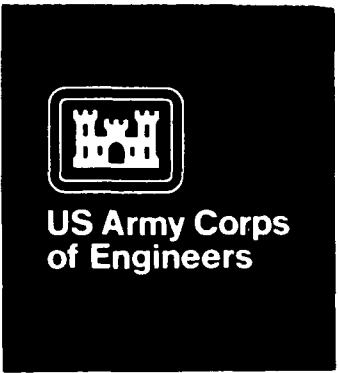


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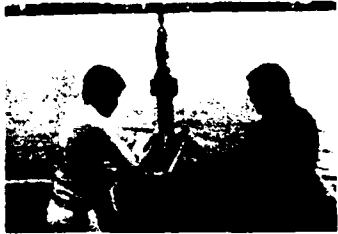
NUMERICAL WATER QUALITY MODEL STUDY OF HARBOR ENHANCEMENTS

by

Ross W. Hall

Environmental Laboratory

AD-A224 980



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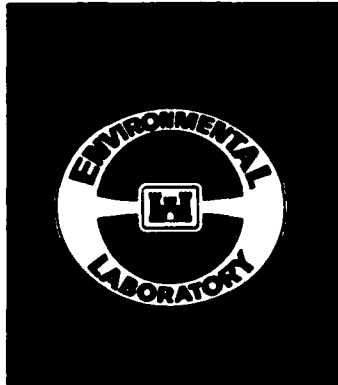


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<p>Plans for the Los Angeles and Long Beach Harbors enhancement include dredging and new landfill. The enhancements may affect water quality through changes in water circulation and flushing. The major water quality concern was possible depression of dissolved oxygen (DO) in poorly flushed, deepened navigation channels. A comparison of flushing and DO between existing (Base) and an enhanced plan (Scheme B) was conducted.</p> <p>A three-dimensional (3-D) numerical water quality model (WQM) was adapted to process the output from the 3-D hydrodynamic model CH3D in order to transport the water quality constituents. The overlaid WQM grid required that the hydrodynamic data be spatially averaged, and the WQM kinetic interactions allowed the data to be temporally averaged. The averaging resulted in 92 percent fewer computational cells in the WQM and allowed a</p>					
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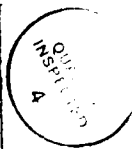
1,400-percent increase in the time step while maintaining computational stability. The reduction in spatial and temporal resolution greatly reduced computer time for the WQM.

Flushing studies consisted of inserting a tracer and observing its movement and dilution with time. The flushing studies identified areas within the harbor that exhibited decreases in flushing. Areas that exhibited decreased flushing were selected for more detailed characterization during subsequent DO simulations. The flushing studies revealed a flow reversal in the main channel from counterclockwise in the Base condition to clockwise in the Scheme B enhancement, and the enhancement accelerated its flushing.

The WQM formulation included the state variables DO, carbonaceous biochemical oxygen demand, ammonia nitrogen, nitrite plus nitrate nitrogen, algal biomass, and orthophosphate. Processes directly affecting DO included tidal circulation; phytoplankton oxygen production and growth as a function of light and nutrients, respiration, and nonpredatory mortality; sediment oxygen demand; biochemical oxidation of organics; nitrification; and reaeration.

The predicted DO was nearly equivalent in Scheme B compared with existing conditions. Measured and simulated results were in general agreement. Discrepancies in agreement are attributed to insufficient initial condition data and the contribution of Los Angeles River flows that were not modeled.

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Preface

The Numerical Water Quality Model Study is a product of the Los Angeles and Long Beach Harbors Model Enhancement (HME) Program. The HME Program has been conducted jointly by the Ports of Los Angeles and Long Beach, California; the US Army Engineer District (USAED), Los Angeles; and the US Army Engineer Waterways Experiment Station (WES). The purpose of the HME Program is to provide state-of-the-art engineering tools to aid in port development. In a feasibility study being conducted by the USAED, Los Angeles, the Ports of Los Angeles and Long Beach are proposing a harbor expansion that includes dredging and new landfill. Changes in water quality due to changes in tidal circulation and harbor flushing need to be examined.

This study was conducted and the report prepared by Mr. Ross W. Hall of the Water Quality Modeling Group (WQMG), Ecosystem Research and Simulation Division (ERSD), Environmental Laboratory (EL), WES, under the supervision of Mr. Mark S. Dortch, Chief, WQMG; Mr. Donald L. Robey, Chief, ERSD; and Dr. John Harrison, Chief, EL. Technical reviews of the report were provided by Mr. Dortch, Mr. Thomas M. Cole, and Dr. Carl F. Cerco, WQMG. The report was edited by Ms. Jessica S. Ruff of the WES Information Technology Laboratory.

Dr. Rao S. Vemulakonda, Mr. Bruce A. Ebersole, and Mr. David J. Mark of the Coastal Engineering Research Center (CERC), WES, provided technical assistance. Dr. Vemulakonda coordinated and provided the hydrodynamic model output data used for the water quality simulations. Mr. William C. Seabergh of the CERC; Mr. Ron Hudson of the USAED, Los Angeles; Ms. Lillian Kawasaki of the Port of Los Angeles, and Dr. Geraldine Knatz of the Port of Long Beach provided invaluable coordination.

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LOS ANGELES AND LONG BEACH HARBORS, CALIFORNIA

MODEL ENHANCEMENT PROGRAM

NUMERICAL WATER QUALITY MODEL STUDY OF HARBOR ENHANCEMENTS

Introduction

Background

1. Los Angeles and Long Beach Harbors (San Pedro Bay), California, are located adjacent to each other and share a common breakwater system (Figure 1). The Ports of Los Angeles and Long Beach have undertaken a long-range cooperative planning effort known as the 2020 Plan. Incorporated in the plan are harbor enhancements that include dredging and new landfill.

Problem identification

2. Harbor enhancements may affect water quality in the study area by changing the tidal circulation and flushing patterns. The major water quality concern was the dissolved oxygen (DO) resource. Channel deepening introduces the possibility of DO stratification where well-oxygenated surface waters overlie oxygen-depressed bottom waters.

Objective

3. The purpose of this study was to compare the flushing and DO resources of existing and plan conditions through numerical model simulations. A three-dimensional (3-D) water quality model (WQM) was used to address possible vertical stratification. Hydrodynamic output from the 3-D hydrodynamic model (HM) CH3D was used as input by the WQM to transport water quality constituents.

Report organization

4. The succeeding sections of the report describe modifications made to the WQM code and the procedure used to interface the WQM and CH3D; the exercises used to ensure that the transport properties of CH3D were maintained with the interfacing; and the flushing and water quality studies. The water quality kinetic routines are detailed in Appendix A.

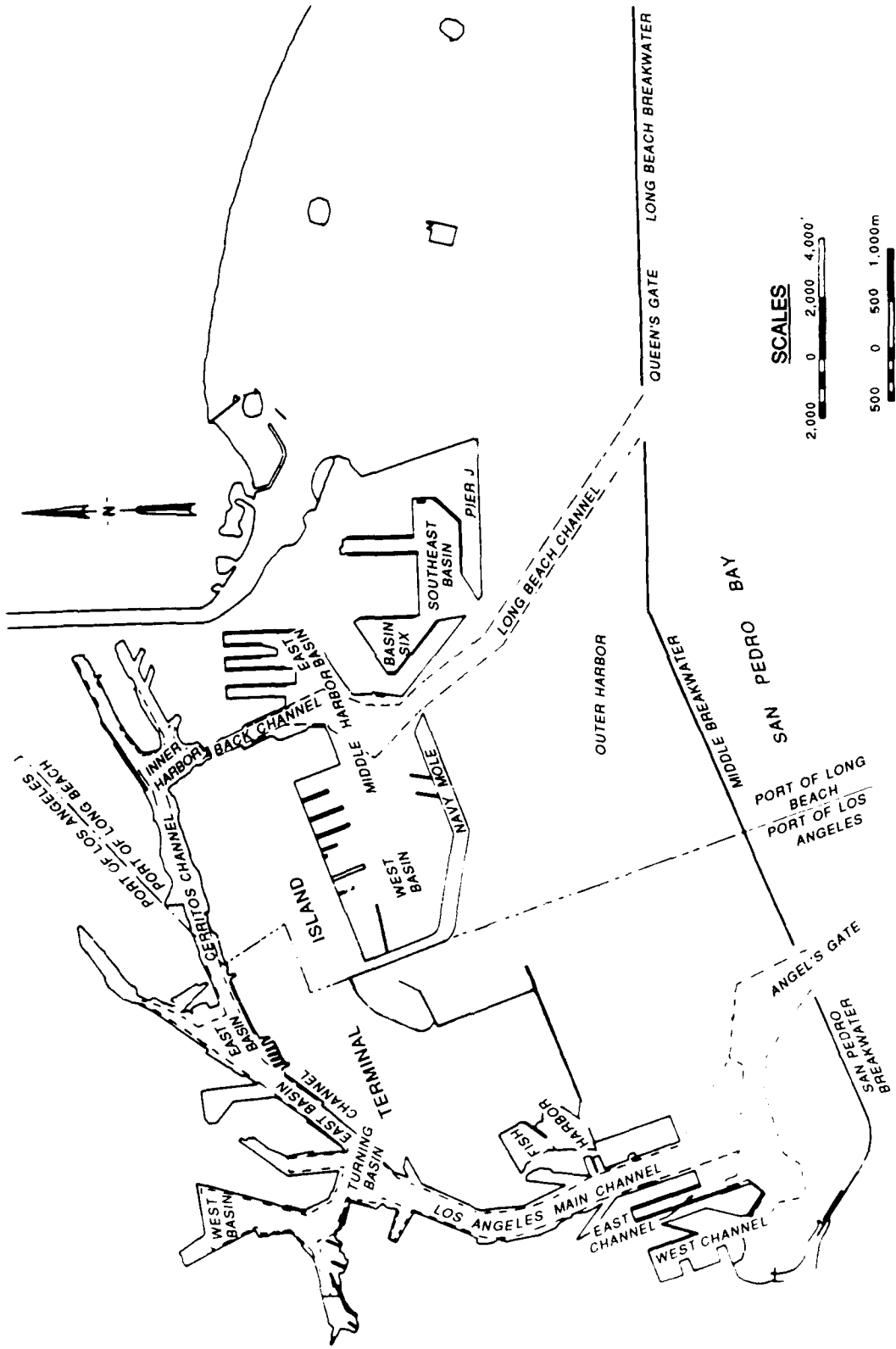


Figure 1. Location of channels and basins in Los Angeles and Long Beach Harbors, California

Water Quality Model

5. The water quality model selected for this study was a modification of the US Environmental Protection Agency WASP code (Ambrose, Vandergrift, and Wool 1986). Major adaptations included (a) improved advective and diffusive transport schemes, (b) provisions for the input and processing of CH3D 3-D hydrodynamic data, and (c) implementation of kinetic routines specific to the San Pedro Bay application.

Advective and diffusive transport schemes

6. The original WASP model formulation considers both advective and diffusive transport through faces of adjacent cells of arbitrary size, shape, and distribution. For the present study, horizontal flows were distinguished from vertical flows, and improved transport schemes were implemented.

7. The advection scheme used in the original WASP provided three advection options: upwind difference, central difference, or a linearly weighted mixed upwind/central difference scheme. These options were unsatisfactory because they either introduced numerical diffusion to the extent that physical diffusive and dispersive transport were entirely masked or required excessively large values of physical diffusion to ensure numerical stability. To improve the horizontal advective transport scheme used in WASP, a modified version of the QUICKEST (Quadratic Upstream Interpolation for Convective Kinematics with Estimated Streaming Terms) scheme (Leonard 1979, Hall and Chapman 1985) was implemented.*

8. The vertical-stretching relationship in the hydrodynamic model accounts for much of the vertical advection through layer thickness expansion or contraction. As a consequence, the vertical velocities were small. Small vertical velocities result in small numerical diffusion with the upwind scheme, and large physical diffusion is not required to maintain stability with the central difference scheme. However, the time step was limited due to the explicit vertical diffusive transport schemes used in the original WASP. Therefore, an implicit vertical advective and diffusive transport scheme was

* Ray Chapman and Associates. 1988. "Analysis and Improvement of the Numerical and Physical Mixing Characteristics of the WASP Box Model," report prepared for US Army Engineer Waterways Experiment Station, Vicksburg, MS.

implemented. Central differences were used for both the advection and diffusion terms.

Model linkage

9. The hydrodynamic and water quality models were linked by spatially and temporally averaging CH3D output to drive the WQM. The hydrodynamic model used extensive spatial resolution to resolve important scales and to minimize the need for parameterization. The CH3D spatial resolution was of the order of 100 m and required a time step of 60 sec for stability. In contrast, the WQM has characteristic time scales on the order of hours, which are determined by the kinetic rate coefficients. The desired analyses of water quality allow a spatial resolution an order of magnitude less than that used by CH3D. Reductions in spatial and temporal resolution greatly reduced computer time required for the WQM.

10. Plate 1 is a schematic of the CH3D grid used for the existing conditions. The CH3D grid consisted of three vertical layers. Existing conditions are referenced in this report as "Base." Since the WQM requires less spatial resolution than CH3D, spatial characteristics of the hydrodynamic grid such as volume, cell surface areas, cell facial areas, and cell lengths were summed, resulting in an "overlaid" WQM grid. Plate 2 represents the resulting WQM grid overlying the CH3D grid for the Base condition. The WQM grid maintained the same vertical resolution as the CH3D grid of three vertical layers. Plate 3 represents the overlaid WQM grid for Scheme B, Phase I, of the 2020 Plan enhancement, which will be referred to as "Scheme B."

11. Coding was appended onto CH3D to initially write to an output file the time-invariant data that included cell surface areas and horizontal cell lengths and to temporally average horizontal flows and facial areas and write this information and volumes to the output file. The hydrodynamic data were averaged over 1-hr intervals. Averaging over shorter intervals did not alter WQM transport results. A mapping file was prepared that was used by the CH3D appended code to relate the hydrodynamic and water quality cells.

12. Table 1 displays the number of computational cells for both CH3D and the WQM. Overlaying the WQM grid decreased the number of computational cells by 94 percent. The larger WQM cell sizes allowed an increase of the time step used from 60 to 900 sec while maintaining computational stability. Reductions in spatial resolution greatly reduced the computer time required for the WQM.

Table 1

Comparison of the Number of Computational Cells in CH3D and the WQM

<u>Plan</u>	<u>CH3D</u>		<u>WQM</u>	
	<u>Layers</u>	<u>Cells</u>	<u>Layers</u>	<u>Cells</u>
Base	3	19,278	3	1,239
Scheme B	3	17,943	3	1,110

Kinetic routines

13. The water quality model study focused on dissolved oxygen resources and flushing characteristics of the harbor system. The WQM simulated the following variables: DO, carbonaceous biochemical oxygen demand (CBOD), ammonia nitrogen ($\text{NH}_4\text{-N}$), nitrite plus nitrate nitrogen ($\text{NO}_2 + \text{NO}_3\text{-N}$), algal biomass as carbon, orthophosphate ($\text{PO}_4\text{-P}$), and a conservative tracer. Initial temperatures were specified horizontally constant yet vertically stratified based on the water quality sampling program conducted during August 1987 by Tekmarine, Inc. However, temperatures varied temporally through the specification of ocean boundary temperatures. Salinity was specified temporally and spatially constant at 32 ppt. The water quality sampling program revealed rather homogenous salinities except near the Terminal Island Treatment Plant (TITP) effluent and the Los Angeles River. Salinities were used in the WQM for calculating DO saturation. Global specification of a constant salinity was adequate since a 2-ppt variation in salinity at the temperatures observed results in only a 1-percent variation in DO saturation.

14. The water quality kinetic algorithms were adapted from the WES two-dimensional, laterally averaged model of hydrodynamics and water quality, CE-QUAL-W2 (Environmental and Hydraulics Laboratories 1986) and the HydroQual, Inc., Potomac Eutrophication Model (Thomann and Fitzpatrick 1982). The water quality kinetic routines are detailed in Appendix A.

Transport Calibration

15. Transport calibration consisted of two studies: comparison of a simulated tracer injection using both the WQM and CH3D, and a comparison between 15- and 60-min CH3D time averaging.

Simulated tracer injection

16. A test was conducted to ensure that the transport properties of CH3D were maintained with the interfacing. After CH3D was calibrated, a tracer injection was simulated. The tracer was injected into the four surface cells overlain by one WQM cell in the outer harbor and simulated for 3 days.

17. The same tracer injection was simulated using the WQM. For this test the CH3D data were time-averaged over 60-min intervals. Plate 4 represents the WQM column where the surface cell was injected with tracer. The circles represent the arithmetic average of the six hydrodynamic cells overlain by the single WQM cell. The figure demonstrates nearly equivalent decline in tracer in both the HM and WQM. The figure also reveals that vertical advection was insignificant in mixing the tracer among layers. The vertical diffusion was set to 0.0 in both models and contributed nothing to vertical mixing.

Hydrodynamic model time averaging

18. Subtidal oscillations, characterized by a pulsating flow pattern with areas of flow direction reversal, were simulated in CH3D. The flow pulsations occurred at a frequency of 1 hr. The influence of the subtidal flow oscillations on the HM time-averaging interval was investigated. A comparison between 15- and 60-min HM time-averaging consisted of two tests. The first test consisted of loading all WQM cells uniformly with a tracer at a concentration of 10. The ocean boundaries were 0.0 concentration. The second test consisted of injecting tracer in the surface, middepth, and bottom cells of a water column in the outer harbor and recording concentrations over 24 hr. The tracer injection corresponded to the location of the CH3D and WQM transport comparison and was located in the "transient" gyre simulated north of Angels Gate.

19. The first test revealed that 15-min averaging resulted in 0.2-percent greater mass loss through the ocean boundaries than 60 min averaging after 24 hr of simulation. Plate 5 represents the WQM cell used for the CH3D and WQM transport comparison. The 15-min results are presented with solid lines while the 60-min results are dotted. The 15- and 60-min results are nearly equivalent. The conclusion from these tests was that 60-min hydrodynamic model averaging is equivalent to 15-min averaging.

Flushing Studies

20. Flushing studies consisted of insertion of a conservative tracer and noting the movement and dilution of the tracer. The flushing studies provided a qualitative comparison between Base and Scheme B conditions. A decrease in the flushing rate prolongs the period of time that oxygen-demanding substances exert their influence on the DO concentration. A decrease in flushing rate can intensify existing water quality problems and indicates that more detailed water quality analyses are required. In this study, the transport comparisons provided identification of areas within the harbor that exhibited major decreases in flushing. Areas that exhibited decreases in flushing were selected for more detailed characterization during subsequent DO simulations.

21. Because the WQM uses flows from the calibrated CH3D model, there is little or nothing to calibrate in the WQM when simulating a conservative tracer. The only parameters that can be adjusted are the diffusion coefficients. Two field dye studies were performed for San Pedro Bay to verify the WQM transport; however, the dye studies were not simulated because the WQM grid was too coarse to resolve the small dye cloud. Field dye studies did provide an order of magnitude estimate for the horizontal diffusion coefficient of $1 \text{ m}^2/\text{sec}$ (Fischer et al. 1979). Simulations were made where the diffusion coefficients were varied, and the results were found to be relatively insensitive. This is not surprising as many surface-water systems, including San Pedro Bay, are advection-dominated, with diffusive transport playing a minor role. The vertical diffusion coefficient used was $0.1 \text{ cm}^2/\text{sec}$. This value is typical of deeper regions of lakes and oceans (Lerman 1971). The selection of this value represented a bias toward maximizing DO depression in the bottom waters through inhibited vertical diffusive transport.

22. Four flushing comparisons between Base and Scheme B are presented: (a) Tracer Simulation 1 - insertion of tracer in all WQM cells interior to the breakwater, (b) Tracer Simulation 2 - insertion of tracer in the East Basin channel, (c) Tracer Simulation 3 - insertion of tracer in the embayment adjacent to the outer harbor located between West Basin of Middle Harbor and Fish Harbor (Seaplane Anchorage), and (d) Tracer Simulation 4 - insertion of tracer in the West Basin of Middle Harbor (Navy Harbor). Tracer Simulation 1 identified areas of less flushing, while Tracer Simulations 2 through 4 examined potential local water quality problems such as accidental spills. The East

Basin Channel comparison was selected because of minimal flushing observed from the simulations; the Seaplane Anchorage was selected because Scheme B appears to isolate these waters; and the Navy Harbor was selected because initial tracer comparisons indicated decreased flushing with harbor enhancement.

23. The boundaries were specified exterior to the breakwaters. Tracer could exit the outer harbor through the breakwater openings, but only water without tracer material could enter the outer harbor from the ocean boundary. The initial tracer concentration was set to 10.0.

24. Plates 6-11 display the dilution of tracer in the Base condition while Plates 12-17 display the dilution of tracer in the Scheme B condition for Tracer Simulation 1, insertion of tracer in all WQM cells. Examination of the figures reveals that circulation through Los Angeles Main Channel is rather static, but slightly counterclockwise in the Base condition and clockwise in the Scheme B condition. The clockwise circulation in the Scheme B condition is apparent through the movement of tracer into Inner and Middle Harbors. It should be noted that flushing in West Basin of Middle Harbor is reduced for Scheme B.

25. Comparison of the Base and Scheme B conditions for Tracer Simulation 2, insertion of tracer in East Basin channel, is displayed in Plates 18-23 for the Base condition and in Plates 24-29 for the Scheme B condition. Tracer Simulation 2 corroborates the clockwise circulation in Scheme B and the counterclockwise circulation in the Base.

26. The tracer concentrations in the five cells corresponding to the initial tracer injection in the East Basin channel (Plates 18 and 24) were averaged and plotted as a function of time (Plate 30). Examination of Plate 30 reveals that the East Basin channel flushes more rapidly in the Scheme B condition than in the existing condition. Tracer concentration in the existing condition was asymptotically approaching 20 percent of initial concentration after 25 days. In contrast, tracer surface layer concentrations achieved 20 percent within 7 days in Scheme B. Bottom layer flushing was slower than the surface; the bottom layer required 9 days to achieve 20 percent of initial.

27. Tracer Simulation 3, insertion of tracer between West Basin of Middle Harbor and Fish Harbor (Seaplane Anchorage, Plates 31-42), revealed that, in the Base, flushing occurred into the outer harbor and through both Angels and Queens Gates. In Scheme B, circulation is largely through Angels

Gate and into the Los Angeles Main Channel. The tracer concentrations in the six WQM cells interior to the embayment were averaged and plotted as a function of time (Plate 43). Plate 43 indicates that flushing occurs slightly less rapidly in Scheme B (20 percent in 14 days) than in the existing condition (20 percent in 10 days).

28. The result of Tracer Simulation 4, insertion of tracer in the West Basin of Middle Harbor (Navy Harbor), is presented as a plot of concentration versus time (Plate 44). All cells in the Navy Harbor were initialized with a concentration of 10.0. The plots were the average of the cells. Plate 44 indicates that 20 percent initial concentration was achieved in 25 days in Scheme B and that 20 percent was achieved in 16 days for the existing condition. The conclusion is that flushing occurs less rapidly in Scheme B than in the existing condition.

29. The four flushing studies indicated areas that exhibited decreased flushing. Nine locations were selected for more detailed characterization during the DO simulations (Figure 2). The selected locations are noted as X-1 through X-9. The locations prefixed with the letter I or B represent the interior and boundary stations sampled during August 1987.*

Water Quality Studies

30. The water quality studies focused on dissolved oxygen. The WQM simulated the following variables: DO, CBOD, $\text{NH}_4\text{-N}$, $\text{NO}_2 + \text{NO}_3\text{-N}$, algal biomass as carbon, and $\text{PO}_4\text{-P}$. Algal biomass was reported in chlorophyll-a.* The relationship 1 mg carbon = 35 mg chlorophyll-a (Thomann and Fitzpatrick 1982) was used to relate chlorophyll-a to algal carbon. The kinetic routines are detailed in Appendix A. The kinetic constants used are listed in Table 2.

Boundary conditions

31. Boundary conditions included observed water quality at the ocean boundary,* sediment oxygen demand (SOD) at the bottom (measured*), light exchange through the surface, and water quality of the Terminal Island Treatment Plant discharge.

* Tekmarine, Inc. 1987. "Water Quality Data Collection Program, San Pedro Bay, California," report prepared for US Army Engineer Waterways Experiment Station, Vicksburg, MS, and US Army District, Los Angeles, Los Angeles, CA.

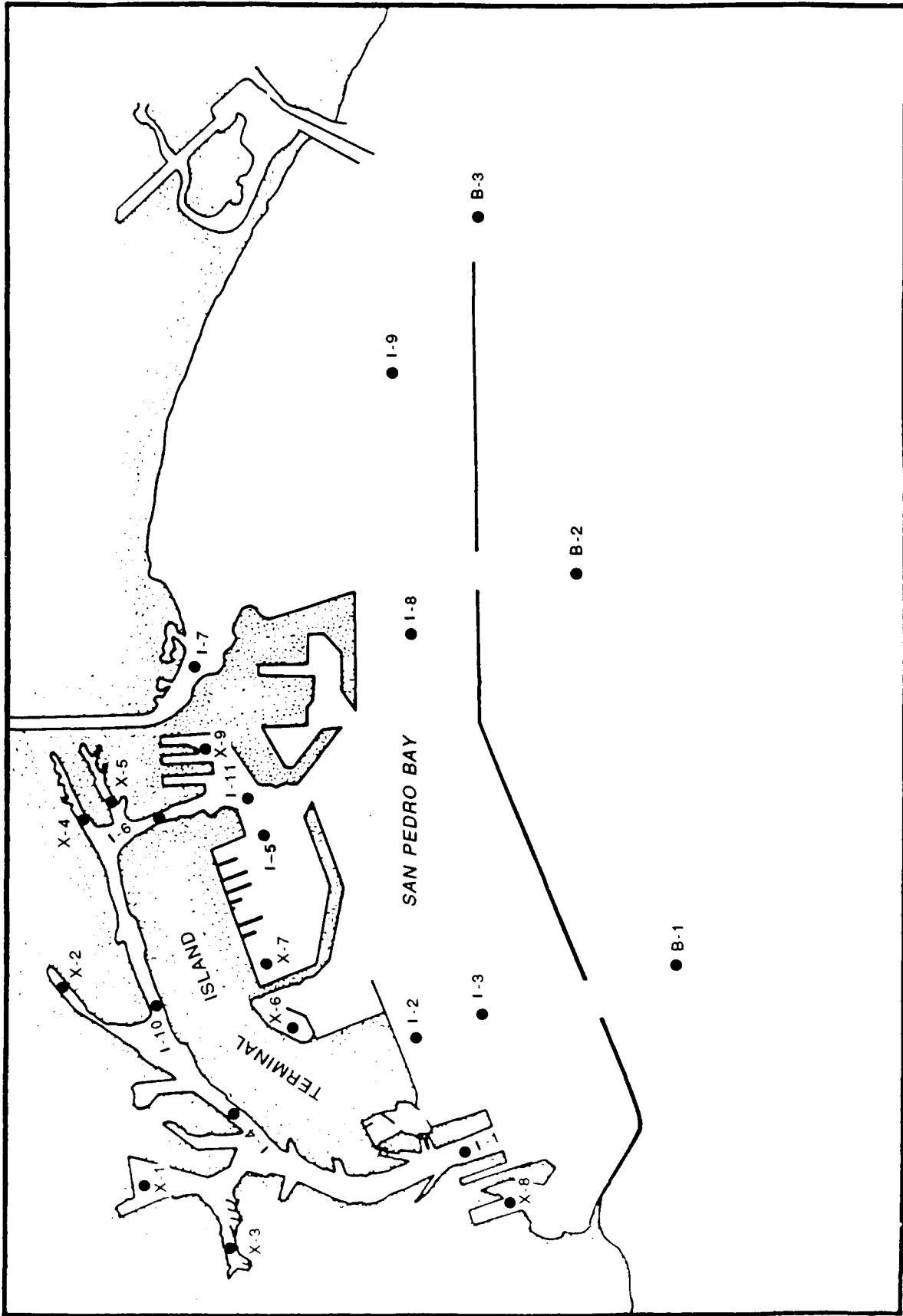


Figure 2. Water quality stations

Table 2
Kinetic Constants

Description	Unit
Solar radiation attenuation constant	0.50/m
Fraction solar radiation absorbed at the surface	0.45
Light intensity at maximum algal photosynthesis	20.0 W/m ²
Fractional daylength	0.5
Half-saturation constant for nitrogen	0.025 g N/m ³
Half-saturation constant for phosphorus	0.001 g P/m ³
Saturated algal growth rate at 20° C	2.0/day
Temperature coefficient for algal growth	1.068
Algal respiration rate at 20° C	0.1875/day
Temperature coefficient for algal respiration	1.045
Algal maximum excretion rate	0.03/day
Algal mortality rate at 20° C	0.02/day
Algal settling velocity	0.1 m/day
Phosphorus to carbon ratio	0.025 g PO ₄ -P/g C
CBOD deoxygenation rate at 20° C	0.2/day
Temperature coefficient for CBOD deoxygenation	1.047
Half-saturation constant for CBOD	0.5 g O ₂ /m ³
Ratio of ultimate CBOD to CBOD5	1.85
Oxygen to carbon ratio	2.67 g O ₂ /g C
Nitrogen to carbon ratio	0.25 g N/g C
Nitrification rate at 20° C	0.1/day
Temperature coefficient for nitrification	1.08
Half-saturation constant for nitrification	2.0 g O ₂ /m ³
Temperature coefficient for SOD	1.08
Half-saturation constant for SOD	0.5 g O ₂ /m ³

32. Solar radiation and wind shear at the water surface were computed from weather information. The computed solar radiation values were used in the algal growth computations, and the wind shear information was used for computing the reaeration coefficient (see Appendix A). Meteorological information was acquired from the National Oceanic and Atmospheric Administration's Tape Deck No. 1440 WBAN Hourly Surface Observations for the Long Beach Airport (Station No. 5085). Computations for solar radiation were based on the Heat Exchange Program (Program No. 722-F5-E1010) available from the US Army Engineer District, Baltimore, Baltimore, MD. Code modifications were necessary to ensure units consistent with the model requirements.

33. The dissolved oxygen at the ocean boundary was specified by linearly interpolating in both space and time the measured data. The constituents algae, PO_4 -P, NH_4 -N, NO_3 -N, and CBOD5 were set constant (Table 3). Examination of the water quality grids (Plates 2 and 3) indicates that the ocean boundary is seaward of the three boundary stations. The boundary stations were used as control points for adjustment of the boundary values.

Table 3
Ocean Boundary Constituent Concentrations (g/m^3)

<u>Variable</u>	<u>Value</u>
Algae	0.0175
PO_4 -P	0.0625
NH_4 -N	0.025
NO_3 -N	0.025
CBOD5	0.05
DO	Interpolated

34. Examination of measured SOD data* indicated that values were less than $2.0 g/m^2/day$. The exceptions were the average measured value of 2.1 at the interior station in the East Basin channel and the trial estimate of 2.1 at the western side of Outer Harbor. All simulations used a "worst-case" global value of $2.0 g/m^2/day$.

35. Constant surface reaeration was assumed. Application of O'Connor's (1983) relationship between wind speed and reaeration revealed that the daily average reaeration coefficient for San Pedro Bay varied between

0.96 and 1.02 m/day; a constant reaeration coefficient of 1.0 m/day was used for the water quality simulations.

36. The Terminal Island Treatment Plant waste effluent was simulated for the Base condition. Monitoring reports of the TITP provided daily estimates of BOD5, weekly estimates of ammonia, and monthly estimates of nitrate. Examination of the ammonia and nitrate values revealed that the data were quite scattered (Table 4). The nitrite plus nitrate estimate for August 1987 was the maximum value measured during the period September 1986 through August 1987.

37. Phosphorus concentration in the final effluent was not measured. A phosphate-phosphorus concentration of 6 g/m³ in the final effluent from the TITP was assumed. This concentration is typical of secondarily treated effluent (HydroQual, Inc. 1987). The simulated TITP effluent discharge is summarized in Table 5.

Table 4
Ammonia and Nitrite + Nitrate TITP Effluent Discharge

<u>Date</u>	<u>NH₄-N, g/sec</u>			<u>NO₂ + NO₃-N, g/sec</u>		
	<u>Average</u>	<u>Maximum</u>	<u>Minimum</u>	<u>Average</u>	<u>Maximum</u>	<u>Minimum</u>
September 1986- August 1987	4.9	18.9	0.1	9.3	15.5	1.4
August 1987	0.9	2.3	0.2	15.5		

Table 5
Simulated Effluent Discharge

<u>Variable</u>	<u>Value, kg/day</u>
CBOD5	1,380
NH ₄ -N	78
NO ₂ + NO ₃ -N	1,340
PO ₄ -P	430

Initial conditions

38. Initial conditions were specified by assuming horizontally constant yet vertically stratified water quality based on the water quality sampling program conducted during August 1987 by Tekmarine, Inc. The initial values represent averages measured during the first week of August 1987 (Table 6). No algae or CBOD5 was detected during the first week of sampling. The monthly average data values of algae were used as initial conditions. The initial phosphorus concentration was substantially inflated by the values measured near the TITP sewage effluent. The "inflated" phosphorus initial concentrations were used in the Scheme B simulations. Temperature was not simulated. The temperature values represent the layer averages measured during the month of August 1987 at the interior stations.

Table 6
Initial Constituent Concentrations

<u>Constituent</u>	<u>Value</u>		
	<u>Surface</u>	<u>Middepth</u>	<u>Bottom</u>
Temperature, °C	18.4	17.2	16.1
Algae	0.24	0.08	0.03
PO ₄ -P	0.16	0.12	0.13
NH ₄ -N	0.002	0.002	0.02
NO ₂ + NO ₃ -N	0.02	0.03	0.06
CBOD5	0.0	0.0	0.0
DO	9.4	8.1	6.7

Water quality results

39. The WQM was calibrated against observed data obtained by Tekmarine, Inc., during August 1987. Plates 45-90 display simulated algae (Alg), orthophosphate, ammonia nitrogen nitrite plus nitrate nitrogen, biochemical oxygen demand, and dissolved oxygen at the surface and bottom. The solid line represents the Base condition, and the dashed line represents Scheme B. The dotted line represents the analytical detection limit, and the circles represent the observed values. The station numbering corresponds to the identification in the water quality sampling program, with the addition of nine locations prefixed with "X" (Figure 2). Water quality station I-3 is not represented in

Scheme B because of landfill. Stations I-10 and I-11 were sampled for SOD and sediment organic nitrogen; therefore, water column constituents were not measured and are not displayed on the plates.

40. The measured and simulated results are in general agreement except for station I-7. Apparently the Los Angeles River is contributing some flows to the bay that were not modeled. The water quality sampling program conducted by Tekmarine, Inc., revealed less saline, nutrient-enriched surface water at station I-7 (Figure 2).

41. Discrepancies at several stations between computed and observed algae concentrations (such as I-4 in East Basin channel, Plate 48) are due to the use of "global" algae and nitrogen nutrient values which exceed initial measured values at some stations. The "global" initial values represented the average over all interior stations for each layer. Algae were nitrogen limited in the simulations; slight variations in initial nitrogen concentrations resulted in variations in the simulated algal concentrations. However, the simulated DO was insensitive to minor variations in initial nitrogen concentrations. The excess nitrogen resulted in rapid growth of algae followed by a gradual decline. Greater algal growth in the existing conditions, particularly at stations X-6 and X-7, are due to TITP effluent contributions of nitrogen.

42. The apparent discrepancies between simulated Base condition and measured algal biomass such as displayed at the surface at station I-1 (Plate 45) are not of concern. Measured algal biomass varies between 0.0 and 0.5 g C/m³ (0 to 14 mg Chl-a/m³), and simulated algal biomass was rather constant near 0.2 g C/m³ (6 mg Chl-a/m³). Water quality standards for algal biomass do not exist. However, it is generally accepted that algal concentrations greater than 25 mg Chl-a/m³ (0.875 g C/m³) are undesirable. Both measured and simulated algal concentrations were below the criterion of 25 mg Chl-a/m³ and much less than the general visible algal concentration of 100 mg Chl-a/m³.

43. Examination of Plates 45-90 reveals that both observed and simulated DO decreased at all stations during August 1987. The decrease in DO was due to a decrease in boundary DO concentration. For example, the measured boundary surface layer DO at Angels Gate (station B-1, Figure 2) decreased from 9.0 g/m³ on 4 August 1987 to 7.4 g/m³ on 25 August.

44. Simulated DO of Scheme B was either equal to or less than existing conditions. Maximum deviations of 0.5 g/m³ occurred in the Inner Harbor-Back

Channel-Middle Harbor of the Port of Long Beach (stations I-5, I-6, I-11, and X-5). It should be noted that Tracer Simulation 1 revealed decreased flushing in these areas.

45. The bottom waters exhibited lower DO relative to the surface waters. The maximum deviations between surface and bottom waters occurred in Cerritos Channel (station I-10), Back Channel (station I-6), Middle Harbor (station I-11), East Basin of Middle Harbor (station X-9), and the dead-end channels connected to Inner Harbor (stations X-4 and X-5). It should be noted that only the stations in Back Channel (I-6) and Middle Harbor (I-11) exhibited differences between existing and enhancement conditions. Differences in DO between existing conditions and Scheme B were not greater than 0.5 g/m^3 . The minimum predicted DO at all stations and all depths was 6.0 g/m^3 . The minimum of 6.0 g/m^3 was predicted in the bottom layer in West Basin of Middle Harbor (station X-7).

Summary and Conclusions

46. The results of this model study indicate that the Phase 1 of Scheme B for Los Angeles and Long Beach Ports harbor enhancement will reduce circulation and flushing in several areas, such as West Basin, Middle Harbor, and Seaplane Anchorage. Residual circulation in the Main Channel is expected to change from counterclockwise (existing conditions) to clockwise for the enhancement scheme, but the flushing of the channel is noticeably increased from existing conditions. Scheme B will result in less rapid flushing in the Inner Harbor-Back Channel-Middle Harbor of the Port of Long Beach.

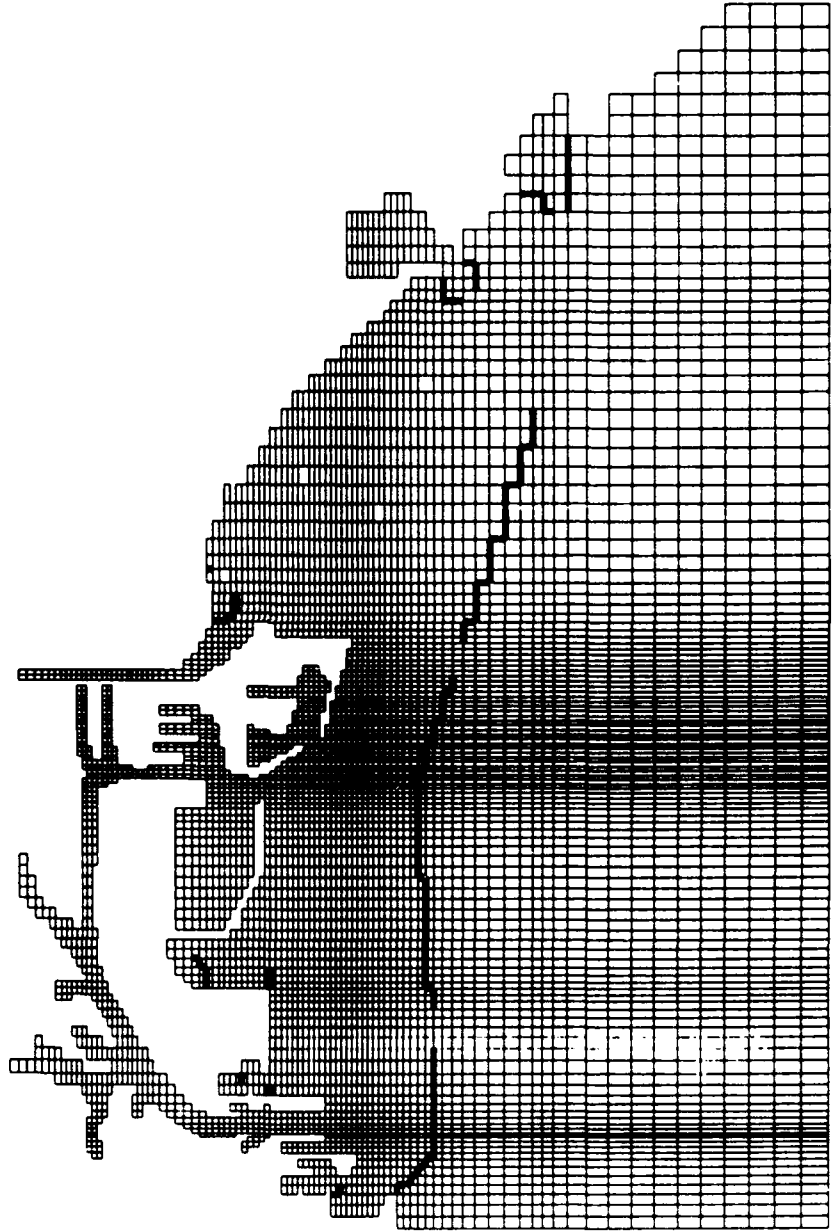
47. The main DO impacts of the enhancement plan would be experienced in the Inner Harbor-Back Channel-middle Harbor of the Port of Long Beach. Simulated differences did not exceed 0.5 g/m^3 . The bottom waters exhibited lower DO than the surface waters, but simulated concentrations were greater than 6.0 g/m^3 .

