture or Other Aquatic Processes, and Economics, Energy and By-Product Utilization. The major emphasis was on pond-oriented and natural marsh systems since this is where most of the research and development efforts have been focused to date.

As indicated by the title of the seminar, the major purpose was to consider the potential of aquaculture technologies for wastewater treatment and not as food and fiber production systems, as waste disposal alternatives, or as mitigation measures of other environmental impacts of a project. Several polyculture and combined aquatic systems in various stages of development or demonstration were described. While systems of this type need further development, they would seem to offer the greatest promise of combining food production with wastewater treatment.

The presentations at the seminar served to clearly define the benchmarks of our current knowledge regarding wastewater aquaculture. These included:

- Aquaculture is being used for all phases of wastewater treatment from primary through advanced wastewater treatment. Many current systems use aquaculture components for removal of specific pollutants such as BOD, SS, metals or nutrients, or are designed as a polishing step after conventional forms of treatment.

- Aquaculture is an alternative wastewater treatment technique whose time has come.

- Aquaculture systems can be energy efficient, economical, and environmentally enhancing under appropriate conditions.

- Aquaculture is not a universal panacea for wastewater treatment. There are still questions and limitations on applications. The basic concepts have been demonstrated, but further work is necessary for process optimization and to define the acceptable ranges (e.g., geographical difference, wastewater types, application rates, etc.) for routine use of the concepts.

- Aquaculture systems that were discussed at the seminar appeared to be cost effective, but in some cases they may be labor intensive at an unskilled level.

- The terminology involved in wastewater aquaculture need clarification to avoid confusion and to more clearly define the major purpose of a particular project. For example, wastewater has been used in aquaculture systems for the production of food and fiber, but these same systems were not necessarily optimized for wastewater treatment.

The presentations at the sminar also helped define what we still need to know and the opportunities for further optimization. These included:

- Further definition on the limits of hydraulic and pollutant loadings and the related reaction kinetics is needed for process optimization. This would include the influence of: harvesting, temperature, light, pH, humidity, TDS, plant and organism types, system depth and configuration, and pollutant removal efficiencies.

- A more precise definition of the fate of metals, toxic organics, pathogens and potential disease or nuisance vectors such as mosquitoes, will assist in selecting aquaculture concepts and the reuse options for final effluent and harvested products.

- Routine operation and management procedures for full scale aquatic systems need further definition. This would include operator training and certification requirements.

- Legal and institutional restrictions limit the use, the sale, and the transport of various aquatic plants and fish, especially nusiance, pest and exotic species. Study is needed to define the actual impact if these escape from a treatment system, or to develop an escape proof, fail-safe system, and/or to use alternative plants and aquatic organisms for treatment. The geographical range for application of aquatic systems may be limited without such work.

- The potential for increased benefits exists, but will require further work for definition of limitations and procedural methodology. For example, these would include: use of plant biomass for methane or other energy production, utilization of harvested animal protein, and recovery of purified water vapor in greenhouse or covered systems.

Coordinating this first seminar of which we hope will be a continuing biannual information exchange program on wastewater aquaculture, has been a very enlightening and pleasurable experience. We were pleasantly surprised at the interest this topic has generated. The meeting was attended by approximately 250 people from throughout the nation and several foreign countries representing many interests and disciplines.

We commend the program moderators and speakers for a job well done. They kept the seminar on its tight schedule, and the papers as a whole, were well presented and thorough. The majority of attendees found them interesting enough to stay through the last presentation!

We would like to extend our thanks especially to Ms. Allison Gotez and Mrs. Shirley Bell of the University of California, Davis, Conference and Campus Services for their assistance. Without their patience and tolerance during our mad scramble to organize this seminar, we would not have attained the high degree of success, that is evident by the papers reproduced in this publication.

WHY IS CALIFORNIA INTERESTED IN AQUACULTURE?

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INTRODUCTION

The people of California are committed to the cleanup of its waters and to the maintenance of water quality in the face of increasing population growth, as shown by its statutes and voter approval of $875 million of Clean Water Bonds. We want to be innovative about how we achieve high water quality because conventional wastewater systems have substantial monetary, environmental and energy costs.

From data on aquaculture treatment systems, use of these systems in some cases in California appears highly promising. Land availability and climate factors seem particularly suitable for use of these systems. California also has the scientific capability for rapid research and development of these systems from inception to implementation.

In the immediate future, we see the potential for application of these systems to small communities. Under the 201 construction grant program, there are approximately 350 small unsewered communities on the current priority list. They are prime candidates for systems which are economical to build and operate.

Further into the future after Federal 201 and Clean Water Bonds have been used to bring all our major population centers to at least secondary treatment levels, aquaculture wastewater treatment systems could be used to expand the capacity of some of the existing facilities to meet the needs of increased populations. It is expected that the lack of State or Federal funding of capital expenses will mean that plants which may be more labor-intensive but less costly to build than those presently in operation, will become more attractive.

California is strongly interested in reuse and reclamation of treated wastewaters which would be furthered by aquaculture systems.

In October 1977, the State Board established an Aquaculture Section in the Division of Planning and Research. The Section's responsibility is to evaluate and demonstrate the use of aquaculture as a wastewater treatment technique and, where practical, to offset the cost of treatment to consider the culture for production of aquatic organisms for sale. Although the primary interest of the Board is in wastewater treatment, disposal, and reuse, all aspects of aquaculture and mariculture technology are also included in the Board's program as it relates to beneficial use of waters of the State and are therefore of interest.

In regard to wastewater treatment, an aquaculture center at U.C. Davis has been established recently to look at the wastewater treatment processes. In addition, the State Board staff have been working closely with the City of San Diego for preparation of a workplan for a 1 mgd pilot project using water hyacinths. State Board staff have also worked very closely with the City of Arcata during the development of a pilot project to demonstrate the feasibility for using marshes for wastewater treatment with additional benefits for wildlife. Construction of this project is expected to begin this month.

In the area of reuse and general aquaculture and mariculture technology, the State Board has established a project at Firebaugh to examine the reuse potential of irrigation drain water for aquaculture of invertebrates and fish. Preliminary results of these studies have been extremely encouraging but the final evaluation will not be completed until July 1980. Before aquaculture can be fully accepted, the engineering and health communities must be convinced that these systems work in terms of treatment capability and reliability, and that their operation is within the capabilities of the average plant operator. In the past, the lack of consistency in reporting treatment parameters among researchers and serious omissions in data have hindered acceptance. Further pilot-scale facilities with extensive control features for operational flexibility have not been used in the past to determine environmental tolerances, production rates and changes in water quality associated with the test organisms. It is hoped that this seminar will help future projects to overcome these shortcomings in the earliest practicable timeframe.

More research is still indicated. Additional work with aquatic plants must be conducted in order to evaluate the potential of extending the geographical and climatic areas for the use of these systems as well as the potential for increased reliability under controlled environmental cconditions as afforded by greenhouse covers. Also developmental research should include utilization of other aquatic macrophytes with restricted ranges for special application. Up to this time research has generally emphasized those species with widespread distribution.

Clearly, much information has been developed and will be presented during the next two days. More data will have to be developed in order to enable decision-makers to have confidence in aquaculture.

It is our hope that this seminar will be more than an interchange of technical informtion, more in the sense that all advocates of aquaculture find the best and quickest way to put this kind of treatment on a solid foundation so that elected and appointed officials can make commitments to the process.

CREATING A PUBLIC POLICY CONTEXT FOR AQUACULTURE SYSTEMS

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If aquaculture systems for wastewater treatment are to be adopted on a meaningful scale, it is necessary to set goals and orient research efforts toward answering questions that policymakers must ask before making investments of public funds. Although work in progress is encouraging, there is a disquieting lack of context that may constrain future development. The current situation in California as described here exemplifies both the promise and problems inherent in aquaculture system implementation.

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I'd like to offer some perspectives on aquaculture and the implementation of alternative methods both here in California and in other areas. My comments will address the state-of-the-art from a policy perspective, and then suggest some directions for the future that could accelerate development.

Many of you in the audience are either students planning to work in aquaculture as engineers or biologists, or are already working as professionals in the field. The perspective that I hope to share with you sheds light on how the decisions are made for funding projects, and how public policy itself is implemented. They reflect the kinds of questions that are asked by the Governor and by the State Department of Finance as they consider whether or not to make investment decisions in various forms of alternative technologies.

When I was asked to be on this panel I sat down and asked myself a few questions, then I decided to call a number of experts around the country to raise the questions with them. My inquiry began by asking, what do we get from what we already have? Where are we going? What is the context for the aquaculture development that currently exists? And I found as I called around that everywhere it is about the same. California is seen as the leader but there are obviously good projects in other states as well. The interesting fact is that in most cases they are run by individuals who are leaders rather than by institutions that have taken the lead.

As I talk I'd like to focus a bit on the realities of what's going on, and to point out that the reality is less encouraging than common perception. Some of the questions that come up are as follows: How do we implement the technology itself? Right now the focus seems to be primarily on basic research. Aquaculture and wastewater treatment are essentially an "ad-hocracy" rather than a bureaucracy at this point. As a scientific discipline and as a practical matter, it lacks organization. It more closely resembles a number of random points than a series of connected points on a line that has some direction. I see the situation as one that both reflects the state-of-the-art while at the same time indicating a need for a joining of forces and a focus to decide where this research is going, to set targets, to set goals. What is the public policy outcome of these various projects in the state? Do we have a target of treatment of a certain amount of wastewater by a certain period of time? Do we have cost targets? They don't seem to exist right now.

In talking with various individuals in research or program administration, I find a common feeling that we're not sure that the right questions have been asked, that we have an answer without adequately defining the question at hand. Nevertheless, experimentation goes on.

For example, the Office of Appropriate Technology and the State Water Resources Control Board worked together to implement the experimental aquaculture center here at the University of California at Davis. Where is that going? What's the function of it? There will be nearly half a million dollars spent on aquaculture research here in Davis in the next three years. What return can the government expect on its investment?

Preliminary cost and energy analysis show aquaculture to be very cost effective when compared with a conventional wastewater treatment facility of 1 million gallons a day. Capital cost comparison for an IMGC plant between aquaculture, primary and water hyacinths and chlorination, and conventional treatment, activated sludge and chlorination, show a cost saving of $682,500 or 42 percent. Operation and maintenance cost show a further saving of $22,500/yr. while energy savings for aquaculture over conventional treatment is 1.03×10^6 kWh/yr. or 47 percent. Such savings are substantial for small communities where the wastewater treatment facility may be the largest energy user in the community. These analyses, though encouraging, are dependent on good design criteria, efficient harvesting methods and ease of operation. If we are to stay in this business then we must strive to accomplish the goal of developing a cost effective and energy resourceful wastewater treatment system. Aquaculture is such a system, but will require initiative and direction.

Other questions arise: What can be done to speed and focus the work to ensure that there is a public value above and beyond research successes? Whose realities are we dealing with? That of the biologist, the engineer, the city manager who faces rising costs in treatment programs and discharge problems? The consensus is that there is a lack of momentum, that if the work remains as it currently is -- with a few good people doing experimental projects -- that our effort will not be enough. We will have foregone opportunities that greater advocacy would have brought us, and we will simply end up three or five years from now at about the same level of non-implementation unless a policy focus and a time-related set of goals is developed. There are numerous barriers that have to be addressed. Legal constraints obviously exist. The economic analysis of alternative treatment needs refinement. Life cycle cost methods in this are in many instances not of a quality to convince a public body to make an investment. There are certainly parochial interests involved, such as the interests of regional boards versus the State board. There remains a great degree of uncertainty regarding the value of the technology or the state of development of the technology. Another conflict exists -- the R&D sector versus the regulatory sector -- in which each has different interests.

I want to talk a moment about one group that cut through some of these questions. Many of you have heard of it, and some of you may have visited the facility that is now under construction in the town of Hercules, California. Hercules is a small town currently having a population of about 4,000 people. It's about thirty miles north of San Francisco. In 1975, the city adopted a general plan which called for planned growth in an ecologically sound manner. Their plan projected a population of 20,000 in 1990, up from 4,000 in 1979. Based on this projection, Hercules faced a problem of what to do with their additional wastewater. Presently, their wastewater flows to an adjacent city's wastewater treatment plan. That plan doesn't have the capacity to handle the future additional load that will be imposed by this growth

Hercules therefore was faced with the choice of investing in an enlargement of the adjacent plant or building their own plant. They opted for building their own plant. Because they decided to grow faster than the allowable rate of two percent which is set by the Air Resources Control Board in California, the city was not eligible for State and federal wastewater treatment grants. The only way the city could grow at their proposed rate would be to fund their own system. They then faced choosing a wastewater treatment system that would both meet their needs and State discharge requirements. Many treatment systems would meet the State requirements but few were ecologically sound, low cost, and resource- and energy-conserving in the local context. Hercules eventually chose an experimental system from Solar Aquasystems which met their needs and the State requirements; and, at the same time, provided options for wastewater reclamation and biomass utilization. The Solar Aquasystem sewage treatment plant is being constructed with completion of the first module expected in the late fall of this year (1980). Construction costs are expected to run about $3.5 million for a 2-million-gallon-per-day plant, or $2 per gallon compared to $4 to $6 per gallon for equivalent water quality from an advanced wastewater treatment facility. Operation and maintenance costs run considerably lower. Depending on the system performance data, reclaimed water may be a revenue-creating commodity.

The important issue to recognize here is that city officials were willing to take a risk. That they were willing to play what we used to call "guts ball" -- they'd just get out there, take some calculated economic risks and some political risks to move the technology ahead. I suggest that we need more of that in the State, and that we can have it if we give our representatives better information on which to base their decisions.

The present complacent attitude in which aquaculture is mired is an unnecessary frustration. Why sit back and watch? The hesitancy on the part of the bureaucrats -- if it works we can claim a victory; and if not, we can back off from alternatives -- is a disservice to those of you whose visions and professional lives are invested in this subject. If you believe in this technology, organize yourselves and seek better support from the policymakers that provide you the tools (dollars and facilities) to make progress. But, as you speak out in your self-interest, remember that you incur a greater responsibility to prove the utility and cost-effectiveness of the systems you propose.

Let me move from Hercules to the UC Davis wastewater aquaculture center. I mentioned before that there were barriers. I'd like you to understand how bureaucracy works. Much to the credit of the State Board and to the University, they adopted late in 1977 the concept of developing an aquaculture wastewater research facility on the campus here. It went through the budget review process and was approved in midsummer of 1978. It was provided money for laboratory equipment, personnel, and for a building in which to do the experiments. About $375,000 was allocated for the first year, with $150,000 or so for each of the two following years. It has taken until late spring of this year, almost a full year, to negotiate overhead rates and to push a contract through the University and through the Board. Now, seventeen months after the money was approved for the facility, we still have no facility.

This is a problem, fairly typical I suppose, that many people will face in changing the status quo. I'd have to say that the difference between the wishful thinking and the reality is that the bureaucratic slowness drains the momentum from projects. In this case, it looks like the project will not get off the ground until mid-1980. If there is to be an incentive and a real commitment rather than rhetoric from the University and from the State Board, it is important to break through the log jams on this project, to move faster and to develop a sustained momentum.

While preparing this speech, I talked to people in Florida, Washington, and many other states. I say, "Well, what's going on in other states?" And they say, "Well, not much; we're watching California." California is seen as the leader. California's Water Resources Control Board is the best in the country; there's no doubt about that. Also, the work that is being done at UC Davis by the scientists here is absolutely top quality.

Yet, if California is the leader; if, in fact, we are setting a model for others to follow, it is important for all of us to understand what is the quality and nature of that leadership. What really is the position of the Board itself regarding aquaculture and what could they do that they are not already doing? I'd like to give you a sense of what has gone on there. On March 16, 1978, the Board made its first resolution concerning alternative wastewater systems. Here's what it said:

> "Therefore be it resolved that the State Water Resources Control Board does hereby announce its support and encouragement to greatly increase effort and emphasis on the use of alternative wastewater disposal systems and that the Board adopt the action plan for wastewater management systems investigation and implementation in California."

Fine. Well done. They have a very good work plan and they have a small staff working in aquaculture. Recently, however, when the issue of alternatives were brought before the Board on June 21, 1979, the resolution was reframed. Listen to the difference in the language:

> "Therefore be it resolved that the State Water Resources Control Board does hereby reaffirm its support and encouragement to increase efforts and emphasis on the use of alternative wastewater systems; that the State Board shall continue to sponsor research and demonstration projects to advance the knowledge and implementation of these systems; that the regional boards are encouraged to issue either waste discharge requirements for experimental systems or approve a general local agency experimental program for alternative systems. The State Board is available for developing alternative programs regardless of the options selected, experimental alternative systems are encouraged to be supported."

A strong reaffirmation. Unfortunately, that resolution was tabled. It was not acted upon. The action plan that currently exists within the Board, the plan that gives greater stress to aquaculture than has ever been made before was also not acted upon at this time. Now that's not meant as a real heavy criticsm of the Board. I'm confident that they will act on it. The important point though is the act and not the good intention. When you table resolutions, you essentially take the wind out of the sails of the projects themselves.

I have a few comments about education. It seems to me that if we are going to develop advocates for alternative treatment systems we also have to train people to understand them better. We have to reduce the amount of uncertainty felt by staff members of the regional boards. That can be done through training. The same would hold for training of members of staff at headquarters. Training opportunities are very limited at this point. They could be much, much stronger.

I have a number of recommendations as I close. The new Board, as it will be constituted when the fifth member is appointed, has a perfect opportunity to speak out in support of practical innovation and reaffirm its commitment to the use of alternative technologies in wastewater treatment. Working with practitioners in the field and with regional boards, they also have the opportunity to develop a context to set goals for aquaculture-based treatment facilities, and to work together to achieve successful implementation.

Education should receive higher priority, and our State should provide continuing services to other states which wish to make a marriage between policy decisions and engineering and technical experimentation that's been done in the field.

In the discussion of the long-range energy and cost implications of aquaculture treatment, there is an evaluation which is sadly lacking at this point; one that answers the question that, if we achieve the goals that we set, what do we accomplish? Where are we in this business?

We encourage our Board to continue their good work and to do more of it.

As you proceed in the conference today, I would suggest that you consider the technical papers and the experiments that are reported to you and try to put them in a policy perspective. See how they can serve the greater public over a period of time. I can tell you that in deliberations on the State budget -- that until evidence is brought forth that this is part of a larger plan, that it is going somewhere -- there will be some reluctance to continue to sponsor individual single projects. At the same time, I can say that the Governor is extraordinarily responsive to implementation of alternatives when they're in context. Again and again, whether it be in transportation, energy, or other issues, when the arguments are presented to the policymakers so that they can see that it has some long-term payoff for the general public, for the people of the State, it's sold. It doesn't take selling; it sells itself. The arguments only come when you can't answer the question, "Where is it going?"

Thank you.

THE FEDERAL ROLE AND INTEREST BY EPA'S CONSTRUCTION GRANTS PROGRAM IN AQUACULTURE SYSTEMS FOR MUNICIPAL WASTEWATER TREATMENT

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INTRODUCTION

Many of the Nation's consulting engineers and public health officials have lead municipalities toward the use of capital and energy-entensive high technologies to treat and dispose of their increasing volumes of wastewater. These technologies depend heavily upon the use of equipment, chemicals, and energy in an effort to maximize their degree of control over the treatment processes while minimizing land requirements for the treatment facilities. The recent dramatic increased in cost of energy, raw materials, construction, and labor will eventually lead even those individuals most dedicated to the use of high technology for the answers to man's problems to seriously re-evaluate the potential use of more self sufficient, managed natural ecosystems in municipal wastewater management systems.

In response to these same pressures, a few imaginative individuals have been striving to develop more innovative wastewater management practices, including techniques that harness natural biological processes to help treat municipal wastewater in a more cost-effective and energy efficient manner while effectively recycling or reusing the municipal wastewater and its constituents. While more land intensive, such natural biological recycle/reuse systems frequently cost less to operate and use less energy and non-renewable resources. They also provide the opportunity to enhance the environment through the management of natural biological processes that can also help improve wildlife production and habitat availability, increase recreational opportunities, produce biomass for use as energy sources, soil amendments, animal feeds, etc.

The Construction Grants Program

Through the municipal wastewater construction grants program of the U.S. Environmental Protection Agency (EPA), in partnership with states and municipalities, the funding of municipal wastewater treatment works has grown from a relatively small federal grant program to become the largest public works endeavor in the world that is specifically directed to improving the environment (Ruckelshaus, 1976). Under the original federal assistance program, 13,764 projects totaling $14 billion in eligible costs were provided with $5.2 billion in grants for the period from 1956 to 1972. The current program effort, which was launched by the Federal Water Pollution Control Act Amendments of 1972 (PL 92-500), has assisted over 17,000 projects costing some $33 billion with over $24 billion in federal grants funded at the rate of 75% of eligible costs (EPA/OWPO, 1979). Projects assisted include the planning, design and construction of new treatment plants, and upgrading of existing treatment facilities, interceptor and collector sewers, pump stations, corrections to infiltration/inflow and combined sewer overflow problems, and sludge management systems.

There has been a clear trend for consulting engineers to rely on the more traditional and widely utilized conventional wastewater treatment technologies in the construction of these facilities. The intent of PL 92-500 and the more recent provisions of the Clean Water Act of 1977 (PL 95-217), however, was clearly to push toward more self-sufficient and permanent long term solutions based upon sound ecological reuse/recycle concepts and to encourage the technological community to find better and less expensive ways to do the job (Muskie, 1976). In fact, Congress has actively encouraged greater use of wastewater management practices which result in the construction of revenue producing facilities that recycle potential sewage pollutants through the production of agricultural, silviculture, and aquaculture products.

The I/A Program

The EPA has developed a program to implement the new provisions of the Clean Water Act, which provide special new incentives for increased use of innovative and alternative (I/A) technologies to overcome the impediments facing increased implementation of I/A technologies through our Construction Grants Program. The new provisions include increased federal funding for the design and construction of I/A technologies (increased from 75% to 85%), a 15% cost-effectiveness preference for I/A technologies over least cost conventional technologies, 100% funding to modify or replace I/A technology facilities should they fail, and specific set-asides in state allotments of construction grant funds to fund only I/A projects.

When Congress passed the Clean Water Act, specific goals were set forth for I/A technologies. These goals, which have been incorporated into the Construction Grant regulations and guidance, focus on:

- o reclamation and reuse of wastewater and wastewater constituents;
- o recovery and conservation of energy;
- o reduction in costs compared to existing conventional technologies.

Under our Construction Grants Program, EPA has defined "alternative" technologies as proven methods which provide for reclamation and reuse of wastewater, productive recycling of wastewater constitutents or recovery of energy. "Innovative" technologies have been defined as developed methods which offer an advancement in the state-of-the-art, but which have not been fully proven in the circumstances of their intended use. These innovative technologies are to be primarily directed at achieving increased reclamation, recycling and recovery of wastewater, beneficial use of wastewater constituents, and energy recovery as well as cost reduction, reduction in use of resources, and other environmental benefits.

An area that appears very promising as an I/A technology is the use of aquaculture systems for municipal wastewater treatment. A wide range of managed aquatic biological systems have been considered and investigated for this purpose, including systems involving natural and constructed wetlands (i.e., marshes, swamps, cypress domes, bogs, etc.), macrophytes or other aquatic vegetation in ponds, ditches, or raceways (e.g., water hyacinths, duck weed, algae, reeds, bullrushes, swagrass, submerged vascular plants such as *Potomogeton*, etc.), and various other systems (e.g., polyculture systems, invertebrates such as *Daphnia*, finfish such as *Tilapia* and carp, shellfish, etc.). Such systems represent a logical extension of the basic land treatment concepts which have been strongly encouraged by Congress and EPA. While aquaculture technology has generally been oriented toward the production of human food rather than the treatment or reuse of wastewater, the same basic biological principles apply to essentially all systems designed for the culture of aquatic organism whether the systems are primarily for waste treatment or production systems (Duffer and Moyer, 1978).

Aquaculture Alternatives, Their Potentials & Needs

To date there have been relatively few types of projects designed primarily to treat municipal wastewater through the use of aquaculture processes. While extensive use has been made of stabilization ponds which utilize algae to help treat wastewater, only limited use has been made of managed aquatic ecosystems involving or constructed wetlands, water hyacinths, finfish and other aquaculture processes as an integral part of municipal wastewater treatment systems. The proceedings of an earlier meeting on biological treatment of water pollution published in 1976 by the University of Pennsylvania (Tourbier and Pierson, 1976) provides an interesting insite into the long term potential role of aquaculture and other biological systems for wastewater treatment.

The functional role of wetlands in absorbing or removing pollutants has been identified as one of the major reasons for preserving our Nation's existing wetlands (Horwitz, 1978). Wetlands treatment projects do exist in Michigan, Florida, California and other states which utilize the capability of managed wetlands to help treat municipal wastewater to high levels in an environmentally acceptable, cost-effective, and energy efficient manner. The systems also effectively recycle nutrients, organic matter and other wastewater constituents while improving wildlife habitat, stabilizing stream flows, recharging ground water, etc. For the most part, however, wetlands have more frequently served as a handy place to dispose of many different types of wastes rather than a part of carefully designed and managed wastewater treatment facilities. Such wetlands disposals practices have in certain cases actually led to serious problems in existing wetlands. Their potential for impacting biotic communities in wetlands must be recognized. Appropriate management practices and adequate monitoring, as well as proper regulation and control of projects, must be implemented to avoid potential ecological problems from developing.

The future of wetlands treatment systems as an I/A technology for municipal wastewater treatment should be a bright one. However, it could be greatly influenced by public opinion as well as the concerns expressed by government officials and scientists who envision wetlands treatment systems as the indiscriminant dumping of raw wastes into wetlands rather than managed ecosystems for treating and recycling wastewater. Active participation by the various groups interested in protecting wetlands in the development of projects involving existing or artificial wetlands for municipal wastewater treatment may help improve the acceptance of these projects. We need to establish wetlands management practices that can be applied to the effective and environmentally acceptable use and treatment of municipal wastewater in existing wetlands as well as guidance on the establishment and management of artificial wetlands created primarily to treat wastewater if these systems are to ever become truly acceptable to the local, state, and federal environmental and regulatory interests.

While considered to be weeds by many, water hyacinths, duckweed and other aquatic plants or combination of plants and animals have been demonstrated to be effective in certain systems required to meet secondary or greater treatment requirements, nutrient removal, and for upgrading existing stabilization ponds. They also show great promise for treating many industrial wastes. Available land, climatic constraints, harvesting problems, special management requirements and other problems must be faced when utilizing many of the aquatic plants for wastewater treatment. However, their ability to effectively utilize solar energy and wastewater nutrients to produce large volumes of biomass allows one to consider energy and resource recovery from these aquatic plant systems to offer a possible means of further reducing the cost of wastewater treatment. Additional potential by-products from such wastewater aquaculture projects include such materials as compost, animal feeds or feed additives, processed products such as protein extracts, bait fish and even processed food products.

The increased use of natural biological processes such as aquaculture systems for wastewater treatment faces special public acceptance problems and institutional constraints. The lack of acceptance as a "proven" wastewater treatment technology by the sanitary engineering profession and public officials has lead to considerable fustration where attempts have been made to establish projects. Their lack of profit opportunities for system designers due to the minimal use of equipment and engineering design requirements as well as their large land requirements and heavy dependence upon "nature" have not been well received by the consulting engineering community for the most part. How quickly the American public can accept the idea of treating municipal wastewater by biological systems which also involve the production of animal feeds, wetlands enhancement or even food production could also become a major factor in public acceptance. We hope, however, that the incentives of the new I/A program, as well as the potential long term savings through lower O&M costs, energy conservation and recovery, by-product production and utilization offered by wastewater aquaculture systems, will allow their further development and use in the coming years.

CONCLUSIONS

The subject of water pollution control and wastewater treatment can be seen as a problem of biology rather than simply one of engineering. The scientific basis for treating and the reuse/recycling of wastewater should give greater emphasis to ecology and the management of natural biological systems. Neither the technological problems of designing biological systems nor the political and institutional constraints facing their implementation should prevent the increased future use of aquaculture systems for wastewater treatment. Where these systems can be made to work they should offer effective solutions to the need for cost-effective, environmentally acceptable, and energy efficient wastewater treatment and recycle/reuse practices. In order to assist in encouraging greater use of these aquaculture systems for wastewater treatment, we need to make sure that the results of past and ongoing research efforts are effectively applied to I/A technology projects funded through the EPA Construction Grants Program.

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THE USE OF AQUATIC PLANTS AND ANIMALS FOR THE TREATMENT OF WASTEWATER: AN OVERVIEW

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ABSTRACT

Aquatic systems employing plants and animals have been proposed as alternatives to conventional wastewater treatment systems. The fundamental difference between conventional and aquatic systems is that in the former, wastewater is treated rapidly in highly managed environments, whereas in the latter, treatment occurs at a comparatively slow rate in essentially unmanaged natural environments. The consequences of this difference are 1) conventional systems require more construction and mechanization but less land than aquatic systems, and 2) conventional processes are subject to greater operational control and less environmental influence than aquatic processes. The major stimulus for further research into the fundamentals, design, and management of aquatic systems is the potential for reducing the construction and operation and maintenance costs for wastewater treatment. The general concepts involved in the design and use of aquatic systems are presented and the implications are discussed in this overview.

WASTEWATER CHARACTERISTICS AND TREATMENT

The characteristics of the wastewater to be treated are of fundamental importance in the selection and design of treatment systems whether conventional or aquatic, employing plants and animals. Further, the performance, reliability, and cost of conventional treatment systems have become the standard against which other treatment systems must be compared. For these reasons, each of these topics is considered in the following discussion.

Characteristics of Wastewater

The principal contaminants of concern in wastewater are summarized in Table 1. The addition of chlorine to treated effluent for disinfection may produce other contaminants of concern such as trihalomethanes, compounds believed to be carcinogenic. At the concentrations found in domestic wastewater, the contaminants of greatest immediate concern are biodegradable organics, suspended solids, and pathogens. Problems stemming from the other contaminants are of a more subtle, long-term nature and are neither well understood nor closely regulated at this time. The composition of typical domestic wastewater before treatment is presented in Table 2. The impact of the constituents reported in Table 2 on aquatic systems is considered later in this paper.

Wastewater Treatment: Conventional/Advanced

In conventional treatment, the prime objective is the removal of biodegradable organics, suspended solids, and pathogenic bacteria (see Table 1). Conventional systems are not usually designed to remove nitrogen, phosphorus, pesticides, refractory organics, or heavy metals. Typically, the basic requirements of a wastewater after receiving secondary treatment and disinfection is that the BOD (biochemical oxygen demand), suspended solids, and coliform bacteria (an indicator organism for pathogens) concentrations be less than 30 mg/L, 30 mg/L, and 20 organisms/100 mL, respectively.

In many cases, conventional secondary treatment of wastewater is not entirely adequate for protection of the aquatic environment. The concentrations of nitrogen and phosphorus compounds in secondary effluents are often sufficient to stimulate the growth of algae and other aquatic plants. Depending on pH and temperature, some of the nitrogenous compounds may be lethal to fish. Refractory organics and heavy metals may be toxic; they also tend to accumulate in plant and animal tissue. The effects of the many other contaminants known to occur in trace amounts in the effluent from secondary treatment systems are either unknown or not well defined. Advanced treatment methods can be used to reduce the concentration of these contaminants (see Table 2), but high cost prohibits their general use. One of the important applications of aquatic systems may be the further treatment of conventional secondary effluent to remove nutrients and trace levels of metals, organics, and other contaminants.

THE USE OF AQUATIC SYSTEMS FOR WASTEWATER TREATMENT

To provide some perspective on the use of aquatic systems and before discussing their design and assessment, it is appropriate to consider the operative contaminant removal mechanisms, some of the plants and animals that might be used, the concept of an aquatic processing unit (APU), the types of APUs that might be used, and the use of aquatic systems in integrated waste management systems.

Contaminant Removal Mechanisms

The principal removal mechanisms for the contaminants of concern in wastewater in aquatic systems employing plants and animals are summarized in Table 3. The removal mechanisms reported in Table 3 have been identified on the basis of observations of 1) natural systems such as marshes and wetlands,

Table 1.--Contaminants of Concern in Wastewater Treatment.[a]

Contaminants	Reason for Concern
Suspended solids	Suspended solids can lead to the development of sludge deposits and anaerobic conditions in the receiving water.
Biodegradable organics	Composed principally of proteins, carbohydates, and fats, biodegradable organics are measured most commonly in terms of BOD (biochemical oxygen demand) and COD (chemical oxygen demand). If discharged to the environment, the biological stabilization of these organics can lead to the depletion of natural oxygen resources and to the development of septic conditions.
Pathogens	Bacteria and viruses capable of causing communicable disease can be transmitted by water routes.
Nutrients	The nutrients essential for growth include carbon, nitrogen, phosphorus, and trace elements. When discharged to the aquatic environment, these nutrients can lead to excessive growths of undesirable aquatic life.
Refractory organic compounds	These organic compounds tend to be toxic in relatively low concentrations. Some may also accumulate in the environment, biologically and on adsorptive surfaces, concurrent with the slow decay of these compounds. Typical refractory organics are surfactants, phenols, and agricultural pesticides.
Heavy metals	Heavy metals are often toxic in relatively low concentrations. These contaminants are elemental, i.e., environmentally conservative. They tend to accumulate biologically and on adsorptive surfaces. Typical examples are mercury, lead, and cadmium.
Dissolved inorganic salts	Inorganic constituents such as calcium, sodium, boron, and sulfate may have to be removed if the wastewater is to be reused.

[a]Adapted from Metcalf and Eddy, 1979.

Table 2.--Typical Composition of Domestic Wastewater Before and After Treatment (All Values Except Settleable Solids and Coliform Bacteria are Expressed in mg/L).

Constituent	Concentration			
	Before Treatment[a]		After Secondary Treatment	After Advanced Treatment
	Range	Typical		
Solids, total	350-1200	720		
Dissolved, total	250-850	500		
Fixed	145-525	300		
Volatile	105-325	200		
Suspended, total	100-350	220	20	<3
Fixed	20-75	55		
Volatile	80-275	165		
Settleable solids, mL/L	5-20	10		
Biochemical oxygen demand, 5-day 20 C (BOD, 20 C)	110-400	220	20	1
Total organic carbon (TOC)	80-290	160		
Chemical oxygen demand (COD)	250-1000	500	80	10
Nitrogen (total as N)	20-85	40	30	2
Organic	8-35	15		
Free ammonia	12-50	25		
Nitrites	0-0	0		
Nitrates	0-0	0		
Phosphorus (total as P)	4-15	8	2	
Organic	1-5	3		
Inorganic	3-10	5		
Chlorides[b]	30-100	50		
Coliform bacteria, MPN/100 mL	10^5-10^9	10^7	20	<2
Heavy metals	0.1-2.5	1.3	.8	<0.1
Refractory organics[c]	0.2-7.4	1.4	.2	<0.1
Alkalinity (as $CaCO_3$)	50-200	100		
Grease	50-150	100		

[a]From Metcalf and Eddy, 1979.

[b]Should be increased by the amount in domestic water supply.

[c]Surfactants, primarily.

Table 3.—Contaminant Removal Mechanisms in Aquatic Systems Employing Plants and Animals[a]

Mechanism	Contaminant Affected[b]: Settleable Solids	Colloidal Solids	BOD	Nitrogen	Phosphorus	Heavy Metals	Refractory Organics	Bacteria and Virus	Description
Physical									
Sedimentation	P	S	I	I	I	I	I	I	Gravitational settling of solids (and constituent contaminants) in pond/marsh settings.
Filtration	S	S							Particulates filtered mechanically as water passes through substrate, root masses, or fish.
Adsorption		S							Interparticle attractive force (van der Waals force).
Chemical									
Precipitation					P	P			Formation of or co-precipitation with insoluble compounds.
Adsorption					P	P	S		Adsorption on substrate and plant surfaces.
Decomposition							P	P	Decomposition or alteration of less stable compounds by phenomena such as UV irradiation, oxidation, and reduction.
Biological									
Bacterial Metabolism[c]		P	P	P			P		Removal of colloidal solids and soluble organics by suspended, benthic, and plant-supported bacteria. Bacterial nitrification/denitrification.
Plant Metabolism[c]							S	S	Uptake and metabolism of organics by plants. Root excretions may be toxic to organisms of enteric origin.
Plant Absorption				S	S	S	S		Under proper conditions significant quantities of these contaminants will be taken up by plants.
Natural Die-Off								P	Natural decay of organisms in an unfavorable environment.

[a]Adopted from Stowell et al., 1979

[b]P=primary effect, S=secondary effect, I=incidental effect (effect occurring incidental to removal of another contaminant).

[c]The term metabolism includes both biosynthesis and catabolic reactions.

and 2) laboratory and pilot scale studies of aquatic systems employing one or more plant and/or animal species. An understanding of these mechanisms is important because the selection of plants and animals for use in aquatic systems will depend on the contaminants to be removed and the removal mechanisms that must be used for their removal. For additional information on removal mechanisms in aquatic systems see Stowell et al. (1980).

In aquatic systems, the plants and animals themselves bring about very little actual treatment. The major treatment in these systems is accomplished by bacterial metabolism. In effect water hyacinth or wetland systems are similar to a large, slow-rate trickling filter with built-in secondary clarification.

Potential Plant and Animal Use in Aquatic Systems

Potential aquatic plants and animals and their probable role in aquatic systems are presented in Table 4. When selecting organisms for use in an APU the designer must consider not only an organism's effect on the aquatic environment but also its compatibility with the climate and environment of the design site. Organisms incompatible with climatic and environmental factors will tend to have unstable populations resulting in fluctuations in aquatic environmental quality and, ultimately, in APU performance, (i.e., unreliability). Plants are expected to play a more dominant role than animals in aquatic systems because of their greater influence on the aquatic environment and greater adaptiveness to harsh and/or fluctuating environmental conditions. Plants have significant impact on the aquatic environment by 1) providing a medium for filtration/absorption of solids and growth of bacteria and 2) affecting gas and radiation transfer between the aquatic environment and atmosphere.

As reported in Table 4, there are three general categories of plants: floating, emergent, and submerged. Floating plants have their photosynthetic parts at or just above the water surface with roots extending below the surface. With floating plants, the penetration of sunlight into the water is reduced and the transfer of gas between water and atmosphere is limited. As a consequence, floating plants in ponds tend to keep the wastewater free of algae and essentially anaerobic. Emergent plants are rooted in the substrate and have their photosynthetic parts extending above the water surface. These plants also reduce light penetration and gas transfer, but to a lesser extent as compared to floating plants. Water in stands of emerged vegetation is usually free of algae and partially aerobic. Submerged plants, including algae, may be suspended in the water column or may be rooted to the substrate. During the sunlight hours this category of plants oxygenates the water.

The primary role of aquatic animals may be to further clean-up or "polish" wastewater treated by removing suspended solids before discharge. Dissolved oxygen and ammonia levels will be critical in APU's using aquatic animals. The control of insect vectors, the accumulation of heavy metal and refractory organics, and their function as bioassay test organisms are important secondary roles served by animals.

Aquatic Processing Units: A Conceptual Model

An aquatic processing unit (APU) is defined as the assemblage of aquatic plants and animals (see Table 4) grouped together to achieve a specific treatment objective (e.g., removal of nutrients and heavy metals). In this context, an APU is a definable physical entity that represents some discrete step in the treatment of a wastewater. For example, one or more APU's could be used in conjunction

Table 4.--Potential Aquatic Plants and Animals for Use in Aquatic Systems for the Treatment of Wastewater.

Organism	Probable role and remarks
Floating aquatic plants	
Water hyacinth (Eichhornia spp.)	Its extensive root system serves as a mechanical filter and a support structure for bacteria. Mats of hyacinth attenuate sufficient light to prevent the growth of algae. Wastewater leaving hyacinth mats is devoid of oxygen, typically. Hyacinths will not winter-over in colder temperate climates. Water hyacinths are potential aquatic pests.
Water primrose (Ludwigia spp.)	This temperate climate plant is similar to the water hyacinth, ecologically. The root system is not as extensive as that of the hyacinth nor is the floating vegetative mat as dense. Water primrose attenuate sufficient light to prevent algae problems. Wastewater leaving primrose mats may contain dissolved oxygen. This plant is a potential nuisance.
Duckweed (Lemna spp.)	The root system of this small plant is not of engineering significance. Duckweed grows in dense mats that effectively restrict gas transfer and attenuate light. Ubiquitous in the United States, duckweed is not considered a major aquatic pest. Wind can disrupt duckweed mats. Duckweed can survive throughout the winter in milder temperate climates.
Emergent aquatic plants	
Cattails (Typha spp.)	The submerged portion of a cattail stand serves as a mechanical filter and a support structure for bacteria. Algae will not grow in dense cattail stands, however, water leaving stands is aerobic, typically. Cattails successfully winter-over even in harsh climates.

continued

Table 4 (continued)

Organism	Probable role and remarks
Bulrush (Scirpus spp.)	Essentially as noted above for cattails except that stands of bulrush tend to be more open. Bulrushes may be more adaptive than cattails to wastewater environments.
Reeds (Phragmites spp.)	Reeds are similar to cattails and bulrushes but tend to grow in comparatively open stands. In certain situations algae growth in reed stands could occur. The "hollow tube" structure of reeds may make these plants more durable where substrate root-zone conditions are anaerobic.
Submerged aquatic plants	
Algae	This broad grouping of unicellular plants accumulates nutrients and dissolved salts into settleable algal solids. Photosynthesis occurs resulting in the release of free oxygen into the water at the expense of increasing the BOD of the water. Blue-green algae may increase the nitrogen content of the water. In general, algae are aesthetic and biological nuisances that, if grown, should be removed in subsequent wastewater treatment processes. Various forms of algae will grow throughout the year in open water.
Pondweeds (Potamogeton sp.)	The value of pondweeds as support structure for bacteria is variable from species to species as is the potential to compete with and shade out algae. Because these plants are for the most part submerged in the wastewater environment, there is greater inherent chance of upset.
Other possible aquatic plants	
Watermilfoil (Myriophyllum) Water velvet (Azolla) Coontail (Ceratophyllum) Alligator weed (Alternanthera) Filamentous green algae	All aquatic species have wastewater treatment potential. The answer to the question "Which to use?" will depend on its treatment potential and function in a given system. Use of these plants will also depend on whether they will become aquatic pests.

continued

Table 4 (continued)

Organism	Probable role and remarks
Aquatic animals	
Zooplankton	These organisms accumulate algae and other suspended particulates into a larger sized particulate. Their presence and effect are sporadic. The management of zooplankton populations has proven to be difficult.
Fish	
Blackfish Carp Tilapia Catfish White amur Mosquito fish	Fish serve in a role similar to that described for zooplankton. Zooplankton retain fewer particles than do most fish. Fish can also be used to reduce the vegetative standing crop, control mosquitoes, or convert plant protein to animal protein. Fish populations are manageable.
Bivalves/clams	Clams filter-feed on particulates. To be most effective, clams should be suspended in the water column rather than be placed on the substrate.
Crustacea	
Crayfish Prawn Shrimp	These omnivores would be useful primarily as test and bioassay organisms. They are sensitive to pollutants.

with conventional treatment methods to achieve a desired degree of wastewater treatment or several APUs could be used together to form an entirely aquatic treatment system. The conceptual use of APUs to accomplish various wastewater treatment objectives is illustrated in Figure 1.

The APUs in Figure 1 are arranged so that the application is from least to most complex. For example, in Figure 1a, the APUs are used for the removal of nutrients, refractory organics, and heavy metals. In contrast to this relatively simple application, the complete treatement of wastewater with an APU is envisioned in Figure 1d. Still more complex is the flowsheet in which an APU is used for the complete treatment of wastewater (Figure 1f), including the removal and disposal of solids handled by the primary treatment facilities used in flowsheets 1a through 1d.

At present, what little is known about the use of plants and animals for the treatment of wastewater is related primarily to the removal of nutrients (nitrogen and phosphorus), refractory organics, and heavy metals from effluents of conventional treatment systems (Figure 1a). While this information is of value, research is needed to define the conditions under which various types and combinations of aquatic species may be used in various types of APUs to accomplish primary, secondary, and advanced levels of wastewater treatment (Figure 1c through 1f). Because nitrogen and phosphorus removal is not normally required by regulatory agencies, the greatest potential for aquatic systems is for secondary treatment.

Types of Aquatic Processing Units

In practice, APUs will contain different types and combinations of aquatic species, be managed or operated in different ways, and have physical features that differ with the function of the APU in the treatment system (see Figure 1). The most common types of APUs that have been tried for wastewater treatment include natural and man-made marshes, wetlands, and various pond systems in which one or more plants are used. Some more complex aquatic systems have been developed in Europe, but their use is not well documented in the literature. Further, a number of these systems are patented. While the use of a low-energy unmanaged system such as a marsh is desirable, some level of control may be required because of environmental conditions or to meet treatment objectives. As an example, a desirable aquatic plant species may not reproduce in certain climates. In such cases, nursery and planting operations might become a part of the treatment system. In another case, a particular harvesting procedure may be necessary to accomplish the treatment objectives assigned to the APU. In still other cases, the APU environment may have to be controlled using physical features such as a greenhouse, aeration systems or artificial substrates. The tremendous variation possible in APUs is a point of confusion, at present, but, as the performance of selected APUs is defined, this flexibility in the selection of APU type should become an asset in the design of aquatic treatment systems for different locations.

Integrated Waste Management Systems

The opportunity to incorporate conventional treatment systems into an integrated waste management system capable of some resource recovery has always existed but up till the present time (1979) has not been done routinely. In conventional treatment systems the principal objective is to reduce the energy

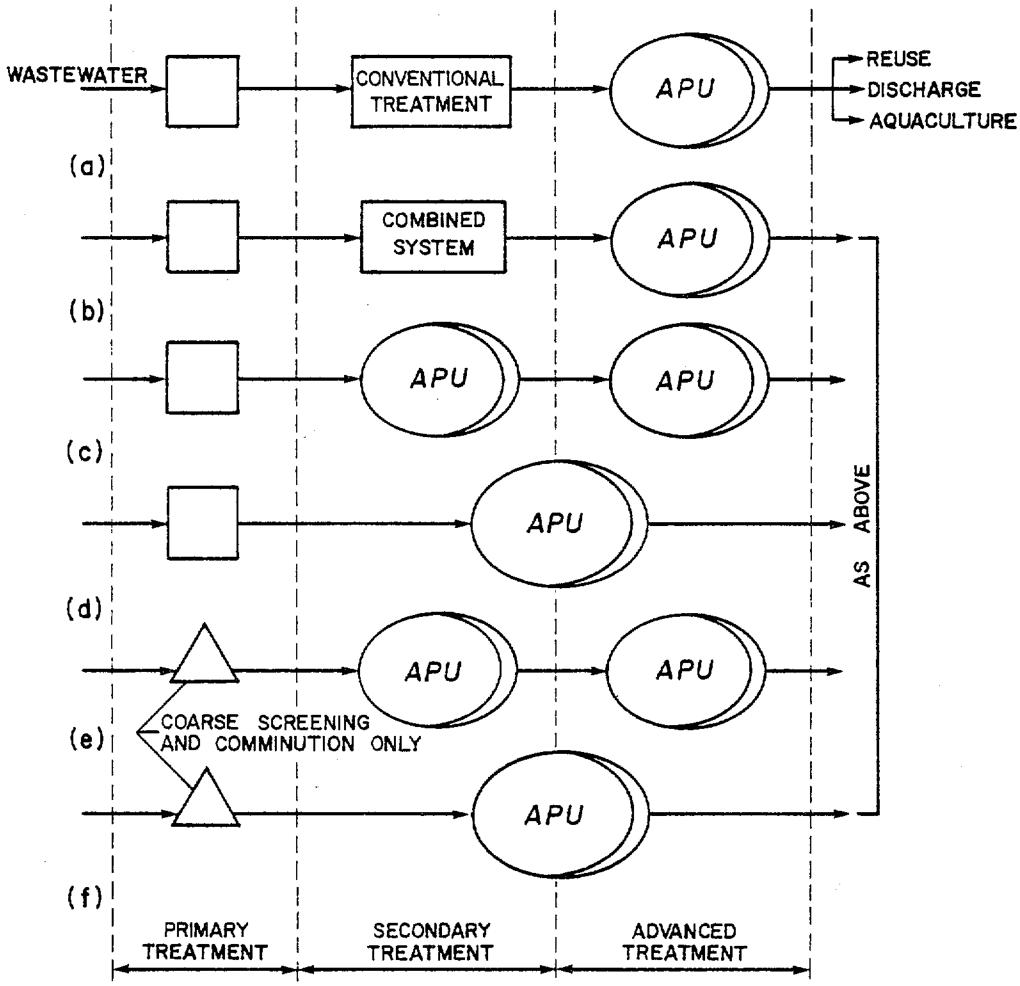

FIGURE 1

APPLICATIONS OF AQUATIC PROCESSING UNITS FOR THE TREATMENT OF WASTEWATER contained in the wastewater (principally in organic compounds as measured with the BOD test) by respiration and to "harvest" as little biomass as possible, which is somewhat at odds with the concept of resource recovery.

By the nature of the contaminant removal mechanisms involved in aquatic systems, there is an opportunity to incorporate these systems into an integrated waste management system. Although aquatic systems lose energy to respiration, they gain energy with the growth of photosynthetic plants. An important feature of aquatic systems is their ability to concentrate energy and nutrients in a more readily usable form, as compared to conventional treatment systems. Harvested materials from aquatic systems may contain up to 20 percent solids, whereas the biological mass removed from conventional systems seldom contains more than one percent solids.

An example of an integrated waste management and recovery system is presented in Figure 2. The option of producing a combination of energy or animal feed is available. As shown, plant tissue from the aquatic systems could be used, singly or in combination with other solid wastes, as feed for fermentation or pyrolysis processes that can be used to produce usable energy and to reduce the volume of solid wastes and sludge. The selection of an operating strategy for an integrated system will depend on local conditions. It must be emphasized, though, that the primary purpose of the aquatic system is the treatment of wastewater and not the production of energy, feed, or other products.

DESIGN CONSIDERATIONS FOR AQUATIC TREATMENT SYSTEMS

Design considerations for aquatic treatment systems are more complex than those for conventional systems because more variables are involved, many of which are beyond the direct control of man. Aquatic species must be found that are capable of removing contaminants while surviving climatic and wastewater conditions. The design and managerial practices for APUs must be formulated to provide the environment necessary for the aquatic species to function as intended. Aquatic systems may have performance reliability problems that will require special designs. The recovery of resources will also affect the design of these systems.

Selection of Species

The selection of aquatic plants and animals to be used for wastewater treatment will be based, to a large extent, on their ability to provide and maintain an environment in which wastewater treatment will occur. Because the functional performance of whatever aquatic species are used will depend on their growth and reproduction, the impact of factors affecting growth and reproduction such as wastewater characteristics, local environmental conditions, and APU managerial practices must be known. A number of related factors must also be considered.

Impact of Wastewater Characteristics. Wastewater characteristics of concern with respect to the aquatic plants and animals that may be used in treatment systems are listed in Table 5. In general, aquatic animals (fish, crustaceans, bivalves) are more sensitive than plants to most wastewater contaminants so that some pretreatment of the wastewater may be necessary using either conventional methods or aquatic plants. When toxic or bioaccumulable chemicals are known to be present in significant quantities a more specific

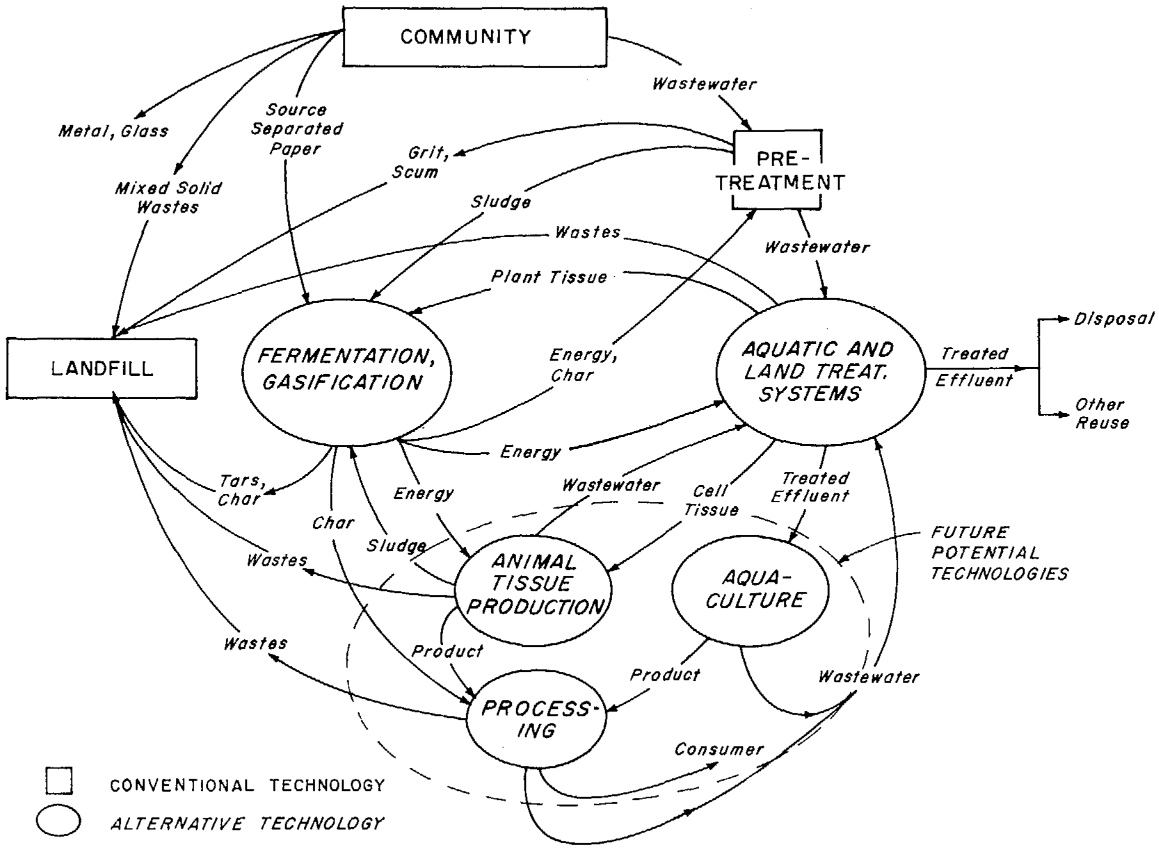

FIGURE 2

AN INTEGRATED WASTE MANAGEMENT SYSTEM EMPLOYING AQUATIC PROCESSING UNITS

Table 5.--Wastewater Characteristics of Concern with Respect to the Use of Aquatic Plants and Animals for Treatment of Wastewater.[a]

Characteristic	Relative Importance To[b]	
	Plants	Animals
Temperature	+++	+++
Suspended solids	0 Emergent species +++ Submerged species	++
Dissolved oxygen	0 Emergent Species +++Submerged species	+++
N_2 supersaturation	0	+
Total nitrogen	+++[1]	+++[2]
Phosphorus	++[1]	0
Heavy metals	++[2]	++[2]
Boron	++[2]	0
Salinity	++	++
Refractory organics	+[2]	++[2]

[a]Any of these parameters could be limiting over a sufficiently wide range. The relative importance ascribed to these parameters here is related to the variation expected in domestic wastewaters.

[b]0 No direct influence
+ Influential
++ Important
+++ Critical
1 Growth nutrient
2 Toxicity (depends on form of chemical compound)

characterization of the wastewater may be necessary so that corrective measures can be taken. The presence of industrial wastes may pose particular problems for aquatic systems. Injury or death of a plant or animal species may reduce the treatment performance of an aquatic system for weeks or months, depending on the recovery or regrowth time of the organism(s) affected.

Impact of Local Environmental Conditions. Local environmental conditions that must be considered include: climatic conditions, substrate characteristics, and local flora and fauna. Based on a preliminary assessment, it appears that the climate at the wastewater treatment site may be the major determinant of the type of aquatic species to be used. Important climatic factors are seasonal averages and diel variations in the air temperature, the average number of overcast days, local photoperiod, light intensity, the duration and intensity of rainfall, the strength and frequency of winds, and the probability of unseasonal weather. For some plant and animal species a good deal of information exists about their climatic tolerances, for other species this information is non-existent. Detailed information on the environmental requirements of aquatic plants (Stephenson et al., 1980), fish (Colt et al., 1979), crustaceans (Colt et al., 1980b), and freshwater bivalves (Colt et al., 1980a) is available. The presence or absence of suitable substrate will be an important factor in the design and operation of aquatic systems. Local flora and fauna similar to those to be used in the system should be investigated for predation so that the possibility of system upsets from indigenous predators can be controlled.

Impact of APU Managerial Practices. Managerial practices for APUs will affect and be affected by the species selected. The match between the environment, as determined by wastewater characteristics and climate, and the environmental requirements of the selected species needed to optimize their function in the treatment process will rarely be perfect. Managerial practices are an additional aspect of the APU concept that, if applied, can create an environment closer to the optimum for the selected species. Typical APU managerial practices may include pretreatment of the wastewater, biomass harvesting, aeration, controlled recirculation, control of residence times, and the use of artificial substrate and organism support materials.

Impact of Other Factors. Many factors in addition to wastewater treatment potential, environmental suitability, and species manageability must be considered when selecting organisms for use in aquatic systems. These additional factors include the quantity and quality of solids produced by the organisms and their subsequent disposal; restrictions on the use of organisms considered aquatic pests; site constraints such as odor production, fog generation, or vector insect problems; and other site-specific factors. Only under prototype or full-scale operation will it be possible to evaluate some of these factors.

Design of Aquatic Processing Units

The rational design of APUs is not yet possible because most of the critical design parameters are either unknown or poorly defined. Additional information on the design of aquatic treatment systems can be found in Stowell et al. (1980) and Ludwig et al. (1980). Species-specific information must be developed about the contaminant removal potential of aquatic plants and animals as a function of the system constraints. Once the treatment potential of each species under consideration is known, the design of APUs and aquatic treatment systems can be undertaken. If combinations of species are to be used within a single APU, then the interaction between these species must be determined. When more than one APU is used, the designer must not overlook the possibility that the effluent from one APU may not be compatible with the organisms of the next APU. Species-specific and system-specific laboratory and pilot scale studies will have to be verified by prototype projects to demonstrate how well aquatic species and systems perform under the varied and often unpredictable conditions that may be encountered in the treatment of wastewater.

System Reliability

An important design consideration is system reliability (freedom from failures in treatment). Aquatic system reliability problems stem from climatic conditions, wastewater characteristics, environmental factors, and disease that disturb, injure, or kill the plants and animals used for treating the wastewater. The potential for and consequences of poor system reliability is greater in aquatic systems than in conventional systems because of greater environmental exposure. Also, a managed community of higher aquatic plants and animals lacks the diversity and rapid growth rate of indigenous bacterial populations. Whereas process upsets in conventional systems last for a matter of hours or days, upsets in aquatic systems may last from days to months, depending on the extent of the damage and the recovery time of the organisms affected. In cases where there is a possibility of relatively long down-times due to climate or the nature of the wastewater, an alternate treatment system may have to be part of the aquatic system design. Ways must be developed to control and minimize the effects of aquatic system process upsets.

Resource Recovery

Because there will be biomass production, the recovery of resources from aquatic systems offers a possible means of reducing the cost of wastewater treatment. Harvested biomass could be used in the production of livestock feed, compost, soil ammendments, or energy. The economics of resource recovery will depend on the availability of local markets and uses for the products. Local consumption of these would reduce the need for expensive processing and transport equipment. When the economics of a resource recovery operation are favorable, criteria related to resource recovery should be considered in the selection of species and in the design systems. Resource recovery should be considered carefully if its inclusion might diminish the performance or reliability of the aquatic treatment system.

ASSESSMENT OF AQUATIC SYSTEMS

The success and acceptance of aquatic systems will depend largely on how well they compare with conventional systems. The bases for comparison will include treatment efficiency, health risks, and costs. Federal legislation and administrative policies will also be an important factor in the application of such systems.

Treatment Efficiency, An Overview

Performance and reliability are important factors in assessing the applicability of aquatic systems for wastewater treatment. At present, insufficient data exist to allow a comparison between aquatic systems employing plants and animals and conventional systems. From an analysis of published data on water hyacinth and wetland systems (Stowell et al., 1980; Ludwig et al., 1980) it has been found that these systems remove 80 to 83 percent of the BOD and SS (suspended solids). The BOD removal characteristics of water hyacinth systems are presented in Figure 3. The upper value of BOD loading was 245 kg/ha•d, approximately 5 times the normal loading rate for conventional wastewater stabilization ponds. The performance capabilities of aquatic systems appear favorable, especially for the removal of nutrients and trace concentrations of toxic substances. Reliability may be a major shortcoming of aquatic systems. Short-term reliability may not be as important as the total quantity of contaminants removed when considering contaminants with chronic rather than acute effects (e.g., nutrients, refractory organics, and heavy metals).

Considering both performance and reliability, at least one use of aquatic systems will be the further treatment of secondary effluents from conventional systems where higher levels of treatment are required. Other uses may be discovered as aquatic species growth, materials uptake, and pathology are defined with respect to the design and operation of aquatic systems. In the initial development of aquatic systems, it will be important to avoid prejudging the usefulness of these systems on an all-or-nothing basis.

Health Risks

Health risks for aquatic systems are probably not higher than for conventional treatment. This is assuming that the animal and plant tissue grown is not used for human consumption and that potential vector problems are controlled. The public health hazards of direct consumption of organisms grown in domestic wastewater are very serious and complicated. State and federal laws do not allow direct consumption of these products (Kildow and Huguenin, 1974). Their use for animal feeds may be possible if the residues of heavy metals, trace organics, and pesticides meet state and federal regulations.

Costs

Based on a preliminary analysis, it has been shown that aquatic treatment systems have lower capital and O&M (operational and maintenance) costs and use less energy (Tchobanoglous et al., 1979). A cost and energy comparison between conventional activated sludge and artificial wetland treatment systems is presented in Table 6 for plant sizes of 0.1, 0.5, and 1.0 Mgal/d. Proper assessment of the costs of these systems will need to be based on prototype or demonstration units. In this regard, it will be important to consider the total cost. This will include the capital and operating costs and the salvage value. Most of the capital costs of aquatic systems will be in land which should have a high salvage worth.

With lesser mechanization, lower energy and resource consumption, and the possibility of some resource recovery, operating costs should be lower for aquatic systems as compared to conventional systems. Further, the useful life of aquatic systems should be longer than for conventional systems. For these reasons, it may be feasible to build aquatic systems with capital costs similar to or even higher than the costs of conventional systems. The societal benefits of using labor intensive aquatic systems that may not be cost-effective when evaluated by current methods should also be considered in assessing the operating

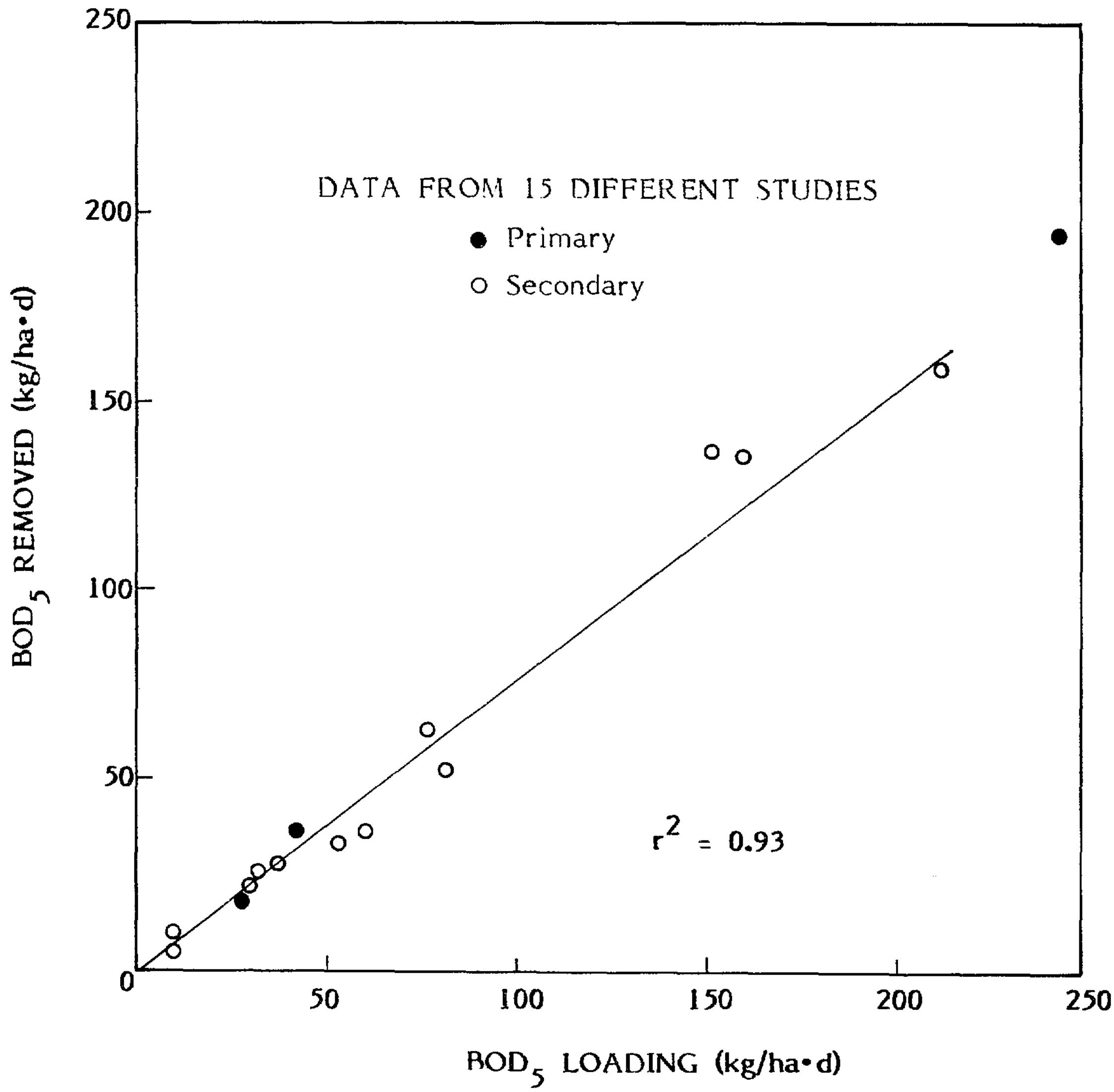

FIGURE 3

EFFECT OF BOD LOADING ON BOD REMOVAL
(from Ludwig et al., 1980)

Table 6

COSTS AND ENERGY UTILIZATION FOR ACTIVATED SLUDGE AND ARTIFICIAL WETLAND TREATMENT SYSTEMS[a]

	PLANT SIZE, mgd					
	0.1		0.5		1.0	
ITEM	CONV.	AQUA	CONV.	AQUA	CONV.	AQUA
Capital cost, $\$ \mathrm{x} 10^{-6}$	0.71	0.37	1.23	0.55	1.60	0.90
O & M cost, $\$/\mathrm{yr} \ \mathrm{x}10^{-3}$	35	21	78	48	117	74
Energy, Btu/yr $\mathrm{x}10^{-9}$	0.88	0.51	3.15	1.20	4.80	2.08

[a]Adapted from Tchobanoglous, et al., (1979).

costs. It is anticipated that consideration of employment opportunities will become more important in the future.

Depending on the site, aquatic systems may have additional costs and/or benefits. Additional costs may include the control of vectors, such as mosquitoes, or other problems relating to the presence of marshlike environments, e.g. fog generation. Beneficially, aquatic systems may serve as recreation areas or greenbelts.

Federal Legislation and Administrative Policy

The passage of the Clean Water Act of 1977 (PL 95-217) encourages the use of innovative and alternative technologies for water reuse. Conventional treatment facilities will not be funded unless alternative treatment processes have been studied and evaluated. Financial bonuses are offered when alternative processes are designed; but many consulting engineers are reluctant to submit treatment-plant designs based on technology that is not nearly as well documented as the conventional treatment systems. Up to 75 percent of the construction costs of new treatment systems is provided for in PL 92-500, but operational funds are not provided. As a result, several advanced wastewater treatment facilities have had to shut down because of excessive operating costs. In the future, rising costs for energy and resources will probably cause the shutdown of additional plants and change the design and operation of others. If they can be shown to be feasible, aquatic systems may offer an alternative. Ultimately it may be necessary to revise the existing discharge requirements to make the use of aquatic systems a reality.

ACKNOWLEDGEMENTS

This work was supported with funds made available from the California State Water Resources Control Board to the Department of Civil Engineering and the Department of Land, Air, and Water Resources, University of California, Davis, California.

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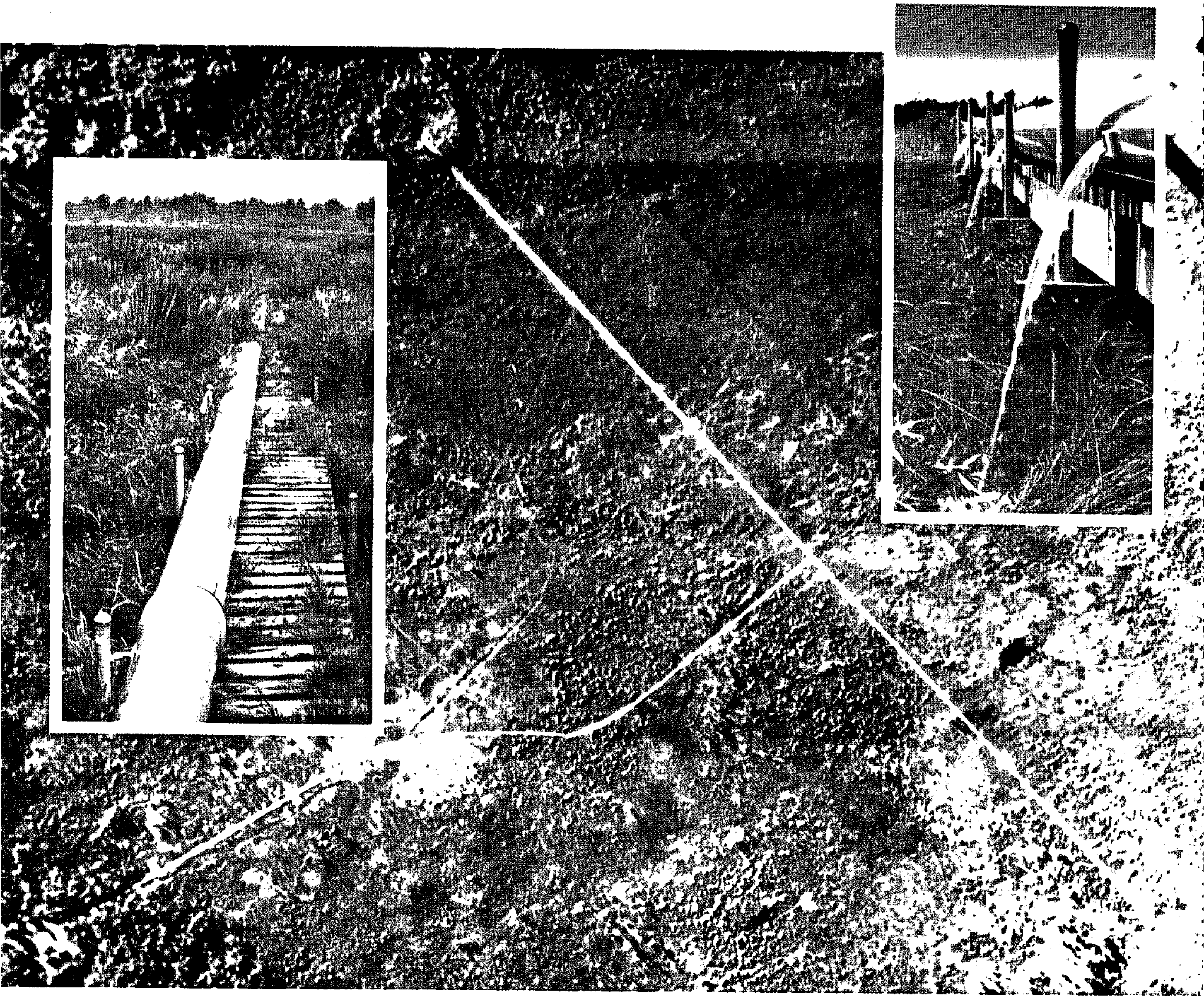
Wetland Processes Session



Color infrared aerial photo of the Houghton Lake, Michigan wetland wastewater treatment facility at the Porter Ranch peatlands. Areas of reddish brown color near the irrigation pipeline depict areas of highest productivity. Partially treated wastewater is pumped through a 12" diameter underground force main to the edge of the wetland. At the lower left hand side of the photo the transfer line surfaces and runs along a raised wooden platform for a distance of about 2,500' to the discharge area in the center of the wetland. Inserts depict the wastewater being distributed into the wetland through 3,200' of gated irrigation pipe.

WETLAND PROCESSES: SESSION SUMMARY

Presentations in this Session cover wastewater treatment utilizing natural and artificial wetlands. Several regions of the United States are represented with projects being located in California, Florida, Massachusetts, Michigan, and Wisconsin.

Results of these studies indicate that discharge of secondary wastewater into natural wetlands can be an effective treatment mechanism. One full-scale municipal system has been established. The wetlands process was the alternative selected for expansion of a sewage treatment plant in northern Michigan. The concept and design were approved by regulatory agencies, and the construction phase of the 201 Facilities Planning process was completed during 1978. This natural wetlands system has been very successful in the removal of nutrients from secondary sewage effluent.

Creation of an artificial marsh has demonstrated substantial environmental benefits. A 21-acre marsh was created in the San Francisco Bay area of California. The primary purpose of establishing the system was to provide additional wildlife habitat. An average of 1,600,000 gallons of secondary sewage is discharged daily into the artificial marsh. The system has been very successful with 86 species of birds, 63 plant species, 34 species of aquatic invertebrates, and 22 species of other animals having been identified. Improved water quality was an additional benefit noted.

These exploratory or "proof of concept" studies constitute an extremely valuable contribution to the technology base required for advanced or developmental studies in the wetlands area of wastewater aquaculture. At this time, the technology base appears adequate to warrant consideration of design and evaluation of pilot-scale wetlands facilities for the purposes of stripping nutrients from secondarily treated wastewater and creating additional wildlife habitat.

Prepared by
William R. Duffer
1/3/80

WETLANDS CREATION FOR HABITAT AND TREATMENT - AT MT. VIEW SANITARY DISTRICT, CA.

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In 1974 the Mt. View Sanitary District (MVSD), near Martinez, California initiated a full scale pilot wetlands creation program on low lying reclaimed tide lands owned by the District. The objective of the program was to demonstrate the feasibility of utilizing plant effluent to create a wetlands environment for the benefit of wildlife and migratory waterfowl and to develop management techniques for improvement of both water quality and wildlife habitat.

The concept of using treated sewage effluent as a freshwater source for the creation and restoration of wetland ecosystems qualifies as an alternative wastewater management technology for meeting the objectives of the 1977 Clean Water Act Amendments promoting the use of land treatment processes that reclaim and reuse municipal wastewater. Wetlands reclamation projects are cost-effective and depending on site conditions, energy requirements are minimal. Wetlands projects also are consistent with EPA's multiple use policy supporting wastewater management practices which combine open space, recreational and educational considerations with such management.

PHYSICAL FACILITIES DESCRIPTION

Treatment Plant

Mt. View Sanitary District was established in 1923. It serves a portion of the City of Martinez and unincorporated areas of Contra Costa County, with a present population of approximately 14,000. The process provides two-stage biofiltration with separate sludge digestion. Facilities include comminution, primary and secondary clarifiers, a rock biofilter with a rotating dual distributor, recirculation pumps and chlorination facilities. Sludge handling facilities include grit removal, sludge thickening and primary and secondary sludge digestion. A belt-filter press and paved drying beds provide for sludge dewatering. The plant is designed to provide full secondary treatment for 1.6 MGD dry weather flow with a hydraulic capacity of 8.0 MGD wet weather flow. Present dry weather flow is approximately .7 MGD. Effluent consistently meets standard secondary treatment requirements of 30 mg/1 biochemical oxygen demand and suspended solids.

Wetlands

The wetland system covers 20.3 acres (8.2 ha) and consists of five inter-connected areas with tributary edge habitat. The total plant flow passes through the ponds and marshes into Peyton Slough which discharges into Suisun Bay. At present flow of .7 MGD there is a ten day detention time. Land useage is 27ac/MG. At the design capacity of the treatment plant, 1.6 MGD, there will be a 5 day detention time and 12ac/MG. This ratio will still provide for a beneficial habitat.

As shown in Figure 1, plant effluent is conveyed by gravity through an outfall pipe and siphon under Peyton Slough to plot D. This area is divided with earthen dikes in serpentine fashion. This method of channelization directs the flow through the emergent vegetation, to guarantee adequate circulation. The final cell of plot D contains Ecofloats (EBC Company) which are strung across the open water. These devices are made of redwood bark, wood, and styrofoam for floatation. They serve as artificial substrate or habitat for aquatic invertebrates which normally colonize the bottom muds and emergent vegetation. Thus they increase the numbers of organisms which can live in open water thereby enhancing the food chain.

The flow passes from the Ecofloat pond over weirs into plots C and E. Marsh plot E is planted to provide food for migratory waterfowl using water grass and alkali bulrush (Echinochloa crusgalli and Scirpus robustus). Since the District wetlands are located on the Pacific Flyway the possibility exists to feed many migratory waterfowl. Marsh plot C is open water with four vegetated islands which provide food, cover and nesting sites removed from predators.

The discharges from plots C and E are combined and flow by gravity through the inverted siphon to the slough from which the flow is directed to both plots A-1 and B. Flow through the wetlands system is entirely by gravity. Dinges[1] points out that high pressure pumps and excessive velocities should be avoided since they harm aquatic invertebrates which are important for maintaining a balanced ecosystem. The water level in each plot is controlled by adjustable weirs and ranges from .3-1m.

Plots A-1, A-2, and B formed the original wetlands system whose objective was to compare the creation of vegetated versus open water habitats. It was determined that both types were successfully created and that the combination provided a more stable, total habitat than either type alone. Plot B is mixed open water and emergent vegetation. Plot A-1 contains emergents and A-2 is an open water area with supplemental invertebrate habitat. Large open water areas are particularly important in attracting migratory ducks, the area must be visible to the waterfowl while flying. The flow is discharged to Peyton Slough from plots A-2 and B.

WATER QUALITY CHARACTERISTICS

The wetlands environment has a positive effect on the treatment plant effluent. Various monitoring programs have been carried out during the life of the project to assess the water quality within the wetlands and also the quality of water discharged from the system.[2] The local climate is mild, average daytime water temperature is 19°C, range 5-29°C. The pH normally remains between 7.0 - 7.4 units; increases up to 8.8 units occur accompanying algal blooms. The District treats only domestic wastewater with very low metal content. Therefore, the wetlands is not monitored for metals. Disinfection with chlorine to achieve a total coliform level of 23 MPN is accomplished prior to the wetlands. The initial portion of plot D is used for dechlorination, the residual entering D is 1.0-4.0 mg/l. APHA Standard Methods, 14th Edition procedures are referenced for each analysis. The data discussed is on only plots A-1, A-2 and B, which have been in operation since the fall of 1974. Plots C, D, and E were constructed in the fall of 1978 and are now being monitored.

Dissolved Oxygen

The levels of dissolved oxygen (DO), measured with a portable meter (method 422F), vary diurnally and seasonally from about 1.0mg/l to supersaturation. Normally levels above 5mg/l are maintained. Due to the shallow depths and frequent wind mixing, the dissolved oxygen levels do not become stratified. The highest levels of DO are caused by algae and occur in summer months. The lower levels of DO occur in the early morning hours. In general, the DO in winter months has a lower, smaller range. Even with the wide range of DO levels there have been no odor problems or anaerobic conditions associated with the wetlands.

Biochemical Oxygen Demand

Figure 2 shows biochemical oxygen demand (BOD, method 507) and suspended solids data in six-month intervals divided into growing season and non-growing season. The water quality in a biological system, such as the wetlands, is affected by the seasonal life processes occurring there. The average BOD loading rate is 172 lbs/day and has been consistently reduced by marsh B; only in two six-month periods did the BOD remain the same as it was in the plant effluent, i.e., influent to the wetlands. The A complex reduced the BOD in the winter months and the summer of 1977, but raised the BOD during the other two summers. It must be stressed, however, that the type of BOD leaving the treatment plant and that leaving the marsh system differ. Materials comprising the BOD in the plant effluent are the degradation products of human waste. The material exerting a BOD in the marsh effluent is partially composed of algae and other living organisms at the very base of the food chain. These constituents are ready to be used by organisms downstream whereas the materials in the plant effluent are not yet in a usable form.

Suspended Solids

Suspended solids (SS, method 208 D) data for the four years to date show that in the strict sense, SS are usually reduced in the winters but not in the summer. The average loading rate to the wetlands is 189 lbs/day. When SS leaving the wetlands are higher than the values found for the plant effluent it can be attributed to algal growth in the pond-like portion of system or silt from winter runoff. Therefore, it is especially important to acknowledge the form in which the SS leave the wetlands because algae comprises the producer level of the food chain. This producer status means that the algae is the base of the food pyramid allowing a healthy, balanced ecosystem to occur in the marshes and slough.

When the results of plots A and B are compared it is apparent that if water quality criteria are placed on a wetland discharge, the system should be designed with a vegetated cell last in the flow scheme. Dinges[3] work with floating vegetation and Spangler et al[4] working with emergents have both concluded that aquatic vegetation is an effective means of improving various water quality parameters.

Nutrients

Nutrient levels in the plant effluent are variously affected by the wetlands. In some cases nutrients are removed and in others, levels remain unchanged. The nutrient analyses were run on grab samples collected during 1975-1978, using the following methods: nitrate 419D, ammonia 418B with distillation, total organic nitrogen 421, total phosphate 425F. Table 1 gives the average, range and percentage of wetlands samples that had a lower level of the nutrient than did the plant effluent sample on the same day. Consistent nitrate removal is accomplished by the wetlands. Nitrification does not occur to any great extent. Phosphorus does not appear to be a limiting nutrient, the amount entering is also discharged. There is a great deal of biological activity in the wetlands, a balance seems to be in affect such that nutrients are neither added to nor extracted from the system. The exception to this is the consistent reduction of nitrate levels.

THE HABITAT

Numerous ponds, marshes and rivers in the United States are fed, in part, with treated wastewater. The unique aspects of this project are 1) a wetlands exists where previously there was none, 2) the sole source of water is treated wastewater, 3) the primary purpose for creating the wetlands is to provide wildlife habitat. The major goal of this research has been to define the components of this newly created wetland habitat. Only after defining what exists can one then proceed to determine success or failure of the project. The habitat types which comprise the wetlands are 1) open water alone or in combination with ecofloats or islands, 2) areas covered by floating vegetation - either free floating such as *Lemna* sp. or rooted on the levees and floating 2-3 ft. out over the water, 3) areas of emergents, 4) cultivated waterfowl food area and accompanying mud flats, 5) levees and adjacent land with grasses, bushes and some trees.

Vegetation

A wetlands community is complex and is composed of both terrestrial and aquatic forms of plants and animals. There are more than 72 species of macrophytes in the MVSD wetlands, none were planted by the District. Twelve of these are emergents: *Typha* spp., *Scirpus* spp., sedges; another 10 are particularly saline tolerant, 29 are native to California. In the early 1800's the site was covered by a brackish water marsh, which was later diked and drained. This accounts for the saline nature of the soil. The remaining plants are field annuals, perennials, herbs and shrubs. The vegetation serves as food, shields animals from predators, provides nesting sites and improves some water quality parameters. Nineteen of the species have seeds that are used by waterfowl for food.[5] As winter progresses food becomes more scarce and the birds and animals eat many plants or plant parts not otherwise eaten. Planting the 2.5 acre plot E in seed producing vegetation will expand the available food supply.

An open water area mixed with stands of emergent vegetation provides the habitat necessary for a greater variety of organisms. This diversity and interdependence of plant and animal species leads to ecological stability.

The surface area of the wetlands is approximately 63% open water combined with 37% covered by emergent vegetation. Voigts notes that this interspersed type of habitat fosters a great variety of aquatic invertebrates and also appears to attract the greatest variety of nesting birds.[6] In a biomass study done on this emergent vegetation it was found that Typha latifolia can produce up to 18 lbs/sq m and Scirpus californicus up to 24 lbs/sq m, both as dry weight.

Algae. The algal growth in the wetlands is highly beneficial. It oxygenates the water, removes ammonia, and serves as a food source for small herbivorous animals such as the zooplankton. The wetlands system has never been plagued by the growth of nuisance algae: no filamentous mats, no blue-greens, no odor producers. The dominant algae present over a two year period were: euglenoids, chlamydomonids, chlorella-like, and naviculates. Light and dark bottle productivity analysis has been carried out over a two year period. The low temperatures and overcast conditions of winter keep productivity very low to non-existent. During the summers studied, 1977 and 1978, algal growth was cyclical. However, numbers of algal cells, therefore oxygen evolution, was much greater in 1978. It is theorized that this increased number of cells can be accounted for by the decrease in zooplankton population and other algal predators. The decrease in the zooplankton was due to the increased number of mosquito fish (Gambusia afinis). This is a humanly created upset in the ecological balance of the wetlands. Marsh management techniques provided the increase in mosquito fish, which successfully eliminated mosquito breeding. However, it also had this marked affect on algal growth. During the fall of 1978 as many as 52 common and snowy egrets were feeding on the mosquito fish, in a four acre area. Some of the excess fish were trapped by other local agencies. It is hoped that in the coming year a balance can again be reached between the numbers of fish and invertebrates.

Animals

Twenty-two species of animals live at the MVSD wetlands: 10 species of mammals, 4 sp. of amphibians, 4 sp. of reptiles, 3 sp. of fish. Rask studied the south levee of plot B and found heavy use by mice (Mus musculus and Reithrodontomys megalotis) and muskrats (Ondatra zibethica).[7] The animal list includes both herbivores and carnivores; many of the species reproduce and live solely on what exists in the manmade wetlands. All of these animals have come to the District on their own.

Birds. Ninety species of birds either live in or stop at the wetlands during migration. This is a very large variety for such a small area, clearly wetlands are critical in the San Francisco Bay area. Schulenburg estimates that 70% of California's wetlands have been lost to draining and filling, since the turn of the century.[8]

An approximate breakdown of species composition is 15 sp. of ducks, 32 sp. of water and shorebirds, 30 passerine species, and 6 sp. of raptors.[4] It appears that many of the migratory birds return each year. If it is not the same individuals it is at least the same species returning at the same time each year. In some cases these birds are somewhat uncommon in the locality, which leads the author to believe it is the same flock returning, for example tri-colored blackbirds. There are two types of usage of the wetlands by migratory birds. Some flocks will stay only a few hours or less, other flocks will spend weeks or months at the wetlands before moving to their destination, usually Canada or Southern California. For example, a flock of approximately 90 ruddy ducks spent two winter months whereas a pair of mallards spent only one morning. Predatory birds, for instance herons and hawks, need a large range and the MVSD wetlands is included in the territory they rely on for food. There are a number of bird families in which many generations have hatched, grown and reproduced entirely dependent on the wetlands. A successful nesting this spring, 1979, of cinnamon teal will be the fourth generation. The quality of the water and chemical content of the vegetation must be acceptable since it enables the organisms feeding on it to continually produce viable offspring. The available food supply appears to define the carrying capacity of the wetlands, for birds. This is why the cultivation of seed bearing plants was initiated.

Aquatic Invertebrates. There are more than 34 species of aquatic invertebrates living in the wetlands: 8 sp. of bugs and beetles, 10 sp. of flies, 7 other insects, 5 sp. of zooplankton, 4 sp. of non-insects.[5] Voights studying four marshes in Iowa found the number of taxa present to be between 20-32, with a maximum of 43.[6] This is clear evidence that a species list of 34 is comparable to that found in other small wetland areas. It is probable that there are more species than have been identified of zooplankton, due to the difficulty of identification. Nearly all of these organisms exist in the wetlands in each of their life stages. For these organisms to be able to reproduce successfully generation after generation they have to be living in high quality water. The volume of invertebrates and the species diversity also are clear indicators that a stable ecosystem has been created. During the summer of 1977 up to 3.8 lbs/hr. of zooplankton, mostly *Daphnia*, were trapped in the outlet weir of plot A-2. This is a considerable volume of food available for use by larger invertebrates and fish living within the wetlands and downstream.

WETLANDS MANAGEMENT

A well designed project reduces the amount of necessary maintenance. The major design objective is to create a balanced habitat and avoid nuisance situations. Much was gained during the first four years of operation of plots A-1, A-2, and B. This knowledge was incorporated in the design of the three areas added in 1978.

Levees

All levees should be wide enough for vehicular traffic so they may be utilized for maintenance when necessary. Some levees are used on a regular basis, others are not and vegetation is allowed to cover them. These vegetation covered levees add to the habitat but provide access when needed. Levees should be at least 10' wide, steep-sided, with 1.5' freeboard, and compacted during construction. There are many wetlands organisms which tunnel in levees: muskrats, gophers, crayfish, and other small mammals. Therefore proper levee design and construction is crucial to keeping maintenance needs minimal.

Erosion

Vegetation is the main form of erosion control and works quite well once established. A minimum of one spring and summer are needed before the vegetation can become established, without specific planting and cultivation. Vegetation is not sufficient around weirs, gates and pipes. These areas must be fortified with riprap. The District is fortunate in this respect because it is located en route to the local landfill and gets all its riprap free of charge.

Plot Design

By dividing the total area designated for the wetlands into plots more habitat goals may be achieved. When a multiple plot system is created flow variation is facilitated. This allows one plot to be isolated from the system in case of major maintenance needs. Multiple plots also allow depth variation. Depth is a key factor in habitat design: it will determine whether or not emergent vegetation will be present and will affect temperature and dissolved oxygen values. Plot shapes may vary but small, constricted areas should be avoided as they would promote stagnation and vector problems. Deciding which groups of organisms are desired in the wetlands and knowing what conditions these organisms normally live under will determine the fundamental components of the design.

Vectors

Botulism. *Clostridum botulinum* is the cause of avian botulism and will not cause botulism in humans. It is, however, deadly to waterfowl and certain measures may be taken to avoid its occurrence. There have been no known cases of avian botulism at the MVSD wetlands. Avoiding anaerobic conditions by keeping the water circulating and maintaining the depth under 3' is an important factor in botulism avoidance. Removal of floating organic debris which collects behind weirs and in corners is regularly done. Steep-sided levees, adjustable broad crested weirs for controlling water levels, conveying water by pipeline, and ability to shunt a plot out of service for draining, are also factors in the botulism avoidance program.

Mosquitoes. Mosquitoes lay eggs in water and the larva grow there undergoing metamorphosis to the adult form. To breathe the larva must hang from the surface film of the water, piercing it with their respiratory tube to obtain oxygen. This knowledge of the mosquito life cycle and habitat needs helps the wetlands manager avoid mosquito breeding problems. Open water areas, subject to wind action and providing easy access for predators, limit mosquito production. Maintaining good circulation in vegetated areas provides for predator access and lessens mosquito production. These factors have been the key to MVSD success in keeping mosquito production minimal in 1978. Figure 3 compares the numbers of adult female mosquitoes caught in a light trap monitored by the Contra Costa County Mosquito Abatement District.[9] The insects are collected and counted weekly, analysis began in August of 1976. The drastic reduction in numbers of mosquitoes trapped in late summer of 1977 and all of 1978 was due to the transplanting of mosquito fish

(*Gambusia afinis*) in the early summer of 1977. Fish were taken out of Peyton Slough and stocked in plots A-1, A-2, and B. By the end of the summer their numbers had increased enough to have the mosquito larvae population greatly reduced. Enough of the fish wintered over such that in the spring of 1978 they multiplied quickly and soon had the mosquito population under control. The rise in numbers at the end of 1978 was due to water trapped on property adjacent to the District's. Good circulation and adequate numbers of predatory fish have allowed MVSD to operate a wetland project which does not produce vector problems.

COSTS AND BENEFITS

The capital cost of the entire 20.3 acre wetlands was $94,000. Average annual operation and maintenance expenditures over 4.5 years have been $1,200/yr. Additional to this figure would be salaries for approximately 10 hrs/wk of system maintenance and 15 hrs/wk for monitoring and management. No pumping costs are associated with the gravity flow wetlands system. The amount of time necessary by personnel depends on the amount of monitoring required and on maintenance needs which vary seasonally and can be greatly reduced by careful design of both the hydraulics and physical features of the system.

