

In cooperation with the Illinois Environmental Protection Agency

Evaluation of Measurements Collected with Multi-Parameter Continuous Water-Quality Monitors in Selected Illinois Streams, 2001–03

Scientific Investigations Report 2005–5060

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By George E. Groschen and Robin B. King

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Conversion Factors, Datums, and Abbreviations

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi ²)	259.0	hectare (ha)
square mile (mi ²)	2.590	square kilometer (km ²)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F}=(1.8\times^{\circ}\text{C})+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$^{\circ}\text{C}=(^{\circ}\text{F}-32)/1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Specific conductivity is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Voltage is given in millivolts (mV).

Evaluation of Measurements Collected with Multi-Parameter Continuous Water-Quality Monitors in Selected Illinois Streams, 2001–03

Abstract

Eight streams, representing a wide range of environmental and water-quality conditions across Illinois, were monitored from July 2001 to October 2003 for five water-quality parameters as part of a pilot study by the U.S. Geological Survey (USGS) in cooperation with the Illinois Environmental Protection Agency (IEPA). Continuous recording multi-parameter water-quality monitors were installed to collect data on water temperature, dissolved-oxygen concentrations, specific conductivity, pH, and turbidity. The monitors were near USGS streamflow-gaging stations where stage and streamflow are continuously recorded. During the study period, the data collected for these five parameters generally met the data-quality objectives established by the USGS and IEPA at all eight stations. A similar pilot study during this period for measurement of chlorophyll concentrations failed to achieve the data-quality objectives. Of all the sensors used, the temperature sensors provided the most accurate and reliable measurements (generally within ± 5 percent of a calibrated thermometer reading). Signal adjustments and calibration of all other sensors are dependent upon an accurate and precise temperature measurement. The dissolved-oxygen sensors were the next most reliable during the study and were responsive to changing conditions and accurate at all eight stations. Specific conductivity was the third most accurate and reliable measurement collected from the multi-parameter monitors. Specific conductivity at the eight stations varied widely—from less than 40 microsiemens (μS) at Rayse Creek near Waltonville to greater than 3,500 μS at Salt Creek at Western Springs. In individual streams, specific conductivity often changed quickly (greater than 25th percent in less than 3 hours) and the sensors generally provided good to excellent record of these variations at all stations. The widest range of specific-conductivity measurements was in Salt Creek at Western Springs in the Greater Chicago metropolitan area. Unlike temperature, dissolved oxygen, and specific conductivity that have been typically measured over a wide range of historical streamflow conditions in many streams, there are few historical turbidity data and the full range of turbidity values is not well known for many streams. Because proposed regional criteria for turbidity in regional streams are based on upper 25th percentiles of concentration in reference streams, accurate determination of the distribution of turbidity in monitored streams is important.

Digital data from all five sensors were recorded within each of the eight sondes deployed in the streams and in automated data recorders in the nearby streamflow-gaging houses at each station. The data recorded on each sonde were retrieved to a field laptop computer at each station visit. The feasibility of transmitting these data in near-real time to a central processing point for dissemination on the World-Wide Web was tested successfully.

Data collected at all eight stations indicate that a number of factors affect the dissolved-oxygen concentration in the streams and rivers monitored. These factors include: temperature, biological activity, nutrient runoff, and weather (storm runoff). During brief periods usually in late summer, dissolved-oxygen concentrations in half or more of the eight streams and rivers monitored were below the 5 milligrams per liter minimum established by the Illinois Pollution Control Board to protect aquatic life. Because the streams monitored represent a wide range in water-quality and environmental conditions, including diffuse (non-point) runoff and wastewater-effluent contributions, this result indicates that deleterious low dissolved-oxygen concentrations during late summer may be widespread in Illinois streams.

INTRODUCTION

The U.S. Environmental Protection Agency (USEPA) has determined the regional stream nutrient criteria as a maximum concentration of total phosphorus, total nitrogen, chlorophyll a (a specific form of chlorophyll), and turbidity allowable in streams and rivers for the Nation. These criteria are based on the concept of nutrient ecoregions (U.S. Environmental Protection Agency, 2000). The USEPA drafted guidance for States to set dissolved-oxygen standards in 1986 (U.S. Environmental Protection Agency, 1986). The USEPA recognized the close link between nutrients and dissolved oxygen in streams and the proposed regional stream nutrient criteria are designed, in part, to help prevent deleterious low dissolved-oxygen concentrations that could result from nutrient enrichment.

In Illinois, the current dissolved-oxygen water-quality standard promulgated in Illinois Pollution Control Board regulations dates from the early 1970s and may not be applicable to present-day (2004) water-quality conditions and reflective of modern water-quality monitoring capabilities. Natural diurnal and interregional variation in dissolved-oxygen concentra-

tion might be greater than recognized with the present standards, particularly in streams and rivers in southern Illinois.

The U.S. Geological Survey (USGS), in cooperation with the Illinois Environmental Protection Agency (IEPA), conducted a study beginning in 2001 to investigate the applicability of the USEPA nutrient criteria to water-quality and environmental conditions in Illinois streams. The study involved the deployment of continuous water-quality monitoring monitors to eight stream or river locations across the State, representing a range of water-quality and environmental conditions (fig. 1). Data were collected on water temperature, dissolved-oxygen concentrations, specific conductivity, pH, and turbidity. Water-quality data were analyzed to provide some context for comparing water-quality standards for the protection of aquatic life.

This report presents the results of a study that monitored selected water-quality parameters continuously at eight stream and river sites in the State of Illinois from 2001 to 2003. The sites are in selected watersheds that represent a range in: land cover, watershed disturbance, climate, and hydrologic characteristics. The stations were operated from July 2001 through September 2003. The report is organized into two parts. In the first part of the report, the accuracy and reliability of water-quality monitors are evaluated. Monitor performance is related, where possible, to environmental and hydrologic factors. In the second part of the report, selected water-quality data from the continuous monitors are analyzed for parameter-specific and temporal relations among temperature, dissolved oxygen, nutrients, diurnal variability, seasonality, and stormflow.

DESCRIPTION OF MULTI-PARAMETER MONITORS

The terms *monitor*, *sensor*, *sonde*, and *telemetry* are defined below as they are used in this report.

Monitor—Complete hydrologic instrument system that measures multiple water-quality parameters of interest. A monitor generally comprises sensors and a sonde, and may have the capacity to operate remotely and in a user-determined manner for an extended period of weeks to months. A monitor may store data internally and/or transmit it to the user through telemetry.

Sensor—Device that measures one or more water-quality parameter(s) and is attached to a sonde. Can be synonymous with the term probe, although sensor is the preferred term in this report.

Sonde—Device that manages the operation of the water-quality sensor(s) in a user-determined manner. Generally, the sonde will be connected to multiple sensors, supply power to the sensors, store the water-quality data, and function as an interface to the telemetry.

Telemetry—Transmission of data measured by the water-quality monitoring system to a remote location where it

is recorded and inspected, or the hardware and physical installation associated with the system.

Wagner and others (2000) describe the major factors that should be considered in the operation of a continuous water-quality monitoring station. These factors include sensor and monitor type, monitor configuration, site selection, sensor location in the stream cross section, and the actual use, calibration, and operation of the continuous water-quality monitor. In this study, the water-quality monitors were deployed in situ (the sensors were immersed continuously in the water being measured) at the eight field stations. Each sonde was equipped with an internal data logging and power-supply system that was able to operate the water-quality sensors and record the data independently of the external power and telemetry. The water-quality monitors were installed during July or August 2001 and remained operational through September 2003. The water-quality monitors usually were serviced about every 2 to 6 weeks. Four of the monitors also were connected to a telemetry system that supplied power to the monitors and transmitted the water-quality data to USGS Illinois Water Science Center computer systems. Streamflow data for the eight stations are stored in the USGS National Water Information System (NWIS), are published in the Illinois Water Science Center Annual Data Report for 2003, and are available at URL: http://il.water.usgs.gov/annual_report/start.htm. The continuous water-quality data recorded by the sondes are also stored in NWIS.