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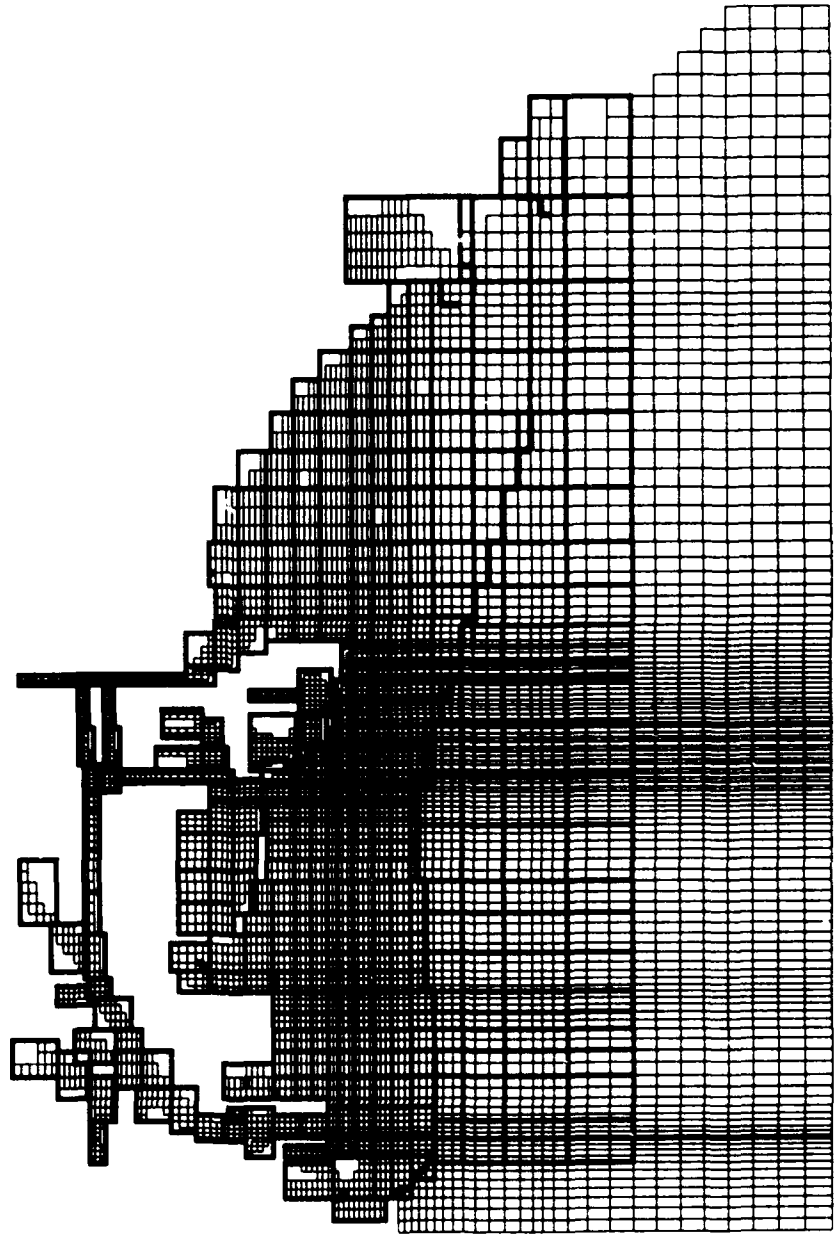
SAN PEDRO BAY - BASE

Hydrodynamic Model Grid



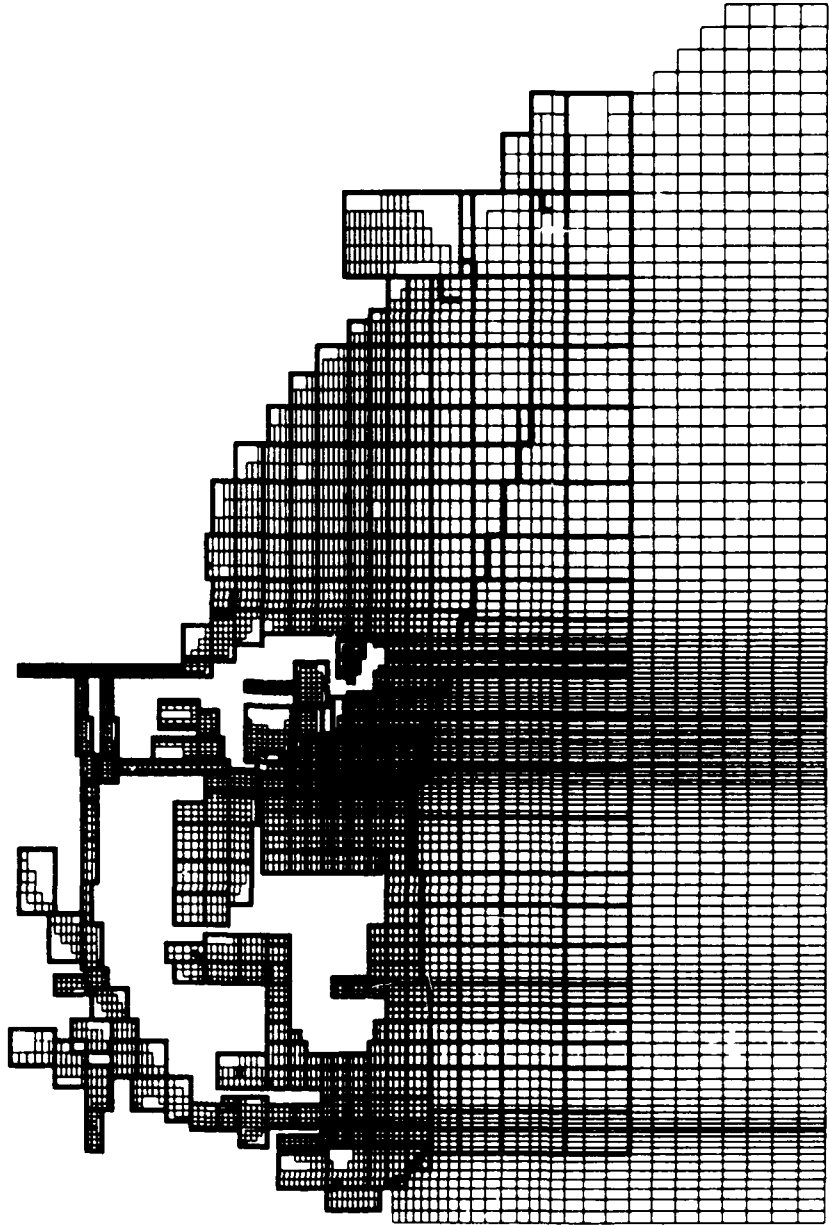
SAN PEDRO BAY - BASE

Water Quality Model Overlay Grid

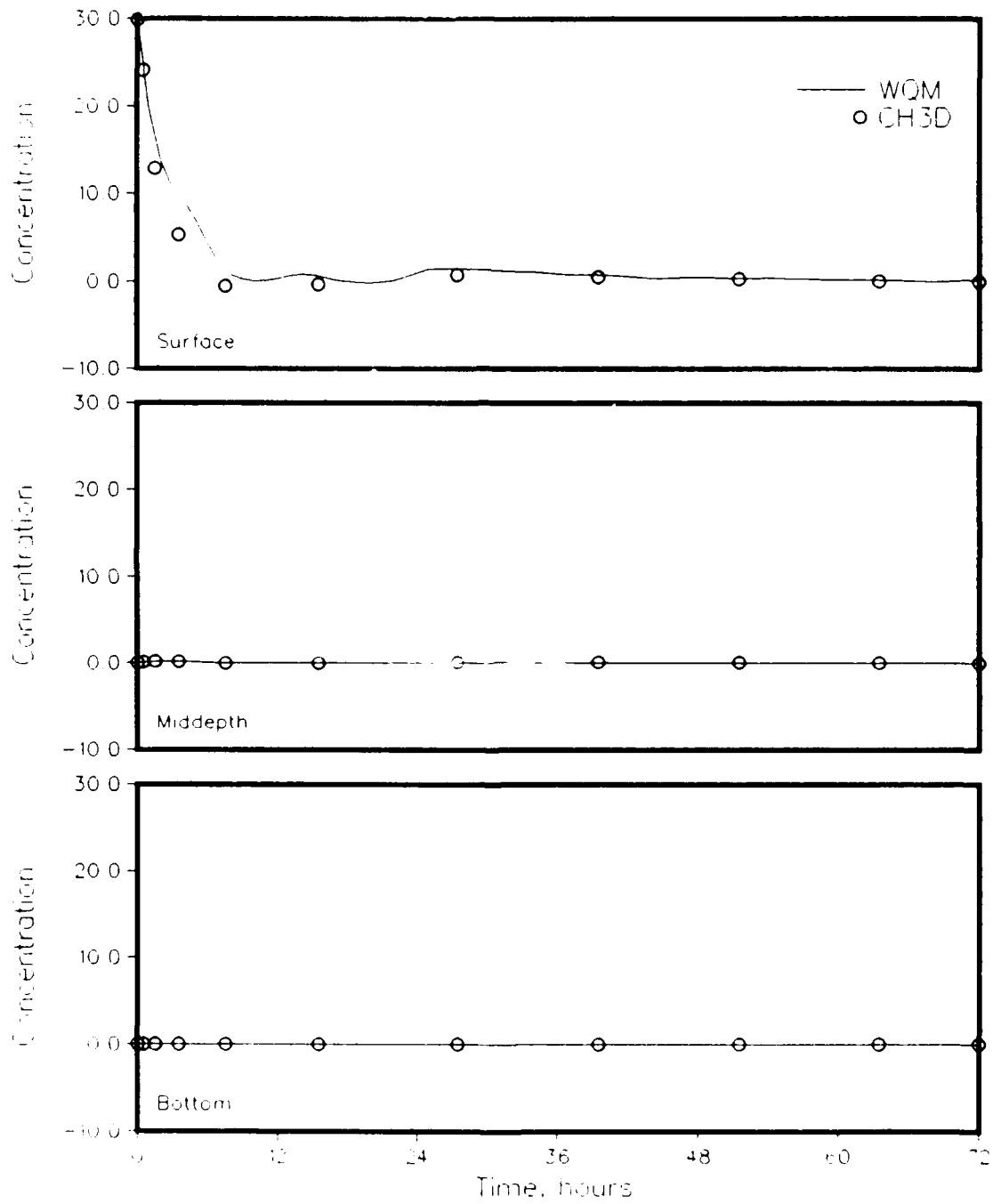


SAN PEDRO BAY - SCHEME B

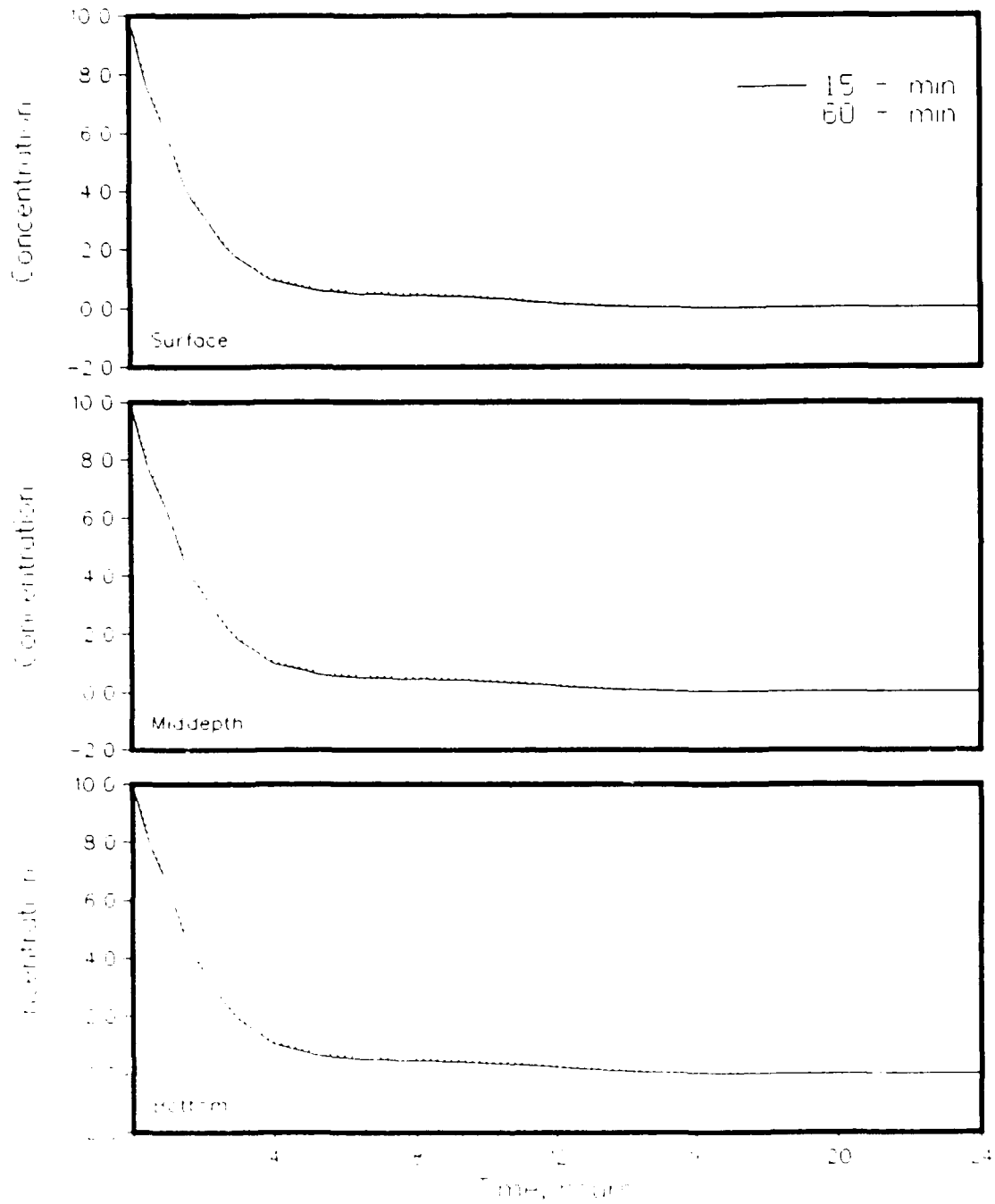
Water Quality Model Overlaid Grid



CH3D & WQM TRANSPORT COMPARISON

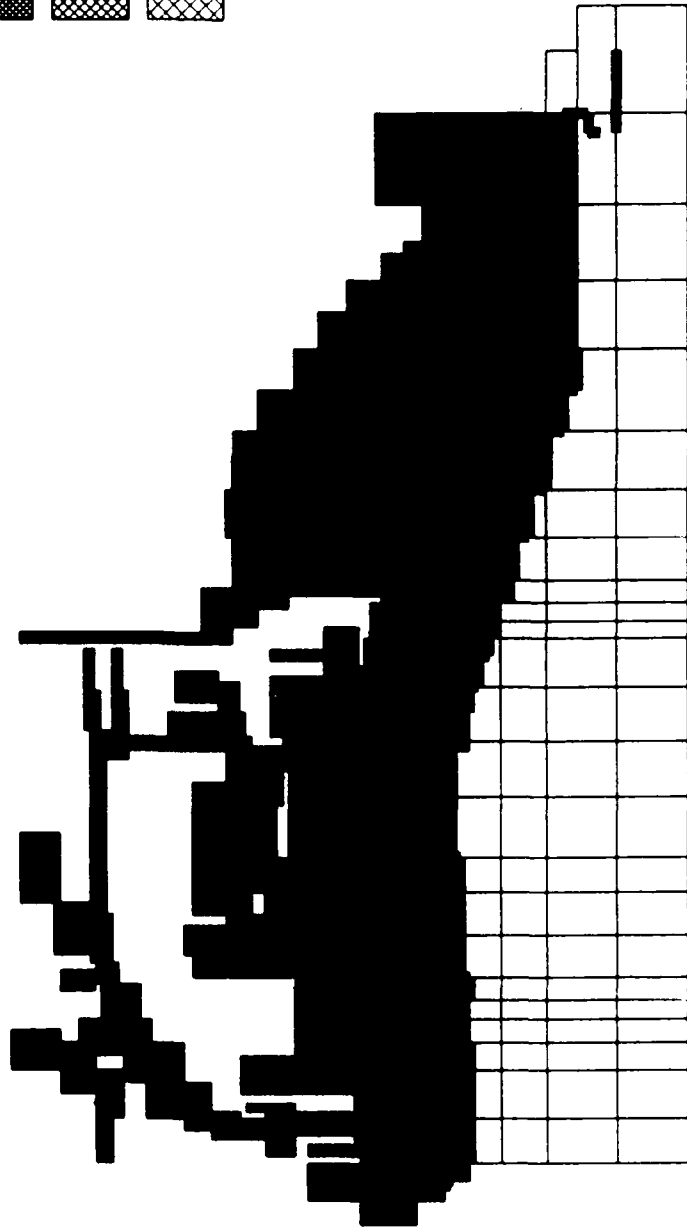
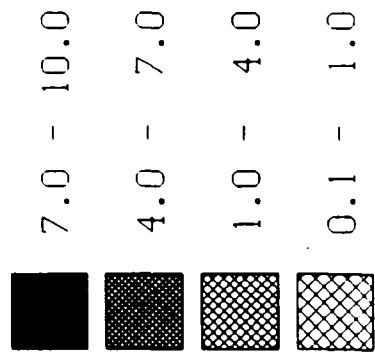


