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DEMONSTRATION OF CONSTRUCTED WETLANDS FOR TREATMENT OF MUNICIPAL WASTEWATERS, MONITORING REPORT FOR THE PERIOD: MARCH 1988 TO OCTOBER 1989

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Chattanooga, Tennessee

August 1990

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DEMONSTRATION OF CONSTRUCTED WETLANDS FOR TREATMENT OF MUNICIPAL WASTEWATERS, MONITORING REPORT FOR THE PERIOD: MARCH 1988 TO OCTOBER 1989

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August 1990

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EXECUTIVE SUMMARY

A constructed wetland is a manmade, engineered, marsh-like area designed and constructed to treat wastewater. It is an attractive alternative to meet domestic wastewater treatment and water quality needs, especially for small rural communities and developments.

Significant advantages over conventional treatment processes include operation and maintenance simplicity and relatively low capital and operating costs. However, the process is relatively unknown outside the scientific and engineering community. Standardized design criteria are currently not available to engineers and regulators. Also, constructed wetlands require greater land area than conventional mechanical systems.

To become more familiar with the processes, the Tennessee Valley Authority (TVA) in cooperation with the Kentucky Division of Water, Environmental Protection Agency (EPA), and the National Small Flows Clearinghouse (NSFC), implemented a demonstration to investigate and promote the feasibility and benefits of using constructed wetlands for treating domestic wastewater. Three full-scale wetland treatment systems were constructed. Constructed wetlands designs, operation status, and performance are described in this report. Based on the findings, changes in the monitoring plan and operations of each system are addressed.

Monitoring results through October 1989 indicate that the three constructed wetlands are effectively removing five-day biochemical oxygen demand, total suspended solids, and fecal coliforms. Limited nitrification occurred in each wetland during most of the period resulting in

higher than desired ammonia nitrogen effluent concentrations. Other conclusions are presented for compliance, performance, and design, construction, and operation factors based on monitoring results, system operation, and field observations.

DEMONSTRATION OF CONSTRUCTED WETLANDS FOR TREATMENT OF MUNICIPAL WASTEWATERS, MONITORING REPORT FOR THE PERIOD: MARCH 1988 TO OCTOBER 1989

INTRODUCTION

A constructed wetlands is a manmade, engineered, marsh-like area designed and constructed to treat wastewater by attempting to optimize physical, chemical, and biological processes of natural wetland ecosystems. It is an attractive alternative to meet domestic wastewater treatment and water quality needs, especially for small rural communities and developments.

Potential advantages of constructed wetland treatment are relatively low capitol and operating costs, consistent compliance with permit requirements, and operational and maintenance simplicity. However, there are also potential disadvantages. Constructed wetlands require greater land area than conventional mechanical systems, the process is relatively unknown outside the scientific community, standardized design criteria are not available to engineers and regulators, and for surface flow systems, mosquito control will probably be needed.

To evaluate the constructed wetland technology, the Tennessee Valley Authority (TVA) implemented a municipal wastewater demonstration project in western Kentucky. Using combined city, State, and TVA appropriated funds, three constructed wetland systems were built at Benton, Hardin, and Pembroke, Kentucky. Demonstration objectives include evaluating relative advantages and disadvantages of these types of systems; determining permit compliance ability; developing, evaluating,

and improving basic design and operation criteria; evaluating cost effectiveness; and transferring technology to users and regulators.

A demonstration monitoring project was implemented with a partnership of funds from the Environmental Protection Agency (EPA) Region IV, other EPA funds through the National Small Flows Clearinghouse (NSFC), and TVA appropriations. TVA is managing the project in cooperation with an interagency team consisting of EPA, Kentucky Division of Water, and NSFC.

This report, which supersedes the first monitoring report (Choate, et al., 1989) of these demonstration projects, describes each constructed wetland system, its status, and summarizes monitoring data and plans for each system.

DESCRIPTION OF CONSTRUCTED WETLANDS

Benton, Kentucky

A wetlands with a design capacity of 1 million gallons per day (mgd) was constructed at Benton, population 5000, to upgrade and polish effluent from the existing lagoon. The original 2-cell (series) 26-acre lagoon system was frequently hydraulically overloaded and National Pollutant Discharge Elimination System (NPDES) permit limits (table 1) for various parameters were occasionally exceeded. The 10-acre secondary lagoon was modified into a 3-cell (parallel) constructed wetland, designed to receive effluent from the primary 16-acre lagoon. The design is summarized in table 2 and illustrated in figure 1. The three cells are equally sized. Cell 3 was designed to operate as a subsurface flow

system with 50 percent of the total flow. Cells 1 and 2, surface flow systems, were to receive 25 percent each.

Each cell contains different combinations of substrates and plants (table 2). Cells 1 and 2 have substrates of native clay to provide surface flow. Cell 1 was planted with mostly Typha latifolia L. (cattail) along with a few decorative plant species including Iris versicolor L. (iris), Sagittaria latifolia Wild. (arrowhead), and Acorus calamus L. (sweetflag). Cell 2 was planted with Scirpus cyperinus (L.) Kunth (woolgrass bulrush), Scirpus validus Vahl. (softstem bulrush), and cattail. Cell 3 has an average of two feet of gravel substrate to provide subsurface flow and is planted with softstem bulrush. Volunteer species in the wetlands include Typha angustifolia L. (narrow leaf), Phragmites australis (Cav.) Trin (common reed), sweetflag, Lemna minor L. (duckweed), and Polygonum (smartweed).

Operation

The wetlands treatment system began operating in January 1987, with all flow from the lagoon directed to cell 3 (subsurface flow cell) while vegetation was being established in the two surface flow cells. Cells 1 and 2 were put in operation January 1988, each receiving 25 percent of the total flow. Demonstration monitoring began in March 1988.

Gravel filtered the wastewater while vegetation developed in all three cells; however, solids and microbiota accumulated quickly and partially filled the voids in the gravel substrate by late summer 1987, resulting in partial surface flow by the end of the first year of operation. In order to reinstitute subsurface flow in cell 3, the interagency team agreed to redistribute the total flow. In June 1989, flow

to cell 3 was decreased so that 12 percent of total flow was directed to cell 3 and 88 percent evenly distributed into cells 1 and 2.

Two mechanical aerators were installed in the primary lagoon and operated periodically during the summer of 1988 to control lagoon odors. These aerators substantially improved the performance of the primary lagoon.

Some short circuiting occurs within each cell, largely because of uneven elevations in the bottom of the cells, the top of the gravel, and the inlet distribution pipes. Some corrections have been made, including filling low spots in the gravel surface around the periphery of cell 3 during spring 1988, modifying the inlet distributors of cells 1 and 2, and repairing a broken pipe segment in cell 3 during August 1988 (before the plug flow study).

Mosquito populations were occasionally found to be very high in surface flow conditions. Control methods are being tested due to their nuisance and potential public health hazard. The larvicide, Bacillus sphaericus, has been found to be very effective.

Vegetation

Wetlands vegetation was planted in stages from the fall of 1986 to the spring of 1988. As a result, each cell has various age groups of vegetation. Root depths and biomass were measured during the summer of 1989. Root depths were found to be very shallow (4 inches for cattails in cell 1, 9 inches for woolgrass in cell 2, and 3 inches for softstem bulrush in cell 3).

Factors that appear to affect root depth include species and age, water levels, nutrient supply, substrate characteristics, and redox conditions. Root depth is particularly important in gravel cells since roots are believed to be the primary source of oxygen for aerobic bacteria. Roots may also be important for stabilization of long-term permeability of the gravel. Shallow roots in the gravel cell probably result from a combination of the above factors. Water levels could not be progressively lowered as desired due primarily to hydraulic limitations imposed by the inlet clogging. Hydraulic gradients required for subsurface flow were much larger than those available through design (bottom slope) and operation (removal of baffle boards in the effluent water level control structure). Nutrients are probably overly abundant in the wastewater which in combination with the permeable gravel substrate, precludes the need for deep roots for acquisition of an adequate nutrient flux for healthy growth. Also, a highly reducing environment resulting from the organic loading to the cell prior to establishment of the plants may discourage deep root penetration. These factors suggest that root depth can be more readily established prior to sustained wastewater loading. If practical, new systems should be allowed at least one growing season to establish the root zone prior to sustained loading. Also, improved design criteria for hydraulic and organic loading should minimize most of the problems identified above that may be restricting root depth. However, even with restrictions removed through improved design, better information is needed for optimal plant management. For example, what are acceptable rates and guidelines for lowering water levels to encourage deeper root penetration without overly stressing

plants? If root depth is increased through water level manipulation, will root depth be sustained over the long-term? What are reliable estimates for the quantity of oxygen "leaked" to the root zone? Are roots (live and dead) important for stabilizing long-term permeability and, if so, to what extent? These aspects are controversial and need resolution.

Water depth affected vegetation in the surface flow cells. Shallow water species such as woolgrass and cattail cannot withstand sustained deep water conditions (greater that 12 to 18 inches). Woolgrass planted in cell 2 has gradually disappeared except in the shallow front half of the cell. Cattails in the outlet areas of cells 1 and 2 are also less dense, which may result more from predation by muskrats rather than water depth (more than 50 muskrats were removed during the winter of 1989-90). Also, species such as woolgrass depend on seed germination for establishing new plants. Seed germination generally requires ideal conditions (typically mudflats rather than sustained flooding). Special operations would be needed to obtain these conditions for a constructed wetland, and these types of operation are undesirable if they can be avoided. Woolgass has almost disappeared in the deeper lower half of the cell and remain in isolated clumps in the shallow upper half. Rhizome species (softstem bulrush, cattail, reed, arrowhead, etc.) are typically spreading rapidly.

In July 1988, the Marshall County Health Department sprayed the wetlands for mosquitoes. Insecticides (Malathion and Sevin) chemically burned most of the wetland vegetation and killed a portion of the invertebrate population, but the system recovered quickly with no apparent long-term effects.

Hardin, Kentucky

A 0.1-mgd gravel-marsh system was built at Hardin, population 545, to polish the effluent from the 0.07-mgd package contact stabilization plant. The existing package plant was overloaded hydraulically by high inflow and infiltration and was physically deteriorated. The NPDES permit limits (table 3) were violated frequently.

The constructed wetland system consists of two equally sized subsurface flow cells that receive equal flow from the contact stabilization plant. The engineering design for the constructed wetlands is summarized in table 4 and illustrated in figure 2.

The cells contain an average depth of two feet of 1/2-inch diameter crushed limestone and river gravel substrate. Subsurface water depth is intended to be about 1 inch below the top of the gravel in the inlet area. A diked hardwood area designed for storage capacity of 1.5 million gallons is used to manage excessive inflow and infiltration entering the collection system during storm events. Excessive stormwater is diverted to the hardwood area and then slowly released to the treatment system after stormflows subside. Alternately, the water stored in the hardwood storage area is sampled and released to Martins Creek if it complies with NPDES permit limits.

Each cell has the same substrate, river gravel and limestone, but different plants. Cell 1 was planted with common reed. Cell 2 was planted with softstem bulrush. Volunteer species, such as smartweed, has also established.

Operation

The wetlands system began operating and demonstration monitoring began in October 1988. Solids flushed from the contact stabilization plant partially clogged the front portion of the two cells. The solids are activated sludge floc carry-over from the final clarifier, and they will be a persistent problem with the system. Solids result primarily from sludge bulking caused by several conditions including inadequate oxygen in the activated sludge system and improper sludge recycle and wasting operations. High flows during rainy periods exacerbate the carry-over problem. The Kentucky Division of Water's Comptrain Team performed a detailed evaluation of the facility in July 1989, resulting in a major rehabilitation of the package plant which is partially completed. Operational assistance is also being provided by the Purchase Area Development District.

Operation of the wetland cells were intermittent during this reporting period due to the need to replant each cell. Details are provided in the next section.

Operation of the hardwood storage facility has not been accomplished as planned. Generally, the water has been allowed to stay much longer than desired before manually draining back to the package plant pumping station. Also, design errors resulted in a higher outlet structure elevation than the back end of the facility, causing continuous flooding of this area until modifications were made in the fall of 1990. Combination of these problems resulted in loss of some hardwoods.

Vegetation

Vegetation was planted in October 1988 but by spring, survival percentages were very low. Poor survival results from water depths that occasionally topped the new plants during rainy periods and dropped below the root zone during dry periods (site operators incorrectly used valves rather than adjustable standpipes for water level control), a large layer of solids (up to 6 inches deep) that accumulated in the front quadrant of the cells, anaerobic conditions, and perhaps winter kill of young plants. Cell 2 was replanted with softstem bulrush in May 1989, and cell 1 with common reed in August 1989. All flow was routed to cell 1 from March to June 1989, to stabilize accumulated solids in cell 2 and help establish the newly planted bulrush. Survival of the bulrush was successful although extreme water level fluctuation due to improper operation of the water control devices severely stressed the plants during late summer. Survival of the replanted common reed was still poor and the cell was again replanted in June 1990.

Pembroke, Kentucky

A wetland with a capacity of 0.09-mgd was constructed at Pembroke, population 1100, to treat the wastewater from the existing 0.07-mgd contact stabilization package plant. This plant was routinely violating NPDES permit limitations (table 5) and the city was under order by EPA to upgrade the treatment system. The constructed wetland is a marsh-pond-meadow system. The design is summarized in table 6 and illustrated in figure 3. The system consists of two parallel and independent systems,

each having in series two parallel marsh cells, a pond, and a meadow. Designs of the two systems are the same except for substrates and marsh vegetation. System A was constructed with gravel substrate in the marsh and meadow cells to provide subsurface flow. System B was constructed with natural clay to provide surface flow.

Operation

After the wetland system began operating and before planting vegetation, the actual base flow was found to be substantially less than the design flow. It was decided to use only one of the two systems, and the surface flow system was chosen (system B). The constructed wetlands began receiving effluent from the existing plant in October 1987. The system filled slowly because of low flows, large capacity of the pond, evaporation, and seepage from the pond (the major factor). Seepage within the system still appears to be significant although the ponds were repaired by adding clay and bentonite to exceed a permeability specification of 10^{-6} cm/sec. A relatively small sinkhole formed in the bottom of the unused pond of system A in November 1988, and the same forces could be affecting the used pond. A hydrologic mass balance of the system was performed using hydrologic information collected during a dye study conducted on March 19 through 23, 1989, to determine the permeability in the used pond. The calculated permeability indicates water is seeping approximately 5 times faster than before addition of clay and bentonite and 200 times faster than the design permeability. However, visual observations during 1990 indicate that meadow effluent flows are higher than during 1989, suggesting that the pond may gradually be sealing.

The effective operational date was December 1988; however, flow was diverted to the gravel system during April and May 1989 during a third attempt to establish Phalaris arundinacea L. (reed canary grass) in the meadow. Demonstration monitoring began in December 1988.

Vegetation

Cattails and softstem bulrushes were planted in the system B surface flow marshes in August 1988. The planting was successful in both marshes. The pond was seeded with duckweed which multiplied rapidly. Reed canary grass was sown three times in the meadow, but the species never became established. Natural vegetation including Panicum dichotomiflorum Michx. (fall panicum) and smartweed established independently in the meadow and has become dense.

MONITORING STRATEGY

Influent and effluent samples were initially collected monthly at each site. After reviewing the data, the interagency team recommended semimonthly nitrogen samples starting May 1989. Influent samples were proportioned to flow with an automated sampler. Monthly and semimonthly sampling locations are shown in figures 1, 2, and 3. Effluent wastewater samples were grab samples. Continuous flow meters at each weir control structure recorded instantaneous and cumulative flows through each cell. Reported flow measurements are 24-hour averages for the sample collection period. Substrate temperature was measured within each constructed wetland cell.

Dye studies were performed at the Benton and Pembroke constructed wetland providing information on flow patterns and spatial wetland performance. Dye was added to the wastewater at the flow splitter box and distributed between the cells. Dye concentrations were monitored at transects located in each cell as shown in figures 1 and 3. Each cell had transects containing sampling points (standpipes in the gravel cell and markers in the surface flow cells). Equal volumes of wastewater were pumped continuously from each location and analyzed for fluorescence with a computer system. A composite of the sample points across a transect was collected by automatic samplers when the peak dye concentration was detected at the transect. After the dye peaked at the first transect, automatic samplers were moved to the next transect, and the process was repeated.

As described in the workplan (TVA, 1988), laboratory and field parameters for the monthly, semimonthly, and dye study samples collected by TVA Field Engineering and analyzed by the TVA Environmental Chemistry Laboratory (EC) included:

Laboratory	Field
Five-day biochemical oxygen-demand (total)	Oxidation reduction potential (semimonthly)
Five-day biochemical oxygen demand (soluble) (dye study only)	Temperature (semimonthly)
Total suspended solids	
Organic nitrogen (semimonthly)	Flow (semimonthly)
Ammonia nitrogen (semimonthly)	
Nitrate nitrite nitrogen (semimonthly)	pH (semimonthly)
Total kjeldahl nitrogen (semimonthly)	Dissolved oxygen (semimonthly)
Phosphorus (total)	Conductivity (semimonthly)
Phosphorus (soluble) (dye study only)	Alkalinity (semimonthly)
Fecal coliform bacteria	

The analytical procedures used by EC are approved by regulatory agencies or standard-setting organizations. EC uses basic quality control techniques published in EPA's Handbook for Analytical Quality Control in Water and Wastewater Laboratories.

RESULTS

Benton

Data for twenty months (March 1988 through October 1989) of demonstration monitoring at the Benton, Kentucky, project has been evaluated. Results from the monthly and nutrient semimonthly data and four dye studies are used to summarize the performance of the constructed wetlands. TVA's monthly and semimonthly concentrations of each cell (table 7) and the total system (all three cells) (table 8) are summarized in table 9 and compared to NPDES summer (May through October) and winter (November through April) periods. The city of Benton's NPDES compliance data are also summarized in table 9 and compared to TVA data. TVA data for the total effluent concentrations were determined by flow-weighting the effluent concentrations of each cell. Performance of each cell and NPDES season are compared by average percent removals for each season (summer and winter) using mass loadings (tables 10 through 12). Performances within each wetland cell are summarized by using results from four dye studies (table 13 through 16). Concentration of key parameters as the wastewater moves through each cell is illustrated for all dye studies in figures 4 through 12.

Hydraulics

The August 1988 dye study was conducted while one-half of the total flow was entering cell 3 and the other half was equally split between cells 1 and 2. During this study, significant surface flow was occurring in cell 3, the gravel cell, because of partial clogging of voids in the gravel from solids filtered out of the lagoon effluent and micro-biological growth in the gravel. As a result, a flow redistribution was made with 12 percent of the total flow entering cell 3 and 88 percent equally split between cells 1 and 2. The June 1989 and the two September 1989 dye studies were conducted with this new flow distribution with only a small portion of surface flow in the front of cell 3.

Dye flow patterns during these studies were similar for cells 1 and 2. In the first quarter of surface flow cells 1 and 2, most of the wastewater traveled through the left (west) side of the cells which contains the deepest water due to not obtaining a zero lateral slope of the cell beds during construction. Flow distribution improved greatly as the wastewater traveled through the cells. This same flow pattern occurred during all dye studies even though the percentage of flow to cells 1 and 2 and plant densities were greater following the first study (August 1988).

In cell 3, flow traveled through the left (west) side in the first quarter, perhaps due to uneven grading as occurred in cells 1 and 2, although this has not been substantiated. Flow was dispersed more uniformly after the first quarter, but some lagging occurred along the right (east) bank. After the second quarter, wastewater was evenly distributed across the cell. The decrease percent of total flow entering

cell 3 in subsequent dye studies did not affect the flow pattern found in the August 1988 dye study.

Theoretical detention times versus measured detention times are presented in table 17. Measured detention times were similar for cells 1 and 2 and shorter than theoretical detention times, reflecting short circuiting in the front half of each cell. Wastewater traveled rapidly through cell 3 in the first dye study (August 1988). During this study, a large percentage of flow was surface flow; as a result dye concentrations measured represented the surface flow component more than the subsurface flow component. Measured detention times of the other dye studies which reflect cell 3 operating primarily as a subsurface flow system were much closer to and in two cases (the September dye studies) were longer than the theoretical times which were based on an assumed average depth and a porosity of 30 percent.

In summary, some short circuiting is occurring in all three cells, especially in the first quarter of each cell. Flow distribution improves greatly after the first quarter of each cell. Measured detention times for cells 1 and 2 were similar and shorter than the theoretical times in all four dye studies. Measured detention times for cell 3 were close to theoretical times when the system was operating as subsurface flow.

Flow distribution data strongly substantiate the need for good construction practices which closely control bed elevations and slopes. Permeabilities of the gravel in cell 3 were calculated using data collected during the two September dye studies and are listed in table 18. Permeabilities were about 16,000 ft/day in the second quarter, 35,000 ft/day in the third quarter, and 53,000 ft/day in the last

quarter. A value for the inlet area (first quarter) could not be determined because the flow rates were still sufficiently high to cause surfacing at the inlet; however, the plotted data (figure 13) indicate the inlet permeability may be very low. Clogging will need to be observed on an annual basis for several years to determine whether permeabilities stabilize or continue to decrease. Dr. Kickuth (Boon, 1985) of Germany suggests that the permeabilities will eventually stabilize at approximately 850 ft/day.

Organic loading is a primary factor contributing to the decrease of porosity in the gravel of cell 3. For the first 14 months of operation, essentially all flow was routed through the gravel cell. No influent data are available for this period, but based on data from March 1988 through March 1989, the biochemical oxygen demand (BOD) loading would have averaged about 150 lb/day during this initial startup period. Unit loading for the inlet cross section would have averaged about 0.52 lb/day/ft^2. Surface flow occurred within the first year under these loading conditions. After cells 1 and 2 become operational, this loading was halved (75 lb/day or 0.26 lb/day/ft^2 for the period March 1988 through March 1989). Following a two-month drying-out period to help reinstitute subsurface flow, the loading was reduced further averaging 15.4/lb/day or 0.054 lb/day/ft^2 from June through October 1989. During this period, surface flow occurred only in the inlet area (the first 100 to 200 ft of the cell) during normal flows (flow averaged 68,500 gpd or, on a unit hydraulic basis, 238 gpd/ft^2 for the inlet cross-sectional area). Based on this information, unit loading rates of 0.05 lb BOD/day/ft^2 organic and 200 gpd/ft^2 hydraulic probably approach those required to minimize surface flow in gravel cells; however, they

need to be refined, verified, and correlated. Since flow capacity of the gravel and the hydraulic conductivity are directly proportional according to Darcy's law, higher hydraulic rates can probably be used with lower organic rates and vice versa. Partial verification is provided by data from another TVA demonstration site, Phillips High School in Bear Creek, Alabama. This gravel cell has not experienced any sustained surface flow during its first year of operation with inlet unit organic and hydraulic loading rates (HLR) of 0.011 lb BOD/day/ft^2 and 101 gpd/ft^2, respectively. Performance of the small school system has been exceptional for all compliance parameters (Watson, 1990).

Evaluation of NPDES Compliance

Summary data collected by the city and TVA are presented in table 9. Municipal data represent the treated wastewater at the point of final discharge. TVA data represent the treated wastewater from each wetland cell and the total system on a flow-weighted basis. TVA data are before chlorination and aeration (wastewater from each wetland cell flows over a baffle and H-flume before combining at the discharge pipe). The lagoon/constructed wetlands system is much more effective and consistent in meeting the BOD and total suspended solids (TSS) NPDES permit limits than the original lagoon system. Biochemical oxygen demand has not exceeded the permit limit since the wetlands became operational. Total suspended solids has not exceeded the permit limit since after the initial startup period (spring 1988) when vegetation was sparse in cells 1 and 2 and water levels were not stabilized. The pH values for both systems, lagoon and lagoon/constructed wetlands are within the NPDES limit.

Fecal coliform reduction in the wetlands results in effluent concentration approaching the permit limit without disinfection; however, disinfection is still needed to consistently meet the limit. Significantly less chlorine is being used since the constructed wetlands system was put in operation, probably due to the decreased suspended solids and chlorine demanding substances. Overall the compliance percentages are similar for before and after wetlands operation due to the absence of an adequate mixing structure following the wetlands system.

Dissolved oxygen (DO) concentrations for the original lagoon system are not available. However, low summer ammonia nitrogen concentrations (maximum 5.8) of the lagoon indicate that DO was present for nitification. The city's DO data for the lagoon/constructed wetlands average 5 mg/l more than the TVA average DO concentration. This increase reflects reaeration as the wastewater flows over the water level control baffles, the H-flumes, and the discharge pipe. The noncompliance percentage for ammonia nitrogen during summer is greater for the wetlands system than for the original lagoon system. Ammonia nitrogen compliance during the winter improves for the wetlands system and is similar to the original lagoon system. The decreased ammonia nitrogen reduction in the wetlands is believed to be due to suppression of DO throughout the wetlands and the resulting inability to sustain a nitrifying bacteria population. Reaeration will be needed to consistently meet the NPDES limit during summer. Recirculation/aeration schemes are being tested to increase the DO and nitrification.

Total Suspended Solids

The wetland cells were extremely effective and consistent in reducing TSS (table 7). Wetland influent TSS were highly variable ranging from 9 to 120 mg/l with a mean of 57 mg/l. The mean effluent concentrations for cells 1, 2, and 3 were 11, 14, and 5, respectively. Concentrations have not exceeded 30 mg/l except during the spring of 1988 when vegetation was still sparse and water levels were not stabilized.

Removal efficiency trends for each cell were similar (tables 10 through 12). The first winter period had lower removals than the other periods. Percent removed for the other three periods remained relatively constant in each cell. The subsurface flow cell 3 had the best TSS removal (68, 96, 94, and 93 percent) followed by cell 1 (40, 90, 83, and 95 percent) and cell 2 (70, 71, 83, and 85 percent), respectively.

During the August 1988 and June 1989 dye studies, most TSS was removed in the first quarter of each cell and the concentrations then remained relatively constant throughout the remainder of the cell lengths (figures 4a and 4b). During the two September 1989 dye studies, TSS were removed in the first half of cells 1 and 2 and in the first quarter of cell 3 (figures 4c and 4d). Recirculation was occurring in cell 1 during the September 1989 dye studies but similar trends for cells 1 and 2 indicated the increased velocities due to recirculation did not cause TSS to increase. Highest flows in cells 1 and 2 (515,000 gpd each) occurred during the June 1989 dye study, but TSS performance was similar (70 percent or greater removal) during this period as during the lowest flow study (August 1988: 113,000 gpd for cells 1 and 2, each), suggesting little sensitivity to HLR in this range. Cell 3 performance will be

more dependent upon the HLR due to surface flow at higher HLR, but even with some surface flow, the performance should be as good or better than cells 1 and 2.

Five-Day Biochemical Oxygen Demand

Like TSS, all three cells effectively reduced BOD. Influent (lagoon effluent) maximum BOD was 45 mg/l with a 26 mg/l mean (table 7). The BOD effluent ranged from 1 to 25 mg/l with means of 10, 12, and 7 mg/l for cells 1, 2, and 3, respectively (table 9).

Biochemical oxygen demand reductions in all three cells for the summer and winter periods followed the same trend as TSS reductions indicating most BOD is suspended and is removed by filtration and sedimentation. Removal efficiency trends for each cell were similar. Removal was less during the first winter period (1988) in all three cells, illustrating effects of less dense vegetation (vegetation planted in stages during 1987 and spring of 1988) and water levels not stabilized. Percent removed for the other three seasonal periods remained relatively constant in each cell while the HLR varied considerably (tables 10 through 12). This along with the small percentage of influent soluble BOD and removal of suspended BOD in the first quarter of the wetland cells indicate that the cells may have reached their maximum removal efficiency for the water depths used (averaging 1.3 feet in cells 1 and 2 and 1.8 feet in cell 3).

Cell 3 had the best total BOD removal efficiency (table 12), gradually increasing each period (41, 76, 77, and 86 percent for the respective periods). This was mainly due to filtration of suspended

organics within the gravel substrate. The trend for cell 1 (table 10) was similar to that for cell 3 except there was a slight reduction during the last period (35, 72, 76, and 74 percent for the respective periods). Cell 2 (table 11) which has flow equal to cell 1 performed poorer (51, 55, 66, and 62 percent) than the other two cells. This reflects effects of less dense vegetation, allowing more algal and duckweed growth and less filtration. Algae contributes to BOD in the effluent.

Most BOD is removed within the first quarter of each cell regardless of flow rate (or detention time) (figures 5a through 5d). Flows in cells 1 and 2 during the dye studies varied from 113,000 gpd in August 1988 to 515,000 gpd in June 1989. This provided loading rates ranging from 0.0313 to 0.1429 mgd/acre (31.5 to 7.0 acres/mgd), respectively. Most BOD is usually suspended which indicates that settling and filtration are effective removal mechanisms in each cell over a wide range of flow conditions. During the late-September 1989 dye study, most influent BOD was in the soluble form and concentrations in cells 1 and 2 fluctuated until the middle of the cells.

Soluble BOD removal efficiency trends for the NPDES periods (tables 10 through 12) were similar with an exception of cell 3. Reductions in soluble BOD for cells 1 (65, 18, and 54 percent), and 2 (69, 10, and 46 percent) were relatively high during the two winter periods and extremely low during the summer period. During winter months, soluble BOD is higher in the influent and readily removed by microorganisms. Low reduction in soluble BOD during summer months in cells 1 and 2 is believed to reflect low influent concentrations. Removal in cell 3

(52, 53, 68 percent) remains relatively constant, suggesting that internal soluble BOD production (from degradation of filtered suspended BOD including plant detritus, such as wetlands vegetation, algae, and duckweed) in gravel systems compared to surface flow systems is not as great during the summer growing period or is removed within the system.

First-order kinetics were evaluated for soluble BOD removal in cell 1 during the September 19 through October 1, 1989, dye study. The calculated value for k, was 3.76/day, compared to 0.0057/day suggested for surface flow wetlands by other investigators (Reed et al., 1988). The high rate is encouraging but the large disparity between investigators indicates need for more information on reaction rates.

Nitrogen

Total nitrogen (organic, ammonia, and nitrate-plus-nitrite nitrogen) summer and winter removal trends for cells 1 and 2 (table 10 and 11) were similar. Cell 3 reductions were similar to cells 1 and 2 (table 12) during the last two periods (winter and summer 1989). Percent removals for the first period (winter 1988) ranged from 14 (cell 3) to 49 (cell 2) percent. During the last two periods (winter and summer 1989) performance of the gravel cell (cell 3) improved substantially and the range between the cells narrowed from 50 (cell 2) to 55 percent (cell 3) during the summer 1989 period. A reduction of the HLR which occurred in April 1989 contributed to the improved performance in cell 3 along with continuing maturation of the vegetation which may be providing more DO for the nitrifying bacteria.

Pounds of total nitrogen removed in each cell were approximately the same even though cell 3 had 50 percent of the total flow and cells 1

and 2 had 25 percent each during the March 1988 through March 1989 period (figure 14). From March through June 1989 when cell 3 was out of operation, total flow was evenly distributed to cells 1 and 2, and the pounds removed in each cell increased with the increased loading. On June 14, 1989, the highest nitrogen loadings were removed from cells 1 and 2 as organics were flushed from the lagoon due to a large storm event. Flow was directed back into cell 3 in mid-June at a reduced loading. Removals in cells 1 and 2 then remained similar and continued to vary from negative to positive values. Removals in cell 3 fluctuated less under the reduced loading conditions.

Dye studies reveal that reductions in total nitrogen typically occurred through the third quarter of the cell, followed by either relatively constant or increasing concentrations in the final effluent of each cell (figures 6a through 6d). Overall removals should continue to improve as nitrification increases.

Organic nitrogen reduction trends (tables 10 through 12) were similar to trends of TSS and BOD for each cell. Reductions for the first winter period were much lower than the subsequent seasonal periods except for cell 2. Reductions for other periods remained relatively constant for cells 1 (79, 78, and 80 percent) and 3 (86, 85, and 86 percent). Cell 2 removed only 62 percent during the summer 1988 period, but removals approached those of cells 1 and 3 for remaining periods (second winter--74 percent, and summer--79 percent). Cell 3 removes the most organic nitrogen followed by cells 1 and 2. This suggests that most organic nitrogen is being removed as suspended solids. This is supported by the dye study data (figures 7a through 7d) which shows organic nitrogen being removed in the first part of the cells.

Effluent ammonia nitrogen concentrations for all three cells (table 7) and the total system (table 9) have frequently exceeded permit limits. The average ammonia nitrogen concentrations for the specific periods for cell 1 (5.3, 8.8, 5.7, and 9.4 mg/l), cell 2 (6.6, 5.9, 4.5, and 8.5 mg/l), and cell 3 (11.9, 12.5, 5.8, 7.5 mg/l) indicated nitrification was slightly greater in cell 2 than the other cells. However, nitrification in cell 3 has shown improvement in the last two periods which is probably contributed to maturation of the vegetation and reduced loading rates.

Ammonia nitrogen reduction is very complex and must be evaluated with consideration to many factors that affect nitrification. The evaluation is made difficult by the wide fluctuation in influent ammonia nitrogen and organic nitrogen loadings. To eliminate problems typically associated with evaluation of concentration data, performance was first evaluated using pounds removed derived from mass loadings.

Frequently, there was a net production of ammonia nitrogen within each cell (figure 15). Generally, cells 1 and 2 followed the same trend with cell 2 usually having greater removals or less net production. During March through June 1988, there was a net reduction in cells 1 and 2 and a net production in cell 3. The net production in cells 1 and 2 were much lower than cell 3 during March 1988 through March 1989 with an exception of two months. However, during this period cell 3 obtained twice the loading as cells 1 and 2 and cell 3 was converting significantly more organic nitrogen to ammonia nitrogen. July and August of the first summer period and June, July, and August of the second summer period had higher pounds of ammonia nitrogen in the effluent than other months. During the second summer period, the

ammonia nitrogen reduction in cells 1 and 2 was less than cell 3. This indicated the impact of reversing the influent loading rate by increasing flow to cells 1 and 2 and decreasing flow in cell 3. During the last three months (August through October 1989) ammonia nitrogen was being reduced in all three cells. Recirculation and cascade aeration of effluent for cell 1 was initiated on August 23, 1989 to increase DO for better nitrification, but its effects appear to be minimal since trends for cells 1 and 2 remain similar. A greater recirculation ratio and other operating schemes were implemented, beginning June 1990, to attempt to obtain DO concentrations greater than 2 mg/l throughout the cell for effective nitrification.

Pounds of ammonia nitrogen reduced during the summer were generally lower than winter months. During September 1988 through February 1989, the water temperature was much lower; effluent DO was significantly higher; and pounds of ammonia nitrogen in the effluent were much less than other months. However, it was also noted that organic nitrogen influent loading was much less than other months, apparently due to significant ammonification and nitrification within the lagoon. Lower organic nitrogen loading and higher DO levels resulted in improved nitrification. However, during September and October 1989, lower organic nitrogen loading occurred but low DO resulted in high ammonia nitrogen effluent concentrations.