Benefits of the wetlands system using treated wastewater include improved water quality, habitat creation, and recreational and educational opportunities. The wetlands is MVSD's contribution to the community, and it receives heavy use. The recreational and educational benefits included in the wetlands are a good example of the intent of section 201(g) (6) of the Clean Water Act of 1977 "The Administrator shall not make grants...(for) treatment works unless the grant applicant has satisfactorily demonstrated to the Administrator that the applicant has analyzed the potential recreation and open space opportunities in the planning of the proposed treatment works." There are visitors of all types ranging from neighborhood children who look for animal tracks to organized group tours for college students and environmental groups. The District has hosted researchers, municipal officials, and nature photographers. The local Audubon Society gave the District an award for its work and has declared the wetlands to be one of the best birding areas in the county. The California Chapter of the Soil Conservation Society of America has also officially commended the District for its work on water reuse and habitat creation. There is broad recreational potential in this type of water reuse project. Table 2 delineates the hourly usage of the wetlands by the public.

A wetlands system also has income possibilities. For example, during the summer of 1978 there was an over abundance of mosquito fish in the ponds. The local mosquito abatement district seined fish out of the ponds for their use. A local wildlife rehabilitation center and museum collects fish as well as duckweed and invertebrates for animal food. The District could charge for the fish and other food products produced.[10] The possibility exists to sell crayfish for bait or aquatic invertebrates for tropical fish food.[11] An option for a large wetlands would be to rent a portion of it to a duck club for hunting.

CONCLUSIONS

The protection, restoration and enhancement of wetlands has become a national goal. The potential environmental benefits derived from utilizing treated municipal wastewater for wetland restoration and enhancement has been demonstrated by the Mt. View Sanitary District's wetlands project. The project also demonstrates a reuse method that combines wastewater and wildlife management for optimum results. Wetlands systems created and maintained with treated wastewater are cost-effective and low in energy requirements. (1) A balanced and healthy wetlands ecosystem, composed of pond and marsh areas, has been successfully created using secondary treated wastewater. (2) The wildlife habitat actively supports 72 sp. of plants, 21 sp. of animals, 90 sp. of birds and 34 sp. of aquatic invertebrates. (3) Mosquito breeding has been reduced to a minimum through the use of natural predators. Avian botulism and odors have been avoided. (4) Redwood bark floats provide supplementary habitat for aquatic invertebrates, thereby increasing their populations in open water. (5) Nitrate removal is consistent. BOD and SS removal is seasonal - if algae was not regarded as a component of SS they would then be consistently lowered. (6) Public support for the wetlands is strong, educational and recreational usage is considerable and increasing.

PART 2 MARSH-FOREST PILOT PROJECT

In December 1978 EBC Company initiated a pilot project at Mt. View Sanitary District. The objectives of this marsh-forest project are to 1) combine wetland and upland habitats, 2) to improve the water quality of the secondary effluent coming from the treatment plant, 3) to produce a cash crop of wastewater irrigated redwood trees. Figure 4 shows the marsh-forest layout. The pond is 20' x 40' x 3' and the forest is 40' x 100'. The pond receives 3600gpd of secondary effluent, the water is then pumped to the underground irrigation system which consists of 1½" PVC pipe connecting K-6 infiltration units under each tree. Water passing through the irrigation system is collected in a splitter box from which some is discharged and some is recirculated. Water quality analyses are performed on the water in this final splitter box: averages of weekly analyses for 8.5 months show BOD and SS levels at 8.1 mg/l and 6.2 mg/l respectively. The redwood trees have grown 1.5' in 7 months.[12] The project appears to be meeting its goals of producing a high quality effluent and the irrigation system is functioning well. The trees are growing rapidly. Eight varieties of aquatic invertebrates have been identified from the duckweed covered pond. The system will continue to be monitored on a weekly basis for BOD and SS, monthly for nutrients, color, turbidity, and TDS.

TABLE I. WETLANDS INFLUENT AND EFFLUENT NUTRIENT LEVEL AVERAGES, 1975-1978.

Nutrient	Average (mg/l) Influent[b]	A[c]	B[d]	Range (mg/l) Effluent	A and B	% Reductions[a] A	B
NO_3-N	7.4	3.3	1.7	.55-18	.06-16	90	97
NH_3-N	7.9	6.7	6.8	.24-15	.1 -19	60	56
Org-N	4.8	4.4	4.6	.4-14	.09-17	56	63
PO_4	9.9	9.1	10	.44-18	.48-18	53	37

a) This is the percentage of samples when the marsh discharge was lower than the marsh influent, i.e., plant effluent.

b) Wetlands influent is secondary treatment plant effluent.

c) Effluent of plot A.

d) Effluent of plot B.

TABLE II. PUBLIC USAGE OF WETLANDS (HOURS).

Year	Education	Recreation	Total	Hours/acre*
1977	292	280	572	52
1978	524	291	815	74

*Unexpanded system of 11 acres.

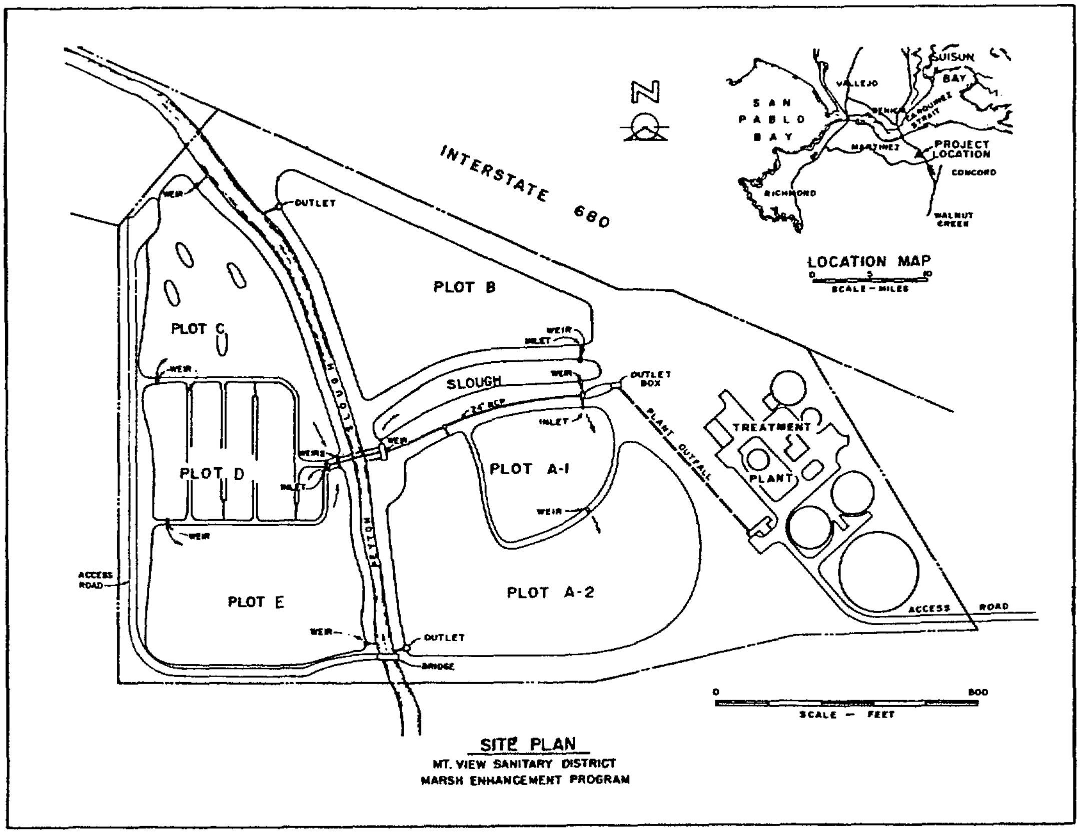


Figure 1 Wetlands Plot Plan

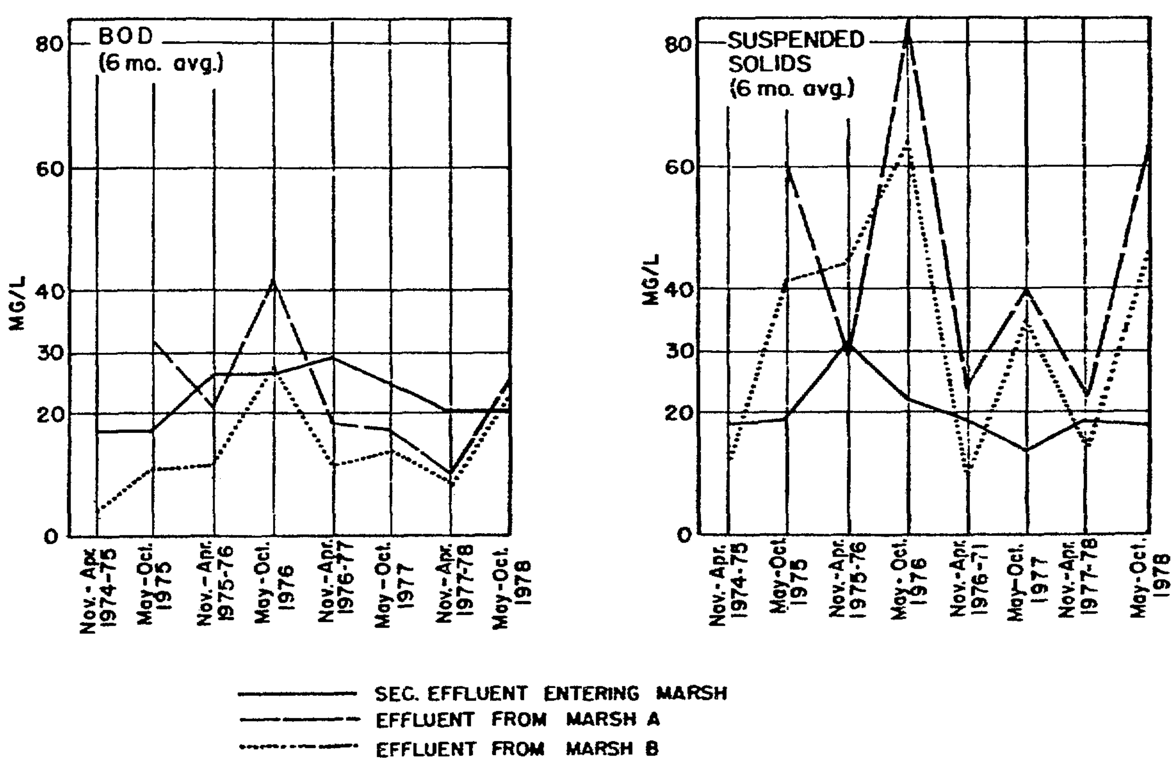
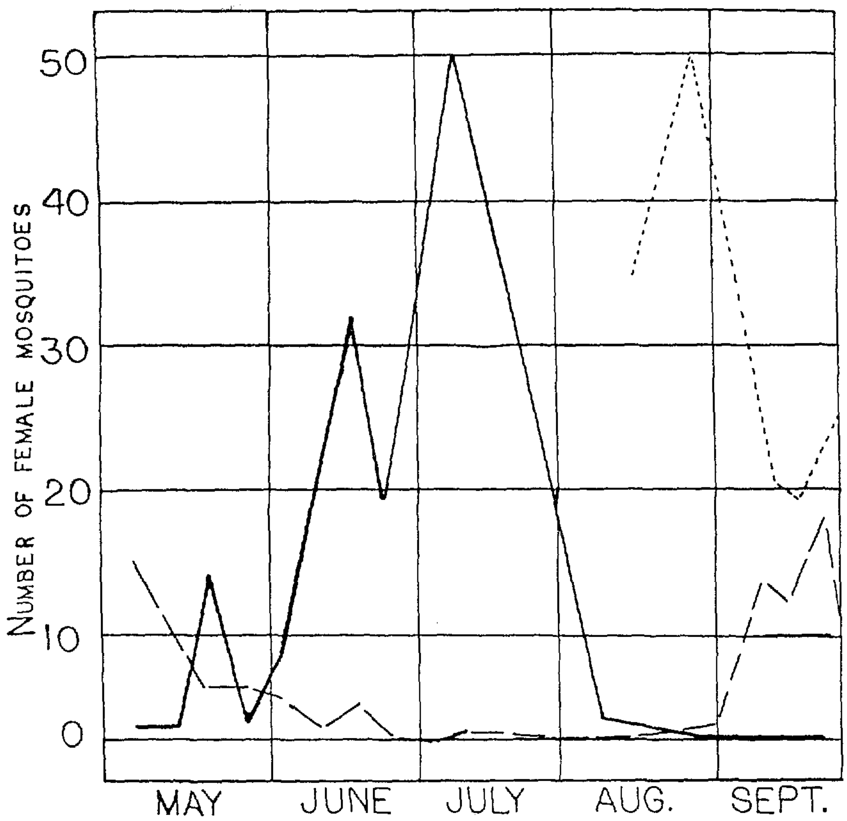


FIG. 2 Biochemical Oxygen Demand and Suspended Solids Data



1976
1977
1978

FIGURE 3

Mosquito Production

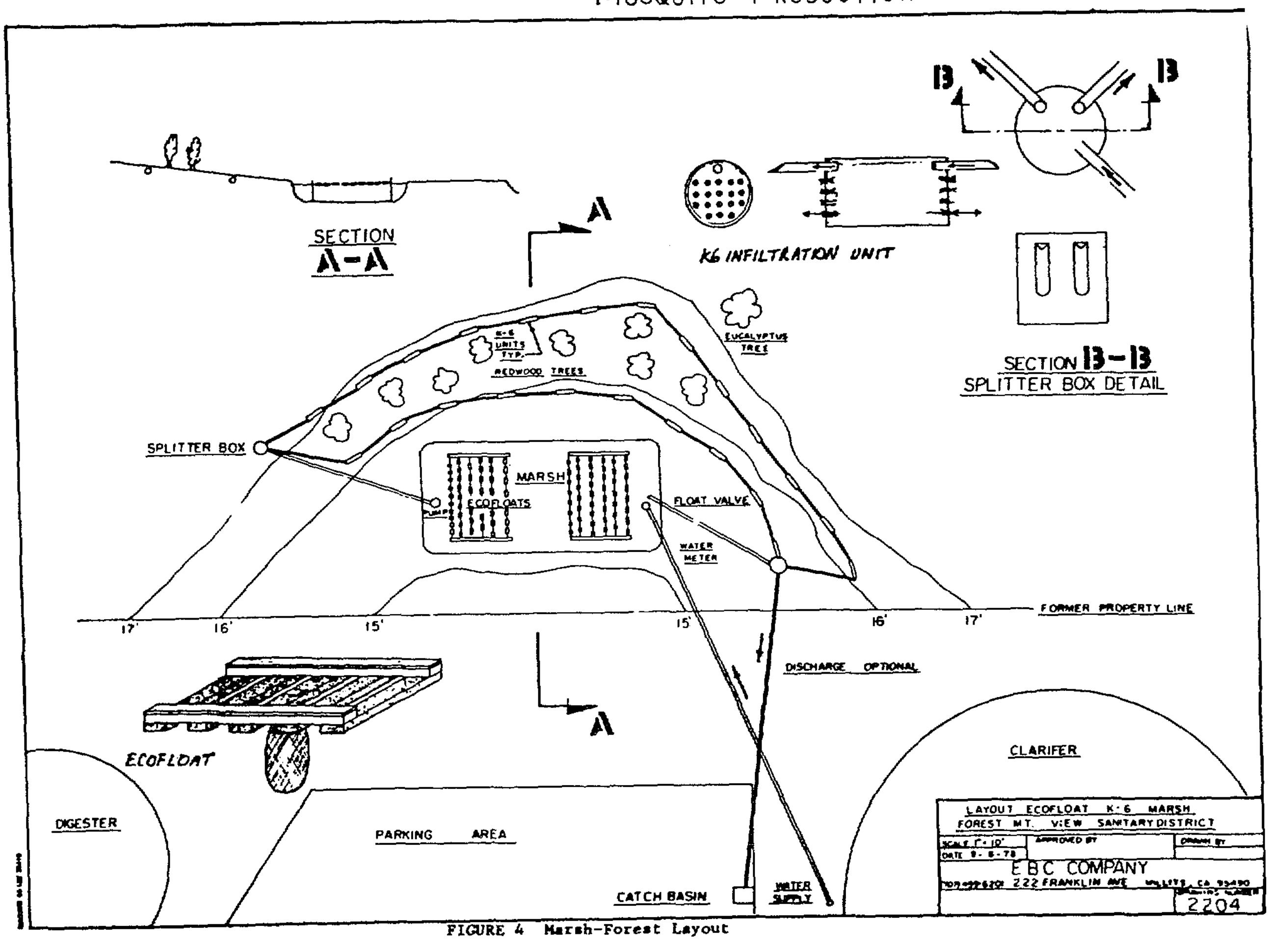


FIGURE 4 Marsh-Forest Layout

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CYPRESS WETLANDS FOR TERTIARY TREATMENT

by
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In 1973, a team of environmental scientists, under the direction of Dr. Howard T. Odum and Dr. Katherine Ewel at the University of Florida's Center for Wetlands, developed the concept of using cypress wetlands as a natural tertiary treatment mechanism for domestic wastewaters. Working under grants from the National Science Foundation and the Rockefeller Foundation, they initiated a field investigation of the method. This demonstration project included an intensive examination of two cypress domes which were supplied with effluent from a small, extended aeration, secondary treatment plant at Whitney Mobile Home Park near Gainesville, Florida. The findings from these domes were compared to the findings from a third dome which was supplied with pure groundwater and a fourth dome which was left in its natural state as "control". Results of the research show that the two "sewage domes" effectively treated the effluent to well within acceptable tertiary treatment standards with no significant adverse effect on the environment.

By 1976, the sponsors at the National Science Foundation were so encouraged with these results that they provided Boyle Engineering Corporation with a grant to convert the existing research into an applied engineering science suitable for implementation. Boyle engineers developed a three-phase approach to this project:

Phase 1—Develop conceptual techniques for using cypress wetlands for tertiary treatment.

Phase 2—Determine the feasibility of utilizing the method.

Phase 3—Develop procedures and preliminary regulations for implementation.

This article will address Phases 1 and 2.

Types of Cypress Wetlands

There are three basic types of cypress wetlands: domes, strands and fringe.

A cypress dome is a roughly circular-shaped cypress swamp, one to twenty-five acres in size, occupying a shallow, saucer-shaped depression which receives water from surrounding higher grounds. The trees are tallest in the center of the area, giving the impression of an inverted bowl or dome. The ecosystem supports lush vegetation including cypress trees.

A cypress strand is a diffuse freshwater stream flowing through a shallow forested depression on a gently sloping plain. Because of the water's relatively low erosive powers, vegetation can grow in the river bed, further slowing water flow and spreading it over a wide area. Marshes may cover shallower parts of the depression with cypress forest in the deeper channels.

Lake fringe or riverine cypress are located at the edge of lakes or rivers. These types of cypress wetlands are not suitable as treatment facilities since they offer no retention time before entering open waterways.

Concepts of Using Cypress Wetlands for Tertiary Treatment

"Natural Dome" Concept This concept requires little or no modification to the cypress dome or surrounding area (see Figure 1). Treated wastewater is applied to the center of each dome and allowed to pond or percolate through the underlying soils to the groundwaters. Biological uptake from the vegetation, combined with filtering action from the organic layer, removes essentially all nutrients, heavy metals, and coliform bacteria from the effluent. Although not yet conclusive, virus contamination appears to be effectively absorbed by the shallow sandy layer immediately underneath the mucky organic floor of the dome.

"Isolated Dome" Concept In their natural state, cypress domes collect storm runoff from surrounding lands, occasionally filling to capacity and spilling over onto surrounding areas. If wastewater is applied to the dome, problems may arise from overflow in certain situations. The Isolated Dome treatment concept virtually eliminates the possibility of spillover, making it a zero discharge system. Isolation is accomplished by constructing an earth dike around the perimeter, thus preventing surface waters from filling the dome and dome waters from escaping (see Figure 2).

Flow Through Systems In a third treatment concept, the secondary effluent is distributed along the upstream side of a cypress strand and allowed to sheet-flow through the strand (see Figure 3). The treatment mechanism relies on biological uptake by vegetation and the absorptive action of the underlying organic layer during overland flow. Discharge is into downstream waterways rather than percolation to groundwaters as in the previous two concepts.

Feasibility Criteria

Cypress wetland treatment of wastewater will be feasible only if it compares favorably over a broad spectrum of variables with other tertiary treatment alternatives. The following series of questions (or criteria) must be answered in order to avaluate the attractiveness of the cypress wetland treatment alternative.

- Will the use of the method attain required treatment results?
- Are the costs competitive with other available treatment methods?
- Are the costs and availability of required energy sources reasonable?
- What are the environmental effects on the dome and surrounding ecology?
- Is the method reliable?
- Is the method available to a significant number of users?
- Under what conditions (rules) will regulatory agencies allow the use of the method?

Treatment Results

The main purpose of tertiary treatment is the removal of nutrients, primarily nitrogen and phosphorus. Normally, tertiary treatment will also remove additional amounts of BOD_5, suspended solids, heavy metals, viruses, and coliform bacteria which are left from the secondary treatment process. Research from the Center for Wetlands' demonstration project clearly shows excellent treatment results. The research determined that 98 percent of the total nitrogen and 97 percent of the total phosphorus was removed before the treated wastewaters entered the underlying groundwater. The concentrations of nutrients and all other monitored parameters in the groundwaters under and surrounding the sewage domes remained essentially the

CYPRESS WETLAND TREATMENT CONCEPTS

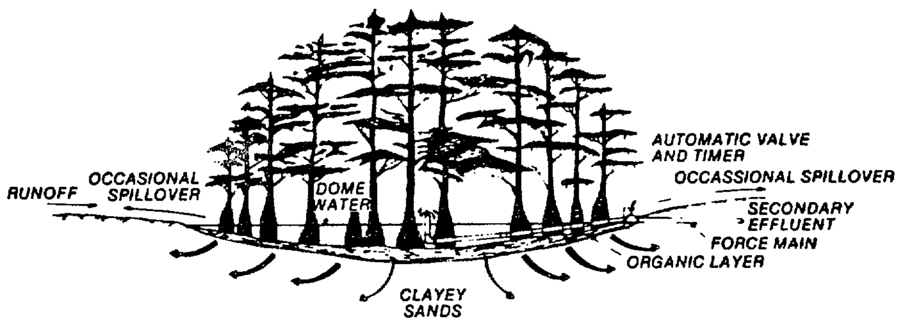


Figure 1

Natural Dome Concept

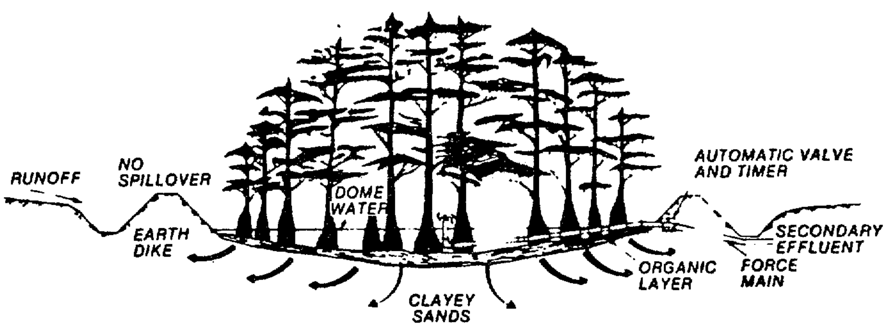


Figure 2

Isolated Dome Concept

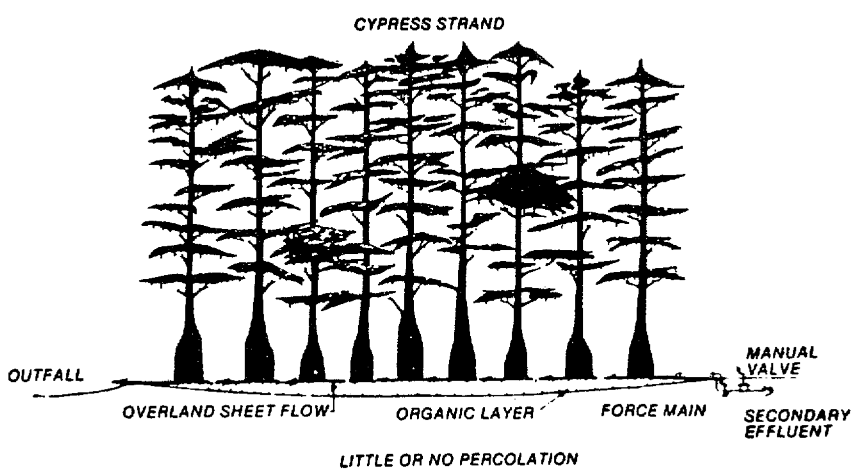


Figure 3

Flow Through System Concept

same as background and measured levels in the control domes. Thus, the groundwater quality remained well within Federal Drinking Water Standards.

Similar results were achieved in a mixed hardwood (with some cypress) "flow through" system near Wildwood, Florida. In this system, which is receiving effluent from a municipal secondary treatment plant, nutrient concentrations in the lower part of the swamp were similar to or less than concentrations in control areas and in Lake Panasofkee, into which the swamp drains. This combined secondary treatment plant-wetland system achieved results well within Florida Advanced Waste Treatment Standards.

Cost-Effectiveness

Cypress wetlands must be economically attractive, compared to other tertiary treatment methods, in order to be considered a viable alternative. The cost-effectiveness of cypress wetland treatment is highly site specific, with the cost of land, length of required force mains, average daily wastewater flow, the type of cypress wetland and surroundings all being important variables. General cost analyses performed by Boyle engineers demonstrate cypress wetlands to to be cost-effective with certain combinations of these variables (see Figures 4-7).

Another cost analysis for an anticipated treatment system in Waldo, Florida indicates tertiary treatment by cypress wetlands to cost 42.2¢ per 1000 gallons compared to 63.0¢ for spray irrigation and $1.07 for a physical/chemical treatment facility.

Cypress strands seem to offer an economic advantage over cypress domes because they are more often available in larger contiguous areas. In many cases, the entire wastewater flow could be served by a single cypress strand, as opposed to multiple cypress domes. This minimizes the total length of required force main and wetland perimeter which often must be diked or fenced. In another site specific cost analysis, the costs of both of these cypress wetland methods were compared for a treatment facility near Orlando, Florida. The results of this analysis revealed that it would cost 22.3¢ per 1000 gallons to use a large wetland strand compared to 71.2¢ per 1000 gallons to use the 44 nearest cypress domes which would be required to treat the 1.2 mgd flow.

Energy Considerations

Potential cypress wetland users are vitally interested in purchased energy requirements because of their affect on revenues, tax structures and budgets. In addition, recent Environmental Protection Agency grant programs have required consideration of purchased energy requirements during the wastewater treatment facility planning process.

Solar energy, through the processes of photosynthesis and evapotranspiration, is the

Figure 4

COST CURVES — 200,000 GPD

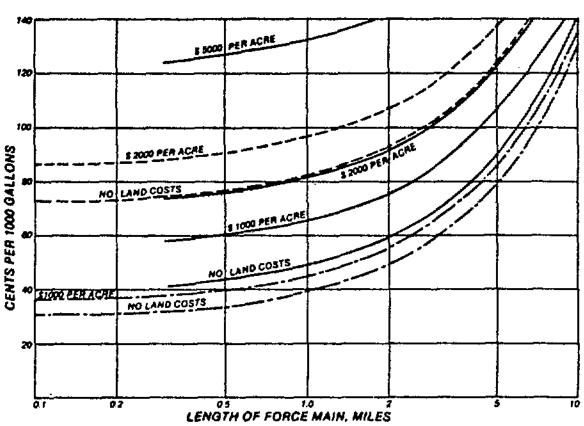
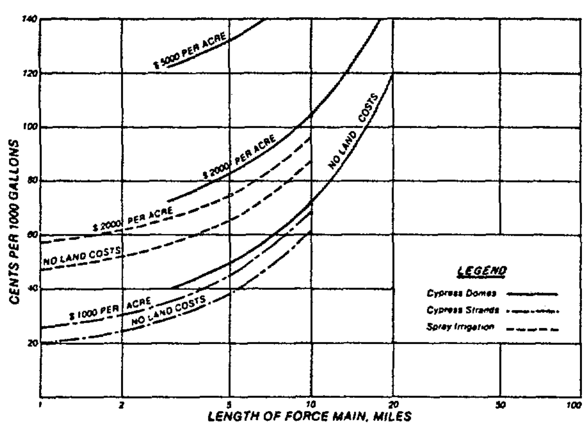


Figure 5

COST CURVES — 500,000 GPD



dominant energy form for cypress wetland treatment. Wetland vegetation uses the energy from the sun and the nutrients from the wastewater to grow and thrive, requiring neither purchased fossil fuel energy nor synthetic chemicals. However, if wetlands are used as part of the treatment process, some purchased energy must be used to pump the treated wastewater to the wetlands, and chlorine may be required for disinfection prior to application.

An analysis of the cypress wetland, physical/chemical, and upland spray irrigation alternatives was conducted to quantify and compare purchased energy requirements. The results of this analysis indicate that wetland application is generally more energy-efficient than either physical/chemical treatment or spray irrigation because it involves no power for aeration beyond secondary treatment, nor does it require any residual head for spraying.

Environmental Considerations

Cypress wetlands are tender wetland ecosystems which have often been neglected or abused. It is of utmost importance to consider the impact on all aspects of the environment within and surrounding each wetland prior to the application of wastewaters.

Many of man's surface drainage control devices, such as canals, drainage ditches and the straightening of rivers, interfere with natural recharge mechanisms, seriously endangering groundwater levels and supplies. Cypress domes serve as a reservoir system by releasing stored surface waters slowly through the organic layer into the underlying sands during times when groundwater is in short supply. The application of wastewater assures a nearly constant surface water supply which has a mollifying effect on groundwater levels, balancing them between wet and dry seasons. Further benefit is derived by reduced fire danger to the dome and surrounding vegetation.

In certain situations, occasional overflows of the treatment dome waters may be a problem. Where unfavorable conditions exist, the problem can be solved by the implementation of the "Isolated Dome" treatment concept.

Cypress domes and underlying sandy clay soil layers have been very effective in preventing coliform and virus contamination of groundwaters directly under the domes, unless the upper soil levels within the wetland are significantly disturbed. In one case, at the Center for Wetlands project, a mild intrusion of fecal coliforms, 8 to 100 per 100 ml, was detected as a result of overflow onto highly porous soils. Bacterial and viral contamination of groundwaters appears not to be a problem if the wastewater which is applied to the dome is sufficiently chlorinated and all possible "short-circuits" to groundwaters are avoided.

Figure 6

COST CURVES — 1.0 MGD

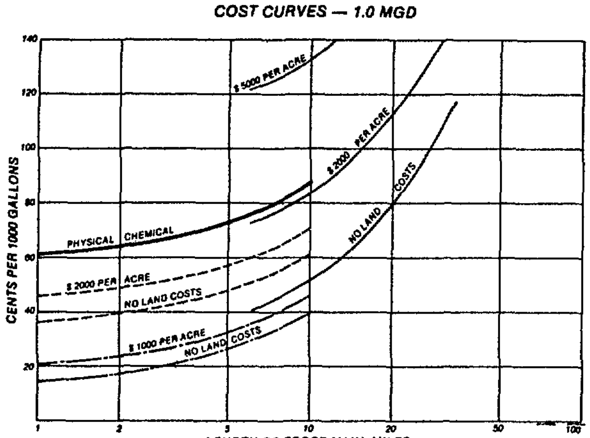
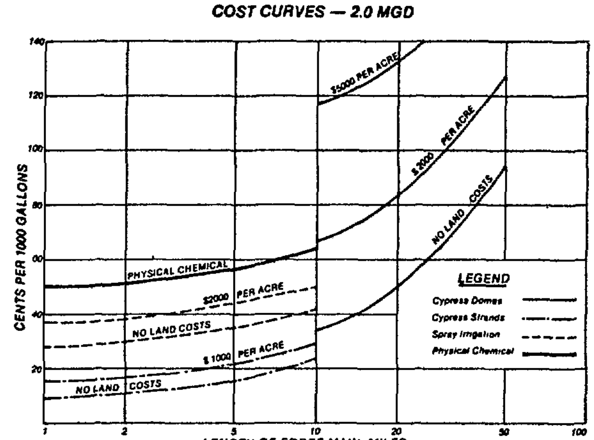


Figure 7

COST CURVES — 2.0 MGD



Cypress trees and other wetland vegetation appeared to suffer no detrimental effects from the introduction of wastewater. Indeed, there is mounting evidence that the trees thrive in effluent. Analysis of the trees in a strand near Waldo, Florida shows that they grew 2.6 times faster after the wastewater was applied.

Introduction of sewage effluent to cypress domes initiates an immediate appearance of duckweed, which readily covers the entire water surface and serves a vital role in the treatment process. The duckweed offsets a reduced treatment capacity of the dormant cypress trees during the winter months. Throughout the year, the duckweed utilizes nearly one-half of the applied nitrogen, two-thirds of the applied phosphorus, and nearly all of the heavy metals. These materials then become part of the organic layer in the wetland floor through decomposition, making them available to the cypress tree root systems.

Reliability

Wastewater production is an every day occurrence, 365 days a year, requiring wastewater treatment systems to be highly reliable. The following criteria for evaluating the reliability of a land application tertiary treatment system has been established by the U.S. Environmental Protection Agency. These criteria apply equally well to wetland application systems.

The system must have the ability to meet or exceed treatment requirements. Center for Wetlands' results have shown a reduction in total nitrogen of 98 percent and total phosphorus of 97 percent for the combined secondary treatment facility/cypress dome system. Essentially, groundwater nutrient levels under sewage domes are the same as under control domes.

Failure rates must be low. Cypress wetland treatment requires little mechanical or electronic equipment, minimizing the chances of failure. The wetlands are always available for full-time operation.

The system must not be vulnerable to natural disasters. One natural disaster which could impair operation is a period of heavy rains, causing a temporary spillover from the dome. Runoff waters during these periods would serve as a dilution agent for the overflowing wastewaters, reducing the danger of contamination. The only other likely natural disaster affecting operation is forest fire. Studies after fires in cypress domes demonstrate cypress trees have a remarkably high survival rate. In addition, the constant presence of water in the domes substantially reduces the risk of fire.

Adequate supplies of required resources must be available. The only resources required for cypress wetland treatment are: 1) wetlands, 2) sunshine, and 3) power for the pumps. The first two occur naturally and the power requirements are much less than other tertiary treatment methods. There are no chemicals, other than chlorine, required for cypress wetland treatment.

The operation must include a sufficient factor of safety. Hydrogeologic and other prerequisite studies are required to determine the quantifying parameters for design. To prevent serious problems from unforeseen circumstances, factors of safety may be employed by the designers when calculating required wetland areas. Furthermore, holding ponds can be installed to allow relatively even application of effluent and to prevent shock effect from peak loading.

Availability

In order for cypress wetland tertiary treatment to be feasible, adequate cypress wetlands must be available to the secondary treatment facilities. To evaluate availability, a survey of approximately 40 percent of the existing wastewater treatment facilities in Florida was conducted to compare treatment facility sites with the location of cypress and other forested wetlands. The results of this survey can be extrapolated to estimate availability for the entire state.

Based on earlier portions of this investigation, each facility was considered to have adequate cypress wetlands available to warrant further investigation into the feasibility of implementation, if 300 acres per mgd (design flow) were located within a reasonable distance. The following distances were considered as reasonable:

1 mile for design flows less than 0.1 mgd,

3 miles for design flows between 0.1 and 1.0 mgd, and

5 miles for design flows over 1.0 mgd.

The following results were found from the survey:

- 253 out of 2327 surveyed facilities have adequate cypress domes. These 253 facilities represent about 3 percent of the total design flow.
- 583 out of 1679 surveyed facilities have adequate forested wetlands (cypress domes and strands, hydric hammocks). These 583 facilities represent about 28 percent of the total design flow.

These results indicate that adequate forested wetlands are available for 35 percent of the wastewater treatment facilities in Florida with a combined design flow of over 350 mgd. If the method is restricted to cypress domes, about 450 facilities, representing 43 mgd design flow, can consider the wetland tertiary treatment alternative.

Regulation

State and Federal regulatory agencies indicate that they believe cypress wetland tertiary treatment shows promise of being a viable tertiary treatment alternative. This is evidenced by their support and interest in the Center for Wetlands' and related projects. However, the general regulatory concensus is that it is premature to create explicit rules for implementation. They do support, however, implementation of the method on a case-by-case basis after demonstration of treatment results, environmental concerns and cost-effectiveness.

Conclusions

The Center for Wetlands' research clearly shows cypress dome treatment to be technically feasible as an alternate method for tertiary treatment. Cypress domes are, however, restricted in their applicability because of low allowable loading rates and the relatively small areal extent of each dome. This necessitates extensive force main networks and creates large total perimeters to be diked or fenced for all but the smallest treatment facilities. Cypress strands, on the other hand, are often fairly extensive areas which will probably allow larger wastewater flows to be treated at a single site. A detailed scientific study of loading rates and treatment mechanisms in a cypress strand is currently underway at Jasper, Florida under the direc tion of Boyle Engineering Corporation.

This material is based upon research supported by the National Science Foundation under Grant No. ENV76-23276.

Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author and do not necessarily reflect the views of the National Science Foundation.

THE DRUMMOND PROJECT - APPLYING LAGOON SEWAGE EFFLUENT TO A BOG: AN OPERATIONAL TRIAL

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INTRODUCTION

The Town of Drummond is located in northwestern Wisconsin approximately 70 miles southeast of Duluth, Minnesota, and within the boundary of the Chequamegon National Forest. The town has a residential population of approximately 280, a regional high school population of 400, and one sawmill as its only industry.

In 1971, Drummond was ordered by the Wisconsin in Department of Natural Resources (WDNR), to develop a sewage treatment system for the town. Existing sewage treatment consisted of individual septic systems which did not function correctly due to heavy clay soils. This condition necessitated the pumping of septic tanks at least twice a year to prevent the discharge of primary effluent to stormwater drainage ditches and Lake Drummond.

A three-cell, contact stabilization system was developed for secondary treatment of the sewage. Twice a year treated secondary effluent was to be discharged to the Long Lake Branch of the White River, a class 1-A trout stream. The U.S. Forest Service became involved with the project because the proposed system was to be built on Forest Service land. Review of the Environmental Impact Statement for the proposed project was not satisfactory to Forest Service personnel, and after several meetings with town officials, the WDNR, and agencies funding the project, it was decided that construction would commence on the lagoon system, but a different alternative for final effluent discharge would be found.

Alternative Analysis

The Forest Service explored several different alternatives trying to find a tertiary treatment system which would effectively treat the effluent, protect the local and downstream environment and not add to the construction costs of an already financially over-burdened town.

The use of a "natural" treatment system was considered as the best method to meet the above objectives. Most of the soils around Drummond are an organic wetland type, therefore, these materials seemed to offer the best hope for treatment.

After an intensive literature review, several natural and artificial wetland treatment systems were found. The artificial wetland (Meadow-Marsh-Pond) system developed by Dr. Maxwell Small was considered, but the costs of construction were too high. The Cypress Dome studies in Florida, by Dr. Howard Odum, were also explored but here the costs of pumping and maintenance of the piping system were considered too high. The Forest Service had developed a tertiary peat-bed filter system using a layered, grass over peat over a rapid sand filter, but again costs of construction and maintenance were considered too high for the town to carry.

A fourth alternative which held some promise was the variable ditch systems of Finland. These systems use a shallow feeder ditch to apply primary effluent to a peat bog. A deeper ditch approximately 20 to 40 meters distant draws the effluent from the shallow ditch through the peat and into the deeper drainage ditch. Thirty years of use in Finland, with good treatement results, made this system look viable, until the costs of construction were calculated.

At this time a similar ditching system was being operated at Bellaire, Michigan. This system functioned for a time until a heavy rainstorm washed the ditch-system out. Dr. Robert Kadlec of the University of Michigan, had studied the Bellaire system and was working on a new system which was to be tried at Houghton Lake, Michigan. This system was to disperse secondary effluent to a wetland using a pipeline system. Speaking further with the consulting engineering firm, Williams and Works, it was determined that this system might be feasible at Drummond.

Investigation at the 10 ha bog southeast of the lagoon construction site at Drummond revealed that a gated irrigation pipe system could be used to apply the sewage effluent to the surface of this bog-wetland.

Description of the Drummond Bog

The Drummond area lies within the end moraine of the Cary-Valders Advances of the Wisconsin Age Glacier; approximately 10 to 12,000 years B.P. The area has a rolling topography with variable soil and vegetative cover. The treatment bog lies within a kettle-hole depression of approximately 25 ha in size. The bog is perched above the local and regional groundwater system due to a natural clay "liner". The watershed surrounding the bog is 15 ha, with a vegetative cover type of northern hardwoods, oak and maple.

The bog is comprised of decayed organic matter, as deep as 11 meters, with a cover mat of spaghnum moss species. Vegetative cover species consist of Black Spruce, Tamarack (Larch), Leather Leaf, Cranbury, and Blueberry.

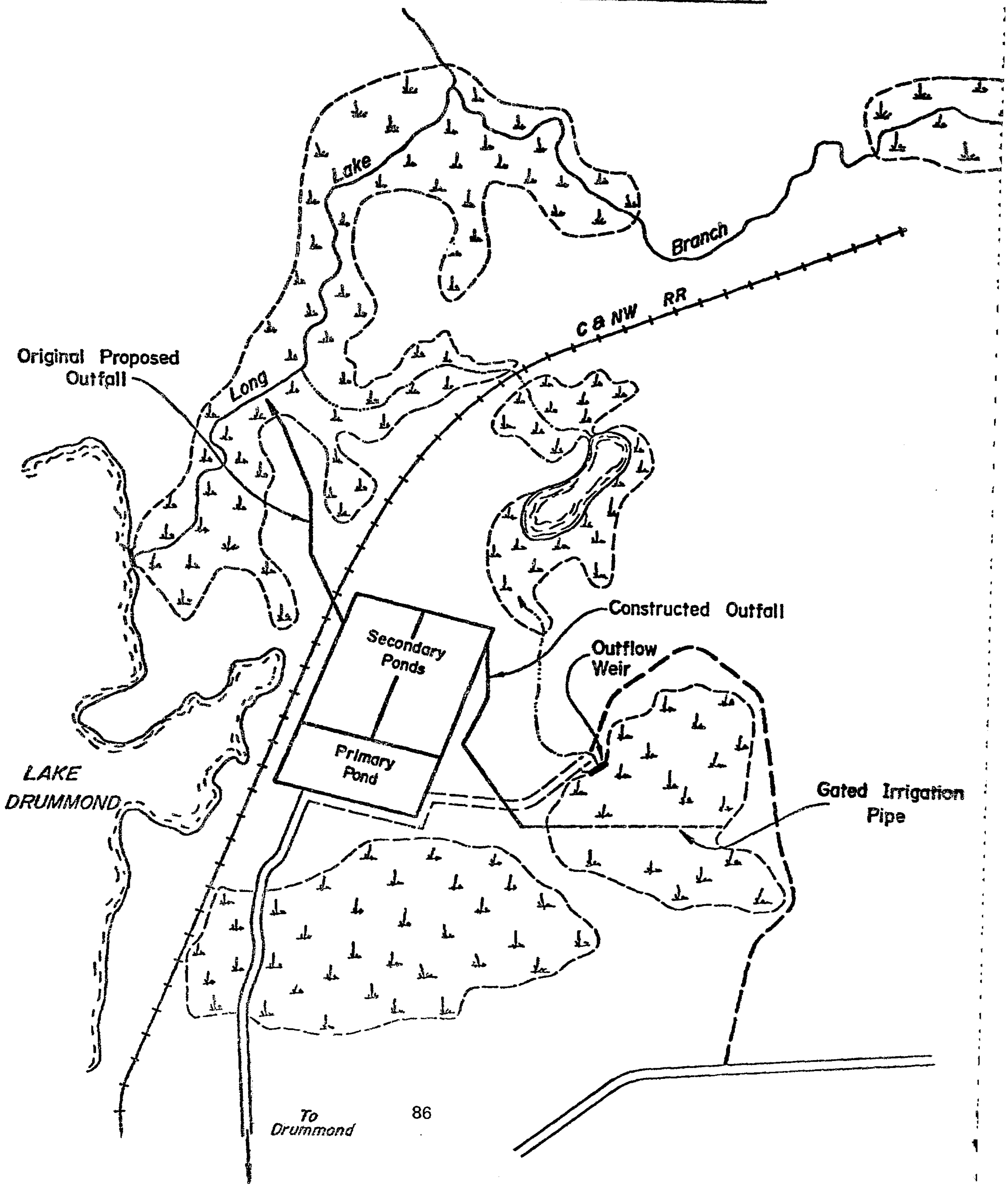
The bog is located in the upper reach of an un-named feeder to the Long Lake Branch. In this position, outflow from the bog only occurs during the spring snowmelt-runoff period and occasionally during heavy summer thunderstorms. During other periods no outflow occurs. Water which does leave the bog flows down to the Weso Lake, a small 2 ha lake which is surrounded by a sedge, cat-tail, spaghnum wetland. A wet weather outflow from Weso Lake moves into another extensive wetland before entering the Long Lake branch in a diffuse flow pattern.

Operation of the Bog Irrigation System

Based upon the hydrology of the bog and the biology of the eco-system, discharges to the wetland only occur between mid-april and early November, when the bog surface is not frozen. During the unfrozen period, the upper surface of the decaying peat, approximately 20 cm, and the growing cover species act as a physical, chemical, and biological filter for the effluent. Physically, suspended solids are filtered out, chemically, the high cation exchange rate of the peat "holds" many of the inorganic nutrients, and biologically, micro-organisms, as well as the vegetative species, take up some of the nutrients of the effluent water as it passes through this living filter. Since this type of wetland is generally nutrient-poor, the addition of nutrient-laden water should act to stimulate vegetative growth within the wetland. This will be discussed in the next section.

The hydrology of the bog will also be altered by the application of the effluent. The effluent discharges are made from the secondary pond onto the bog surface through the use of 215 meters of gated irrigation pipe. The gates on the pipe are adjusted so even dispersal of the effluent, across the bog surface, is accomplished. The designed daily discharge is 100,000 gallons. The application takes place over a three to four hour period, early in the morning, to take advantage of peak evapo-transpiration rates during mid-day. On the day of a discharge, local and regional weather forecasts are followed to ascertain if any heavy rainfall (>2.5 cm) will occur in the next 24 hours. If the weather looks good, the outflow weir is checked to note the present discharge. Based upon the pretreatment water budget, if the outflow discharge is less than .06 cfs a discharge can be made every day. If the outflow rate is higher, .06 to .12 cfs, discharge can be every other day, or if the discharge is above .12 cfs, no discharge is made. The discussion of how these rates were determined if found in the next section.

DRUMMOND
TERTIARY SEWAGE TREATMENT
DEMONSTRATION PROJECT



Research Projects

The research effort, at the treatment bog, encompasses four major areas; a water-quality study, a vegetative study, a small animal study, and a water and nutrient budget study. The following section summarizes each study and the status of the work to date. Most sutdies, except the small animal study, have at least one year of pretreatment data. Discharges to the bog began in May 1979, and most of this year's data has yet to be analyzed against pretreatment data, but in recent discussions with most researchers, nothing unexpected has occurred, yet.

An annual research meeting is held each spring at UW-Stevens Point where the past year's data is summarized and the next year's plans are discussed. These meetings are open to anyone interested in the project. An active mailing list is maintained by the Forest Service; biannual updates on the project are prepared and an active interchange of ideas is always encouraged.

Water Quality

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Stevens Point, Wisconsin 54481

Funding - Upper Great Lakes Regional Commission

This study consists of sampling water quality from the lagoon system, through the treatment bog and downstream into the Weso Lake system. In the bog, 15 clusters of wells, consisting of a combination of surface, near-surface (0.5m) and deep wells (3.0 m) are used to sample water quality as the effluent moves through the bog system. Samples are taken on a bimonthly basis during treatment and monthly otherwise. Samples are analyzed for temperature, pH, conductivity, alkalinity, total and calcium hardness, chlorides, D.O., COD, BOD_5, BOD_{20}, ortho and total phosphorus, NH_4, NO_{2-3}, Kjeldahl N, and fecal coliforms.

Pretreatment data has shown that each well cluster reacts independently of any other. Therefore, analysis of changes in water quality, as effluent moves through the bog, will have to be made on a spatial and temporal basis, rather than the surface wells reacting as a surficial unit.

Based upon analyses through August 11, 1979, there has been no change in water quality leaving the treatment bog. Analyses of lagoon water versus surface wells in the bog display a substantial reduction in phosphorus and nitrogen to within "normal" pretreatment ranges at respective well sites throughout the bog. Chlorides, which are being used as a trace of effluent movement within the bog have shown an increase in the wells near the pipeline and along an unsuspected flow path toward the outlet weir. This will be studied further to determine whether the pipeline should be moved to another location in the bog. No changes in water quality have been observed in the near-surface and deep wells due to the lack of water movement in these zones.

Vegetative Study

Dr. Forest Stearns, Dr. Glenn Gutenspergen
University of Wisconsin - Milwaukee
Milwaukee, Wisconsin 53201

Funding - U.S. Forest Service

Dr. Dean Knighton, Dr. Sandy Verry, Dr. Dale Nichols
North Central Forest Experiment Station
Grand Rapids, Minnesota 55744

Funding - U.S. Forest Service

Dr. Douglas Wikum, Dr. Martin Ondrus
University of Wisconsin - Stout
Menomonie, Wisconsin 54751

Funding - University, Forest Service

The vegetative study is composed of two parts: productivity and nutrient uptake capabilities of the predominate species of the bog, UW-Milwaukee and Stout, and the vegetative composition of the bog, North Central Experiment Station. The nutrient uptake study encompasses four permanent plots within the bog as well as selected individual trees and a small number of destructive plots in which present year growth vegetative samples are taken for nutrient analysis. Pretreatment data has shown that the nutrient quality of various species fall within published data for those respective species, in their natural state. Other vegetative studies are also taking place in the bog lagg zone (perimeter) and downstream in the Weso Lake wetland.

Data during this year's application period have yet to be analyzed, but will be ready for the spring research review at UW-Stevens Point.

The bog species composition study is being accomplished through aerial and bog level stereo photography. The bog level photo points are both within and outside the permanent plots. These pictures are evaluated with the data collected within the permanent plots and projected over the entire bog.

Small Animal Study

Dr. Ray Anderson, Dennis Kent
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Steven Point, Wisconsin 54881

Funding - U.S. Fish and Wildlife Service

The fauna study began in the sping of 1979. This study is designed to observe populations of small mammals, birds, amphibians, and invertebrates within the bog system and in the upland areas surrounding the bog. The study will note how changes in the hydrology of the bog as well as any vegetation changes affect the movements, composition, and numbers of species that use the wetland.

The only point of interest so far in this study is the use of the various research boardwalks by many of the small animals. These boardwalks were built to protect the fragile bog surface and aid the researchers in collecting their data. They have also changed some faunal usage patterns by making movement much easier on these mini highways versus the pre-existing animal trails.

Water and Nutrient Budget Study

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Chequamegon National Forest
Park Falls, Wisconsin 54552

The water budget is rather simplified since the bog is "perched" above the regional ground water system. The typical annual budget is:

Precipitation - Evapotranspiration - Outflow = Storage

During the discharge period, mid April through October, assuming no effluent discharge, and assuming an average daily discharge of 0.03 cfs* the budget is:

Precipitation - Evapotranspiration - Outflow = Storage
25.9 (inches) - 20.2 (inches) - 5.8 (inches) = -.1 inch

Assuming an effluent discharge to the bog equivalent to 3/4 design capacity (11 million gallons of effluent) during this same period and an average discharge of 0.12 cfs** the budget would be:

Precipitation + Effluent - Evapotranspiration - Outflow = Storage
25.9 (in.) - 18.3 (in.) - 20.2 (in.) -23.2 (in.) = 0.8 inches

As can be seen from this crude budget, the additional effluent water could be added to the bog and would cause a doubling of flow leaving the bog. The critical point here is timing the effluent discharge to the timing of flows leaving the bog; the longer the "contact time" for the effluent in the bog, the better the treatment. As explained earlier these discharges of effluent to the bog are made dependent on weather conditions and flow leaving the bog. Discharges are also planned to coincide with peak evapotranspiration rates. Therefore, a bulk of the discharges occur between June and September and each discharge is planned for early in the morning.

* 1/2 the average daily discharge during the period April-October 1978.

** Twice the average daily discharge during the period April-October 1978.

During the months of May, June, and July of 1979, approximately 2.8 million gallons of effluent have been applied. The weather has been extremely wet and has reduced the number of planned discharges. An evaluation of this year's discharge record will be made to possibly redesign next year's "operations manual." Also, the results of a related nutrient uptake study at the North Central Forest Experiment Station has suggested that a greater number of discharges should occur earlier in the year when the nutrient uptake capabilities of the plants are greater. This alteration in the effluent discharge pattern will be discussed at the next joint research meeting.

The nutrient budget is a joint project for members of the study team. Since the data must be pooled from various sources the first budget will be prepared for the Spring 1980 meeting.

Conclusion

The Drummond Project is a multi-resource study of a spaghnum bog and its response to the application of sewage effluent. The intent of the project is to understand the dynamics of this type of wetland as well as determining whether this type of wetland can be used to effectively treat and assimilate residential sewage effluent. Up to this time, little was known of the dynamics or treatment capabilities of spaghnum peat wetland. This study will hopefully answer, in a few short years, the capabilities of this type of wetland, as well as adding to our general knowledge of the peat bog ecosystem.

If further information is desired on any part of this study, contact the principle researcher or the Forest Hydrologist, Chequamegon National Forest, Park Falls, Wisconsin 54552.

EFFECTIVENESS OF A WETLAND IN EASTER MASSACHUSETTS IN IMPROVEMENT OF MUNICIPAL WASTEWATER

Donald A. Yonika, IEP, Inc., 534 Boston Post Road, P.O. Box 438, Wayland, Massachusetts 01778

The Town of Concord, Massachusetts Sewage Treatment Plant currently discharges secondary level wastewater to a 48 acre deep marsh which is part of the Great Meadows National Wildlife Refuge. The effectiveness of this wetland in further renovating effluent quality was assessed as part of an 18 month feasiblity study on the use of wetlands in the Commonwealth for advanced stages of wastewater treatment. This research was conducted by IEP, Inc. for the Massachusetts Division of Water Pollution Control.

The Treatment Plant serves 6,000 of the total town population of 18,000. Of the area serviced, roughly 80 percent of the design flow of 1 MGD is derived from residential uses and the remaining 20 percent from light commercial, institutional and industrial use. During the actual study period inflow to the plant average .98 MGD. Outflow as measured by flow over the chlorine contact chamber weir, averaged .61 MGD.

The Plant presently provides an acceptable level of secondary treatment with 83 percent suspended solids and 90 percent BOD removal. The system basically consists of an Imhoff Tank and outdoor sand filter beds underdrained to the chlorine contact chamber. Each of the nine three quarter acre filter beds is periodically closed for a 24 hour period and rested for eight days. Solids remaining on the surface are removed and disposed of. Chlorinated secondary effluent is discharged directly to the wetland surface of a 48 acre deep marsh that is owned by the Fish and Wildlife Service.

The wetland functions as two units. Just below the outfall is an approximately 6 acre section of wetland that can be described as a combination of both shallow marsh and shrub swamp. Vegetation is extremely dense, and almost impenetrable on foot. The effluent travels in no distinct channel, but flows through the vegetative mat, maximizing contact between the wastewater and wetland soils and plants. After seeping through the 6 acre section, the wetland broadens out into a deep marsh, with considerably more open water. Retention time during the study period was calculated to be about 57 days. Water fluctuations within the 48 acre wetland were only slight during the growing season, varying no more than two-tenths of a foot. During the winter and spring however, fluctuations were much more severe, varying by more than two feet over normal water elevation.

During the life of the study, the average concentrations of wastewaters discharging to the wetland were 8.0 mg/l ammonia nitrogen, 3.1 mg/l nitrate nitrogen, .019 mg/l nitrite nitrogen, 10.0 mg/l total kjeldahl nitrogen, 2.1 mg/l total phosphorus, 1.6 mg/l ortho phosphorus and 38.2 mg/l for BOD.

A water sampling program was devised to attempt to quantify the change in both concentration and loading between the secondary outfall and the discharge point from the wetland to the Concord River. Five sampling stations were established, as indicated on Figure 1, entitled Water Quality Sampling Station Locations. Station 1 is the Treatment Plant outfall. Station 2 is located at the periphery of the 6 acre shallow marsh - shrub swamp section. Station 3 is located at the drop-inlet discharge point from the wetland to the Concord River. Stations 4 and 5 are located on the mainstream of the River, with Station 4 upstream, and 5, just downstream of the Station 3 outfall in a location where complete mixing of mainstream and wetland waters has occurred.

Nine rounds of sampling were accomplished during the study period. Table 1 below presents the average concentrations for selected parameters tested at each station.

Table 1 Water Quality Sampling Results

Ammonia Nitrogen

Station	mg/l
1	8.0
2	5.4
3	1.8
4	.15
5	.15

Nitrate Nitrogen

Station	mg/l
1	3.1
2	1.3
3	1.0
4	.67
5	.47

Nitrite Nitrogen

Station	mg/l
1	.019
2	.070
3	.040
4	.010
5	.010

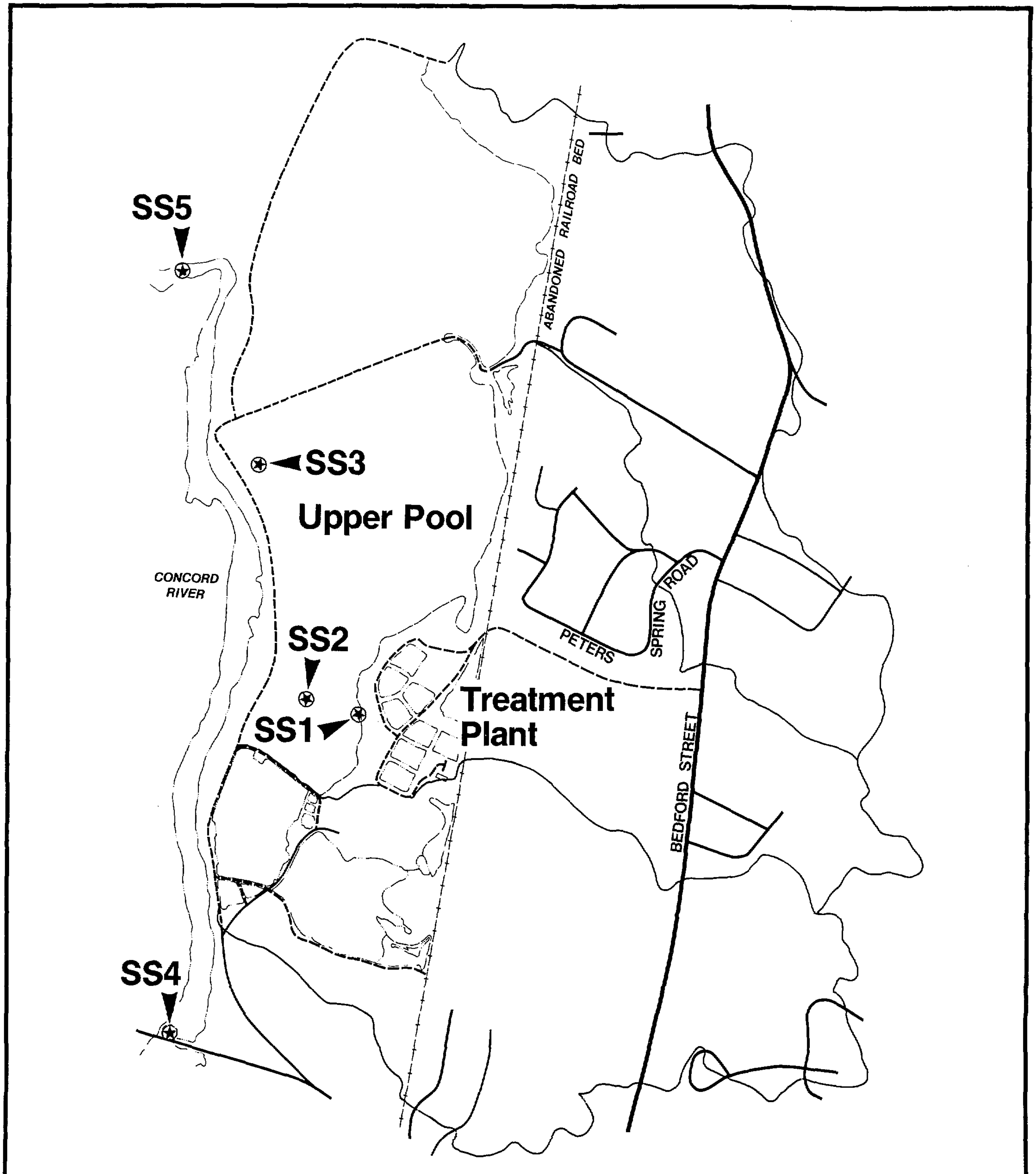

FIGURE 1

Water Quality Sampling Stations Locations

A FEASIBILITY STUDY:

WETLAND DISPOSAL OF WASTEWATER TREATMENT PLANT EFFLUENT

CLIENT: MASSACHUSETTS DIVISION OF WATER POLLUTION CONTROL CONTRACTOR: IEP, INC. WAYLAND, MASSACHUSETTS

Total Kjeldahl Nitrogen

Station	mg/l
1	10.0
2	7.2
3	3.4
4	.75
5	.77

Total Phosphorus

Station	mg/l
1	2.1
2	.97
3	.50
4	.16
5	.17

Ortho Phosphorus

Station	mg/l
1	1.6
2	.67
3	.38
4	.11
5	.10

Biological Oxygen Demand

Station	mg/l
1	38.2
2	8.5
3	5.8
4	2.2
5	2.3

As can be readily seen, as the effluent travels through the wetland, the concentrations of each parameter are considerably diminished (with the exception of nitrite nitrogen).

In order to remove the influence of dilution on the results, a loading analysis was conducted for each Sampling Station for the parameters listed in Table 1.

Table 2 summarizes the data in terms of total pounds per day load for each of the selected parameters at each Station during the study period.

Table 2 Results of Loading Analysis

Ammonia Nitrogen

Station	Loading, Pounds Per Day
1	40
2	39
3	17
4	322
5	340

Nitrate Nitrogen	Station	Loading, Pounds Per Day
	1	13.0
	2	9.9
	3	10.4
	4	982
	5	784

Nitrite Nitrogen	Station	Loading, Pounds Per Day
	1	.10
	2	.54
	3	.39
	4	17.4
	5	16.6

Total Kjeldahl Nitrogen	Station	Loading, Pounds Per Day
	1	49.8
	2	52.4
	3	32.5
	4	1366
	5	1448

Total Phosphorus	Station	Loading, Pounds Per Day
	1	9.34
	2	7.51
	3	4.94
	4	240
	5	253

Ortho Phosphorus	Station	Loading, Pounds Per Day
	1	7.2
	2	4.6
	3	3.7
	4	166
	5	171

Biological Oxygen Demand	Station	Loading, Pounds Per Day
	1	188
	2	63
	3	62
	4	3841
	5	4547

Reducting further the calculations noted above, Table 3 presents the average annual removal efficiencies of the 48 acre wetland for the selected parameters.

Table 3

Average Annual Removal Efficiencies
For The Great Meadows Wetland

Ammonia Nitrogen	58%
Nitrate Nitrogen	20%
Nitrite Nitrogen	(292%)
Total Kjeldahl Nitrogen	35%
Total Phosphorus	47%
Ortho Phosphorus	49%
Biological Oxygen Demand	67%

( ) Indicates Release

The loading data were further manipulated to see whether there were any seasonal variations in removal efficiencies. The several rounds of sampling results were grouped according to growing season applicable to the Great Meadows area, from early spring to early, mid and late growing season, to fall and early winter, and finally to mid-winter. The data were plotted by season, and expressed as either removal or release rate. Figure 2 is an example of the type of seasonal variation commonly reflected by most of the tested parameters. The results, for nitrate nitrogen show high removal efficiencies during the growing season, and a rapid release of this member of the nitrogen series as the plants were killed back by frost action in the fall. This seasonal removal efficiency may be of significant interest to water quality managers trying to reduce in-stream concentrations of eutrophying nutrients during the high-use summer recreational season, or when stream low flow may be a problem.

Removal efficiencies were calculated not only for the various seasons, but also for the two different wetland subtypes found within the Great Meadows Refuge. This data is also portrayed on Figure 2 for nitrate nitrogen. Station 1 to 2 analysis indicates function of the 6 acre shrub swamp section. Station 1 to 3 analysis portrays the function of the overall 48 acre predominantly deep marsh wetland relative to seasonal removal or release rates.

Of the considerable more interest to wastewater design engineers is data on absolute removal amounts. Figures 3 and 4 are included as examples of the results obtained for ortho phosphorus and BOD, respectively, relative to pounds of each removed per day per acre of wetland. Closer inspection of either graphic indicates a significant seasonal variation in the amount removed per acre of wetland as well as considerable difference betwen wetland subtypes.

The mean annual uptake rate for BOD for the deep marsh section of the wetland is 2.6 pounds per acre per day. The amount removed by the shrub swamp - shallow marsh 6 acre section immediately adjacent to the Sewage Treatment Plant outfall is much higher - 20.8 pounds per acre per day.

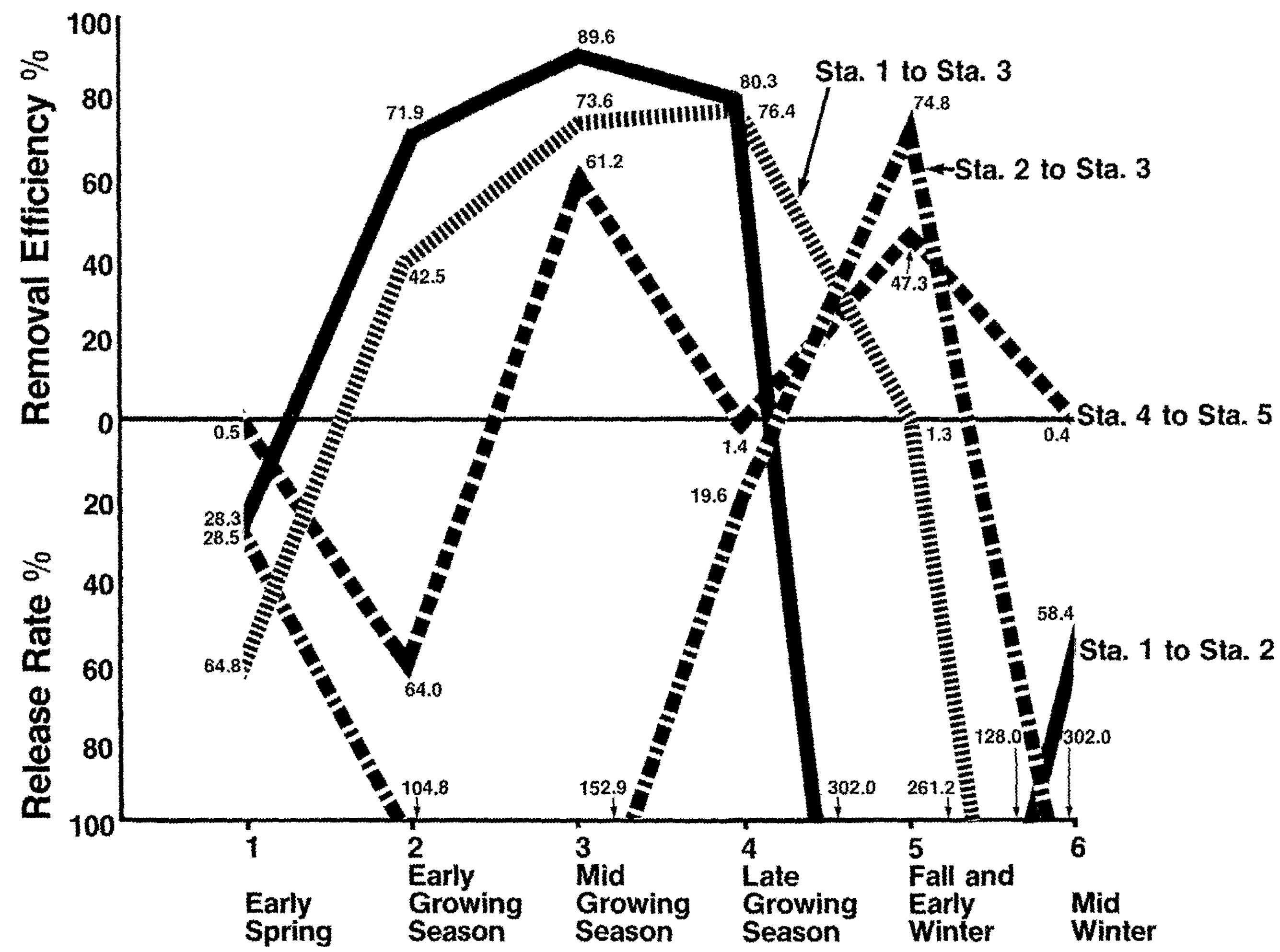

FIGURE 2

Removal Efficiency for Nitrate Nitrogen, Loading

Yearly Removal (Release) Efficiencies:

Sta. 1 to Sta. 2	24%
Sta. 2 to Sta. 3	(5%)
Sta. 1 to Sta. 3	20%
Sta. 4 to Sta. 5	20%

A FEASIBILITY STUDY:

WETLAND DISPOSAL OF WASTEWATER TREATMENT PLANT EFFLUENT

CLIENT: MASSACHUSETTS DIVISION OF WATER POLLUTION CONTROL CONTRACTOR: IEP, INC. WAYLAND, MASSACHUSETTS

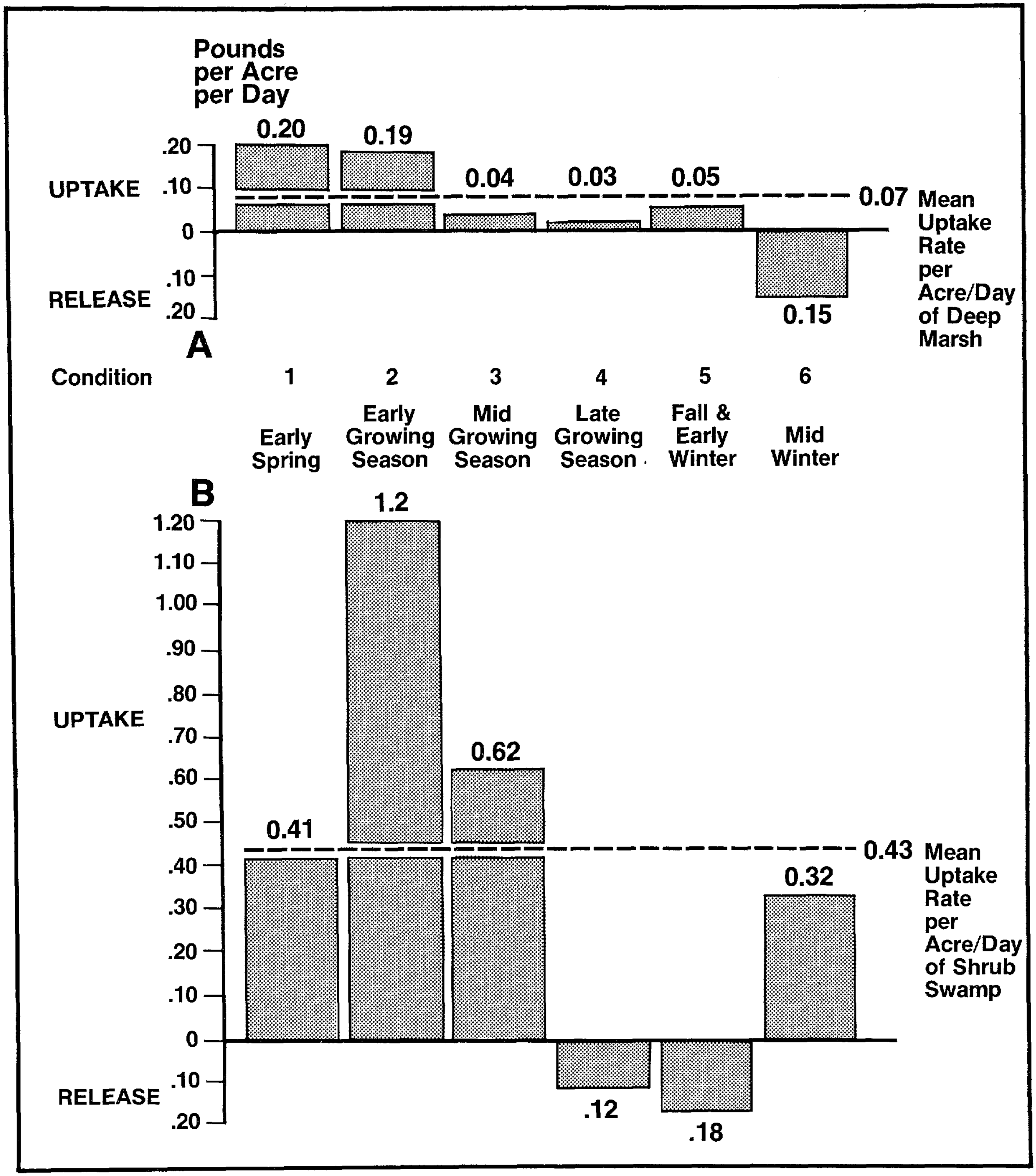

FIGURE 3

A - Ortho Phosphorus Uptake & Release Rates Stations 1 to 3

B - Ortho Phosphorus Uptake & Release Rates Stations 1 to 2

A FEASIBILITY STUDY:

WETLAND DISPOSAL OF WASTEWATER TREATMENT PLANT EFFLUENT

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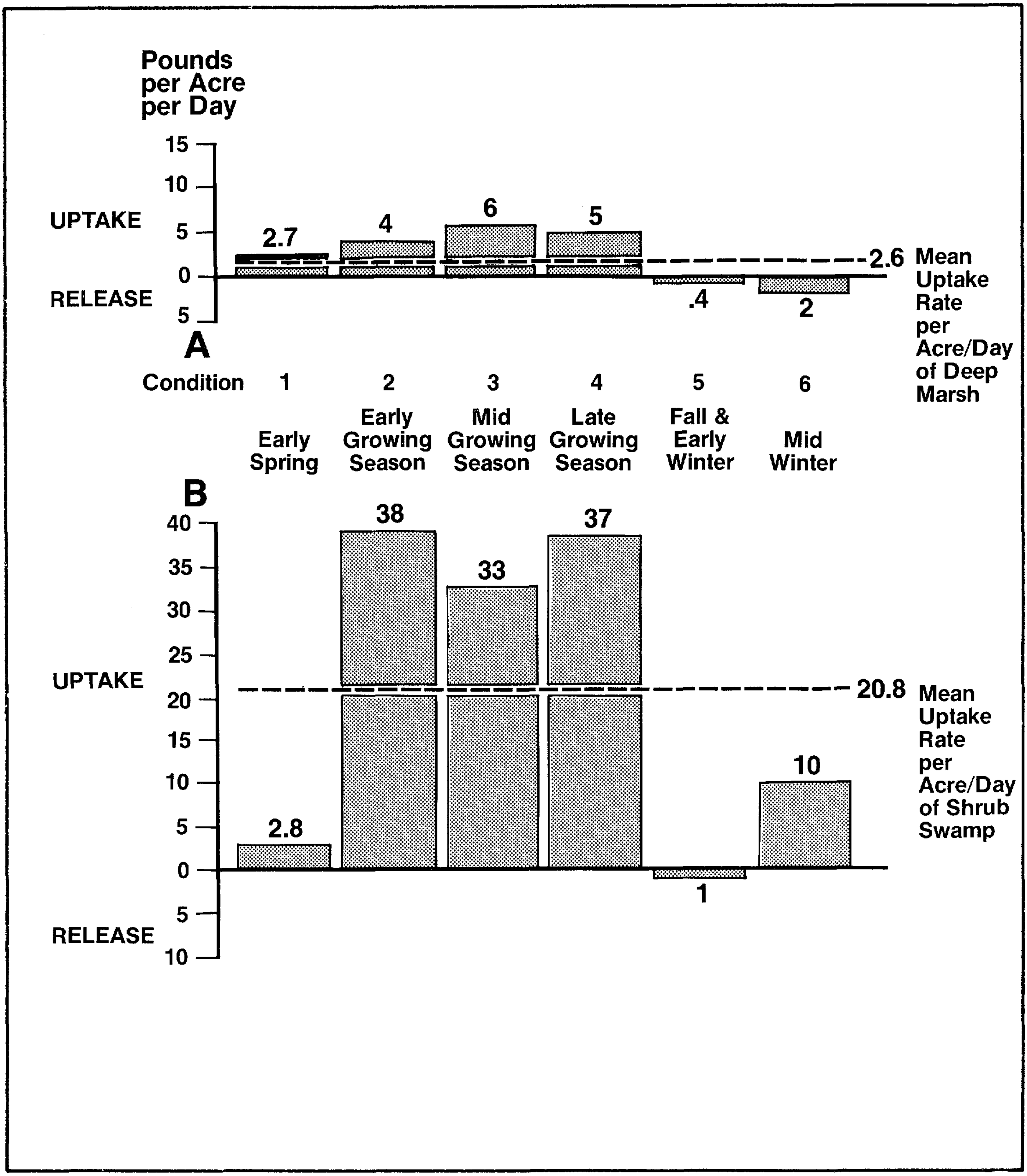

FIGURE 4

A - BOD
Uptake & Release Rates
Stations 1 to 3

B - BOD
Uptake & Release Rates
Stations 1 to 2

A FEASIBILITY STUDY:

WETLAND DISPOSAL OF WASTEWATER TREATMENT PLANT EFFLUENT

CLIENT: MASSACHUSETTS DIVISION OF WATER POLLUTION CONTROL CONTRACTOR: IEP. INC. WAYLAND, MASSACHUSETTS

The same variable patterns hold for the nitrogen and phosphorus series. The shrub swamp portion of the wetland removed, on the average, .43 pounds per acre per day of ortho phosphorus, and .30 pounds of total phosphorus. The deep marsh section was considerably less efficient, with values of only .07 and .09 pounds per acre per day for ortho and total phosphorus, respectively.

Ammonia nitrogen at the rate of .17 pounds per acre per day was removed by the shrub swamp section: the entire deep marsh averaged .48 pounds per acre per day. Nitrate nitrogen removal comparisons were just the opposite for the same wetland subtypes with .50 pounds per acre per day removed by the shrub swamp, and .06 pounds per acre per day for the deep marsh.

These figures agree well with the majority of investigations that have been conducted throughout the north central and north eastern sections of the country, albeit the number of studies very limited. Generally, however, removal rates for phosphorus and the nitrogen series are low, in the range of one half pound per acre per day for these nutrients, which computes to a population equivalent of only 10 to 50 people per acre of wetland, depending on whether nitrogen or phosphorus is of concern.

Of notable exception to our study and the majority of the others are the results obtained by Dr. Maxwell Small in New York. The absolute removal rates recorded by far exceed those obtained during this study.

Overall, our results indicate that use of wetlands for secondary wastewater polishing may not be economically feasible in states where larger wetlands are scarce near population centers, or where wetland acquisition costs are high.

Thus, a need exists to identify those characteristics or components of wetlands which, in combination, would significantly increase the efficiency (seasonal and year-round) of wetlands to renovate secondary waste. Construction of artificial wetlands or identification of natural wetlands with components selected for maximizing renovating efficiency, and matched to the particular secondary waste characteristics of the plant, may make the concept of wetlands for wastewater renovation more viable in other than rural areas.

WETLAND TERTIARY TREATMENT
AT HOUGHTON LAKE, MICHIGAN

Robert H. Kadlec, Department of Chemical Engineering
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For five cosecutive summers, secondary wastewater was discharged to areas within a peatland in central Michigan. All nitrogen and phosphorus were removed from 100,000 gallons per day within a five acre area. The maximum water depth increases were 10-15 cm, at the center of the discharges. Some dissolved species, such as chloride flowed through the treatment area with very little change; others such as pH dropped rapidly to background levels. No soil erosion or plant mortality occurred. Suspended solids deposited close to the discharge. Odor problems were slight. No net virus or coliforms were transported to the wetland. Animal populations have not yet responded to the discharge.

FLOOD IRRIGATION SYSTEMS

The Houghton Lake sewage treatment plant serves a community of population 6-8,000, which varies seasonally for this central Michigan resort location. The developed area is a strip bordering Houghton Lake. The septic fields of the 1960's discharged into this shallow water body, leading to excessive eutrophication, and leading to the construction of a collection system and a centralized treatment facility. This treatment plant went on stream in late 1974.

The treatment facility consists of two aeration ponds in series. Sludge settles to the bottom of these ponds, and wastewater overflows to a 29 acre holding pond. The original design calls for the water to be pumped from the holding pond to seepage beds; or, after chlorination, to be spray irrigated onto rye fields. The capacity of the holding pond is sufficient for nine months storage, thus permitting summer disposal of the treated wastewater. Details of this system are shown in Figure 1.

This research project tested a third alternative for disposal of the treated water from the holding pond: flood irrigation onto a State-owned peatland. A pilot transfer system was constructed, in June 1975, capable of pumping 100,000 gallons per day to the peatland. This system consisted of:

(1) a buried, drainable force main from holding pond to marsh edge;
(2) a buffer storage pond at marsh edge (for storage and de-chlorination);
(3) an irrigation pump station at marsh edge.

From the buffer storage pond, the water was distributed over the northeastern end of the marsh, using 1700 feet of 3-inch agricultural irrigation pipe, laid on the surface.

Two study sites were developed: one for a linear trickle discharge (Site A) and one for a single point discharge (Site B). Details are shown in Figure 2. During the period July 24 - September 15, 1975, 2.12 million gallons of wastewater were pumped to site A, at the average daily rate of 40,000 gpd. Nozzles were located every 30 feet, for a total of 22 holes. These were sized to give approximately the same flow from each hole. During the period May 25 - September 26, 1976 a total of 10.26 million gallons of treated effluent was pumped to the wetland and distributed via the same 3 inch gated surface irrigation pipe. The average pumping rate was 360 m^3/day (95,000 gal/day). On an average mound area of 65,000 m^2 (16 acres), this amounts to 3.9 cm/week, or 70 cm during the entire summer. The only pumping problem encountered was intake clogging by algal debris at the sewage plant holding pond. All gates in the peatland pipe remained open, even the smallest holes.

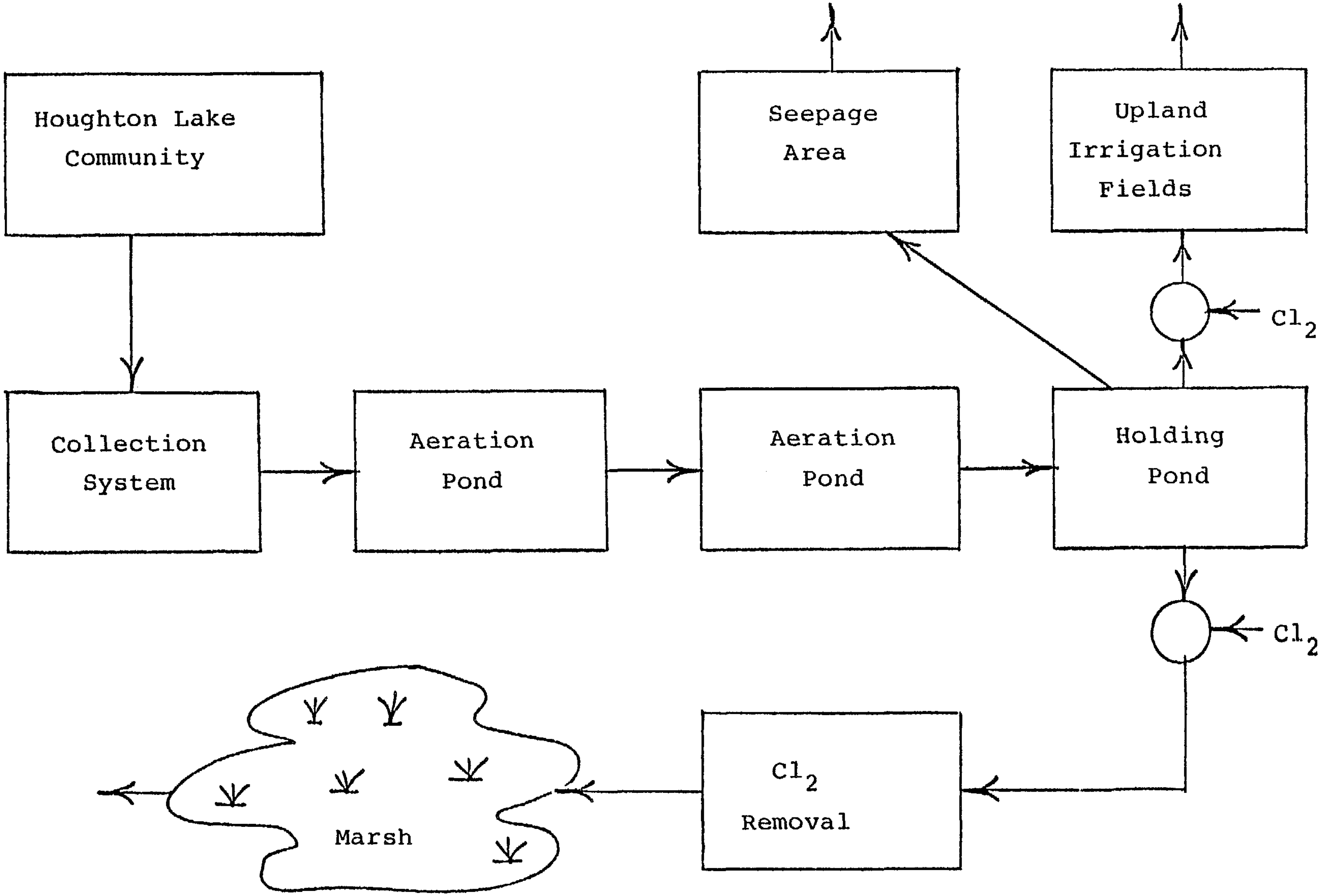


Figure 1. The Houghton Lake treatment system.

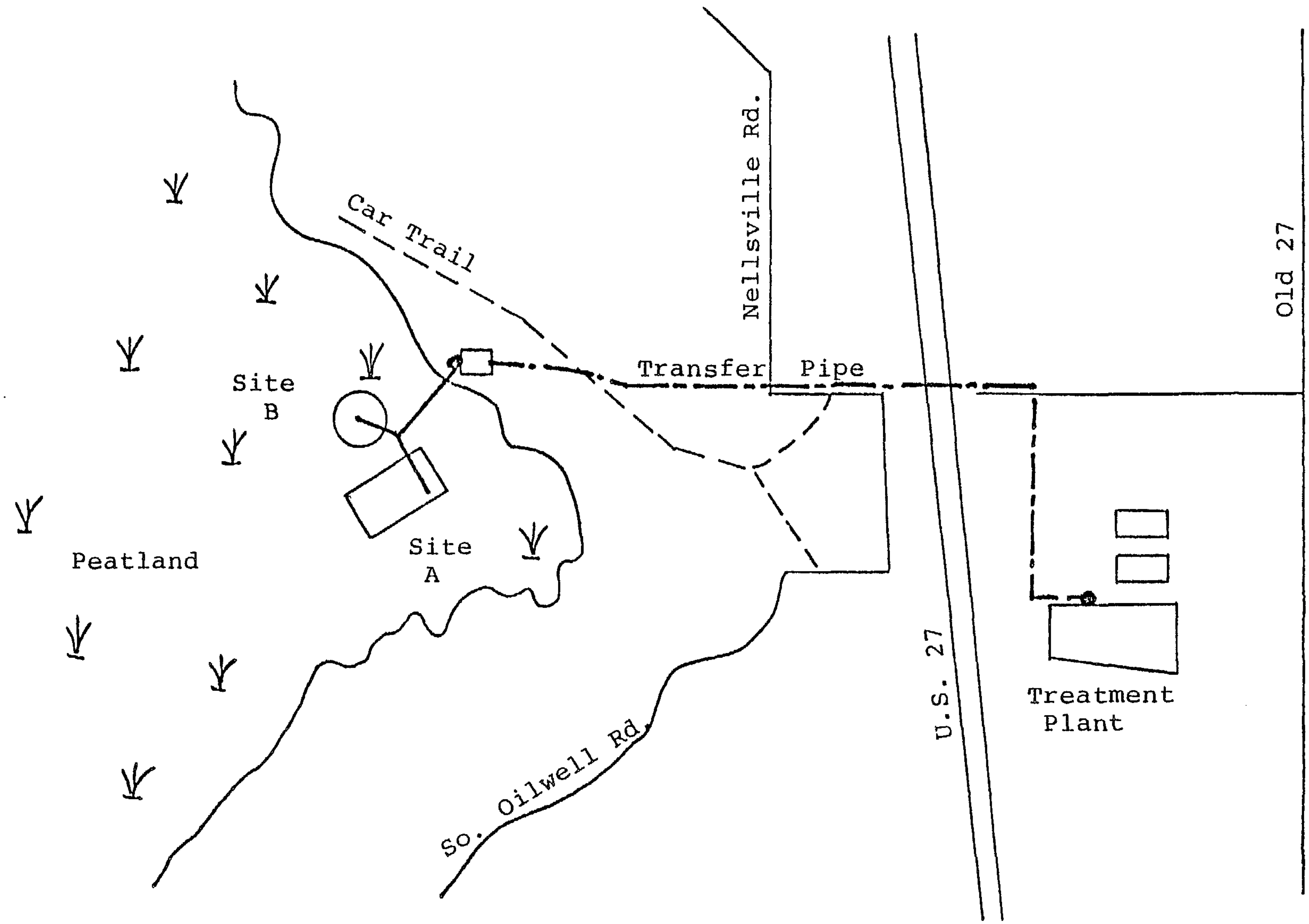
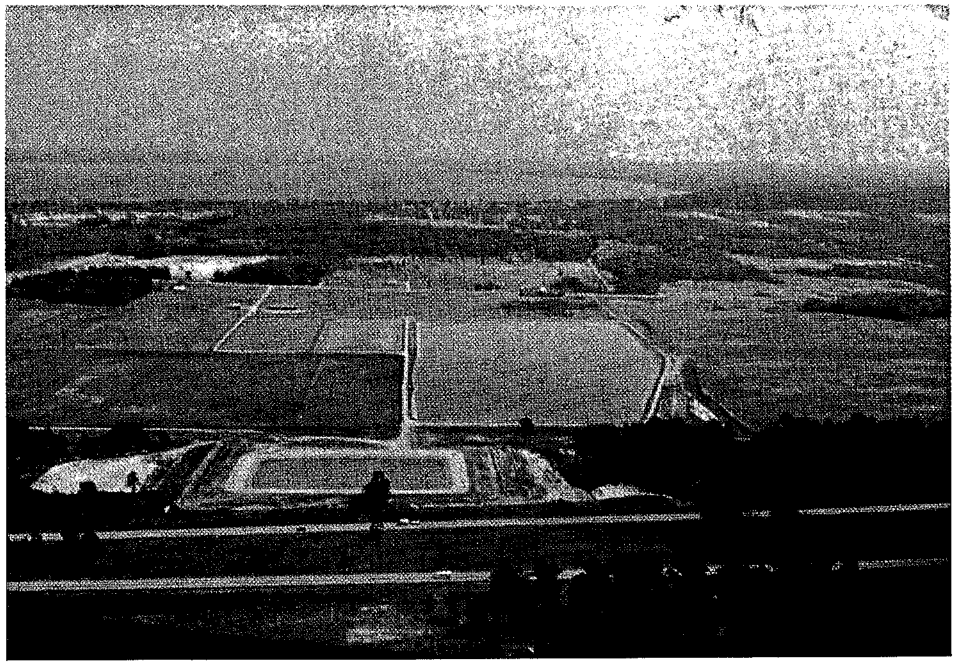


Figure 2. Flood irrigation system.