HM TIME-AVERAGING COMPARISON



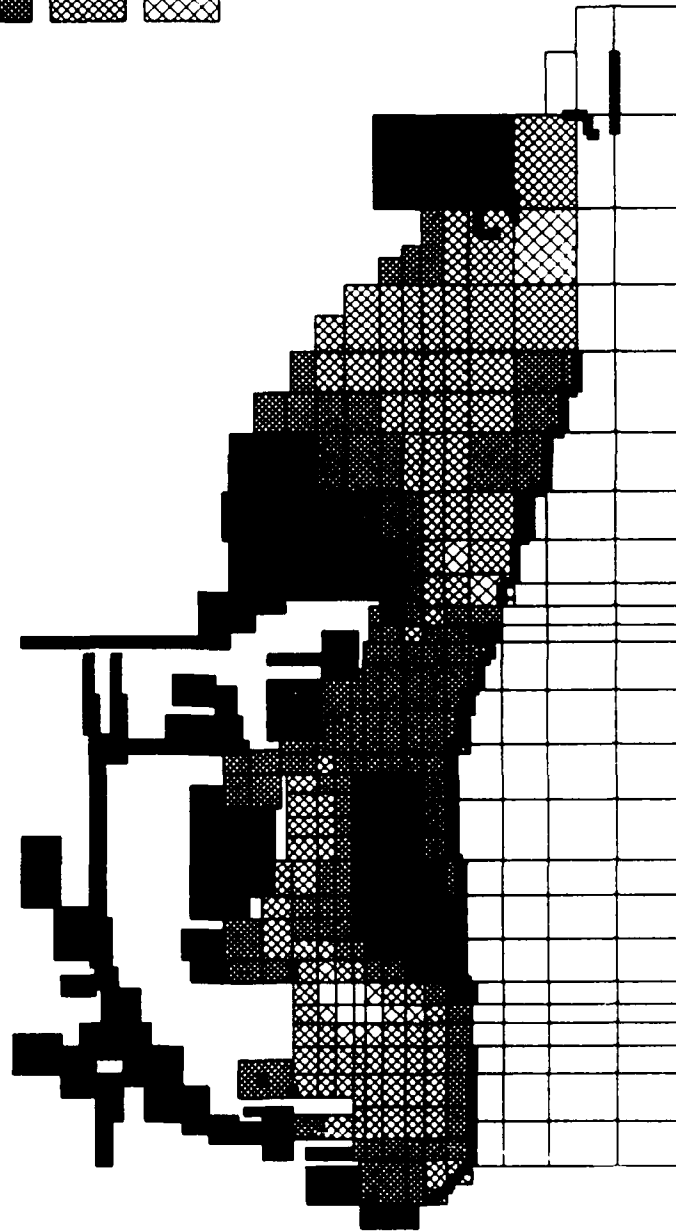
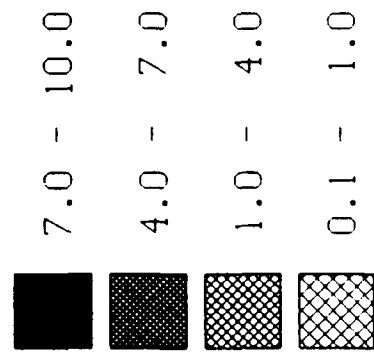
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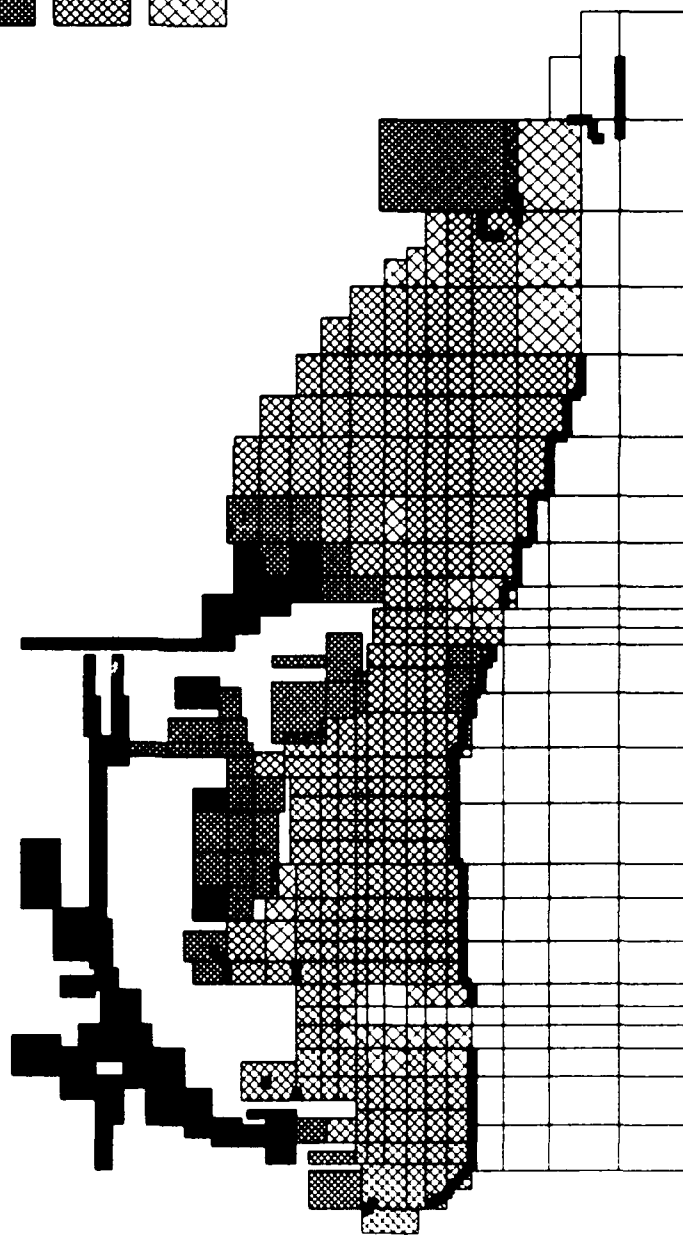
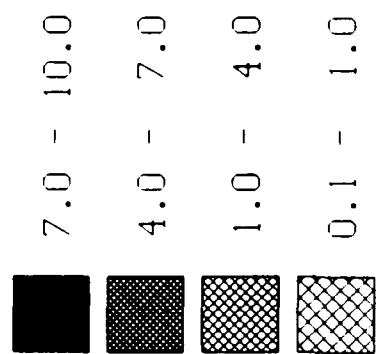
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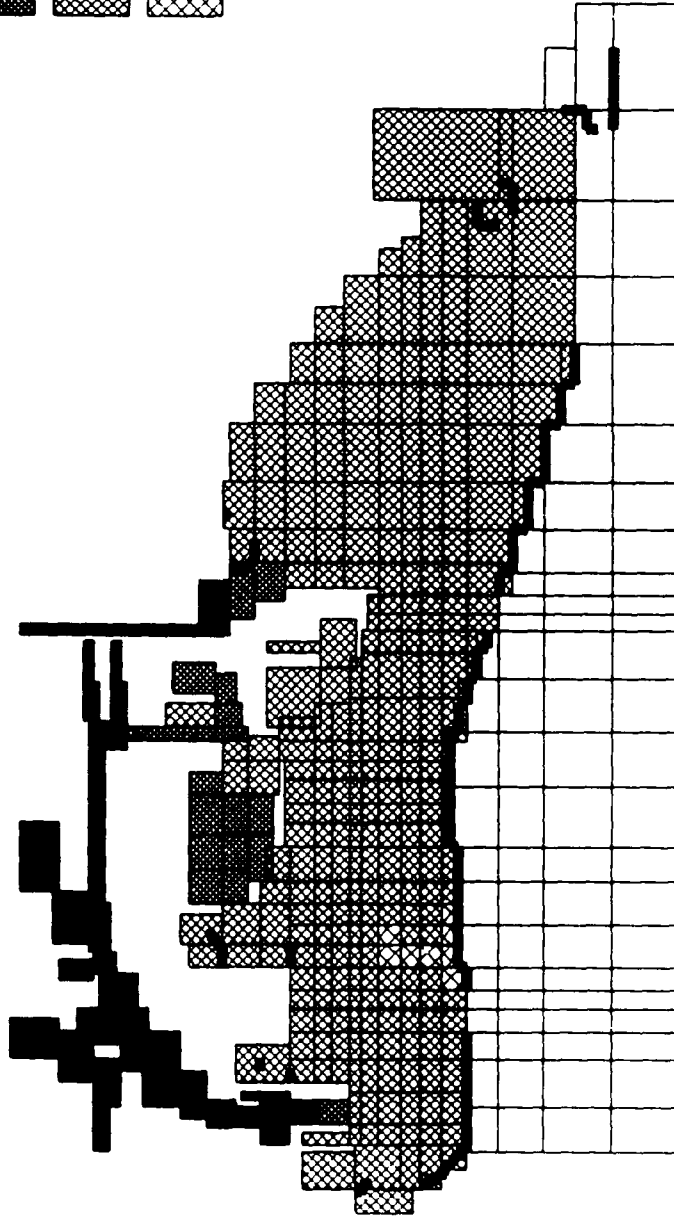
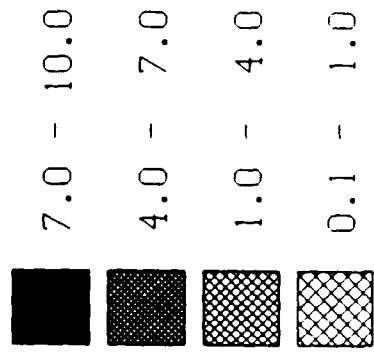
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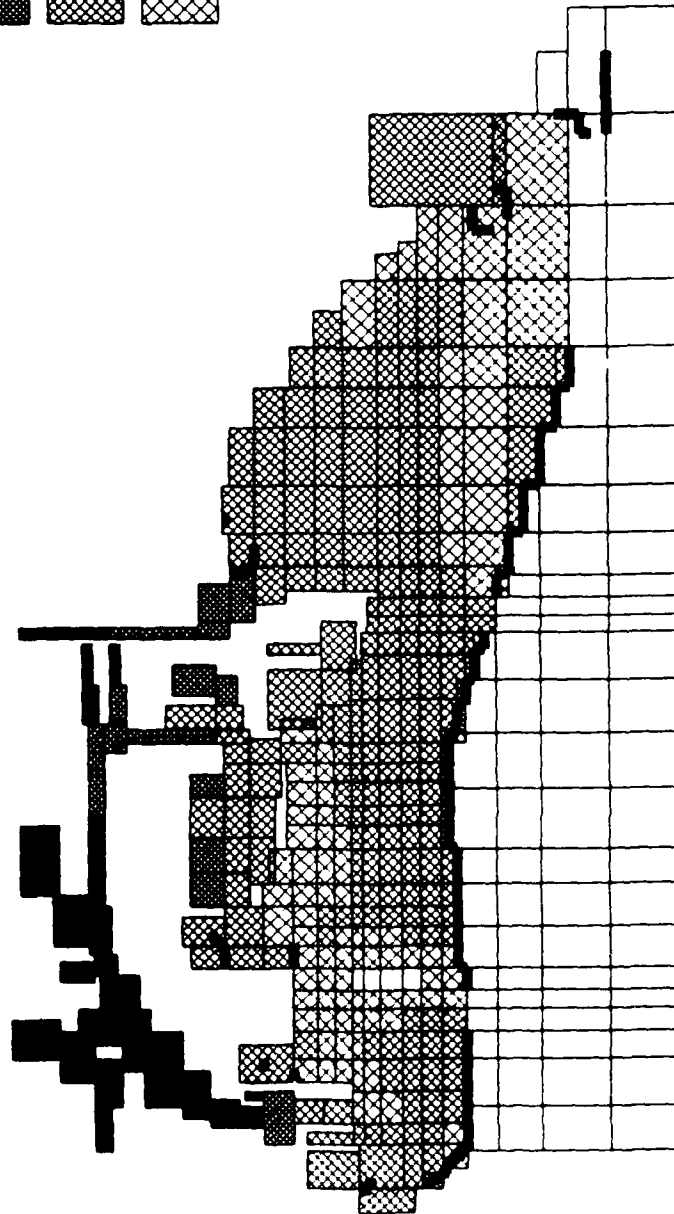
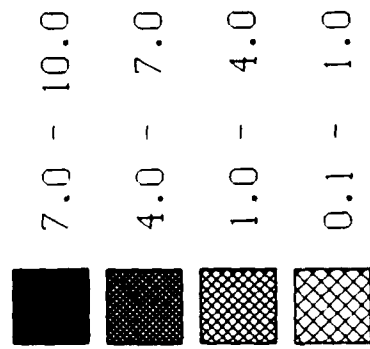
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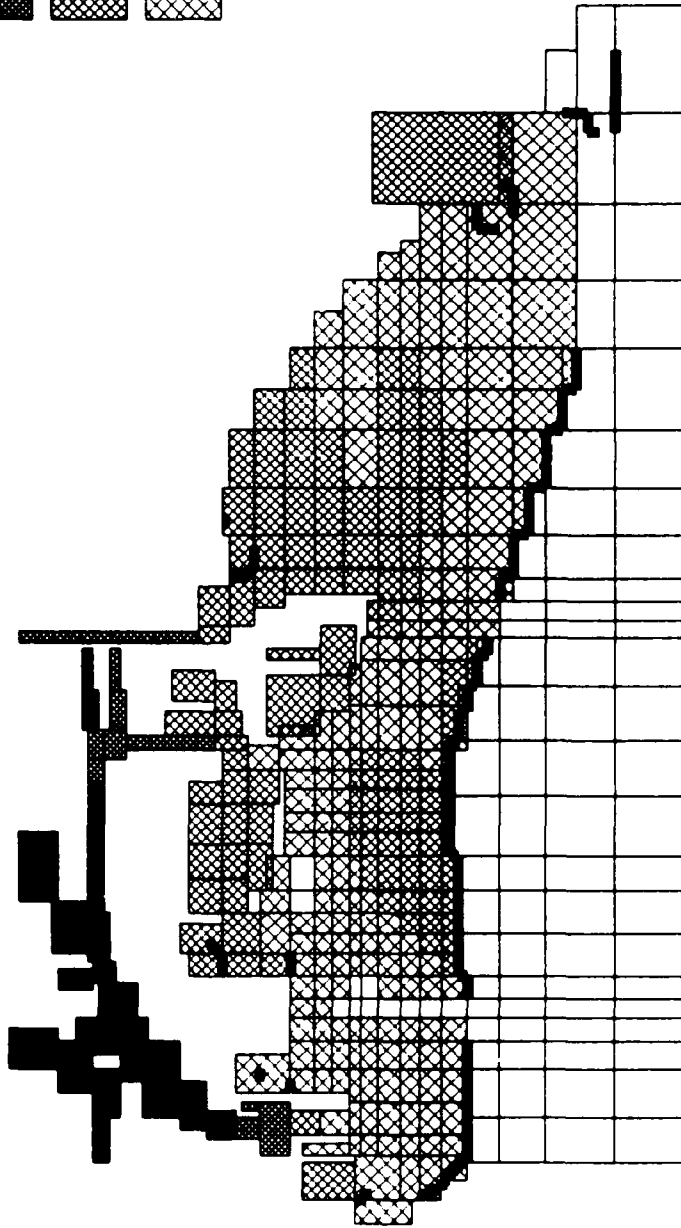
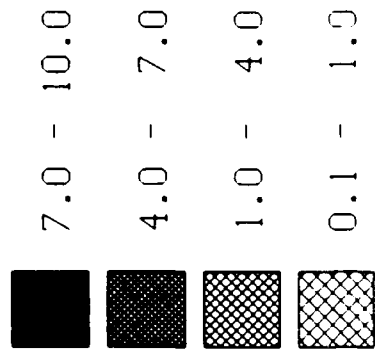
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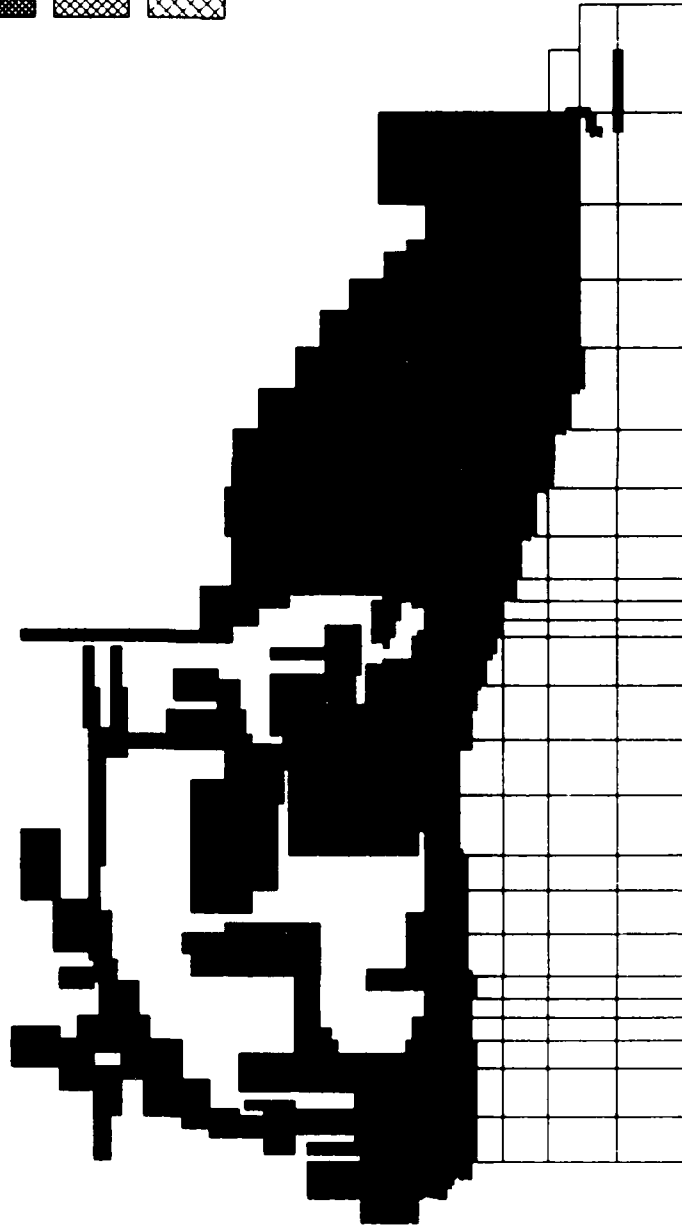
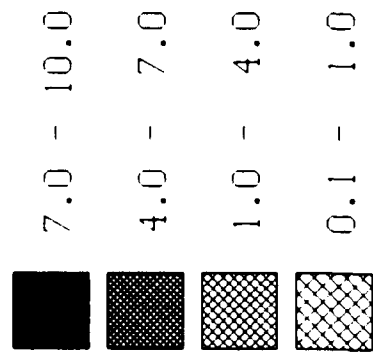
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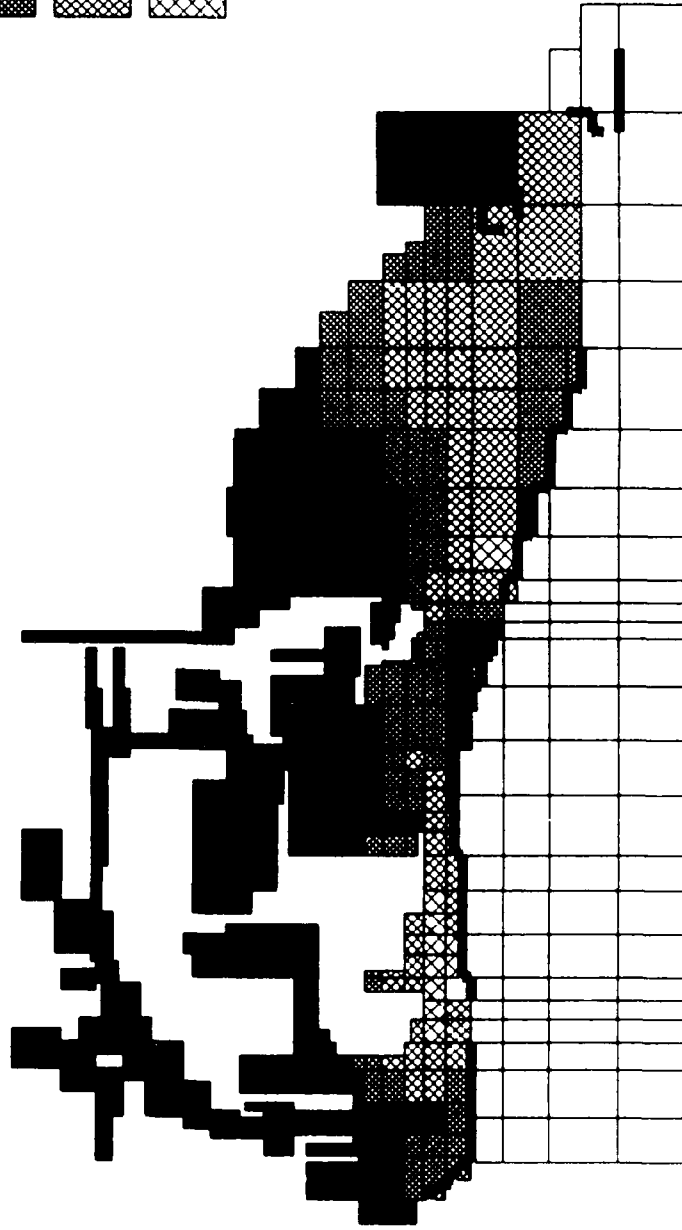
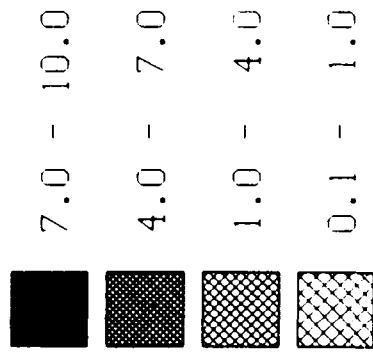
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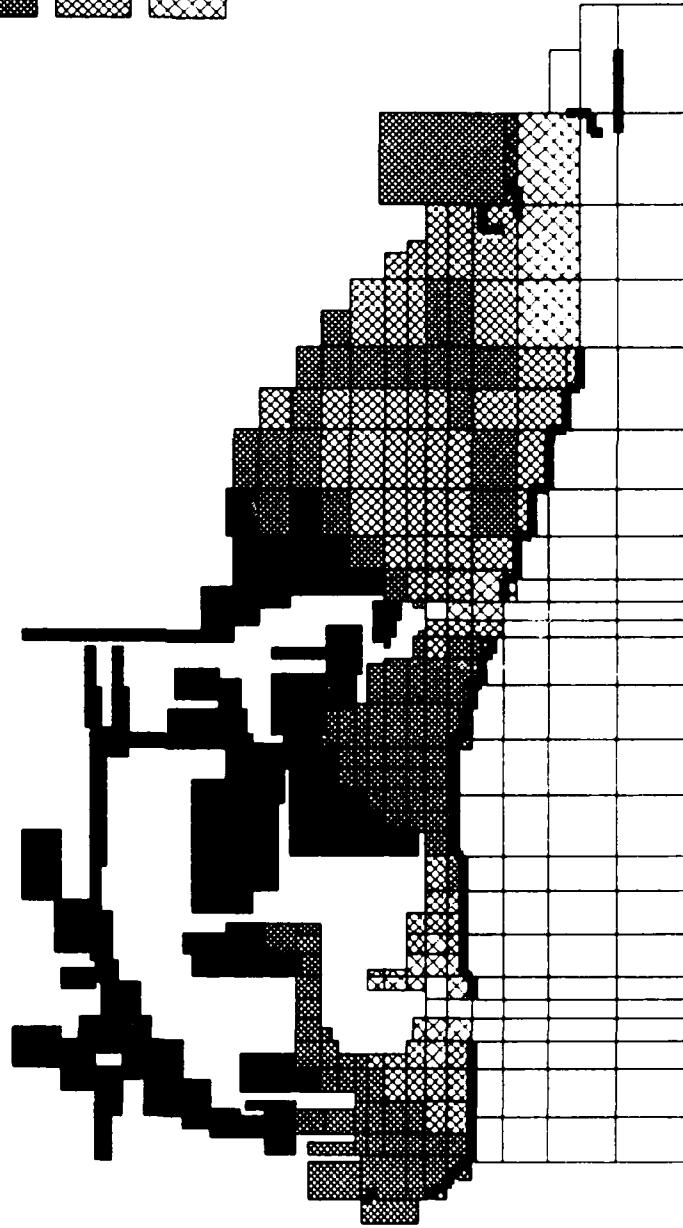
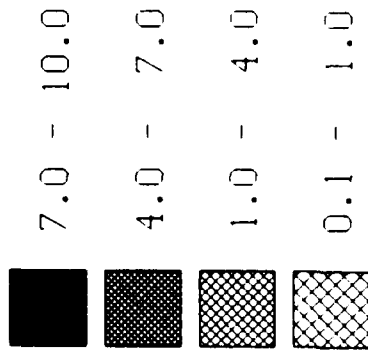
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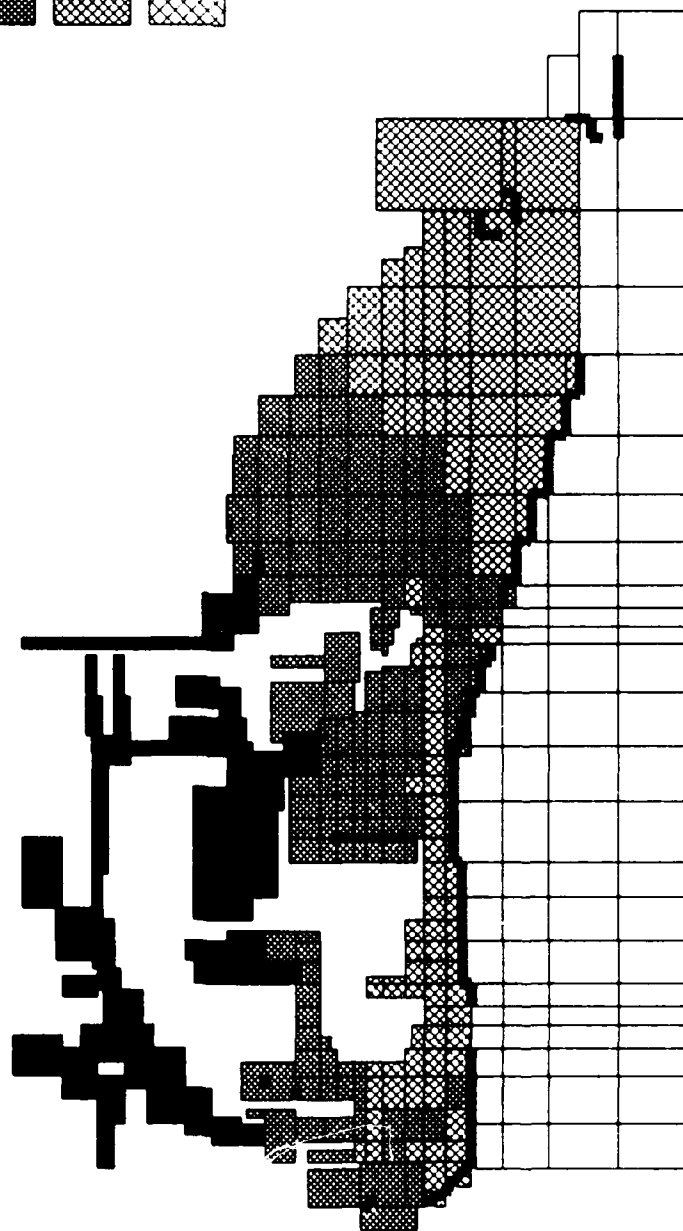
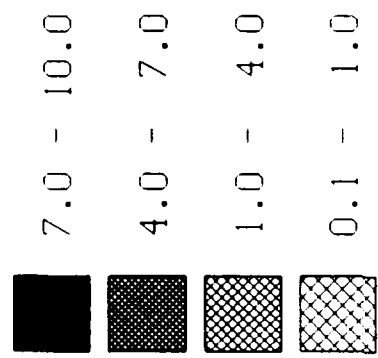
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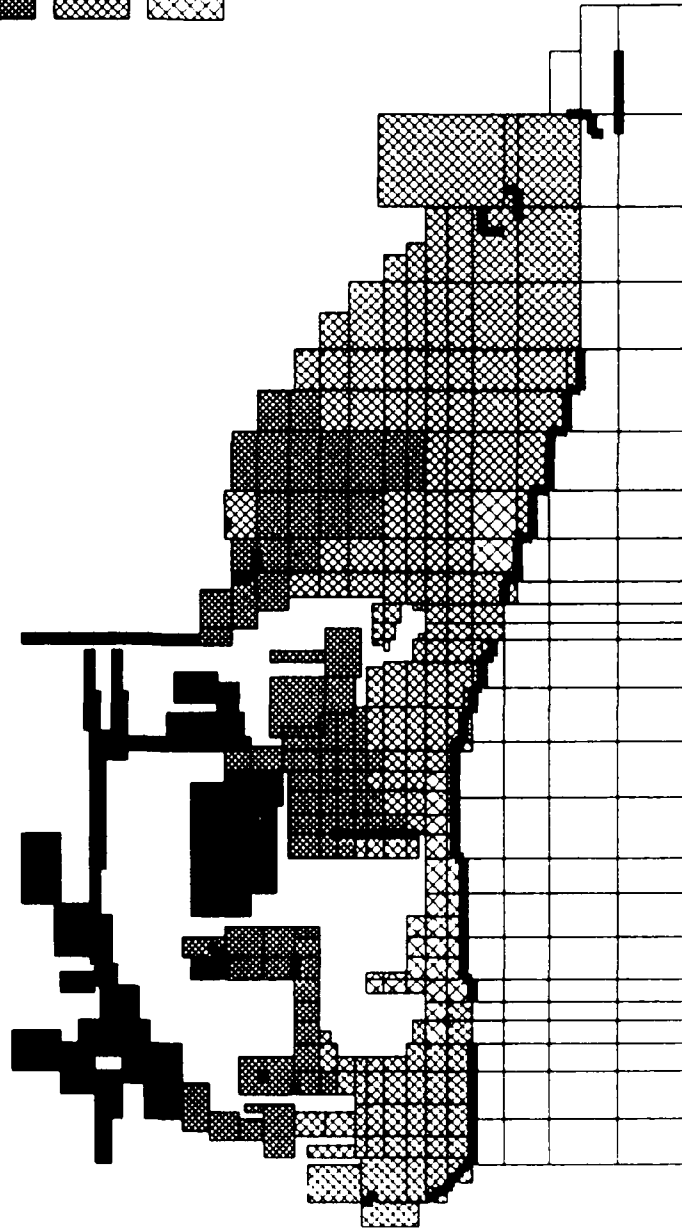
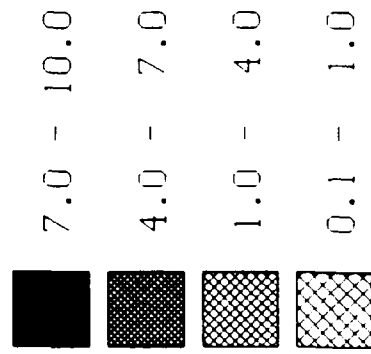
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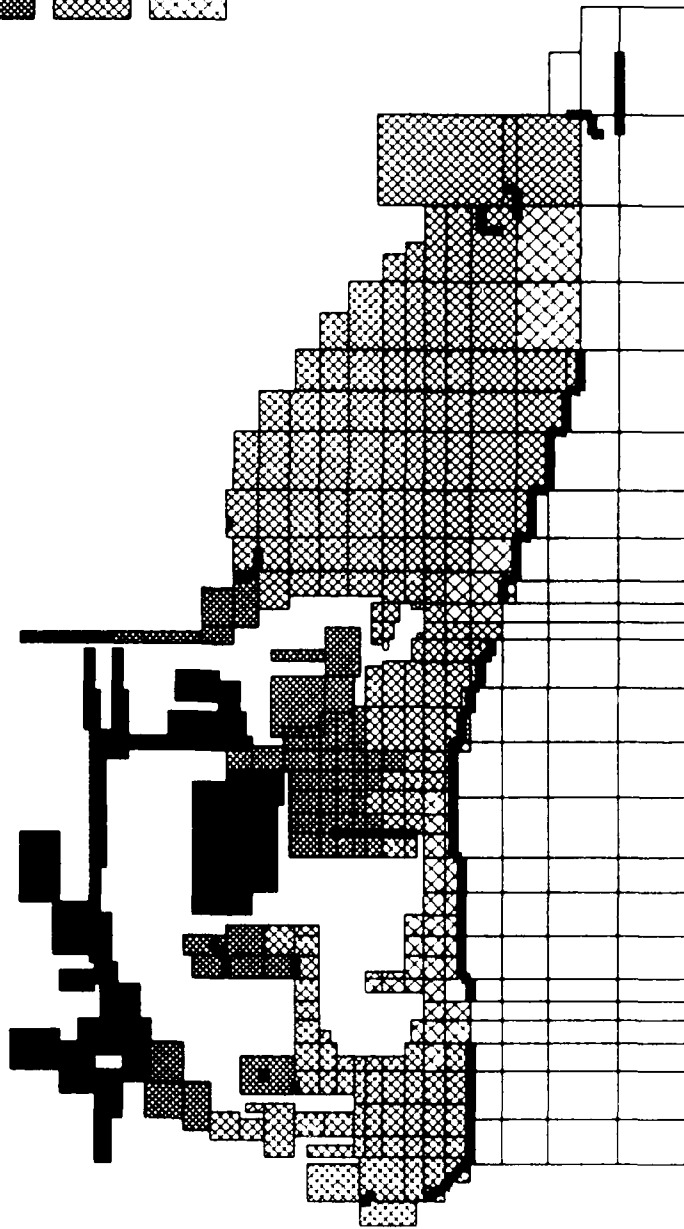
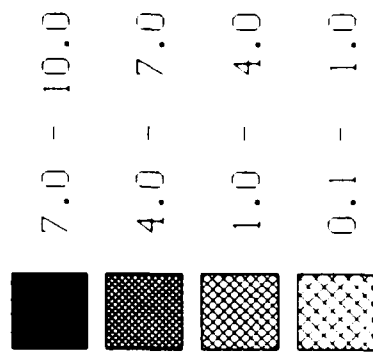
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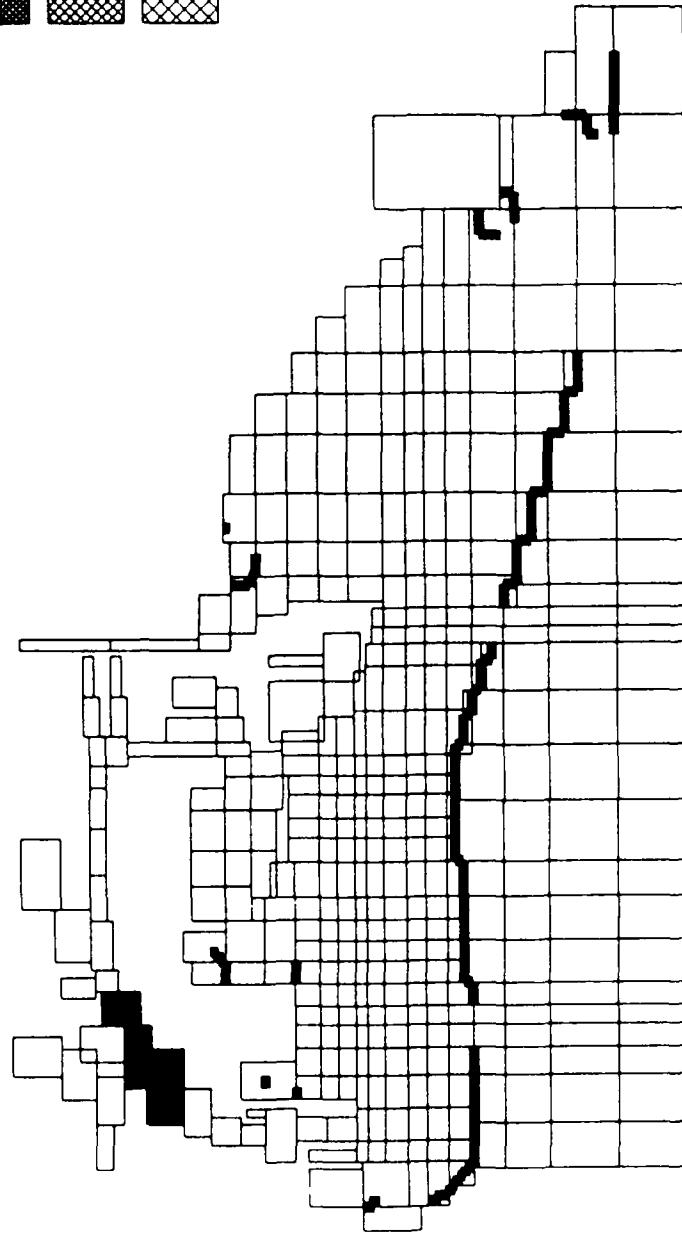
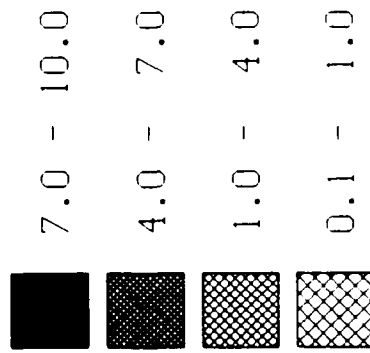
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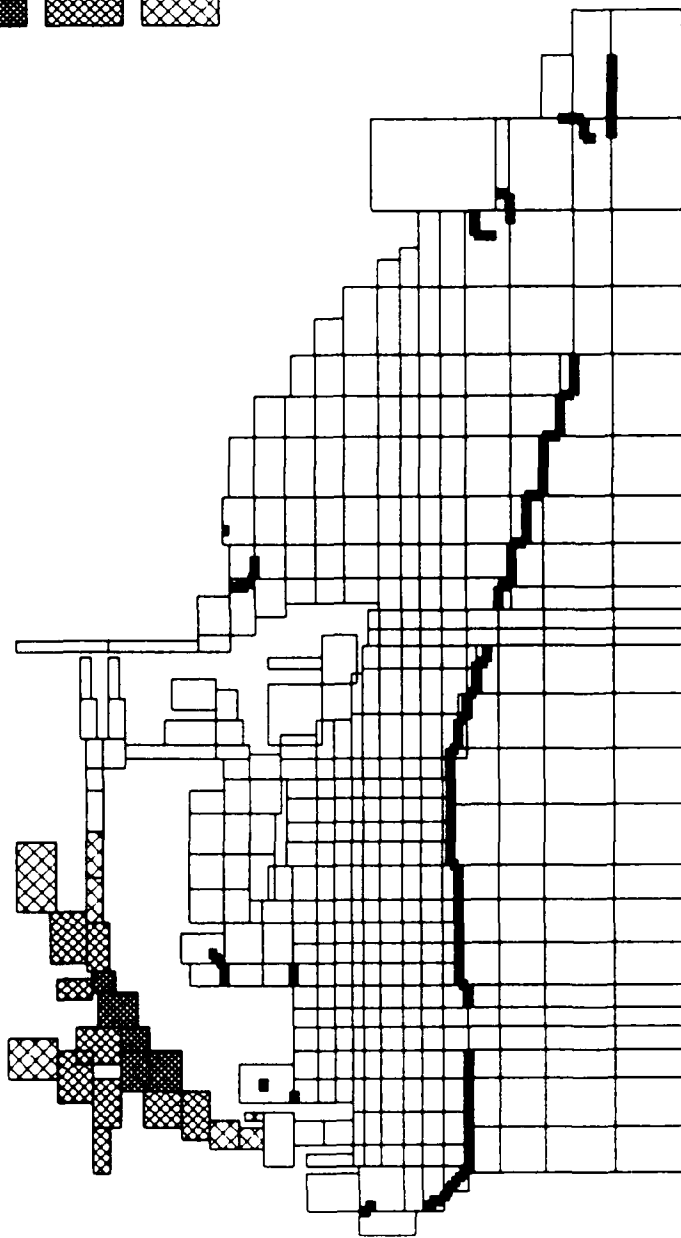
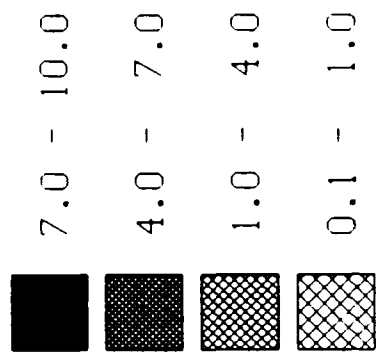
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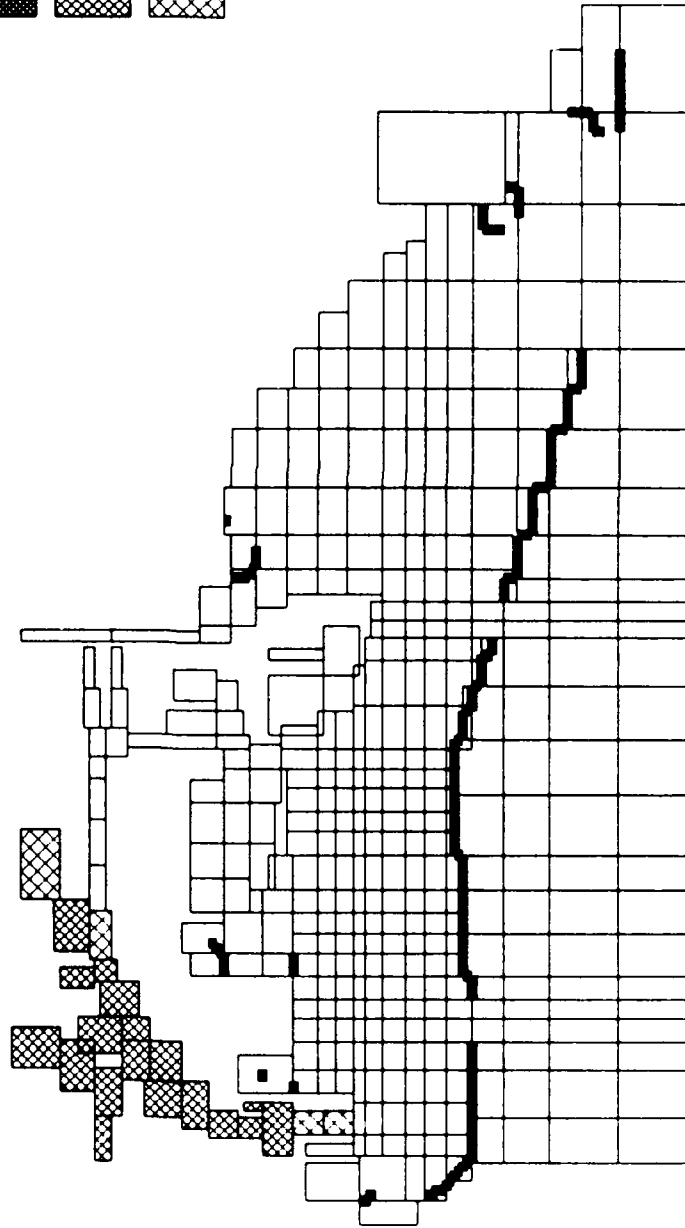
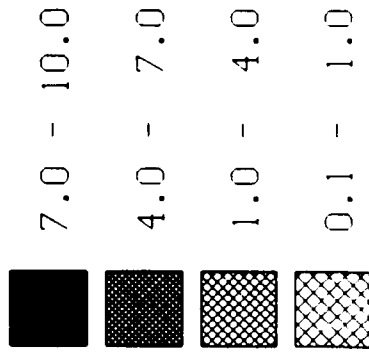
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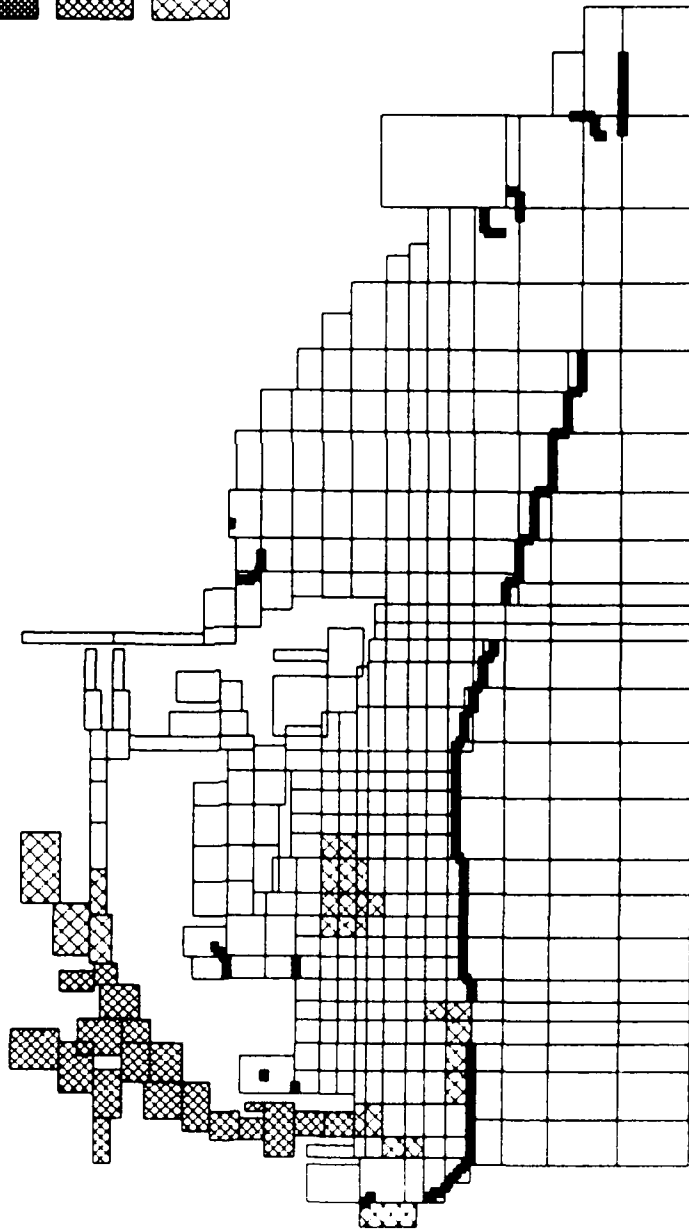
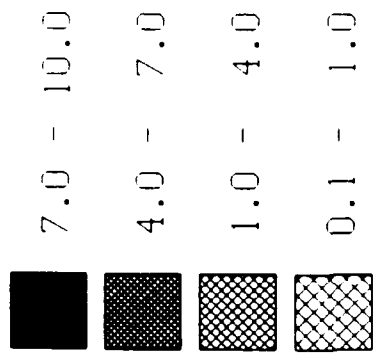
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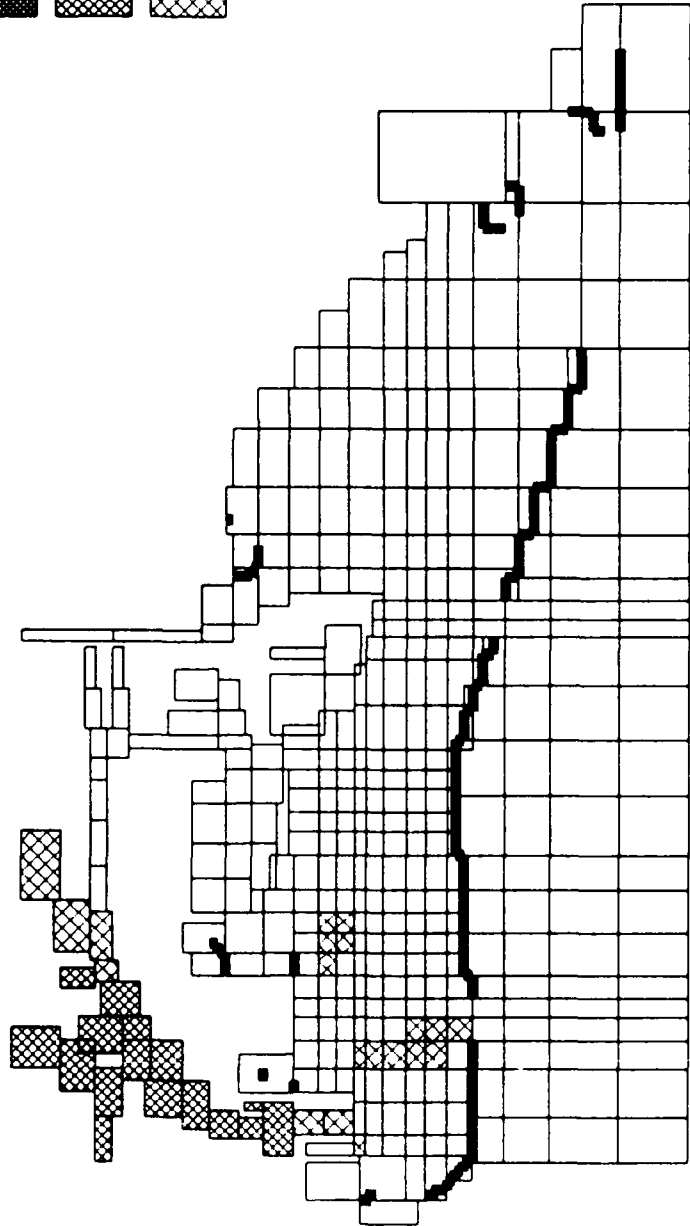
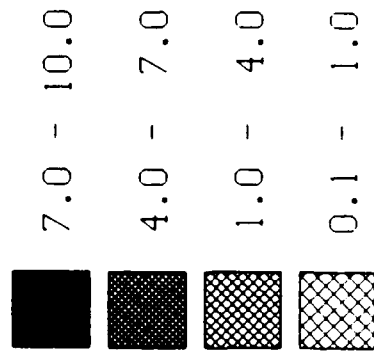
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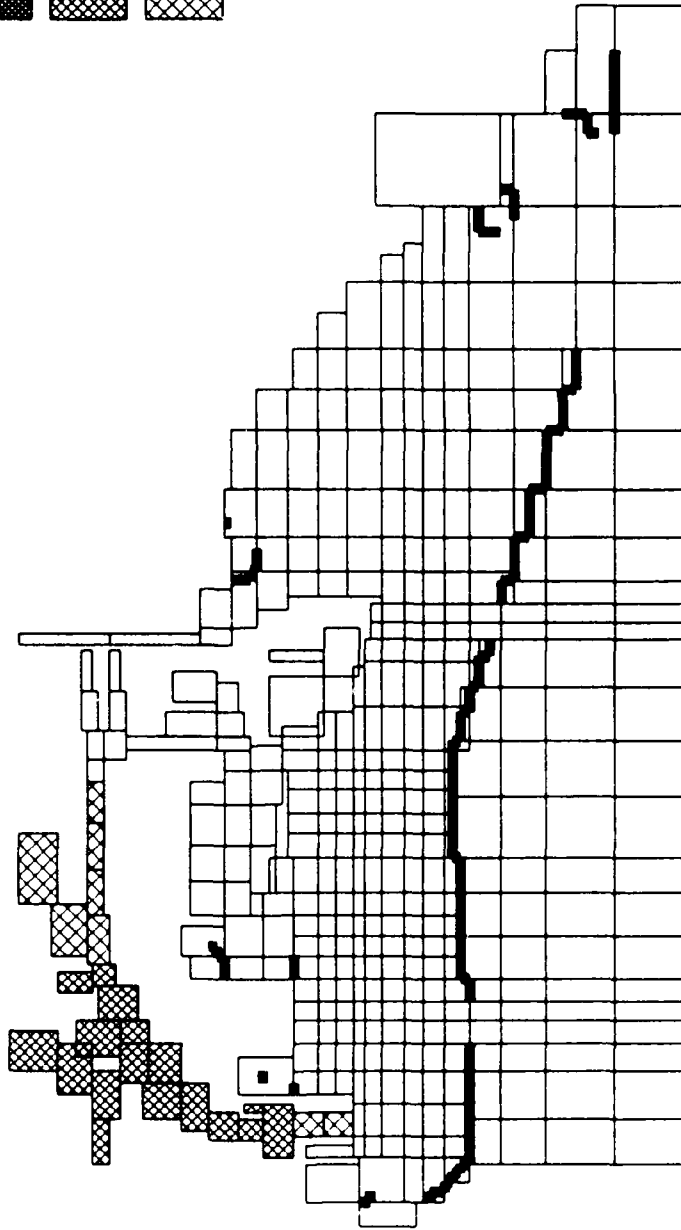
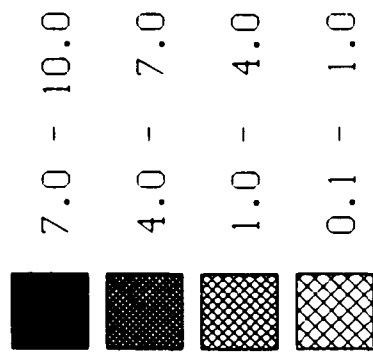
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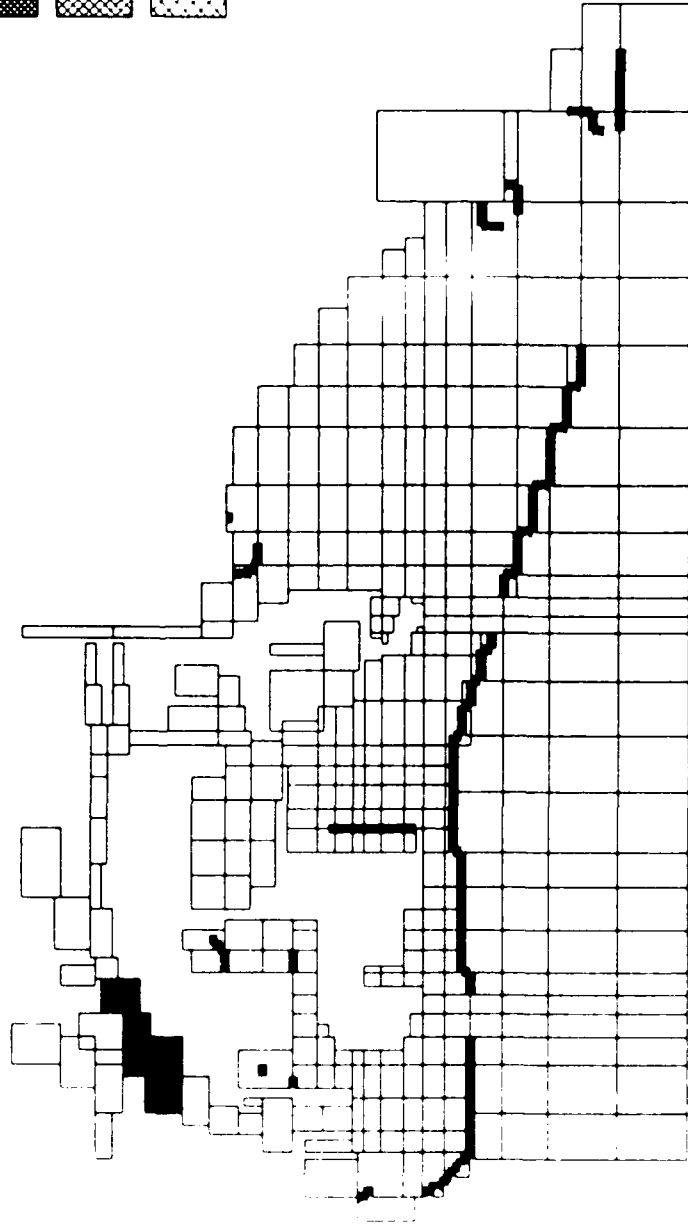
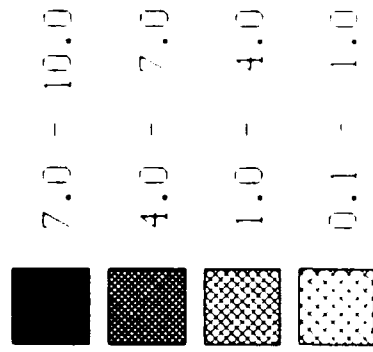
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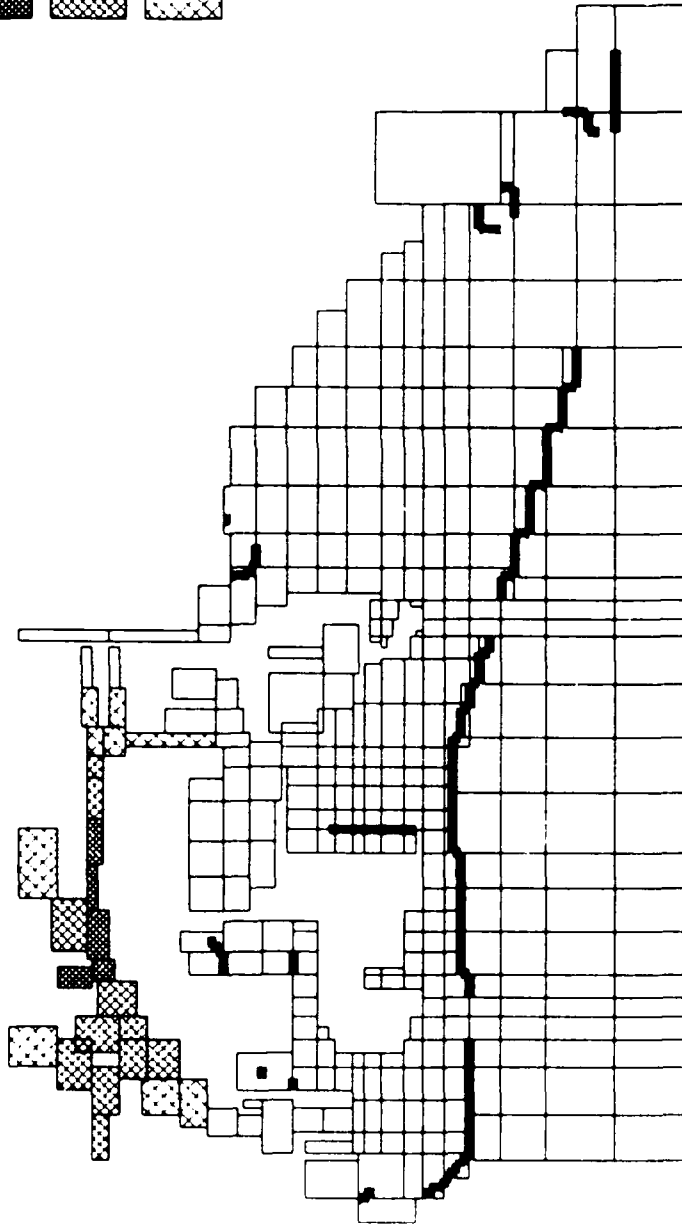
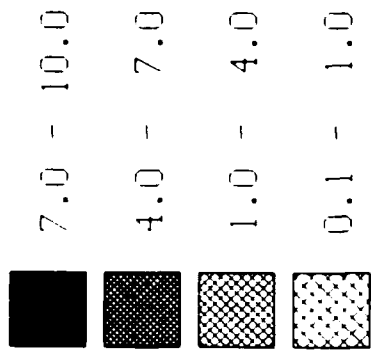
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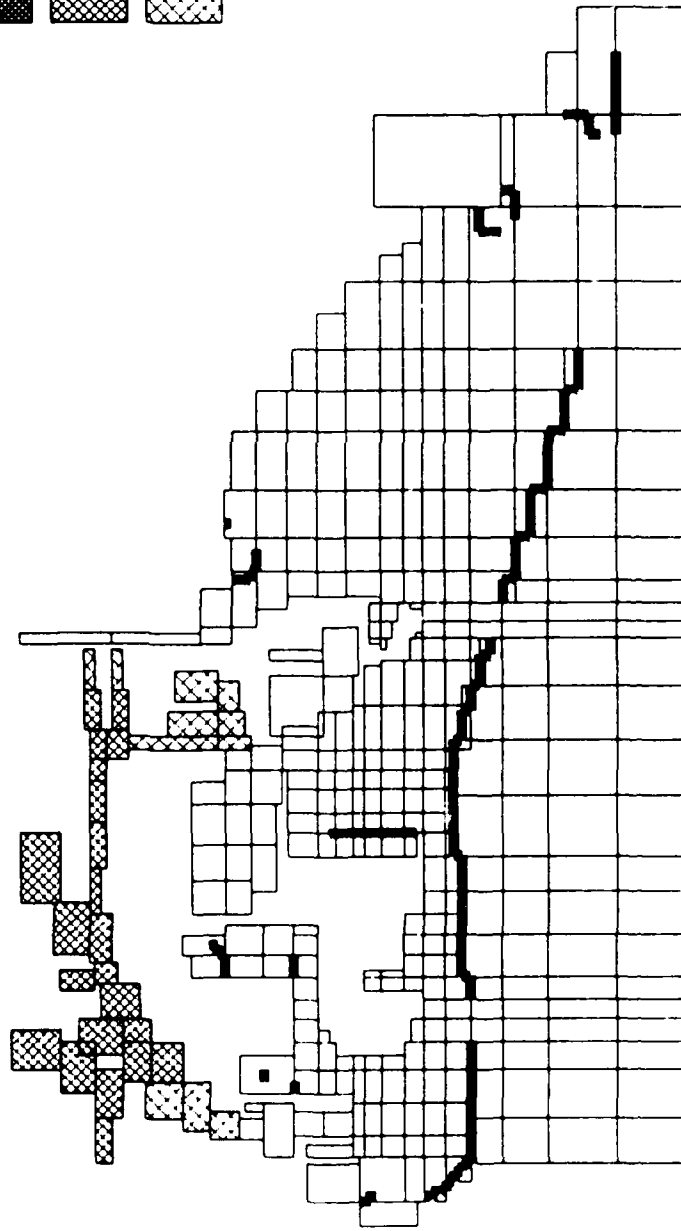
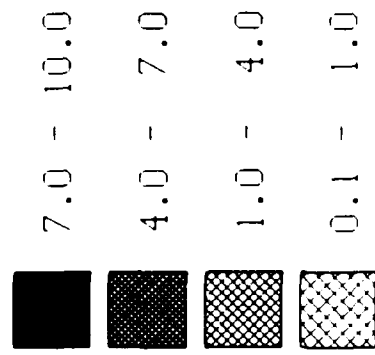
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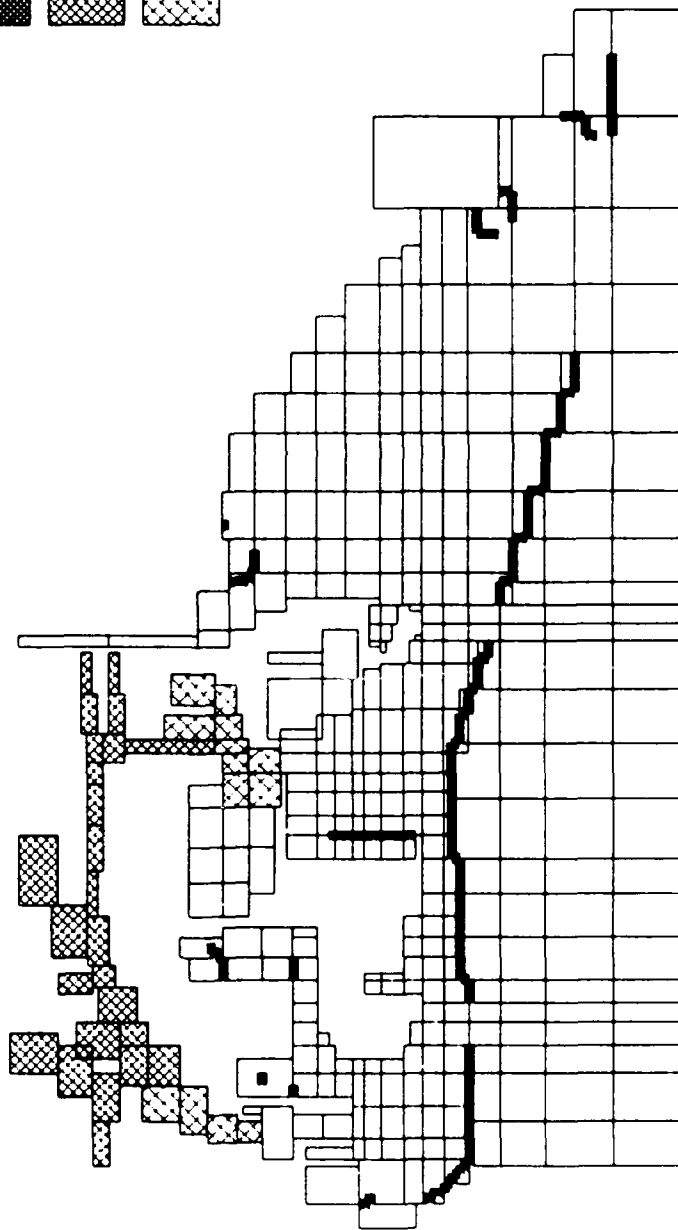
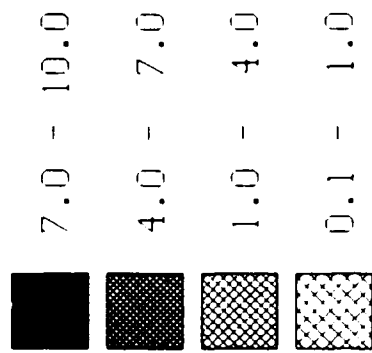
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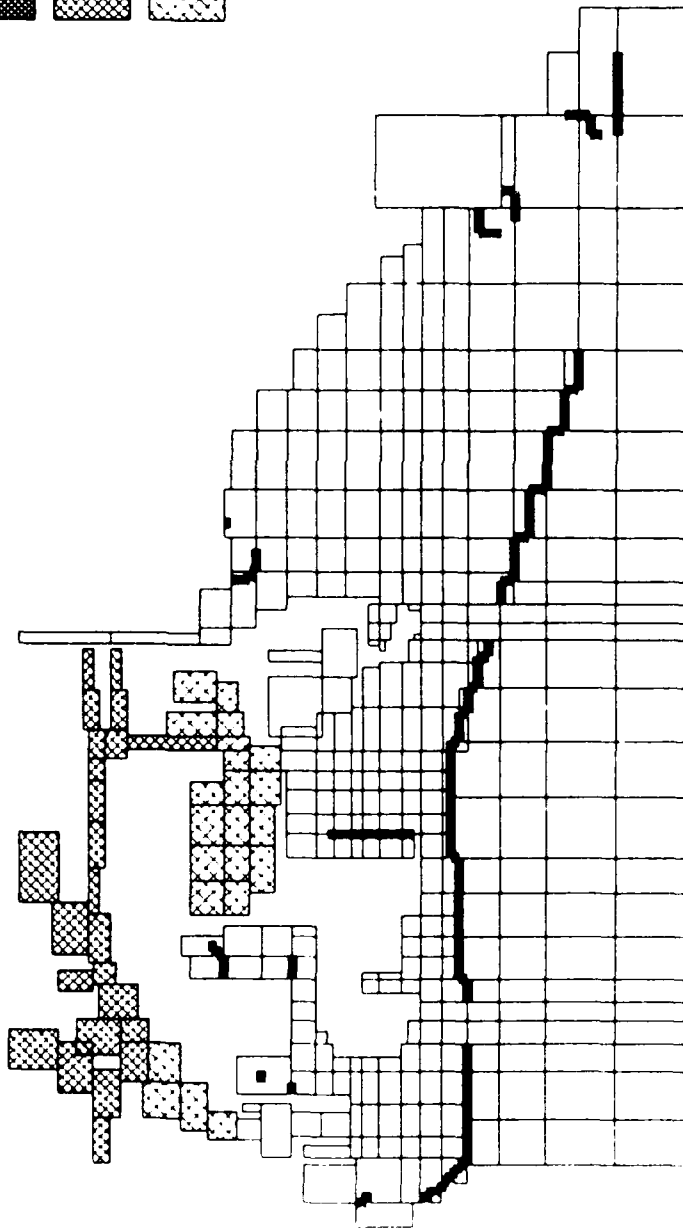
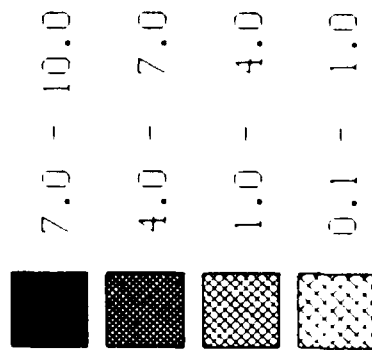
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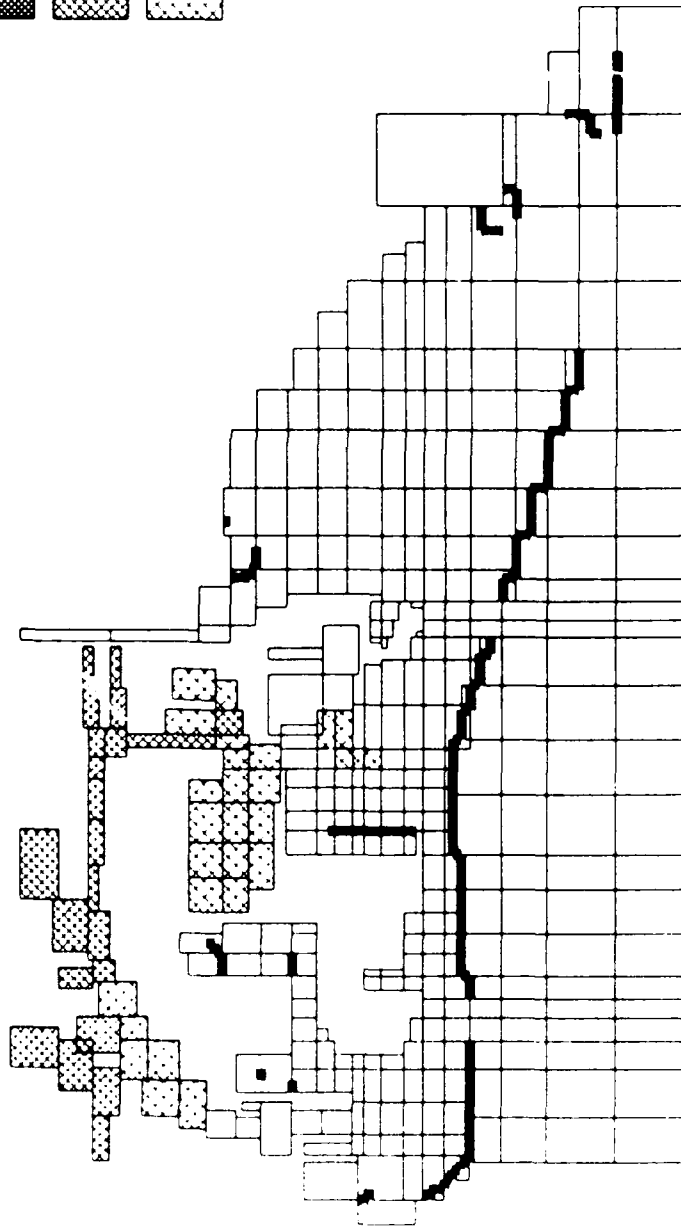
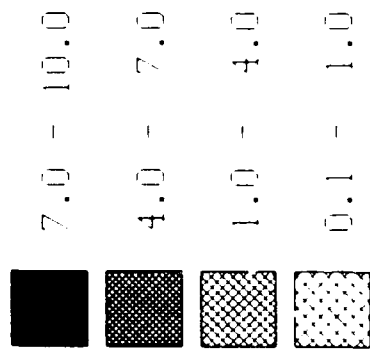
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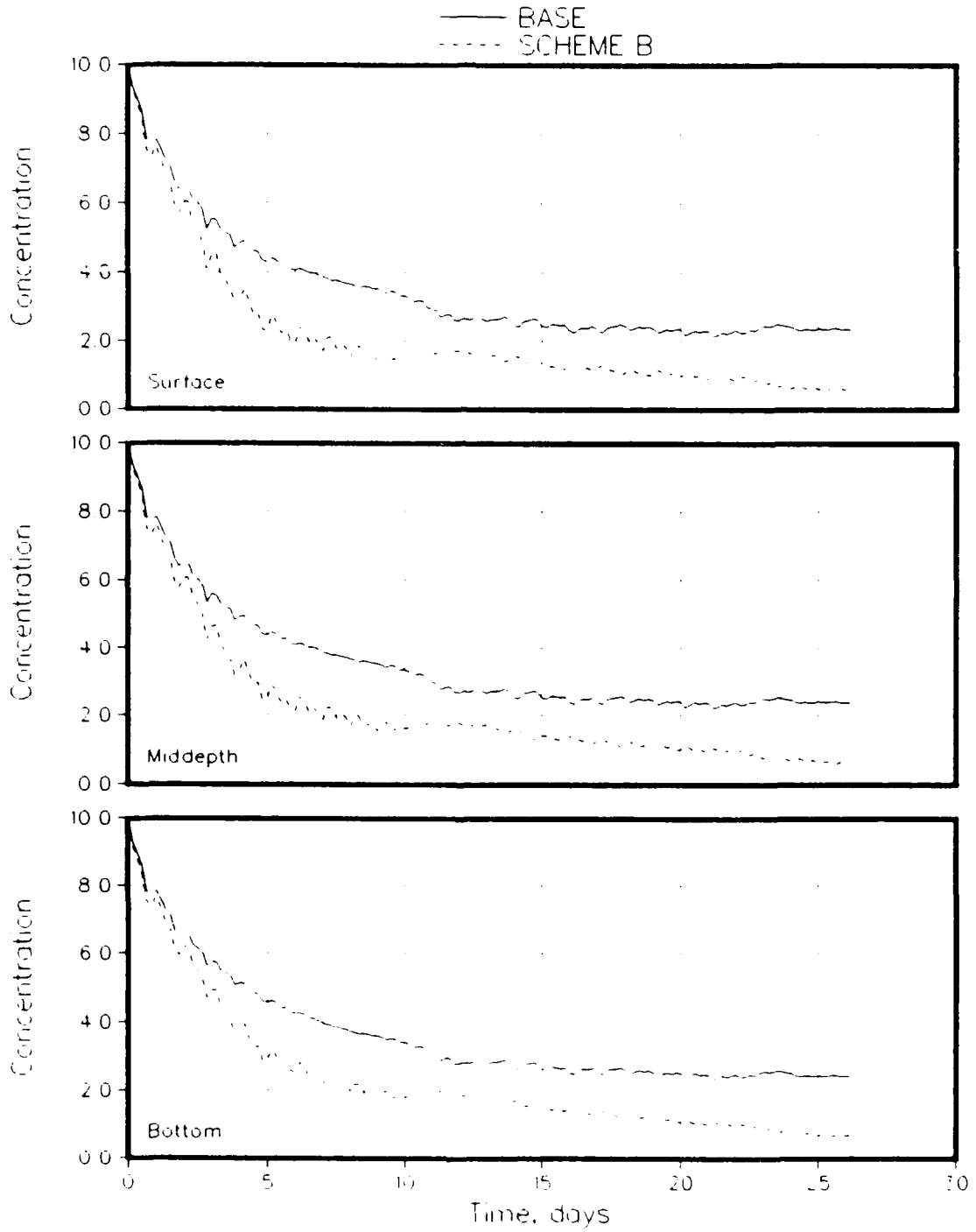


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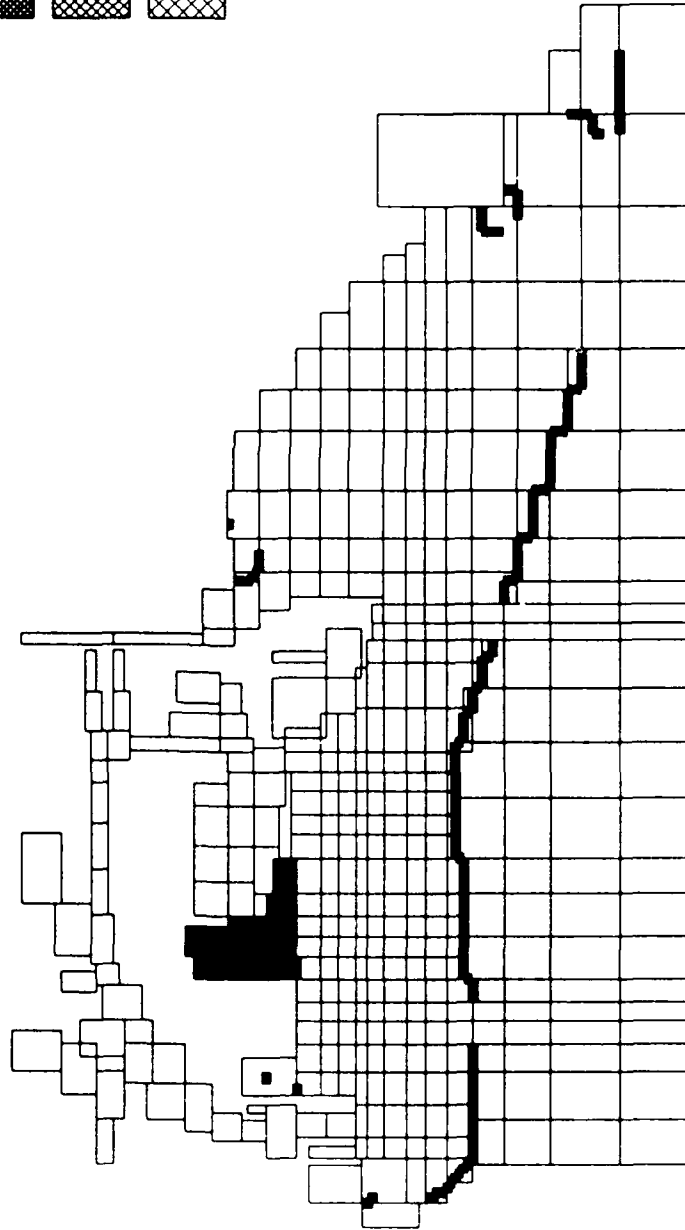
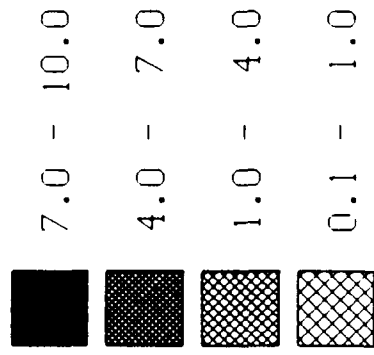