All four dye studies revealed that in the first quarter of each cell, organic nitrogen significantly decreases (figures 7a through 7d) and ammonia nitrogen rapidly increases (figures 8a through 8d). Afterwards, organic nitrogen generally remained relatively constant while ammonia nitrogen began decreasing between the second and third quarter

of the cell length. During three of the four studies (August 1988, September 4 through 15, 1989, and September 19 through October 1, 1989), ammonia nitrogen concentrations continued to decline or remained constant in the last quarter of the cells. These data indicate that nitrification is occurring but is not being completed due to insufficient DO.

Nitrification improved substantially in the gravel cell (cell 3) after reduction of hydraulic and organic loading in April 1989. Although ammonia nitrogen concentrations remain high (averaging 6.8 mg/l for June through October 1989), they are consistently less than cells 1 and 2 for the same period (9.0 and 9.6 mg/l, respectively). Reductions in cell 3 are obvious in the three dye studies conducted during 1989 (figures 8b, 8c, and 8d), especially during the two September studies when nitrate nitrite concentrations also increased in the last quarter of the cell (figures 9c and 9d).

All four dye studies showed that there was very little fluctuation in nitrate nitrite concentrations except in cell 3 (figures 9a through 9d). Even in cell 3, concentrations remain less than 0.5 suggesting that nitrate nitrite added during nitrification is rapidly converted by denitrification.

Fecal Coliform

Fecal coliform bacteria were effectively reduced in all three cells by natural processes (without chemical disinfection). Wetland influent fecal coliform values ranged from 100 to 57,000 colonies/100 ml (table 7). Influent geometric means for specific periods (summer 1988, winter 1988, summer 1989, and winter 1989) were 17,146; 3,904; 1,641;

and 10,882 colonies/100 ml. Geometric mean removals for these periods for cells 1 (96, 84, 90, and 68 percent), 2 (99, 98, 98, and 90 percent), and 3 (93, 98, 99, 98 percent) remained relatively constant with an exception of the last period of cell 1, which may be caused by an increase in wildlife. Visual observations indicated that more wildlife (birds and muskrats) were attracted to the cattails and bulrushes in cells 1 and 3, respectively. However, cell 3 (gravel cell) is able to filter most of the bacteria.

Dye studies reveal that removal of most fecal coliforms generally occurred in the first quarter of the cells similar to removal of BOD, TSS, and organic nitrogen. This suggested that most of the coliforms are tied to the suspended material.

Phosphorus

Total phosphorus reductions for summer and winter periods in cells 1 and 2 ranged from 17 to 35 percent (tables 10 and 11). Cell 2 has summer/winter trends with highest removals occurring during summer months which may relate to duckweed coverage. Cell 3 (table 12) performance improved substantially (9 to 53 percent removal) after reduction of flow and reestablishment of subsurface flow. The cells released more phosphorus than that contained in the influent during April 1988 and March 1989, suggesting that decomposition of dead vegetation may be important in the early spring.

Soluble phosphorus reduction trends for cells 1 and 2 (table 10 and 11) were different from cell 3 (table 12). Small reductions (27 to 31 percent) occurred during the summer period, but concentrations increased in cells 1 and 2 during the winter periods. Reductions in

cell 3 were similar (18 and 14 percent) during the last two seasonal periods (summer 1988 and winter 1989). This indicates that removals in cell 3 are probably due primarily to physico-chemical processes within the gravel while those in cells 1 and 2 are related to plant uptake during the growing season.

Dye study data indicate that total phosphorus concentrations in cells 1 and 2 varied as wastewater flows through the cells (figures 10a through 10d). Reductions were small and inconsistent. Soluble phosphorus typically increased within the cells (figures 11a through 11d). However, reductions in both total and soluble phosphorus consistently occurred in cell 3 during each dye study conducted after subsurface flow was reestablished in mid-June 1989.

Dissolved Oxygen

Influent (primary lagoon effluent) DO varied from 0.4 to 19.1 mg/l (table 7). This variation probably resulted from diurnal variation in algal production, water temperature, sampling time, and periodical mechanical aeration. Supersaturated values reflect high algal concentrations in the lagoon. Average influent DO concentrations for four winter and summer periods beginning with winter 1988 were 10, 7.3, 11.7, and 6.5 mg/l.

Seasonal levels of effluent DO for cells 1 (5.6, 0.4, 0.7, and 0.3 mg/l), 2 (6.0, 3.3, 2.9, and 0.5 mg/l), and 3 (2.6, 0.4, 1.9, 0.5 mg/l) were relatively low. Summer effluent DO concentrations of cells 1 and 3 were significantly lower than winter effluent concentrations probably due to reduced solubility flux rates and increased biological reaction rates during summer. These factors are partially

offset in cell 2 by DO produced by algae and duckweed in the open water areas. Effluent concentrations for each period have gradually decreased with time with the possible exception of cell 3. After reduction of flow during mid-June of 1989 and continued maturity of vegetation, average DO concentrations appear to be increasing within cell 3, along with improved overall performance such as nitrification.

Summer dye studies revealed that reductions in DO concentrations have occurred within the front half of the cells (figures 12a through 12d). Recirculation of the effluent and cascade aeration in cell 1 had a very small net effect during the September 4 through 15, 1989 dye study. Oxygen added through recirculation and cascade aeration was quickly utilized within the first quarter of the cell.

Hardin

TVA's monthly sampling data for each cell are presented in table 19. Effluent data based on flow proportioned calculations for combined effluents from the two gravel cells are contained in table 20. Data are summarized with respect to NPDES permit compliance (table 21). Influent and effluent mass loadings illustrated in figures 16 through 22 are used to compare performances of the wetland cells (tables 22 and 23).

Hydraulics

Influent flow fluctuated from 47,900 to 333,100 gpd (table 19). This provided a wetlands HLR of 0.0299 to 0.2439 mgd/acre (33.4 to 4.1 acres/mgd) for the gravel cells. The highest HLR of 0.2439 mgd/acre (4.1 acres/mgd) occurred in cell 1 when cell 2 was out of operation.

High flows were related to storm events and excessive infiltration/inflow entering the system. Water levels in the wetland cells fluctuated significantly as attempts were made to dry sludge accumulated on the beds from overflow of the mechanical treatment plant, protect newly planted vegetation, and encourage roots to grow deeper within the gravel. Also, use of emergency shutoff valves rather than adjustable standpipes resulted in water levels being too high during rainy periods and too low during dry periods. All flow was routed to cell 1 during the period of March through May 1989 when cell 2 was being dryed and replanted.

Inlet plugging, causing significant surface flow, occurred within weeks after the system became operational, primarily due to the solids washout from the package plant sealing the surface of the gravel. Under normal baseflow conditions, surface flow occurs in the initial 100 ft of bed length. Hydraulic inlet cross-sectional loading rates for the monitoring period (October 1988 through October 1989) have averaged 720 and 525 gpd/ft^2 for cells 1 and 2, respectively. Organic inlet cross-sectional loading (which contributes to clogging) have averaged 0.34 and 0.30 lb BOD/day/ft^2 for cells 1 and 2, respectively.

Evaluation of NPDES Compliance

Summary data collected by the city and TVA are presented in table 21. Municipal data represent the treated wastewater at the point of discharge to Martin's Creek while TVA data represent the treated wastewater that has just exited the wetlands cell before aeration of the wastewater flow over the rotating standpipes.

The use of constructed wetlands has reduced noncompliance for BOD, TSS, and winter ammonia nitrogen and increased noncompliance for summer

ammonia nitrogen and DO. Compliance with the fecal coliform limit has been roughly equivalent to prewetland levels; however, no chlorination has occurred after the wetlands were placed in operation. No problems exist with compliance for pH either before or after wetlands.

Based on TVA data, the NPDES monthly average BOD permit limit of 10 mg/l was exceeded only during February through May 1989 in cell 1 and February 1989 in cell 2. These excursions occurred with the highest HLR during intensive rainfall periods and without benefits of a good stand of vegetation. After cell 2 was back in operation, no excursions beyond the permit limit have occurred. Total suspended solids concentrations during March and August 1989 in cell 1 and June 1989 in cell 2 exceeded the monthly average NPDES permit limit of 30 mg/l. However, each excursion occurred during the replanting period for the bulrushes and reeds when all flow was diverted to only one cell.

Improved performance is anticipated as vegetation matures, package plant upgrades are completed, and operational procedures improve.

Total Suspended Solids

The wetland cells were extremely effective in reducing TSS. Wetland influent TSS were highly variable ranging from 30 to 470 mg/l with a mean of 125 mg/l (table 19). Effluent concentrations ranged from 1 to 95 mg/l with means of 20 and 10 mg/l in cells 1 (common reed) and 2 (bulrush), respectively. It is believed that cell 2 had a significantly better mean effluent concentration due to its much better stand of bulrush than reed in cell 1. Concentrations greater than 30 mg/l were infrequent, occurring in August 1989 in cell 1 and June 1989 in cell 2. Each excursion occurred during periods when all flow was diverted to

only one cell. There was little difference between performance of each cell when operations were stabilized (figures 16a and 16b). With an exception of some months the system's operations were variable, removal of TSS did not appear to be dependent upon HLR (figures 23a and 23b). Lower percent removals in some months were due to very low influent concentrations.

Five-Day Biochemical Oxygen Demand

Both cells effectively removed BOD. Influent BOD ranged from 11 to 180 mg/l with a mean of 54 mg/l (table 19). Effluent BOD ranged from 1 to 38 mg/l (table 21). Concentrations were greater than 10 mg/l during February through May 1989 in cell 1 and in February 1989 in cell 2. These excursions occurred during high HLR caused by intensive rain events (February) and directing all flow to cell 1 while vegetation was scarce (March through May). The performance of each cell was similar when both were operational (figures 17a and 17b). Removal efficiencies appeared to depend on HLR (figures 24a and 24b). For example, in both cells, lowest removals (50 to 65 percent) occurred at the highest HLR 0.125 to 0.25 mgd/acre (8 to 4 acres/mgd), or while highest removals (80 to 99 percent) occurred at HLR ranging from 0.0303 to 0.1 mgd/acre (33 to 10 acres/mgd). Three months of relatively low removals (65 to 75 percent) occurred with extremely low influent concentrations. This indicates that effluent concentrations will be consistently low (less than 20 mg/l) at HLR of 0.1 mgd/acre (10 acres/mgd) or less.

Influent soluble BOD ranged from 11 to 67 percent of total BOD while effluent soluble BOD ranged from 57 to 100 percent of total BOD. This again substantiates the fact that most suspended BOD is filtered

and settled out as wastewater moves through the wetland cells. However, bacterial metabolism was also an important removal process because influent soluble BOD was significantly reduced in each wetland cell. Average removals for cells 1 and 2 were 61 and 44 percent, respectively (tables 22 and 23). This occurred when vegetation did not play a practical role.

Nitrogen

Total nitrogen removal (tables 22 and 23) averaged 47 and 52 percent for cells 1 and 2, respectively. Performance of cells 1 and 2 was similar during the first five months of the study period, October 1988 through February 1989 (figures 18a and 18b). Percent removed remained relatively consistent with previous months while influent and effluent loadings increased substantially during the period when all flow was routed to cell 1 in order to replant cell 2 (March through May 1989). Upon returning to operation, cell 2 outperformed cell 1. During this period, much of the flow in cell 1 was surface flow due to clogging from solids washed out of the existing treatment plant. Drying and replanting rejuvenated cell 2, resulting in predominately subsurface flow and improved performance. Performance of cell 1 also improved substantially after drying the surface sludge and replanting (mid-August through mid-September). Removals during this initial monitoring period varied widely regardless of the loading rate.

Removal of organic nitrogen was relatively high (table 22 and 23), averaging 85 and 82 percent for cells 1 and 2, respectively. Both cells usually performed similarly (figures 19a and 19b). Effluent concentrations were relatively constant even though influent concentrations varied largely (table 19).

Ammonia nitrogen reduction was very low, averaging only 6 and 3 percent for cells 1 and 2, respectively, based on influent ammonia nitrogen loadings. Since these values do not consider the organic nitrogen converted to ammonia nitrogen within the cells, actual reduction percentages are higher, but desired level of nitrification is still severely limited. The probable limiting factor is again DO which was typically less than 1 mg/l in the effluents. After cell 2 was replanted, it consistently outperformed cell 1 (figures 20a and 20b), possibly indicating that the more dense vegetation in cell 2 was indeed increasing desired oxygen to the nitrifiers or cell 2 had time to rejuvenate while out of operation.

Fecal Coliform

Influent fecal coliform bacteria ranged from 30,000 to 500,000 colonies/100 ml, with a geometric mean of 176,000 colonies/100 ml (table 19). Fecal coliform bacteria removals in the wetland cells were very high for each cell, averaging more than 99 percent. Geometric means for effluent fecal coliform bacteria were 1200 and 260 colonies/100 ml for cells 1 and 2, respectively. Overall, cell 2 removed more bacteria than cell 1 because cell 2 had more dense vegetation, and did not experience as high HLR as cell 1. Even though removals were very high, the effluent counts still routinely exceeded 200 colonies/100 ml, the NPDES monthly permit limit.

Phosphorus

Total phosphorus removal in cells 1 and 2 were similar. Total phosphorus influent concentrations ranged from 0.6 to 11.8 mg/l

(table 19). Influent loadings were less during the summer months. For both cells, percent removal was not affected by the HLR.

Moderate removal of phosphorus occurred within the wetlands (tables 22 and 23). Removals averaged 55 and 47 percent in cells 1 and 2, respectively. Each cell performed similarly until all flow was diverted to cell 1 (figures 21a and 21b). After flow to both cells was reinitiated, the performance of each is again becoming similar.

Generally, most phosphorus was soluble. Removal of soluble phosphorus was in the same range as that for total phosphorus, averaging 48 and 53 percent for cells 1 and 2, respectively. This indicates that chemical and/or biological removal mechanisms are important in addition to the physical processes of filtration and sedimentation. Each cell performed similarly (figures 22a and 22b).

Dissolved Oxygen

Influent DO loadings were higher during the colder months, November 1988 through March 1989 (tables 22 and 23) for two of the months in cell 1 and only one month for cell 2. Except for the initial operation period, DO was depleted to less than 1 mg/l in both cells (table 19), which limited nitrification.

Pembroke

TVA's monthly concentrations are presented in table 24. Effluent data are summarized with respect to NPDES permit compliance in table 25. Performance within each cell is summarized by using dye study results (table 26). Concentration of each parameter as the wastewater moves through the system is presented in figures 25 through 30.

Hydraulics

Influent flow fluctuated from 40,000 to 170,000 gpd, averaging 76,000 gpd (table 24). This provided HLR of 0.0420 to 0.1923 mgd/acre (23.8 to 5.2 acres/mgd) for the two surface flow marshes. High flows were related to storm events and excessive infiltration/inflow entering the system. Due to the significant seepage in the pond and evapotranspiration, effluent flows continued to be much lower than influent flows, averaging only 24,000 gpd. Assuming effluent flow equals meadow influent flow, HLR was determined to range from 0.0036 to 0.2041 mgd/acre (275.0 to 4.9 acres/mgd) in the meadow.

A dye study was conducted during March 19 through 23, 1989, to determine the performance within the system and the permeability in the used pond (pond 'B'). The study revealed that the flow traveled through the bulrush marsh B1 (68.7 hours), which contained more dense vegetation, much slower than the cattail marsh B2 (54.6 hours). The detention time in the pond was only 22 hours, indicating short circuiting. In the meadow, most of the wastewater traveled along the left (east) side of the cell.

The permeability of the pond's clay liner determined from hydrologic information obtained during the dye study was substantially less than the calculated permeability derived before attempting to repair the leaking ponds. Therefore, concentrations instead of mass loadings are used to discuss the performance of the system.

Evaluation of NPDES Compliance

Summary data collected by the city and TVA are presented in table 25. Municipal data represent treated wastewater from the package

plant including chlorination at the point of discharge prior to constructed wetlands operation. The city discontinued collecting NPDES compliance data once wastewater was routed to the constructed wetlands.

The constructed wetland system substantially reduced noncompliance for BOD, TSS, and ammonia nitrogen and increased noncompliance for fecal coliforms and DO. No problems exist with compliance for pH either before or after wetlands.

Biochemical oxygen demand concentrations did not exceed the permit limit of 10 mg/l except in March and June 1989 which were immediately before and after planting the meadow and reflect effluent quality without significant vegetation in the meadow. No TSS noncompliances have occurred since the wetlands system became operational. Also, no noncompliances for winter ammonia nitrogen have occurred, but three (June, September, and October) of the six summer months exceeded the ammonia nitrogen summer limit of 4 mg/l.

High ammonia nitrogen concentrations in September and October are believed to be related to low DO concentrations. Dissolved oxygen concentrations were less than the permit limit of 7 mg/l during June, August, September, and October 1989. Fecal coliforms exceeded the permit limit of 200 colonies per 100 ml in all samples except one (February 1989); however, chlorination has not been used since the wetlands became operable.

Overall, performance at the Pembroke constructed wetlands is very encouraging. Performance should improve for all parameters as vegetation matures and other changes are made. A factor that could negate the positive effects of a maturing system is the high solids discharged from the package plant (see the following section). Also, additional treatment

after wetlands may be needed to consistently meet fecal coliform and DO limits during summer; however, these facilities are typically reliable and relatively inexpensive.

Total Suspended Solids

Wetlands were extremely effective and consistent in reducing TSS. Wetland influent TSS were highly variable ranging from 42 to 170 mg/l with a mean of 92 mg/l. The mean effluent concentration was 8 mg/l and the maximum value was only 17 mg/l. Average removal was 91 percent.

Most solids were removed within the marshes. The cattail marsh (B1) produced slightly better effluent concentrations than the bulrush marsh (B2), averaging 22 and 15 mg/l, respectively. Most suspended solids were removed in the first half of the marshes (figure 25). The pond effluent concentration slightly increased from the marshes effluent, probably due to algae and duckweed produced in the pond. The meadow performed as a polishing system removing suspended solids as the wastewater traveled through it.

High influent concentrations due to poor performance of the package treatment plant represent a potential problem for the wetlands system. Solids are rapidly removed in the marshes, but the marshes are also being prematurely filled, and long-term degradation of the organic portion of the solids places an added burden upon the marshes. Future monitoring will determine the overall impact of solids on the performance of the system.

Five-Day Biochemical Oxygen Demand

Like TSS, the system effectively reduced BOD (table 24). Influent (contact stabilization package plant effluent) BOD ranged from 22 to

130 mg/l with a 67 mg/l mean. Effluent BOD concentrations ranged from 2 to 24 mg/l, averaging 9 mg/l. Average removal was 86 percent.

Most BOD is removed within the marshes. Mean effluent concentrations for marsh B1 and B2 were 15 and 9 mg/l, respectively, resulting in removal efficiencies of 71 and 83 percent. Similar to the TSS removal, the cattail cell (marsh B1) provided better BOD treatment. Visually, the cattail marsh had more dense vegetation than the bulrush marsh, thus probably providing better filtration of solids.

Soluble BOD was analyzed only during the first four months (table 24). Soluble BOD ranged from 20 to 50 percent of total BOD in the influent and 17 to 50 percent in the effluent, indicating that most BOD in domestic wastewater is usually suspended. Average removal was 88 percent.

Influent BOD concentration during the dye study was much lower than the monthly mean. Total BOD concentrations increased in the first quarter (probably due to degradation of settled sludge in the inlet area), drastically dropped in the second quarter, and remained relatively constant through the rest of the marsh, pond, and meadow (figure 26). The largest portion of soluble BOD was removed in the marshes. Very little removal occurred in the pond. Concentrations were slightly reduced in the meadow (which had very little vegetation at the time of the dye study). Performance of each marsh was similar for soluble BOD removal.

Nitrogen

Total nitrogen removal was relatively good, averaging 81 percent. Total nitrogen influent concentrations varied from about 14 to

97 mg/l having a mean of 31 mg/l while meadow effluent concentrations only varied from 2.5 to 13 mg/l having a mean of 6.3 mg/l. Most of the reduction occurred in the marshes. Marsh B1 removed 53 percent and marsh B2 removed 48 percent. There was little difference in monthly performance of the two.

The dye study confirmed the above findings, but the study also revealed that removal was still occurring at the end of the marshes (figure 27). Flow through the pond resulted in a slight increase followed by continued removal in the meadow.

The composition of total nitrogen entering the wetland system is dependent on performance of the package treatment plant. In five of nine monthly samples, ammonia nitrogen was the predominant form while organic nitrogen was predominant the other four months.

Organic nitrogen reduction was relatively high, averaging 90 percent. Effluent concentrations for both the marshes and meadow varied little. Practically, all reduction occurred in the marshes, where effluent concentrations averaged 2.7 and 3.6 mg/l for marsh B1 and B2, respectively. Average meadow effluent concentration was 1.8 mg/l.

During the dye study, organic nitrogen concentration in the wetlands influent was relatively low (7 mg/l). The marshes reduced the concentrations to 3.2 mg/l in marsh B1 and 2.3 mg/l in marsh B2, but concentrations increased in both the pond and meadow, resulting in a final effluent value of 5.9 mg/l (figure 28). The increases may have been related to the production of algae and duckweed in the pond and meadow (which had very little vegetation during this period).

Ammonia nitrogen removal was also relatively high, averaging 73 percent (neglecting production from removal of organic nitrogen). Monthly effluent concentrations ranged from 0.2 to 12.0 mg/l. Concentrations during the winter NPDES period were below the limit, 10 mg/l, but concentrations during June, September, and October exceeded the NPDES permit limit of 4 mg/l. During September and October 1989, ammonia concentrations in the marsh effluents were high, and DO concentrations were significantly lower in the meadow effluent than previous months (table 24), indicating that low DO may be limiting nitrification.

Dye study results during March 1989 revealed that ammonia nitrogen increased from 10 to 18 mg/l in the first quarter and gradually decreased to 2 mg/l as the wastewater moved through the system (figure 29). All components reduced ammonia nitrogen.

Fecal Coliform

Fecal coliform bacteria were effectively removed in the wetland system. The wetland influent fecal coliform values were relatively high varying from 6,100 to 740,000 colonies/100 ml (table 24). Influent and effluent geometric means were 166,000 and 266 colonies/100 ml, respectively.

Dye study results revealed that most of the fecal coliform bacteria were being removed within the first quarter of the marshes (figure 30); however, the bacteria continued to gradually decrease as the wastewater moved through the rest of the system.

Phosphorus

Average phosphorus removal was 47 percent (from 6.0 to 3.2 mg/l). Total phosphorus influent and effluent concentrations fluctuated from 1.9 to 8.6 mg/l and 1.1 to 6.1 mg/l, respectively. There was little difference in performance between the two marshes. Most phosphorus was soluble in both influent and effluent. Average reductions in soluble phosphorus was 57 percent.

During the dye study, 64 percent of influent total phosphorus was soluble. Both total and soluble phosphorus increased in the first quarter of the marshes (probably due to degradation of settled sludge in the inlet area) but gradually decreased as the wastewater continued to travel through the marshes. In the pond, total phosphorus increased while dissolved phosphorus decreased. Total phosphorus (100 percent soluble) decreased in the meadow, resulting in a very small net removal for the system. Soluble phosphorus increased in the first quarter of the meadow and decreased at the effluent. There was a net system increase of 52 percent for soluble phosphorus.

Dissolved Oxygen

Influent DO concentrations were relatively low, averaging 1.8 mg/l. Monthly effluent DO in the marshes was less than 1 mg/l except for October. Effluent DO concentrations in the meadow were relatively high in winter and low in summer.

During the March 1989 dye study, DO increased from 2.3 mg/l at the influent to 4.8 and 4.3 mg/l at the end of marsh B1 and B2, respectively. DO decreased at the end of the pond (1.7 mg/l) and rapidly increased as the wastewater traveled through the meadow (6./1 mg/l).

CONCLUSIONS

Based on monitoring results, system operation and field observations for the demonstration period to date, conclusions are presented below for compliance, performance, and design, construction and operation factors.

Compliance

Constructed wetlands can provide consistent compliance for typical secondary and advanced level permit limits for BOD, TSS, and pH over a wide range of loading rates.

To achieve consistent compliance for ammonia nitrogen, aeration may be needed to provide adequate DO for nitrification after carbonaceous BOD demand has been reduced.

For consistent compliance for fecal coliform, DO, and phosphorus, system configuration and design variables must be carefully selected considering reaction kinetics. Compliance for fecal coliform and DO may be more efficiently achieved with supplemental unit operations following constructed wetlands.

Performance

Measured detention times in surface flow cells were shorter than theoretical detention times. Similar results occurred for gravel cells when a large portion of the flow was surface flow; however, upon reestablishing subsurface flow, measured detention times approached theoretical times.

All three systems effectively removed TSS and BOD. Concentrations exceeded the monthly average NPDES permit limit only during initial operation when vegetation was still very sparse and water levels were not stabilized. Dye studies indicated that TSS and BOD were removed in the first half of the marshes.

During system maturation, there is nominal change in BOD and TSS removal effectiveness.

Ammonification reduced organic nitrogen in all three systems. Nitrification occurred in each system but was limited by available DO. Ammonia nitrogen concentrations frequently violated NPDES permit limits.

Nitrification is beginning to improve in cell 3 (subsurface cell) at Benton due to a combination of factors including vegetation maturation and decreased hydraulic loading.

Denitrification readily occurred in each system. Nitrate-nitrite nitrogen concentrations were typically less than 0.5 mg/l.

All three systems, surface flow and subsurface flow cells, effectively reduced fecal coliform without effluent disinfection. However effluent values were frequently higher than the NPDES permit limit. Plug flow studies at Benton indicated random variability in the data that may be due to TSS and wildlife that inhabit the wetlands. Supplemental effluent disinfection is necessary to consistently meet NPDES limits at these three sites.

Effluent DO from the constructed wetlands cells is usually low, less than 1 mg/l. Most oxygen depletion occurs in the first half of the cells, where most carbonaceous BOD reduction occurs. Although the low BOD effluent reaerates very easily, passive or mechanical reaeration will be necessary to meet most effluent DO limits.

Improved overall performance is anticipated as vegetation continues to mature, operational procedures improve, and package plant upgrades are completed (Hardin).

The diked hardwood storage area of Hardin has been used to effectively manage excessive storm flows, eliminating sewage bypass to the stream.

Loading Rates

Effective suspended pollutants removal will occur even at high hydraulic and organic loading rates. Removals of 70 percent or greater occurred in the front half of the cells at HLR as high as 0.14 mgd/acre (7 acres/mgd).

Short circuiting of both surface and subsurface flow systems and plugging of subsurface flow substrates can be caused by high inlet hydraulic and organic loading rates.

Preliminary conservative inlet hydraulic and organic loading rates for minimizing surface flow in gravel substrates are 200 gpd/ft^2 and 0.05 lb BOD/ft^2, respectively; a higher rate for one may require a lower rate for the other.

The first order kinetics k value for soluble BOD was significantly higher at Benton (3.76/day) than those reported in the literature.

System Type

Surface flow cells are more adaptable and cost-effective for handling high levels of suspended pollutants. However, high solids concentrations can rapidly fill inlet areas and should be removed prior to wetland cells unless the cells are specifically designed as "roughing" wetlands and sludge management and composting units.

Both surface and subsurface flow substrate type systems are effective for BOD and TSS; however, subsurface flow gravel cells are more effective on a unit basis even when partially clogged.

In surface flow cells, natural reaeration is limited by laminar flow and dense vegetation; therefore, available DO is inadequate for high nitrification at demonstration loading rates.

Solids (including plant detritus) which accumulated in both types of systems increase oxygen demands and may adversely affect the systems' ability to nitrify.

Bed Length and Length:Width Ratio

With surface HLR of less than 0.1 mgd/acre (10 acres/mgd), bed lengths for BOD and TSS loadings were conservative for all three projects since most removal occurred in the first quarter to half of the cell lengths.

Even with long and narrow surface flow cells, short circuiting can still be significant due to poor inlet flow distribution, uneven lateral slopes and elevations of the cell bed (caused by poor construction grading), nonuniform vegetation density, and solids and plant detritus deposition.

A bed length to width ratio criterion for gravel systems is inappropriate since it neglects hydraulic concepts. Gravel cell design needs to be based on Darcy's law (or other appropriate hydraulic concepts) which relates flow to hydraulic conductivity of the substrate, hydraulic slope and the area of the cell cross-section, resulting in no standard length to width ratio.

Hydraulic Conductivity

Initial permeability of gravel cells is high. However, permeability will decrease with time due to solids deposition, root biomass, and microbiota. Design should be based on relatively low long range values and lower organic loading for inlet areas.

Darcy's law, which incorporates hydraulic conductivity, is applicable for subsurface flow cells having permeable gravel substrates.

After 21 months of operation the hydraulic conductivity of the Benton subsurface flow gravel cell ranged from 16,000 ft/day to 53,000 ft/day between to 25 and 75 percentile cell lengths. This is significantly greater than Dr. Kickuth's estimated long range 850 ft/day. A representative inlet value should be obtained from 1990 studies.

Construction

Construction is relatively simple but is critical toward the constructed wetlands performance.

Grading tolerances for the bottom of cells and top of gravel need to be within 0.1 ft to minimize short circuiting and assure uniform water depths for vegetation management.

Substrates

Gravel or other porous substrate in subsurface flow systems can become clogged as the result of high inlet organic loadings or high influent solids concentrations. Substrate clogging can be reduced or eliminated by restricting inlet loading rates (see preliminary rates identified above) and reducing excessive influent solids.

Vegetation

More information is needed for optimal plant management.

Although it may not be practical for most sites, vegetation should ideally have at least one growing season before receiving sustained loading.

Vegetation species do not appear to be a significant factor in overall performance under the loading conditions to date for surface flow cells. (The current status of vegetation in gravel cells precludes this type of evaluation.)

Species probably will be important to treat soluble pollutants so that surface area is maximized for bacteria colonization in surface flow systems and maximum oxygen is transferred to the root zone of subsurface systems.

Emergent vegetation such as cattail, bulrush, and reed establish and spread quickly under ideal conditions related to season and water depth (i.e., plant early spring to midfall; maintain 1 to 2 inches water depth above top of substrate, never topping stems of young plants).

Cattails, bulrush, and reeds are surviving and spreading in high solids deposition areas but probably not nearly as good as in low solids areas.

Cattails and woolgrass do not appear to be appropriate choices for deep water depths (greater than 12 to 18 inches).

Vegetation root depth in the substrate of subsurface flow cells is still very limited (less than 3 inches in the Benton gravel cell after two growing seasons), probably due to species and age, water levels, nutrient supply, substrate characteristics, and redox conditions.

Reed canary grass is difficult to establish by seeding without being able to carefully control the moisture condition of the substrate.

Species that spread by rhizomes and roots are better for surface flow systems since they spread quickly and do not require water level manipulation to germinate seeds.

Some vegetation species such as woolgrass have not spread and have even decreased in the surface flow cells, probably due to high water levels for the specific species and not creating the necessary seed germination condition.

Local natural wetlands vegetation will also establish in constructed wetlands, providing a variety of vegetation.

Operation

When a constructed wetlands is designed to treat the discharge of a poorly performing package treatment plant as at Pembroke and Hardin, solids will accumulate at the front of the wetland cells. The solids contribute additional long-term pollutant loads (due to resolubilization) that must be removed within the wetland system. The solids will clog the gravel cells as at Hardin where surface flow occurs in the front quarter of the cells. The net effect is a significant reduction in both effectiveness and the life of the cell. Planning, design, and operation of a system must recognize and avoid these potential problems.

Due to poor operation and design of the Hardin hardwood storage area, water remained in the storage area for several months resulting in death of several hardwoods.

Controlling the water level in the wetland cells is critical for proper vegetation management. At Hardin, water level adjustment by using emergency shutoff valves rather than adjustable standpipes contributed to poor vegetation establishment due to too high water levels during stormy periods and too low water levels during dry periods. Practical use of standpipes require easy access or simple mechanical methods for adjustments.

Water levels should be kept very shallow in surface flow systems until plants begin rapid growth and spreading. Depths should never exceed the plant stems.

Water depths in excess of 12 to 18 inches are inappropriate for woolgrass and cattails.

Maintaining water depths 1 to 2 inches above the top of gravel cells helps quickly establish transplants. Solar heating of gravel can stress and kill young plants when water levels are below the gravel surface.

Lowering water depths in gravel cells to stimulate vertical root growth throughout the substrate depth is a suggested procedure; but specific implementation guidelines need to be developed, and effectiveness of the procedure needs to be determined.

Mosquitoes must be controlled in surface flow systems. Larvicide *Bacillus sphaericus* have been tested and found to be very effective.

PLANNED ACTIVITIES

The following modifications and activities are planned for 1990 at the three constructed wetlands based on review by the interagency team guiding the demonstration project:

Postpone monthly monitoring and seasonal dye studies at all three systems while modifications are being implemented and vegetation is maturing.

Benton

Continue using the cascade/aeration apparatus constructed for cell 1. Increase recirculation in cell 1 from a 1:1 to a 5:1 ratio.

Design and install orifices at the influent of cells 1 and 3 to stabilize influent flow. Route excess flow to cell 2.

Decrease water levels in cells 1 and 2 to prevent plant stress and allow quicker recovery from muskrat depredation.

Once DO reaches 2 mg/l in cell 1 effluent conduct dye studies to evaluate nitrification.

Evaluate clogging in cell 3.

Hardin

Continue to assist operators in improving system performance.

Obtain cost estimate on designing and installing orifices at the influent of both cells and diverting excess flow to the existing pond (borrow pit).

Pembroke

Repair sinkhole in the unused pond.

Design and install orifices to stabilize influent flow and route excess flow to the unused gravel marsh system.

If funds are adequate, conduct dye study to obtain more information on k-rates or collect influent/effluent monthly samples during July, August, and September.

Determine modifications necessary to allow the meadow to function in an overland flow mode.

