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Water Quality and Habitat Suitability Assessment: Sangamon River between Decatur and Petersburg

by Robert S. Larson, Thomas A. Butts, and Krishan P. Singh
Office of Surface Water Resources & Systems Analysis
and Office of River Water Quality

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Shundar Lin, Ph. D., P.E.
Illinois State Water Survey
Box 697, Water Quality Section
Peoria, IL 61652

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Illinois State Water Survey
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Champaign, IL 61820-7495

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INTRODUCTION

Support of viable riverine fisheries requires both suitable flow conditions and adequate water quality. One or both of these factors may limit the utility of a river for aquatic life.

The Sangamon River in central Illinois is a vital natural resource. In addition to aquatic life support, it provides drainage for agricultural and urban areas, as well as streamflow for recreation, wastewater assimilation, and public water supply. In order to optimize the use of the Sangamon River and to plan water allocations to meet these needs, the quality and quantity of water required to satisfy each need must be determined.

A tributary of the Illinois River, the Sangamon River has a drainage area of 5,419 square miles (mi^2) above its confluence with the Illinois River. The Sangamon has three main branches: the main stem above Riverton (1,443 mi^2 drainage area), the South Fork Sangamon (885 mi^2 drainage area), and Salt Creek (1,868 mi^2 drainage area). Due to physiographic differences in these three basins, the Sangamon River basin may be divided into three hydrologically homogeneous basins (Singh et al., 1986). These differences can be attributed to the history of glaciation in the area. The upper portion of Salt Creek and the main stem of the Sangamon River upstream of Decatur lie within a physiographic region known as the Bloomington Ridged Plain, which was created during the Wisconsinan glacial advance. The rest of the Sangampn River basin , (approximately 60 percent) lies within the Springfield Plain, which was created during the Illinoian glacial advance. Streams within the Bloomington Ridged Plain have higher baseflows than streams within the Springfield Plain, due tomore permeable soils, thicker drift layers, and more deeply entrenched streams. More detailed discussions of the geomorphology of the Sangamon River basin can be found in Leighton et al. (1948), Singh (1971), and Singh et al. (1986).

Objectives

The overall objective of this study was to evaluate the relationships between water quality, water quantity, stream channel characteristics, and aquatic habitat suitability in the Sangamon River from Lake Decatur to Petersburg. Phase 1 of this study involved the assessment of water quality in the study reach, with the key water quality indicator being dissolved oxygen (DO). The relationships between flow, channel characteristics, and aquatic habitats were investigated during phase 2.

The specific objectives of phase 1 were to:

- Determine diurnal variations in DO and associated water quality parameters.
- Compare variations in water quality conditions with respect to discharge at each of the selected sites, as well as from one site to the next.
- Determine primary productivity (algal photosynthesis/respiration) using dark and light chamber techniques.
- Determine sediment oxygen demand (SOD).
- Estimate the physical reaeration capacity of the river at each site.

The objectives of phase 2 were to:

- Collect field data on local depths and velocities in riffle-pool sequences at three different discharges at each of the three selected reaches.
- Develop joint probabilistic distributions of the depths and velocities for each study reach.
- Integrate these distributions into a basinwide flow model.
- Integrate the flow model into an existing fish habitat suitability model, and use the model to explore the influence of flow characteristics on the expected physical habitat of three fish species.
- Explore the interaction between water quantity ari water quality as they affect quality offish habitat.

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WATER QUALITY ASSESSMENT AND DISSOLVED OXYGEN AVAILABILITY

The availability of dissolved oxygen or DO in flowing streams is highly variable because of several factors. Seasonal and daily variations in DO have been observed. Seasonal variations are largely attributable to changes in temperature that affect DO saturation levels. The diurnal variations are primarily induced by algal productivity. The ability of a stream to absorb (or reabsorb) oxygen from the atmosphere is affected by flow factors such as depth and turbulence, and it is expressed as the reaeration coefficient. Factors that may represent significant sources of oxygen use or depletion are sediment oxygen demand (SOD) and biochemical oxygen demand (BOD), including carbonaceous BOD (CBOD) and nitrogenous BOD (NBOD). BOD may be the product of both naturally occurring oxygen use in the decomposition of organic material, and oxygen depletion in the stabilization of effluents discharged from wastewater treatment plants (WTPs). The significance of any of these factors depends on the specific stream conditions. One or all of these factors may be considered in the evaluation of oxygen use and availability.

The intent of this study was to provide an overview of the availability of DO as it relates to minimum concentration levels needed to support indigenous fish species. These minimum concentrations are specified in standards developed by the Illinois Environmental Protection Agency (State of Illinois, 1990). In particular, subpart B, section 302.206 of the standards states that:

> "Dissolved oxygen shall not be less than 6.0 mg/L during at least 16 hours of any 24-hour period, nor less than 5.0 mg/L at any time."

Local stream conditions immediately downstream of the Decatur Sanitary District WTP discharge were monitored in concert with two other locations farther downstream: one below the two Springfield Sanitary District treatment plant discharges and the other between Decatur and Springfield. *In situ* monitoring and sample collections were made during mid-August and early September of 1991 when DO levels are normally the lowest. The data generated from this study provided information on the diurnal fluctuations in DO, algal productivity, SOD, stream reaeration capacity, and general water quality for these locations along the Sangamon River.

Diurnal Water Quality/DO Monitoring

Three sites (or stations) were selected to represent conditions from different drainage areas along a reach of the Sangamon River extending from Decatur to Salisbury (figure 1). Field data collection and assimilation were performed by the Illinois State Water Survey's Office of River Water Quality. Locations of selected sites and their respective drainage areas are:

Site Locations and Drainage Areas

Site	*Location*	*Description*	*River mile*	*Drainage area (mi^2)*
WQ1	T16NR2ES19	Wyckles Rd. bridge, downstream of Decatur WTP	124.5	1036.4
WQ2	T15NR2WS8&9	Approximately 3 miles east of Roby	102.5	1244.0
WQ3	T17N R6W S27	Downstream of Salisbury	59.9	2909.0

Field Procedures

On August 16 (event 1 or run 1) and September 6, 1991 (event 2 or run 2), five Hydrolab DataSonde I model 2070-DS water quality monitoring units were deployed at each site for 72 hours to collect hourly data. The time periods included weekends extending from Friday to Monday. Startup times for stations WQ1, WQ2, and WQ3 during event 1 were noon, 10 a.m., and 2 p.m., respectively. Startup times for stations WQ1, WQ2, and WQ3 during event 2 were 11:00 a.m., 9 a.m., and 11 a.m., respectively. Hourly measurements were made for temperature (° C), pH, conductivity (millisemens per centimeter, ms/cm), DO (milligrams per liter, mg/L), and salinity (parts per thousand, ppt).

An ambient monitor, a light chamber monitor, and a dark chamber monitor were placed in the deepest portion of the river at each site. The dark chambers consist of 40-inch lengths of white PVC pipe and the light chambers consist of 35-inch lengths of 6 1/2-inch diameter clear plastic tubing. The top and bottom of each light chamber were sealed with clear Plexiglas plates bolted to flanges glued to the tubing. A clear plastic gasket was secured between the plate and the flange for sealing purposes. The net water volumes of the light and dark chambers with the DataSondes in place were 13.830 and 12.875 L, respectively. The ambient monitors were protected inside 36-inch long, open-ended lengths of 6-inch diameter PVC pipe.

The light and dark chambers and ambient housing, designed to be suspended in the water, were laid flat (because of the shallowness of the sampling locations) with the axis of each cylinder in line with the streamflow. The chambers were filled in a prone position, and care was exercised not to disturb bottom sediments upstream of the fill openings. The caps and plates were installed to minimize air entrapment. The chambers and ambient housing were secured in the stream by a cable anchored on both banks.

In addition to the three "on-site" monitors, two "remote" monitors were placed somewhat upstream or downstream of each site to determine SOD rates and "remote" ambient DO concentrations. The remote units were placed 225 feet and 5150 feet upstream of stations WQ1 and WQ2, respectively; whereas, placement was 1025 feet downstream at station WQ3. The remote monitors were secured to steel posts driven into the streambed. The SOD monitor was placed in a respiration chamber consisting of a 6-inch white PVC pipe driven into the benthic sediments and sealed with a watertight screw-cap below the water line. The remote ambient DO monitors were shrouded and placed in a prone position just as the ambient units at the "on-site" locations.

Attendant to the installation of the DataSondes, water samples were collected for physical, chemical, and biological analyses in the laboratory. Water samples were collected for analyses of turbidity, suspended solids, total dissolved phosphorus ($P0_4$-P), ammonia (NH3-N), nitrites ($N0_2$-N), nitrates ($N0_3$-N), 20-day carbonaceous BOD ($CBOD_{20}$), 20-day nitrogenous BOD ($NBOD_{20}$), and algae populations.

Remote ambient DO readings were generated for use in calculating reaeration coefficients (K_2). The use of remote ambient DO data in the K_2-calculations is a modification and improvement in the basic procedure developed and used for calculating K_2 at three sites along the upper Sangamon River (Broeren et al., 1991).

Flows were measured at each site on August 6, 1991 during monitor placement (event 1) and on September 9, 1991 at each site during monitor removal (event 2). Personnel from the Office of Surface Water Resources and Systems Analysis performed these measurements.

Data Reduction and Analyses

Because the DataSonde DO probe is less responsive at low stream velocities, correction factors (DO flow factors) were applied to meet hydraulic conditions as recommended by the manufacturer. The correction factors used for high (>1.0 feet per second or fps), medium, and low flows were 1.000, 1.042, and 1.087, respectively. All the chamber unit DO outputs and the ambient outputs for sites WQ1 and WQ3 for both events were analyzed using the low-flow factor of 1.087, whereas, the medium flow factor of 1.042 was used at site WQ2 for both events. Additionally, the DO outputs were corrected relative to calibration values developed for each DataSonde unit under controlled laboratory conditions. For example, under controlled conditions the unit used for the ambient output at site WQ3 during event 1 produced DO values averaging only 96.9 percent of those measured using the Winkler titration method (APHA, 1985). The combined flow/calibration correction factors used are summarized as follows:

Calibration Factors

Site	*Event*	*Ambient monitor*	*Light chamber*	*Dark chamber*	*SOD*	*Remote Ambient*
1	1	0.918	1.108	1.029	1.000	1.076
	2	0.918	1.108	1.029	1.000	0.988
2	1&2	0.996	1.116	1.084	0.981	1.035
3	1&2	0.969	1.017	1.007	1.007	0.964

The DataSonde units must be programmed for one of three specific ranges of conductivity: 0-1.5, 1.5-15, or 15-150 ms/cm. The lowest range is routinely used when the units are deployed in surface waters in the northern half of the state, so this range was used for the study since unusually high conductivity values were not suspected to occur in this reach of the Sangamon River. However, when downloading the data for sites WQ1 and WQ2 (event 1), it was discovered that the conductivities did indeed exceed 1.5 ms/cm at times. To salvage some of the missing conductivity values, a regression equation was developed relating conductivity to salinity using 202 datasets for which both conductivity and salinity were available. The resultant conversion equation is:

$$C = 0.94+1.763S \quad (1)$$

where

C = conductivity, ms/cm

S = salinity, ppt

This equation was used to estimate conductivity values when $S > 0.30$ ppt.

Adjustments were made in the pH values generated by the light chamber DataSonde at site WQ2 during event 1. The light chamber DataSonde pH values were significantly higher than those for the ambient, dark, and remote ambient units. Since all parametric values should be equal at the beginning of the monitoring period, the initial pH readings were averaged and the average value was subtracted from the initial reading of the light chamber unit. This yielded a value of 0.29, which was subtracted from the remaining light chamber unit pH values.

Twelve hours of data were lost during event 1 for the ambient unit at site WQ1, the light chamber unit at site WQ2, and the dark chamber unit at site WQ3 because the time clocks were set incorrectly.

The raw (and uncorrected) hourly parametric values are not incorporated in this report. However, this information is available *in toto* or in statistically summarized form on floppy disk via the format presented in Broeren et al. (1991).

Reaeration Coefficient Analysis

Estimates of physical reaeration and the associated effects of algal photosynthetic oxygen production (primary productivity) were based on the schematic formulations:

Physical aeration = ambient DO - light chamber DO + SOD (2)

Algal productivity:

gross = light chamber - dark chamber (3 a)

net = light chamber at end - light chamber at beginning (3 b)

The physical reaeration computational procedure is based upon estimating inputs relative to basic reaeration theory succinctly expressed by the formulation:

$$\frac{dD}{dt} = -K_2 D \quad (4)$$

where dD is the absolute change in the dissolved oxygen deficit, D, over an increment of time dt due to an atmospheric exchange of oxygen at the air/water interface effected by the reaeration coefficient K_2. This formation is based upon the derivative to the logarithmic base *e*. Integrating equation 4 from time t_1 to t_2 gives

$$\log_e \frac{D_2}{D_1} = -K_2(t_2 - t_1)$$

$$= -K_2 \Delta t \quad (5)$$

$$\therefore K_2 = -\frac{\log_e \frac{D_2}{D_1}}{\Delta t}$$

Input approximations and computations using observed data are:

dD = Reaeration (REA), mg/L

Δt = reach time of travel (t_2 - t_1), days

D = DO deficit, mg/L

REA = $C_2 - C_1$ - POP - PAP + TBOD + SOD (6)

where

C_2 and C_1 = observed DO concentrations in mg/L at t_2 and t_1, respectively.

POP = net periphytonic (attached algae) oxygen production (mg/L) for the time period, t_2-t_1.

PAP = net planktonic algae (suspended algae) oxygen production (mg/L) for the time period, $t_2 - t_1$.

TBOD = total biochemical oxygen usage (mg/L) for the time period, $t_2 - t_1$.

SOD = net sediment oxygen demand (mg/L) for the time period, $t_2 - t_1$.

The clear periphytonic chamber was not employed if the periphytonic productivity/respiration was deemed insignificant, i.e., POP = 0. The combined effect of TBOD - PAP is represented by the gross output of the light chamber, and the SOD is equal to the gross SOD chamber output less the dark chamber output.

$$D = \frac{S_1 + S_2}{2} - \frac{C_{1+} C_2}{2} \tag{7}$$

where S_1 and S_2 are the DO saturation concentrations (mg/L) at t_1 and t_2, respectively, for the average water temperature (T) in the reach.

DO saturation concentrations for various water temperatures were computed using the American Society of Civil Engineers (1960) DO saturation formula:

$$S_T = 14.652 - 0.41022T + 0.007991T^2 + 0.000077774T^3 \tag{8}$$

where

S_T = DO saturation concentration, at sea level, mg/L

T = water temperature, ° C

This formula represents saturation levels for distilled water (the contaminant factor b = 1.0) at sea-level pressure. Water impurities can increase the saturation level ($b > 1.0$) or decrease the saturation level ($b < 1.0$), depending upon the surfactant characteristics of the contaminant. For this study, b was assumed to be unity. The sea-level concentrations produced by the formula must be corrected for differences in air pressure caused by air temperature changes and for elevations above sea level. The following formula was developed for use during this study:

$$f = \frac{2116.8 - [(0.08 - 0.000115s)(E)]}{2116.8} \tag{9}$$

where

f = correction factor above sea level

s = air temperature, ° C

E = site elevation, feet above mean sea level (ft-msl)

The elevations for the sampling sites were taken from U.S. Geological Survey (USGS) quadrangle maps. The elevations for sites WQ1, WQ2, and WQ3 were 580, 540, and 520 ft msl, respectively.

Equation 4 shows that natural physical reaeration of water occurs at a rate proportional to the DO saturation deficit, i.e., water nearly devoid of DO will add oxygen at a much faster rate than will water that is nearly saturated with DO. Similarly, water containing supersaturated DO concentrations, due to algal productivity, will lose DO at a rate proportional to the excess up to 200 percent of saturation. This means that water containing 200 percent of saturation will lose DO at the same rate that oxygen is gained when the water is totally devoid of DO (0 percent saturation). Butts and Evans (1978a) have shown that any supersaturation above 200 percent is immediately lost upon disturbance. Consequently, water saturated at 250 percent will be immediately reduced to 200 percent when any physical disturbance is encountered.

The periphytonic oxygen production (POP in equation 6) was not measured during this study. Consequently, reaeration (REA) was computed using the gross outputs of the light chamber and SOD chamber. The upstream or downstream remote ambient DO values were matched with ambient site values on a lag-time basis by using the computed time of travel between the two sites for the matchup.

Empirical K_2 Formulations

A relatively large number of empirical and semi-empirical algorithms and equations have been developed to estimate the reaeration coefficient (K_2). Three equations that are widely known and employed in stream work are:

$$K_2 = \frac{7.63V}{H^{1.33}} \quad \text{Langbein and Durum (1967)} \tag{10}$$

$$K_2 = \frac{11.57V^{0.969}}{H^{1.673}} \quad \text{Churchill et al. (1962)} \tag{11}$$

$$K_2 = \frac{13.0V^{0.5}}{H^{1.5}} \quad \text{O'Conner and Dobbins (1958)} \tag{12}$$

where

K_2 = reaeration coefficient, day^1

V = average velocity, fps

H = average depth, feet

Biological Factors

Algae were enumerated and identified in the laboratory, and the data were used in assessing the- extent that primary productivity (algae activity) affected the DO resources of the river at the time of the field work. A biologic diversity index, which provides a means of evaluating the richness of species within a biological community using a mathematical computation, was computed for each site and monitoring event. A community consisting solely of one species has no diversity or richness and takes on a value of unity. As the number of species increases and as long as each species is relatively equal in number, the diversity index increases numerically. A diversity index would approach infinity when a large number of individual organisms are present, each belonging to a different species.

The Shannon-Weiner diversity index formula, as given by Smith (1980), was used to evaluate algal conditions. The formula is:

$$S = 3.322\left(\log N - \left(\sum_{i=1}^{k} n_i \times \log n_i\right) / N\right) \qquad (13)$$

where

S = Shannon-Weiner diversity index

N = total number of all organisms

n_i = number of organisms for a given species

$i = 1, 2, \ldots k$ where k is the number of species

Both algae productivity/respiration (P/R) and SOD are biologically associated factors that are normally expressed in terms of grams per square meter per day ($g/m^2/day$). Conversion of these areal rates to mg/L for use in computing the physical reaeration (REA) using equation 6 was accomplished using the following expression:

$$G' = \frac{3.28G \times t}{H} \qquad (14)$$

where

G' = DO usage per reach, mg/L

G = SOD or P/R rates, $g/m^2/day$

t = time of travel through the reach ($t_1 - t_2$), days

H = average depth, feet

Biochemical Oxygen Demand (BOD) Data

Generally, the long-term BOD or DO usage in a stream is modeled as a first-order exponential reaction, i.e., the rate of biological oxidation of organic matter is directly proportional to the remaining concentration of unoxidized material. The integrated mathematical expression representing this reaction is:

$$L = L_a \left[1 - e^{-K_1 t}\right] \quad (15)$$

where

L = oxygen demand exerted up to time t

L_a = ultimate oxygen demand

K_1 = reaction rate per day

t = incubation time, days

e = base of natural logarithm, 2.7183

When a delay occurs in oxygen uptake at the onset of a BOD test, a lag time factor, t_0 is included and the equation becomes:

$$L = L_a \left[1 - e^{-K_1 (t - t_o)}\right] \quad (16)$$

However at times, neither equation 15 nor 16 provides a good model for observed BOD progression curves generated for samples collected in some streams and wastewaters. The BOD often consists primarily of high-profile second-stage or nitrogenous BOD (NBOD), and the onset of the exertion of this NBOD is often delayed by one or two days. The delayed NBOD curve and the total BOD (TBOD) curve, dominated by the NBOD fraction, often exhibit an S-shaped configuration. The general mathematical model used to simulate the S-shaped curve is:

$$L = L_a \left[1 - e^{-K_1 (t - t_o)^x}\right] \quad (17)$$

where x is a power factor.

Butts et al. (1975) used statistical procedures to show that a power factor of 2.0 in equation 17 best represents S-shaped BOD curves generated for the ammonia-laden waters of the upper reaches of the Illinois waterway. Substituting x = 2 in equation 17 yields:

$$L = L_a \left[1 - e^{-K_1 (t - t_o)^2}\right] \quad (18)$$

Three types of BOD curves were developed for this study: total (TBOD), carbonaceous (CBOD), and nitrogenous (TBOD). TBOD (uninhibited) and CBOD (inhibited) were measured directly, while NBOD was computed by subtracting CBOD values from TBOD values for given time elements.

All the **BOD** curves generated during this study were fitted to equations 15, 16, and 18. The observed data were fitted to these equations using a statistical process known as the method of steepest descent (or slope). This interactive process can best be applied using computer techniques. Use of these computer solutions can provide accurate estimates of L_a, K_1, and t_0.

Results and Discussion

A summary of all the parameters for which field or laboratory data were collected or generated is presented in table 1 and SOD in table 7. Plots of the DataSonde-generated data are presented according to parameter, site, and event. DO is given in figures 2 and 3; pH, figures 4 and 5; temperature, figures 6 and 7; conductivity, figures 8 and 9; salinity, figures 10 and 11; SOD, figures 12 and 13; and BOD, figures 14 and 15.

The instantaneous flow data presented in table 1 indicate that the discharges at each site were similar for both events. However, cursory examination of antecedent flow values indicate that the overall hydrologic/hydraulic conditions were somewhat dissimilar throughout the study area as shown by the flow and precipitation values presented in table 2. This difference is best exemplified by the USGS Riverton gage data. During event 1, the Riverton discharge hydrograph exhibited a steady decline prior to the placement of the monitors on August 16, which persisted throughout the monitoring period ending on August 19. However, prior to event 2, a large storm (1.92 inches of rain in the Springfield area (table 2) on September 3) produced steady daily increases in flow. The flow peaked the day prior to placement of the monitors on September 6. A steady decline in flow set in and persisted until monitor removal on September 9. The effects of the differences in the dynamics of the hydrologic/hydraulic conditions prior to and during each event produced some significant differences in water quality between both events. These differences will be discussed on a selective basis.

Grab Sampling

The higher turbidity and suspended solids values (table 1) that occurred at sites WQ1 and WQ3 during event 2 probably resulted from the significant antecedent rainfall and subsequent runoff during this period of the study. Turbidity at site WQ3 during event 2 was more than twice that observed for event 1; suspended solids for event 2 were 60 percent greater than that for event 1. During the upper Sangamon River study (Broeren et al., 1991) high flows preceded one of the events, and the turbidities and suspended solids ranged from 17-46 nephelometric turbidity unit (NTU) and 22 - 66 mg/L, respectively. Both of these ranges are significantly smaller than those for similar conditions occurring during this study.

Nutrient (phosphorus and nitrogen) concentrations are very high (table 1). These elevated levels are caused by nonpoint runoff and tile drainage from the intensely farmed watershed and from point discharges; namely, the Decatur WTP and the two Springfield WTPs (table 2). The phosphate level at site WQ1, 2.6 miles downstream of the Decatur outfall, as measured on August 16, was more than ten times the maximum value measured at any site on any date during the upper Sangamon River study. The nitrate ($N0_3$-N) level at this site was 62% greater. Note from table 1, that during the "drier" antecedent conditions of event 1, the phosphorus and nitrate concentrations generally decrease downstream, indicating a diluting effect as flows naturally increase downstream. However, during the "wetter" antecedent conditions during event 2, the nitrate concentrations remained elevated at about the same level throughout the study area, and the September 6 value of 7.56 mg/L was significantly higher than the August 16 value of 5.09 mg/L. This indicates that rainfall in the area creates runoff with high nitrogen levels.

The data for phosphorus, albeit limited, indicate that runoff does not raise total $P0_4$-P levels in the Sangamon in the same manner or magnitude as it does nitrates. Similarly, the ammonia-N concentrations decreased downstream under both "wet" and "dry" antecedent conditions. The majority of the small amount of ammonia, which does occur in the river, originates in the Decatur and Springfield treated wastewaters. Stoichiometrically, the biochemical oxidation of 1.0 mg/L of NH_3-N produces 4.54 mg/L of $N0_3$-N. Consequently, the complete stabilization of the 0.58 mg/L of NH_3-N observed at site WQ1 on September 6 would create 2.6 mg/L of $N0_3$-N for uniform flow conditions before reaching site WQ3. Considering that the flow increased four-fold, dilution would reduce the $N0_3$-N concentration (attributable to ammonia oxidation) to 0.65 mg/L.

The BOD in its three forms, i.e., total (TBOD), carbonaceous (CBOD), and nitrogenous (NBOD), represents the dissolved oxygen required by microbes to stabilize dissolved organics and ammonia in water during their metabolic life processes. The five-day BOD test (BOD_5) is the test normally employed by WTPs to determine the efficiency of their biological treatment processes. Table 3 provides a comparison of study area event 1 data collected for the Sangamon with other streams and waterways in central and northern Illinois. The Kankakee River, a relatively clean unpolluted stream, exhibits the lowest BOD values while the Fox River, a stream recipient of much treated wastewater, exhibits the highest BOD values. The BOD values in this Sangamon River study reach fall between the extremes but appear somewhat higher than the other inclusive values.

The general water quality characteristics of the Sangamon River at sampling site WQ1 during warm-weather low-flow conditions closely mirror those of well-treated domestic wastewater (table 4). Note that during events 1 and 2 when the flow in the Sangamon upstream of the Decatur WTP outfall was less than 0.3 cfs (table 2), all the site 1 Sangamon River parametric values, except those for suspended solids, were similar to those of the WTP effluents (table 4).

The results of the samples collected on August 16 and September 6 for algae identification and enumeration are presented in table 5. The total cell counts were very low at all three sites during both events. The average counts of the six samples were only 157 cells/mL. This compares with a six-sample average of 496 cells/mL observed during the upper Sangamon study (Broeren et al., 1991). Even a count of 496 cells/mL is not particularly high. The existence of low algal densities observed in the study area are somewhat surprising since the inordinately high phosphorus and nitrogen levels are normally conducive to prolific algal growths of bloom proportions (counts in excess of 500 cells/mL).