TRACER SIMULATION 2



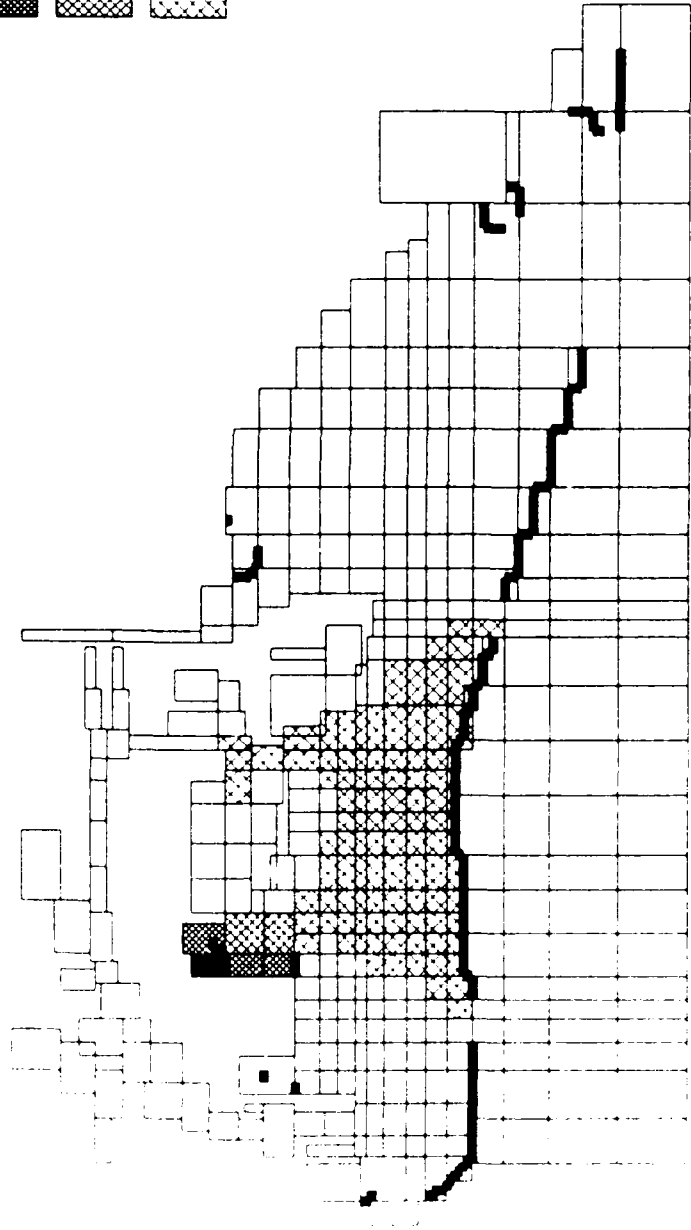
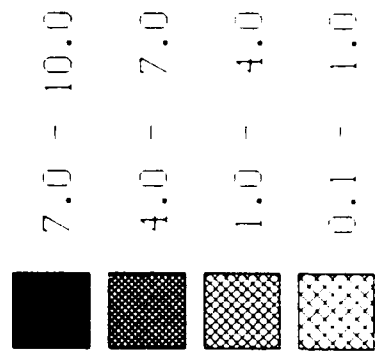
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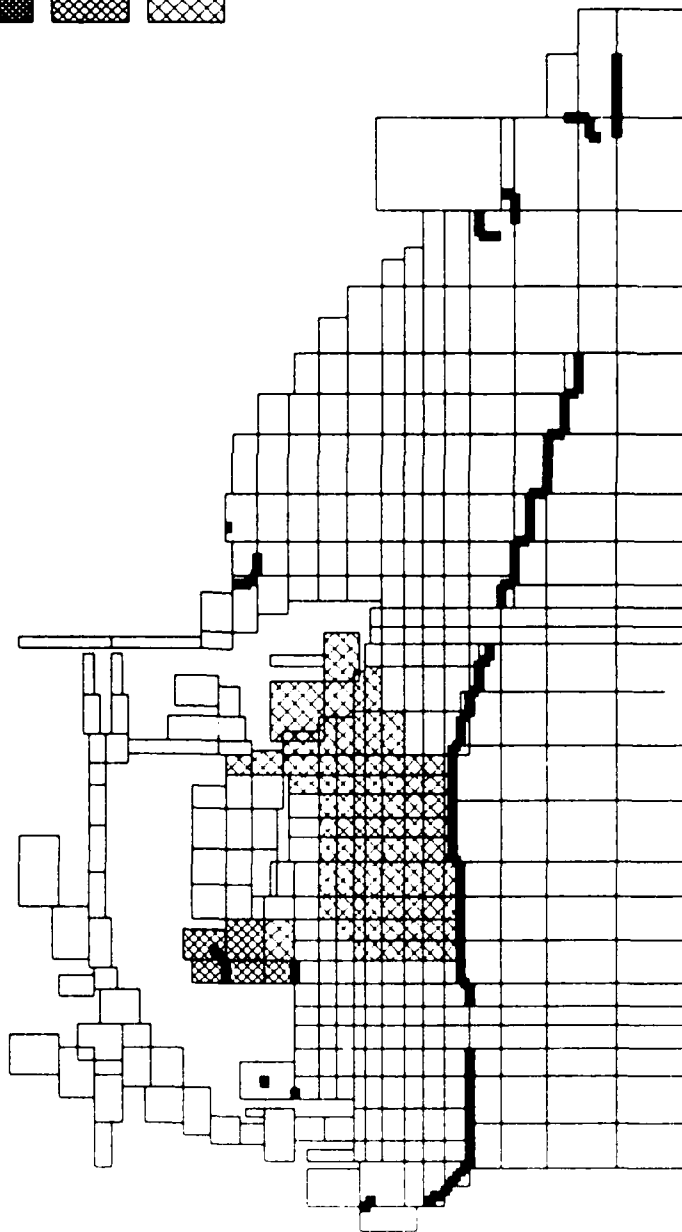
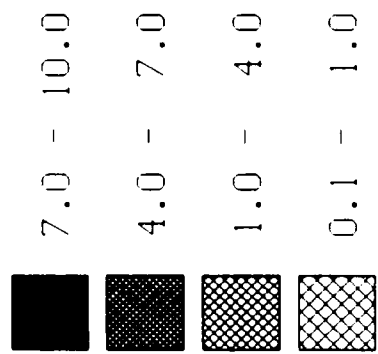
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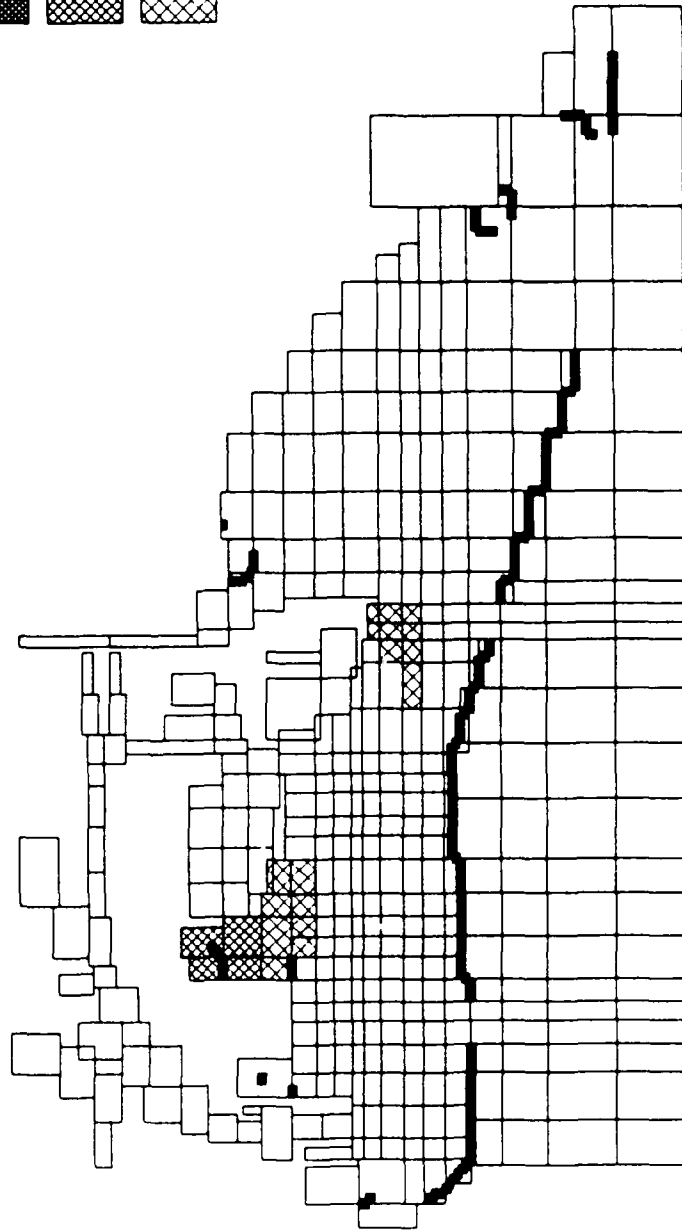
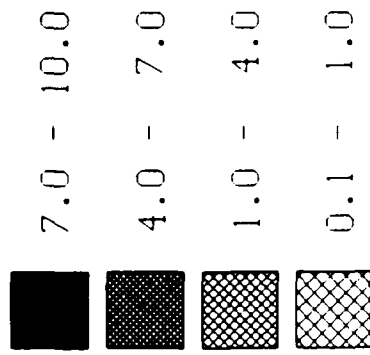
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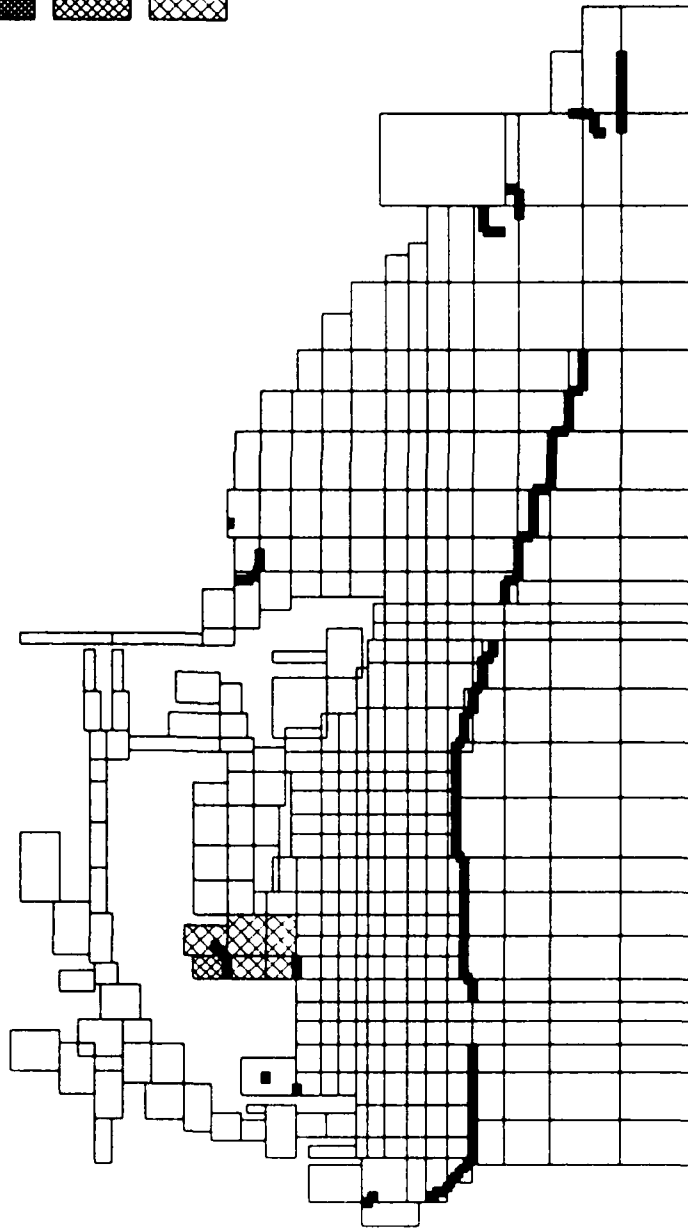
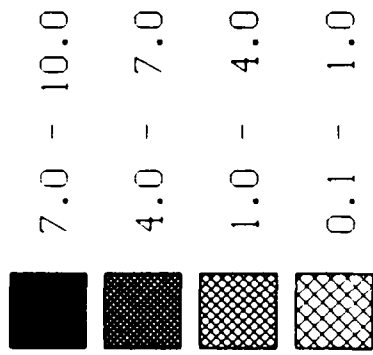
TRACER SIMULATION 3 - BASE

Time = 15 days



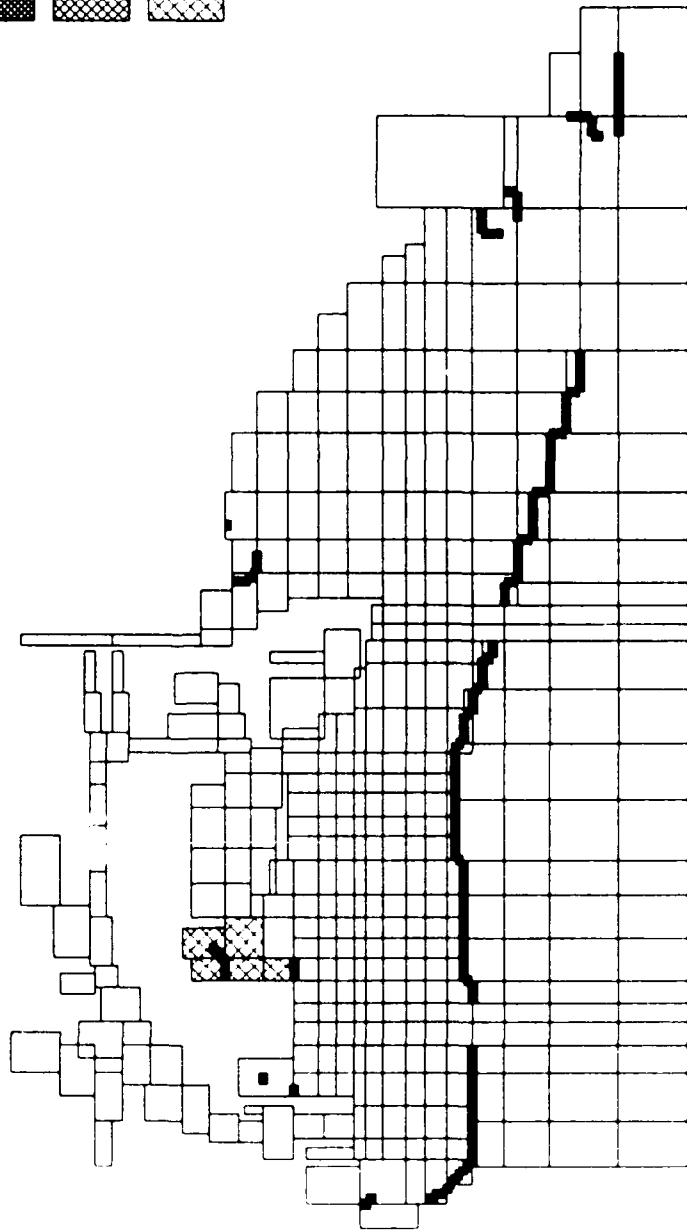
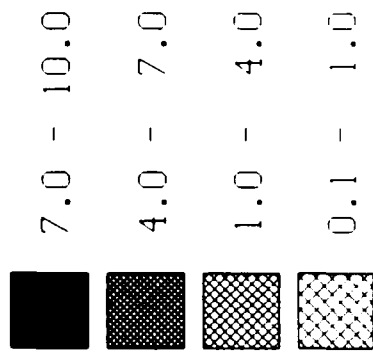
TRACER SIMULATION 3 - BASE

Time = 20 days



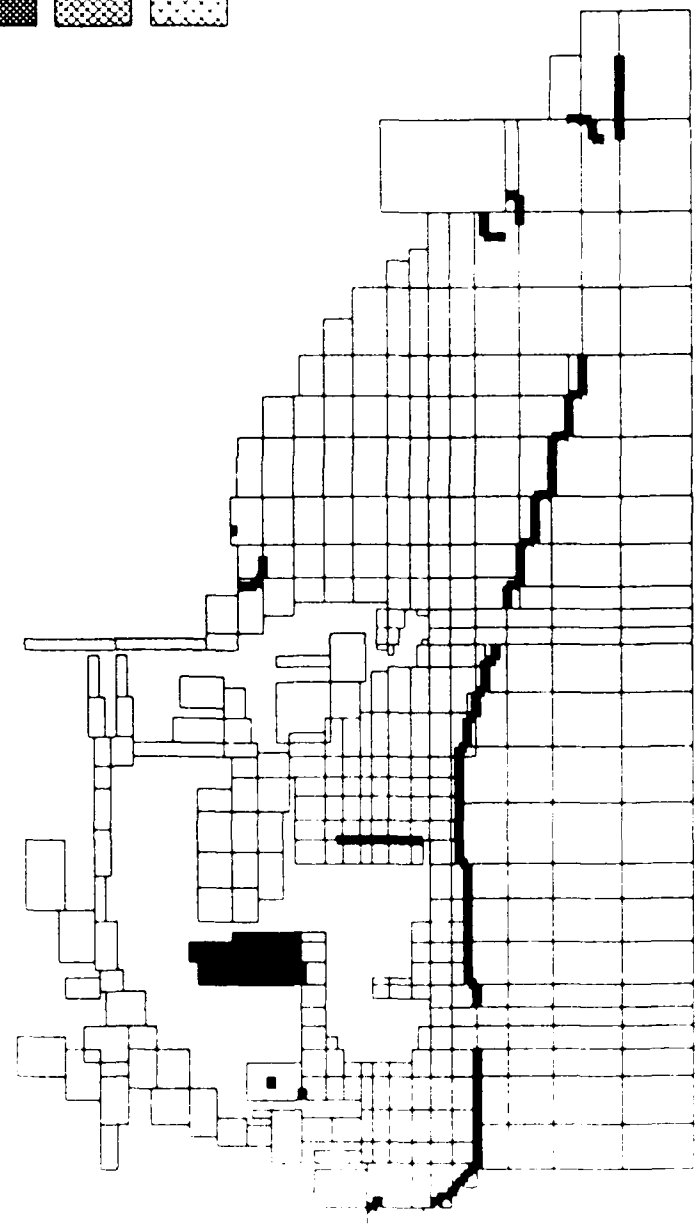
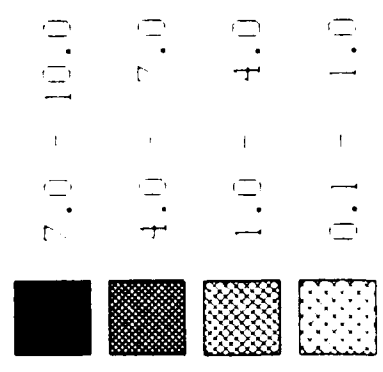
TRACER SIMULATION 3 - BASE

Time = 25 days



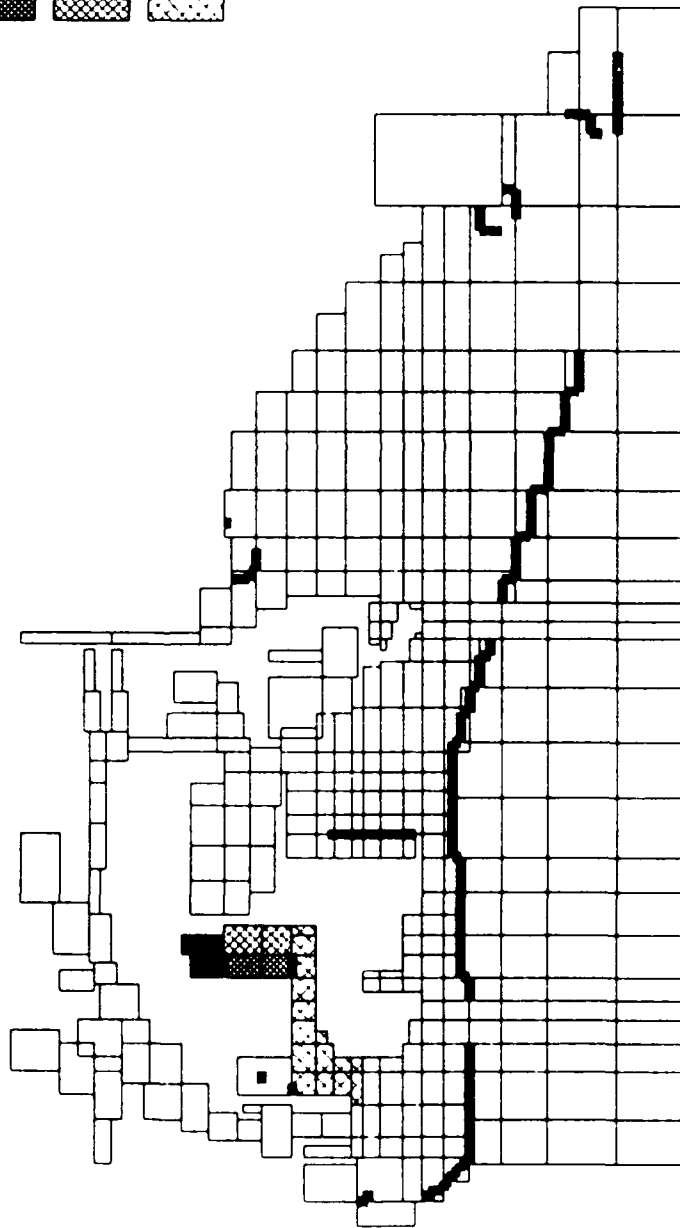
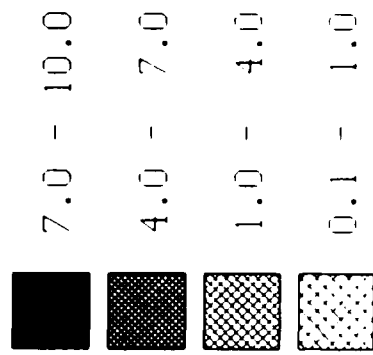
TRACER SIMULATION 3 - SCHEME B

Time = 0 days



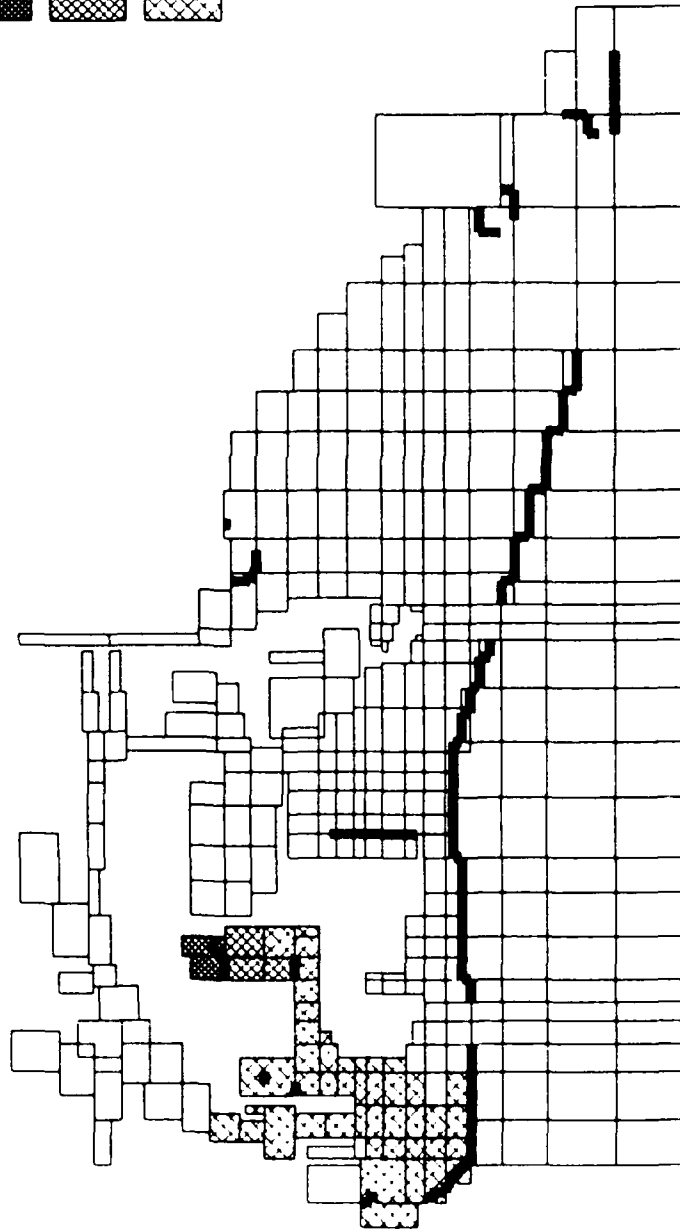
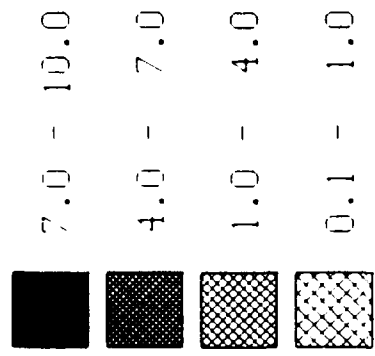
TRACER SIMULATION 3 - SCHEME B

Time = 5 days



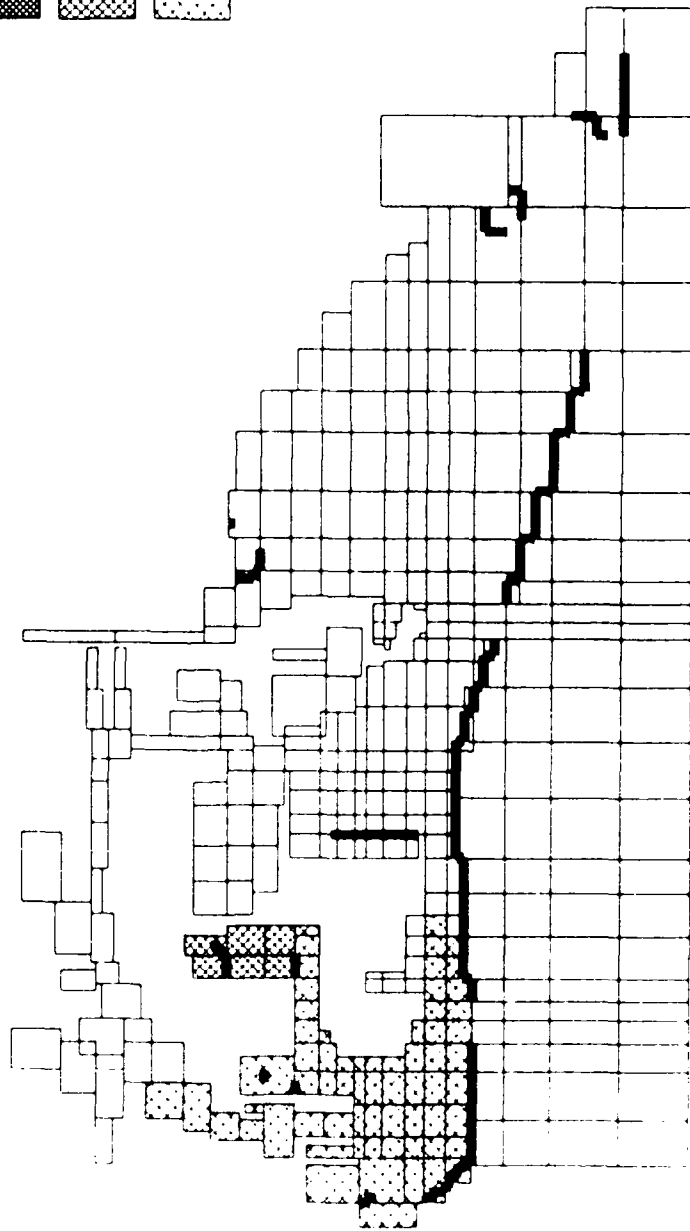
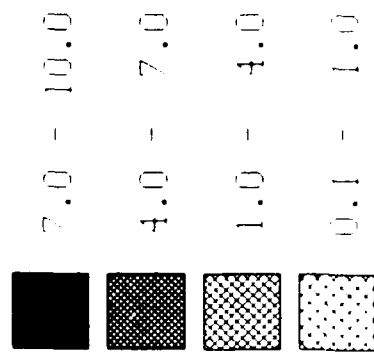
TRACER SIMULATION 3 - SCHEME B

Time = 10 days



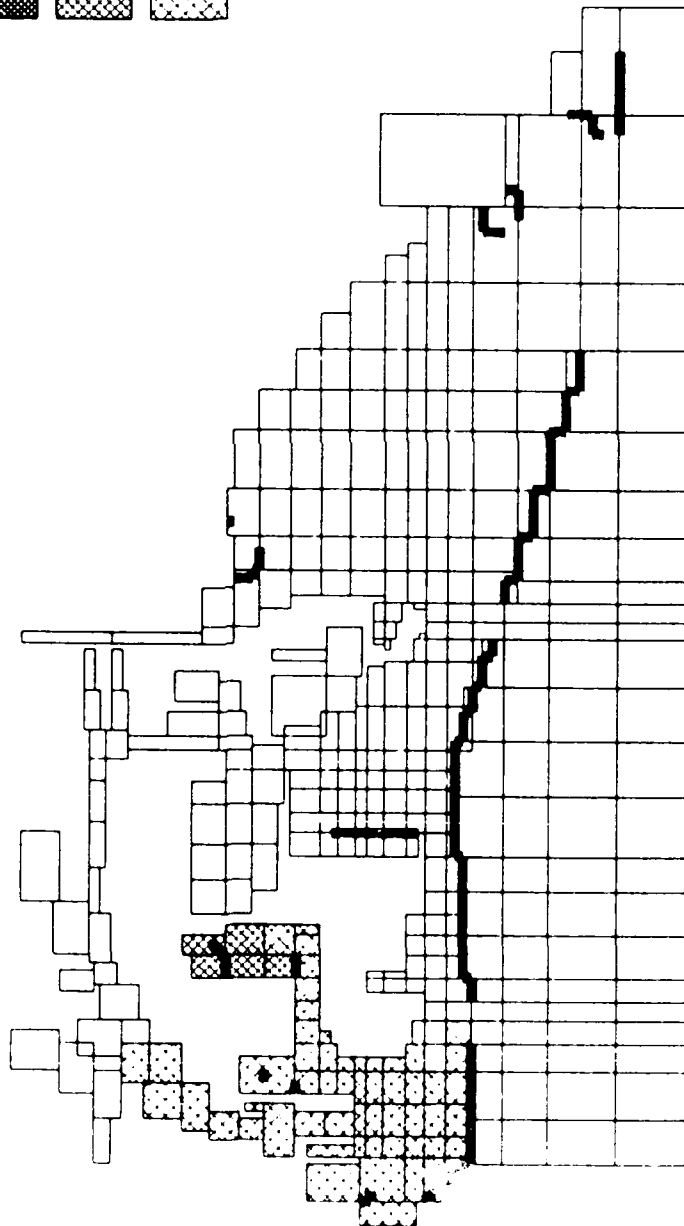
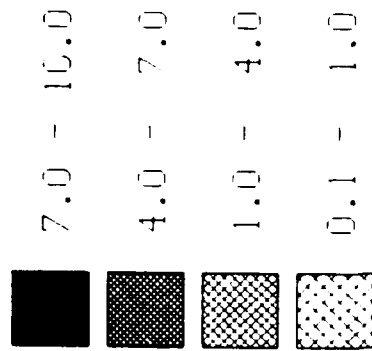
TRACER SIMULATION 3 - SCHEME B

Time = 15 days



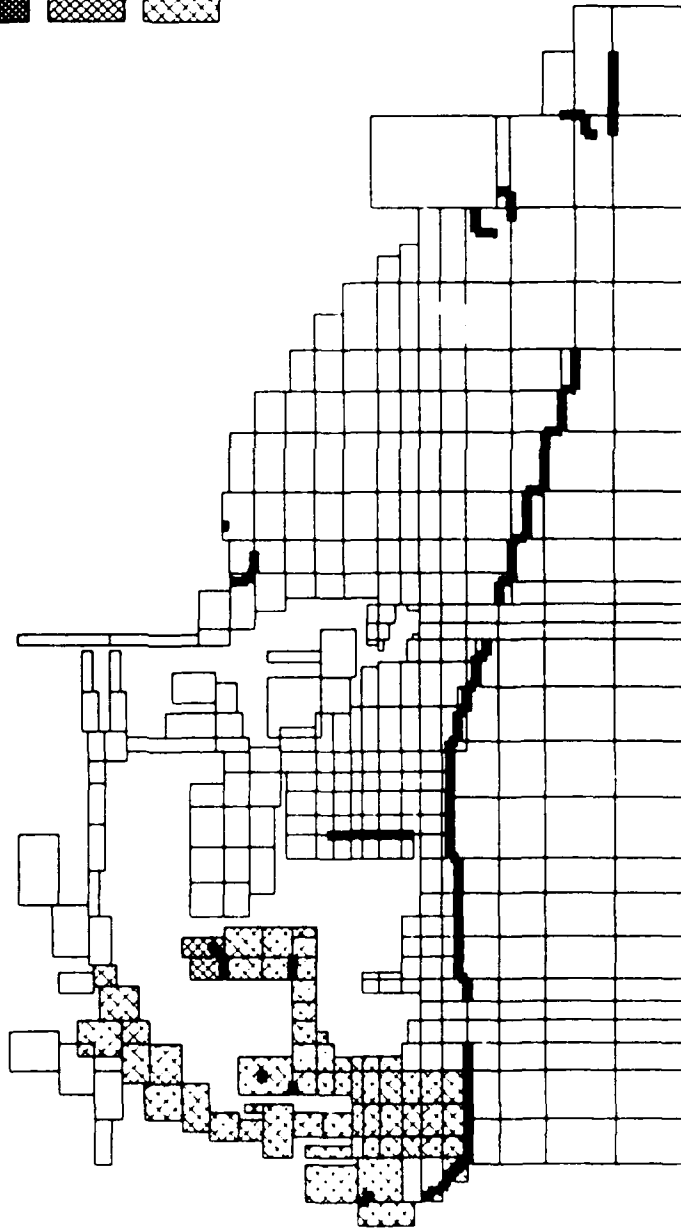
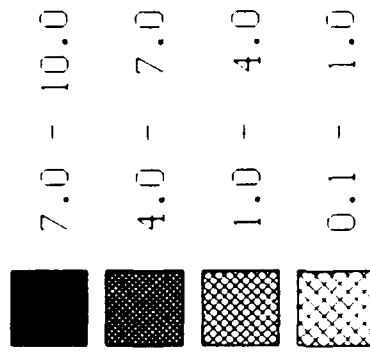
TRACER SIMULATION 3 - SCHEME B