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TABLES

Table 1. Benton, Kentucky, NPDES Permit Limits

Parameter	Monthly Average Limit	
	Winter (November - April)	Summer (May - October)
5-Day Biochemical Oxygen Demand, mg/l	25	25
Total Suspended Solids, mg/l	30	30
Fecal Coliform, colonies/100 ml	200	200
Ammonia Nitrogen, mg/l	10	4
Dissolved Oxygen, mg/l	7	7
pH	6-7	6-7

Table 2. Benton, Kentucky, Constructed Wetland Sewage Treatment System, Gravel and Surface Marshes

Design Flow: 0.048 m^3/s (1,000,000 gpd) average

Pretreatment: Sedimentation and biochemical oxidation in 6.5 ha (16-acre) primary lagoon

Marsh: Secondary lagoon converted to three parallel cells, 1, 2, and 3

Application rate--292 ha per m^3/s (10 acres per mgd)

Total surface area--4.4 ha (10.8 acres), 3 cells equal size

Length/width ratio--7.6:1 each cell

Slope--0.1%

Liner--3.0 to 4.6 m (10-15 ft) in-situ impermeable clay

	Cell 1	Cell 2	Cell 3
Vegetation	*Typha*, *Iris*, *Sagittaria*,	*Scirpus cyperinus*	*Scirpus validus*
Water depth	0 to 0.5 m (0 to 1.5 ft)	0 to 0.5 m (0 to 1.5 ft)	-0.6 to +0.5 m (-2.0 to +1.5 ft)
Substrate	native soil	native soil	46 cm (18 in.) base of 1.9-2.5 cm (3/4"-1") limestone, and 15 cm (6 in) cap of 3/8" - 3/4" limestone

Posttreatment: Chlorination

Table 3. Hardin, Kentucky, NPDES Permit Limits

Parameter	Monthly Average Limit	
	Winter (November - April)	Summer (May - October)
5-Day Biochemical Oxygen Demand, mg/l	10	10
Total Suspended Solids, mg/l	30	30
Fecal Coliform, colonies/100 ml	200	200
Ammonia Nitrogen, mg/l	10	4
Dissolved Oxygen, mg/l	7	7
pH	6-7	6-7

Table 4. Hardin, Kentucky, Constructed Wetland Sewage Treatment System, Gravel-Marshes

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Design Flow: 0.0044 m^3/s (100,000 gpd)

Pretreatment: Comminution; aeration

Marsh: Two parallel gravel marsh cells

Application rate--146 ha per m^3/s (15.8 acres per mgd)

Total surface area--0.64 ha (1.58 acres), 2 cells equal size

Length/width ratio--6.6:1 each cell

Slope--bottom 0.2%
top 0.0%

Vegetation--*Phragmites australis* (cell 1)
Scirpus validus (cell 2)

Liner--15 cm (6 in.) compacted clay

Water depth--+0.3 to -0.6 m (+1.0 to -2.0 ft)

Substrate--0.6 m (2.0 ft) of 1/2 inch crushed limestone and river gravel

Hardwood Storage Facility: storage for excess inflow/infiltration

Capacity--5678 m^3 (1.5 million gallons)

Surface area--0.6 ha (1.5 acres)

Vegetation--Existing trees and planted *Quercus*

Water depth--0.9 m (3 ft) max

Posttreatment: Chlorination and/or aeration added if necessary.

Table 5. Pembroke, Kentucky, NPDES Permit Limits

Parameter	Monthly Average Limit	
	Winter (November - April)	Summer (May - October)
5-Day Biochemical Oxygen Demand, mg/l	10	10
Total Suspended Solids, mg/l	30	30
Fecal Coliform, colonies/100 ml	200	200
Ammonia Nitrogen, mg/l	10	4
Dissolved Oxygen, mg/l	7	7
pH	6-7	6-7

Table 6. Pembroke, Kentucky, Constructed Wetland Sewage Treatment System, Marsh-Pond-Meadow

Design Flow: 0.0039 m^3/s (90,000 gpd)
Pretreatment: Comminution; aeration

Marsh: Two parallel systems, A and B, 2 cells each system
Application rate--185 ha per m^3/s (20 acres per mgd)
Total surface area--0.7 ha (1.8 acres), cells equal size
Length/width ratio--8.2:1 each cell
Slope--0.1%

	System A	System B
Substrate	0.6 m (2.0 ft) sized limestone	Native topsoil
Liner	15 cm (6 in.) compacted native clay	Native clay under bed
Water depth	-0.6 to +0.5 m (-2.0 to +1.5 ft)	3 to 15 cm (0.1 to 0.5 ft)
Vegetation	Cell 1--*Typha latifolia* Cell 2--*Scirpus validus*	Cell 1--*Scirpus validus* Cell 2- *Phragmites australis*

Pond: Two parallel cells, for Marsh A and Marsh B, total volume--9137 m^3 (2.414 MG)

Total area--4249 m^2 (1.05 acres)
Liner--compacted native clay
Depth--2.4 m (8.0 ft)
Vegetation--Duckweed, algae

Meadow: Two parallel systems, A and B, 1 cell each system
Application rate--92 ha per $m^{3/s}$ (10 acres per mgd)
Total surface area--0.35 ha (0.87 acres), cells equal size
Length/width ratio--5.3:1, Slope--0.1%

	System A	System B
Substrate	0.6 m (2.0 ft) sized limestone	Native topsoil
Liner	15 cm (6 in.) compacted clay	None
Water depth	-0.6 to +.2 m (-2.0 to +0.75 ft)	0 to 15 cm (0.0 to 0.5 ft)
Vegetation	*Phalaris arundinacea*	*Phalaris arundinacea*

Posttreatment: Chlorination and/or aeration added if necessary.

Table 7. TVA Constructed Wetland Demonstration Monthly Monitoring, Benton, Kentucky

INFLUENT

DATE	SOIL TEMP Celsius	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
03/30/88		16.0	0.9592	8.6	17.7	312	71	85	9800	83	28	12	3.7	2.6	5.5	0.15	11.0	16.5	16.65
04/27/88		18.1	0.2253	6.9	2.4	367	172	90	30000	30	30	12	4.5	3.0	12.0	0.02	5.0	17.0	17.02
05/25/88		22.3	0.6001	7.1	8.1	413	199	117	< 1000	49	34	7	6.8	5.5	12.0	0.02	8.0	20.0	20.02
06/29/88		26.7	0.3582	7.0	2.0	380	199	106	10500	63	18	3	7.8	6.8	5.2	0.02	11.0	16.2	16.22
07/27/88		26.7	0.3703	8.1	8.3	351	181	88	1200	110	19	4	5.6	4.1	3.1	< 0.01	12.3	15.4	15.41
08/30/88		26.2	0.4993	8.4	16.8	352	143	114	7800		20	4	9.7	5.4	0.1	0.09	9.9	10.0	10.09
09/28/88		22.7	0.4265	7.1	2.4	374	127	140	2000	59	14	4	5.7	5.6	4.1	< 0.01	9.6	13.7	13.71
10/25/88		12.9	0.5051	7.5	6.2	392	151	125	18000	54	24	6	6.6		9.8	0.36	7.1	16.9	17.26
11/29/88		8.9	1.3347	7.2	10.8	266	437	75	220	31	22	13	3.4	2.3	3.8	0.74	6.5	10.3	11.04
12/13/88		4.3	0.5536	8.2	19.1	277	158	85	2700	54	38	11	3.3	2.9	4.8	0.40	6.3	11.1	11.50
01/24/89		8.0	0.9268	7.2	13.0	254	233	84	17300	31	24	10	3.7	0.7	3.1	0.51	1.5	4.6	5.11
02/22/89		6.7	1.9190	7.0	10.0	204	183	56	100	9	23	9	1.4	0.9	1.0	0.57	4.3	5.3	5.87
03/28/89		18.4	1.0740	7.2	8.3	271	293	79	1000	29	24	10	2.6	1.1	2.0	0.25	6.0	8.0	8.25
04/26/89		23.9	0.6689	7.8	9.0	304	184	142	19000	53	26	8	2.9	2.3	3.0	0.24	12.0	15.0	15.24
05/10/89		19.8	0.5549	8.5	16.2	287	139	88							4.0	0.34	14.0	18.0	18.34
05/24/89		23.1	0.3576	7.1	3.1	318	72	70	10200	89	42		3.1		2.9	2.30	5.6	8.5	10.80
06/14/89		25.0	2.5973	7.7	13.3	279	197								0.2	0.54	15.0	15.2	15.72
06/27/89		27.9	0.7108	6.9	0.8	293	-40	80	2500	120	45		3.1		1.4	0.01	13.7	15.1	15.11
07/11/89		28.2	0.6322	7.2	5.2	247	8								0.1	< 0.01	10.9	11.0	10.99
07/25/89		28.8	0.4319	8.2	9.5	272	194	89	12000	120	10		4.0		0.1	0.01	18.9	19.0	19.01
08/02/89		28.3	0.4029	6.8	0.4	324	-154	80							2.1	< 0.01	15.1	17.2	17.21
08/15/89		26.1	0.3899	7.1	1.6	384	120	118	28000	24	27		3.8		6.8	0.06	8.2	15.0	15.06
09/20/89		24.2	0.5520	7.3	10.0	368	27	138	3400	20	15		4.8		11.0	0.09	7.5	18.5	18.59
10/11/89		17.4	0.6546	7.2	3.5	411	268	143							14.0	< 0.01	6.5	20.5	20.51
10/24/89		16.3	0.7909	7.3	7.7	389	132	106	57000	50	29		4.5		9.0	0.30	9.7	18.7	19.00
AVERAGES AND PERCENT REMOVALS*																			
OVERALL		20.3	0.7398	7.2	8.2	324	148	100	4747	57	26	8	4.5	3.3	4.8	0.28	9.4	14.3	14.55
03-04/88		17.1	0.5923	7.8	10.0	340	122	88	17146	57	29	12	4.1	2.8	8.8	0.08	8.0	16.8	16.84
05-10/88		22.9	0.4599	7.3	7.3	377	167	115	3904	67	22	5	7.0	5.5	5.7	0.08	9.7	15.4	15.45
11/88-04/89		11.7	1.0795	7.2	11.7	263	248	87	1641	35	26	10	2.9	1.7	3.0	0.45	6.1	9.1	9.50
05-10/89		24.1	0.7341	7.2	6.5	325	88	101	10882	71	28		3.9		4.7	0.33	11.4	16.1	16.39

Table 7. (continued)

									EFFLUENT CELL 1											
DATE	SOIL TEMP Celsius	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
03/30/88	13.9	14.8	0.2036	7.1	7.9	333	83	95	40	44	17	3	2.8	2.1	3.1	0.29	3.1	6.2	6.49
04/27/88	15.0	14.5	0.1254	7.1	3.3	367	67	96	< 10000	36	20	6	3.7	2.0	7.5	0.06	7.6	15.1	15.16
05/25/88	19.1	18.9	0.1254	6.9	0.2	378	63	117	< 1000	11	9	4	5.4	4.7	9.5	< 0.01	1.5	11.0	11.01
06/29/88	21.1	21.5	0.0631	6.6	0.2	399	-286	137	690	31	10	7	7.9	7.9	3.6	0.01	4.2	7.8	7.81
07/27/88	22.8	21.9	0.0853	6.6	0.3	415	-257	140	1100	5	16	10	5.4	4.0	7.8	< 0.01	1.2	9.0	9.01
08/30/88	20.0	21.5	0.1175	6.7	0.2	421	-230	154	1600	3	5	4	6.5	5.9	12.5	< 0.01	2.5	15.0	15.01
09/28/88	16.0	19.5	0.0750	6.7	0.2	429	-231	138	220	1	4	4	7.5	6.4	9.5	0.03	4.1	13.6	13.63
10/25/88	8.3	9.2	0.1212	6.1	1.5	400	274	120	200	3	4	2	4.7		10.0	0.10	1.9	11.9	12.00
11/29/88	12.8	6.1	0.3136	6.8	0.8	281	370	85	120	3	4	2	4.0	3.2	5.2	0.16	0.7	5.9	6.06
12/13/88	1.1	3.4	0.1042	6.9	0.5	306	60	112	120	4	7	6	3.4	2.9	6.8	0.08	1.6	8.4	8.48
01/24/89	7.0	5.8	0.2031	7.0	0.8	269	152	87	20	3	6	5	1.9	1.5	4.6	0.21	1.6	6.2	6.41
02/22/89	5.0	4.9	0.4859	6.9	1.6	221	157	66	50	2	8	6	1.1	1.0	2.5	0.27	0.8	3.3	3.57
03/28/89	20.0	17.5	0.1889	6.8	0.2	308	131	117	1000	24	16	10	4.6	3.7	5.8	< 0.01	3.0	8.8	8.81
04/26/89	21.0	19.1	0.1361	6.6	0.3	359	52	133	1300	15	8	8	3.3	2.2	9.0	< 0.01	6.0	15.0	15.01
05/10/89	18.0	14.7	0.1619	6.7	0.3	337	62	137							10.0	< 0.01	5.8	15.8	15.81
05/24/89	17.0	18.8	0.0638	6.6	0.2	432	-13	158	4600	11	25		4.7		13.3	< 0.01	2.3	15.6	15.61
06/14/89	18.0	22.7	0.6590	6.6	0.3	304	-34								3.3	0.01	4.6	7.9	7.91
06/27/89	20.0	25.6	0.3181	6.6	0.2	348	-213	123	> 20000	4	9		2.5		5.6	< 0.01	4	8.0	7.96
07/11/89	21.7	26.1	0.3465	6.5	0.3	311	-199								6.4	< 0.01	0	10.4	10.41
07/25/89	20.6	25.5	0.1843	6.7	0.3	364	-190	135	27000	2	5		3.2		9.2	< 0.01	1.5	11.7	11.71
08/02/89	21.3	26.0	0.2642	6.5	0.3	425	-190	151							11.2	< 0.01	2.4	13.6	13.61
08/15/89	20.0	21.9	0.1641	6.8	0.3	433	-131	158	1800	3	6		4.3		12.0	< 0.01	1.6	13.6	13.61
09/20/89	20.0	20.1	0.2014	6.9	0.2	394	23	166	100	1	4		4.3		11.0	< 0.01	1.3	12.3	12.31
10/11/89	15.0	14.0	0.2140	7.0	0.3	417	-89	152							12.0	< 0.01	3.2	15.2	15.21
10/24/89	17.0	15.7	0.3020	6.9	0.4	408	-72	131	4200	7	10		3.2		9.2	< 0.01	2.2	11.4	11.41
AVERAGES AND PERCENT REMOVALS*																			
OVERALL	16.5	17.2	0.2091	6.7	0.8	362	-26	126	698	11	10	5	4.2	3.7	8.0	0.05	2.9	10.9	10.96
% REMOVAL			71.7	6.4	89.8	-12.0	117.4	-26.5	85.3	81.3	62.3	31.4	7.2	-10.0	-65.8	80.6	69.4	23.6	24.7
03-04/88	14.5	14.7	0.1645	7.1	5.6	350	75	96	632	40	19	5	3.3	2.1	5.3	0.18	5.4	10.7	10.83
% REMOVAL			72.2	9.0	44.3	-3.1	38.3	-9.1	96.3	29.2	36.2	62.5	20.7	26.8	39.4	-105.9	33.1	36.4	35.7
05-10/88	17.9	18.8	0.0979	6.6	0.4	407	-111	134	614	9	8	5	6.2	5.8	8.8	0.03	2.6	11.4	11.41
% REMOVAL			78.7	9.6	94.1	-8.0	166.7	-16.8	84.3	86.6	62.8	-10.7	11.4	-5.5	-54.4	66.7	73.4	25.9	26.1
11/88-04/89	11.2	9.5	0.2386	6.8	0.7	291	154	100	163	9	8	6	3.1	2.4	5.7	0.12	2.3	7.9	8.06
% REMOVAL			77.9	5.1	94.0	-10.7	38.0	-15.2	90.1	75.4	69.0	38.6	-5.8	-42.4	-91.5	72.7	62.6	12.3	15.2
05-10/89	18.9	21.0	0.2618	6.7	0.3	379	-95	146	3512	5	10		3.7		9.4	0.01	2.9	12.3	12.32
% REMOVAL			64.3	6.9	95.8	-16.8	208.6	-43.8	67.7	93.5	64.8		4.5		-100.3	97.0	74.2	23.3	24.8

Table 7. (continued)

EFFLUENT CELL 2

DATE	SOIL TEMP Celsius	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
03/30/88	14.6	15.6	0.2243	7.2	6.0	332	4	90	50	27	15	4	3.0	3.0	6.6	0.20	2.4	9.0	9.20
04/27/88*																			0.00
05/25/88	20.4	20.7	0.1331	8.3	11.5	341	150	107	< 1000	53	18	2	4.4	3.2	3.4	0.54	4.5	7.9	8.44
06/29/88	23.6	23.4	0.0490	6.7	0.3	395	-61	133	200	23	6	6	6.5	5.8	0.4	0.01	4.2	4.6	4.61
07/27/88	23.4	23.2	0.0853	6.8	0.2	402	-257	127	310	27	19	11	5.4	5.4	5.3	< 0.01	1.5	6.8	6.81
08/30/88	18.9	24.1	0.1216	7.0	1.4	395	-162	140	70	11	11	6	5.5	5.3	8.6	< 0.01	4.9	13.5	13.51
09/28/88	17.7	22.9	0.0853	7.0	3.6	414	40	123	10	9	9	5	6.6	5.8	8.4	0.02	7.2	15.6	15.62
10/25/88	10.0	11.0	0.1438	6.6	2.5	386	243	230	20	2	5	3	4.4		9.0	0.17	2.4	11.4	11.57
11/29/88	5.6	7.6	0.3480	7.1	4.0	272	346	79	140	4	8	5	3.4	2.8	4.6	0.55	1.0	5.6	6.15
12/13/88	2.8	4.5	0.2220	7.0	3.3	286	130	93	3	3	7	4	3.1	2.8	3.8	0.76	2.4	6.2	6.96
01/24/89	8.0	7.7	0.2203	7.1	4.8	251	145	74	10	2	9	5	1.3	1.4	3.1	0.82	1.5	4.6	5.42
02/22/89	5.0	4.9	0.4661	6.9	3.8	208	158	62	20	2	9	6	1.2	1.2	2.7	0.34	1.0	3.7	4.04
03/28/89	21.0	19.6	0.2097	6.9	1.2	287	152	120	10	20	12	8	3.8	3.7	2.0	0.15	3.0	5.0	5.15
04/26/89	22.0	21.0	0.1361	6.7	0.2	383	31	142	400	14	16	12	4.5	4.1	11.0	0.01	4.2	15.2	15.21
05/10/89	21.0	17.4	0.0877	6.9	2.7	332	64	132							9.0	0.08	9.5	18.5	18.58
05/24/89	17.0	19.8	0.0562	6.7	0.2	388	-43	144	800	23	24		5.1		8.9	< 0.01	3.9	12.8	12.81
06/14/89	17.3	22.9	0.6655	6.7	0.3	294	-37								2.8	< 0.01	5.4	8.2	8.21
06/27/89	21.1	26.0	0.3149	6.6	0.2	333	-220	108	2900	16	15		2.7		4.5	0.01	2.9	7.4	7.41
07/11/89	22.8	26.4	0.3630	6.5	0.3	293	-204								5.3	< 0.01	4.5	9.8	9.81
07/25/89	21.7	26.6	0.2234	6.6	0.2	347	-232	130	4400	6	12		3.4		7.8	< 0.01	1.7	9.5	9.51
08/02/89	22.2	26.9	0.2842	6.6	0.2	390	-196	132							9.7	< 0.01	2.8	12.5	12.51
08/15/89	21.1	22.9	0.1359	6.8	0.3	419	-130	153	1600	15	11		4.1		10	< 0.01	4.1	14.1	14.11
09/20/89	21.1	20.4	0.2069	6.8	0.1	387	-127	160	100	2	6		3.7		11.0	< 0.01	0.2	11.2	11.21
10/11/89	15.5	14.6	0.1534	7.1	0.2	421	-130	158							14.0	< 0.01	2.7	16.7	16.71
10/24/89	17.5	17.0	0.3595	7.1	1.0	401	-90	124	1200	16	12		3.7		10.0	0.15	0.9	11.0	11.15
AVERAGES AND PERCENT REMOVALS*																			
OVERALL	17.1	18.6	0.2206	6.9	2.0	348	-18	126	135	14	12	6	4.0	3.7	6.7	0.16	3.3	10.0	9.79
% REMOVAL			70.2	4.1	75.4	-7.6	112.0	-25.6	97.2	74.5	53.9	26.7	12.3	-11.6	-39.4	42.4	65.2	29.7	32.7
03-04/88	14.6	15.6	0.2243	7.2	6.0	332	4	90	50	27	15	4	3.0	3.0	6.6	0.20	2.4	9.0	4.60
% REMOVAL			62.1	7.7	40.3	2.2	96.7	-2.9	99.7	52.2	48.3	66.7	26.8	-7.1	24.6	-135.3	70.0	46.3	72.7
05-10/88	19.0	20.9	0.1030	6.9	3.3	389	-8	143	98	21	11	6	5.5	5.1	5.9	0.13	4.1	10.0	10.09
% REMOVAL			77.6	5.5	55.5	-3.1	104.7	-24.6	97.5	68.9	47.3	-17.9	22.3	6.9	-2.5	-49.0	57.3	35.1	34.7
11/88-04/89	10.7	10.9	0.2670	7.0	2.9	281	160	95	26	8	10	7	2.9	2.7	4.5	0.44	2.2	6.7	7.16
% REMOVAL			75.3	3.5	75.4	-7.0	35.3	-9.4	98.4	78.3	61.0	34.6	0.0	-57.2	-53.7	3.0	64.2	25.8	24.7
05-10/89	19.8	21.9	0.2591	6.7	0.5	364	-122	138	1119	13	13		3.8		8.5	0.03	3.5	12.0	12.00
% REMOVAL			64.7	6.9	91.9	-12.1	239.7	-36.1	89.7	81.6	52.4		2.4		-80.5	91.3	69.1	25.5	26.8

Table 7. (continued)

EFFLUENT CELL 3

DATE	SOIL TEMP Celsius	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
03/30/88	20.0	15.1	0.4162	7.4	4.1	392	-140	124	150	29	14	4	3.3	3.2	8.7	0.09	4.2	12.9	12.99
04/27/88	16.4	15.3	0.2088	7.0	1.0	462	-288	153	< 10000	8	22	9	4.3	3.2	15.0	0.01	1.8	16.8	16.81
05/25/88	20.3	19.4	0.2650	7.0	0.1	491	-278	187	< 1000	7	15	5	5.3	5.3	14.0	< 0.01	2.0	16.0	16.01
06/29/88	28.4	23.5	0.1183	6.9	0.2	560	-281	233	360	3	6	3	6.7	6.1	10.6	0.01	2.6	13.2	13.21
07/27/88	25.6	23.5	0.1603	7.1	0.2	559	-268	226	100	1	3	2	5.2	5.2	14.7		0.3	15.0	15.00
08/30/88	26.0	22.2	0.2146	7.1	0.2	504	-203	194	30	1	3	2	6.5	5.7	14.5	< 0.01	1.0	15.5	15.51
09/28/88	21.0	20.3	0.1440	7.3	0.2	541	-208	197	10	6	2	1	7.3	5.5	10.8	0.01	4.1	14.9	14.91
10/25/88	21.1	11.0	0.2707	6.3	1.7	474	434	160	70	1	4	2	4.6		10.2	2.60	0.6	10.8	13.40
11/29/88	7.6	8.3	0.6476	6.8	1.7	315	327	91	50	3	3	2	2.5	0.01	2.4	2.60	1.0	3.4	6.00
12/13/88	4.5	2.0	0.2110	7.2	1.2	345	188	120	20	2	5	3	3.1	2.5	3.1	1.90	1.8	4.9	6.80
01/24/89	7.0	7.2	0.3941	7.3	2.8	311	112	114	10	3	6	5	2.2	2.3	5.0	0.26	1.6	6.6	6.86
02/22/89	4.8	4.3	0.7040	7.1	5.1	246	150	77	< 10	1	6	4	1.0	0.9	2.8	0.72	0.9	3.7	4.42
03/28/89	19.0	19.0	0.4791	7.1	0.3	349	84	146	40	2	14	9	3.1	2.9	7.6	< 0.01	0.4	8.0	8.01
04/26/89	21.5	18.9	0.0341	7.0	0.1	546	-40	250	30	6	12	3	2.5	1.9	14.0	0.03	2.3	16.3	16.33
05/10/89	20.5	16.3	0.0518	7.3	0.2	508	80	255							16.0	< 0.01	0.4	16.4	16.41
05/24/89	18.0	21.1	0.1305	7.1	1.5	555	-4	194	10	8	1		6.5		12.0	0.06	3.4	15.4	15.46
06/14/89	20.5	22.6	0.0449	7.0	1.4	531	13								0.1	0.05	2.4	2.5	2.50
06/27/89	23.2	24.0	0.0819	6.9	0.2	523	-192	227	5450	1	3		1.3		4.7	0.01	0.7	5.4	5.40
07/11/89	23.9	24.8	0.1036	6.8	0.3	447	-210								4.5	< 0.01	2.7	7.2	7.21
07/25/89	23.9	24.8	0.0628	7.0	0.3	522	-246	245	1100	6	4		1.8		7.5	0.04	0.4	7.9	7.94
08/02/89	23.3	24.6	0.0587	6.9	0.5	648	-167	225							5.9	0.01	0.5	6.4	6.37
08/15/89	21.1	21.7	0.0276	7.0	0.6	624	-143	250	90	1	1.4		2.5		8	< 0.01	0.1	8.1	8.11
09/20/89	18.9	20.3	0.0519	7.0	0.1	511	-108	206	100	1	2		2.5		9.2	< 0.01	1.6	10.8	10.81
10/11/89	15.0	15.9	0.0667	7.3	0.3	468	-68	189							8.1	< 0.01	1.1	9.2	9.21
10/24/89	14.4	14.7	0.1035	7.4	0.4	481	-31	156	110	1	4		1.2		6.1	0.31	0.4	6.5	6.81
AVERAGES AND PERCENT REMOVALS*																			
OVERALL	18.6	17.6	0.2021	7.0	1.0	477	-59	183	99	5	7	4	3.7	3.4	8.6	0.37	1.5	10.1	10.50
% REMOVAL			72.7	2.8	88.0	-47.3	140.3	-83.6	97.9	92.0	74.5	51.7	19.3	-3.5	-78.1	-29.5	83.8	28.9	27.8
03-04/88	18.2	15.2	0.3125	7.2	2.6	427	-214	139	1225	19	18	7	3.8	3.2	11.9	0.05	3.0	14.9	14.90
% REMOVAL			47.2	7.7	74.6	-25.8	276.1	-58.3	92.9	67.3	37.9	45.8	7.3	-14.3	-35.4	41.2	62.5	11.3	11.5
05-10/88	23.7	20.0	0.1955	7.1	0.4	522	-134	200	95	3	6	3	5.9	5.6	12.5	0.53	1.8	14.2	14.67
% REMOVAL			57.5	2.7	94.1	-38.3	180.4	-73.5	97.6	95.3	74.4	46.4	15.6	-1.5	-118.3	-521.2	81.8	7.4	5.0
11/88-04/89	10.7	10.0	0.4117	7.1	1.9	352	137	133	22	3	8	4	2.4	1.7	5.8	0.92	1.3	7.2	8.07
% REMOVAL			61.9	1.6	84.0	-34.0	44.8	-53.2	98.7	91.8	70.8	56.6	16.9	-3.0	-97.2	-103.7	78.1	21.0	15.1
05-10/89	20.2	21.0	0.0713	7.0	0.5	529	-98	216	198	3	3		2.6		7.5	0.05	1.2	8.7	8.75
% REMOVAL			90.3	2.8	92.0	-62.9	211.7	-113.5	98.2	95.7	90.7		32.0		-59.3	85.6	89.0	45.8	46.6

* pH - median values and fecal coliform - geometric mean values

Table 8. TVA Total Constructed Wetland System Performance, Benton, Kentucky

DATE	pH	D.O. mg/l	F. COLI #/100 ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
03/30/88	7.3	5.5	97	32	15	4	3.1	2.9	6.8	0.17	3.5	10.2	10.4
04/27/88	7.0	1.9	10000	19	21	8	4.1	2.7	12.2	0.03	4.0	16.2	16.2
05/25/88	7.3	3.0	1000	20	14	4	5.1	4.6	10.2	0.14	2.5	12.7	12.9
06/29/88	6.8	0.2	416	15	7	5	7.0	6.5	6.5	0.01	3.4	9.9	9.9
07/27/88	6.9	0.2	412	9	10	6	5.3	4.9	10.5	0.01	0.8	11.3	11.3
08/30/88	7.0	0.5	447	4	6	4	6.2	5.6	12.4	0.01	2.4	14.8	14.8
09/28/88	7.1	1.2	62	6	4	3	7.2	5.8	9.8	0.02	5.0	14.8	14.8
10/25/88	6.3	1.9	86	2	4	2	4.6		9.8	1.38	1.4	11.2	12.6
11/29/88	6.9	2.1	91	3	5	3	3.1	1.5	3.7	1.47	0.9	4.6	6.1
12/13/88	7.1	1.9	32	3	6	4	3.2	2.7	4.1	1.08	2.0	6.1	7.2
01/24/89	7.2	2.8	12	3	7	5	1.9	1.9	4.4	0.40	1.6	6.0	6.4
02/22/89	7.0	3.7	25	2	7	5	1.1	1.0	2.7	0.48	0.9	3.6	4.1
03/28/89	7.0	0.5	239	11	14	9	3.6	3.3	5.9	0.04	1.6	7.5	7.5
04/26/89	6.7	0.2	759	14	12	9	3.7	3.0	10.4	0.01	4.8	15.2	15.2
05/10/89	6.9	1.0							10.7	0.03	5.9	16.7	16.7
05/24/89	6.9	0.9	1356	12	12		5.7		11.6	0.04	3.2	14.9	14.9
06/14/89	6.7	0.3							3.0	0.01	4.9	7.9	7.9
06/27/89	6.6	0.2	10801	9	11		2.5		5.0	0.01	2.4	7.4	7.4
07/11/89	6.5	0.3							5.7	0.01	4.1	9.7	9.7
07/25/89	6.7	0.3	12812	4	8		3.1		8.3	0.01	1.8	10.1	10.2
08/02/89	6.6	0.3							10.0	0.01	2.4	12.4	12.4
08/15/89	6.8	0.3	1573	8	8		4.1		10.8	0.01	2.5	13.3	13.4
09/20/89	6.9	0.2	100	1	5		3.8		10.8	0.01	0.8	11.6	11.6
10/11/89	7.1	0.3							12.1	0.01	2.7	14.8	14.8
10/24/89	7.1	0.7	2237	10	10		3.2		9.2	0.12	1.4	10.5	10.7
AVERAGES*													
OVERALL	6.9	1.2	381	9	9	5	4.1	3.6	8.3	0.22	2.7	10.9	11.2
03-04/88	7.2	3.7	985	25	18	6	3.6	2.8	9.5	0.10	3.7	13.2	13.3
05-10/88	6.9	1.2	272	9	8	4	5.9	5.5	9.9	0.26	2.6	12.5	12.7
11/88-04/89	7.0	1.9	74	6	8	6	2.8	2.2	5.2	0.58	2.0	7.2	7.7
05-10/89	6.8	0.4	2010	7	9		3.7		8.8	0.02	2.9	11.8	11.8

* pH - median values and fecal coliform - geometric mean values

Table 9. Evaluation of NPDES Compliance, Benton, Kentucky

		Municipal Data[a]									
		Before Wetlands Operations (Jan 86 to Dec 86)					After Wetlands Operations (Jan 87 to Oct 89)				
					Samples Not Meeting Limit					Samples Not Meeting Limit	
Parameter	Monthly Ave NPDES Limit	Ave	Max	Min	No.[b]	%	Ave	Max	Min	No.[b]	%
BOD_5, mg/l	25	29	102	7	3/11	27	9	23	1	0/34	0
TSS, mg/l	30	160	1335	4	9/11	82	12	42	1	3/34	9
NH_3-N, mg/L											
May-Oct	4	3.4	5.8	1.3	2/5	40	8.6	14.7	1	15/18	83
Nov-Apr	10	6.2	13.8	1.8	2/6	33	7.3	16.4	1	4/16	25
FC, #/100 ml[c]	200	21[d]	5000	1	4/11	36	68[d]	60000	1	12/34	35
pH, units	6-9	7.1[e]	8.2	6.8	0/11	0	7.2	7.8	6.5	0/34	0
DO, mg/l	≥7	Not Available					6.4	11	2.5	18/33	55

		TVA Data (Mar 88 to Oct 89)[f]																			
		Cell 1					Cell 2					Cell 3					Total System[g]				
					Samples Not Meeting Limit					Samples Not Meeting Limit					Samples Not Meeting Limit					Samples Not Meeting Limit	
Parameter	NPDES Limit	Ave	Max	Min	No.[c]	%	Ave	Max	Min	No.[c]	%	Ave	Max	Min	No.[c]	%	Ave	Max	Min	No.[c]	%
BOD_5, mg/l	25	10	25	4	0/20	0	12	24	5	0/19	0	7	22	1	0/20	0	9	21	4	0/20	0
TSS, mg/l	30	11	44	1	3/20	15	14	53	2	1/19	5	5	29	1	0/20	0	9	32	1	1/20	5
NH_3-N, mg/l																					
May-Oct	4	9.2	12.5	3.6	11/12	92	7.3	12	0.4	9/12	75	10.0	14.7	2.4	11/12	92	9.4	12.4	4.0	11/12	92
Nov-Apr	10	5.6	9	2.5	0/8	0	4.8	11	2	1/7	14	7.3	15	2.4	2/8	25	6.3	12.2	2.7	2/8	25
FC, #/100 ml	200	698[d]	27000	20	14/20	70	135[d]	4400	3	8/19	42	99[d]	10000	10	5/20	25	381[d]	12812	12	12/20	60
pH, units	6-9	6.8[e]	7.1	6.1	0/20	0	6.9[e]	8.3	6.6	0/19	0	7.0[e]	7.4	6.3	0/20	0	6.9[e]	7.3	6.3	0/20	0
DO, mg/l	≥7	1.0	7.9	0.2	19/20	95	2.4	11.5	0.1	18/19	95	1.1	5.1	0.1	20/20	100	1.3	5.5	0.1	20/20	100

a. Measured at point of discharge
b. Number of samples not meeting limit/total samples
c. Most Probable Number Technique: 1/87 - 8/87
Membrane Filter Technique - 9/87 - 10/89
d. Geometric Mean
e. Median
f. Measured at end of wetland cell (before chlorination)
g. Calculated based on flows and concentrations of cells 1-3

Table 10. TVA Constructed Wetland Demonstration Mass Loading Summary of Cell 1, Benton, Kentucky