The overall net effects of algal production/respiration on the daily DO balance at the three monitoring sites are shown in figures 2 and 3. Photosynthetic oxygen production and attendant algal respiration have a cyclical effect on a diurnal basis. Sinuosity develops when excess oxygen is gradually produced during daylight hours and consumed via respiratory processes during the night or during dark, cloudy days. Note the well-defined, almost sinusoidal, serpentine nature of the ambient (AMB) and remote ambient (R-AMB) DO curves for site WQ2 — event 1 (figure 2b) and site WQ3 ~ event 1 (figure 2c). Less dramatic but still discernible are the sinuosities of the AMB and R-AMB curves for sites WQ2 and WQ3 during event 2. The DO curves for site WQ1 for both events are relatively flat, displaying little sinuosity. These results are somewhat puzzling since the algal counts at site WQ1 arc the highest observed at any of the three sites during event 1 and are the second highest during event 2. Furthermore, the fact that during event 1 sites WQ2 and WQ3 produced sinusoidal curves with such large amplitudes is also surprising since the algal densities are relatively low. It is not possible to suggest causes for these anomalies without further data collection. The peaks for sites WQ2 and WQ3 during event 2 are attenuated relative to the corresponding event 1 peaks. This was probably due, at least in part, to the increase in turbidity and suspended solids (table 1) resulting from rainfall and runoff and increasing flow rates antecedent to event 2.

Continuous Monitoring Data

Continuous hourly monitoring using the DataSonde units produces a wealth of information over short periods of time that permits some in-depth assessments of water quality conditions that normally would not be attainable using grab sampling and/or monitoring techniques even when employed long-term. Short interpretations and assessments will be given for individual parameters.

The DO curves, which were lacking a serpentine nature, were discussed above. Probably the most significant finding relative to the DO characteristics of the Sangamon River in the study area is that the minimum DO standard (5.0 mg/L) was violated at some time during the study at the AMB and R-AMB locations at all three monitoring sites (table 1, figures 2a, 2b, 3 a, and 3 c).

Furthermore, the AMB and R-AMB DO at site WQ1 during both events was less than 6.0 mg/L during the entire 72-hour monitoring periods. During event 1, the DO was actually less than 5.0 mg/L over the entire 72-hour period (figure 2a), while during event 2, DO at site WQ1 was less than 5.0 mg/L over the final 39 hours of monitoring (figure 3a). The "no less than 6.0 mg/L per 16-hour period" standard was also violated at site WQ3 during event 2: the DO was less than 6.0 mg/L between hours 11 and 27 (figure 3c). Also noteworthy is that the DO at site WQ2 during event 1 dropped almost 12 mg/L between hours 7 and 22 (figure 2b). Such low DO and large fluctuations over short periods of time is not conducive to a stable aquatic habitat.

The pH curves (figures 4 and 5) closely follow the shape or serpentine nature of the corresponding DO curves. This similarity is the result of algal activity associated with photosynthetic oxygen production and cellular respiration. During photosynthesis, carbon dioxide ($C0_2$), either as a free gas or in its half-bound state as a bicarbonate ($HC0_3$), is extracted from the water and used in conjunction with water to manufacture cellular material:

$$6CO_2 + 6H_2O \xrightarrow{\text{light}} C_6H_{12}O_6 + 6O_2 \qquad (19)$$

Dissolved $C0_2$ produces acid conditions in water via carbonic acid. When $C0_2$ is biologically extracted, the pH of the aquatic environment is raised in proportion to phytoplanktonic activity. Since little photosynthetic activity appears to occur at site WQ1, the pH curves are relatively flat throughout the 72-hour periods during both events (figures 4a and 5a). The pH range was only 7.52 - 7.66 during event 1 and 7.47 - 7.75 during event 2 (table 1). The average values for these two periods are nearly equal to the pH of the treated wastewater effluents being discharged to the study reach (table 4).

The pronounced photosynthetic activity at site WQ2 during both events is reflected in the well-defined sinusoidal shape of the curves (figures 4b and 5b). The amplitudes mirror those of the respective DO curves in classic "textbook" fashion (figures 2b and 3b). The pH ranged from 7.73 - 8.83 and 7.56 - 7.98 for events 1 and 2, respectively. The 8.83 value is near the maximum value that can be expected to be induced biologically in surface waters of central and northern Illinois.

The matchup between the DO and pH curves for either event at site WQ3 is not as good as for site WQ2, however, the two parameters are still highly correlated. During event 1, the pH at site WQ3 remains high (8.05-8.80) over the 72-hour period, although the sinuosity is not as well defined (figure 4c) as it is for the DO curve (figure 2c). During event 2, the relatively poorly defined sinuosity of the pH curve (figure 5c) and the lower pH and smaller pH range (7.37-7.85) reflect the nature of the DO curve (figure 3c). The antecedent high flows probably "washed out" and/or diluted the algal photosynthetic responses in this area of the study reach.

The DO and pH in the water contained in the light and dark chambers varied according to expectations. Extremes are exemplified by the results for event 1 at sites WQ1 and WQ2. In the absence of significant algal productivity at site WQ1, the pH values in both chambers were nearly equal, stable, and slightly below ambient values throughout the 72-hour study period (figure 5 a). At site WQ2, in the presence of a high rate of productivity, the light-chamber and dark-chamber pH diverged significantly with the light-chamber values being sinusoidal and slightly less than the ambient values (figure 5b). At site WQ2, the dark-chamber pH curve was flat and fell well below the ambient and light-chamber values (figure 5b). Similar scenarios were evident for each of the other site/event combinations (figures 4c-5c).

Water temperatures exhibited diel fluctuations typical of warm, sunny, low-flow conditions. Event 1 averages were about 1° C higher per site than those during event 2. This small difference could have been seasonal (mid-August versus early September), or it could have been due, at least in part, to cloud cover over the study area during the final 24 hours. Note that the temperature curves for the last 24 hours of events for all three sites during event 2 are relatively flat with small amplitudes (figure 7), indicating significant thermal insulation due to cloud cover. The temperatures declined slightly over time at all sites during event 1 (figure 6), whereas during event 2, the peaks and valleys were essentially equal during the first 48 hours until cloud cover set in. These data indicate that the Sangamon Fiver reacts significantly to daily climatic conditions during the summer low-flow conditions.

Conductivity and salinity data (especially salinity) are usually of little interest when evaluating water quality of streams in the northern half of Illinois. This was not the case for this study, although initially the assumption was made that normal northern Illinois stream conductivities and salinities would persist. Conductivity values (much higher than anticipated) prevailed for lengthy periods. Many values exceeded the maximum calibration range, necessitating the development of equation 1 so that salinity could be used to estimate missing conductivity values. The occurrence of high salinity values in the study area (table 1) is surprising. If such values persist over lengthy periods, they could have an adverse impact on the aquatic habitat in the study area.

Table 6 compares conductivity/salinity values for the study area and other stream locations in northern Illinois. Infrequently, measurable levels of salinity occur in the Illinois waterway at Lockport and Starved Rock but never of the-magnitude that occurred at sites WQ1 and WQ2 during this study. Commensurately high conductivity values are associated with these salinity readings. The source of these inordinately high values appears to be "rooted" in the Decatur area since site WQ1 conductivity values for both periods are essentially equal to the Decatur WTP effluent values (tables 4 and 6). This assumption is also supported by significant decreases in the conductivity and salinity values at the downstream sites (table 1, figures 8-11). Significant diel fluctuations in conductivity/salinity occur in the study area, as evidenced by the site WQ2 event 2 conductivity (figure 9b) and salinity (figure 1 lb) plots.

The DO curves associated with the SOD tube respiration chambers are presented as figures 12 and 13. The final results are presented in table 7. Negative values indicate that the rate of DO usage in the dark chamber (BOD and algal respiration) was greater than that in the SOD chamber. The results in some cases are illogical, exhibiting inconsistency between sites per event and between events per site. No results were derived for site WQ1 (event 2) because the DataSonde probes were inadvertently pushed into the sediments.

Although the SOD results are not consistent or easily interpreted, a general conclusion could be reached. Overall, the bottom sediments in the study reach do not exert a particularly high oxygen demand. Butts and Evans (1978b) consider SOD rates of 1.0 - 2.0 g/m^2/day at 25° C to be representative of slightly degraded bottoms while values of 0.5 - 1.0 g/m^2/day are representative of moderately clean sediments. Values in the range of 5.0 - 10.0 g/m^2/day are considered to be highly polluted. The SOD rate of 10.14 g/m^2/day at 25° C for site WQ2 (event 2), for the period 0 - 7 hours (table 7), appears to be an anomaly. At the same location during event 1, a maximum rate of 2.59 g/m^2/day at 25° C was observed. In general, an average rate of less than 1.0 g/m^2/day appears appropriate for the study reach. The WTPs do not appear to be contributing significantly to Sangamon River SOD rates.

The 20-day BOD test results are presented as figures 14 and 15. The plots show progressive oxygen use due to the stabilization of dissolved carbonaceous material (CBOD) and dissolved ammonia/nitrites (NBOD) by nitrifying bacteria. The NBOD is determined by inhibiting the growth of the nitrifiers and subtracting the inhibited BOD or CBOD from the uninhibited BOD or TBOD.

The Decatur WTP does a good job of removing ammonia. This is reflected not only in the low NH_3-N values observed at site WQ1 and reported in the plant effluent (table 4), but also in the characteristics of the BOD curves for both events (figures 14a and 15a). Note that NBOD is only a small fraction of the TBOD, and none of the TBOD or NBOD curves follow the nitrifying S-shape curve as defined by equation 18. Furthermore at site WQ3 during event 2, the NBOD fraction was almost nil. In contrast during event 1, the NBOD appeared to constitute a highly significant portion of the TBOD at site WQ2 (figure 14b). This is not readily explainable.

Reaeration and Oxygen Production

The reaeration rates (K_2) computed, using the algorithm amalgamated as equations 4-9, are presented in table 8. Computed reaeration coefficients were rejected when the values were negative or greater than 10. Broeren et al. (1991) provide the justification for doing this. The maximum number of acceptable values would be 72 since recordings were hourly. Consequently, as can be seen from table 8, the rejection rate was slightly higher on the average than what occurred for the upper Sangamon River study.

The average K_2-values changed little between events for sites WQ1 and WQ2. At site WQ3, the coefficient was somewhat greater during event 1 than during event 2. A generalization could be made that, overall, the reaeration rate varied little over space and time during the study. The average site values indicate this reach of the river has a high capacity to assimilate organic, oxygen-consuming wastes even in the absence of primary productivity. However, this middle to lower reach of the Sangamon does not have nearly the reaeration capacity of the shallower, swifter reaches of the upper river (table 8). Table 9 compares the results from computing K_2 using three published formulas. Overall, the O'Connor/Dobbins equation appears to produce K_2-values closest to those experimentally derived during the study.

The USGS conducted an extensive water quality study of the Sangamon River between miles 85.59 and 126.61 during 1982 (Schmidt and Stamer, 1987). Attendant to this study, direct measurements were made of the reaeration coefficients for various subreaches on September 15 - 16, 1982, using a modified dye tracer/dissolved gas technique. The fluorescent tracer dye, Rhodamine WT, was injected in conjunction with ethylene gas, and gas losses were measured with time of travel downstream. Two of the USGS sub-reaches bracketed sub-reaches used during this study, specifically sites WQ1 and WQ2. For the site WQ1 area, the USGS derived a K_2-value of 2.91 day^{1} for warm, low-flow conditions, which compares very favorably with the 3.05 day^{1} and 3.06 day^{1} values derived in this study (table 8). Similarly, for site WQ2, the USGS derived a K_2-value of 3.04 day^{1}, which compares reasonably well with the values of 2.49 day^{1} and 2.38 day^{1} developed in this study.

Algal activity is a credit to the oxygen balance of a stream only when total photosynthetic oxygen production exceeds cell respiratory needs. If respiratory oxygen consumption exceeds photosynthetic oxygen production, oxygen depletion occurs and algal cells become a liability to the DO resources. Table 10 summarizes the gross and net primary productivity for all complete 24-hour periods monitored during the study. The gross productivity represents the difference over time between the light and dark chamber DO concentrations (equation 3 a), whereas, the net productivity represents the difference over time in the DO concentration in the light chamber (equation 3 b).

Net productivity is the best indicator as to whether algal activity is a debit or credit to the oxygen resources of a stream. The negative values in table 10 indicate more oxygen was used for algal respiration than was produced. Except for all three 24-hour periods at site WQ2 and event 1, all 24-hour values are negative, indicating that algai activity generally posed a 'liability to the DO balance in the study area during both events. Schmidt and Stamer (1987) measured a small positive net primary productivity rate at site WQ1 and a small negative net primary productivity rate at site WQ2 between September 15-16, 1982. They made an implicit conclusion that photosynthetic oxygen production is not an important source of DO in this reach of the Sangamon when they stated "... atmospheric reaeration was the primary process that increased the DO in those river reaches with the lowest DO concentrations." This study reaches the same conclusion with the added, more explicit statement that at times algal activity may even severely strain the DO resources of the river in critical low-DO areas.

K_2 Sensitivity Analysis

This study used a new procedure for estimating K_2 employing stationary field monitoring procedures and techniques to generate data that can be used to directly solve the theoretical reaeration equation (equation 4). As discussed, this methodology appears to be a quick, practical, relatively inexpensive way to obtain accurate estimates of K_2. However, this methodology requires improvement and refining. To aid in improving future results when employing this procedure, a sensitivity analysis was performed to determine which input parameters or factors affect K_2 the most.

The relationships were determined between the variability of K_2 and four input parameters: ambient DO (DO_a), time of travel (TOT), DO saturation (DO_s), and SOD. Each parameter was varied at each site, incrementally, in a plus or minus direction around the given observed value. For a given percent change in a parameter, a percent change in the average K_2 was recorded. The overall results are presented in figures 16 and 17. Table 11 summarizes data at the small percentage-change end of the scale to facilitate an understanding of the relative importance of each parameter. Clearly, the most important factor is the accuracy of the ambient DO measurements, followed by the accuracy of the DO saturation formulation used (in this case equation 8) and temperature measurements. The finite accuracy of the time-of-travel measurement has a small but probably statistically significant bearing on the accuracy of K_2. SOD has little effect on the derivation of K_2. Water temperature is the only major parameter not evaluated. However, its effect is probably represented to a great extent by that observed for DO since DO is directly related to temperature. In future work, highly structured quality control/quality assurance programs must be implemented to limit errors in recording ambient water temperatures and DO concentrations so that fewer outlier and negative K_2-values result.

Summary and Conclusions

A successful short-term, concentrated water quality study was conducted on the middle and lower reaches of the Sangamon River during August and September 1991. General water quality, algal productivity, and physical reaeration characteristics of the main stem of the river were evaluated at three sites: WQ1, WQ2, and WQ3. The study was patterned after a similar study conducted at three sites along the Upper Sangamon and reported by Broeren et al. (1991).

Conclusions reached as a result of this work are:

1. *The low-flow, warm-weather water quality characteristics of the Sangamon River immediately below Decatur closely resemble those of the Decatur Sanitary District WTP effluent.* This results from a lack of dilution water during low flow since very little flow is released from Lake Decatur immediately upstream of the treated wastewater outfall.
2. *IEPA stream DO water quality standards are routinely violated in the river at all WQ stations downstream of Decatur.* Violations of both the 6.0 mg/L "16-hour" regulation and the 5.0 mg/L minimum regulations are common. Figure 18 summarizes these findings and subsequent conclusions.
3. *Algal numbers and algae diversity are low in this reach of the Sangamon River.* Albeit the algal numbers are low, their effects on diurnal oxygen pulses are dramatic beginning at least 20 miles downstream of Decatur. Figure 18 summarily depicts this phenomenon. Algal counts are low in spite of very high levels of nitrate-N and dissolved phosphorus throughout the study area.
4. *Unusually high levels of salinity and conductivity occur in the river immediately below Decatur.* This could have deleterious effects on the aquatic environment and should be studied in more detail.
5. *Physical aeration appears to be the only consistent, reliable source of DO to the river in the study area.* Although algal photosynthetic oxygen production has pronounced effects on daily DO pulses, the net affect of algal activity is that the organisms use more oxygen than they produce on an average daily basis. In a 1982 USGS water quality study of the same reach of the river reached, a similar conclusion in a more obtuse manner.
6. *The SOD in the study area is very low.* The sediments are generally clean sand free of organic contaminants. Thus they exert little demand on the oxygen resources of the river.
7. *DO depletion in the study area no longer appears to be primarily the result of nitrification.* Low ammonia-N concentrations were detected in the river water grab samples and the long-term (20-day) BOD analyses indicate that oxygen depletion is due primarily to carbonaceous BOD (CBOD), not nitrogenous BOD (NBOD). This is in contrast to the 1982 USGS study, which reached the conclusion that NBOD was the primary cause of oxygen depletion.

8. *A new technique was developed to accurately calculate reaeration coefficients (K_2) from diurnal DO curves and basic water quality parameters.* Very accurate ambient DO measurements must be achieved to make the method useful and reliable according to a detailed sensitivity analysis using ambient DO, saturation DO, time of travel, and SOD as parameter inputs.

BASINWIDE HYDRAULIC MODEL AND FISH HABITAT ANALYSIS

Background Information

Hydraulic Geometry Relations

In natural rivers and streams, average width (W), depth (D), and velocity (V) of flow vary in a consistent and predictable manner with discharge. The power function relationship between stage (S) and discharge (Q), $S = aQ^b$, is well documented and widely used at streamgaging sites. Similar power function relationships have been proposed for W, D, and V at a stream cross-section as a function of Q (Leopold and Maddock, 1953). Hydraulic geometry relationships have also been developed, which relate hydraulic parameters as a function of drainage area (DA) and flow duration (F). A variety of mathematical formulations for basinwide relationships have been proposed (Stall and Fok, 1968; Singh et al. 1986; Singh and Broeren, 1989; McConkey and Singh, 1992).

Instream Flow Incremental Methodology

The Instream Flow Incremental Methodology (IFIM) was developed by the Cooperative Instream Flow Service Group of the U.S. Fish and Wildlife Service to relate flow parameters (depth, velocity, and substrate) and usable fisheries habitat. Fisheries supported by a given water body are indicative of overall stream habitat conditions as fish are the top consumers of the aquatic food chain. By providing a link between flow, stream characteristics, and aquatic habitat suitability, the IFIM can be used to assess whether these characteristics are limiting factors to fisheries support or may become limiting with flow or channel modifications.

Usable habitat availability is quantified by the calculation of a habitat variable, the weighted usable area (WUA). A stream's WUA can be calculated for a variety of fish species at different life stages under various flow conditions.

In the IFIM, habitat availability is determined by conceptually segmenting the stream into vertical cells, each representing a different hydraulic environment characterized by depth, velocity, and substrate. The habitat utility of each cell is independently evaluated for various fish species and their life-stages, using preference indices for each of the relevent parameters (Bovee and Milhous, 1978; Bovee, 1982). The Instream Flow Group (IFG) has developed preference data (preference curves) for more than 500 fish species (Milhous et al., 1984). The Illinois Natural History Survey (INHS) has developed preference curves for several fish species for the low-gradient, prairie stream environment common to Illinois (Wiley et al., 1987).

The WUA of each reach was calculated by summing the product of the cell suitability indices for particular channel characteristics and the flow surface area of the cell:

$$WUA = \sum_{i=1}^{n} S(d_i) \times S(v_i) \times S(b_i) \times a_i \quad (20)$$

where S(d), S(v), and S(b) are preference index values for depth (d), velocity (v), and substrate (b) of cell i, a, is the surface area of the cell, and N is the total number of cells in the study reach.

Calculation of the WUA provides information on the suitability of the microhabitat as defined by the stream channel and hydraulic conditions. Other factors that influence the habitability of a stream, such as water quality parameters, are treated as macrohabitat factors in the IFIM approach. These factors are evaluated first as part of a scoping process to identify potentially critical conditions. After determining the suitability of the water quality of a stream segment, the calculated WUA per unit stream length for a given discharge is multiplied by the length of the stream having suitable water quality to support specific fish species. Using multiple stream reaches to characterize aquatic habitat conditions, the total habitat available (HA) for a given flow is calculated as:

$$HA = \sum_{i=1}^{n} WUA_i \times L_i \quad (21)$$

where n is the number of reaches that make up the total length under consideration and L_i is the length of reach i with suitable water quality and with weighted usable area, WUA,.

A critical aspect of instream flow analysis is hydraulic modeling. A common approach to hydraulic modeling for habitat analysis is the use of the step-backwater model supported by the IFG. This model, commonly referred to as the water surface profile or IFG-2 model, requires extensive data collection efforts. However, there is neither a reliable means to extrapolate the results of study reaches to other reaches in the river basin, nor any basinwide application. Furthermore, many of the assumptions used in the model preclude the extrapolation of the results to low- and medium-flow regimes. Singh et al. (1986) provide a critical analysis of the use of the IFG-2 model in habitat analysis. At low flows, riffles and pools dominate and the flow cannot be modeled as uniform flow under such conditions as done in the IFG-2.

Basinwide Flow Model

A methodology for basinwide flow modeling and habitat assessment using the IFIM but with a modified hydraulic submodel has been developed and successfully applied to the Sangamon River basin above Riverton and to the Vermilion River basin in Illinois (Singh et al., 1986, 1987).

The basis of the hydraulic submodel lies in hydraulic geometry relations that define average stream width, depth, and velocity as a function of drainage area (DA) and flow duration (F). The equations are of the form:

$$\log (VAR) = a + (b \times F) + c \times (\log DA) \quad (22)$$

where F corresponds to the annual flow duration ($0<F<1$) and a, b, and c are regression coefficients.

Basin hydraulic geometry relations are used to define average width (W), depth (D), and velocity (V) for a given flow duration of a stream reach with a specified drainage area. These relations are determined from field measurements routinely made by the USGS for establishing and updating rating curves at gaging stations. The range and frequency of local values of depth and velocity occurring in riffle-pool sequences are determined from probabilistic distributions developed from field data. Substrate size and distribution data can also be collected in the field and used to add the influence of substrate on habitat suitability.

The basinwide flow model supplies needed hydraulic data for habitat assessment using MM without the prohibitive cost of individual site surveys for different discharge events at various sites.

Station and Basin Hydraulic Geometry

Station Hydraulic Geometry

Flow measurement data at three USGS gaging stations are available for the Sangamon River between Decatur and Petersburg. Hydraulic geometry relations were previously developed by Singh et al. (1986) for two stations, gage 05573650 (Sangamon River near Niantic) and gage 05576500 (Sangamon River at Riverton). Data for gage 05578000 (Sangamon River at Petersburg) were obtained and used to develop hydraulic geometry relations at this station. The only other gaging station within the study area with a continuous flow record, gage 05573540 (Sangamon River at Illinois Highway 48), was not considered in the analysis due to the possible effects of gate operation at the Lake Decatur dam. The drainage area above the Niantic station is 1054 mi^2 and above Lake Decatur 935 mi^2. Thus the low to medium flows at Niantic are largely governed by about 40 cfs effluent from the Decatur WTP. Furthermore, the Niantic station is a water quality station, not a continuous discharge record station. The flow durations developed from Knapp et al. (1985) consider the flows released from Lake Decatur, effluents from the Decatur WTP, and flows contributed by the intervening 119 mi^2 area. Thus the flow duration at Niantic does not represent that of a natural stream with similar drainage area.

Log-log plots of width W, depth D, and velocity V versus flow discharge Q were developed for the Petersburg gage (figure 19). Regression analysis was used to fit the third-order polynomial equation to the data. Coefficients for the Niantic and Riverton gages were obtained from Singh et al. (1986), and table 12 lists the regression coefficients for the three stations.

Basin Hydraulic Geometry

Basin hydraulic geometry relations define the average values of W, D, and V for a given flow duration and drainage area. Prior studies for hydrologically homogeneous basins have shown these parameters to increase consistently and predictably with flow duration and drainage area. To check if this held true for the current study, the station equations were used to compute values of W, D, and V at nine flow durations. Flows for these durations were calculated using the microcomputer streamflow assessment program developed by Knapp et al. (1985). The results were then plotted to see the progression in these parameter values at the three stations with respect to drainage area and flow duration (figure 20).

A plot of parameter values versus flow duration (figure 20) shows how a parameter changes at a station with a change in flow duration. If the parameter were to increase in a consistent manner, the three curves (one for each station) on each plot would stay approximately parallel. This is clearly not the case, however. In the plot of width versus flow duration, the lines for Niantic and Riverton cross at approximately 40 percent flow duration. The plot for depth shows the lines for Petersburg and Riverton to cross between 65 and 70 percent flow duration. All three lines cross each other in the plot for velocity.

Based on the results for these three stations, it is not possible to develop basinwide hydraulic geometry relations using available data for the main stem of the Sangamon River between Decatur and Petersburg. Several factors have caused these uncharacteristic results:

1. Confluence with a major tributary: The South Fork Sangamon joins the Sangamon River two miles upstream of the Riverton gaging station. The addition of the South Fork Sangamon and Sugar Creek increases the drainage area from 1443 mi^2 above the confluence to 2618 mi^2 at the Riverton gage. The characteristics of the South Fork Sangamon River watershed are significantly different than those of the main stem Sangamon River watershed.
2. Sediment deposition in Lake Decatur: It may cause increased bed erosion and stream entrenchment for 20-30 miles downstream of the dam. Greater stream entrenchment causes a more confined floodplain, and will result in less stream width at higher flow durations. It also seriously modifies the flow regime (especially low to medium flows), which is further affected by a significantly large quantity of effluent from the Decatur WTP.
3. Past channelization activity in much of the river between Decatur and the confluence with the South Fork Sangamon makes this river reach significantly different from that below Riverton to Petersburg.

Given additional information, it is possible that basin hydraulic geometry relations could be developed for the Sangamon River below the confluence of the South Fork. At present, however, there is only one USGS gaging station in this reach and a limited number of other observations such as those developed in the current study. Therefore, values of W, D, and V in three study reaches were developed at flow durations of 90, 85, 75, 60, and 50 percent using the field information as well as information from the nearby gaging stations.

Field Study

Study Reaches

Field investigations were conducted to measure depths and velocities in pools and riffles under a variety of flow conditions. This information was collected to develop probabilistic distributions of depth and velocity for use in habitat analyses.

Three study reaches on the main stem Sangamon River between Decatur and Petersburg were selected. Drainage areas of the study reaches ranged from 1244-2909 mi^2. Field measurements were conducted at three different discharges at each of the three sites. Locations of the reaches, labeled RP1, RP2, and RP3, are listed below and also shown in figure 1.

Reach Locations and Drainage Areas

Reach site	*Location*	*Description*	*River mile*	*Drainage Area (mi^2)*
RP1	T15NR2WS8,9	Approximately 3 miles east of Roby	102.5	1244
RP2	T16NR4WS25 SW 1/4	Downstream of Dawson WTP	88.0	1428
RP3	T17NR6WS27 SE 1/4	Downstream of Salisbury	59.9	2909

An effort was made to select reaches in natural and unaltered channels where flow was not altered by nearby dams or bridges, and which provided suitable access for launching the small boat used in the field study. However, such a site could not be found in the upstream portion of the study area. Site RP1 is located in an area that has been channelized and straightened sometime in the past.