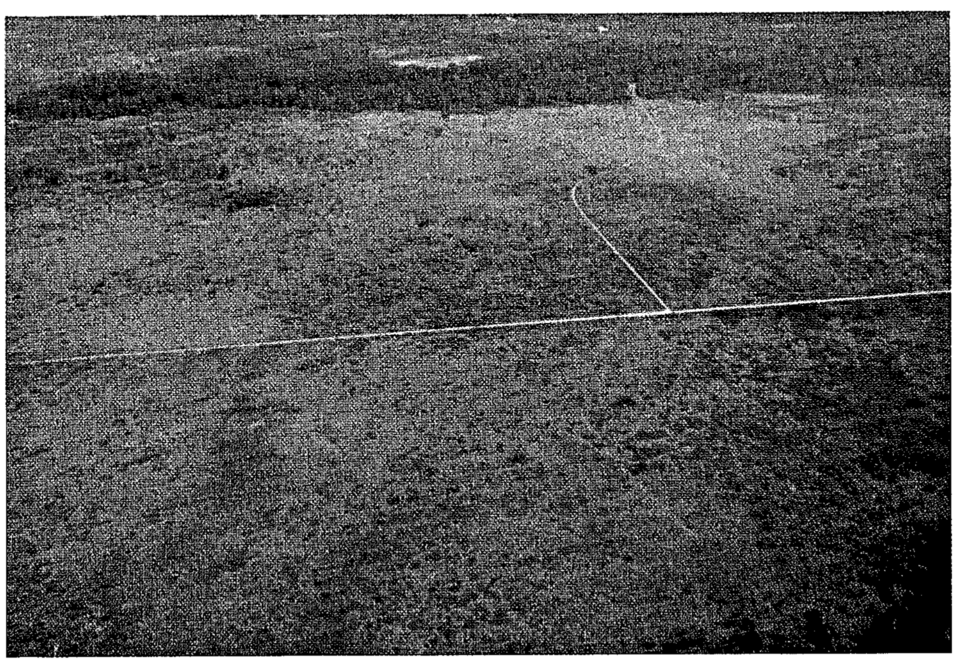
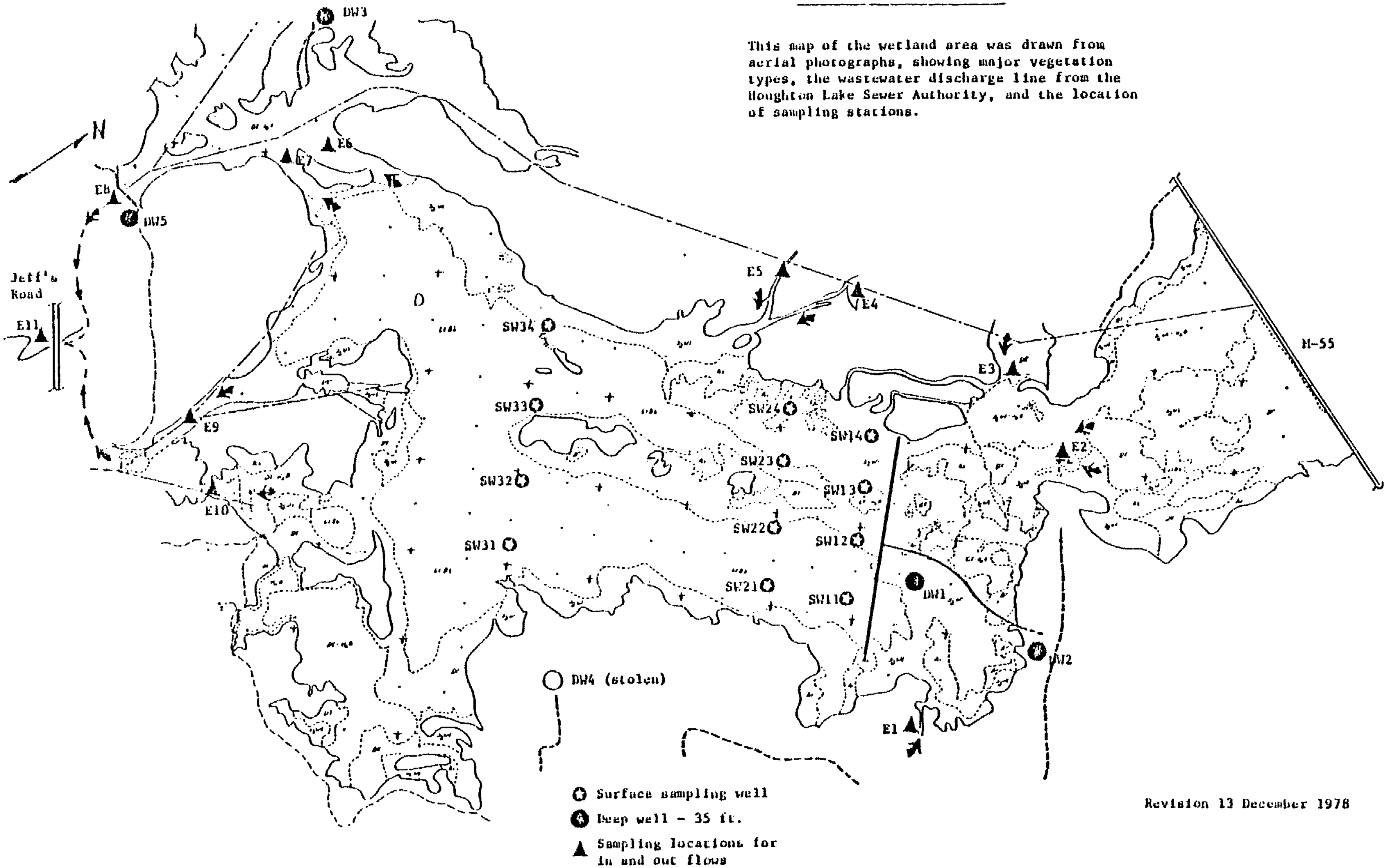


Figure 3. Aerial photographs of the wetland wastewater treatment system at Houghton Lake, Michigan.

Figure 4.
PORTER RANCH PEATLAND

This map of the wetland area was drawn from aerial photographs, showing major vegetation types, the wastewater discharge line from the Houghton Lake Sewer Authority, and the location of sampling stations.



Revision 13 December 1978

During the summer of 1977, 6.21 million gallons of secondarily treated sewage was pumped into the marsh during two periods of 44 and 23 days (June 3 - July 22; August 11 - September 3). This severe loading test was conducted to observe the effects on the peat soil and plant communities. 92,000 gpd was applied using a point discharge in site B.

An approximately flat area in the sedge meadow was chosen for Site B. A pipe support and walkway was constructed of untreated pine 2" x 4" in a ladder-like fashion. The walkway supported the 3" aluminum pipe above the peat soil and served as a working platform. The walkway protected the marsh from becoming channeled, since previous experience showed that walking trails left visible scars and produced a preferential path for water flow. The walkway was 50 m in length and terminated about 5 m from the discharge point.

During the winter of 1977-78, a large scale flood irrigation facility was constructed. A small dechlorination pond was added at the treatment plant, together with a 1700 gpm transfer pump. Treated wastewater from the dechlorination pond is pumped through a 12" diameter underground force line to the edge of the Porter Ranch peatland. There the transfer line surfaces and runs along a raised platform for a distance of about 2500 feet to the discharge area out in the wetland. The wastewater flowing in the transfer line is split between two halves of the discharge pipe which runs 1600 feet in each direction. Figure 3 is two aerial photographs, of the treatment plant, and of the transfer and discharge pipes looking down the Porter Ranch wetland (toward the east). The water is distributed evenly across the width of the peatland through small gated openings in the discharge pipe. Each of the 100 gates discharges approximately 16 gallons per minute, under typical conditions, and the water spreads slowly over the peatland. Figure 4 shows the location and overall layout of the wastewater disposal system.

The wetland treatment system was designed by Williams and Works, Inc., based upon research results obtained at the University of Michigan over the five years 1972-77. This facility has been operated by the Houghton Lake Sewer Authority (HLSA) during the summers of 1978 and 1979. Over 60 million gallons of secondarily treated wastewater were transferred to the peatland in 1978, and over 100 million gallons in 1979. In addition to continued research by the University of Michigan, a small research program is conducted by the HLSA, in addition to routine monitoring.

HYDROLOGY

The Houghton Lake peatland is a perched wetland - a peat bed of depth varying from 1-5 meters, underlain by a thin, possibly intermittent sand layer (10 cm), which rests

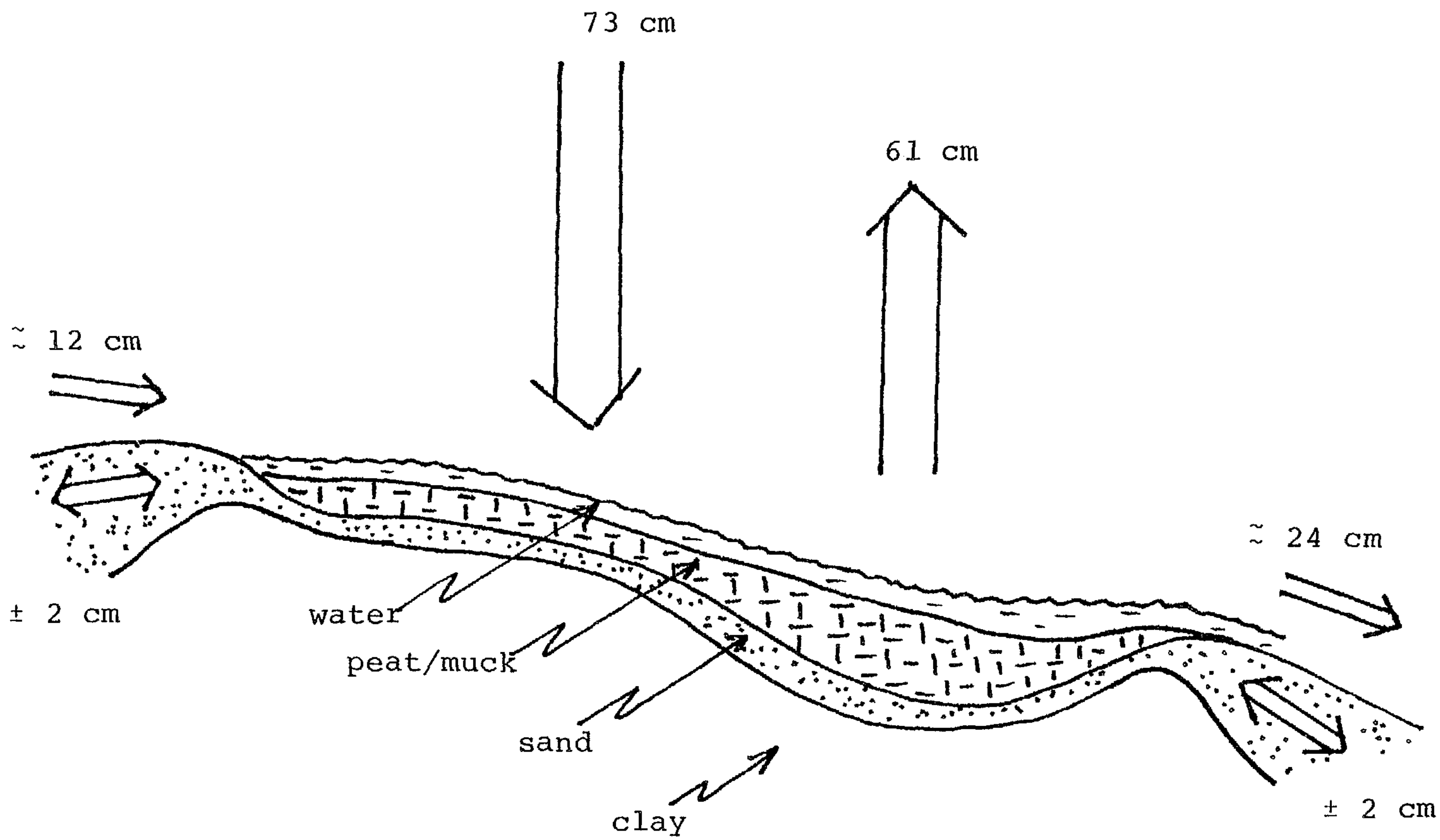


Figure 5. Approximate annual water budget for the Houghton Lake peatland.

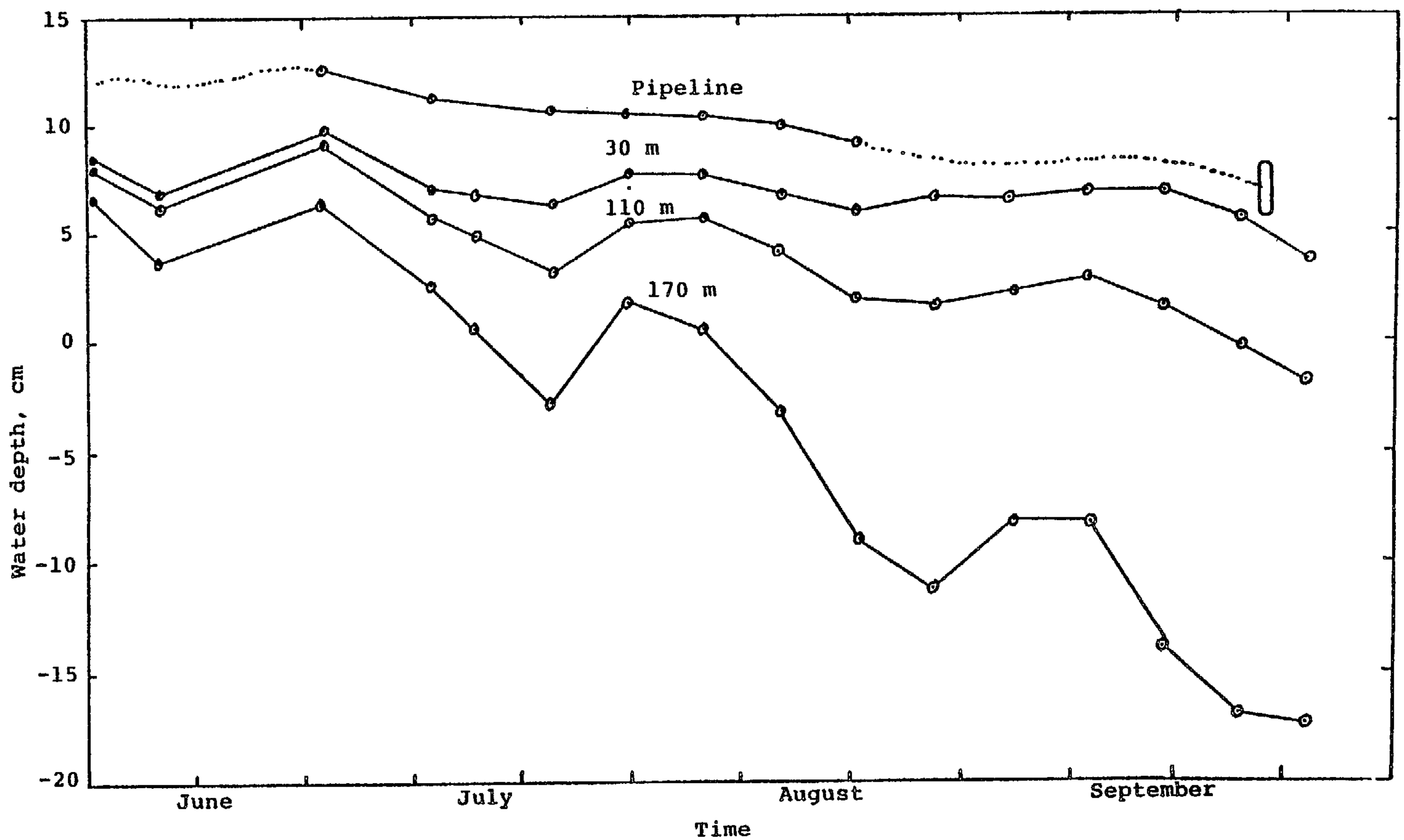


Figure 6. Water depth versus time at various distances from irrigation pipe, 1976.

on a thick clay layer. Thus, communication with deep aquifers is effectively blocked, and the hydrological process of interest involve surficial water storage and movement. Precipitation and evapotranspiration are the transfers from and to the atmosphere; surface and shallow subsurface flows represent transfers across the perimeter of the wetland. Redistribution of the surface and subsurface water pool in the peatland occurs via overland sheet flow, and soil suction mechanisms. Figure 5 illustrates a typical annual water budget for the entire wetland.

Water depths are typically in the 2-8 cm range, with -35 cm to +35 cm being the range over 1972-77. Surface runoff water moves into the peatland from the north and east and leaves through the west and south. Much of the water that goes through the peatland is surface flow and a heavy rain may temporarily raise water levels several centimeters on the peatland. The water level is generally highest in the spring and lowest in the late summer. Within any one year levels fluctuate depending on rainfall.

During 1975 and 1976, depths of the water mound were measured weekly at eight stations, and continuously at two stations equipped with recorders in 1976; and some detailed depth traverses were made. Water depths for 1976 are shown in Figure 6.

The 1977 point discharge resulted in a roughly circular mound of water of average depth 6-7 cm. Flow through this mound occurred radially, through approximately 1/3 of the total available surface area. The advance of a front of rhodamine dye showed water spreading radially outward from the point of discharge. Although the dye did not spread in perfectly concentric circles, there was a relatively even distribution of water flowing outward from the discharge point. The length of the start-up transient was on the order of 5-10 days, that of the shut-down was shorter - on the order of 1-3 days. Pumping established a maximum center depth 6-8 cm greater than depths located a long distance from the center of the ring.

The full scale studies of 1978-79 show similar results. The soil elevations in the discharge area are extremely flat, with a gentle slope toward the Dead-Horse Dam outlet. As a consequence, the addition of wastewater along the 3,200 feet of gated irrigation pipe gives rise to a mound of water with high points along the discharge pipe. Water movement within the discharge area was evaluated by transect measurements of water depth, flow rate and direction. Sixteen float gages and four Stevens Recorders provided a continuous record of water depth from the end of May through October, 1978; 29 staff gages and four recorders were used from March to September 1979.

Table 1 gives approximate water depths on three transects within the discharge area in 1978. It can be seen that the water sheet thins in the downgradient direction, and has variable depth as one proceeds toward the upgradient

Table 1. Approximate Water Depths During Wastewater Discharge. Transects on August 30, 1978.

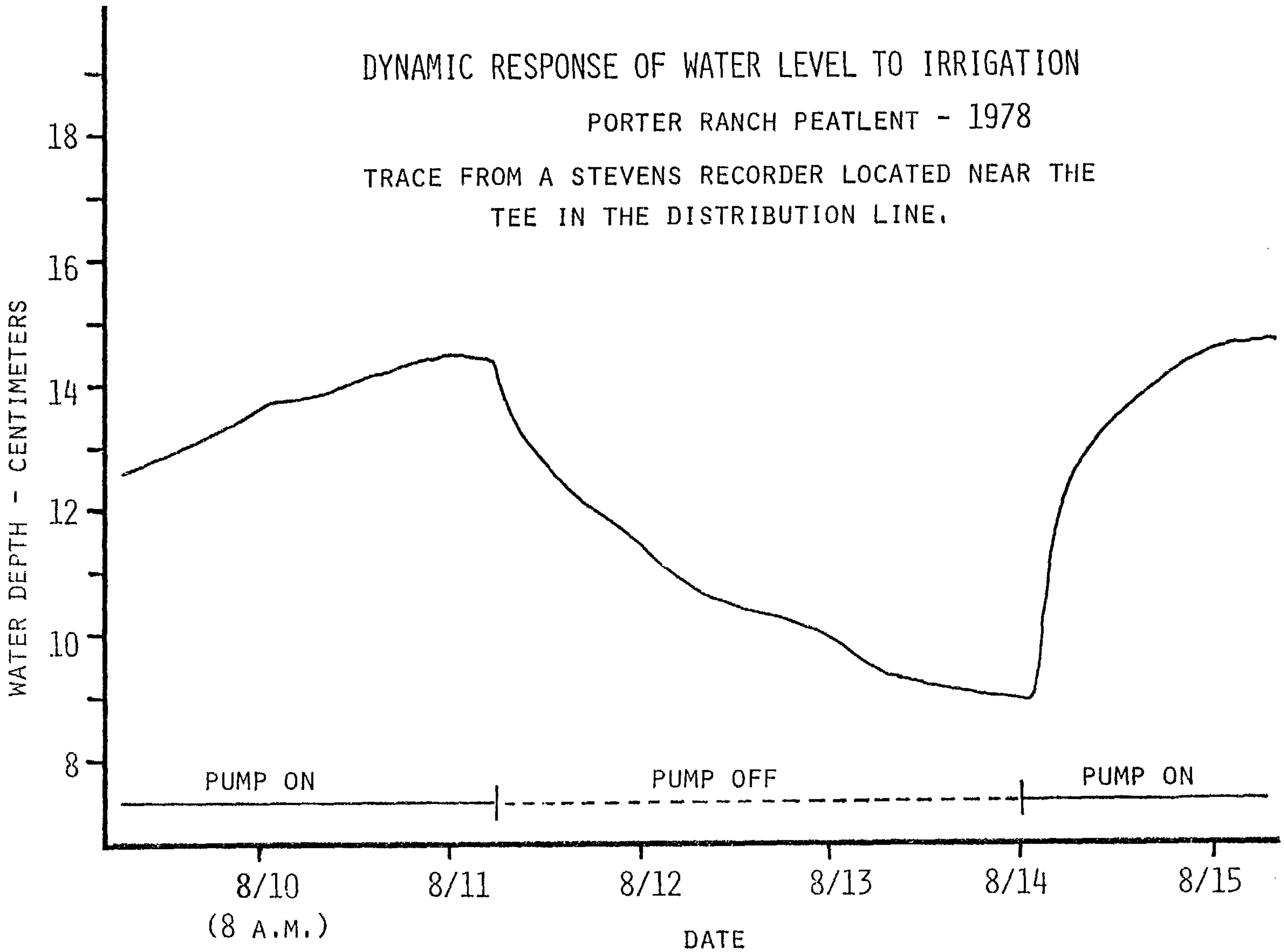
Meters from Discharge Downgrade	Leatherleaf[1] Transect	Sedge-Willow[2] Transect	Cattail[3] Transect
0	7.0 cm	13.8 cm	7.1 cm
+ 20	7.0 cm	10.5 cm	18.3 cm
+ 50	3.4 cm	7.9 cm	28.6 cm
+100	6.3 cm	8.2 cm	30.0 cm
+200	2.8 cm	8.6 cm	29.0 cm
+300	-	5.7 cm	6.3 cm
+400	-	6.1 cm	-
+500	-	5.2 cm	-
Toward Shore			
- 20	6.7 cm	9.7 cm	7.9 cm
- 50	9.3 cm	11.8 cm	9.0 cm
-100	5.9 cm	9.8 cm	17.4 cm
-200	3.6 cm	9.0 cm	5.8 cm
-300	-	10.0 cm	4.3 cm

(1) Located near SW 11 on Figure 4.

(2) Located near SW 12 on Figure 4.

(3) Located near SW 13 on Figure 4.

Figure 7.


DYNAMIC RESPONSE OF WATER LEVEL TO IRRIGATION
PORTER RANCH PEATLENT - 1978
TRACE FROM A STEVENS RECORDER LOCATED NEAR THE TEE IN THE DISTRIBUTION LINE.
WATER DEPTH - CENTIMETERS
18
16
14
12
10
8
PUMP ON
PUMP OFF
PUMP ON
8/10
(8 A.M.)
8/11
8/12
8/13
8/14
8/15
DATE

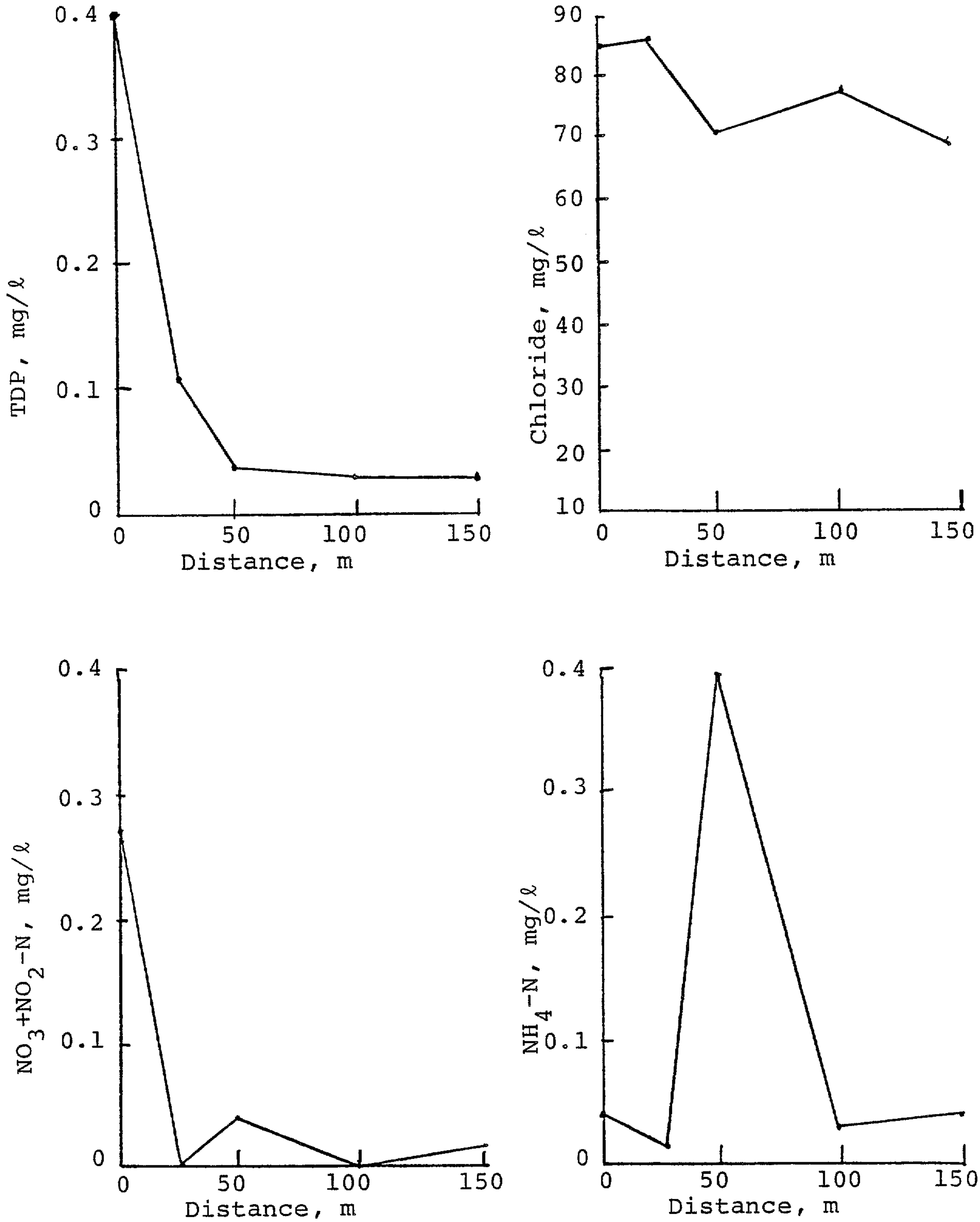


Figure 8. Surface water parameters within the treatment area on July 30, 1976.

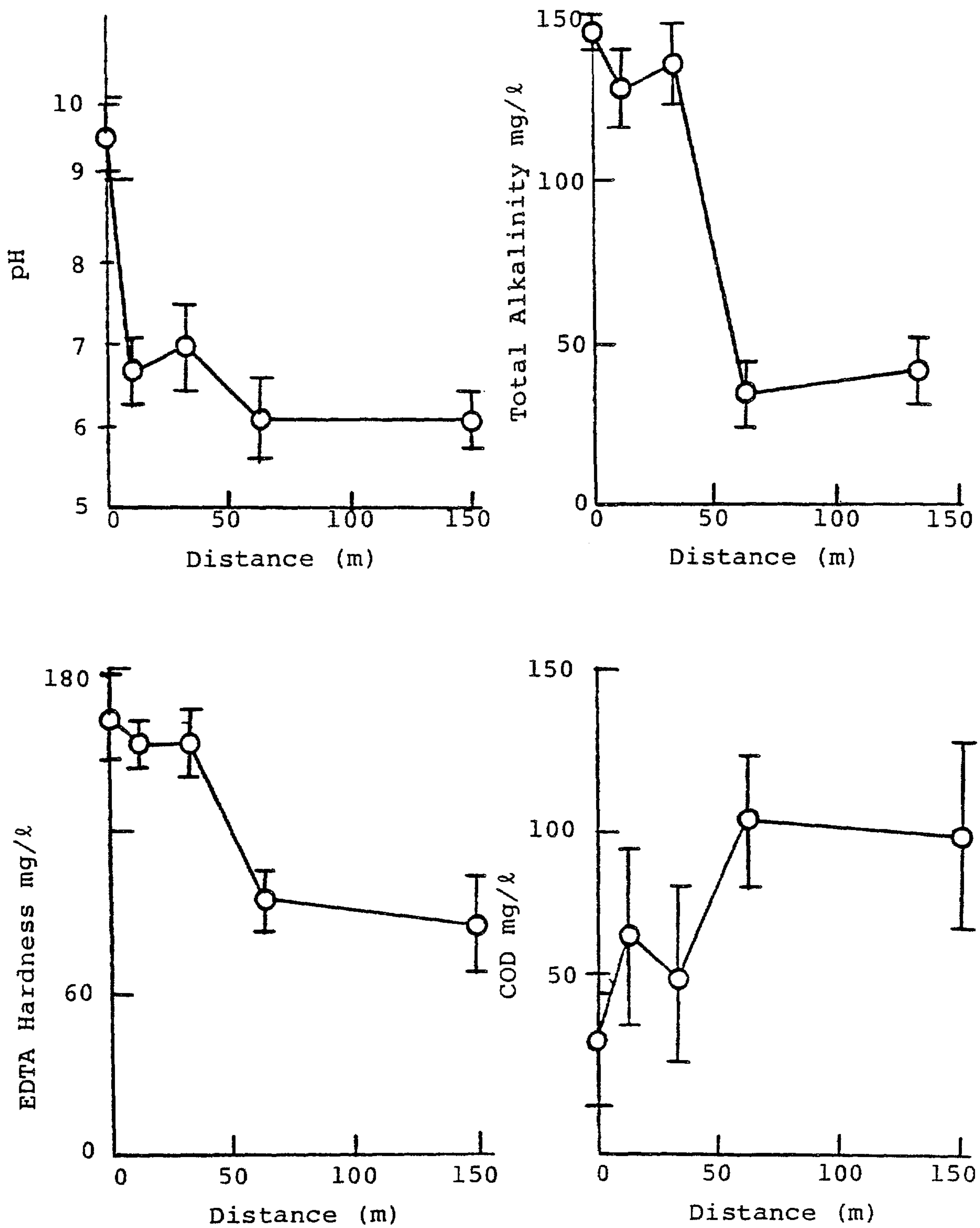


Figure 9. Surface water parameters within the treatment area averaged from June to August. Samples were collected weekly.

shore. The cattail transect was taken intentionally in one of the isolated depressions within the wetland, leading to the largest observed water depths at any point in the irrigation area.

Surface water velocities ranged from 20-60 cm/min for the sedge-willow cover type on August 30. These data are subject to extreme variability, and reflect the fact that only a small fraction of the peatland surface is available for flow. This information, when coupled with the depth information, indicates a relatively uniform moving sheet of water proceeding through a wide variety of channels and clumps on its course downgradient through the peatland.

The time response of water depth to the initiation of or cessation of pumping is shown in Figure 7. When the pump was turned off on August 11, there was an immediate decline in water levels near the pipeline, at approximately 3 cm per day. When pumping commenced on August 14 there was an immediate rise in water level to the old level established by prior pumping, with the entire transient occurring within the space of one day. Thus, the transient response of the deepest water area, at the irrigation pipe, is very fast. The transients at remoter locations are considerably slower.

WATER QUALITY

The shallow tea-colored waters of this peatland are normally acidic, and laden with dissolved organic material. The background pH is in the range of 5-7 during summer months. Conductivity is also low for the natural wetland, with values in the vicinity of 280 μmho/cm. With respect to many water quality parameters, the wetland waters contain relatively small amounts of dissolved material. Typical background data for different depths and cover types are given in Table 2. Subsurface interstitial water has a somewhat elevated nitrogen content compared to surface waters. There are also notable seasonal changes in some dissolved materials. All data display a rather large variability, which appears to be characteristic of this wetland.

During the pilot scale treatment of effluent in 1975, relatively clean water was discharged in late summer. Concentrations of dissolved constituents in surface waters, and 15 and 45 cm below ground, are shown in Table 3. The data show no influence of the effluent on nutrient concentrations in water samples at any distance from the pipeline.

Typical 1976 patterns of surface water chemistry with distance from the effluent discharge are shown in Figures 8 and 9. Chloride concentrations were comparatively high within the treatment site primarily as a result of the effluent discharge. Nitrate-nitrite-N was consistently removed from the effluent within 30 m of the discharge

Table 2. Dissolved Nutrient Status in Several Plant Communities. Undisturbed Houghton Lake Peatland, 1973. (mg/ℓ) Means over depth and time. Second number is standard deviation.

	Leatherleaf-Bog Birch	Sedge-Willow	Mixed Deeper Water Areas	1972 Rain
Approximate No. of Samples	230	115	90	70
NH_4-N	1.9±1.7	1.1±0.8	1.5±1.4	0.29
NO_3+NO_2-N	0.066±0.035	0.056±0.023	0.060±0.038	0.45
TDP	0.066	0.077	0.098	0.040
Ca	21±8	31±12	40±26	
Mg	4.0±1.6	5.9±2.3	7.4±4.2	
Na	5.6±4.2	6.4±5.0	5.2±4.3	
SiO_2	1.4±1.2	1.3±1.1	2.0±1.8	
Cl	29±21	27±21	20±21	

Table 3. Effluent and Wetland Water Quality on August 22, 1975 in the Wetland Wastewater Treatment Area.

Distance from source (m)	NH_4-N	NO_3+NO_2-N	TDP	Cl	K	Na	Ca	Mg
	mg/ℓ							
Surface Samples								
0	0.70	0.9	0.33	64	0.9	12	8	4
30	0.47	0.23	0.04	39	0.5	10	8	3
110	0.23	0.05	0.03	16	0.5	8	10	2
170	0.50	0.13	0.05	35	0.3	6	11	2
15 cm deep								
0	*	*	*	*	*	*	*	*
30	0.52	0.20	0.04	21	0.7	6	27	4
110	0.30	0.06	0.03	22	0.1	7	20	4
170	0.42	0.18	0.04	51	0.3	6	8	1
45 cm deep								
0	*	*	*	*	*	*	*	*
30	0.75	0.25	0.04	16	0.2	3	19	4
110	0.21	0.11	0.08	63	0.4	7	19	4
170	0.81	0.15	0.21	43	1.9	11	30	6

* Not sampled.

during the entire pumping schedule. NH_4-N concentrations were higher at some stations in the treatment area than in the effluent. Concentrations of total dissolved P decreased sharply with distance through most of the discharge period, although TDP concentrations in samples 30 m from the pipeline tended to increase through the summer.

Total alkalinity, hardness, and pH decreased rapidly with distance from the discharge source, while COD increased. The increase in COD was due to high concentrations of dissolved organic matter in wetland surface waters.

Heavy metal (Pb, Cu, Ni and B) concentrations were below the detection limits of our equipment. June, July, and August samples from the effluent and several stations in the wetland were less than 1.0 mg/ℓ for Pb, 0.50 mg/ℓ for Cu and Ni, and .05 mg/ℓ for Zn.

The 1977 sampling stations were established in 6 concentric circles around the point discharge. Nutrient removal was effective with background concentrations being reached at 80 meters for TDP and at 30 meters for NO_3-N. Nutrient mass balances for the point source irrigation were calculated using water chemistry and hydrologic information. Dissolved nitrogen storage within the first 40 meters was 82%; that for TDP was 67%.

Suspendable solids varied erratically with distance from the discharge. Although it is difficult to accurately sample the marsh waters for the weight parameter, the color changes and chemical changes exhibited by the suspendable solids with distance were obvious. The water velocity is nearly inversely proportional to the square of the radius in this circular geometry, leading to a sedimentation profile which changes dramatically with radial distance. Solid material could be entrained close to the discharge, and redeposited later. Some of these solids were clearly algae, as indicated by the green color of the sediments.

The full scale system was studied in similar detail in 1978 and 1979.

Transects were made throughout, and after the pumping season, which consisted of collection and analysis of water samples at regular intervals, beginning at the discharge pipe and extending up to 500 meters in each direction. Transects were made in each of the three principal cover types: sedge-willow, leatherleaf and cattail. Samples were also taken at some sites at 15 cm and 45 cm depths. Measurements of conductivity, pH, dissolved oxygen and redox potential were also made, in the field, co-incident with the collection of transect samples. Peat samples were collected, and the interstitial water separated and analysed.

Water samples were typically analysed for pH, conductivity, ammonium-N, nitrate-N, chloride, total dissolved phosphorus and various metallic cations. Ammonium, nitrate and chloride levels were measured using specific ion

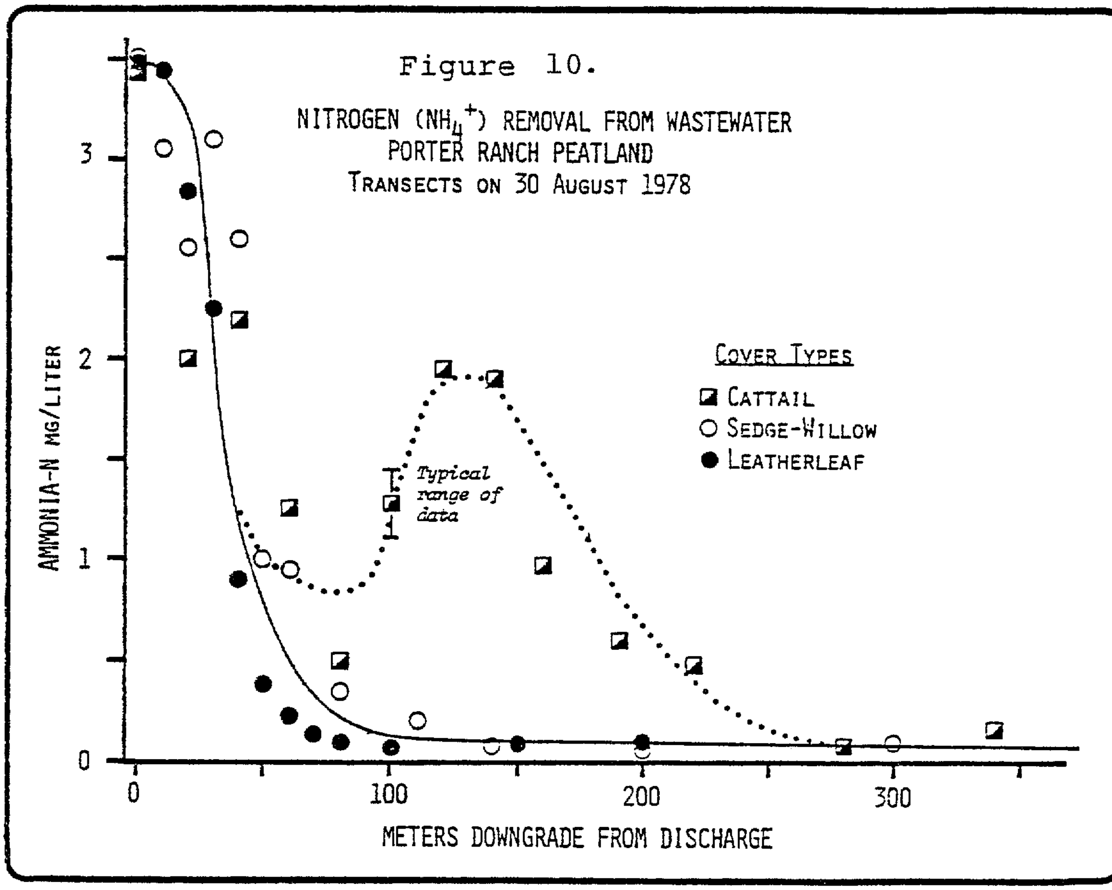


Figure 10.
NITROGEN (NH_4^+) REMOVAL FROM WASTEWATER
PORTER RANCH PEATLAND
TRANSECTS ON 30 AUGUST 1978
AMMONIA-N MG/LITER
METERS DOWNGRADE FROM DISCHARGE
COVER TYPES
CATTAIL
SEDGE-WILLOW
LEATHERLEAF
Typical range of data
0
1
2
3
0
100
200
300

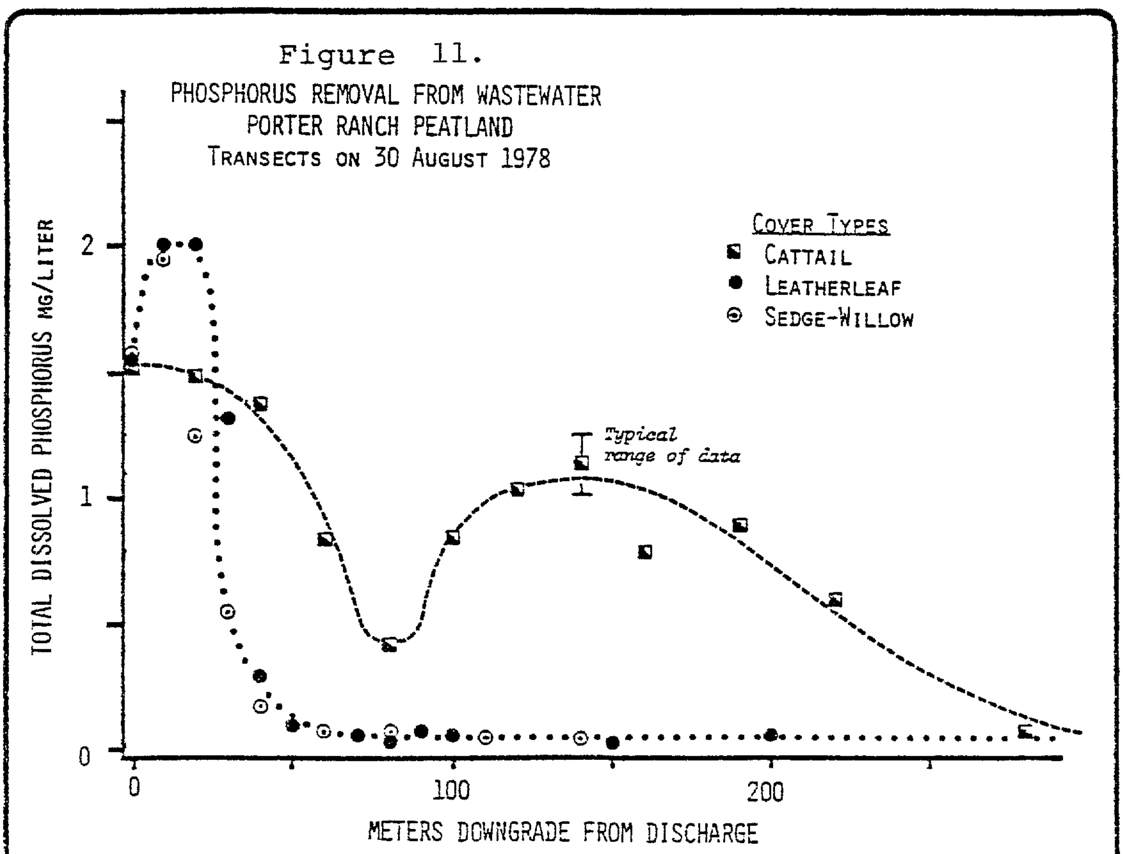


Figure 11.
PHOSPHORUS REMOVAL FROM WASTEWATER
PORTER RANCH PEATLAND
TRANSECTS ON 30 AUGUST 1978
TOTAL DISSOLVED PHOSPHORUS MG/LITER
METERS DOWNGRADE FROM DISCHARGE
COVER TYPES
CATTAIL
LEATHERLEAF
SEDGE-WILLOW
Typical range of data
0
1
2
0
100
200

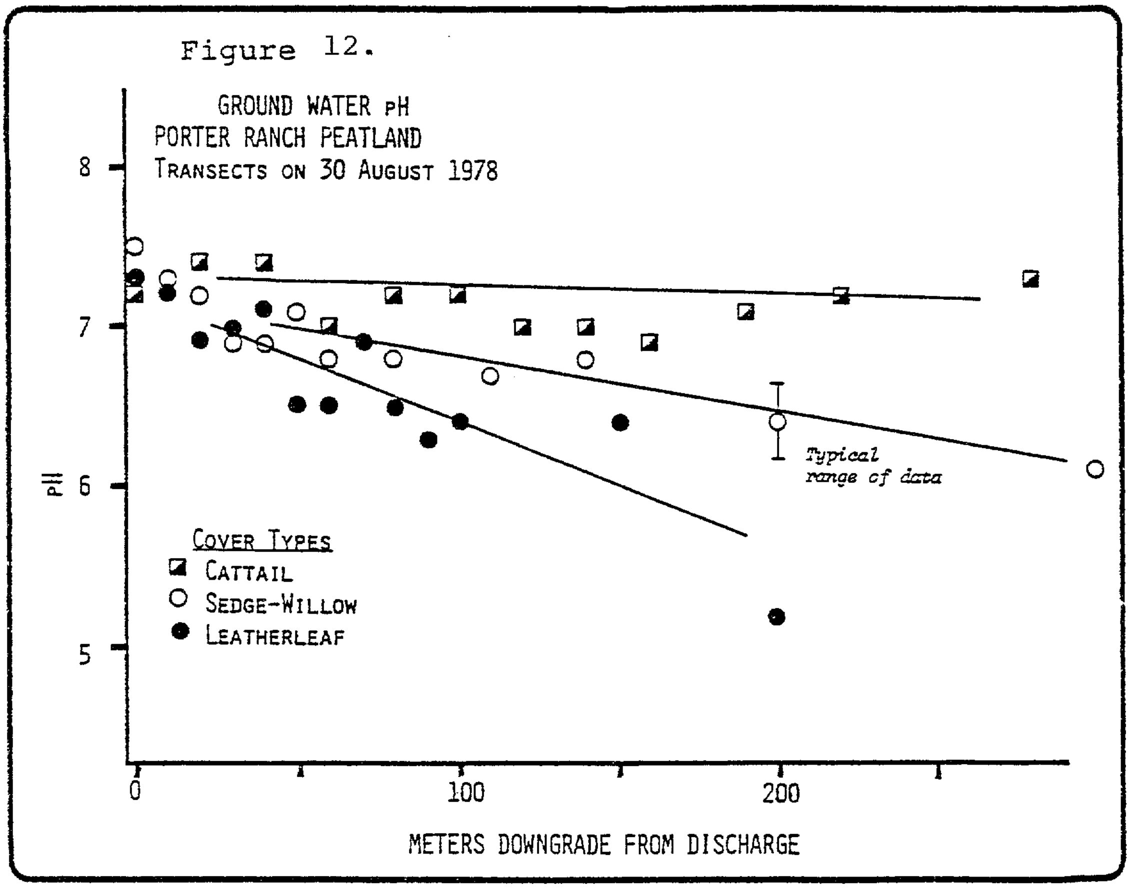


Figure 12.
GROUND WATER pH
PORTER RANCH PEATLAND
TRANSECTS ON 30 AUGUST 1978
8
7
pH 6
5
Typical range of data
COVER TYPES
CATTAIL
SEDGE-WILLOW
LEATHERLEAF
0
100
200
METERS DOWNGRADE FROM DISCHARGE

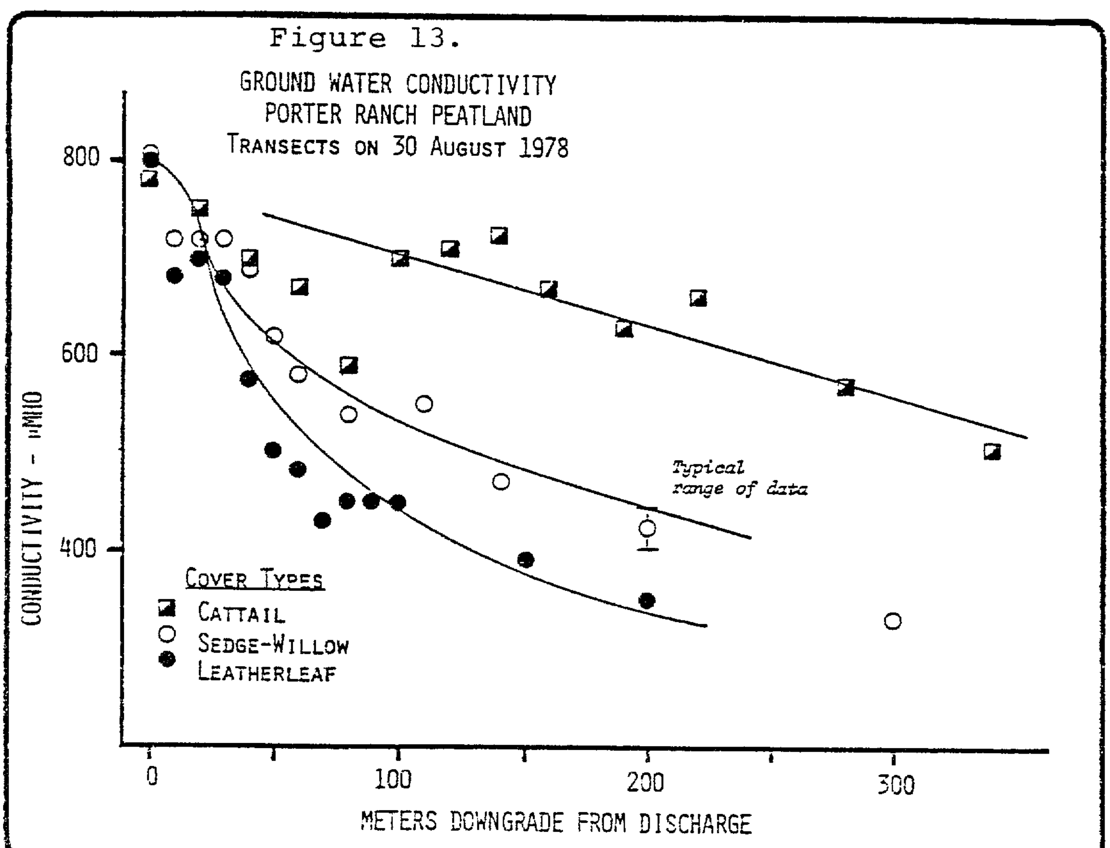


Figure 13.
GROUND WATER CONDUCTIVITY
PORTER RANCH PEATLAND
TRANSECTS ON 30 AUGUST 1978
800
600
400
CONDUCTIVITY - μMHO
Typical range of data
COVER TYPES
CATTAIL
SEDGE-WILLOW
LEATHERLEAF
0
100
200
300
METERS DOWNGRADE FROM DISCHARGE

electrodes. Total dissolved phosphorus (TDP) was determined using a colorimetric (ascorbic acid) technique, after digestion of the filtered water sample by sulfuric acid and ammonium persulfate. Atomic absorption spectroscopy was employed to determine concentrations of sodium, magnesium, copper, iron and nickel in solution. A comparison of surface water and interstitial water nutrient status is given in Table 4.

Data from transects of the three cover types on August 30th are presented in Figures 10 through 13. The declines of dissolved nutrients are quite similar to those in the pilot-scale experiments, except for the deep water cattail cover type. Comparable results have been obtained in 1979.

Table 5 shows neutron activation analyses of discharge and background water samples. Within the scope of this analysis, only sodium displayed elevated levels at the discharge. Atomic absorption analysis shows magnesium is also higher in the discharge area.

SOILS

The peat deposits in this wetland range from 0.5 to 3.0 meters thick. They contain wood fragments, and occasional deposits of sand and clay. Chemical analyses of Houghton muck, a histosol, reveals that the highest levels of carbon and soluble phosphorus are found in the upper layers of the profile. Acidity and potassium in both cover types decrease with depth. Higher carbon but lower phosphorus and potassium levels are found in the leatherleaf-bog birch cover type. The chemical composition of the Houghton muck closely follows the characteristics of organic soils reported by many others.

Table 6 compares the chemical composition of peat samples at two distances from the 1976 effluent pilot discharge. Total P, Na, and Mg were significantly ($P < .05$) higher in peat samples from the 0-5 cm depth 3 m from the discharge compared to 30 m. Total N, K, and Ca were also higher in peat samples from the 0-5 cm depth near the pipeline but the differences were not statistically significant.

Soil samples were obtained in 1978 and 1979 along transects perpendicular to the pipeline. Each core was divided into three segments (0-5 cm, 5-10 cm, and 10-20 cm) and analyzed for total N and P. Table 7 shows no probable increase in P or N within the surface horizon.

VEGETATION

The vegetation in the peatland is typical of northern peatland systems. The two dominant cover types, sedge-willow (*Carex* spp. and *Salix* spp.) and leatherleaf-bog birch (*Chamaedaphne calyculata* (L.) Moench. and *Betula pumila* L.),

Table 4. Nutrient Analysis of Surface and Interstitial Water from Top 10 cm of Litter and Peat Soil, Houghton Lake Wetland. Sedge-Willow transect, 30 August 1978.

Distance from Discharge (m)	$N-NH_4$ mg/ℓ		Total Dissolved Phosphorus mg/ℓ	
	Interstitial	Surface	Interstitial	Surface
0	35	3.8	1.25	1.58
10	16.8	3.1	0.67	1.95
20	24.0	2.6	2.96	1.25
30	32.4	2.8	2.59	0.55
40	24.3	2.6	0.17	0.17
50	16.8	1.0	0.11	0.09
60	15.5	0.94	0.06	0.07
80	14.8	0.35	0.08	0.065
110	12.1	0.21	0.09	0.055
140	9.4	0.09	0.38	0.055
200	14.2	0.07	0.08	0.04
300	13.1	0.12	0.09	0.055
400	9.8	0.18	0.07	0.035
500	12.1	0.09	0.07	0.06

Note: Soil samples stored frozen before removing interstitial water.

Table 5. Multi-element Analysis by Neutron Activation Analysis. Water Samples Taken August 29, 1978 in Porter Ranch Peatland.

Element	Wastewater Inflow at pipe mg/ℓ	Background Water Sample (500 m downgrade) mg/ℓ
Sm	< 0.0027	< 0.0027
Lu	< 0.0016	< 0.0017
U	< 0.0336	< 0.0328
Th	< 0.0173	< 0.0177
Cd	< 0.2458	< 0.2533
Au	< 0.0014	< 0.0015
Ba	< 3.5962	< 3.4246
Nd	< 0.5728	< 0.6625
As	< 0.0826	< 0.0747
Br	0.2065 ±0.0112	0.2253 ±0.0112
Na	62.9354 ±2.0204	26.1746 ±1.3751
La	< 0.0068	0.0348 ±0.0028
Ce	< 0.0380	< 0.0366
Se	< 0.0304	< 0.0321
Hg	0.0244 ±0.0033	0.0339 ±0.0034
Cr	< 0.0456	< 0.0683
Hf	< 0.0030	< 0.0033
Ag	< 0.0154	< 0.0188
Cs	< 0.0039	< 0.0054
Ni	< 0.3409	< 0.5031
Tb	< 0.0021	< 0.0034
Sc	< 0.0004	0.0006 ±0.0001
Rb	< 0.1399	< 0.1573
Fe	3.1278 ±0.6840	< 3.0348
Zn	0.2799 ±0.0394	6.9600 ±0.1249
Ta	< 0.0031	< 0.0037
Co	0.0034 ±0.0008	0.0069 ±0.0009
Eu	< 0.0015	< 0.0017
Sb	< 0.0083	< 0.0039

Table 6. Total Element Concentrations in Peat Samples From the Sedge-Willow Cover Type at Distances From the Discharge Site. Samples Were Collected in Late June 1976. Values in Parentheses are Standard Errors of the Mean.

Distance from Effluent Source and Depth of Sample	N %	P %	K %	Na µg/g	Mg %	Ca %
3 m from Source						
0-5 cm	2.55 (.08)*	0.13 (.01)	0.10 (.005)	210 (36)	0.17 (.01)	1.30 (.06)
5-10 cm	2.85 (.17)	0.11 (.007)	0.07 (.003)	80 (36)	0.13 (.01)	1.32 (.10)
10-15 cm	2.80 (.03)	0.08 (.006)	0.06 (.003)	48 (18)	0.12 (.007)	1.66 (.05)
30 m from Source						
0-5 cm	2.32 (.09)	0.10 (.01)	0.09 (.004)	100 (13)	0.14 (.003)	1.19 (.04)
5-10 cm	2.05 (.38)	0.08 (.01)	0.08 (.01)	10 (11)	0.13 (.01)	1.12 (.19)
10-15 cm	2.39 (.19)	0.07 (.01)	0.07 (.01)	8 (3)	0.14 (.01)	1.53 (.17)

* n=4

Table 7. Nutrient Analyses of Soil Samples at Various Distances from the Wastewater Discharge, Full Scale Operation, Sedge-Willow Community. (% DW)

Phosphorus

Core Section, cm		Distance, m		
		2.5	30	60
1978	0-5	0.14	0.14	0.13
	5-10	0.11	0.12	0.10
	10-15	0.07	0.08	0.08
1979	0-5	0.13	0.13	-
	5-10	0.12	0.11	-
	10-15	0.07	0.11	-
	15-20	0.08	0.06	-

Nitrogen

1978	0-5	2.38	2.15	2.54
	5-10	2.83	2.60	2.43
	10-20	2.55	2.44	2.90
1979	0-5	2.09	1.88	-
	5-10	2.13	2.05	-
	10-15	2.21	2.34	-
	15-20	2.24	1.97	-

account for about 88% of the peatland. Open water areas (5%) provide the main habitats for a variety of aquatic plants such as Potamogeton spp. and Utricularia spp. Cattail (Typha latifolia L.) stands are closely associated with depressions in the peatland and occupy 2% of the total area. Alder (Alnus rugosa (Duroi) Spreng.) is found primarily around the edges of the peatland and accounts for 3% of the ground cover. Aspen (Populus tremuloides Michaux.), the primary upland cover, is occasionally found in small stands in the peatland and these patches make up 2% of the total area. Irrigation sites A and B were primarily in the sedge-willow community, but the full scale project encompasses all cover types.

Data from earlier research on nutrient additions indicated potential uptake of phosphorus and nitrogen by the vegetative communities, including litter. The vegetation in August 1975 was studied 30 m and 150 m from the pipeline and in a control area outside the experimental area. The mass of live Carex spp. both above and below ground was not significantly different among sampling locations. Furthermore, although considerable variation existed, the concentration of N, P, Ca, Mg, K, and Na was not significantly higher in samples of Carex spp. leaves, Carex spp. roots, surface litter and standing dead plant material from experimental areas compared to control areas.

The amounts of total live, standing dead, and litter were not significantly different ($P < .05$) among sample locations in 1976. Foliar N and P concentrations of plant species near the discharge area were higher near the pipeline compared to concentrations measured in 1973 and 1974. Nitrogen concentrations in live, dead, or litter compartments were not significantly different among sampling locations. Phosphorus concentrations, however, were higher in litter and Carex spp. leaves nearer the pipeline than other areas. P concentrations in standing dead compartments did not appear to increase as did the live and litter compartments.

While biomass measurements were not significantly different, cattail (Typha latifolia) dimensions were larger in the discharge area. Cattail maximum height averaged 170 ± 25.6 cm ($X \pm s$; $n = 60$) within 6 m of the discharge area compared to 145 ± 24.2 cm approximately 50 m from the discharge. Circumference of the shoot base was also significantly different with mean values of 13.3 ± 3.7 and 9.4 ± 2.95 within 6 m and 50 m of the discharge area, respectively.

An additional indication of the response of the vegetation to the wastewater discharge was chlorophyll *a* content of sedge leaves. Sedges near (6 m) the pipeline appeared greener compared to sedges further away. Chlorophyll *a* concentrations were 110 mg/g fresh weight of tissue compared to 80 mg/g fresh weight away from the discharge area.

In the full scale project, above ground standing crop in the sedge community near the pipeline increased in response to the nutrient additions. Measurements taken in 1978 after cessation of effluent discharge showed that the total above ground standing crop was approximately twice as much at the pipeline than at stations 90 m from the source of wastewater. In 1979, increased standing crops were prevalent out to and beyond 90 m.

Dramatic changes in species composition have not appeared in the early years of the discharge, but baseline data has been taken for future reference.

A zone of foliar N and P enhancement has developed, extending to and beyond 90 meters from the pipeline. The mass of N and P in the above ground standing crop decreased with distance in 1978, but not in 1979. (Table 8.)

Nitrogen and phosphorus in the litter were measured as percent of dry weight. The data in Table 9 shows increased P near the discharge in 1978, but not increased N. In 1979, the zone of increased P extended to and beyond 100 m.

ALGAE

The response of the algal community of the Porter Ranch Wetland to nutrient enrichment was studied by 3 methods during the summer of 1976. Continuous flow bioassay chambers were designed and constructed to measure <u>in situ</u> increases of <u>Cladophora</u> sp. dry weight and to provide continuous monitoring for potential toxic discharges. Aquatic community metabolism was measured by the examination of diurnal oxygen fluctuations. Productivity estimations for epiphytic algae were made by determination of Chlorophyll <u>a</u> concentrations on artificial substrates of known surface area. This method was also used to determine the effects of increasing water depth in epiphytic algal production.

Nutrient uptake by the algal community was estimated by calculation procedures based on measurements of nutrient concentrations of the bioassay algae, coupled with bioassay growth rate estimates.

Growth rate of the bioassay algae at the pipeline (nutrient enriched) study site was 2656 mg dry wt m^{-2} day^{-1} for the period between June 12, 1976 and July 3, 1976. Growth rates in the control area were 85 mg dry wt m^{-2} day^{-1}, for the same time. The standing crop of <u>Cladophora</u> at the enrichment site was 41 g dry wt m^{-2} on July 7, 1976. On the same date, the standing crop of Cladophora at the control site was 5 g dry wt m^{-2}.

Aquatic community productivity as measured by the dissolved oxygen method were an average of 225% higher in the discharge site, compared to the control site. Dissolved oxygen values in excess of 250% saturation were commonly recorded in the surface water of the discharge

Table 8. Standing Crop Biomass and Nutrient Status in the Sedge-Willow Community at Various Distances from the Discharge. Ranges of Data Over Triplicates are Typically ±30%.

Distance	Biomass gm DW/m^2		Nitrogen gm/m^2		Phosphorus gm/m^2	
	9-21-78	8-29-79	9-21-78	8-29-79	9-21-78	8-29-79
2.5	525	556	10.6	10.2	1.7	2.2
30	380	620	6.2	9.5	1.3	1.7
60	190	-	2.8	-	0.6	-
90	270	712	3.9	10.8	0.4	1.92

Table 9. Nutrient Concentrations in Litter, Sedge-Willow Community. (% DW)

Distance from Discharge, m	Nitrogen 8/30/78	Nitrogen 8/29/79	Phosphorus 8/30/78	Phosphorus 8/29/79
0	1.73	2.10	0.22	0.26
30	2.20	2.40	0.22	0.31
60	1.87	-	0.10	-
80	2.58	-	0.11	-
100	-	2.25	-	0.52
110	2.38	-	0.11	-

site. In the late summer, simultaneous dissolved oxygen consumption in full sunlight, pH values in excess of 10.0 and dissolved O_2 supersaturation strongly suggest that photorespiration of the algal community plays an important part in the seasonal pattern of algal productivity under conditions of nutrient enrichment.

There was no significant difference in chlorophyll a concentrations at study sites in the wetland.

Nutrient uptake rates of the bioassay algae were 12 mg P m^{-2} day^{-1} and 55 mg N m^{-2} day^{-1}. End of the growing season values for total nitrogen and phosphorus content of the bioassay algae were 4.3 g N m^{-2} and 0.96 g P m^{-2}, respectively.

PATHOGENS

A variety of surface water samples were analyzed for both total coliforms and fecal coliforms by the most probable number method, both during the 1975 and 1976 irrigation seasons, and during 1974. The 1974 sampling program was intended to provide background data on coliforms in the wetland, its inlets, outlets, and neighboring receiving water bodies. The results of this work are given in Table 10.

Coliform levels at all locations at all times displayed considerable variability. The sewage plant aeration ponds displayed the expected high levels, but the sewage plant holding pond, from which wastewater was pumped, showed fairly low levels during all pumping periods. At no time during the summers of 1975 through 1979 did the pumped water exhibit more than the legally allowable 200 fecal coliforms per 100 ml of water. This information allowed the operator to refrain from chlorination during all irrigation periods.

The fecal coliform levels were considerably lower than total coliform levels both during the background year of 1974 and during the pumping years of 1975 and 1976. Within the natural wetland, fecal levels ranged from 0 to 20% of the total coliforms reported in Table 10. Within the study sites in 1975 and 1976, the percent fecal coliform ranged from 0 to 50%.

It is known that raw sewage contains human enteric viruses, and that sewage treatment plants reduce these concentrations. In late summer 1977, a field test was undertaken to determine the profile of virus concentrations at various stages of wastewater treatment, and in the wetland irrigation site. Samples were collected and preconcentrated in Michigan, and subsequently analyzed at the University of New Hampshire under the direction of Dr. Theodore G. Metcalf.

The results of these analyses are given in Table 11. The recoveries of virus from the standards was not good,

Table 10. Total Coliform Bacteria, Houghton Lake Wetland. (MPN method) (Number per 100 ml) (Averages)

	Natural Inflows	Natural Outflows	Interior Points (Control)	Discharge	Discharge Area	Receiving Water Bodies
1974						
4/21	-	-	1100			250
5/28	390	264	7122			1393
7/14	270	435	452			860
8/9	110	120	92			8070
8/27	585	170	563			640
9/30	2765	6585	1960			3400
1975						
5/17	140	20	20	none	270	25
7/4	270	80	140	none	3667	183
8/15	140	110	20	53	25	83
1976						
6/4	-	-	-	80	483	-
7/1	1700	715	2787	710	7623	1700
7/12	-	-	-	850	1330	-
7/27	-	-	-	965	1685	-
8/24	-	-	-	40,000	46,000	-

Table 11. Recovery and Identification of Virus Isolants from the Houghton Lake Sewage Treatment Plant, Pilot Irrigation Site B, and an undisturbed Wetland Site. (50 gallon samples)

Sample	Virus Isolant Recovered	Number Isolants Recovered (PFU)	Isolant Identity
Aeration Pond #1	+	1	Echovirus 32
Aeration Pond #2	+	1	Echovirus 32
Holding Pond/ Discharge	0	0	-
20 meters from Discharge	0	0	-
40 meters from Discharge	0	0	-
Wetland Background	0	0	-
Standard 1 (2500 PFU)	+	14	
Standard 2 (2500 PFU)	+	142	

in that only 1.5% of the low concentration was recovered. The estimated analytical recovery (New Hampshire) was 25%, leading to an estimated sampling recovery (Michigan) of 6% for the low concentration levels encountered. This is not surprising in view of the extreme difficulty of sample collection and pre-processing in the wetland situation, and the unavoidable delays in sample transport and storage occasioned by the large distances between the site and the laboratories.

A study of the full scale site in fall 1978, conducted entirely within Michigan, yielded quite different results. Both reovirus and poliovirus were found at all locations in the treatment plant and the wetland, with a hundred-fold reduction occurring on passage through the treatment plant. The wetland (control site) and the treated wastewater exhibited the same total virus. The surface water of the wetland was experimentally determined to be hostile to poliovirus, but not to reovirus.

VERTEBRATE AND INVERTEBRATE FAUNA

Data on wetland wildlife populations from 1975-1977 consists of mist net caputres of birds, transect data for herptiles and field observations for larger mammals. There were no dramatic changes in either species abundance or species composition of wetland birds between the summers of 1973 and 1975. In 1973 (background) mist netting resulted in the capture of .54 birds per mist net hour. In 1975 (pilot project) mist netting yielded a capture rate of .38 birds per mist net hour. Species composition of the mist net captures was similar during both years, with swamp sparrows and yellow throats comprising 79% of the birds caught in 1975 and 62% of the birds caught in 1973.

During the pumping season of 1976, one new muskrat lodge was established near the pilot area discharge site, since this was the only standing water available. After pumping ceased, the lodge was abandoned. White-tailed deer were the only other mammals observed in the pilot area of the marsh during 1975-77. Deer sightings remained at constant frequency during this period.

In 1978, under the auspices of the HLSA, several methods were used in the collection and enumeration of the vertebrates and invertebrates of the marsh in the area of discharge. Selective dipnetting, in water zones, was used to collect aquatic insects prior to pumping. Wire mesh cones located in front of the discharge pipe collected the influx of invertebrates and fish from the treatment plant holding ponds. Core extractions were used to determine zone effects of aquatic insects and invertebrates. Non-aquatic insects were collected in sweepnet samples from the various habitats in the area of discharge. Shading and basking platforms were set up to provide observation sites for herps, minnow traps were useful in entraping amphibians and fish. Small rodents were collected in live traps, larger mammals by observation only.

This research is continuing in 1979, with the goal of understanding long term impacts on these populations. No significant effects have yet been quantified; it is still too early in the life of the project.

SUMMARY AND CONCLUSIONS

For five consecutive summers, secondary wastewater has been discharged to a peatland in central Michigan. Thus far, this is a successful means of advanced treatment. Results indicate that this is indeed an effective means of nutrient removal. The wetland is large (7 square kilometers), and therefore retained 100% of all added nutrients. But further, all nitrogen and phosphorus were stored or removed within a five acre area, at a discharge rate of 100,000 gallons per day; and within a 50 acre area at 1,000,000 gpd. The maximum increase in water depth was 15 cm at the center of a single point discharge. During the 1976 drought, the discharge created the only remaining surface water.

Nutrient fronts appear to be moving slowly downgradient.

Inactive dissolved species, such as chloride, flowed through the active area with very little change. The pH of the added water was high compared to the slightly acid wetland waters, but dropped rapidly to background levels as the water traveled across the wetland. There was a similar pattern for conductivity: high entering values, dropping rapidly to background.

Neither a linear discharge, through numerous gates in irrigation pipe, nor a point discharge from a single pipe, caused any soil erosion or plant mortality. Suspended solids from the treatment plant deposited very close to the area of discharge, and were not transported with the wastewater. Visual effects were minimal: itensified green color in plants, and slightly (5-10 cm) deeper water near the discharge. Odor problems were slight or non-existent. The wastewater was of quite low heavy metal content, and hence no information on this potential contaminant was obtained. Coliform bacteria and virus were present in both the discharge and in the natural wetland in comparable numbers.

The animal populations exhibited little response to the discharge. There was no change in bird activity or numbers, nor was there noticeable effect on larger mammals.

The fate of the added nutrients is in the soil, litter and plants near the discharge. Exact proportions cannot be determined, because of the large natural pool of these materials. Based on lab studies, it is clear that processes such as sorption, ion exchange, and precipitation remove some added constituents, such as phosphorus. It is quite likely that microbial denitrification plays an important role in nitrogen removal. Uptake by algae and vascular plants provides at least a temporary storage for some nutrients, and perhaps a permanent storage of some fraction of the added material.

This peatland can accept treated wastewater during the summer months without noticeably changing the character of the wetland over periods of one to two years. The nutrients (nitrogen and phosphorus) are removed, but some dissolved materials (sodium and chloride) are not.

ACKNOWLEDGMENTS

The Houghton Lake Wetland Treatment System was built and placed in operation during the first six months of 1978. An operation and maintenance plan has been developed, and the system operates successfuly. This remarkable achievement was made possible by the excellent cooperation of the National Science Foundation, Environmental Protection Agency, Michigan Department of Natural Resources, the U.S. Fish and Wildlife Service, Roscommon County, the Houghton Lake Sewer Authority, Williams and Works, Inc., and the University of Michigan.

This paper is based on the work of many people, including all those referenced in the Related Publications list. In addition, University of Michigan field operations were successfully guided by Mr. Richard J. Kruse.

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ENGINEERING, ENERGY AND EFFECTIVENESS FEATURES OF MICHIGAN WETLAND TERTIARY WASTEWATER TREATMENT SYSTEMS

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ABSTRACT

Two markedly different Michigan wetlands are receiving pond stabilized secondary treated non-chlorinated wastewater. Both operations result in removal of 98%-100% of phosphorus through contact with reactive soils.

At Vermontville (42°37'N, 85°01'W) flood irrigation fields (11.5 acres) overgrown with volunteer wetland vegetation (mainly cattail) treat and dispose of wastewater principally by slow seepage (4 in./wk) through phosphorus-adsorbing clayey-silty glacial till. Occasional uncontrolled runoff of wetland surface waters releases phosphorus, BOD, and suspended solids in concentrations slightly above permitted limits. Seepage wetlands offer potential advantages compared to upland spray irrigation for small communities. Savings of 25% and greater on capital plus land costs can be expected for flow below 0.1 MGD average flows. Field maintenance may not be needed, and irrigation energy costs need be no higher than those for surface irrigation of uplands.

At Houghton Lake (44°18'N, 85°50'W), natural state-owned wetlands (600 acres) treat and dispose of wastewater by overland flow across a reactive peat substrate. Construction and maintenance in 1978 involved negligible ecological impact. Construction was done in the dormant months between March and June. The wetland transmission and irrigation pipelines are strapped to a wooden walkway suspended 2.5 ft above the wetland on pole pilings anchored in clay. The cost of the wetland wastewater distribution system was $21.00/ft (1979 dollars). Irrigation electrical energy costs were approximately $7.21 in 1979. The wetland capital and land costs represent savings of approximately $1 million compared to upland irrigation.

FOREWORD

The engineering-related features of the Houghton Lake and Vermontville, Michigan, wetland wastewater treatment systems are presented and discussed herein. The environmental responses and details of wetland water quality at the Houghton Lake site are presented in this volume in a separate paper by Robert H. Kadlec. The phytosociology, phenology, and wildlife habitat attributes of the Vermontville wetland site were studied by Frederick B. Bevis and have been previously distributed and presented (1,2). Some of the included engineering documentation related to Vermontville was distributed or presented earlier this year (1,3) and similarly for Houghton Lake (4,5). Additional background on the Houghton Lake facility is presented in reference 15.

PART I: VERMONTVILLE

INTRODUCTION

The municipal wastewater treatment system at Vermontville, Michigan (population 975), consists of two facultative stabilization ponds of 10.9 acres, followed by four diked surface (flood) irrigation fields of 11.5 acres constructed on silty-clayey soils. The system is located on a hill with the ponds uppermost and the fields at descending elevations (Figures 1 and 2). Now in their seventh year of operation, the fields are nearly overgrown with volunteer emergent aquatic vegetation, mainly cattail.

The Vermontville system is one of several pond and irrigation systems constructed for sanitary wastewater treatment in the late 1960's and early 1970's in Michigan. It was one of the first such systems to go into operation in this state. There was one very specific need among others which led to the introduction of upland irrigation systems in Michigan. That need was phosphorus (P) removal. In 1968 the Lake Michigan Enforcement Conference of the FWPCA (the EPA forerunner) determined that communities in the Lake Michigan Basin must remove 80% of the P from sanitary wastewater before discharging it to streams.

Vermontville's system was conceived and designed with phosphorus removal and economy of operation in mind. The ponds would receive raw wastewater alternately with a week-on, week-off schedule. The upper pond (P1, Figure 2), has separate discharge lines into fields F1 and F2 and the lower pond (P2) has separate discharge lines into fields F3 and F4. Pond-stabilized wastewater would be released into each field by gravity flow through 10-in. main and 8-in. manifold pipe having several ground level outlets in each field. Irrigation of terrestrial grasses would take place during six of the spring-summer-fall months. Up to 4 inches of wastewater applied each week would flood the fields briefly until the water seeped away. Should the water level exceed 6 in. or so, water would overflow to the next field by means of a standpipe drain. It was expected that all applied water would seep into the ground before leaving the treatment area.

The system's actual operation and the general hydraulic behavior of the fields are essentially as conceived; although in actual operation the fields often do overflow when wastewater is being released into them, or following hard rainfall, nearly all of the irrigated wastewater seeps into the ground. But there are some significant departures from the conceived system. Water stands in the fields for hours or days at a time, and the fields are heavily overgrown with wetland vegetation. Actually, cattails began to establish a year before irrigation was begun and while the ponds were being filled for the first time. Also, although the final field (F4) is never irrigated, there is at all times a surface discharge from F4 into a stream. At most times this surface discharge is dominantly recycled wastewater, which is wastewater that has seeped through the ground from the upper fields, and then re-emerged as springs into F4. The quality of the spring water is very high. The spring water is occasionally augmented with surface wastewater overflow from F3, under which condition the quality of the surface

FIGURE 1. ◉ MICHIGAN LOCATIONS WHERE MUNICIPAL WASTEWATER-WETLAND EFFECTS ARE BEING INVESTIGATED

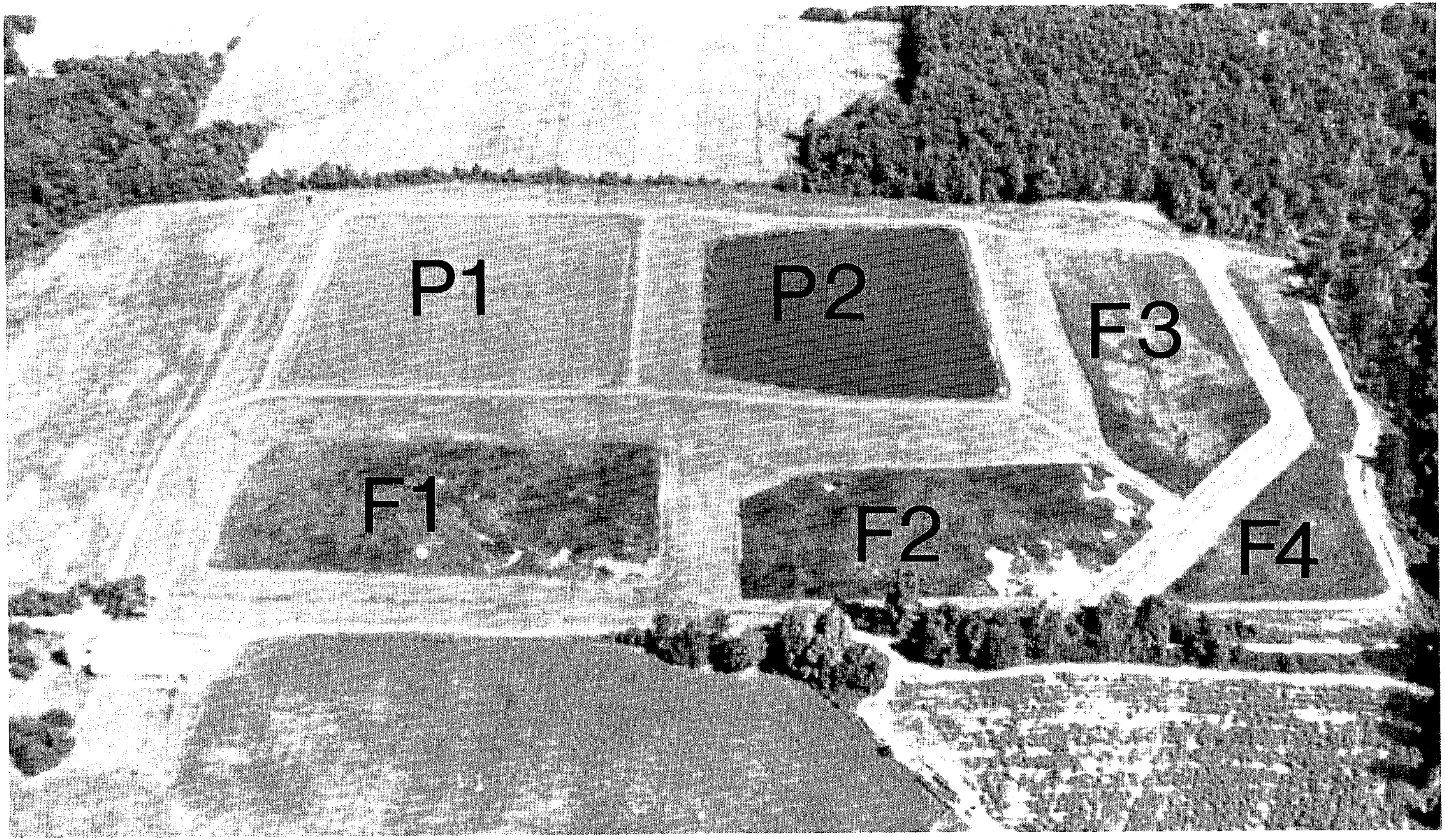

FIGURE 2. WASTEWATER STABILIZATION PONDS (P) AND IRRIGATION FIELDS (F): VERMONTVILLE.

discharge from F4 is not as high as it is required to be. Both of these departures - wetlands in place of terrestrial vegetation and the related existence of the surface discharge of variable quality, invite questions about the economics and effectiveness of treatment attending incidental or deliberate inclusion of seepage wetlands. In 1978, the National Science Foundation granted us funds to investigate the Vermontville system to identify any features which might be advantageous in economical wastewater treatment for small communities (NSF ENV-20273).

SOILS AND THE RATE OF SEEPAGE

The treatment site is located on glacial till. Extensive cutting and filling of the till soils were necessary to rough grade the irrigation fields at the time of construction. Numerous borings taken in the irrigation fields reveal the upper 4 1/2 ft of inorganic soils to be sandy clay, silty clay, and clayey silt, with subordinate clay, clayey sand, silty sand, and fine-gravelly variants of most of the forenamed textures.

Fifteen (15) split-spoon soil samples from the upper 4 1/2 ft including most of the mixed soil types named above were tested for hydraulic conductivity (h.c.) in the laboratory using falling-head permeameters. The observed range of the lab h.c. is 1.3×10^{-8} cm/sec for an impure clay to 1.4×10^{-5} cm/sec for one impure sand sample. Among all samples, only the impure sand showed a higher h.c. than 5.8×10^{-7} cm/sec.

The seepage wetlands transmit wastewater at the observed average rate of at least 4 in./wk, or 2.5×10^{-5} cm/sec, similar to the h.c. of the impure sand sample tested. Yet a total of 27 borings in the overall treatment site indicates that sand as clean as the impure sand is a minor soil type here. The higher actual field permeability compared to the lab samples could be due to compaction of soil samples in the lab in spite of counter-efforts, or to the (undiscovered) occurrence of sandy zones which may be areally minor, but effective as seepage areas. Equally likely is residual looseness within the extensive volumes of clayey fill in the wetlands, with attendant random networks of irregular openings which facilitate seepage. Most areas of filling are low-lying compared to the cut areas, and have been so since shortly after final grading. This feature does not, however, appear to shed useful light on the state of openness of the fill. One, or a combination of the named factors, could be significant with respect to the observed rate of seepage.

ENVIRONMENTAL WATER QUALITY

The average quality of the influent, pond effluent, wetland water, ground water and final surface overflow is shown in Figure 3. Incidental to the more important quality aspects, but requiring explanation nevertheless, is the dilution of wastewater (chloride) as it flows across the system. Chloride decreases persistently from 280 mg/l in the influent to 123-124 mg/l in the ground and final overflow waters. Heavy snow diluted the influent wastewater accumulating

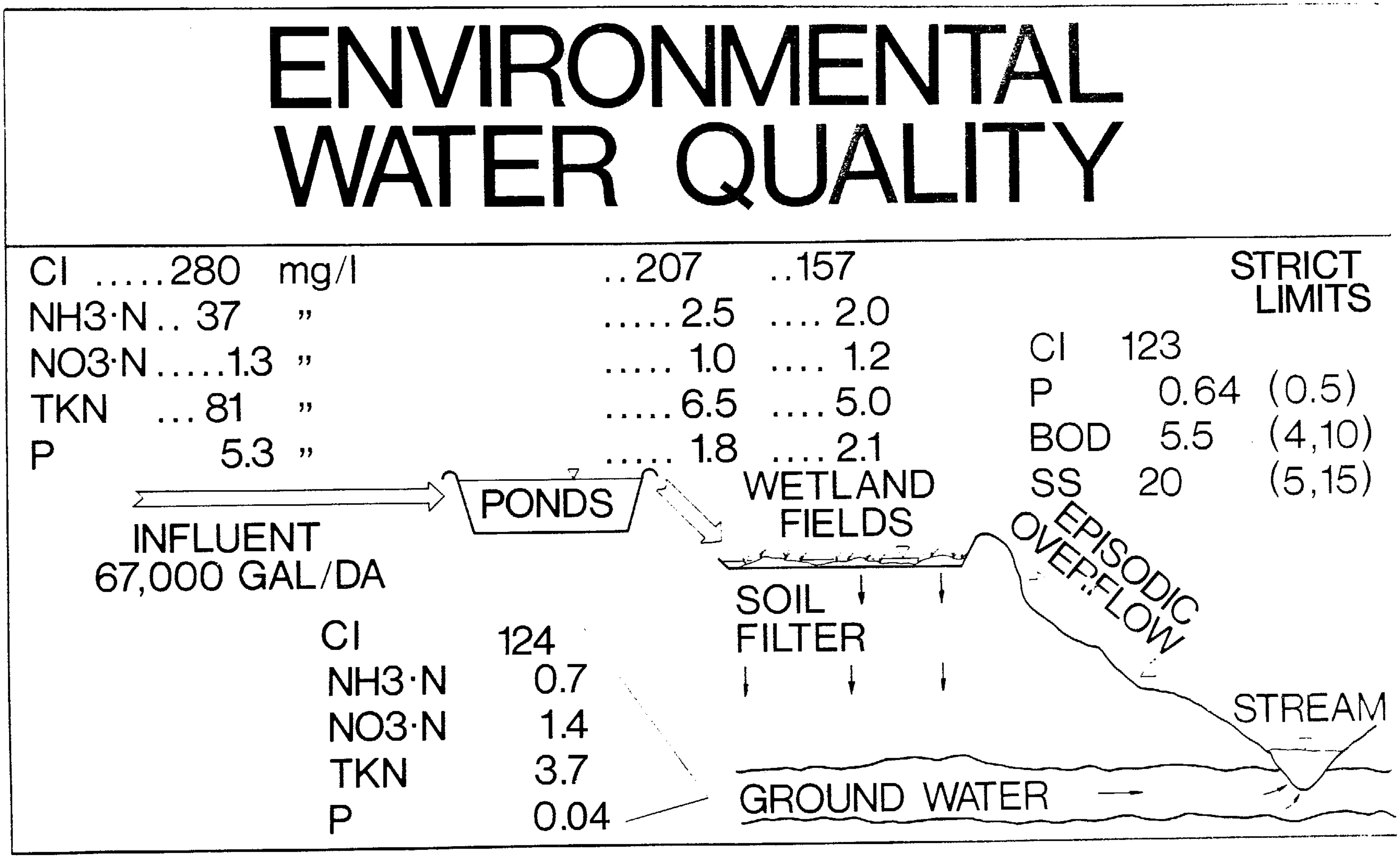

FIGURE 3. ENVIRONMENTAL WATER QUALITY: VERMONTVILLE

in the ponds between late fall, 1977 and June, 1978, such that the average pond effluent showed 207 mg/l Cl over the June-to-December 1978 irrigation season. Rainfall 50% above normal, and the coincidence of several sampling visits with rainy periods, account for the 30% dilution of wetland standing water relative to pond effluent. The seepage-derived ground water is 25% to 30% diluted with respect to wetland water because of mixing with ambient ground water. The final surface overflow consists of soil-filtered wastewater derived from the three upper wetlands which is further diluted by rainwater in the fourth and final field.

Phosphorus is higher in the wetland fields than in the pond effluent. Even with dilution, total phosphorus increases from 1.8 mg/l (pond discharge) to 2.1 mg/l in the wetland waters. Decomposing detrital organic matter is a likely source of additional P. Also, the standing wetland crop loses P over the irrigation season. Some amount of the lost P is perhaps stored in plant roots and rhizomes, but much of the lost P is likely released directly into the wetland water. Approximately 97% removal of P occurs between the wetland fields and the ground water, which is sampled from monitoring wells placed at depths ranging from roughly 10 ft to 25 ft below the wetland floors. Most removal of P occurs in the upper 3 ft of soils judging from a small number of porous cup lysimeter samples which average 0.1 mg/l total P and 0.06 mg/l ortho-P, with ranges of 0-0.3 mg/l and 0-0.2 mg/l, respectively. The average removals of P effected in the upper 3 ft of soils are approximately 95%. Phosphorus is reduced to 0.04 mg/l in the ground water which is well below local NPDES stream discharge requirements of 0.5 mg/l P.

The immediate foregoing information documents the wetlands as an incidental factor in the treatment effected through the flood irrigation system, which reduces P to values well below the required 20% quantity and 0.5 mg/l concentration limits.

If the wetland waters were permitted to overflow into a receiving stream, the NPDES limits for P of 0.5 mg/l (final column of numbers, Figure 3) could not be met. In fact, occasional surface overflow of wastewater from F3 into F4 causes the average final overflow from F4 to be slightly in excess of the NPDES limits for P, BOD and SS (final two columns of numbers, Figure 3). Neither BOD nor SS was measured in the ground water samples. General absence of literature and first hand data which would imply significant levels of BOD and SS remaining in sanitary wastewater filtered through several feet of fine textured soils made us believe the BOD and SS would be unremarkable in the ground water.

The F4 overflow quality data support data obtained by others under somewhat different circumstances which suggest that the flow-through process in wetlands, absent filtering of wastewater through native soils, might not provide satisfactory removal of phosphorus and other potential pollutants (references 6 through 9).

OPERATION AND MAINTENANCE

The Seepage Area

The wetland fields have not been maintained since they were put into use in 1973. They seem not to require maintenance. Maintenance factors which characterize upland irrigation such as encrustation of the uppermost soil surface (tightening of soils), and accumulation of the standing crop (necessitating removal to control animal pests, for example) do not appear to be present.

The potentially harvestable wetland biomass (mostly cattail) is reduced to a cattail straw mat over the dormant months. The wastewater wetlands may act similarly to natural seepage wetlands established on glacial soils which have apparently seeped effectively for centuries. The absence of fine detrital inorganic sediments is a plausible common factor in the seepage longevity of both the wastewater-developed and natural seepage wetlands. Mineral silt and clay in the raw wastewater may effectively settle out in the stabilization ponds. The irrigation inlet pipe inverts are only 1.5 ft above the sloping (1:3) pond sides, but the inlet points are located shoreward of the entire shallow settling basin of each pond, which may also help minimize the entrainment of mineral detritus during irrigation.

Energy Requirement

The operators visit the site to open (morning) and close (afternoon) manually-operated irrigation valves twice each workday during the 6-month irrigation season. Each morning they record the daily influent volume at the final collection system lift station, and from there they make the first daily visit to the site, a round trip site visit of one mile. The second site visit (early afternoon) is a separate round trip of two miles. The Village pick-up truck will use around 0.1 gal./mile on these excursions. Approximately one-third of the site time is devoted to inspection of the ponds.

The annual cost of gasoline involved with irrigation of the wetlands, based on the above, is:

$$26 \text{ wk} \times \frac{5 \text{ da}}{\text{wk}} \times \frac{3 \text{ miles}}{\text{da}} \times \frac{0.1 \text{ gal.}}{\text{mile}} \times \frac{\$1}{\text{gal.}} \times \frac{2}{3} = \$26.00.$$

Approximately $20.00 worth of gasoline is involved in mowing the long wetland-facing berm slopes.

Use of electrical energy to operate the wetlands is indirect. The ponds are elevated with respect to the wetlands in order that irrigation may be done by gravity. Extra lift of 22.3 ft (the average difference between the elevation of the ponds and fields) is involved, and the total lift from the final collection system lift station to the influent wetwell at the ponds is 84 feet. The energy consumed at the final lift station in 1978 was 16.225 kwh for which the Village was charged $0.06 per kwh. A monthly service charge of $5.00 was added to each billing. The annual electrical energy cost to operate the wetlands is:

$$(16{,}225 \text{ kwh} \times \frac{\$0.06}{\text{kwh}} \times \frac{22.3 \text{ ft}}{84 \text{ ft}}) + (12 \times \frac{\$5.00}{\text{mo}}) = \$318.44.$$

In 1978, 28.5 million gallons were irrigated at an average electrical energy cost of:

$318.44/28.5 MG = $11.17/MG.

The total energy costs including site visits for irrigation are $364 per year -- roughly $1.00 per day or $12.81/MG.

Not uncommonly, the electrical energy costs of seepage wetland operation would be much lower than at Vermontville. One hypothetical situation involves a pre-existing secondary treatment facility from which effluent could be drained by gravity into a new lower-lying wetland. Another situation would obtain where design of new secondary facilities and gravity-fed seepage wetlands need not include extra collection system lift station capacity to enable gravity operation of the wetlands.

Labor

Approximately ten man-weeks are invested in the wetland facility during late spring-early autumn irrigation season by the wastewater treatment staff. No time is given to the facility in the off-season.

Analytical

Monitoring of the surface overflow from the final wetland field (F4) involves costs of $260/month for eight months, or approximately $2,000/year. This cost figure is roughly twice that for a hypothetical seepage wetland system without a surface overflow but which might be monitored with three ground water wells on a quarterly schedule.

DELIBERATE DESIGN OF SEEPAGE WETLANDS

Factors which may mandate conscientious planning and design to optimize wastewater treatment and wildlife habitat, while minimizing construction and O&M costs and adverse environmental impact, are:

1. Ground water quality regulations (environmental impact).

2. Need for "slow" seepage and spatial variation in water depth with interspersion to promote variety (wetland habitat development).