Temperature

The effect of water temperature on the development and growth of aquatic systems is well understood (Laws, 2000, chap. 8; Allan, 1995, p. 69–78). Aquatic organisms grow most efficiently over a limited temperature range. Deviations from this limited range may cause reduced growth rates, although translating water-temperature changes directly into environmental stress indicators usually is difficult because other stress indicators generally are present in the aquatic system.

In this study, water temperature was measured with a high-precision thermistor. The thermistor is constructed of a thin-walled titanium sleeve and operates with an algorithm that converts internal electrical resistance to water temperature. The accurate performance of the water-temperature sensor especially is critical because other water-quality sensors (including chlorophyll, dissolved oxygen, pH, specific conductivity, and turbidity) rely on concurrently measured temperature data to operate correctly. The water-temperature sensor is considered maintenance-free by the manufacturer and requires no field calibration. However, the performance of the water-temperature sensor at each station was compared to a certified thermometer about twice per year using methods described by Radtke, Kurklin, and Wilde (1998).

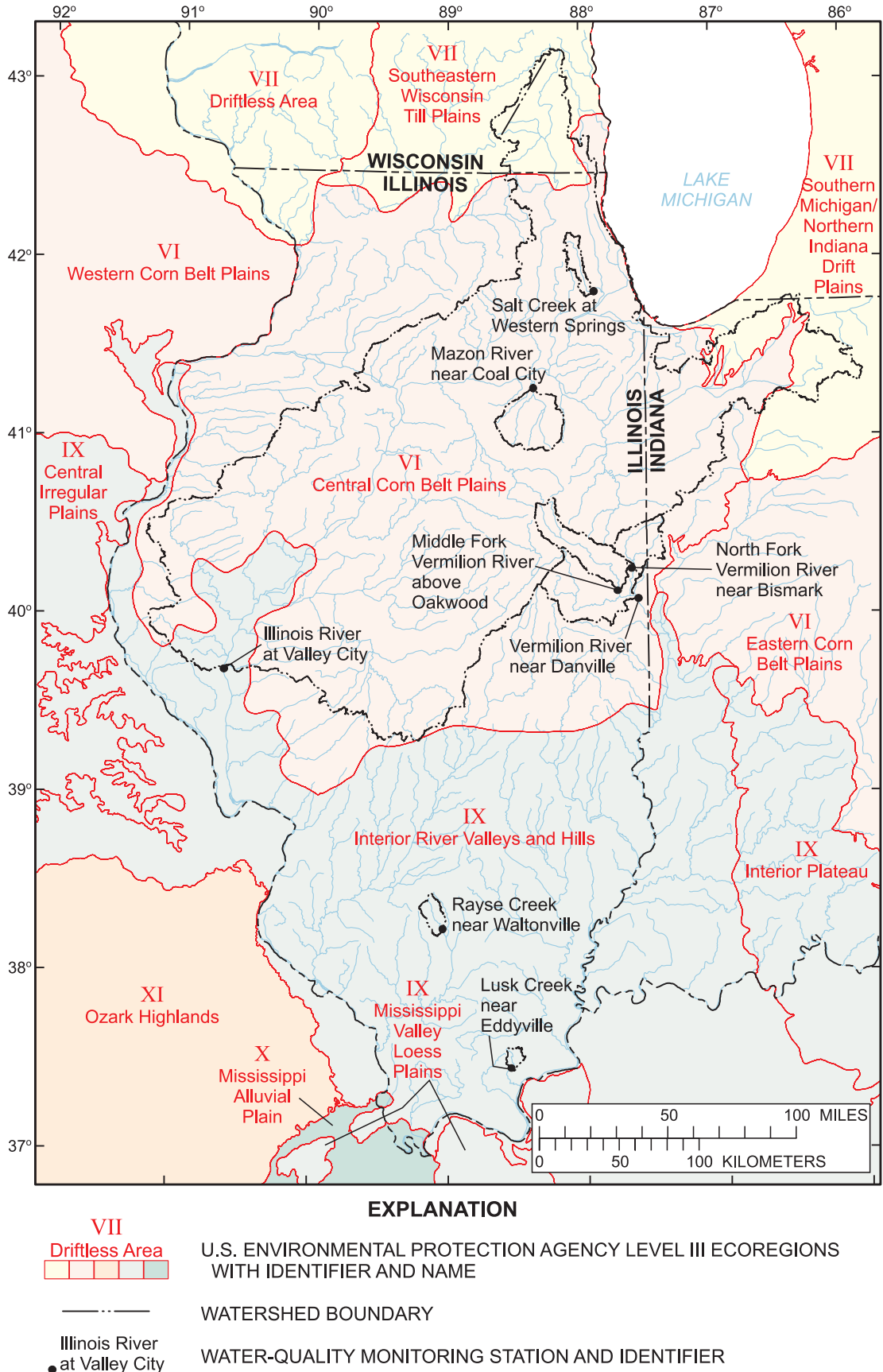


Figure 1. Ecoregions in Illinois and locations of study watersheds and monitoring stations (modified from Omernik, 1995).

Dissolved oxygen

Dissolved oxygen is the most important dissolved gas in the aquatic environment because it is essential to aerobic respiration, and many chemical and biological reactions depend on the presence of oxygen in water. The main factors affecting dissolved oxygen in aquatic ecosystems are atmospheric reaeration (source and sink of oxygen), the photosynthetic activities of green aquatic plants, and respiration by aquatic organisms (Radtke, White, and others, 1998; Boyd, 2000, chap. 4; among many others). Dissolved oxygen can be depleted indirectly because of excessive nutrients in water bodies. Excessive nutrients encourage the rapid growth of algal biomass that, in turn, increases the growth of oxygen-consuming bacteria. In daytime, photosynthetic activity outstrips respiration and reaeration, and the dissolved-oxygen concentration in the water body increases. At night, photosynthetic activity stops, but respiration continues and decreases dissolved-oxygen concentrations.

In this report, the dissolved oxygen is reported as a concentration in units of milligrams per liter (mg/L). A rapid pulse, temperature-compensated, dissolved-oxygen Clark-cell amperometric sensor with an instrument warm-up time of 48 seconds per measurement was used in this study. The sensor was calibrated at each station visit according to monitor manufacturer methods (Yellow Springs Instruments, 2003).

pH

The pH of water is important because many reactions that affect water quality are pH-dependent. The pH of water is a measure of the effective hydrogen-ion concentration that is represented by the negative base-10 logarithm of hydrogen-ion activity, in moles per liter (Radtke, Busenberg, and Kurklin, 1998). The pH is affected by interrelated chemical reactions that either produce or consume hydrogen ions (Hem, 1992, p. 61-65). The pH of natural water is an indicator of the status of aqueous chemical reactions. The pH of pure water at 25°C is 7.00, although the pH of river water is generally in the range 6.5 to 8.5. The pH can be affected by the presence of dissolved gases, particularly carbon dioxide. Photosynthesis by aquatic organisms will cause pH to increase because photosynthesis consumes carbon dioxide which is a weak acid in water. Algal respiration, which occurs primarily at night in water bodies, will cause pH to decrease because carbon dioxide is the major product of respiration.

A temperature-compensated ion-selective electrode (ISE) sensor that includes an integral reference electrode was used to measure pH. The ISE is calibrated in the field with solutions of known pH, to establish a relation between ISE electrical output and pH. Internal sonde software then is used to automatically correct the pH values for the water temperature at the time of the sensor measurement.