Field work was conducted between June and September of 1992. Flow during the measurements ranged from 50 to 85 percent flow duration. Flow durations were calculated using the microcomputer streamflow assessment program developed by Knapp et al. (1985).

Field Procedures

Each selected reach consisted of three riffles and two pools. The terms riffle and pool refer to relative differences in flow conditions and bed materials, and are not precisely defined in terms of hydraulics. Other studies of Illinois streams (for example, Singh and Broeren, 1985) have shown that sometimes silt-laden shallow areas in pools can be easily mistaken for riffles if only flow characteristics are considered. In this study, the initial site visits were made during medium-flow conditions. It is sometimes more difficult to distinguish between riffles and pools since the riffles may be completely submerged. For this study, a subjective procedure was developed to distinguish riffles from other shallow areas.

During initial site visits, depth and velocity measurements were taken at several locations along the thalweg and midway between the thalweg and each bank. This identified shallow areas to be investigated further. Bed materials were visually examined and compared to samples taken from deeper parts of the pools. Cross-sections where the bed materials were similar to deeper parts of the pool were eliminated from consideration. Three consecutive rifflelike cross-sections were selected from the remaining ones and used as the riffles for the site.

Thirteen transverse transects were established in each reach and consisted of three riffles with two pools between the riffles. Depths and velocities were measured at six approximately equally spaced points along each transect for a total of 78 measurement points within each reach. Transects 1, 7, and 13 were located along the center of the riffles. The other transects were located in the pools and spaced approximately equally between the riffles.

A Marsh-McBirney model 201 electromagnetic flowmeter was used to measure velocities at 0.6 times depth where the depth was less than 2.5 feet, and at 0.2, 0.6, and 0.8 times depth otherwise. Measurements were conducted by wading across the transect if the maximum water depth along the transect was less than 3 feet or from a boat for greater depths of flow.

Analysis of Field Data

The point measurements of depth and velocity are assumed to represent flow conditionsa in a portion of the reach designated by a quadrilateral flow surface area, a_k. The mid-distance points between measurements define the surface boundaries of the quadrilateral area. A weighting factor, W_k, proportional to the ratio between the surface area of the quadrilateral area and the total surface area of the riffle-pool sequence, A_{rp}, was computed for each datapoint. The weighting factors were used in all statistical computations.

Discharge, flow duration, starting date of field work, and average parameter values of the reach are listed in table 13. The three measured events at each study reach are designated as a, b, and c. The relationships of average W, D, and V with flow duration were examined graphically by plotting the log of each variable versus flow duration. Each point on the plots was labeled with the flow duration of the measurement, as shown in figure 21. The value of each variable at flow durations of 50, 60, 75, 85, and 90 percent was then interpolated. Each point was checked to assure that the flow computed from Q = W x D x V approximated the modeled flow for the flow durations used. Parameter values were adjusted as necessary.

Riffles and Pools

Riffle to riffle spacing along the stream length is typically reported to be five to seven times the channel width (Leopold and Madock, 1953; Harvey, 1975). Channel width, and thus the distance between riffles, increases with drainage area. The distance between riffles was found to correlate closely with the W_{20}, the average flow width calculated from hydraulic geometry equations for the 20 percent flow duration (Harvey, 1975). Singh and Broeren (1985) found an average ratio of riffle spacing to W_{20} of about 5 for the main stem Sangamon River above Riverton and the South Fork Sangamon River.

Table 14 lists W_{20}, distances between riffles, and the ratio of riffle spacing to W_{20} at each study reach. Sites RP2 and RP3 have ratios close to 5, while site RP1 has greater ratios (6.2 and 6.5). The larger ratios at site RP1 may be due to the past history of channelization activity at the site. Channelization disrupts the riffle-pool characteristics of a river. With the passage of time, however, geomorphological processes will act to partially restore the riffles and pools. Apparently the restorative processes at site RP1 are still ongoing.

Depth Distribution

Average depth, D, computed for each discharge, ranged from 0.93 to 3.24 feet. The distribution of depths in each reach was investigated by computing the standard deviation, S_d, of the point depth measurements. Table 15 lists S_d of depths for each measurement in each of the three reaches. The table shows that at each site, S_d tends to increase as flow duration decreases, or as discharge increases.

For each site, S_d was plotted against flow duration. A straight line best fitting the data was then drawn by hand. Plots for the three sites are shown in figure 22.

The variation of depth in a stream channel is predominantly influenced by the riffle and pool formation of the stream. Table 15 lists the difference in reach average pool and riffle depth Ad and drainage area A_d for each reach. The difference in Ad is generally greater with increasing drainage area.

To predict the range of velocities at a station for a given flow duration, a value of D is first selected from the appropriate best-fit line in figure 21, and a value of S_d is similarly selected from figure 22. The distribution of normalized depths, Z, in a reach are given by the normal cumulative probability distribution:

$$p(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} \exp\left(-z^2/2\right) dz \qquad (23)$$

where

P = nonexceedance probability

$Z = (d - D)/S_d$

D = reach average velocity

d = actual depth for which P is calculated

Values of Z are computed for each level of nonexceedance probability using a numerical solution to the inverse standard normal probability distribution function. Values of Z for ten nonexceedance probability levels (0.05, 0.15,....0.85, 0.95) are given in table 16.

The depth d for a given nonexceedance probability i is obtained by substituting appropriate values of S_d , Z, and D, and solving for d_i. This method can be used to predict expected values of depths at various nonexceedance probabilities from the following equation:

$$d_i = Z_i(S_d) + D \qquad (24)$$

Velocity Distribution

The average velocities measured in a reach ranged from 0.89 to 1.51 feet per second (fps). The standard deviation of velocity, S_v, was computed for the three events in each reach to investigate the variation of velocities within the reaches. Little correlation to drainage area was found. Rather, the variation in velocities was strongly correlated with mean velocity, as shown in figure 23. This finding is consistent with prior studies in the Sangamon (Singh et al., 1986) and Vermilion (Singh et al., 1987) basins.

The relationship between S_v and V was examined by regression analysis using the least-squares method. This produced the following equation:

$$S_v = 0.0998 + 0.5123V \qquad (25)$$

with a correlation coefficient r^2 of 0.961. This function is shown in figure 23 as the solid line. The regression coefficients are similar to results previously obtained for the Sangamon River above Riverton and the South Fork Sangamon (Singh et al., 1986).

Joint Distribution of Depth and Velocity

Using the methodology developed by Singh et al. (1985) and Singh et al. (1987), the joint distribution of depths and velocities was explored. This method groups velocities according to the cumulative probability of the simultaneously measured depth. Cumulative probability intervals of 0.1 were used, resulting in ten depth divisions of equal probability. Point velocities were normalized by dividing the observed velocities by the reach average velocity. These normalized values were plotted versus the concurrently measured depth division for each discharge. The variation of normalized velocities within each depth probability division for each reach and discharge were then examined. Although a fairly wide range of velocities occur at any depth due to local nonuniformities in flow condition, overall greater variation in the velocities occurred at the lesser depths. Two distinct types of flow characteristics are associated with the shallow water: 1) shallow water that occurs in riffles is often accompanied by higher flow velocities, and 2) along the streambanks of pool areas, side friction reduces velocities.

In a comparison of the plots it was evident that greater normalized velocities occurred when the reach average velocity was low. Each site appeared to respond similarly at similar values of reach average velocity.

The data were partitioned into two subsets: $V \leq 1.0$ fps, and $V > 1.0$ fps. Figure 24 shows the relative frequencies of normalized velocity for five depth probability classes for each subset. The greater scatter of the normalized velocities at the lesser depths can be clearly seen.

For each depth probability class, a velocity distribution was constructed from observations of the plots of velocity ratios. Two distributions were developed: $V \leq 1.0$ fps and $V > 1.0$ fps. Ten velocity ratios were selected for each depth probability class, which range between 0.2 and 2.0 of the average velocity ratio for the class. The distributions are shown in figure 25. The dashed line in the figure shows the average velocity ratio for each class, and the plotted points are the velocity ratios that comprise each distribution. The average of the 100 velocity ratio points used in the distributions is 1.0.

Since the variates are defined by ratios to the mean, and the mean of the velocity ratios is 1.0, the coefficient of variation equals the standard deviation. The standard deviation of the velocity ratios used in the distribution is 0.52, a value compatible with the observed coefficients of variation for velocities in the range of 0.45 and 0.6.

Habitat Response Curves and Weighted Usable Area (WUA) Calculations

Habitat response curves showing the relative abundance of suitable habitat for various flow conditions were generated using the basinwide flow and aquatic habitat model. The fish species used in the analysis were the channel catfish, common carp, largemouth bass, and smallmouth bass. All four species are found in the Sangamon River below Lake Decatur (Herricks and Himelick, 1981; Smith, 1979). Two life stages, adult and juvenile, were considered for each species.

The habitat response of each species and life stage were evaluated for the three study reaches at five flow durations ranging from 50 to 90 percent.

The flow model was used to provide the necessary hydraulic information for calculation of the WUA. Use of the model to provide the required hydraulic data for computation of WUA required the following steps. These steps are repeated for each drainage area and flow duration.

1. For each site and flow duration, mean values of width, depth, and velocity were obtained from figure 21.
2. The standard deviation S_d of depth D for each site and drainage area was obtained from figure 22. Using the reach average depth D, S_d, and the ten values of z_i given in Table 16, equation 24 was evaluated for each z_i value. This yielded ten depth d_i values, each with an equal probability of occurrence within a riffle-pool sequence at the given flow duration.
3. For each depth obtained in step 2, ten velocities were obtained that have an equal probability of occurrence at that depth. The velocities are obtained using figure 25, which gives ten ratios of local velocity to reach average velocity. When multiplied by the reach average velocity V, each ratio yields a local velocity value. When this step is performed for each depth obtained in step 2, the result is 100 pairs of depth d_i and velocity v_{ij}, each representing 1/100 of the surface area of a pool-riffle sequence.
4. Next the flow surface area (A_R) of the reach was computed. The reach average width computed in step 1 was multiplied by the riffle-to-riffle distance, which can be estimated as five times W_{20}, the average width at a 20 percent flow duration.
5. Each depth and probability pair d_i and v_{ij} were then used to evaluate the habitat suitability indices [(S(dj) and $S(v_{ij})$] for the desired life stage and fish species. The WUA was computed from a modification of equation 20:

$$WUA = \frac{A_R}{100} \sum_{i=1}^{10} \sum_{j=1}^{10} S(d_i) \times S(v_{i,j}) \qquad (26)$$

Figure 26 shows suitability indexes for depth and velocity for adults and juvenile smallmouth bass.

Weighted Usable Area (WUA) Relations

Habitat response curves relating flow duration to WUA were developed using the model proposed above. Plots of WUA versus flow duration for adult and juvenile life stages of carp, channel catfish, largemouth bass, and smallmouth bass are shown in figures 27-30. In each figure, habitat responses are plotted at flows from 50 to 90 percent flow duration for each site. Figure 27 shows the habitat response of carp. The curves suggest that the adult of the species is much less tolerant of low flow conditions than the juveniles. There is much more WUA for the juveniles at site RP3.

The habitat response of channel catfish is shown in figure 28. In the Sangamon River, WUA is limited during low-flow conditions. This concurs with distributional maps of the species

(Smith, 1979), which indicate that specimens have been collected from the Sangamon River below Springfield, but not from the section between Decatur and Springfield. The lack of channel catfish in this section of the river may also be caused by the poor water quality conditions mentioned earlier in this report.

The habitat response of the largemouth bass and the smallmouth bass are shown in figures 29 and 30, respectively. While the response curves indicate that much better habitat is available for adult smallmouth bass than for adult largemouth bass, collection records indicate just the opposite. Distribution maps in Smith (1979) indicate no collections of smallmouth bass from the Sangamon River between Lake Decatur and Petersburg, but several collections of largemouth bass in the same area. There are several possible causes for this discrepancy. The Sangamon River is near the southernmost limit of the geographical distribution for the smallmouth bass, which is widespread throughout northern Illinois but sporadic in the southern third of the state. The largemouth bass, an ecolologically tolerant species, occurs in virtually all types of water, while the smallmouth bass has much stricter requirements — it prefers clear, gravelly streams that stay relatively cool during the summer (Smith, 1979).

Incorporation of Water Quality in Aquatic Habitat Assessment

Maintenance of a viable aquatic ecosystem requires that both water quality and physical habitat be suitable for indigenous organisms. The habitat analysis performed so far in this study provides information only about the physical habitat.

The Illinois Pollution Control Board has issued water quality standards for the protection of aquatic life. The standards stipulate that DO should not fall below 6.0 mg/L for 16 or more hours during any 24-hour period, and that DO should not fall below 5.0 mg/L at any time. In the water quality portion of this study the first standard was violated at stations WQ1 and WQ2, and the second standard was violated at all three water quality stations.

To assess the long-term impact on aquatic organisms, however, we need to know how often such violations occur. Water flows have predictable seasonal differences that affect physical habitat suitability. Similarly, water quality parameters have seasonal differences related to Q. During late summer and early fall, low flows are common in the Sangamon River.

The relationship between Q and the ability of a stream to assimilate organic wastes is not a simple one, and it is determined by several site-specific factors. A few generalizations, however, may be made:

- The ability of a stream to absorb oxygen from the atmosphere decreases with increasing Q because the surface area of the stream exposed to the atmosphere is smaller in relation to the volume of water in the stream.

- During low-flow conditions less streamflow is available to dilute the wastes. In some situations most of the flow in the river during low flow conditions is comprised of WTP plant effluents. This is the case in the Sangamon River below the Decatur WTP discharge.
- In central Illinois, the occurrence of low flow coincides with the time of highest water temperatures. During these times the saturation concentration of oxygen is less.

In a similar study of the upper Sangamon River, Broeren et al. (1991) tabulated monthly average values of DO and Q at 20 USGS gaging stations in the Sangamon River basin, including five gaging stations within the current study area. Table 17 gives the monthly average and minimum DO values at the five gages. Broeren et al. (1991) also computed seasonal average oxygen deficits D (table 18) and developed seasonal correlations between D and Q (table 19). The relationship between D and Q is especially useful, as D also incorporates seasonal temperature differences.

While it is possible to make comparative observations of the correlations, Broeren et al. (1991) determined the results to be statistically insignificant because of the inherent variability of the data and the small number of sample points, typically 5-13 per year per station. The utility of the USGS data (Schmidt and Stamer, 1987) to assess possible impacts on aquatic life is also limited because the majority of the samples were obtained during mid-day (10:00 a.m. -2:00 p.m.) when DO values are increasing due to photosynthetic activity. DO values measured during this time of the day often miss both the minimum and maximum DO. Some of the comparative observations of DO and oxygen deficit, D, for the five stations in the study area will be reviewed here.

The first station below Lake Decatur, 05573540 (Sangamon River at Highway 48) showed strong negative correlations between Q and D during all seasons (r ranged from -0.563 to -0.856). A negative correlation indicates that decreasing D values accompany rising Q. The negative correlation at the Route 48 station may be due to DO production by algal activity in Lake Decatur and reaeration caused by water flowing over the spillway. Average seasonal D was greatest in the fall (5.730) and smallest in the spring (-0.076). This station also showed the lowest average monthly DO values, 4.09 and 4.01 mg/L, during September and October, respectively. Violations of the 5.0 mg/L standard were detected in January and in all months from June to November (period of practically very low flows over the Decatur Dam spillway). The violations in January are likely due to oxygen depletion in Lake Decatur, and the ice cover on the stilling basin downstream. Average monthly DO values were below the standard from September to November.

The next station, 05573650 (Sangamon River near Niantic), is 9.5 miles below the Decatur WTP outfall and also showed strong negative correlations between Q and D for all seasons (r ranged from -0.593 to -0.830). During low flows a significant portion of the streamflow at this station consists of effluent from the WTP. The largest seasonal D (4.059) was in the fall and the smallest (1.438) in the spring. Violations of the 5.0 mg/L standard were found in all months from May to January. Average monthly DO values were below the 5.0 mg/L standard for only the month of September.

Conditions improve somewhat at the next station, gage 05573800 (Sangamon River at Roby). The correlation between Q and D is very weak in the spring (r = -0.062), and summer (r = 0.198), and moderately negative in the fall (r = -0.571) and winter (r = -0.486). Average seasonal D was greatest in the fall (3.217 mg/L) and lowest in the summer (1.149 mg/L). Violations of the 5.0 mg/L DO standard were observed in all months from June to November except August, and in no month was the average monthly DO below the standard.

At the station below the confluence of the South Fork Sangamon River, gage 05576500 (Sangamon River at Riverton), correlations between Q and D become more positive, ranging from -0.443 in the fall to 0.528 in the summer. The average seasonal D values were highest in the fall and lowest in the summer, and were similar to the Roby station (within 0.3 mg/L) in all seasons except summer, when it was 0.57 mg/L less. Only in September was a violation of the 5.0 mg/L standard reported.

Station 0557800 (Sangamon River at Petersburg) showed a strong positive correlation between Q and D (r ranged from 0.225 in the fall to 0.700 during summer). The average seasonal D was 1.659 mg/L in the fall, and below 1.0 mg/L in all other seasons. No violations of the 5.0 mg/L standard were reported.

The historical data reviewed here indicate that violations of the water quality standard for DO have been detected at all stations except Petersburg, and that violations may occur with high frequency from Lake Decatur to Roby in the summer and fall. It is likely that aquatic communities from Decatur to Roby or up to the confluence with the South Fork Sangamon River are limited by poor water quality due to scanty releases from Lake Decatur and large effluents from the Decatur WTP. The upper portion of the study area D and Q exhibit a strong negative correlation due to the influence of Lake Decatur and the Decatur WTP effluent. With increasing drainage area the correlation becomes more positive, as these influences decrease in importance.

Summary and Conclusions

This study demonstrates how water quality data can be integrated with a flow and habitat model to define areas where water quality is limiting the potential of a stream fish community, given the physical and hydraulic conditions of the basin.

Fish habitat suitability was assessed at three locations in the Sangamon River between Lake Decatur and Petersburg. The physical habitat assessment was based on incremental methodology developed by the Instream Flow Group of the U.S. Fish and Wildlife Service and on the flow model developed by Singh and Broeren at the State Water Survey.

Diurnal fluctuations of water quality parameters related to DO were monitored at three locations for two 72-hour periods. Historical DO data from water quality monitoring stations were also reviewed.

The conclusions reached from this study are:

1) Due to the heterogeneous nature of the Sangamon River from Decatur to Petersburg, the development of a basinwide flow model is not possible using available data. Hydrologic conditions above the confluence with the South Fork Sangamon River are significantly different than below the confluence. Data are particularly scarce for the section from Riverton to Petersburg.

2) Aquatic communities may be limited by low DO concentrations in the Sangamon River from Lake Decatur downstream to the confluence with the South Fork Sangamon River. The diurnal water quality monitoring detected severe violations of the established DO standards for support of aquatic life. This finding was supported by review of the historical data, which indicate frequent violations in this section of the Sangamon River, especially during summer and fall, when flow over the Lake Decatur dam are low, and thus a significant portion of streamflow is treated wastewater effluent from Decatur.

3) The diurnal study also indicated a violation of the DO standards below Springfield. Since historical data for that portion of the river are not available, it is not possible to conclude that water quality is a limiting factor there.

4) Integration of water quality and physical habitat assessments could be improved by additional development of flow, habitat, and water quality models. The development of a basinwide flow and habitat model would require additional data collection between Riverton and Petersburg. A steady-state water quality model, such as the USEPA's QUAL2E model, could be used as a planning tool to assess alternate approaches to improve water quality. Potential impacts from increased effluent loading or diversion of water (or, conversely, improvements by increased wastewater treatment or flow augmentation) could then be evaluated.

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FIGURES

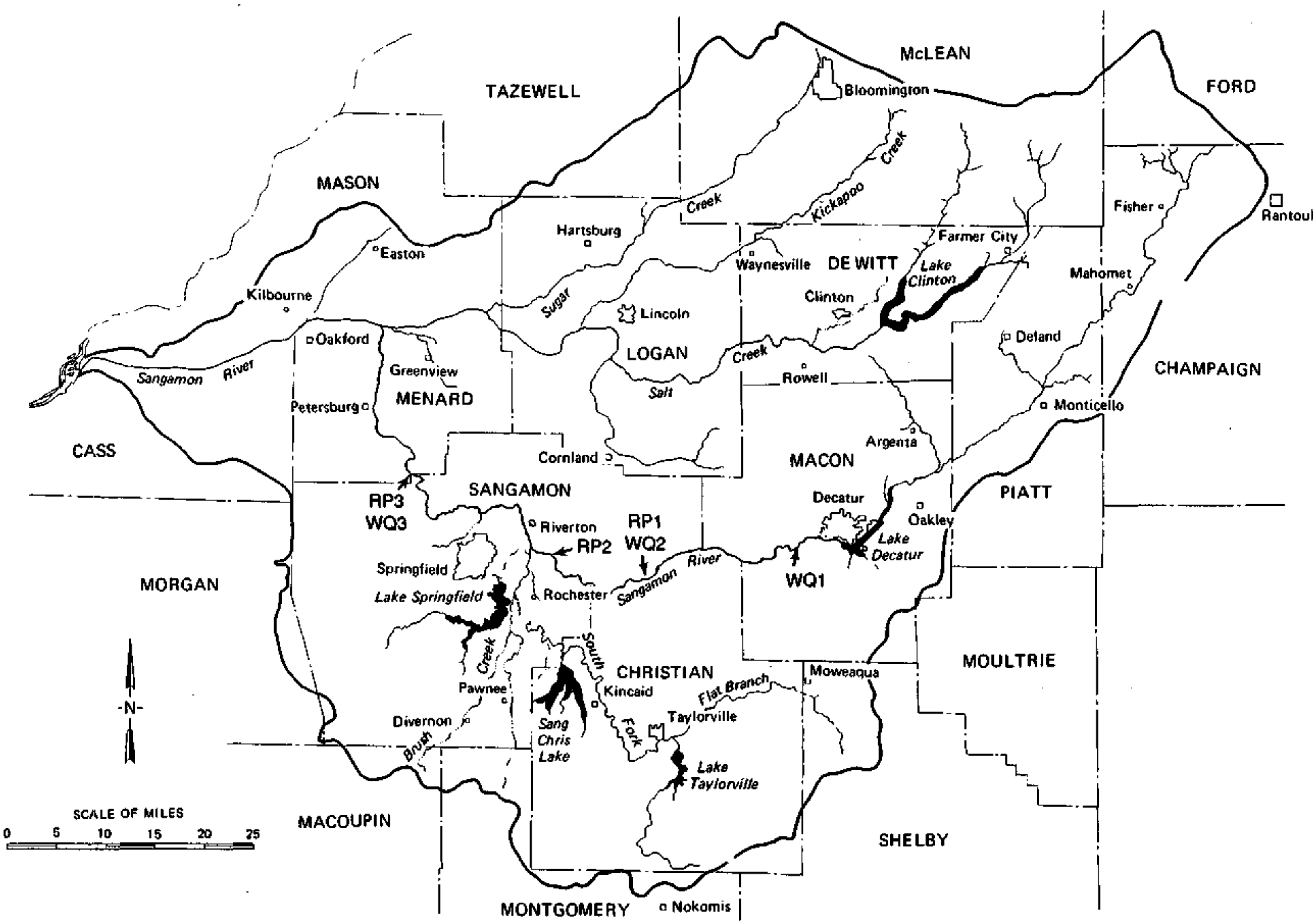


Figure 1. Sangamon basin map showing water quality (WQ) stations/sites
and study reach (RP) locations