	CELL 1													
DATE	FLOW	HLR	D.O.	ALK CaCO3	TSS	BOD5	DIS BOD5	TOT P	DIS P	NH3-N	NO3-NO2	ORGANIC N	TKN	TN
	MGD	MGD/acre	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day
INFLUENT AVERAGES														
OVERALL	0.2621	0.0728	20.59	175.8	93.5	45.6	15.0	6.9	4.4	8.31	0.730	22.38	30.7	31.4
03-04/88	0.1609	0.0447	18.84	115.7	94.4	38.2	16.1	5.2	3.6	9.48	0.160	12.84	22.3	22.5
05-10/88	0.1173	0.0326	7.52	113.7	61.8	22.0	4.8	6.9	5.3	6.01	0.090	9.20	15.2	15.3
11/88-04/89	0.3026	0.0841	27.30	214.1	77.3	62.7	24.8	6.8	4.0	6.60	1.192	15.61	22.2	23.4
05-10/89	0.3372	0.0937	24.38	205.1	135.9	34.8		7.6		10.29	0.930	35.00	45.3	46.2
EFFLUENT AVERAGES														
OVERALL	0.2091		1.48	183.4	13.6	13.2	7.4	5.3	3.8	12.25	0.117	4.90	17.1	17.3
03-04/88	0.1645		8.44	130.9	56.2	24.9	5.7	4.3	2.8	6.56	0.278	6.61	13.2	13.4
05-10/88	0.0979		0.39	108.8	6.3	6.3	3.9	4.9	3.6	7.62	0.025	1.93	9.5	9.6
11/88-04/89	0.2386		1.84	178.4	13.2	15.4	11.4	5.4	4.3	9.47	0.328	3.45	12.9	13.3
05-10/89	0.2617		0.61	248.1	6.9	14.0		5.9		17.32	0.022	7.01	24.3	24.3
PERCENT REMOVALS														
OVERALL	20.2		92.8	-4.3	85.5	71.1	50.9	23.8	13.9	-47.3	84.0	78.1	44.2	45.1
03-04/88	-2.237		55.2	-13.1	40.4	34.9	64.7	17.4	21.8	30.8	-74.0	48.5	41.0	40.2
05-10/88	16.560		94.8	4.3	89.8	71.6	18.4	29.2	31.1	-26.7	71.8	79.0	37.3	37.5
11/-04/89	21.160		93.2	16.7	82.9	75.5	54.1	20.9	-8.3	-43.5	72.5	77.9	41.8	43.4
05-10/89	22.386		97.5	-21.0	94.9	74.4		23.0		-68.3	97.7	80.0	46.3	47.4

Table 11. TVA Constructed Wetland Demonstration Mass Loading Summary of Cell 2, Benton, Kentucky

CELL 1

DATE	FLOW MGD	HLR MGD/acre	D.O. lbs/day	ALK CaCO3 lbs/day	TSS lbs/day	BOD5 lbs/day	DIS BOD5 lbs/day	TOT P lbs/day	DIS P lbs/day	NH3-N lbs/day	NO3-NO2 lbs/day	ORGANIC N lbs/day	TKN lbs/day	TN lbs/day
INFLUENT AVERAGES														
OVERALL	0.2698	0.0749	21.38	181.2	98.1	47.3	15.6	7.4	4.6	8.34	0.760	23.18	31.5	32.3
03-04/88	0.2447	0.0680	36.14	173.6	169.5	57.2	24.5	7.6	5.3	11.23	0.306	22.46	33.7	34.0
05-10/88	0.1173	0.0326	7.52	113.7	61.8	22.0	4.8	6.9	5.3	6.01	0.090	9.20	15.2	15.3
11/88-04/89	0.3026	0.0841	27.30	214.1	77.3	62.7	24.8	6.8	4.0	6.60	1.192	15.61	22.2	23.4
05-10/89	0.3372	0.0937	24.38	205.1	144.9	57.1		8.5		10.29	0.930	35.00	45.3	46.2
EFFLUENT AVERAGES														
OVERALL	0.2206		3.54	187.1	19.5	18.3	8.7	5.5	4.7	11.17	0.349	5.43	16.6	16.9
03-04/88	0.2243		11.23	168.5	50.5	28.1	7.5	5.6	5.6	12.35	0.374	4.49	16.8	17.2
05-10/88	0.1030		3.34	128.2	17.9	9.9	4.3	4.5	3.9	5.54	0.167	3.46	9.0	9.1
11/88-04/89	0.2670		7.27	191.7	13.3	21.3	13.4	5.7	5.3	8.77	1.018	4.00	12.8	13.8
05-10/89	0.2591		0.92	225.3	22.1	21.9		6.3		15.45	0.064	7.36	22.8	22.9
PERCENT REMOVALS														
OVERALL	18.2		83.4	-3.2	80.1	61.4	43.8	24.9	-2.1	-34.0	54.1	76.6	47.3	47.5
03-04/88	8.3367		68.9	2.9	70.2	50.9	69.4	25.7	-5.8	-10.0	-22.2	80.0	50.0	49.4
05-10/88	12.214		55.6	-12.7	71.0	54.9	10.3	35.3	26.6	7.9	-85.4	62.4	40.9	40.3
11/88-04/89	11.777		73.4	10.5	82.9	66.0	46.0	15.2	-32.9	-32.8	14.6	74.3	42.5	41.1
05-10/89	23.160		96.2	-9.8	84.8	61.6		25.7		-50.2	93.1	79.0	49.6	50.4

Table 12. TVA Constructed Wetland Demonstration Mass Loading Summary of Cell 3, Benton, Kentucky

CELL 3														
DATE	FLOW MGD	HLR MGD/acre	D.O. lbs/day	ALK CaCO3 lbs/day	TSS lbs/day	BOD5 lbs/day	DIS BOD5 lbs/day	TOT P lbs/day	DIS P lbs/day	NH3-N lbs/day	NO3-NO2 lbs/day	ORGANIC N lbs/day	TKN lbs/day	TN lbs/day
INFLUENT AVERAGES														
OVERALL	0.2551	0.0709	21.32	194.2	97.7	55.8	27.7	9.2	8.1	9.16	0.687	15.26	24.4	25.1
03-04/88	0.309	0.0858	36.18	222.3	181.3	73.4	30.9	10.0	7.0	18.20	0.306	24.65	42.9	43.2
05-10/88	0.2252	0.0626	14.44	218.4	118.6	42.2	9.2	13.3	10.1	11.54	0.173	17.66	29.2	29.4
11/88-04/89	0.5689	0.1580	53.25	341.1	121.3	116.5	48.5	12.5	6.7	11.99	2.488	23.09	35.1	37.6
05-10/89	0.0679	0.0189	2.81	60.6	32.6	12.9		1.9		3.34	0.042	6.23	9.6	9.6
EFFLUENT AVERAGES														
OVERALL	0.2281		3.54	274.2	10.8	16.1	11.4	6.9	7.2	13.84	1.455	2.80	16.6	18.0
03-04/88	0.3125		7.99	348.6	57.3	43.5	14.8	9.5	8.3	28.18	0.165	8.86	37.0	37.2
05-10/88	0.1954		0.85	315.2	5.2	10.0	4.3	9.3	8.3	20.51	1.187	2.57	23.1	24.1
11/88-04/89	0.4871		10.33	422.8	8.7	26.9	18.5	8.9	5.8	16.34	4.504	4.14	20.5	25.0
05-10/89	0.0695		0.18	111.5	1.1	1.8		0.9		3.69	0.040	0.62	4.3	4.3
PERCENT REMOVALS														
OVERALL	10.6		83.4	-41.1	88.9	71.1	58.8	24.8	11.0	-51.1	-111.8	81.7	31.9	28.2
03-04/88	-1.1		77.9	-56.8	68.4	40.8	52.2	5.6	-20.0	-54.8	46.1	64.1	13.6	13.8
05-10/88	13.2		94.1	-44.4	95.6	76.3	52.9	29.8	17.7	-77.8	-586.3	85.5	21.0	18.1
11/88-04/89	14.4		80.6	-23.9	92.8	76.9	61.9	28.9	14.0	-36.3	-81.0	82.1	41.6	33.5
05-10/89	-2.4		93.5	-83.9	96.7	85.9		52.8		-10.4	4.5	90.1	55.0	54.8

Table 13. TVA Constructed Wetland Dye Study Results, Benton, Kentucky, 08/23-27, 1988

CELL 1

LOCATION	TIME Minutes	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
INFLUENT																			
D-1	0		0.1130	6.99	2.9	401	244	113	3500	96	17	5	8.4	7.8	7.5	< 0.01	9.50	17.0	17.01
D-2	0		0.1130	6.99	2.9	401	244	115	4000	95	19	5	7.0	6.5	7.5	< 0.01	4.00	11.5	11.51
D-AVG	0		0.1130	6.99	2.9	401	244	114	3750	95	18	5	7.7	7.2	7.5	< 0.01	6.80	14.3	14.31
C-1 ROW A	705	26.0		6.52		441	306	142	51000	8	7	5	7.4	6.5	15.0	< 0.01	< 0.02	15.0	15.03
C-1 ROW B	1275			6.76		409	16	141	4800	14	9	5	7.1	6.5	11.0	< 0.01	24.00	35.0	35.01
C-1 ROWC	2355			6.80		450	139	144	2000	8	7	4	6.0	4.5	14.0	< 0.01	0.50	14.5	14.51
C-1 EFF	4365	21.8	0.1041	6.71		452	-6	154	2000	8	7	5	8.7	6.7	14.0	< 0.01	1.00	15.0	15.01

CELL 2

LOCATION	TIME Minutes	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
INFLUENT																			
D-1	0		0.1130	6.99	2.9	401	244	113	3500	96	17	5	8.4	7.8	7.5	< 0.01	9.50	17.0	17.01
D-2	0		0.1130	6.99	2.9	401	244	115	4000	95	19	5	7.0	6.5	7.5	< 0.01	4.00	11.5	11.51
D-AVG	0		0.1130	6.99	2.9	401	244	114	3750	95	18	5	7.7	7.2	7.5	< 0.01	6.80	14.3	14.31
C-2 ROW A	493	27.5		6.11		437	114	157	800	11	8	5	7.8	6.5	14.0	< 0.01	0.50	14.5	14.51
C-2 ROW B	1275			6.76		437	13	144	5700	13	9	6	7.5	6.5	13.0	< 0.01	6.50	19.5	19.51
C-2 ROW C	2625			6.60		419	116	167	800	19	10	6	6.5	4.8	11.0	< 0.01	3.50	14.5	14.51
C-2 EFF	4365	23.9	0.1183	6.81	1.4	421	33	141	220	25	10	6	9.8	6.7	9.5	< 0.01	2.00	11.5	11.51

CELL 3

LOCATION	TIME Minutes	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
INFLUENT																			
D-1	0		0.2170	6.99	2.9	401	244	113	3500	96	17	5	8.4	7.8	7.5	< 0.01	9.50	17.0	17.01
D-2	0		0.2170	6.99	2.9	401	244	115	4000	95	19	5	7.0	6.5	7.5	< 0.01	4.00	11.5	11.51
D-AVG	0		0.2170	6.99	2.9	401	244	114	3750	95	18	5	7.7	7.2	7.5	< 0.01	6.80	14.3	14.31
C-3 ROW A	405	27.0		7.36		510	64	194	1200	24	10	5	7.3	6.5	15.0	0.15	2.20	17.2	17.35
C-3 ROW B	675			6.36		506	314	156	2100	11	10	5	7.6	6.7	15.0	< 0.01	2.40	17.4	17.41
C-3 ROW C	885			7.03		519	303	194	700	38	10	4	7.9	6.7	15.0	0.01	2.60	17.6	17.61
C-3 EFF	990		0.4162	6.72	1.5	535	47	186	7400	5	6	4.6	8.2	6.7	12.0	< 0.01	3.50	15.5	15.51

D-1 and D-2 Influent samples - Quality Control
C represents Cell

Table 14. TVA Constructed Wetland Dye Study Results, Benton, Kentucky, 06/19-23, 1989

CELL 1

LOCATION	TIME Minutes	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
INFLUENT																			
D-1	0	24.0	0.5143	7.0	14.5	279	118	77	4300	76	33	4	3.7	1.2	0.6	0.54	10.2	10.8	11.35
D-2	0	24.0	0.5143	7.0	14.5	279	118	77	8000	75	33	4	2.4	1.3	0.7	0.60	5.7	6.4	7.00
D-AVG	0	24.0	0.5143	7.0	14.5	279	118	77	6150	76	33	4	3.1	1.3	0.7	0.57	8.0	8.7	9.27
C-1 ROW A	360	27.1		6.6	0.3	296	-47	92	1400	10	8	3	4.3	1.7	3.1 <	0.01	9.7	12.8	12.81
C-1 ROW B	630	24.4		6.5	0.2	293	-93	95	1000	6	6	3	2.2	1.8	3.2 <	0.01	2.2	5.4	5.41
C-1 ROW C	1305	22.9		6.6	0.5	284	-26	107	500	5	6	5	2.8	2.0	3.9 <	0.01	2.6	6.5	6.51
C-1 EFF	2205	24.7	0.4573	6.5	0.4	316	-36	102	620	7	6	4	2.2	2.1	3.5	0.01	2.3	5.8	5.81

CELL 2

LOCATION	TIME Minutes	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
INFLUENT																			
D-1	0	24.0	0.5143	7.0	14.5	279	118	77	4300	76	33	4	3.7	1.2	0.6	0.54	10.2	10.8	11.35
D-2	0	24.0	0.5143	7.0	14.5	279	118	77	8000	75	33	4	2.4	1.3	0.7	0.60	5.7	6.4	7.00
D-AVG	0	24.0	0.5143	7.0	14.5	279	118	77	6150	76	33	4	3.1	1.3	0.7	0.57	8.0	8.6	9.27
C-2 ROW A	190	31.1		6.5	0.8	298	108	83	300	14	8	3	2.2	1.7	2.6 <	0.01	3.3	5.9	5.91
C-2 ROW B	500	26.8		6.9	3.6	298	104	82	330	16	8	4	2.3	1.4	2.2	0.02	3.6	5.8	5.82
C-2 ROW C	1135	19.2		6.9	1.3	284	-29	86	70	14	9	5	2.4	1.7	2.3 <	0.01	3.0	5.3	5.31
C-2 EFF	2115	22.1	0.4573	6.6	0.8	310	-48	96	620	11	9	5	2.9	1.9	2.5	0.01	3.7	6.2	6.21

CELL 3

LOCATION	TIME Minutes	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
INFLUENT																			
D-1	0	24.0	0.1403	7.0	14.5	279	118	77	4300	76	33	4	3.7	1.2	0.6	0.54	10.2	10.8	11.35
D-2	0	24.0	0.1403	7.0	14.5	279	118	77	8000	75	33	4	2.4	1.3	0.7	0.60	5.7	6.4	7.00
D-AVG	0	24.0	0.1403	7.0	14.5	279	118	77	6150	76	33	4	3.1	1.3	0.7	0.57	8.0	8.6	9.27
C-3 ROW A	630	24.7		6.8	0.4	648	-152	151	2200	14	9	4	3.5	2.2	6.1 <	0.01	3.5	9.6	9.61
C-3 ROW B	2695	22.7		6.7	0.6	397	-32	201	400	6	4	3	2.1		4.9 <	0.01	1.9	6.8	6.81
C-3 ROW C	4760	27.2		6.6	0.1	569	-255	251	370	3	2	2	1.5		1.4	0.08	2.7	4.1	4.18
C-3 EFF	5735	23.4	0.1446	6.7	0.2	574	-226	241	200	2	1	1	1.6		3.8 <	0.01	1.8	5.6	5.61

D-1 and D-2 Influent samples - Quality Control
C represents Cell

Table 15. TVA Constructed Wetland Dye Study Results, Benton, Kentucky, 09/04-15, 1989

CELL 1

LOCATION	TIME Minutes	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
INFLUENT																			
D-1	0	25.9	0.2910	6.8	1.6	389	105	115	22000	57	5	1	4.2	3.4	9.0	< 0.01	7.9	16.9	16.91
D-2	0	25.9	0.2910	6.8	1.6	389	105	115	42000	55	5	1	4.4	2.1	9.0	< 0.01	9.3	18.3	18.31
D-AVG	0	25.9	0.2910	6.8	1.6	389	105	115	32000	56	5	1	4.3	2.8	9.0	< 0.01	8.6	17.6	17.61
C-1 ROW A	405	29.9		6.8	1.4	407	109	135	500	31	4	1	4.8	4.4	10.0	< 0.01	4.5	14.5	14.51
C-1 ROW B	600	24.8		6.6	0.2	397	-83	133	800	10	4	1	4.6	4.2	10.0	< 0.01	2.7	12.7	12.71
C-1 ROWC	1050	21.1		6.9	1.3	405	-27	140	300	4	5	1	4.7	4.4	10.0	< 0.01	1.5	11.5	11.51
C-1 EFF	3015	23.7	0.2166	6.6	0.2	415	-160	141	230	3	5	4	4.6	4.1	9.5	< 0.01	2.0	11.5	11.51

CELL 2

LOCATION	TIME Minutes	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
INFLUENT																			
D-1	0	25.9	0.2910	6.8	1.6	389	105	115	22000	57	5	1	4.2	3.4	9.0	< 0.01	7.9	16.9	16.91
D-2	0	25.9	0.2910	6.8	1.6	389	105	115	42000	55	5	1	4.4	2.1	9.0	< 0.01	9.3	18.3	18.31
D-AVG	0	25.9	0.2910	6.8	1.6	389	105	115	32000	56	5	1	4.3	2.8	9.0	< 0.01	8.6	17.6	17.61
C-2 ROW A	315	28.0		6.7	1.1	394	112	134	2200	28	7	2	4.8	4.4	10.0	< 0.01	2.5	12.5	12.51
C-2 ROW B	850	24.2		7.0	0.2	378	3	130	800	15	5	2	4.5	4.1	9.2	< 0.01	5.6	14.8	14.81
C-2 ROW C	2875	23.2		6.8	0.2	363	-119	129	280	6	7	5	4.9	4.2	8.6	< 0.01	0.6	9.2	9.21
C-2 EFF	4340	23.8	0.2280	6.8	0.2	401	-146	140	420	11	14	7	4.4	4.2	8.3	< 0.01	0.7	9.0	9.01

CELL 3

LOCATION	TIME Minutes	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
INFLUENT																			
D-1	0	25.9	0.0794	6.8	1.6	389	105	115	22000	57	5	1	4.2	3.4	9.0	< 0.01	7.9	16.9	16.91
D-2	0	25.9	0.0794	6.8	1.6	389	105	115	42000	55	5	1	4.4	2.1	9.0	< 0.01	9.3	18.3	18.31
D-AVG	0	25.9	0.0794	6.8	1.6	389	105	115	32000	56	5	1	4.3	2.8	9.0	< 0.01	8.6	17.6	17.61
C-3 ROW A	2845	22.1		7.0	1.0	491	-119	194	240	1	7	3	4.9	4.2	12.0	< 0.01	1.2	13.2	13.21
C-3 ROW B	5745	21.4		7.1	0.3	514	-162	216	370	1	8	8	4.3	4.1	12.0	< 0.01	1.6	13.6	13.61
C-3 ROW C	10260	23.0		7.4	4.8	515	132	215	30	1	4	2	4.2	3.8	11.0	< 0.01	1.1	12.1	12.11
C-3 EFF	15975	21.0	0.0551	7.3	6.0	268	321		6100	2	8	5	2.7	2.5	11.0	0.30	1.0	12.0	12.30

D-1 and D-2 Influent samples - Quality Control
C represents Cell

Table 16. TVA Constructed Wetland Dye Study Results, Benton, Kentucky, 09/19-10/01, 1989

CELL 1

LOCATION	TIME Minutes	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
INFLUENT																			
D-1	0	21.6	0.2410	7.1	0.9	389	177	140	3400	14	24	15	5.1	4.5	12.0	0.01	4.0	16.0	16.01
D-2	0	21.6	0.2410	7.1	0.9	389	177	140	4400	16	23	14	5.2	4.5	12.0	0.01	5.4	17.4	17.41
D-AVG	0	21.6	0.2410	7.1	0.9	389	177	140	3900	15	24	15	5.2	4.5	12.0	0.01	4.7	16.7	16.71
C-1 ROW A	275	28.8		6.8	1.2	407	25	147	8000	7	24	19	4.8	4.2	12.0 <	0.01	3.8	15.8	15.81
C-1 ROW B	505	28.0		6.5	1.5	406	-38	146	280	1	10	4	4.7	4.2	11.0 <	0.01	1.5	12.5	12.51
C-1 ROWC	1000	16.6		6.9	0.5	394	23	145	330	3	7	4	4.4	4.0	11.0 <	0.01	0.7	11.7	11.71
C-1 EFF	2268	18.5	0.2007	6.9	1.8	398	19	150	200	1	3	3	7.6	4.2	10.0 <	0.01	3.0	13.0	13.01

CELL 2

LOCATION	TIME Minutes	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
INFLUENT																			
D-1	0	21.6	0.2410	7.1	0.9	389	177	140	3400	14	24	15	5.1	4.5	12.0	0.01	4.0	16.0	16.01
D-2	0	21.6	0.2410	7.1	0.9	389	177	140	4400	16	23	14	5.2	4.5	12.0	0.01	5.4	17.4	17.41
D-AVG	0	21.6	0.2410	7.1	0.9	389	177	140	3900	15	24	15	5.2	4.5	12.0	0.01	4.7	16.7	16.71
C-2 ROW A	220	24.6		6.9	0.7	410	-42	155	1200	11	9	7	5.1	4.6	13.0 <	0.01	2.6	15.6	15.61
C-2 ROW B	970	20.2		7.0	0.9	387	92	140	260	3	7	4	4.3	4.2	11.0 <	0.01	1.5	12.5	12.51
C-2 ROW C	2930	18.2		6.8	0.2	391	-45	154	100	3	2	2	7.5	4.0	11.0 <	0.01	3.1	14.1	14.11
C-2 EFF	4435	20.5	0.1956	6.9	0.2	386	-116	147	78	12	8	5	4.7	4.3	9.9 <	0.01	4.6	14.5	14.51

CELL 3

LOCATION	TIME Minutes	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
INFLUENT																			
D-1	0	21.6	0.0657	7.1	0.9	389	177	140	3400	14	24	15	5.1	4.5	12.0	0.01	4.0	16.0	16.01
D-2	0	21.6	0.0657	7.1	0.9	389	177	140	4400	16	23	14	5.2	4.5	12.0	0.01	5.4	17.4	17.41
D-AVG	0	21.6	0.0657	7.1	0.9	389	177	140	3900	15	24	15	5.2	4.5	12.0	0.01	4.7	16.7	16.71
C-3 ROW A	3010	20.2		7.1	0.9	492	-112	210	260	1	3	2	7.4	4.0	12.0 <	0.01	2.3	14.3	14.31
C-3 ROW B	7295	14.0		7.4	0.4	491	-150	215	10	2	1	1	4.7	4.3	9.9 <	0.01	4.6	14.5	14.51
C-3 ROW C	13283	18.0		7.2	0.3	471	-79	210	400	1	3	1	3.7	3.1	10.3 <	0.01	0.3	10.6	10.61
C-3 EFF	17720	19.2	0.0715	7.2	0.3	545	-86	185	300	4	3	2	1.6	1.4	6.5	0.06	10.2	16.7	16.76

D-1 and D-2 Influent samples - Quality Control
C represents Cell

Table 17. Detention Times During Dye Studies Conducted at Benton, Kentucky

Dye Study	August 23-27, 1988			June 19-23, 1989			September 4-15, 1989			September 19 - October 1, 1989		
Cell Number	1	2	3	1	2	3	1	2	3	1	2	3
Flow, MGD	0.1130	0.1130	0.2170	0.5143	0.5143	0.1403	0.2910	0.2910	0.0794	0.2410	0.2410	0.0657
Detention Time (days)												
theoretical	4.8	4.8	2.2	2.1	2.1	4.5	4.0	4.4	8.1	4.4	5.3	9.7
measured	3.0	3.0	0.7	1.5	1.5	3.9	2.1	3.0	11.1	1.6	3.1	12.3

Theoretical detention times determined by (1) area of cell, (2) actual measured cell depths for cells 1 and 2 for the June and September dye studies and average theoretical depths for cells 1 and 2 for the August dye study and cell 3 for all dye studies, (3) 24-hour average influent/effluent flow measured during sample collection, and (4) estimated porosities (90 percent for cells 1 and 2 and 30 percent for cell 3).

Table 18. Hydraulic Gradients and Calculated Permeabilities of Cell 3, Benton, Kentucky

HYDRAULIC GRADIENTS (FT) BETWEEN TRANSECTS
BENTON CELL # 3

Date	A/B	B/C	C/EFF
09/04/89	0.56	0.28	0.245
09/07/89	0.55	0.26	0.15
09/09/89	0.55	0.26	0.175
09/19/89	0.535	0.215	0.195
09/21/89	0.54	0.22	0.16
09/23/89	0.53	0.2	0.195
09/26/89	0.535	0.195	0.17
09/28/89	0.55	0.3	-0.255
09/30/89	0.69	0.34	-0.24
10/01/89	0.55	0.255	0.215
Median	0.55	0.26	0.215

Calculations: Assume average water depth of 1.8 feet at a flow of 8,596 ft3/day

K(a/b)=Q/AS=8,596 ft3/day/((144 ft*1.8 ft)*(0.55 ft/273.5 ft))=16,491 ft/day=>16,000 ft/day

K(b/c)=8,596 ft3/day/((144 ft*1.8 ft)*(0.26 ft/273.5 ft))=34,886 ft/day=>35,000 ft/day

K(c/eff)=8,596 ft3/day/((144 ft*1.8 ft)*(0.17 ft/273.5 ft))=53,355 ft/day=>53,000 ft/day

Check for laminar flow: (Taylor, D. W. Fundamentals of Soil Mechanics, John Wiley and Sons, Inc., New York, 15th Printing, October 1965, p. 122)

N=VD / q=((3.84*10-4 ft/sec)*0.48 ft*62.3 lb/ft3)/((2.05*10-5 lb-sec/ft2)*32.2 ft/sec2)=1.74

A Reynolds Number of 1 or less is considered a conservative value for laminar flow in soils. The calculated value of 1.74 is assumed to sufficiently close that laminar or transitional flow conditions exist and Darcy's Law is probably appropriate.

Table 19. TVA Constructed Wetland Demonstration Monthly Monitoring, Hardin, Kentucky

DATE	SOIL TEMP Celsius	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	INFLUENT F. COLI #/100Cml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
10/25/88		14.2	0.0479	7.2	5.0	1004	128	102	300000	470	35	4	2.8	2.8	3.7	5.80	7.1	10.8	16.60
11/29/88		15.0	0.1373	7.2	4.6	815	53	121	300000	220	180	56	11.8	8.4	11.5	1.30	18.0	30.0	31.30
12/13/88		14.0	0.0858	7.0	8.1	646	173	130	180000	40	25	8	0.6	0.5	14.5	0.03	0.7	15.2	15.23
01/24/89		13.3	0.1010	6.9	8.7	358	226	120	52000	37	11	7	2.2	1.5	4.2	0.01	5.2	9.4	9.41
02/22/89		10.1	0.3331	7.0	10.0	263	210	74	64000	81	70	> 15	2.8	1.4	2.7	1.60	7.3	10.0	11.60
03/28/89		13.8	0.1951	7.1	6.3	353	270	128	360000	94	49	33	4.6	3.1	9.7	0.01	7.8	17.0	17.01
04/26/89		16.5	0.1318	6.7	3.5	426	264	129	109000	78	44		4.8		13.0	< 0.01	14.0	26.5	26.51
05/24/89		19.6	0.1171	7.2	4.1	554	145	141	300000	130	34		6.3		16.4	< 0.01	10.0	26.5	26.51
06/27/89		21.1	0.0826	7.0	3.3	494	-39	129	340000	240	110		6.1		10.0	0.01	22.0	31.8	31.81
07/25/89		23.2	0.0674	7.0	3.8	793	-142	132	118000	36	43		6.5		9.2	0.02	6.7	21.5	21.52
08/15/89		22.6	0.0869	6.8	5.4	419	78	120	500000	55	37		2.8		6.7	< 0.01	6.5	13.2	13.21
09/20/89		23.2	0.0678	7.0	2.1	870	52	138	30000	30	19		4.5		14.0	0.01	3.0	17.0	17.01
10/24/89		20.1	0.1241	6.8	3.0	515	138	172	420000	110	61		6.5		6.0	0.32	6.5	25.0	25.32
AVERAGES*																			
OVERALL		17.4	0.1214	7.0	5.2	578	120	126	176424	125	55	21	4.8	2.9	9.4	0.70	8.8	19.5	20.23
10/88		14.2	0.0479	7.2	5.0	1004	128	102	300000	470	35	4	2.8	2.8	3.7	5.80	7.1	10.8	16.60
11/88-04/89		13.8	0.1640	7.0	6.9	477	199	117	138479	92	63	24	4.5	3.0	9.3	0.49	8.8	18.0	18.51
05/89-10/89		21.6	0.0910	7.0	3.6	608	39	139	205733	100	51		5.5		10.4	0.96	9.1	22.5	22.56

Table 19. (continued)

DATE	SOIL TEMP Celsius	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	EFFLUENT CELL 1 F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
10/25/88	9.2	10.5	0.0159	7.1	4.0	906	181	165	5	12	1	1	0.2	0.2	0.2	3.50	0.4	0.6	4.10
11/29/88	5.5	10.5	0.0731	7.8	4.8	561	178	144	1400	4	7	4	1.7	0.8	7.4	0.19	6.2	3.6	3.79
12/13/88	1.7	4.3	0.0379	7.6	0.4	578	87	150	200	1	4	3	0.5	0.5	5.7	0.59	2.5	8.2	8.79
01/24/89	7.0	6.9	0.0460	7.5	1.0	445	182	138	800	2	4	3	1.1	0.0	5.0	0.48	0.8	5.8	6.28
02/22/89	7.0	4.8	0.4085	7.1	3.0	278	184	88	940	2	13	8	1.9	1.0	3.7	0.58	0.2	3.8	4.38
03/28/89	19.0	16.6	0.1162	7.3	0.4	464	135	170	25000	78	> 14	> 13	3.1	3.0	11.5	< 0.01	1.3	13.0	13.01
04/26/89	22.0	21.7	0.0732	7.0	0.1	592	93	280	7800	14	38		2.4		17.0	0.02	1.9	18.9	18.92
05/24/89	17.5	21.4	0.0821	7.0	0.4	687	-12	222	6800	8	24		3.5		22.0	< 0.01	0.5	22.5	22.51
06/27/89	26.7	26.4	0.0562	6.9	0.5	581	-185	190	8100	17	5		1.9		12.8	0.02	0.2	13.0	13.02
07/25/89	26.7	25.6	0.0322	6.9	0.2	592	-187	212	2300	8	5		1.2		13.0	0.01	8.5	21.5	21.51
08/15/89	24.4	24.9	0.0536	6.8	0.5	587	-116	183	2000	95	5		3.0		12.0	0.06	1.2	13.2	13.26
09/20/89	19.4	20.9	0.0529	7.0	0.2	810	-129	195	900	12	4		1.2		17.0	0.07	0.8	17.8	17.87
10/24/89	15.0	15.4	0.0146	7.1	0.5	831	-38	184	150	9	5		1.3		14.0	< 0.01	0.5	14.5	14.51
AVERAGES AND PERCENT REMOVALS*																			
OVERALL	15.8	16.1	0.0817	7.1	1.2	609	29	179	1162	20	10	5	1.8	0.9	10.9	0.43	1.9	12.0	12.46
% REMOVAL			32.7	-1.5	76.4	-5.4	76.0	-41.9	99.3	83.8	81.9	74.0	63.1	69.6	-16.2	39.3	78.3	38.4	38.4
10/88	9.2	10.5	0.0159	7.1	4.0	906	181	165	5	12	1	1	0.2	0.2	0.2	3.50	0.4	0.6	4.10
% REMOVAL			66.8	1.4	20.0	9.8	-41.4	-61.8	100.0	97.4	97.1	75.0	93.6	93.6	93.8	39.7	94.8	94.4	75.3
11/88-04/89	11.0	10.8	0.1258	7.4	1.6	486	143	162	1857	17	13	6	1.8	1.0	8.4	0.31	2.1	8.9	9.20
% REMOVAL			23.3	-5.7	76.4	-2.0	28.2	-38.2	98.7	81.6	78.9	73.9	60.1	65.1	9.5	36.8	75.8	50.7	50.3
05/89-10/89	21.6	22.4	0.0486	7.0	0.4	681	-111	198	1802	25	8		2.0		15.1	0.03	2.0	17.1	17.11
% REMOVAL			46.6	0.2	89.2	-12.2	387.5	-42.5	99.1	75.2	83.9		63.0		-45.7	52.6	78.6	24.1	24.2

Table 19. (continued)

DATE	SOIL TEMP Celsius	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	EFFLUENT CELL 2 F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
10/25/88	8.7	10.6	0.0159	7.2	1.5	874	172	166	1	2	1	1	0.1	0.1	0.7	3.00	0.3	0.9	3.90
11/29/88	9.6	7.2	0.0610	7.5	0.6	498	185	145	400	2	4	3	1.4	0.8	4.9	0.50	0.6	5.5	6.00
12/13/88	3.2	3.6	0.0344	7.5	1.2	563	102	145	630	1	5	4	6.2	0.4	8.5	0.01	1.0	9.5	9.51
01/24/89	7.0	7.0	0.0372	7.6	0.4	441	161	142	900	3	4	2	0.8	0.7	5.6	0.12	1.1	6.7	6.82
02/22/89	8.0	5.2	0.3956	7.1	1.2	287	184	88	920	3	11	9	1.7	0.9	3.8	0.40	0.8	4.6	5.00
03/28/89**																			
04/26/89**																			
05/24/89**																			
06/27/89	26.1	25.7	0.0343	6.9	0.4	553	-171	185	3400	64	4		3.9		6.3	0.01	1.8	8.1	8.11
07/25/89	26.1	24.5	0.0354	6.8	0.2	610	-134	208	200	9	3		2.4		6.0	0.01	6.9	12.9	12.91
08/15/89	21.6	22.4	0.0399	6.8	0.4	611	-119	205	30	6	1		1.3		6.1	< 0.01	1.1	7.1	7.11
09/20/89	19.4		0.0273					163	400	9	4		1.1		13.0	0.08	0.2	13.2	13.28
10/24/89	13.3	14	0.0523	7.3	0.3	606	-76	190	940	1	4		1.9		10.0	0.05	1.3	11.7	11.75
AVERAGES AND PERCENT REMOVALS*																			
OVERALL	14.3	13.4	0.0733	7.2	0.7	560	34	164	263	10	4	4	2.1	0.6	6.5	0.42	1.5	8.0	8.44
% REMOVAL			39.6	-2.8	86.8	3.0	71.8	-30.1	99.9	92.0	92.5	81.5	56.7	80.4	30.6	40.4	82.9	58.9	58.3
10/88	8.7	10.6	0.0159	7.2	1.5	874	172	166	1	2	1	1	0.1	0.1	0.7	3.00	0.3	0.9	3.90
% REMOVAL			66.8	0.0	70.0	12.9	-34.4	-62.7	100.0	99.6	97.1	75.0	96.4	96.4	81.9	48.3	96.5	91.7	76.5
11/88-04/89	7.0	5.8	0.1321	7.5	0.9	447	158	130	676	2	6	5	2.5	0.7	5.7	0.26	0.9	6.6	6.83
% REMOVAL			19.5	-7.4	87.6	6.2	20.7	-11.1	99.5	97.5	90.5	81.1	43.6	76.6	38.5	47.8	90.0	63.5	63.1
05/89-10/89	21.3	21.7	0.0378	6.9	0.3	595	-125	190	378	18	3		2.1		8.3	0.03	2.3	10.6	10.63
% REMOVAL			58.4	1.0	90.9	2.1	423.3	-37.2	99.8	82.2	93.5		61.1		20.3	49.5	75.2	52.9	52.9