Specific conductivity

Specific conductivity is an operationally defined measurement of electrical conductivity in water, normalized to a unit length and unit cross section at a specified temperature (Radtke, Davis, and Wilde, 1998). Although there is no absolute theoretical relation between concentration of dissolved solids and specific conductivity, the capacity of water to conduct an electrical current generally is a function of the electrical charge and the concentrations of dissolved ions that make up the majority of dissolved solids in the water. Usually, an empirical relationship between specific conductivity and dissolved ions can be developed for a specific water type or at a specific sampling site. In this report, specific conductivity is reported in microsiemens per centimeter ($\mu\text{S}/\text{cm}$) at 25°C.

Turbidity

Turbidity is an operationally defined measure of water clarity and is used as an indicator of the condition and productivity of aquatic systems (Wilde and Gibbs, 1998). The primary causes of turbidity include clay, silt, organic and inorganic matter, soluble colored compounds, phytoplankton, and microscopic organisms (American Public Health Association and others, 1992). Turbidity can be determined by measuring the scattering effect that suspended solids have on a light beam; the greater the light scatters in water, the greater the turbidity. The measurement of turbidity is quantitative between 0 and 1,000 formazin nephelometric units (FNU), however, it often cannot be directly correlated to the concentration of suspended solids in the water column. A station-specific or matrix-specific relation can usually be developed between turbidity measurements and suspended solids after collection of sufficient data. During the course of this study, turbidity in most streams exceeded the 1,400 FNUs upper limit of quantitation; therefore, it may not be possible using this sensor to develop a sufficiently accurate relation between turbidity and suspended solids.

In this study, turbidity was measured in terms of FNUs according to method 7027 of the International Organization for Standardization (ISO) (Anderson, 2004). The scatter from a near-infrared light beam at a wavelength of 860 nanometers (nm), ± 30 nm is measured with this method. The optical face of the sensor was cleaned before each measurement with an automated wiper mechanism and the turbidity over a 12-second time interval was averaged and recorded. A data-filtering algorithm was used to suppress occasional data spikes that can be caused by large particles or air bubbles passing in front of the turbidity sensor at measurement time. The turbidity sensor was calibrated during each field inspection, as necessary, to zero using a zero turbidity solution. Occasionally, a two-point calibration was performed, using both the zero solution and a diluted formazin suspension, which can be prepared to simulate turbidity at the desired FNU. The turbidity sensor was designed and manufactured to provide reliable monitor

performance to an upper limit of about 1,000 FNUs. During this study, the sensor appeared to reliably perform to an upper limit of about 1,400 FNUs; therefore, data values below 1,400 FNU only are included in this report. The data above 1,400 FNU are stored in the USGS NWIS database but are of unknown quality.

DESCRIPTION OF STUDY AREA AND MONITOR INSTALLATIONS

The State of Illinois has a total area of 55,600 mi² and has a population of about 11.8 million people (U.S. Department of Commerce, 2003a). The study area included in the water-quality network is 28,700 mi², although 3,850 mi² (13.4 percent) is outside of the State of Illinois. Some of the study area watersheds include area in adjoining States—primarily Indiana and Wisconsin. The population in the parts of Illinois in the study area is about 10.4 million people (modified from the U.S. Department of Commerce, 2003b) and includes the metropolitan areas of Chicago, Decatur, Kankakee, Peoria, and Springfield. The study area includes approximately 45 percent of the land area in Illinois (fig. 1). Most of the land is used for agriculture, particularly the production of corn and soybeans. The climate in Illinois is classified as continental; typically, summers are warm and humid and winters are cold and dry. In northern Illinois, the average temperature is -4°C in January and 24°C in July. In southern Illinois, the average temperature is 2°C in January and 26°C in July (National Oceanic and Atmospheric Administration, 2003). The average annual rainfall ranges from about 35 in. in the north to about 48 in. in the south, whereas average annual snowfall ranges from about 40 in. in the north to about 12 in. in the south (Illinois State Water Survey, 2000).

The installation of a water-quality monitoring system requires the consideration of multiple and sometimes conflicting station-selection factors such as, but not limited to, stream-channel morphology, water depth, and flow regime. Ideally, the water-quality sensors should be placed in a location that best represents the section of the stream being monitored, while considering the likely range of flow conditions. However, other factors, such as station accessibility, bank stability, avoidance of high-water debris damage, monitor fouling potential, and protection from vandalism also must be considered (Wagner and others, 2000). For this study, the following specific factors were considered important: (1) the sensors were placed at sufficient depth to stay submerged during low-flow conditions; (2) the sonde housing structures were designed to be accessible during most flow conditions; (3) the sonde housing structures were designed to withstand the forces of high-flow conditions (in particular, the collisions with moving instream debris, such as large trees, that occur during floods); and (4) the streams generally were well mixed and cross-sectional variability was small.

Eight sites on rivers and streams with a range of environmental and hydrologic conditions across the State were selected for monitoring. The primary criteria in station selection were watershed area, location type, and station type (table 1). The eight stations are on rivers or streams ranging in drainage area from 42.9 mi² to 26,700 mi². The State was divided into three general regions—northern, central, and southern—and at least two field stations were selected from within each region (table 1). The availability of stream chemistry data was the final criterion in station selection. The watershed areas of the eight stations selected further were classified into one of three types: least disturbed, slightly disturbed, and disturbed. Watershed disturbance is an IEPA qualitative measure that considers biological conditions, historical nutrient concentrations, and State regulatory agency concerns (R. Smogor, Illinois Environmental Protection Agency, written commun. 2005). The watersheds of seven of the eight stations were classified as either disturbed or slightly disturbed (table 1).

The watershed areas monitored with the water-quality network collectively make up approximately 40 percent of the land area of Illinois. However, most of this area is within a single watershed, the drainage area above Illinois River at Valley City (fig. 1). Land cover in each watershed is shown by category in table 2.

Illinois River at Valley City

The Illinois River at Valley City watershed drains 26,700 mi². However, diversion of the Chicago River that began January 17, 1900, added to the flow of the Illinois River streamflow that originally went to Lake Michigan (Lanyon, 2000). Where the USGS streamflow-gaging station and water-quality monitor (station 5586100) were installed, the river channel was relatively straight for 3-5 mi both upstream and downstream and the nearby banks generally were covered with a heavy growth of trees and forbs. The streambed comprised silt, sand, and gravel. The Illinois River is an important navigable waterway with substantial barge traffic. During the course of the study, barges usually passed within about 50 to 100 feet (ft) of the water-quality monitor, which was on the streamward side of a concrete bridge-support pier near the shelter for the USGS streamflow-gaging station. The water-quality sensors were positioned at a water depth of 1.2 ft of stage, which is about 0.8 ft below typical low-flow stage and about 15 ft above the streambed. At low-flow conditions (below 2.0 ft of stage), the stream velocities at the sensors always were measurable and the stream was well mixed at all stages.

Land cover during 1999–2000 in the watershed upstream of the Illinois River at Valley City (table 2) was 77.5 percent agricultural, 9.1 percent forest, 9.3 percent urban and built-up, 2.6 percent wetland, 1.4 percent surface water, and 0.1 percent barren and exposed (modified from the Illinois Department of Agriculture, 2002).

Table 1. Station name, U.S. Geological Survey (USGS) station number, basin area, watershed disturbance, and general location for water-quality monitoring stations in Illinois, 2001–03.