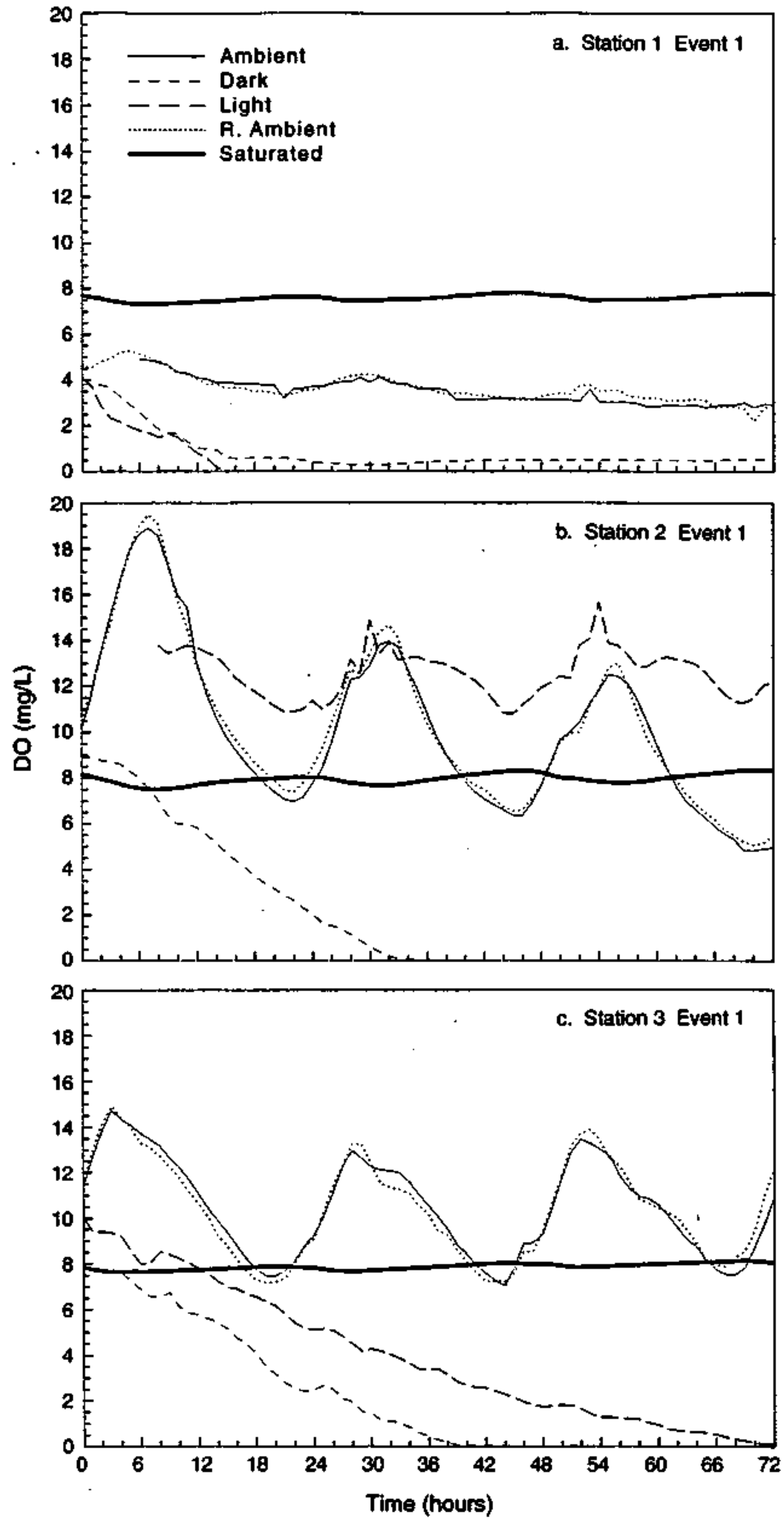


Figure 2. Diurnal DO variation at WQ stations during event 1

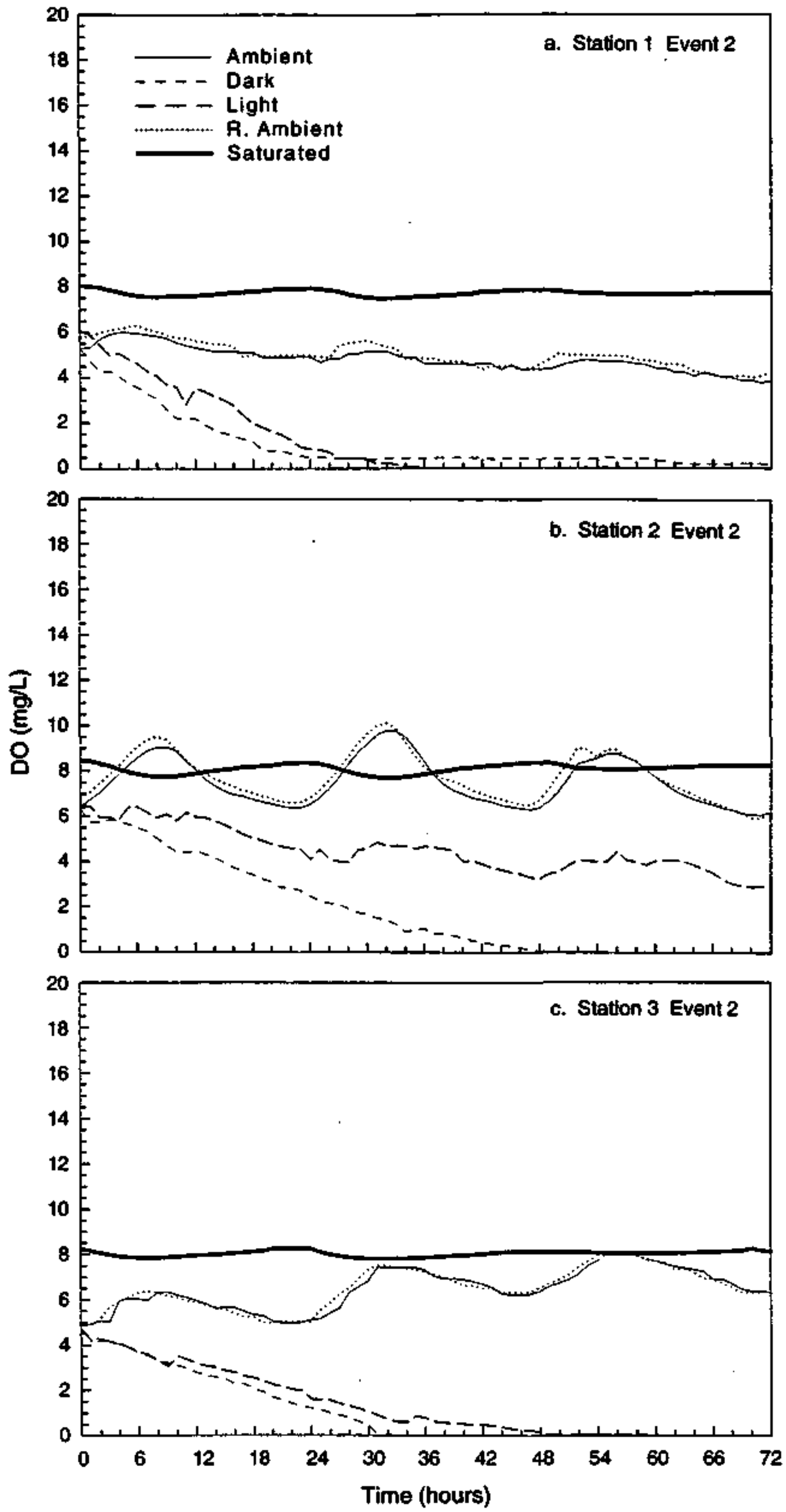


Figure 3. Diurnal DO variation at WQ stations during event 2

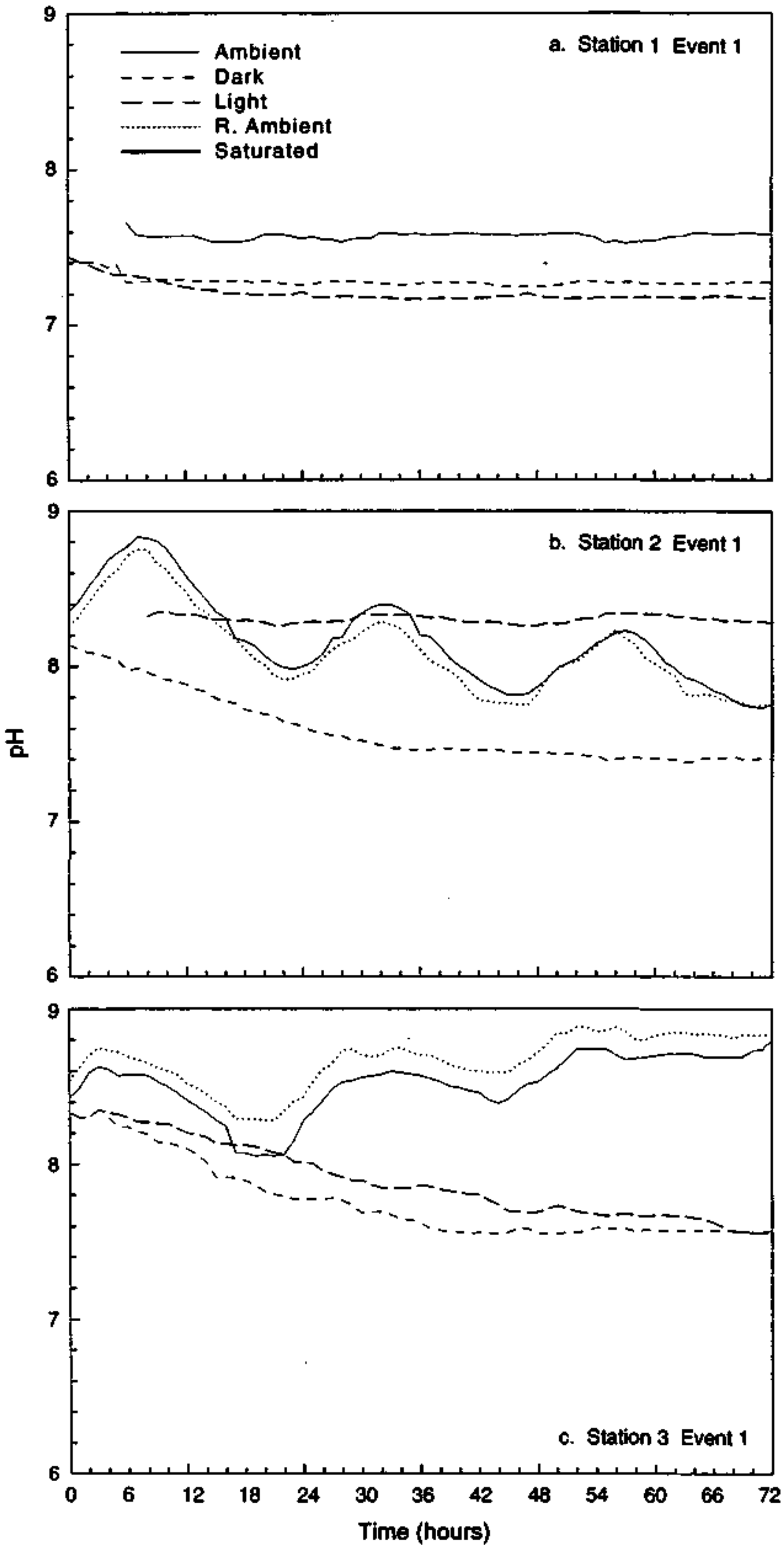


Figure 4. Diurnal pH variation at WQ stations during event 1

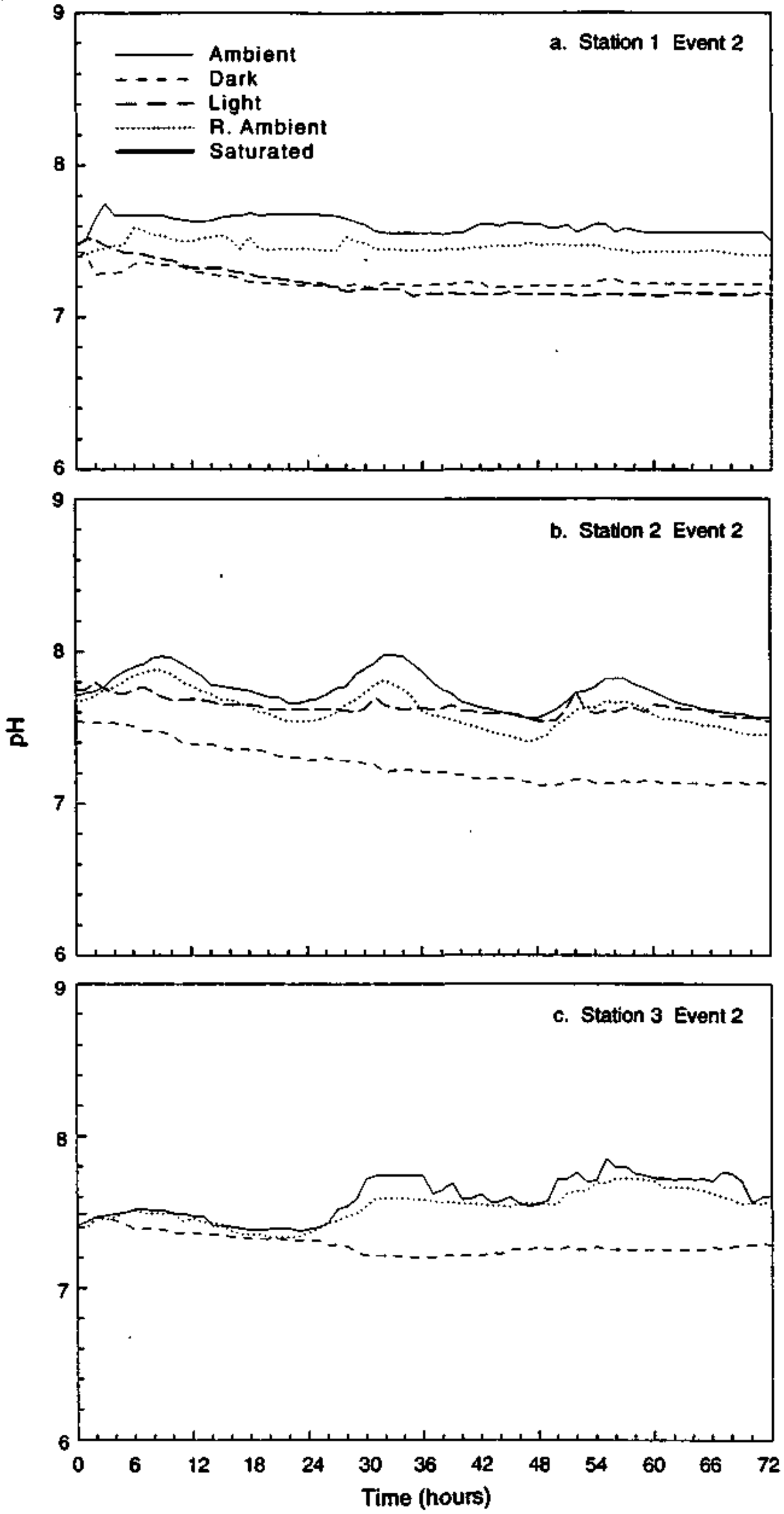


Figure 5. Diurnal pH variation at WQ stations during event 2

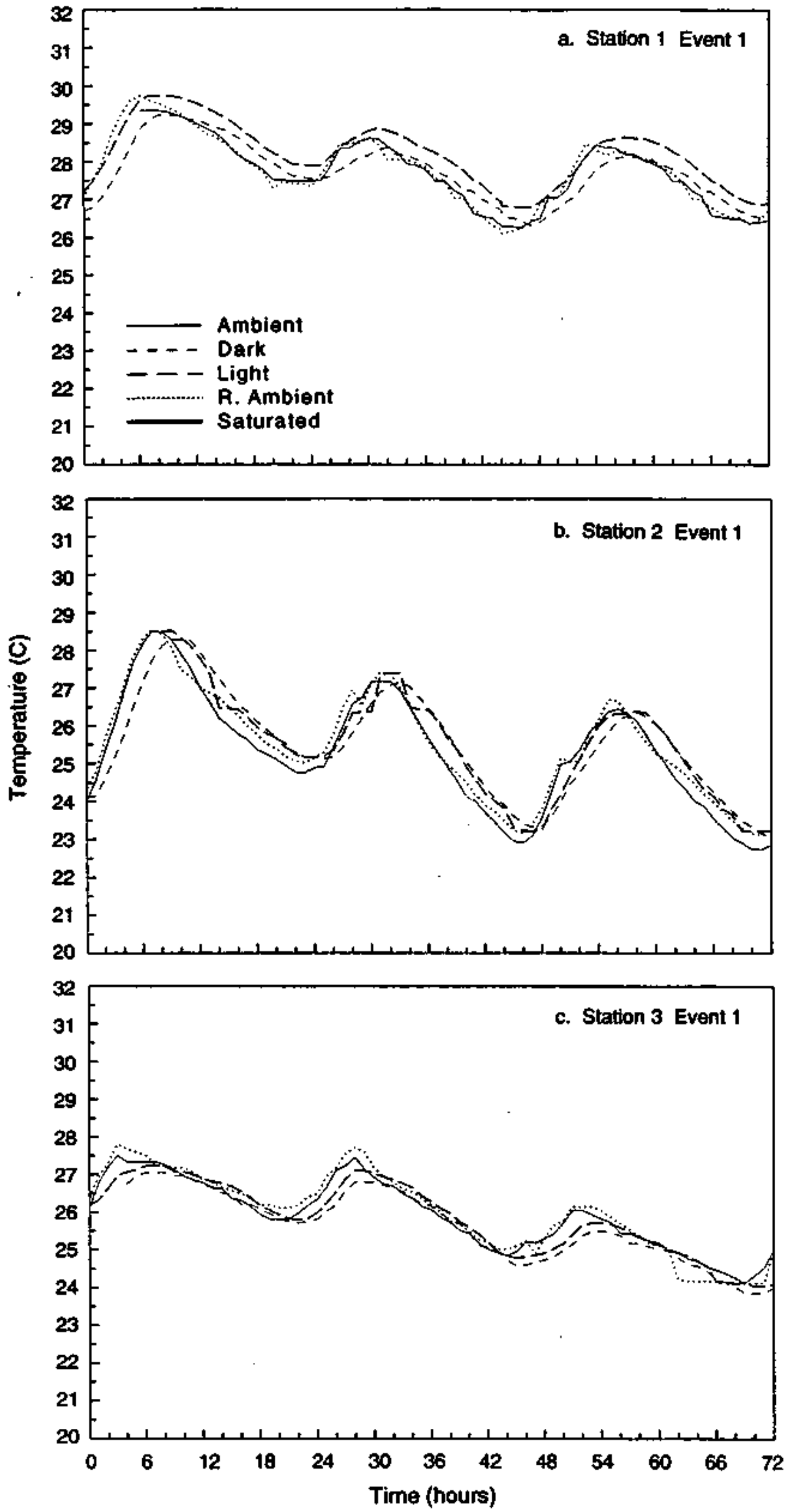


Figure 6. Diurnal temperature variation at WQ stations during event 1

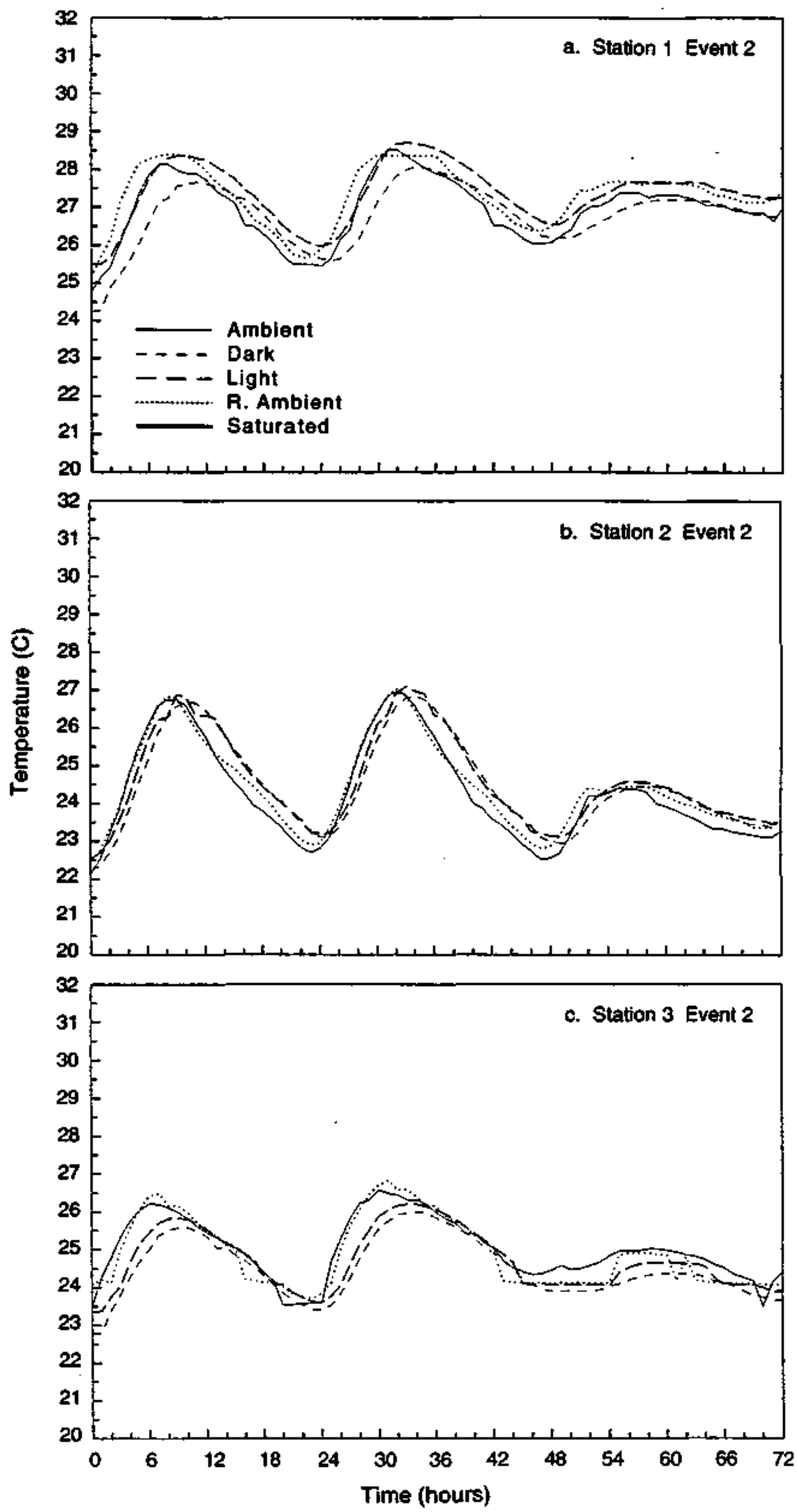


Figure 7. Diurnal temperature variation at WQ stations during event 2

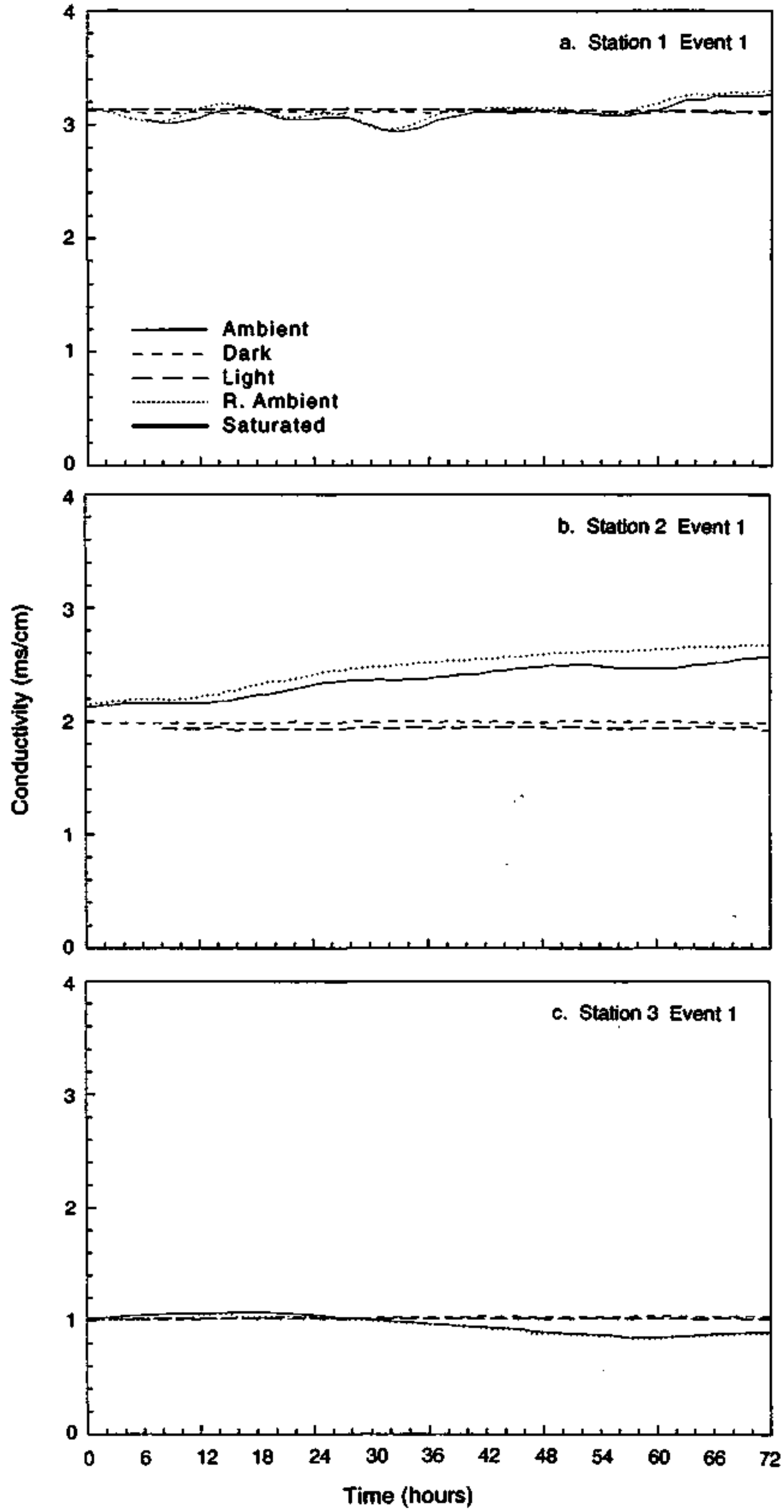


Figure 8. Diurnal conductivity variation at WQ stations during event 1

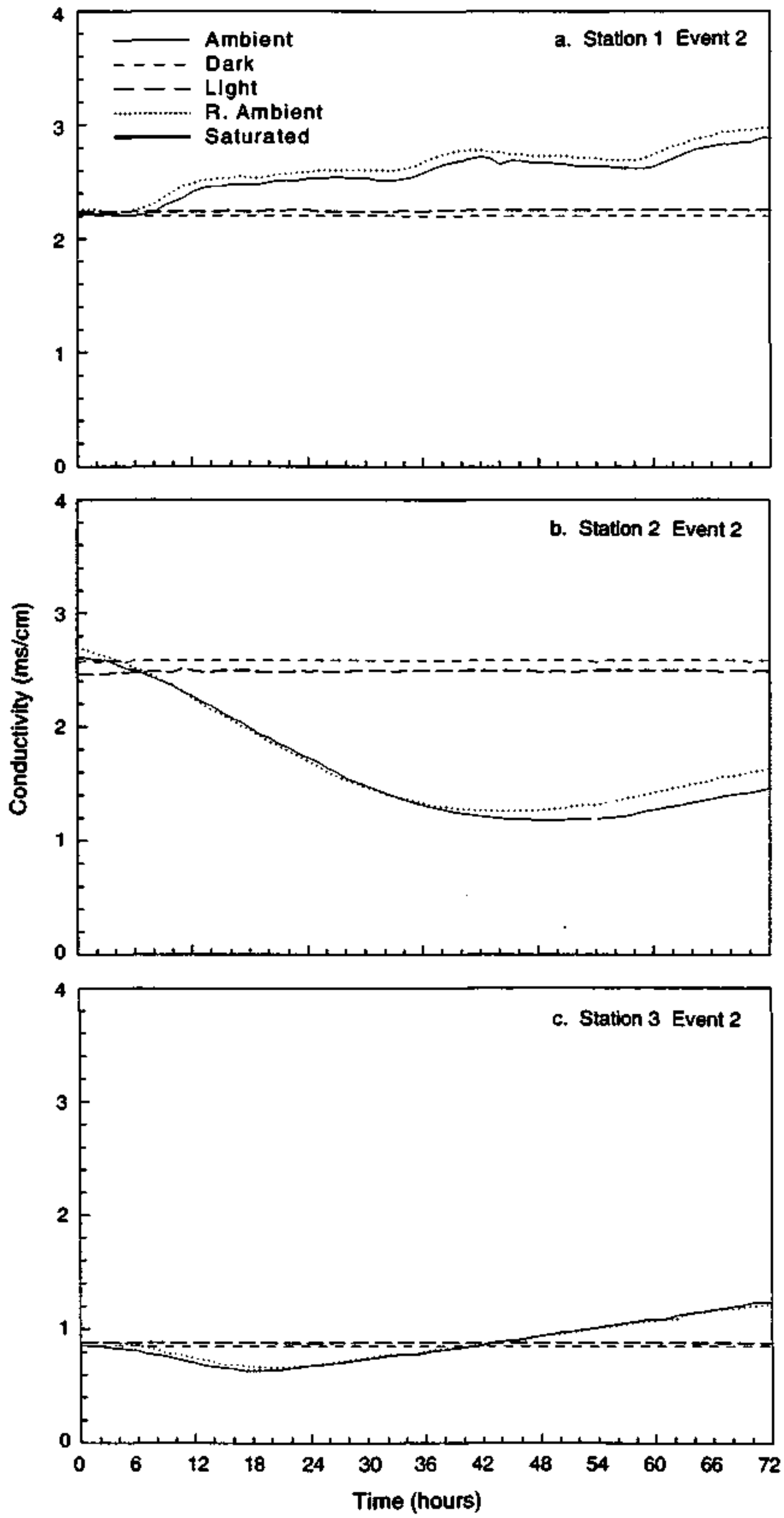