Time = 20 days

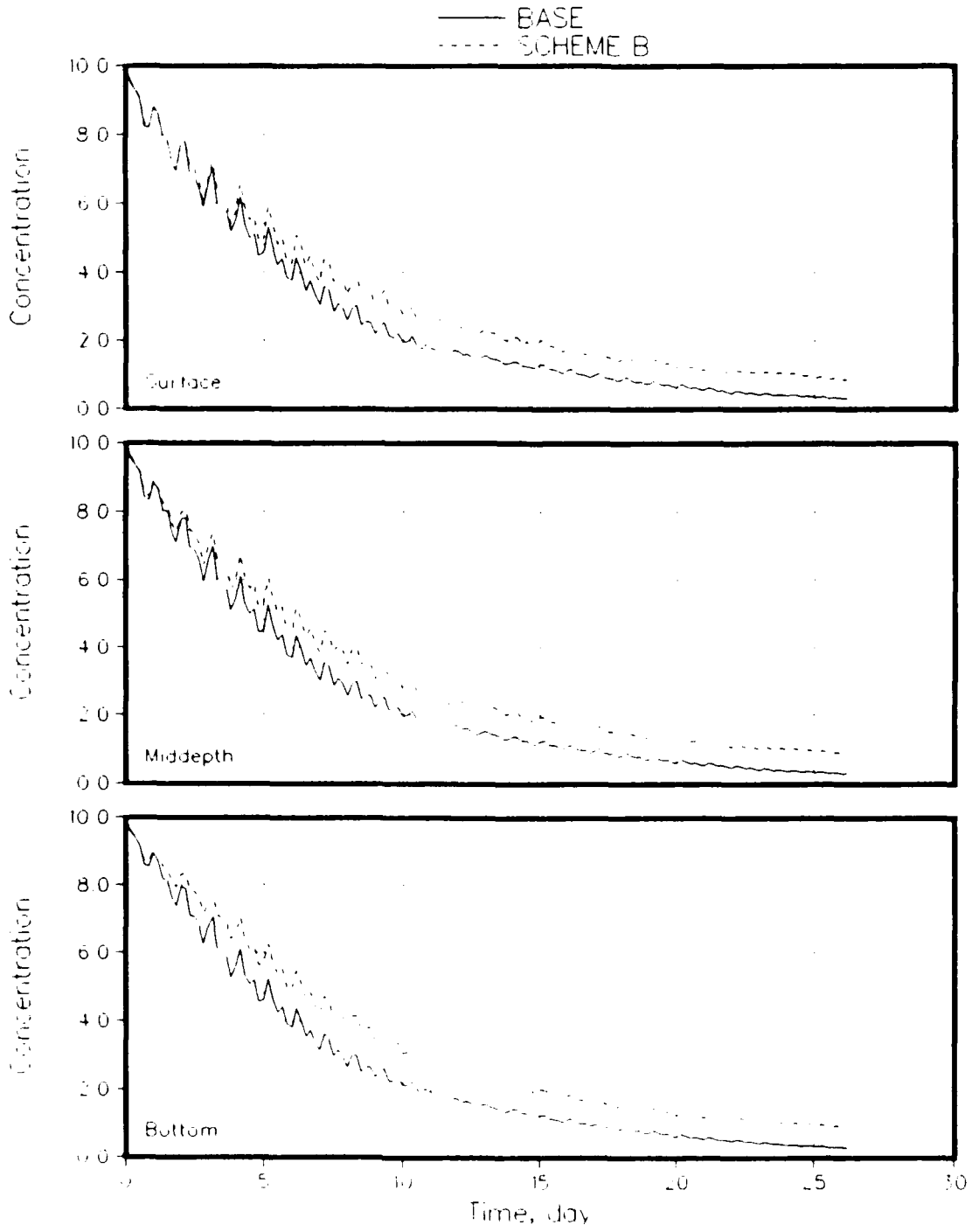


TRACER SIMULATION 3 - SCHEME B

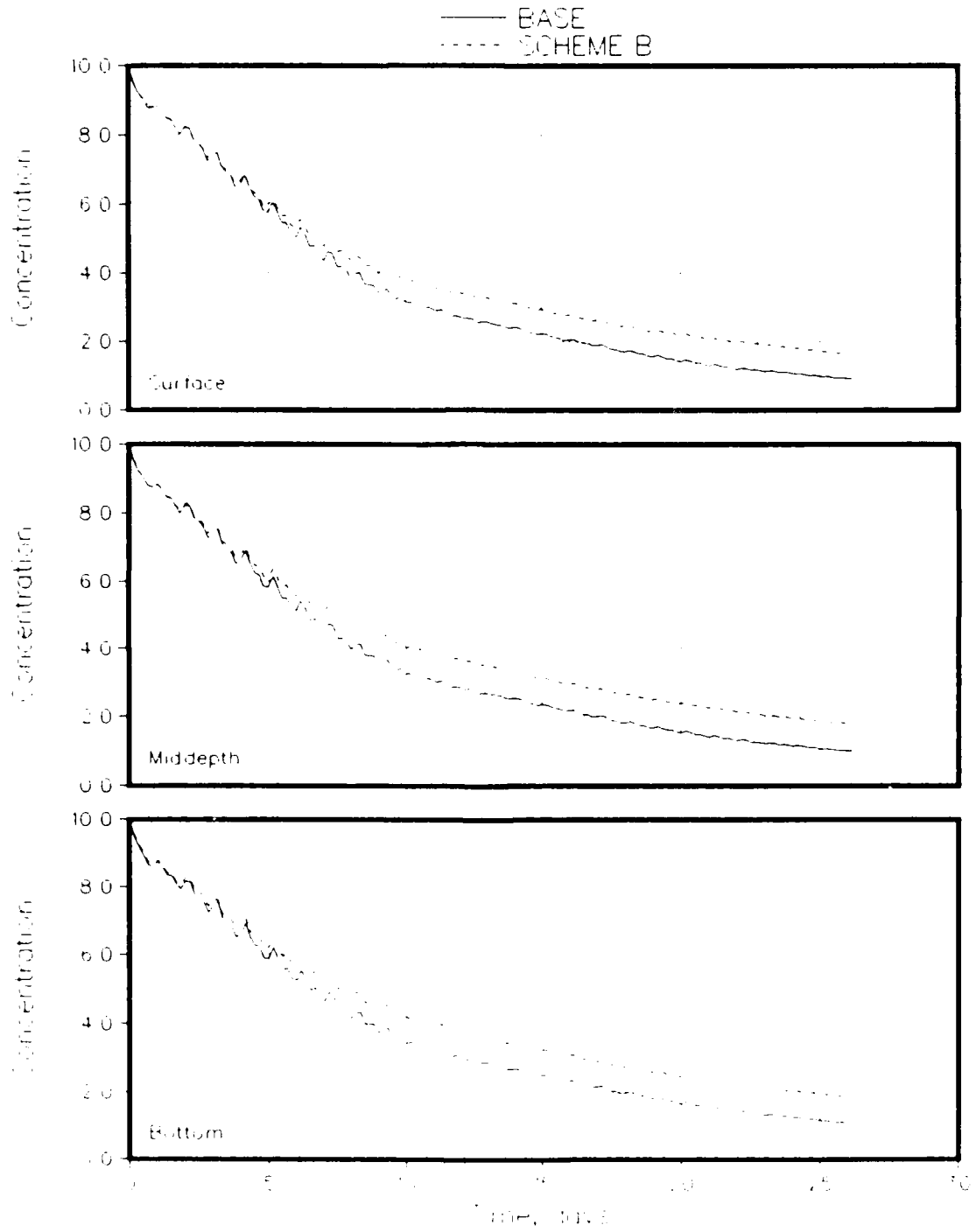
Time = 25 days



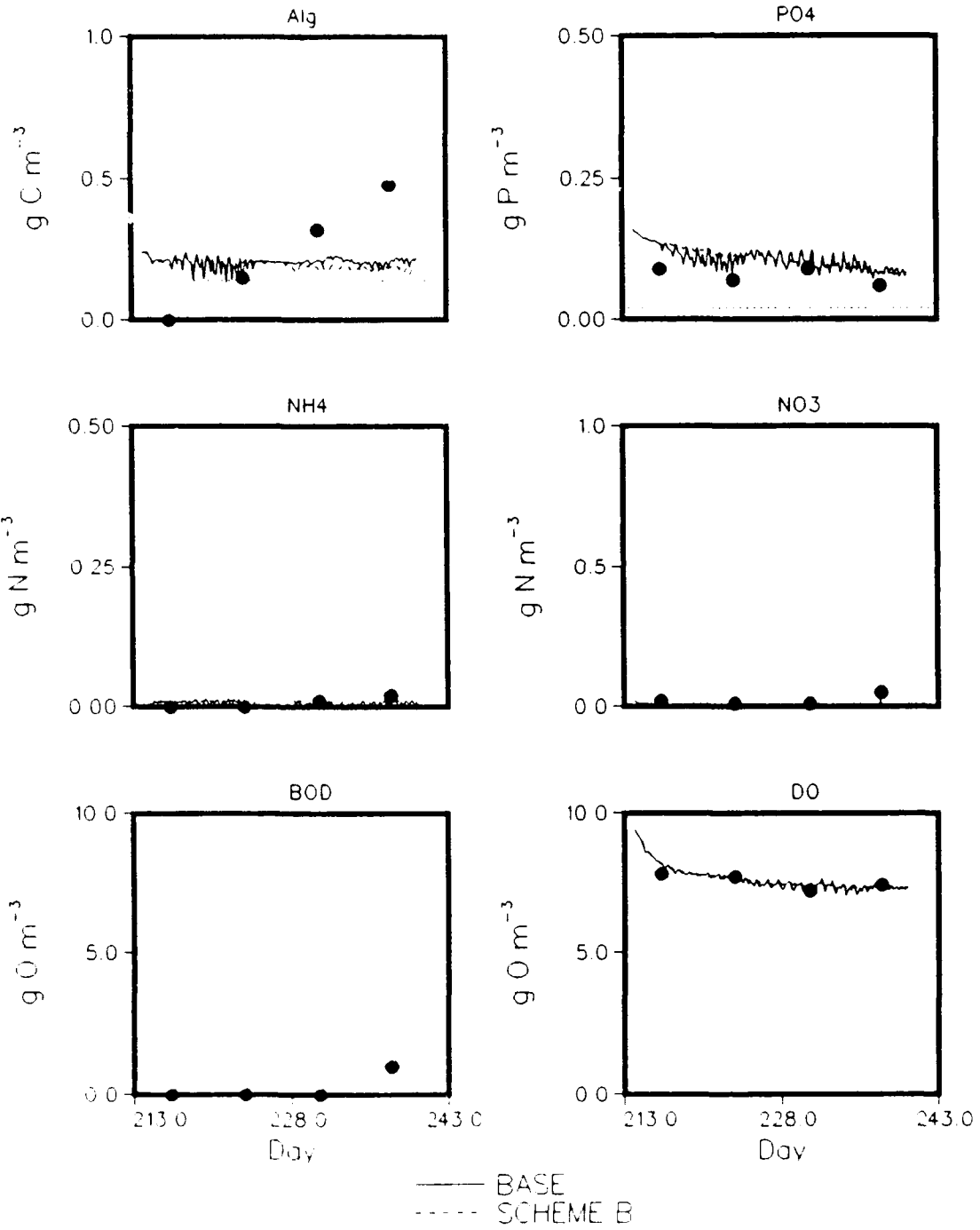
TRACER SIMULATION 3



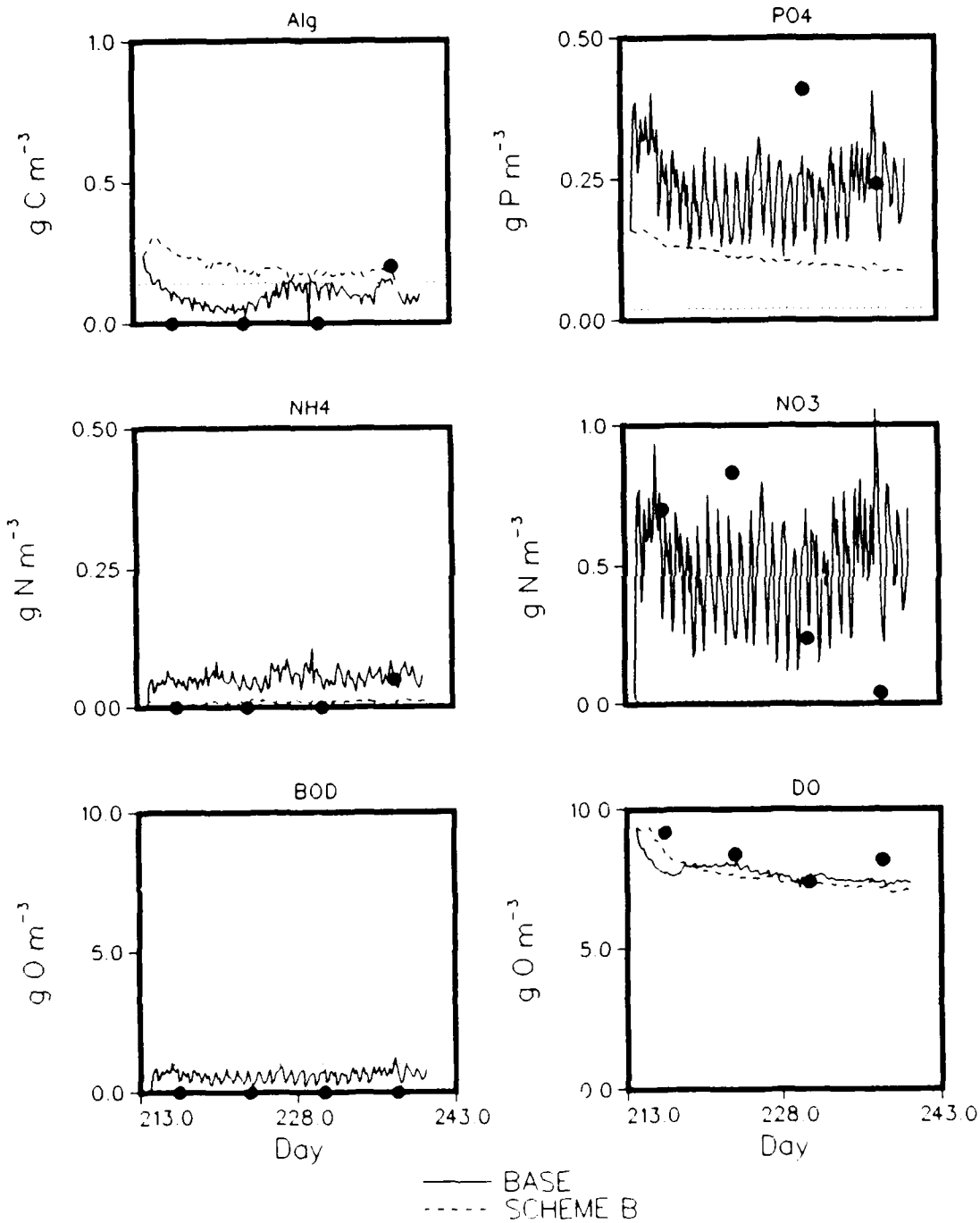
TRACER SIMULATION 4



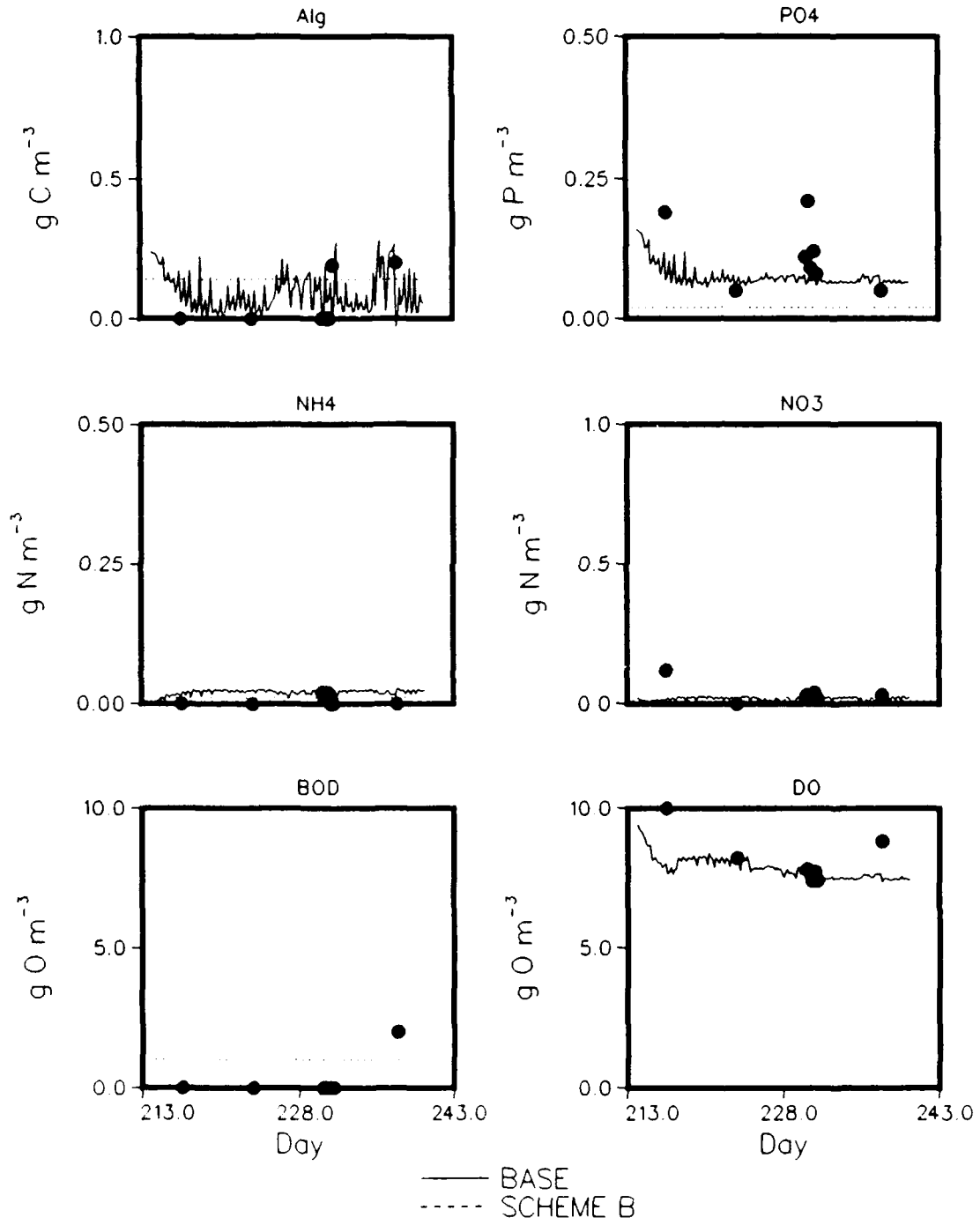
WO Station I-1
Surface



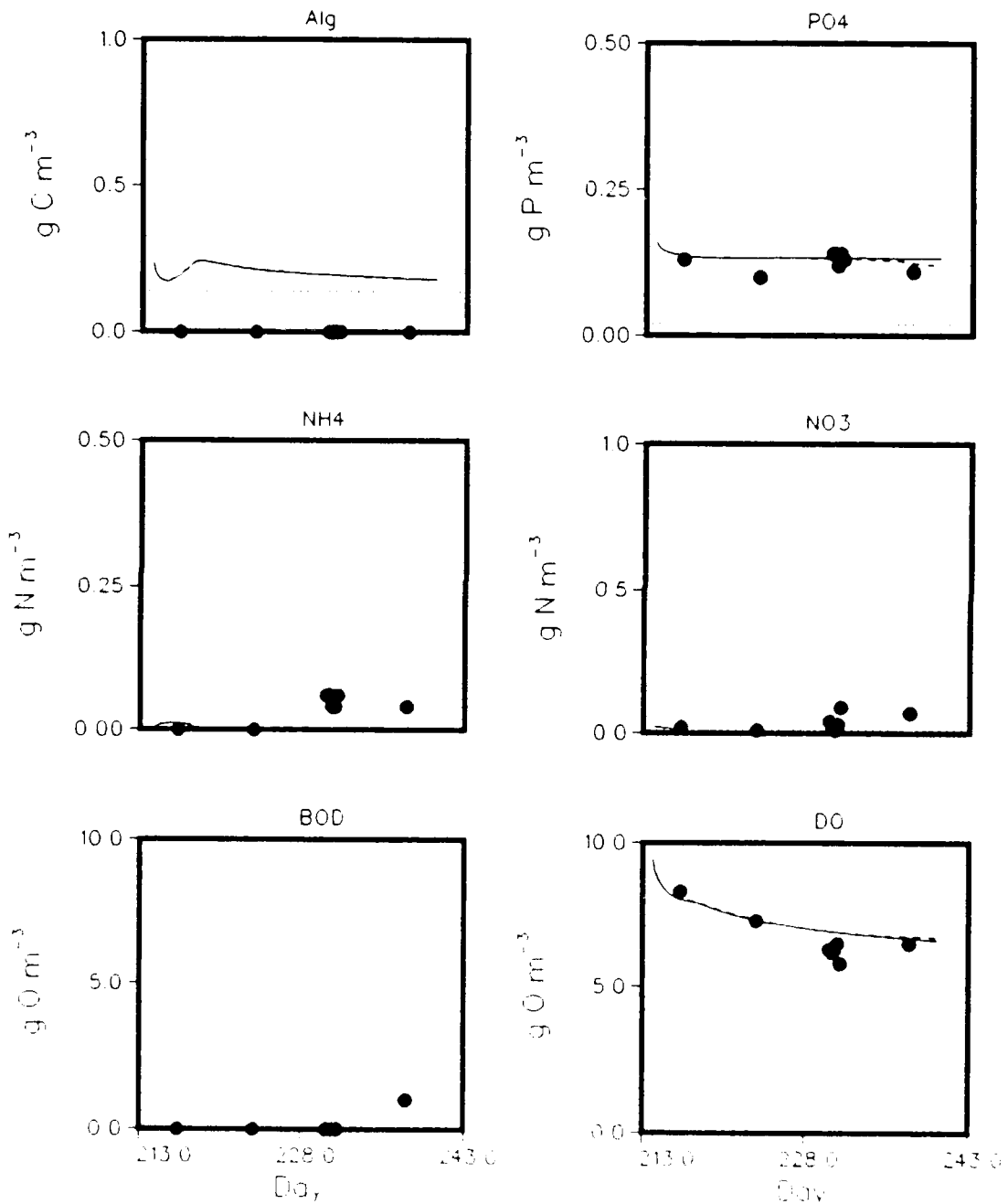
WQ Station I-2
Surface



WQ Station 1-3
Surface

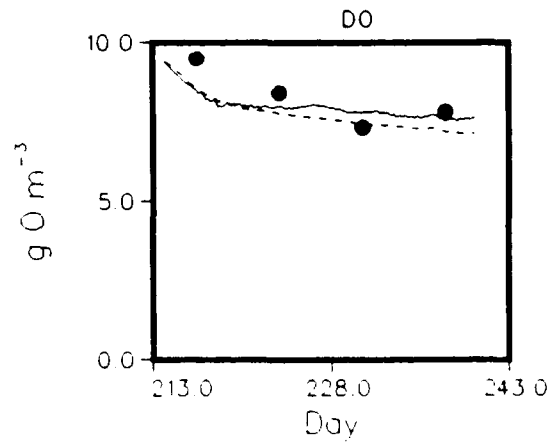
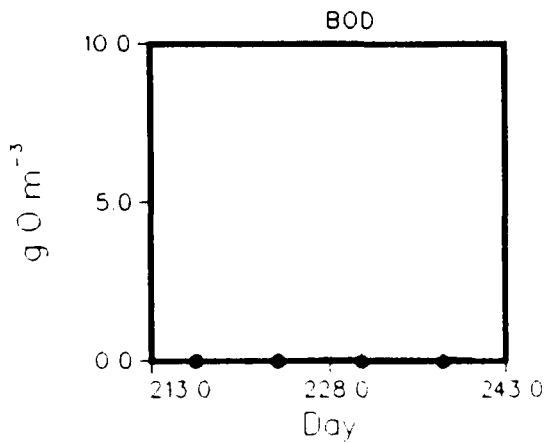
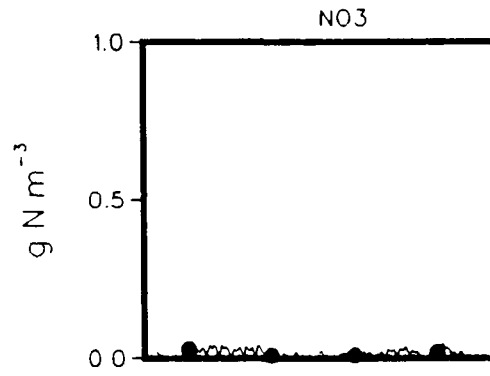
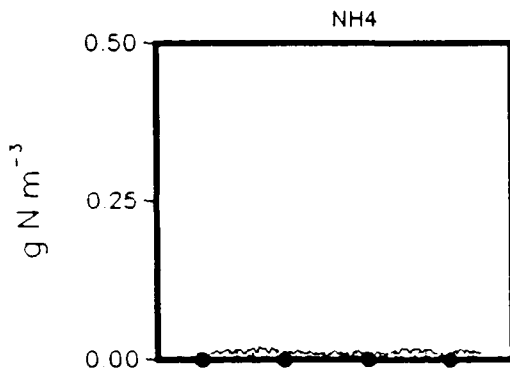
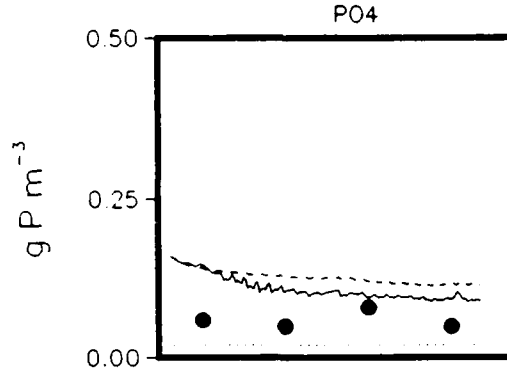
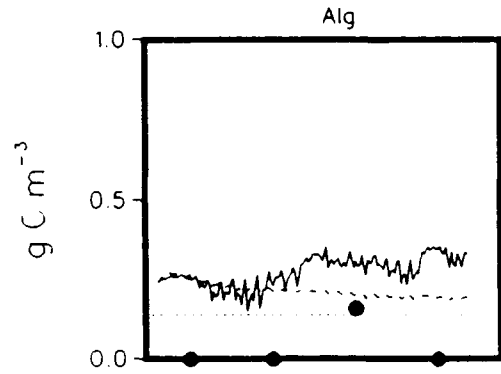


WQ Station I- 4 Surface



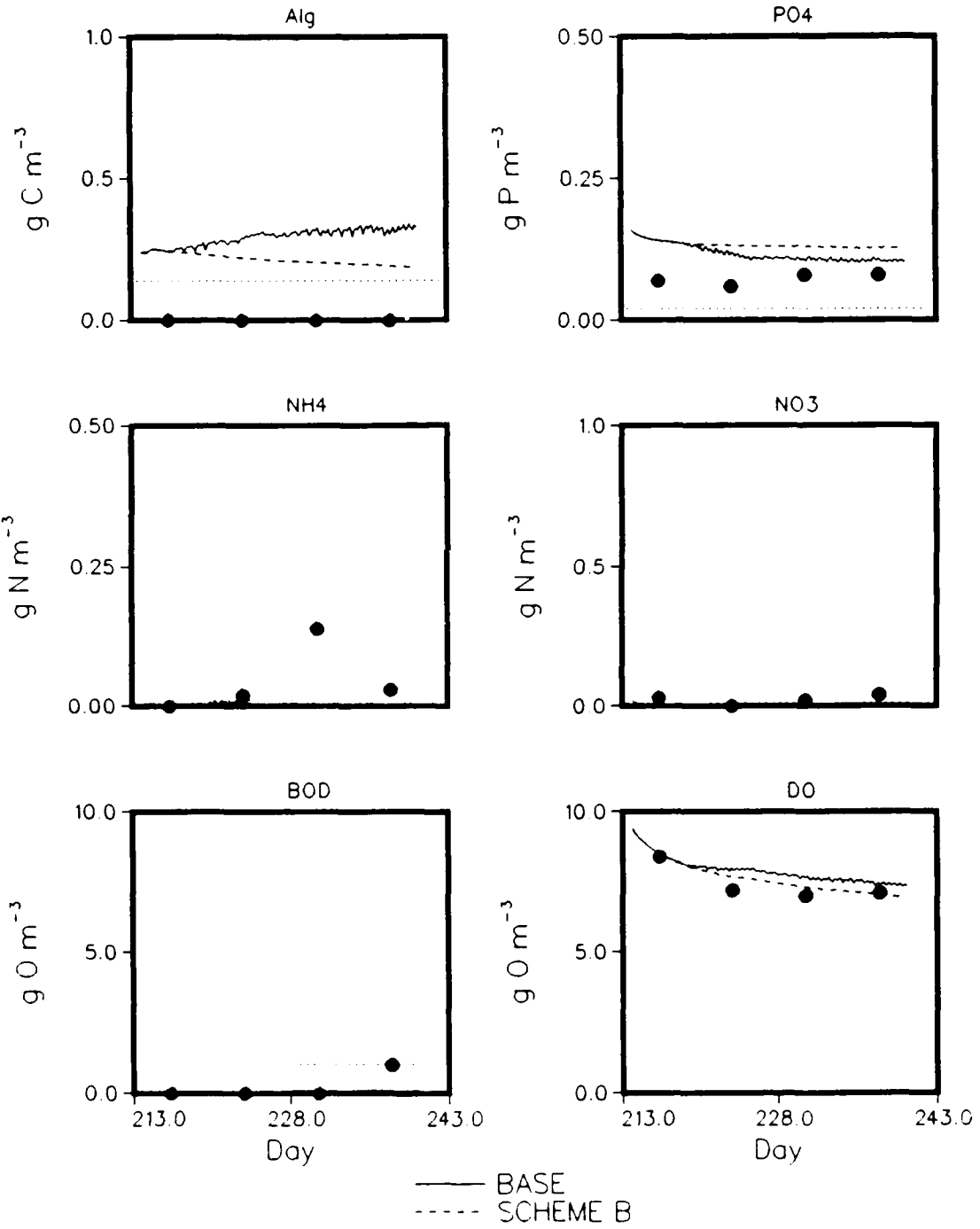
—— BACE
 ····· SCHEME

WQ Station I- 5
Surface

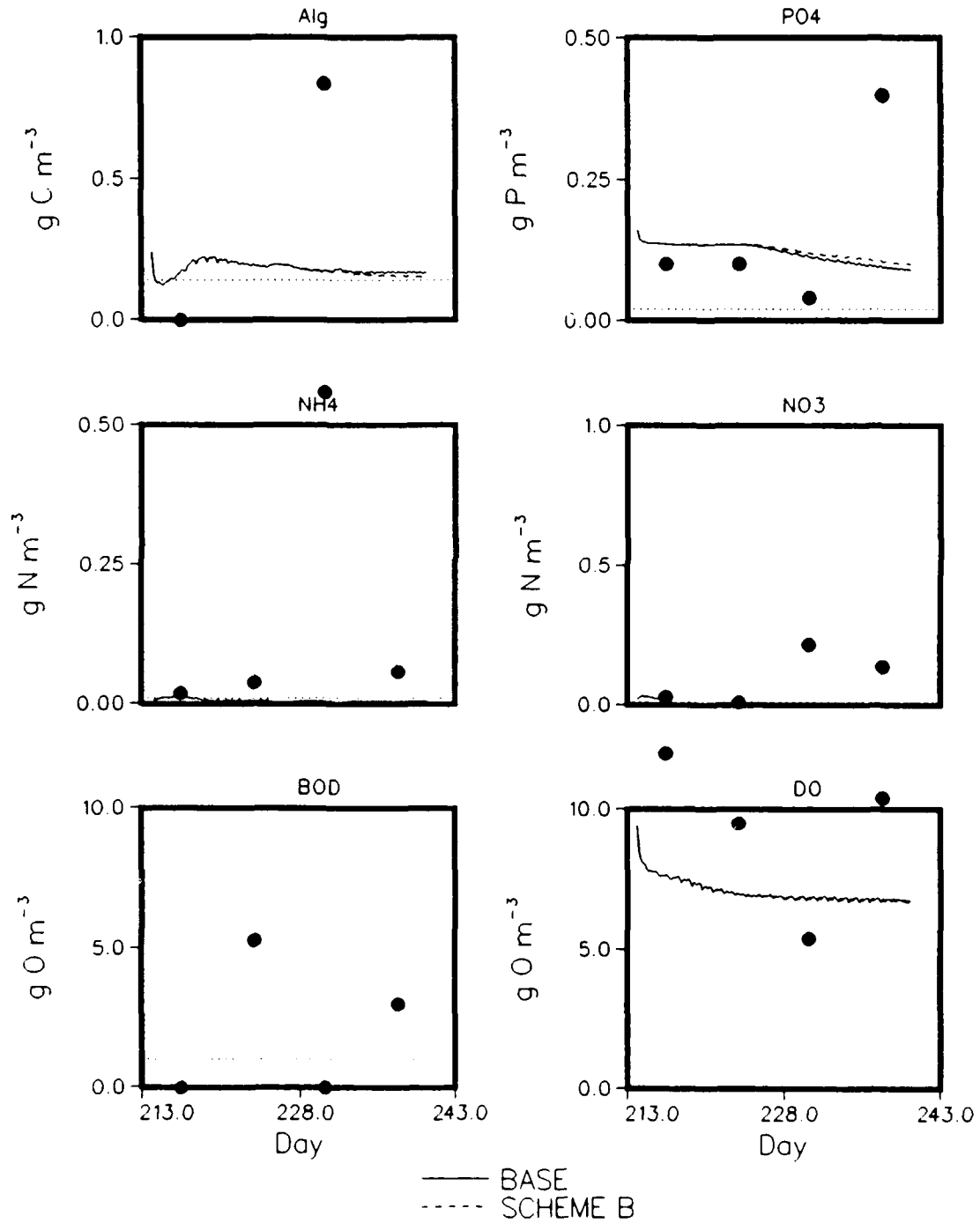


— BASE
- - - SCHEME B

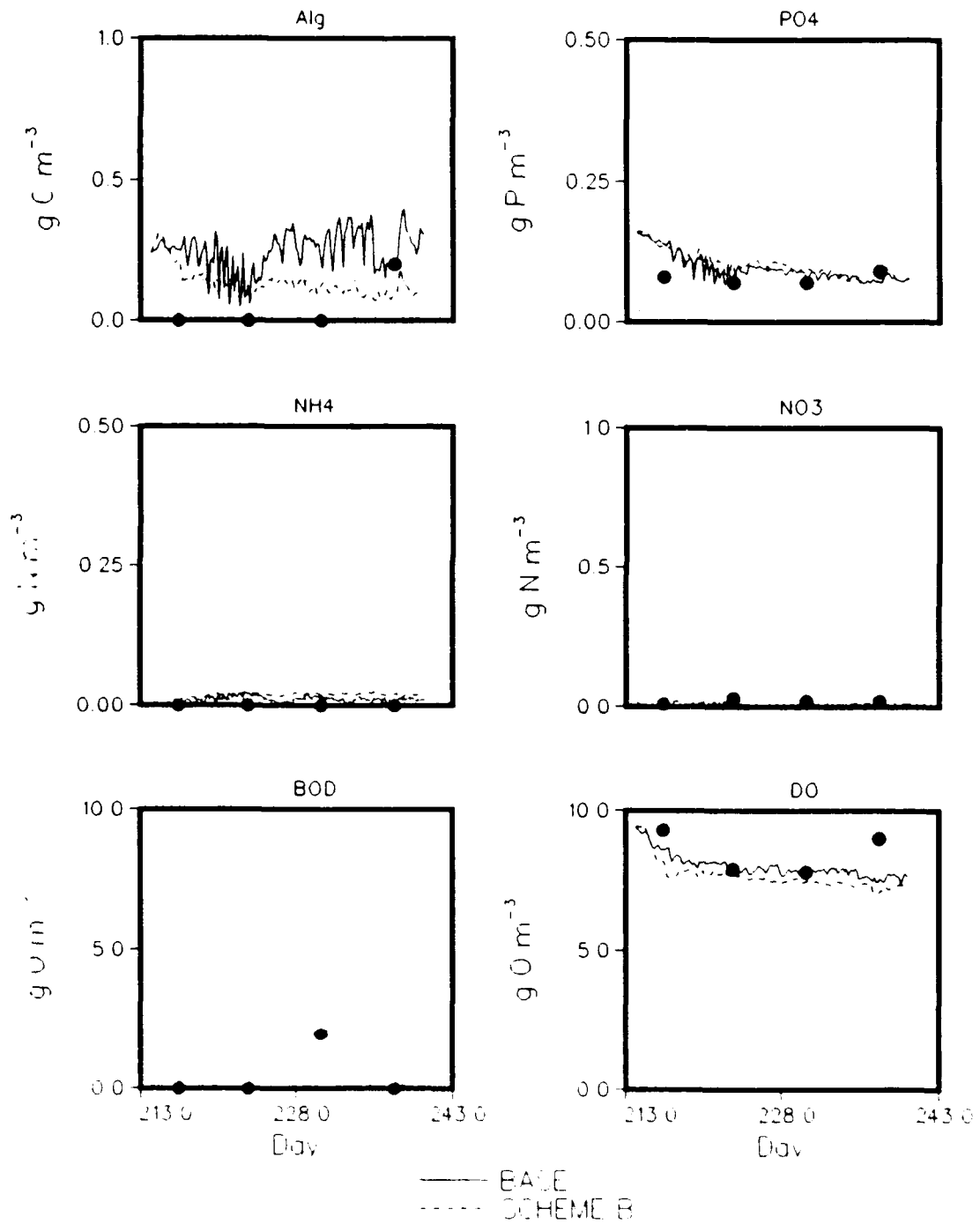
WQ Station I- 6
Surface



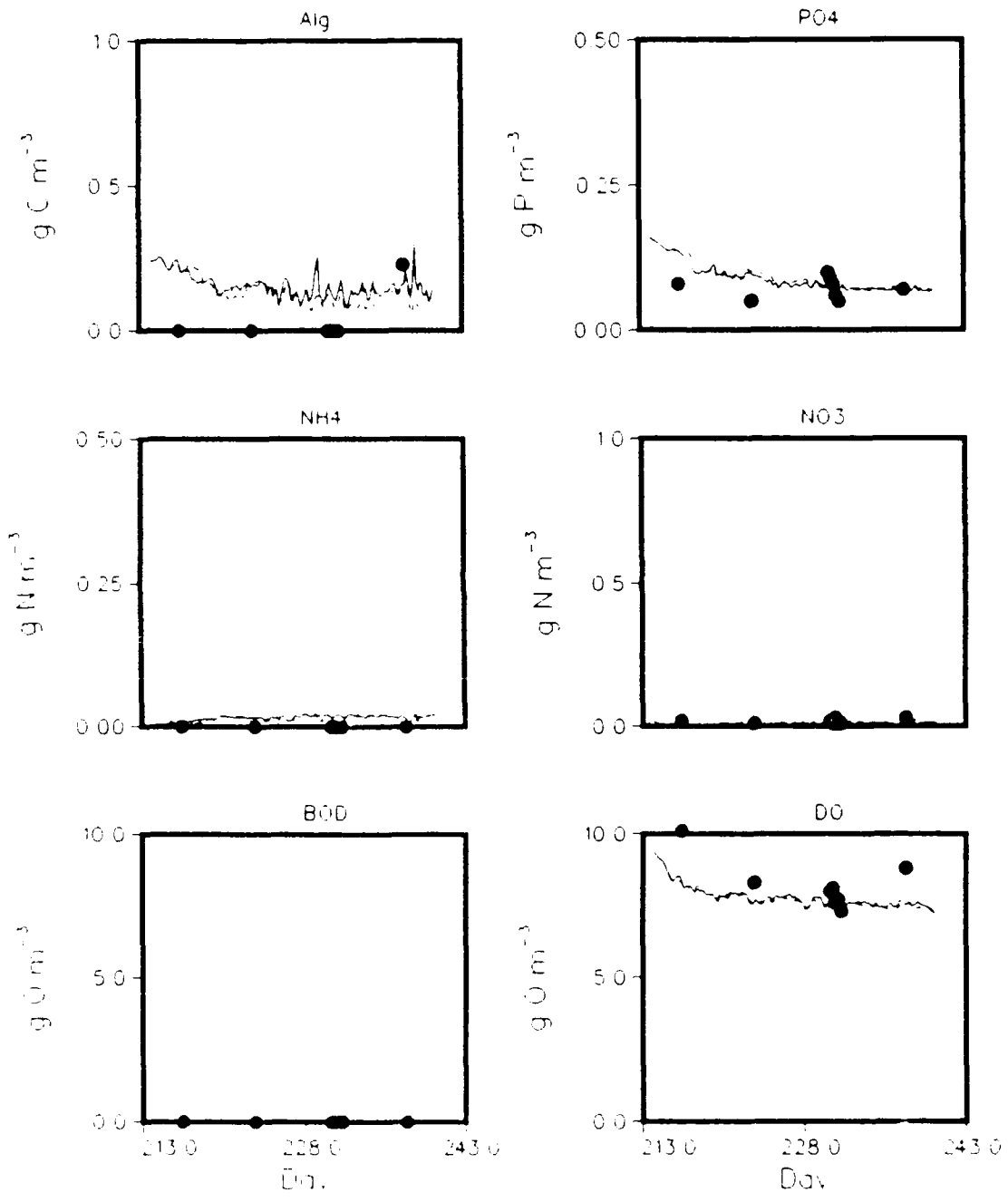
WQ Station I-7
Surface



WQ Station I- 8
Surface

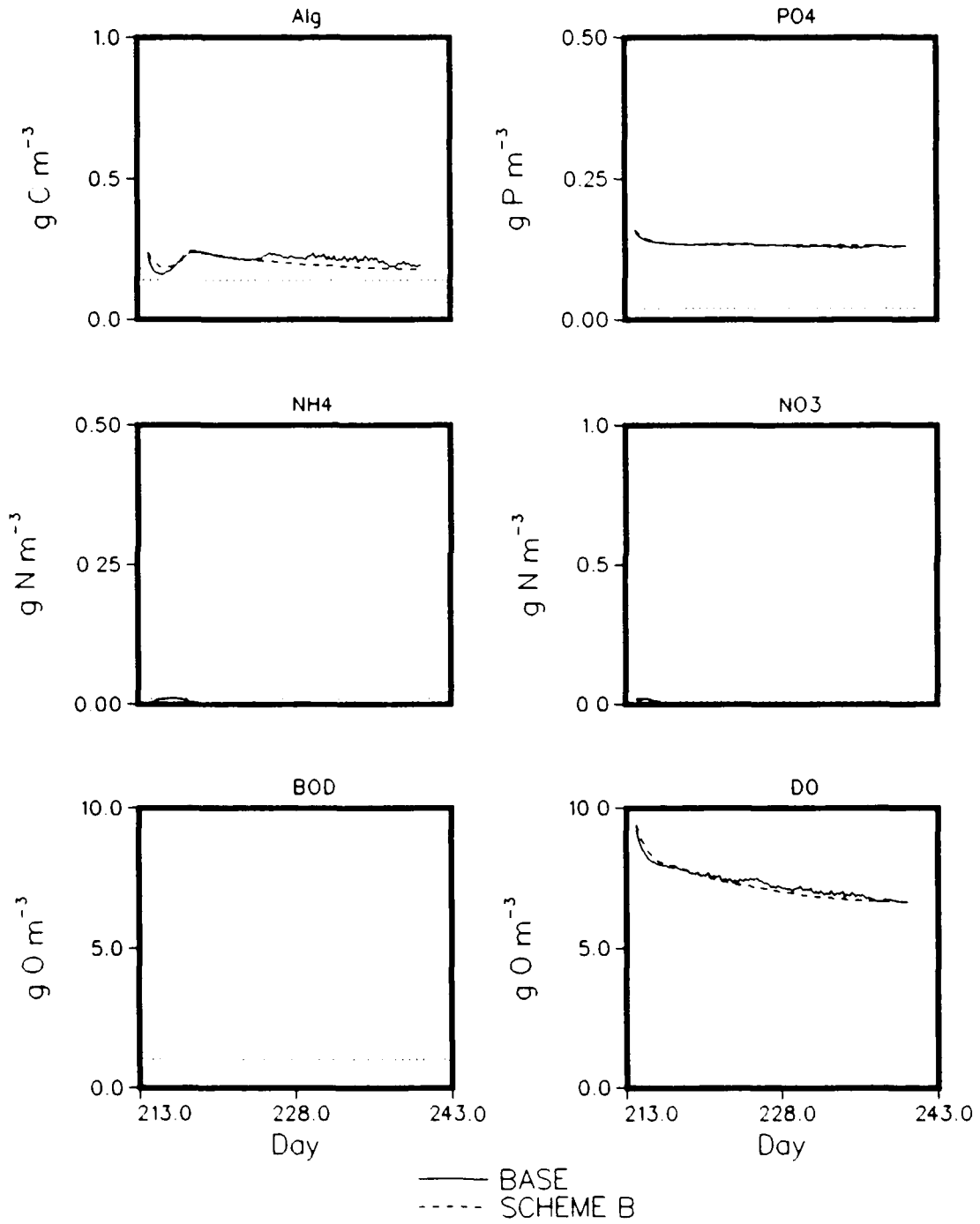


WQ Station I-9
Surface

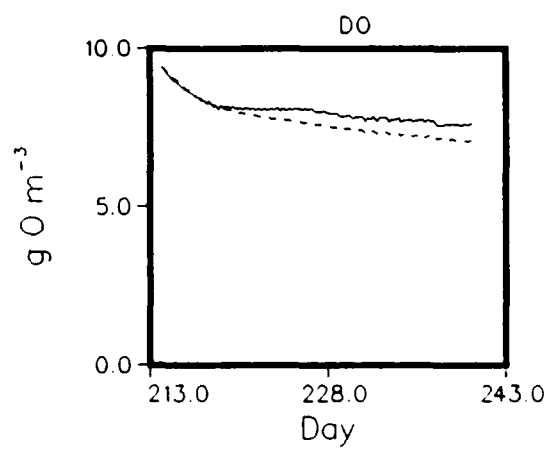
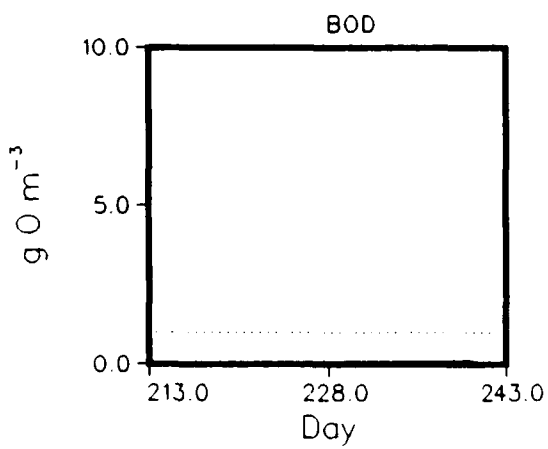
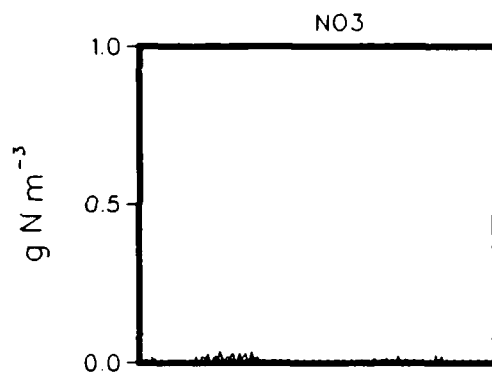
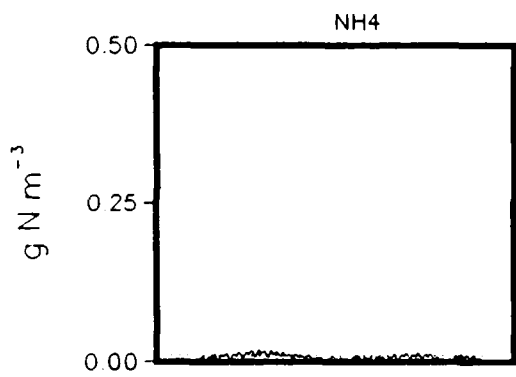
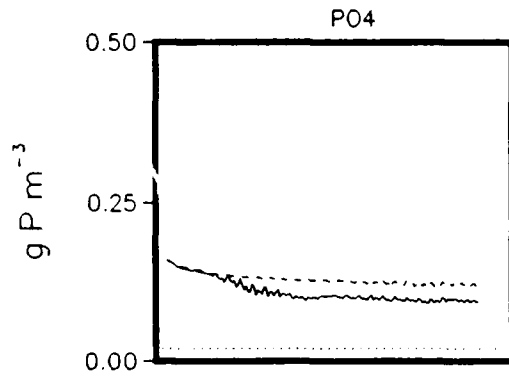
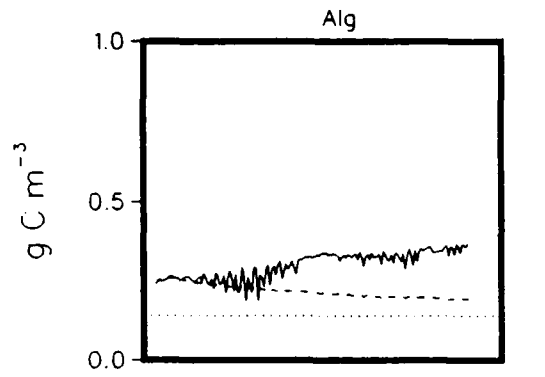


— BASE
- - - SCHEME B

WQ Station I-10
Surface

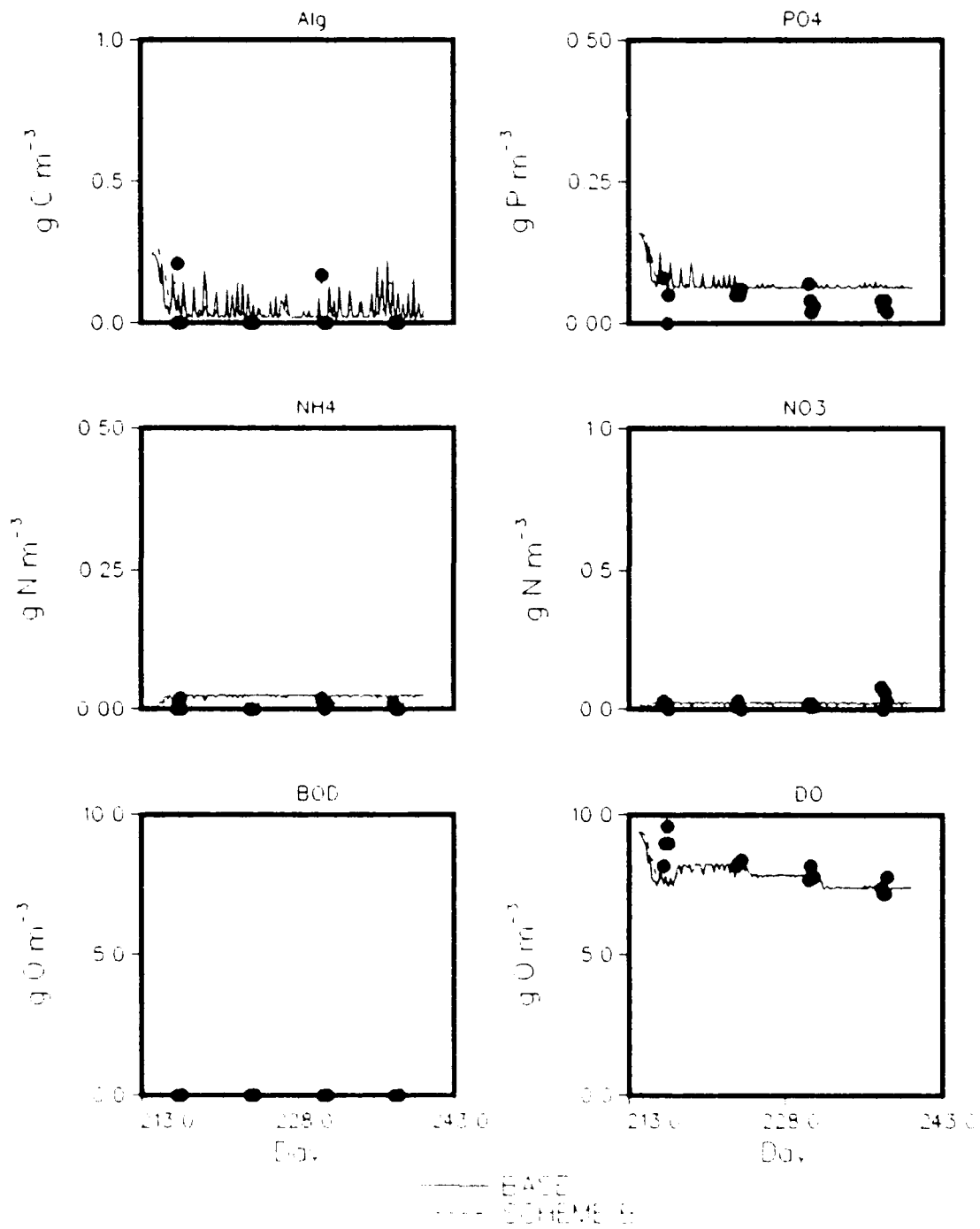


WQ Station I-11
Surface

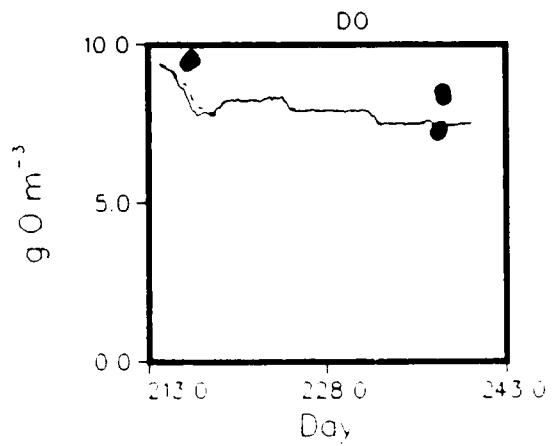
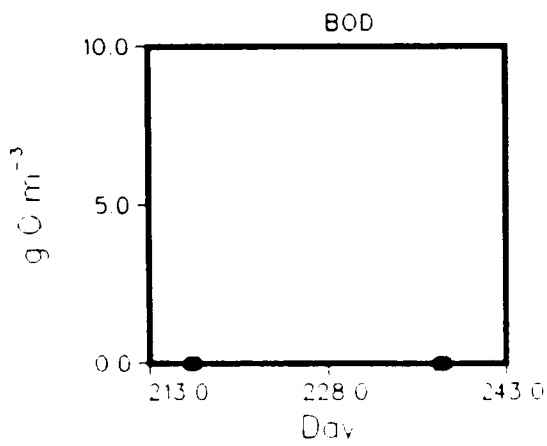
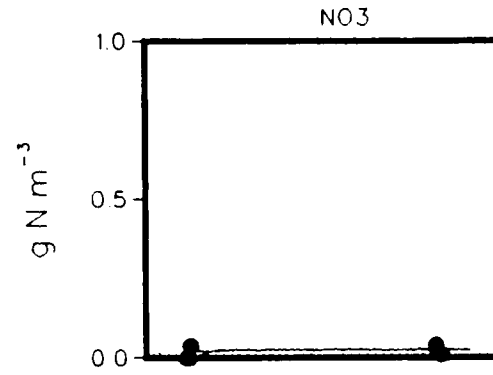
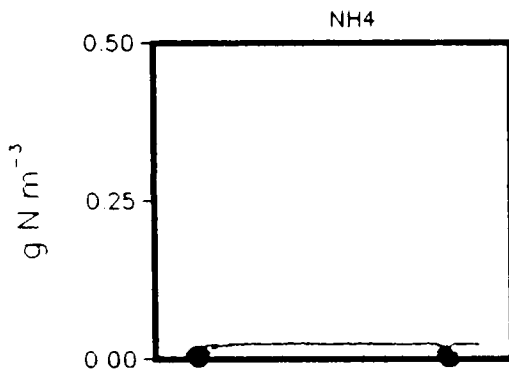
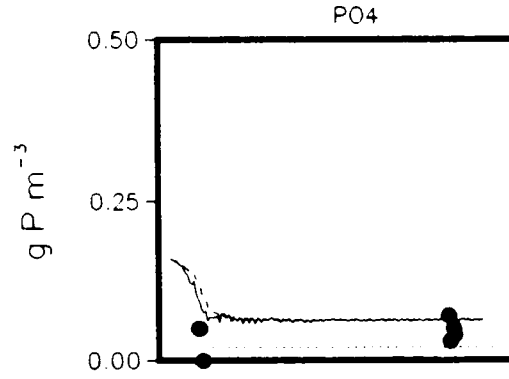
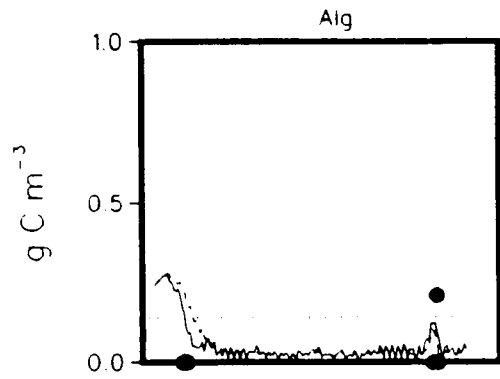