3. Need for rapid enough seepage to infiltrate all applied wastewater without uncontrolled runoff (treatment).

The use of seepage wetlands for wastewater treatment adds soil-filtered wastewater to the existing ground water. The soils will likely remove phosphorus, bacteria, suspended solids, and BOD adequately to meet stream water quality requirements. Nevertheless, state ground water quality regulations often specify that disposal of wastewaters shall not degrade a usable aquifer. The regulations may apply even where filtered wastewater meets drinking water quality standards. Where the use of a potential site would result in degradation of a developable portion of an aquifer contrary to regulations, then some means of post-seepage retrieval of the filtered wastewater and approved final discharge must be designed. In Michigan, this condition with respect to upland irrigation has often involved a choice between recovery of irrigated wastewater with purge wells followed by discharge to a stream, versus selection of a different site located on the nearest developable property to an influent stream. In Michigan, a nearby stream or its bordering lowland would almost always be the natural line of discharge for the most shallow ground water zone within an indefinite distance landward of the floodplain. A seepage wetland site at or near such a stream floodplain boundary would be acceptable without the need for post-seepage treatment. The availability of such a location would offer clear O&M advantages compared to pumping irrigated water out of the ground prior to discharge to a stream.

Design and construction of seepage wetlands would be more straightforward if the requirements for physical control of wastewater were the same as in conventional upland irrigation on well-drained soils. The basic upland requirements include soils which are adequately open to accept the design amount of wastewater, and depth to the unconfined ground water adequate to prevent excessive rise in the water table due to irrigation. The range of allowable application rates is limited on the low side, but almost never on the high side. With seepage wetlands, however, the rate of application is usually limited on both the high and low ends because of the need to establish wetland vegetation and to prevent uncontrolled runoff, respectively. The low limit insures standing water for many hours to several days at a time, while the high limit prevents surface water from rising to the level of uncontrolled overflow.

A seepage wetland could be constructed and operated to follow one of several schemes. Assume humid-temperate conditions and low-relief wetland contouring to provide water depth interspersion over a depth range of, say, +0.3 ft (drained, but poorly) to -3 ft (well submerged).

On a site with natural conditions of uniformly restrictive soils, the design weekly increment of wastewater applied intermittently during the week should be planned to seep away in a little under a week's time to avoid overflow during rainy periods. There would be some time-variation in water depth on a weekly cycle, typically two inches or more. The relative variation would be greater in the shallower water areas than in the deeper water environments. More uniform water depths could be maintained, if desired, by applying water continuously at a constant rate, equal to the rate of seepage, with interruption of irrigation during significant rainfall. With the latter approach, the length of the irrigation season would probably be little different from that ensuing with intermittent irrigation.

A number of unified soil classes could be acceptable for seepage wetland settings (Figure 4). Siltiness is a general indication of suitability. Most soils within the five more suitable classes -- GM, SM, SC, OL, and MH are prevalently or significantly silty. Mixtures of the finer sand grades and clayey sands within

FIGURE 4

UNIFIED SOIL CLASSES
WITH HYDRAULIC CONDUCTIVITY

10^{-3} to 10^{-6} cm/sec

CLASS	TYPICAL NAMES	WORKABILITY
GM	SILTY GRAVELS & GRAVEL-SAND-SILT	GOOD
SM	SILTY SANDS & SAND SILT MIXTURES	FAIR
SC	INORGANIC SILTS VERY FINE SANDS SILTY OR CLAYEY FINE SANDS CLAYEY SILTS (LOW PLASTICITY)	FAIR

10^{-4} to 10^{-6} cm/sec

OL	ORGANIC SILTS ORGANIC SILTY CLAYS (LOW PLASTICITY)	POOR
MH	INORGANIC SILTS MICACEOUS OR DIATOMACEOUS- FINE SANDY OR SILTY SOILS ELASTIC SILTS	POOR

MOST DESIRABLE RANGE 10^{-4}-10^{-5} cm/sec the named soil classes may also be suitable. In their natural condition, the forenamed classes could be too permeable for wetland vegetation to self-establish. For example, design for four inches per week application would call for hydraulic conductivity of around $10^{-4.8}$ cm/sec, which is close to the lower limit of infiltration indicated for the first three classes named. But the openness of the soils can be reduced during construction through compaction. Because compaction may decrease the soil's water intake rating by an order of magnitude or more, care in achieving the right degree of compaction is called for. The GM, SM, and SC soils may be readily compactible (fair to good workability). The OL and MH materials are usually difficult to work and to compact, and the OL soils may support only light equipment.

An alternative approach to construction and operation is selective compaction to achieve a suitable surface for direct application of wastewater (Figure 5) and primary wetland establishment. An uncompacted perimeter area contiguous with the compacted surface would receive and seep away any overflow from the compacted zone. The entire area would be enclosed with low berms to prevent uncontrolled runoff. In soils which cannot be adequately tightened by compaction, closure could be achieved with bentonite or clay while preserving an open-soil perimeter for overflow control. This procedure might be more expensive than selective compaction, but with it the seepage wetland solution is technically applicable in highly permeable sandy terrane as well as in silty soils. The non-uniform soil infiltration approach to seepage wetland construction would allow uniform water depth to be maintained, even with considerable latitude in application frequency, while preventing uncontrolled runoff.

Where soil manipulation is employed, the affected soil depth will usually be one foot or less. To maintain the integrity of the thin "seal," young willow and any other trees should be cut down at the whip stage, because if these trees were to fall over at maturity a substantial part of the seal would be destroyed as roots tear free of the ground. Annual hand cutting during late winter or early spring dormancy should be a low cost routine.

CAPITAL AND LAND COSTS

Seepage Wetlands vs Upland Spray Irrigation

Capital costs for seepage wetlands are calculated and compared to costs for spray irrigation. The land required for direct use is assumed to be the same for both methods at application rate of 4 in. per week. Therefore, the purchase costs of land for direct application, land clearing costs, costs for access roadways, and costs for monitoring wells are considered to be the same for both methods. Costs related to transmission pipeline from secondary treatment facilities including installation and pumping station are also considered to be the same for both methods. Square shape application areas and square total areas including isolation land are assumed.

The cost differences between the two methods arise in requirements for chlorination, isolation land, site grading, electrical power and irrigation

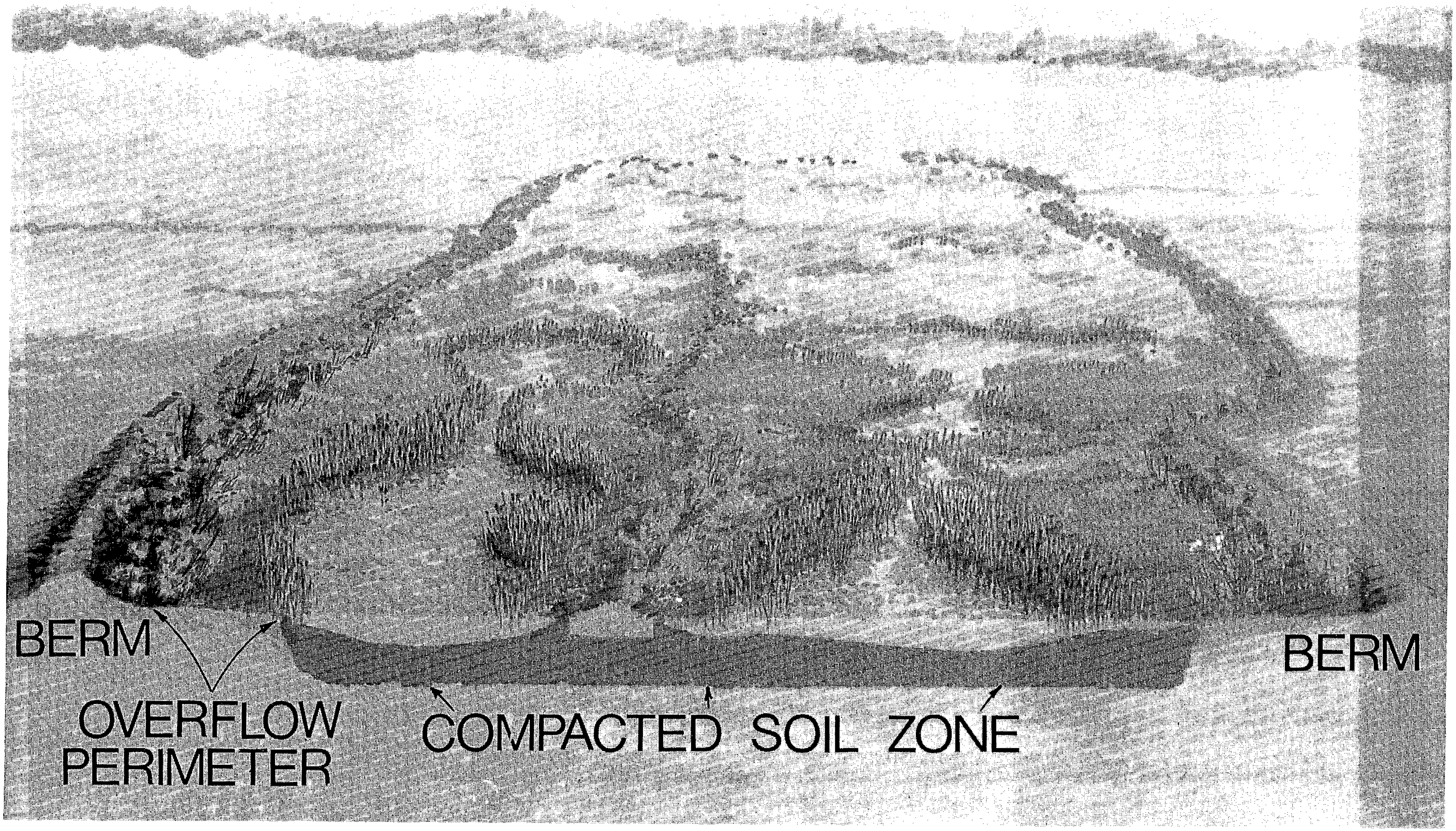

FIGURE 5. RENDERING OF A SEEPAGE WETLAND

Table 1. Unique Unit Costs Assumed for Spray Irrigation and Seepage Wetland Systems.

	ITEM	January 1977[1]	January 1979[2]
GENERAL	LAND	$1,000/ac.	$1,154/ac.
SPRAY IRRIGATION	CHLORINATION FACILITIES	$25,000	$28,838
	POWER FACILITIES	$10,000	$11,535
	SPRAY EQUIPMENT	$3,000/ac	$3,460/ac.
SEEPAGE WETLAND	SITE GRADING	--	$4,000/ac.
	GATED IRRIGATION PIPE	$21/ft	$24.22/ft

1 Michigan approximate cost figures (reference 10).

2 Update of costs to January, 1979 (reference 11).

structures. Spray irrigation is assumed to require pre-chlorination and an owned isolation perimeter 800 ft deep around the application site, as well as irrigation structures and an electrical power facility. No site grading is assumed for spray irrigation. Seepage wetlands are assumed to require 200 ft of owned isolation land, site grading (irregular leveling and construction of low berms), and irrigation structures. Chlorination and an electrical power facility are assumed not to be needed for the seepage wetland areas. The "no power facility" assumption is conditional upon effective gravity flow between the secondary treatment site and the wetland. An irrigation structure in the form of gated piping and support fixtures is assumed for seepage wetlands. The length of the structure is assumed equal to one edgelength (square) of the wetland area.

The assumed unit costs for unique components of the two methods are given in the included Table 1. The costs are based on general cost figures for Michigan as of January, 1977 (10) and updated to January, 1979 (11). The present wetland irrigation structure costs may be nearer the tabulated 1977 value of $21.00 per foot than the $24.22 figure (Table 1), because the Houghton Lake wetland irrigation structure costs $21.00 per foot in 1979 dollars.

Table 2. Assumed General Conditions, Unique Capital Costs for Seepage Wetlands and Spray Irrigation, and Overall Cost Differences

	CONDITIONS		IRRIGATION 4-IN./WEEK, 6 MO/YR						
GENERAL	POPULATION AT THESE UNIT FLOWS	70 gal./cap-da	444	1,000	1,778	2,778	4,000	5,444	7,111
		100 gal./cap-da	311	700	1,245	1,945	2,800	3,811	4,978
	TOTAL DAILY FLOWS (MGD)		0.031	0.07	0.124	0.194	0.28	0.38	0.50
	TREATMENT ACREAGE		4	9	16	25	36	49	64
SPRAY IRRIGATION	ADDITIONAL ISOLATION ACREAGE		78	90	101	113	124	136	148
	ADDITIONAL ISOLATION LAND COSTS (C)		90,012	103,860	116,554	130,402	143,096	156,944	170,792
	SPRAY FACILITIES COSTS		13,840	31,140	55,360	86,500	124,560	159,540	221,440
	CHLORINATION COSTS		28,838	28,838	28,838	28,838	28,838	28,838	28,838
	POWER FACILITY COSTS		11,535	11,535	11,535	11,535	11,535	11,535	11,535
	SUBTOTAL SPRAY COSTS (A)		144,225	175,373	212,287	257,275	308,029	366,857	432,605
SEEPAGE WETLAND	GATED PIPE AND FIXTURES		10,100	15,165	20,200	25,275	30,330	35,385	40,400
	SITE GRADING COSTS		16,000	36,000	64,000	100,000	144,000	196,000	256,000
	SUBTOTAL WETLAND COSTS (B)		26,100	51,165	84,200	125,275	174,300	231,385	296,400
COST DIFFERENCES	A - B		118,125	124,208	128,087	132,000	133,729	135,472	136,205
	...ASSUMING LOWER LAND COST=$577/ac		73,119	72,278	69,810	66,799	62,181	57,000	50,809
	...ALSO ASSUMING LOWER GRADING COST=$2,500/ac		79,119	85,778	93,810	104,299	116,181	130,500	146,809
COST DIFFERENCE RANGE ($)			70,000-120,000	70,000-125,000	70,000-130,000	65,000-135,000	60,000-135,000	55,000-140,000	50,000-150,000

Table 2 gives a detailed tabulation of unique costs for spray irrigation and seepage wetlands, subtotals for each method, and overall cost differences for daily wastewater flows in the range 0.031 to 0.5 MGD and the corresponding application areas of up to 64 acres.

With the assumptions of Table 1, the costs of spray irrigation exceed the seepage wetland system costs by nearly constant amounts within the given range of flows, averaging $129,689 with a standard deviation of $6,632 for the entire range of flows. With a different assumption that land might be bought for one-half the earlier assumed cost, or $577 per acre, spray irrigation systems would cost $73,119 more at 0.031 MGD, and $50,809 more at 0.5 MGD. Add to this assumption the further assumption of site grading costs at $2,500 per acre instead of $4,000 per acre, and the spray method costs exceed those for the wetland method by $79,119 at 0.031 MGD and $146,809 at 0.5 MGD. Combining the several assumptions, the approximate range of cost differences under different assumed conditions would be $70,000 to $120,000 at 0.031 MGD and $50,000 to $150,000 at 0.5 MGD.

Overall Capital Costs

Capital costs for spray irrigation systems were calculated in great detail for ten Michigan communities in 1977 (10). All spray irrigation sites were located within three pipeline miles of secondary facilities. The range of wastewater flows among the ten communities is 0.07 to 0.24 MGD. The assumed rate of application of wastewater in the earlier study was 2 in./wk. Adjustment of these earlier calculations with allowance for the new assumed rate of application of 4 in./wk and for increases in costs over the two intervening years yields an expression, $C = 2{,}600\ F + 145$, where C is the capital-plus-land cost in 1,000's of dollars and F is wastewater influent flow in MGD. This expression must be further adjusted upward by 15.4% to reflect changes in construction costs (11) and assumes similar changes in land costs between January, 1977 and January, 1979. The new cost versus flow expression for spray irrigation systems is $C = 3{,}000\ F + 167.3$. In Figure 6, a spray irrigation cost curve based on this equation, and the seepage wetland costs and cost savings listed as A-B costs in Table 2, are plotted. Seepage wetland capital cost savings are greater than 26% where flows are less than 0.1 MGD, 14% at 0.25 MGD flows and 8% at 0.5 MGD flows.

DISCLAIMER

The Vermontville studies are supported through a grant from the National Science Foundation to Williams & Works. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

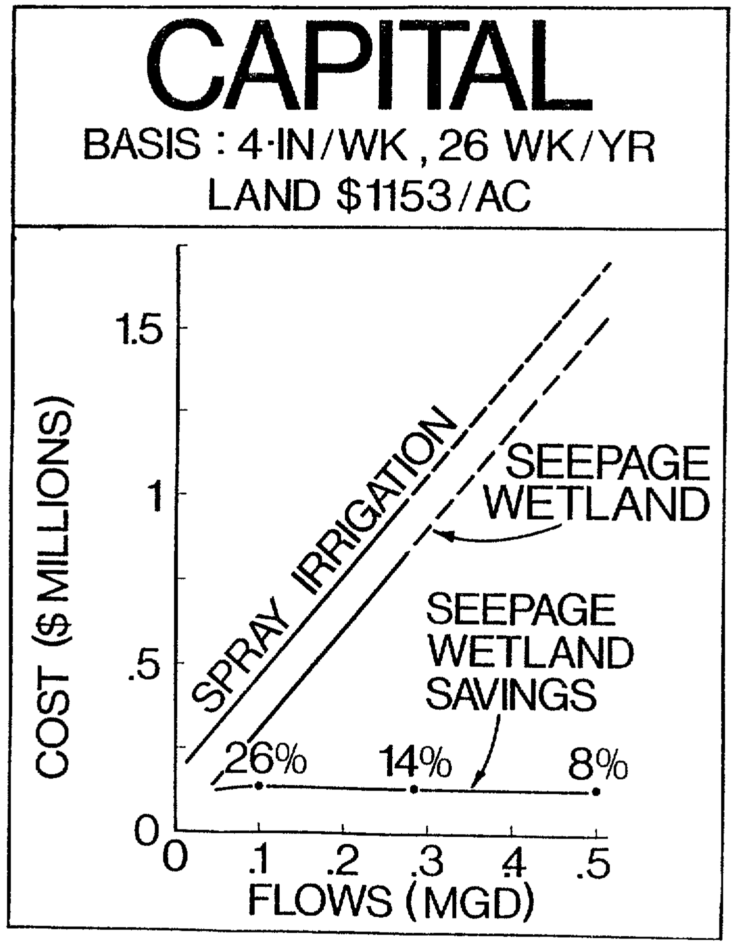

FIGURE 6. CAPITAL COST COMPARISON

PART II: HOUGHTON LAKE

BACKGROUND

Houghton Lake in Roscommon County (Figure 7) is Michigan's largest inland lake, and is a vacation haven for city dwellers from Michigan and surrounding states. The Houghton Lake area's Tri-Township treatment plant (Figure 8) serves a seasonally variable population. The winter and off-season population is approximately 5,300, and the peak summer season population is around 13,500. These figures are expected to increase to 8,000 and 16,900 by 1988, and to 10,300 and 22,400 by 1998.

Construction of "conventional" treatment facilities for stabilization and land treatment of wastewater to serve the Houghton Lake community through 1978 was completed in 1975. Two aeration ponds of 5.2 acres each and 10 ft working depth are followed by three holding ponds of 29.5 acres total area and 8.5 ft working depth. The holding ponds are designed to discharge into eight seepage beds of 5 acres, and into five flood irrigation fields totaling 85 acres. There is holding pond storage capacity for 140 million gallons over the six winter months, and the seepage and flood irrigation areas can treat 208 million gallons annually--the 1978 design flow on an average 81 gal./cap.-da basis.

The need for collection and treatment of wastewater from around Houghton Lake was realized in the 1960's as residential and commercial septic system failures threatened the economic well-being of the area. Even with increasing numbers of summer lake dwellers and year around cottage homes--major contributors to the problem--the area's financial base continued to be modest. How to treat wastewater affordably was a question very much on everyone's mind in 1968. In this rural setting, stabilization ponds were the best choice among secondary treatment alternatives, we thought. Then in 1968, the Lake Michigan Enforcement Conference of the Federal Water Pollution Control Administration (an EPA precursor) established that 80% removal of phosphorus would be required before discharging into streams tributary to Lake Michigan.

At the time, there were no thoroughly tested alternatives to expensive mechanical-chemical-biological phosphorus removal systems. The Pennsylvania State University studies of the living filter system (12), however, were attracting much interest. The Michigan Department of Natural Resources (DNR) was cognizant of the new burden that the phosphorus rule placed on rural communities. Thus, in 1970 when we recommended flood irrigation facilities, we had the needed support of the state even though very few municipal irrigation facilities were yet in operation in Michigan.

By 1971, the Houghton Lake community had a conceived treatment system designed for 600,000 gal. per day that would serve them until 1978. And it only remained

FIGURE 7. LOCATION OF HOUGHTON LAKE, MICHIGAN

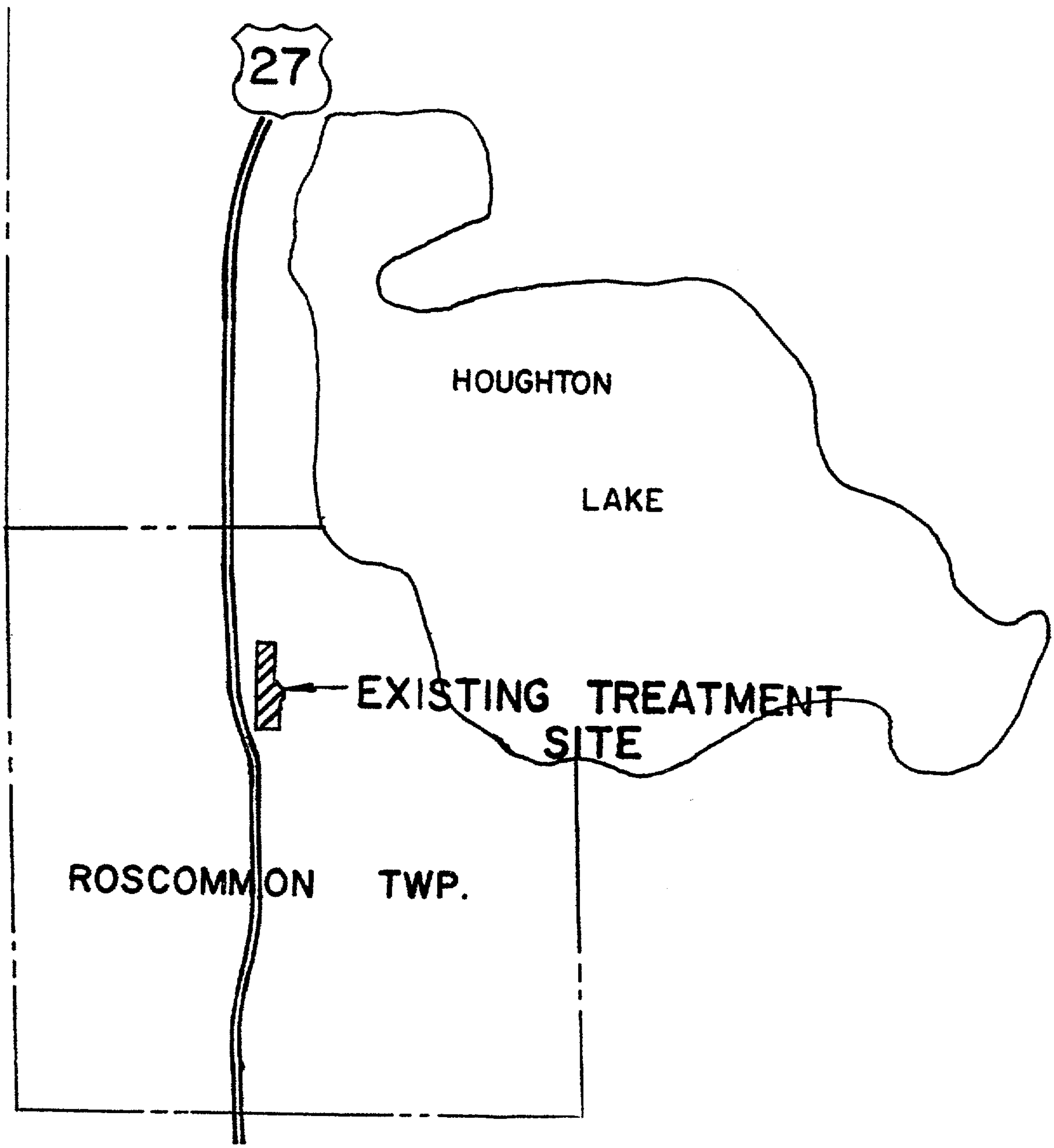

FIGURE 8. LOCATION OF TRI-TOWNSHIP WASTEWATER TREATMENT SITE, NOT INCLUDING WETLANDS

to locate land for expansion to 1998 design capacity. But the cost of upland property was increasing, and although the option to purchase additional upland remained open until the spring of 1977, efforts to develop a more attractive alternative were initiated in 1971 and continued for seven years.

Houghton Lake is in the very poorly drained headwaters of the Muskegon River, and there are thousands of acres of swamps within a few miles of the service area population. It occurred to us that swamp lands south or west of the treatment area might be able to take the pond effluent and give it tertiary treatment. The lands were largely owned by the state and we thought they might be usable at little cost. Early in 1971 we met with the division chiefs of the Michigan DNR to discuss the idea. There was some discussion of the swamps being infertile and unproductive, and perhaps wastewater nutrients would be just the thing to bring them to productive life. The DNR was interested but there were many questions and few reliable answers about the idea. There was, of course, little published information or experience at the time to support any far reaching decisions. But the DNR was interested enough to request that researchers at the University of Michigan, John and Bob Kadlec, develop an environmental feasibility study and report. Through the efforts of these researchers, the National Science Foundation came in to assist with virtually complete funding of the wetland studies beginning in mid-1972.

Between 1972 and 1977, the researchers identified the baseline characteristics of a wetland tract known as the Porter Ranch peatland, and tested the peatland with up to 100,000 gal./da quantities of pond stabilized wastewater. The peat soil substrate, which is up to 4 ft and greater in thickness, is fragile. During the experimental period, the research project team took special care to minimize marking the wetland with evidence of their ingress and study activities. This care was rewarded in there being only one or two faint path marks which persist today. The evident sensitivity of the peatland pointed to the need for design which would allow environmentally compatible irrigation pipeline construction and operation.

TREATMENT EXPANSION ALTERNATIVES

The facilities plan (13) compares capital and O&M costs for the wetland treatment system (A), physical-chemical-biological treatment (B) and expansion of the existing upland irrigation treatment system (C). Table 3 below is a tabulation of the January, 1976 costs estimated for the three alternatives, A, B, and C.

Table 3. Capital Cost Comparison for Alternative Treatment Methods

	A	B	C
Capital ($1,000's)			
Construction	591	1,730	1,108
Miscellaneous	158	370	262
Land	0	0	184
I. Total Capital	749	2,100	1,554
II. O&M (20 years)	320.5	901.3	316.5
III. Salvage Value (20 years)	32.5	54.3	127.5
Net Present Worth (I+II-III)	1,037	2,947	1,743

Savings of \$805,000 in capital costs were projected for the wetland alternative compared to expanding the existing upland irrigation system. Updating to January, 1978, when construction contracts were awarded, involved an increase in capital costs of approximately 16% (11), or projected capital savings of approximately \$934,000.

DESIGN

The Wetland Irrigation System

The wetland irrigation pipeline (Figures 9 and 10) is located approximately one-half mile out into the wetland, in the downgradient direction (southwest) of surface water movement. It was anticipated that backflow or backup of the slowly-moving wetland surface water would occur during irrigation, and the resulting flow, water level and treatment effects could best be documented by allowing abundant upgradient distance and area between the pipeline and the northeast edge of the wetland.

Beneath the peat floor lie several tens of feet of glacial lake bed clay. Although the peat would be of no use as a bed for a conventional pipeline arrangement, the underlying clay would present no foundation problems. Several experiments, including flotation and pilings as support mechanisms, resulted in the adopted design.

Wastewater is carried into the wetland through a 2500 ft-long 12-in. aluminum header pipeline. This pipeline makes a tee connection at the center of a 3,200 ft-long gated aluminum irrigation pipeline. Each arm of the irrigation pipeline is stepped down in size (Figures 10 and 11) from the tee connection to outer end with 400 ft each of 12-in., 10-in., 8-in., and 6-in. piping. Wastewater flow into each irrigation arm can be controlled separately by 12-in. aluminum butterfly valves (Figure 11). Irrigation gates are positioned at 15-ft intervals.

The transmission and irrigation pipelines are supported above the wetland surface on a wooden walkway. The walkway in turn is supported above the wetland surface on a frame which is anchored in the clay substrate.

The walkway consists of 2-in. x 6-in. x 32-in. hardwood planks nailed on 8-in. centers to 2-in. x 8-in. rails. The support frame for the walkway is made up of separate units, each consisting of a pair of 2-in. ID pipe poles anchored in the clay, and joined together by 2-in. x 6-in. x 48-in. hardwood planks. The planks are fastened to the pipe poles "edge-up," with two U-bolts per pole. The frame units are spaced 10 ft apart (Figure 12).

The pipelines are supported on one edge of the walkway directly over a 2-in. x 8-in. rail. The pipelines are strapped to the rail with aluminum straps on 8 ft centers, and are supported laterally by contact with the 2-in. pile pipes (Figure 12).

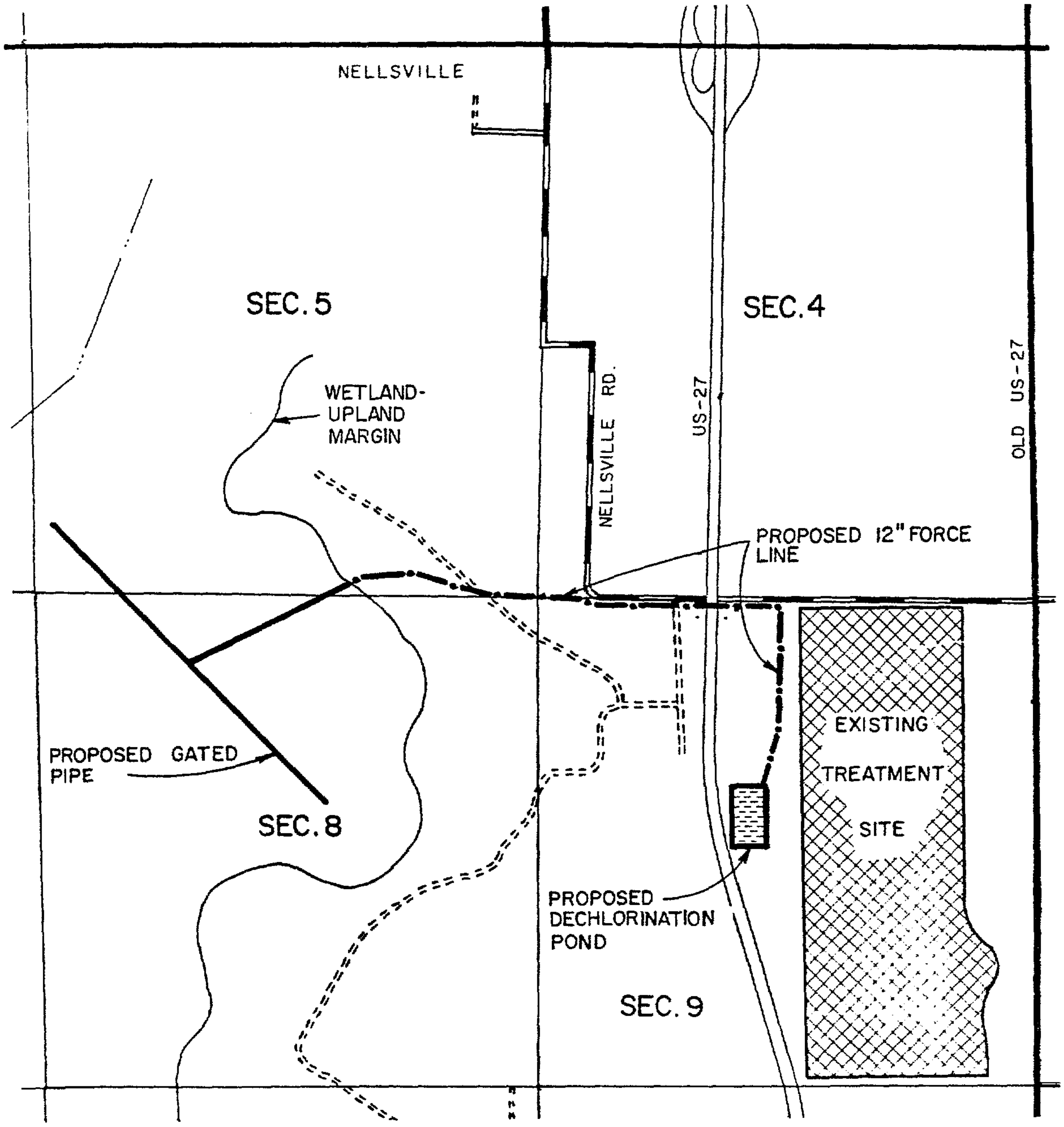

FIGURE 9. LOCATION OF OLD ("EXISTING") AND NEW ("PROPOSED") TREATMENT FACILITIES

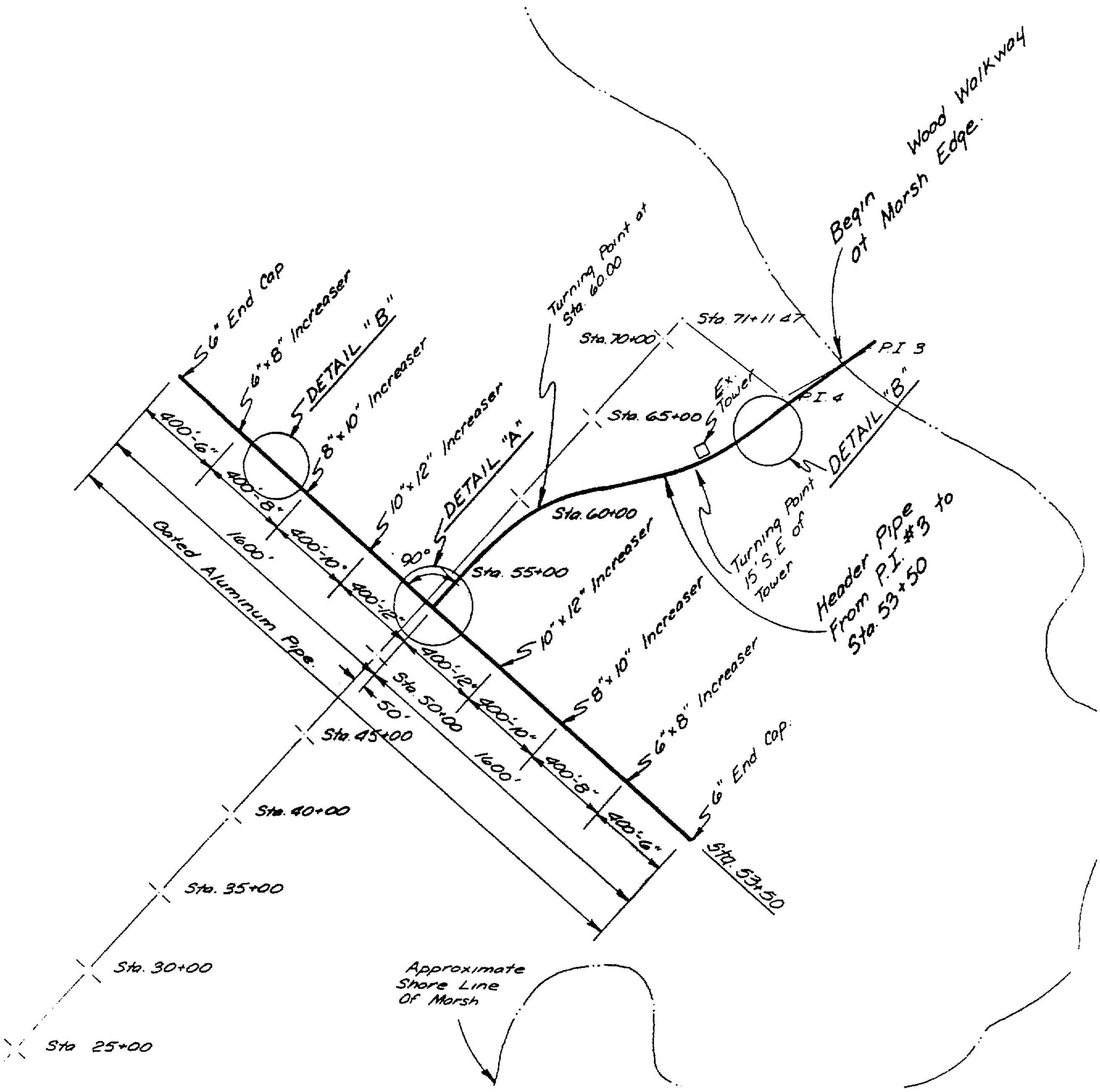

FIGURE 10. SCHEMATIC LAYOUT OF WETLAND HEADER AND IRRIGATION PIPELINES: HOUGHTON LAKE

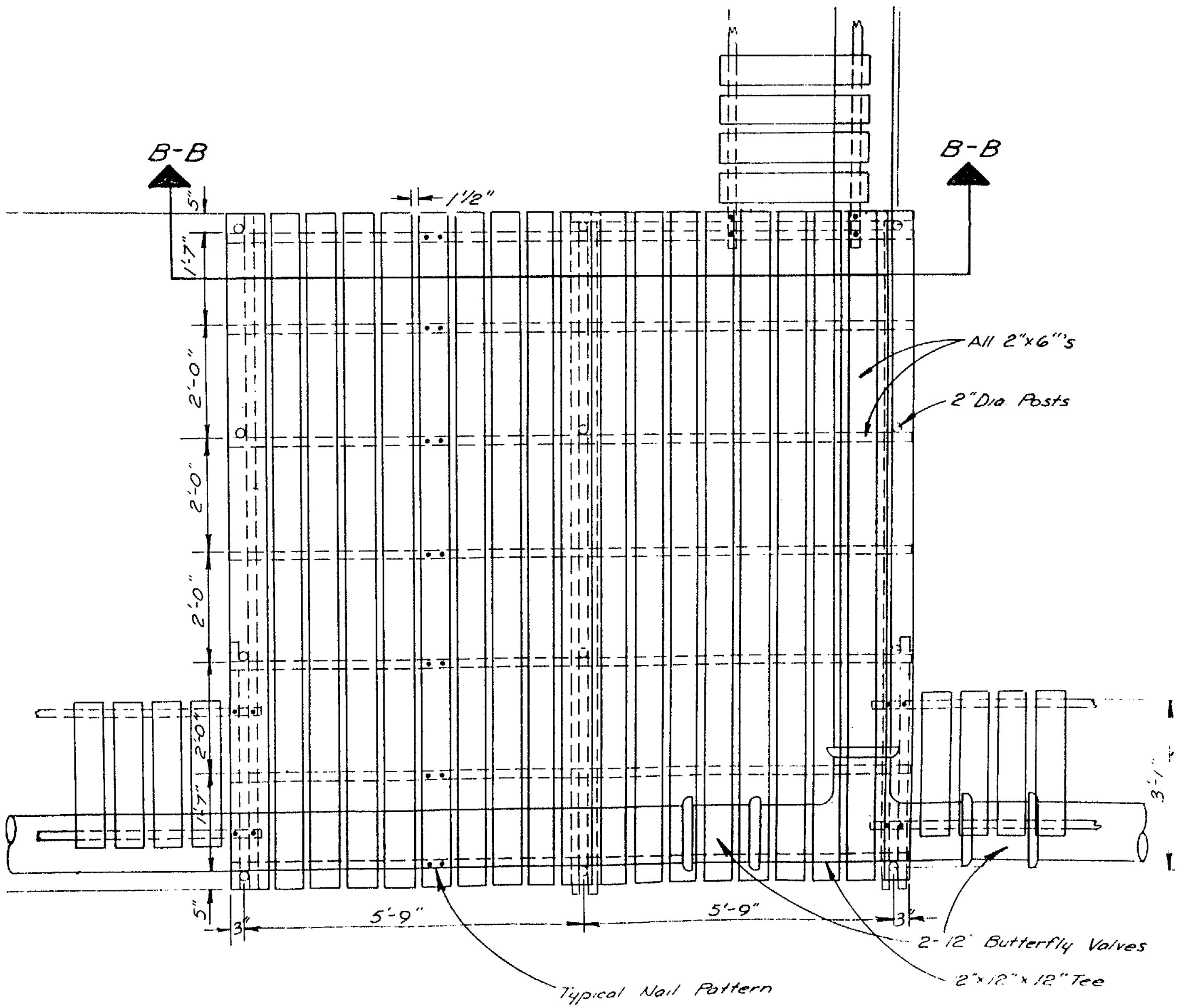

FIGURE 11. TEE AREA OF WETLAND IRRIGATION SYSTEM: HOUGHTON LAKE

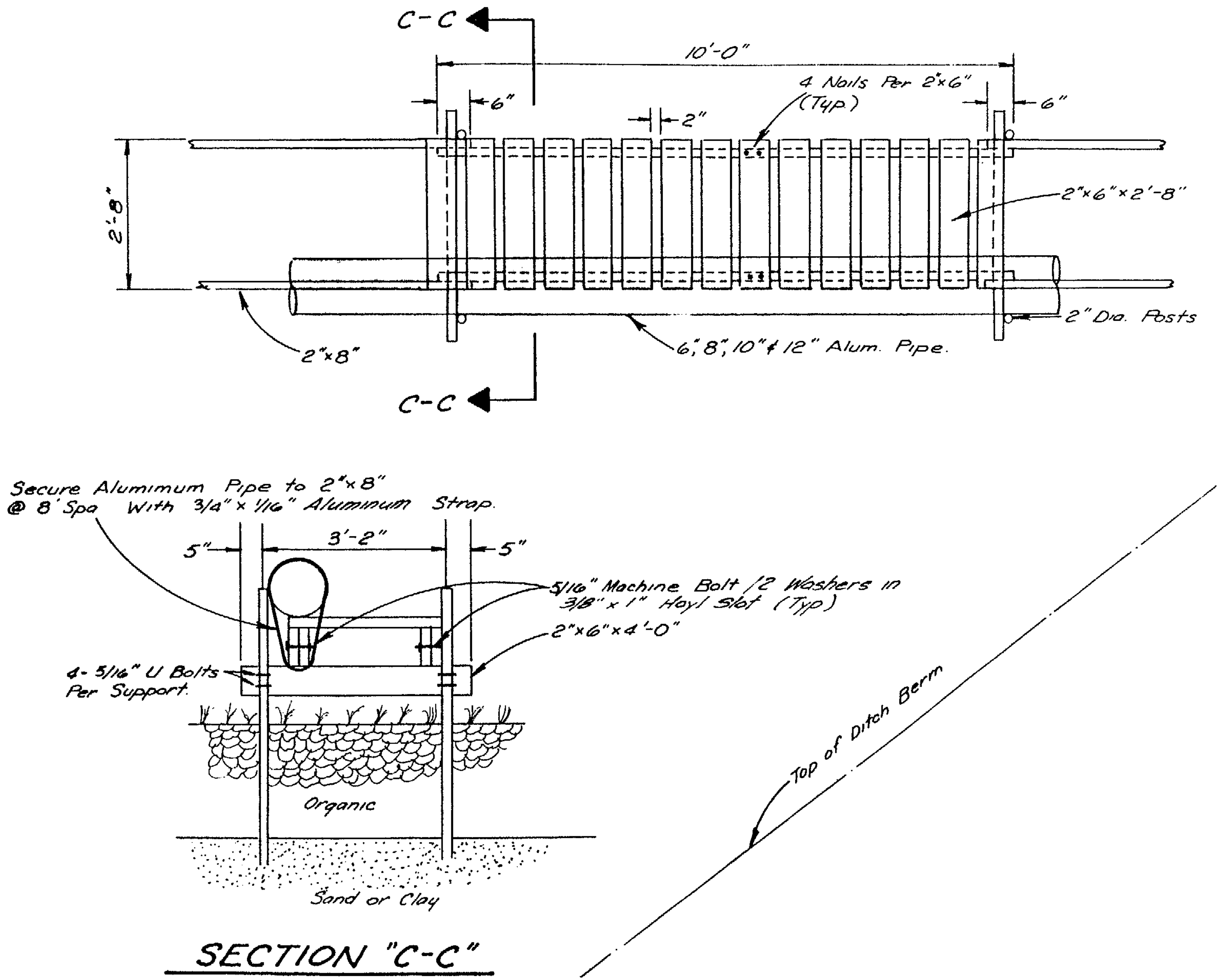

FIGURE 12. DETAIL OF WOODEN WALKWAY AND PIPELINE SUPPORT STRUCTURES IN THE WETLAND: HOUGHTON LAKE.

The header and irrigation pipelines, fittings, and valves are welded aluminum alloy with lock-ring couplers and gaskets. The irrigation slide gates are of high strength nylon and delrin. The gates slide over rectangular orifices cut in the pipe, in side-to-side fashion, from fully open to fully closed.

Other

Construction related to the wetland treatment scheme included modifications and additional structures at the upland treatment site. Also, the regulatory authority wanted assurance that neither pathogens nor residual chlorine would reach the wetland. Hence, the most significant new structure is a dechlorination pond (DP) of 2.6 acres area and 12 ft depth (location shown in Figure 9). In fact, the concern over pathogens which might survive the stabilization ponds has diminished because fecal coliform standards (200/100 ml) are being met without chlorination. Chlorination has not been done, and the dechlorination pond has been used as an intermediate holding pond with two days capacity at 2 MGD.

CAPITAL COSTS

The capital costs include materials and labor for modifying the final holding pond, construction of the dechlorination pond, forceline to the wetland, irrigation header, irrigation lateral, wetland support structures, and monitoring and analytical equipment. The capital costs itemized below are complete except for engineering*, and except for research funds extended by the National Science Foundation for the initial proof-of-concept period.

Holding Pond Modification

Auxiliary pump structure	=	$ 6,500	
New and modified control structures	=	4,400	
Leveling	=	900	
Transfer pipe (to DP), 20-in., 1,605 ft @ $16.69	=	26,787	
Subtotal		$38,587	$38,587

Dechlorination Pond

Site preparation and excavation	=	$84,103	
Transfer pump structure	=	57,907	
Metering and control structures	=	11,200	
Subtotal		$153,210	$153,210

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* Design, construction inspection, hydrogeological studies, soils studies, O&M manual, startup assistance, etc.

Pond-Wetland Transmission

Forceline, 12-in., 5,589 ft @ $14.00, plus bends	=	$80,646	
Air-release and cleanout manholes	=	3,000	
Subtotal		$83,646	$83,646

Irrigation Header System

Header pipe, 12-in., 2,500 ft @ $7.50	=	$18,750	
Support Structure, 2,500 ft @ $12.97	=	32,425	
Subtotal		$51,175	$51,175

Irrigation Lateral System

Gated pipe (12-in., 10-in.,.... 6-in.)	=	$18,864	
Support structure 3,200 ft @ $12.97	=	41,504	
Valves, bends, reducers, end caps, tee	=	1,224	
Subtotal		$61,592	$61,592

Monitoring

Wells	=	$ 1,830	
Analytical equipment	=	7,890	
Subtotal		$ 9,720	$ 9,720
Total Capital Cost	=		$397,930
	≈		$400,000

Capital costs were offset by an 80% construction grant from the USEPA through the 201 facilities planning program. The design and award of Step 3 funds occurred ahead of the Clean Water Act of 1977 (14). At present the Houghton Lake Sewer Authority is applying to the state and federal construction granting agencies to secure retroactive alternative and innovative status for the wetland irrigation facility.

OPERATION AND MAINTENANCE COSTS

Wastewater Composition

Raw wastewater contains approximately 80-100 mg/l BOD, 60-80 mg/l suspended solids, and chloride of 100-110 mg/l. The wastewater is comparatively weak, probably because of long sewer lines. Phosphorus and the nitrogens are typical of normal domestic wastewaters. Wastewater applied to the wetland has COD of 12 to 27 mg/l, total phosphorus of 4 to 5 mg/l, total dissolved phosphorus of around 2 mg/l, nitrate-N of 1.2 mg/l, ammonia-N of 0-3.5 mg/l, fecal coliform of 150/100 ml and fecal streptococcus of 10/100 ml.

Electrical Energy for Wetland Irrigation Pumping

Energy consumption for irrigating the wetland includes that consumed in pumping from the dechlorination pond (DP) to the wetland.

In 1979, 101 MG were applied to the wetland between June 18 and August 20, with one week of shutdown for forcemain repairs. The average rate of irrigation in this period was 2 MGD, with water being applied at rates up to 3 MGD. Irrigation was often done round the clock.

Layne-single stage vertical turbine pumps (Model 14THC) operate between the DP and the wetland, with roughly 82% efficiency at 1600 rpm and 40 ft TDH.

The 1979 cost of pumping to the wetlands from the DP is, therefore, approximately:

$$101\text{x}10^6 \text{ gal. x } \frac{1 \text{ ft}^3}{7.49 \text{ gal.}} \text{ x } \frac{62.4 \text{ lb}}{\text{ft}^3} \text{ x } \frac{1 \text{ hp-sec}}{550 \text{ ft-lb}} \text{ x } \frac{1 \text{ hr}}{3{,}600 \text{ sec}} \text{ x } \frac{0.746 \text{ KW}}{\text{hp}}$$

$$\text{x } 40 \text{ ft TDH x } \frac{\$0.04}{\text{KWH}} \text{ x } \frac{1}{\text{p.e.}(82\%)} \text{ x } \frac{1}{\text{m.e.}(85\%)} = \$727.75$$

The calculated cost per million gallons is $7.21/MG.

Other O&M for Wetland Irrigation

Other O&M costs include repair, inspection, environmental monitoring and equipment. For the first seven months of 1979 the itemized costs are:

Irrigation pump (DP to wetland) and valve repair	$ 191.00
Semi-weekly inspection of the wetland system	400.00
Ecological monitoring (graduate student) and lab analyses of environmental waters	5,800.00
Laboratory equipment purchased	1,200.00

For the remaining months of 1979, assume repair and inspection costs to continue as shown, ecological monitoring to continue as shown through October and no new lab equipment. The total anticipated O&M for wetland irrigation in 1979, including irrigation energy, is therefore,

$$\$728 + \frac{12}{7}(191 + 400) + \frac{10}{7}(5{,}800) + \$1{,}200 = \$11{,}227 \text{ or } 111/\mathrm{MG}\,.$$

Environmental monitoring by the University of Michigan wetlands ecosystem research group continues with National Science Foundation support. This support is in addition to the $11,227 figure given above.

Overall Operating Costs

The wetland system O&M is approximately 20% of the total treatment O&M budget for the Tri-Township system. Total 1978 O&M costs for the complete Tri-Township treatment facility include maintenance and clerical salaries ($28,500 including benefits), electrical energy to pump wastewater ($13,409 including the final collection system lift station), insurance ($8,362), HVAC ($3,724), repair and replacement parts ($1,500), gasoline ($1,000), laboratory equipment ($654), postage and telephone ($500), custodial supplies ($370), and treatment personnel education ($150). The total 1978 figure is $58,169. Upward adjustment by 7.2% to the 1979 timeframe (11) yields $62,357 for current annual O&M costs.

The wastewater treated and disposed in 1979 was 101 MG (wetland) and 29 MG (seepage beds), for a total of 130 MG. The unit O&M costs for the entire Tri-Township treatment system are around $300/MG, because the flow to the treatment site is 198.5 MG/year with 68.5 MG being pond leakage or meter disagreement.

Because so many of this system's costs are fixed costs unrelated to flow, we calculate (without inflation) that, at design flow, the total O&M cost (including both collection and AWT) will fall to around $200/MG.

The design flows for the year 1998 are:

Annual average of 1.1 MGD
Eight-day peak flow of 1.85 MGD

The residential sewage service charge is $75/year, regardless of days of occupancy. Front foot assessments for local sewer construction ranged from $10 to $13/front foot.

Williams & Works' operation and management staff screened, hired and trained all permanent operating personnel, because the operating authority (Houghton Lake Sewer Authority) was a newly created public agency.

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Aquatic Plant Processes Session

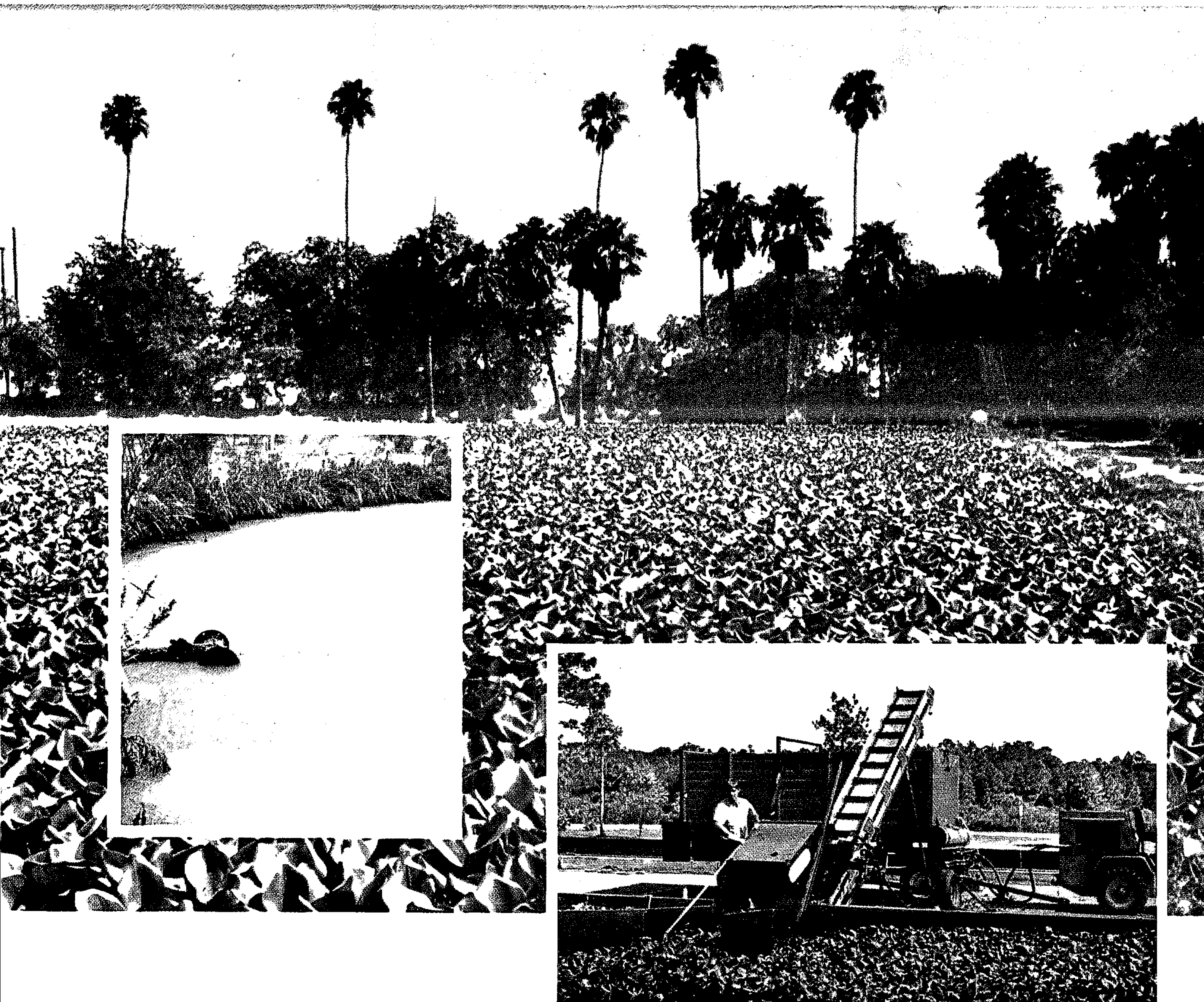

Photo of a large pond in San Juan, Texas covered by water hyacinths to help improve water quality. Inserts depict water hyacinths being harvested from the Disneyworld water hyacinths testing facility at Lake Buena Vista, Florida and a duckweed covered treatment pond near North Biloxi, Mississippi.

AQUATIC PLANT PROCESSES: SESSION SUMMARY

Presentations in this session covered wastewater treatment utilizing vascular aquatic plants with water hyacinth (Eichhornia crassipes) being the predominate plant discussed. The potential of more cold tolerant plants such as duckweed for treating domestic wastewater was briefly discussed.

Results of these studies clearly demonstrate the potential of higher plants in both domestic and industrial wastewater treatment. Wastewater lagoons are the most popular and inexpensive method of treating domestic wastewater in small communities. Data on upgrading sewage lagoons in Mississippi and Texas presented during the seminar demonstrated the potential for using this technology for improving the performance of lagoons located in warmer regions of the United States. Potential problems associated with using water hyacinth to upgrade sewage lagoons were identified along with suggested solutions.

When plant coverage is complete, single cell lagoons with BOD_5 loading rates in excess of 40 kg/ha/day without aeration are subject to producing odors, especially at night when the plants are not photosynthesizing. Multi-celled lagoons with surface aerators in the raw sewage cell and single cell lagoons with maximum BOD_5 loading rates of 30 kg/ha/day are the best candidates for upgrading these lagoons using water hyacinth or duckweed.

Data on the use of water hyacinth for tertiary treatment in Florida was presented. The data suggest that all parameters for tertiary treatment with the possible exception of phosphorus can be met in south Florida using approximately one acre of water hyacinth per 379 m^3/day of wastewater effluent from an activated sludge plant. Because the ratio of N:P in water hyacinth plant tissue is approximately 6:1 and the ratio in wastewater approximately 3:1, nitrogen is depleted first and becomes a limiting factor before the phosphorus is reduced below 1 mg/l.

Engineering data was also given for designing optimal water hyacinth and duckweed sewage treatment systems to achieve secondary and possibly tertiary treatment quality in small communities.

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4/28/80

ENGINEERING DESIGN DATA FOR SMALL VASCULAR AQUATIC PLANT WASTEWATER TREATMENT SYSTEMS

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A general background of the research findings of the National Aeronautics and Space Administration's Vascular Aquatic Plant Program using higher plants such as the water hyacinth (*Eichhornia crassipes*) and duckweed (*Lemna* sp. and *Spirodela* sp.) to treat domestic wastewater is presented. New data on a small two cell lagoon system using only duckweed is included. Further laboratory experiments were conducted to correlate BOD_5 removal with known wet masses of water hyacinths. The data from these experiments with domestic wastewater indicates that an average total BOD_5 removal rate of 4.0 mg BOD_5/gram WW (wet weight) could be achieved with a seven day retention time. When a phenol solution is substituted for the wastewater, the average total BOD_5 removal is 3.5 mg BOD_5/gram WW (wet weight) in seven days. This data along with the results of the previous field experiments is used to develop design criteria for small domestic wastewater treatment systems servicing a maximum of 3,000 people. The criteria for these systems addresses the problems of BOD_5 reduction, total suspended solids reduction, odor control, and sludge accumulation.

INTRODUCTION

In the United States, wastewater lagoons are the most popular and inexpensive method of treating domestic wastewater in small communities. Thousands of these lagoons exist throughout the United States for treating domestic sewage and various type animal and industrial wastewaters. Wastewater treatment lagoons vary from single to multiple celled systems. Some of the earlier sewage lagoons were improperly designed and constructed causing short circuiting, reducing the effective detention time and contributing to high BOD and suspended solids in the lagoon effluent. Today sufficient information is available to provide a basis for rational design and construction of wastewater treatment lagoons. For in depth information on wastewater treatment lagoons see Gloyna,[1] Middlebrooks[2] and Oswald.[3,4] Lagoon systems constructed in recent years are usually effective in BOD reduction; however, excess algae can still cause high suspended solids in the lagoon effluent during warm, summer months.

NASA at the National Space Technology Laboratories (NSTL) has been using higher plants for five years to upgrade wastewater treatment lagoons and treat chemical wastewaters.[5,6,7] NSTL has also been conducting studies directed toward using higher plants to recycle waste in future space stations. The controlled use of higher plants such as water hyacinths (*Eichhornia crassipes*) and duckweeds (*Spirodela* sp., *Lemna* sp. and *Wolffia* sp.) in conjunction with waste stabilization ponds not only increased the BOD removal capacity of these systems, but also reduced the high total suspended solids normally associated with sewage lagoons. Higher plants reduce suspended solids in lagoon effluents by reducing algae which make up a large portion of the suspended solids. Nitrogen, phosphorus, potassium, sulfur, calcium and other minerals can be removed from domestic sewage by harvesting the plant biomass. This harvested plant material is also a potential source of energy, fertilizer, feed, food and other products.

One important question about the design of vascular aquatic plant waste treatment systems that has not fully been determined or fully understood yet is the BOD removal rate that can be expected for this type system. The experiments in this report were designed to address this unknown and achieve reproducible and quantitative answers to this question. Results of these experiments and previous field studies were combined to develop design parameters for energy-efficient waste treatment systems for small communities using vascular aquatic plants.

BACKGROUND

In addition to upgrading all wastewater treatment systems at NSTL using water hyacinths and duckweeds, NASA has conducted several field studies with local communities in South Mississippi directed toward improving their lagoon systems using higher plants. Systems described here will include two single cell lagoons, one at NSTL and one at Lucedale, Mississippi, and two multi-cell lagoons at Orange Grove and Cedar Lake developments at Gulfport and Biloxi, Mississippi, respectively.

The single cell lagoon at NSTL has a surface area of 2 hectares and an average depth of 1.22 meters. The average flow rate of 475 m^3/day resulted in a detention time of approximately 54 days. The BOD_5 loading rate in this lagoon averages 26 kg/ha/day, which constitutes a relatively light load. Before water hyacinths were added to this lagoon, the raw sewage entering at the center of the system averaged 91 mg/l BOD_5 and 70 mg/l total suspended solids (TSS) with effluent averages of 17 mg/l BOD_5 and 49 mg/l TSS. Concentrations of BOD_5 and TSS during a 14 month water hyacinth covered study period were: influent BOD_5 110 mg/l and TSS 97 mg/l, and effluent BOD_5 7.4 mg/l and TSS 10 mg/l.[6] Plants harvested from this lagoon contained 2.73% kjeldahl nitrogen and 0.45% total phosphorus (dry plant weight).

A single cell facultative lagoon located at Lucedale, Mississippi was studied extensively with and without water hyacinth coverage.[8] This lagoon has a surface area of 3.6 hectares (9 acres) and an average depth of 1.73 meters. Lagoon effluent flow rates during 100% water hyacinth coverage averaged 935 m^3/day. The BOD_5 loading rate was 44 kg/hectare/day. Before water hyacinths were added to this lagoon, the raw sewage entering averaged 127 mg/l BOD_5 and 140 mg/l TSS with effluent averages of 57 mg/l BOD_5 and 77 mg/l TSS. Concentrations of BOD_5 and TSS during the study period with complete plant coverage were: influent, 161 mg/l BOD_5 and 125 mg/l TSS; effluent, 23 mg/l BOD_5 and 6 mg/l TSS. With complete water hyacinth coverage this lagoon was almost entirely anaerobic with only traces of dissolved oxygen near the surface in the plant root zone. This condition produced odors at night when the plants were not photosynthesizing. The BOD_5 loading rate of 44 kg/hectare/day produced odors at night from this lagoon; whereas, a loading rate of 26 kg/hectare/day in the NSTL lagoon produced a relatively odor free system when covered with water hyacinths. Plants harvested from this system contained 3.56% kjeldahl nitrogen and 0.89% total phosphorus (dry plant weight).

A complex lagoon system at Orange Grove, Mississippi was used for conducting a 12 month study with water hyacinths in effluent from aerated lagoons.[9] This system consisted of two large aerated lagoons followed by three parallel unaerated lagoons. The flow rate into the water hyacinth covered lagoon averaged 1000 m^3/day. This lagoon had a surface area of 0.28 hectare and an average depth of 1.83 m. The flow rate resulted in an average detention time of 6.8 days. The BOD_5 of the influent entering this lagoon averaged 50 mg/l with an annual effluent average of 14 mg/l. The total suspended solids entering averaged 49 mg/l with an effluent average of 15 mg/l. A parallel, control lagoon without water hyacinth demonstrated effluent concentrations of 37 mg/l BOD_5 and 53 mg/l TSS. Freezing temperatures occurred during this 12 month study period killing the tops of the plants, and the decay of this large amount of biomass elevated the BOD_5 and TSS levels in the effluent during the months of January, February, and March. However, the water hyacinth covered lagoon still maintained the low effluent BOD_5 and TSS averages well below the permit levels of 30 mg/l each. Because of the 1.83 m (6 ft) depth, the dissolved oxygen averaged 2.0 mg/l in the effluent but was increased to 5 mg/l following a 0.91 m (3 ft) drop to a drainage ditch. Plants harvested from this system contained a 3.74% kjeldahl nitrogen and 0.85% total phosphorus (dry plant weight). Evapotransporation rates can be expected to reach as high as 40% of the total influent volumes per day during hot summer months. This characteristic was not considered in the interpretation of these field studies; therefore, the effluent BOD_5 and TSS concentrations should be up to 40% less during the summer months.

A fourth system which is still being studied is a two cell lagoon system located at Cedar Lake development in North Biloxi, Mississippi. This system shown in Figure 1 has been in operation for 9 years. It has been receiving its present load of approximately 49.2 m^3/day (13,000 gal/day) from 51 homes for 7 years. This system was designed as a conventional, two cell lagoon with aeration in the first cell. The first cell has a surface area of approximately 0.08 hectare (0.20 acre) and an average depth of 2.4 m (8 ft). The average flow rate of 49.2 m^3/day results in a detention time of approximately 36 days. The BOD_5 loading in this lagoon is approximately 128 kg/ha/day (114 lb/ac/day). The second cell has a surface area of 0.07 hectare (0.18 acre) and an average depth of 1.5 m (5 ft) with a detention time of approximately 22 days. Four years ago duckweed coverage of the second, unaerated cell occurred through natural means, and NSTL started monitoring this system in April 1979. Prior to this date monitoring had not been conducted; therefore, background data without duckweeds is not available at this time. In May approximately 50% of the duckweed coverage was removed for the first time in four years. The 5 hp surface aerator in the first cell was reduced to operating only at night. From May to December 1979 (see Table 1)

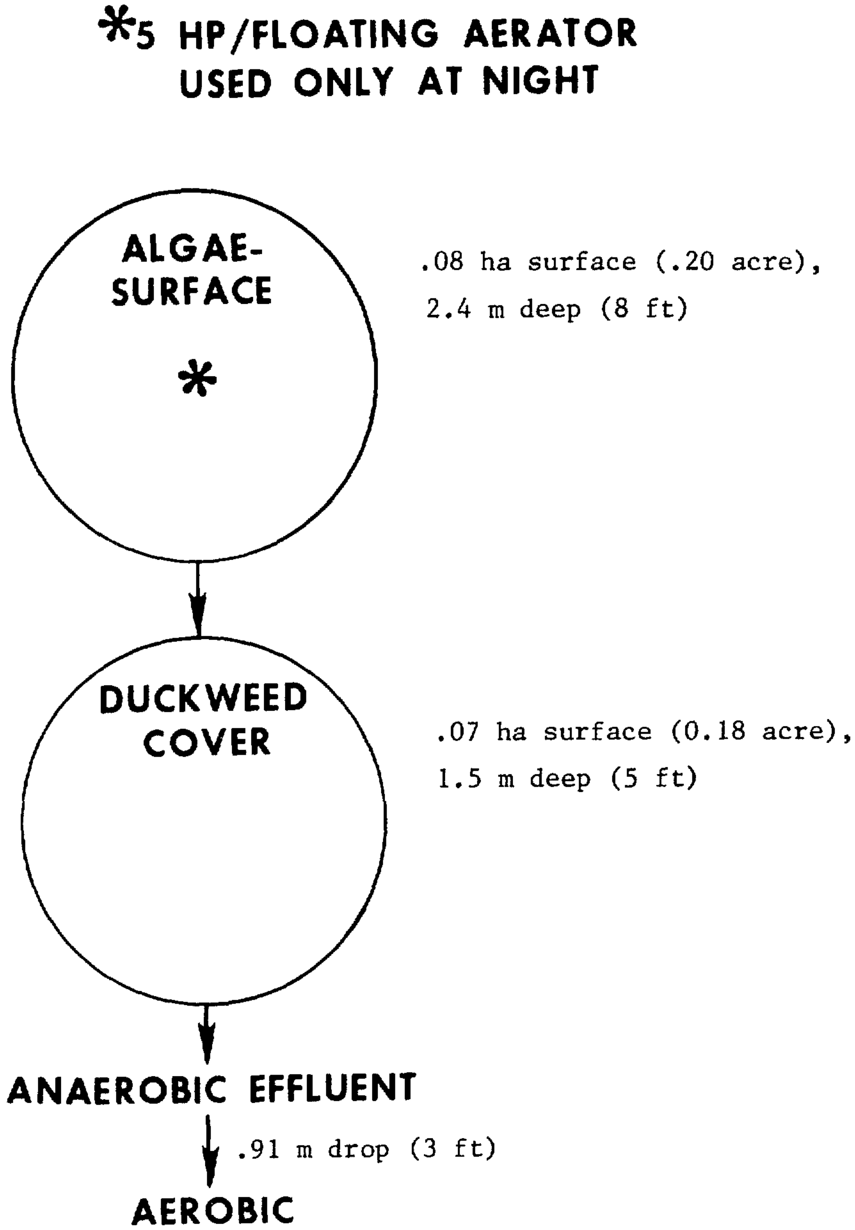

Figure 1. Sewage Lagoons Serving Approximately 200 People--Cedar Lake Development Biloxi, Miss.

Table 1. Monthly Average Data of TSS and BOD_5 for Duckweed Lagoon System Located at Cedar Grove Development in Biloxi, Mississippi.

Month, 1979	TSS, mg/l			BOD_5, mg/l		
	Aerated Lagoon		Duckweed Lagoon	Aerated Lagoon		Duckweek Lagoon
	Influent	Effluent*	Effluent	Influent	Effluent*	Effluent
May	178	397	10	200	64	20
June	194	176	9	203	67	28
July	420	108	16	138	34	13
August	271	113	8	160	13	10
September	233	132	22	173	20	17
October	173	96	19	171	15	8
November	142	61	11	290	29	10

*Also Influent to Duckweed Lagoon

the raw sewage entering the aerated cell averaged 191 mg/l BOD_5 and 230 mg/l TSS. Average influent and effluent concentrations of BOD_5 and TSS of the second duckweed-covered cell were: influent, 35 mg/l BOD_5; effluent 15 mg/l BOD_5; influent, 155 mg/l TSS; effluent, 14 mg/l TSS. The duckweed coverage on the second cell averaged 2 cm in depth producing an odor free anaerobic system 24 hours a day. The effluent dissolved oxygen concentration was 0.5 mg/l leaving the lagoon, but increased to 5 mg/l after dropping 0.91 m (3 ft) to a drainage ditch.

REMOVAL OF BIOCHEMICAL OXYGEN DEMANDING (BOD) SUBSTANCES BY HIGHER PLANTS

From field studies' data where water hyacinths were grown in domestic sewage lagoons, one can readily see that an additional reduction in BOD is taking place that can be attributed to the plants.[6,8] Because of the nature of most sewage lagoons with their long detention times and complex microbial make-up, controlled laboratory studies are desirable on BOD removal rate to obtain more exact quantitative data. Laboratory studies were conducted at NSTL under wide spectrum growth lights with 14 hour photoperiods in an effort to obtain more exact BOD data. Phenol, an organic chemical, was also used in these studies to further demonstrate the ability of water hyacinths to absorb, metabolize and remove BOD in a similar manner to microorganisms. Domestic wastewater consists of a complex mixture of chemicals including phenol and related organics. The initial volumes of raw sewage or phenol solutions were varied in order to vary the depth and surface to volume ratio. Some containers were left free of water hyacinths as controls to determine the bacterial contribution to BOD removal. In order to assure the same type of bacteria would be present in the controls that were associated with the water hyacinth roots, the plant roots were first dipped in all control solutions for bacterial seeding. Total bacterial counts and 5-day biochemical oxygen demands (BOD_5) were analyzed according to Standard Methods.[10]

Results of these experiments are shown in Tables 2-4. This data indicates that the water hyacinth alone can be expected to reduce BOD_5 of domestic sewage by an average of 1.5 mg BOD_5 per gram of plant mass (wet weight) with liquid detention times of 6 to 7 days. Water hyacinths and microorganisms together can be expected to remove an average of 4.0 mg BOD_5/gram plant mass (WW) with the same detention times.

The ability of water hyacinths to remove BOD_5 produced by other substances such as phenol is demonstrated in Table 4. This data indicates that water hyacinths and microorganisms can remove 3.5 mg BOD_5/gram plant mass (WW) from aqueous solutions in 7 days containing 100 mg/l phenol. The BOD_5 removal due entirely to the water hyacinth was 1.4 mg BOD_5/gram plant mass (WW). These values are consistent with those found with domestic sewage.

These BOD removal rates were achieved with daily growth rates of 3-4%; whereas, field studies have shown average daily growth rates as high as 6% when water hyacinths were grown in sewage lagoons in South Mississippi.[12] The BOD and suspended solids removal rates are not entirely dependent on growth and harvesting rates; whereas the removal of nutrients such as nitrogen and phosphorus is dependent on these variables. The BOD removal rate is dependent on root absorption and metabolic functions; the suspended solids reduction appears to be associated with algae elimina-

Table 2. 5-day Biochemical Oxygen Demand (BOD_5) and Bacteria Concentrations in Raw Sewage With and Without (Control) Water Hyacinths.

Experiment	Fresh Mass WHS, g	Total BOD_5 mg/l			mg BOD_5 removed/ 6 days	mg BOD_5 removed/ g WHs (6 day exposure)	Bacteria, count/100 ml		
		Initial	3rd Day	6th Day			Initial	3rd Day	6th Day
1. w/WHs	1,860	60	---	5	4,070	2.2	8.0×10^5	---	3.0×10^4
2. Control	0	60	---	24	2,664	---	8.0×10^5	---	3.1×10^4
3. Control	0	60	---	35	1,850	---	8.0×10^5	---	2.3×10^4
4. w/WHs	2,140	180	48	9	12,664	5.9	7.7×10^5	1.0×10^4	1.0×10^4
5. w/WHs	2,000	180	36	7	12,802	6.4	7.7×10^5	6.5×10^4	5.0×10^3
6. Control	0	180	100	65	8,510	---	7.7×10^5	3.6×10^4	1.4×10^4

Conditions: Mean Atmospheric Temperature: 22°C

Volume of Raw Sewage: 74 l

Depth: 61 cm

Table 3. 5-day Biochemical Oxygen Demand (BOD_5) And Bacteria Concentrations in Raw Sewage With and Without (Control) Water Hyacinths.

Experiment	Fresh Mass WHS, g	Total BOD_5 mg/l			mg BOD_5 removed/ 7 days	mg BOD_5 removed/ g WHs (7 day exposure)	Bacteria, Count/ 100 ml		
		Initial	4th Day	7th Day			Initial	4th Day	7th Day
1. w/WHs	506	190	36	20	2040	4.0	TNTC	1.0×10^5	38×10^5
2. w/WHs	429	190	40	20	2040	4.7	TNTC	3.0×10^5	231×10^5
3. w/WHs	413	190	38	21	2030	4.8	TNTC	1.0×10^5	208×10^5
4. Control	0	190	170	85	1260	---	TNTC	1.0×10^5	44×10^5
5. w/WHs	376	112	*50	**21	**1090	**2.9	7.0×10^6	*3.3×10^6	**2.5×10^6
6. w/WHs	412	112	46	18	1130	2.7	7.0×10^6	4.3×10^6	2.7×10^4
7. w/WHs	386	112	42	22	1080	2.8	7.0×10^6	2.7×10^6	1.2×10^5
8. Control	0	112	76	48	768	---	7.0×10^6	*** TNTC	4.5×10^5
9. Control	0	112	69	60	624	---	7.0×10^6	3.1×10^6	3.1×10^6
10. Control	0	112	60	48	768	---	7.0×10^6	2.2×10^6	3.6×10^5

* 3rd day for experiments 5-10

** 6th day for experiments 5-10

*** TNTC - Too numerous to count

Conditions: Mean Atmospheric Temperature: 29°C

Volume of Raw Sewage: 12 l

Depth: 15 cm

Table 4. 5-day Biochemical Oxygen Demand (BOD_5) and Bacteria Concentrations in 100 mg/l Phenol Solutions With and Without (Control) Water Hyacinths

Experiment	Fresh Mass WHs, g	Total BOD_5, mg/l		mg BOD_5 removed/7 days	mg BOD_5 removed/ g WHs (7 day exposure)	Bacteria, Count/100 ml	
		Initial	7th Day			Initial	7th Day
1. Control	0	160	114	184	---	106×10^5	250×10^4
2. Control	0	160	120	160	---	148×10^5	51×10^4
3. Control	0	160	115	180	---	115×10^5	174×10^4
4. w/WHs	155	160	35	500	3.2	110×10^5	61×10^4
5. w/WHs	200	160	37	492	2.5	37×10^5	82×10^4
6. w/WHs	298	160	35	500	1.8	143×10^5	24×10^4
7. Control	0	235	136	396	---	3×10^4	34×10^5
8. Control	0	235	115	480	---	1×10^4	TNTC
9. Control	0	235	116	476	---	2×10^4	---
10. w/WHs	120	235	26	836	7.0	1×10^4	60×10^6
11. w/WHs	242	235	15	880	3.6	1×10^4	3×10^5
12. w/WHs	293	235	29	824	2.8	1×10^4	TNTC

Conditions: Mean Atmospheric Temperature: 29°C

Volume of Phenol Solution: 4 l

Depth: 13 cm

tion prior to discharge.

DESIGN PROPOSAL FOR DOMESTIC WASTEWATER TREATMENT SYSTEMS USING HIGHER PLANTS

Field and laboratory data collected during the past five years at NSTL indicate that a combination of conventional sewage technology and the controlled growth of higher plants such as the water hyacinth and duckweed can produce cost effective, advanced wastewater treatment systems in warm to moderate climate zones. Proposed designs for sewage lagoons using water hyacinths and duckweeds to treat domestic wastewater for small communities of 500 people or less is shown in Figure 2. The same type system for treating wastewater for communities of 1000 to 3000 people is shown in Figure 3. In arriving at the following proposed design characteristics, four problems had to be addressed: (1) sludge accumulation, (2) odor control, (3) BOD reduction, and (4) total suspended solids removal. Nitrogen and phosphorus removal must also be considered if tertiary treatment is required.

In order to minimize sludge handling problems, deep lagoons approximately 3 m (10 ft) in depth, with small surface areas appear to be the most practical method for initial treatment and sludge collection. Deep lagoons receiving raw sewage have advantages and disadvantages. These lagoons act as anaerobic digesters, producing foul odors due to the liberation of hydrogen sulfide gas during the sewage digestion process. Approximately 114g (0.25 lb) of slude per person is generated daily in domestic sewage. The total settled solids in sewage can be reduced by 40-50% and given off as gases if the sludge is anaerobically digested.[11] Yearly sludge accumulation per person after anaerobic digestion is approximately 23 kg (51 lbs). The proposed design in Figure 2 should allow approximately 100 years of operation with 500 people before presenting a sludge removal problem. The design in Figure 3 should operate for approximately 30 years with 3,000 people before sludge removal is needed. Anaerobic digestion for the initial treatment of raw sewage not only reduces the sludge solids, but also reduces the complexity of BOD substances and the concentration of toxic heavy metals when present. Sulfides produced during anaerobic digestion will react with soluble heavy metal ions to form a metallic sulfide precipitate that is relatively insoluble at pH near 7.0. Approximately 1.8 to 2.0 mg of heavy metals can be precipitated as metal sulfides by 1.0 mg of sulfide ($S^=$).[1]

In order to eliminate odor emission when anaerobic treatment is used in the first step, it is essential for the first lagoon to contain a photosynthetic aerobic zone, mechanically aerated surface zone, surface sealer, or a combination of these features. The most reliable means of assuring an aerobic surface zone for odor control appears to be the limited use of surface aerators. Studies in Mississippi with the system depicted in Figure 1 have shown that the use of surface aerators during dark hours and photosynthetic algae during daylight hours effectively controls odors with minimum aeration cost. A limited amount of research has been conducted by NASA on the use of duckweed as a photosynthetic surface sealer for small anaerobic lagoons. The use of duckweeds would eliminate the energy requirements of supplemental mechanical aeration. BOD_5 reductions in excess of 70% at hydraulic detention times of 1.2 days in anaerobic ponds was noted by Oswald et al.[3] Detention periods of up to 5 days were recommended to compensate for

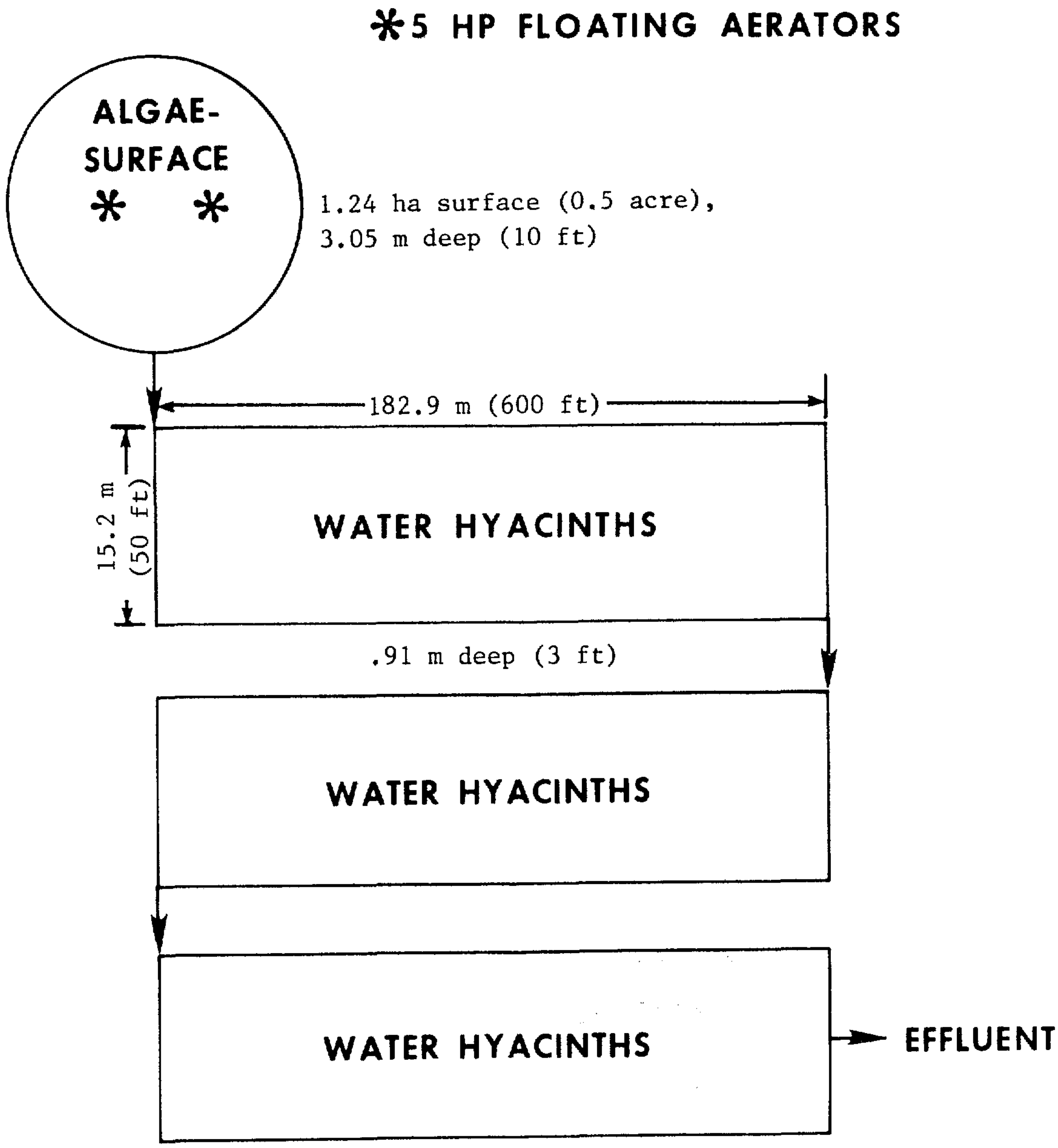

Figure 3. Water Hyacinth Sewage Treatment System Which Will Achieve Secondary to Tertiary Treatment Levels for Wastewater from 1000 - 3000 People.

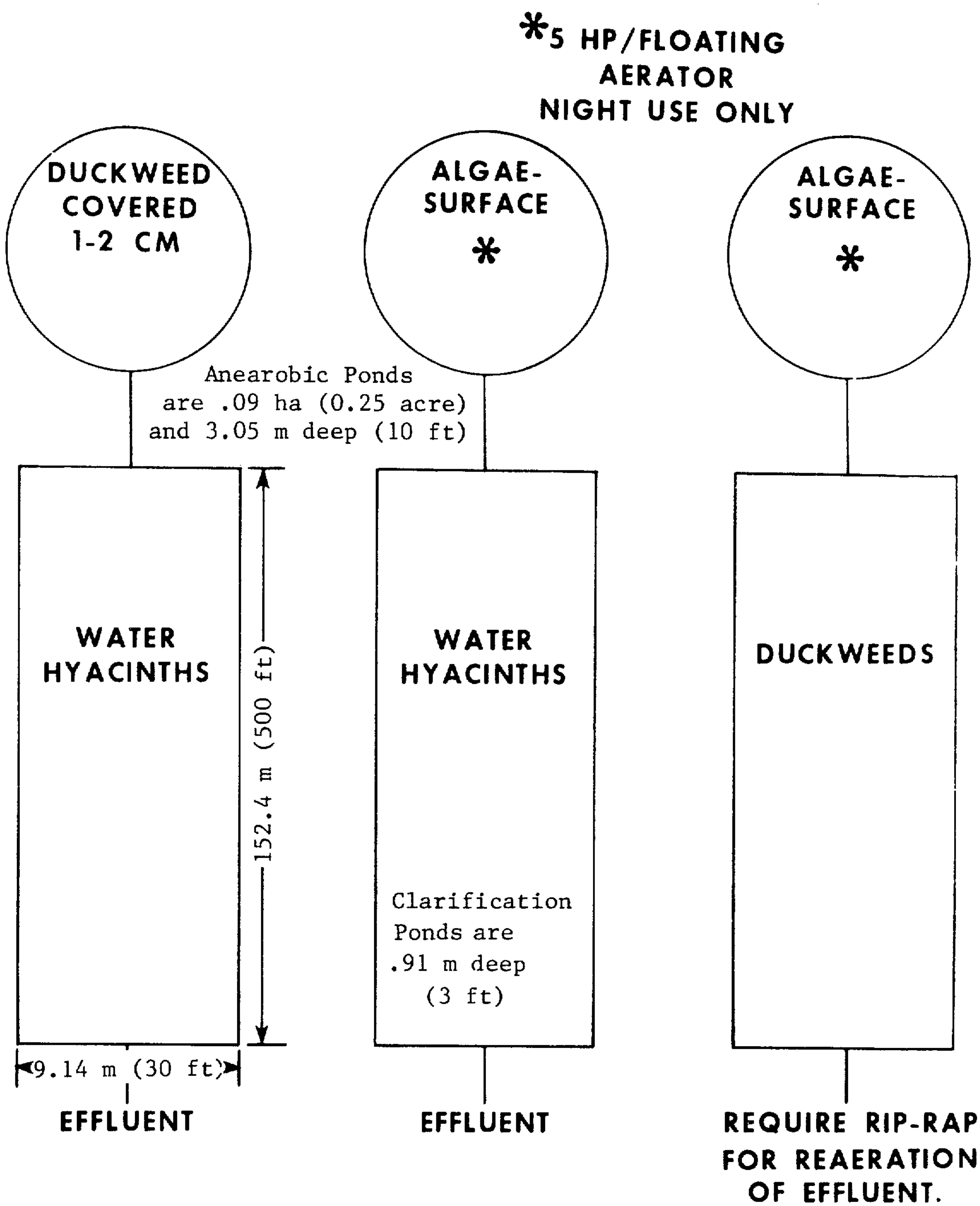

Figure 2. Water Hyacinth, Duckweed and a Combination Water Hyacinth-Duckweed Sewage Treatment Systems Which Achieves Secondary to Tertiary Treatment for Wastewater from 250-500 People.

decreased bacterial activity during cold weather. Detention times of 15 and 5 days are proposed for the anaerobic lagoons in Figure 2 and 3 respectively. When surface aerators are used, additional BOD removal at the rate of 24 kg/ha/day can be achieved.

The designs shown in Figures 2 and 3 are based on influent wastewater containing 150 mg/l BOD_5. These designs assume a 50% BOD_5 removal in the first anaerobic lagoon. Water hyacinth covered lagoons can be expected to remove approximately 1045 kg BOD_5/hectare every seven days or 148 kg BOD_5/hectare/day based on the results of the experiments and field data presented in this paper and an average standing crop of 220 mt/hectare (100 ton/ac).

If tertiary standards must be met, the total nitrogen and phosphorus must be reduced to 3 and 1 mg/l, respectively. Assuming a sewage influent containing 35 mg/l kjeldahl nitrogen and 7 mg/l total phosphorus with a daily increase and harvest rate of 5% plant mass, then the design in Figure 2 should achieve tertiary treatment levels for the waste of 250 people and Figure 3 for 1500 people. This is assuming a standing crop of 220 mt/hectares and a 0.91m (3 ft) depth in the elongated water hyacinth lagoons shown in Figures 2 and 3. Total suspended solid concentrations are reduced by water hyacinth coverage due to shading effects and possibly nutrient reduction.

Plant material harvested from this type system can be processed into usable products. Studies at NASA have shown that the simplest product produced from water hyacinths is compost, a complete plant growth media produced by aerobic decomposition. Plants such as cucumbers, squash, corn, tomatoes, peas, sorghum, etc., have been grown successfully using decomposing water hyacinths as the sole source of soil and food.

Another potential product from the harvested biomass is methane. Methane is produced by anaerobically digesting the fresh plant material. Current experiments at NSTL demonstrate that 0.18 m^3 (6.3 ft^3) of methane can be produced per dry kilogram of plant material in 24 days or less digestion time at 37°C.

An engineering handbook on the construction of vascular aquatic plant wastewater treatment systems will be available by January 1980.

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DEVELOPMENT OF HYACINTH WASTEWATER TREATMENT SYSTEMS IN TEXAS

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INTRODUCTION

Field observations revealed that turbid, enriched waters (municipal wastes, cannery wastes, and sugar refinery wastes) were clarified and stabilized after passage through natural water areas covered by water hyacinth (Eichhornia crassipes (Mart.) Solms). Staff of the Wastewater Technology and Surveillance Division began to speculate on the possibility of utilizing controlled hyacinth culture for improving stabilization pond effluent. Other possible uses of hyacinth culture envisioned included the clarification of turbid river waters used as domestic water supply sources and the demineralization of brackish ground waters.

Simple, solar-powered stabilization ponds have a number of positive advantages, including the reduction of adverse chemical and biological agents (Dinges, 1979). A decided disadvantage is that their effluents are filled with single-celled algae, nutrients, and excessive levels of fecal organisms (Dinges and Rust, 1970). Several hundred stabilization pond systems are used in Texas for treating municipal, industrial and agricultural wastewaters. Many pond systems discharge to small streams and to watercourses with intermittent flow. Some of these waterways enter reservoirs utilized as sources for domestic water supply and for recreation. Sludge banks and foul, stagnant pools of water are not at all uncommon below the discharges of stabilization ponds. Smallhorst (1963) expressed the need for research to improve stabilization pond effluent quality by biological means.

Preliminary observations on hyacinths grown in wastewaters were commenced in 1970. A basin was constructed at a private residence in Dale, Texas for that purpose. The basin was about 2-m in width, 9-m in length, and operated at a a depth of 1-m. Septic tank effluent was diverted into the basin and the desired water level maintained by periodic addition of well water. Plants grew well in the diluted septic tank effluent and waters at the lower end of the basin remained clear.

Field Study

An opportunity was afforded to evaluate the effect of hyacinths on water quality in 1972. The City of Gregory, Texas is served by an overloaded wastewater treatment facility. Plant effluent discharges into a drainage ditch which empties into a 1.2-ha impoundment (Butterfly Lake). Overflow from Butterfly Lake goes into Corpus Christi Bay. The ditch and the lake have been covered by hyacinths for years.