Figure 9. Diurnal conductivity variation at WQ stations during event 2

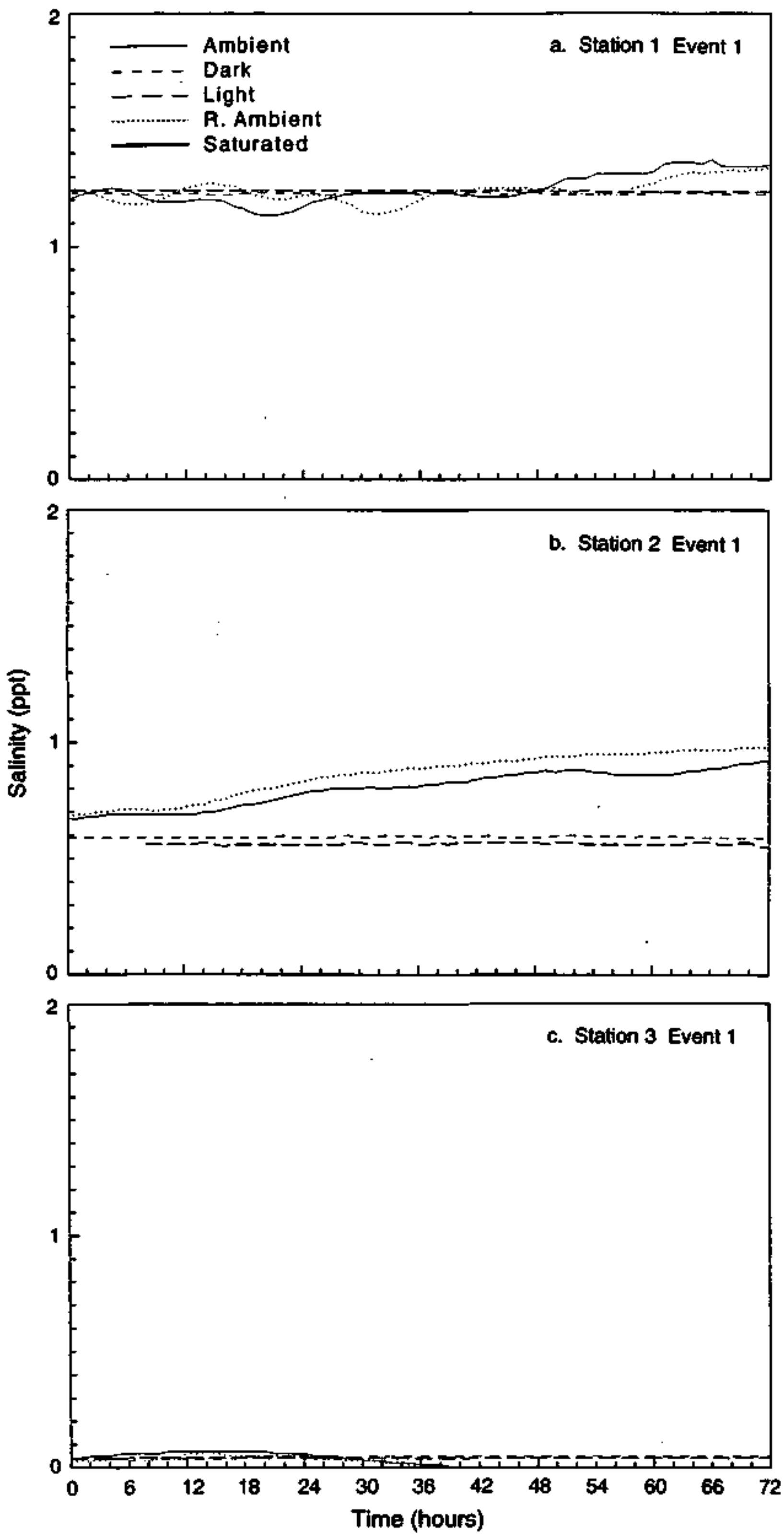


Figure 10. Diurnal salinity variation at WQ stations during event 1

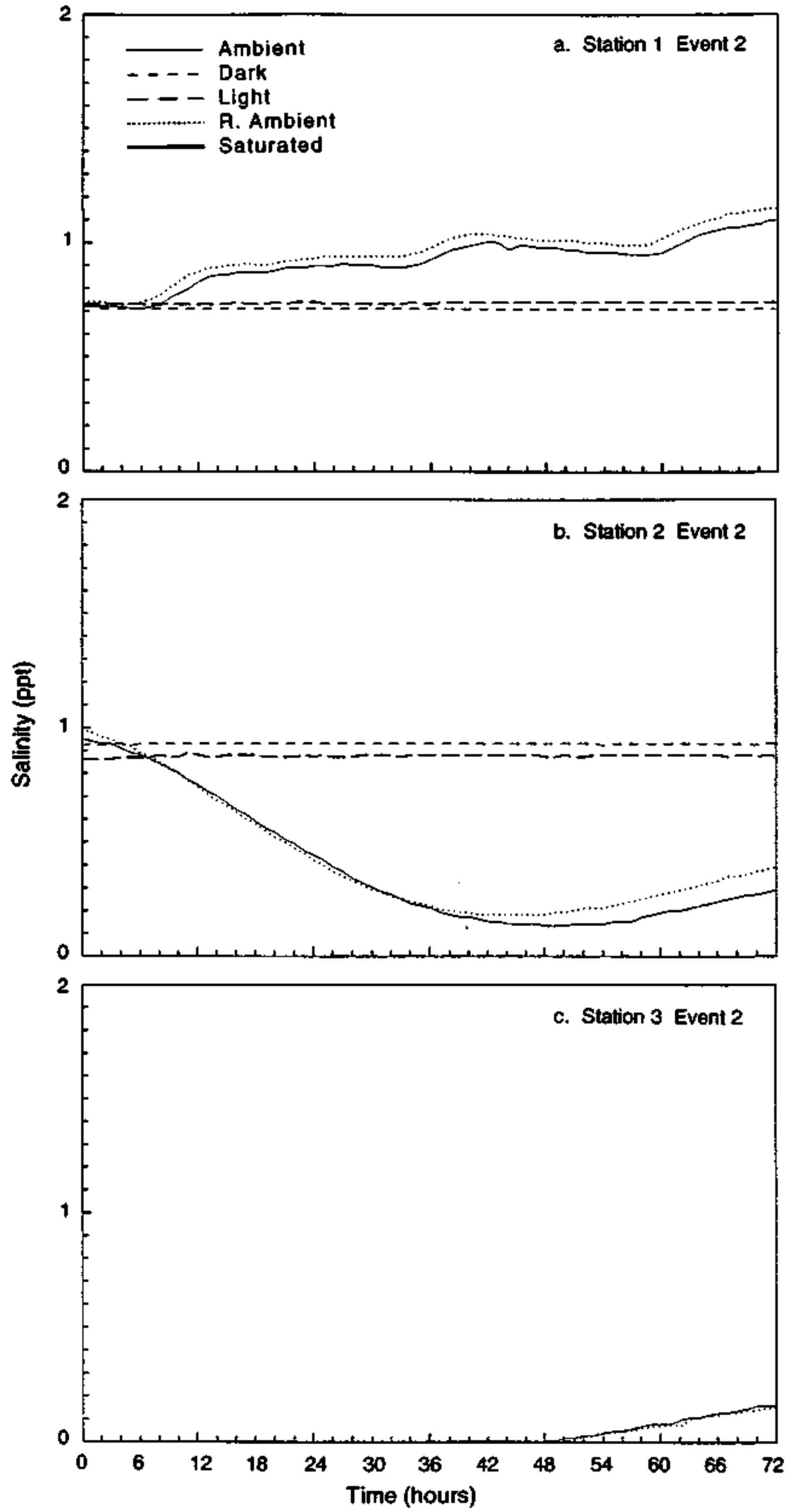


Figure 11. Diurnal salinity variation at WQ stations during event 2

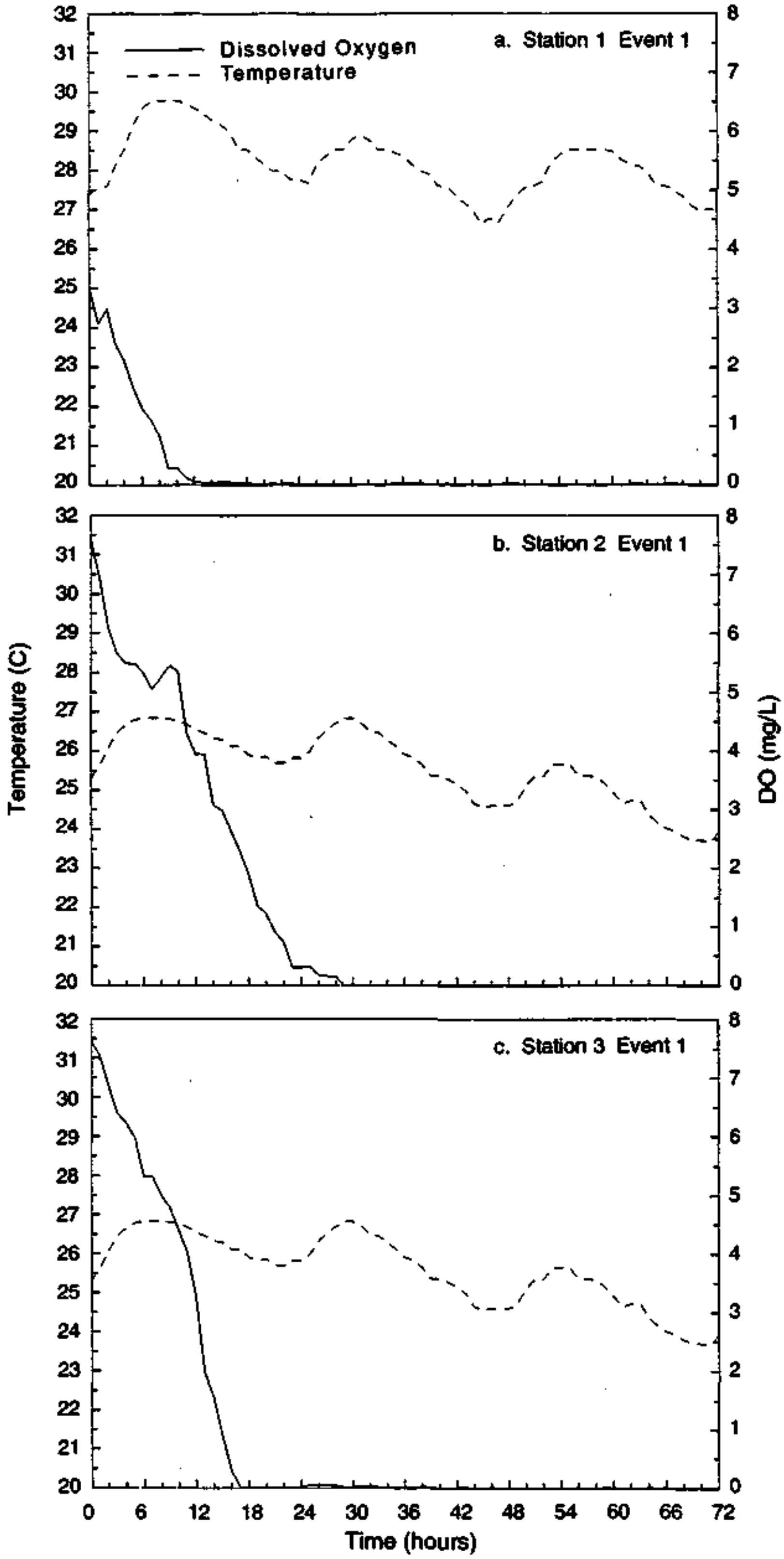


Figure 12. DO usage by SOD and water temperatures at WQ stations during event 1

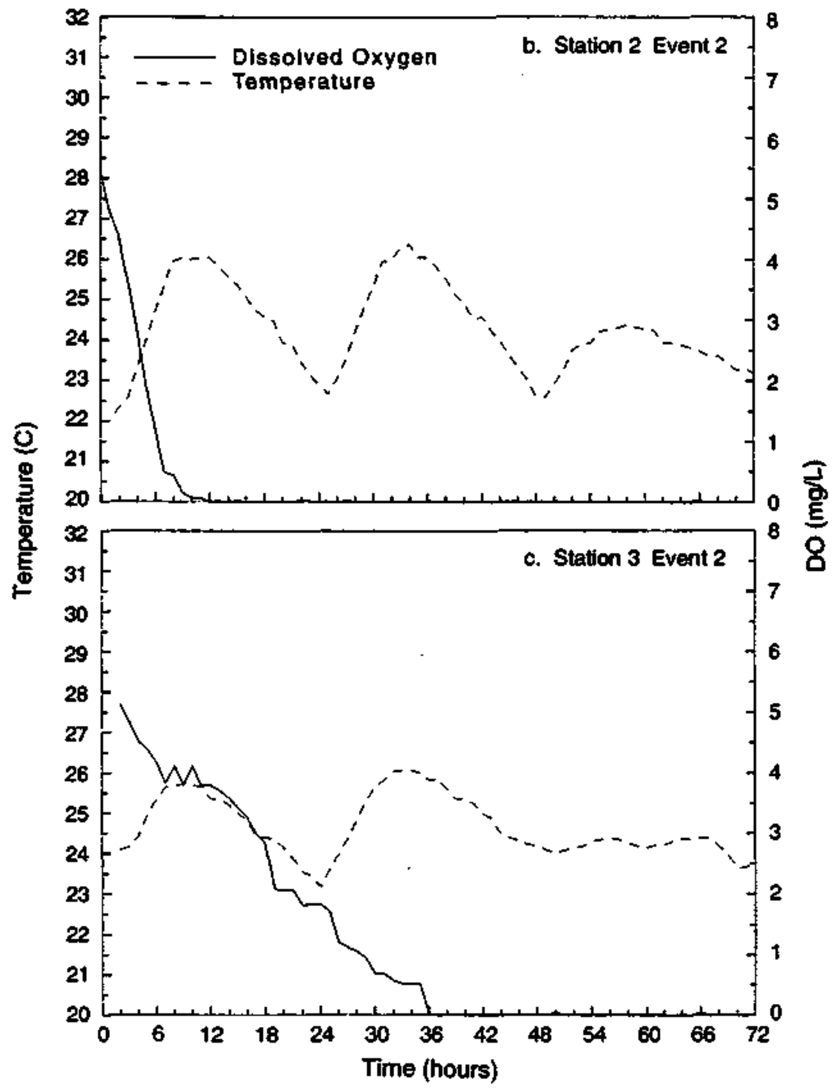


Figure 13. DO usage by SOD and water temperatures at WQ stations during event 2

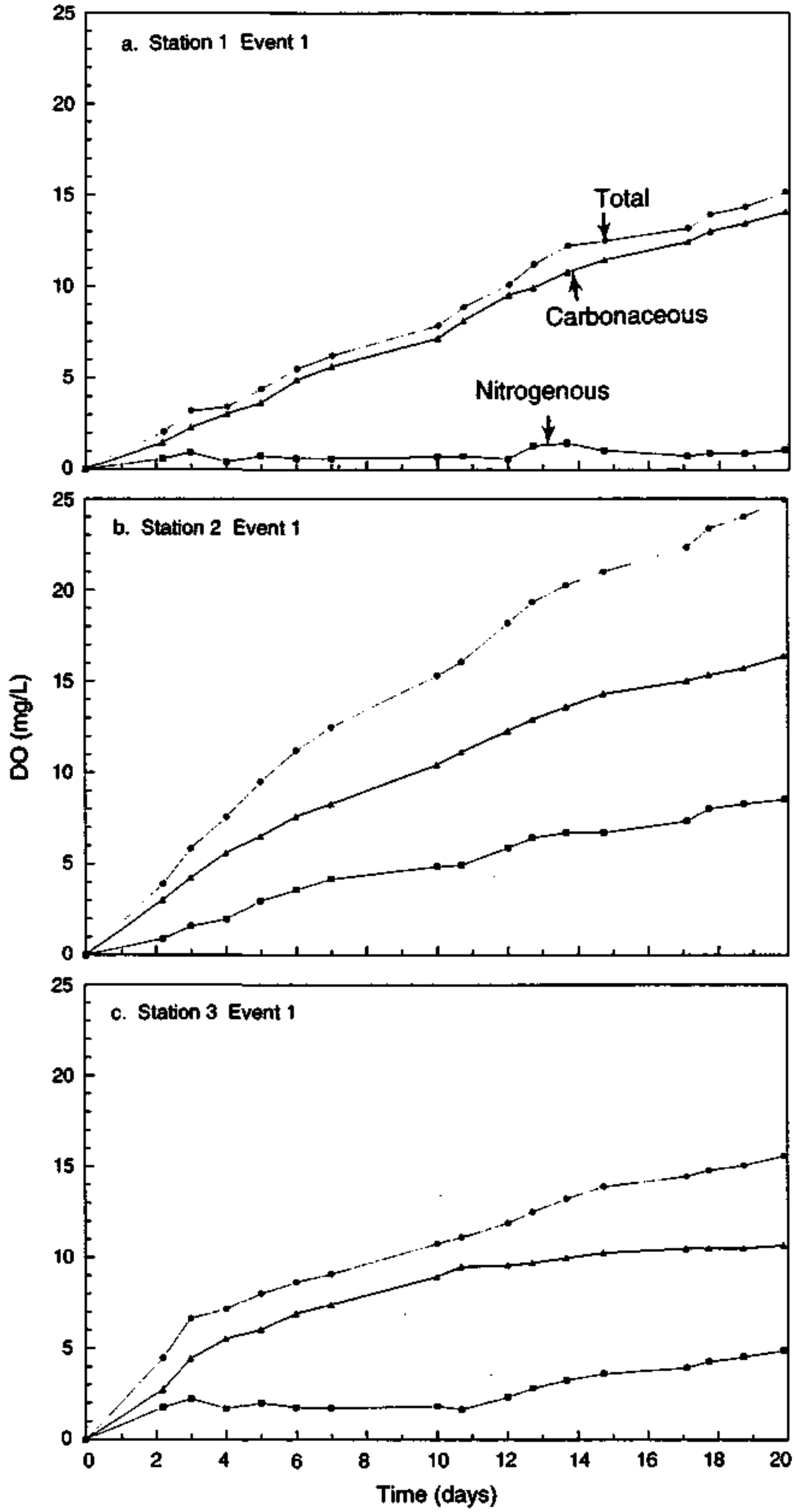


Figure 14. DO usage by BOD at WQ stations during event 1

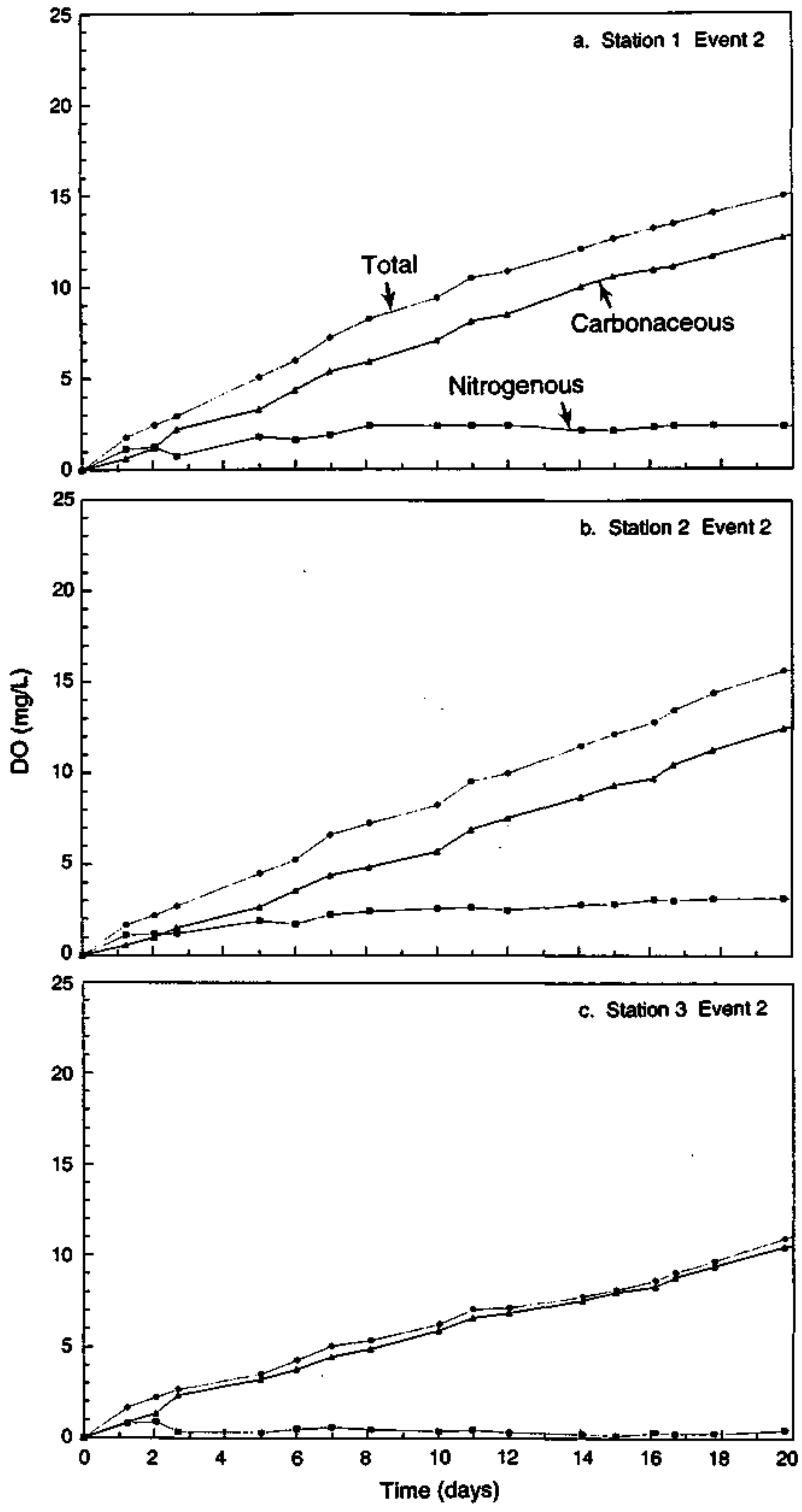


Figure 15. DO usage by BOD at WQ stations during event 2

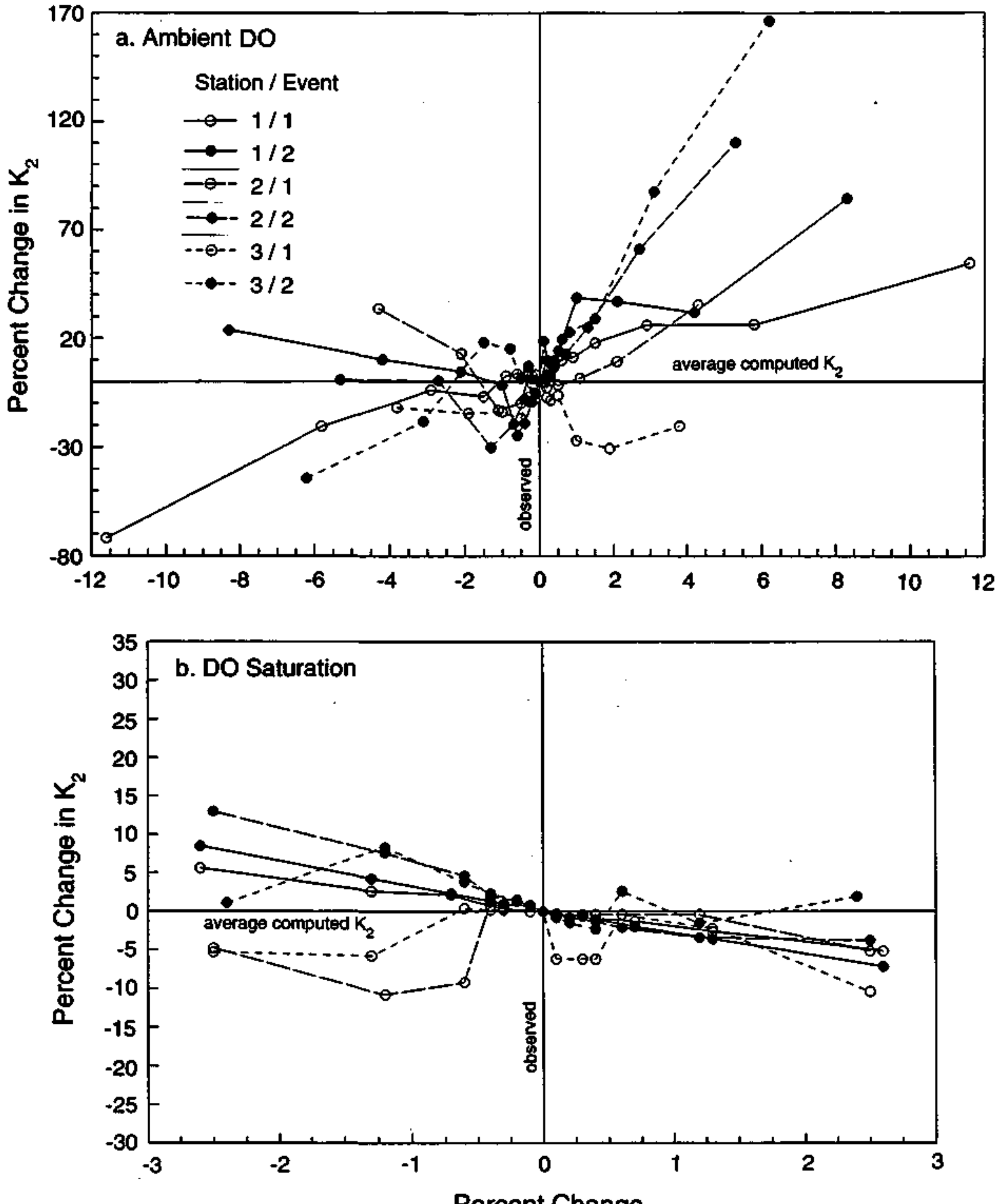
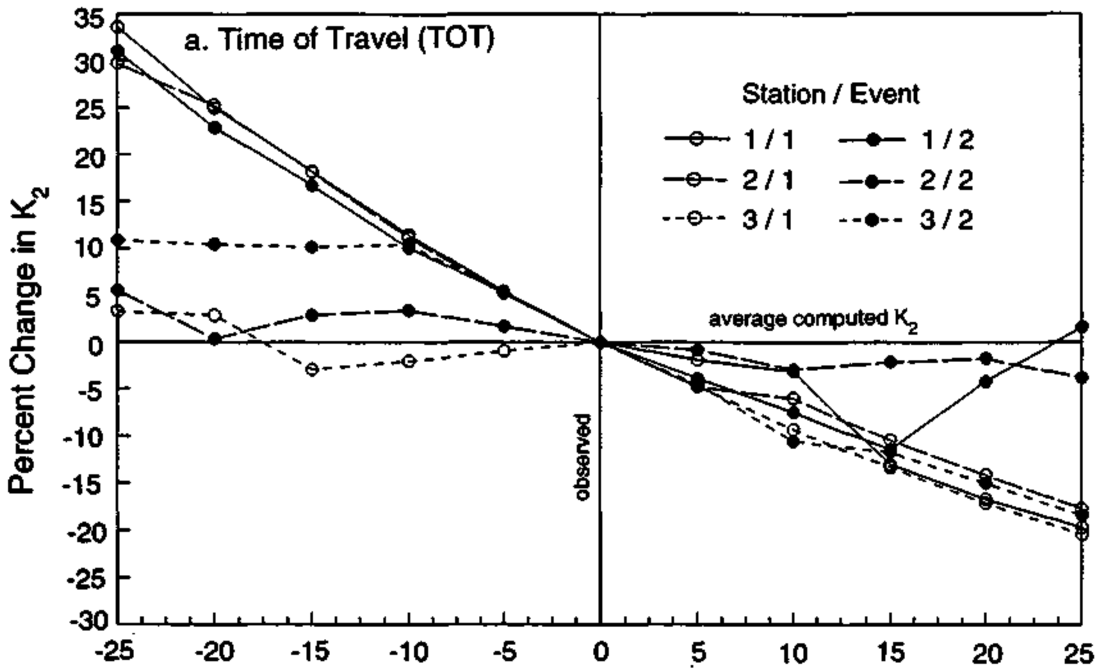