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- - - SCHEME B

WO Station B-1
Surface

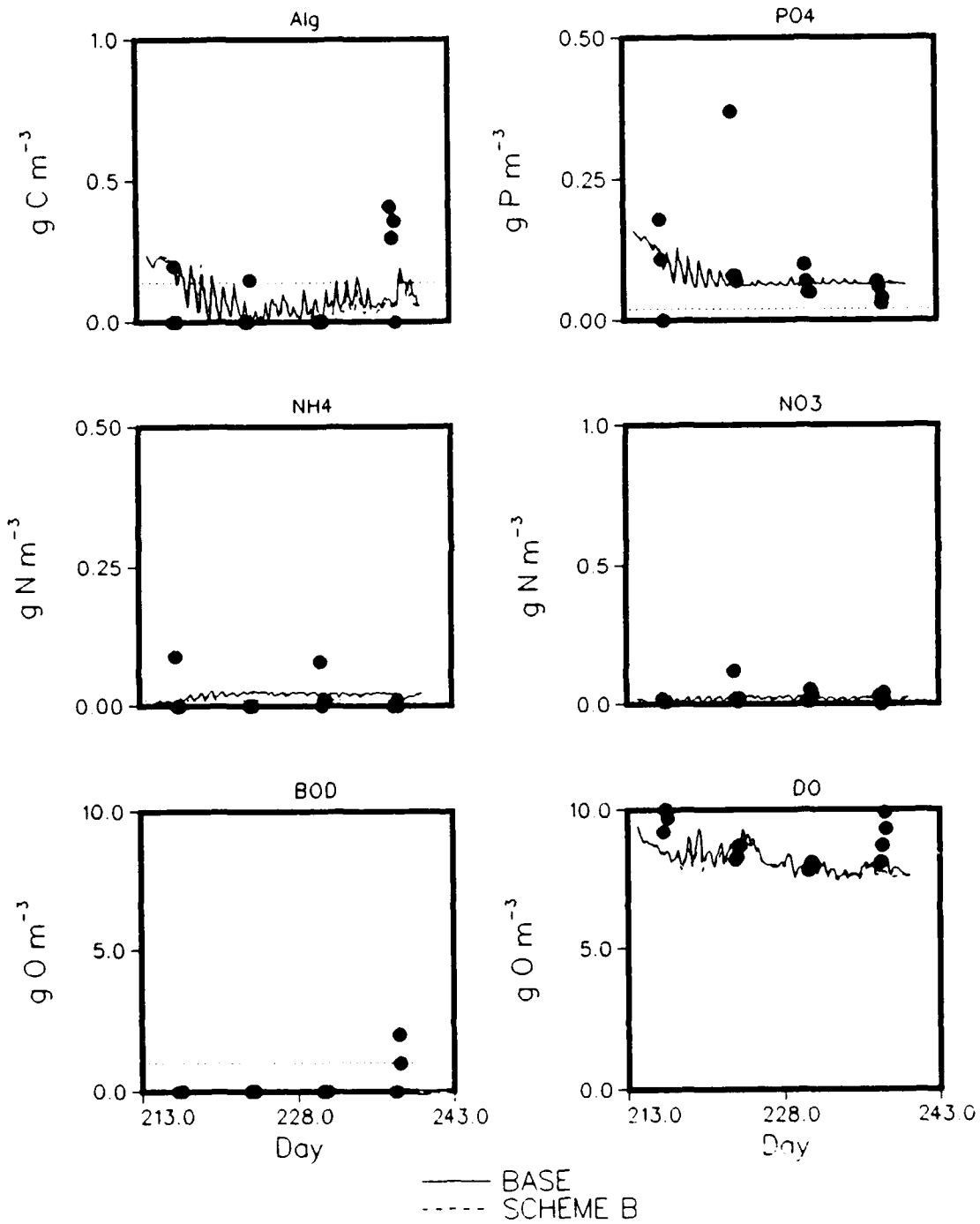


WQ Station B-2
Surface

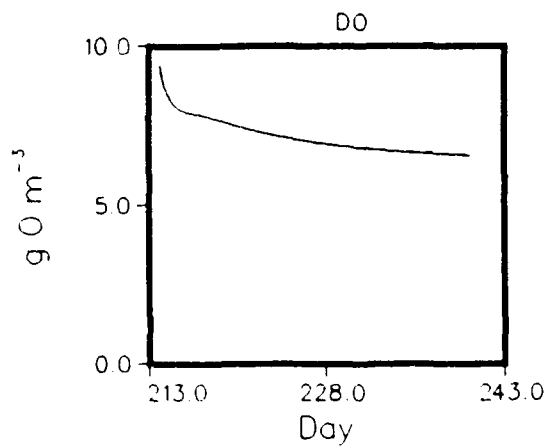
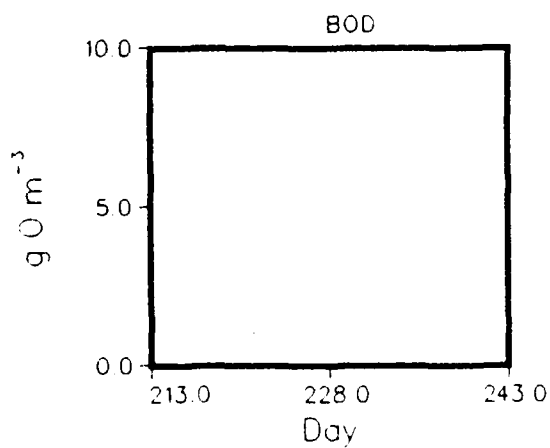
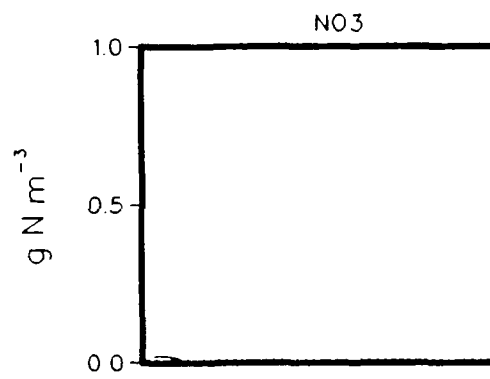
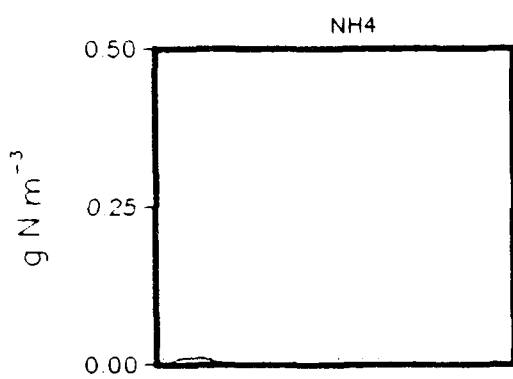
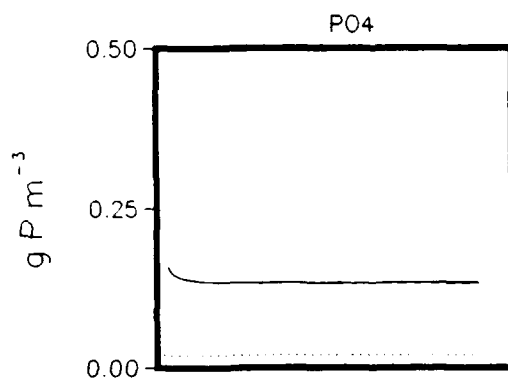
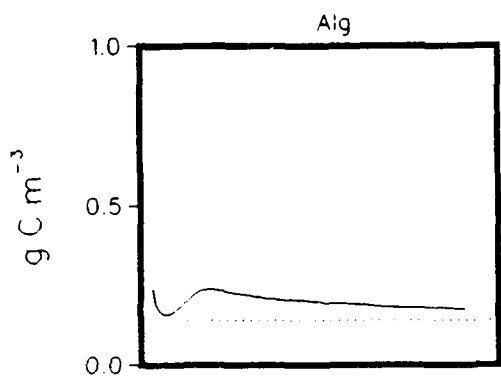


— BASE
- - - SCHEME B

WQ Station B- 3
Surface

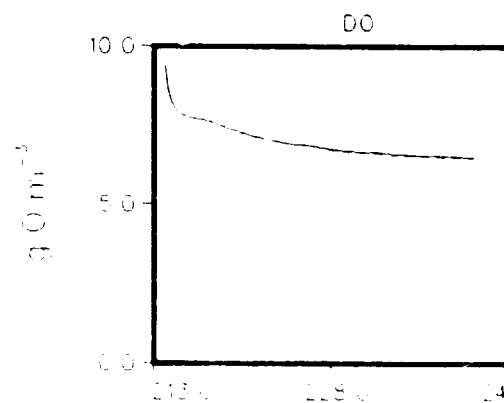
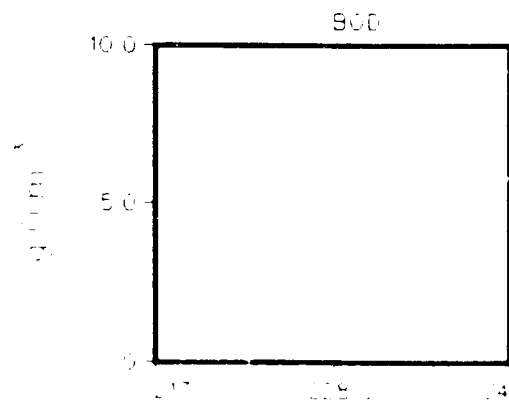
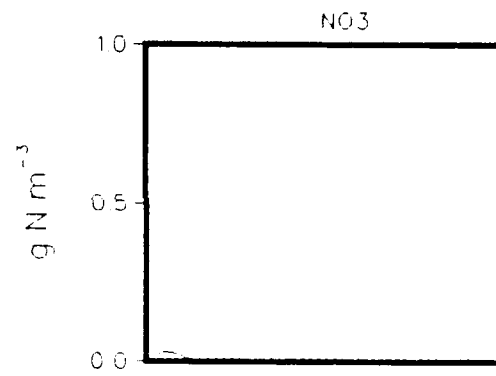
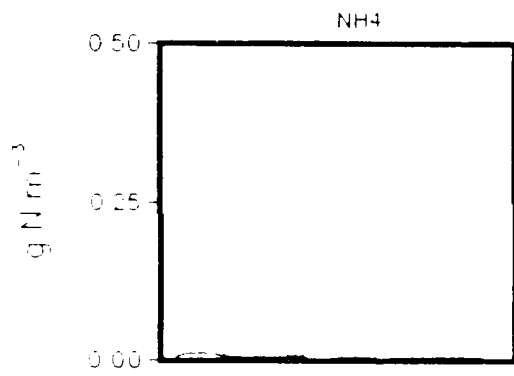
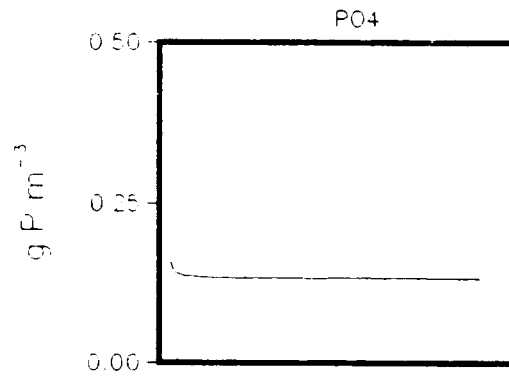
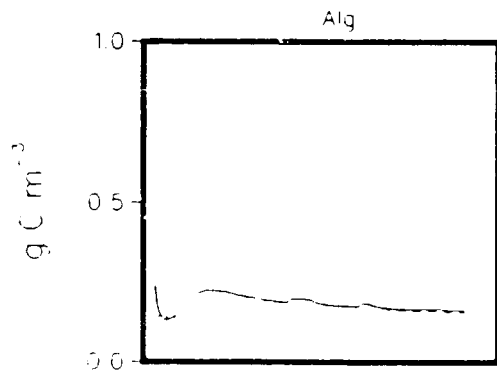


WQ Station X-1
Surface



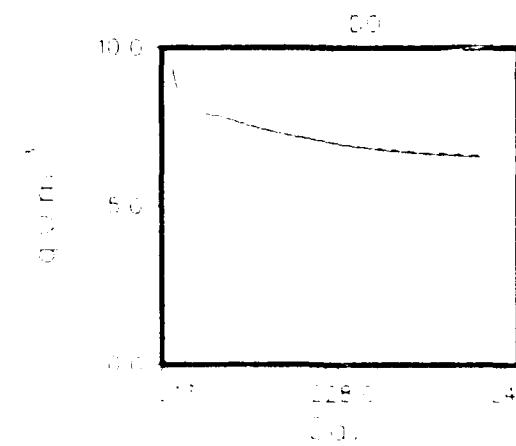
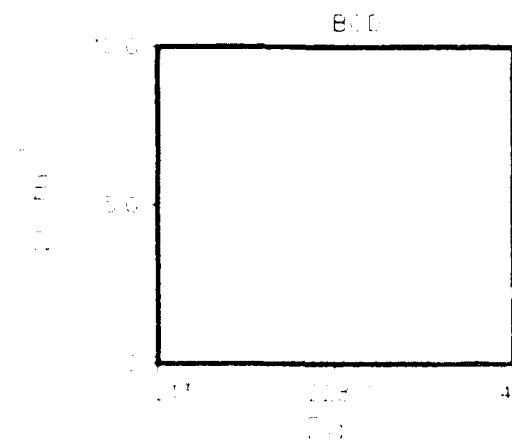
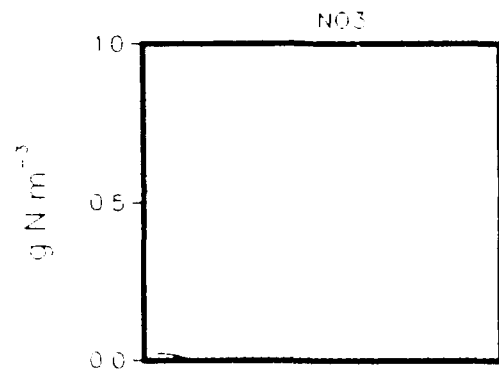
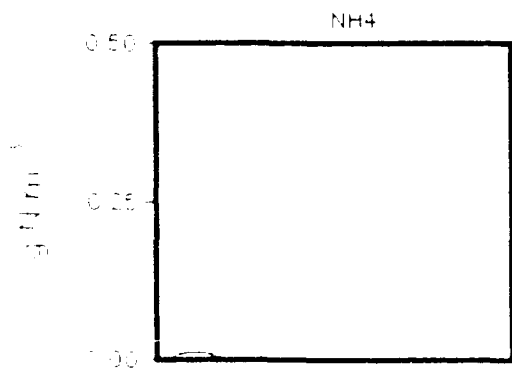
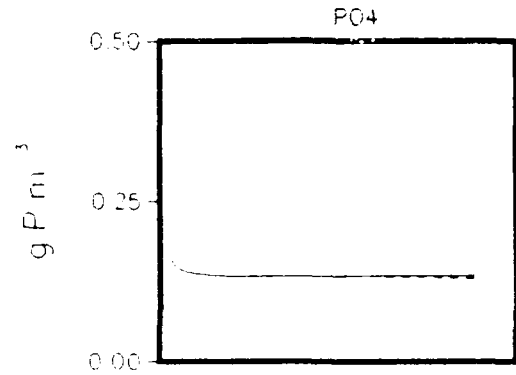
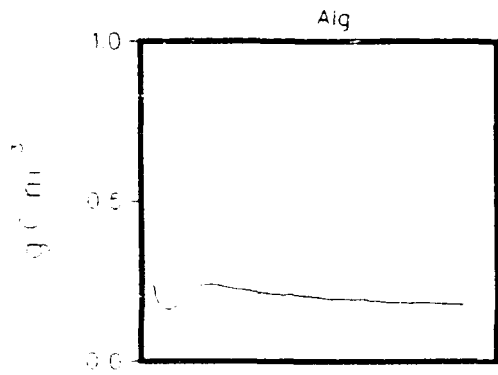
— BASE
- - - SCHEME B