[Watershed disturbance is an Illinois Environmental Protection Agency qualitative measure that considered biological conditions, historical nutrient concentrations, and State regulatory agency concerns (R. Smogor, Illinois Environmental Protection Agency, written commun. 2005)]

Station name	USGS station number	Basin area, in square miles	Watershed Disturbance	General location within Illinois
Illinois River at Valley City	5586100	26,700	Disturbed	Central
Lusk Creek near Eddyville	3384450	43	Least disturbed	Southern
Mazon River near Coal City	5542000	455	Slightly disturbed	Northern
Middle Fork Vermilion River above Oakwood	3336645	432	Slightly disturbed	Central
North Fork Vermilion River near Bismarck	3338780	262	Slightly disturbed	Central
Rayse Creek near Waltonville	5595730	88	Disturbed	Southern
Salt Creek at Western Springs	5531500	115	Disturbed	Northern
Vermilion River near Danville	3339000	1,290	Slightly disturbed	Central

At Illinois River at Valley City, the long-term (Oct. 1980–Sept. 1996) average concentration of total nitrogen (total Kjeldahl nitrogen plus nitrite and nitrate nitrogen) as nitrogen (N) was 5.7 mg/L and the average concentration of total phosphorus (total-P) was 0.31 mg/L (Short, 1999, appendix, p. B-15). During August 2001 through September 2003, the average concentration of total-N was 6.6 mg/L, which is 116 percent of the long-term average and total-P was 0.40 mg/L, which is 129 percent of the long-term average.

Lusk Creek near Eddyville

The Lusk Creek near Eddyville watershed drains 42.9 mi². The water-quality monitor was on a gentle bend near the left bank (while looking downstream) and the sonde was submerged in a shallow pool. The channel was fairly straight for 150 ft upstream and then turned gently to the right (while looking upstream). Looking downstream from the water-quality monitor, the channel bent gently to the left and then was fairly straight for about 500 ft. The USGS streamflow-gaging station number 03384450 was about 300 ft downstream from the water-quality monitor. The local banks were steep and covered with heavy growth of trees and forbs and the streambed comprised sand, pebbles, cobbles, and boulders. At low flow, a sand-and-gravel riffle 30 ft downstream controlled the depth of water at the sonde. The water-quality sensors were positioned at a water depth of 1.8 ft of stage, which was about 0.2 ft below the point of zero flow and about 0.3 ft above the streambed. At low-flow conditions (below about 2.5 ft of stage), the stream velocities at the sensors sometimes approached the point of being immeasurable. Under very low-flow conditions (below about 1.5 ft of stage), the stream mixing was poor. The stream mixing usually was good at all other flow conditions. The streambed immediately beneath the water-quality sen-

sors consisted mostly of sand and small amounts of scattered pebbles. In the summer months, the streambed was covered with heavy vegetation both upstream and downstream from the water-quality monitor.

Land cover during 1999–2000 in the Lusk Creek near Eddyville watershed (table 2) was 76.4 percent forest, 17.8 percent agricultural, 4.0 percent wetland, 1.6 percent urban and built-up, and 0.2 percent surface water (Illinois Department of Agriculture, 2002).

Mazon River near Coal City

The Mazon River near Coal City watershed drains 455 mi². The water-quality monitor was on a straight section of channel near the right bank, about 20 ft upstream of a bridge. The channel was fairly straight for more than 500 ft upstream. Looking downstream from the water-quality monitor, the channel bent gently to the left and then was fairly straight for about 500 ft. The USGS streamflow-gaging station (05542000) was about 75 ft downstream of the water-quality monitor. The local banks were steep and covered with forbs and a moderate density of trees. The sonde was positioned with the sensors submerged in a shallow pool (less than 3 ft deep) about 30 ft downstream of a rock-and-gravel riffle. At low flow (below 1.0 ft of stage), the stream velocities at the sensors ranged down to immeasurable, and the streamflow was confined to a small outlet on the upstream riffle, about 25 ft instream. The water-quality sensors were positioned at a water depth of 0.2 ft of stage, which is approximately the point of zero flow and about 0.2 ft above the streambed. The streambed immediately beneath the water-quality sensors comprised silt, although the streambed in the general vicinity comprised bedrock, gravel, and scattered rocks.

Table 2. Land cover, in percent of watershed, in Illinois study watersheds. [NA, not applicable]

[Codes in parentheses in column headings are Illinois Environmental Protection Agency station identifiers]

Anderson level 2 land-cover category	Area in land-cover category, by watershed (percent)							
	Illinois River at Valley City (D-32)	Lusk Creek near Eddyville (AK-02)	Mazon River near Coal City (DV-04)	Middle Fork Vermilion River above Oakwood (BPK-07)	North Fork Vermilion River near Bismarck (BPG-09)	Rayse Creek near Waltonville (NK-01)	Salt Creek at Western Springs (GL-09)	Vermilion River near Danville (BP-08)
11 Corn	NA	0.64	45.4	44.5	NA	14.6	0.19	NA
12 Soybeans	NA	2.36	42.4	38.6	NA	29.5	.16	NA
13 Winter wheat	NA	.01	.25	.15	NA	5	0	NA
14 Other small grains and hay	NA	.18	.22	0	NA	1.73	0	NA
15 Winter wheat/soybeans	NA	0	.13	.09	NA	6.05	0	NA
16 Other agriculture	NA	.2	.02	.01	NA	1.28	0	NA
17 Rural grassland	NA	14.4	5.91	9.99	NA	11.8	1.78	NA
TOTAL AGRICULTURE	77.5	17.8	94.3	93.4	95.5	158	2.13	90.8
21 Upland	NA	55.8	0.56	2.23	NA	18.4	10.1	NA
25 Partial canopy/savannah upland	NA	2.38	.36	.47	NA	1.26	4.52	NA
26 Coniferous	NA	18.1	0	0	NA	0	0	NA
TOTAL FOREST	9.07	76.4	0.92	2.69	1.43	19.6	14.7	2.67
31 High density urban and built-up land	NA	0.05	0.69	1.07	NA	0.47	13.9	NA
32 Low/medium density urban and built-up land	NA	1.16	1.25	.54	NA	.75	43.4	NA
35 Urban open space	NA	.41	.62	.27	NA	.51	22.2	NA
TOTAL URBAN and BUILT-UP	9.25	1.62	2.55	1.89	2.18	1.73	79.6	4.15
41 Shallow marsh/wet meadow	NA	0.08	0.04	0.02	NA	1.03	0.9	NA
42 Deep marsh	NA	0	0	.01	NA	.27	.22	NA
43 Seasonally/temporally flooded	NA	0	.16	.02	NA	.34	0	NA
44 Flood-plain forest	NA	3.79	.52	1.49	NA	6.42	.14	NA
48 Swamp	NA	0	0	0	NA	0	0	NA
49 Shallow water	NA	.14	.03	.04	NA	.19	0	NA
TOTAL WETLAND	2.6	4.01	0.75	1.57	0.71	8.25	1.26	1.54
51 Surface water	1.43	0.25	1.43	0.48	0.17	0.28	2.34	0.73
TOTAL SURFACE WATER	1.45	0.25	1.43	0.48	0.17	0.28	2.34	0.73
52 Barren and exposed land	0.13	0	0.03	0.01	0	0.09	0.03	0.09
TOTAL BARREN and EXPOSED	0.13	0	0.03	0.01	0	0.09	0.03	0.09

Land cover during 1999-2000 in the watershed upstream of the Mazon River near Coal City (table 2) was 94.3 percent agricultural, 2.6 percent urban or built-up, 1.4 percent surface water, 0.9 percent forest, and 0.8 percent wetland (Illinois Department of Agriculture, 2002). At Mazon River near Coal City, the long-term average concentration of total-N was 9.6 mg/L and the average concentration of total-P was 0.09 mg/L (Short, 1999, appendix, p. B-27). During August 2001 through June 2003, the average concentration of total-N was 11.4 mg/L, which is 119 percent of the long-term average and total-P was 0.09 mg/L, which is 100 percent of the long-term average.