Figure 16. Sensitivity analyses: K_2 versus ambient DO and saturation DO



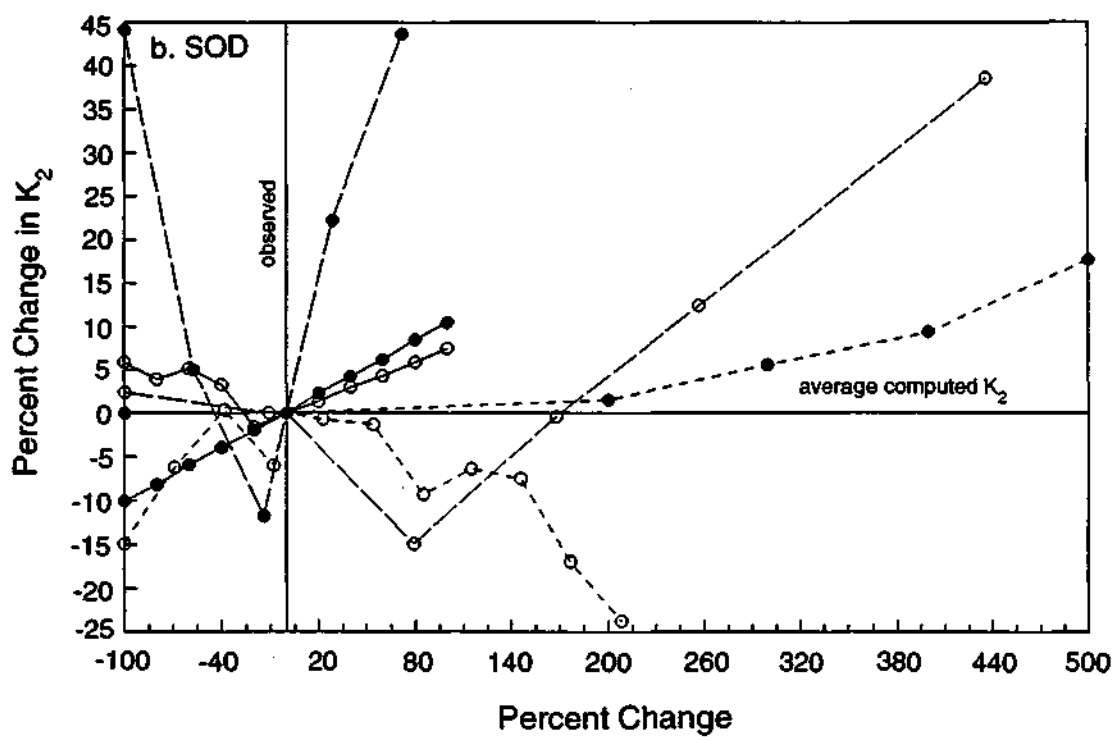


Figure 17. Sensitivity analyses: K_2 versus time of travel and SOD

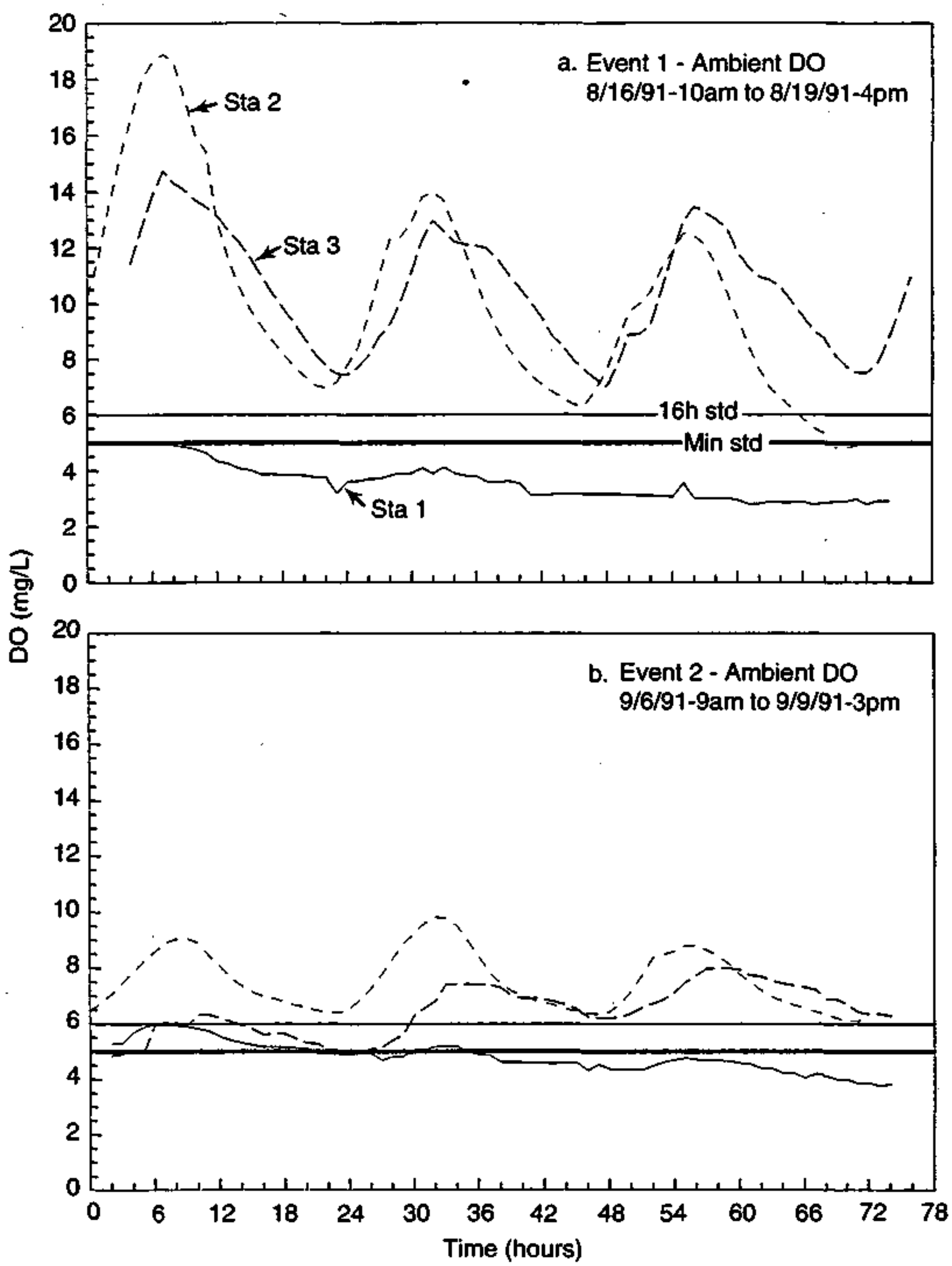


Figure 18. Violations of DO standards at WQ stations during events 1 and 2

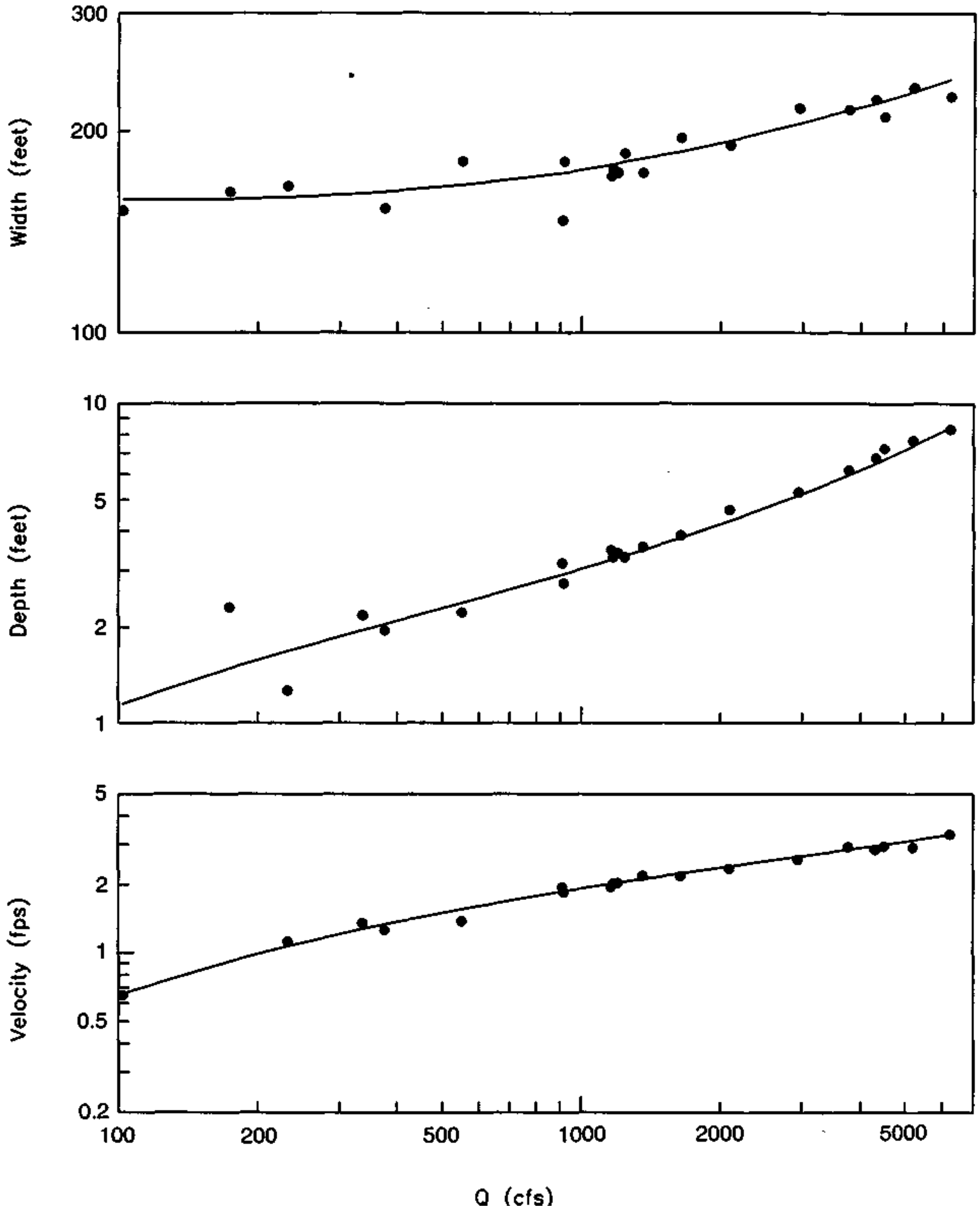


Figure 19. Station hydraulic geometry, Sangamon River at Petersburg

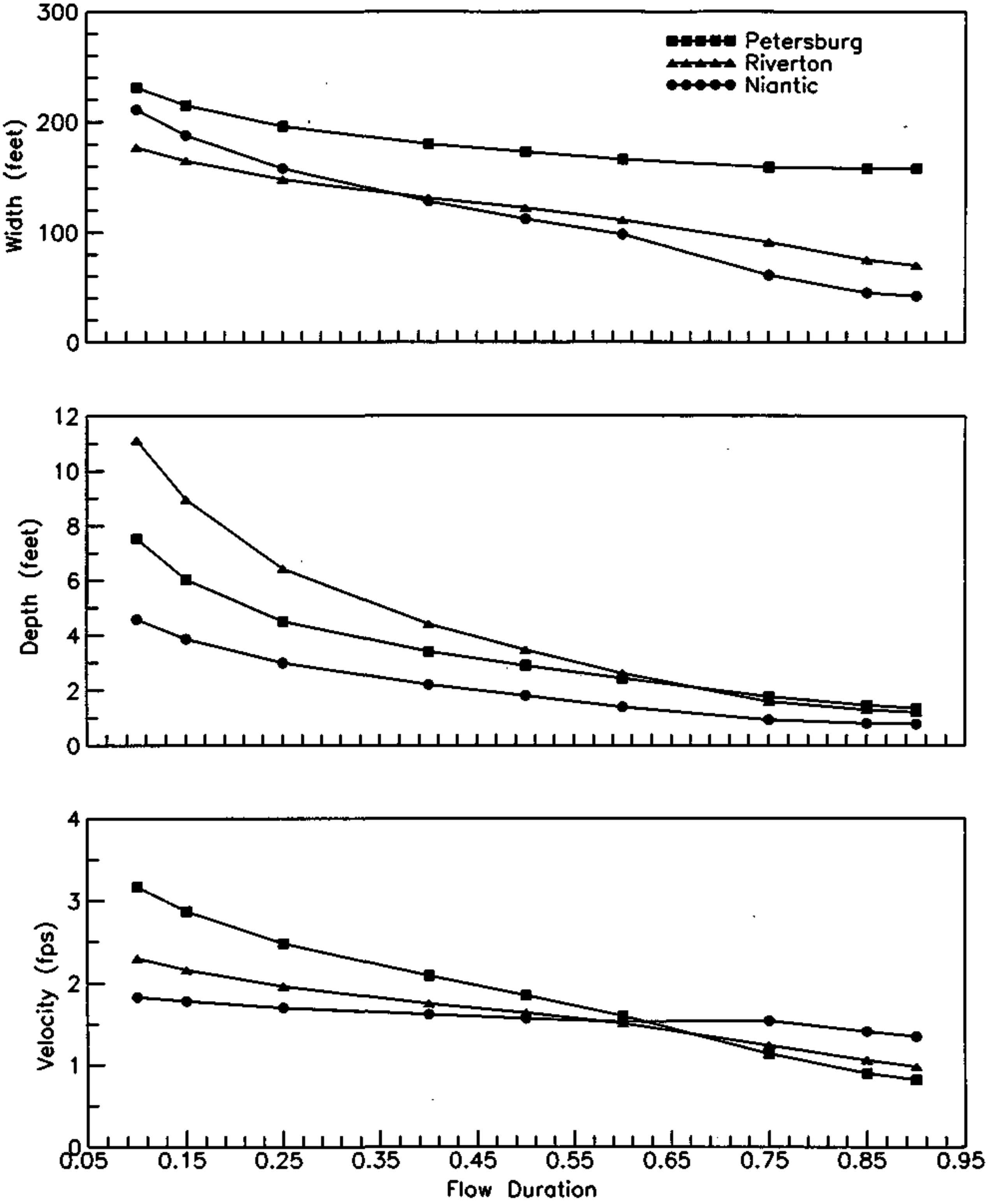


Figure 20. Hydaulic geometry parameters versus flow duration
at three Sangamon River gaging stations

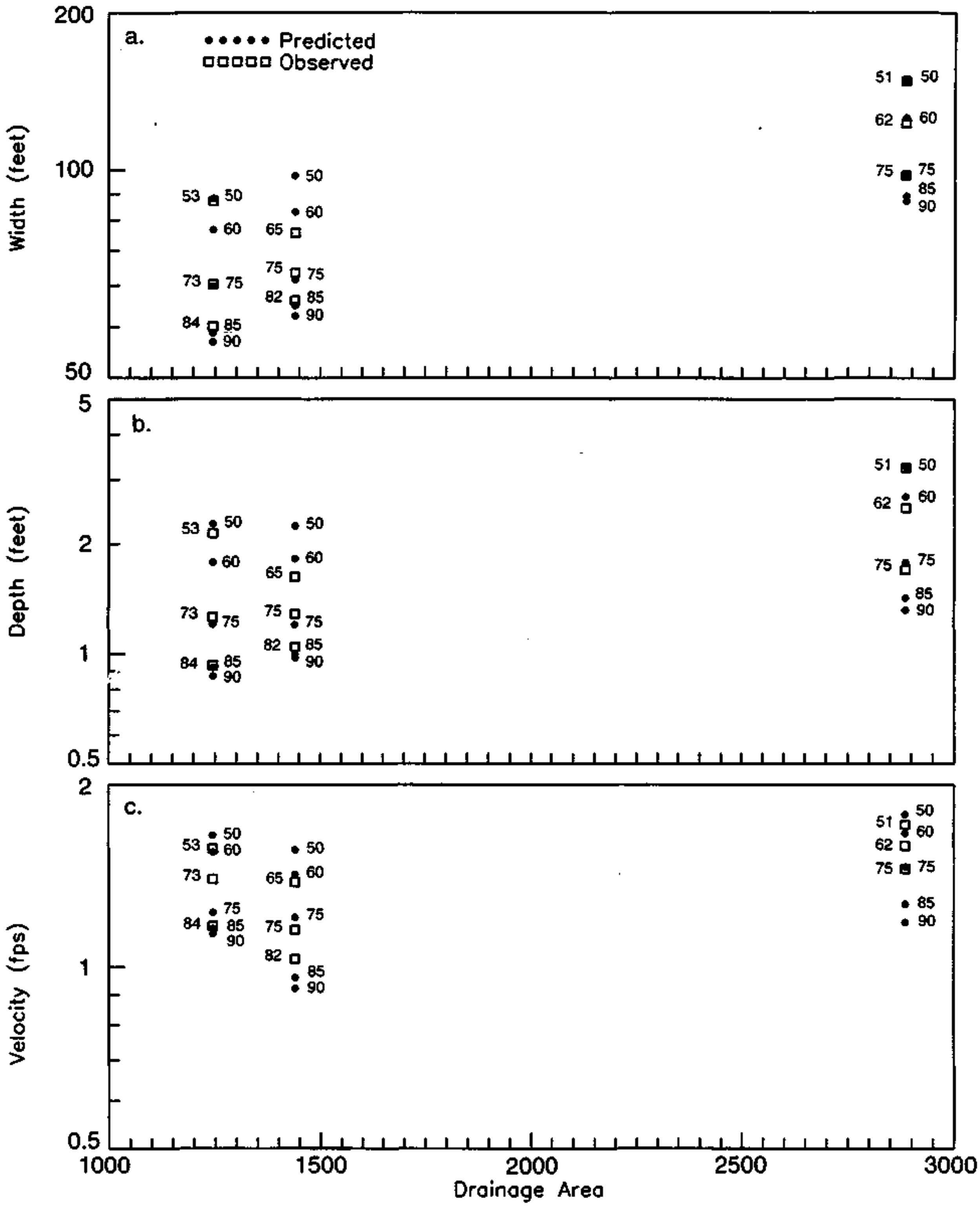


Figure 21. Observed and predicted hydraulic geometry parameters for the study reaches

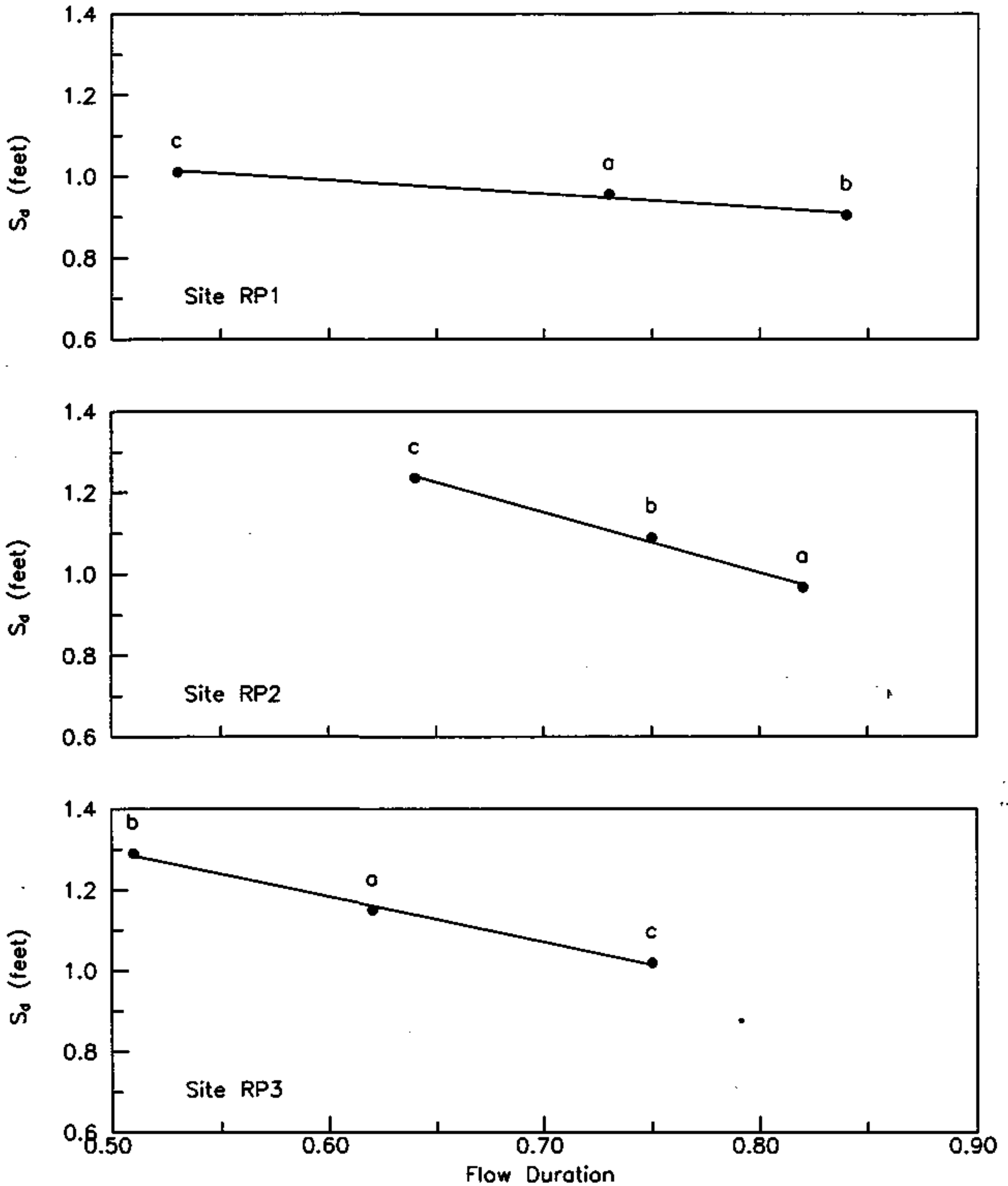


Figure 22. Standard deviation of depth (S_d) versus flow duration for the study reaches (a,b, and c refer to the three field measurements of flows)