* pH - median values and fecal coliform - geometric mean values
** no flow in Cell B

Table 20. TVA Total Constructed Wetland System Performance, Hardin, Kentucky

DATE	pH	D.O.	F. COLI	TSS	BOD5	DIS BOD5	TOT P	DIS P	NH3-N	NO3-NO2	ORGANIC N	TKN	TN
		mg/l	#/100ml	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
10/25/88	7.2	2.8	3	7.0	1.0	1.0	0.1	0.1	0.5	3.25	0.3	0.8	4.00
11/29/88	7.7	2.9	945	3.1	5.6	3.5	1.6	0.8	6.3	0.33	3.7	4.5	4.80
12/13/88	7.6	0.8	405	1.0	4.5	3.5	3.2	0.4	7.0	0.31	1.8	8.8	9.13
01/24/89	7.5	0.7	845	2.4	4.0	2.6	1.0	0.3	5.3	0.32	0.9	6.2	6.52
02/22/89	7.1	2.1	930	2.5	12.0	8.5	1.8	0.9	3.7	0.49	0.5	4.2	4.69
03/28/89	7.3	0.4	25000	78.0	14.0	13.0	3.1	3.0	11.5	0.01	1.3	13.0	13.01
04/26/89	7.0	0.1	7800	14.0	38.0		2.4		17.0	0.02	1.9	18.9	18.92
05/24/89	7.0	0.4	6800	8.0	24.0		3.5		22.0	0.01	0.5	22.5	22.51
06/27/89	6.9	0.5	6319	34.8	5.0		2.7		10.3	0.02	0.8	11.1	11.16
07/25/89	6.8	0.2	1200	8.5	3.9		1.8		9.3	0.01	7.7	17.0	17.01
08/15/89	6.8	0.5	1159	57.0	3.7		2.3		9.5	0.04	1.2	10.6	10.64
09/20/89	7.0	0.2	730	11.0	3.8		1.2		15.6	0.07	0.6	16.2	16.31
10/24/89	7.3	0.3	768	2.7	4.5		1.8		10.9	0.04	1.1	12.3	12.35
AVERAGES*													
OVERALL	7.1	0.91	1146	17.7	9.5	5.3	2.0	0.9	9.9	0.38	1.7	11.2	11.61
10/88	7.2	0.75	3	18.5	10.3	6.2	2.2	1.1	10.7	0.14	1.8	12.1	12.25
11/88-04/89	7.4	0.56	1971	20.0	10.7	6.9	2.2	1.2	11.1	0.12	1.7	12.8	12.93
05/89-10/89	7.0	0.57	1795	21.5	11.1	7.3	2.1	1.3	11.4	0.13	1.7	13.0	13.15

* pH - median values and fecal coliform - geometric mean values

Table 21. Evaluation of NPDES Compliance, Hardin, Kentucky

Parameter	Monthly Ave NPDES Limit	Municipal Data[a] Before Wetlands Operations (Jan 88 to Sept 88) Ave	Max	Min	Samples Not Meeting Limit No.[b]	%	After Wetlands Operations (Oct 88 to Oct 89) Ave	Max	Min	Samples Not Meeting Limit No.[b]	%
BOD_5, mg/l	10	23	56	8	7/9	78	11	27	3	5/13	38
TSS, mg/l	30	32	84	2	4/9	44	9	22	1	0/13	0
NH_3-N, mg/l											
May-Oct	4	12.4	21.4	6.3	3/5	60	11.6	19.3	1.1	6/7	86
Nov-Apr	10	7.4	13.5	1.1	3/4	75	6.8	10.7	1.8	2/6	33
FC, #/100 ML	200	3059[c]	60000	5	8/9	89	928[c]	60000	5	9/13	69
pH, units	6-9	7.1[d]	7.6	6.6	0/9	0	7.1[d]	7.8	6.6	0/13	0
DO, mg/l	≥7	5.3	9.4	0.1	5/9	56	7.8	10	1	3/13	23

Parameter	Monthly Ave NPDES Limit	TVA Data[e] (Oct 88 to Oct 89) Cell 1 Ave	Max	Min	Samples Exceeding Limit No.[b]	%	Cell 2 Ave	Max	Min	Samples Exceeding Limit No.[b]	%	TVA Data (Oct 88 to Oct 89) Total System[f] Ave	Max	Min	Samples Exceeding Limit No.[b]	%
BOD_5, mg/l	10	10	38	1	4/13	31	4.1	11	1	1/10	10	10	38	1	4/13	31
TSS, mg/l	30	20	95	1	2/13	15	10	64	1	1/10	10	18	78	1	3/13	23
NH_3-N, mg/l																
May-Oct	4	13	22	0.2	6/7	86	7.0	13	0.7	5/6	83	11.2	22	0.5	6/7	86
Nov-Apr	10	8.4	17	3.7	2/6	33	5.7	8.5	3.8	0/4	0	8.5	17	3.7	2/6	33
FC, #/100 ML	200	1162[c]	25000	5	11/13	85	263[c]	3400	1	7/10	70	1146[c]	25000	3	12/13	92
pH, units	6-9	7.2[d]	7.8	6.8	0/13	0	7.2[d]	7.6	6.8	0/9	0	7.1[d]	7.7	6.8	0/13	0
DO, mg/l	≥7	1.2	4.8	0.1	13/13	100	0.7	1.5	0.2	9/9	100	0.9	2.9	0.1	13/13	100

a. Measured at point of discharge
b. Number of samples not meeting limit/total samples
c. Geometric Mean
d. Median
e. Measured at end of wetland cell
f. Calculated based on flows and concentrations of each cell

Table 22. TVA Constructed Wetland Demonstration Mass Loadings of Cell 1, Hardin, Kentucky

INFLUENT CELL 1

DATE	FLOW	HLR	D.O.	ALK CaCO3	TSS	BOD5	DIS BOD5	TOT P	DIS P	NH3-N	NO3-NO2	ORGANIC N	TKN	TN
	MGD	MGD/acre	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day
10/25/88	0.0240	0.0150	1.00	20.4	93.9	7.0	0.8	0.6	0.6	0.74	1.159	1.42	2.2	3.3
11/29/88	0.0687	0.0429	2.64	69.3	126.0	103.1	32.1	6.8	4.8	6.59	0.745	10.31	17.2	17.9
12/13/88	0.0429	0.0268	2.90	46.5	14.3	9.0	2.9	0.2	0.2	5.19	0.011	0.25	5.4	5.5
01/24/89	0.0505	0.0316	3.67	50.6	15.6	4.6	2.9	0.9	0.6	1.77	0.004	2.19	4.0	4.0
02/22/89	0.1666	0.1041	13.90	102.8	112.6	97.3	20.8	3.9	1.9	3.75	2.224	10.15	13.9	16.1
03/28/89	0.1951	0.1219	10.26	208.4	153.0	79.8	53.7	7.5	5.0	15.79	0.016	12.70	27.7	27.7
04/26/89	0.1318	0.0824	3.85	141.9	85.8	48.4		5.3		14.30	0.011	15.40	29.1	29.2
05/24/89	0.1171	0.0732	4.01	137.8	127.0	33.2		6.2		16.03	0.010	9.77	25.9	25.9
06/27/89	0.0413	0.0258	1.14	44.5	82.7	37.9		2.1		3.45	0.003	7.58	11.0	11.0
07/25/89	0.0337	0.0211	1.07	37.1	10.1	12.1		1.8		2.59	0.006	1.88	6.0	6.1
08/15/89	0.0435	0.0272	1.96	43.5	19.9	13.4		1.0		2.43	0.004	2.36	4.8	4.8
09/20/89	0.0339	0.0212	0.60	39.0	8.5	5.4		1.3		3.96	0.003	0.85	4.8	4.8
10/24/89	0.0621	0.0388	1.55	89.1	57.0	31.6		3.4		3.11	0.166	3.37	13.0	13.1
AVERAGES														
OVERALL	0.0778	0.0486	3.73	79.3	69.7	37.1	18.9	3.1	2.2	6.13	0.335	6.02	12.7	13.0
10/88	0.0240	0.0150	1.00	20.4	93.9	7.0	0.8	0.6	0.6	0.74	1.159	1.42	2.2	3.3
11/88-04/89	0.1093	0.0683	6.20	103.3	84.6	57.0	22.5	4.1	2.5	7.90	0.502	8.50	16.2	16.7
05-10/89	0.0553	0.0345	1.72	65.2	50.9	22.3		2.6		5.26	0.032	4.30	10.9	10.9

EFFLUENT CELL 1

DATE	FLOW	HLR	D.O.	ALK CaCO3	TSS	BOD5	DIS BOD5	TOT P	DIS P	NH3-N	NO3-NO2	ORGANIC N	TKN	TN
	MGD	MGD/acre	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day
10/25/88	0.0159		0.53	21.9	1.6	0.1	0.1	0.02	0.02	0.03	0.464	0.05	0.1	0.5
11/29/88	0.0731		2.93	87.8	2.4	4.3	2.4	1.0	0.5	4.51	0.116	3.78	2.2	2.3
12/13/88	0.0379		0.13	47.4	0.3	1.3	0.9	0.2	0.1	1.80	0.187	0.79	2.6	2.8
01/24/89	0.0460		0.38	53.0	0.8	1.5	1.2	0.4	0.004	1.92	0.184	0.29	2.2	2.4
02/22/89	0.4085		10.23	300.0	6.8	44.3	27.3	6.5	3.3	12.61	1.977	0.51	13.0	14.9
03/28/89	0.1162		0.37	164.8	75.6	13.6	12.6	3.0	2.9	11.15	0.010	1.26	12.6	12.6
04/26/89	0.0732		0.07	171.0	8.6	23.2		1.5		10.38	0.012	1.16	11.5	11.6
05/24/89	0.0821		0.28	152.1	5.5	16.4		2.4		15.07	0.007	0.34	15.4	15.4
06/27/89	0.0562		0.23	89.1	8.0	2.5		0.9		6.00	0.009	0.09	6.1	6.1
07/25/89	0.0322		0.06	57.0	2.1	1.5		0.3		3.49	0.003	2.28	5.8	5.8
08/15/89	0.0536		0.22	81.9	42.5	2.4		1.3		5.37	0.027	0.54	5.9	5.9
09/20/89	0.0529		0.09	86.1	5.3	1.7		0.5		7.50	0.031	0.35	7.9	7.9
10/24/89	0.0146		0.06	22.4	1.1	0.6		0.2		1.71	0.001	0.06	1.8	1.8
AVERAGES AND PERCENT REMOVALS														
OVERALL	0.0817		1.20	102.7	12.4	8.7	7.4	1.4	1.1	6.27	0.233	0.89	6.7	6.9
% REMOVAL	-5.1		67.9	-29.4	82.3	76.5	60.7	55.4	48.2	-2.4	30.6	85.3	47.2	46.8
10/88	0.0159		0.53	21.9	1.6	0.1	0.1	0.02	0.02	0.03	0.464	0.05	0.1	0.5
% REMOVAL	33.6		46.9	-7.4	98.3	98.1	83.4	95.7	95.7	95.9	59.9	96.5	96.3	83.6
11/88-04/89	0.1258		2.35	137.4	15.8	14.7	8.9	2.1	1.4	7.06	0.414	1.30	7.4	7.8
% REMOVAL	-15.2		62.1	-33.0	81.4	74.2	60.5	48.9	46.1	10.6	17.4	84.7	54.7	53.5
05-10/89	0.0486		0.16	81.4	10.7	4.2		0.9		6.53	0.013	0.61	7.1	7.2
% REMOVAL	12.0		90.8	-24.9	78.9	81.2		64.1		-24.1	59.2	85.8	34.6	34.6

Table 23. TVA Constructed Wetland Demonstration Mass Loadings of Cell 2, Hardin, Kentucky

INFLUENT CELL 2

DATE	FLOW	HLR	D.O.	ALK	TSS	BOD5	DIS BOD5	TOT P	DIS P	NH3-N	NO3-NO2	ORGANIC N	TKN	TN
				CaCO3										
	MGD	MGD/acre	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day
10/25/88	0.0240	0.0150	1.00	20.4	93.9	7.0	0.8	0.6	0.6	0.74	1.159	1.42	2.2	3.3
11/29/88	0.0687	0.0429	2.64	69.3	126.0	103.1	32.1	6.8	4.8	6.59	0.745	10.31	17.2	17.9
12/13/88	0.0429	0.0268	2.90	46.5	14.3	9.0	2.9	0.2	0.2	5.19	0.011	0.25	5.4	5.5
01/24/89	0.0505	0.0316	3.67	50.6	15.6	4.6	2.9	0.9	0.6	1.77	0.004	2.19	4.0	4.0
02/22/89	0.1666	0.1041	13.90	102.8	112.6	97.3	20.8	3.9	1.9	3.75	2.224	10.15	13.9	16.1
03/28/89														
04/26/89														
05/24/89														
06/27/89	0.0413	0.0258	1.14	44.5	82.7	37.9		2.1		3.45	0.003	7.58	11.0	11.0
07/25/89	0.0337	0.0211	1.07	37.1	10.1	12.1		1.8		2.59	0.006	1.88	6.0	6.1
08/15/89	0.0435	0.0272	1.96	43.5	19.9	13.4		1.0		2.43	0.004	2.36	4.8	4.8
09/20/89	0.0339	0.0212	0.60	39.0	8.5	5.4		1.3		3.96	0.003	0.85	4.8	4.8
10/24/89	0.0621	0.0388	1.55	89.1	57.0	31.6		3.4		3.11	0.166	3.37	13.0	13.1
AVERAGES														
OVERALL	0.0567	0.0354	3.04	54.3	54.1	32.1	11.9	2.2	1.6	3.36	0.433	4.04	8.2	8.7
10/88	0.0240	0.0150	1.00	20.4	93.9	7.0	0.8	0.6	0.6	0.74	1.159	1.42	2.2	3.3
11/88-04/89	0.0821	0.0514	5.78	67.3	67.1	53.5	14.7	2.9	1.9	4.33	0.746	5.73	10.1	10.9
05/10-89	0.0429	0.0268	1.26	50.6	35.6	20.1		1.9		3.11	0.036	3.21	7.9	8.0

EFFLUENT CELL 2

DATE	FLOW	HLR	D.O.	ALK	TSS	BOD5	DIS BOD5	TOT P	DIS P	NH3-N	NO3-NO2	ORGANIC N	TKN	TN
				CaCO3										
	MGD	MGD/acre	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day	lbs/day
10/25/88	0.0159		0.20	22.0	0.3	0.1	0.1	0.01	0.01	0.09	0.398	0.03	0.1	0.5
11/29/88	0.0610		0.31	73.8	1.0	2.0	1.5	0.7	0.4	2.49	0.255	0.31	2.8	3.1
12/13/88	0.0344		0.34	41.6	0.3	1.4	1.1	1.8	0.1	2.44	0.003	0.29	2.7	2.7
01/24/89	0.0372		0.12	44.1	0.9	1.2	0.6	0.2	0.2	1.74	0.037	0.34	2.1	2.1
02/22/89	0.3956		3.96	290.5	9.9	36.3	29.7	5.6	3.1	12.54	1.321	2.71	15.2	16.5
03/28/89														
04/26/89														
05/24/89														
06/27/89	0.0343		0.11	53.0	18.3	1.3		1.1		1.80	0.003	0.52	2.3	2.3
07/25/89	0.0354		0.06	61.4	2.7	0.7		0.7		1.77	0.003	2.04	3.8	3.8
08/15/89	0.0399		0.13	68.3	2.0	0.5		0.4		2.03	0.003	0.37	2.4	2.4
09/20/89	0.0273			37.1	2.1	0.9		0.3		2.96	0.018	0.05	3.0	3.0
10/24/89	0.0523		0.13	82.9	0.4	1.7		0.8		4.36	0.022	0.57	5.1	5.1
AVERAGES AND PERCENT REMOVALS														
OVERALL	0.0733		0.6	77.5	3.8	4.6	6.6	1.2	0.8	3.22	0.206	0.72	4.0	4.2
% REMOVAL	-29.3		80.4	-42.7	93.0	85.6	44.3	47.0	53.0	4.0	52.3	82.1	52.0	52.0
10/88	0.0159		0.2	22.0	0.3	0.1	0.1	0.0	0.0	0.09	0.398	0.03	0.1	0.5
% REMOVAL	33.8		80.1	-8.0	99.7	98.1	83.4	97.8	97.8	88.0	65.7	97.7	94.6	84.3
11/88-04/89	0.1320		1.18	112.5	3.0	10.3	8.3	2.1	0.9	4.80	0.404	0.91	5.7	6.1
% REMOVAL	-60.7		79.5	-67.2	95.5	80.8	43.8	29.3	49.4	-11.1	45.9	84.1	43.7	43.9
05-10/89	0.0378		0.11	60.5	5.1	1.0		0.7		2.59	0.010	0.71	3.3	3.3
% REMOVAL	11.8		91.2	-19.5	85.7	95.0		65.5		16.8	72.9	78.0	58.1	58.2

Table 24. TVA Constructed Wetland Demonstration Monthly Monitoring, Pembroke, Kentucky

INFLUENT

DATE	SOIL TEMP Celsius	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
12/13/88		11.8	0.0480	7.3	0.5	888	154		740000	80	130	26	8.1	6.6	25.5	0.80	5.5	31.0	31.80
01/25/89	9.0	13.7	0.0688	7.3	1.3	990	124	367	690000	140	109	50	8.0	4.5	22.0	< 0.01	4.5	26.5	26.51
02/23/89	5.0	10.9	0.1100	7.3	5.6	535	208	185	97000	47	41	10	1.9	1.2	2.0	4.70	6.8	8.8	13.50
03/29/89	21.0	17.2	0.0806	7.4	0.2	1176	25	330	60000	99	69	32	8.6	5.1	21.4	< 0.01	76.0	97.0	97.01
April																			
May																			
06/29/89	20.0	23.6	0.0378	7.3	1.8	832	36	294	6100	55	68		3.8		11.7	0.12	8.3	20.0	20.12
07/26/89	27.0	25.4	0.0407	7.2	1.7	908	45	292	32000	42	22		4.0		5.5	0.15	6.4	11.9	12.05
08/16/89	21.7	23.7	0.0706	7.2	2.2	964	244	325	700000	44	60		5.1		16.0	0.07	4.0	20.0	20.07
09/20/89	20.5	22.2	0.0540	7.2	0.9	1530	80	400	560000	170	24		8.6		1.1	1.00	46.0	47.0	48.00
10/25/89	18.0	20.1	0.1717	7.2	1.8	1175	298	370	420000	150	84		6.2		16.0	< 0.01	7.0	23.0	23.01
AVERAGES*																			
OVERALL	17.8	18.7	0.0758	7.3	1.8	1000	135	285	165959	92	67	29	6.0	4.4	13.5	0.76	18.3	31.7	32.45
12/88-04	11.7	13.4	0.0769	7.3	1.9	897	128	221	233480	92	87	29	6.6	4.4	17.7	1.38	23.2	40.8	42.21
05/89-10	21.4	23.0	0.0750	7.2	1.7	1082	141	336	126300	92	52		5.5		10.1	0.27	14.3	24.4	24.65

MARSH B1

DATE	SOIL TEMP Celsius	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
12/13/88																			
01/25/89																			
02/23/89																			
03/29/89																			
April																			
May																			
06/29/89		25.9		7.2	0.4	824	-183	175	2300	50	11		2.0		0.6	0.13	3.2	3.8	3.93
07/26/89		31.0		7.0	0.2	771	-220	213	< 10	20	25		3.5		1.5	< 0.01	3.9	5.4	5.41
08/16/89		21.8		7.1	0.3	1030	-107	253	6000	15	7		5.7		6.0	< 0.01	2.6	8.6	8.61
09/20/89		19.1		7.2	0.2	950	-142	310	3200	18	16		4.8		12.0	0.12	1.2	13.2	13.32
10/24/89		15.5		7.3	3.2	1120	35	331	230	8	14		4.3		13.0	0.58	2.4	14.7	15.28
AVERAGES AND PERCENT REMOVALS*																			
OVERALL		22.7		7.2	0.9	939	-123	256	633	22	15		4.1		6.6	0.17	2.7	9.1	9.31
% REMOVAL				0.9	48.2	13.2	187.8	23.7	99.5	75.9	71.9		26.7		34.1	37.0	81.5	62.5	62.2

Table 24. (continued)

MARSH B2

DATE	SOIL TEMP Celsius	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
12/13/88																			
01/25/89																			
02/23/89																			
03/29/89																			
April																			
May																			
06/29/89		26.6		7.1	0.3	823	-180	240	2900	17	9		3.0		4.4	< 0.01	5.0	9.4	9.41
07/26/89		30.8		7.1	0.3	775	-210	194	200	22	11		3.4		1.9	< 0.01	3.5	5.4	5.41
08/16/89		21.5		7.1	0.2	1025	-106	282	6400	18	6		5.3		7.0	< 0.01	3.6	10.6	10.61
09/20/89		20.3		7.2	1.0	962	30	282	4800	14	11		4.5		12.0	< 0.01	4.1	16.1	16.11
10/24/89		16.4		7.5	3.1	1045	10	295	770	6	7		5.1		13.0	0.54	2.0	14.7	15.24
AVERAGES AND PERCENT REMOVALS*																			
OVERALL		23.0		7.1	1.0	926	-91	259	1688	15	9		4.3		7.7	0.12	3.6	11.2	11.36
% REMOVAL				1.7	41.3	14.4	164.9	23.1	98.7	83.3	82.8		23.1		23.9	57.0	74.6	53.9	53.9

EFFLUENT

DATE	SOIL TEMP Celsius	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/l	COND umhos/cm	ORP	ALK CaCO3 mg/l	F. COLI #/100ml	TSS mg/l	BOD5 mg/l	DIS BOD5 mg/l	TOT P mg/l	DIS P mg/l	NH3-N mg/l	NO3-NO2 mg/l	ORGANIC N mg/l	TKN mg/l	TN mg/l
12/13/88		4.1	0.0000	8.1	16.9	738	148		460	12	13	2	3.0	2.9	0.4	3.30	0.3	0.7	4.00
01/25/89	10.0	9.4	0.0000	9.0	21.0	442	135	190	< 10	4	4	2	1.1	0.8	0.2	1.50	0.9	1.1	2.60
02/23/89		2.7	0.0903	7.5	10.8	513	183	250	40	3	6	3	2.1	2.1	4.5	0.90	1.2	5.7	6.60
03/29/89	22.0	22.3	0.0377	8.8	14.9	570	85	187	220	17	18	7	2.7	1.9	2.0	0.98	3.3	5.3	6.28
April																			
May																			
06/29/89	26.8		0.0026	7.8	6.9	590	28	243	390	13	24		2.5		4.7	< 0.01	3.6	8.3	8.31
07/26/89	29.7		0.0016	7.6	8.7	809	42	235	630	14	8		3.0		0.7	0.15	2.8	3.5	3.65
08/16/89	23.9		0.0271	7.3	3.3	937	64	265	230	2	2		3.1		0.6	0.06	1.7	2.4	2.46
09/20/89		18.2	0.0369	7.3	0.6	958	24	332	5800	4	5		4.8		12.0	< 0.01	1.2	13.2	13.21
10/24/89		13.4	0.0162	7.6	2.0	1096	100	292	500	5	5		6.1		5.0	0.95	1.2	6.2	7.15
AVERAGES AND PERCENT REMOVALS*																			
OVERALL	22.5	13.2	0.0266	7.6	8.5	739	83	249	266	8	9	4	3.2	1.6	3.7	0.57	2.0	5.7	6.03
% REMOVAL			65.0	-4.6	-380.2	26.1	38.5	12.6	99.8	91.3	86.7	86.4	47.0	63.2	72.5	25.3	89.1	82.0	81.4
12/88-04	16.0	11.5	0.0427	8.4	15.6	508	134	209	80	8	9	4	2.0	1.6	2.2	1.13	1.8	4.0	5.16
% REMOVAL			44.5	-15.1	-716.1	43.3	-5.2	5.2	100.0	91.3	89.3	86.4	70.4	63.2	87.5	18.4	92.2	90.1	87.8
05/89-10	26.8	15.8	0.0169	7.6	4.3	878	52	273	696	8	9		3.9		4.6	0.24	2.1	6.7	6.96
% REMOVAL			77.5	-5.2	-159.0	18.8	63.0	18.8	99.4	91.3	82.6		29.6		54.3	11.1	85.4	72.5	71.8

* pH - median values and fecal coliform - geometric mean values
** effluent collected at pond

Table 25. Evaluation of NPDES Compliance, Pembroke, Kentucky

Parameter	Monthly Ave NPDES Limit	Municipal Before Wetlands Operations[a] (Nov 86 to Oct 87) Ave	Max	Min	Samples Not Meeting Limit No.[b]	%
BOD_5, mg/l	10	50	85	14	10/10	100
TSS, mg/l	30	81	132	32	10/10	100
NH_3-N, mg/l						
May-Oct	4	25	25.9	21.7	6/6	100
Nov-Apr	10	12	21	3	3/6	50
FC, #/100 ml[c]	200	4[d]	342	1	1/10	10
pH, units	6-9	7.3[e]	7.5	6.8	0/10	0
DO, mg/l	≥7	8.2	12	4.0	1/10	10

Parameter	Monthly Ave NPDES Limit	TVA Data (Feb 89 to Oct 89) Meadow Effluent[f] Ave	Max	Min	Samples Not Meeting Limit No.[b]	%
BOD_5, mg/l	10	10	24	2	2/7	29
TSS, mg/l	30	8	17	2	0/7	0
NH_3-N, mg/l						
May-Oct	4	4.6	12	0.6	3/5	60
Nov-Apr	10	3.3	4.5	2.0	0/2	0
FC, #/100 ml[g]	200	392[d]	5800	40	6/7	86
pH, units	6-9	7.6[e]	8.8	7.3	0/7	0
DO, mg/l	≥7	6.7	14.9	0.6	4/7	57

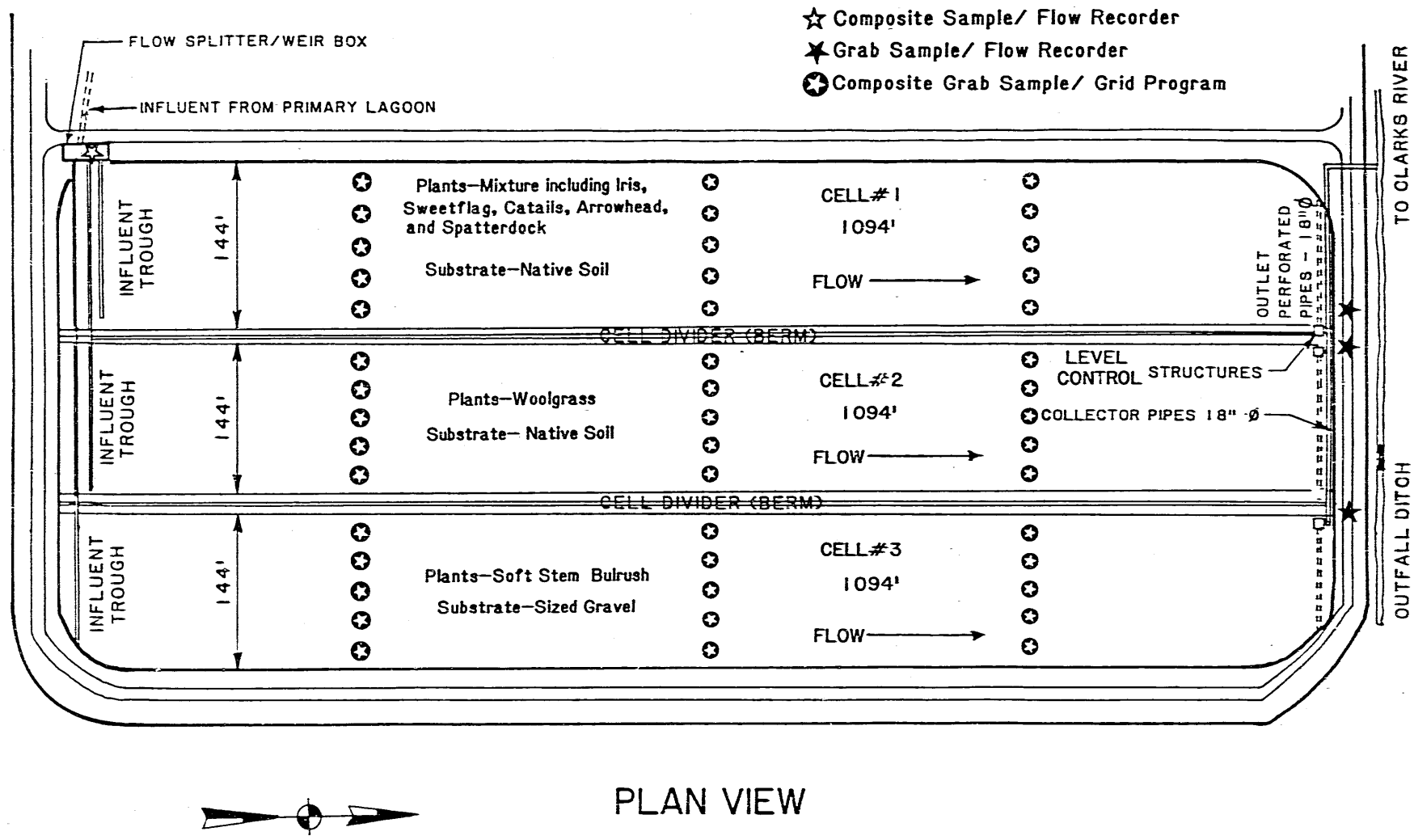
a. Measured at point of discharge
b. Number of samples not meeting limit/total samples
c. Most Probable Number Technique 11/86 - 10/87
d. Geometric Mean
e. Median
f. Measured at end of meadow (excluding Dec 88 and Jan 89 data collected from the pond)
g. Membrane Filter Technique 12/88 - 10/89

Table 26. TVA Constructed Wetland Dye Study Results, Pembroke, Kentucky, 03/19-23, 1989

LOCATION	TIME * Minutes	SOIL TEMP Celsius	WATER TEMP Celsius	FLOW MGD	pH	D.O. mg/L	COND umhos/cm	CRP	ALK CaCO3 mg/L	F. COLI #/100mL	TSS mg/L	BOD5 mg/L	DIS BOD5 mg/L	DIS P mg/L	TOT P mg/L	NH3-N mg/L	NO3-NO2 mg/L	ORGANIC N mg/L	TKN mg/L	TN mg/L
Influent	-45		12.6	0.0576	7.3	2.3	858	103	277	600000	72	42	24	2.3	3.6	10 <	0.01	7.00	17.0	17.01
Marsh B 1																				
Row A	285		16.4		8.0	3.7	860	134	430	85000	49	80	13	4.8	6.2	18.0 <	0.01	5.00	23.0	23.01
Row B	1194		9.7		7.5	0.7	843	121	280	70000	24	14	14	4.8	5.5	15.0 <	0.01	6.00	21.0	21.01
Row C	4129		2.8		7.7	4.8	729	225	262	12000	16	21	9	3.3	3.1	10.0	0.04	3.20	13.0	13.04
Marsh B 2																				
Row A	169		16.2		7.6	0.6	895	43	332	100000	70	102	30	4.8	6.4	18.0 <	0.01	7.00	25.0	25.01
Row B	930		10.7		7.6	0.6	812	132	270	86000	21	32	8	4.1	4.7	14.0 <	0.01	5.00	19.0	19.01
Row C	3432		6.0		7.9	4.3	735	216	259	1600	12	14	10	3.4	3.1	10	0.09	2.3	12.0	12.09
Pond	1320		10.6		7.6	1.7	724	208	240	6000	21 >	14	11	2.9	4.2	9.2 <	0.01	4.8	14.0	14.01
Meadow																				
Row A	360		2.8		8.0	7.0	688	191	225	2700	17	18	8	3.8	3.7	6.0	1.20	4.3	10.0	11.20
Effluent	1261		13.1	0.0097	7.3	6.1	650	268	216	100	9	14	6	3.5	3.4	2	1.20	5.9	7.9	9.10

* Dye was injected separately into each cell system. Time represents the amount of time it took the dye to travel through each individual system.