Middle Fork Vermilion River above Oakwood

The Middle Fork Vermilion River above Oakwood watershed drains 432 mi². The water-quality monitor was on a fairly straight section of channel near the right bank, at USGS streamflow-gaging station (03336645). A bridge is about 250 ft downstream. The banks, especially the banks near the water-quality monitor, were steep to vertical and were actively eroding and slumping into the channel during the study period. The banks were covered with a dense growth of forbs and trees. The monitor sensors were submerged in a shallow pool about 350 ft upstream of a sand, gravel, boulder, and bedrock riffle at a water depth of 0.2 ft of stage, which is approximately the point of zero flow and about 0.3 ft above the streambed. On some occasions after high flow, large uprooted trees were deposited near or on the monitor housing structure—interfering with the natural flow near the sonde—and these trees were moved as soon as practical. At low flow (below about 1.0 ft of stage) the stream velocities in the pool generally were measurable (greater than 0.2 feet per second) and sufficient to maintain adequate mixing. The streambed immediately beneath the water-quality sonde comprised silt and sand, although generally, the streambed near the sonde comprised bedrock, boulders, and gravel.

Land cover during 1999-2000 in the watershed upstream of the Middle Fork Vermilion River above Oakwood (table 2) was 93.4 percent agricultural, 2.7 percent forest, 1.9 percent urban or built-up, 1.5 percent wetland, and 0.5 percent surface water (Illinois Department of Agriculture, 2002).

North Fork Vermilion River near Bismarck

The North Fork Vermilion River near Bismarck watershed drains 262 mi². The water-quality monitor was beneath a bridge on the left bank and was attached to a concrete revetment at the USGS streamflow-gaging station (03338780). The channel was straight and there was a rock-and-gravel riffle about 300 ft downstream of the water-quality monitor and a similar riffle about 200 ft upstream. The banks comprised sand and mud, and were densely covered with trees and forbs. The streambed comprised pebbles, cobbles, and some scattered small boulders. The water-quality sensors were positioned at a water depth of 4.9 ft of stage, which is the point of zero

flow and about 2.5 ft above the streambed. At low flow (below about 5.5 ft of stage), the stream velocities always were sufficient to maintain adequate mixing at the sensors. The streambed immediately beneath the water-quality sensors comprised silt and cobbles.

Land cover during 1999-2000 in the watershed upstream of the North Fork Vermilion River near Bismarck (table 2) was 95.5 percent agricultural, 1.4 percent forest, 2.2 percent urban or built-up, 0.7 percent wetland, and 0.2 percent surface water (Illinois Department of Agriculture, 2002).

Rayse Creek near Waltonville

The Rayse Creek near Waltonville watershed drains 88.0 mi². The water-quality monitor was beneath a bridge on the right bank and was attached to a concrete block at USGS streamflow-gaging station (05595730). The channel was straight for about 50 ft upstream and 100 ft downstream. There was a mud-and-sand riffle about 150-200 ft downstream and the streambed comprised mud, pebbles, and cobbles, along with various types of debris. The banks were high and steep with dense growth of trees and forbs. The water-quality monitor and surrounding area occasionally were buried beneath trees and other natural debris, that were removed as soon as practical. The water-quality sensors were positioned at 0.5 ft of stage, which is about 0.2 ft below the point of zero flow and about 1.5 ft above the streambed. At low-flow conditions (below about 1.0 ft of stage), the stream velocities at the sonde ranged down to immeasurable. The streambed immediately beneath the water-quality sensors comprised mostly silt, although some pebbles and cobbles were present.

Land cover during 1999-2000 in the watershed upstream of Rayse Creek near Waltonville (table 2) was 70.0 percent agricultural, 19.6 percent forest, 8.3 percent wetland, 1.7 percent urban or built-up, 0.3 percent surface water, and 0.1 percent barren and exposed (Illinois Department of Agriculture, 2002).

Salt Creek at Western Springs

The Salt Creek at Western Springs watershed drains 115 mi². The water-quality monitor was attached to the upstream side of the left bridge pier, at USGS streamflow-gaging station (05531500). The channel was straight for over 1,500 ft upstream and downstream. The streambed comprised mud, pebbles, cobbles, and some scattered small boulders. The banks were low with gentle slopes and were densely covered with trees and forbs. The water-quality monitor occasionally was buried beneath floating tree branches and other natural debris, although these burials almost always occurred above the submerged sensors. The sensors were positioned at a water depth of 0.8 ft of stage, which is approximately the point of zero flow and about 0.4 ft above the streambed. At low-flow conditions (below 1.5 ft of stage), the stream velocities at the sonde always were measurable, although sometimes the

stream mixing at the sonde was incomplete. The streambed immediately beneath the water-quality sensors comprised pebbles and cobbles.

Land cover during 1999-2000 in the watershed upstream of the Salt Creek at Western Springs (table 2) was 79.6 percent urban or built-up, 14.7 percent forest, 2.3 percent surface water, 2.1 percent agricultural, and 1.3 percent wetland (Illinois Department of Agriculture, 2002).

Vermilion River near Danville

The Vermilion River near Danville watershed drains 1,290 mi². The water-quality monitor was attached to the right bank about 100 ft downstream of the water-treatment plant bridge, at USGS streamflow-gaging station (03339000). The channel was straight for about 300 ft upstream and for over 1,500 ft downstream. The streambed comprised sand, pebbles, and cobbles, with some scattered small- to medium-sized boulders lying on top of bedrock. The banks were high with steep to vertical slopes and were densely covered with trees and forbs. The water-quality sensors were positioned at 1.4 ft of stage, which is approximately the point of zero flow and about 0.7 ft above the streambed. At low-flow conditions (below 2.0 ft of stage), the stream velocities at the sonde always were measurable, although they were usually much slower (less than 0.5 ft/s) near the sonde than in the middle of the stream. At low flow, stream mixing usually was poor around the sensors but was good at all higher flow conditions (above 2.0 ft of stage). The streambed immediately beneath the water-quality sensors comprised silt and sand.

Land cover during 1999-2000 in the watershed upstream of Vermilion River near Danville (table 2) was 90.8 percent agricultural, 4.2 percent urban or built-up, 2.7 percent forest, 1.5 percent wetland, and 0.7 percent surface water, and 0.1 percent barren or exposed (Illinois Department of Agriculture, 2002).

EVALUATION OF WATER-QUALITY MEASUREMENTS

Data-quality objectives for the study were to obtain and record fair to excellent data (see table 5, p. 11) from the multi-parameter monitors at least 75 percent of the deployment for temperature, dissolved-oxygen concentration, specific conductivity, pH, and turbidity at the eight stations.

The major sources of uncertainty (error) in continuous water-quality monitoring data include monitor fouling, instrument drift, and cross-sectional location. When the error caused by monitor fouling and instrument drift exceeds a specified threshold, then a correction needs to be applied to the data (table 3). The correction from monitor fouling and drift is applied by prorating the observed error between monitor service visits over the associated time interval, as described

in Wagner and others (2000). An example correction applied to the dissolved-oxygen data record at Middle Fork Vermilion River above Oakwood for the time period from March 26, 2002, to April 11, 2002, is shown figure 2. The dissolved-oxygen sensor, which had been cleaned and calibrated and was operating accurately after the March 26, 2002, service visit, had a measurement error of 1.4 mg/L of dissolved oxygen on April 11, 2002, service visit. This 1.4 mg/L error was prorated backward in time, to the point of the previous monitor service visit, 16 days prior. The records for all the continuously monitored water-quality data at the eight field stations were evaluated similarly, by parameter, and corrections were applied as necessary. Because the cross-sectional variability at the eight stations generally was small, cross-sectional error was considered negligible during this study.