Hyacinths were sprayed with broadleaf herbicide on two occasions in November, 1972. A field study was conducted from July through October, 1973 to determine water quality changes during regrowth of the plants (Dinges, 1973-1976). Water overflow from Butterfly Lake at that time was of good quality and contained 2 mg/l BOD_5 and 10 mg/l of total suspended solids. The unplanned hyacinth wastewater treatment system at Gregory is still functioning. Primary study emphasis was not directed towards organic quality improvement, but upon the capability of hyacinths to demineralize water. Water samples for chemical anaylsis were collected weekly from a 650-m section of the ditch having an estimated detention time of about 8 days. Results indicated a mean reduction in total dissolved solids of 59.3%. A portion of the observed decrease may possibly be attributed to ion exchange mechanisms associated with the peaty organic deposits present in the ditch.

Pilot Studies

Facilities. The City of Austin was approached and agreed to provide a pilot scale experimental hyacinth culture basin at the Williamson Creek wastewater treatment facility in November, 1974. The pilot unit was completed in April, 1975. See Figures 1 and 2.

Two wastewater treatment plants are located at the Williamson Creek facility. Plant A consists of an aerated basin equipped with a surface aerator, a clarifier and three stabilizaiton ponds. Sludge is returned to the aerated basin with excess sludge and clarified effluent being discharged to the ponds. The three ponds, which are about 1.2-ha in size, are operated in series and at a depth of about 2.44-m. There is no discharge from the system and excess water is pumped to a large pond of Plant B by an electric driven pump rated at 31.54-l/sec that is activated by a float switch. Design capacity of Plant A is 757-m^3·d and it receives controlled flows of 1,325 to 1,438-m^3·d.

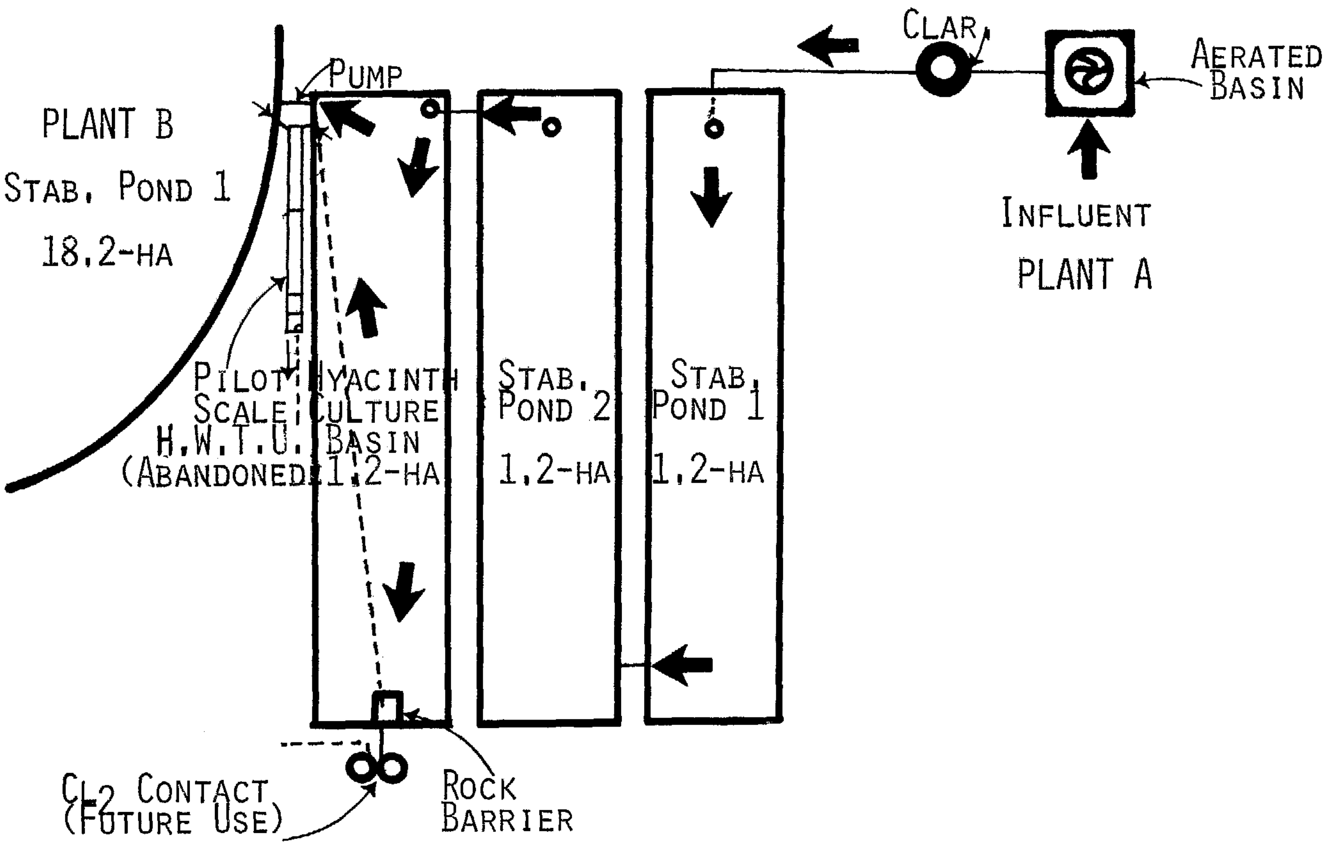
Plant B receives the remainder of daily flow, which averages 12,500-m^3·d. This plant consists of two aerated basins operated in parallel and three stabilization ponds. The three ponds are 18.2-ha, 15.4-ha and 13.0-ha in size and are 2.7-m deep.

An excavation 9.1-m wide and 64-m long (585-m^2) was constructed between Pond 3 of Plant A and Pond 1 of Plant B and divided into four sections by barriers of crushed stone 10 to 15-cm in diameter. Section 1 was 30.5-m in length and 0.6-m in depth. One half of the second section, which was 18.3-m long, was 0.6-m deep, and the other half was 3-m deep. Both of the remaining sections were 7.6-m long and 0.8-m deep.

Fig. 1 Austin, Texas-Williamson Creek Experimental Hyacinth Treatment Pilot System, 1975.

(Courtesy of S. Hart)

FIG. 2 CITY OF AUSTIN, TEXAS
WILLIAMSON CREEK EXPERIMENTAL
HYACINTH WASTEWATER TREATMENT FACILITIES



During the first study phase (June 1975 to February 1976), the experimental system was furnished with water obtained from Pond 3 of Plant A using an electrically-driven centrifugal pump rated at 3.15-l/sec. A 5-cm diameter steel pipe was used for water delivery. A waste line with a gate valve was provided to regulate inflow by discharging excess water back to the stabilization pond.

A more enriched water was acquired from Pond 1 (18.2-ha) of Plant B in the second study phase, which extended from May through August, 1976. Water was provided to the experimental facility by gravity flow through a 6.4-cm diameter steel pipe equipped with a gate valve for flow control.

A rectangular plastic (polyethylene) container 35.5-cm x 12.7-cm was placed in each section to serve as a sedimentation pan.

Mean water depth in the experimental system during the first study phase was 1-m. At a flow rate of 1.26-l/sec, theoretical system detention time was 5.3 days. Operational mean water depth was maintained at 85-cm in the second study phase and the detention period was 4.5 days at a flow rate of 1.26-l/sec. A 1.26-l/sec rate of flow was found to be about the maximum hydraulic loading that could be accpeted without causing breakthrough of solids. Flow introduced into the system amounted to 109-$m^3 \cdot d$, or the wastewater contribution of a community of about 300 people.

Surface organic loading on the experimental system was 4.34 $g/m^2 \cdot d$ BOD_5 in the first study phase and 8.93 $g/m^2 \cdot d$ in the second study phase. Influent-effluent samples were collected weekly and analyzed by accepted procedures.

Results. Extensive testing of system influent-effluent revealed that significant quality improvement in stabilization pond effluent was obtained by hyacinth treatment. Detailed results of the pilot studies have been reported upon previously (Dinges, 1976). A brief summary of selected water quality parameters evaluated are presented in Table 1.

Approximately 50 percent of influent phosphorus (P) and 80 percent of potassium (K) were removed in summer months. Leaching of P and K from the system occured during the winter. The standing crop of hyacinths at the end of a growing season represented a dry weight biomass production of 3,184 gm/m^2. This compares favorably to the similar measurement (2,970 gm/m^2) made by Wooten and Dood (1976). Mean moisture content of the plants was 94 percent and they had a mean ash content of 19.6 percent. Hyacinths accumulated heavy metals, other minerals, and trace organics from the water during the growing season.

Table 1

Pilot Studies-Indicated Mean Reductions in Selected Wastewater Quality Parameters Affected by Hyacinth Treatment

	First Study Phase June 1975-February 1976			Second Study Phase May 1976-August 1976		
	Influent	Effluent	% Reduction	Influent	Effluent	% Reduction
Chlorophyll a, mg/l	0.351	0.028	93	0.35	0.017	95
BOD_5, mg/l	22.6	5.2	77	46.5	5.7	87
TSS, mg/l	43.3	7	84	117	7.5	93
COD, mg/l	84	40	52	184	51	72
MBAS, mg/l	0.17	0.03	82	0.13	0.04	66
TN, mg/l	8.16	2.47	69	9.94	3.59	63
TON, mg/l	4.33	1.25	71	7.59	1.63	78
Fecal Coliform Bacteria/100ml	2895	31	98	27423	363	98

Pollutant Removal. Waters of a basin completely covered by a hyacinth mat are quite still, have a pH near neutral, and are almost totally shaded. Temperature fluctuations are moderated and stratification prevails during the summer. Phytoplanktonic algae growth is precluded due to light restriction and sedimentation is enhanced in the stilled waters. Coagulation of incoming algae cells and heavy sludge deposition occurs in the influent vicinity of the basin. Surface basin waters contain low levels of dissolved oxygen and bottom waters are anoxic. Free carbon dioxide levels are high. Hyacinth roots serve as a barrier to the horizontal movement of suspended solids.

The hyacinth overstory; surface water; root area; free water beneath the mat; and the basin bottom may be viewed as being biotic zones. Most biota reside in the surface and root zones. Extensive biological activity occurs in the influent region of a basin, resulting in a veritable "rain" of organic debris, much of which is not readily biodegradable. Bacteria, fungi, predators, filter feeders, and detritovores are present in large numbers. The biological reduction, oxidation, and consumption processes performed by the complex community of organisms in a hyacinth culture basin serve to stabilize water by releasing stored potential energy. Organic residues accumulate in the basin due to the physical processes of filtration and sedimentation.

Hyacinths obtain carbon dioxide from the air. Otherwise, hyacinth biomass is derived from soluble substances from the wastewaters in which they are growing. Plant uptake of materials from the water is restricted to the period of active growth. The overall improvement of waters passing through a culture basin may be attributed to the removal of suspended particulates fostered by the physio-chemical and biological factors related to the habitat provided. This fact becomes quite clear when waters exiting a basin are of high quality even in the winter when the hyacinths are frozen down to the water surface.

Plant Scale Study

Following the successful conclusion of the pilot studies, a full-scale facility treating an amount of wastewater which might be expected from a population of about 3,500 people was provided and placed into operation. See Figures 2 and 3. The experimental hyacinth culture basin is being operated as if it were an integral unit of the Williamson Creek wastewater treatment plant in order to learn more about operational-management procedures. Routine effluent quality evaluation is restricted to those parameters commonly included in discharge permit requirements.

Facility. The last 1.2-ha stabilization pond of Plant A was drained, cleaned, and converted into a hyacinth culture basin in October, 1977. A crushed stone barrier approximately 2.4-m in height and 21-m x 21-m in size was constructed at the lower end of the basin to prevent escape of the plants and to create a clear outlet zone. Influent is admitted to the basin from the second stabilization pond by an adjustable gate. Water depths have been varied from 0.7-m to 1.3-m in the hyacinth culture basin. System effluent is transferred to one of the nearby stabilization ponds of Plant B by an electrically driven pump rated at 31.5-l/sec. Flow to the wastewater treatment plant varies between 1,325 and 1,703 $m^3 \cdot d$. A somewhat lesser amount of water passes through the hyacinth basin due to seepage and evaporation losses. Test results from October, 1977 until August, 1979 are presented in Table 2.

Fig. 3 Austin, Texas-Outlet Area of the Williamson Creek Experimental Hyacinth Treatment System, 1979.

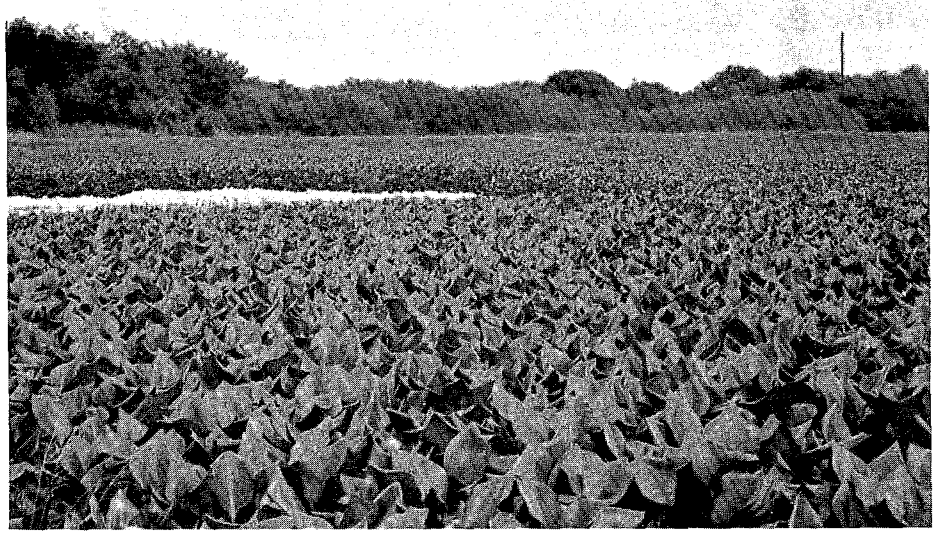


Table 2

Influent-Effluent Quality - Williamson Creek
Full-Scale Hyacinth Treatment System.

	October 1977 - August 1979				
	Influent	n	Effluent**	n	% Reduction
BOD_5, mg/1	41.9	(40)	12	(41)	71
TSS, mg/1	40	(41)	8.8	(42)	78
Fecal Coliform/	5388*	(28)	302	(31)	94

* One test result of 10 x 10^6 organisms not used in calculation of mean
** Includes data collected during two winter periods when plants had been frozen and were in a state of decay.

The culture basin was drained, cleaned and planted with hyacinths in May, 1979. Basin debris removed was buried in trenches at the plant site.

Other Municipal Hyacinth Treatment Systems

All municipal hyacinth treatment systems in Texas are considered to be experimental at the present stage of process development. Hyacinth treatment facilities are being monitored to learn more about system design, operation, and management procedure.

Austin-Hornsby Bend Sludge Treatment Ponds. Excess activated sludge from the Govalle and the Walnut Creek wastewater treatment plants is transferred to the Hornsby Bend pond system by force main. The facility consists of a 34.4-ha pond followed by two other ponds 26.3-ha and 16-ha in size. See figures 4 and 5. The system receives about 7,570 $m^3 \cdot d$ of excess activated sludge. A 1.4-ha hyacinth culture basin has been provided to treat the sludge pond system overflow. The upper end of the rectangular culture basin is quite shallow and deepens gradually towards the outlet. Maximum water depth is about 2.46-m and the mean basin depth is estimated to be 1.23-m. A section near the outlet has been fenced to provide a clear area and to serve as a chlorine contact zone. Chlorine is introduced at the fence line through perforated plastic tubing. A 90^o V-notch weir has been installed in the outlet drop box for flow measurement. Hyacinths were planted in the basin in late May, 1979. About 6,050 $m^3 \cdot d$ passes through the culture basin. Very little change between influent and effluent quality is evident at this hydraulic loading rate.

San Juan-Rio Grande Valley Pollution Control Authority. San Juan has a population of about 6,800 persons. Mean daily inflow to the wastewater treatment plant is 1,514 m^3, with peak flows being around 3,785 m^3.d. Influent to the plant is usually septic. The facility consists of a 0.97-ha raw sewage pond provided with a surface aerator; a 0.97-ha stabilization pond; two hyacinth culture basins 1-ha each in size; and a chlorine contact chamber. See Figures 6 and 7. Mean organic loading on the stabilization ponds is about 15.6 $g/m^2 \cdot d$ of BOD_5, or four times greater than suggested in the Texas "Design Criteria for Sewerage Systems." For short periods during canning operations, plant ponds may receive more than 30 times that amount of organic loading which would be appropriate. The surface aerator is to be enclosed within a small diked area within the raw sewage pond in the near future in order to increase oxygen transfer efficiency and treatment capability. System effluent quality from April, 1978 to March, 1979 is presented in Table 3.

The two hyacinth basins, which have been designated as A and B may be operated at depths from 15-cm to 1.4-m. Water from the second stabilization pond is delivered to the basins through pipes equipped with gate valves. Culture basins receive variable flow rates as there is little excess storage capacity in the feeder stabilization pond.

FIG. 4 CITY OF AUSTIN, TEXAS
HORNSBY BEND SLUDGE TREATMENT FACILITY

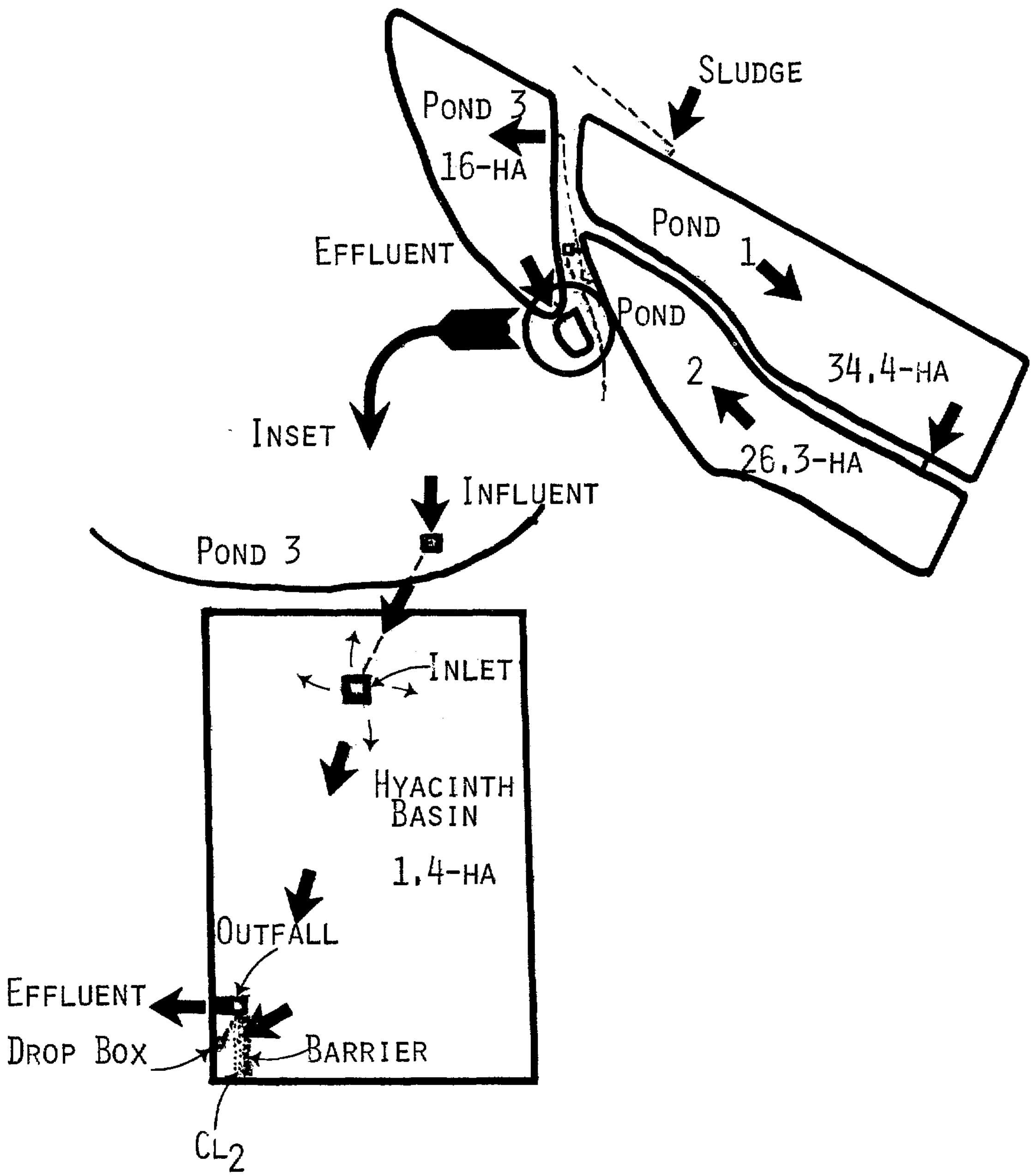


Fig. 5 Austin, Texas-Hornsby Bend Hyacinth Treatment System, 1979.

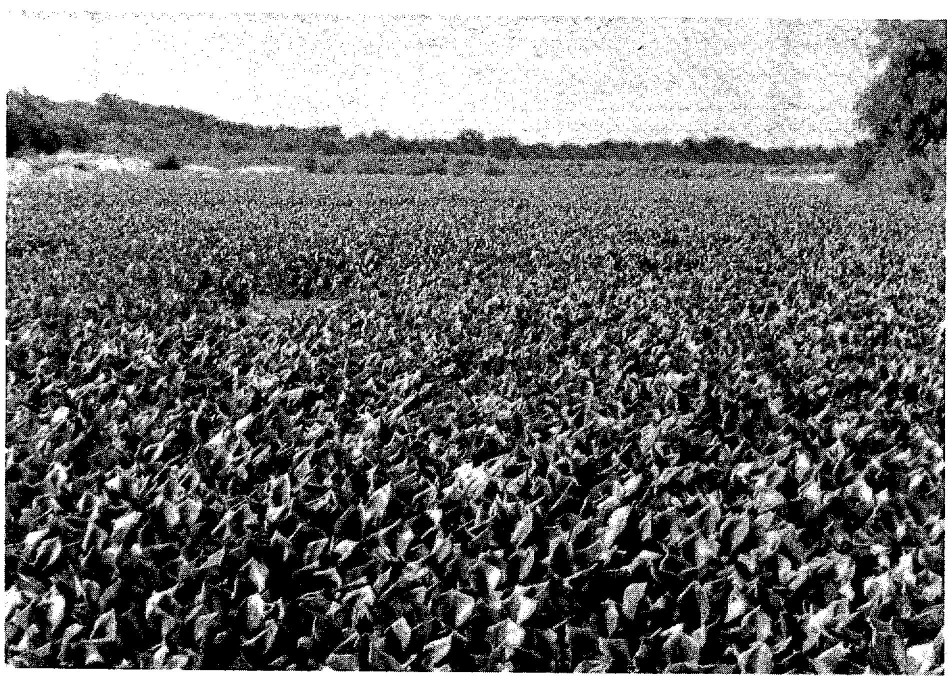


FIG. 6 RIO GRANDE VALLEY POLLUTION CONTROL AUTHORITY SAN JUAN, TEXAS

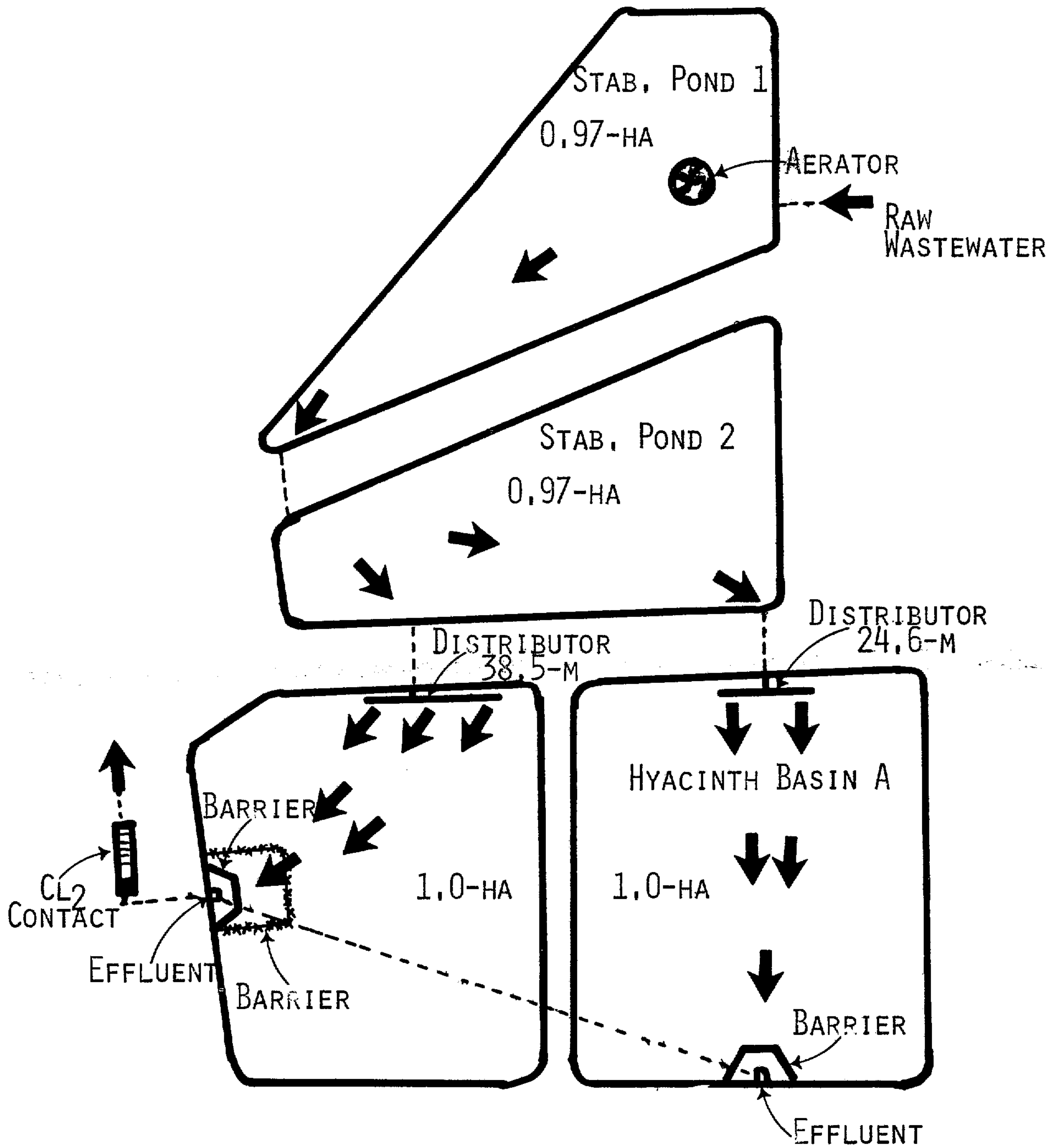


Fig. 7 San Juan, Texas-Hyacinth Basin A, 1979.

(Courtesy of H. Nordmeyer)

Table 3

San Juan Effluent Quality Data*

	April, 1978 - March, 1979	
	Annual Mean	Maximum Recorded
BOD_5, mg/l	23	40
TSS, mg/l	24	54

* One hyacinth unit in operation--Basin A.

Water is distributed to Basin A through a 24.6-m length of plastic pipe having 5-cm diameter openings at 3-m intervals. The basin outlet is located opposite the distribution pipe at a distance of 115-m. In designing a culture basin, it should be assumed that water will flow directly from the inlet to the outlet. Therefore, the "minimum effective zone" of Basin A is only 0.13-ha. It is planned to extend the distribution pipe along the entire inlet side of the basin (95.3-m) at the time the unit is drained for removal of hyacinths and basin debris. This will increase the effective zone to 0.52-ha, or one-half of the total basin area.

A wire screen is located a short distance in front of the outlet structure. An additional wire fence creating a clear zone of about 185 m^2 will be installed in the future to allow for reaeration of the water prior to discharge and prevent the discharge of debris drawn from beneath the mat by outflow velocity. An open water area around the outlet is especially important in the Rio Grande Valley where the natural waters contain elevated sulphate levels.

The San Juan hyacinth wastewater treatment system is being tested in cooperation with the Rio Grande Pollution Control Authority. Basin A has been operated at various depths and flow rates since July, 1978. Water samples are collected by personnel of the Rio Grande Valley Pollution Control Authority, refrigerated, and forwarded to the Department central laboratories for analysis. Test results are presented in Table 4.

Alamo-Rio Grande Valley Water Pollution Control Authority. Alamo has a population of about 5,500 persons. Mean daily inflow to the wastewater treatment plant is 1,514 m^3, with peak flows of 3,785 m^3. The plant facility consists of an Imhoff tank; a trickling filter; an aerated basin equipped with a surface aerator (2,838 m^3 capacity); two 4.04-ha stabilization ponds operated in parallel; two hyacinth culture basins (1.35-ha and 1.05-ha); and a chlorine contact tank. See figures 8 and 9.

Domestic wastewater flow is estimated to be 1,060 $m^3 \cdot d$ and is treated in the Imhoff tank and trickling filter. Cannery wastes and domestic effluent are introduced to the aerated basin. One-half of the discharge from the aerated basin is diverted to each of the stabilization ponds, thence into the hyacinth culture basins. Organic loading on the stabilization ponds is estimated to be about $4.6/m^2 \cdot d$ of BOD_5. Hyacinth culture basins were recently completed and planted with hyacinths. Effluent quality of the system from April, 1978 through March, 1979 prior to the introduction of hyacinths averaged 33 mg/l BOD_5 and 86 mg/l TSS. Monthly means of effluent BOD_5 and TSS were 38 and 68 mg/l in May, 1979 and 50 and 82 mg/l in June. The basins were partially covered by hyacinths during this period (<25%).

San Benito. San Benito has a population of about 17,500 persons. Mean daily flow to the wastewater treatment facility is 2,460 m^3, with peak flows up to 6,737 $m^3 \cdot d$. Plant influent is septic. The treatment facility consists of a 7.86-ha raw sewage stabilization pond, followed by four more stabilization ponds having a total surface area of 13-ha. The last pond has been divided into three sections by earthen dikes to serve as an experimental hyacinth treatment facility. Basins 1 and 2 are 0.8-ha each and Basin 3 is 2-ha in size. The three basins are designed to operate in series. About one-half of Basin 2 was covered by hyacinths and Basin 3 was completely covered with plants when the facility was inspected in June, 1979. See figures 10 and 11.

Table 4

San Juan-Rio Grande Valley Pollution Control Authority
Effluent Quality of Hyacinth Basin A at Various Loadings
and Operating Depths

n	Raw Sewage		July, 1978 - May, 1979 Basin A Effluent		Depth, cm.	Flow, m^3	Total % Removed	
	BOD_5, mg/l	TSS, mg/l	BOD_5, mg/l	TSS, mg/l			BOD_5	TSS
1	90	111	20	30	61	870	77.7	72.9
4	86.2	113.2	9.2	<11.2	91	852	89.3	90.1
7	265.7	221.5	35	30.4	91	1552	86.8	86.2
10	319.4	282	31	32.3	137	1855	90.3	88.5

FIG. 8 RIO GRANDE VALLEY
POLLUTION CONTROL AUTHORITY
ALAMO, TEXAS

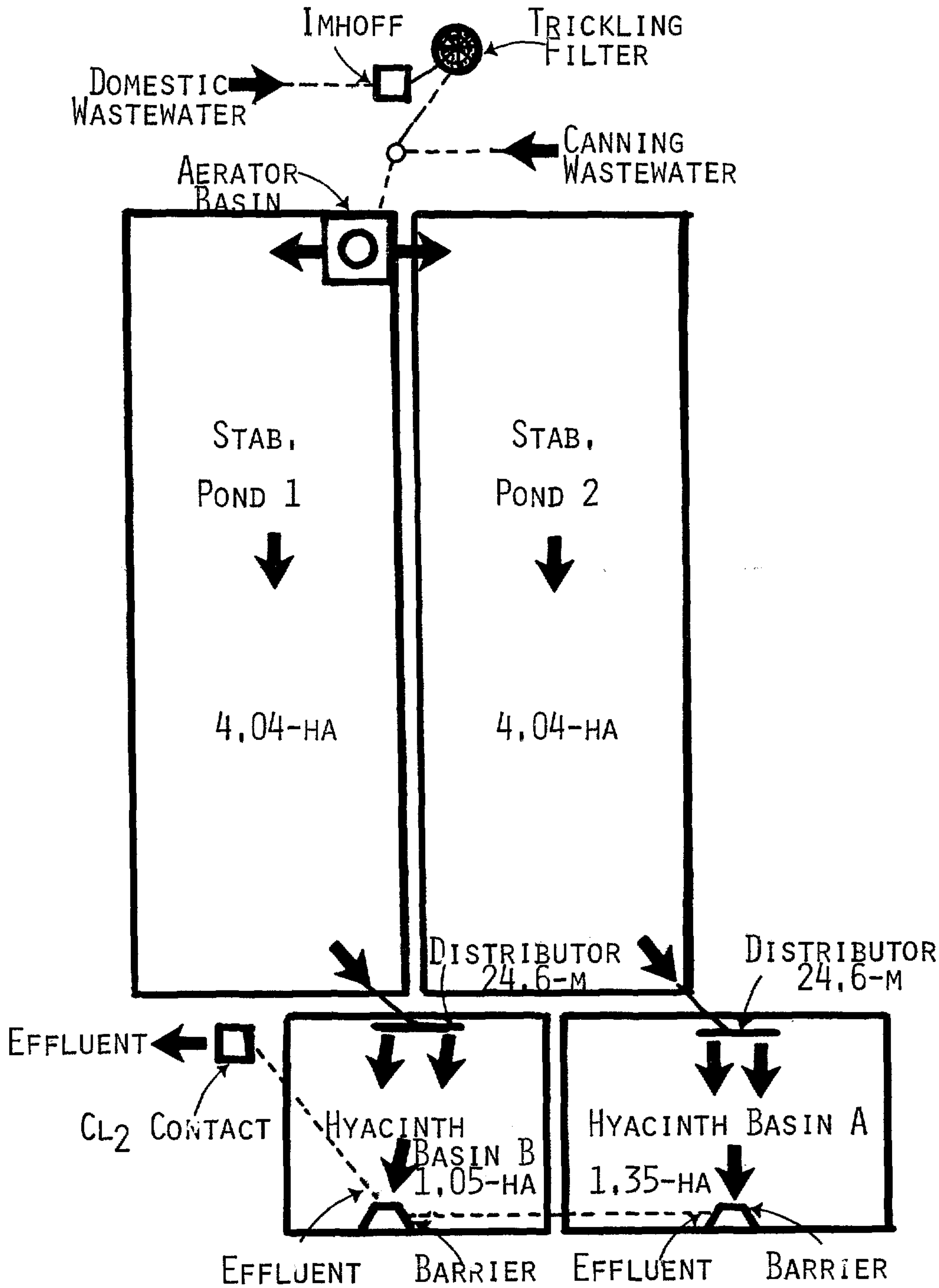
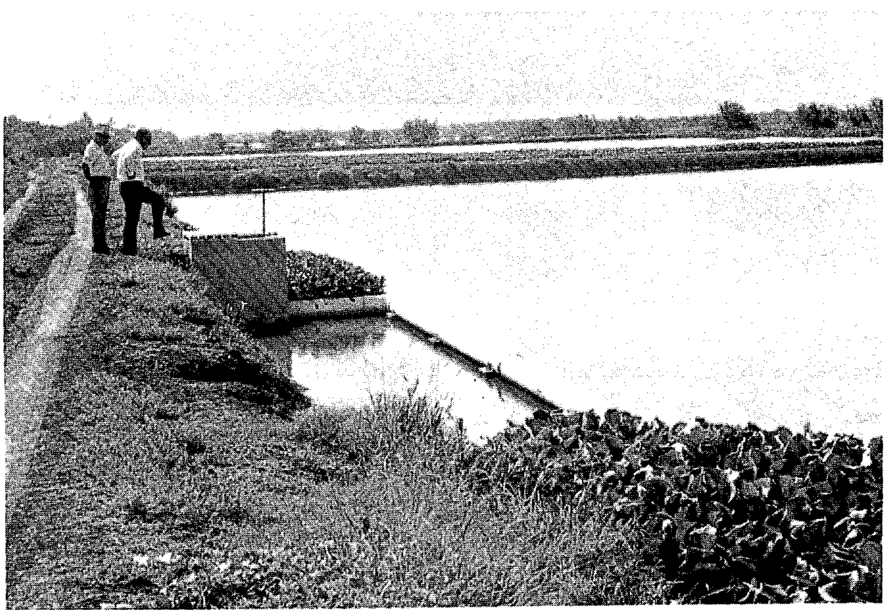


Fig. 9 Alamo, Texas-Distribution Pipe of Hyacinth Basin B. Basin A in Background, 1979.



(Courtesy of H. Nordmeyer)

Fig. 10 CITY OF SAN BENITO, TEXAS

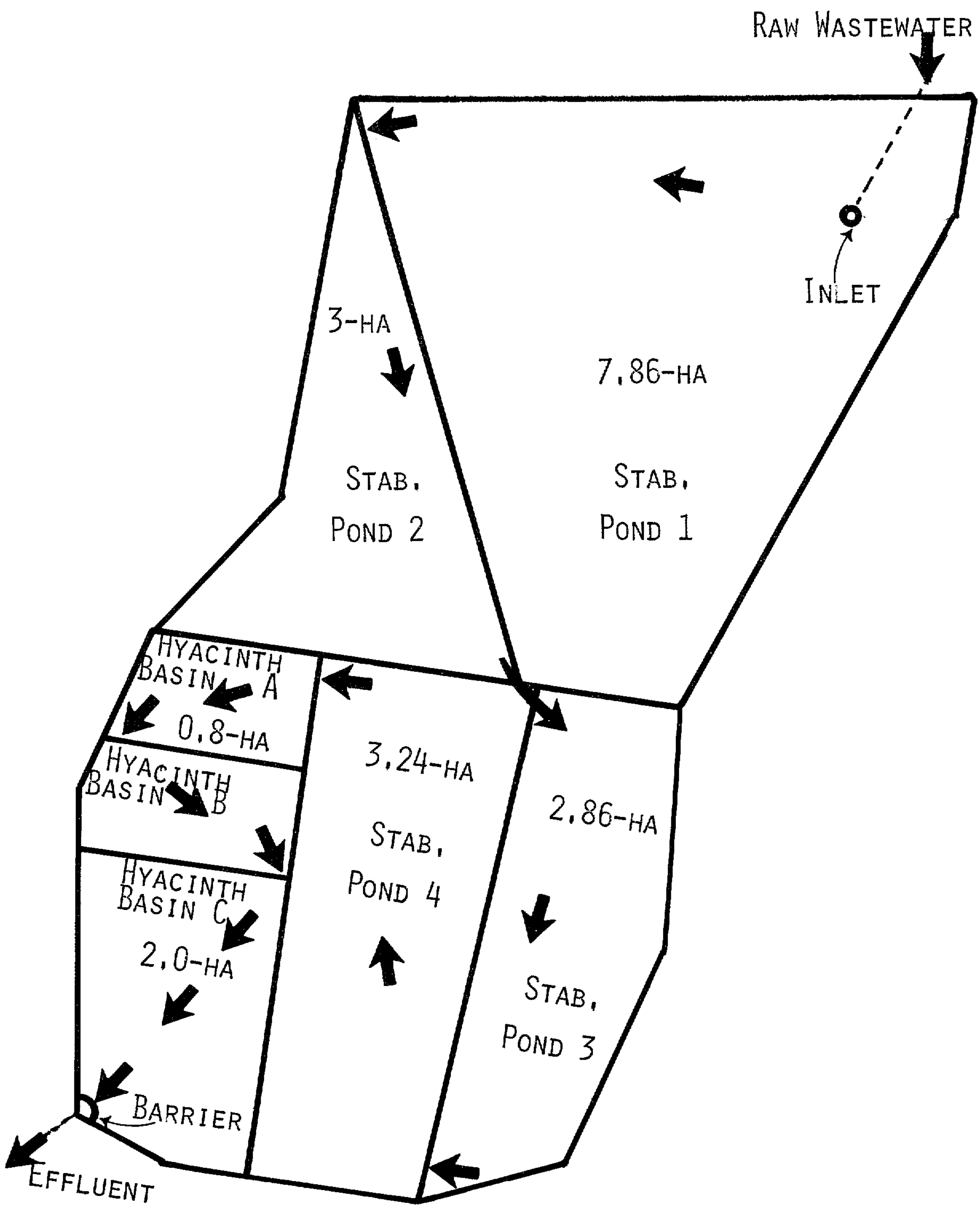
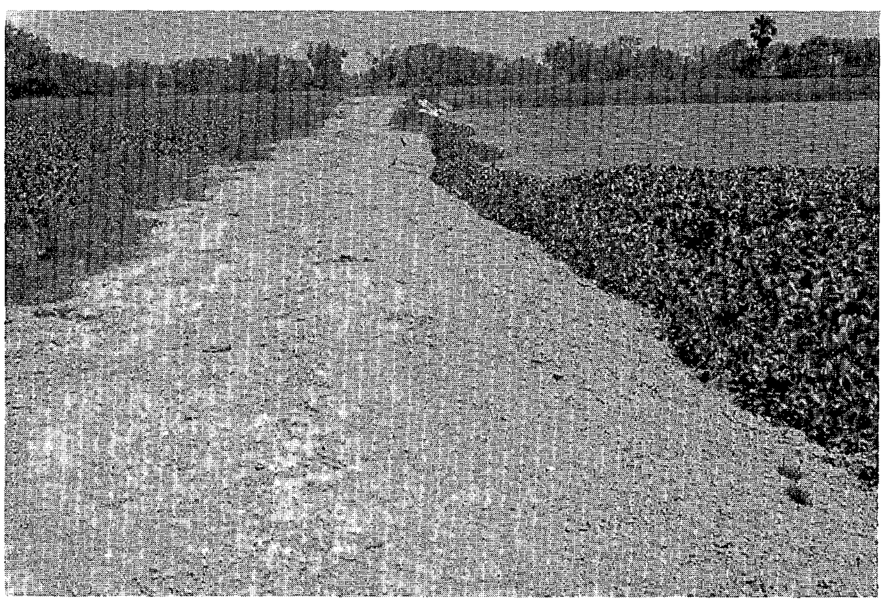


Fig. 11 San Benito, Texas–Two of Three Hyacinth Basins, 1979.



(Courtesy of H. Nordmeyer)

A wire fence barrier is located a short distance in front of the outlet. Changes in the design and operation of the system are being considered. Mean effluent quality from April, 1978 through March, 1979 averaged 17 mg/l BOD_5 and 35 mg/l TSS. The means of effluent BOD_5 and TSS were 17 and 20 mg/l for June, 1979.

Rio Hondo. Rio Hondo has a population of about 1,300 persons. A 0.8-ha raw sewage stabilization pond was constructed in 1950 to serve the city. The pond became filled with sludge over the years. Effluent quality from the pond had deteriorated to the extent that it was comparable to that of the raw wastewater. Hyacinths were planted in the pond a few years ago. Pond effluent quality improved somewhat. Sludge deposition was enhanced by the hyacinths and increased in depth until only a few centimeters of water remained in the pond.

Three 0.41-ha hyacinth culture basins have been constructed. Basins 1 and 2 are rectangular and Basin 3 is square. The raw sewage stabilization pond was bypassed and raw wastewater now discharges to Hyacinth Basin 1. Basin 1 and 2 are connected by piping. Water from Basin 2 is pumped to Basin 3, with a pump controlled by a float switch. Most of the surface areas of the three basins are now covered by plants. See figure 12.

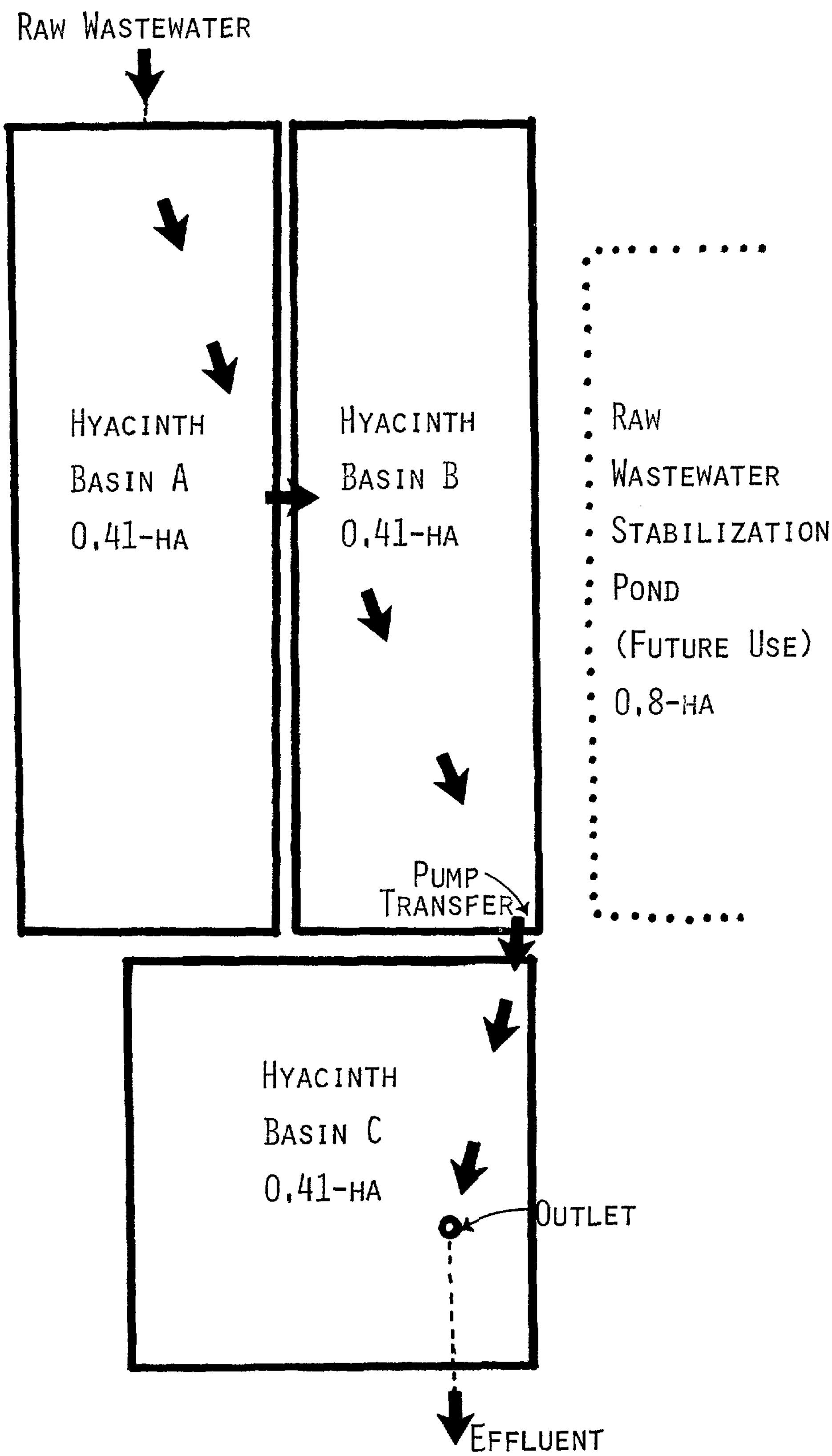
Raw sewage flow to the system is about 454 $m^3 \cdot d$. Hyacinth Basin 1 has an organic loading estimated to be 19.7 $g/m^2 \cdot d$ of BOD_5. Total system surface area has an organic loading of 6.6 $g/m^2 \cdot d$ of BOD_5. Effluent quality from July, 1978 through May, 1979 was 16 mg/l BOD_5 and 24 mg/l TSS. Monthly means of effluent BOD_5 and TSS were 10.5 and 6 mg/l in May and 14.5 and 12 mg/l in June, 1979.

The city plans to remove the sludge and restore the dikes of the raw sewage stabilization pond and place it back into operation. Modifications are also to be made to improve distribution of water through the hyacinth culture basins.

Design Considerations

Hydraulic Loading. Neuse (1976) conducted a study to define the hydraulic capability of a pilot hyacinth basin designed to remove suspended solids from stabilization pond effluent. A pilot unit having a channel configuration and with a surface area of 18.58 m^2 was constructed at the Williamson Creek wastewater treatment plant in Austin, Texas. The plastic lined channel had a width to length ratio of 12.5:1. Hydraulic loading rate on the system varied from 0.44 l/sec to 0.63 l/sec. Neuse concluded from his study that a second identical unit operated in series would be as efficient in solids removal as the first unit, but the amount of solids removed would be less. He postulated that a culture basin could be sized properly for any given hydraulic loading rate and proposed a broad rectangular configuration (channel replication) with even distribution of influent on one side and the discharge of effluent over an extended weir along the opposite side.

FIG. 12 CITY OF RIO HONDO, TEXAS



Operation of the Williamson Creek pilot hyacinth treatment system had revealed that hydraulic loading is a foremost design consideration. The basin produced low TSS levels at a sustained flow rate of 1.26 l/sec. Increasing the flow to 1.89 l/sec resulted in solids breakthrough. A culture basin which is not hydraulically overloaded should consistently produce <10 mg/l BOD_5 and TSS. Organic loading on a basin should normally be <10 $g/m^2 \cdot d$ of BOD_5 when input is stabilization pond waters.

When the pilot scale system was abandoned and allowed to dry out after two years operation, it was noted that most sludge accumulation had occurred in a semi-circle near the influent. The dried sludge layer was about 10-cm thick. Drainage of the full-scale hyacinth system at Williamson Creek for cleaning after two years of continuous operation revealed a fan-shaped area in the influent vicinity with a sludge (wet) depth of about 0.6-m.

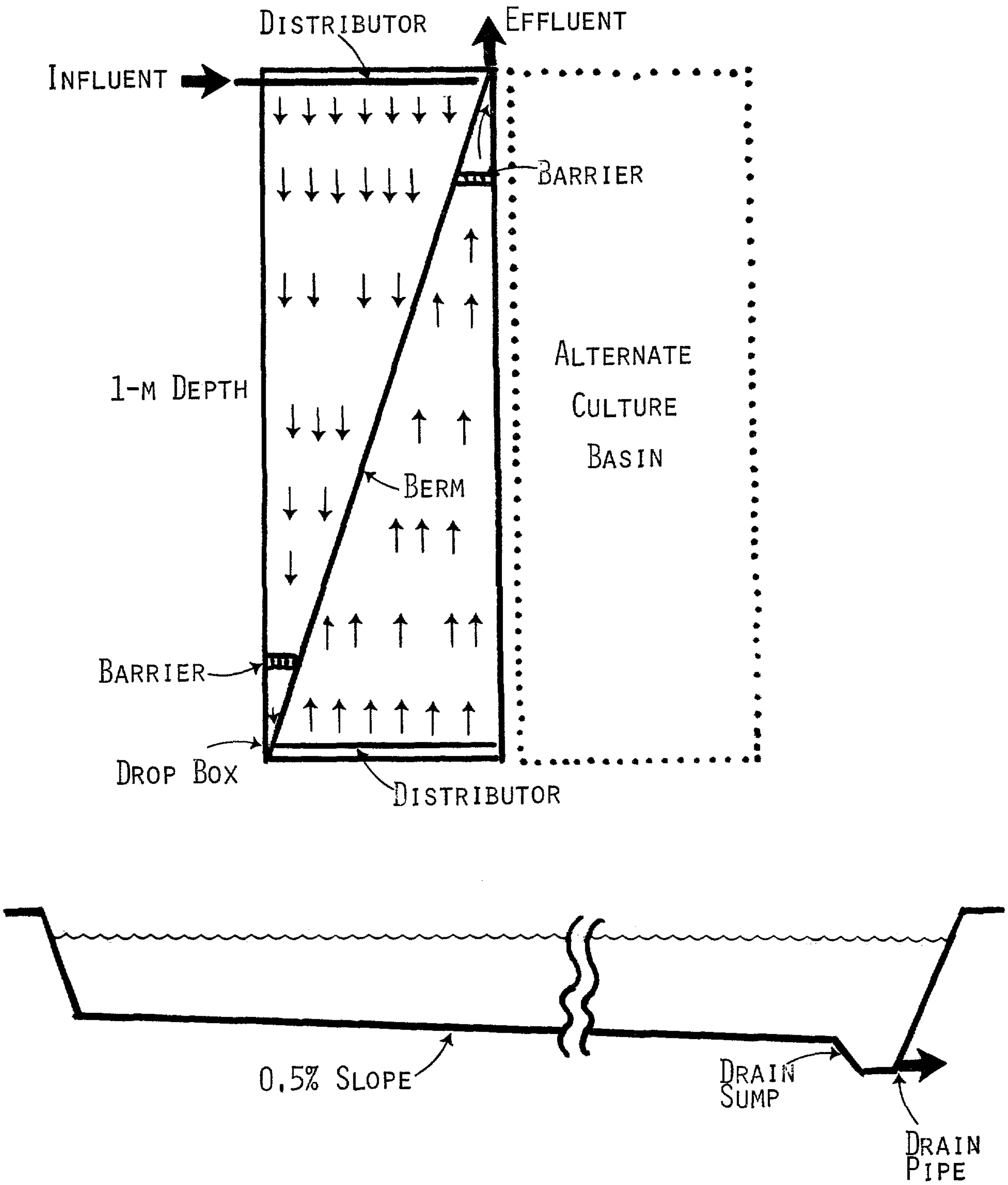
An elongated rectangle may be satisfactory in some instances, but it is certainly not an efficient configuration for a hyacinth culture basin. The broad rectangular shape would be efficient, but the extended discharge weir and the barrier required would be costly. It is also difficult to maintain the integrity of an extended weir. It was suggested by S.W. Hart, Chief, Engineer, Wastewater Technology and Surveillance Division, that a triangular basin might be appropriate. Influent could be distributed over a broad front and an even flow throughout the entire basin area would be assured. However, triangular basins do not represent efficient land use. This objection was met by joining the two triangles to form a rectangular shaped unit as depicted in Figure 13. It is believed that this suggested basic design would maximize efficiency and be economical for open basins. Determination of optimum depth and detention is contingent upon the provision of a basin with hydraulic efficiency.

The Texas Department of Health recommendations for the construction and operation of hyacinth basins for upgrading stabilization pond effluent is in the Appendix. Adequate information is available for the design of hyacinth culture basins which are to be employed in tropical or sub-tropical regions. Optimum design parameters will be required in temperate climates using greenhoused hyacinth culture basins.

Discussion

Objectives. Residues (organic debris, animals, fish, plants, etc.) resulting from advanced biological wastewater treatment (ABWT) are viewed as being valuable products to be used for food, fuel, and fertilizer (National Academy of Sciences Report, 1979). There is an increasing universal interest in using wastewaters for the production of useful products (Dinges, 1980). Future development of ABWT is not restricted to technical consideration alone, but will be determined by social (philosophical) political and economic factors.

FIG. 13 SUGGESTED BASIC HYACINTH CULTURE BASIN DESIGN



Hyacinths may be used for livestock feed, fuel generation, and to improve micro-nutrient levels and moisture retention capability of soils in arid areas. Wastewaters have been considered as a liability in the past. Hyacinth culture is a means to reduce the negative economic impact of wastewater renovation.

A dichotomy exists, however, between the two desirable goals of optimum, efficient wastewater treatment and maximum hyacinth production. Efficient nutrient elimination is an objective of wastewater treatment. Conservation and optimum utilization of fertilizer is a goal of hyacinth production. Hyacinth production would require large land area and entail costs for harvest machinery, labor, and energy. These expenditures would need to be balanced against the value of the product obtained. The potential quantity of product would be limited by the volume of wastewater available. It follows that cities having large wastewater flows would be the most likely candidates for mass hyacinth production.

Nutrient Management. Conserving and circulating nitrogen would be a paramount consideration to maximize production. Use of plant material for methane generation would contribute to nitrogen conservation as it is not lost during anaerobic fermentation. Supernatant return to culture units would restore nitrogen and permit the fixation of additional carbon via plant growth.

Hyacinths accumulate large amounts of potassium, but it is unlikely that this macro-nutrient would be limiting in most instances. Adequate micro-nutrients would be available in incoming wastewaters. Phosphorus is present in wastewaters at levels which far exceed plant growth requirements. One possible economical means of excess phosphorus removal might be the addition of aluminium sulphate (alum) to the return digestor supernatant. Resulting sludge would be removed from the system.

Much more efficient nitrogen removal may be obtained in properly designed stabilization ponds than by hyacinth culture if the goal being sought is effective wastewater treatment. Nitrogen reduction could best be accomplished by utilizing a combination stabilization pond--hyacinth culture system.

Temperature. The hyacinth is a tropical plant. This does not preclude their seasonal culture in northern areas. Corn is also a tropical species. Water temperature is a controlling factor in hyacinth growth. Water temperature near the freezing point will result in death of the plants. Francois (1977) determined hyacinth growth characteristics at varying water temperatures in a phytotron. It was found that active growth was restricted to the range of 10 to 35^{o} C. Optimum growth was obtained in the range from 25 to 27.5^{o} C. Two days of exposure to a water temperature of 45^{o} C killed the plants.

Villamil, et al. (1979) obtained sustained production of near 108.2 kg/ha·d, or 39.5 MT/yr (dry weight) of hyacinth biomass in the ideal climate of Puerto Rico. It should be pointed out that these productivity measurements were based upon the vegative multiplication of plants. It is believed that an even higher rate of production might result if only plant stems and leaves were removed (mown) on a periodic basis.

Continuous culture in open basins in Texas is feasible only in the sub-tropical climate of the Lower Rio Grande Valley. Greenhouse protection will be required elsewhere. A single layer greenhouse cover will probably suffice in most areas of Texas. Insulated, double layered greenhouse covering may be needed in the Panhandle region. Raw sewage temperatures are usually above 10^{o} C even in cold regions in the abscence of excessive infiltration into sewers. There is also the possibility of installing solar collecting panels on properly oriented earthen berms inside the greenhouse to enhance temperature conditions. Deep culture basins (3-m) supplied with diffused aeration as proposed by Stewart, et al. (1979) might be advantageous. A 0.4-ha aerated hyacinth treatment system (open basin) receiving up to 1890 $m^3 \cdot d$ of raw and partially treated wastewaters is to be placed into operation in the near future at Port Arthur, Texas.

Residue Management. With one exception, continuous hyacinth harvest is not being practiced in Texas. A single, annual harvest is being suggested to remove dried plants and basin debris from culture basins.

Sludge constitutes a greater proportion of basin debris than that of plant biomass. Continuous harvest in small hyacinth treatment systems serves to disrupt treatment. Open areas in the mat allows algal growth and desirable biota are removed with the plants.

Application. Hyacinth culture may be used in almost any instance where there is a need to improve organic, or mineral water quality. Hyacinth culture can be used as a complete treatment process with unscreened raw sewage being introduced directly into the culture unit. Effluent quality from such a properly designed system may be expected to equal, or exceed that obtainable by conventional secondary processes.

Seasonal hyacinth cultivation could be employed to remove excess nutrients from small lakes. Water from the subject lake would be pumped to a hyacinth culture unit and return by gravity flow. The culture basin would be taken out of operation, drained, and the accumulated debris removed at the end of each growing season.

Upgrading secondary wastewater treatment plant effluent quality, biomonitoring, pre-treatment of raw water supplies, removal of specific chemical compounds, and the demineralization of brackish waters are other possible uses for hyacinth culture.

Concepts

Biological Demineralization. Many arid areas of the World are underlain by aquifers whose waters are saline. Biological demineralization of brackish waters by hyacinth culture is an exciting possibility.

About 20 percent of dry hyacinth biomass is ash (minerals). Plants grown in the Williamson Creek pilot system contained a mean chloride content of 6.35 percent on a dry weight basis. Boyd (1970) reported a chloride level of 5.95 percent (dry weight) in hyacinths. Parra and Hortenstine (1974) determined the chemical composition of wild hyacinth populations in Florida. Maximum dry weight percentages of elements found were: Potassium - 6.5; calcium - 2.41; magnesium - 1.86; and sodium - 1.54. Wolverton and McDonald (1976) recorded a 14 percent decrease in total dissolved solids content of wastewaters treated in an open hyacinth basin at Orange Grove, Mississippi.

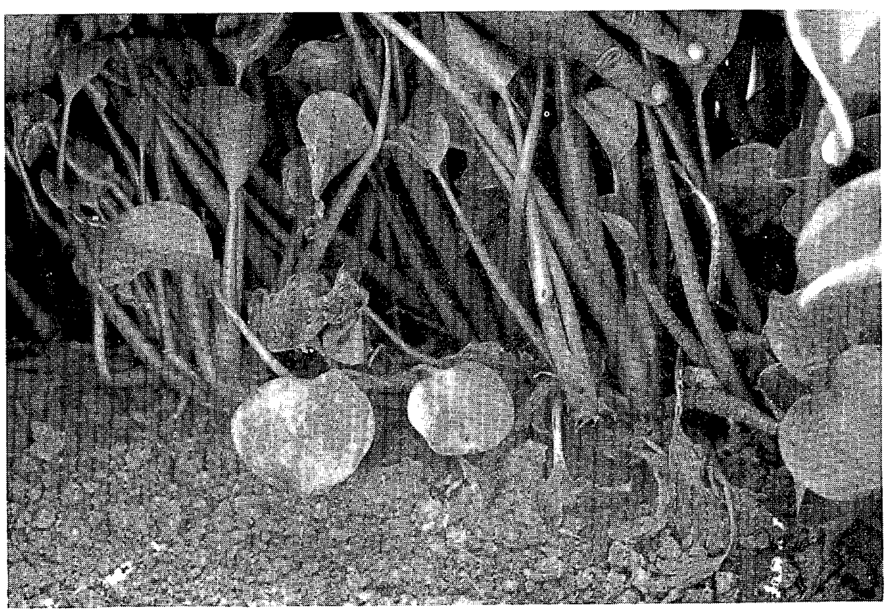
Several million dollars would be required to construct and fully evaluate an experimental prototype biological demineralization facility. Should the concept prove feasible, subsequent systems would be quite economical as most energy requirements would be met through the generation of methane from harvested hyacinths. A possible design of such a facility would involve the provision of lined basins covered with greenhouses having triple layers of clear plastic. Nutrient input could be livestock wastes. Appropriate recirculation of effluent to dilute incoming flow to a salinity level permitting hyacinth growth would be necessary. Refrigerated air would pass through the inner layer of the cover to enhance condensation of water vapor produced from evapotranspiration and to reduce interior air temperature. Collected condensate would be returned to the influent. Continuous hyacinth harvest would be practiced and ammonia extracted from digestor supernatant would return to the culture basins.

Crop Production. Hyacinths normally float upon a water surface. They will grow equally well in moist, enriched soil as shown in Figure 14. The possibility exists to grow hyacinths as a field crop utilizing flood irrigation. Conceptual design of a field crop production system is presented in Figure 15. Production paddies would be drained and allowed to dry somewhat prior to harvest. Plants could be mown periodically with light weight machines equipped with ballon tires. (This would depend upon a favorable response of plants to cropping.)

Transport. Vehicular transport of fresh hyacinths is energy intensive as 95 percent of the cargo consists of water. Transport of hyacinths for short distances to methane generation digestors, or to livestock feed processing facilities may possibly be accomplished via pipeline. Sufficient water would be added to fine chopped plant material to form a slurry which could be pumped through piping.

Aquatic Harvest. One approach to continual harvest of plant material for nutrient removal without interfering with treatment efficiency might be such a scheme as depicted in Figure 16. Land based harvest equipment could be employed for mowing the plants. Leaves and stems would represent a more desirable product for livestock feed than the entire plants.

Fig. 14 Rooted Plants Growing in Moist Soil Adjacent to a Hyacinth Culture Basin, 1979.



(Courtesy of H. Nordmeyer)

Fig. 15 CONCEPT - HYACINTH CROP PRODUCTION IN IRRIGATED SHALLOW PADDIES

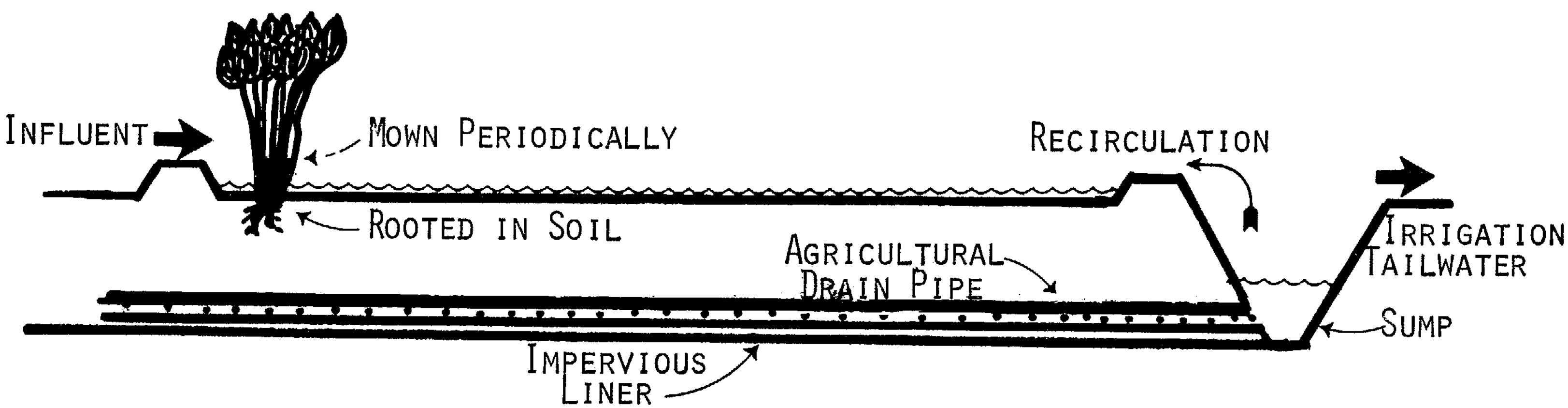
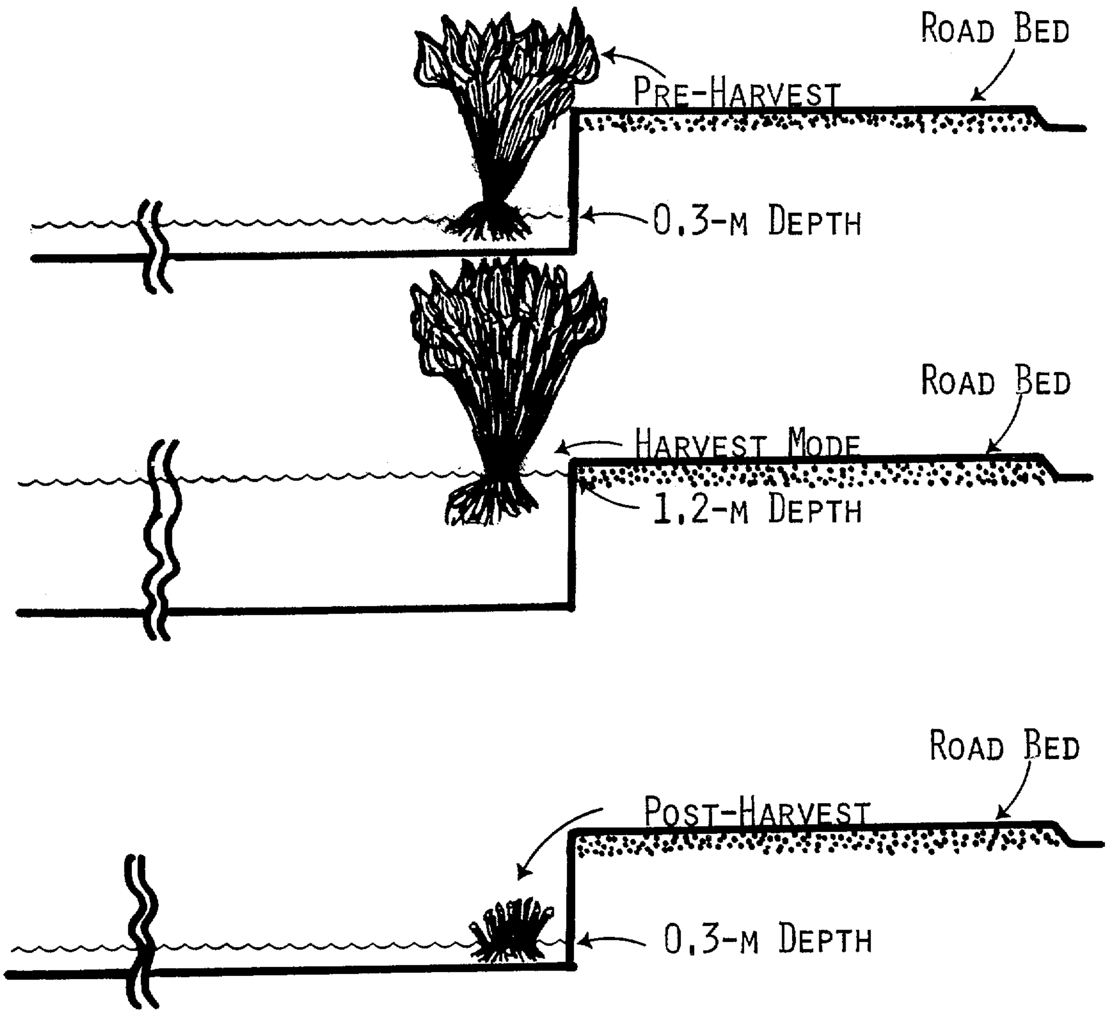


FIG. 16 CONCEPT - HYDRAULIC ELEVATION OF
CHANNEL GROWN HYACINTH
TO FACILITATE MACHINE
HARVEST BY MOWING



CONCLUSIONS

1. Sufficient information is available for designing hyacinth treatment facilities to be employed in warm climates.

2. Optimal design of culture basins is necessary to minimize areal requirements and greenhouse costs in temperate climates.

3. Hydraulic loading is the most critical consideration in culture basin design.

4. The primary pollutant removal mechanism of hyacinth treatment is the reduction of suspended particulate content.

5. Harvest of hyacinths disrupts treatment. Provision of multiple culture basins to allow alternate operation is desirable. Each culture basin should be drained and the accumulated sludge and plant debris removed on an annual basis.

6. Hyacinth culture may be employed as a complete treatment process.

7. Nitrogen management is a key factor in utilizing hyacinths for wastewater treatment, or for biomass production. Stabilization ponds can be designed for effective nitrogen reduction. Hyacinth culture will remove most remaining nitrogen in pond effluent, especially that which is in the organic form (algae).

8. Stabilization ponds followed by hyacinth culture constitutes a highly effective wastewater treatment system.

9. A hyacinth treatment system is capable of producing effluent having a mean content of <10 mg/l BOD_5 and TSS.

ACKNOWLEDGEMENTS

Our gratitude is extended to the City of Austin for facilities provided for the pilot studies and the full-scale study underway at the Williamson Creek wastewater treatment plant. Special thanks are given to Mr. Herbert Nordmeyer, Enforcement Division, Texas Department of Water Resources, for assembling data on hyacinth wastewater treatment systems in the Rio Grande Valley and for photos provided. We also wish to acknowledge the cooperation of officials of the Rio Grande Valley Pollution Control Authority, the City of Rio Hondo, and the City of San Benito.

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* A P P E N D I X *

TEXAS DEPARTMENT OF HEALTH

RECOMMENDATIONS FOR THE CONSTRUCTION AND OPERATION OF HYACINTH BASINS FOR UPGRADING STABILIZATION POND EFFLUENT

May 4, 1979

These recommendations are subject to modification as more information on operating systems becomes available

DESIGN

1. Basin Sizing - Hyacinth basins should be sized for a maximum surface loading rate of 0.2 mgd/acre with a mean water depth of three feet. A maximum basin size of one acre is recommended.

2. Basin Configuration - Rectangular basins having a length to width ratio of at least 3:1 would be preferable. Basins should be designed to approach plug-flow conditions. Influent should be introduced at intervals along the upper margin of the basin. This may be accomplished via a perforated pipe having a minimum diameter of 10 inches. Perforations should be spaced at a maximum distance of 10 feet apart and be at least two inches in diameter. Increased efficiency may be attained by dividing a rectangular basin into equal parts by a diagonal, low earthen dike. Influent would be distributed along the base of one right triangle, collected at the apex, and reintroduced along the base of the other triangle.

3. Basin Construction - Basins should be constructed by excavating and diking the required area. Exterior dikes should have a top width of ten feet and sides with a vertical to horizontal slope of 1:3. Minimum freeboard should be two feet. An access ramp must be provided with a width of at least 10 feet. Basins should be designed for rapid drainage. The bottom of a culture unit would be smooth and slope at least 0.5 percent from the upper to lower end of the basin. A sump should be excavated at the lower end of a culture unit to facilitate removal of residual waters by draining or pumping back to the stabilization pond.

4. Dual Systems - Duplicate systems, each having a capacity to treat the permitted average daily flow of the facility, must be provided. Constant inflow, controlled by a valved pipe, should be maintained to a culture basin. The feeder stabilization pond should serve for flow equalization with the water level being allowed to fluctuate. An appropriate transfer structure should be provided to permit only surface stabilization pond waters to enter a hyacinth culture basin.

5. Basin Piping - Piping should be installed in such a manner as to allow parallel, or series operation of the culture basins. Basins should be interconnected at the lower ends by a valved pipe having a minimum diameter of 10 inches. A valved drain pipe must be provided in each basin and laid on a level with the bottom of the excavated sump near the basin outlet.

6. Barrier - A fixed barrier creating a clear zone of approximately 1.0% of the basin surface area must be installed around the outlet to retain the hyacinth plants, allow for reaeration, and prevent the discharge of plant debris. While screen may be used as a barrier material, a permeable crushed rock or gravel dike is preferred. If screens are used at least two must be provided with the outer screen having a mesh size of not more than one inch and the inner screen having a mesh size of not more than 1/4 inch. An outlet box with an adjustable flow measuring weir must be provided and located in the clear zone.

7. Mosquito Control - Galvanized wire mesh exclosures eight to ten feet in diameter and at least four feet in height should be placed at intervals throughout a basin to furnish clear areas to enhance fish production for mosquito control.

8. Fencing - The hyacinth basins must be enclosed by a man-proof fence with a locked gate.

9. Depth Control - A gauge should be provided to indicate water depth in a hyacinth basin.

OPERATION

1. Continuous Operation - In areas where hyacinths may be grown year-round, the basins may be operated on a continuous basis with each basin receiving one-half the average daily wastewater flow. Once each year the basins should be cleaned by diverting all the wastewater through one basin while dewatering and removing hyacinth plants and sludge from the other basin. The cleaned basin should then be refilled via the interconnected piping with effluent from the full basin and restocked with hyacinth plants.

2. Seasonal Operation - In colder regions only seasonal operation will be permitted since the hyacinth plants freeze at a temperature less than $32^{o}F$ with a resulting decrease in treatment efficiency. At the time when plants are frozen or a decrease in effluent water quality is noted the culture basin should be drained immediately, allowed to dry and cleaned. Wastewater must be stored or treated in some other approved manner during this period if it is not of sufficient quality to meet Texas Department of Water Resources permit requirements. The standby alternate basin may be filled and planted when the danger of frost is over.

3. Cleaning - Draining of a hyacinth basin is initiated by closing the influent valve and opening the drain valve. Rainwaters collecting in the drain sump during the drying period should be removed quickly by pumping into the stabilization pond. The basin should be cleaned thoroughly using appropriate equipment. Dried plants and sludge removed from a basin may be landfilled, converted into compost for use in parks or nurseries, or used for soil amendment of agricultural land used for grazing, or the production of grain and fiber crops. Care should be excercised in handling materials removed from culture basins to assure that it does not gain access to public waters.

4. Records - Sampling - Careful records should be maintained on the water depth, flow rate and other operating parameters of the system. It would be desirable to sample the raw wastewaters and influent-effluent of the hyacinth basin on a weekly basis.

5. Mosquito Control - Hyacinth basins should be stocked with *Gambusia* (mosquite fish-pot bellied minnows-top water minnows) to assure that mosquito production is supressed. Other species which may be stocked to supplement mosquito fish are Poecilia (green sailfin mollies) and *Astyanax* (Texas tetra-Rio Grande jumping minnow-mud minnow).

A WATER HYACINTH ADVANCED WASTEWATER TREATMENT SYSTEM

Dan Swett, Development Research Manager, Coral Ridge Properties, Coral Springs, Florida

A one year field experiment at the 378,530 lpd (100,000 gpd) level has demonstrated that a system of 5,035 m^2 (54,200 ft^2) of water hyacinth (Eichornia crassipes) lagoons can provide advanced treatment to effluent from an activated sludge plant by achieving removal rates of 67% for total suspended solids, 98% for biochemical oxygen demand, 97% for total nitrogen and 79% for total phosphorus. Biomass produced by the system offers a potential for energy, fertilizer or fodder production.

PROJECT DEVELOPMENT

Coral Springs, Florida, is a "New Town" developed by Coral Ridge Properties, a wholly owned subsidiary of Westinghouse Electric Corporation, located in the northwestern portion of Broward County. With a current population of 30,000, Coral Springs is adding population and dwelling units at a rate of 7.5% per year making it the fastest growing municipality in the Fort Lauderdale urban complex.

Almost all of the current growth and development is occurring in the southern portion of the city where water, sewer and wastewater treatment services are provided by the Coral Springs Improvement District, a special taxing body created by act of the state legislature. The District's wastewater treatment plant has a design capacity of 7.6 mld, that will ultimately be expanded to 20.6 mld. Method of treatment is by activated sludge, with effluent disposal into a closed seepage lagoon.

Although the treatment plant produces a secondary effluent that meets current state and county standards, the Broward County Commission has adopted an ordinance requiring that, as of January 1, 1980, all non-ocean effluent discharges meet the advanced wastewater treatment standards of 5 mg/l total suspended solids, 5 mg/l BOD_5, 3 mg/l total nitrogen and 1 mg/l total phosporus.

This situation is further complicated by the fact that Broward County is committed to the regional treatment system concept and has received an EPA grant for installation of such a system. The Coral Springs Improvement District has been asked by the county to join the regional system as soon as sufficient capacity becomes available, which is expected to occur sometime between 1983 and 1985. Some portions of this system are in place, others under construction, and others still in the planning stage.

The District is thus faced with the necessity of upgrading its existing secondary treatment system to meet AWT standards by 1980. Under normal circumstances, installation of conventional AWT facilities with twenty year amortization would impose a large financial burden on the District. This burden would be rendered totally intolerable should the new facilities have to be abandoned within three to five years upon integration of the District into the Broward County regional wastewater treatment system. Project Hyacinth represents an effort by Coral Ridge Properties to find a low-cost way out of this dilemma for the Coral Springs Improvement District.

Funded entirely by Coral Ridge Properties, Project Hyacinth was designed by Gee and Jenson, the District's consulting engineers, to bring 378,530 lpd (100,000 gpd) of the treatment plant effluent to AWT standards. Constructed on 0.93 hectares (2.31 acres) of District-owned land, the system consists of a series of five ponds with a total water surface area of 0.5 hectares (1.25 acres) (Fig. 1). Design treatment time at the 378,530 lpd capacity is two days in Pond A and one day in each of Ponds B through C, for a total of six days. Water depth throughout the system is 38.1 cm (1.25 feet). An impermeable asphalt seal on sides and bottoms of the ponds prevents seepage loss (Table 1). Total construction cost of the system was less than $65,000. On completion of construction, ponds were filled with effluent and "seeded" with approximately 7.64 m^3 (10 $yds.^3$) of water hyacinth plants (<u>Eichornia crassipes</u>) per pond. This was accomplished on January 27, 1978.

Increase in the plant biomass was slower than anticipated, due primarily to excessive chlorination of the effluent at the treatment plant. When this condition was corrected and chlorine residual of influent into the system reduced to approximately 1 mg/1, plant biomass increased rapidly. Some harvesting was accomplished during the biomass increase period to remove dead and malnourished plants.

SPLIT FLOW OPERATION

Data collection began May 15, 1978, with 90% coverage in all ponds. The project sampling plan called for simultaneous 24-hour composite sampling at the Pond A influent point and the Pond E effluent point to establish levels of analytical variables achieved by treatment in the full system at the design time of six days, and thereafter movement of sampling forward to outflow points of Ponds D, C and B to establish levels achieved by curtailing treatment time to five, four and three days. This plan was adhered to through November, 1978, except that effective June 13, composite sampling time was increased to 48 hours, halving the number of samples to be analyzed each month.

Metering of influent and effluent flows established a high evapotranspiration loss, amounting to 16.24 x 10^5 lpd (42,900 gpd) or 32.35 lpd/m^2 (0.7915 gpd/ft^2) of water surface. This loss appears constant due to the high liquid uptake of the plants and therefore is unaffected by flow into the system.

In December, 1978, because surge overloads at the treatment plant were causing high solids inflows into the system, the sampling plan was amended to include grab sampling every other day at the outflow point of each pond to trace progress of solids and nutrients through the system. This grab sampling revealed a consistent drop in levels of analytical variables between the influent point and the Pond A outflow point, then an increase in these variables at the Pond B outflow point, followed by decreases at the outflow points of Ponds C, D and E. To insure that the increase in analytical variable levels from Pond A to Pond B was not related to the time of grab sampling, four additional composite samplers were placed in operation on February 1, 1979, and 48 hour composite samples drawn from the Pond A influent point and the effluent point in each pond.

This composite sampling verified that concentrations of analytical variables increased in Pond B and decreased thereafter. Removal of hyacinth plants from the inflow end of Pond B revealed that influent was entering the pond from two points -- from Pond A and also directly from the treatment plant influent line. On investigation, valves installed to permit shunting of influent flow into either Pond A or Pond B were both found to be open, resulting in simultaneous flow into both ponds. Closure of the valve to Pond B restored the system to its original operational plan on February 28, 1979.

Simultaneous 48 hour composite sampling at the Pond A influent point and at the outflow point of each pond was continued. Engineering calculations established that during the period May 15, 1978 - February 28, 1979, the divided influent flow resulted in 45% going into Pond A and 55% into Pond B. An equation was formulated to enable calculation of total flow into Pond B, consisting of outflow from Pond A (inflow into Pond A less evapo-transpiration loss plus flow into Pond B directly from the treatment plant). A second equation was formulated to calculate the combined concentration of analytical variables entering Pond B as a result of the combined inflow from Pond A and from the treatment plant (appendix).

Adjusted influent loadings into Pond B during the split flow period for liters per day, total nitrogen and total phosphorus are shown in Table 2. Because effect of the split flow on total suspended solids and BOD_5 was neglibible, no adjustment of these variables was made.

Results of the hyacinth treatment, based on the system of Ponds B through E, are shown in Table 3. Treatment times shown in this table are based on total loadings into Pond B and are adjusted for evapo-transpiration loss in each pond. All grab samples from Ponds C and D during January were taken at the peak flow time of 9:30 to 10:00 a.m.

UNITARY FLOW OPERATION

Flow into Pond A only was restored on February 28, 1979, and data collection during the period March 1 - May 31, 1979, was accomplished by 48 hour composite sampling at the Pond A influent point and at the outflow point of each pond. Influent flow was maintained at 435,102 lpd (115,000 gpd) throughout, except for 48 hours in April and 12 hours in May when flows were reduced to zero. Knowledge gained from the previous nine months of experimental operation was used to operate the system for maximum efficiency.

During the period, nitrogen removal rates ranged from 62% to 96%, and phosphorus removal rates ranged from 18% to 60%. Reductions in mass loadings for these two variables, adjusted for evapotranspiration loss, and removal rates achieved according to treatment time are contained in Tables 4 and 5.

Treatment plant operations during the months of April and May were erratic due to construction activities and were reflected in abnormal variability of pollutant concentrations in influent into the hyacinth system. On April 17, construction was completed on 3,785,300 lpd (1 mgd) of new treatment plant capacity and inflow into the hyacinth system was completely shut off for 48 hours to enable rapid filling of the new tanks. Problems with the new plant operation necessitated its shutdown on April 19 for debugging, with restoration of flow into the hyacinth system, as which time transfer back to the old plant resulted in a heavy inflow of untreated solids into the hyacinth system.

On April 25, unusual weather conditions dumped 36.8 cm (14.5 inches) of rain on the area in less than 24 hours. This rainstorm, calculated as having a probability of occurrence of less than once in 200 years, created temporary flood conditions that again caused plant operational problems and heavy inflows of untreated solids into the hyacinth system for 48 hours. Despite these two treatment upsets, the only effect on the hyacinth system was the onset of chlorosis in plants in Pond E, caused by undernourishment resulting from the two day shutdown of flow into the system.

During May, efforts to restore normal treatment in the plant caused pollutant concentrations in the influent into the hyacinth system to rise steadily from the first of the month, culminating in highs of 22 mg/l total suspended solids, 110 mg/l BOD_5, 132.29 mg/l total nitrogen and 44.52 mg/l total phosphorus on the 21st. In addition, influent flow into the system was shut down from 10:00 p.m. on the 22nd to 10:00 a.m. on the 23rd.

It is noteworthy that during the period of the heaviest pollutant concentration inflow, the hyacinth system demonstrated the highest degree of efficiency in nutrient removal, apparently as a result of increase in the N:P ratio. When the N:P ratio was at its highest, 2.97:1, on May 21, total nitrogen and total phosphorus concentrations at the Pond C outflow point were 0.86 and 0.87 mg/l, respectively, on May 26th and 0.74 and 0.71 mg/l on May 28th. This indicates that the most effective nutrient removal occurs when the influent N:P ratio is approximately 3:1.

Influent loadings into the system and analytical variable concentrations at the outflow point of each pond for the March 1 - May 31 period are contained in Table 6. Extremely high variability in loading concentrations of each variable during May are shown by the standard deviations. These concentrations were reduced to almost negligible amounts as they flowed through the system. Because the overall effect of any effluent discharge is more a function of the total amount of each pollutant contained in the effluent than the concentration thereof, it is worthwhile to consider total contents of each variable on a mass loading basis at the hyacinth system influent point and at the outflow point of each pond. Table 7 presents these data for the period March 1 - May 31, 1979, based on daily flow into the system and adjusted for evapo-transpiration loss in each pond.

CONCLUSIONS

Because achievement of nitrogen removal is the most difficult and expensive aspect of conventional advanced wastewater treatment processes, treatment time required by a hyacinth system to achieve any desired concentration of total nitrogen in final effluent is a crucial planning factor. The scattergram (Figure 2) portrays the actual relationships between treatment times and total nitrogen concentrations achieved by Project Hyacinth (grab sampling data not included). Analysis of the total nitrogen-treatment time relationship by linear regression enables use of the least squares equation to predict the treatment time required to achieve any desired concentration of total nitrogen.

Data contained in Table 6 yields the least squares prediction equation:

$$Y = 3.91 + (-0.65)X,$$

in which Y = mg/l total nitrogen and X = days' treatment time. Correlation coefficient for the equation is -0.60. By this prediction equation, for a Y value of 3.00 mg/l nitrogen, 1.4 days treatment is required over a system with 1 m^2 of water surface per 86 lpd effluent. Standard deviation of the predicted Y at this level of X is 1.34, thus to achieve the indicated confidence levels, treatment times as follows would be required:

Confidence Level	Days' Treatment
99%	4.95
97.5%	4.3
95%	3.77
90%	3.21

Experience gained during the year of Project Hyacinth operation indicates that, while the system can successfully cope with a variety of stresses, health of the plants must be maintained for most effective treatment. While the water hyacinth is a hardy, disease-resistant plant that thrives at all above freezing temperatures, its growth rate and nutrient uptake efficiency can be compromised.

Presence of a high chlorine residual definitely inhibits plant growth. If possible, effluent chlorination should be accomplished subsequent to hyacinth treatment. If local conditions dictate pre-hyacinth chlorination, care should be taken that chlorine residual in the influent does not exceed 1 mg/l. Plant health is also adversely affected by chlorides. Early in the project's operation 189 liters (50 gallons) of a 40,000 mg/l NaCl solution were injected at the influent point in an effort to trace progress of the solution through the system by continuous conductivity readings. Three days of readings along the length of Pond A showed no chloride presence, indicating total uptake of the solution by the plants. Three days later, plants in a fifteen foot wide strip down the middle of Pond A exhibited severe chlorosis (leaf yellowing).

Maintenance of nourishment is essential to plant health. Hyacinth has a voracious appetite, which if not satisfied also results in chlorosis and decreased uptake efficiency. Least efficient performance of the system was obtained during periods of significantly reduced influent flow and during periods when influent nitrogen concentration dropped below 10 mg/l. Plant health is also adversely affected by overcrowding. During July and August, 1978, no plants were harvested for a period of more than six weeks to determine effect of overcrowding. Chlorosis began to appear after four weeks and increased in severity rapidly, accompanied by a decrease in uptake efficiency.

The best indication of plant health is an abundant growth of dark green leaves. Any appearance of stunted leaf growth with yellowish green leaves in immature plants or of leaf yellowing in mature plants should be investigated immediately.

Intense sun with temperatures in the mid-nineties may cause some leaf browning and wilting. This is not a serious condition if new growth is present, beneath the brown wilted leaves. Wilted-leaved plants may be removed during the normal harvest cycle by selective harvesting.

Healthiest plant condition and best system performance was obtained when ponds were maintained in a loosely packed condition by a four week harvest cycle. From 15 to 20% of the plants should be removed at each harvest. Uncovering more than 20% of pond surface area will result in an algae problem. Harvest biomass on the four week cycle averaged 137.6 m^2 (180 yds^3), or 1 m^3/36.6 m^2 of pond surface.

During the year of Project Hyacinth operation, the biomass growth rate appeared totally unaffected by seasonal temperature variations. Fahrenheit temperatures ranged from the mid-thirties to low seventies during January and February, from the forties to low eighties in the spring and fall, and from the upper seventies to upper nineties during the summer months.

When Project Hyacinth was designed, it had been planned to harvest with a weed bucket-equipped front-end loader. This proved impractical because the 38.1 cm water depth affected the front-end loader's hydraulic system. A Gradall was used for two harvests but was discontinued because hydraulic fluid from the boom dripped into the ponds, and also because of its high cost. The best performing harvesting equipment was a weed-bucket equipped, truck-mounted dragline. This equipment, with a dump truck, was able to accomplish a normal harvest in six to seven hours. Had the ponds been fifteen feet narrower, dragline harvesting efficiency would have been improved considerably.

Throughout Project Hyacinth, persistent clogging of the influent flow meter made accurate determination of influent flow rates difficult. Occasional shut-off, both intended and non-intended, of influent flow also caused serious problems. In a full-scale system, reliable influent and effluent flow metering and an influent flow system not subject to shut-off or clogging would be essential.

In Project Hyacinth, harvested plants were placed on a concrete drying pad between Ponds A and E, draining into Pond A. Two to three weeks' drying resulted in a 75% volumetric reduction in the biomass. The dried biomass was removed to a tree nursery and composted. It proved to be a superior fertilizer.

Project Hyacinth has proven that a 0.4 hectare/378,530 lpd (one acre/100,000 gpd) water hyacinth treatment system is capable of bringing secondary wastewater effluent to AWT standards for total suspended solids, BOD_5 and total nitrogen in three to five days, depending on confidence level required. Further investigation is underway to determine if the influent N:P ratio can be increased sufficiently by ammonia addition to achieve sufficient phosphorus uptake to meet the AWT standard for this element. If so, it must also be determined if such ammonia addition is cost-effective compared to chemical precipitation for phosphorus removal.

At any rate, there appears to be no doubt that even with addition of chemical phosphorus removal, a water hyacinth AWT system can be much more cost-effective in both capital and operations and maintenance costs than a conventional AWT system.

Given the present state of the art, for small sun-belt communities, in which freezing temperatures are of very short duration and land is available, water hyacinth treatment now provides an excellent low cost means of bringing small activated sludge plant effluent flows (400,000 lpd or less) to AWT standards. For larger communities with effluent flows in excess of 400,000 lpd, disposition of the harvested hyacinth biomass may require a byproduction process. Depending on local geographic and economic considerations, the harvested biomass may be used for energy, fertilizer or fodder production. Additional field research is required in these areas.

Appendix

1. Adjustment equation for influent flow split between Ponds A and B:

$$Q_B = Q - E_A$$

where Q = total flow into system, lpd,
Q_B = flow into Pond B, lpd, and
E_A = evapo-transpiration loss in Pond A, lpd.

2. Adjustment equation for concentration of any variable entering Pond B as result of split influent flow:

$$C_{Bi} = \frac{0.55QCi + (0.45Q-E_A)\ C_{Ae}}{Q_B}$$

where Q, Q_B and E_A are as in Equation 1, and
Ci = concentration in influent into system, mg/l,
C_{Bi} = concentration entering Pond B, mg/l, and
C_{Ae} = concentration leaving Pond A, mg/l.