FIGURES



PLAN VIEW

Figure 1. Benton, Kentucky, Constructed Wetland Sewage Treatment System, Gravel and Surface Flow Marshes

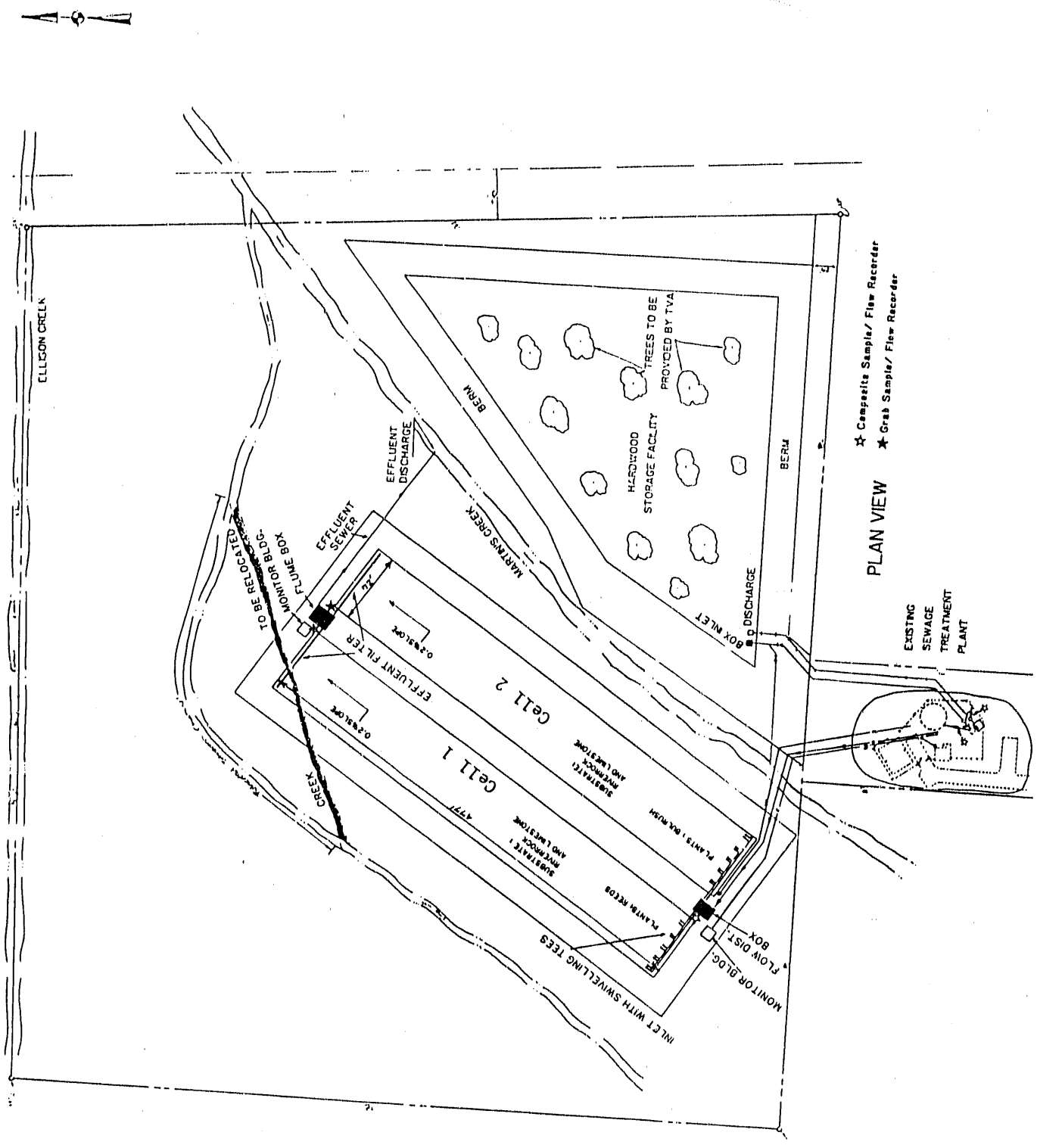


Figure 2. Hardin, Kentucky, Constructed Wetland Sewage Treatment System, Gravel Marshes

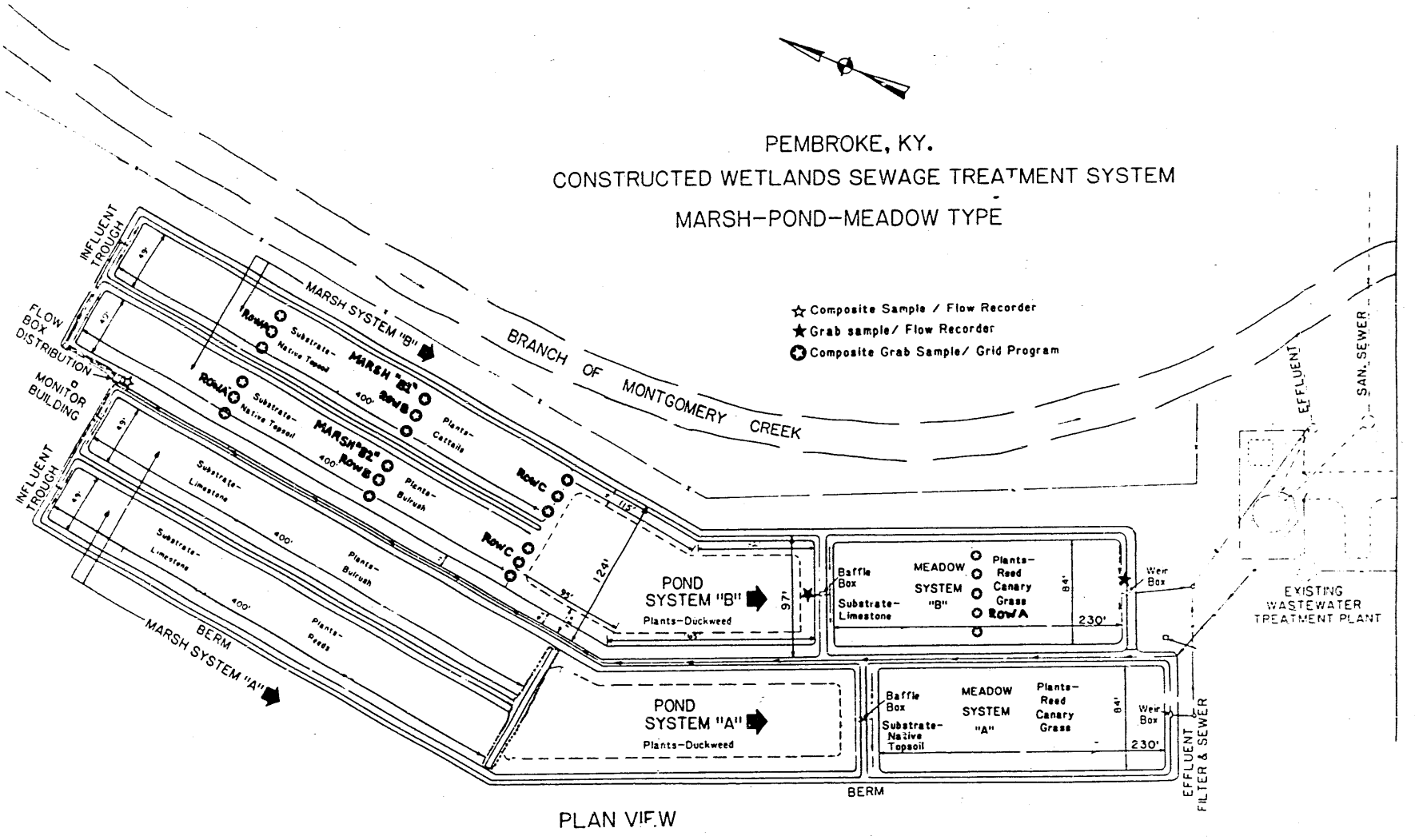
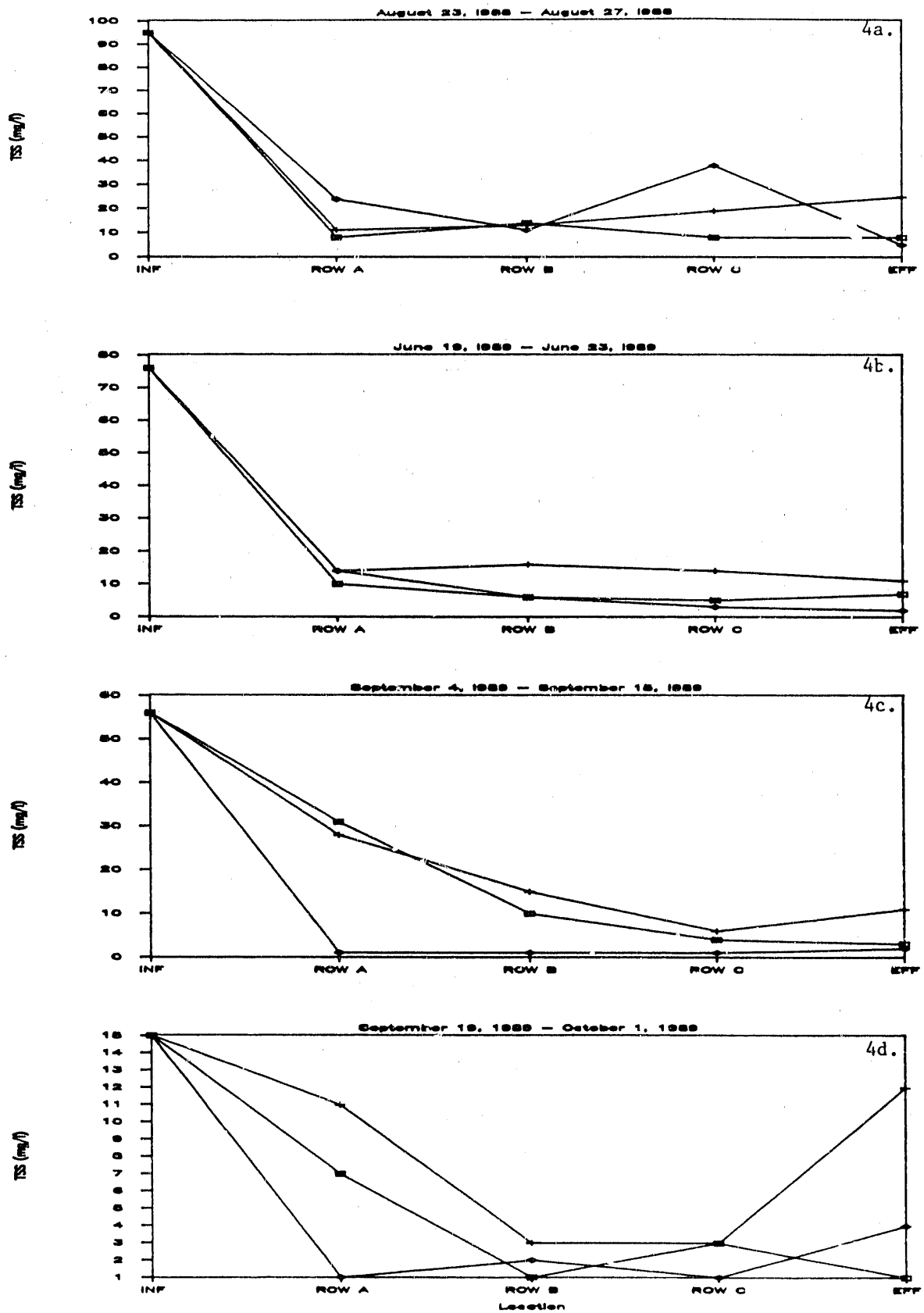
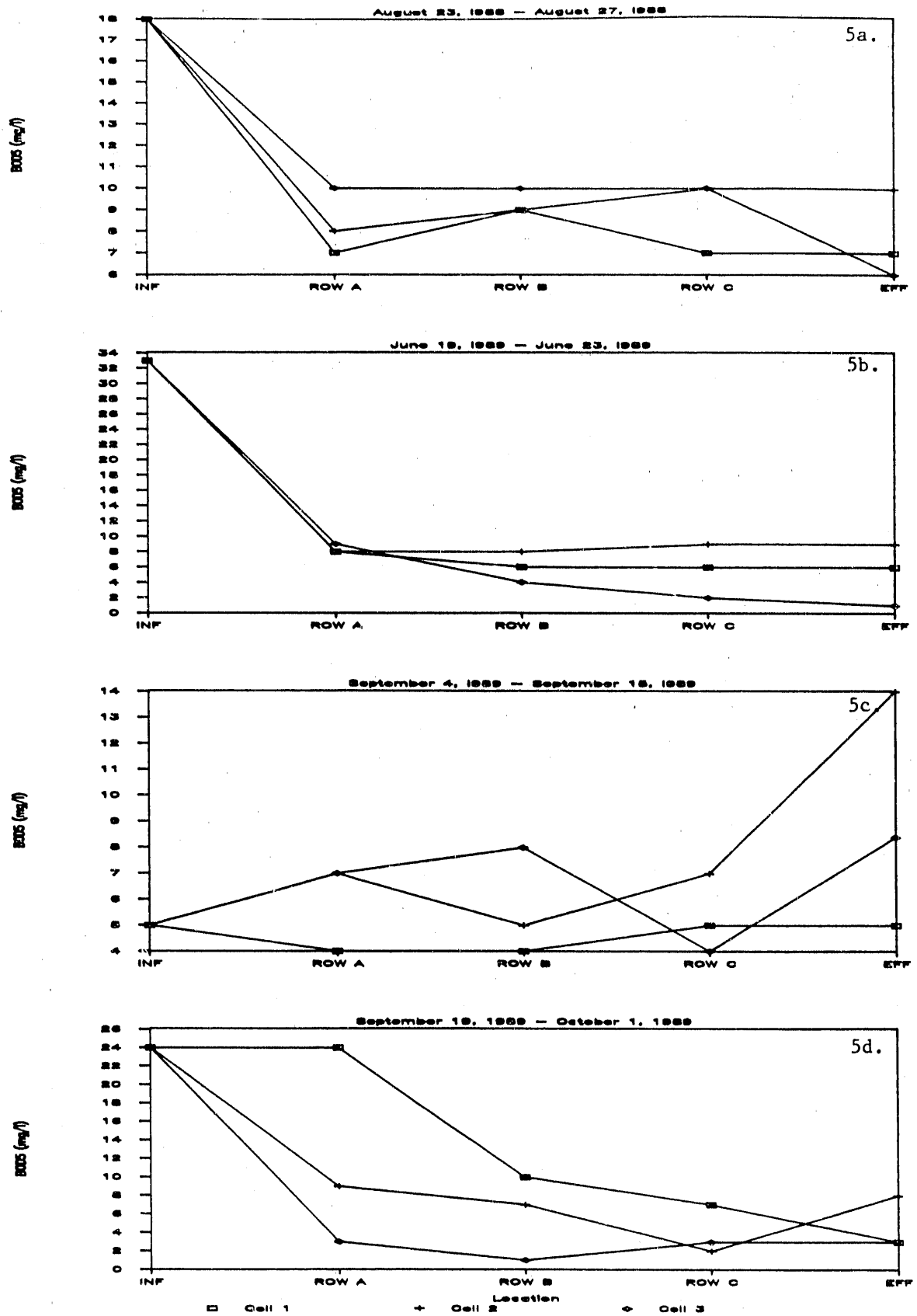


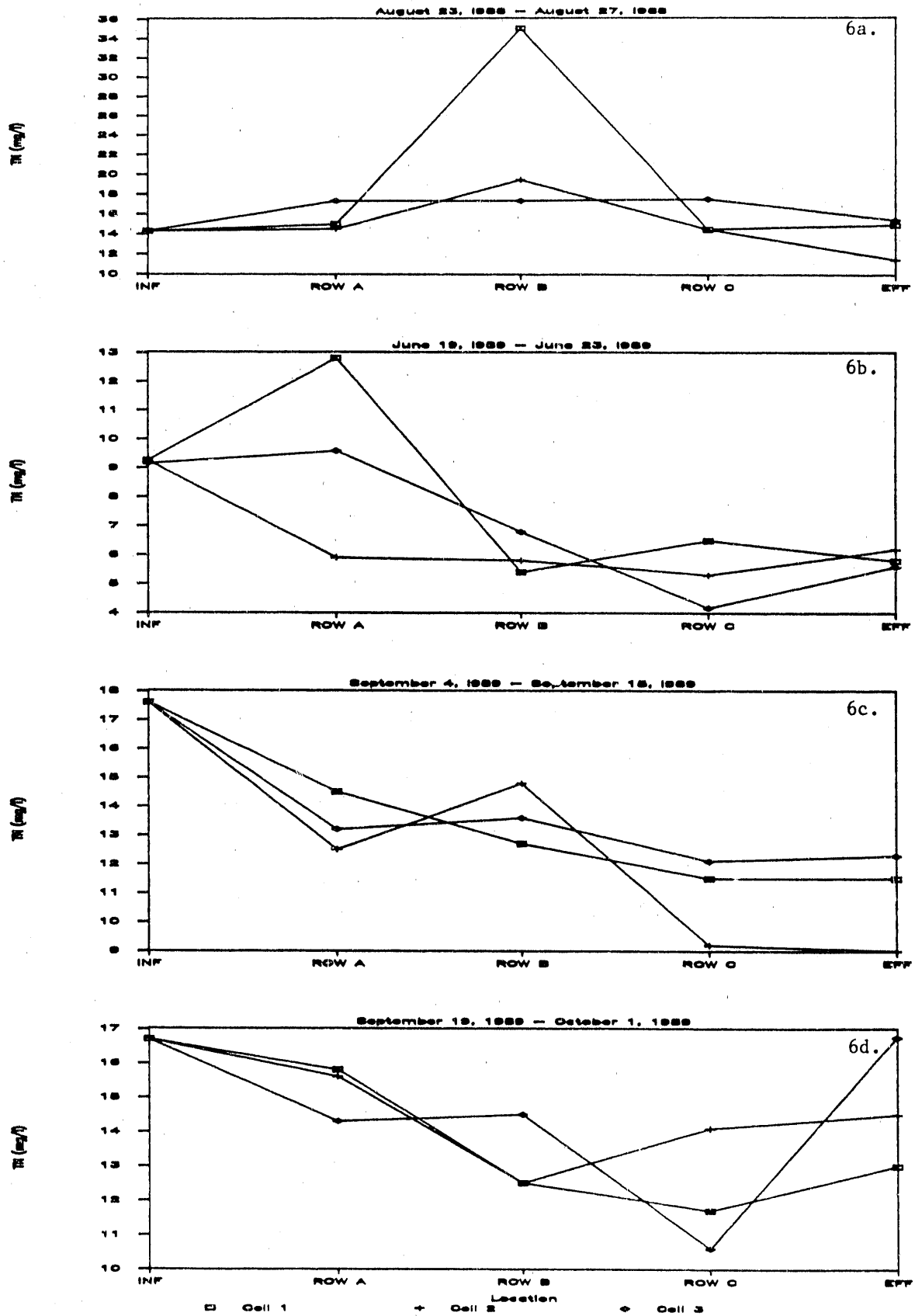
Figure 3. Pembroke, Kentucky, Constructed Wetland Sewage Treatment System, Marsh-Pond-Meadow



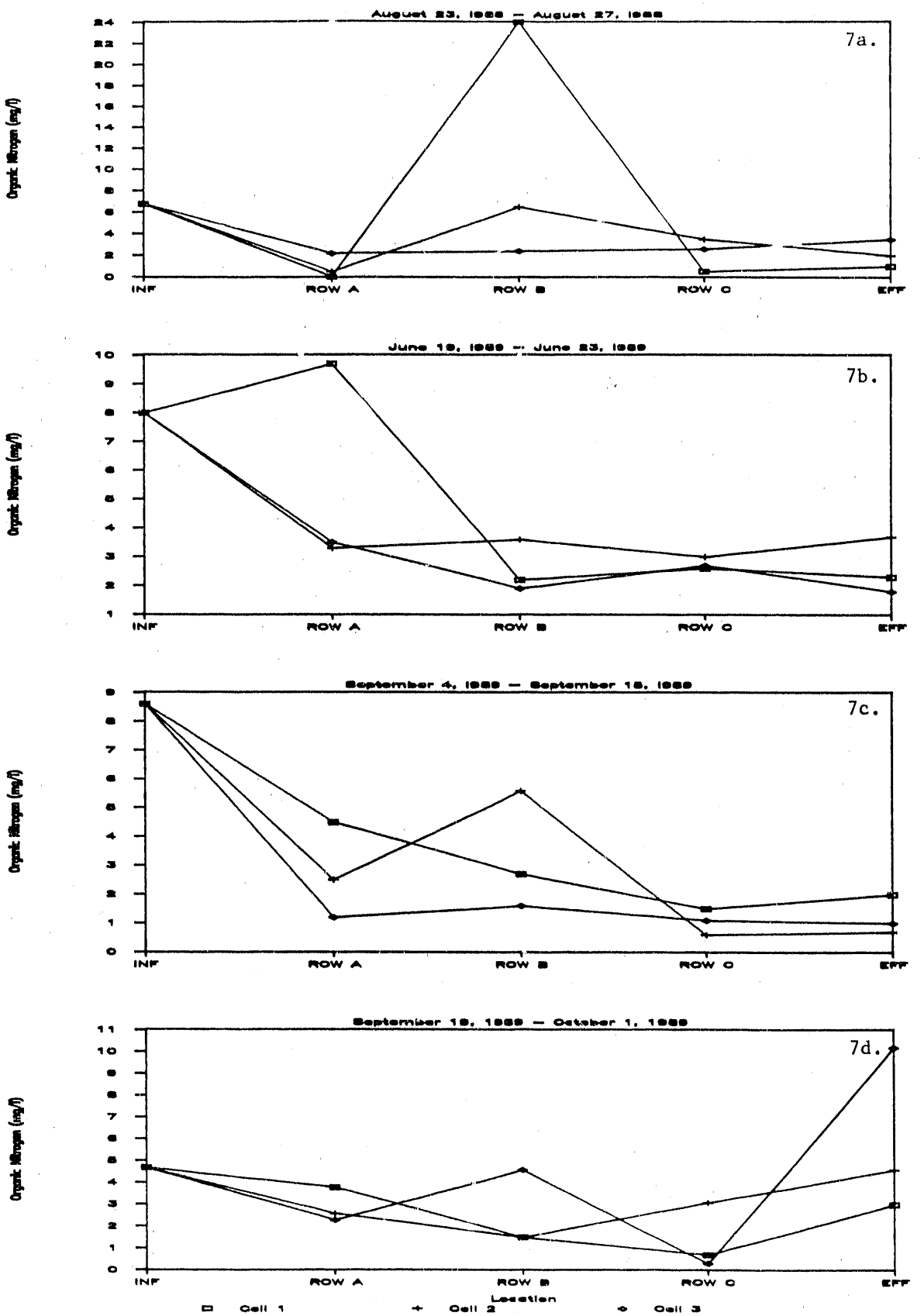
Figures 4a. - 4d. Benton, Kentucky, Dye Study Results of Total Suspended Solids



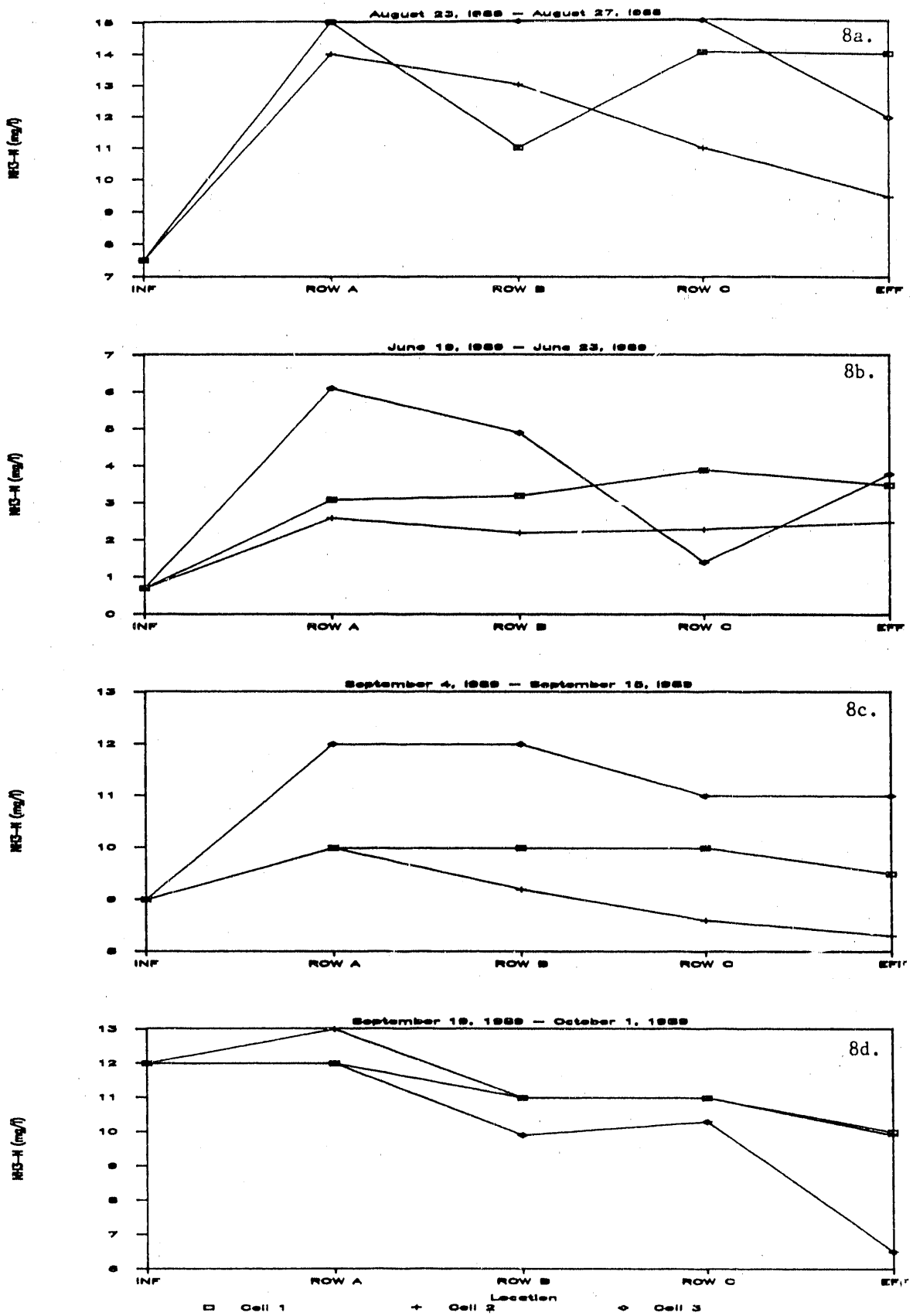
Figures 5a. - 5d. Benton, Kentucky, Dye Study Results of Five-Day Biochemical Oxygen Demand



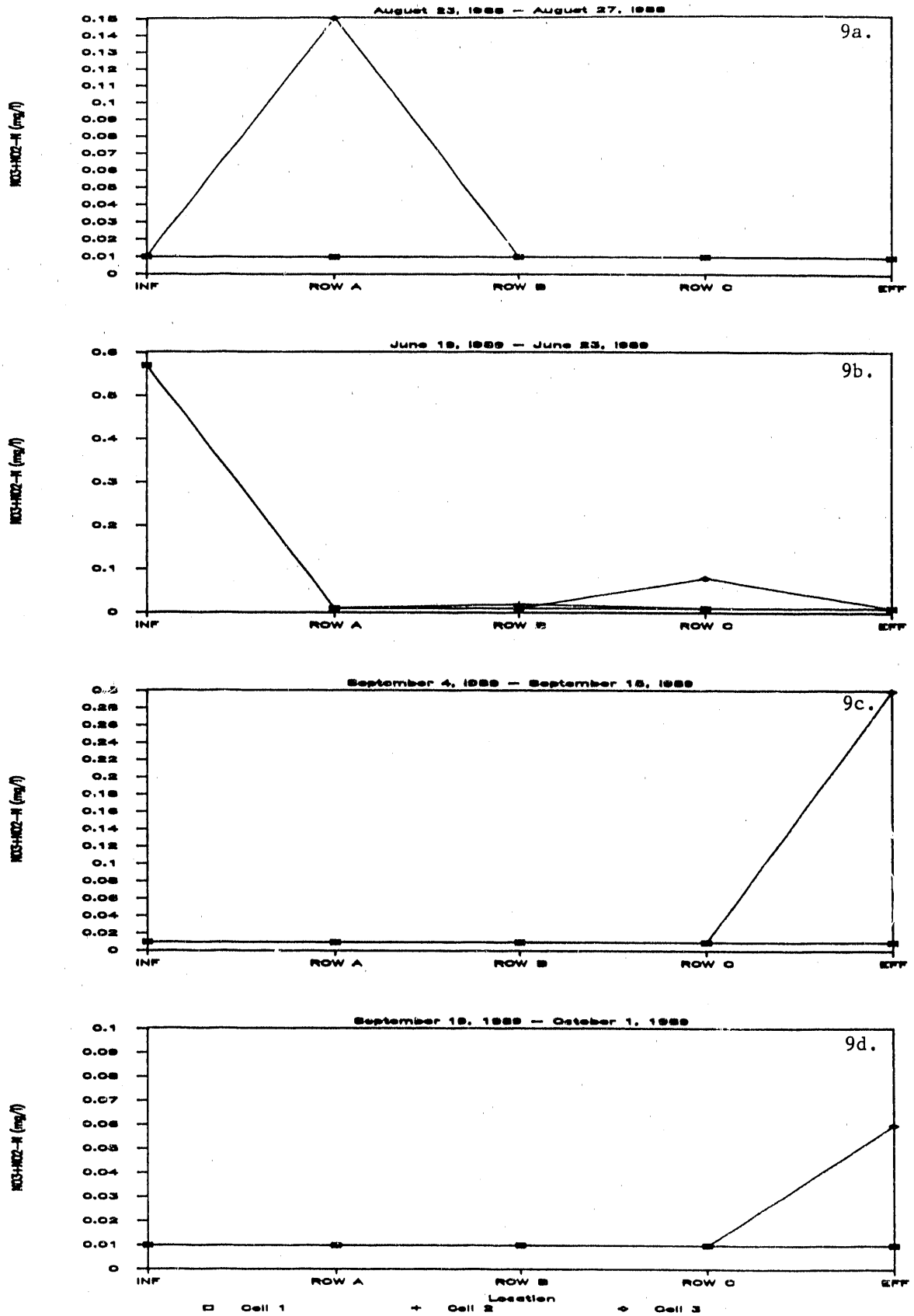
Figures 6a. - 6d. Benton, Kentucky, Dye Study Results of Total Nitrogen



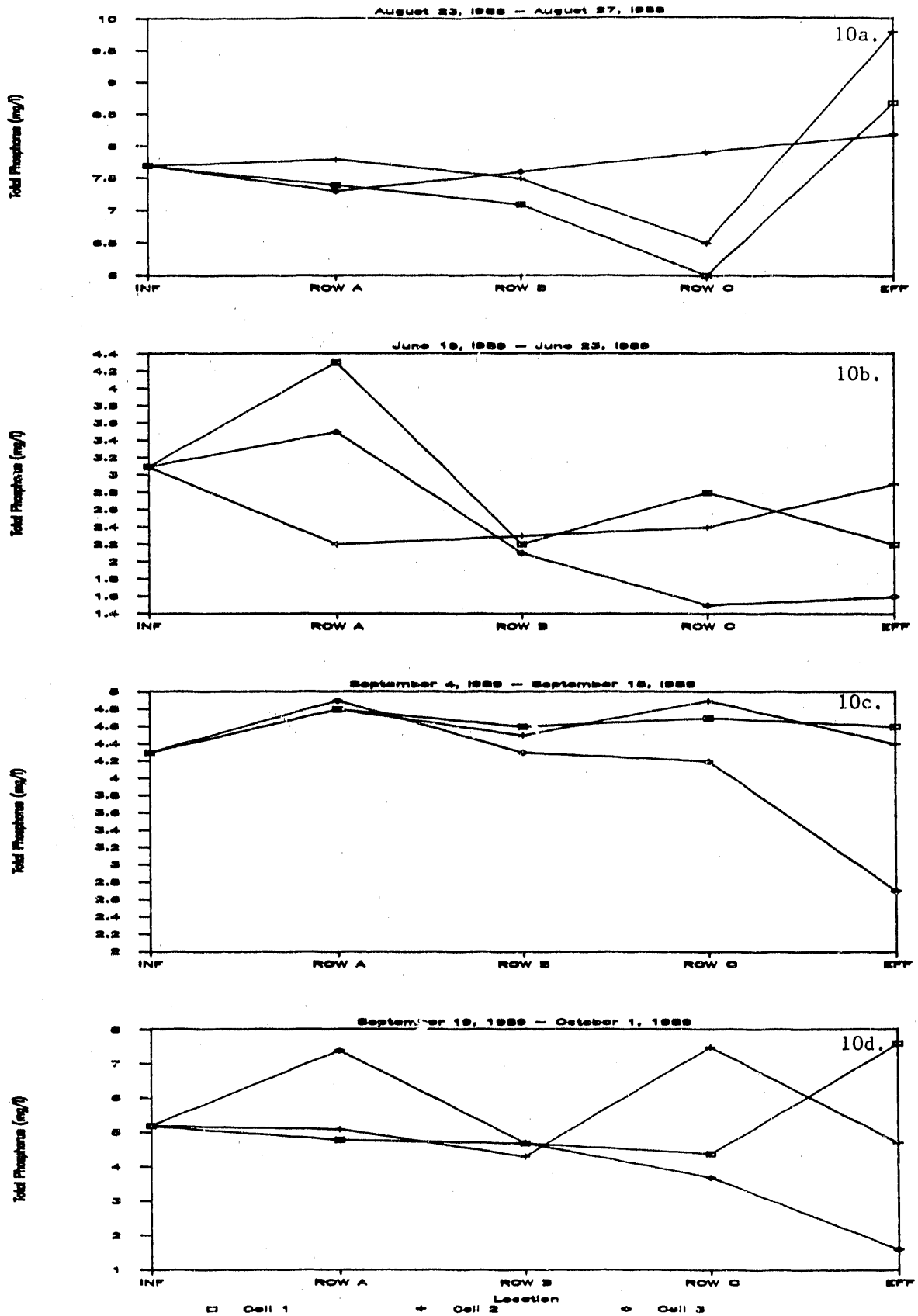
Figures 7a. - 7d. Benton, Kentucky, Dye Study Results of Organic Nitrogen



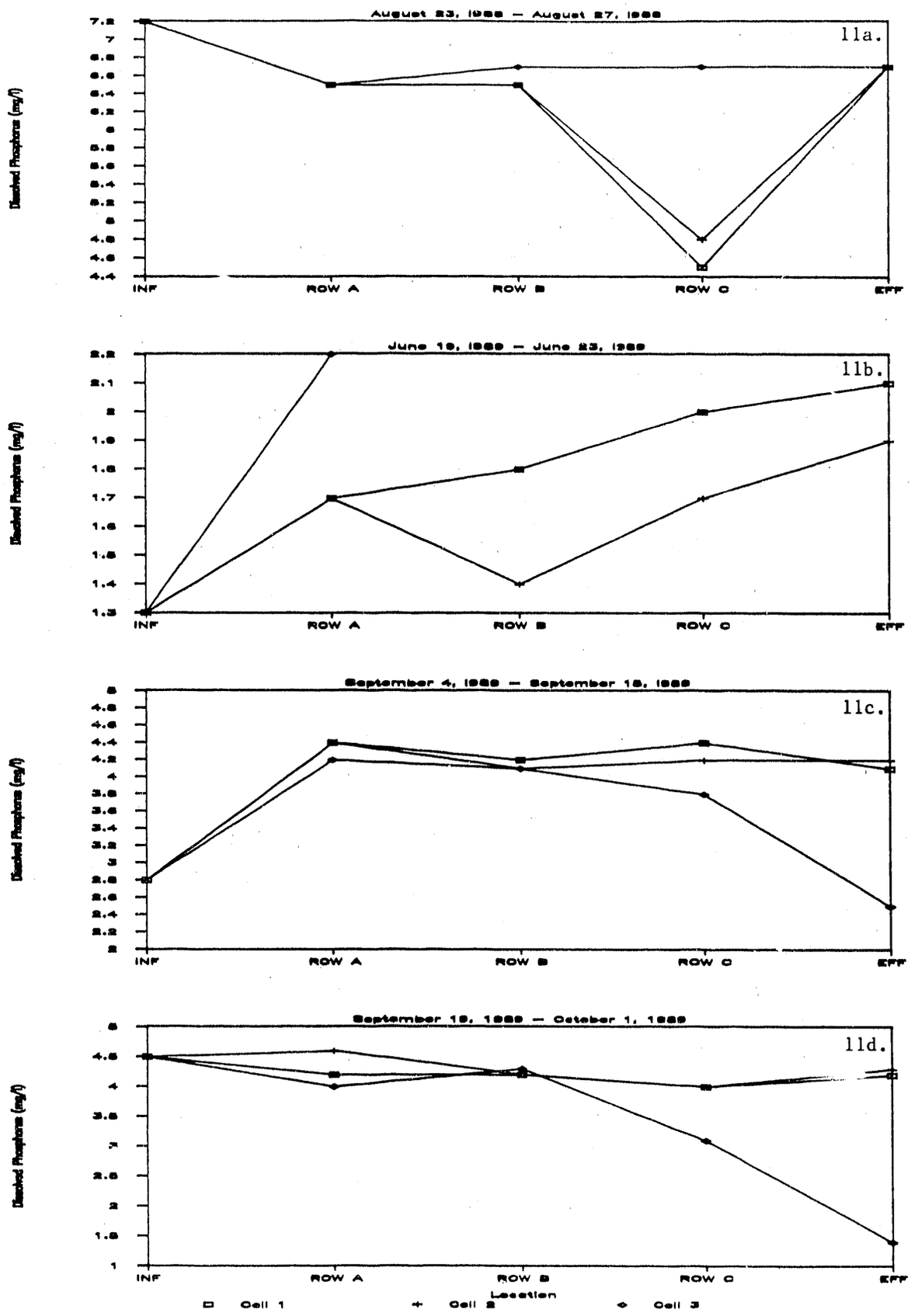
Figures 8a. - 8d. Benton, Kentucky, Dye Study Results of Ammonia Nitrogen