The maximum allowable limits for reporting data from continuous water-quality monitoring sensors vary by parameter (table 4). Data that differ by more than the maximum allowable limit were not used in computations or published. Wagner and others (2000) established the maximum allowable limits as the data value that is 10 times the accuracy resolution of the water-quality sensor, although stricter criteria are used for dissolved oxygen and turbidity. A maximum allowable limit is not specified for chlorophyll, because the chlorophyll sensor manufacturer does not claim any specific accuracy for this monitor. Occasionally, one or more individual sensors provided acceptable data for a short period, but completely failed between the service visits. For example, after a dissolved-oxygen sensor was cleaned and calibrated, it operated within acceptable accuracy after a routine service visit, but then suddenly and completely failed without warning before the next service visit, perhaps because of a ruptured membrane. In such cases, the dissolved-oxygen sensor provided acceptable data up to the time of the failure, but no dissolved-oxygen data would be retained between the failure and the next service visit. Another complication that usually is more common than sensor failure is the error introduced by gradual monitor fouling or instrument drift. Reasonable judgment was used to identify the point in the water-quality data record when the errors exceeded the maximum allowable accuracy limits. To assist in making this judgment, the water-quality monitor provides diagnostic data on sensor performance that are recorded with the sensor-data values. The diagnostic data sometimes provided additional insight into sensor performance and data quality, and aided decision-making regarding when the maximum allowable limits were exceeded.

After the water-quality data had been evaluated and screened with respect to the maximum allowable limits, the resultant verified data from each sensor were classified into one of four possible accuracy grades: excellent, good, fair, and poor (table 5). These accuracy grades were assigned based on the sensor values that were recorded before any corrections were made to the data. The accuracy grades for dissolved oxygen, pH, and water temperature are considered in terms of their associated reporting units (mg/L, pH standard units, and °C, respectively), whereas the accuracy grades for specific

conductivity and turbidity are considered in terms of the percentage deviation from their associated true value. No attempt was made to assess the accuracy of the chlorophyll data in this data-quality classification scheme.

Rating continuous water-quality measurements

The water-quality measurements, including the daily values for the minimum, maximum, and mean, were evaluated. A final set of criteria for publication or other data distribution (table 6) are listed below and were considered when collating these daily values (Wagner and others, 2000):

- If less than 100 percent of the data values are available on a specific day, the expected daily minimum and expected daily maximum values must be present to compute the mean value.
- If less than 100 percent of the data values are available on a specific day, the daily minimum, daily maximum, and daily mean data values will be computed if flow conditions are steady or gradually changing; the minimum and maximum data values occur at a reasonable

time; and sufficient data values are present according to the following parameter-specific criteria:

- Dissolved oxygen—At least 25 percent of the data values are present.
- pH—At least 25 percent of the data values are present.
- Specific conductivity—At least 50 percent of the data values are present.
- Turbidity—At least 50 percent of the data values are present.
- Water temperature—At least 25 percent of the data values are present.

Except for dissolved-oxygen concentration daily maximums and minimums, discussed later, daily values are not used or discussed in this report.

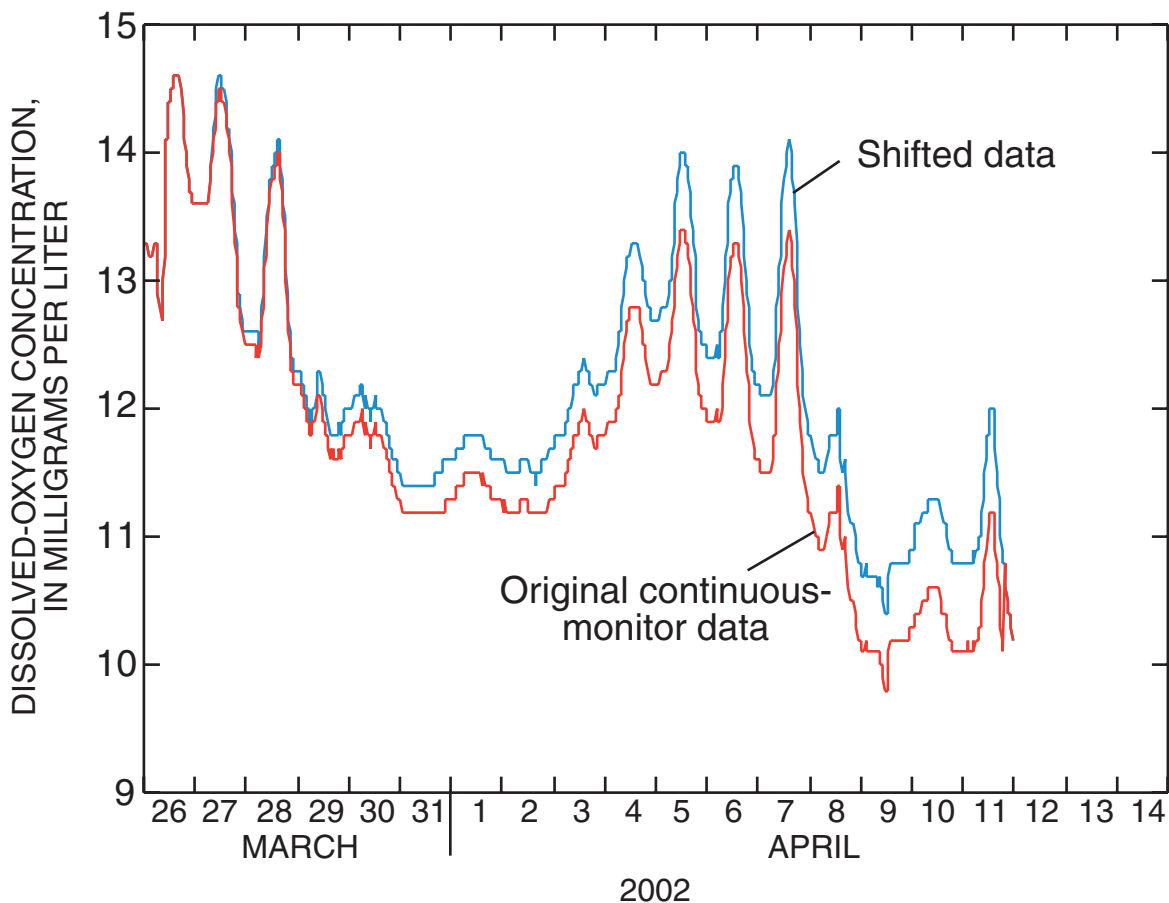


Figure 2. Example correction applied to dissolved-oxygen concentrations for Middle Fork Vermilion River above Oakwood, Illinois, March 26–April 11, 2002.

Table 3. Criteria for water-quality data shifts for this study (modified from Wagner and others, 2002).

[°C, degree Celsius; μ S/cm, microsiemens per centimeter; mg/L, milligram per liter; FNU, formazin nephelometric units]

Parameter	Shift criteria (apply shift when deviation exceeds this value)
Temperature (may affect the other properties)	$\pm 0.2^{\circ}\text{C}$
Specific conductivity	The greater of $\pm 5 \mu\text{S/cm}$ or ± 3 percent of the measured value
Dissolved oxygen	$\pm 0.3 \text{ mg/L}$
pH	$\pm 0.2 \text{ pH standard unit}$
Turbidity	The greater of $\pm 2 \text{ FNU}$ or ± 5 percent of the measured value

Table 4. Maximum allowable limits of acceptability for water-quality sensor values used in this study (modified from Wagner and others, 2000).