3. Adjustment equations for treatment time:

a. Pond A, Split influent Flow:

$$T_A = \frac{2\ V_A}{Q(0.45) + (Q(0.45)-E_A)}$$

where Q and E_A are as in Equation 1,
T_A = Time in Pond A, days, and
V_A = Volume of Pond A, liters.

b. Pond A, Unitary Flow:

$$T_A = \frac{2\ V_A}{Q + (Q-E_A)}$$

c. Ponds B through E:

$$T_{B.....E} = \frac{2\ V_{B.....E}}{Q_{iB.....E} + Q_{oB.....E}}$$

where $T_{B.....E}$ = Time in designated pond, days,
$V_{B.....E}$ = Volume of designated pond, liters,
$Q_{iB....E}$ = Inflow into designated pond from preceding pond, lpd,
$Q_{oB....E}$ = Outflow from designated pond; i.e., inflow from preceding pond minus evapo-transpiration loss in designated pond.

d. Adjusted system treatment time:

$$T_S = T_A + T_B + \ldots\ldots T_E$$

where T_S = Time in system, days.

4. Table of volumes and evapo-transpiration losses:

Pond	Volume (liters)	Evapo-Transpiration Loss (lpd)	Cumulative Loss (lpd)
A	645,772	58,369	58,369
B	282,761	26,005	84,374
C	282,761	26,005	110,379
D	282,761	26,005	136,384
E	282,761	26,005	162,389

Table 1
Project Hyacinth Design Data

	Pond A	Ponds B-E ea.	Total System
Dimensions (Inside)	26.82 m x 83.82 m	26.82 m x 39.62 m	61.87 m x 131.67 m
Water Surface Area	1,810 m^2	806 m^2	5,035 m^2
Water Capacity	645,772 1	282,762 1	1,776,820 1
Treatment Time at 378,530 lpd	2 days	1 day	6 days

Influent to Pond A; through 7.62 cm (3 inch) i.d. pipe

Pond connecting pipes: 30.5 cm (12 inch) i.d.

Berms: 4.57 m (15 feet) between ponds, 1.83 m (6 feet) outside of ponds.

Effluent from Pond E: Outflow over 90° V-notch wier, 15.2 cm (6 inch) deep. Maximum capacity, 730.6 lpm (193 gpm).

Meters:

Influent - Badger model MLFT-SGH 7.6 cm (3 inch) propeller meter.

Effluent - Leupoldt Stevens model 61R flow recorder.

Table 2
Pond B
Adjusted Influent Loadings

Dates	LPD	TSS* Mean mg/l	TSS* Std. Dev. mg/l	BOD_5* Mean mg/l	BOD_5* Std. Dev. mg/l	Total N Mean mg/l	Total N Std. Dev. mg/l	Total P Mean mg/l	Total P Std. Dev. mg/l
5/15-6/5/78	3.2×10^5	6.40	4.18	5.81	1.29	7.78	1.90	5.55	1.57
6/13-7/31/78	2.33×10^5	5.80	5.60	8.33	8.81	7.47	1.45	5.18	1.36
8/1-31/78	2.32×10^5	2.80	0.99	3.25	0.43	8.08	2.46	5.51	1.18
9/1-30/78	3.45×10^5	2.87	0.62	2.67	0.47	6.58	1.33	5.93	1.47
10/1-31/78	3.0×10^5	2.43	0.49	3.00	0.70	7.68	1.03	6.29	1.10
11/1-30/78	3.28×10^5	--	--	--	--	8.96	1.24	4.74	1.28
12/1-31/78	3.54×10^5	16.33	21.07	7.75	2.69	9.84	1.47	6.72	1.29
1/1-31/79	3.77×10^5	7.20	3.71	4.25	0.43	9.39	1.82	5.88	0.49
2/1-28/79	3.77×10^5	3.93	1.10	4.25	0.43	7.81	1.17	4.99	1.48

* Unadjusted Loading

Table 3
Pond C Effluent

Dates	Adj. Treatment Time (Days)	TSS Mean mg/l	TSS Std. Dev. mg/l	BOD_5 Mean mg/l	BOD_5 Std. Dev. mg/l	Total N Mean mg/l	Total N Std. Dev. mg/l	Total P Mean mg/l	Total P Std. Dev. mg/l
9/1-30-78	2.27	3.80	0.65			3.22	1.15	5.31	0.53
10/1-31/78	2.33	3.75	0.43			3.90	0.91	6.00	0.34
11/1-30/78	2.10	--	--			5.10	2.34	4.39	0.85
12/1-31/78	2.10	--	--			6.13	1.47	4.12	0.63
1/1-31/79*	1.93	4.33	0.87			4.71	1.21	5.53	0.36
2/1-28/79	1.93	3.71	0.79			3.43	1.19	4.75	0.11

Pond D Effluent

Dates	Adj. Treatment Time (Days)	TSS Mean mg/l	TSS Std. Dev. mg/l	BOD_5 Mean mg/l	BOD_5 Std. Dev. mg/l	Total N Mean mg/l	Total N Std. Dev. mg/l	Total P Mean mg/l	Total P Std. Dev. mg/l
8/1-31/78	6.43	4.07	1.29	3.67	0.94	1.00	0.37	4.95	0.96
10/1-31/78	4.21	--	--	--	--	1.85	0.54	--	--
11/1-30/78	3.71	3.60	1.36	--	--	2.53	1.09	4.03	0.74
12/1-31/78	3.33	5.16	0.90	--	--	4.00	1.15	4.33	0.43
1/1-31/79*	3.04	4.13	1.36	--	--	3.39	1.52	5.19	0.50
2/1-28/79	3.04	3.21	0.56	--	--	2.20	0.90	4.61	0.39

Pond E Effluent

Dates	Adj. Treatment Time (Days)	TSS Mean mg/l	TSS Std. Dev. mg/l	BOD_5 Mean mg/l	BOD_5 Std. Dev. mg/l	Total N Mean mg/l	Total N Std. Dev. mg/l	Total P Mean mg/l	Total P Std. Dev. mg/l
5/15-6/5/78	5.51	3.77	1.42	3.90	0.88	0.66	0.18	3.65	0.89
6/13-7/31/78	9.83	3.28	1.30	3.83	0.69	0.53	0.14	3.74	0.56
10/1-31/78	6.09	3.17	0.69	3.33	1.50	1.57	0.54	5.37	0.82
11/1-30/78	5.30	3.71	0.88	--	--	1.66	0.76	4.43	0.43
12/1-31/78	4.70	2.67	0.94	3.33	0.47	1.64	0.63	5.49	0.10
1/1-31/79	4.30	3.20	0.70	3.25	0.43	2.56	0.72	5.26	0.47
2/1-28/79	4.30	3.07	0.59	3.00	0.71	1.52	0.68	4.32	0.58

* Grab sampling

Table 4
Nitrogen Concentrations, Mass Loadings & Removal Rates*
5/15/78 - 2/28/79

Influent		Treatment Time	Effluent		
Concentration mg/l	Mass Load kg/day	days	Concentration mg/l	Mass Load kg/day	Removal Rate (%)
7.78	2.49	5.51	0.66	0.14	94
7.47	1.74	9.83	0.53	0.07	96
8.08	1.87	6.43	1.00	0.15	92
6.58	2.27	2.27	3.22	0.94	58
7.68	2.31	6.09	1.57	0.31	87
8.96	2.94	5.30	1.66	0.37	87
9.84	3.48	4.70	1.64	0.41	88
9.39	3.54	4.30	2.56	0.70	80
7.81	2.94	1.93	3.43	1.11	62
7.81	2.94	3.04	2.20	0.66	77
7.81	2.94	4.30	1.52	0.41	86

* Adjusted for Evapo-transpiration Loss

Table 5
Phosphorus Concentrations, Mass Loadings & Removal Rates*
5/15/78 - 2/28/79

Influent		Treatment	Effluent		
Concentration mg/1	Mass Load kg/day	Time days	Concentration mg/1	Mass Load kg/day	Removal Rate (%)
5.55	1.78	5.51	3.65	0.79	56
5.18	1.20	9.83	3.74	0.48	60
5.51	1.28	6.43	4.95	0.76	41
5.93	2.05	2.27	5.31	1.56	24
6.29	1.89	6.09	5.37	1.05	44
4.74	1.55	5.30	4.43	0.99	36
6.72	2.38	4.70	5.49	1.37	42
5.88	2.22	4.30	5.26	1.44	35
4.99	1.88	1.93	4.75	1.54	18
4.99	1.88	3.04	4.61	1.38	27
4.99	1.88	4.30	4.32	1.18	37

* Adjusted for Evapo-transpiration Loss

Table 6
Pond A Influent
Loading Rate: 435,102 lpd

Month 1979	TSS Mean mg/l	TSS Std. Dev. mg/l	BOD_5 Mean mg/l	BOD_5 Std. Dev. mg/l	Total N Mean mg/l	Total N Std. Dev. mg/l	Total P Mean mg/l	Total P Std. Dev. mg/l
March	3.33	0.79	3.50	0.50	10.12	1.34	6.12	1.46
April	4.27	3.21	3.00	0.71	5.75	2.14	5.03	1.38
May	9.33	4.75	8.73	44.60	42.74	35.16	20.08	12.26
March-May	5.64	4.22	13.08	29.27	22.41	25.27	10.95	9.35

Pond A Effluent
Adjusted Treatment Time: 1.59 Days

Month 1979	TSS Mean mg/l	TSS Std. Dev. mg/l	BOD_5 Mean mg/l	BOD_5 Std. Dev. mg/l	Total N Mean mg/l	Total N Std. Dev. mg/l	Total P Mean mg/l	Total P Std. Dev. mg/l
March	3.20	0.92	--	--	3.71	1.35	5.11	1.06
April	3.33	1.19	--	--	5.75	2.14	5.03	1.38
May	4.00	0.63	--	--	0.89	0.23	3.50	0.99
March-May	3.51	0.81	--	--	3.51	2.47	4.55	1.17

Pond B Effluent
Adjusted Treatment Time: 2.37 Days

Month 1979	TSS Mean mg/l	TSS Std. Dev. mg/l	BOD_5 Mean mg/l	BOD_5 Std. Dev. mg/l	Total N Mean mg/l	Total N Std. Dev. mg/l	Total P Mean mg/l	Total P Std. Dev. mg/l
March	3.20	0.83	--	--	2.18	1.14	4.57	0.77
April	3.20	0.65	--	--	3.08	1.98	4.61	1.13
May	4.13	0.62	--	--	0.89	0.22	2.28	0.70
March-May	3.51	0.83	--	--	2.05	1.60	3.82	1.23

Pond C Effluent
Adjusted Treatment Time: 3.21 Days

Month 1979	TSS Mean mg/l	TSS Std. Dev. mg/l	BOD_5 Mean mg/l	BOD_5 Std. Dev. mg/l	Total N Mean mg/l	Total N Std. Dev. mg/l	Total P Mean mg/l	Total P Std. Dev. mg/l
March	3.13	0.80	--	--	1.49	0.76	4.24	0.74
April	3.87	0.80	--	--	1.71	0.95	4.28	0.84
May	4.47	0.52	--	--	0.74	0.14	2.01	0.88
March-May	3.82	0.92	--	--	1.31	0.82	3.49	1.35

Pond D Effluent
Adjusted Treatment Time: 4.12 Days

Month 1979	TSS Mean mg/l	TSS Std. Dev. mg/l	BOD_5 Mean mg/l	BOD_5 Std. Dev. mg/l	Total N Mean mg/l	Total N Std. Dev. mg/l	Total P Mean mg/l	Total P Std. Dev. mg/l
March	2.71	0.80	--	--	1.13	0.47	3.92	0.71
April	4.00	0.89	--	--	1.30	0.54	4.28	0.78
May	3.47	0.50	--	--	0.76	0.12	2.09	0.80
March-May	3.41	0.99	--	--	1.01	0.48	3.41	1.40

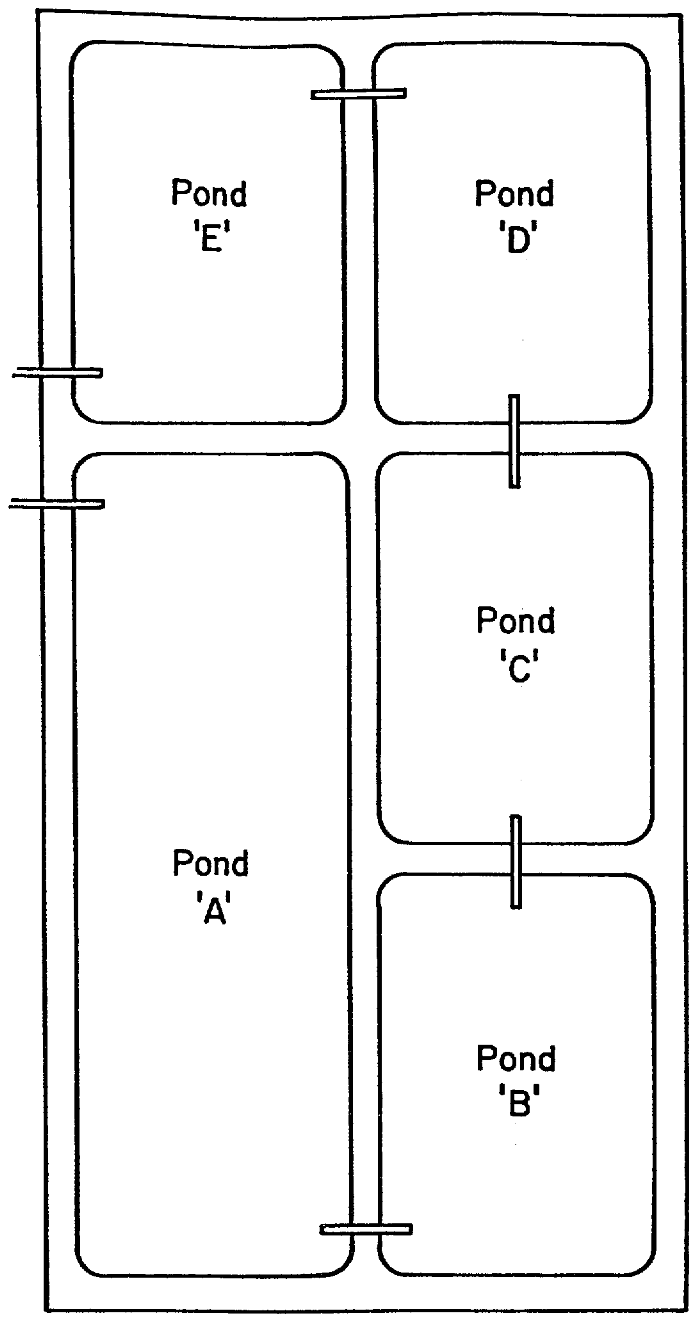
Pond E Effluent
Adjusted Treatment Time: 5.11 Days

Month 1979	TSS Mean mg/l	TSS Std. Dev. mg/l	BOD_5 Mean mg/l	BOD_5 Std. Dev. mg/l	Total N Mean mg/l	Total N Std. Dev. mg/l	Total P Mean mg/l	Total P Std. Dev. mg/l
March	2.90	0.54	2.50	0.50	0.94	0.26	3.77	0.65
April	2.87	0.50	2.50	0.50	1.24	0.55	4.49	0.75
May	3.20	0.54	3.75	0.43	0.82	0.25	2.56	0.45
March-May	2.95	0.81	2.92	0.76	1.00	0.42	3.60	1.01

Table 7
Total Loadings and Total Effluent Content & Removal Rates
March 1 - May 31, 1979

Sampling Point	TSS kg/day	TSS Removal Rate %	BOD_5 kg/day	BOD_5 Removal Rate %	Total N kg/day	Total N Removal Rate %	Total P kg/day	Total P Removal Rate %	Adj. Treatment Time (Days)
Influent	2.45	--	56.62	--	9.75	--	4.77	--	--
Pond A Outflow	1.32	46	--	--	1.32	43	1.71	64	1.59
Pond B Outflow	1.23	50	--	--	0.72	93	1.34	72	2.37
Pond C Outflow	1.24	43	--	--	0.42	96	1.13	76	3.21
Pond D Outflow	1.02	58	--	--	0.30	97	1.02	79	4.12
Pond E Outflow	0.80	67	0.85	98	0.27	97	0.98	79	5.11

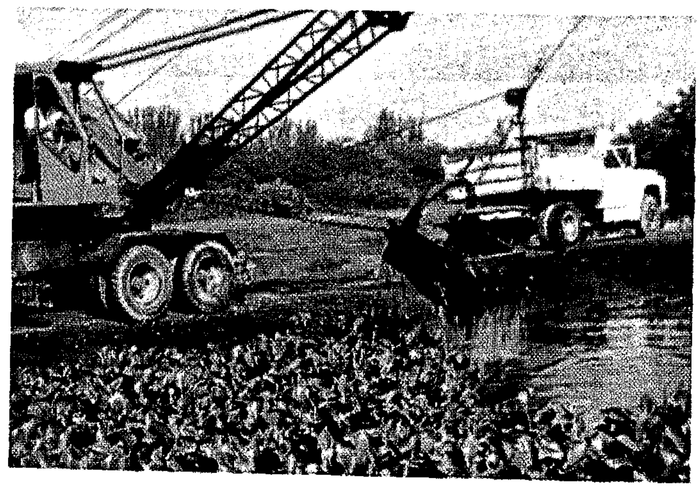
Figure 1
Hyacinth System Schematic

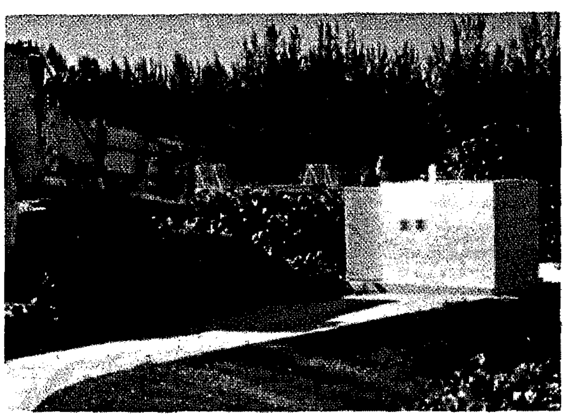


Water hyacinth covered ponds operated by the Coral Springs Improvement District.

6/14/78

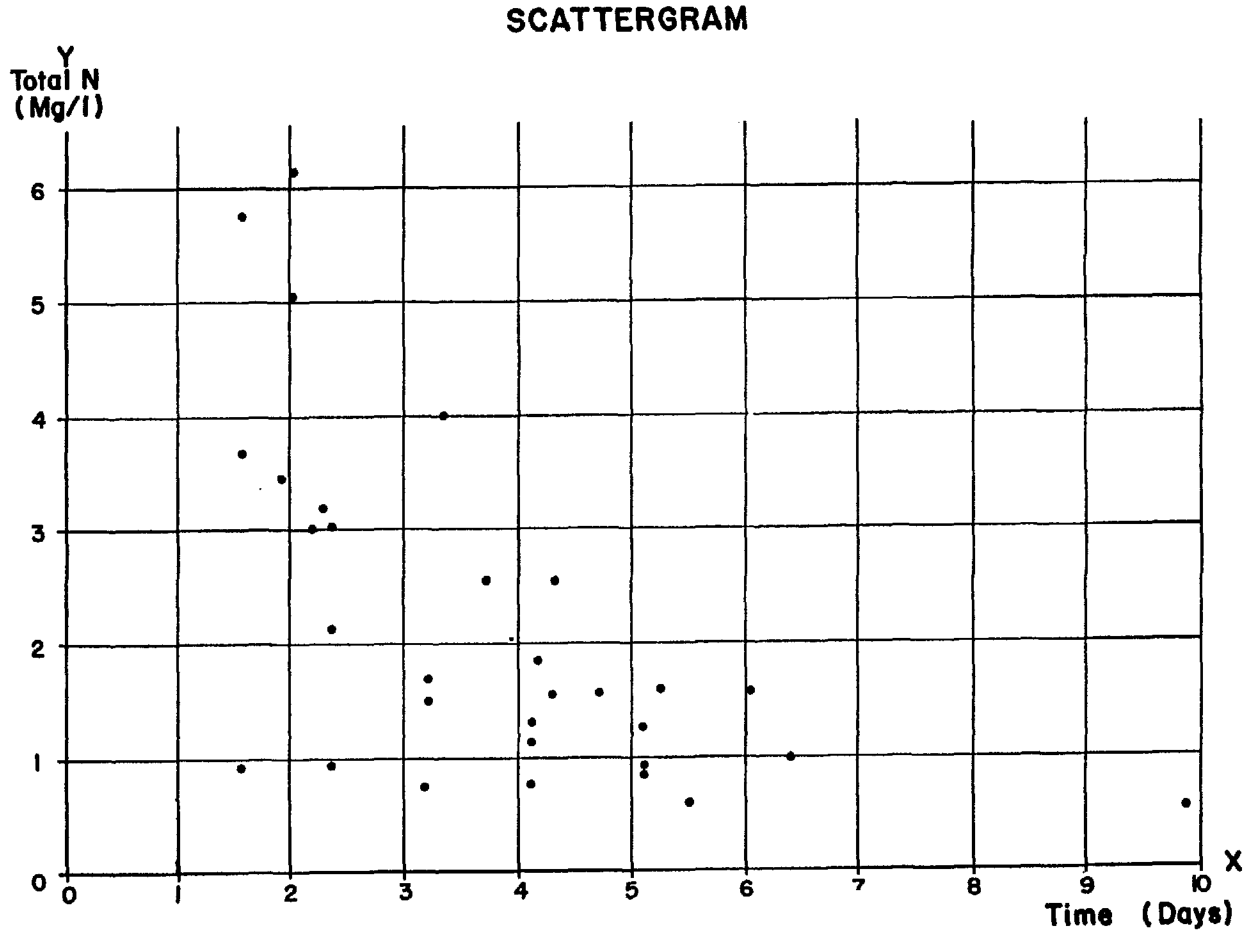
Harvesting water hyacinths with a weed-bucket equipped, truck mounted drag line.





Water hyacinths being placed on a concrete solar drying pad.

Figure 2



Acknowledgments

Dr. B. C. Wolverton, National Space Technology Center, Bay St. Louis, Miss., whose pioneering work in water hyacinth wastewater treatment led to the inception of Project Hyacinth, for his guidance and suggestions.

Dr. William Duffer, Robert Kerr Environmental Research Laboratory, Ada, Oklahoma, for his interest, guidance and suggestions.

Dr. Ronald F. Lewis, Municipal Environmental Research Laboratory, E.P.A., Cincinnati, Ohio for his interest and suggestions.

Dr. Thomas deS. Furman, et al., Department of Engineering Science, University of Florida, Gainesville, Florida, whose studies of nutrient removal by water hyacinth provided data for engineering design of Project Hyacinth.

WATER HYACINTH WASTEWATER TREATMENT SYSTEM AT WALT DISNEY WORLD

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INTRODUCTION

Pioneering scientific studies sponsored by the National Aeronautics and Space Administration and performed by the National Space Technology Laboratories at Bay St. Louis, Mississippi, have shown that vascular aquatic plants, such as the water hyacinth (*Eichhornia crassipes*), can be remarkably effective in the removal of nutrients and toxic materials from municipal and industrial sewage. The potential for utilization in both secondary and tertiary wastewater treatment systems has been demonstrated (refs. 1 and 2). In addition, the prospects for developing useful products from the harvested plant are promising (ref. 3). Although these studies have demonstrated feasibility, the ultimate commercialization of a water hyacinth wastewater treatment system requires its comparative evaluation with alternative wastewater treatment systems, both economically and with regard to typical water quality standards and requirements.

A study performed by the Battelle Columbus Laboratories (ref. 4), addressed the potential market for such wastewater treatment systems. They found that the lack of existing systems and verified design data was a major obstacle to accomplishment of their study. However, they concluded the following:

- o Under ideal conditions, water hyacinth based systems can be designed which are highly effective in tertiary treatment of municipal wastewater.
- o Operationally verified design parameters are needed for hyacinth systems.

- For municipal systems designed to meet stringent effluent standards, hyacinth-based systems offer a possibility for appreciable cost savings over competitive processes in construction of completely new facilities.

- The cost advantage will be greater in many types of upgrading activities.

- Considering only the southern Florida municipal application, it appears that a reasonable estimate of the savings offered by hyacinth systems is $165 million over the next 25 years, with the largest share of this within the next decade.

- Hyacinth treatment systems are in a comparatively early stage of development. It is quite possible that further engineering will improve the competitive position of hyacinth systems.

- Present information on the characteristics of hyacinth systems is not adequate to bring about implementation on a significant scale. If, however, the potential advantage suggested by this analysis can be demonstrated and verified in actual use, market penetration should be rapid, at least in southern Florida.

As a result of the Battelle and NASA work, WED Enterprises, a subsidiary of WALT DISNEY PRODUCTIONS, was sufficiently interested in the potential for such a system to further investigate its feasibility by hosting a meeting of technical experts in July 1976 to review a plan for a pilot project (ref. 5). The consensus opinion was that the project had sufficient merit that WED should proceed with a pilot plant system. This pilot plant, sized for 50,000 GPD, would be the necessary precursor to the design and economic assessment of a prototype 1 MGD system.

WED acted on this recommendation by forming a team of participants interested in the further development of this technology and by structuring a program that addresses the complete system; i.e., ultimate disposal of the hyacinths as well as wastewater treatment. The program was submitted to EPA for grant funding and was approved August 1, 1978. The original participants included:

- Aquamarine Corporation, the nation's largest producer of aquatic plant harvesting equipment. They designed and built the harvesting system for the project.

- Boyle Engineering, a consulting engineering firm that designs advanced wastewater treatment systems. Headquarterd in California, the company has branch offices in the Gulf Coast area as well as in Florida, the market areas for the hyacinth system. Boyle in Orlando participated in the preliminary design phase and produced the final plans and specifications.

- Environmental Protection Agency through the Robert S. Kerr Environmental Research Laboratory in Ada, Oklahoma is acting as the lead federal organization in this project and is supervising the spending of grant funds.

- National Aeronautics and Space Administration through the National Space Technology Laboratories is providing both expert advice and grant funding for the project.

- Reedy Creek Improvement District is a special legislative district in Florida which includes all of WALT DISNEY WORLD. Its legislative charter calls for the district "to promote and create favorable conditions for the development and practical application of new and advanced concepts." The grant request to EPA was made through RCID which provides budget management and water quality analysis for the project.

- United Gas Pipe Line Company, the major subsidiary of United Energy Resources, Inc. United is expanding into areas intended to complement its natural gas transmission business, particularly the search for alternate sources of supply. U.G.P.L. has funded extensive research by the Institute of Gas Technology and has also provided funds for this project.

- Walt Disney Productions through its subsidiaries WED Enterprises and Reedy Creek Utilities Company developed the project from conception and is providing program management, engineering and operations personnel.

Recently additional participants have joined the project:

- University of Arizona's Environmental Research Laboratory has done considerable research in hyacinth production and will perform supporting studies for the project in the areas of growth optimization and nutrient requirements. They are also involved in the design of a cover over one channel.

- Department of Energy through an interagency agreement with the EPA will also support the project financially which will allow for a broadening of the project objectives.

- Gas Research Institute will fund extensive studies in methane generation with various feedstocks and sewage sludge from WALT DISNEY WORLD.

Objectives & Schedule

The objectives as stated in the grant proposal were broad but simple: (1) demonstrate a hyacinth system capable of meeting tertiary and secondary wastewater treatment standards, (2) demonstrate an energy conservative wastewater treatment system, (3) determine the optimum system performance characteristics and (4) determine the economics of a hyacinth based system. None of these objectives have changed but there has been a shift in emphasis from tertiary to secondary treatment. A new objective has also been added with the recent addition of DOE and GRI as participants in the project. It is to experiment with means of increasing biomass production and converting biomass into energy.

August 1, 1978 marked the beginning of a four year project. The final plans and specification were completed by mid November and construction began February 1, 1979. The end of construction on May 11, also marked the beginning of operation. Two months were allowed for seeding and establishing a hyacinth crop. On July 16, 1979 the project started into the Preliminary Operation Phase which will last three or four months (see figure 1). The objectives of the Preliminary Operation Phase are to quickly learn if there is an advantage to operating the system at a low water depth of 15" or a relatively high depth of 36" and if a rapid harvesting rate of twice per week is preferred over a slower rate of twice per month.

After the Preliminary Operation Phase two, one year periods, will follow of relative steady state operation. By the start of the first winter season a cover will be added over one of the channels. The influent to the hyacinth ponds shall be primary effluent the first year and secondary effluent the second. During the steady state periods the three channels will be used to determine the differences between covered and uncovered channels and between end and side harvesting. The optimum water depth and harvesting rate determined during the Preliminary Operation Phase will be used during the steady state period and will not be changed unless supporting studies dictate a change.

After two years of steady state operation, the remaining eight to nine months of the project will be devoted to experimentation with growth optimization.

Project Components

The project can be broken down into several systems or components: (1) Production System, (2) Harvesting System, (3) Composting System, (4) Monitoring Systems and (5) Supporting Studies. Components of the production system include the three 1/4 acre production channels, the system piping, utility tie-ins hydraulic control devices, and pumping stations.

Two submersible pumps, one in the primary clarifier effluent channel and the other in a filter pump wetwell of the existing RCID Wastewater Treatment Plant provide the system with primary and/or secondary effluent. An industrial water supply line has also been constructed to the project. The three pond influents are metered into the channels through a flow splitter system. Industrial water and

Figure 1

PRELIMINARY OPERATION PLAN

Channel	*Preliminary Operation 3-4 Mo.	Steady State 1st Yr.	Steady State 2nd Yr.	Other Operation 9 Mo.
1	1' Depth 2/Week Harvest Primary Effluent Parallel Flow No Cover	2' Depth 1/Week Harvest Primary Effluent Parallel Flow No Cover	2' Depth Control Second. Effluent Parallel Flow No cover	Possible Operations Series Flow Maximum Growth with High Nutrients and Rapid Harvest More Experience with Harvesting Nutrient Addition
2	3' Depth 2/Week Harvest Primary Effluent Parallel Flow No Cover	2' Depth 1/Week Harvest Primary Effluent Parallel Flow No Cover	2' Depth 1/Week Harvest Second. Effluent Parallel Flow No Cover	
3	3' Depth 2/Month Harvest Primary Effluent Parallel Flow No Cover	2' Depth 1/Week Harvest Primary Effluent Parallel Flow Cover	2' Depth 1/Week Harvest Second. Effluent Parallel Flow Cover	

secondary effluent are controlled by turbine meters and control valves. Control of the primary effluent is by weirs and control valves. The flow splitter system allows one, two, or three influents in the three channels. The channels are also interconnected hydraulically to provide for a variety of experimental modes of operation. (See Figure 2).

The walls of the channels were constructed of reinforced concrete block on a cast-in-place, reinforced concrete foundation. The channels (29' x 360') were lined with 20 mil PVC and tacked to the top of the walls with lumber. PVC booms are tied off to cleats along the top of the channel walls with lumber. PVC booms are tied off to cleats along the top of the channel walls and act as a corral preventing the hyacinths from packing together at one end of the channel. The water level in the channels is adjustable by use of effluent weirs. The water depth can be maintained at 15, 24, or 36 inches. Each of three channels incorporates the capability to be operated independently and at varied depth if desired.

The production system is designed hydraulically to handle flows up to 200,000 gpd but will probably operate at 50,000 gpd. The flow rate will be set during the fall or spring seasons at the maximum flow rate which will meet the given effluent standards. The system has been designed and built to provide the needed flexibility and experimental control and not as the least expensive way to grow hyacinths.

A cover over one channel will be constructed by December of 1979. It is currently in the design phase and may include the capacity for CO_2 enrichment studies.

There are three pieces of equipment used for harvesting: (1) a front end loader, (2) a double belt conveyor-chopper and (3) a forage wagon. All mechanisms in the system are powered by hydraulic motors connected to the hydraulic pump in the front end loader. The harvesting system is designed with a capacity of 50 tons per hour, far in excess of the system requirements.

Harvesting is accomplished by pushing the hyacinths onto the primary conveyor with a long handled hook. At the end of the primary conveyor a flail chopper cuts the plants into smaller pieces. The secondary conveyor loads the chopped plants into the forage wagon which has a live bed for ease of loading and unloading. With this method a thick 900 sq. ft. interwoven mat of mature water hyacinths can be harvested in approximately one hour. Set up and take down time is also approximately one hour. These times should drop as experience is gained with the system.

The three channels will be divided in cells 60' long x 29' wide by floating booms. The harvesting system is completely mobile and can accomodate harvesting both from the sides and ends of the channels.

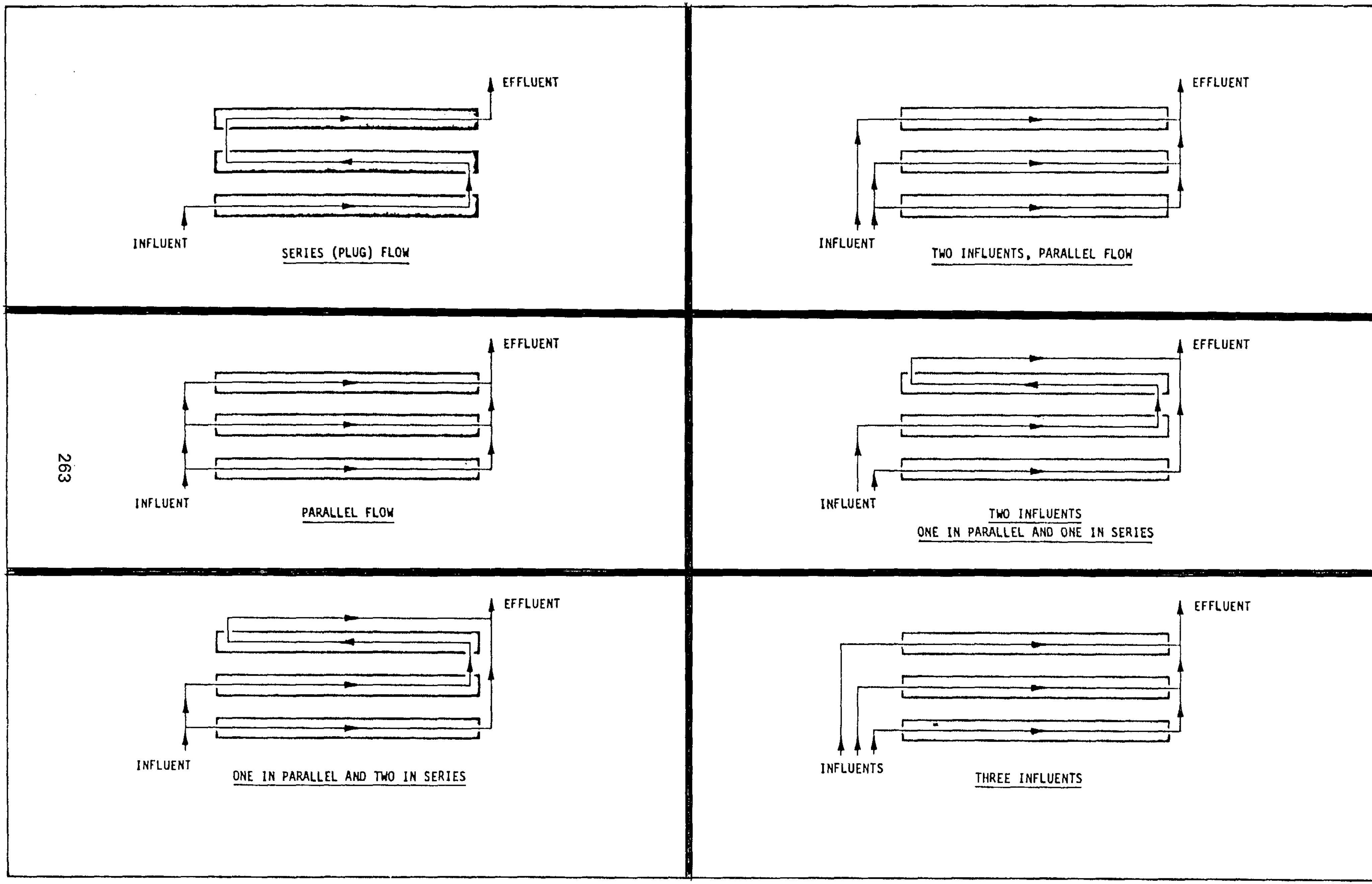

Figure 2
SYSTEM MODES

One channel will be covered during the winter and may require end harvesting only. During the steady state operation, a second uncovered channel would then be end harvested for comparison with the covered channel and third channel could be side harvested for comparison with the second. In all three channels the same harvesting rate, total hyacinth coverage and individual cell coverage would be maintained. The floating booms will be used to push the hyacinths in each cell into a uniform density, thereby allowing measurement of the hyacinth covered area before and after harvesting. Once a week a 5 square foot area of plants in each cell would be weighed to get the hyacinth density.

The composting system is a windrow system utilizing a composting pad and a front end loader. Once the forage wagon is full, it is moved to the composting pad and unloaded by means of the live bed. All hyacinth harvested that day are put into a pile. A new pile will be turned three times during the first week, and once per week for the remaining five weeks. Temperature and free moisture will be monitored in the piles for composting control. The desired values are 50-60 percent moisture and 140-150° F. The compost product will be analyzed quarterly and will be given to the W.D.W. Grounds Maintenance Department for use on their ornamental tree farm.

The monitoring role can be divided into two functions: (1) baseline date acquisition and (2) intensive studies. The baseline monitoring program will provide the long term data on how well the hyacinth system operates and what can be expected from it, while the intensive studies will provide the answers to specific questions.

Table 1 is a summary of the baseline monitoring program. The operators are responsible for recording the daily environmental conditions such as water and air temperature while chemical analysis of the pond influent and effluent is performed twice per week by the RCID laboratory. Bi-weekly chemical analysis is considered sufficient in light of the long hydraulic detention times in the channels (7 to 15 days).

The monitoring system includes equipment, such as four automatic samplers and an automatic analyser, as well as a record keeping system. The record keeping system is set up on a daily, weekly, monthly and quarterly basis depending on the parameter being analysed or recorded. The daily date summaries kept by the project operator includes flows, water temperatures, dissovled oxygen concentrations and other environmental information. The weekly data summaries include laboratory analysis, a summary of the daily records and the composting and harvesting data. Similarly the montly records are a summary of the weekly data summaries.

In order to keep a record of hyacinth production for harvesting and data analysis purposes it was necessary to devise a method for determining hyacinth density. The method involves using the floating booms to get a uniform density and the percentage of water surface area covered with hyacinths. A five square foot area is segregated

Table 1

BASELINE MONITORING

MEASUREMENT	PERFORMED BY	LOCATION	FREQUENCY	REPORTED
Flow	WWTP Operator	I&E	3/day	I&E; Daily Average
H_2O temperature	" "	IM&E	3/day	IM&E; Daily Average
pH	" "	IM&E	3/day	IM&E; Daily Average
DO	" "	IM&E	3/day	IM&E; Daily Average
Humidity	" "	Pond Vicinity	Continuous	Low/High; Daily Average
Air temperature	" "	" "	Continuous	Low/High; Daily Average
Rainfall	" "	" "	Continuous	Daily
Solar Insolation	CEP	CEP	Continuous	Btu/day - m^2
pH	Lab	I&E	2/week	
TSS	"	"	2/week	
TDS	"	"	2/week	
BOD	"	"	2/week	
TOD	"	"	2/week	
TOC	"	"	2/week	
NH_3 - N	"	"	2/week	
Org - N	"	"	2/week	
Nitrite - N	"	"	2/week	
Nitrate - N	"	"	2/week	
Ortho - P	"	"	2/week	
Total P	"	"	2/week	
Total Alkalinity	"	"	2/week	
Total Coliform	"	"	2/week	

from the rest of the uniformly bunched hyacinths by using a tool similar to a cookie cuttler. The segregated hyacinths are then moved into a basket attached to a hanging scale and are weighed. The weight divided by 5 square feet gives the density of the hyacinths in that area and using the densities of the other areas, the weight of the whole crop can be established.

The major pieces of monitoring equipment are (1) an automatic analyzer, (2) four refrigerated automatic samplers, (3) moisture and temperature probes for the composting operation, (4) flow meters and (5) meteorological instruments.

The RCID laboratory has purchased an automatic sampler in connection with the project to perform daily water quality analysis and the intensive studies. This piece of equipment augments a very well equipped lab which includes an atomic absorption spectrophotometer and gas chromatograph.

Three composite and one discrete automatic samplers are used at one influent and three effluent sampling points. The samples are collected over a 24 hour period but are not proportional to flow. A flow meter has been purchased which when hooked up to one of the composite samplers will give a proportional to flow sample.

The monitoring of the composting operation is done with two pieces of equipment, an insitu moisture meter and a temperature probe. The control of the operation and the determination of the end of the composting process will be based on free moisture and temperature.

Flow in and out of the ponds will be recorded from turbine meters and with rainfall data will be used to determine evapotranspiration which may be very large in hyacinth systems.

The meteorological instruments include a pyranometer for solar insolation measurement and an air temperature and humidity meter and recorder.

The intensive studies will include any monitoring requirements beyond the baseline monitoring program. Some studies will answer very specific questions while others provide essential information to the data base of the project. The intensive studies will include:

(1) Comparison of proportional to flow samples with regular composite samples.

(2) Determination of day to day variations and hour to hour variations in effluent BOD, SS, N, P valves.

(3) Determination of BOD, SS, N, P channel profiles.

(4) Performing laboratory water quality analysis quarterly for metals, pesticides, etc.

(5) Performing plant characterization quarterly; relate to size to plant and location in pond.

(6) Performing compost characterization quarterly.

It may be necessary in the future to incorporate some of the quarterly analysis into the baseline monitoring program.

The supporting studies are a very important part of the overall project. The objective of the supporting studies is to provide information through laboratory scale research which could influence the operation of the project. Specific areas of needed research include growth optimization through micro and/or macronutrient addition, optimum harvesting schedule, duckweed performance during hyacinth dormant periods and energy conversion.

The University of Arizona has had for some time an extensive research program with water hyacinths. They have joined the project as a participant and will perform many of the supporting studies. Mr. John Groh of the Environmental Research Laboratory at the University of Arizona is also involved in the design of the cover.

The energy conversion supporting studies will be performed through the Gas Research Institute. Anaerobic digestion performed in the lab of hyacinths, sewage sludge and mixtures of the two will be the subject of the first studies.

Data Analysis

Water quality analysis was started halfway through the two month crop establishment period. Secondary effluent was used during this period because of its high nutrient content and low-potential for causing anaerobic conditions in the ponds. On May 14, each of the three channels was seeded with 30 feet of water hyacinth, roughly 10 percent of the total surface area. In two months the coverage was 100 percent which gives a doubling time of approximately two weeks. With full coverage, the pond was meeting the tertiary effluent standard of 5 mg/l BOD, 5 mg/l SS, 3 mg/l T.N., but was not meeting the phosphorus standard of 1 mg/l T.P. (see Table 2). However, this data is not sufficient to make any conclusions about the systems effectiveness in the tertiary treatment mode.

On July 16, 1979, the pond influent was switched to primary effluent and the Preliminary Operation Phase was started. The summary of data collected during the month of August is presented in Table 3. The raw influent to the Reedy Creek Improvement District (RCID) treatment plant averaged 200 mg/l SS and 300 mg/l BOD during August. The pond effluent averaged 22.9 mg/l SS and 27.9 mg/l BOD. Taking into account a reduced effluent flow rate due to evapotranspiration the combination of primary clarification and hyacinth treatment does meet the secondary treatment standard of 90 percent removal of BOD and SS. However, the data is not sufficient to make any further conclusion at this time due to the limited time of operation.

Table 2

HYACINTH PROJECT DATA SUMMARY

WEEK ENDING 7/15/79

PARAMETER	SECONDARY EFFLUENT	POND EFFLUENT
1. FLOW (gpd)	50000	
2. pH	6.4	6.4
3. TSS (mg/l)	10.0	2.0
4. BOD (mg/l)	16.0	3.0
5. NH_3-N (mg/l)	11.1	0.08
6. ORG.-N (mg/l)	6.87	1.27
7. NO_3-N (mg/l)	0.20	<0.01
8. TOTAL-N (mg/l)	18.17	1.35
9. ORTHO-P (mg/l)	3.76	2.15
10. TOTAL-P (mg/l)	4.50	2.18
11. H_2O TEMP. (^{0}C)	27	
12. H_2O D.0 (mg/l)	1.6	
13. AIR TEMP. (^{0}F)	83	
14. HUMIDITY (%)	76	
15. INSOLATION (BTU/ft^2-day)	1170	

Summary based on one set of data points.

TABLE 3
HYACINTH PROJECT DATA SUMMARY

AUGUST 1979

PARAMETER	PRIMARY EFFLUENT	POND EFFLUENT
1. FLOW (gpd)	50000	42000*
2. pH	6.9	6.9
3. TSS (mg/l)	83.2	22.9
4. TDS (mg/l)	285	237
5. BOD (mg/l)	160	27.9
6. NH_3 - N (mg/l)	18.38	14.76
7. ORG. - N (mg/l)	9.10	7.18
8. NO_3 - N (mg/l)	0.01	0.01
9. TOTAL - N (mg/l)	27.49	21.95
10. ORTHO - P (mg/l)	4.61	4.13
11. TOTAL - P (mg/l)	6.20	4.80
12. ALK. (mg/l)	122	147
13. TOTAL COLI. (mpn/100ml)	$1.05 \cdot 10^8$	$1.43 \cdot 10^6$
14. H_2O TEMP. (^0C)	27	
15. H_2O D.O (mg/l)	0.6	
16. AIR TEMP (^0F)	81	
17. HUMIDITY (%)	83	
18. INSOLATION (BTU/ft^2-day)	1300	

Summary based on 8 sets of data points.
*Flow based on one week's data.

The first compost piles were started August 8. The data on the composting operation indicates that water does need to be periodically added to keep the free moisture content up to 50 percent. No odors are detectable at the site which also indicates that more water can be added. The temperature of the piles has not reached the desired level but it is not clear whether this is due to improper temperature measurement or lack of sufficient free moisture. A new temperature probe is being acquired for the composting operation.

Data analysis is considered a very important part of the project and in the future loading rates, detention times, hyacinth growth, nutrient mass balances, removal rates and removal efficiency will be calculated as part of the data analysis. The most important factors are the appropriate removal rates which will be correlated with loading rates, hyacinth growth and environmental conditions.

SUMMARY

In general all of the components of the project are operating as planned but there have been problems. For example, when the ponds were first seeded the hyacinths were hand picked and placed into the channels. This was too slow, so a backhoe was used to finish the seeding. This was a mistake because a great deal of dollarweed and grass was brought in with the hyacinths. Some of the unwanted species were removed but total segregation was not possible. The unwanted plant species were harvested out of the system only after much effort.

The only major concern at this time is whether or not the system can effectively handle primary effluent. The dissolved oxygen concentrations are very low, floating sludge in the open areas has appeared and there are many fly larvae where the ponds once flourished with thousands of mosquito fish. Fortunately mosquitoes have not been a problem so far.

In summary, the hyacinth project at WALT DISNEY WORLD is still in the process of start up. The scope of the project is quite large and there are many details to be worked out. The system is unique in its attempt to provide all the data needed by engineers to design a water hyacinth wastewater treatment system.

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UTILIZATION OF WATER HYACINTHS FOR CONTROL OF NUTRIENTS IN DOMESTIC WASTEWATER -- LAKELAND, FLORIDA

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The use of water hyacinths (Eichhornia crassipes) for removal of nutrients and solids during a demonstration project in Lakeland, Florida indicates that removals are as a result of more than hyacinth uptake. Therefore, if design of a hyacinth system is based upon the uptake and growth kinetics of the plants during cool weather periods, it appears that an ample safety margin can be maintained. The hyacinth growth rates were found to be similar to those found in other studies. A first order design equation based upon the Monod concept using total nitrogen as the limiting nutrient is presented. Other aspects of the hyacinth system such as harvesting, crop processing, and marketing have been investigated, but are still in need of additional field work before maximum effectiveness is realized.

INTRODUCTION

Utilizing local funds, the City of Lakeland and Polk County, Florida have implemented a demonstration project intended to investigate the possibility of utilizing water hyacinths for removal and recovery of nutrients from secondary effluent prior to discharge into the nearby Peace River System. This demonstration project presently is over half completed. It has resulted in the development of a better understanding of the potential of hyacinths in nutrient removal. It has also revealed that these systems can be successful only if directed by an intensive and effective management program designed for efficient crop handling, selective harvesting, and rapid processing and movement into the selected market.

SYSTEM DESIGN

While there are presently a few water hyacinth systems in operation throughout the Southern U.S., there are several factors related to the Lakeland situation which make its design considerations somewhat unique. First of all, the nutrient removal requirements are extremely stringent--1.5 mg/l-TN and 0.4 mg/l-TP. Secondly, the concept is being groomed to become part of a regional 201 plan, meaning the size of the system could be as large as 49,200 cubic meters/day (13 mgd). This means that unlike smaller systems, there will be a most urgent need to handle the harvest quickly and efficiently. In essence, the Lakeland Demonstration Project was intended to investigate the potential of water hyacinth treatment as a large scale treatment methodology.

The physical design of the demonstration ponds as shown in Figure 1 is intended to allow the operator some flexibility in manipulating such critical parameters as depth, pollutant and hydraulic loading, and retention time. The three-ponds-in-series concept allows easier assessment of productivity responses to changes in water quality.

Three harvesting channels intended to accommodate a Hidrostal E5KL solids pump or a aqua-guard self-cleaning bar screen were included as part of the design. Both of these two harvesting possibilities showed potential for removing large quantities of material at a low energy and labor input. An efficient harvesting system is one necessary requirement for a large scale hyacinth system.

PROJECT GOALS

The Lakeland demonstration project, as noted, was intended to review all aspects of water hyacinth treatment, and to provide some guidance in developing a design for a large scale system. Basically, there are three major design questions which must be confronted.

At what rate and by what mechanism(s) do hyacinths remove nutrients, and what parameters control these rates?

Can the hyacinths be effectively harvested, processed and dried without over-escalating operating costs?

Are there any marketing potentials for water hyacinths, and to what degree can the sale counter operating costs?

DESIGN CONSIDERATIONS FOR NUTRIENT REMOVAL

Construction of the three, 0.405 hectare (one-acre) lagoons as shown in Figure 1 was sufficiently completed by 12/6/78 to permit filling. This was done through a 6-inch siphon line from the easternmost secondary clarifier at a rate of 0.719 cubic meters/sec. (190 gpm). By 12/20/78, the ponds were completely full. At this time about 0.91 metric tons (1 ton) of hyacinths were introduced into each pond. This represented an approximate surface area of 23 square meters/pond (250 square feet) or a 0.5 percent coverage of the total surface.

Productivity was monitored by setting a 0.093 square meter (1 sq. ft.) chamber within each pond, seeding it with a small plant and measuring weekly growth changes on a wet weight basis. Later in the program dry weight density estimates from random samples will be used to project productivity.

As is shown in Figure 2, there is a good exponential relationship between change in wet weight and time. Also, there is a notable change in the rate of growth between the different ponds. It was also noted

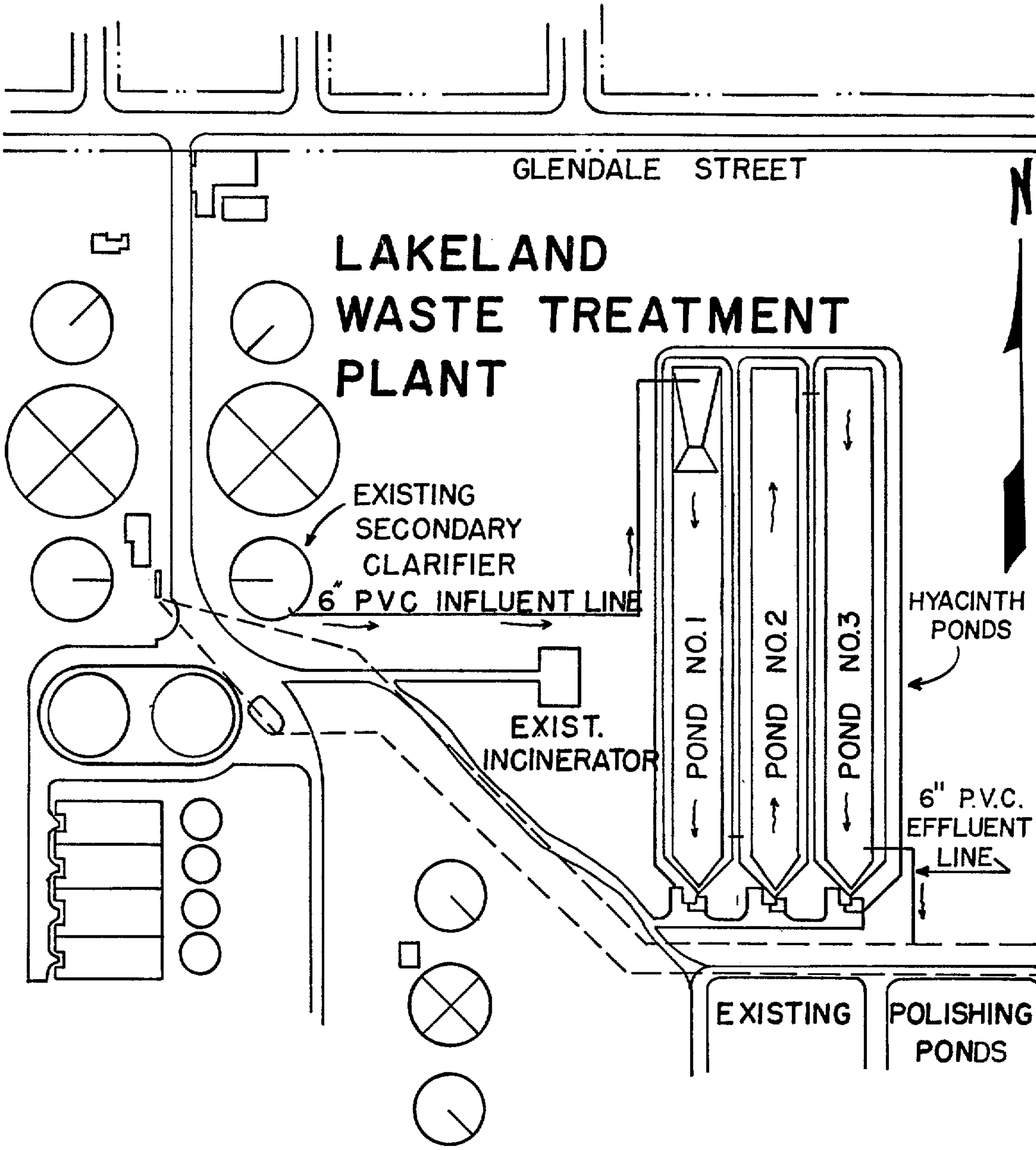

Figure 1: Site Plan for Water Hyacinth Treatment Demonstration Project -- Lakeland, Florida

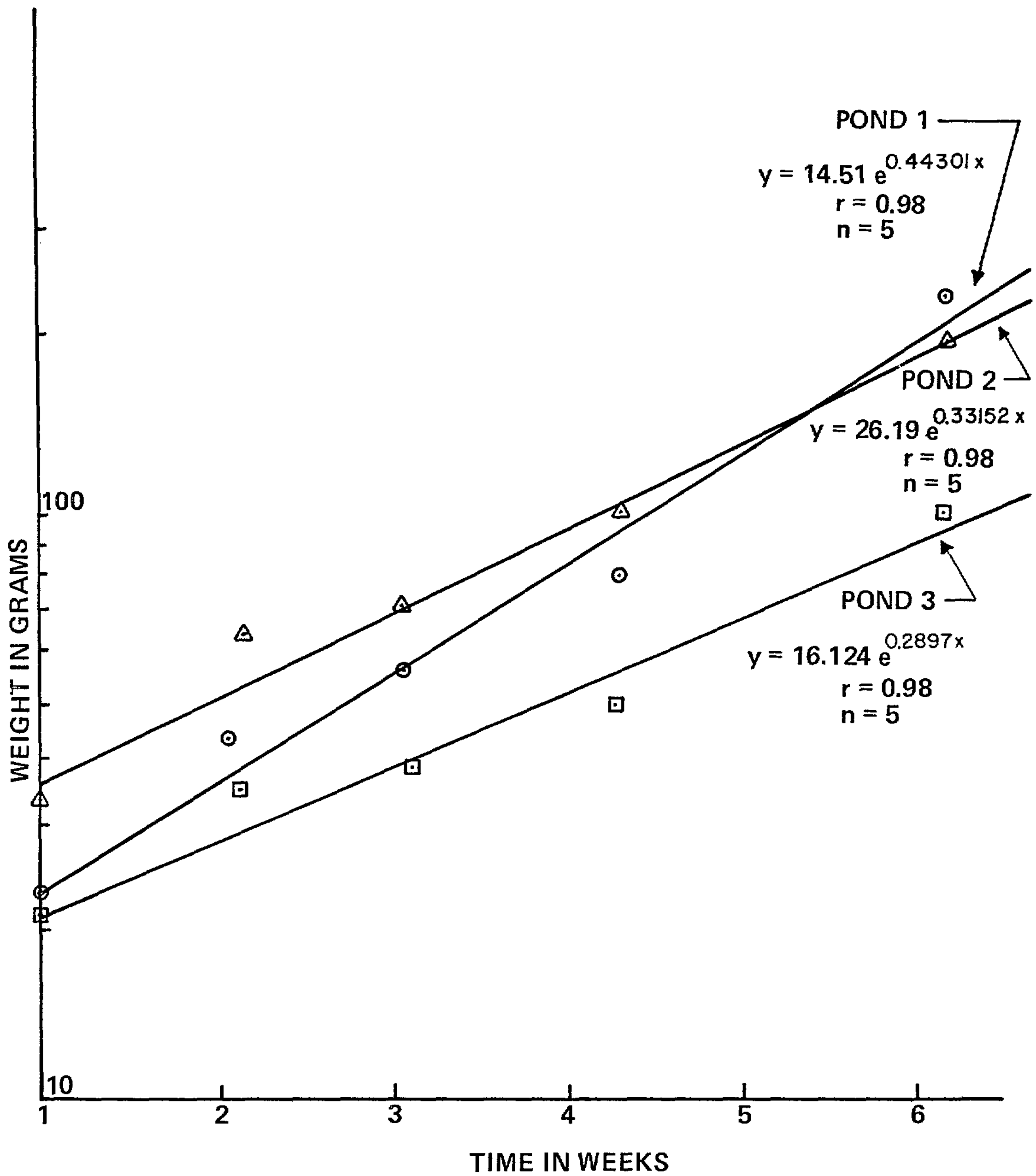

Figure 2: Growth Kinetic Equations for Lakeland Hyacinth Study

that the chlorophyll content and general health of the plants declined from Pond 1 to Pond 3. This change was interpreted as a nutrient or vitamin deficiency. Nitrogen, carbon, and phosphorus levels were observed to be adequate in all three ponds. Further investigations showed no changes in potassium or magnesium. Iron, however, was noted to decline from 0.125 mg/l to 0.05 mg/l throughout the system. This latter concentration is low even for many natural waters in Florida. Because of this, and because water hyacinths are known to effectively take up iron, it was decided that iron might be the present limiting nutrient. To compensate for this deficiency, ferrous sulfate was added to the ponds at such a rate that the concentration of iron was maintained near 0.30 mg/l. This replenishment resulted in a general cessation of this chlorosis.

The equation, as shown in Figure 2, for Pond 1, can be modified if it is realized that the constant 14.51 represents the initial standing crop. If this is converted to a variable (Z), this new equation can be utilized as a design equation for winter conditions as follows:

$$y = Ze^{0.44301x}$$

where y = wet weight produced (metric tons)
x = time in weeks

Based upon the literature it may be legitimately assumed that dry weight is 0.05 y, total P by dry weight is 0.5 percent, and total N by dry weight is 4.0 percent. Average winter air temperature is 14.4°C (58°F) as indicated in Figure 3.

The desired winter standing crop can now be determined by equalibrating with the incoming load of nutrients. For 378.5 cubic meters/day (100,000 gpd), using 25 mg/l-TN and 6 mg/l-TP, the load is equal to 9.53 kg/day (21 lbs./day) nitrogen and 2.27 kg/day (5.0 lbs./day) phosphorus. This is equivalent of 756 kg/day (16,667 lbs./day) of wet hyacinths or 52,967 kg/week (116,667 lbs./week) of wet hyacinths. This value can be seen to be equal to Y-Z or $\triangle Z$. This allows the design equation to be expressed as follows:

$$Y - Z = \triangle Z = Ze^{0.44301x} - Z = 52,967 \text{ kg}$$

Setting x as one week, it is found that the desired standing crop (Z) is 95,027 kg (209,310 pounds wet weight. Using a desired plant length of 64-76 cm (25-30 inches) and a density of 225 metric tons/ha (100 tons/acre) (see Figure 4), the indication is that 0.43 ha (1.06 acres) of hyacinths at a wet density of 225 metric tons/ha would handle, in the winter, 378.5 cubic meters/day (100,000 gpd) of secondary effluent, using a weekly growth rate coefficient of 0.44301. This amounts to about 11.8 hectares/million cubic meters daily (11 acres/mgd). Considering only 75 percent coverage and anticipating a decline in growth rates in the latter stages, it appears that 21.5 hectares/million cubic meters daily (20 acres/mgd) would be more realistic. (This corresponds to a growth rate coefficient of about 0.33).

With this density and acreage the incoming nutrient load would theoretically be reduced to negligible levels. Unfortunately, the

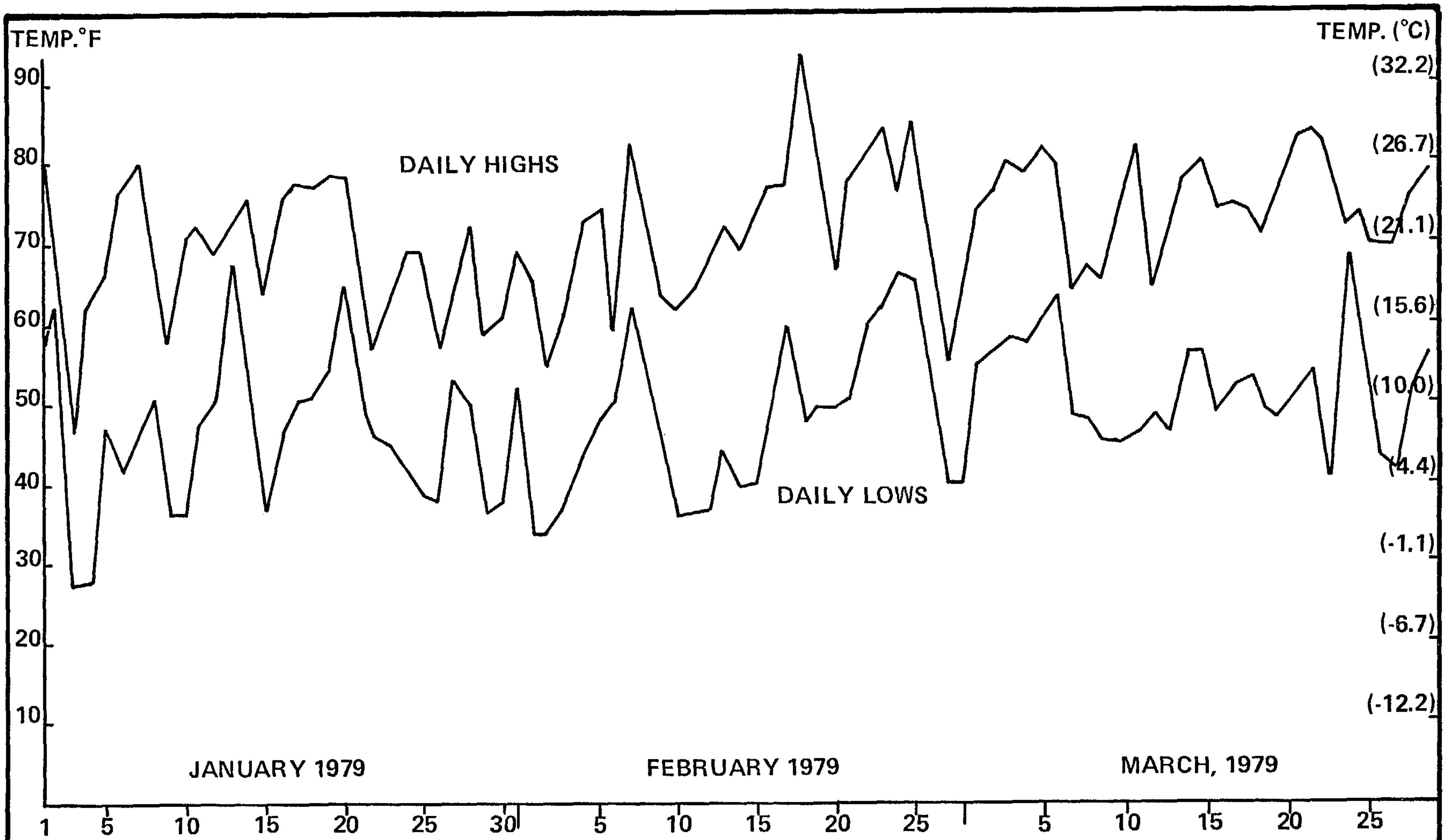

Figure 3: Temperature Profiles at Lakeland WWTP During Phase 1 of the Hyacinth Demonstration Project

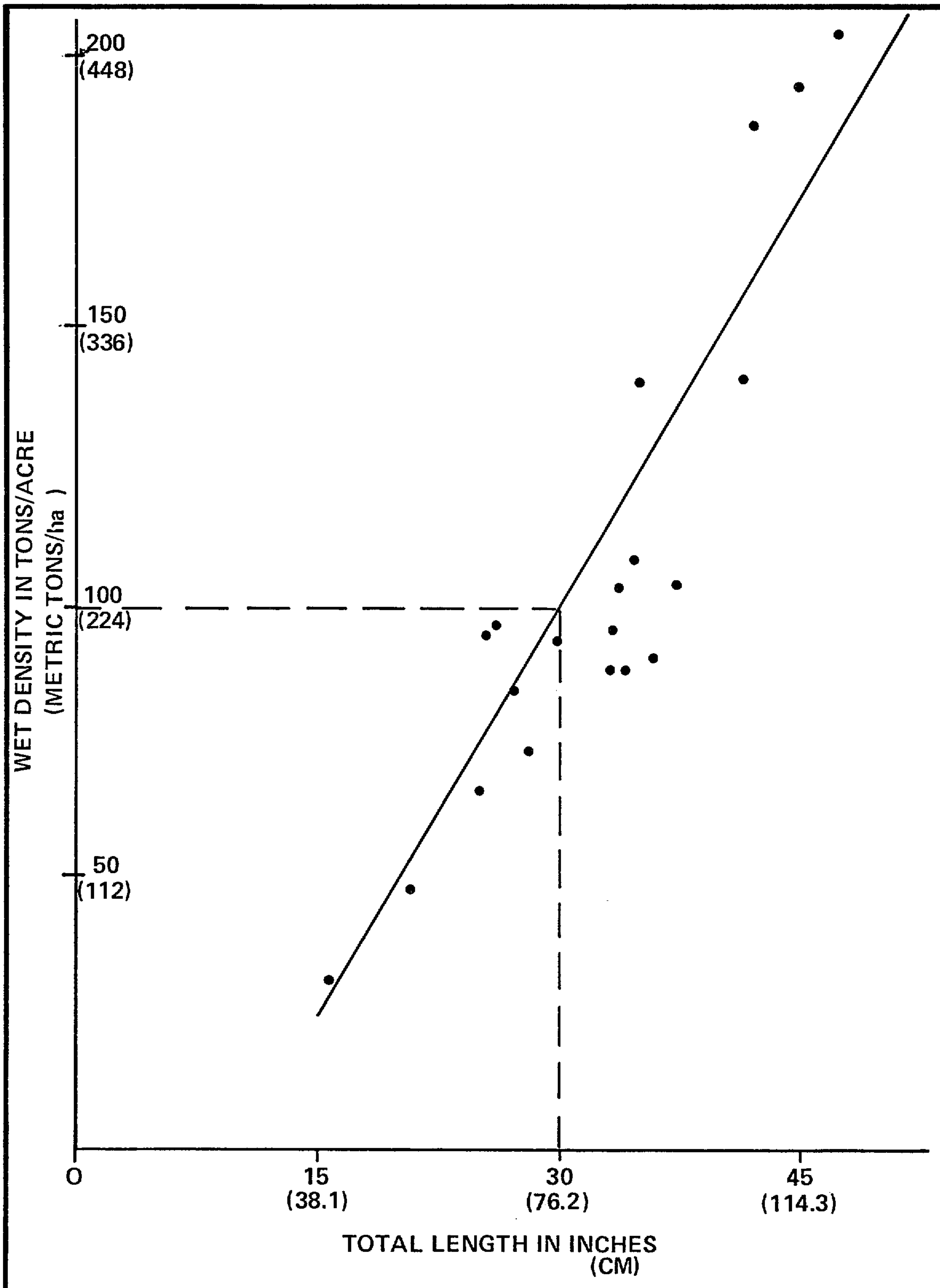

Figure 4: Estimated Hyacinth Density Based Upon Plant Length [Wolverton, 1977]

nitrogen to phosphorus ratio of the plant material is lower in the wastewater than in the plant material. This means that at some point nitrogen may become a limiting factor and productivity will decline much in the way when iron was noted to be deficient in Pond 3. The question is, at which concentrations will this occur?

Musil and Breen (1977), two South African researchers, evaluated the growth kinetics of water hyacinths through the Monod limiting nutrient enzyme equation --

$$U = \overline{U}\left(\frac{S}{K_s+S}\right).$$

where U = specific growth rate
$\overline{U}$ = maximum specific growth rate
S = limiting nutrient concentration
K_s = half saturation constant; i.e. when $U = 0.5\overline{U}$.

This equation is similar to that used in determining bacterial growth kinetics in activated sludge. In their investigations, Musil and Breen (1977) determined that nitrate (NO_3^-) was the limiting growth factor. In fact, they implied that other nitrogen forms are not utilized by the hyacinths.

"NH_4-N supplied in culture, however, had no effect on growth. This is in agreement with Sculthorpe (1967) who suggested that the NH_4^+ ion does not act as a nitrogen source for hyacinth plants."

Unfortunately, the concept of nitrate as being the most important, and perhaps the only nitrogen source for hyacinths, does not agree with data collected so far in the Lakeland study. For example, Musil and Breen (1977) projected that K_s for NO_3^- is 21.74 mg/l as NO_3^- or 4.91 mg/l NO_3^- as N. The concentration in Pond 1 during this period of testing averaged 0.25 mg/l NO_3^- as N, while in Pond 3 it averaged 4.0 mg/l NO_3^--N. Applying this information to the Monod equation, the projected growth rates would be 0.06 $\overline{U}$ for Pond 1 and 0.48 $\overline{U}$ for Pond 3. Obviously such a difference did not occur. They further determined that the maximum growth rate ($\overline{U}$) for hyacinths is 0.1145 g-wet weight/g-day. This implies that in Pond 1 the growth should be 0.00687/day and Pond 3 should be 0.05496/day. In reality, using the best fit equations for Pond 1 and Pond 3, it can be determined that the growth rates averaged 0.065/day for Pond 1 and 0.043/day for Pond 3.

If total nitrogen, instead of just nitrate (NO_3^-) is used with the Musil and Breen (1977) findings, then with Pond 1, at an average TN concentration of 19.8 mg/l-TN and with Pond 3 at an average concentration of 10.5 mg/l-TN, the projected growth rates are 0.091/day for Pond 1 and 0.081/day for Pond 3 at 25°C. Using the Van'tHoff rate for adjustment to temperature, it is projected that at 15°C (59°F) the maximum growth rate would be 0.057/day and the subsequent rates in each pond would be 0.046/day for Pond 1 and 0.041/day for Pond 3. This is a fairly close projection for Pond 3 but somewhat low for Pond 1. The projected trend, however, is comparable to actual field data.

The work of Misil and Breen (1977) is most helpful in developing and understanding the growth kinetics of hyacinths in the Lakeland situation. Some caution must be taken, however, when trying to express growth rate kinetics in terms of one nutrient.

There was noticeable change in water quality as the percent in hyacinth coverage changed as is shown in Table 1, and Figures 5 and 6. The most relevant observations were as follows:

Oxygen levels were maintained at adequate levels, even below the hyacinth mats. In Pond 1, where the lowest levels would be expected, the DO rarely fell below 2.0 mg/l anywhere in the system. Oxygen levels were often above saturation in Pond 3 because of the dominance of phytoplankton.

Changes in pH were from neutral or near neutral to slightly alkaline. Again, this was due to algae production in Pond 3.

BOD_5 and SS were reduced somewhat, particularly later in the program. Constant algae blooms in Pond 3, however, keep these levels higher than what will be expected when coverage is complete.

Nitrogen and phosphorus uptake exceeded that expected for the measured crop density of 99 metric tons/ha (44 wet tons/acre) as is shown in Figures 5 and 6. This additional uptake apparently is related to uptake within other compartments of the ecosystem.

Water color and turbidity were reduced noticeably throughout the system except during extremely active algae blooms.

Dissolved solids were noted to decrease somewhat despite the high evapotranspiration. This is probably due to selective uptake of certain ions such as ferrous ion, calcium, and chlorides.

Coliform reduction was quite dramatic. This correlates well with the literature.

Nitrogen transormation appeared at first to be towards nitrification. As coverage increased, however, nitrate was noted to decrease throughout the system. The exact nature of nitrogen transformation throughout the ponds is undoubtedly quite complex. The fact is, however, that whether the hyacinths are directly using organic and ammonia nitrogen, or whether they are using only nitrate which is being supplied by nitrifying bacteria, a limiting growth factor related to the nitrogen species present is not demonstrated by this study. If hyacinths are in fact dependent upon nitrate, as suggested by Musil and Breen (1977), then they are quite effective in supporting an active nitrifying population within their root systems.

Perhaps the most dramatic change noted throughout the system was the change in biological composition and diversity. Pond 1 was characterized by large hyacinths with a root to total plant length ratio of about 1:3 to 1:4. The roots often supported an extensively developed bacterial slime. In areas exposed to light, epiphytic algae was also noted. Macroinvertebrates were restricted to chironomid larvae, larvae of the mosquito Culex quincifaciatus and a small unidentified snail. Populations of two fish species, Gambusia affinis and Poecilia latipinna were noted to be surviving quite well. At one point the fish population appeared to approach about 11 fish per square meter. Young fish were noted in late February, indicating successful breeding.

Mosquito larvae population at its peak approached about 2.6 million/cubic meters or an estimated 2642 grams wet or 264 grams dry weight per cubic meter. Assuming that these larvae are about 1.5 percent phosphorus on a dry weight basis, it can be estimated that about 15 kg (33 pounds) of phosphorus are tied up in their biomass. If 5 percent hatch

TABLE 1

BIWEEKLY WATER QUALITY DATA SHEET (COMPOSITE SAMPLES)
WATER HYACINTH DEMONSTRATION PROJECT

Date		Flow cfs mgd	Water T	Air T AVG	pH*	DO* mg/l	NO_3-N mg/l	TKN mg/l	TN mg/l	Ortho P mg/l	TP mg/l	BOD_5* mg/l	SS mg/l	TS mg/l	Fecal* Coliforms No./100 ml	Remarks and Observations
12/15	Influent	0.190		66		2.9	0.56	19.06	19.62		6.94	-	-			% coverage - 0%
	Effluent	-		-		6.7	0.30	21.6	21.90		7.39	-	-			
12/29	Influent	0.190	-	67		3.2	0.37	19.20	19.57	4.72	6.67	-	-			% coverage - 1%
	Effluent	-		-		8.0	0.41	14.30	14.71	4.99	5.61	-	-			
1/22	Influent	0.190	-	52		4.0	0.34	20.14	20.48	-	6.59	-	-			% coverage - 3%
	Effluent	-		-		7.5	1.70	12.24	13.94	-	6.14	-	-			
1/25	Influent	0.190	-	65		4.5	0.24	23.20	23.44	-	6.93	-	-			% coverage - 4%
	Effluent	-				8.5	1.52	12.80	14.32	-	6.93	-	-			
2/12	Influent	0.085	61	55	7.23	2.2	0.1	20.7	20.8	6.1	7.7	24	12	411	TNTC	% coverage - 12%
	Effluent		60	-	7.67	8.2	6.0	7.4	13.4	5.3	6.5	15	7	403	840	
2/14	Influent	0.084	60	57	7.38	3.4	0.3	22.1	12.4	6.0	6.9	13	5	409	TNTC	% coverage - 12%
	Effluent	0.065	68	-	8.67	15.0	5.0	7.1	12.1	5.0	4.9	10	2	395	870	
2/19	Influent	0.086	66	57	7.40	5.8	0.4	24.0	24.4	5.5	12.5	50	17	411	TNTC	% coverage - 16%
	Effluent	0.049	68	-	9.10	11.0	3.6	6.8	10.4	2.5	9.0	36	30	376	500	
2/21	Influent	0.084	72	66	7.22	3.9	0.45	19.5	20.0	4.8	6.0	18	39	423	TNTC	% coverage - 16%
	Effluent		70	-	9.42	14.8	2.9	5.5	8.4	2.0	2.6	11	39	423	130	
2/26	Influent	0.086	62	53	7.40	4.4	0.06	21.4	21.46	5.5	5.5	20	5	394	TNTC	% coverage - 23%
	Effluent		58		8.95	9.6	2.5	5.5	8.0	2.0	2.5	18	28	386	780	
2/28	Influent	-	-	-	-	8.0	0.2	20.3	20.5	5.5	8.0	24	14	-	-	% coverage - 23%
	Effluent	-	-	-	-	18.6	2.0	5.8	7.8		0.5	18	28	-	-	
3/5	Influent	0.072	68	70	7.15	2.9	0.36	16.5	16.9		4.5	12	10	379	TNTC	% coverage - 32%
	Effluent		66		9.0	6.7	0.2	4.5	4.7	1.8	2.2	7	20	374	700	

* Grab samples instead of composite at influent and effluent stations.

TABLE 1
(Continued)
BIWEEKLY WATER QUALITY DATA SHEET (COMPOSITE SAMPLES)
WATER HYACINTH DEMONSTRATION PROJECT

Date		Flow cfs mgd	Water T AVG	Air T	ph*	DO* mg/l	NO_3-N mg/l	TKN mg/l	TN mg/l	Ortho P mg/l	TP mg/l	BOD_5* mg/l	SS mg/l	TS mg/l	Fecal* Coliforms No./100 ml	Remarks and Observations
3/7	Influent	0.071	68	58	7.12	3.5	0.36	17.3	17.7	4.5	4.5	18	22	380	TNTC	% coverage - 38%
	Effluent		67		9.13	1.2	0.42	4.2	4.6	2.0	2.7	14	20	342	680	
3/14	Influent	0.065	68	68	7.0	3.6	0.71	12.9	13.6		2.5	15	15	326	TNTC	% coverage - 42%
	Effluent		72		7.95	5.4	0.01	4.3	4.3		0.7	17	16	321	650	
3/21	Influent	0.064	75	68	7.05	6.2	0.54	15.1	15.6	4.0	5.0	24	45	420		% coverage - 45%
	Effluent		73		8.80	4.2	0.20	5.7	5.9	0.8	1.2	21	18	376		
3/27	Influent		70	59	6.85	3.2	0.64	18.6	19.2	4.25	5.0		92	447		Spraying for
	Effluent		67		7.53	4.1	0.006	3.7	3.7	5.5	7.0		8	378		Mosquito Larvae
6/20	Influent	0.258	84	83	7.10	4.2	0.2	11.8	12.0		4.3	19	13	366		
	Effluent		82	83	6.80	1.6	0.1	2.0	2.1		5.6	10	1	339		
6/27	Influent	0.240	82	79	7.10	4.2	0.3	8.5	8.8		4.8	8	4	345		
	Effluent		81	79	6.65	1.6	0.0	1.6	1.6		3.5	4	0	321		
7/12	Influent	0.154	84	83	7.09	2.2	0.13	6.6	6.7		3.3	20	8	294		
	Effluent		83	83	6.54	1.0	0.06	0.9	1.0		0.6	3	1	323		
7/19	Influent	0.120	85	85	7.10	6.4	0.20	13.4	13.6		3.0	24	13	355		
	Effluent		83	85	6.80	3.2	0.012	1.1	1.1		1.8	1	10	294		
7/26	Influent	0.177	87	87	7.00	3.4	0.17	13.7	13.9		3.8	28	23	357		
	Effluent		87	87	6.90	5.1	0	0.8	0.8		2.3	1	0	263		
8/9	Influent	0.225	85	83	6.76	1.6	0	13.4	13.4		5.0	32	36	377		
	Effluent		84	83	6.62	2.6	0	1.4	1.4		3.1	3	7	258		
8/23	Influent	0.235	84	83	6.63	0.70	0.0	27.2	27.3		5.0	24	14	328		
	Effluent		83	83	6.90	4.8	0	4.2	4.2		3.8	7	12	231		

*Grab samples instead of composite at influent and effluent stations.

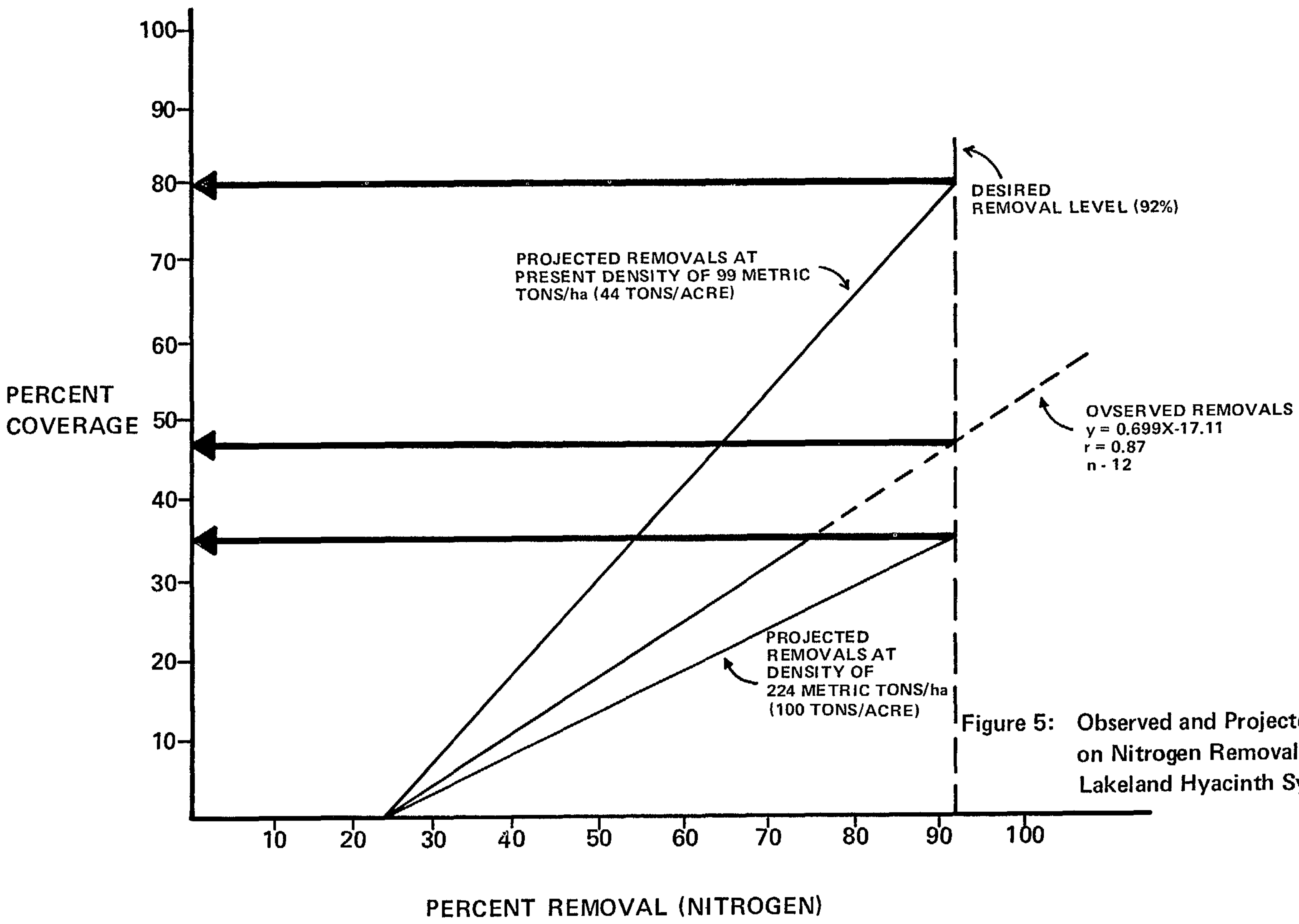

Figure 5: Observed and Projected Trends on Nitrogen Removal Within the Lakeland Hyacinth System

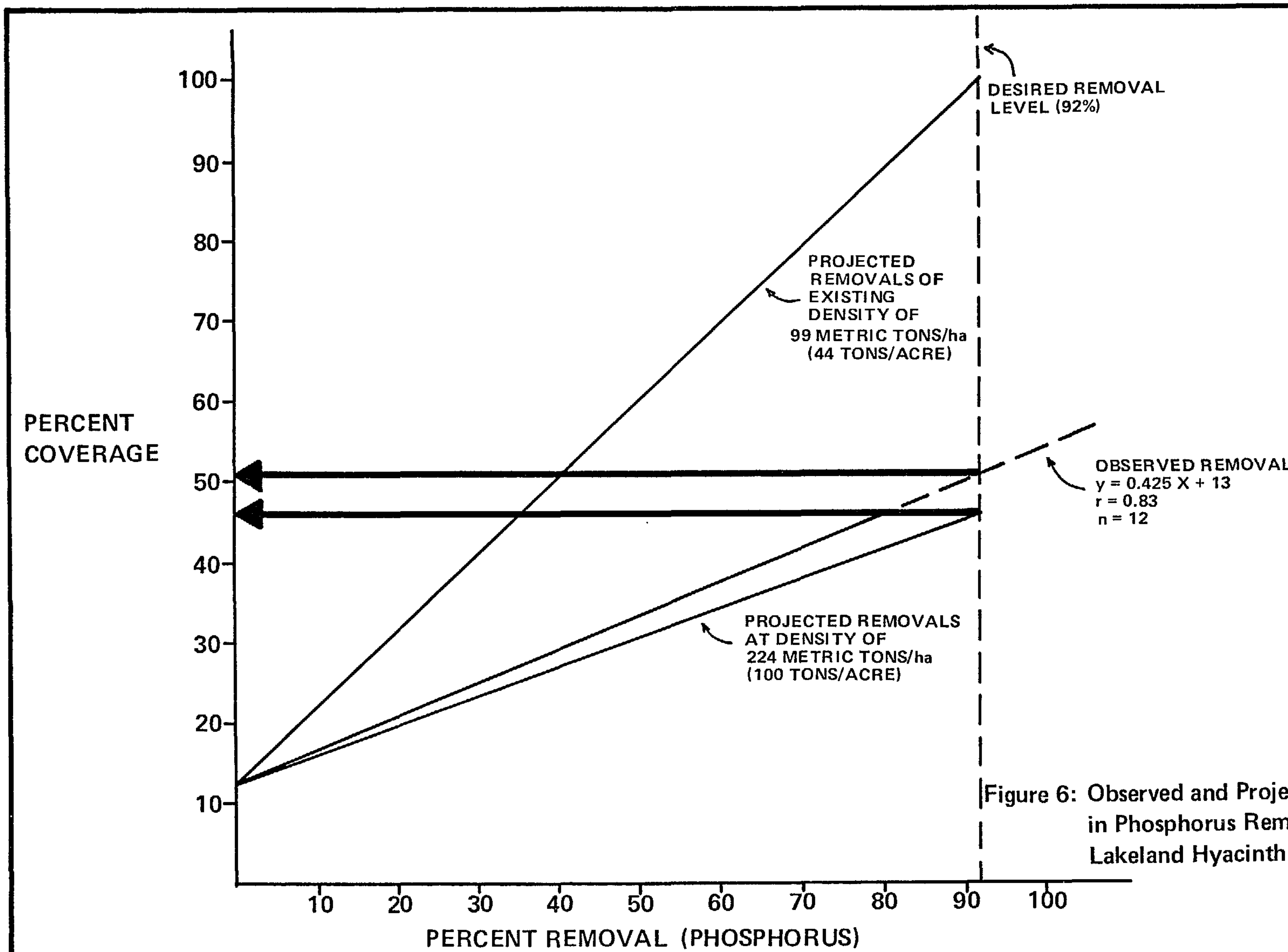

Figure 6: Observed and Projected Trends in Phosphorus Removal Within the Lakeland Hyacinth System

each day, it can be determined that about .75 kg (1.65 pounds) of phosphorus is removed daily by mosquitoes alone. This accounts for a 33 percent removal of the daily load. Looking at Figure 6 it now becomes evident why the observed nutrient removals can be greater than the projected removal from productivity alone. Unfortunately, mosquito larvae are not a desirable larval form. Other insects, however, might well provide some assistance in nutrient control within the ponds.

The impact of the food web upon nutrient removal, particularly phosphorus, was demonstrated following an intensive spraying of diesel fuel for mosquito control. Upon dying, the larvae apparently released their phosphorus into the pond systems, causing the effluent concentration to increase from 0.7 mg/l to over 6.0 mg/l. It is important then to adopt a mosquito control program that does minimal harm to other invertebrates and plants and assures that a large mosquito larvae population does not develop.

In Pond 2 the ecosystem appeared to be much more diverse. The fish population grew extremely fast, as the fish appeared to favor this particular lagoon. The invertebrate population consisted of a dragonfly larvae, amphipods, damselfly larvae, various water beetles and their larvae, several types of freshwater mollusks, cray fish, snapping shrimp, and oligochaete and annelid worms. In addition to *Gambusia* and *Poecilia* populations, several *Fundulus* species (topwater minnows) were noted as well as a killifish species. Tadpole populations were also noted to be developing. Tadpoles, which are a vertebrate larval form, may also serve in nutrient control, much in the same manner as mosquito larvae.

The hyacinths in Pond 2 suffered slightly from chlorosis (a noted iron deficiency). The root to total plant length was about 1:2 to 1:3. The roots were clean as compared to Pond 1, and often supported many invertebrate species. The larvae of the Culux mosquito were noticeably scarce, often showing population of less than 270 per square meter.

Pond 3 showed an even greater diversity of invertebrate and fish life. Mosquito larvae were virtually absent except in small isolated areas. The hyacinths were very chlorotic prior to iron treatment, with a root total plant ratio of 1:1.5 to 1:2.

A detailed population and species diversity study was not made during this first phase of the project. Once a stable ecosystem has been established, however, an attempt will be made to identify the more critical species involved in the nutrient dynamics.

Based upon the water quality and flow data and the productivity rates, a nutrient and water budget for the ponds was projected. This information is graphically illustrated in Figures 7 and 8. Shown in Figure 7 is a projection of the fate of nutrients and water during the 104 days of Phase 1. Presented in Figure 8 is a projection of nutrient flows for a stable system based upon the data collected during Phase 1. Figure B is based upon weekly harvesting with an average growth rate coefficient of 0.33 and the assumption that at 1.5 mg/l total nitrogen, the growth rate will have decreased by 75 percent. The interesting point here is that nitrogen may have to be added to the system, perhaps as much as is contributed initially by the wastewater. This may accommodate complete phosphorus control. The need and cost for this "fertilizer" nitrogen will be determined during Phase 2.