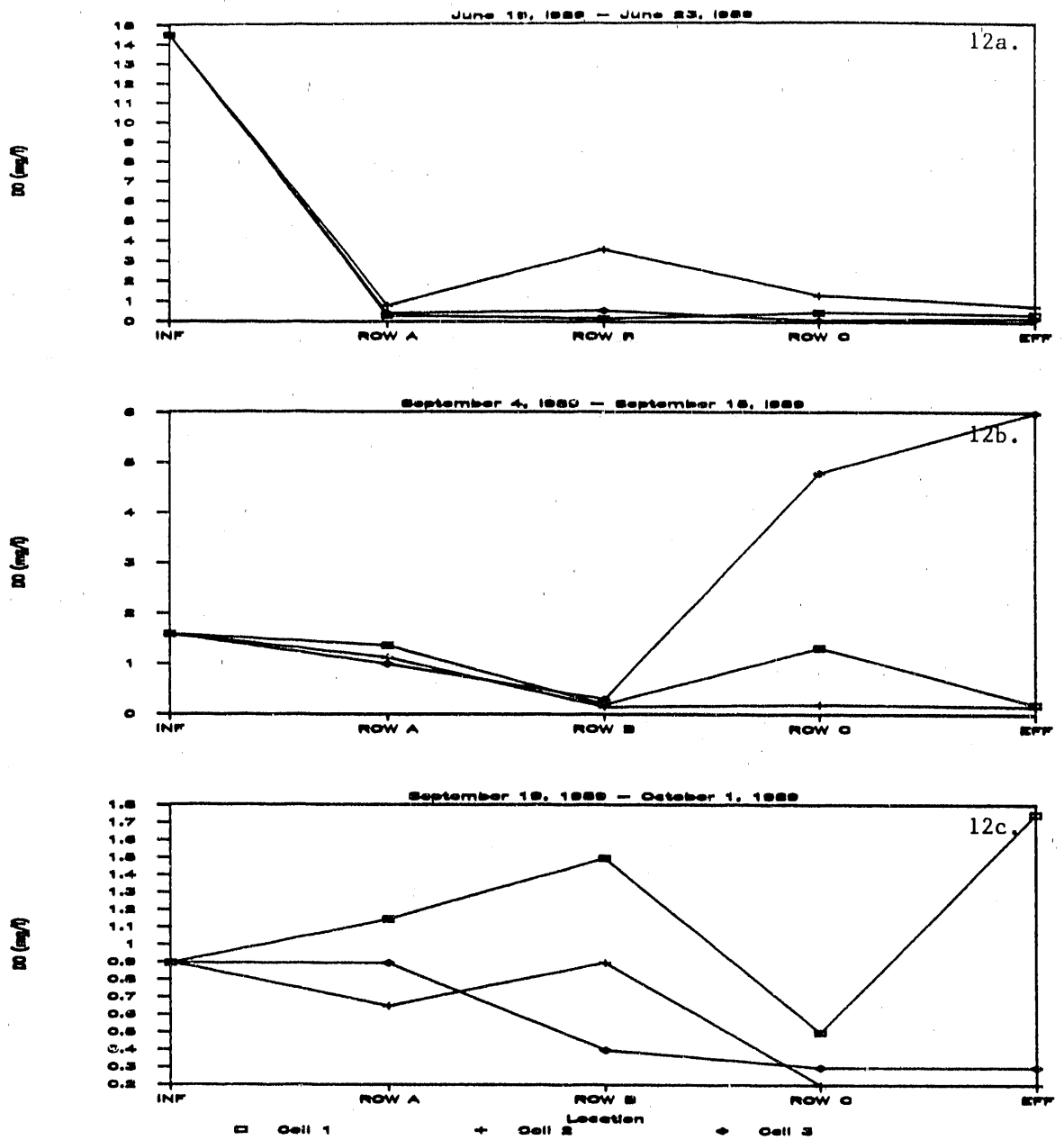
Figures 9a. - 9d. Benton, Kentucky, Dye Study Results of Nitrate - Nitrite Nitrogen



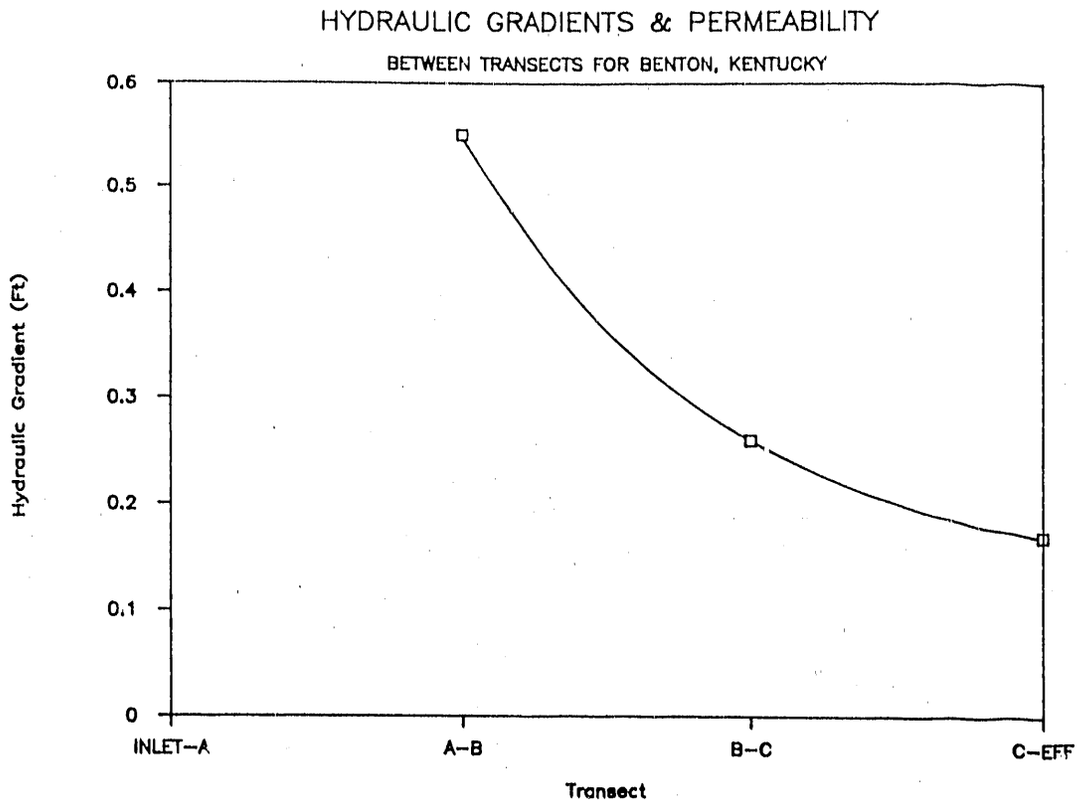
Figures 10a. - 10d. Benton, Kentucky, Dye Study Results of Total Phosphorus



Figures 11a. - 11d. Benton, Kentucky, Dye Study Results of Dissolved Phosphorus



Figures 12a. - 12c. Benton, Kentucky, Dye Study Results of Dissolved Oxygen



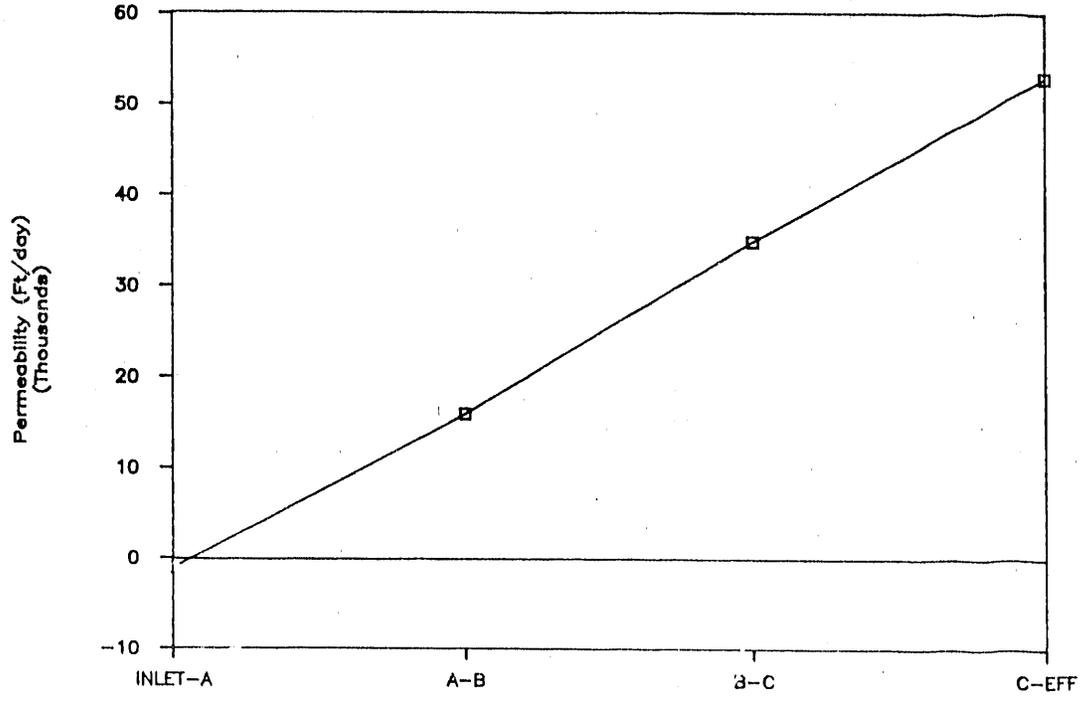


Figure 13. Benton, Kentucky, Hydraulic Gradients and Calculated Permeabilities

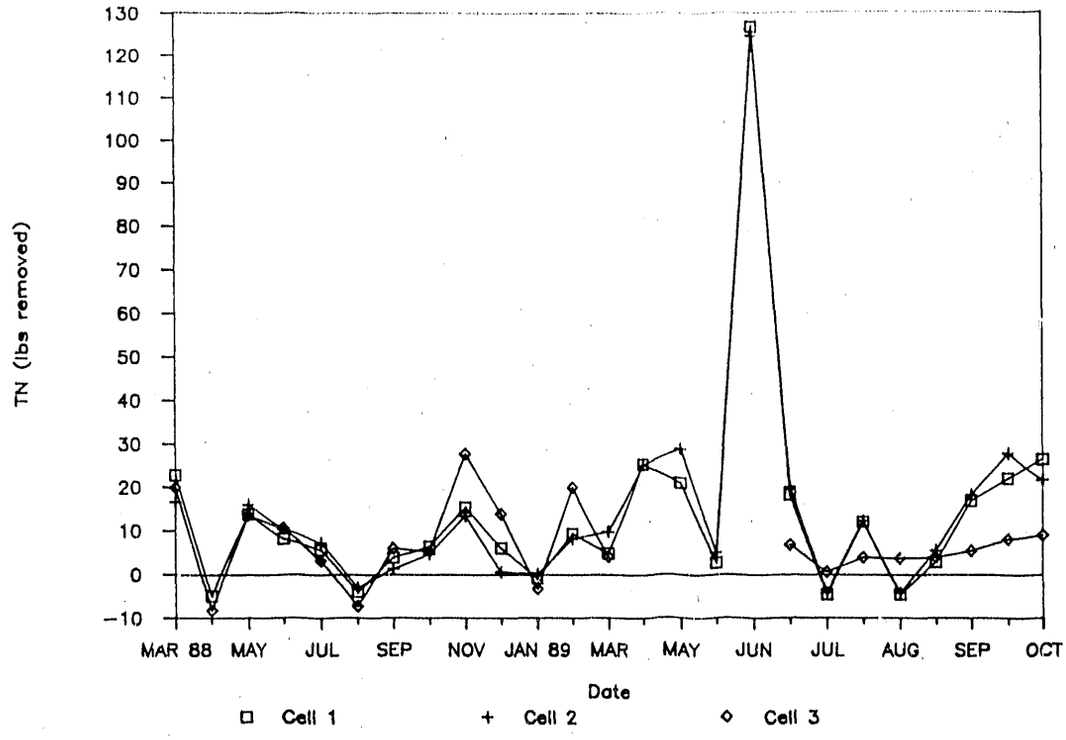


Figure 14. Benton, Kentucky, Pounds of Total Nitrogen Removed

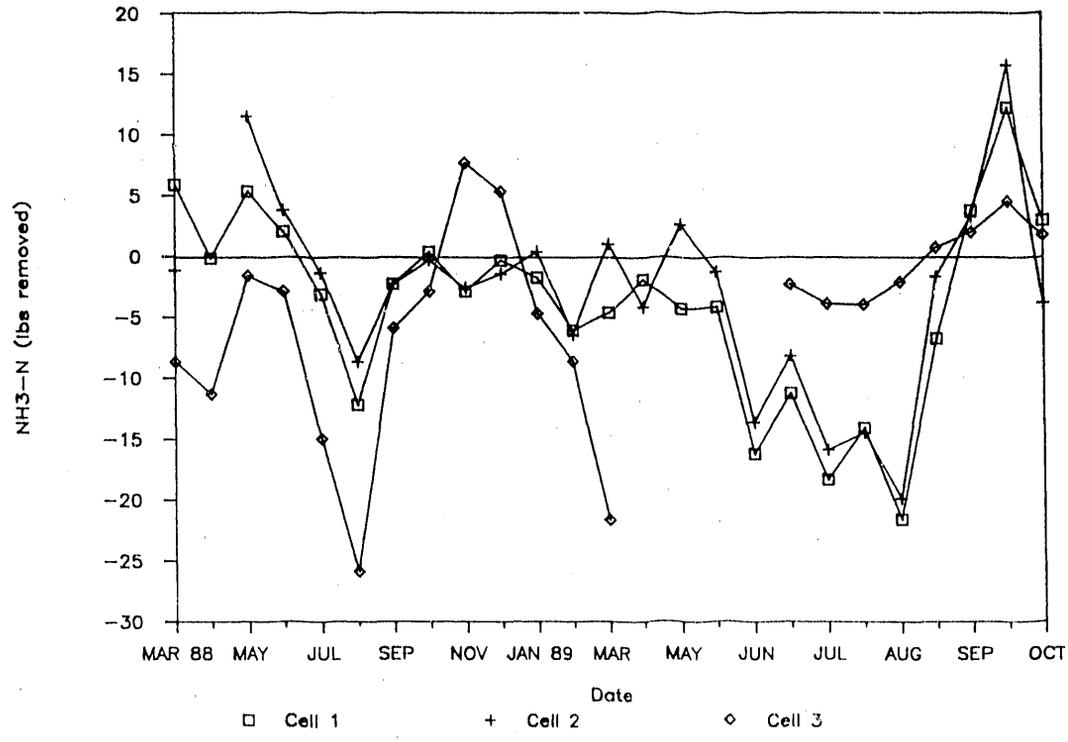


Figure 15. Benton, Kentucky, Pounds of Ammonia Nitrogen Removed

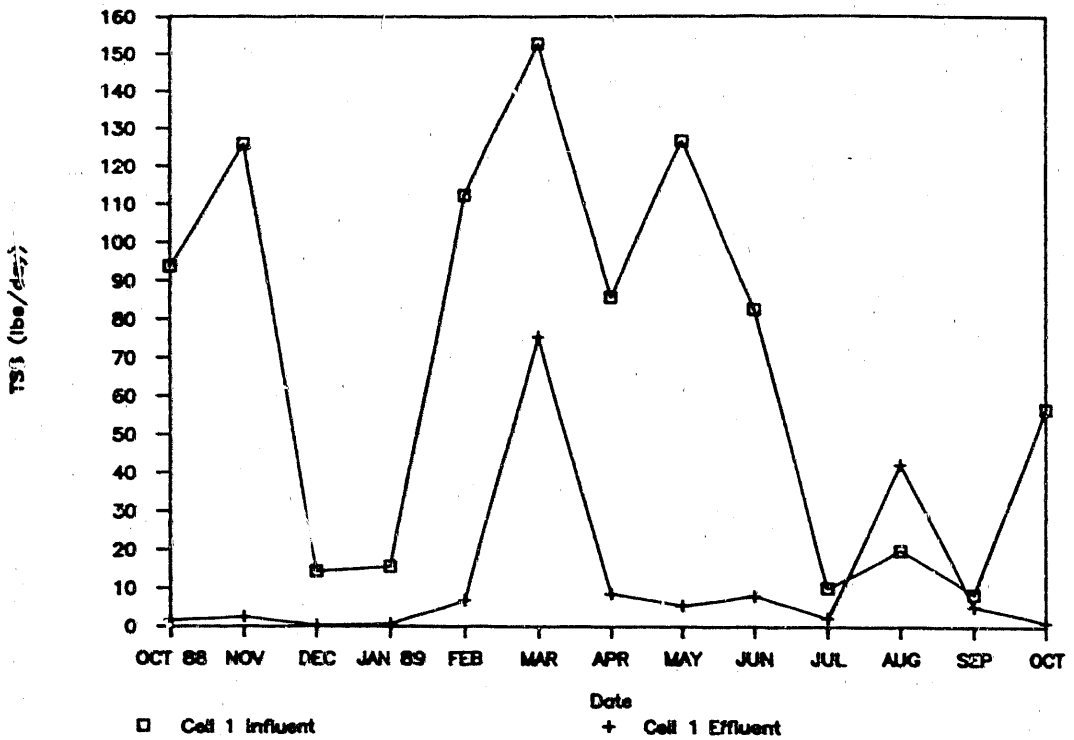


Figure 16a. Hardin, Kentucky, Total Suspended Solids Mass Loadings of Cell 1

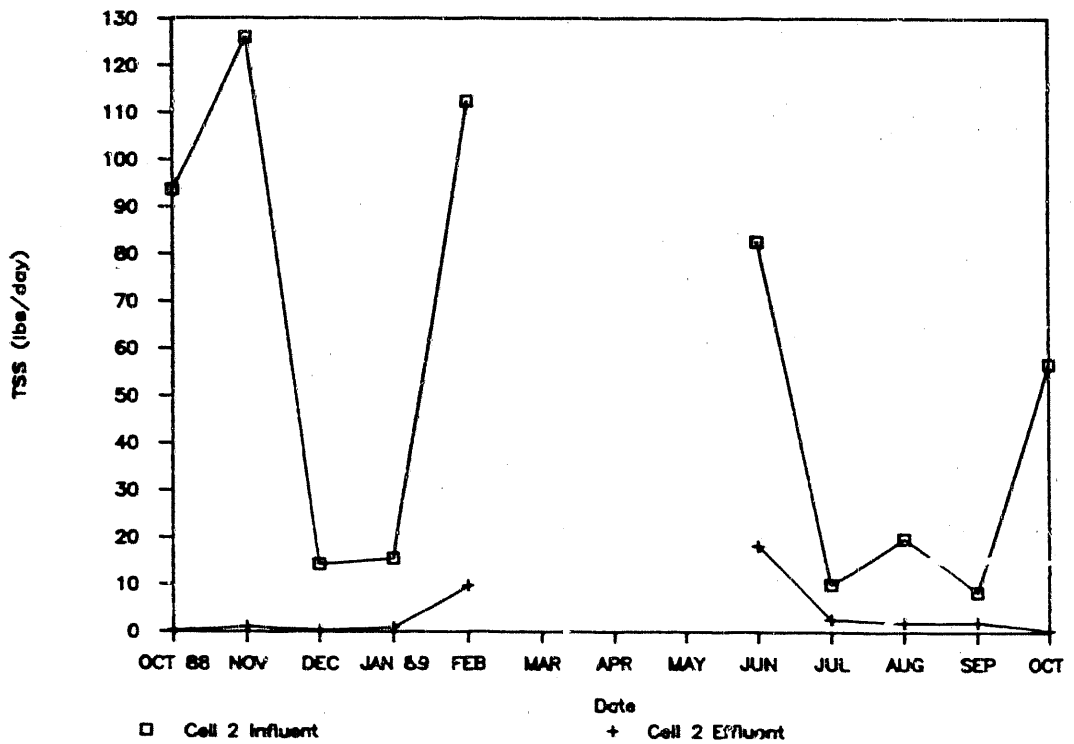


Figure 16b. Hardin, Kentucky, Total Suspended Solids Mass Loadings of Cell 2

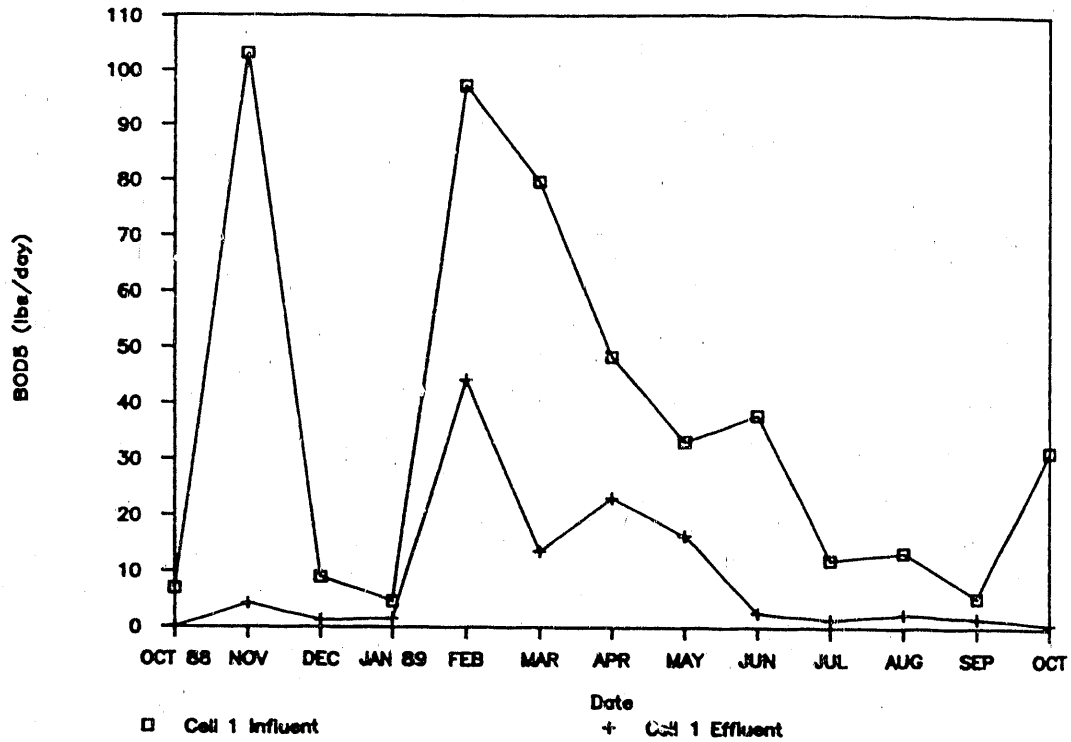


Figure 17a. Hardin, Kentucky, Five-Day Biochemical Oxygen Demand Mass Loadings of Cell 1

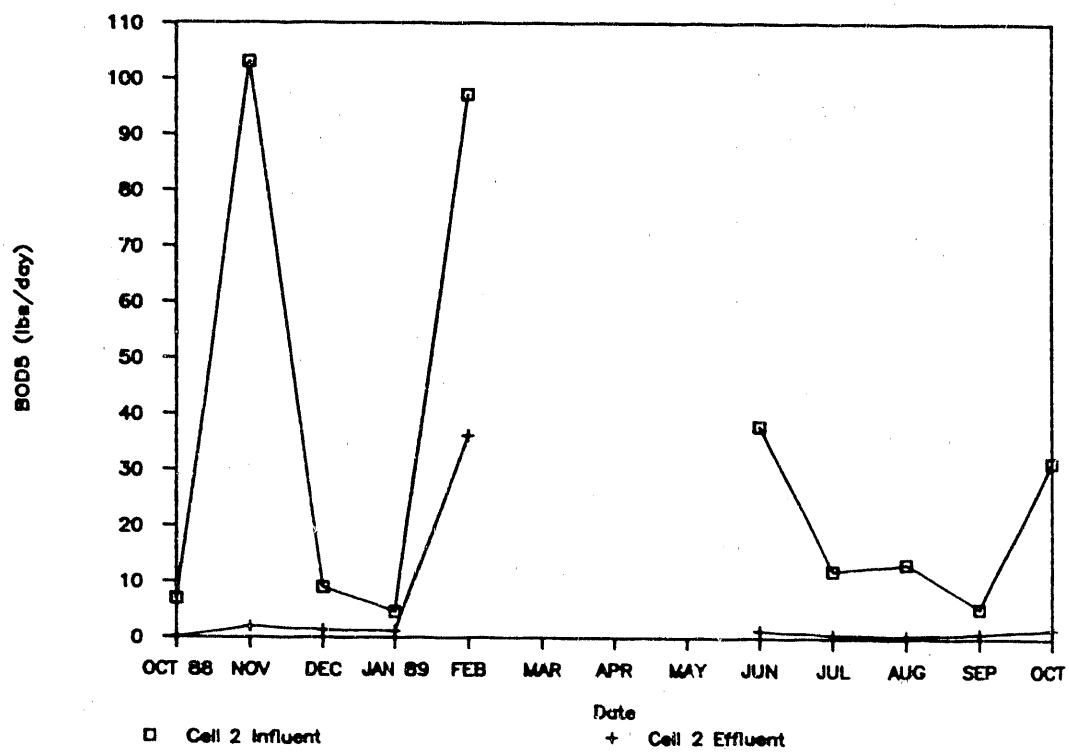


Figure 17b. Hardin, Kentucky, Five-Day Biochemical Oxygen Demand Mass Loadings of Cell 2