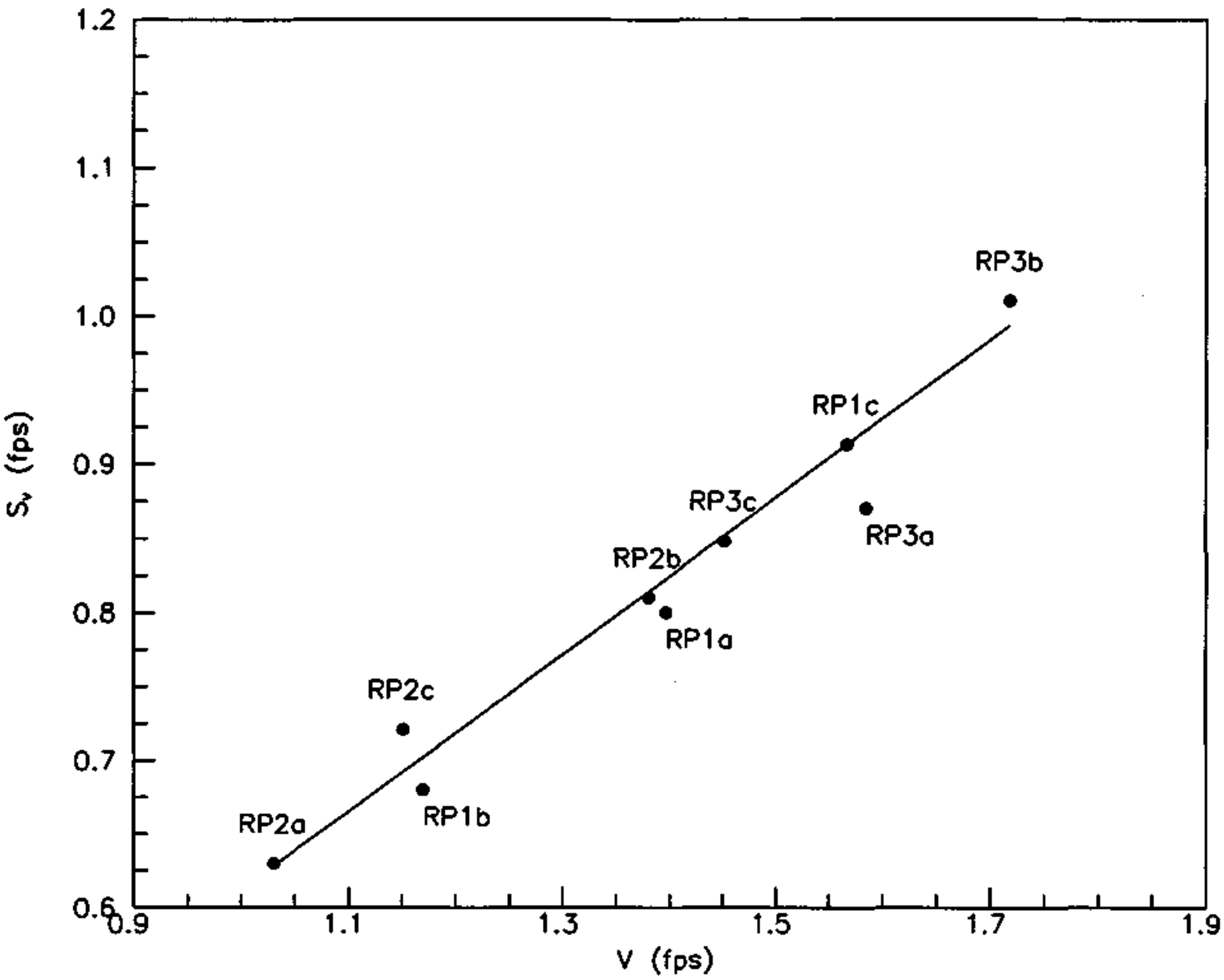


Figure 23. Standard deviation of velocity (S_v) versus mean reach velocity (V)

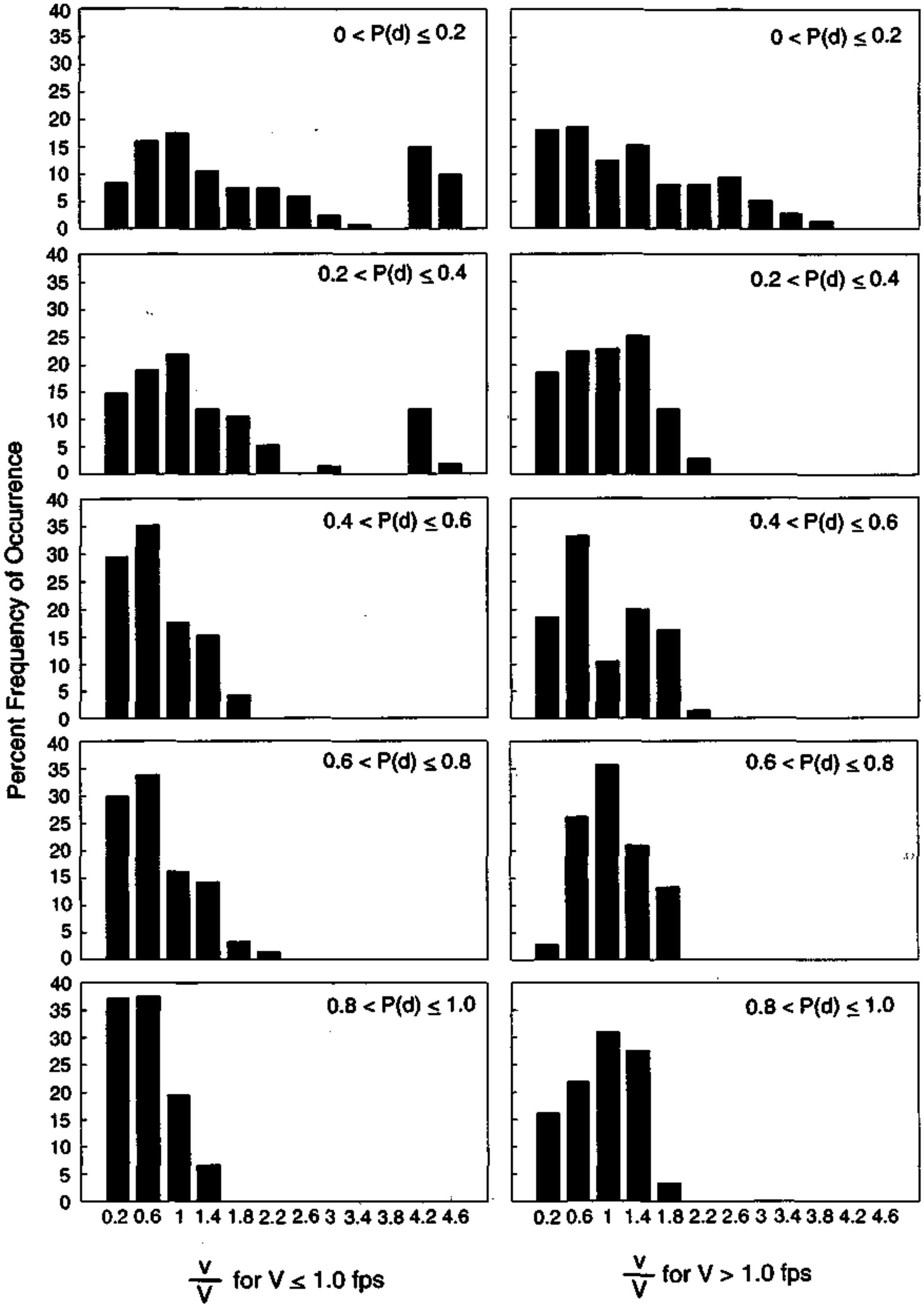


Figure 24. Frequency of occurrence of normalized velocities, v/V, for specified depth probability intervals

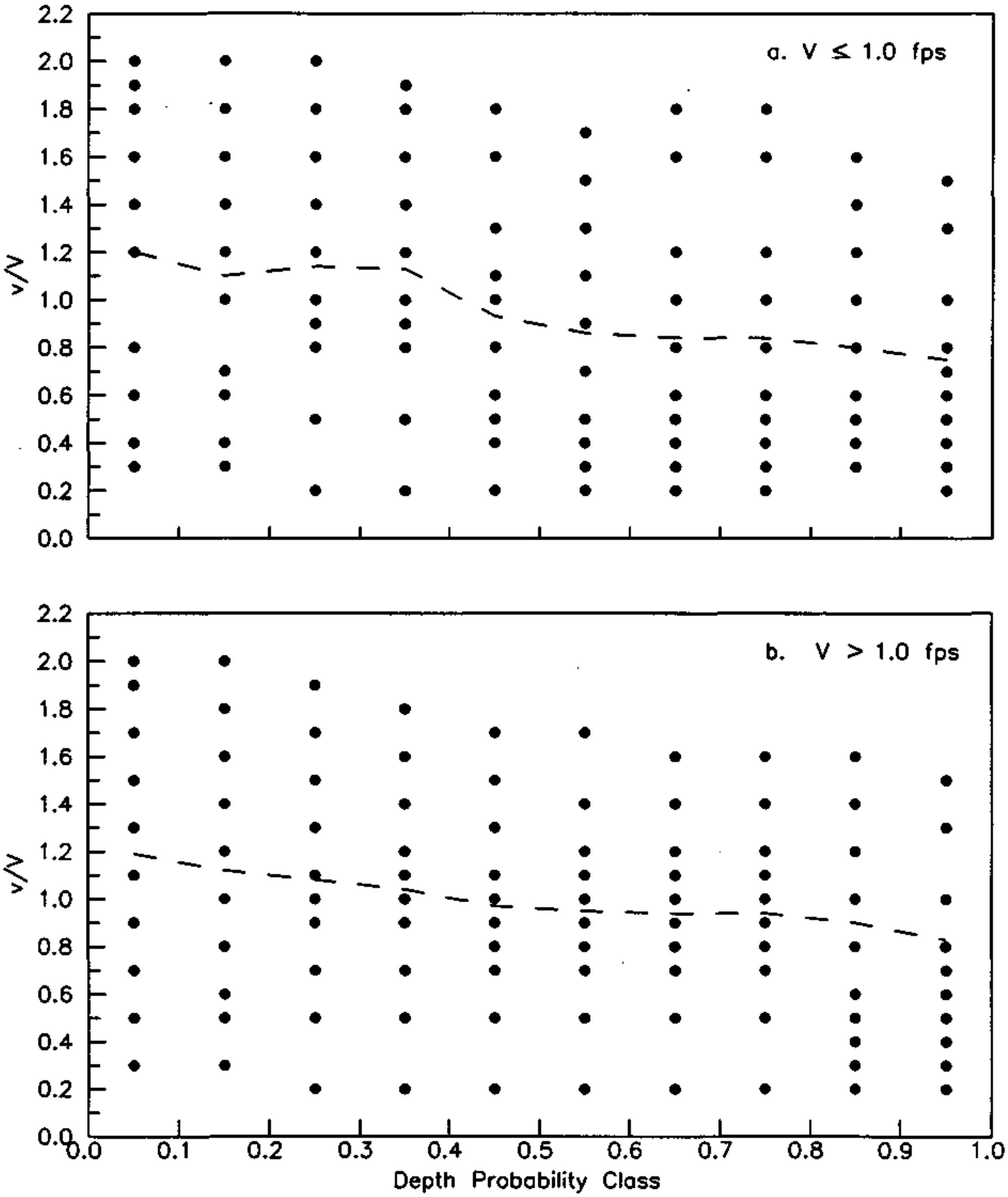


Figure 25. Non-dimensional joint distribution of velocities and depths

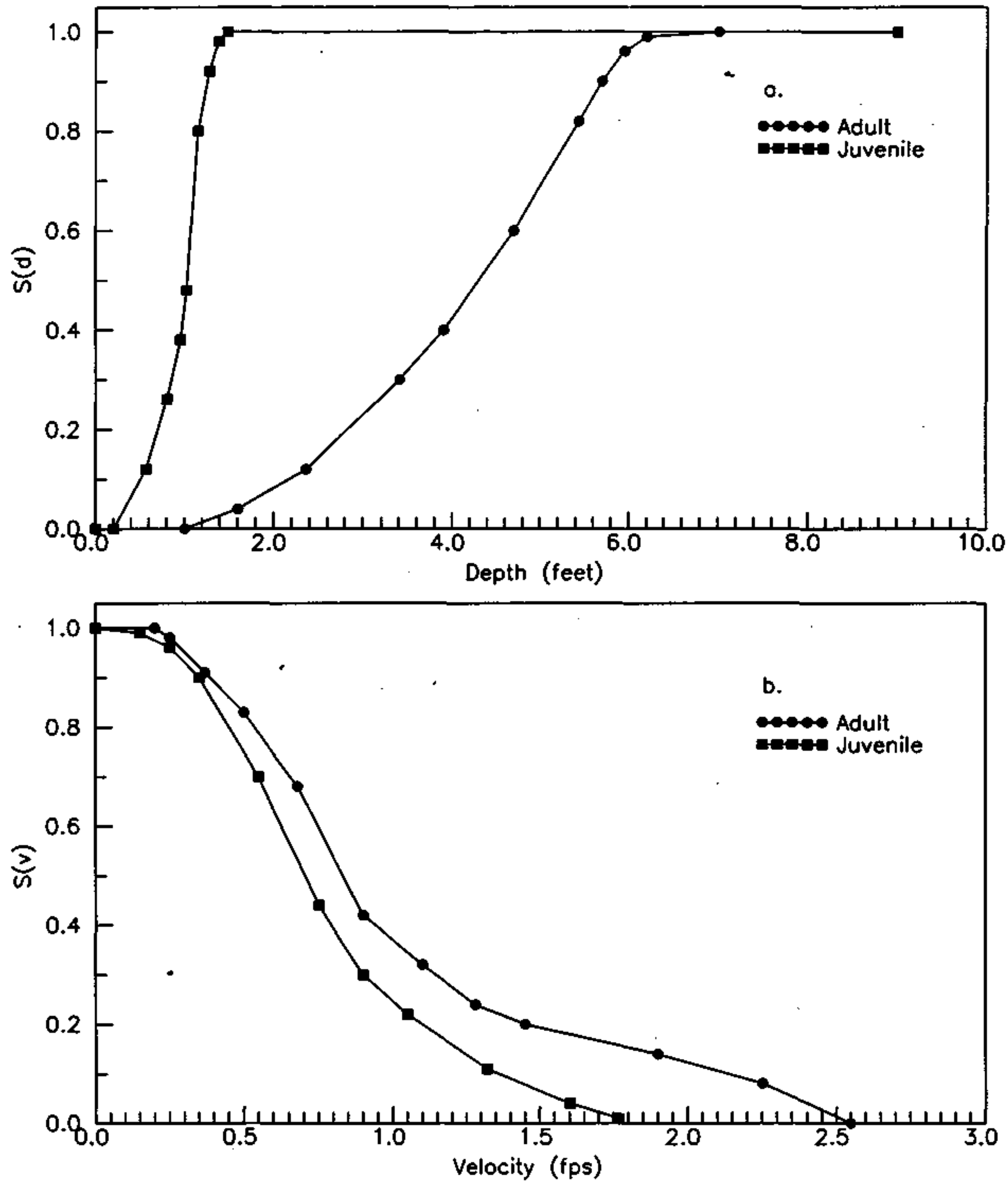


Figure 26. Depth and velocity suitability curves for adult and juvenile smallmouth bass