[°C, degrees Celsius; mg/L, milligrams per liter]

Parameter	Maximum allowable limits for water-quality sensor values
Temperature	$\pm 2.0^{\circ}\text{C}$
Specific conductivity	± 30 percent
Dissolved oxygen	Greater of $\pm 2.0 \text{ mg/L}$ or 20 percent
pH	$\pm 2 \text{ pH standard units}$
Turbidity	± 30 percent

Table 5. Rating continuous water-quality data collected in this study (modified from Wagner and others, 2000).

[\leq , less than or equal to; $>$, greater than; °C, degrees Celsius; mg/L, milligram per liter]

Parameter	Excellent	Good	Fair	Poor
Dissolved oxygen	$\leq \pm 0.3 \text{ mg/L}$	$> \pm 0.3$ to 0.5 mg/L	$> \pm 0.5$ to 0.8 mg/L	$> \pm 0.8 \text{ mg/L}$
pH	$\leq \pm 0.2 \text{ standard unit}$	$> \pm 0.2$ to $0.5 \text{ standard unit}$	$> \pm 0.5$ to $0.8 \text{ standard unit}$	$> \pm 0.8 \text{ standard unit}$
Specific conductivity	$\leq \pm 3$ percent	$> \pm 3$ to 10 percent	$> \pm 10$ to 15 percent	$> \pm 15$ percent
Temperature	$\leq \pm 0.2^{\circ}\text{C}$	$> \pm 0.2$ to 0.5°C	$> \pm 0.5$ to 0.8°C	$> \pm 0.8^{\circ}\text{C}$
Turbidity	$\leq \pm 5$ percent	$> \pm 5$ to 10 percent	$> \pm 10$ to 15 percent	$> \pm 15$ percent

Table 6. Summary of field visits and quality of data for five parameters at eight Illinois stations (40 sensors) during August 2001–June 2003.

[°C degree Celsius; mg/L, milligram per liter]

Parameter	Number of service visits	Time in calibration, percent	Time out of calibration, percent	Time excellent data, percent	Time good data, percent	Time fair data, percent	Time poor data, percent	Mean error	Median error
Temperature	268	88.1	11.9	50.4	26.8	5.9	5	0.2°C	0.1°C
Specific conductivity	265	86	14	46.9	24.7	6.1	8.3	5.1 percent	2.6 percent
Dissolved oxygen	268	77.9	22.1	21.9	16.3	19.3	20.4	0.6 mg/L	0.6 mg/L
pH	265	84.9	15.1	51.1	22.3	6.4	5.1	0.4 standard unit	0.2 standard unit
Turbidity	227	72	28	13.1	6.4	19	33.5	13 percent	11 percent

Temperature

The performance of the water-temperature sensor at each field station was compared to a certified thermometer about twice per year using methods described by Radtke, Kurklin, and Wilde (1998). The water-temperature sensors were serviced in the field 268 times during August 2001 through September 2003. The water-temperature sensors either exceeded the maximum allowable limit ($\pm 2^\circ\text{C}$) or otherwise failed to provide usable water-temperature values at 11.9 percent of the service visits. During the remaining 88.1 percent of the visits, the water-temperature data values were within the maximum allowable limit and were rated as follows: 50.4 percent were excellent; 26.8 percent were good; 5.9 percent were fair; and 5.0 percent were poor. The mean error was 0.2°C and the median error was 0.1°C for the 88.1 percent of visits when the water-temperature sensors were reading within the maximum allowable limit. Performance characteristics for temperature and the other four parameters monitored during July 2001 through June 2003 are summarized in table 6.

Dissolved oxygen

The dissolved-oxygen sensors were serviced in the field 268 times during August 2001 through September 2003. The dissolved-oxygen sensors exceeded the maximum allowable limit (the greater of ± 2.0 mg/L or ± 20 percent of the correct value) or otherwise failed to provide usable dissolved-oxygen values at 22.1 percent of the visits. During the remaining 77.9 percent of the visits, the dissolved-oxygen data values were within the maximum allowable limit and were rated as follows: 21.9 percent were excellent; 16.3 percent were good; 19.3 percent were fair; and 20.4 percent were poor. The mean error was 0.9 mg/L and the median error was 0.7 mg/L at the 77.9 percent of visits when the dissolved-oxygen sensors were reading within the maximum allowable limit.

pH

The pH sensors were serviced in the field 265 times during August 2001 through September 2003. The pH sensors exceeded the maximum allowable limit (± 2 pH standard units) or otherwise provided unusable pH values at 15.1 percent of the visits. During the remaining 84.9 percent of the visits, the pH data values were within the maximum allowable limit and were rated as follows: 51.1 percent were excellent; 22.3 percent were good; 6.4 percent were fair; and 5.1 percent were poor. The mean error was 0.4 pH standard unit and the median error was 0.2 pH standard units for the 84.2 percent of visits when the pH sensors were reading within the maximum allowable limit.

Specific conductivity

The specific-conductivity sensors were serviced in the field 265 times during August 2001 through September 2003. The specific-conductivity sensors either exceeded the maximum allowable limit (± 30 percent of the correct value) or otherwise failed to provide usable specific conductivity values at 14.0 percent of the service visits. During the remaining 86.0 percent of the service visits, the specific-conductivity data values were within the maximum allowable limit and were rated as follows: 46.9 percent were excellent; 24.7 percent were good; 6.1 percent were fair; and 8.3 percent were poor. The mean error was 5.1 percent and the median error was 2.6 percent for the 86.0 percent of visits when the specific-conductivity sensors were reading within the maximum allowable limit.

Turbidity

The turbidity sensors were serviced in the field 227 times during August 2001 through September 2003. The turbidity sensors exceeded the maximum allowable limit (± 30 percent of the correct value) or otherwise failed to provide usable turbidity values at 28.0 percent of the visits. During the remaining 72.0 percent of the visits, the turbidity data values were within the maximum allowable limit and were rated as follows: 13.1 percent were excellent; 6.4 percent were good; 19.0 percent were fair; and 33.5 percent were poor. The mean error was 13.3 percent and the median error was 10.6 percent at the 72.0 percent of visits where the turbidity sensors were reading within the maximum allowable limit.

Environmental conditions that affect the measurement quality

Low ionic strength affects the responsiveness and reliability of pH measurements—especially for the rugged gel-filled pH sensors used in this study. For most Illinois streams, low ionic strength may not be an issue; however, one station (Lusk Creek near Eddyville) generally had low ionic strength. This low ionic strength may have affected the responsiveness of the pH sensor in Lusk Creek (see p. 21). Potentially, pH measurements in other streams in watersheds similar to Lusk Creek near Eddyville may be affected. Large suspended-sediment concentrations also can affect pH measurements (Radtke, Busenberg, and Kurklin, 1998).

Ideally, sondes would be placed in streams where they would remain completely submerged for the entire period of deployment without being moved. Furthermore, the sonde would be in the well-mixed and representative part of the stream channel. In many smaller or shallow streams considered here, such as Mazon River near Coal City, there are riffle zones too shallow for sonde placement where there is greater oxygen exchange between the atmosphere and streamwater. These riffle zones may be more representative of the overall

stream dissolved-oxygen concentration. To assure that the sonde is underwater even under the lowest flow conditions, they are generally placed in “pools” or deeper zones within shallow streams with slower moving water that may not be as well-oxygenated as the shallow riffle zones. Therefore, the placement of some sondes in these deeper and sometimes stagnant flow zones tends to bias the dissolved oxygen toward lower concentrations than other placements. This bias likely is negligible during conditions of moderate to high flow for a particular stream; however, low dissolved oxygen usually is more frequent during low-flow conditions, in part, because low flows tend to occur in late summer to early fall when water temperatures are generally highest.