WO Station X-2
Surface



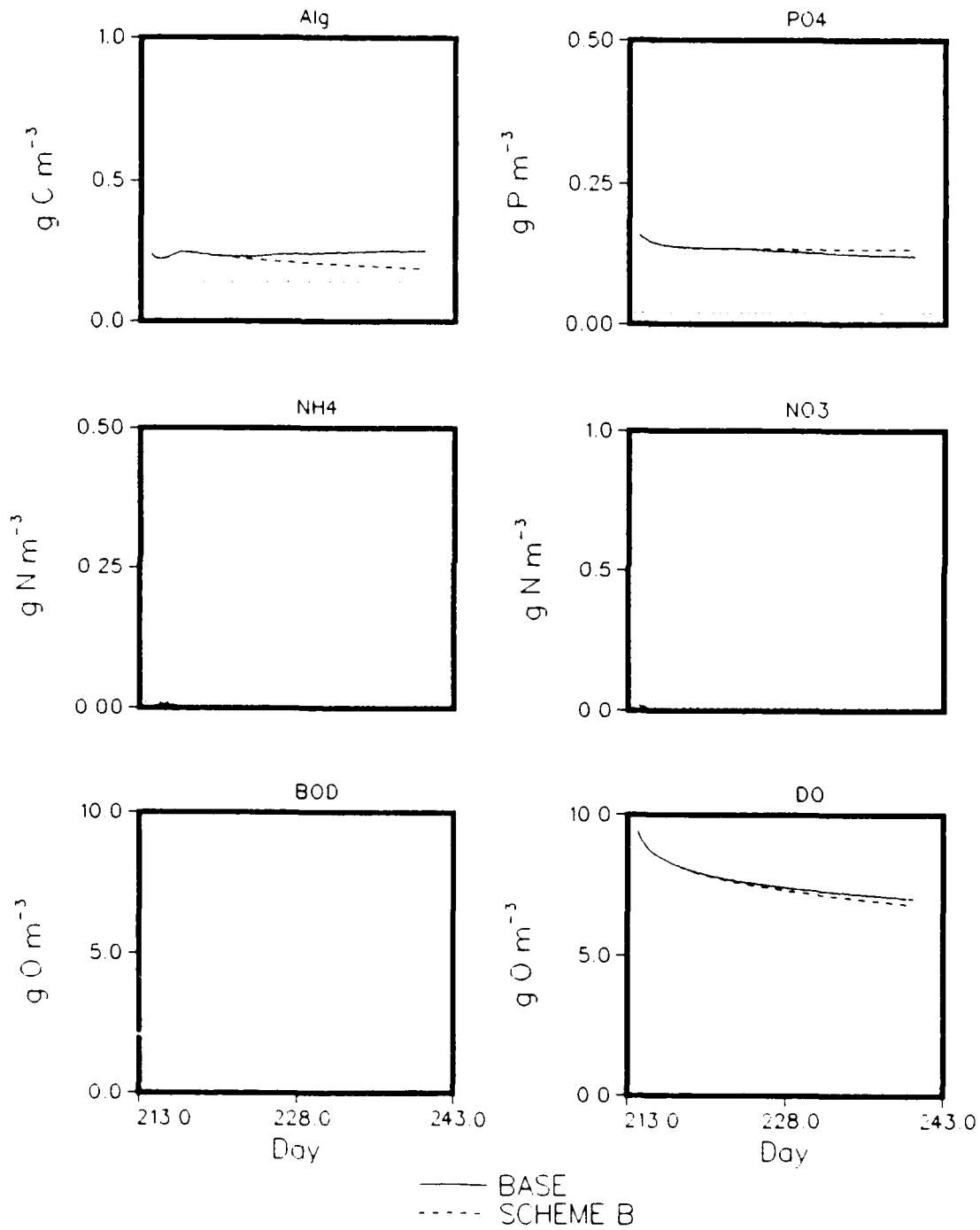
1988
02-17-88

WQ Station 4-3 Surface

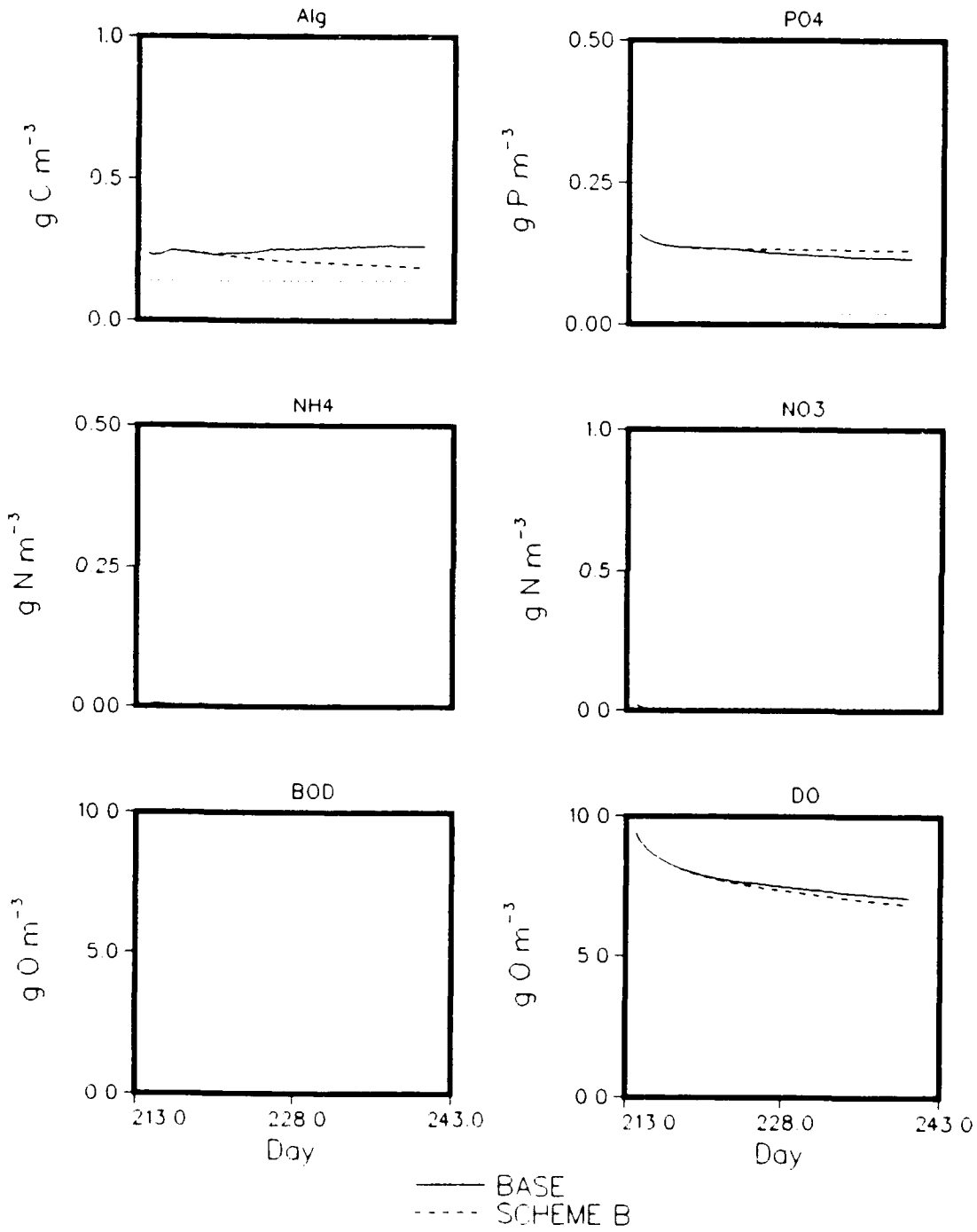


Date: 10/14/00
Time: 10:00 AM

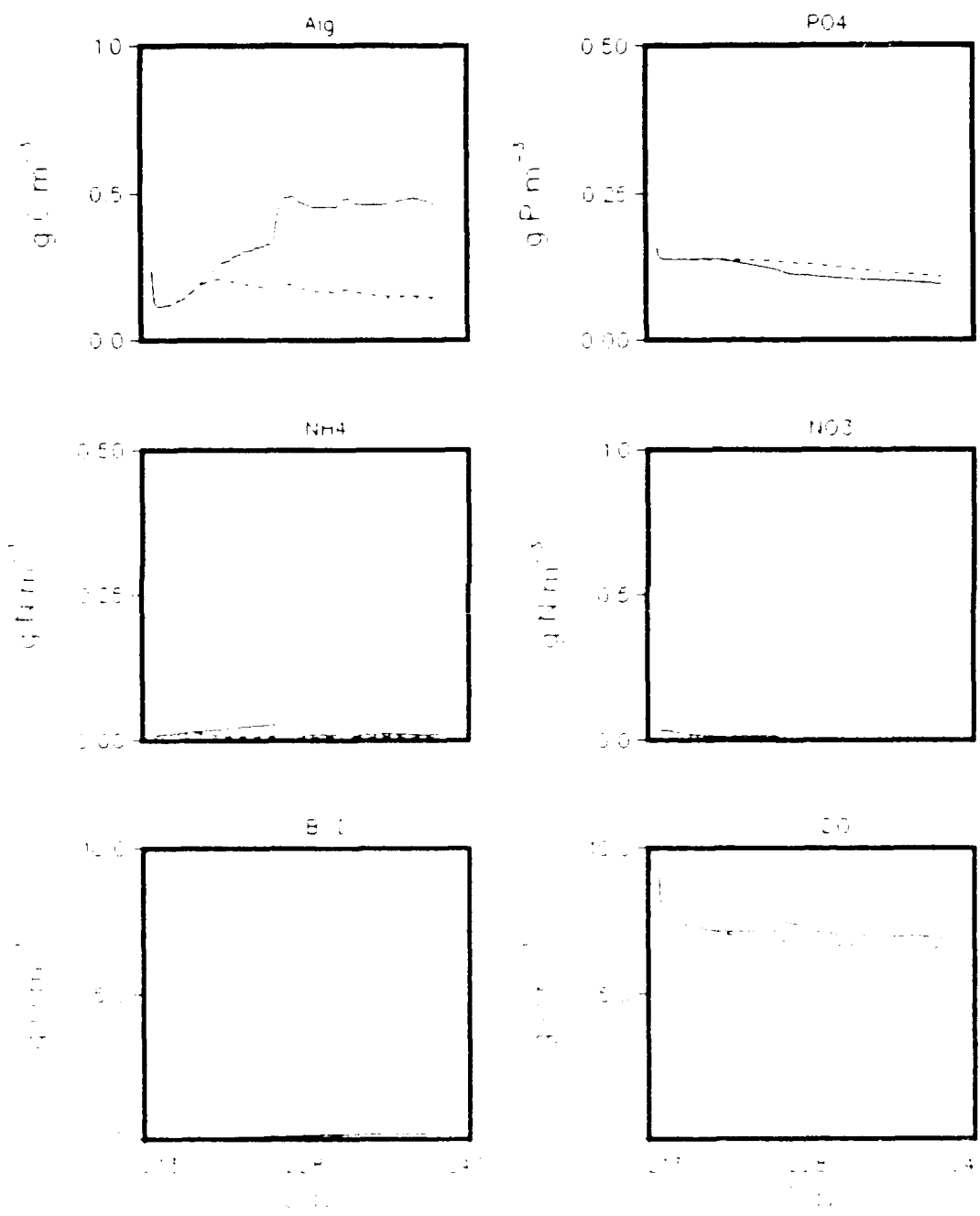
WQ Station X-4
Surface



WO Station X-5
Surface

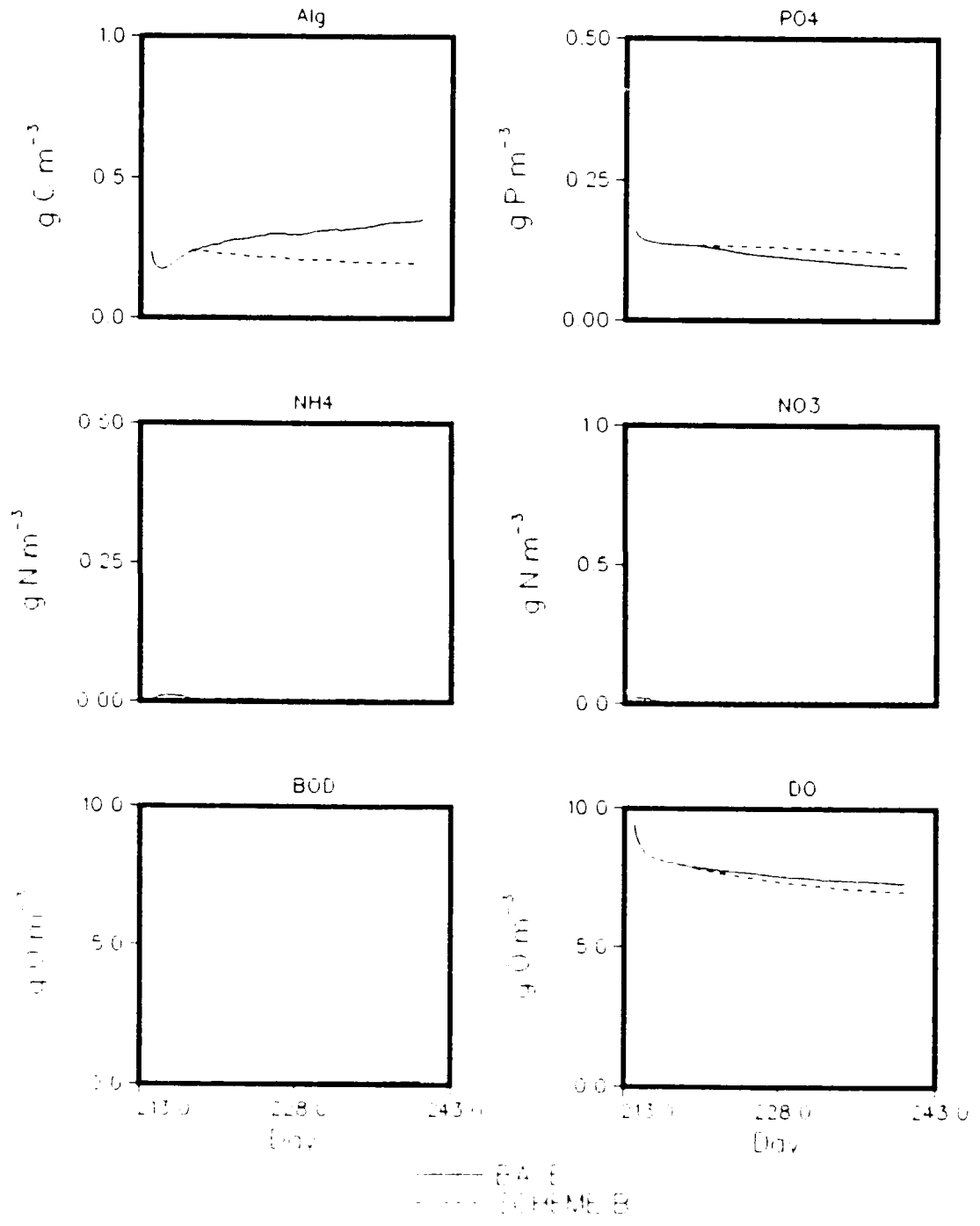


WO Station Y-6 Surface

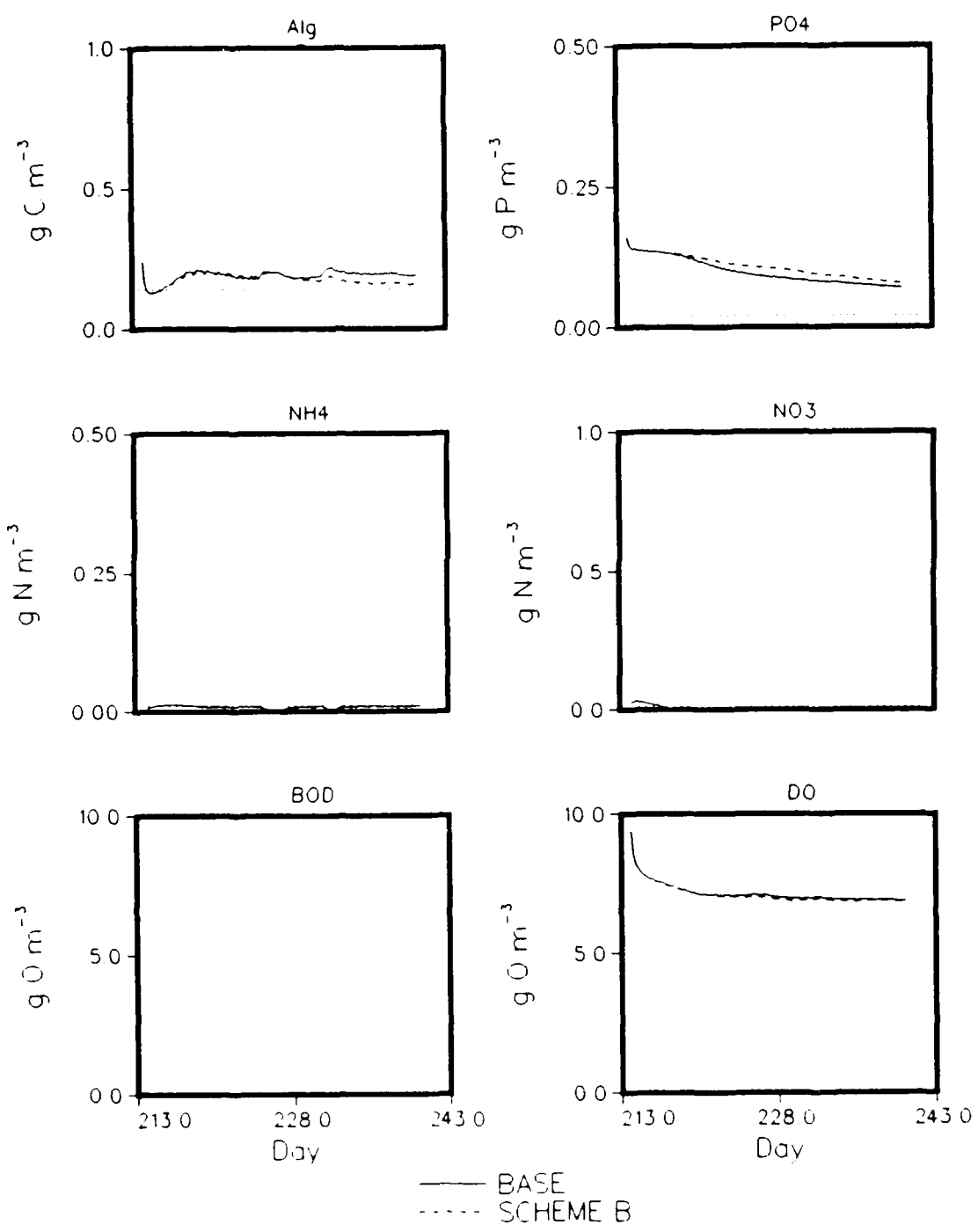


1/18 1/21 1/24
Days

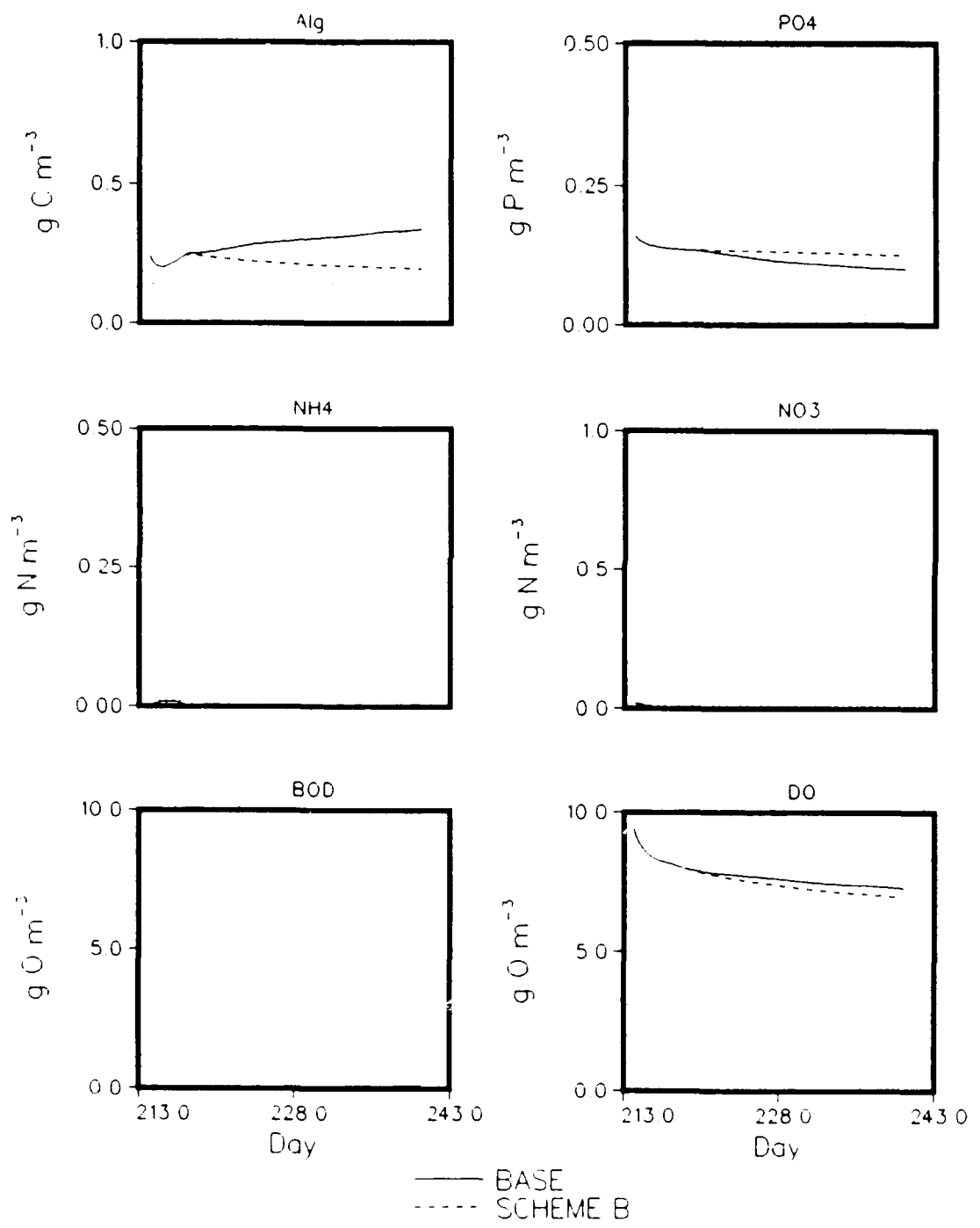
WQ Station X-7 Surface



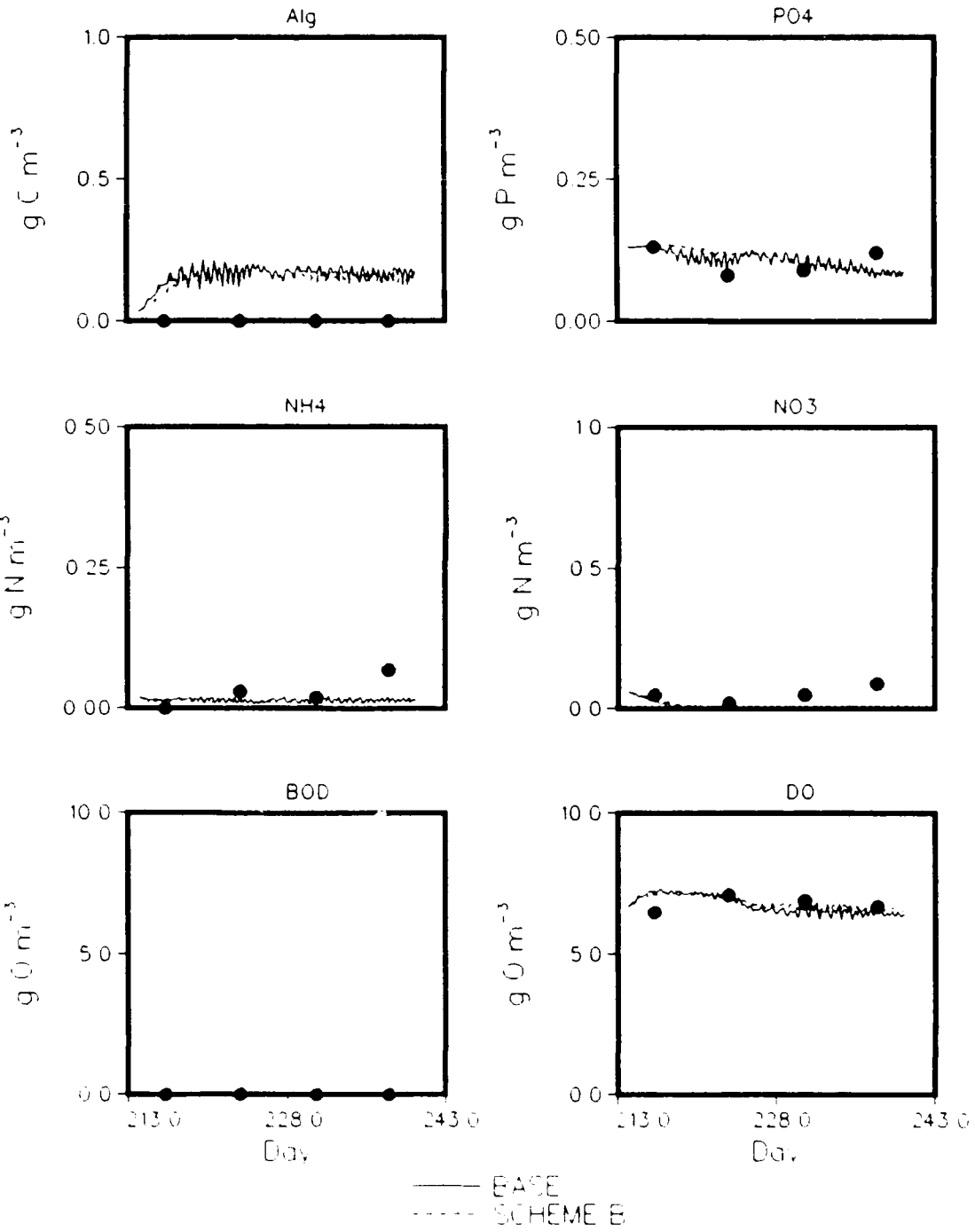
WQ Station X-8
Surface



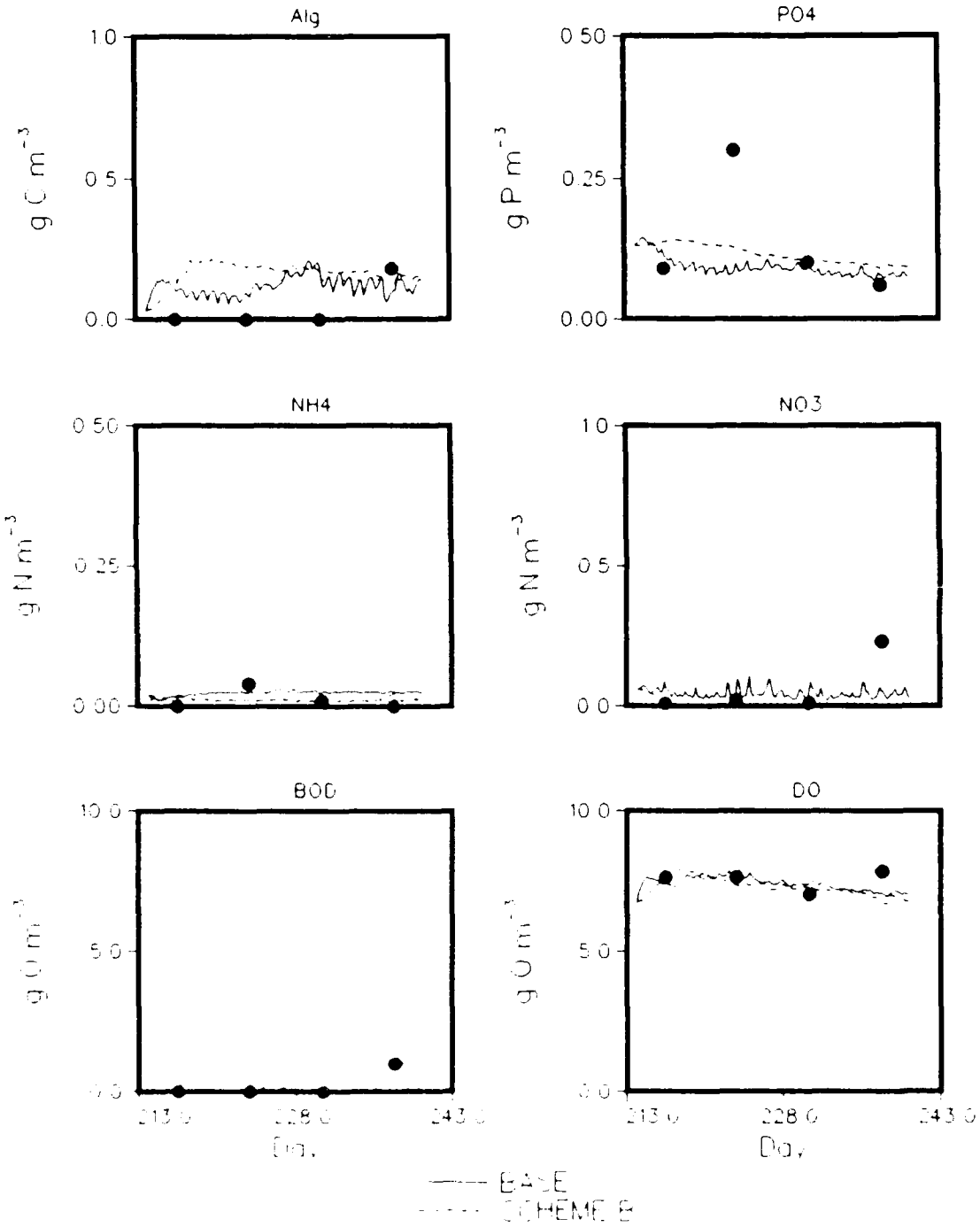
WO Station X-9
Surface



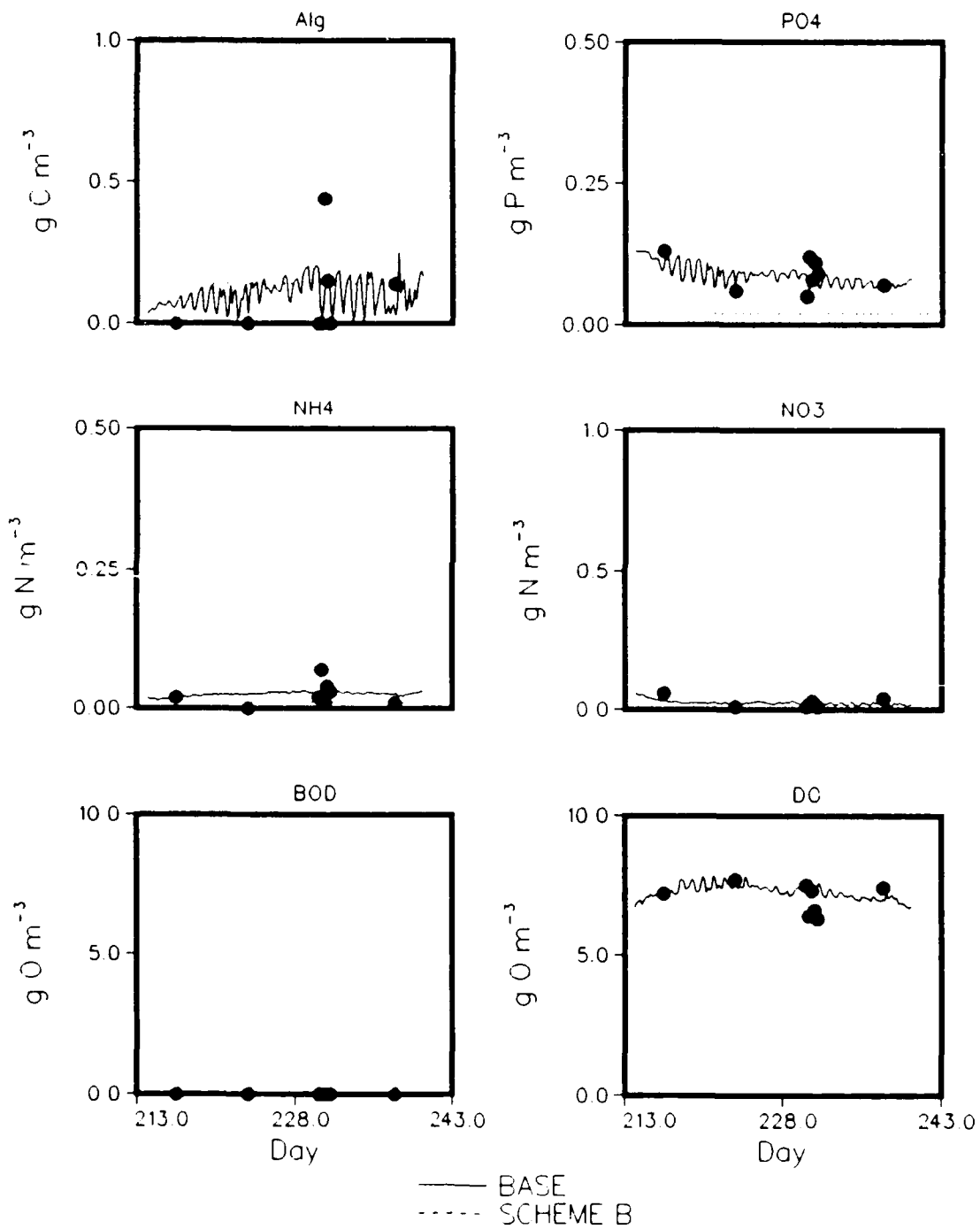
WO Station I-1
Bottom



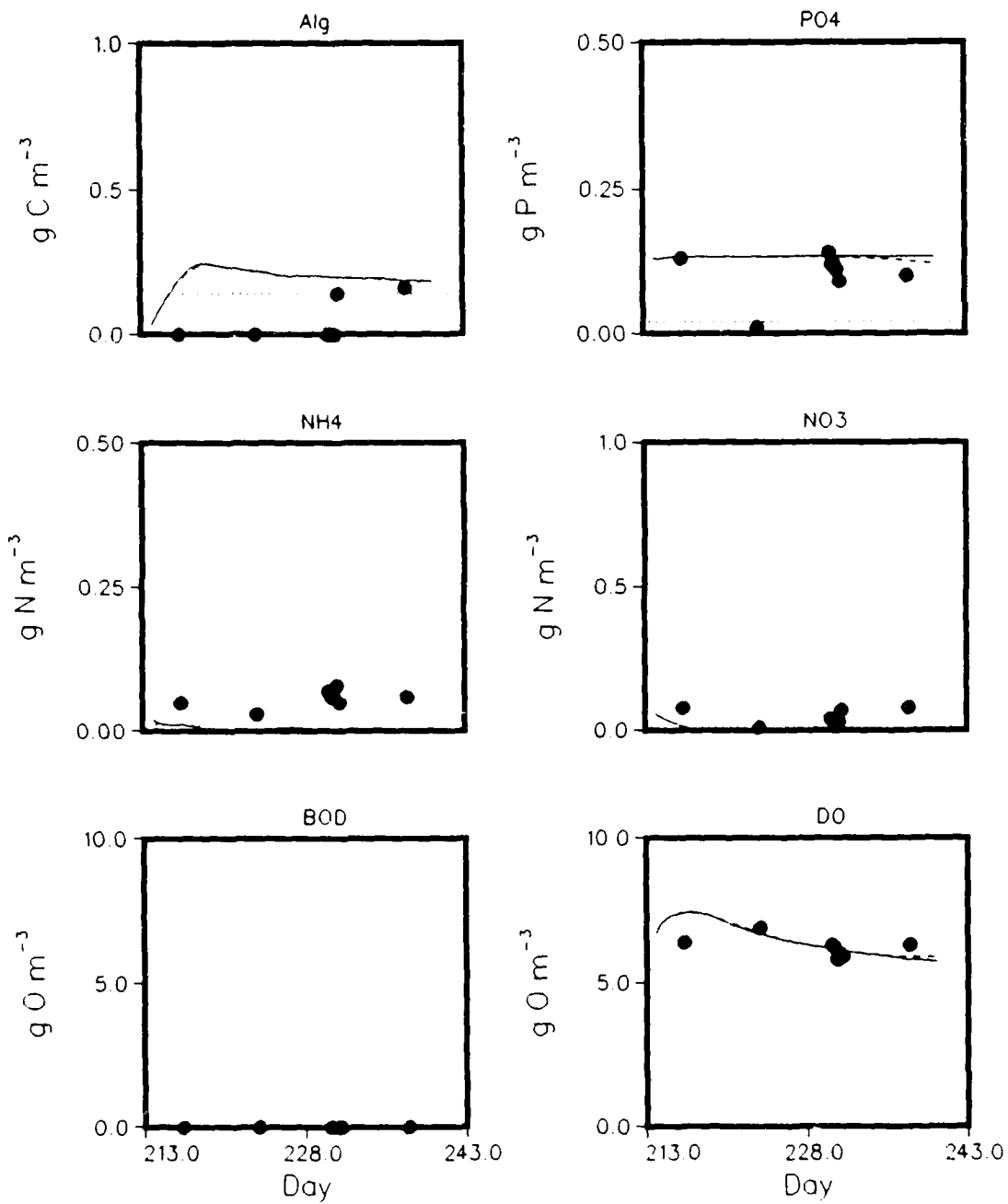
WO Station I-2
Bottom



WQ Station I- 3
Bottom

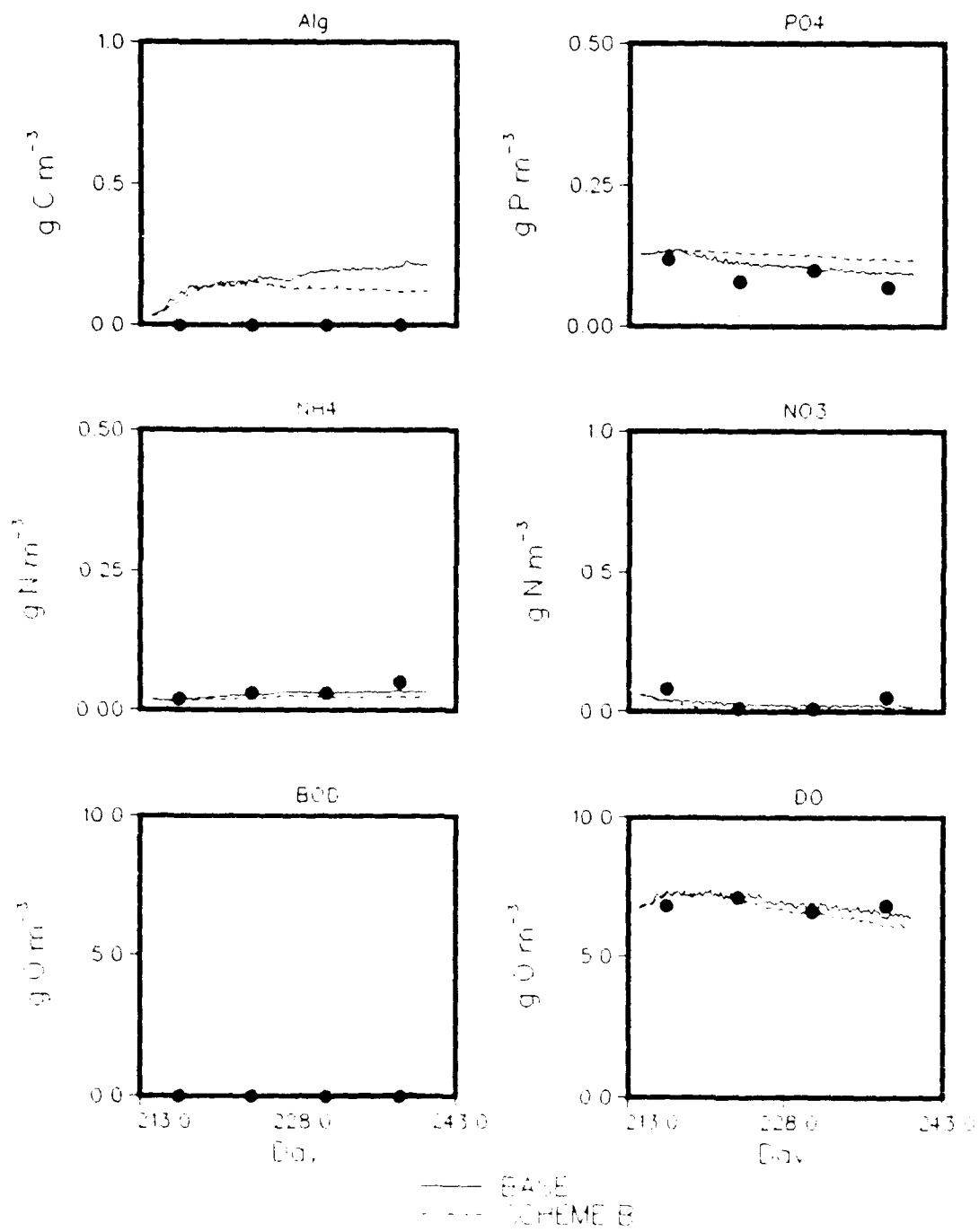


WQ Station I- 4
Bottom

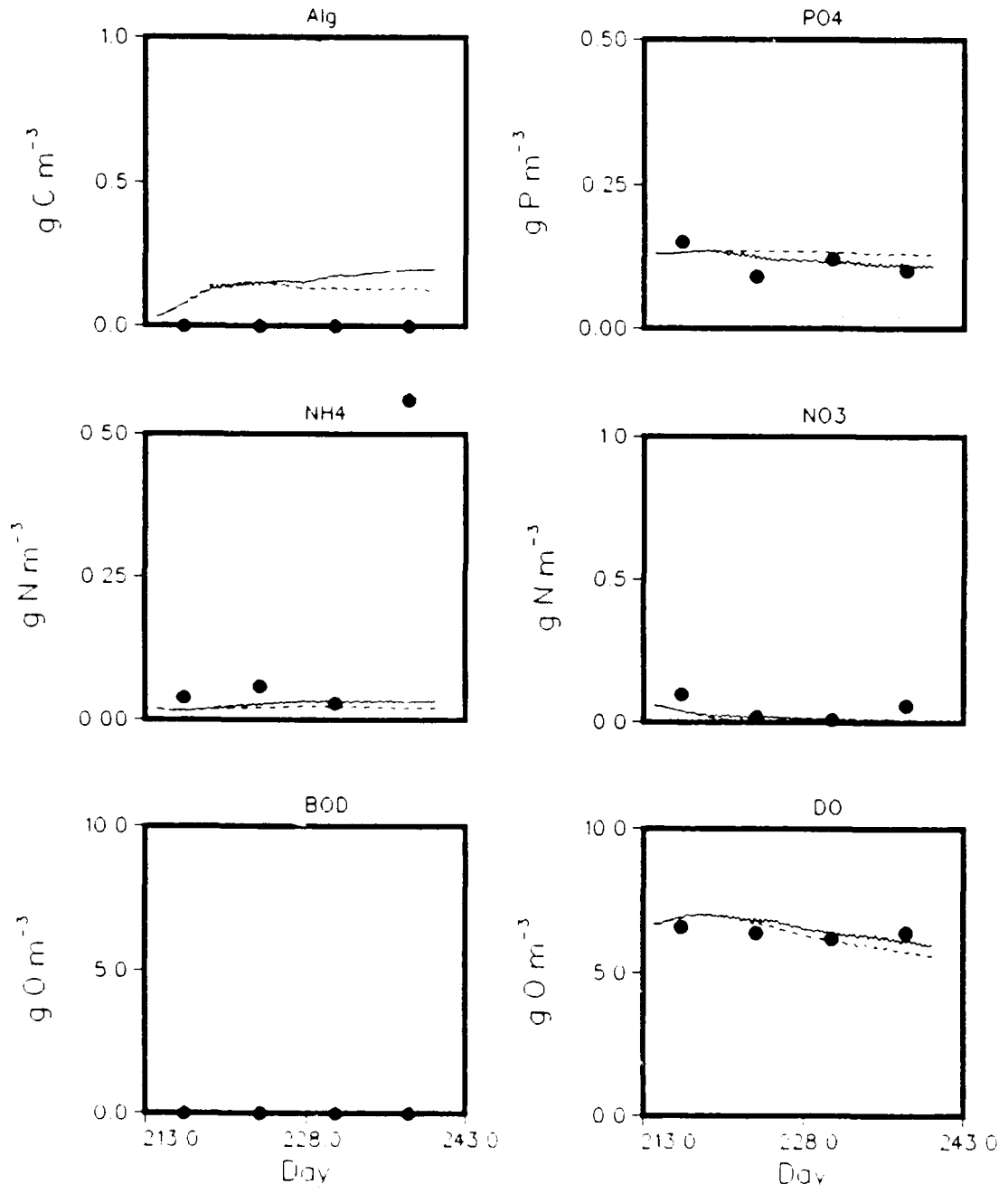


— BASE
- - - SCHEME B

WQ Station I-5
Bottom

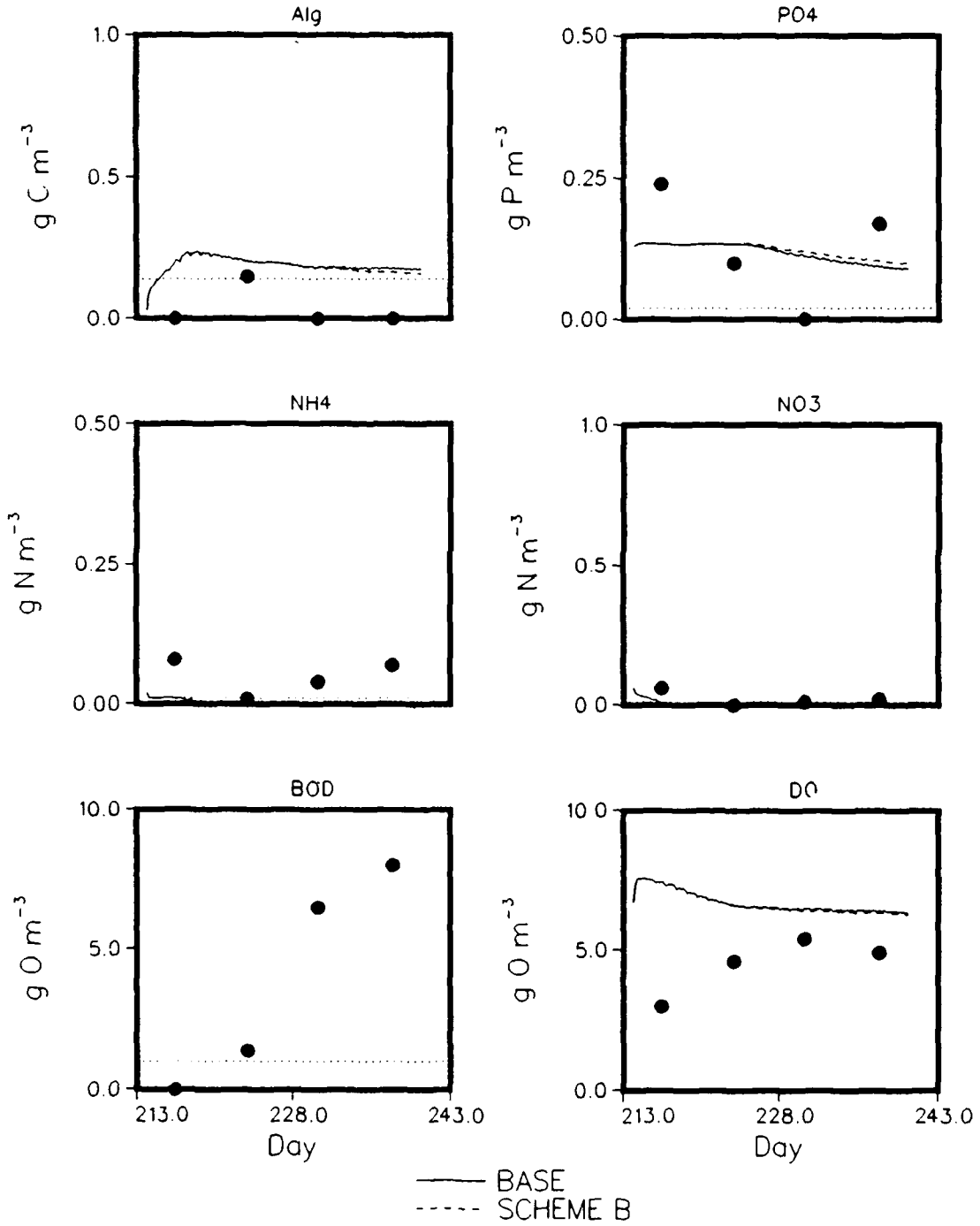


WQ Station I-6
Bottom

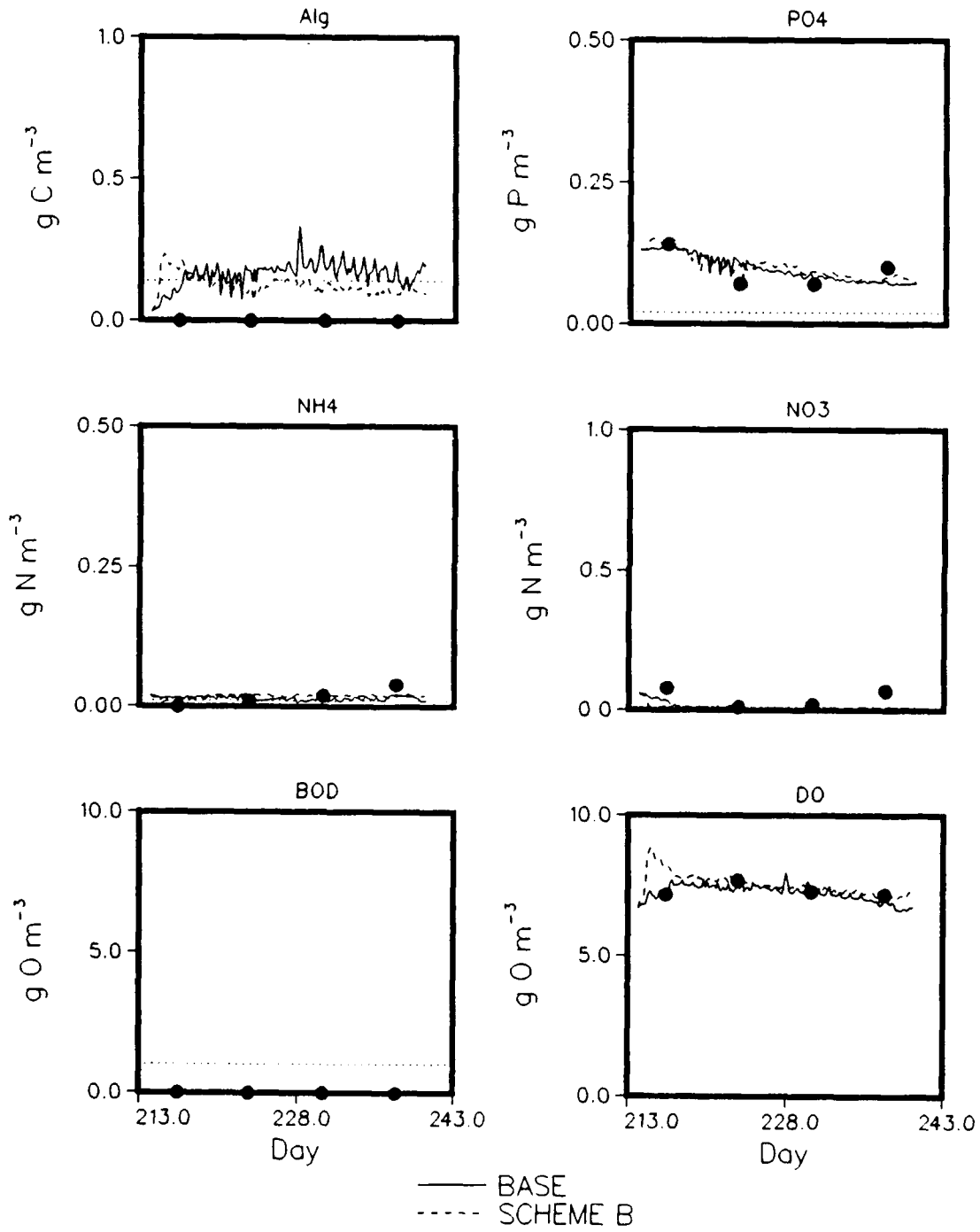


— BASE
- - - SCHEME B

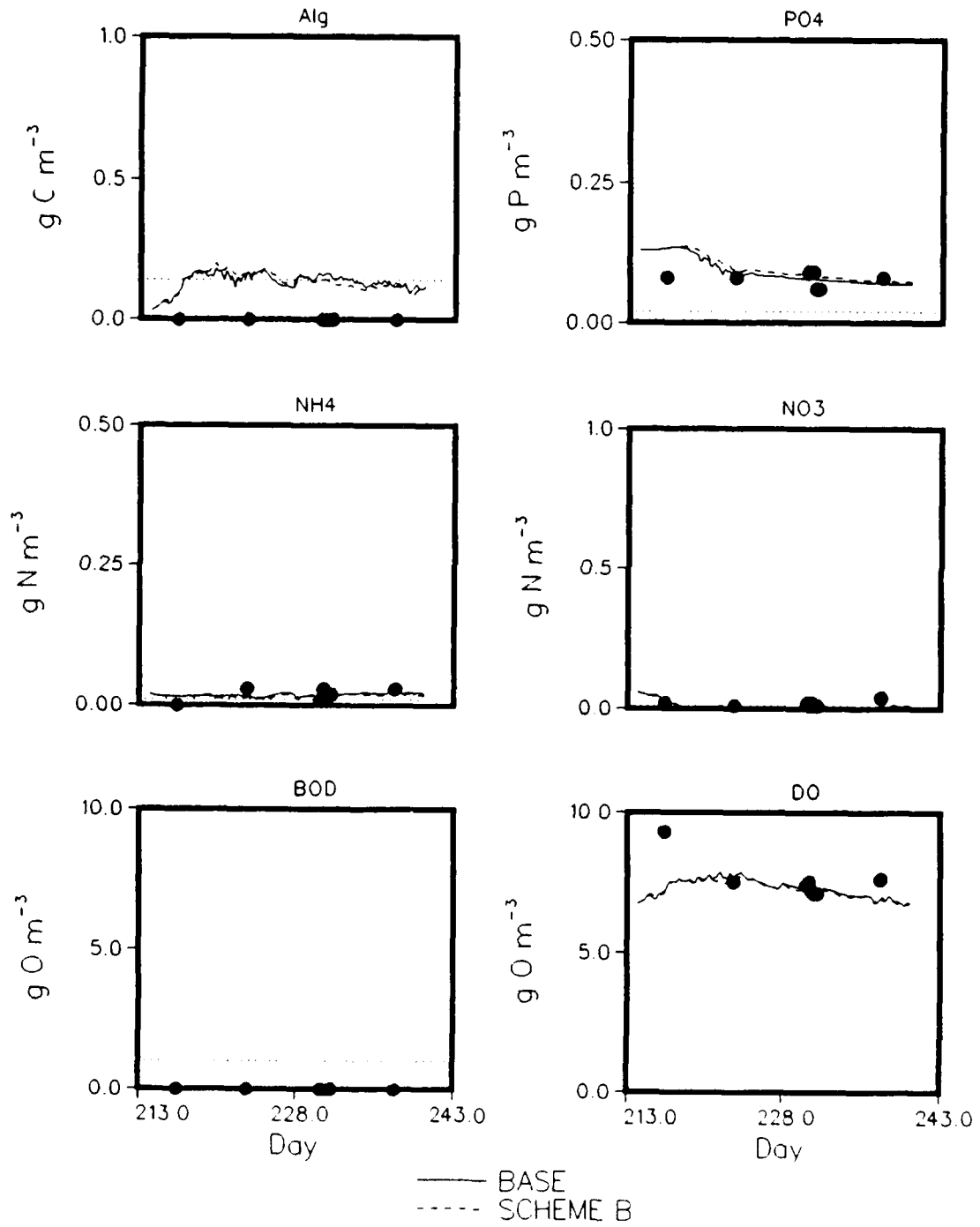
WQ Station I-7
Bottom



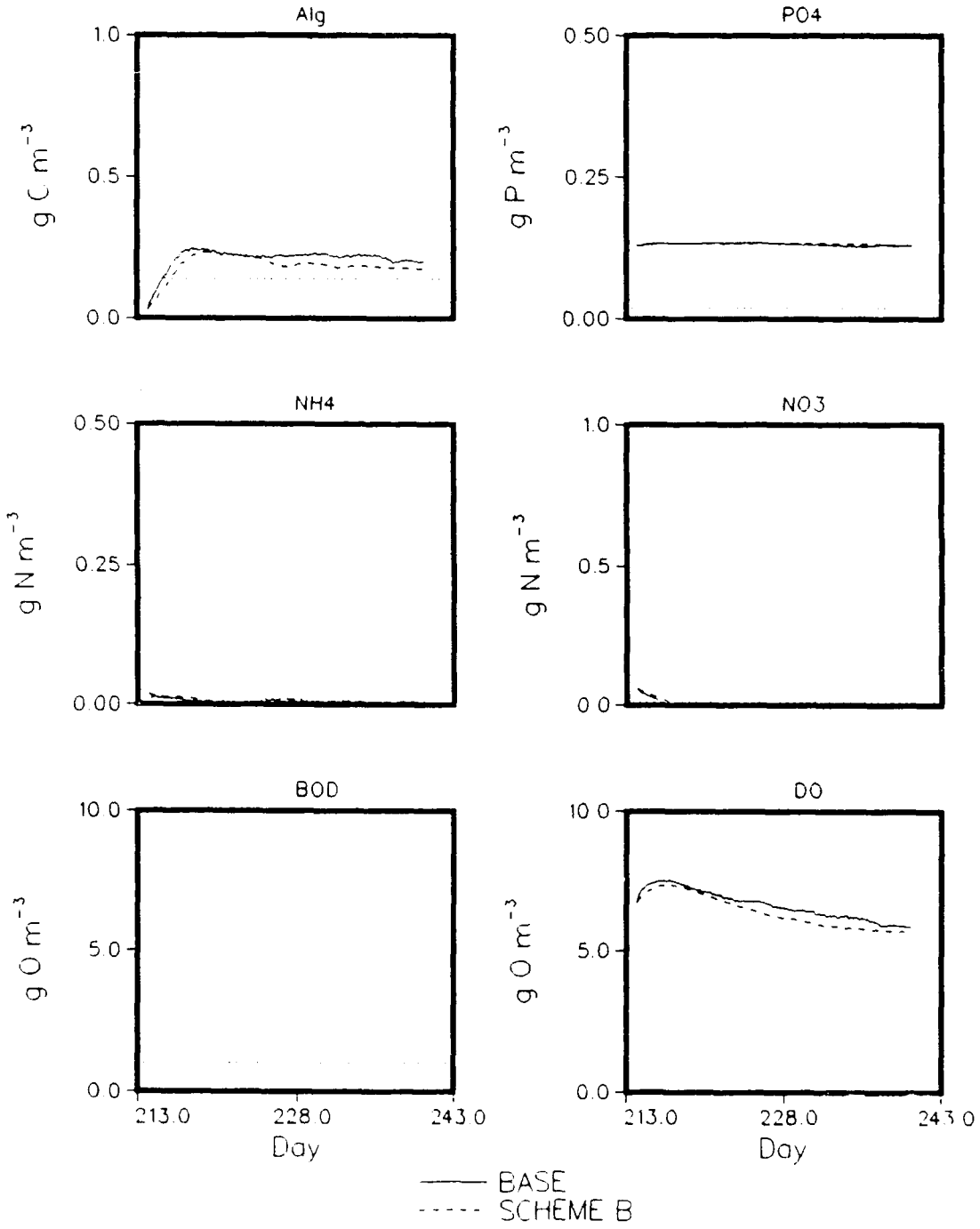
WQ Station I- 8
Bottom



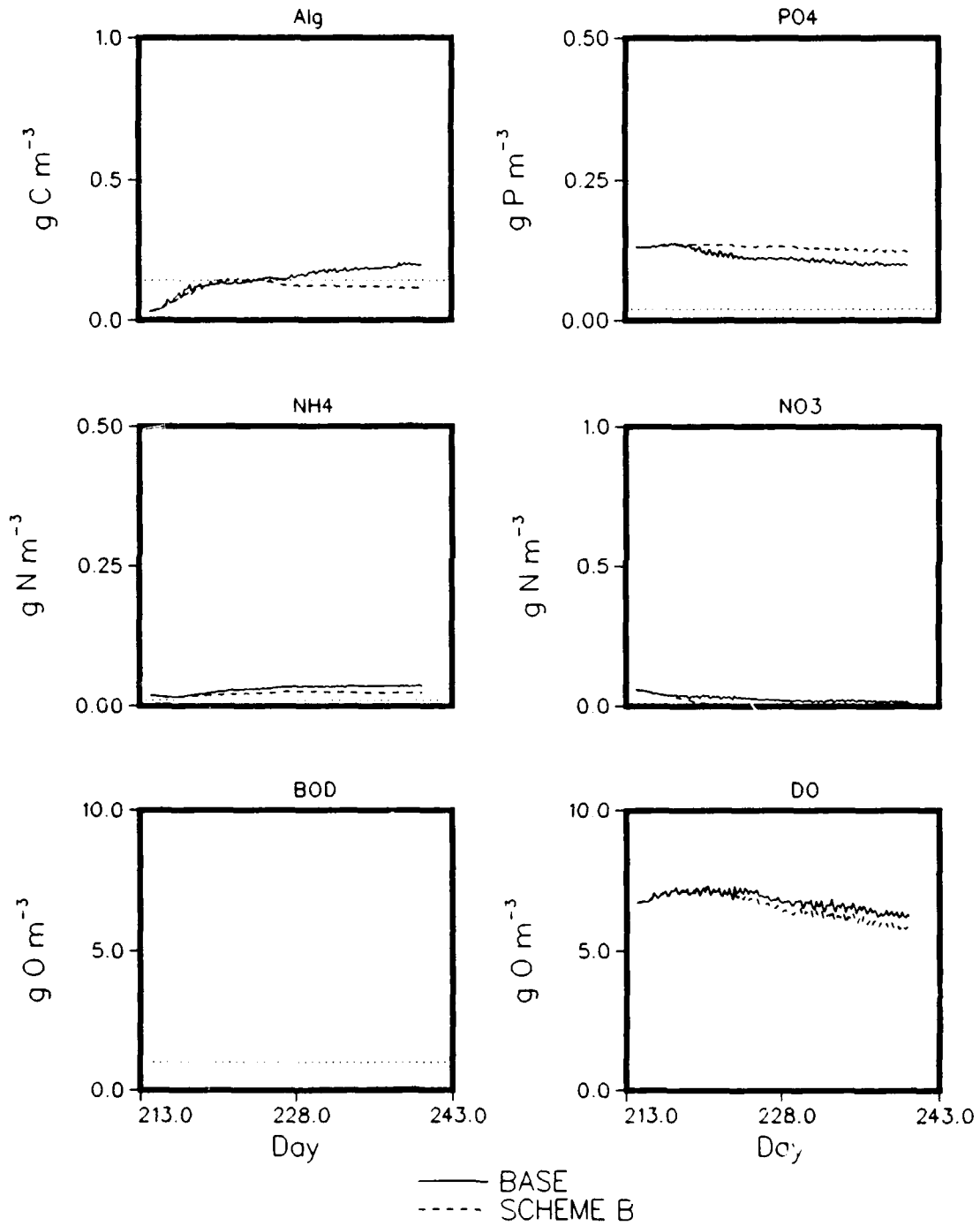
WQ Station I-9
Bottom



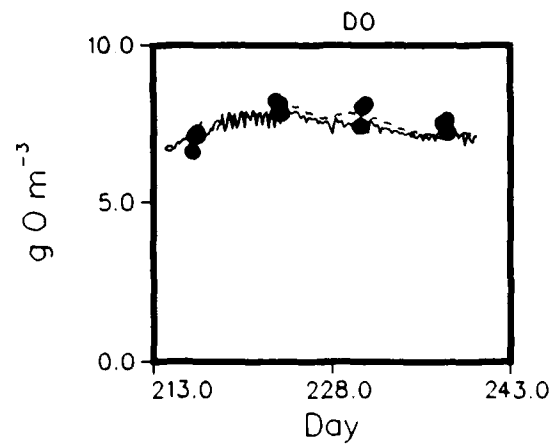
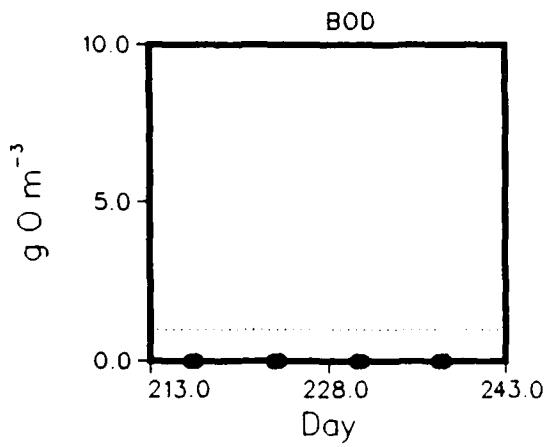
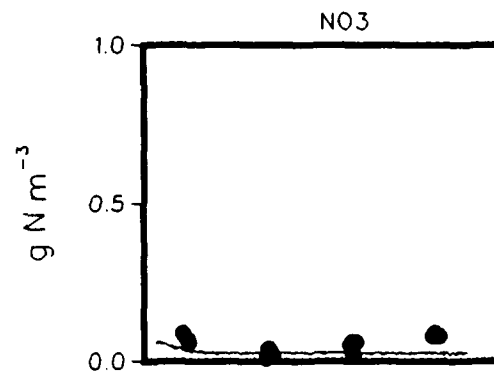
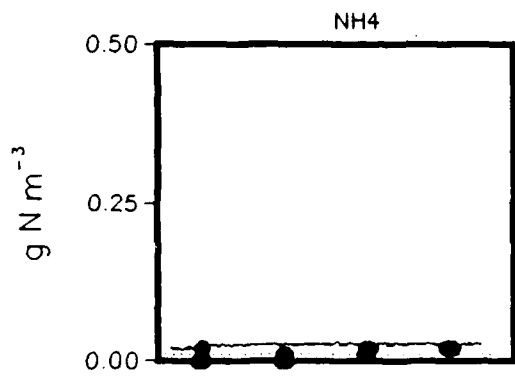
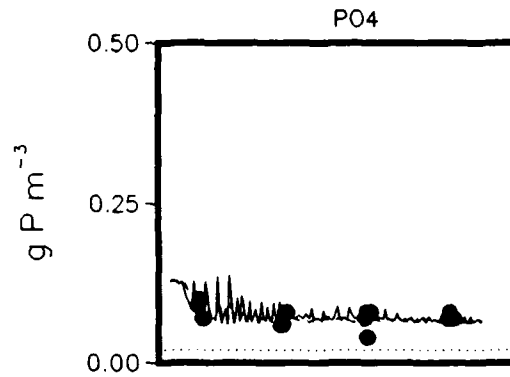
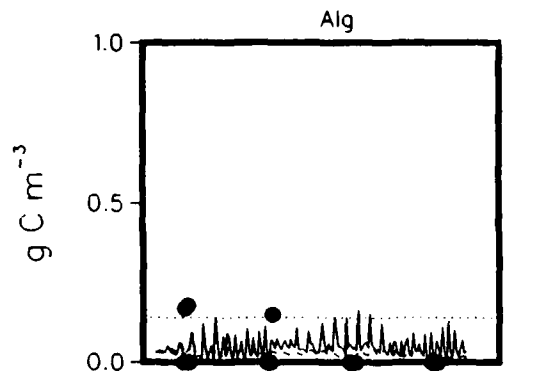
WQ Station I-10
Bottom



WQ Station I-11
Bottom

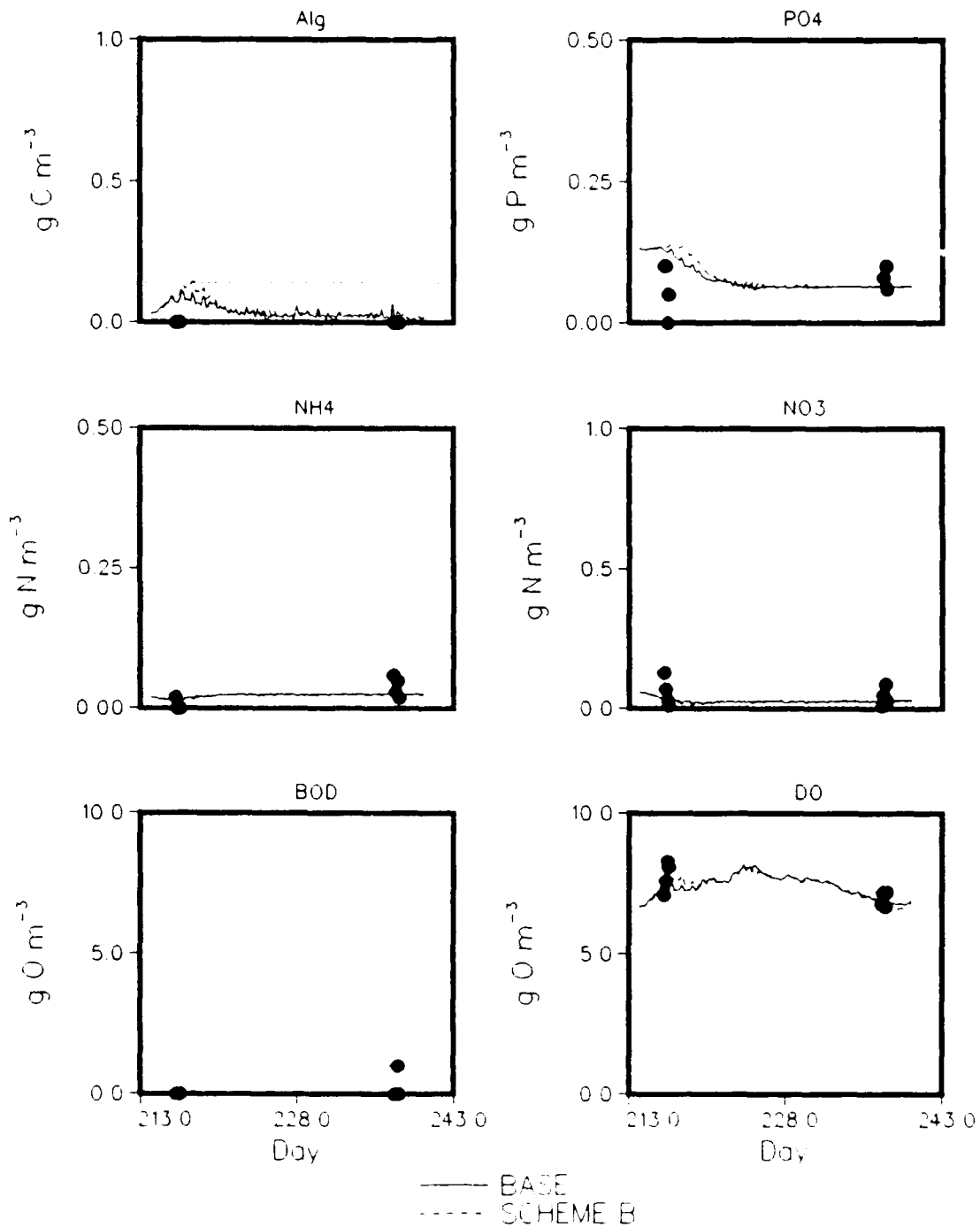


WQ Station B-1
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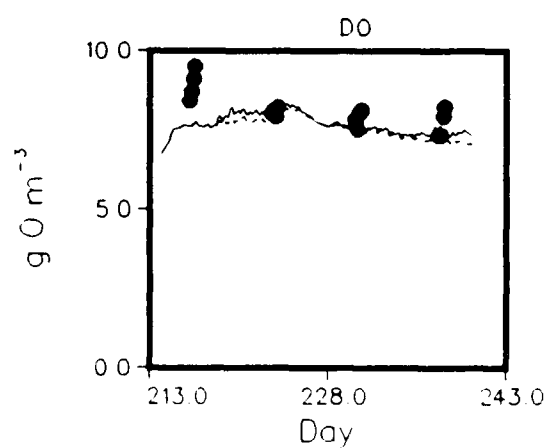
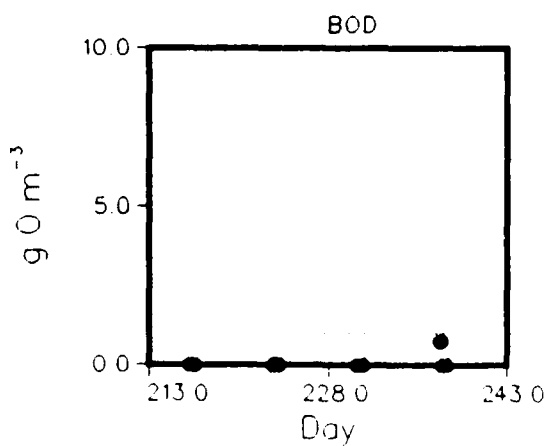
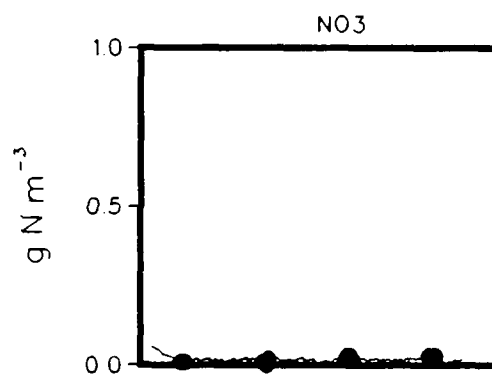
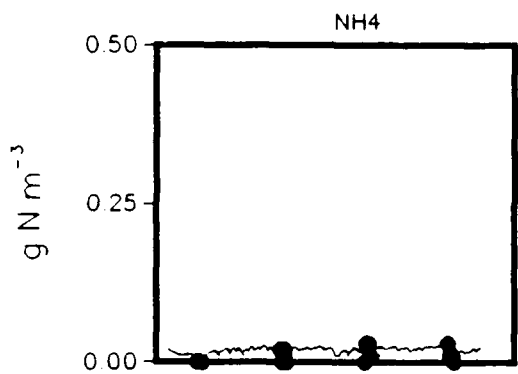
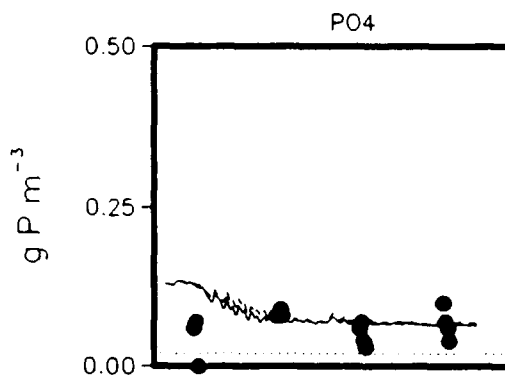
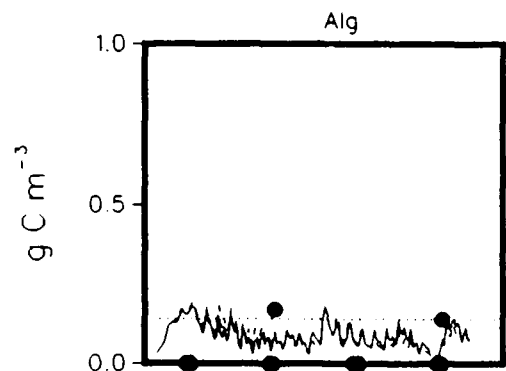