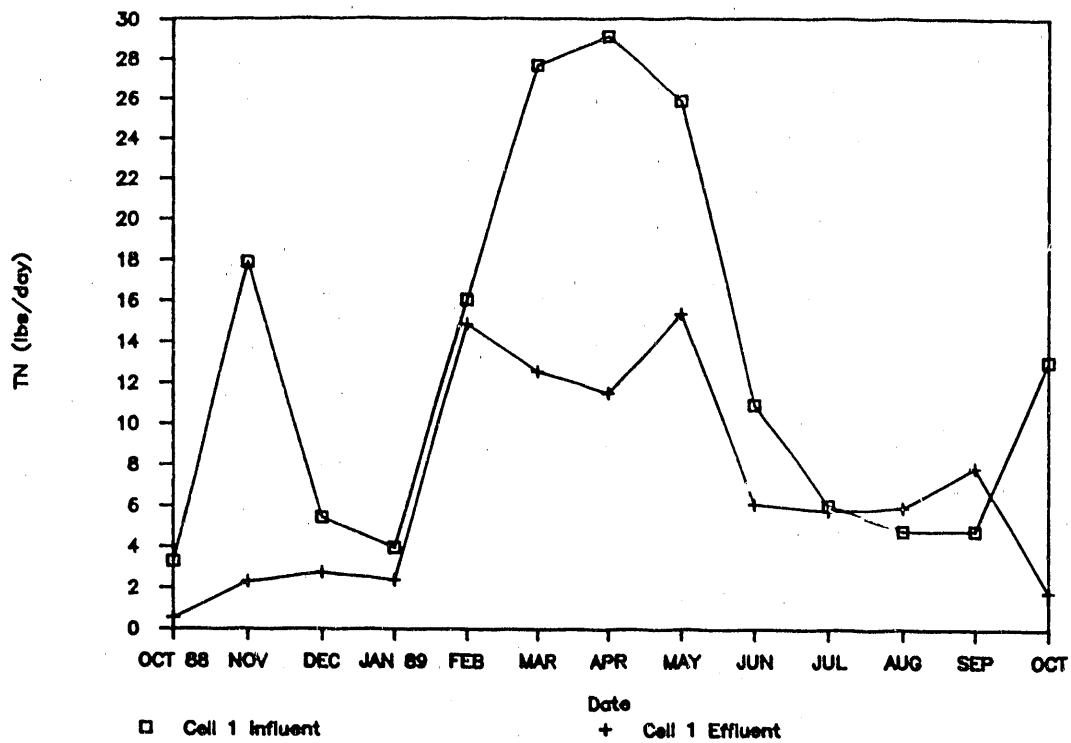


Figure 18a. Hardin, Kentucky, Total Nitrogen Mass Loadings of Cell 1

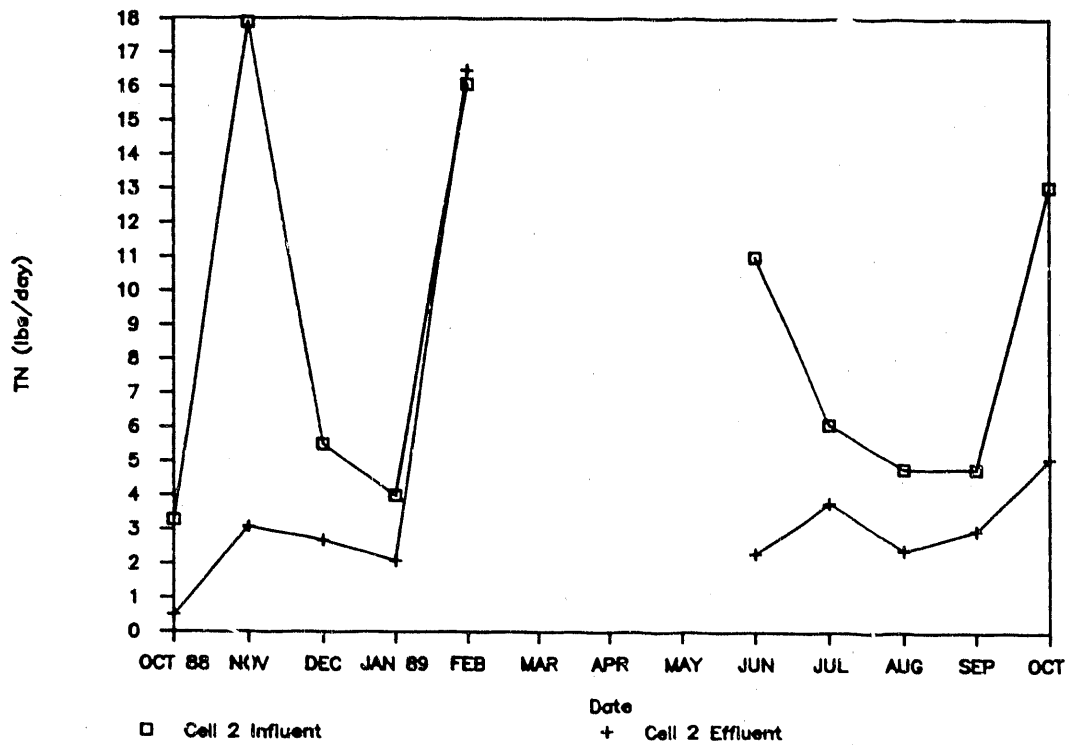


Figure 18b. Hardin, Kentucky, Total Nitrogen Mass Loadings of Cell 2

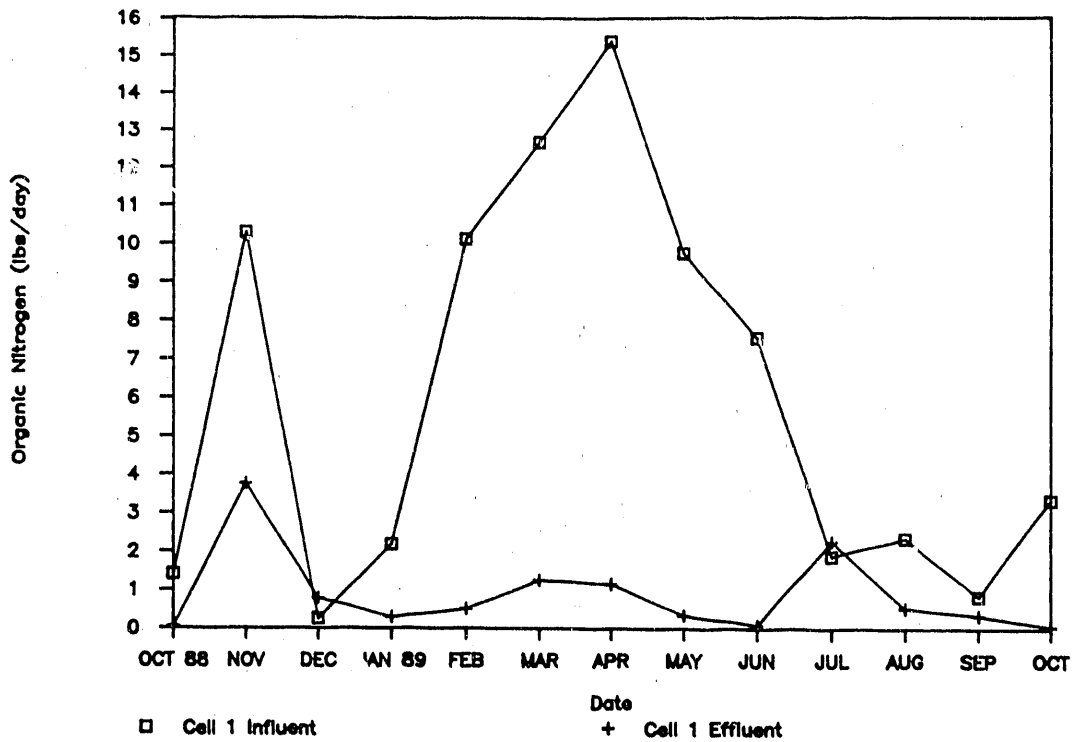


Figure 19a. Hardin, Kentucky, Organic Nitrogen Mass Loadings of Cell 1

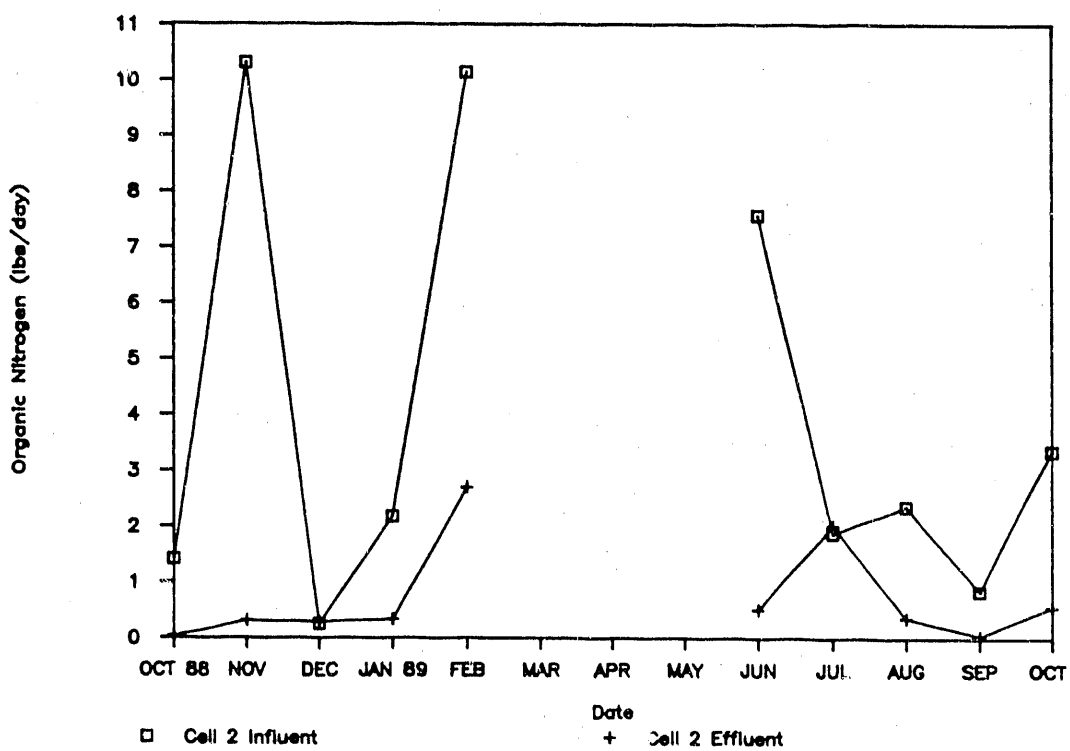


Figure 19b. Hardin, Kentucky, Organic Nitrogen Mass Loadings of Cell 2

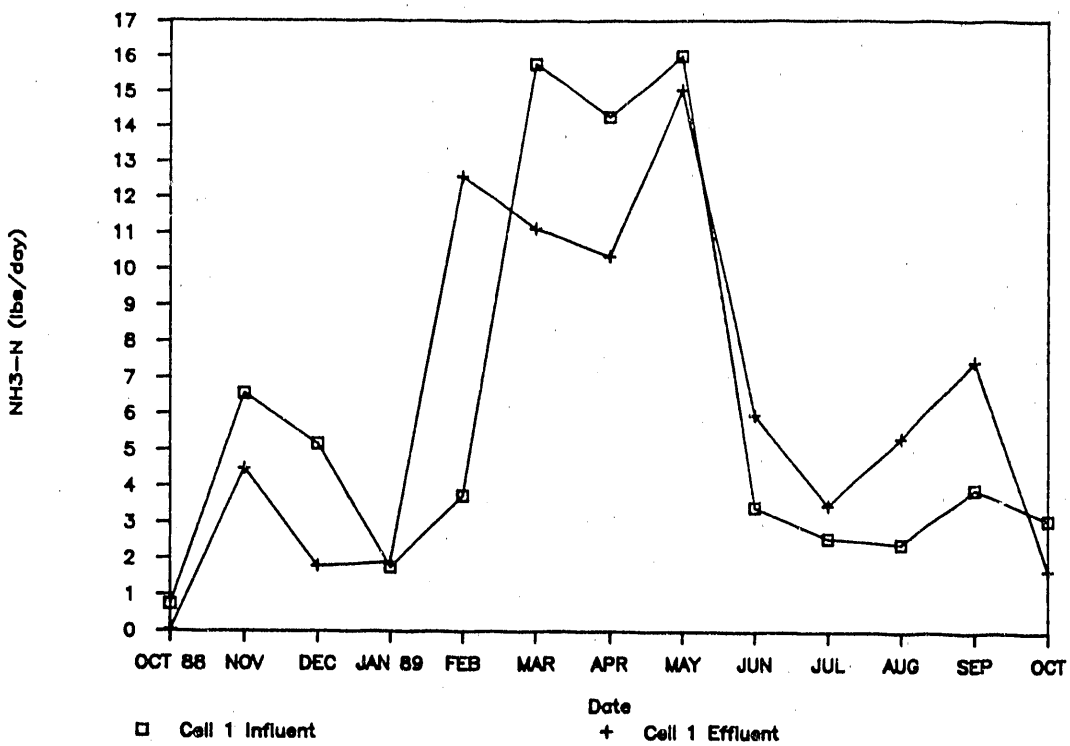


Figure 20a. Hardin, Kentucky, Ammonia Nitrogen Mass Loadings of Cell 1

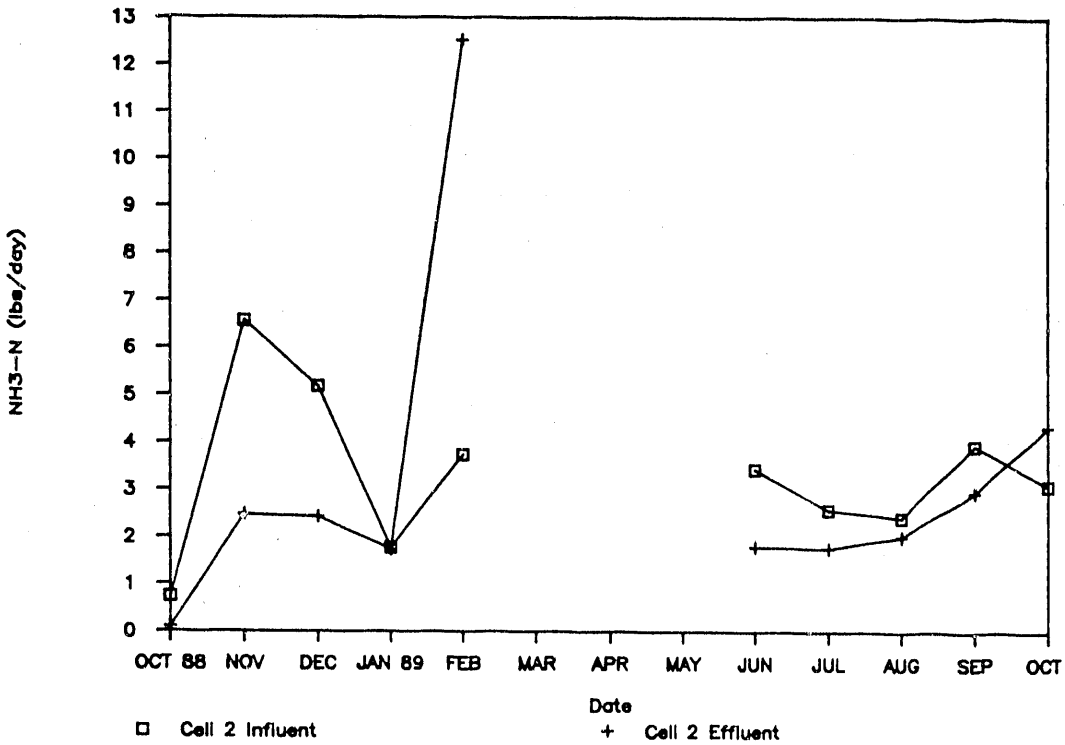


Figure 20b. Hardin, Kentucky, Ammonia Nitrogen Mass Loadings of Cell 2

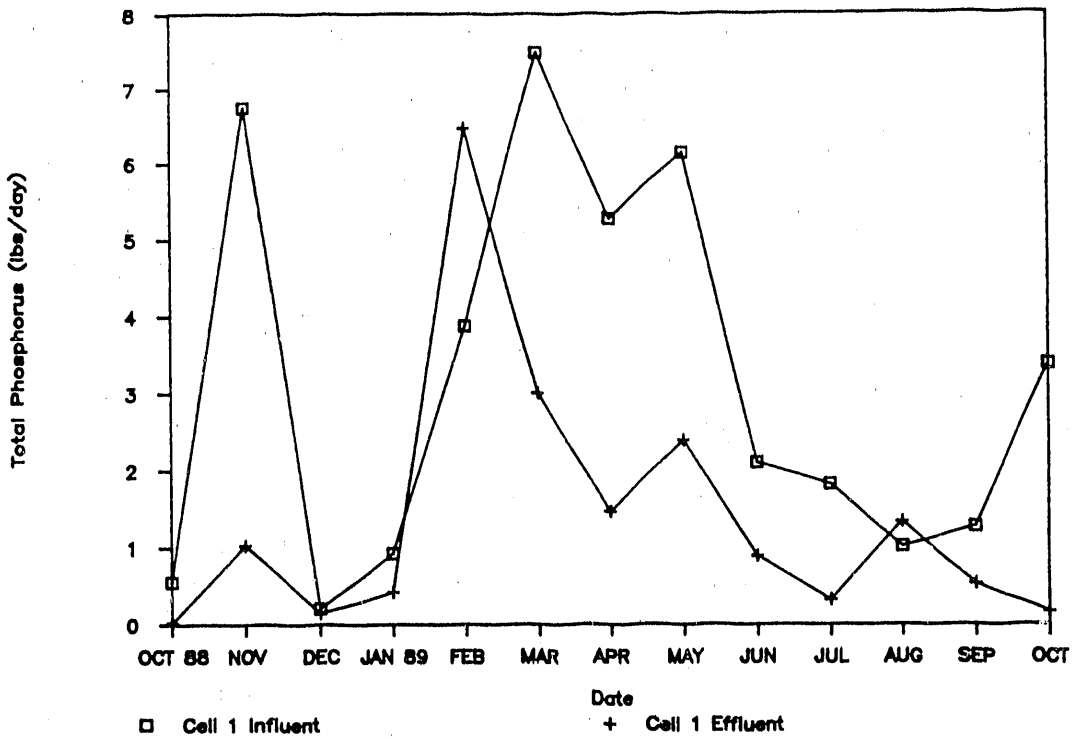


Figure 21a. Hardin, Kentucky, Total Phosphorus Mass Loadings of Cell 1

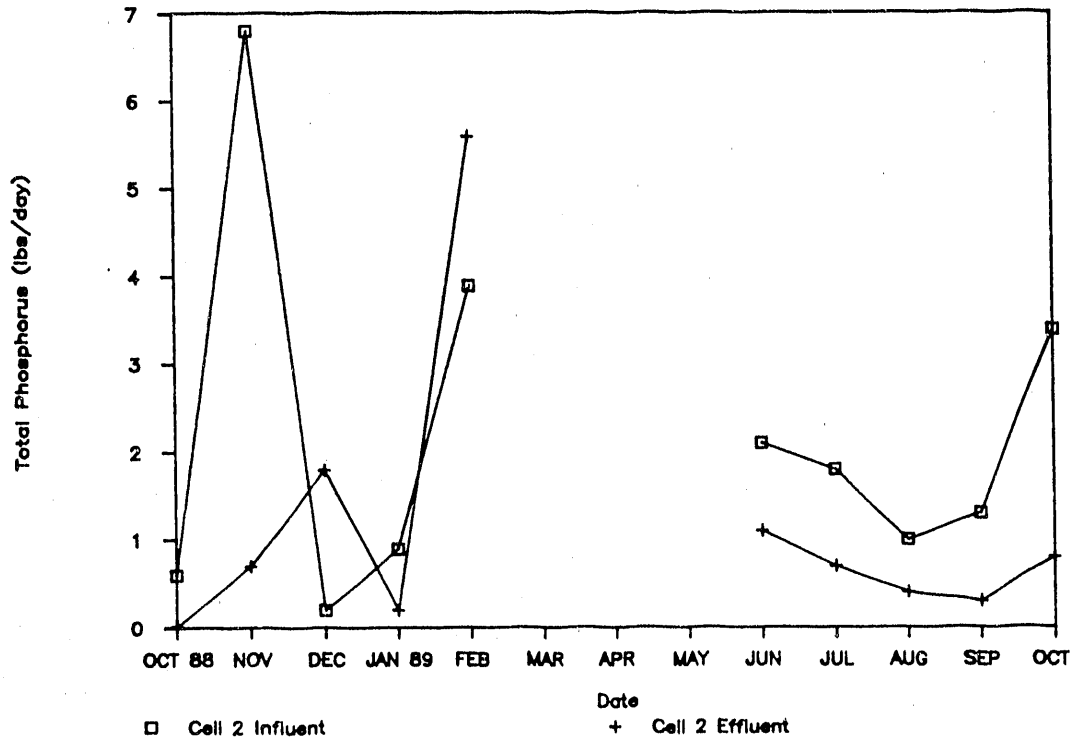


Figure 21b. Hardin, Kentucky, Total Phosphorus Mass Loadings of Cell 2

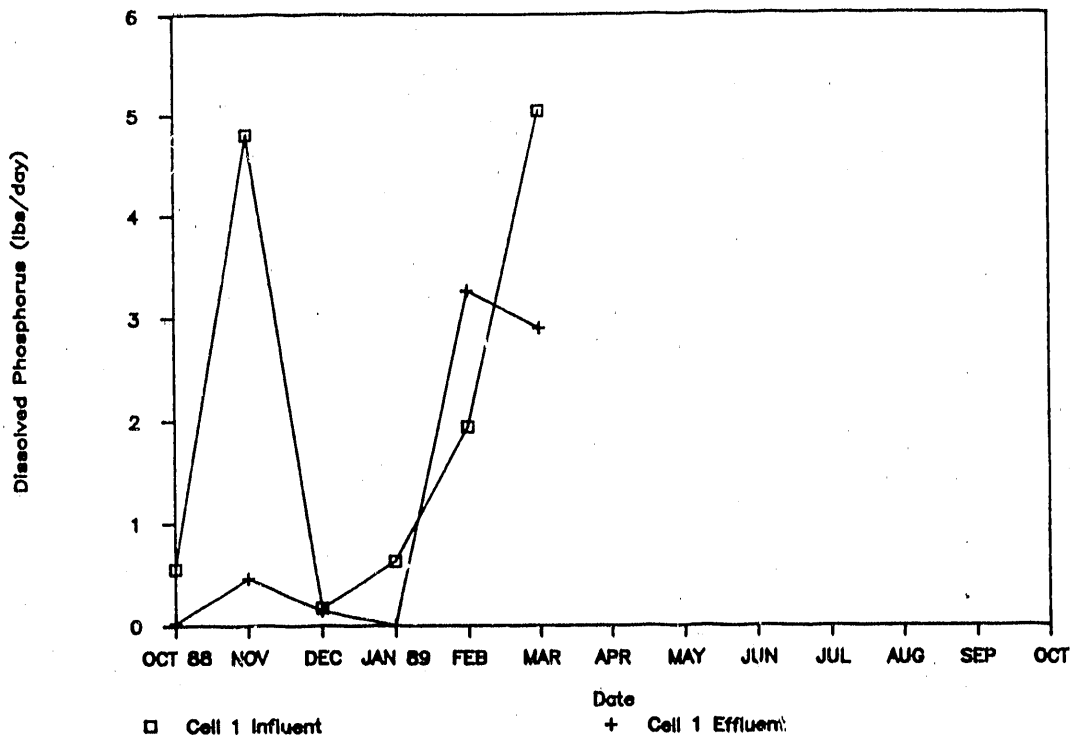


Figure 22a. Hardin, Kentucky, Disselved Phosphorus Mass Loadings of Cell 1

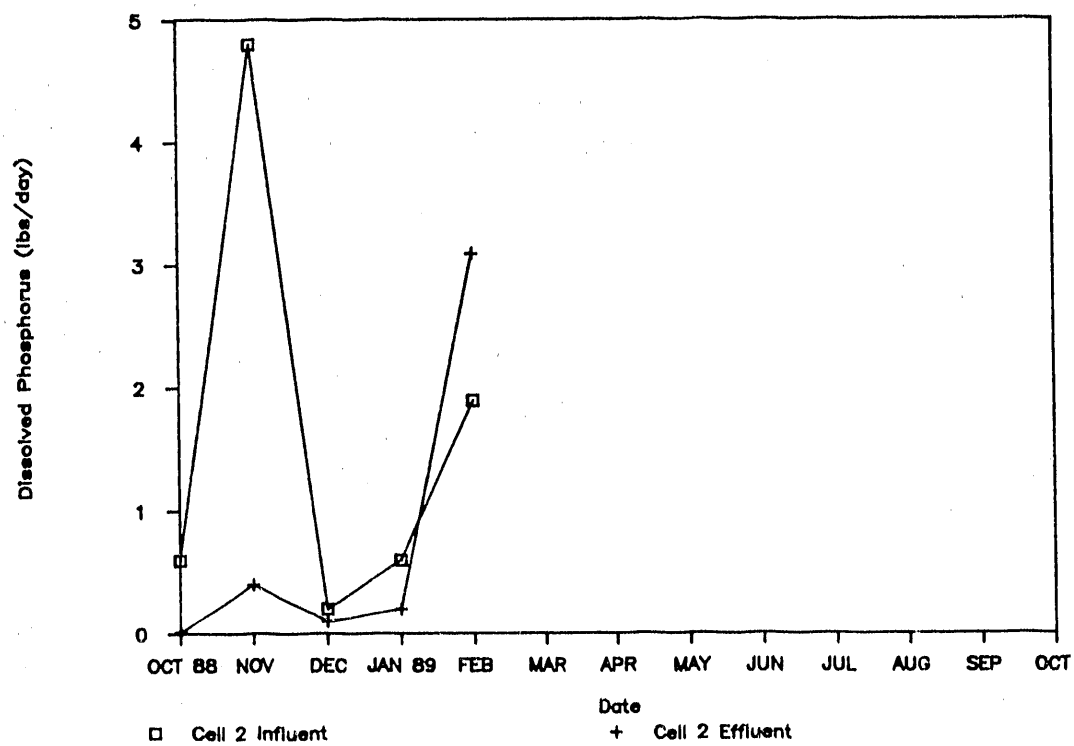


Figure 22b. Hardin, Kentucky, Dissolved Phosphorus Mass Loadings of Cell 2

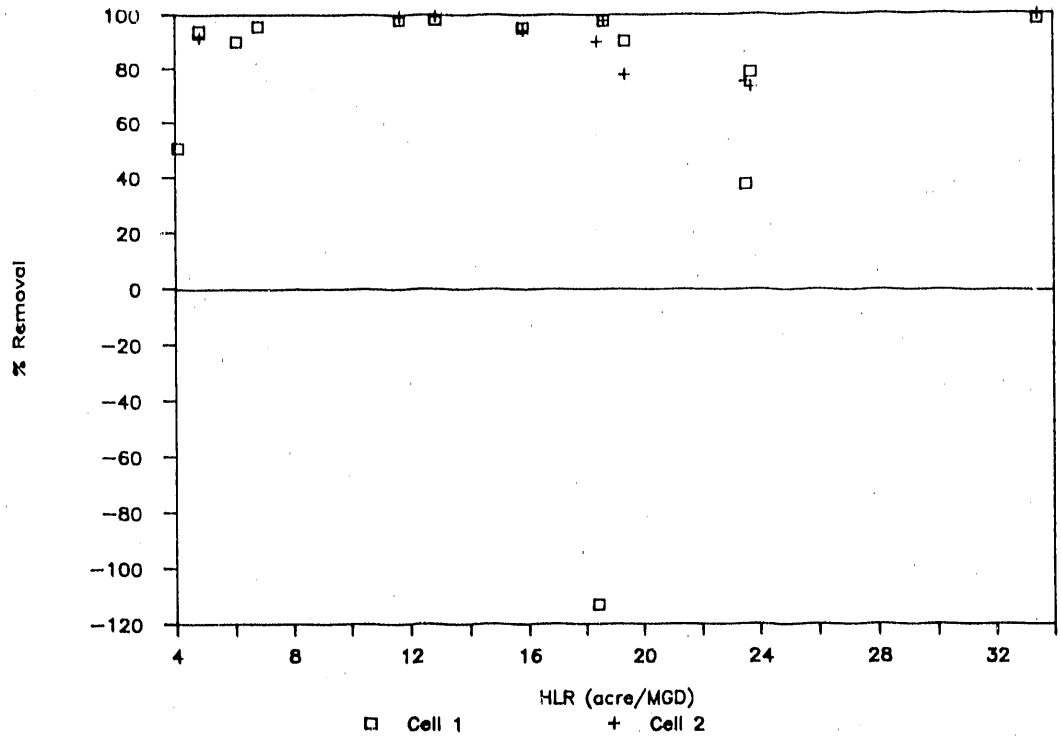


Figure 23. Hardin, Kentucky, Total Suspended Solids Removal Versus Hydraulic Loading Rate

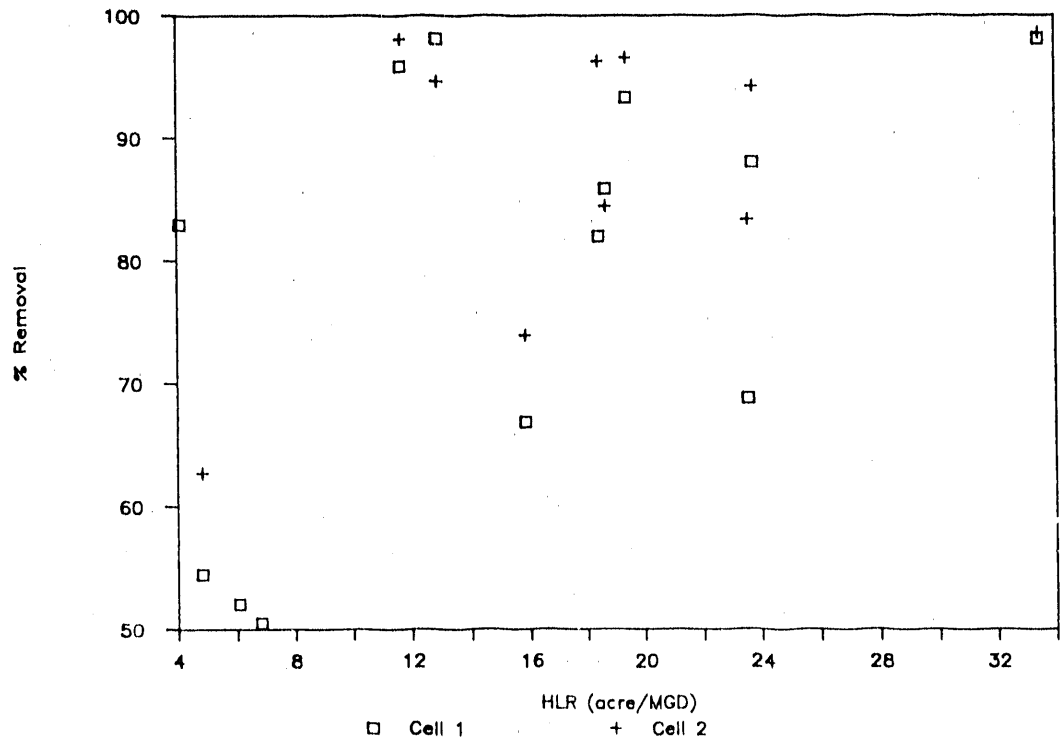


Figure 24. Hardin, Kentucky, Five-Day Biochemical Oxygen Demand Removal Versus Hydraulic Loading Rate

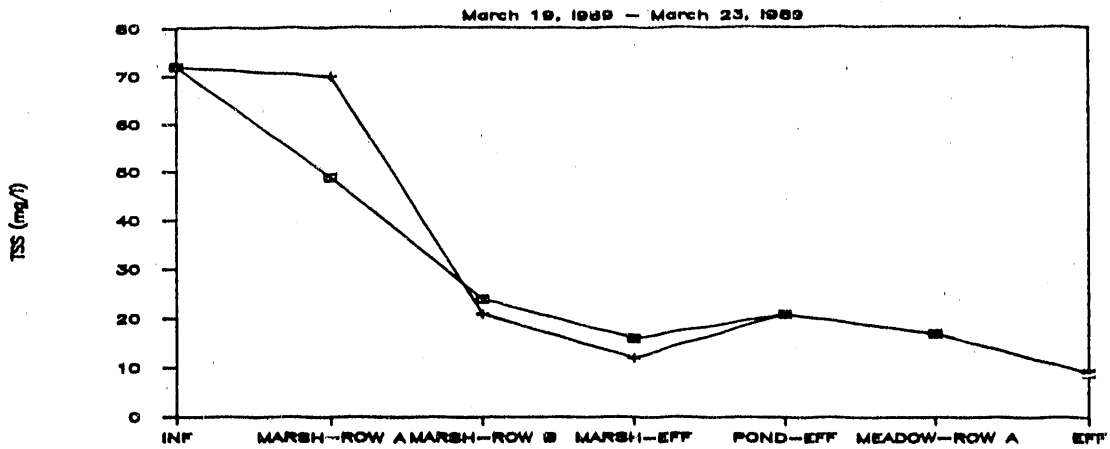


Figure 25. Pembroke, Kentucky, Dye Study Results of Total Suspended Solids

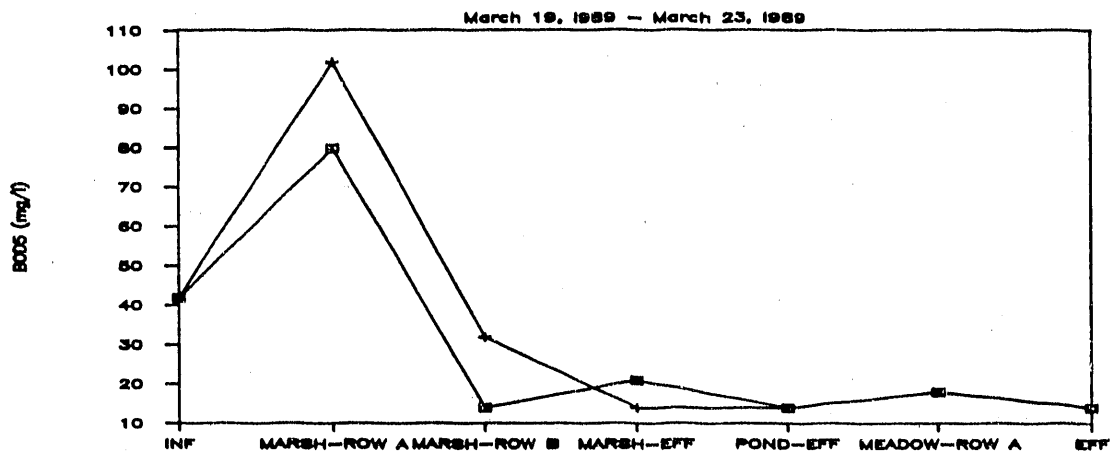


Figure 26. Pembroke, Kentucky, Dye Study Results of Five-Day Biochemical Oxygen Demand

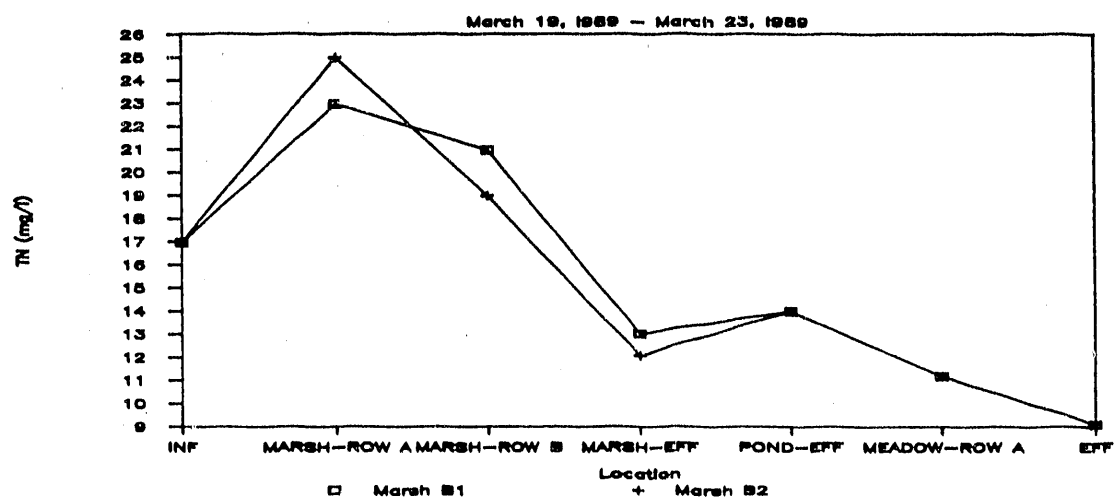


Figure 27. Pembroke, Kentucky, Dye Study Results of Total Nitrogen

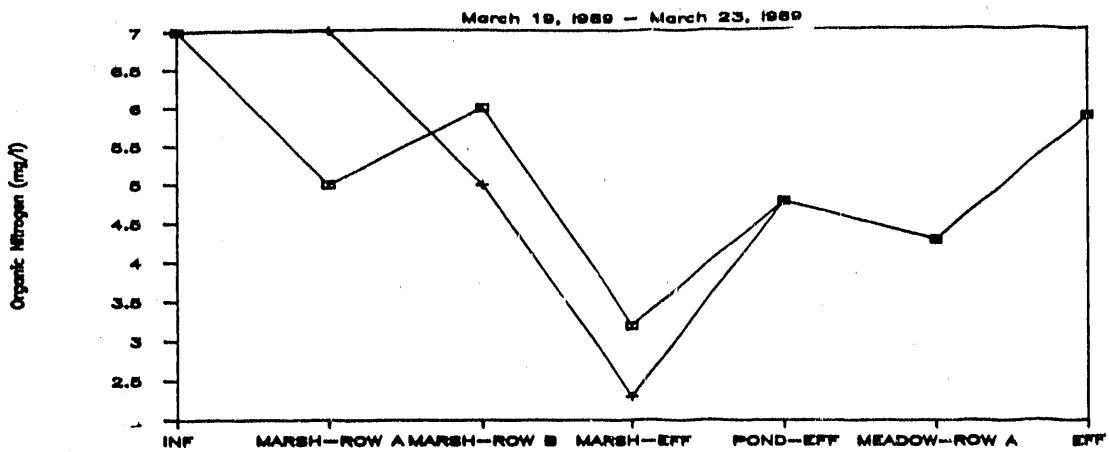


Figure 28. Pembroke, Kentucky, Dyc Study Results of Organic Nitrogen

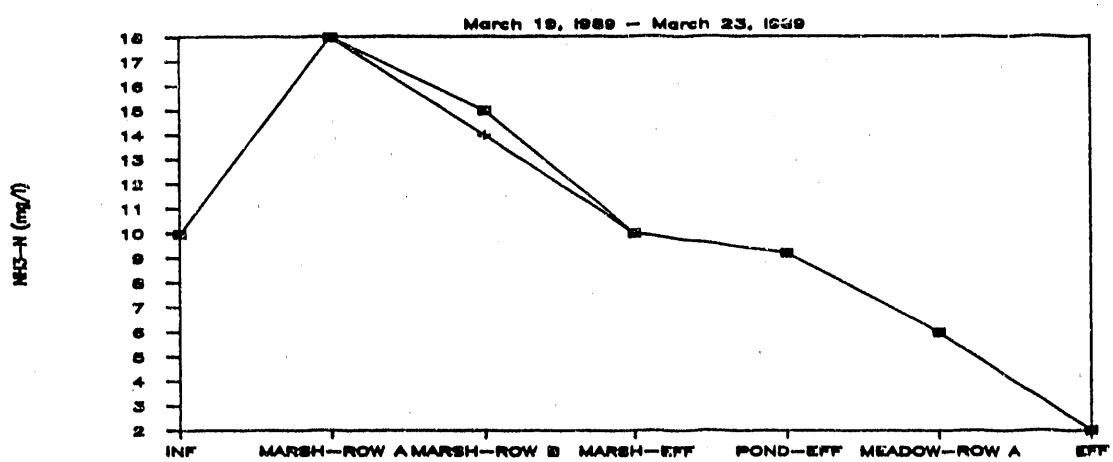


Figure 29. Pembroke, Kentucky, Dye Study Results of Ammonia Nitrogen

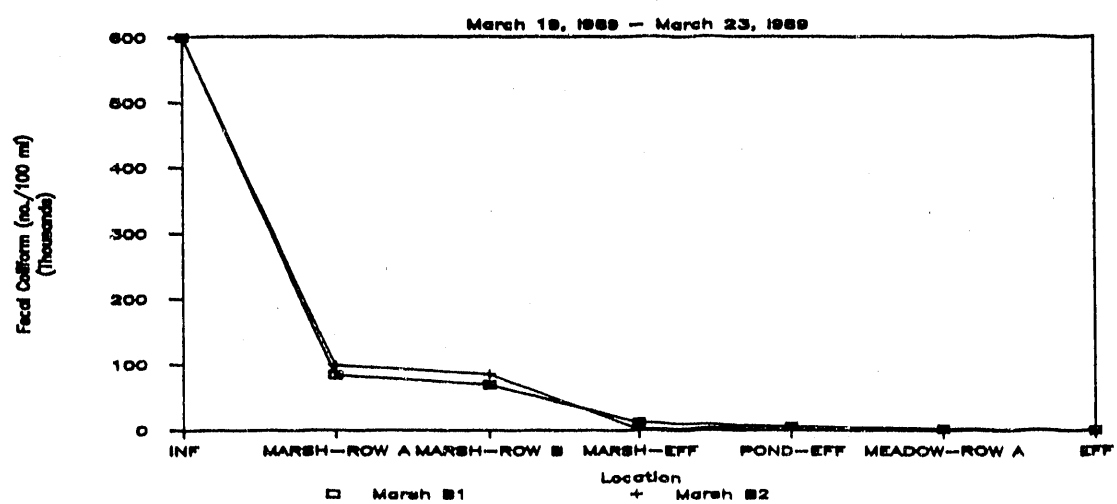


Figure 30. Pembroke, Kentucky, Dye Study Results of Fecal Coliform

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