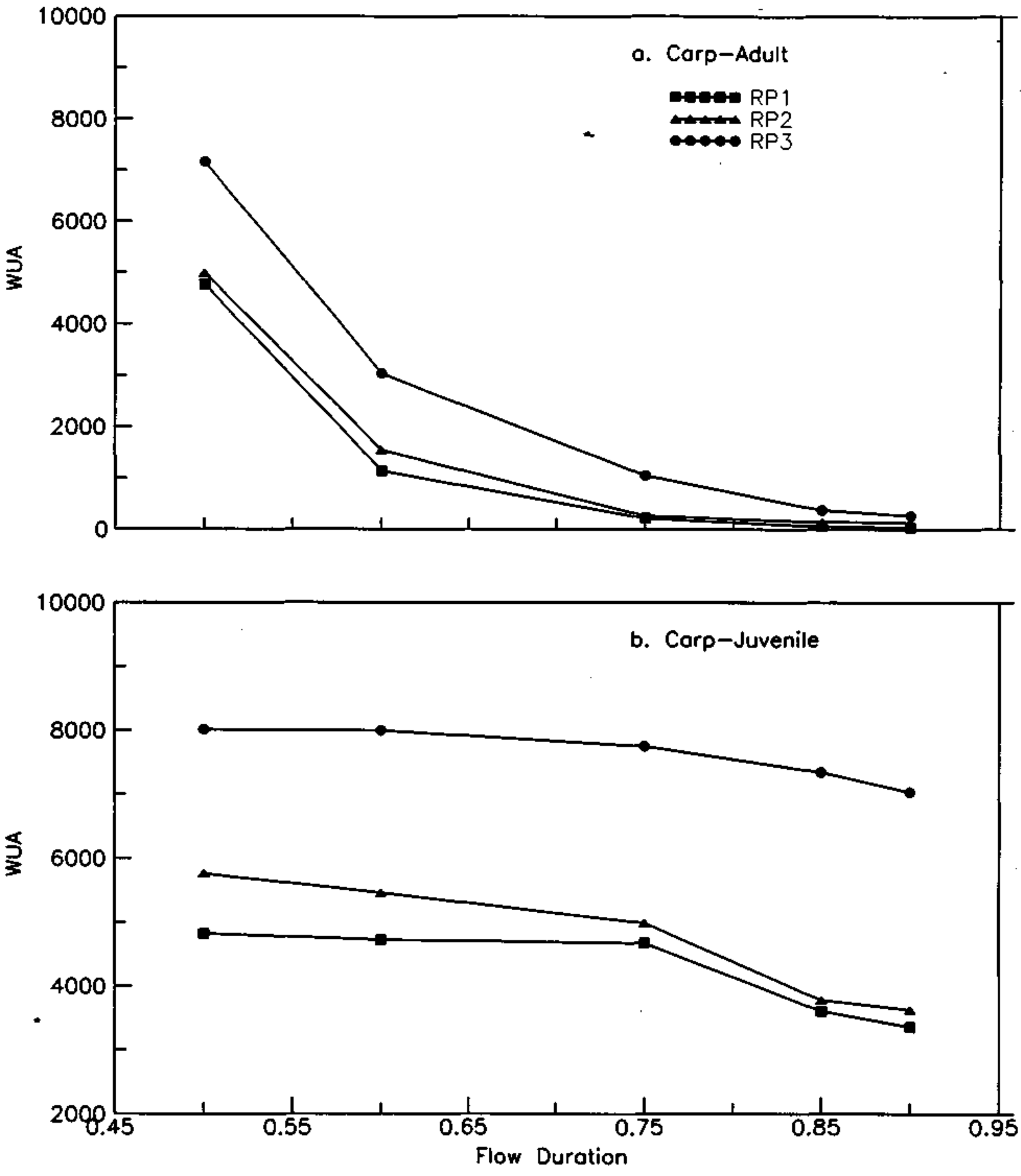


Figure 27. WUA versus flow duration for carp in the study reaches

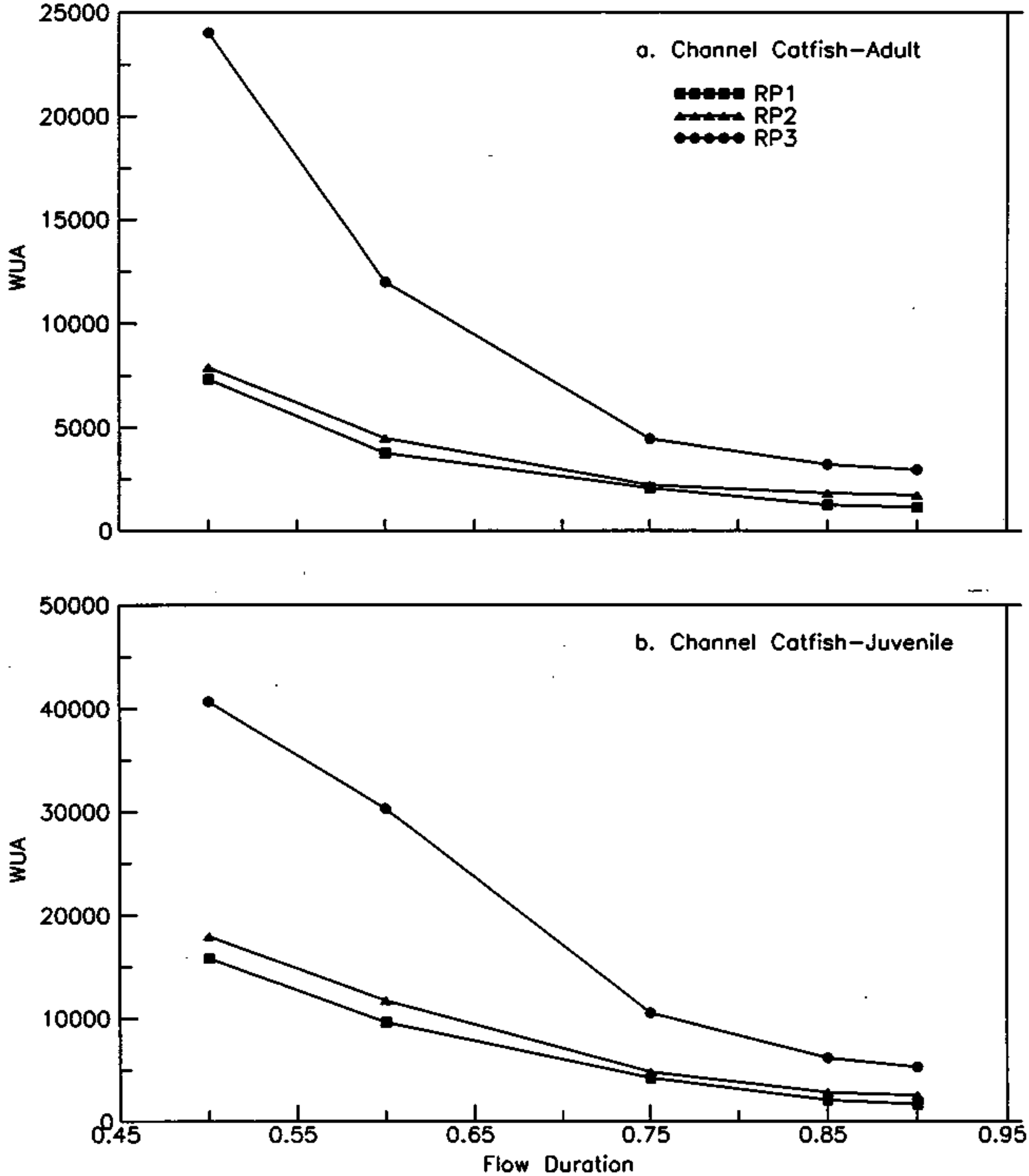


Figure 28. WUA versus flow duration for channel catfish in the study reaches

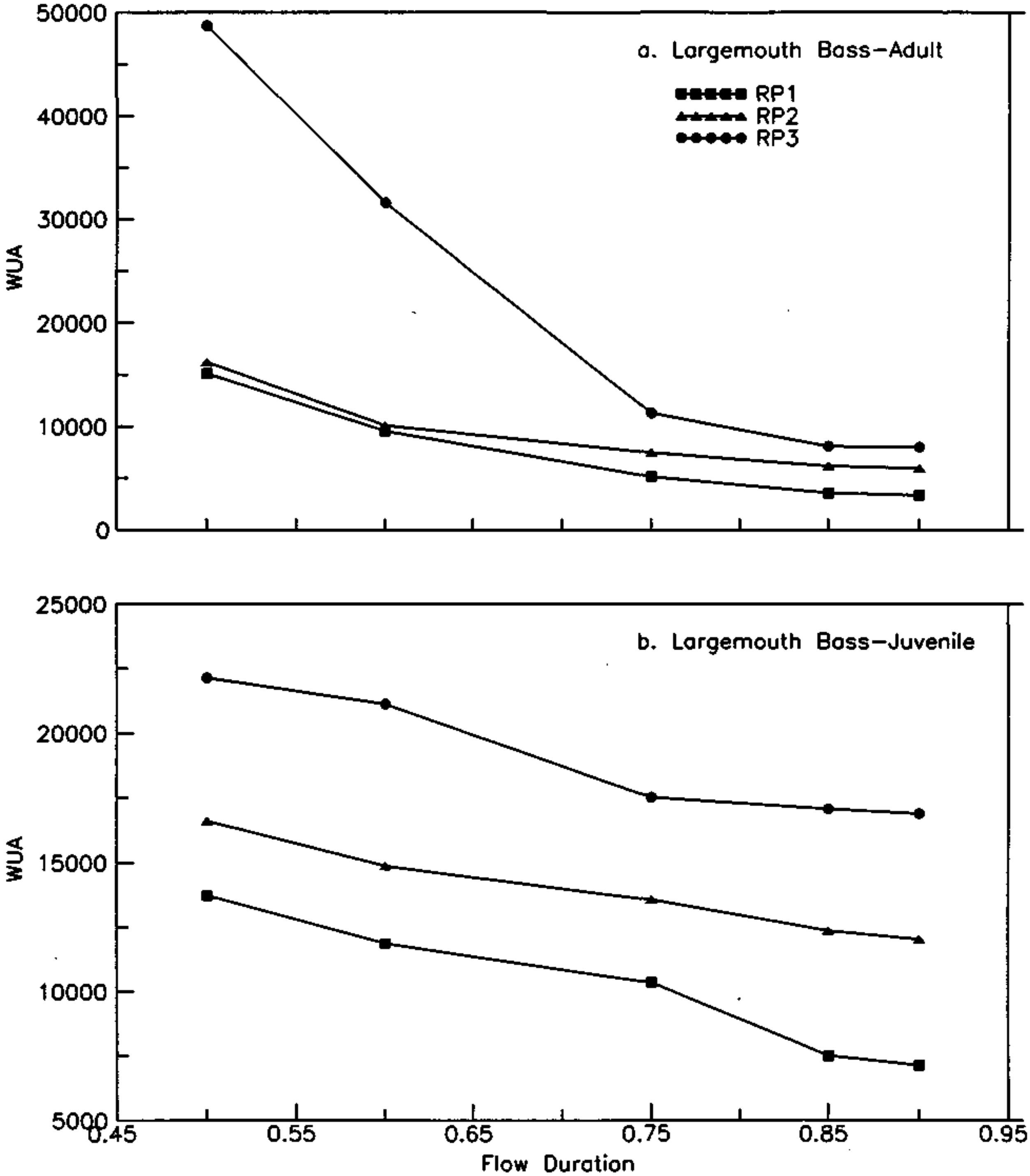


Figure 29. WUA versus flow duration for largemouth bass in the study reaches

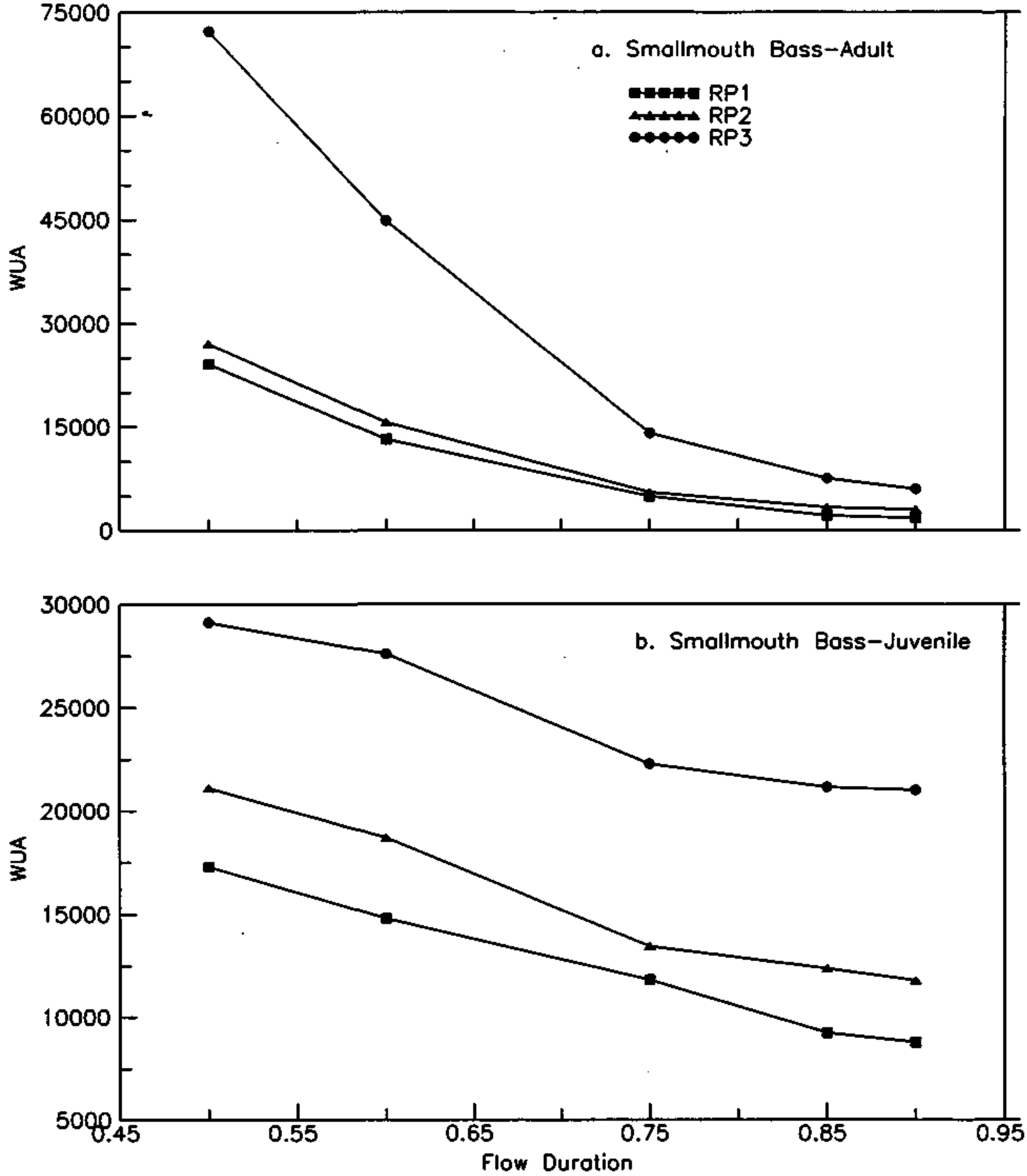


Figure 30. WUA versus flow duration for smallmouth bass in the study reaches

TABLES

Table 1. Summary of Ambient Water Quality Conditions, Sangamon River - 1991

Parameter		Site WQ1 8/16	Site WQ1 9/16	Site WQ2 8/16	Site WQ2 9/6	Site WQ3 8/16	Site WQ3 9/6
Flow(cfs)		33.27	41.80	58.68	51.49	145.30	165.01
Velocity (fps)		0.15	0.20	0.77	0.82	0.34	0.39
Average depth (ft)		2.61	2.50	1.23	0.93	2.33	2.85
Maximum depth (ft)		3.12	3.12	1.75	2.00	3.67	4.33
Width (ft)		87	85	62	68	181	150
Turbidity (NTU)		26	49	44	47	47	101
Suspended solids (mg/L)		37	48	50	38	51	82
pH(Lab)		7.90	7.86	8.61	8.10	8.72	7.87
Total $P0_4$-P (mg/L)		7.38	4.40	2.98	3.11	1.33	1.28
Dissolved NH_3-N (mg/L)		0.50	0.58	0.09	0.18	0.08	0.16
Dissolved $N0_3$-N (mg/L)		9.39	7.60	4.32	8.62	5.09	7.56
$TBOD_{20}$ (mg/L)		15.19	15.35	24.95	15.89	15.62	11.64
$CBOD_{20}$ (mg/L)		14.10	13.17	16.40	12.73	10.69	10.85
$NBOD_{20}$ (mg/L)		1.09	2.18	8.55	3.16	4.93	0.79
$TBOD_5$ (mg/L)		4.45	5.05	9.51	4.53	8.04	3.54
$CBOD_5$ (mg/L)		3.69	3.28	6.52	2.64	6.03	3.24
$NBOD_5$ (mg/L)		0.76	1.77	2.99	1.89	2.01	0.30
Temperature (° C)	72-hr min	26.25	24.77	22.73	22.14	24.12	23.48
	avg	27.70	26.94	25.32	24.26	25.92	25.00
	max	29.33	28.53	28.52	26.96	27.50	26.57
pH	72-hr min	7.52	7.47	7.73	7.56	8.05	7.37
	avg	7.57	7.61	8.17	7.74	8.52	7.59
	max	7.66	7.75	8.83	7.98	8.80	7.85
Conductivity	72-hr min	2.94	2.20	2.13	1.18	0.85	0.63
(ms/cm)	avg	3.10	2.56	2.36	1.63	0.97	0.88
	max	3.27	2.89	2.57	2.62	1.07	1.24
DO (mg/L)	72-hr min	2.77	3.76	4.82	6.09	7.03	4.85
	avg	3.48	4.81	10.15	7.53	10.46	6.45
	max	4.89	6.00	18.89	9.83	14.75	8.01
DO saturation	72-hr min	7.37	7.49	7.50	7.72	7.65	7.93
(mg/L)	avg	7.60	7.71	7.97	8.13	7.88	8.18
	max	7.81	8.04	8.37	8.47	8.16	8.42
Salinity (ppt)	72-hr min	1.13	0.71	0.67	0.13	0.00	0.00
	avg	1.22	0.92	0.80	0.39	0.03	0.03
	max	1.32	1.10	0.92	0.95	0.07	0.16

Parameter values for sites

Table 2. Stream Flows, Wastewater Treatment Plant (WTP) Discharges, and Precipitation

		Flow (cfs)									
		Decatur gage Sang R.	Decatur Stevens Cr. WTP	Site WQ1 Sang R	Site WQ2 Sang R	Springfield Sugar Cr. WTP	Riverton gage Sang R.	Springfield Spring Cr. WTP	Site WQ3 Sang R.	Precipitation (in)	
Event	Date/mile	129.0	126.4	124.5	102.5	85.3	83.1	73.4	59.9	Decatur	Riverton
1	8/12/91	1.1	23.1			10.8	149.0	22.3		-	-
	8/13/91	0.6	23.5			10.2	126.0	21.5		-	-
	8/14/91	0.4	23.6			8.5	116.0	21.3	145.3	-	-
	8/15/91	0.3	22.7			9.1	112.0	20.8		-	-
	8/16/91	0.3	22.3	33.3	58.7	8.7	108.0	21.3		-	-
	8/17/91	0.5	23.6			9.0	103.0	21.4		0.02	0.16
	8/18/91	0.3	23.9			9.1	100.0	24.0		-	0.49
	8/19/91	0.4	22.8			8.5	97.0	19.8		0.07	-
2	9/02/91	1.0	25.1			12.7	120.0	36.9		-	0.23
	9/03/91	10.0	36.4			21.2	134.0	98.9		-	1.92
	9/04/91	4.1	27.6			11.6	136.0	39.7		0.82	0.05
	9/05/91	1.5	25.5			8.5	145.0	27.8		-	-
	9/06/91	0.7	25.1			7.9	124.0	24.0		-	-
	9/07/91	0.4	23.5			7.7	110.0	22.3		-	0.42
	9/08/91	0.1	23.8			8.6	104.0	31.9		-	-
	9/09/91	<0.1	26.5	41.8	51.5	17.9	96.0	50.8	165.0	0.04	-

Table 3. Comparison of Study Area $TBOD_{20}$ and $TBOD_5$ Values with Those of Other Central and Northeastern Illinois Streams for Warm Weather/Low Flow Conditions During Mid-August

Water Course	$TBOD_5$ (mg/L)	$TBOD_{20}$ (mg/L)	$TBOD_5/TBOD_{20}$ (%)
Dlinois Waterway at Lockport	3.0	9.6	31
Des Plaines River*	4.1	10.9	38
DuPage River*	4.4	11.9	37
Kankakee River*	2.3	7.1	32
Fox River*	11.5	30.2	38
Vermilion River*	4.0	12.0	33
Sangamon River Site WQ1	4.5	15.2	30
Sangamon River Site WQ2	9.5	26.0	37
Sangamon River Site WQ3	8.0	15.6	51

Note:
* **Above mouth of river.**

Table 4. Comparison of Water Quality Parameters at Site WQ1 with Those for Decatur and Springfield Wastewater Effluents

	August 16, 1991				September 9, 1991			
	Sangamon River	Decatur	Springfield WTPs		Sangamon River	Decatur	Springfield WTPs	
Parameter	Site WQ1	WTP	Sugar Cr.	Spring Cr.	Site WQ1	WTP	Sugar Cr.	Spring Cr.
Flow (cfs)	33.30	22.25	8.66	21.33	41.80	26.51	17.87	50.83
pH	7.57	7.72	7.80	7.60	7.61	7.74	7.60	7.80
Suspended Solids (mg/L)	37.00	13.00	12.00	4.00	48.00	4.20	9.00	10.00
Total PO_4-P (mg/L)	7.38	8.95	-	-	4.40	5.34	-	-
NH_3-N (mg/L)	0.50	0.43	0.75	1.10	0.58	0.00	1.50	1.40
NO_3-N (mg/L)	9.39	9.22	-	-	7.60	11.10	-	-
$TBOD_5$ (mg/L)	4.45	5.90	-	-	5.06	2.60	-	-
$CBOD_5$ (mg/L)	3.69	4.70	4.00	2.00	3.28	1.80	3.00	1.00
$NBOD_5$ (mg/L)	0.76	1.20	-	-	1.77	0.80	-	-
DO (mg/L)	3.48	-	6.90	4.60	4.81	-	6.10	3.50
Temperature (°C)	27.70	23.20	-	-	26.94	22.50	-	-
Conductivity (ms/cm)	3.10	3.30	-	-	2.56	2.84	-	-

Table 5. Algae Identification and Enumeration, Sangamon River - 1991

		Cell counts (#/mL) for sites					
		WQ1		WQ2		WQ3	
Classification	Genus/Species	8/16	9/6	8/16	9/6	8/16	9/6
Blue green	*Aphanizomenon flos-aquae*						40
	Oscillatoria sp.				19		
Green	*Coelastrum microporum*			11		8	
	Crucigenia rectangularis			59		63	
	Crucigenia tetrapdia					8	
	Oocystis borgei			13			
	Pediastrum duplex		29		17		
	Pediastrum simplex	19				8	
	Schedesmus dimorphus	32		23	13	11	25
Diatom	*Caloneis amphisbaena*	15			15		
	Cyclotella ocellata			113			
	Cymbella postrata	6					
	Gyrosigma kutzingii	21					6
	Gyrosigma macrum			25			
	Melosira granulata	42	29				
	Navicula cryptocephala	118	48				
	Surirella ovata			8			
Flagellate	*Euglena gracilis*			57			
	Euglena viridis		13				
	Phacus pleuronectes			6	4	4	
	Trachelomonas crebea		15				
	Total (cells/mL)	253	134	177	206	102	71
	Total taxa	7	5	7	7	6	3
	S-W Diversity Index	2.27	2.17	2.33	2.10	1.82	1.30

Table 6. Study Area Conductivity and Salinity Values Compared to Other Central and Northeastern Illinois Stream Values

	Conductivity Range (ms/cm)		Salinity Range (ppt)	
Water Course	Mid-August	Early-September	Mid-August	Early September
Chicago S. & S. Canal at Lockport	0.593-0.812	0.613-1.030	0.000-0.000	0.000-0.047
Illinois River at Starved Rock	0.202-1.126	0.243-1.290	0.000-0.101	0.000-0.195
Upper Sangamon R. Site 1	0.683-0.739	0.566-0.639	0.000-0.000	0.000-0.000
Upper Sangamon R. Site 2	0.697-0.716	0.541-0.621	0.000-0.000	0.000-0.000
Upper Sangamon R. Site 3	0.596-0.659	0.595-0.620	0.000-0.000	0.000-0.000
Lower Sangamon R. Site WQl	2.939-3.274	2.199-2.886	1.130-1.320	0.710-1.100
Lower Sangamon R. Site WQ2	2.128-2.569	1.182-2.622	0.670-0.920	0.130-0.950
Lower Sangamon R. Site WQ3	0.849-1.073	0.634-1.236	0.000-0.070	0.000-0.160
Decatur WTP Effluent	2.750-3.300	2.300-2.840	--	--

Table 7. Sediment Oxygen Demand (SOD) Rates

		Time (hrs)			Gross SOD ($g/m^2/day$) at			Dark Chamber ($g/m^2/day$) at			Net SOD ($g/m^2/day$) at		
Station	Event	Start	Stop	T° C	T° C	20° C	25° C	T° C	20° C	25° C	T° C	20° C	25° C
WQ1	1	0	12	28.9	2.80	1.86	2.34	3.60	2.40	3.01	-0.80	-0.54	-0.67
		2	12	29.1	3.02	1.99	2.50	4.26	2.80	3.53	-1.24	-0.81	-1.03
		0	9	28.8	3.46	2.30	2.90	3.64	2.43	3.05	-0.18	-0.13	-0.15
		2	9	29.2	3.96	2.59	3.26	4.60	3.01	3.78	-0.64	-0.42	-0.52
	2	-	-	-	-	-	-	-	-	-	-	-	-
WQ2	1	0	29	26.4	5.23	3.91	4.92	4.27	3.19	4.01	0.96	0.72	0.91
		0	23	26.5	6.32	4.69	5.90	4.42	3.28	4.13	1.90	1.41	1.77
		10	29	25.8	5.66	4.35	5.46	2.97	2.28	2.87	2.69	2.07	2.59
		10	23	25.8	7.80	5.99	7.53	6.04	4.64	5.83	1.76	1.35	1.70
	2	0	12	25.0	7.69	6.10	7.68	2.00	1.59	2.00	5.69	4.51	5.68
		0	7	24.3	12.02	9.86	12.41	2.20	1.80	2.27	9.82	8.06	10.14
WQ3	1	0	17	26.9	4.69	3.42	4.30	4.36	3.17	3.99	0.33	0.25	0.31
		7	17	26.7	5.56	4.09	5.14	4.73	3.47	4.37	0.83	0.62	0.77
	2	2	36	25.4	2.00	1.56	1.96	2.26	1.76	2.22	-0.26	-0.20	-0.25
		2	26	25.0	2.17	1.73	2.18	2.10	1.67	2.11	0.07	0.06	0.07
		10	36	25.7	2.09	1.61	2.02	2.27	1.74	2.19	-0.18	-0.13	-0.17

Table 8. Reaeration Coefficients (K_2) Computed Using Observed Field Data

Study	Site	Event	Number Useable*	K_2 (day^{-1}) Minimum	Average	Maximum	Std. dev.
Present	WQ1	1	32	0.06	3.05	7.40	2.41
		2	22	0.64	3.06	7.35	2.16
	WQ2	1	30	0.02	2.49	8.07	2.27
		2	44	0.07	2.38	7.67	1.65
	WQ3	1	21	0.62	4.51	9.99	2.90
		2	45	0.14	2.66	8.90	2.50
Broeren	1	1	36	0.14	5.39	9.99	4.20
etal.,		2	34	0.34	6.96	9.99	3.53
1991	2	1	49	0.26	4.15	9.99	3.08
		2	33	0.27	7.65	9.99	3.62
	3	1	35	0.36	6.67	9.99	3.69
		2	41	1.19	6.33	9.99	3.33

Note:
*** Denotes the number of hourly DataSonde measured values used in K_2 determinations.**

Table 9. Reaeration Coefficients

Study	Site	Event	K_2 (day^{-1}) Langbein & Durham (eq. 10)	Churchill et al. (eq. 11)	O'Connor & Dobbins (eq. 12)
Present	WQ1	1	0.32	0.37	1.19
		2	0.45	0.53	1.47
	WQ2	1	4.46	6.35	8.36
		2	6.89	10.78	8.63
	WQ3	1	0.84	0.99	2.13
		2	0.74	0.81	2.32
Broeren et al., 1991	1	1	7.62	12.19	14.59
		2	6.71	11.41	15.50
	2	1	13.41	22.20	21.67
		2	26.83	53.64	48.38
	3	1	1.76	2.05	3.20
		2	3.15	4.46	6.76

Table 10. Calculated Primary Productivity

Station	Event	Start Date	Start Time	Stop Date	Stop Time	Hours	T (° C)	GPP at T° C	GPP at 20° C	GPP at 25° C	NPP at T° C	NPP at 20° C	NPP at 25° C
WQ1	1	8/16	12:00	8/17	12:00A	12	28.8	-1.21	-0.81	-1.02	-4.52	-3.02	-3.80
	2	9/06	11:00	9/07	11:00A	24	26.6	-0.22	-0.16	-0.20	-3.61	-2.66	-3.35
WQ2	1	8/16	10:00	8/17	10:00	24	26.2	5.18	3.89	4.90	0.77	0.58	0.73
		8/17	10:00	8/18	10:00	24	25.1	4.85	3.84	4.83	0.39	0.31	0.39
		8/18	10:00	8/19	10:00	24	24.6	4.67	3.78	4.75	0.21	0.17	0.21
	2	9/06	9:00	9/07	9:00	24	24.5	0.91	0.70	0.87	-1.56	-1.27	-1.60
		9/07	9:00	9/08	9:00	24	24.6	1.21	0.97	1.22	-0.57	-0.47	-0.59
		9/08	9:00	9/09	9:00	24	23.6	1.63	1.37	1.73	-0.15	-0.13	-0.16
WQ3	1	8/16	14:00	8/17	14:00	24	26.6	0.24	0.18	0.22	-3.39	-2.50	-3.15
		8/17	14:00	8/18	14:00	24	26.0	0.29	0.21	0.27	-2.34	-1.78	-2.24
		8/18	14:00	8/17	14:00	24	26.6	0.24	0.18	0.22	-3.39	-2.50	-3.15
	2	9/06	11:00	9/07	11:00	24	24.9	0.03	0.02	0.03	-2.18	-1.74	-2.19
		9/07	11:00	9/08	11:00	24	25.4	0.96	0.75	0.94	-1.66	-1.29	-1.63

Notes:
GPP = Gross Primary Productivity
NPP = Net Primary Productivity

Table 11. Abridged K_2 Sensitivity Analysis Results

		Maximum absolute percent change in K_2 due to a											
		0.5% change in				2.5% change in				5% change in			
Station	Event	DO_a	DO_s	TOT	SOD	DO_a	DO_s	TOT	SOD	DO_a	DO_s	TOT	SOD
1	1	8.2	1.2	0.5	0.0	23.6	5.5	2.7	0.2	26.1	11.0	5.4	0.4
	2	14.6	1.6	0.5	0.1	35.9	6.2	2.6	0.3	42.0	16.7	5.2	0.6
2	1	10.0	5.2	0.5	0.1	16.6	5.2	2.6	0.2	36.0	10.4	5.2	0.9
	2	11.9	3.4	0.2	0.4	57.9	13.0	0.9	2.1	99.0	26.0	1.7	4.2
3	1	17.1	3.3	0.5	0.4	27.6	10.4	2.4	1.9	14.2	20.8	4.7	3.8
	2	14.2	3.1	0.5	0.0	51.1	2.0	2.7	0.0	135.9	2.0	5.3	0.1
Average		12.7	3.0	0.5	0.2	26.3	7.1	2.3	0.8	58.9	14.5	4.6	1.7

Notes:
DO_a = ambient DO, DO_s = saturation DO, TOT = time of travel, SOD = sediment oxygen demand.

Table 12. Station Hydraulic Geometry Coefficients at Three Gages for
$Log(var) = a_0 + a_1(\log Q) + a(\log Q)^2 + a_3(\log Q)^3$

Station	Variable	a_0	a_1	a_2	a_3	R	Q_{min}	Q_{max}
Niantic	W	3.288	-3.481	2.089	-0.35764	0.930	36.8	3040
	D	1.272	-2.107	0.949	-0.1080	0.908		
	V	-4.690	6.773	-3.123	0.4782	0.370		
	W	1.123	0.037				300	2768
	D	-1.093	0.540					
	V	-0.030	0.090					
Riverton	W	3.786	-3.400	1.794	-0.2864	0.660	24	430
	D	-0.958	1.284	-0.647	0.1355	0.749		
	V	-2.869	3.186	-1.187	0.1581	0.819		
	W	1.157	0.200				430	6690
	D	-1.220	0.620					
	V	-0.297	0.180					
Petersburg	W	2.564	-0.326	0.073	0.000	0.841	102	6230
	D	-2.397	2.292	-0.711	0.089	0.949		
	V	-3.069	2.450	-0.624	0.060	0.988		

Notes:
W = water surface width in feet, D = flow depth in feet, V = velocity in feet/second, and Q = discharge in cfs.

Table 13. Discharge and Average Values of W, D, and V, Measured in Study Reaches

Study reach	Event	Start date	Q (cfs)	Flow duration	Average values W	D	V
RP1	a	6/26/92	107	73	60	1.26	1.40
	b	8/05/92	52	84	50	0.93	1.17
	c	9/21/92	288	53	87	2.14	1.57
RP2	a	8/08/92	62	82	56	1.05	1.03
	b	8/20/92	94	75	64	1.29	1.15
	c	9/15/92	170	65	76	1.60	1.38
RP3	a	6/30/92	513	62	123	2.51	1.58
	b	8/13/92	832	51	148	3.24	1.72
	c	8/02/92	251	75	98	1.70	1.45

Notes:
W = water surface width in feet, D = flow depth in feet, V = velocity in feet/second, and Q = discharge in cfs.

Table 14. Riffle Spacing and Stream Width (feet) at 20 Percent Flow Duration, W_{20}, and Ratio of Riffle Spacing to W_{20}

Reach	Riffle to riffle pacing	W_{20}	Ratio
RP1	961	155	6.2
	1008	155	6.5
RP2	895	169	5.3
	878	169	5.2
RP3	1188	253	4.7
	1290	253	5.1

Table 15. Standard Deviation of Depths S_d

Site	Event	Flow duration (Percent)	S_d(ft)
RP1 (1244 mi^2)*	a	73	0.956
	b	84	0.905
	c	53	1.011
RP2 (1428 mi^2)	a	82	0.968
	b	75	1.090
	c	64	1.236
RP3 (2909 mi^2)	a	62	1.150
	b	51	1.290
	c	75	1.020

Note:
*** Number in parentheses refers to size of drainage area.**

Table 16. Selected Values of the Inverse Normal (0,1) Probability Distribution Function

Cumulative probability of non-exceedance Pi(x)	$Z_i=(d_iD)/S_d$
0.05	-1.645
0.15	-1.036
0.25	-0.674
0.35	-0.385
0.45	-0.126
0.55	0.126
0.65	0.385
0.75	0.674
0.85	1.036
0.95	1.645

Table 17. Monthly Minimum and Average Dissolved Oxygen (mg/L) at Sangamon River Gages (adapted from Broeren et al., 1991)

USGS gage Drainage area (mi^2)	5573540 (938)	5573650 (1054)	5573800 (1264)	5576500 (2618)	5578000 (3063)
			Minimum Dissolved Oxygen		
January	3.4	4.7	8.5	8.9	11.8
Febuary	7.2	9.3	9.4	10.6	10.8
March	8.6	7.9	9.1	10.4	10.3
April	7.4	7.6	6.7	7.7	8.3
May	8.4	4.8	5.6	6.9	7.4
June	2.2	2.1	4.0	5.7	5.1
July	1.9	3.1	4.9	5.5	5.6
August	0.6	0.4	5.0	5.2	5.2
September	0.1	0.9	3.6	4.7	6.4
October	0.9	3.8	4.9	5.1	6.4
November	0.8	0.8	3.4	5.3	7.6
December	6.4	4.8	9.6	10.3	11.2
			Average dissolved oxygen		
January	12.14	10.64	12.15	12.09	13.38
Febuary	12.28	11.47	11.64	12.13	12.13
March	11.96	10.77	11.45	11.25	11.98
April	10.75	9.19	9.69	9.58	9.87
May	9.94	7.98	7.60	7.87	7.85
June	7.82	6.02	6.65	7.32	7.19
July	6.25	5.28	6.18	5.72	6.90
August	5.55	5.27	6.84	8.54	6.94
September	4.09	4.50	6.46	6.94	8.05
October	4.01	7.14	6.12	6.86	7.68
November	4.86	5.34	7.66	8.57	9.40
December	11.74	10.66	12.25	11.41	11.95

Table 18. Seasonal Average Dissolved Oxygen Deficits (mg/L) at Sangamon River USGS gages (adapted from Broeren et al., 1991)

	USGS gage				
Season	5573540	5573650	5573800	5576500	5578000
Dec. - Feb.	0.982	2.125	1.727	1.653	0.966
March-May	-0.076	1.438	1.323	1.192	0.964
June-Aug.	1.817	2.616	1.149	0.573	0.967
Sept. - Nov.	5.730	4.059	3.217	2.910	1.659

Table 19. Simple Correlation Coefficients (r) between Q and Oxygen Deficit D at Sangamon River USGS Gages (adapted from Broeren et al., 1991)

	USGS gage				
Season	5573540	5573650	5573800	5576500	5578000
Dec. - Feb.	-0.629	-0.601	-0.486	-0.120	0.225
March-May	-0.563	-0.648	-0.062	0.310	0.467
June - Aug.	-0.856	-0.593	0.198	0.528	0.700
Sept. - Nov.	-0.803	-0.830	-0.571	-0.448	0.261