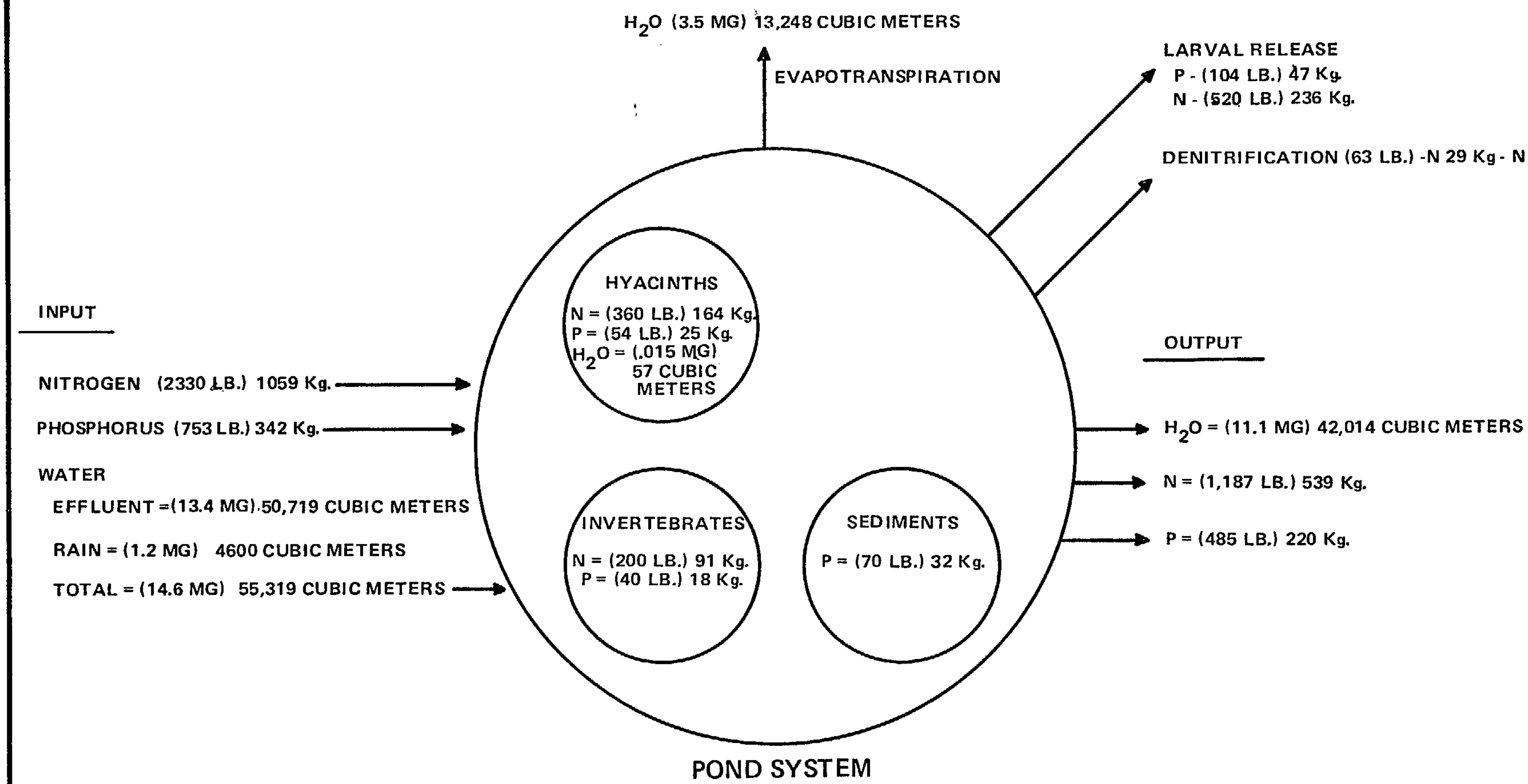

Figure 7: Nutrient and Water Budget Projected During 104 Days of Phase I of the Hyacinth Demonstration Project

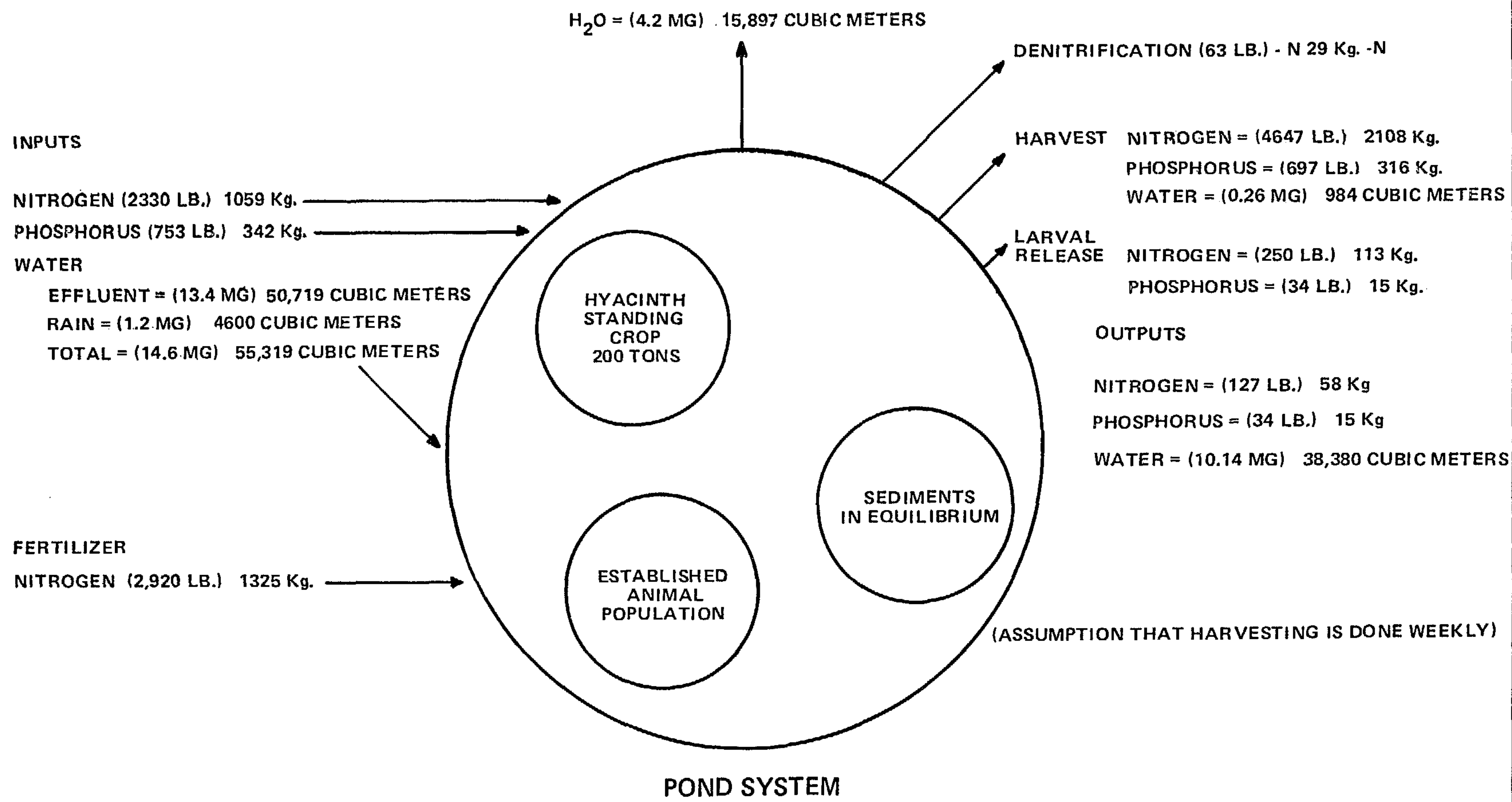

Figure 8: Projected Nutrient and Water Budget During Typical 104 Days During Stabilized Conditions of Hyacinth Treatment System

HARVESTING, PROCESSING AND DRYING

Most of the work dealing with harvesting, processing and drying was modeled after the work by Bagnall (1976). Using a 30.4 cm (12-inch) screw press designed by Dr. Bagnall, it was found that from 1.8-3.6 metric tons (2-4 tons) of wet hyacinths could be processed per hour. The press was driven by a 50 HP tractor with power take-off. If a properly designed feed system were used, it would be quite possible for the press to require only one operator. Estimated energy consumption for pressing whole hyacinths is approximately 6.2 kwh/ton or a cost of approximately 28¢/metric ton (25¢/ton). The press results in a reduction of moisture content from 95 percent to approximately 85 percent. The resultant water loss is about 666 kg/metric ton (1,330 lbs./ton) or a volume loss of 666 liters/ton (160 gallons/ton). The juice is extremely high in solids -- over 2 percent -- and in nutrients. It is estimated that about 47,850 liter/day (10,000 gallons/day) of this juice will be produced for each 3.785 cubic meters/ day (one million gallons/day) of plant capacity. Handling of this material represents an additional design problem. Its similarity to sewage sludge makes it somewhat compatible with several existing technologies. Bagnall (1979) presently is investigating the use of this material for methane production. Other possibilities are to settle and recover the suspended solids and incorporate these with the remaining pressed harvest. The supernatent could be returned to the influent side of the treatment facility.

If the hyacinths are chopped prior to pressing, it is possible to increase the rate of pressing to about 6.4-9.0 metric tons/hour (7-10 tons/hour). It was found that by placing a cutting element on the Hidrostal pump used for harvesting that the plants could be effectively chopped during the harvesting phase. Early tests on a 5"-5 HP/1150 RPM pump reveal a potential harvest rate of about 1.8 metric tons/hour (2 tons/hour). Considerable difficulty, however, was encountered with intake blockage. This made the pumping operation inefficient and labor intensive. It is felt that with a larger intake and higher drive unit (17 HP) that the pump could be successfully modified to harvest about 20 tons/hour. The energy consumption for the pump in this case would amount to about 0.64 kwh/ton or 2.8¢/metric ton (2.5¢/ton). Labor costs, considering one operator at $10/hour, amount to 55¢/metric ton (50¢/ton). Compared to the conventional approach of using a dragline which harvests at about the same rate the total cost of 57.8¢/metric ton (53¢/ton) is quite inexpensive. The dragline operating cost is approximately $1.87/metric ton ($1.70/ton).

The other harvesting consideration is to use a conveyor type system such as a self-cleaning bar screen. Bagnall (1979) has designed a harvester with a 1/2-1 HP drive unit that can remove up to 18 metric tons/hour (20 tons/hour). Again, considering a one man operation, it appears that this method of harvesting may cost only slightly more than 55¢/metric ton (50¢/ton), with the energy demand about 0.004 kwh/metric ton (0.04 kwh/ton). However, with the conveyor, a separate chopping system will be required.

Once pressed the hyacinths are dried upon a direct insolation solar dryer. At a loading rate of about 12.2 kg/square meter (2.5 lbs./sq. ft.) these dryers, when protected from the rain, have shown the capability to consistently reduce the moisture content to about 20 percent in five days. The present dryers cost approximately $10.78/sq. meter ($1/sq. ft.). If they were to be built in such a way that they were logistically efficient and physically strong enough to last at least five years, however, it is estimated that the cost would be about $32.28/sq. meter ($3/sq. ft.). This would elevate the capital cost estimate for drying to about $66,050/million liters-day ($250,000/mgd), not including land purchase. Properly designed, however, the solar dryer system will have virtually no energy demand, and labor costs should be no more than two persons per 4,650 sq. meters (50,000 square feet) of dryer. This amounts to approximately 93¢/wet metric ton (85¢/wet ton) of harvested hyacinths for drying. It is felt that certain design features could be added to the dryers to decrease the drying time, and subsequently reduce the overall labor costs. The most notable of these improvements would be to make it possible to easily turn and spread the material on the dryer on a daily basis. Another idea is to augment the drying process with a continuous, heated air type dryer. This would relieve the demands upon the direct insolation dryers from 15-20 percent to 40-55 percent moisture. The continuous flow dryer would be an integral part of a feed pelletizing system.

MARKETING POTENTIAL

While there may be several marketing pathways for water hyacinths, the Lakeland study has placed more emphasis on their feed potential. It is felt that a feed produced from water hyacinths, fiber concentrate, and taste and vitamin additives will make up the major portion of a complete dairy or beef feed rationing. Working with a local feed producer, hyacinths at 20 percent moisture have already successfully been included as a pelletized feed on a small scale. These hyacinths, which contain around 20 percent crude protein on a dry weight basis, theoretically represent an inexpensive, high quality source of digestible nutrients and minerals when fed at about 20 percent of the total ration. Their estimated value, at 20 percent moisture is about $22-$33/metric ton ($20-$30/ton). This amounts to an estimated cost recovery of about $30,383/million liters-day ($115,000/mgd).

As of yet, this feed has not been fed to actual test animals. More detailed work will be needed to check levels of toxic materials which may interfere with the concept's viability. Preliminary laboratory tests, however, indicate that the material is suitable. Presently, the City of Lakeland is awaiting reply on a request for EPA funding to further investigate this feed option.

The market potential in Florida alone for dairy cattle is about 4,085 metric tons/day (4,500 tons/day) of feed. The hyacinth demand would be twenty percent of this, or 817 metric tons/day (900 tons/day) (at 20 percent moisture). This correlates to what would be produced daily by about 0.22 million cubic meters/day (58 mgd) of domestic wastewater. There is evidence, therefore, that water hyacinth treatment would have to be utilized by approximately 20 percent of all wastewater systems within Florida before the State's dairy market would become saturated. Considering the possibility of an expanded national and international market, and the possibility of use with other livestock, it can be deduced that there is a rather expansive potential market.

PROBLEM AREAS

Frost

During the winter months the temperature fell below freezing twice. During the most intensive exposure, temperatures were at -3°C (27°F) for three hours. This resulted in some damage to the outer leaves, but did not destroy the plants, nor did it noticeably retard their productivity. According to Penfound and Earle (1948), the hyacinth will not be injured to a point where recovery will not occur until the temperatures fall below -5°C (23°F) for 12 continuous hours, or below -3°C (27°F) for 48 continuous hours. Such occurrences are extremely rare in Florida. To counter the impacts of such rare instances, a spray system could be utilized to protect 30 percent of the crop. The remaining 70 percent could be harvested. Replacement of this standing crop would occur in approximately 15 days, during which time the nutrient allocation may be exceeded. This, however, would be a brief violation, which would not result in an actual violation based upon annual or monthly allowances. The assessment at this point is that the winters in Lakeland will pose no major threat to the systems viability, nor will any measures taken to prevent frost damage be cost prohibitive. The actual projected costs for frost prevention will be presented in the final project evaluation.

Mosquitoes

The major problem encountered during the early phase of the project was the development of huge populations of the mosquito *Culex quincifaciatus*. Once a large fish population was established, however, and the system stabilized, the mosquito population virtually was eliminated. As of yet, they have not reappeared. Control measures considered along with fish populations are parasitic nematodes (Peterson; 1975) and monomolecular alcohols (Levy; 1979). From review of other hyacinth projects, it appears that biological control is adequate for elimination of significant mosquito populations.

Phosphorus Removal

During the summer months, once the ponds filled with hyacinths, it was found that an effluent could be consistently produced at concentration of 2.0 mg/1-TN, 4 mg/1-BOD, and 4 mg/1-SS. Phosphorus levels, however, have fluctuated between 0.2 mg/1 and 4 mg/1. As noted, the nutrient ratios in the wastewater are not conducive to phosphorus removal. Furthermore, it is felt that sloughing of tissue from older plants may be contributing to this problem. Regardless, it appears that additional management practices or perhaps additional treatment regimes may be required to control phosphorus. One concept is to apread the recovered effluent on a rapid infiltration system prior to final disposal. More consistent and selective harvesting, more intensive ecological management, and increased detention times may also be utilized for enhancement of phosphorus removal capabilities. Considerable work is needed in evaluating the phosphorus removal mechanisms within these hyacinth systems.

Politics and Funding

Since its first consideration as a feasible treatment method to be included in 201 planning in Lakeland, the use of water hyacinths have met almost constant opposition from state and federal environmental agencies. The basic reasoning has been that it was not a proven technology. The fact is that almost all advanced waste treatment methods are not really proven technologies. This has been the major force which instigated the innovative and alternative technology support written into PL95-217. Fortunately, water hyacinths are now included as an innovative land application method, although the quoted nutrient removal reliabilities may be somewhat conservative. No 201 in the country at this time, however, is receiving Federal dollars for design and construction of a water hyacinth system.

As noted, this demonstration project was totally funded by local dollars -- despite a formal request to EPA for $80,000 R&D funds. The rejection of these funds came shortly after a nearby private group received almost ten times that amount to construct and implement a hyacinth project. This gesture was understandably interpreted as an inequity. As might be expected, it encouraged a feeling of distrust towards the Federal government. This continual refusal of participation by EPA has created a generally cautious attitude in some of the local officials. Dealing with some of these political problems, which, in all truthfulness, have been largely created by EPA's reluctance to properly interpret and implement the directives of PL95-217, will undoubtedly be the major obstacle confronting completion of this project and the Lakeland 201.

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Other Aquatic Processes Session

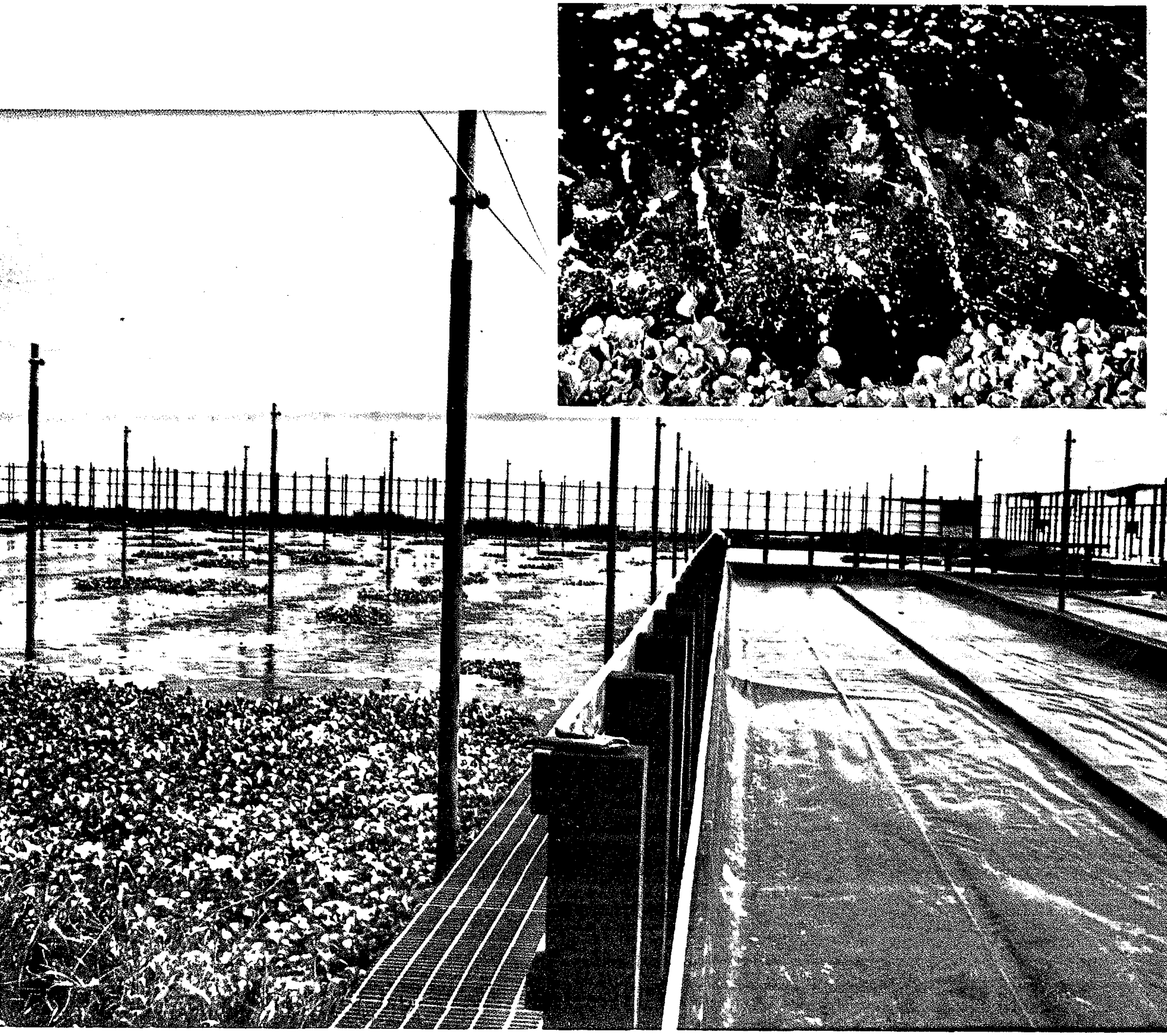

Photo of the recently completed Solar AquaCell system built at Hercules, California. Comminuted wastewater passes through the two stage anaerobic AquaCells on the right side of the picture, designed to provide 12-20 days detention. The waste water then passes through an aerated facultative AquaCell to maximize oxygen transfer and additional AquaCells covered with water hyacinths and duckweeds. The insert depicts plastic BIOWEB structures that provide increased surface area for microbial growth in the anaerobic and aerated AquaCell units.

OTHER AQUATIC PROCESSES: SESSION SUMMARY

The session on "Other Aquatic Systems for Wastewater Treatment," as the title implies, included diverse papers. It is revealing to consider the reasons for the many different approaches to wastewater treatment that have been represented at this seminar. If there is one thing common to all of these practices, it is that each has a unique set of man-made and natural ecological constraints.

Among the man-made constraints are: (1) the volume and make-up of the waste to be treated, characteristics of which vary from community to community, seasonally and diurnally, and with the degree of pretreatment provided; (2) the standards for wastewater effluent discharge that must be met by the treatment system; and, (3) the economic basis and the resources available for the project.

Ecological laws, of course, form the basis for our efforts to utilize natural aquatic processes to treat and recycle waste, and lead to much of the diversity seen in aquaculture treatment systems. Although many aquatic plants are cosmopolitan, some will perform better than others under particular climatic conditions. Similarly, the choice of organisms for use in wastewater treatment will vary with the type of waste to be treated; an organism's tolerances of the chemical and physical extremes of the wastewater environment will in part determine its suitability for use in a given aquaculture treatment system. Finally, impounded wastewater forms no less complex an ecosystem than natural surface waters. Many of the same natural processes that produce fluctuations in dissolved oxygen and carbon dioxide content, light intensity, reproduction rates, and a host of other chemical, physical and biological parameters in natural waters, also operate in wastewater treatment projects involving aquaculture systems.

The possible combinations of these man-made and natural variables alone guarantee that a wide range of conditions will occur in aquaculture treatment systems. To this point, the speaker's responses have been almost as varied and can be best summarized by the following quote from the speaker Darrell L. King:

> "A great variety of biological, chemical, and physical factors interact and feedback to set limits on the ability of natural ecosystems to process wastewater. An understanding of these ecological limits allows better design of alternative wastewater management systems which can be tailored to fit local environmental and wastewater conditions relative to local wastewater effluent standards."

Session Moderators:

A. W. Knight, Professor
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SOME ECOLOGICAL LIMITS TO THE USE OF ALTERNATIVE SYSTEMS FOR WASTEWATER MANAGEMENT

Darrell L. King, Institute of Water Research, Michigan State University, East Lansing, Michigan 48824

A great variety of biological, chemical, and physical factors interact and feedback to set limits on the ability of natural ecosystems to process wastewater. An understanding of these ecological limits allows better design of alternative wastewater management systems which can be tailored to fit local environmental and wastewater conditions relative to local wastewater effluent standards. Ecological interactions responsible for oxygen supply for BOD satisfaction, plant production, and nutrient removal and recycle by alternative wastewater systems are considered for aquatic ecosystems and combinations of aquatic and terrestrial ecosystems.

INTRODUCTION

When considering the use of natural ecosystems as means of wastewater treatment, it is tempting to picture a series of ponds, perhaps coupled with a terrestrial irrigation system, which will satisfy many different desires. Often such conjecture includes a natural solar powered wastewater recycling system which produces large amounts of food stocks, serves as a recreational site, produces minimal sludge and recharges groundwater or surface water with water from which all nitrogen, phosphorus, deleterious organics, metals, bacteria, and viruses have been removed. Zero surface discharge and optimal fish cultures are other attributes often desired from such systems. But, accumulating information from various operating aquatic, terrestrial, and combination aquatic-terrestrial wastewater recycle systems casts serious doubt on the ability to meet these various goals with any one system with current management practices.

This suggests certain limits to the use of such systems, but it does not indicate that these natural systems have no place in wastewater treatment. The standard of comparison should not be whether or not these natural systems meet all of these utopian goals, but rather how they compare with modern mechanical systems in meeting wastewater standards. In the long term, the most meaningful comparison may well be that of wastewater treatment efficiency per fossil fuel energy input.

But, to truly judge their effectiveness, such alternative systems must be designed and operated to take full advantage of the various natural processes within the constraints imposed by the complex physical, chemical, and biological interactions which characterize, control, and limit natural ecosystem function. Without careful attention to such ecological limits, these alternative wastewater management systems may fail to yield desired results in any of several different areas.

The purpose of this paper is to consider some of the ecological limits to various suggested uses of alternative wastewater management systems which rely on natural ecological processes.

THE AQUATIC ECOSYSTEM

The usual comparison between conventional mechanical wastewater treatment systems and those which use natural ecological processes stress the differences and minimize the similarities. And yet, even the modern activated sludge process relies on biological concentration of organics by a portion of the aquatic ecosystem supported by mechanical intervention. Oxygen required for bacterial respiration is supplied by mechanical means and excess respiratory biomass is mechanically removed as sludge; but, even in this ecologically simple, largely controlled system, shifts in species of biota at times cause an undesirable change in performance.

Ponds of some sort are an integral feature of most alternative wastewater treatment systems where their use may range from BOD reduction to storage of wastewater prior to application to some type of terrestrial system. Regardless of the use of the pond, impoundment of wastewater markedly increases the complexity of the aquatic system used as a wastewater treatment process. The decreased reliance on energy demanding mechanical processes is accompanied by a loss of control of the system. The efficiency of wastewater renovation is then dependent upon the limits imposed by the natural pond ecosystem.

The first use of the pond ecosystem for wastewater treatment in this country was the sewage lagoon. Initiated in Texas and North Dakota the use of lagoons expanded greatly after the study at Fayette, Missouri, (1) indicated their significant removal of BOD_5 and coliform bacteria.

The most widely used lagoon is the faculative lagoon usually operated from three to six feet deep with an anaerobic bottom covered by an aerobic surface layer maintained by planktonic algae. The aquatic process responsible for wastewater renovation in lagoons is often viewed (2)(3) as a symbiotic arrangement in which bacterial release of nutrients from waste organics supports algal photosynthesis which in turn supplies oxygen to the bacteria. The aquatic ecosystem of the lagoon is far more complex than this and relies heavily on the alkalinity system for the carbon dioxide required for algal photosynthesis (4). In fact, the carbonate-bicarbonate alkalinity system serves as a bank from which carbon dioxide can be withdrawn during the daylight hours for sufficient photosynthetic oxygen production to meet the night respiratory demands. Night respiratory release of carbon dioxide recharges the alkalinity system prior to the next sunrise if the lagoon is in some degree of balance. This process which allows capture of respiratory carbon dioxide and allows diurnal variation of dissolved oxygen from near 1 mg O_2/ℓ to levels in excess of 30 mg O_2/ℓ and diurnal pH variation of up to 3 pH units is depicted in equations 1, 2, and 3 as the sum of the first and second dissociations of carbonic acid.

$$HCO_3^- + H^+ \rightleftharpoons CO_2 + HOH \tag{1}$$

$$HCO_3^- \rightleftharpoons CO_3^= + H^+ \tag{2}$$

$$2\ HCO_3^- \rightleftharpoons CO_2 + CO_3^= + H^+ \tag{3}$$

The significantly greater departure of the dissolved oxygen concentration of the lagoon from atmospheric saturation during daylight supersaturation than during the undersaturation of the night yields a net loss of photosynthetic oxygen to the air when light intensity and temperature allow active algal photosynthesis. This leads to a net extraction of carbon dioxide from the alkalinity, an increase in pH, and a decrease in the free carbon dioxide concentration of the water as a function of increased time of detention of the wastewater within the lagoon (5). The resulting decreased carbon dioxide level causes changes in algal species culminating in dominance by the blue-green algae (4). The probability of establishment of blue-green algal dominance thus increases as a function of increased detention time of the wastewater within the lagoon. The blue-green algae, buoyed up by their gas vacuoles, do not readily sink in the lagoon and thus increase the algal content of the effluent from the pond, thereby yielding elevated effluent suspended solids concentrations.

Regardless of the algal type, production of oxygen by the lagoon algae is accompanied by the production of considerable organic matter in the form of algal protoplasm. Use of photosynthetic oxygen to meet the oxygen demand imposed by bacterial respiration of waste organics leaves an oxygen demand in the water in the form of algal protoplasm which must be satisfied at a future time. Exportation of algal laden lagoon effluent to receiving streams places the burden of meeting oxygen demand imposed by the lagoon algae on the stream ecosystem (6)(7).

The expansion of the use of lagoons was based largely on the results of studies which showed lagoons to yield excellent removals of both coliform bacteria and BOD_5. Subsequently, it was shown that for algal laden lagoon effluents the conventional measurement of BOD_5 included only about 20 percent of the ultimate BOD (6)(7) because the algae do not lyse and release their contents for bacterial attack in the five day incubation period within the BOD bottle. However, as long as the standard applied was BOD_5, lagoons generally met standards. Addition of a suspended solids standard forced consideration of the algae in the effluent, not adequately measured by BOD_5, and most lagoons no longer met standards. This called for an energy dependent mechanical intervention for removal of algae and some of the apparent advantage of the lagoon was lost.

NUTRIENT REMOVAL BY PONDS

Continued upgrading of wastewater standards has in many areas included imposition of nutrient limits on wastewater effluents, with the nutrients most commonly considered for elimination being phosphorus and nitrogen. Harvest of aquatic vegetation and animal products, sorption on the pond bottom and chemical precipitation under the high pH conditions generated in such ponds are all viewed as good methods of nutrient removal within wastewater ponds.

The potential for natural aquatic systems to remove nutrients is under study at the Water Quality Management Facility (WQMF) at Michigan State University. This facility, charged with 0.5 MGD of good quality secondary effluent, allows evaluation of the potential of both aquatic and terrestrial systems for the management of nutrient rich wastewater (8). Within the WQMF, the wastewater flows by gravity through a series of four ponds to a pumphouse from which it is applied as spray irrigation to a 130 ha site containing oldfields, forest, and crop land. The ponds range from 3.23 to 4.98 ha with a total pond surface area of 16 ha. Maximum pond depth is 2.4 m at the outlet and mean operating depth is 1.8 m to place the entire pond bottom within the photic zone to encourage growth of aquatic macrophytes. The secondary domestic effluent conveyed to the WQMF contains 16-20 mg N/ℓ and about 5 mg P/ℓ with a BOD_5 usually less than 10 mg/ℓ. The secondary effluent coming into the pond can be routed directly to the pumphouse or water from any of the four ponds can be routed to the pumphouse for spray irrigation on the terrestrial site.

In response to the nutrient enriched wastewater which enters the WQMF ponds, aquatic photosynthesis occurs at a rapid rate markedly accelerating the biogeochemical cycle of carbon, nitrogen, and phosphorus. Carbon dioxide uptake from the alkalinity by the algae and macrophytes within the ponds is accompanied by significant oxygen production and pH values often well in excess of 10 during the spring, summer, and fall months.

PHOSPHORUS REMOVAL

The three mechanisms for phosphorus removal within the pond systems are sorption on the pond bottom, precipitation as a variety of phosphates under high pH, and uptake by plants. Sorption on the bottom sediments is finite and after slightly over a year of operation, the phosphorus content in the outlet of the fourth WQMF pond exceeded the Michigan effluent standard of 1 mg P/ℓ. Phosphorus is precipitated during periods of high pH, but these precipitates are dissolved during low pH characteristic of respiratory periods. Macrophyte harvest, even if 100 percent efficient, would allow only about 10 percent removal of annual phosphorus load (9). In effect, then, there is no natural mechanism at work in pond ecosystems which will allow sufficient phosphorus removal in ponds to meet the Michigan phosphorus discharge standard at any reasonable loading rate. For a short period immediately after construction, ponds may show excellent phosphorus removal. But, this will cease once the pond bottom becomes saturated with phosphorus at equilibrium with the wastewater phosphorus concentration. Thus, it appears that pond systems will remove phosphorus just long enough for the designer and contractor to collect their fee and leave town.

NITROGEN REMOVAL

Incoming nitrate nitrogen is rapidly taken up by both the algae and macrophytes, but particularly by the algae in the WQMF. The resulting plant mass is in turn rapidly cycled through the remainder of the aquatic community, particularly the bacteria, with the nitrogen being released as the ammonium ion. Under the high pH maintained within the pond by continued photosynthetic extraction of carbon dioxide from the alkalinity, the ammonium ion is rapidly dissociated to free ammonia gas according to equation 4 for which the pK is about 9.3 at summer temperatures.

$$NH_4^+ \rightleftharpoons NH_{3(g)} + H^+ \qquad (4)$$

The free ammonia thus generated is rapidly lost to the air. During occasional periods of respiration following collapse of an algal bloom, the lowered pH and decreased oxygen concentration may allow some denitrification with the consequent release of nitrogen gas. However, the generally very low nitrate concentrations, high pH, and high oxygen concentrations suggest that the overwhelming bulk of the nitrogen loss from the WQMF occurs as direct ammonia loss to the atmosphere. Harvest of macrophytes yields some nitrogen removal but even with near maximal harvest only 9 percent of the observed nitrogen loss was accounted for in plants harvested from the WQMF ponds (9).

The extreme dynamic nature of the ponds and the associated loss of nitrogen to the atmosphere as ammonia yields an efficient means of removing nitrogen from wastewater. During 1976, when 0.5 MGD of secondary effluent was passed through the four pond system, total nitrogen concentration decreased as function of detention time as shown in equation 5.

$$N_t = N_o\, e^{-.03t} \qquad (5)$$

Where: N_t = total nitrogen concentration mg N/ℓ at time t
N_o = initial total nitrogen concentration in mg N/ℓ
t = time in days

Fifteen to twenty mg/ℓ total nitrogen entering the WQMF ponds was reduced to about 0.5 mg total nitrogen/liter with a detention time of 120 days, while inorganic nitrogen concentration was at times as low as 0.05 mg N/ℓ in the fourth pond after about a 120 day detention period.

MEETING EFFLUENT STANDARDS

The rapid cycling of nitrogen to ammonia and the elevated pH, both maintained in wastewater ponds by the abundance of phosphorus available to support aquatic photosynthesis, yields an extremely efficient system for the removal of nitrogen from wastewater. However, phosphorus removal by the pond ecosystem is not sufficient to allow effluent from the ponds to meet the effluent phosphorus standards currently in force in the state of Michigan. To meet this effluent phosphorus standard, the WQMF pond effluent is spray irrigated on an adjacent terrestrial system. This integral step required for phosphorus removal allows some recycle of nutrients to terrestrial biomass. To gain such recycle, the WQMF must be operated as a combination aquatic and terrestrial system.

In Michigan, during the period from April to October, the active growth of terrestrial vegetation incorporates nutrients from the wastewater applied to the land. To allow nitrogen addition to the land to meet plant needs during this period, it is necessary to minimize detention time in the ponds where nitrogen in the wastewater is rapidly lost to the air. This is accomplished on the WQMF by irrigating a mixture of secondary effluent and water from the first pond during the spring and summer months. With the absence of terrestrial vegetative growth during the remainder of the year, nitrogen in the wastewater applied to the land is not removed and infiltrates to the groundwater. Water irrigated on the land during the winter infiltrates well (10). But, to protect the groundwater from nitrate nitrogen, the wastewater applied to the land during the winter must have an extremely low nitrogen content. Nitrogen is efficiently removed from the wastewater impounded in the ponds during the spring and summer months. By October the ponds are full of wastewater with a sufficiently low nitrogen content to allow wastewater irrigation during the fall and winter months without elevation of groundwater nitrogen levels.

The ability of terrestrial vegetation to remove nitrogen from wastewater during the spring and summer is dependent on the type of terrestrial vegetation. Oldfield grasses are quite efficient, agricultural crops show variable efficiency, depending on the crop type, and forests are not efficient at removing nitrogen before it infiltrates to the groundwater (11). Overall, the combination of ponds and land which comprise the WQMF can be operated in a fashion which meets the stringent effluent water standards of Michigan. Nitrogen is lost to the air as ammonia and nitrogen gas and phosphorus is either sorbed on the terrestrial soils or harvested as terrestrial biomass. Operated in this manner, the WQMF approaches zero wastewater discharge.

AQUACULTURE IN WASTEWATER PONDS

The long history of pond culture of a variety of fish in the Orient in ponds charged with wastewater suggests an intriguing potential for converting water-borne wastes to foodstocks within the United States. However, it should be recognized that the wastewater aquacultural successes of the Orient are allowed because they do not have to meet either the environmental standards on the effluent from their ponds or the public health standards on the product, both of which must be met within the United States. Our wastewater effluent standards include BOD and suspended solids removal and in some locations nutrient limitations as well. Before aquacultural products from such systems can be marketed as foodstocks in this country, they must be shown to be free from pathogenic bacteria and viruses as well as having an extremely low burden of the great variety of toxic and carcinogenic materials characteristic of wastewater from a highly technical society.

Even if such public health considerations can be overcome, there is great difficulty in operating a pond system to meet modern effluent standards while simultaneously maximizing aquacultural yield. It is obvious that any attempt at aquaculture in wastewater ponds must not impair the ability of the pond ecosystem to renovate wastewater.

The nutrient content of wastewater is not in balance with the needs of pond biota. Phosphorus availability far exceeds nitrogen availability which in turn far exceeds carbon availability relative to plant needs. Carbon dioxide can be gained from the air while nitrogen is lost as ammonia or nitrogen gas to the air. Phosphorus is removed only by plant uptake or by some portion of the phosphorus sedimentary cycle.

When wastewater is impounded, photosynthesis by phytoplankton algae, attached periphytic algae, and submerged macrophytes extracts carbon dioxide from the alkalinity system at a rate greater than it can be resupplied from respiration and from the air, thereby raising the pH of the water. The amount of pH elevation is directly related to the detention time in that the longer the water is held the greater is the carbon extraction from the alkalinity. A continually lowered carbon dioxide content associated with continued detention yields a change in algal species culminating in the buoyant blue-green algae (12).

Such rapid photosynthesis supplies the energy necessary for rapid cycling of the various nitrogen forms to ammonia, which, at the existing high pH, is lost to the atmosphere as a gas. Thus, with increased detention time, the ammonia nitrogen concentration will be reduced to the point where it is no longer toxic to fish. However, at this point the nitrogen concentration often is no longer sufficient for any algae except those blue-green algae which can fix atmospheric nitrogen. These blue-green algae cannot be harvested readily and since they are readily utilized only by bacteria, they represent an oxygen demand which will be exerted in the pond. Within the WQMF, bacterial use of such nitrogen fixing blue-green algae has caused sufficient oxygen depletion to yield both summer and winter fish kills.

If sufficient zooplankton are present in the pond to control the mass of green algae and diatoms, the carbon extraction from the alkalinity may not proceed to the point where blue-green algae dominate. The addition of zooplanktivorous fish to such systems can reduce the zooplankton control of the algae to the point where sufficient algal mass accumulates to force a carbon dioxide level low enough for blue-green algal dominance (13). Phytoplanktivorous fish, such as some of the oriental carp, would be able to maintain a green algal dominance if the fish stocking rate was matched with the wastewater detention time and the algal growth rate in such a manner that the algal content of the effluent did not exceed effluent suspended solids standards. This is an extremely difficult balance to maintain and it is illegal to import such fish into most states.

Attempts to raise and harvest submerged macrophytes can be thwarted by adding fish which crop the zooplankton, thereby allowing rapid expansion of algal populations to the point where they limit the light available to the macrophytes. In this instance, macrophytes are replaced by phytoplankton, often blue-green algae.

Cage culture of fish in wastewater ponds is limited by the characteristic high pH of the ponds. The waste products of the fish in the cage represent a point source of ammonia which, at the high pH, rapidly dissociates to ammonia gas which is toxic to fish. While such ammonia production may not kill the fish, the growth rate of the fish is retarded (14).

The necessity of balancing this complex set of interacting variables to produce a product of value without impairing wastewater treatment efficiency, coupled with the improbability of marketing the product, does not indicate a great potential for wastewater aquaculture of foodstocks in the United States at this time.

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UTILIZATION OF SILVER AND BIGHEAD CARP
FOR WATER QUALITY IMPROVEMENT

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ABSTRACT

Filter feeding fishes, the silver and bighead carp, were stocked in an existing lagoon treatment system in 1975-76 for a preliminary evaluation of the effect of the fish on water quality and the potential of this nutrient source for fish production. Positive results have led to an ongoing Environmental Protection Agency funded study of the efficacy of finfish as a treatment method in a full scale, six cell (24 acre) treatment facility at Benton, Arkansas.

Information concerning water quality improvement, fish production, product utilization and some design considerations are presented. The promising results, design adaptability, and pay back possibilities make this an attractive, innovative alternative.

INTRODUCTION

Fertilization of fish ponds has long been recognized by the fish culturist as a method of increasing production. The production of finfishes as a method of reducing fertility is a relatively new approach that has been stimulated by the increasing need for effective, low cost treatment of wastewater by small municipalities. The initial emphasis on this and other "alternative" strategies as opposed to conventional methods was largely a result of more stringent effluent guidelines and the high cost of construction and operation of conventional plants. It seems, however, that the even more recent realization of the need to conserve energy sources and to recycle what has previously been discarded as a troublesome waste product has provided the impetus for exploring new technologies. Also, even the remote possibility of producing a useful and/or valuable product from wastewater treatment demands attention.

The Arkansas Game and Fish Commission's interest in this project evolved from the importation into the state of two species of Chinese carps by a private fish farmer. The silver carp, _Hypopthalmichthyes molitrix_, and bighead carp, _Aristichthyes nobilis_, were brought into Arkansas in 1973 with initial interest resulting from the fact that they were unknown, exotic species and the possibility of these low trophic level filter feeders being a beneficial addition to fish production ponds. Conversations with Dr. S. Y. Lin who did pioneering work with the Chinese carp species in Taiwan and a visit to the Quail Creek Sewage Treatment Project in Oklahoma during 1973-74 led to the current interest in wastewater aquaculture.

The fact that many finfish species ranging from the lowly esteemed common carp, Cyprinis carpio, to the prize sport fish the muskellunge, Esox masquinongy, have been produced in wastewater ponds attests to the variety of species amenable to production in nutrient rich wastewaters under specific conditions. The fact that X pounds of fish are produced without supplemental feeding obviously shows that in one fashion or another, energy and nutrients are transformed into the very stable form of fish flesh. This is the reasoning behind one of the basic tenets of fish culture and management i.e., that within certain limits the natural productive capacity of a given body of water is increased by increasing available nutrients. The fish culturist may draw on a rather large body of available literature resulting from research and practical experience in determining the proper type and amounts of fertilizer to add to the culture pond.

If, on the other hand, the objective is to utilize available nutrients, little is known about the effectiveness of finfish in general or of any particular species. Common sense dictates that those fishes that have adapted to feeding at the lower trophic levels would be most efficient at converting nutrients. Therefore, those that are able to feed on the primary productivity, the herbivores, should be considered the most likely candidates for achieving the objective of nutrient utilization. A group of fishes known as the Chinese carps, in particular the silver carp, meets this criterion and is the key species in this study.

Silver and Bighead Carp

The silver and bighead carp are native to the Amur River basin along the Sino-Soviet border. Stocks of these fish have been propagated by the Arkansas Game and Fish Commission since 1973 for use in this and other research projects. Both are filter feeding fishes that feed on free-floating or free-swimming planktonic organisms throughout their life. These fishes are capable of reaching a size of 18-23 kg (40-50 lbs.) in four to five years.

The silver carp exhibits certain characteristics that make it more desirable for this type of program than native filter feeding species. The specially adapted gill rakers that have evolved as the filter for this species are somewhat unique and are very efficient at filtering extremely small particles from the water that passes through them. The gill rakers of the silver carp are similar to a sponge-like plate and are capable of removing particles as small as four microns in size. The diet of the silver carp is composed primarily of phytoplankton.

The gill rakers of the bighead are filaments that widen at the distal end and overlap to form a more or less solid filtering surface. The filter of the bighead is comparable to many native filter feeders and is not as efficient at removing the smaller particles as is the silver carp. The majority of the bigheads diet consists of zooplankton and the larger phytoplankton species. Both the silver and the bighead are capable of rapid growth, are not particularly susceptible to common fish diseases, and are capable of withstanding relatively low dissolved oxygen levels. For these reasons mentioned above it is believed by the author that the silver carp should be the central species in a finfish treatment system. The bighead has certain desirable attributes but could be replaced by other native fishes.

Description of Project Site

The wastewater treatment plant of the Benton Services Center was chosen as the site for the study. The primary reasons for its selection were the multiple ponds available, the capability of controlling the pattern of flow through the system, and state ownership which provides greater cooperation and control in operation of the plant.

The Benton Services Center is under the direction of the Arkansas Department of Human Services. The center provides both mental and alcohol rehabilitation programs, a nursing home facility, and serves as a work release center for the Arkansas Department of Corrections. While numbers vary, there are approximately 1,000 persons residing at the center full time. Other than daytime and around-the-clock patient care personnel, the center maintains its own water treatment plant, fire station, laundry, food services department and a rather large maintenance and grounds staff. There are also several residences for staff members located on the grounds. There are, in all, approximately 1,000 full time employees at the center with some contributing to the wastewater load during working hours six days per week and others around-the-clock.

Other than the collective individual needs, the biggest contributors of wastewater to the system are the laundry and food services. The laundry is in operation six days per week supplying the needs of the entire Benton facility and food services prepares three meals per day for all residents and at least one for every employee. The character of the raw wastewater is fairly typical of that produced by small municipalities with no major industrial users.

The physical facilities of the wastewater treatment plant include (1) a bar screen and grinder for reducing the size of larger debris entering the system, (2) a clarifier, (3) an aerobic digester (this is a converted anaerobic system providing mechanical aeration to the solids from the clarifier, majority of the water enters the lagoons from the clarifier), and six oxidation ponds with a total surface area of 10.2 ha (24 acres). The average daily flow of wastewater into the system is 1,711m^3/day (0.45MGD), the average organic load is 444 kg (977 lbs.) of BOD_5 per day, and 208.6 kg (459 lbs.) of suspended solids per day.

Preliminary Study (1975-76)

Methods

In 1975, a preliminary study using only the silver and bighead carp was begun at the Benton site. At the outset of the study, the flow pattern through the ponds was arranged so there would be two completely independent three pond series. The total influent load was passed through a division weir with one-half of the total volume going into the initial pond in each of the series. The ponds in each series were numbered in the order the water passed through them i.e., Ponds 1A and 1B received the sewage influent and the water was discharged from 3A and 3B. The ponds designated the "A" series were stocked with fish and the "B" series received no fish and was used as the control. (See Appendix IA)

The "A" ponds were stocked with fish as follows:

Pond 1A (1.76 ha) -	450	grass carp (5-7 cm each)
	1,275	silver carp (10-13 cm each)
	280	bighead carp (10-13 cm each)
Pond 2A (1.55 ha) -	400	grass carp (5-7 cm each)
	5,250	silver carp (5-7 cm each)
	380	bighead carp (10-13 cm each)
Pond 3A (1.56 ha) -	20,000	silver carp (5-7 cm each)
	400	bighead carp (10-13 cm each)

Water samples were taken twice weekly from each of the six ponds. One sample was taken at sunrise and the other at midday. One liter grab samples were taken at the effluent from each pond. Water quality characteristics measured for each sample were:

Dissolved Oxygen	Carbon Dioxide	Suspended Solids
Air/Water temperature	Color	Phosphate, Total
Turbidity	Fecal Coliform	NH_3 - N
Conductivity	Plankton Count	NO_2 - N
pH	BOD_5	NO_3 - N

HACH pre-measured reagents and spectrophotometric methods were used in making most determinations. Many testing procedures did not comply with accepted Standard Methods.

Results

There being no other apparent differences in the two sets of ponds, it is assumed that any differences in effluent quality can be attributed to the presence of the fish.

The most notable differences in effluent quality were found to be in BOD_5 and the types of phytoplankton organisms present. Both are felt to be interrelated. For the annual average, the BOD_5 of the effluent from the ponds without fish was 37.6% higher than the series containing the fish. The phytoplankton population in Pond 3A (fish present) was never dominated by blue-green species and no plankton die-offs were observed or recorded. In Pond 3B (no fish present), dense blue-green blooms, floating mats, periodic die-offs and associated odors were frequent occurrences throughout the warmer months. The continued healthy green phytoplankton population with continuous O_2 production in Pond 3A with no die-offs causing additional oxygen demands is attributed to the constant "grazing" of the fish which resulted in decreased BOD_5 levels. For the most part, the remaining parameters measured were lower for the ponds containing the fish as compared to those without. With the exception of an overall reduction of NH_3-N of 27% in the fish ponds, the differences were small. While the accuracy of the methods used are questionable, it is believed that they lend themselves to direct comparison. Graphic representation of parameters measured during this preliminary study are presented in Appendix IB.

Fish Production:

Based on preliminary water quality data, it was considered very doubtful that fish could tolerate the low DO levels in Pond 1A and none survived longer than the fourth week after introduction. DO levels in Pond 2A appeared marginal for the support of fish life, however, it seemed the feeding activity of the fishes themselves provided a stabilizing influence on the usually wide diurnal fluctuations of oxygen concentration. Oxygen related fish kills occurred in winter and early spring in this pond as a result of abrupt seasonal changes as is typical of fertile surface waters. In both cases, fish were restocked replacing those lost. No problems occurred throughout the year in Pond 3A as oxygen levels remained well within limits necessary for propagation of these fish.

The fish were harvested at the end of this study and weighed for total production figures. A total of 6,546 kg/ha (6,003.8 lbs. per acre) were produced during the period from August, 1975 to December, 1976. This encompassed one full growing season in Arkansas. Total weight gain can be attributed to utilization of natural food produced within the ponds as no supplemental feeds were added to the ponds at any time.

Present Investigations (1977-1980)

The promising results of the preliminary study described above have led to continuing efforts at further evaluating this method of wastewater treatment. A research grant from EPA provided funds for minor site alterations and upgrading water quality monitoring techniques to acceptable Standard Methods for wastewater. An additional federal grant from the National Marine Fisheries Service is supporting further investigations in the possibility of fish production and product utilization.

Site Alterations and Present Pond Operation

The Benton Services Center treatment plant is again being used. Minor alterations in the existing facility were made prior to stocking the fish and instituting routine water quality monitoring. The existing six ponds were dewatered, sludge buildup was removed and the ponds regraded to their original contour with some minor changes to facilitate the harvest of the fish. All ponds average 1.2-1.3 m in depth with the bottoms being graded to the deepest point of approximately 2 m. The flow pattern was arranged so the wastewater flows through each of the six ponds in series with the ponds numbered one-six in the order they receive the wastewater. All wastewater entering the plant is lifted by pumping into Pond 1 where it travels by gravity flow - drop in elevation of approximately 0.76 m (2.5 ft.) - to the surface discharge from Pond 6.

By utilizing the existing piping system, the water flows into each of the ponds at the midpoint of one levee and out an adjacent side. To prevent short circuiting and provide maximum retention time, baffles were constructed diagonally, three-quarters of the distance across each of the ponds. (See Appendix IIA) The influent flow rate of 1,711 m^3/day (0.45 MGD) allows for a residence time for the water in the entire six pond system of 72 days. The individual ponds are approximately equal in size (range from 1.55-1.8 ha) with a retention time of about 12 days per pond. Four recording flow meters have been installed across the six ponds. One is placed in a six inch Parshall Flume measuring influent, two are placed at the outfall of ponds two and four and the last at the end of the system recording effluent flow.

All wastewater flows directly into Pond 1 and then serially through the remaining ponds. Ponds 1 and 2 serve as stabilization and plankton culture ponds and were not stocked with fish. The remaining four ponds were stocked with fish as follows:

Pond 3 (1.55 ha) -	20,270	silver carp (41 g each)
	4,103	bighead carp (32 g each)
Pond 4 (1.8 ha) -	12,198	silver carp (41 g each)
	2,052	bighead carp (32 g each)
Pond 5 (1.67 ha) -	12,070	silver carp (41 g each)
	2,052	bighead carp (32 g each)
Pond 6 (1.56 ha) -	8,100	silver carp (41 g each)
	600	bighead carp (32 g each)
	600	channel catfish (300 g each)
	100	buffalofish (1.6 kg each)
	40	grass carp (0.5 kg each)

Water Quality Monitoring

For the present study, one liter grab samples are taken once weekly (between 7-10 am) from the effluent of each of the six ponds. All sampling and testing is performed according to APHA Standard Methods for the Examination of Water and Wastewater, 14th Edition. Samples are taken and preserved at the site as prescribed and delivered to the lab facilities of the Arkansas State Department of Pollution Control and Ecology in Little Rock, Arkansas where all testing of water quality is conducted. Water quality parameters measured weekly from each of the six ponds are:

Air/Water Temperature	NO_3-N
Dissolved Oxygen	Conductivity
BOD_5	Suspended Solids
Turbidity	Total P
NH_3-N	Fecal Coliform
NO_2-N	Plankton Count & Enumeration

The wastewater entering the plant has an average BOD_5 of 260 mg/l with suspended solids concentration averaging 140 mg/l.

The loading rate for the initial pond is 242.5 kg/ha/day (244 lbs./acre/day) of BOD_5 and 113 kg/ha/day (114.7 lbs./acre/day) of suspended solids. When this loading rate is applied to the total available area within all six ponds it amounts to 43.5 kg/ha/day of BOD_5 and 20.4 kg/ha/day of suspended solids.

During the first eight months of operation, the system has reduced BOD_5 by 96.4% and suspended solids by 86%.

The present monitoring program has been in effect for nine months and is scheduled to continue for one full year. Because of the time factor involved, all water quality data presented in this report is taken from the first eight months of the study - December, 1978 through July, 1979.

During this period, the effluent has been within criteria established for secondary treatment and in many instances approached levels for advanced secondary treatment. A complete listing of effluent quality by month is presented in Appendix IIB and the overall effect on the water quality in each of the ponds is listed in Appendix IIC.

Fish Production

To monitor the growth rate of the fish within this system, monthly samples have been taken throughout the growing season and individual fish weighed, measured, and returned to the pond. It has been difficult to obtain adequate samples of species other than the silver and bighead carps due to relatively low stocking densities and the inefficiency of sampling techniques. Based on sampling information as of August 1 and assuming a realistic survival rate of 85% of the fish initially stocked, there is an estimated standing crop of fishes in excess of 22,777 kg (50,000 lbs.) in the four ponds containing fish. This amounts to a total average production of 3,344 kg/ha (3,125 lbs./acre) with approximately three months remaining in Arkansas' growing season.

Product Utilization

Among the many organisms that have been proposed at one time or another as biological filters for use in wastewater lagoons, finfish are one of the most easily controlled and harvested for use utilizing existing state-of-the-art methods. Present technology exists for processing fisheries products for an existing market. There is, however, a bureaucratic "catch 22" preventing any product directly derived from wastewater being sold for human consumption. While public health concerns should not be minimized, a low cost source of high quality protein should not be overlooked with such a flippant attitude.

Realizing the problems of consumer acceptance and legal constraints associated with the utilization of fishery products from wastewater lagoons, a testing program was established at the beginning of this project. While it is certainly beyond the scope and budget of this project to consider all possible contaminants, a private testing lab was contracted to determine levels of what was considered to be the most likely pesticides, heavy metals and pathogenic bacteria present in the system. Samples of fish flesh (edible portion) and water from the influent and the ponds themselves is being used for the testing. All procedures follow accepted standard methods. Quality control measures practiced by the private lab have been approved by the Arkansas Department of Pollution Control and Ecology.

Prior to beginning the project, baseline data was established by testing influent wastewater and samples of flesh from hatchery reared fish to be stocked in the lagoons. Subsequent quarterly sampling has been done on influent wastewater and both water and fish flesh from two of the four ponds stocked. The ponds sampled are alternated each quarter. In all sampling, those contaminants considered were:

Pesticide Scan	Metal Scan	Path. Bacteria Screen
Aldrin	Lead	Salmonella/shigella
Dieldrin	Copper	Staphylococcus
Endrin	Cadmium	Edwardsiella
Mirex	Mercury	Clostridium
DDT (and derivitives)	Arsenic	
Toxaphene		
Kepone		
PCB		

With the exception of the metals, copper and mercury, and staphylococcus bacteria, all samples have shown less than the standard detection limits or have been negative. In no instance has any sample been above action guidelines established by FDA or the Arkansas Department of Health.

Cost Effectiveness

According to EPA report 600/2-76-293 entitled Economic Assessment of Wastewater Aquaculture Treatment Systems by Upton Henderson and Frank Wert, 1976, only when finfish aquaculture was not capable of meeting water quality objectives was it deemed not to be cost effective when compared to conventional systems. The report went further to state that aquaculture wastewater alternatives appear to be economically attractive regardless of the market for products if water quality goals are met.

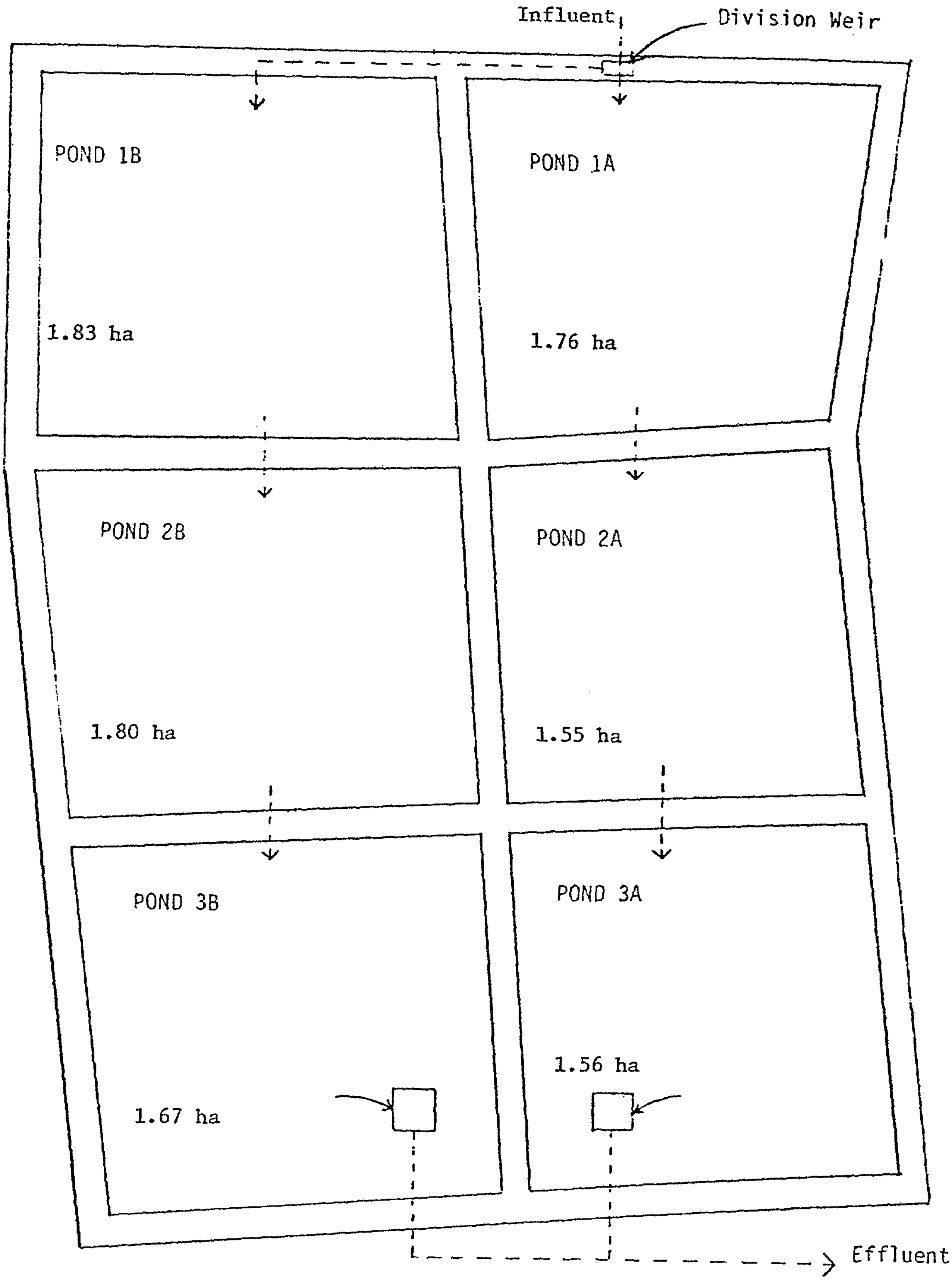
Although there are several possibilities and likely many useful fishery products yet to be developed, it appears that the long and the short of the present market lies with the sale of the product as a food item and by processing it into fish meal for use as an animal feed supplement. It should be understood that in present day fresh water pond aquaculture the greatest overhead costs are land, feed, fertilizer and water. By utilizing this system of wastewater aquaculture, these costs would be borne by the primary function of water treatment. By accepting this and other rather basic assumptions within the framework of present markets, some rather cursory economic projections can be made.

Silver and bighead carp from the preliminary study were rendered into fish meal which assayed at a crude protein content of minimum 55-57%. This is compared to 62% crude protein for Menhaden meal considered the best product now available. Oil and fat content were not considered. There was an estimated 18% return of meal from fresh fish by weight. Current market prices for pure fish meal, F.O.B. Little Rock, vary from $4-500 per ton in bulk quantities depending on season and harvest source. Based on a price of seven-nine cents per kg (three-four cents per pound) for live fish and an annual production rate of 6,546 kg/ha as seen in the preliminary study, a gross return of $430-$575/ha/year ($180-$240/acre/year) could be realized by processing the fish in this way.

If, on the other hand, the fish were marketed for direct human consumption at a conservative in the round price of 55-65 cents per kg (25-30 cents/lb.) the gross annual return would be $3,600-$4,525/ha ($1,500-$1,800/acre). Whatever the market, any profit realized would certainly be welcomed by small municipalities to offset treatment costs.

APPENDIX IA

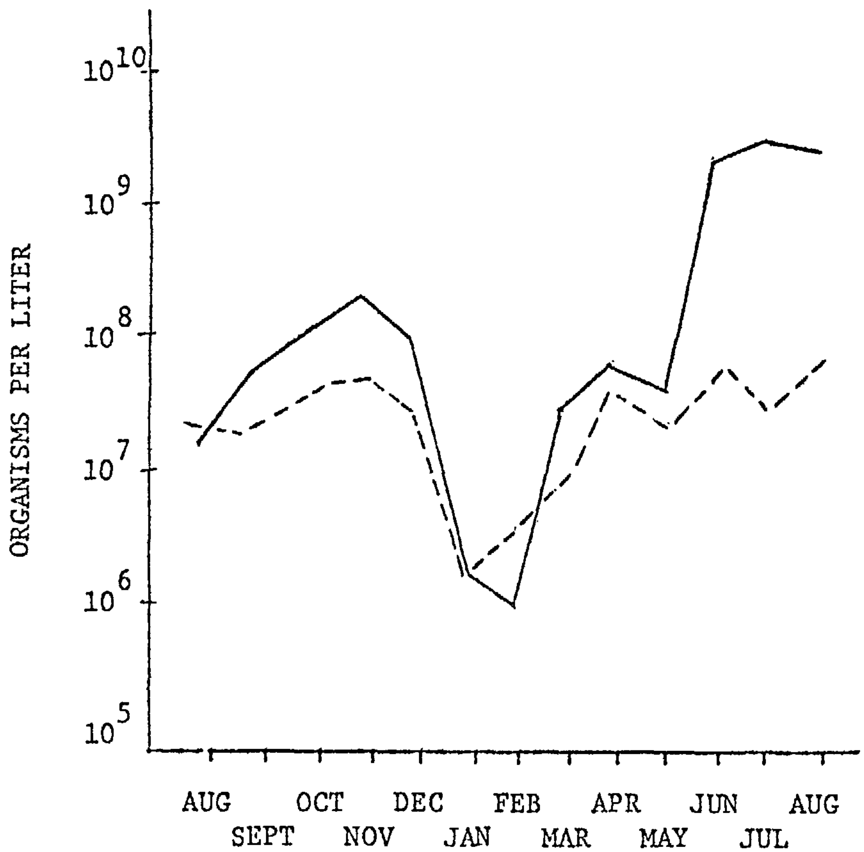
Flow pattern and method of operation of the lagoons used during the preliminary study, 1975-76.



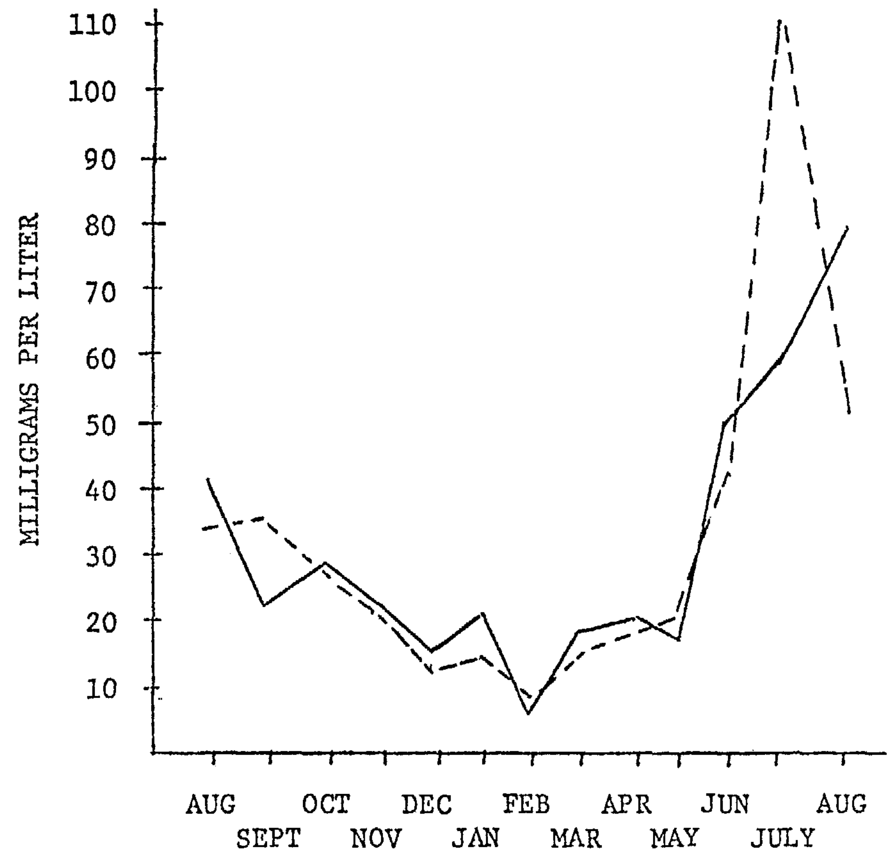
Benton State Hospital Sewage Lagoons. "A" series of ponds stocked with fish. "B" series of ponds not stocked with fish and used as control.

APPENDIX IB

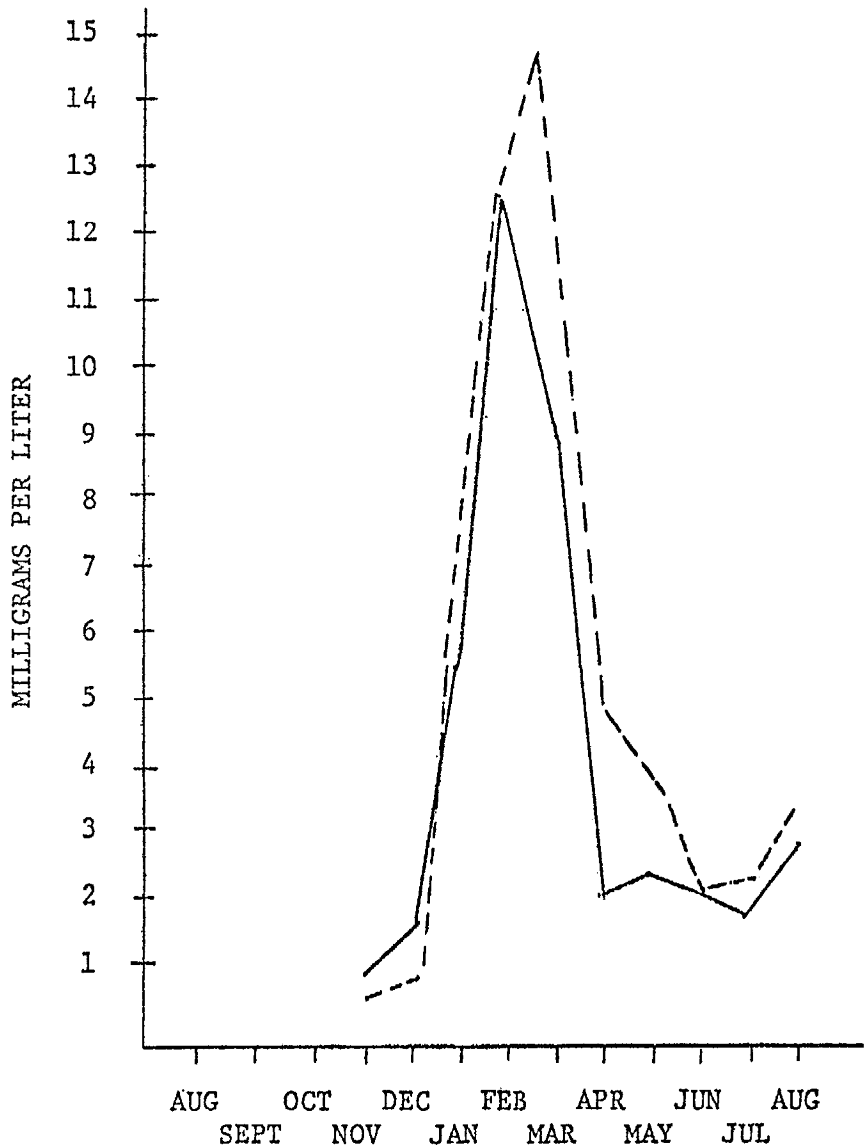
Comparison of average monthly water quality data of effluent from the series of ponds with and without fish during the preliminary study, 1975-76.



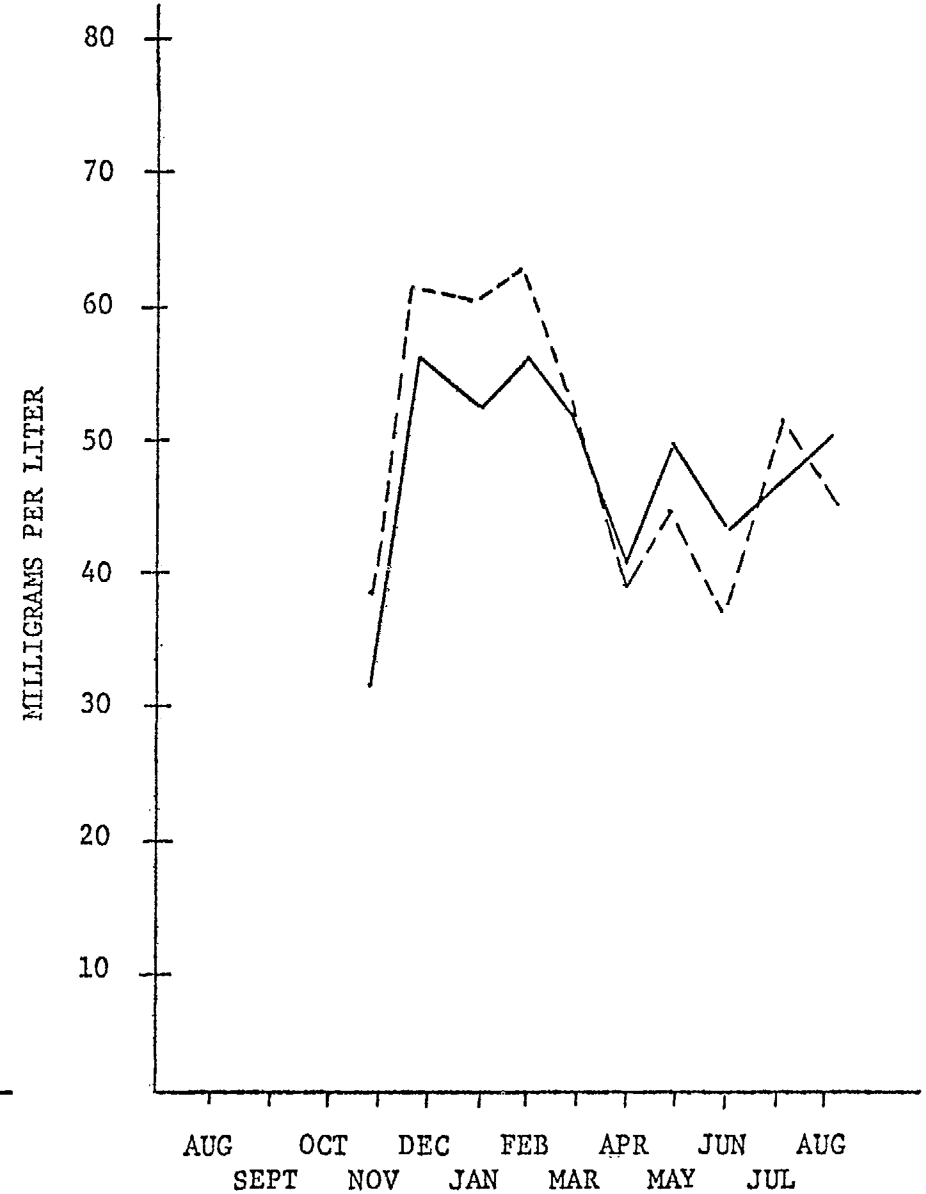
TOTAL NUMBER OF PLANKTON ORGANISMS PER LITER. Pond 3A represented by solid line, Pond 3B by broken line.



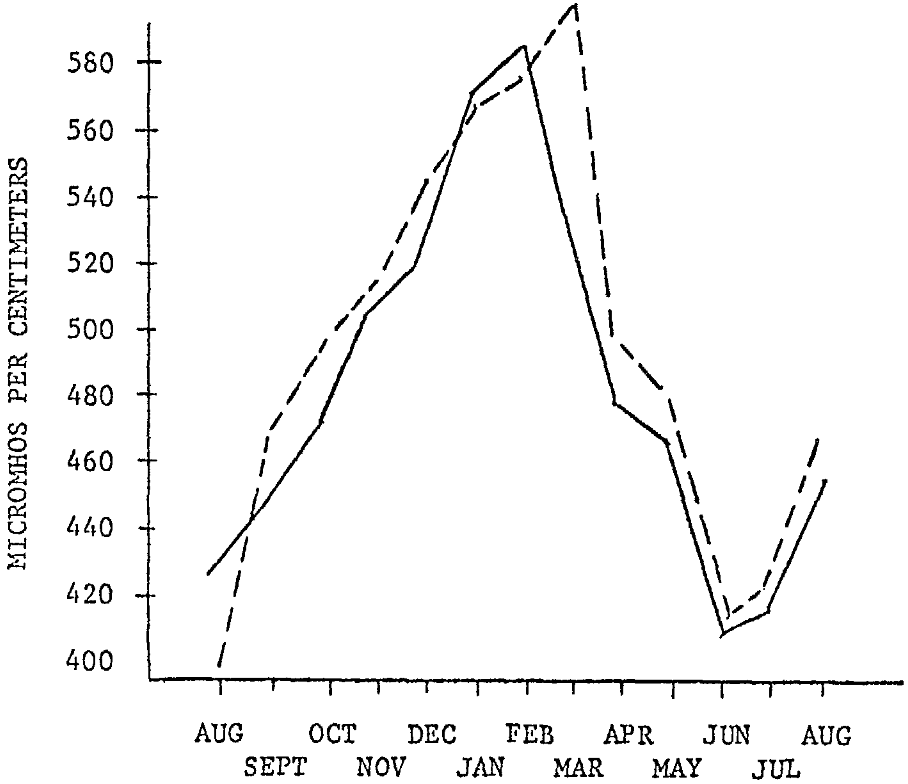
TOTAL SUSPENDED SOLIDS. Pond 3A represented by solid line, Pond 3B by broken line.



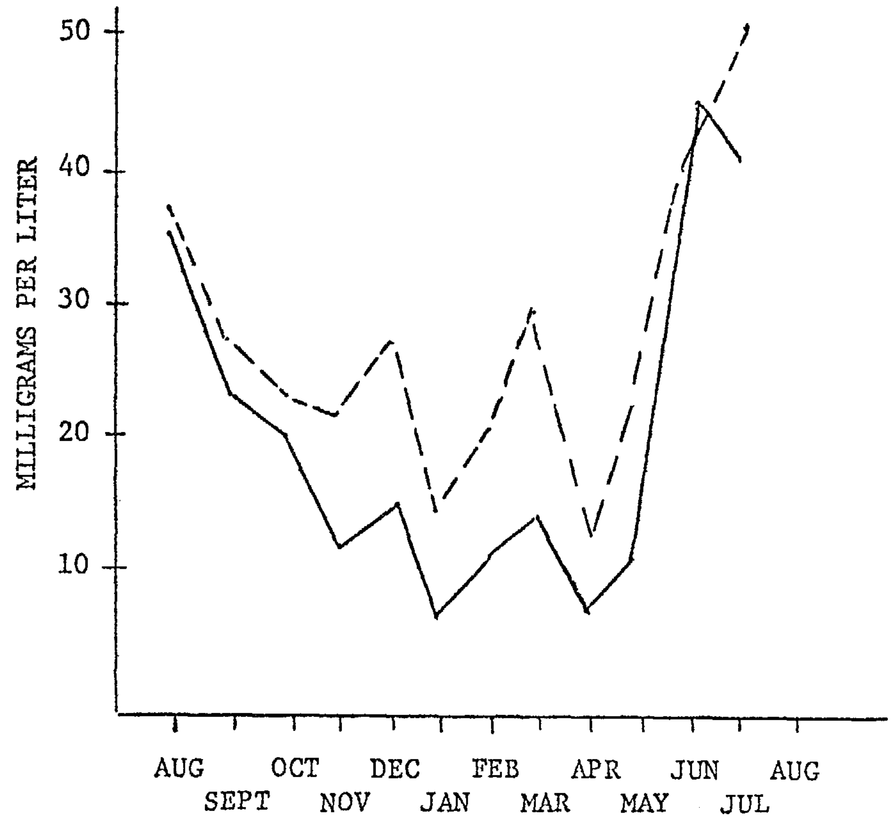
AMMONIA-NITROGEN. Pond 3A represented by solid line, Pond 3B by broken line.



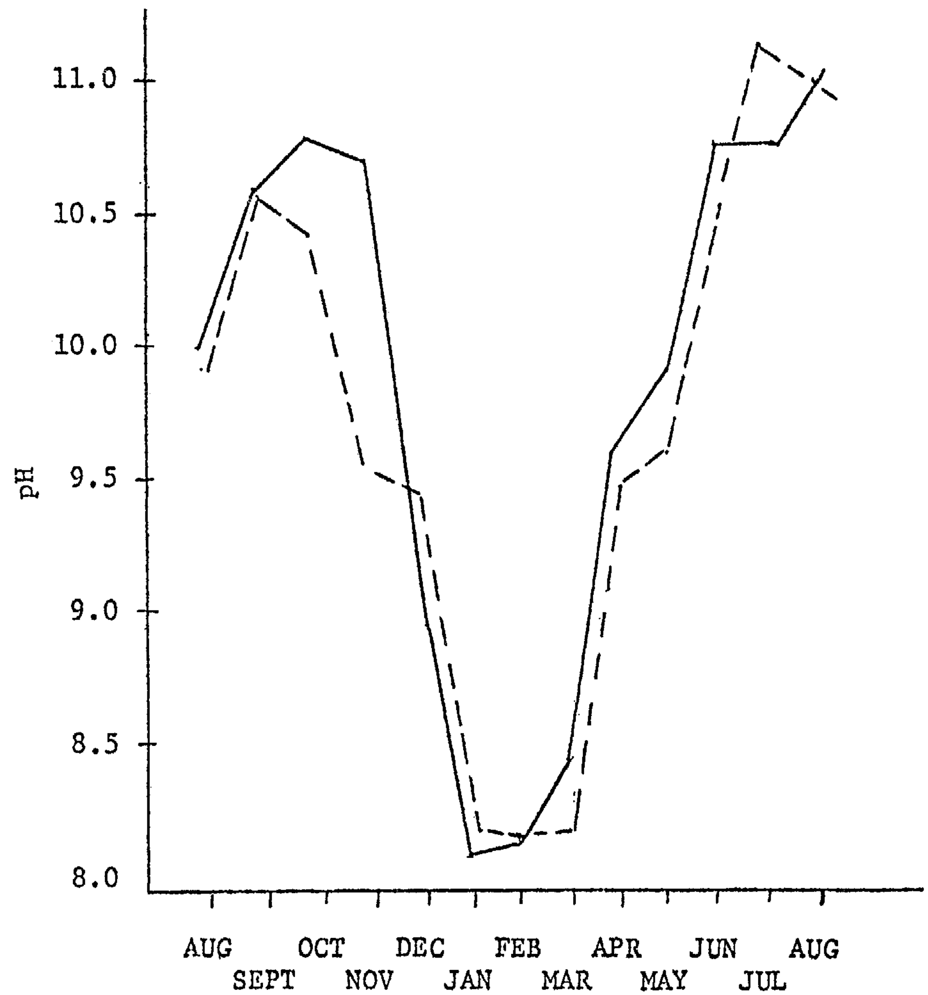
TOTAL PHOSPHATE. Pond 3A represented by solid line, Pond 3B by broken line.



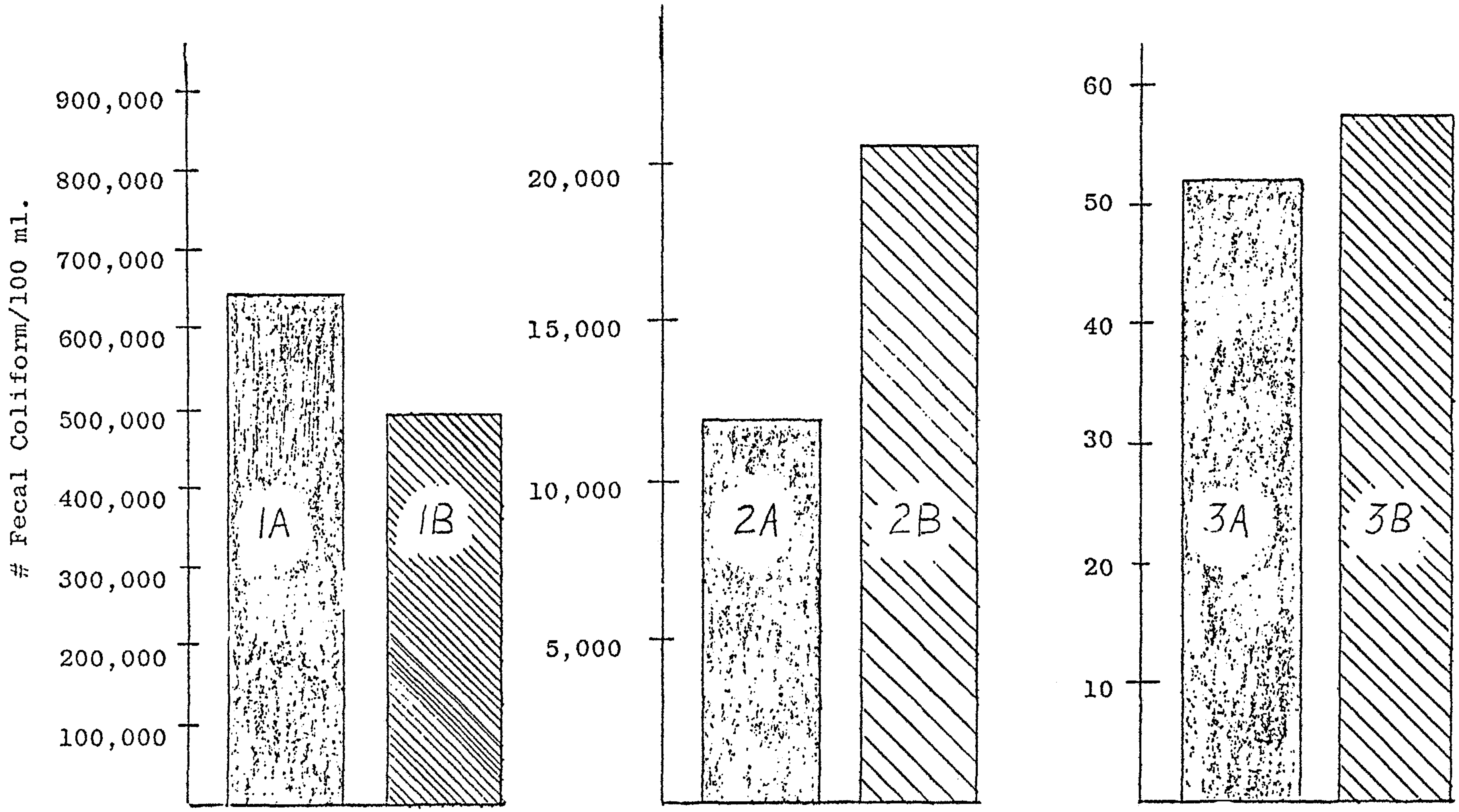
CONDUCTIVITY. Pond 3A represented by solid line, Pond 3B by broken line.



BOD_5. Pond 3A represented by solid line, Pond 3B by broken line.



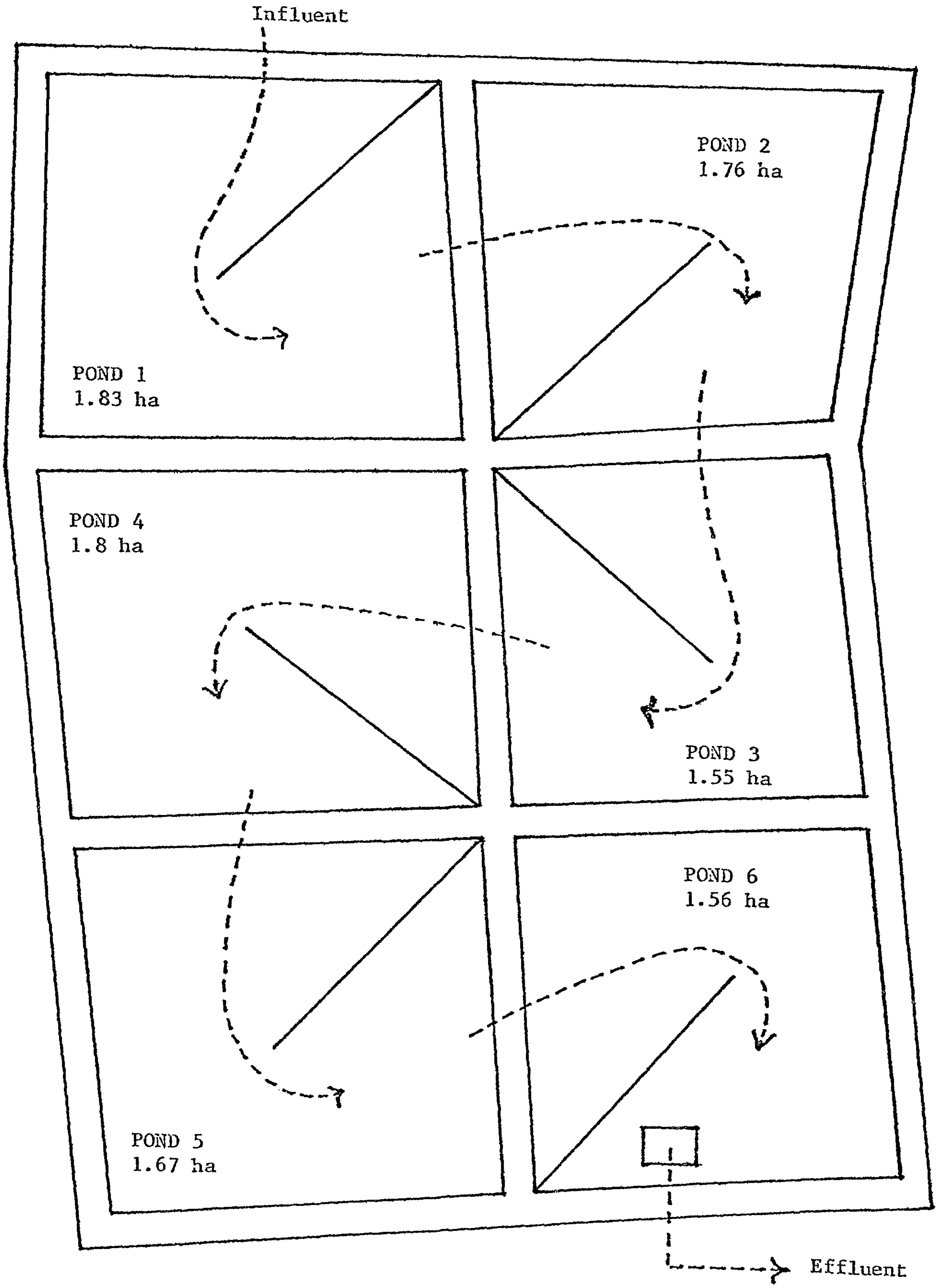
pH. Pond 3A represented by solid line, Pond 3B by broken line.



Fecal Coliform. Average number of fecal coliform bacteria found in each pond during study period.

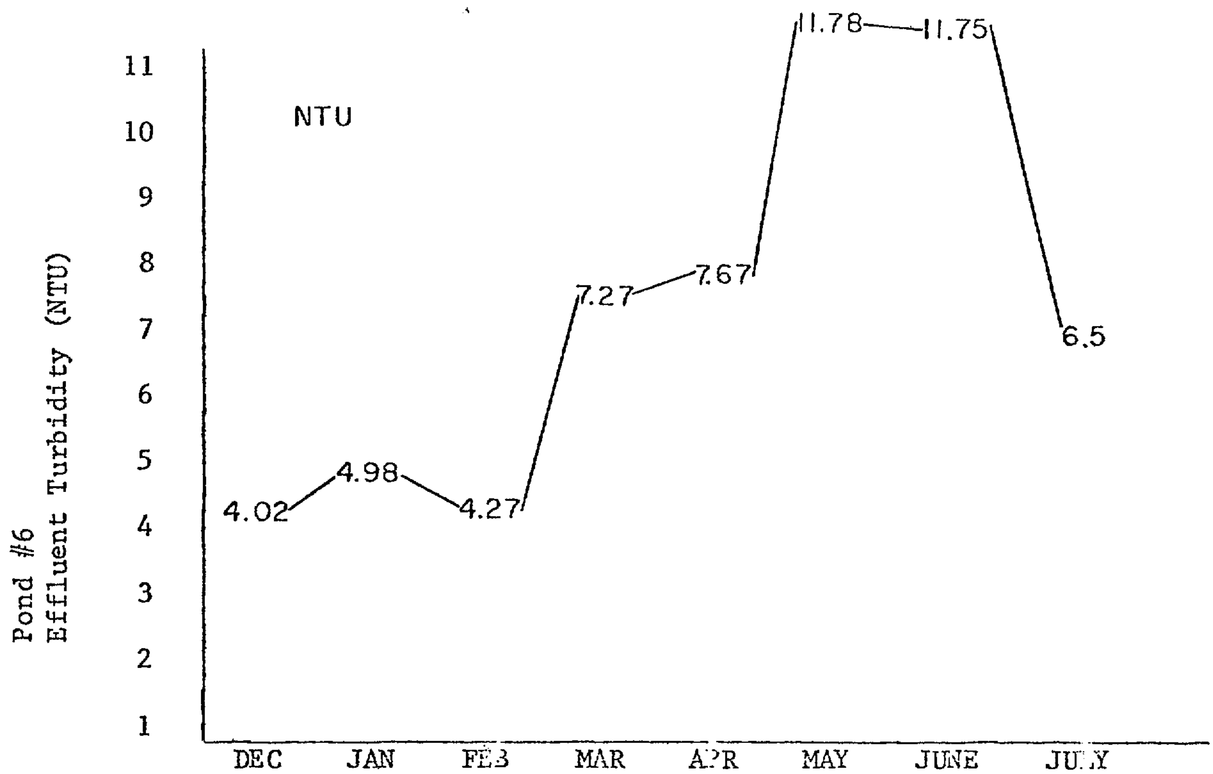
APPENDIX IIA

Flow pattern and method of operations of the lagoons used during present investigations.