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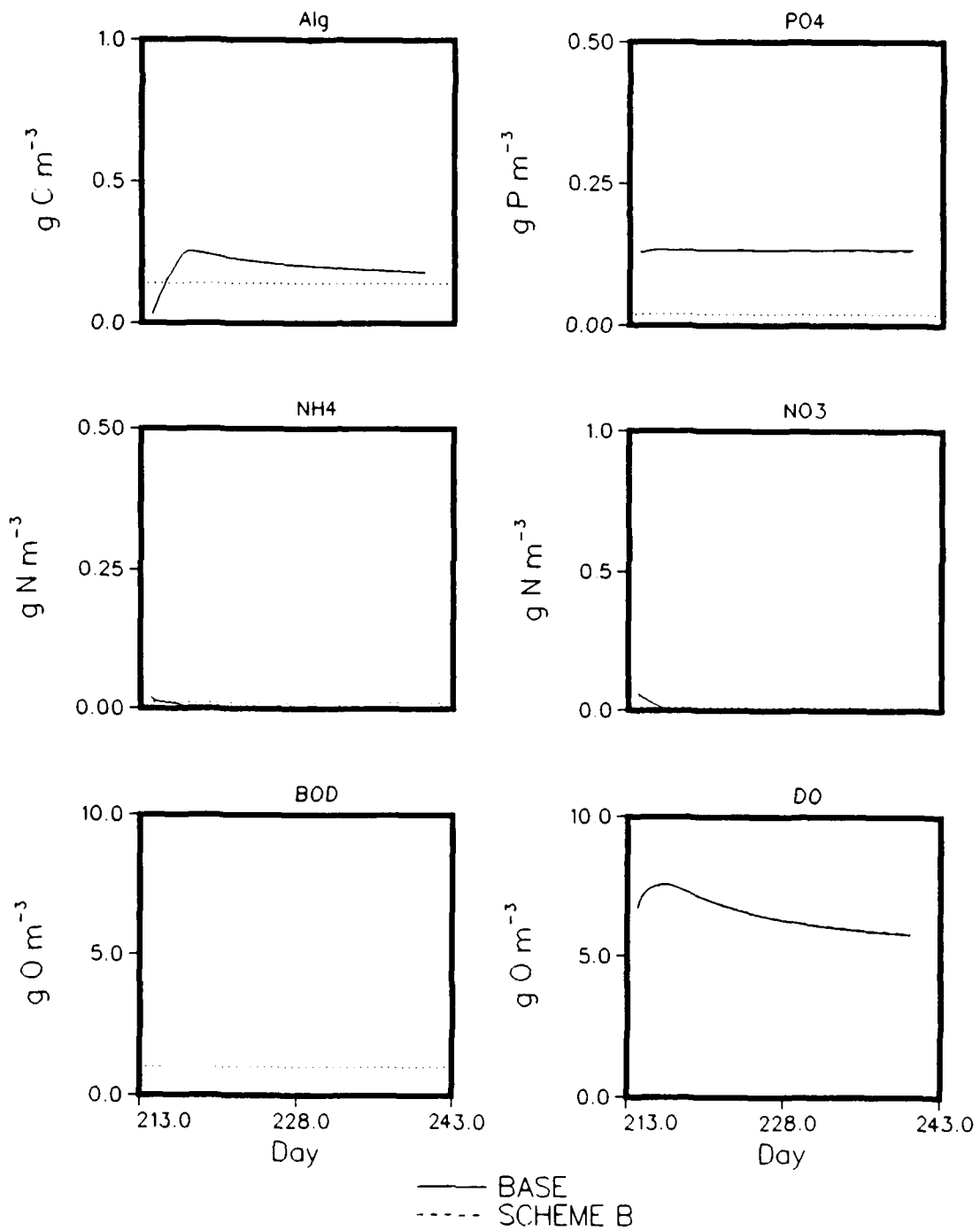


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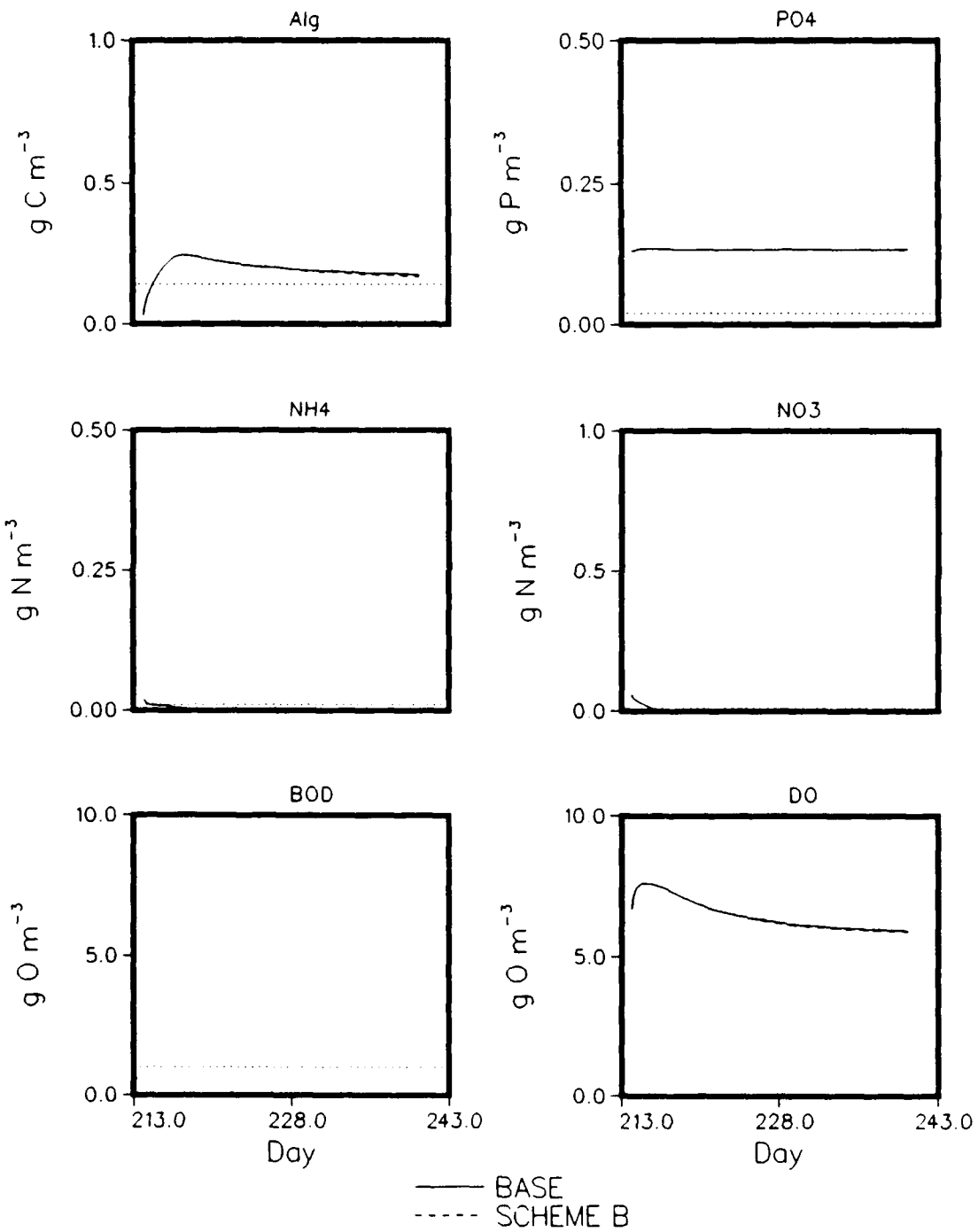


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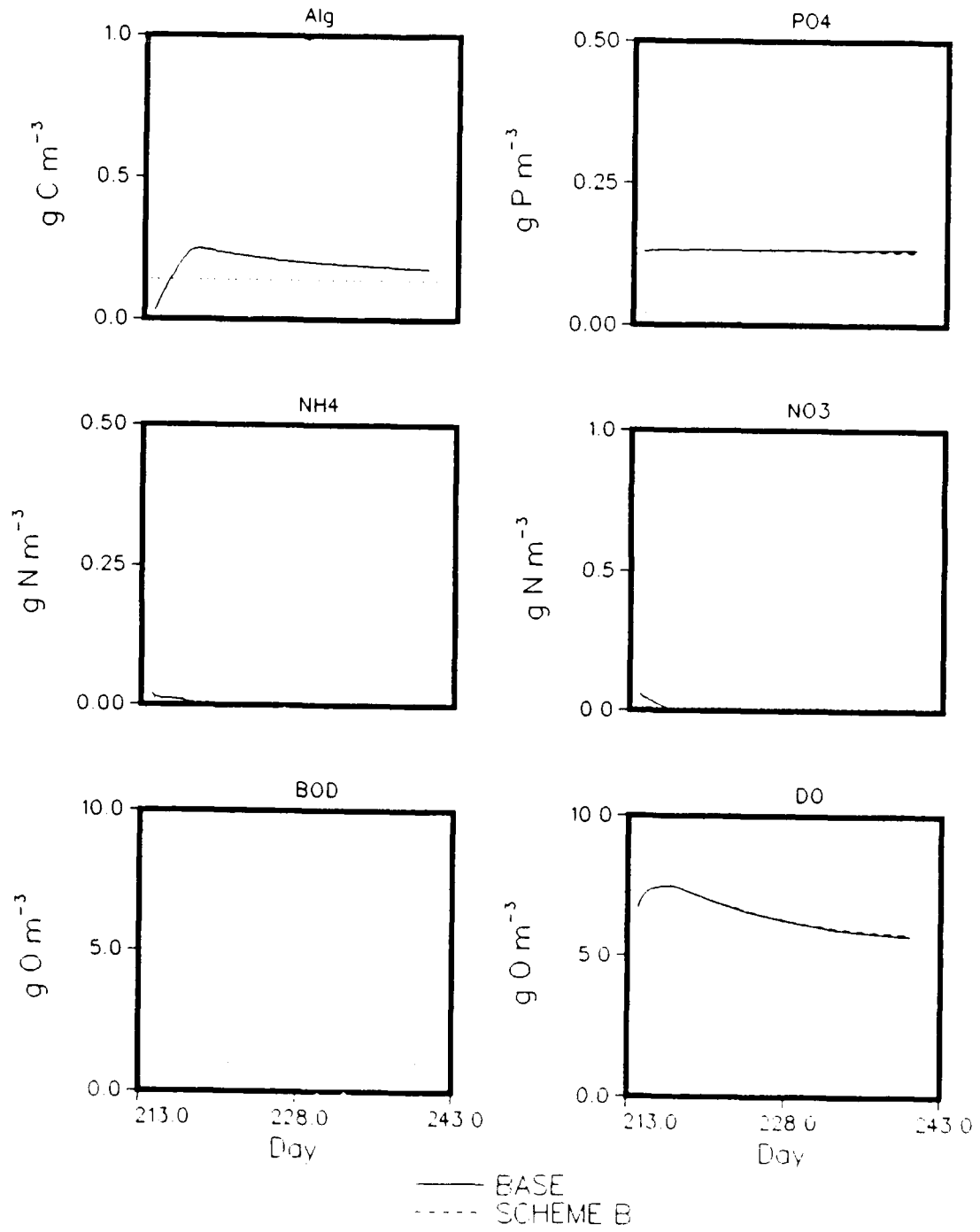
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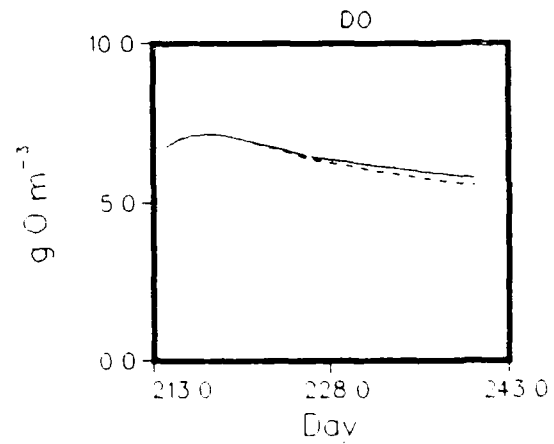
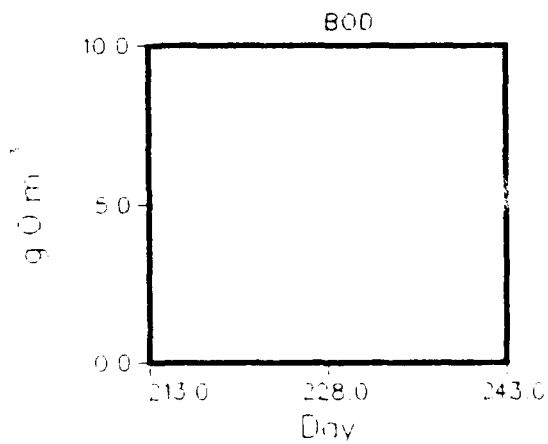
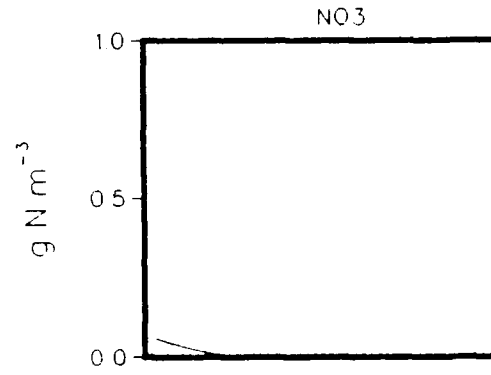
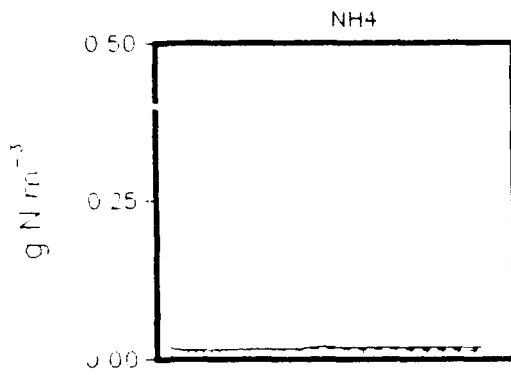
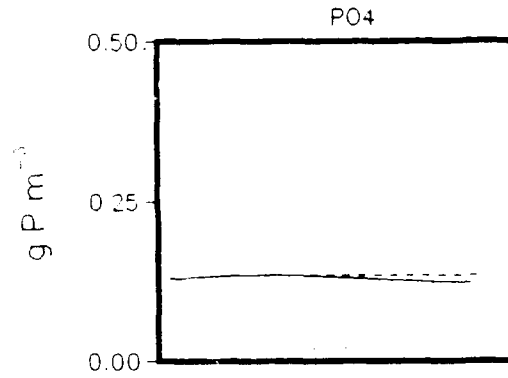
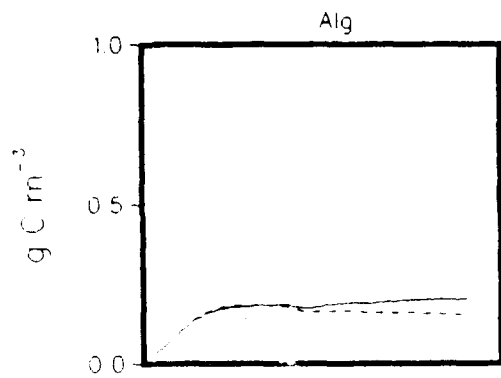
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WQ Station X- 3
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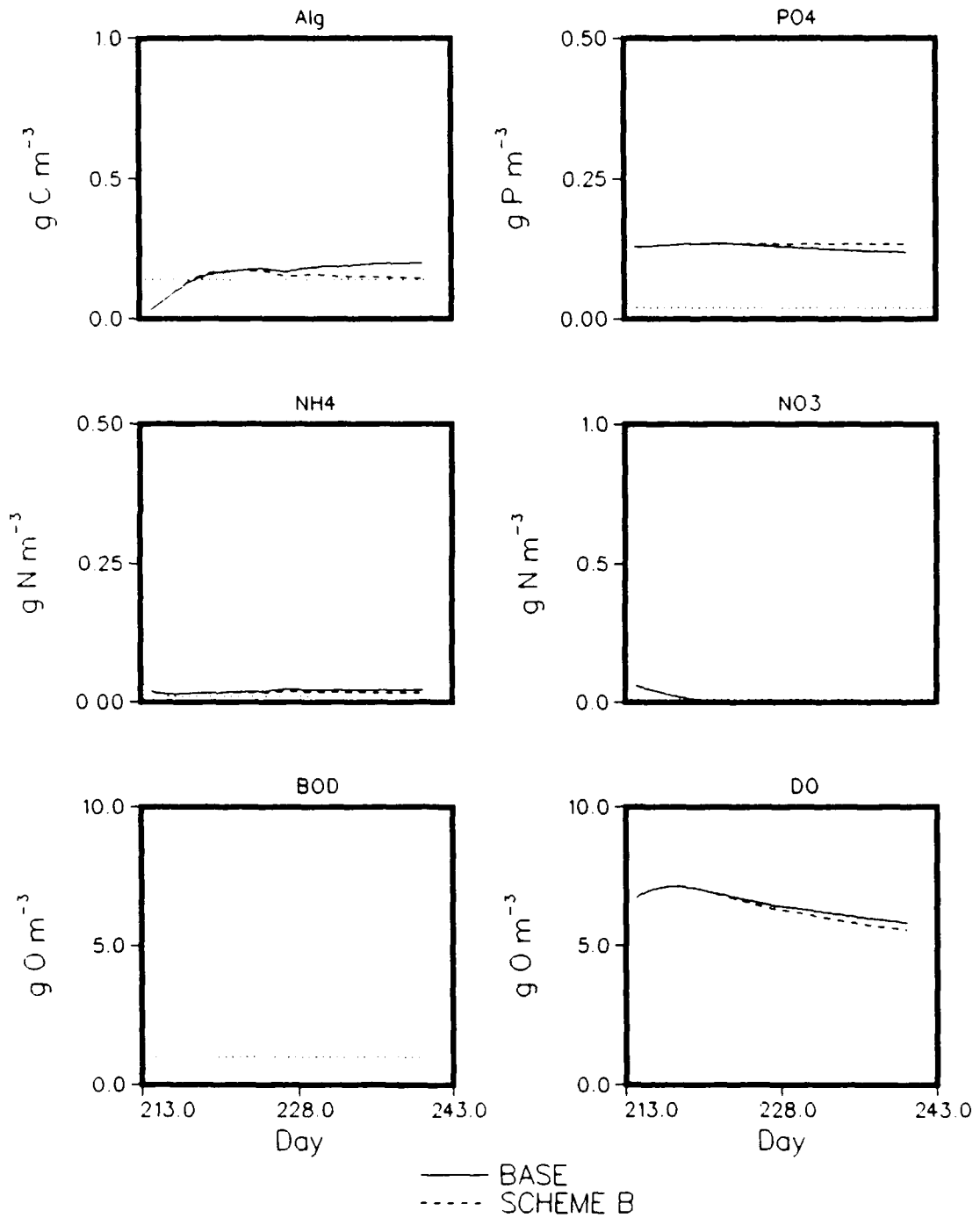


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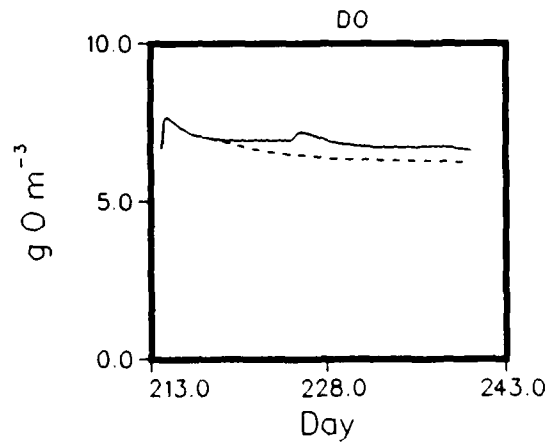
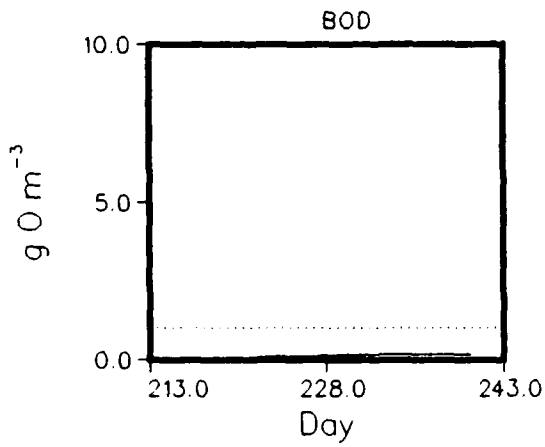
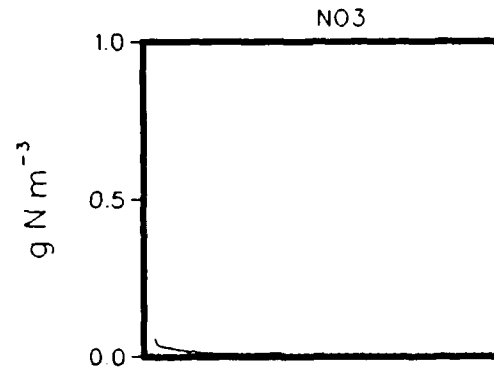
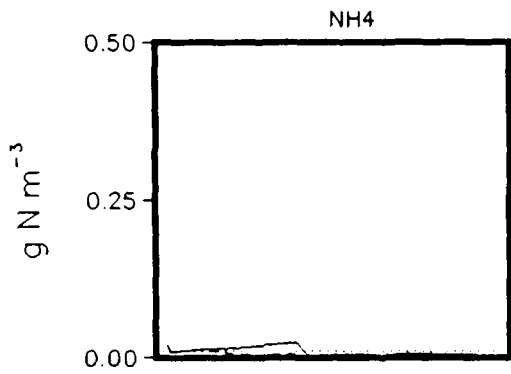
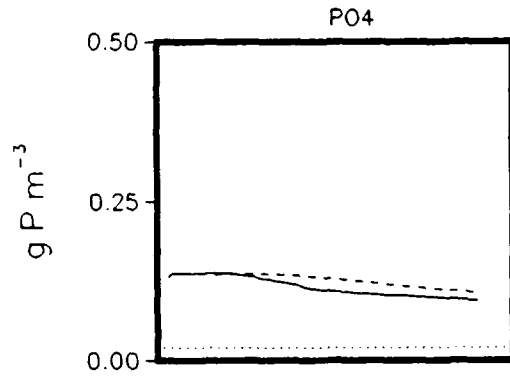
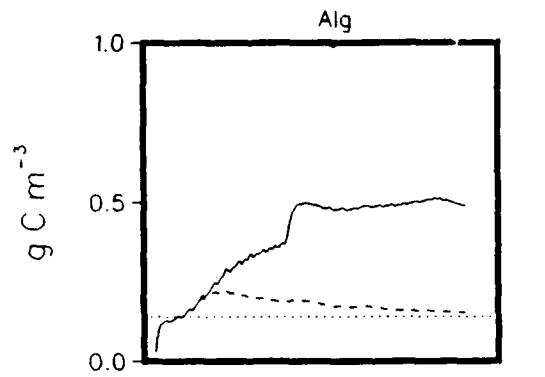


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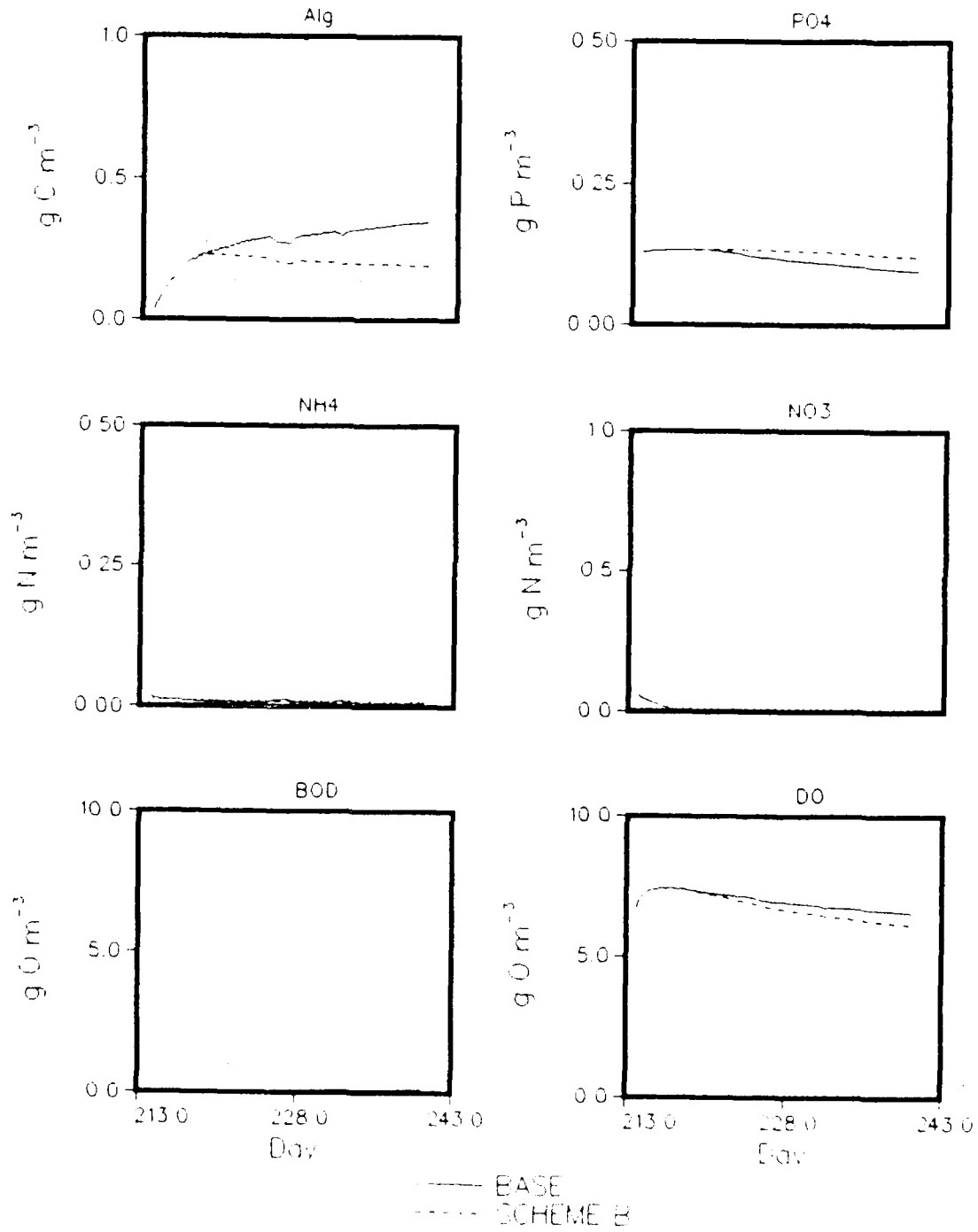


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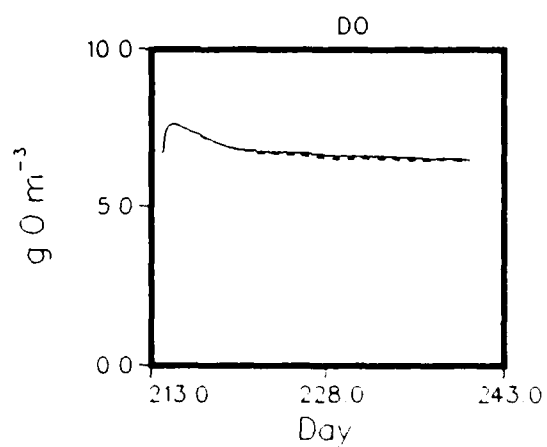
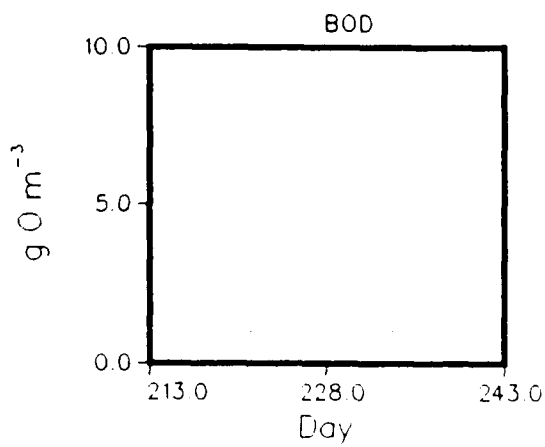
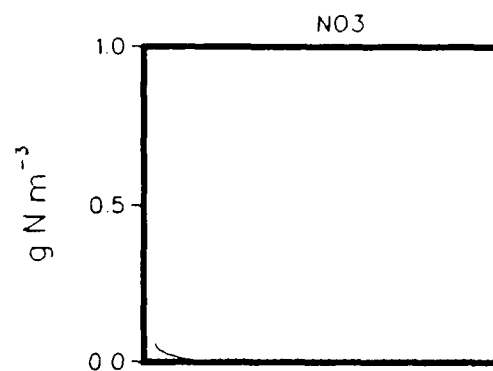
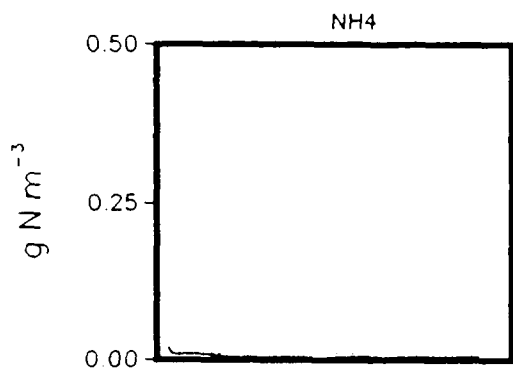
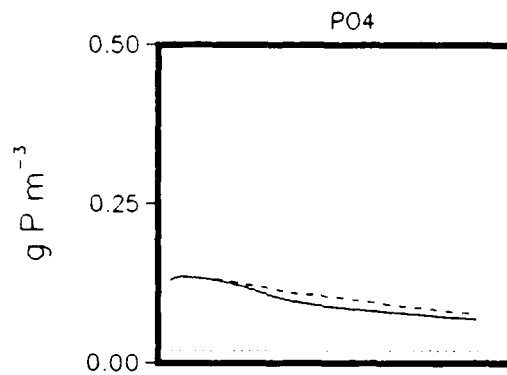
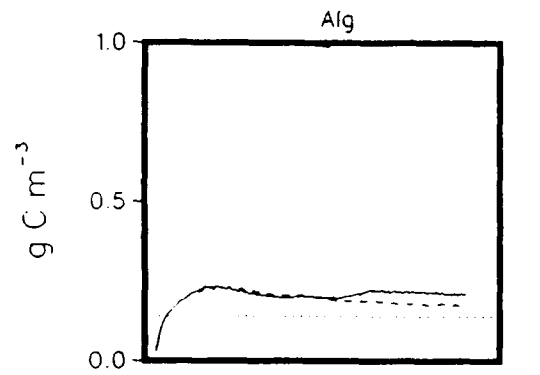


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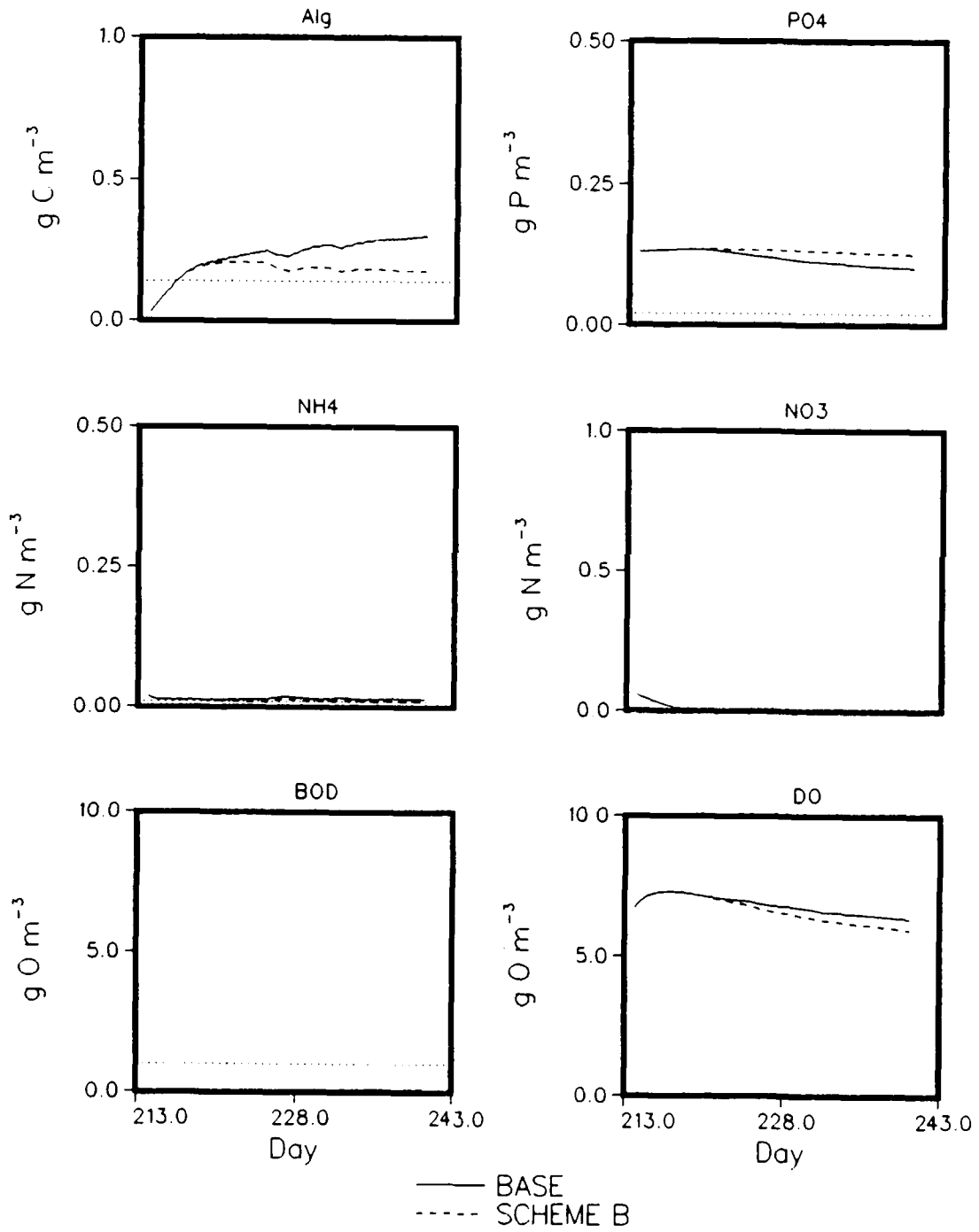


WQ Station X- 8
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WQ Station X-9
Bottom



Appendix A: Kinetic Routines

1. Ten state variables are included in the Los Angeles and Long Beach Harbors eutrophication model:

- a. Temperature.
- b. Salinity.
- c. Tracer.
- d. Suspended solids.
- e. Phytoplankton.
- f. Dissolved inorganic phosphorus ($\text{PO}_4\text{-P}$).
- g. Ammonia ($\text{NH}_4\text{-N}$).
- h. Nitrate + nitrite ($\text{NO}_3\text{-N} + \text{NO}_2\text{-N}$).
- i. Five-day carbonaceous biochemical demand.
- j. Dissolved oxygen.

2. The water quality studies simulated a tracer phytoplankton, dissolved inorganic phosphorus, ammonia, nitrate + nitrite, 5-day carbonaceous biochemical oxygen demand, and dissolved oxygen. Temperature and salinity were held constant. Suspended solids was not modeled.

3. The following description includes only the source/sink terms. The advection and diffusion terms are omitted in the state variable equations.

Temperature

4. Temperature kinetics are formulated as surface heat exchange coupled with absorption of solar shortwave radiation (Environmental and Hydraulics Laboratories 1986*). The heat exchanged in the surface layer is equal to the contribution due to the surface heat exchange minus the solar radiation (S) that passes through the surface layer. A fraction (β) of the solar radiation that arrives at the water surface is absorbed in the top approximately 0.6 m. The remaining shortwave radiation decays exponentially with depth according to Beer's Law. These processes are expressed

$$\frac{\partial TV}{\partial t} = \begin{cases} A \left[K(E - T) - (1 - \beta) \frac{S}{\rho C} \exp(-\gamma h) \right] & \text{Surface segment} \\ A \left\{ (1 - \beta) \frac{S}{\rho C} \exp(-\gamma d) [1 - \exp(-\gamma h)] \right\} & \text{Otherwise} \end{cases} \quad (A1)$$

* See References at the end of the main text.

where

- T = water temperature, °C
V = segment volume, m³
t = time, sec
A = surface area, m²
K = coefficient of surface heat exchange, m/sec
E = equilibrium temperature, °C
β = fraction of S absorbed at the surface
S = solar shortwave radiation, W/m²
ρ = water density, 1,000 kg/m³
C = heat capacity, 4,186 J/(kg °C)
γ = attenuation coefficient, 1/m
h = segment height, m
d = depth of segment surface, m

Salinity

5. Salinity is a conservative material and has no internal sources and sinks. Therefore,

$$\frac{\partial \Psi V}{\partial t} = 0 \quad (\text{A2})$$

where Ψ is salinity, in parts per thousand.

Tracer

6. Tracer is coded as a conservative material similar to salinity (Equation A2).

Suspended solids

7. Suspended solids is coded as a conservative material similar to salinity (Equation A2).

Phytoplankton

8. One system is used to represent phytoplankton assemblages. The aggregation forces a gross representation of phytoplankton dynamics and increased reliance on site-specific characteristics for system parameterization and interpretation. However, the inclusion of phytoplankton does allow simulation of the interactive dynamics of nutrients, phytoplankton, and dissolved oxygen. The rate equation for phytoplankton is expressed

$$\frac{\partial \phi V}{\partial t} = V \left[\left(K_g - K_r - K_e - K_m + \frac{K_s}{h} \right) \right] \phi \quad (A3)$$

where

- ϕ = phytoplankton concentration, g carbon/m³
- K_g = phytoplankton growth rate, 1/sec
- K_r = phytoplankton respiration rate, 1/sec
- K_e = phytoplankton excretion rate, 1/sec
- K_m = phytoplankton mortality rate, 1/sec
- K_s = phytoplankton settling rate, m/sec

9. The phytoplankton growth rate, K_g , is computed by modifying an optimum growth rate, G_{20} , at 20° C by the environmental factors temperature, light, and available nutrients. The relationship is given by

$$K_g = G_{20} \Theta_{\phi}^{T-20} \min (\Lambda_L, \Lambda_N, \Lambda_P) \quad (A4)$$

where

- G_{20} = phytoplankton maximum growth rate at 20° C, 1/sec
- Θ_{ϕ} = temperature coefficient for phytoplankton growth
- Λ_L = light limitation multiplier
- Λ_N = nitrogen limitation multiplier
- Λ_P = phosphorus limitation multiplier

10. The rate multiplier for light limitation is based upon the Steele (1962) function where

$$L = \frac{I}{I_s} \exp \left(-\frac{I}{I_s} + 1 \right) \quad (A5)$$

where

- L = limiting factor
- I = available light, W/m²
- I_s = saturating light intensity, W/m²

11. The above expression allows for simulation of photoinhibition at light intensities greater than the saturating value. Light penetration decreases with depth:

$$I = (1 - \beta)S \exp(-\gamma d) \quad (A6)$$

12. The average effect of light on phytoplankton growth in a particular segment can be obtained by combining Equations A5 and A6 and integrating over the segment depth to obtain (Chapra and Reckhow 1983)

$$\Lambda_L = \frac{2.72f}{\gamma h} [\exp(-\alpha_2) - \exp(-\alpha_1)] \quad (A7)$$

where

f = fractional daylength ($0 \leq f \leq 1$)

$$\alpha_1 = \frac{(1 - \beta)S}{I_s} \exp(-\gamma d)$$

$$\alpha_2 = \frac{(1 - \beta)S}{I_s} \exp[-\gamma(d + h)]$$

13. The rate multiplier for nitrogen and phosphorus limitation is computed using the Monod relationship. The Monod relationships for nitrogen and phosphorus are written

$$\Lambda_N = \frac{N}{H_n + N} \quad (A8)$$

$$\Lambda_P = \frac{P}{H_p + P} \quad (A9)$$

where

N = $(NO_2-N + NO_3-N) + NH_4-N$, g/m^3

H_n = nitrogen half-saturation constant, g/m^3

P = phosphorus concentration, g/m^3

H_p = phosphorus half-saturation constant, g/m^3

14. Phytoplankton respiration, K_r , is written

$$K_r = R_{20} \theta_r^{T-20} \quad (A10)$$

where

R_{20} = phytoplankton respiration rate at 20° C, 1/sec

θ_r = temperature coefficient for phytoplankton respiration

15. Phytoplankton excretion, K_e , is evaluated using an inverse relation to the light multiplier:

$$K_e = (1 - \Lambda_L)A_e \quad (A11)$$

where A_e is the maximum excretion rate, 1/sec. Phytoplankton mortality is assumed constant.

16. Phytoplankton that settle from a segment serve as a source for the segment below. Phytoplankton that settle from a bottom segment are accumulated in a sediment compartment. At present, however, no sediment mechanism for degradation with nutrient release is planned.

Dissolved inorganic phosphorus

17. Phosphorus is assumed to be in a completely available form as orthophosphate (PO_4) for uptake by phytoplankton. The sources of phosphorus are phytoplankton respiration and CBOD mineralization; the phosphorus sink is phytoplankton growth. The rate equation for phosphorus is given by

$$\frac{\partial PV}{\partial t} = V \left[(K_r - K_g) \delta_{PC} \phi + K_{v20} \theta_v^{T-20} \left(\frac{O}{H_v + O} \right) T \frac{\delta_{B5} \delta_{PC}}{\delta_{OC}} \right] \quad (A12)$$

where

δ_{PC} = ratio of phosphorus to carbon

K_{v20} = CBOD decay rate at 20° C, 1/sec

θ_v = temperature coefficient for CBOD decay

O = dissolved oxygen concentration, g/m^3

H_v = O_2 half-saturation constant for CBOD decay, g/m^3

T = carbonaceous biochemical demand, $g O_2/m^3$

δ_{B5} = ratio of ultimate CBOD to $CBOD_5$

δ_{OC} = ratio of oxygen to carbon

Ammonia

18. The sources of ammonium nitrogen are phytoplankton respiration and CBOD mineralization. The sinks of ammonium nitrogen include phytoplankton uptake and nitrification. The rate relations are expressed

$$\frac{\partial \Xi V}{\partial t} = V \left[(K_r - \Omega K_g) \delta_{NC} \Phi + K_{v20} \theta_v^{T-20} \left(\frac{O}{H_v + O} \right)^T \frac{\delta_{B5} \delta_{NC}}{\delta_{OC}} - K_{\xi 20} \theta_{\xi}^{T-20} \left(\frac{O}{H_{\xi} + O} \right) \Xi \right] \quad (A13)$$

where

Ξ = ammonium nitrogen concentration, g/m³

Ω = ammonia preference

$$= \frac{\Xi \Pi}{(H_n + \Xi)(H_n + \Pi)} + \frac{\Xi + H_n}{(\Xi + \Pi)(H_n + \Pi)}$$

Π = nitrate nitrogen concentration, g/m³

δ_{NC} = ratio of nitrogen to carbon

$K_{\xi 20}$ = nitrification rate at 20° C, 1/sec

θ_{ξ} = temperature coefficient for nitrification

H_{ξ} = O₂ half-saturation constant for nitrification

Nitrate

19. The system represents nitrite plus nitrate nitrogen. The source of nitrate is nitrification, while the sink is phytoplankton uptake. The rate equation is written

$$\frac{\partial \Pi V}{\partial t} = V \left[K_{\xi 20} \theta_{\xi}^{T-20} \left(\frac{O}{H_{\xi} + O} \right) \Xi - (1 - \Omega) \delta_{NC} K_g \Phi \right] \quad (A14)$$

CBOD5

20. The oxidation of carbonaceous material is the classical BOD reaction. The model simulates the 5-day CBOD as the indicator of equivalent oxygen demand for carbonaceous material (HydroQual, Inc. 1987). Although the model simulates 5-day CBOD, it is the ultimate CBOD which affects the dissolved oxygen system and scales nutrient regeneration from the carbonaceous component. Sources of CBOD5 are phytoplankton excretion and mortality; the sink is oxidation. The rate equation is written

$$\frac{\partial TV}{\partial t} = V \left[\frac{(K_e + K_m) \delta_{OC}}{\delta_{B5}} \Phi - K_{v20} \theta_v^{T-20} \left(\frac{O}{H_v + O} \right)^T \right] \quad (A15)$$

Dissolved oxygen

21. Sources of dissolved oxygen include surface reaeration and phytoplankton growth. Dissolved oxygen sinks are algal respiration, nitrification, oxidation of CBOD, and sediment oxygen demand.

22: A distinction is made between phytoplankton growth using CO_2 and NH_3 and phytoplankton growth using CO_2 and NO_3 (HydroQual, Inc. 1987). The rate equation is written

$$\frac{\partial \text{OV}}{\partial \tau} = v \left\{ \left[\frac{32}{12} \Omega K_g + \left(\frac{8}{3} + \frac{16\delta_{\text{NC}}}{35} \right) (1 - \Omega) K_g - K_r \delta_{\text{OC}} \right] \phi \right. \\ \left. - \frac{64}{14} K_{\xi} 20^{\theta_{\xi}^{\text{T}-20}} \left(\frac{O}{H_{\xi} + O} \right) \Xi - K_v 20^{\theta_v^{\text{T}-20}} \left(\frac{O}{H_v + O} \right)^{\text{T}\delta_{\text{B5}}} \right\} \quad (\text{A16}) \\ + A \left[R(O_s - O) - \theta_{\sigma}^{\text{T}-20} \left(\frac{O}{H_{\sigma} + O} \right) \Sigma \right]$$

where

R = reaeration coefficient, m/sec

O_s = dissolved oxygen saturation, g/m^3

θ_{σ} = temperature coefficient for SOD

H_{σ} = O_2 half-saturation constant for SOD decay, g/m^3

Σ = sediment oxygen demand at 20°C