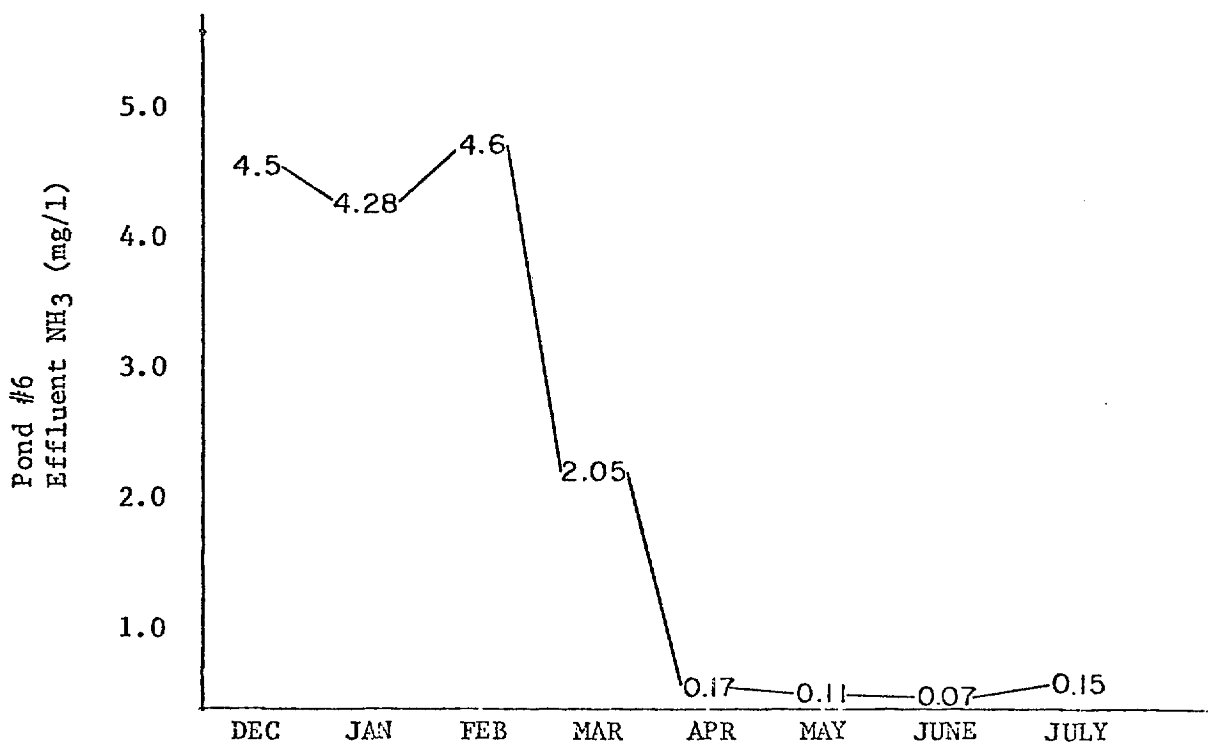

Influent
POND 2
1.76 ha
POND 1
1.83 ha
POND 4
1.8 ha
POND 3
1.55 ha
POND 6
1.56 ha
POND 5
1.67 ha
Effluent

APPENDIX IIB

Average monthly water quality data from samples taken of final effluent (Pond 6).

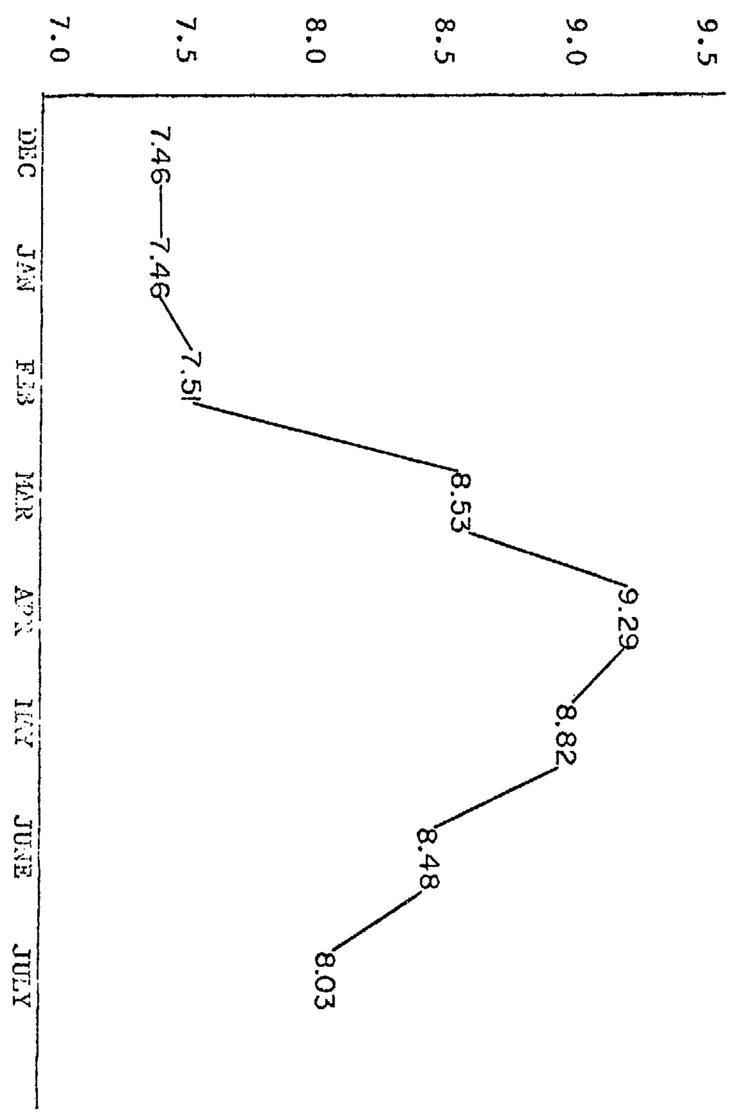


Pond #6
Effluent Turbidity (NTU)
NTU
11
10
9
8
7
6
5
4
3
2
1
4.02
4.98
4.27
7.27
7.67
11.78
11.75
6.5
DEC
JAN
FEB
MAR
APR
MAY
JUNE
JULY

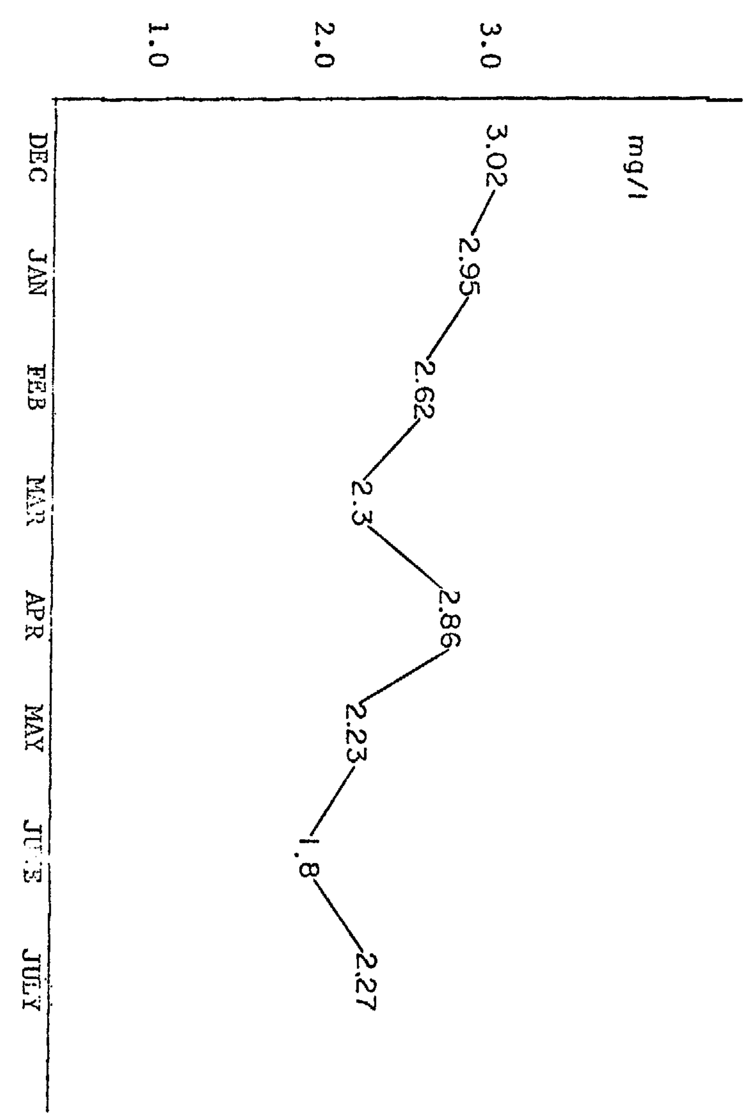


Pond #6
Effluent NH3 (mg/l)
5.0
4.0
3.0
2.0
1.0
4.5
4.28
4.6
2.05
0.17
0.11
0.07
0.15
DEC
JAN
FEB
MAR
APR
MAY
JUNE
JULY

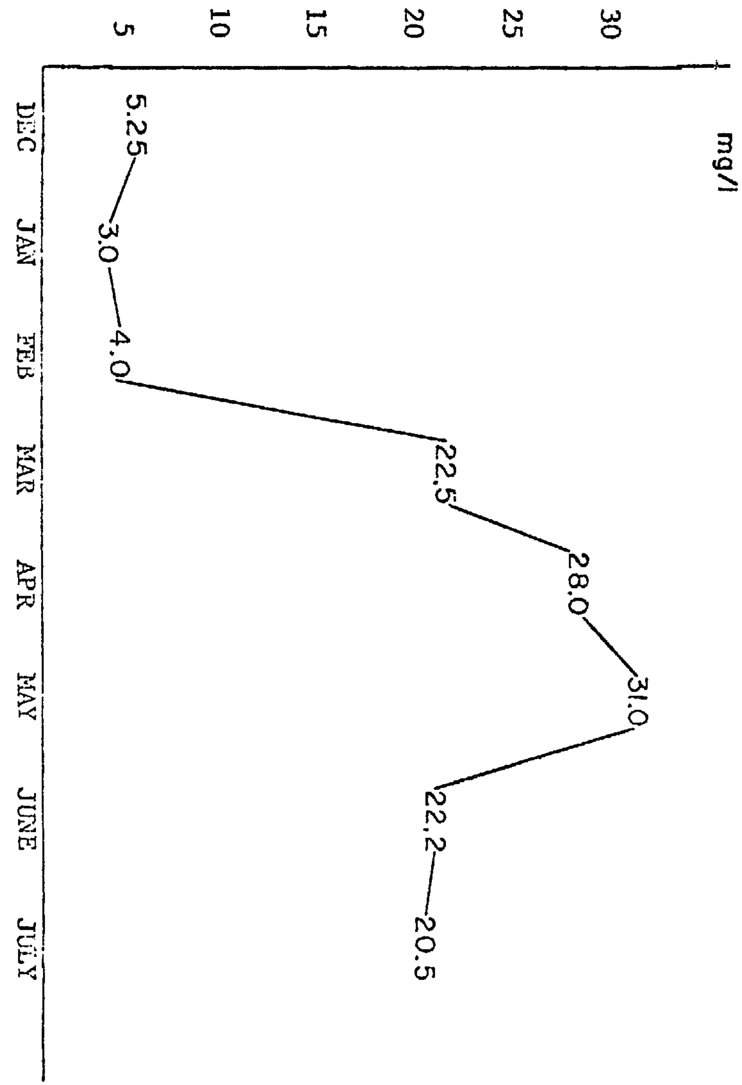
Pond #6
Effluent pH



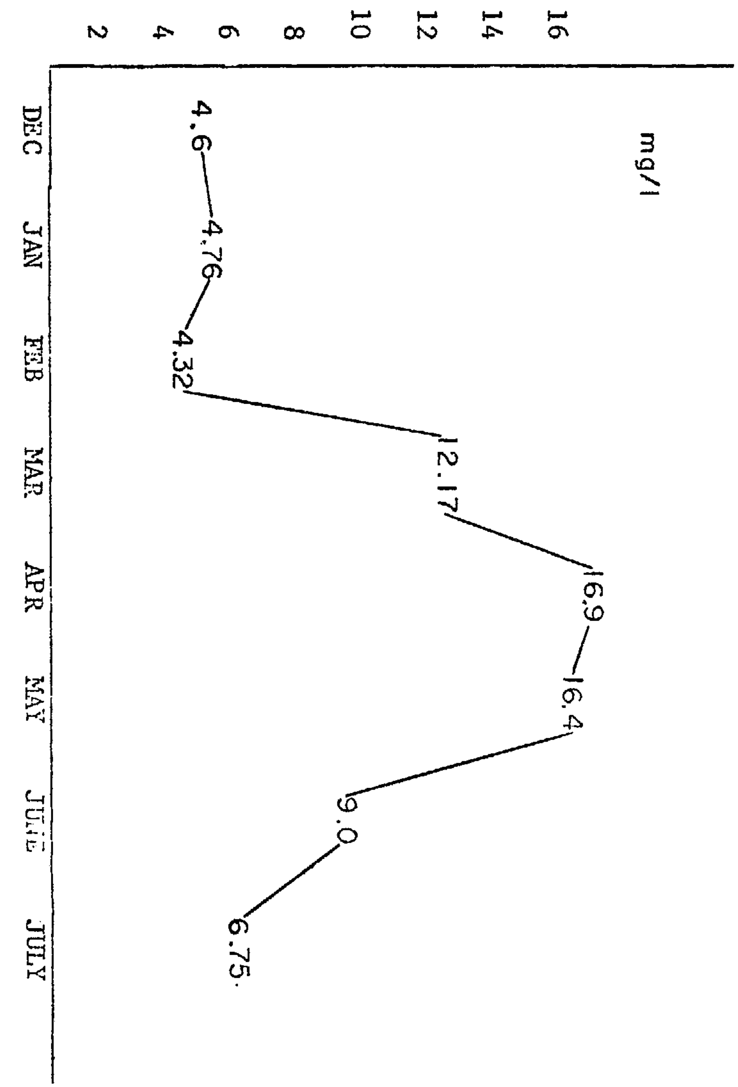
Pond #6
Effluent Total P (mg/l)



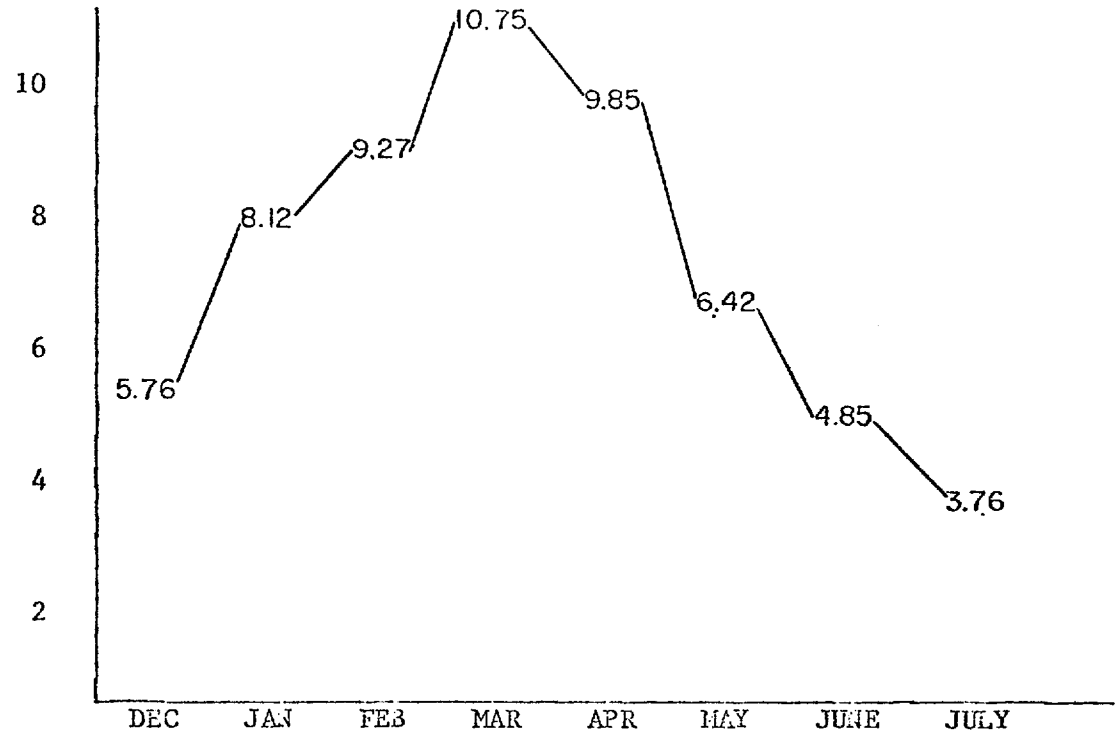
Pond #6
Effluent TSS (mg/l)



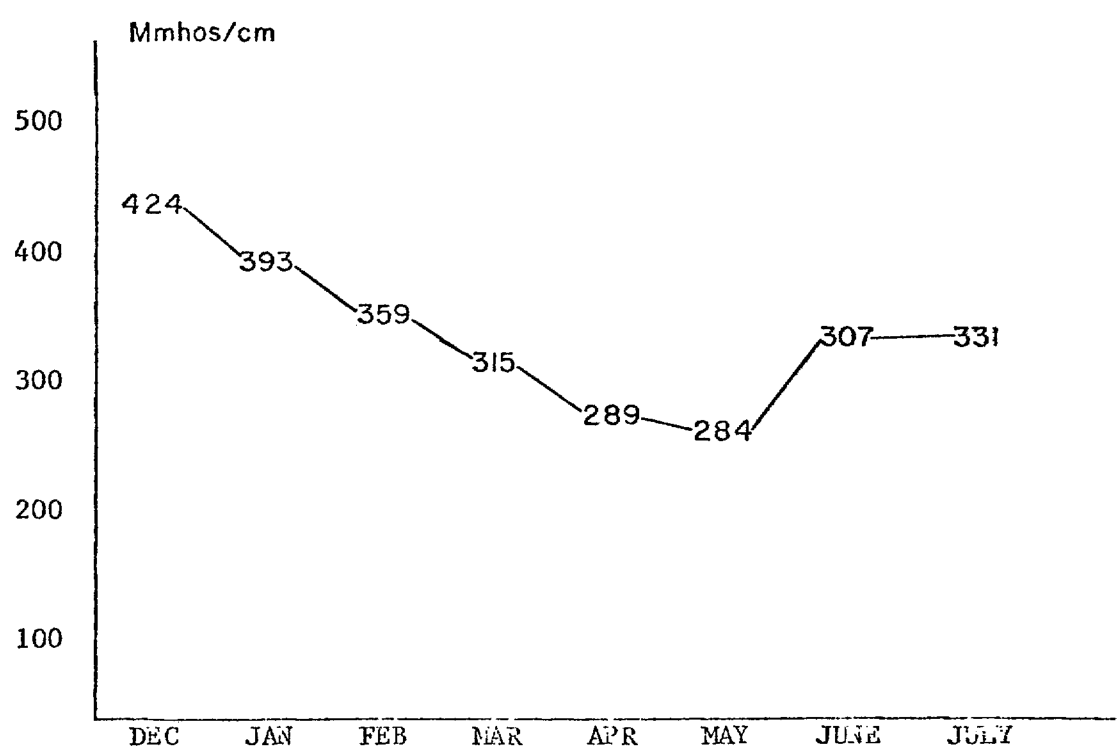
Pond #6
Effluent BOD (mg/l)



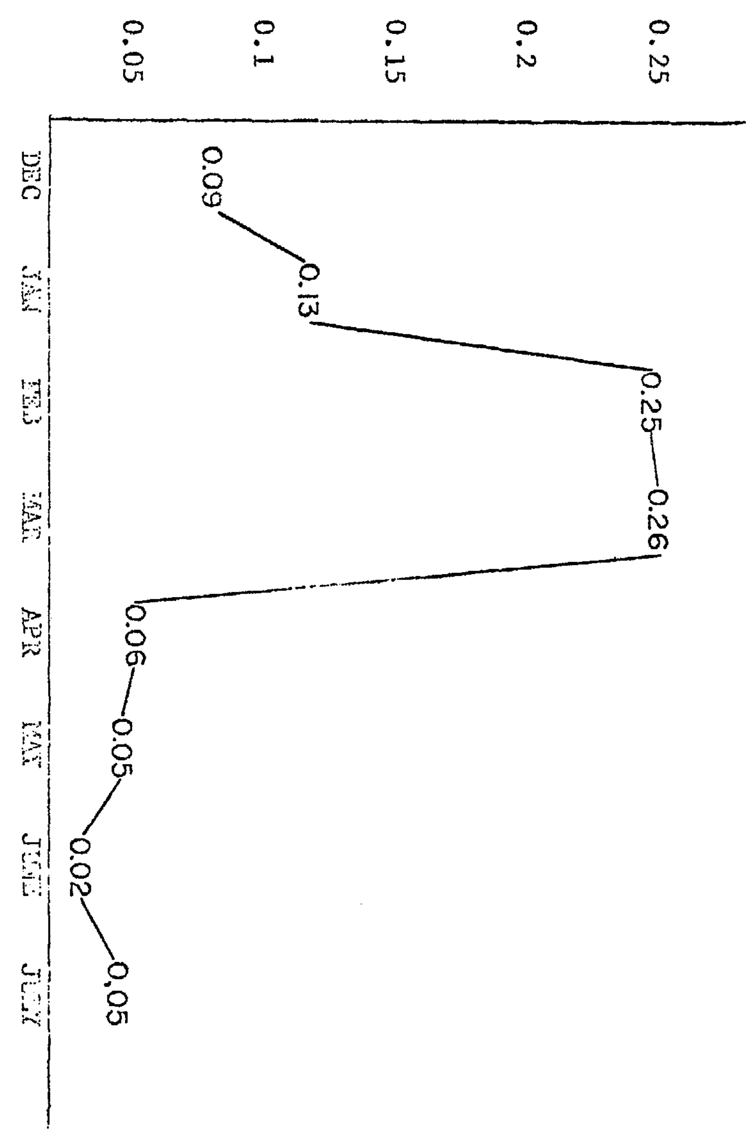
Pond #6
Effluent DO (mg/1)



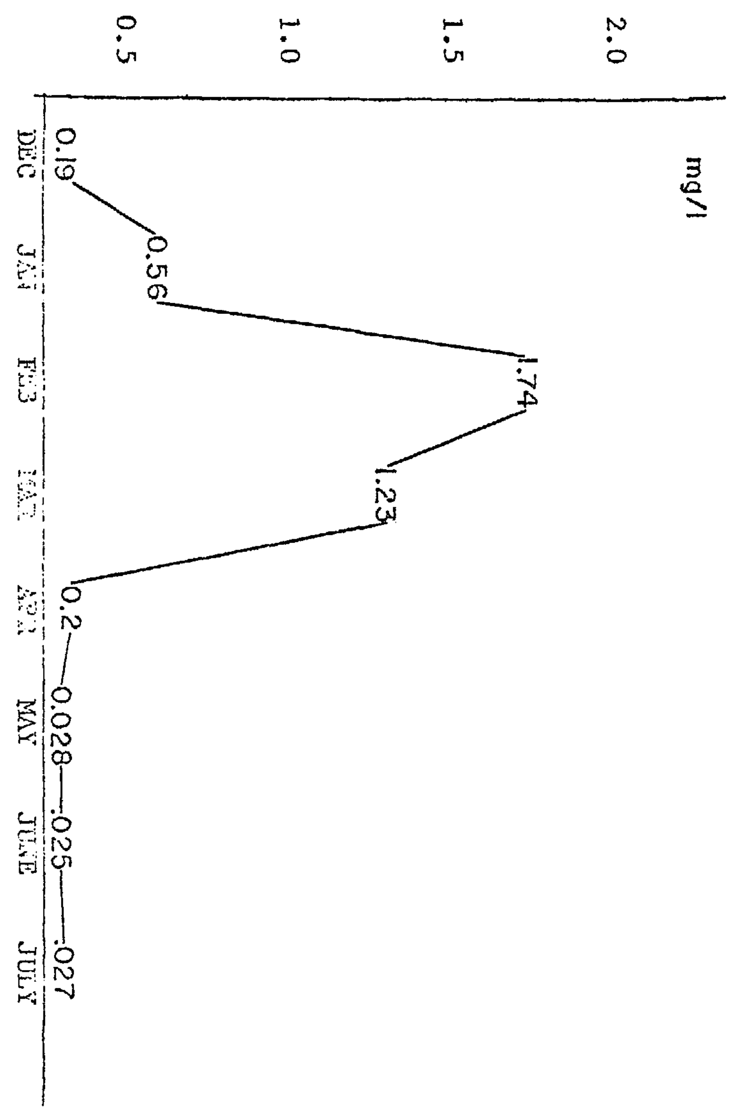
Pond #6
Effluent Conductivity (micromhos/cm)



Pond #6
Effluent NO_2 - N (mg/l)

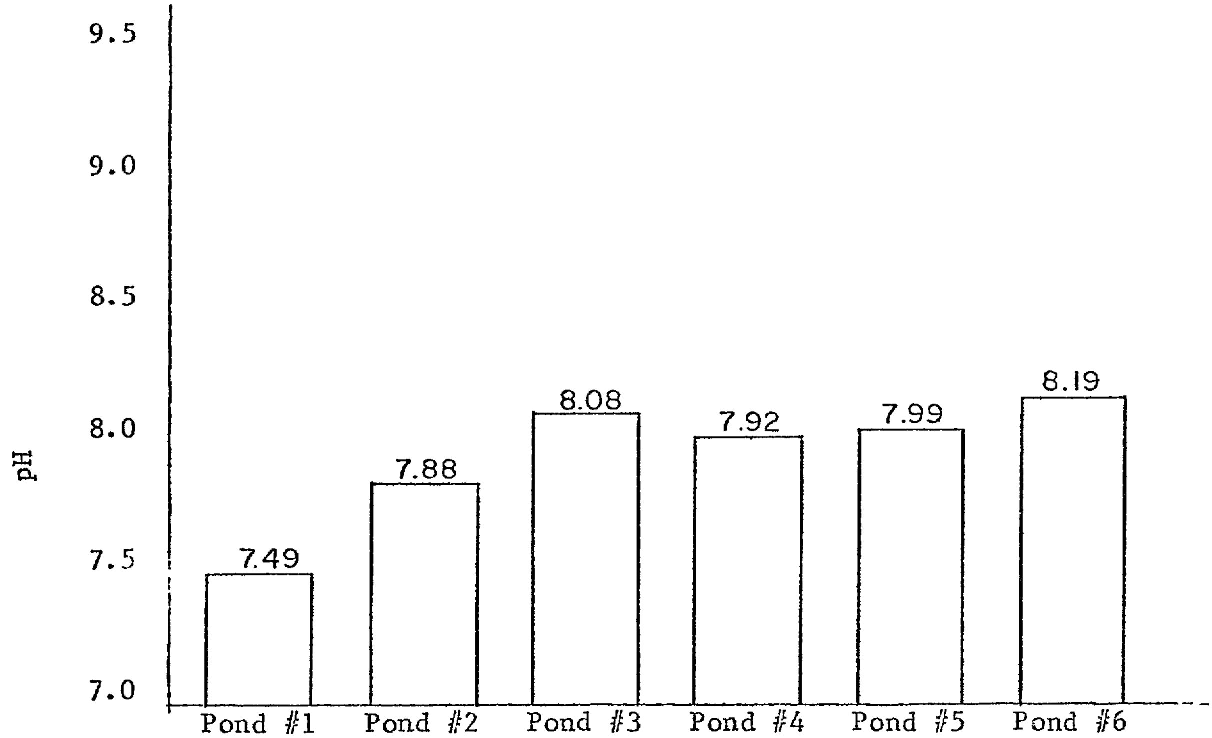


Pond #6
Effluent - NO_3 -N (mg/l)

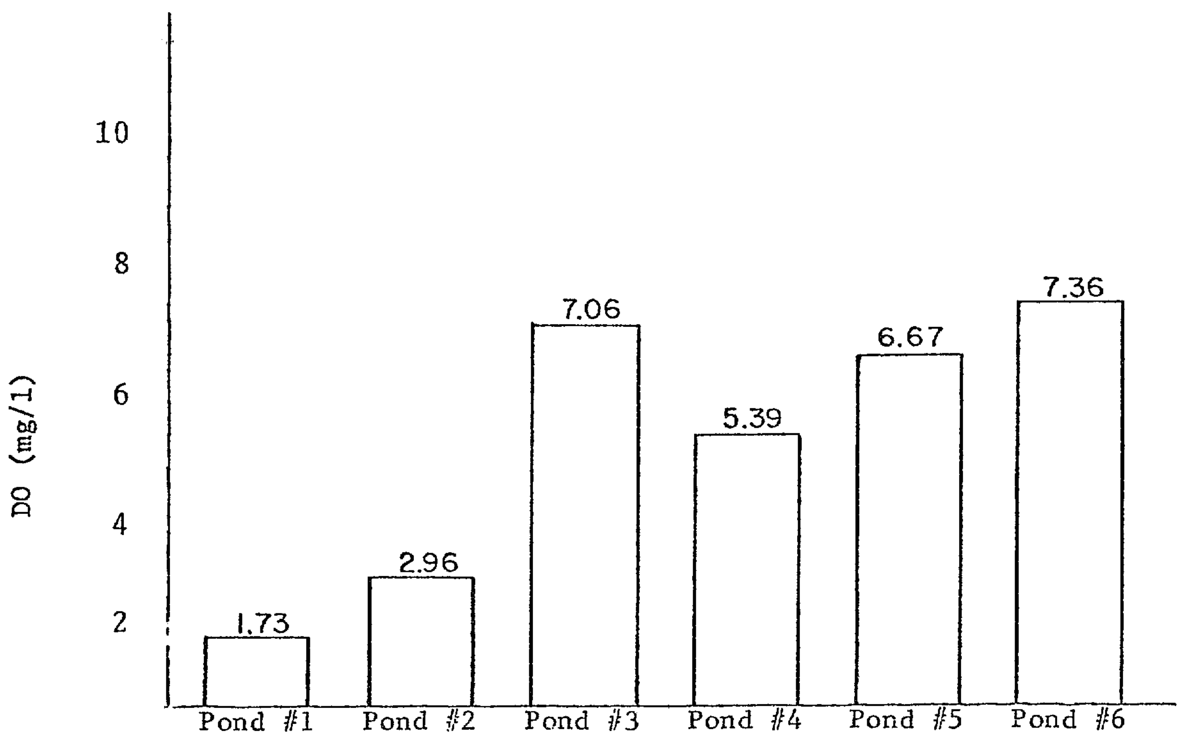


APPENDIX IIC

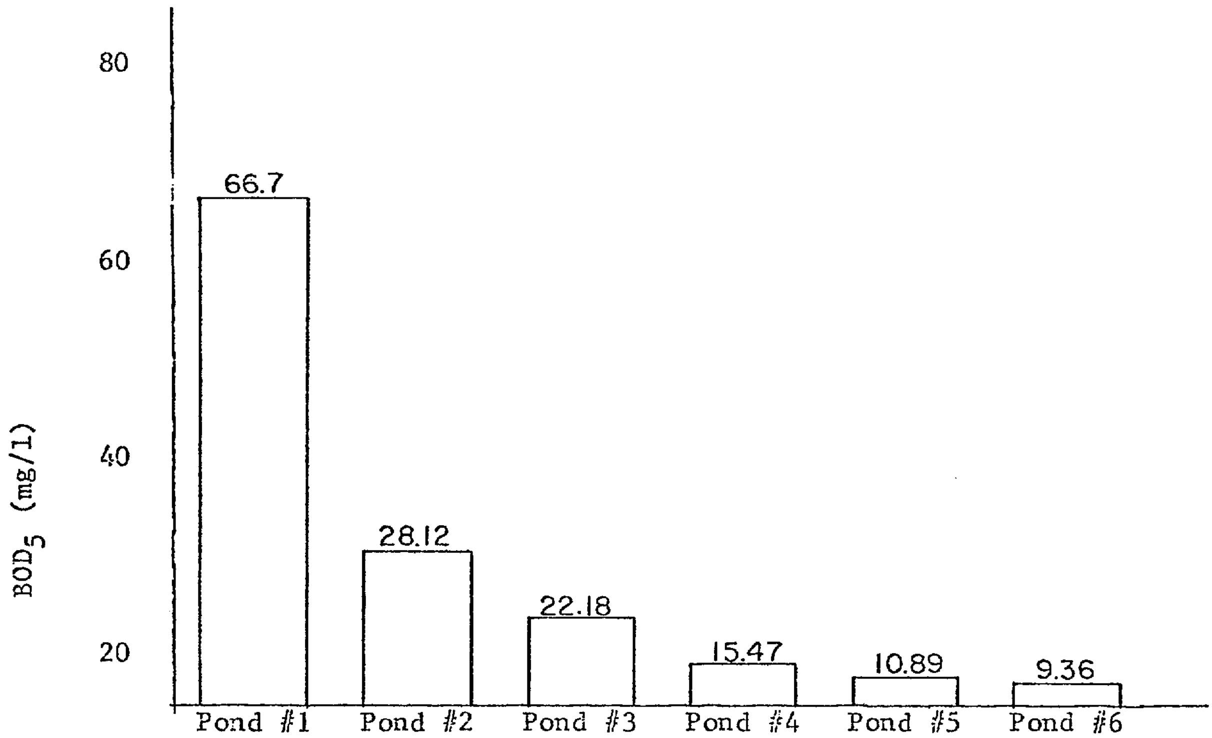
Change in water quality as flow progresses through each pond in the series. Values listed represent the average of weekly samples taken during the first eight months of the study. December, 1978 - July, 1979



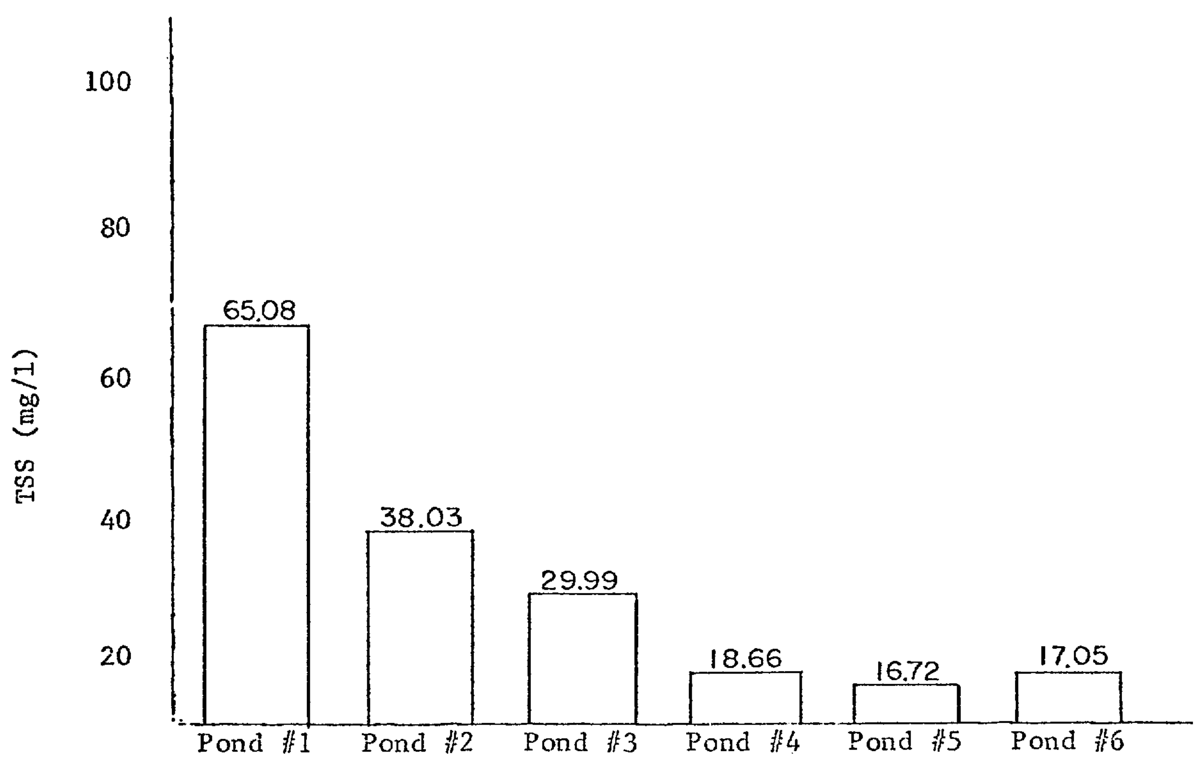
9.5
9.0
8.5
8.0
7.5
7.0
pH
7.49
7.88
8.08
7.92
7.99
8.19
Pond #1
Pond #2
Pond #3
Pond #4
Pond #5
Pond #6



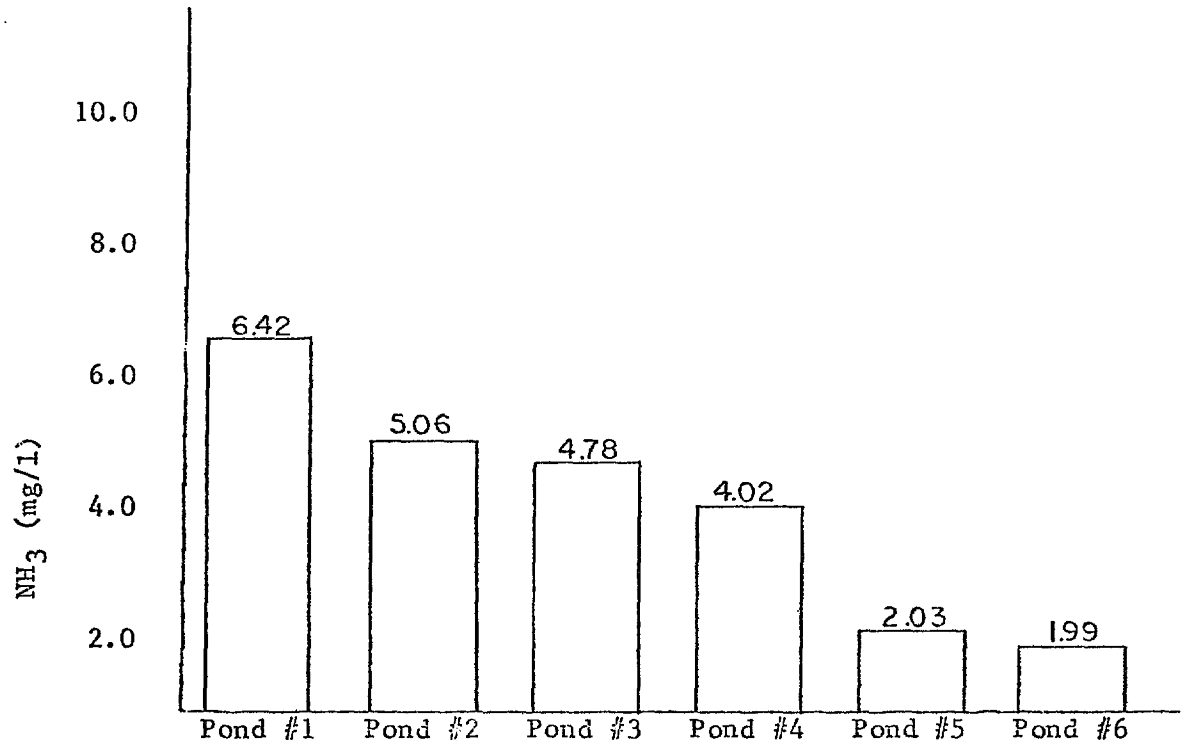
10
8
6
4
2
DO (mg/1)
1.73
2.96
7.06
5.39
6.67
7.36
Pond #1
Pond #2
Pond #3
Pond #4
Pond #5
Pond #6

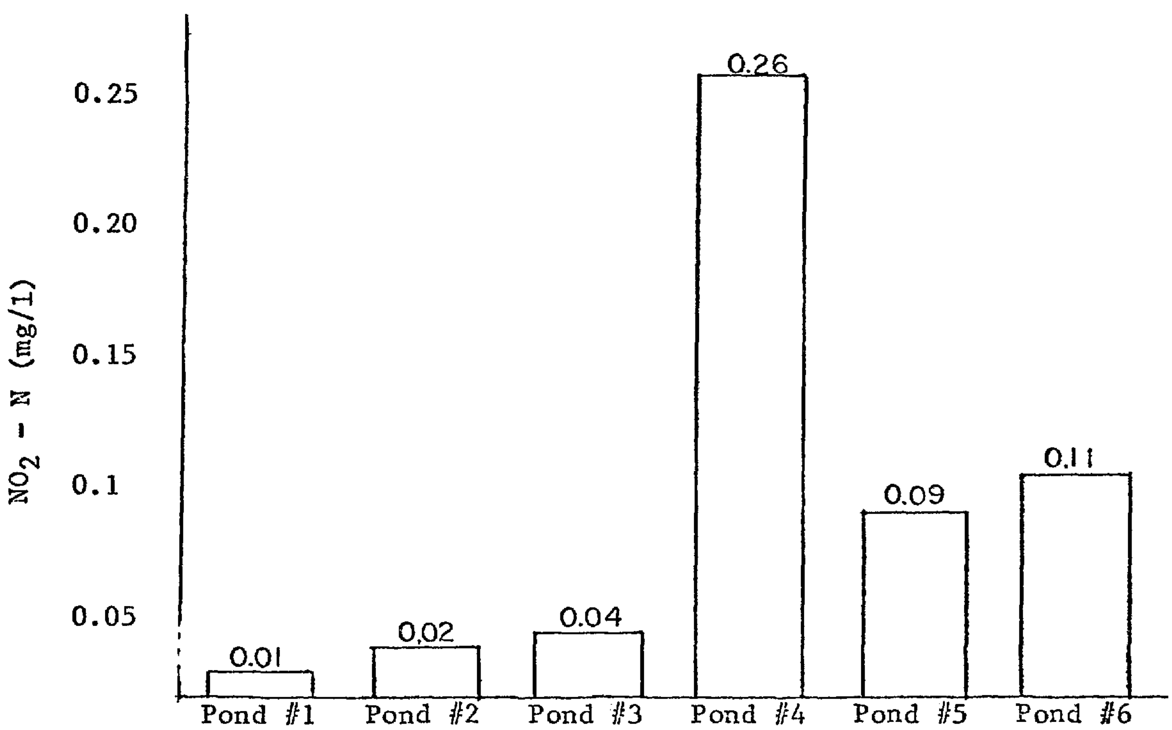


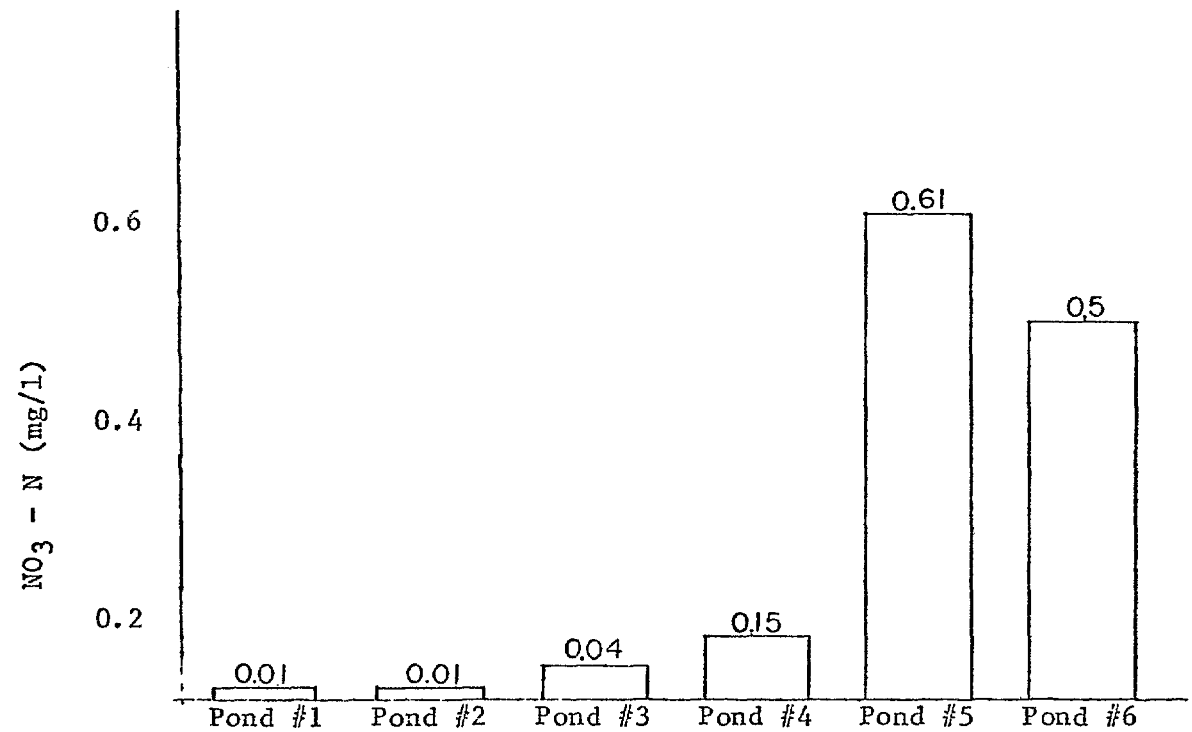
80
60
40
20
BOD5 (mg/1)
66.7
28.12
22.18
15.47
10.89
9.36
Pond #1
Pond #2
Pond #3
Pond #4
Pond #5
Pond #6

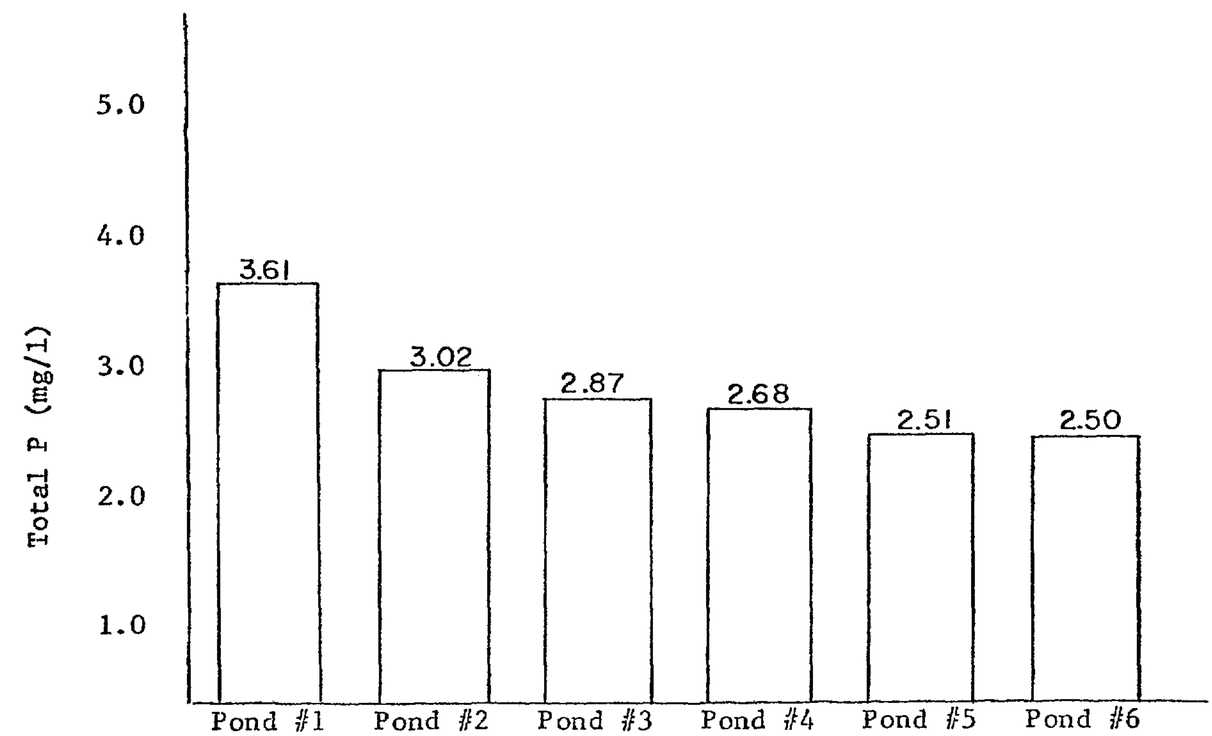


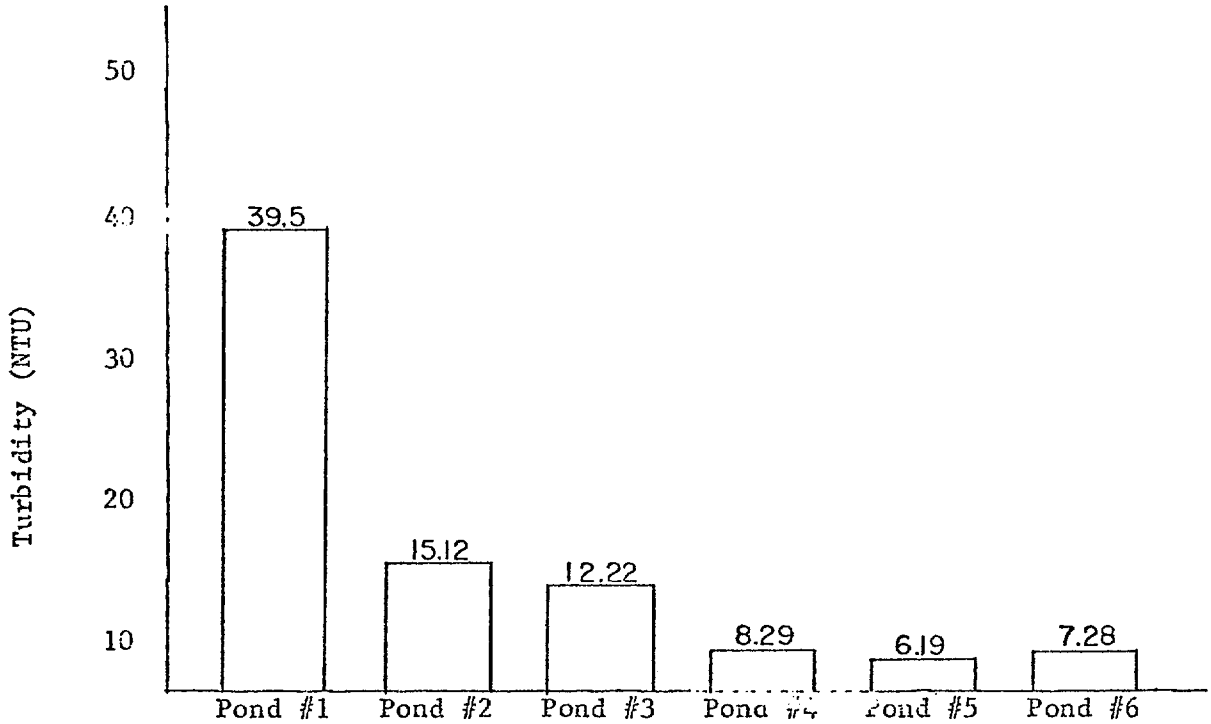
100
80
60
40
20
TSS (mg/1)
65.08
38.03
29.99
18.66
16.72
17.05
Pond #1
Pond #2
Pond #3
Pond #4
Pond #5
Pond #6

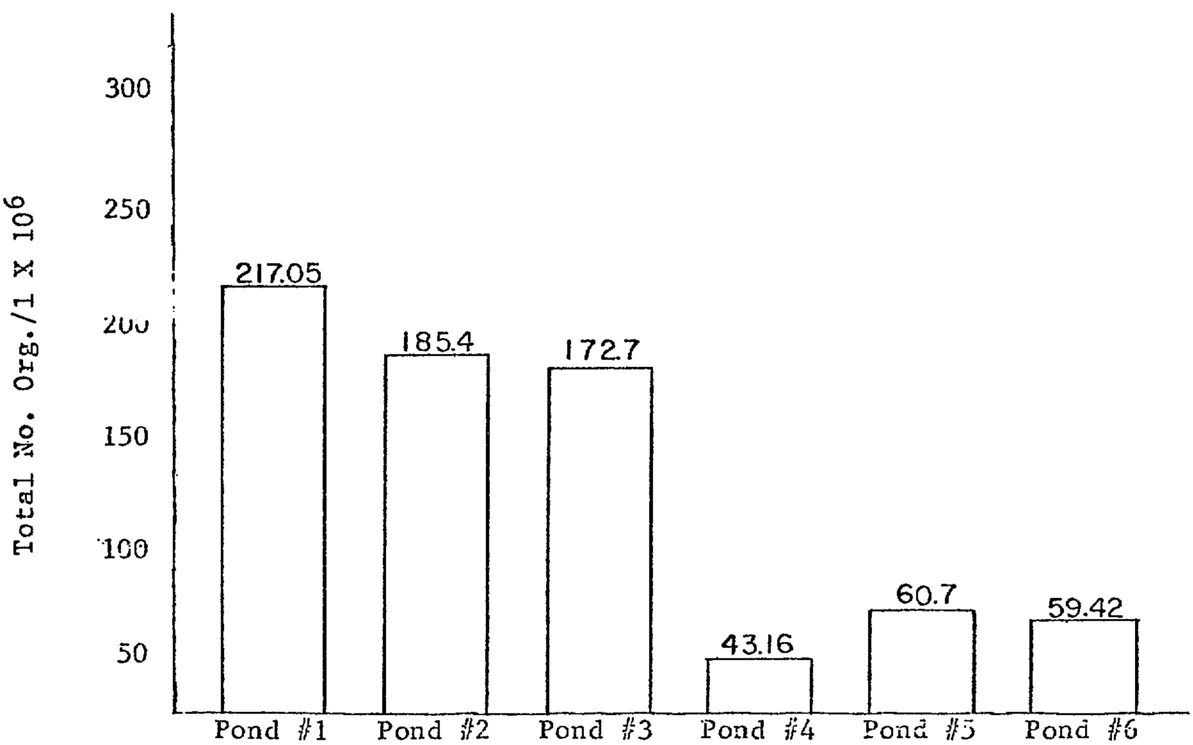

10.0
8.0
6.0
4.0
2.0
NH_3 (mg/1)
6.42
5.06
4.78
4.02
2.03
1.99
Pond #1
Pond #2
Pond #3
Pond #4
Pond #5
Pond #6

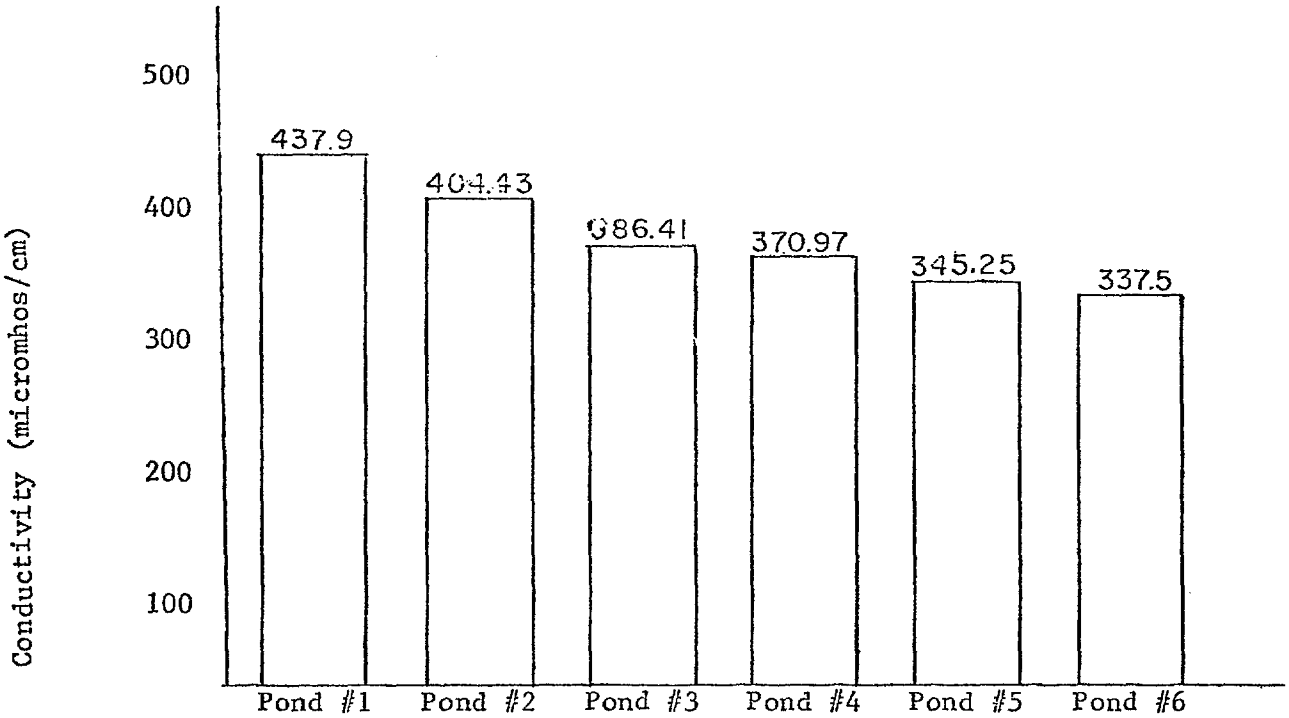

0.25
0.20
0.15
0.1
0.05
NO_2 - N (mg/1)
0.01
0.02
0.04
0.26
0.09
0.11
Pond #1
Pond #2
Pond #3
Pond #4
Pond #5
Pond #6


0.6
0.4
0.2
NO_3 - N (mg/1)
0.61
0.5
0.15
0.04
0.01
0.01
Pond #1
Pond #2
Pond #3
Pond #4
Pond #5
Pond #6


5.0
4.0
3.0
2.0
1.0
Total P (mg/1)
3.61
3.02
2.87
2.68
2.51
2.50
Pond #1
Pond #2
Pond #3
Pond #4
Pond #5
Pond #6


Turbidity (NTU)
50
40
30
20
10
39.5
15.12
12.22
8.29
6.19
7.28
Pond #1
Pond #2
Pond #3
Pond #4
Pond #5
Pond #6


Total No. Org./1 X 10⁶
300
250
200
150
100
50
217.05
185.4
172.7
43.16
60.7
59.42
Pond #1
Pond #2
Pond #3
Pond #4
Pond #5
Pond #6


Conductivity (micromhos/cm)
500
400
300
200
100
437.9
404.43
386.41
370.97
345.25
337.5
Pond #1
Pond #2
Pond #3
Pond #4
Pond #5
Pond #6

TREATED SEWAGE EFFLUENT AS A NUTRIENT SOURCE FOR MARINE POLYCULTURE

John H. Ryther, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543

INTRODUCTION

A biological tertiary sewage treatment-marine aquaculture system was developed, tested, and evaluated for two years on a "pilot-plant" scale at the Woods Hole Oceanographic Institution's Environment Systems Laboratory (ESL - Fig. 1). The effluent from secondary sewage treatment, mixed with seawater, was used as a source of nutrients to grow single-celled marine algae (phytoplankton) in mass (35,000 gallon), continuous flow-through cultures. Harvest from the algal cultures (experimentally varied from 25% to 75% of the culture volume/day), diluted with seawater, was fed into 40' x 4' x 5' (deep) cement raceways containing stacked trays of shellfish. The latter, stocked at densities ranging from 75,000 to 150,000 animals/raceway (1,500 - 3,000 per tray) have consisted of different species of oysters and clams, and smaller numbers of other shellfish.

The phytoplankton removed the nutrients from the sewage effluent, which varied experimentally from 10 percent to 50 percent in the effluent-seawater mixture. The shellfish removed the phytoplankton from the water. Effluent from the shellfish cultures (i.e., the pond harvest and diluting seawater) prior to its discharge was passed through a culture of seaweeds, grown in suspended culture in raceways adjacent to the shellfish cultures, which serve as a final polishing step, removing nutrients not initially assimilated by the phytoplankton and those regenerated by excretion of the shellfish and decomposition of their solid wastes. After initial experimentation with several seaweed species, research was concentrated on two red algae of potential commercial value, *Gracilaria tikvahiae* and *Neoagardhiella baileyi* (which contain the polysaccharides, agar and carrageenan respectively).

Solid wastes produced by the shellfish and uneaten phytoplankton supported dense populations of small invertebrates (amphipods, polychaete worms, etc.). These served as food for secondary commercial crops of marine animals, the American lobster (Homarus americanus) and the winter or blackback flounder (Pseudopleuronectes americanus) which were stocked in respective raceways with the shellfish.

The primary objective of the research was to develop a biological tertiary sewage treatment process capable of removal of all inorganic nitrogen from secondary sewage effluent prior to its discharge into the environment. Earlier studies (1, 2) had established the fact that nitrogen is the nutrient limiting and controlling algal growth in and eutrophication of the coastal marine environment. Thus nitrogen removal may be considered as synonomous with tertiary sewage treatment of effluents to be discharged to the sea.

The second objective of the process was to develop a marine aquaculture system consisting of a primary crop of shellfish and secondary crops of other commercially-valuable marine organisms (seaweeds, lobsters, finfish), the value of which would pay for or help defray the cost of the tertiary sewage treatment process.

Procedures and Results

A. Algae culture and nutrient removal.

Phytoplankton cultures were maintained continuously in five of the six 35,000 gallon, 2,500 ft^2 algae ponds (the sixth pond was held out of production). The culture ponds, which were approximately 50' x 50' x 3' deep, were constructed from shaped sand and fine gravel lined with 20 mm black PVC. The exposed edges of the PVC liners were further covered with a 10 mm PVC "sacrificial" sheet that could be replaced when and if sun damage occurs. When filled to a depth of three feet, the pond volume was 35,000 gallons.

The cultures were kept in gentle circulation with two one-third HP (40 gal/min) cast iron pumps on opposite corners of the ponds. These recirculated the culture, the return jets entering above the surface to provide both momentum and aeration. This action was normally sufficient to keep the algal cells in suspension.

Eight thousand gallons/day of effluent from the Town of Wareham, Massachusetts, activated sludge secondary sewage treatment plant was trucked to ESL and discharged into one of three buried 8,000 gallon fiberglass nutrient storage tanks. From there, the effluent was pumped to a headbox in the ESL mechanical room and then distributed by gravity to the ponds.

Two to four of the pond cultures were grown on various mixtures of sewage effluent and seawater and the remainder on an inorganic nutrient medium which was adjusted to the nitrogen and phosphorus levels of sewage effluent (typically 20-25 mg/l N and 10-15 mg/l P). The number of ponds operated on sewage effluent depended upon the sewage concentration and flow rate (percent pond exchange/day) employed. For example, at 50 percent pond turnover with 25 percent sewage effluent and 75 percent seawater, over 4,000 gallons/day of effluent is required for each pond, over half the daily supply. Since it was desired to obtain maximum performance data of the algal cultures without any chance of their being nutrient limited, the usual procedure was to operate only two ponds with sewage effluent, at concentrations and turnover rates comparable to the above example, particularly during the high productivity period in summer, even although all nutrients were not removed.

Three times a week (M, W, F) the inorganic nitrogen and phosphorus input (sewage and seawater) and discharge (pond harvest) and the particulate (i.e., algal) carbon and nitrogen in the discharge were monitored. From these data, daily nutrient uptake and algal production could be calculated and expressed on a per volume and per area basis. This information is summarized in Table 1 on a seasonal basis, extrapolated to show areal requirements in acres per MGD of effluent (10,000 capita) for complete tertiary treatment (nitrogen removal). This ranged from 26 acres in summer to 77 acres in winter, with 19 acres for the best short-term performance in midsummer.

In contrast to earlier experience with effluent from other treatment plants, in which the nitrogen is predominantly in the form of ammonia, the Wareham effluent is highly oxidized with 0 - 30 percent ammonia (depending upon time of year, performance of the plant, and perhaps other factors), the remaining nitrogen fraction being nitrate. This apparently does not affect algal production, though there is evidence that the ammonia is preferentially used first by the plants if a mixture of the two forms is present. To more nearly simulate sewage effluent in the cultures that were fed inorganic chamical nutrient medium, the ammonium chloride was replaced by an equivalent amount of sodium nitrate. However, the latter proved unsuccessful, possibly due to toxic contaminants in the industrial-grade chemicals used, so practice reverted to the use of ammonium chloride. Generally speaking, the performance of the cultures with respect to algal growth and nutrient removal were the same whether sewage effluent or the chemical nutrient medium, adjusted to the same nitrogen concentration, were used.

During a period of approximately two months, due to malfunction or poor operation of the treatment plant, the effluent was of poor quality, containing large quantities of undigested suspended solids. The resulting turbidity inhibited algal production and the dissolved and particulate organic matter made monitoring of nutrient utilization and algal production impossible during that period. That experience points out the necessity for high quality, completely oxidized, and clear secondary effluent for the successful operation and monitoring of the algal growth system.

Table 1. Mean phytoplankton production and nitrogen removal in effluent-enriched cultures, on a seasonal basis. (Figures rounded)

	Winter	Spring-Fall	Summer	Maximum
Mean algal production				
g dry weight/m^2/day (ash-free)	3	6	9	12
Nitrogen removal				
g/m^3/day	0.3	0.6	0.9	1.2
lbs/acre/day (cultures 1 m deep)	2.7	5.4	7.1	10.8
Equivalent volume effluent treated[1]				
MGD/acre	.013	.026	.039	.052
Area requirement				
acres/MGD effluent treated	77	37	26	19

[1]Assuming 24 mg N/1 effluent or 200 lbs N/million gallons effluent.

Despite considerable effort and experimentation, including filling the algae ponds with 1μ-filtered seawater and inoculation with large (several hundred liter) cultures of several different species of unicellular algae, no success was obtained in controlling the species of algae that developed and persisted in the ponds. Cultures were always virtually unispecific, the species varying with the season. In winter, at temperatures between 0° and 9°C, the diatom Skeletonema costatum occurred. During most of the remaining part of the year, at water temperatures of 10° - 25°C, the diatom Phaeodactylum tricornutum, was the persistent alga. During a brief period of about one month in midsummer, when pond temperatures exceeded 25°C, unidentified green flagellates replaced the Phaeodactylum cultures. It is unlikely that the species of algae present affect rate of algal production or nutrient utilization, so this in not an important factor with respect to the tertiary treatment role of the system. However, some species are well recognized and documented as better food organisms than are others for bivalve molluscs (3). Although Skeletonema is generally regarded as one of the better shellfish foods, Phaeodactylum is variously reported as poor to indifferent. The implications of that problem will be discussed further below, but phytoplankton species control remained a chronic and unresolved problem.

Two of the algae ponds could be heated by circulating their contents through heat exchangers in the laboratory. These were operated at 15° - 20°C throughout the winter when temperatures in the unheated ponds ranged from 0° to 5° C. Surprisingly, there was no difference in algal production between the heated and unheated ponds. Seasonal variations in algal production of three- fourfold and even species succession and dominance are apparently due to changes in incident solar radiation, with temperature a second order factor, at least in winter. This is an important finding, as it eliminates the need to consider heating an extensive area of shallow algal ponds in winter in any commercial application of the process in temperate latitudes. Unfortunately, however, the algal culture must still be heated to at least 10°C and preferentially 15 - 20°C before it can be utilized by the shellfish.

The continuous-flow cultures could be maintained for months at a time with little or no maintenance. Gradually, the accumulation of organic matter on the bottom and the development of a fringe of epiphytic green algae (usually Enteromorpha) at the water's edge around the periphery of the pond causes a reduction in algal production. This was exacerbated if the sewage effluent contained significant amounts of suspended solids. When that occurred, normally at intervals of 3-6 months, the ponds were drained, cleaned, sprayed with dilute sodium hypochlorite, sundried, refilled, and reinoculated with an adjacent culture. This required one or two days of effort per pond, and the new culture could be brought on line into production in about four days.

At pond temperatures exceeding 15°C when Phaeodactylum was the dominant alga in the cultures, one or more species of colorless protozoan flagellates, roughly the same size as the Phaeodactylum cells (i.e., 20-30μ in diameter) appeared in the cultures and fed upon the diatoms. Unpredictably and very quickly the flagellate at times proliferated throughout the culture and eliminated the algae. Such cultures could be discarded and restarted, as described above, but if left alone, the flagellate population quickly subsided, presumably through lack of food, and the Phaeodactylum population reestablished itself in about the same time (3-5 days) that it took to start a new culture. Such predation did not occur often enough to be a serious problem, but caused an undesirable interruption in algal production when it did happen. No means of controlling the predator(s) were found.

B. Bivalve mollusc culture.

Harvest from the phytoplankton pond cultures (equivalent in volume to the daily turnover rate of the ponds) flowed by gravity into respective cement raceways 40' long x 4' wide x 5' deep. At its point of entry to the raceway, the algae culture was diluted with coarse-filtered seawater at ratios ranging from 1 to 5 parts seawater to 1 part culture, depending upon the season and other related factors. Reasons for the dilution were: 1) to dilute the algal suspension to the degree necessary for the shellfish to filter and assimilate the food organisms most efficiently, a concentration of the order of 10^5 cells/ml; 2) to provide a more rapid flow of water through the raceway to enhance shellfish feeding; 3) to prevent the accumulation of metabolites of the animals, particularly ammonia, to toxic levels; and 4) through use of heated seawater when and as needed, to bring the combined flow of algae and seawater to a temperature at which the shellfish would feed and grow throughout the year. Phytoplankton will grow equally well on heated and unheated pond cultures in winter, as discussed above, but the unheated cultures must be heated to 10° - 20°C before they are presented to the animals.

The facility did not have the capacity to raise temperatures of the combined algal culture-seawater mixture, at the desired flow rates, to levels above approximately 15°C in winter. Nor did it have the capability of providing a range of different temperatures to the raceway system while holding other factors (i.e., flow rates) constant. Finally, there was no capacity to cool water, and solar heating of the algal pond cultures together with the diluting seawater could result in peak summer raceway temperatures of 25°C. It was therefore not possible to control temperatures in the animal culture system beyond a seasonal range of 15° - 25°C. This led to some problems in attempting to assess shellfish growth over long periods of time as a function of other variables, such as food species, food concentration, flow rates, etc.

The algae culture-seawater mixture entered one end of the 40-foot raceway and passed in a linear flow to the opposite end, where it entered the adjacent seaweed-stocked raceway, for final "polishing" of the effluent. Shellfish were stocked in wooden-frame, vexar-lined trays (mesh size depending upon size of the shellfish) at an initial density, for the 1/2 - 1" seed, of 1,500 to 3,000 animals per tray, which was later to be thinned appropriately as the bivalves grow (Fig. 2). The trays were stacked vertically, 7-8 trays per stack, the raceways accommodating 8 such stacks of trays, holding a total of some 150,000 seed shellfish. An airline extended along the side of the raceway on the bottom to provide aeration and vertical mixing of the water throughout its length. This was found essential for mixing thoroughly the algae culture and diluting seawater and preventing a stratified flow down the length of the raceway, particularly in cold weather when heated seawater was used. In addition, aeration was important in maintaining high levels of oxygen and low levels of metabolites, particularly ammonia, everywhere in the raceway and especially near the bottom.

The initial attempt at shellfish culture involving the stocking of three raceways with 300,000 seed oysters (*Crassostrea virginica*) from Flower Brothers Hatchery, Bayville, Long Island (NY) and 150,000 seed hard clams (*Mercenaria mercenaria*) from Long Island Oyster Farms, Northport, Long Island (NY) was largely unsuccessful. Neither species grew significantly during the following 18 months and most of the oysters died. Two possible explanations for this lack of success were suggested: 1) The seed shellfish in question were stunted or otherwise inferior stocks or they had suffered stress or injury during transport from their sources. 2) The phytoplankton grown in the mass algal cultures, predominantly *Phaeodactylum tricornutum* during most of the year, was inferior and unsuitable as food for the shellfish.

The first of those explanations was subsequently ruled out. New stocks of American oysters were obtained from the same Long Island hatchery that were newly-set, healthy, actively-growing seed obtained in two separate lots during the spring. In addition, small lots of both oysters and clams of the same species were obtained from other sources. In no case did either species grow or even survive in the culture system.

Since *Phaeodactylum* and various green algae were already known to be poor to indifferent foods for larval and very young juvenile clams and oysters, the second explanation therefore appeared to be the correct one, and success of the system appeared dependent upon the ability to control the species and to grow other, more desirable food organisms in the mass algal cultures.

At the same time these tentative conclusions were reached, however, small numbers of juvenile Manila clams (*Tapes japonica*) and European oysters (*Ostrea edulis*) were obtained. Both species survived well and grew within the culture system and on the same food that failed to support *C. virginica* and *M. mercenaria*. *Tapes* grew slowly, though apparently not unusually so for the species (Fig. 3). *Ostrea* grew very rapidly, from 3.5 cm seed to 9.5 cm marketable adults in about five months (Fig. 4).

As a result of this experience new, larger lots of O. edulis were obtained from several sources and stocks of Japanese oysters (Crassostrea gigas) were also obtained and introduced to the raceway system. The results with O. edulis were somewhat equivocal, some growing well and others dying, but the reason for this is believed to be damage or injury of some of the seed during shipment (i.e., from as far as the U.K.). The C. gigas stocks all grew well.

Thus, the earlier problem of the inability to control species in the algal ponds and to produce phytoplankton suitable as food for the indigenous species of oysters and clams, if not solved, appeared to have been circumvented by use of exotic shellfish species capable of utilizing the kinds of algae that could be mass produced. Very preliminary results also indicated that the local bay scallop (Argopecten irradians) may be included among the latter group, but evaluation of that species was hindered by scarcity of seed stock. The interesting question of why some bivalve species but not others can subsist on the phytoplankton "weeds" remains to be answered.

Lack of research support for the project after the second year prevented any quantitative evaluation of the system as a whole for shellfish production. Smaller scale studies during an additional year, with a different but reduced level of support, did permit a study of the comparative growth of six species of bivalves using phytoplankton produced in the wastewater-enriched cultures (4).

C. Seaweed culture.

Seaweeds were used in the polyculture system as a "polishing step" to remove nutrients not initially assimilated by the phytoplankton and those put back into the culture system by excretion of the shellfish and other animals and the decomposition of their solid wastes. The objective was to achieve a nutrient-free final effluent than would meet standards of tertiary sewage treatment at the same time producing a crop of commercially valuable plants.

Seaweed research was restricted to red algae of several species that are of existing or potential commercial value for their content of agar or carrageenan. These included Chondrus crispus, Gracilaria tikvahiae, Neoagardhiella baileyi, and Hypnea musciformis. Of these, Gracilaria and Neoagardhiella proved most successful. The following discussion concerns primarily the results obtained with Gracilaria (Fig. 5).

As explained in the preceding section, water leaving the shellfish raceways passed through the adjacent raceway in the opposite direction where it was exposed to suspended cultures of seaweed before being discharged back to the ocean. The latter had the same dimensions as the shellfish raceway (40' x 4' x 5' deep) but were modified with a sloping plywood bottom with a depth ranging from two feet, on the high side to the bottom (five feet) on the low side. An air line

Table 2. Mean seaweed production and nitrogen removal in effluent-enriched cultures, on a seasonal basis. (Figures rounded).

	Winter	Spring-Fall	Summer	Maximum
Mean production				
g dry weight/m^2/day (ash-free)	3	5	13	16
Nitrogen removal				
g/m^3/day	0.1	0.2	.5	.6
lbs/acre/day (cultures 1 m deep)	0.9	1.8	4.5	5.4
Equivalent volume effluent treated[1]				
MGD/acre	.004	.008	.022	.027
Area requirement				
acres/MGD effluent treated	223	112	45	37

[1]Assuming 24 mg N/1 effluent or 200 lbs N/million gallons effluent.

on the bottom at the five-foot depth provided the vigorous circulation needed to keep the seaweed in suspension and to bring it continuously to the surface and to exposure to sunlight. The sloping bottom eliminated a dead area in the circulation cell in the corner opposite the air line, in which the seaweed would otherwise settle and collect (Fig. 6).

Once a week, the seaweed population was harvested from the raceways with dip nets, drained, and weighed. Net production over the previous week was removed, returning a constant starting biomass of 50 kg/raceway. The routine was varied experimentally during the year, but that figure was found empirically to be optimum for maximum daily production, which ranged from a mean of 3 grams dry weight (organic matter) m^2/day in winter to 10 grams/m^2/day in summer (dry weight is 10 percent of wet weight and contains an average of 40 percent ash in Gracilaria tikvahiae).

Occasionally fouling organisms, in particular the green alga Enteromorpha, invaded the seaweed cultures and grew epiphtically upon the cultured species. Under extreme conditions, the cultures had to be discarded. Epiphytic growth is probably the single greatest problem in and constraint to commercial seaweed culture particularly in the tropics and subtropics where conditions are otherwise ideal for such practices. However, for reasons not fully understood, this problem was never a critical one in the Woods Hole experiments.

During the second year, new experiments were initiated in which seaweeds were grown alone, in a single-step waste recycling system, using mixtures of seawater and secondary sewage effluent in a continuous flow-through mode of operation. A series of plywood tanks 8' x 6' x 3' painted with white epoxy were used in these experiments (Fig. 7).

Maximum yields of Gracilaria of 16 grams ash-free dry weight/m^2/day were achieved for short periods of time in summer, while average yields of 3 g/m^2/day in winter and 12 g/m^2/day in summer were sustained over long periods of time. Table 2 shows yields and nitrogen removal capacity for the seaweeds grown on sewage effluent and seawater mixtures in the experimental tanks described above. As in Table 1, the data have been extrapolated to show the potential and areal requirement of such a system in nutrient removal per MGD effluent. It may be seen that seaweed production is comparable to and, in summer, slightly better than unicellular algae production. However, because the seaweeds contain on the average less nitrogen per unit of ash-free dry weight (4 percent for seaweeds and about 10 percent for unicellular algae), the equal or higher rate of growth of seaweed is more than offset by its lower capacity for nitrogen removal per unit growth.

In one experiment, three of the above seaweed tanks were operated in series, with an input of 25 percent sewage effluent - 75 percent seawater mixture introduced into the first tank and then passing through the second and third tanks at flow rates equivalent to 50 percent of the individual tank volume turnover per day. The three tanks were initially stocked with 5,000, 3,000, and 1,000 grams respectively of Gracilaria, and the growth increment allowed to accumulate during the one-month period of the experiment. Inorganic nitrogen and phosphorus were monitored in the water entering and leaving each of the tanks. The data from this experiment is summarized in Table 3, where it may be seen that the three tank cultures progressively removed 99 percent of the incoming nitrogen. Nitrogen deficiency of the Gracilaria in the third tank was evident both in its pale yellow coloration, in contrast to the deep reddish-brown color of the plants in the first tank, and in its carbon: nitrogen ratio, which was 28 in contrast to 10 in the first tank. This has some practical significance, as the commercial product of the seaweeds (agar in Gracilaria) is elaborated more rapidly and to a greater degree in nitrogen-deficient plants. In a commercial seaweed culture application, using a raceway or channel-type culture configuration with a linear flow of water and nutrients, the seaweed should presumably be moved downstream in the system, away from the source of nutrients, and harvested from the far end following a period of exposure to nitrogen-free conditions. Further evaluation of the production of the seaweeds and their hydrocolloids in the wastewater recycling system is presented in a separate report (5).

D. Nutrient removal efficiency of the system as a whole.

As pointed out earlier, algal pond cultures were operated during the first year deliberately at nutrient (sewage effluent) concentrations higher than could be completely utilized by the phytoplankton. This was done to develop information on the maximum potential growth and nutrient assimilative capacity of the algae under non-nutrient limited conditions. The amount of nitrogen taken up by the algae from solution or the amount contained in the algal harvest, by direct measurement, could then be used to calculate the daily assimilative capacity of the system and this, in turn, to calculate the daily input of sewage effluent per unit area of algal pond for complete nitrogen removal. That information, based on a year's observation, is presented in Table 1, also including the comparable data for a seaweed-based tertiary treatment system.

The above data, interpreted in terms of the ESL pond culture system, means that complete nitrogen removal could be expected in winter operating at a 25 percent pond volume turnover per day with an input of 10 percent sewage effluent and 90 percent seawater. In spring and fall, the effluent strength can be increased to 20 percent or the turnover rate doubled (50 percent), resulting in either case in doubling the nutrient input rate. In summer, the system should be able to assimilate completely the nitrogen from 30 percent effluent - 70 percent seawater mix at 25 percent turnover, or a 10 percent effluent - 90 percent seawater at 75 percent turnover rate per day.

Table 3. Nitrogen removal in experimental seaweed (Gracilaria tikvahiae) tanks operated in series under steady-state, continuous flow-conditions.

Tank No.	Effluent N concentration[1]	% N removal (cumulative)	Seaweed production $g/m^2/day$ (ash-free)	C:N in seaweed
1	0.96	60	3.4	10
2	0.07	77	2.5	12
3	0.02	99	1.2	28

[1]Initial N concentration (input to Tank 1) = 2.41 ppm.

Since it is costly to pump seawater, the higher effluent concentration at the lower exchange rate is the more economical mode of operation. There is some evidence, however, that stability of the cultures may be enhanced by low nutrient levels at high turnover rates, so the costs of labor (for cleaning and restarting cultures) and of building and operating stand-by cultures to provide for down-time may exceed the cost of pumping additional seawater.

Table 4, shows typical steady-state mass flow of nitrogen through the three-step system under late spring operating conditions as defined above. Of the nitrogen (nitrate, nitrite, and ammonia) daily entering the pond as sewage effluent (84 grams) and seawater (1g), over 98 percent (83.4 g) was removed by the phytoplankton. The remaining 1.5g, together with the algae, was fed to the shellfish raceway, where it was mixed with twice its volume of seawater. Since the latter contained the same concentration of inorganic nitrogen as the pond effluent (0.04 ppm), the seawater contributed twice as much nitrogen as the effluent (total 4.5 g). To this, the shellfish raceway added 22.5 g of dissolved inorganic nitrogen through excretion, decomposition, or other sources, roughly 25 percent of the amount that entered the raceway as phytoplankton. Of the total output of 27 g nitrogen from the shellfish raceway, 18 g were removed by the seaweeds, leaving a final residual of 9 grams, 10 percent of the initial input of the sewage effluent and seawater, for a total removal efficiency of the system as a whole of 90 percent. Since the seaweed removed two-thirds of the regenerated nitrogen, it could be assumed that expansion of the seaweed culture by one-third (from 160 ft^2 to 240 ft^2 in the pilot facility) would result in complete nitrogen removal of the final effluent.

E. Culture of secondary animal crops.

Solid wastes (feces and pseudofeces) produced by the shellfish and/or uneaten phytoplankton cells which settle out from suspension in the shellfish raceways provided sources of food for large quantities of several species of small, invertebrate detritovores that presumably entered the system as larvae in the coarse-filtered seawater use to dilute the phytoplankton pond harvest. Prominent among such invertebrates were amphipods (*Corophium*, *Jassa*, and *Gammarus*), polychaetes (*Capitella capitata*), bryozoans, tunicates, and mussels. This small invertebrate fauna served the dual purpose of preventing the accumulation of solid organic wastes in the raceways and providing a source of food for secondary crops of carnivores or omnivores of potential commercial value. The latter included the American lobster (*Homarus americanus*) and the winter or blackback flounder (*Pseudopleuronectes americanus*) (Table 5).

In July, 474 juvenile (0 to 1 year class) flounder were collected locally and stocked in one of the oyster raceways. Their size distribution was, of course, bimodal for the two-year classes, but averaged 7.0 cm. In October, the raceway was drained and 124 fish recovered, averaging 11.0 cm in length. The following April, 69 fish were recovered,

Table 4. Mass flow of inorganic nitrogen (ammonia, nitrite, and nitrate) through the phytoplankton-oyster-seaweed system.

	grams N/day	
1. Phytoplankton pond input		
sewage effluent	84	
seawater	1	85
2. Phytoplankton pond output		1.5
3. Shellfish raceway input		
phytoplankton pond harvest	1.5	
seawater	3.0	4.5
4. Shellfish raceway output		27
(= seaweed raceway input)		
5. Seaweed raceway output		
(final effluent from system)		9.4
Total N removal efficiency (including seawater)		89.3%
Effluent N removal efficiency		93.6%

Table 5. Growth and survival of winter flounder and American lobsters in oyster raceways.

Winter flounder (*Pseudopleuronectes americanus*)			
Days	Number	% survival	Size (mm)
0	474	----	70
120	99	21	110
300	69	14.5	167

American lobster (*Homarus americanus*)			
Days	Number	% survival	Size (mm)*
0	390	----	9.0
90	256	66	13.4
240	124	32	25.0

*Carapace length.

averaging 16.75 cm in length. The surviving fish thus more than doubled in size in 9 months. If the observed linear growth rate were to continue, the fish would reach a marketable size of 25 cm (1/2 - 1 lb) in another 9 months, or 18 months from the time of stocking as juveniles.

Egg-bearing lobsters were obtained from commercial fisherman, by special permit, and were held in the laboratory until the eggs hatched (i.e., in spring, when water temperatures reach 15° - 20°C). The larvae were transferred to specially-constructed larval rearing tanks where they were fed live or frozen brine shrimp (*Artemia salina*). After metamorphosis to juvenile lobsters (10 - 14 days), they were segregated into small containers, to prevent cannibalism, and fed the same food until they had molted an additional 3 - 4 times and attained a mean size of 9 mm carapace length and 0.18 grams. A total of 390 of these lobsters were then stocked in September in segregated (screened-off) portions of two oyster raceways, each group together with two stacks (16 trays) of oysters. The following April, a total of 124 lobsters were recovered which had a mean size of 25 mm carapace length and a mean weight of 18 grams. These ranged widely, however, in their size distribution, from 10 to 52 mm carapace length. The larger individuals, some 150 mm total length, attained a size in eight months that is not reached by wild lobsters in New England in less than three years, and is comparable to the best growth obtained with segregated lobsters held in captivity at elevated temperatures and fed artificially.

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Figure Legends

Figure 1. Environmental Systems Laboratory, Woods Hole Oceanographic Institution.

Figure 2. Wooden frame, vexar-mesh trays with seed oysters in shellfish raceway.

Figure 3. Growth of *Tapes japonica* after five months.

Figure 4. Growth of *Ostrea edulis* after five months.

Figure 5. The red seaweed *Gracilaria tikvahiae* grown in ESL raceway system.

Figure 6. The ESL raceway system with shellfish raceways covered and seaweed raceways exposed.

Figure 7. Plywood tanks used for growing seaweeds directly on sewage effluent.

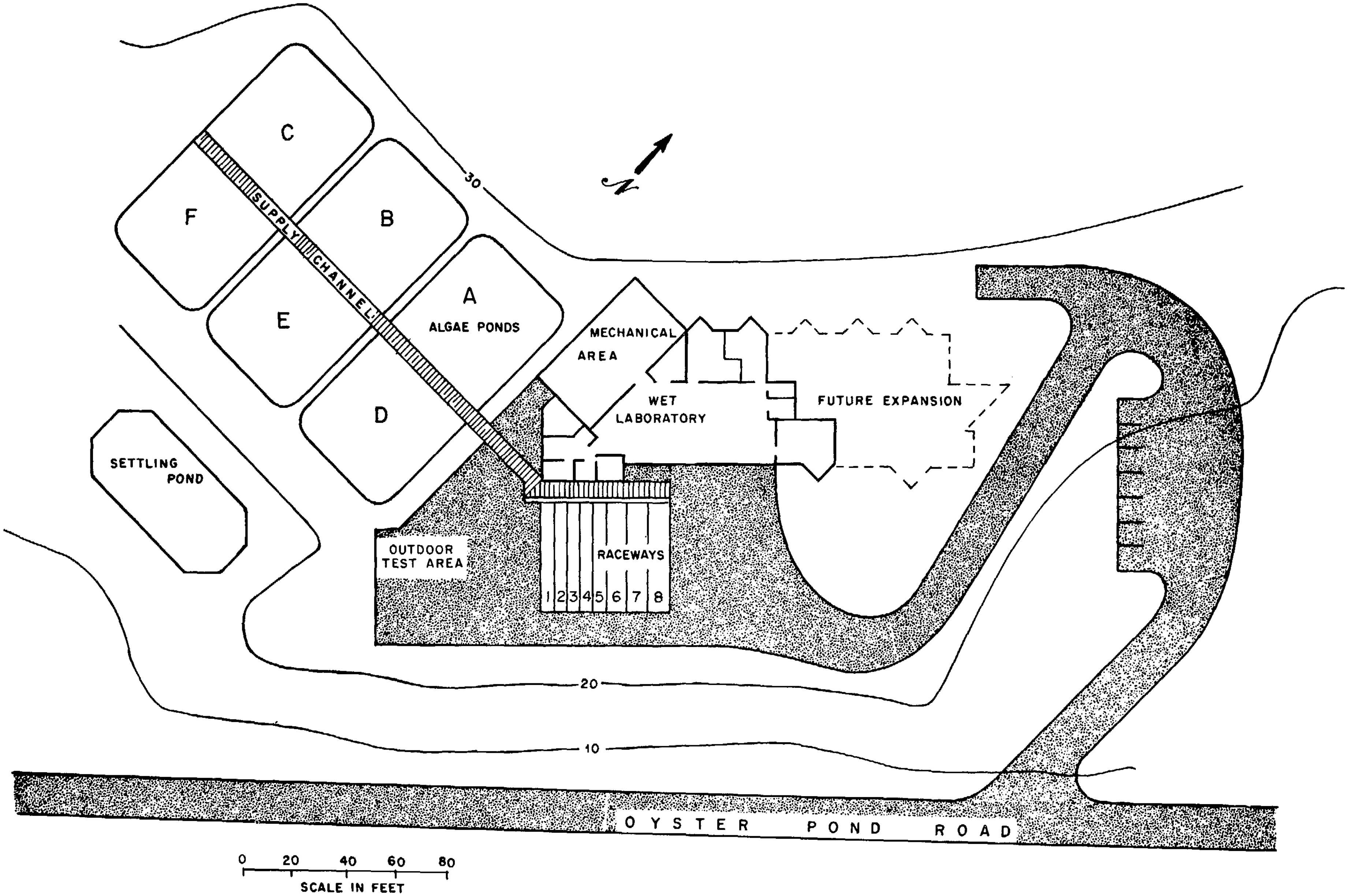

FIGURE 1
ENVIRONMENTAL SYSTEMS LABORATORY
WOODS HOLE OCEANOGRAPHIC INSTITUTION

FIGURE 2

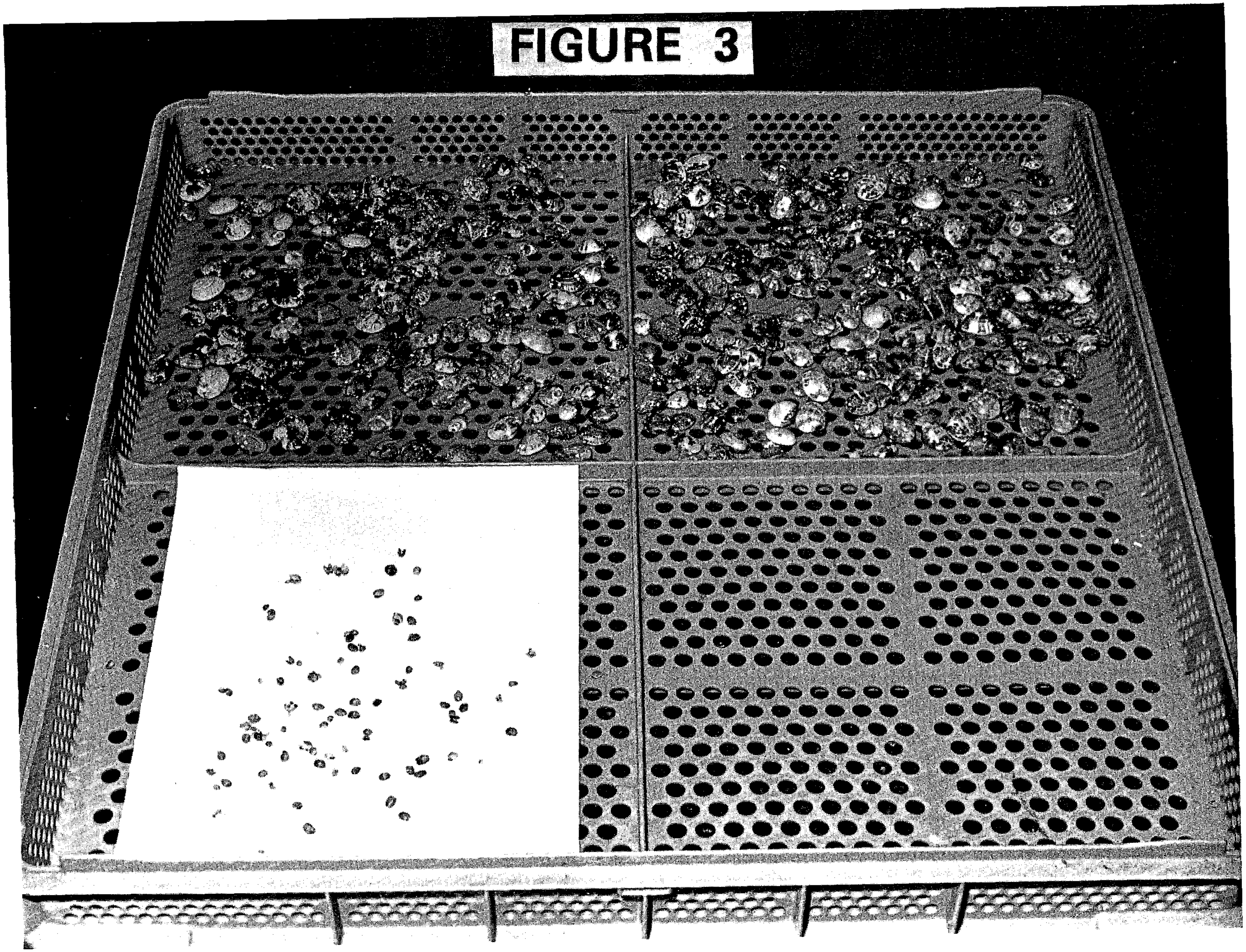
FIGURE 3