Because placement of the sondes is limited to a single point within the stream channel, they are of limited utility in poorly mixed streams or stream segments. Weather and streamflow have substantial effects on the capability of the sondes to record accurate data.

Major Reasons for Lost or Unusable Data

Lost or unusable (quality worse than poor and rejected) water-quality values were caused by various factors, including sensor failure, sensor internal drift, excessive sensor fouling, total sonde failure, and other directly related factors. On some occasions, failure was simultaneously caused by more than one factor, and when this happened, the most important factor has been considered the cause of the failure. For example, total sonde failure also caused sensor failure; however, in this circumstance, the cause of the data loss was classified as total sonde failure rather than sensor failure. Each factor is discussed below (along with selected related factors) and the estimated percentage of missing or unusable data relative to all data loss is reported. The distinction between sensor failure and total sonde failure is important; sensor failure results in lost data for a single parameter, whereas total sonde failure results in loss of all parameters for the station. If the monitor recorded no data, the data were considered missing. If the monitor recorded data but the data exceeded the maximum allowable limit (table 4), the data were considered unusable and were rejected.

Sensor Failure

About 15 percent of oxygen-sensor failures were caused either by membrane rupture or membrane leakage. The membrane, fastened to the sensor with a rubber O-ring, is a thin (0.002 inch) hydrophobic oxygen-permeable material that separates the electrodes from the environmental water, and is easily damaged. Membrane ruptures were sudden with no warning, typically caused by objects such as woody debris or aquatic organisms, and resulted in immediate sensor failure. By contrast, membrane leakage generally was slow, usually caused by a loose or failing O-ring or a slightly abraded membrane, and the sensor gradually failed over a period of hours

or sometimes days. The majority of membrane-related failures were caused by rupture, and identifying unusable oxygen values (defined as errors greater than maximum allowable limit) in this circumstance was obvious upon inspection of the dissolved-oxygen concentration data values. When unusable oxygen values resulted from membrane leakage, and if the distinction between usable and unusable data was not obvious upon inspection, then the distinction was made with a diagnostic parameter that measured oxygen-sensor performance. On some occasions (about 3 percent of deployment time), the oxygen sensor failed without warning because of an internal electronic malfunction. When internal failure of the sensor occurred, collection of oxygen data immediately ceased and the defective sensor required replacement.

Most failures (about 13 percent) of the pH sensors were caused by small fractures in the thin glass membrane that separates the pH electrode from the environmental water. The glass membrane has a small protective shield. However, objects occasionally breached the membrane; as a result, reference solution was lost and the pH sensor failed immediately. Rarely (about 3 percent), the pH sensors failed because of internal failure, as indicated by the inability to restore operability to nonresponsive sensors that were clean and structurally intact.

Among the water-quality sensors used in this study, the turbidity sensors were the most prone to failure. The turbidity sensors were self-cleaning and operated by measurement of optical backscatter. The turbidity sensors usually failed for one of two main reasons. Most turbidity sensor failures (38 percent) were caused by malfunction of the automated-cleaning mechanism, and about 19 percent were caused by internal sensor failure.

Water temperature and specific conductivity were measured with a single, combination sensor. Only about 7 percent of water-temperature and specific-conductivity data losses were caused by internal failure of the combination sensor, and all such data losses were caused by failure of the water-temperature sensor. Failure of the water-temperature sensor, though rare, resulted in failure of the dissolved-oxygen, pH, and specific-conductivity sensors, all of which required water-temperature data to operate. The combination temperature and specific conductivity sensor rarely failed independently of other failures, and there was never an internal failure of the specific-conductivity sensor that occurred independently of some other failure.

Sensor Internal Drift

Unusable sensor values caused by internal sensor drift were relatively rare, accounting for about 3.9 percent of data loss for the specific-conductivity sensor and no data loss for the water-temperature sensor. Data losses from sensor internal drift were more common for dissolved oxygen (5.9 percent) and pH (13 percent). The data losses from internal drift in the oxygen and pH sensors were quantified using diagnostic electrical measurements, collected concurrently with the

water-quality data. For example, the pH sensor had an associated diagnostic parameter that recorded the difference, in millivolts (mV), of the electrical voltage across the pH reference electrode at a user-specified pH standard. If the user-specified standard had a pH value of 7, then the associated pH reference electrode voltage should have been in the range ± 30 mV. Voltage in excess of this range indicated the pH sensor was operating beyond the maximum allowable error limit and needed replacement. Internal drift was of little or no importance for the two self-cleaning optical sensors that measured turbidity and chlorophyll.

Sonde Failure

Sonde failure was a major cause (66 percent) of lost data. Sonde failure was caused by any of three possible events, including internal sonde flooding, software failure, and operator error. Sonde failure caused all sensors to cease operation and data recording to stop. The sensor values stored internally prior to the failure usually were erased or corrupted, and if the sonde was not connected to telemetry prior to the sonde failure, all measurements made after the previous field visit and subsequent to the field visit in which the failure was identified usually were irretrievably lost. The relative percentage that each type of failure contributed to all the sonde failures and resultant data losses are described below.

About 15 percent of sonde failures were the result of internal sonde flooding. When one or more of the internal compartments were breached, streamwater entered the sonde. The battery compartment was most often flooded, though in some instances, the circuitry compartment, adjacent to the battery compartment, was breached. Breaches of the sonde resulted from small fractures in the battery compartment lid—in close proximity to the locking screws—or fracture of the main casing, usually near the end of the sonde where the sensors were attached.

During the winter of 2001–02, a software upgrade failed, affecting multiple stations during a period when field visits were relatively infrequent (usually every 3 weeks). The manufacturer's software upgrade was intended to improve the function of the optical-port wiping mechanisms. However, an error in the software caused rapid internal-memory saturation and battery-power depletion, resulting in partial to total shutdown of the affected sondes subsequent to the upgrade and shortly after they were redeployed. This software error caused about 13 percent of the sonde failures.

If the water at the sensors was not frozen, generally the sondes performed best in cold weather. This is because fouling was negligible in the near-freezing water. The most important negative effect of low temperature (defined as air temperature below 0°C) was field servicing became much more difficult and sometimes impossible, because some sondes occasionally were stuck in, or under, ice. This lack of sonde access, in turn, resulted in data-quality problems and sometimes loss of all sensor data for the period that the sonde could not be accessed. Subfreezing temperatures resulted in some sondes being out-

of-service for substantial periods of time, particularly when the sonde was operating only on internal battery power. The stations where icing prevented timely access were, in order of more to less frequent problems, Mazon River at Coal City, North Fork Vermilion River near Oakwood, and Illinois River at Valley City. The problems at Coal City were most severe; there were periods in the winter of 2001–02 when that sonde was stuck under ice for weeks at a time.

Fouling

Excessive sensor fouling caused about 10 percent of all unusable values. Fouling generally did not cause complete data loss. Observation of the performance of the sensors after field cleaning and during calibration allowed identification of unusable values that resulted from sensor fouling. Usually, the errors caused by sensor fouling decreased greatly or disappeared after field cleaning and, if so, the sensor usually then calibrated without difficulty. Fouling was most severe during periods of low streamflow and during peak water temperature, often in late summer. These conditions sometimes caused growth of biofilm on the sensors that interfered with the proper operation. The biofilm sometimes rapidly grew to considerable thickness, and as biofilm thickness increased, the quality of the measurements could decrease to inutility. Generally, the oxygen and pH sensors were most vulnerable to biofilm fouling—about 29 percent of dissolved-oxygen data losses and 11 percent of pH data losses were the result of fouling. The water-temperature sensor never failed because of excessive fouling. Assuming the automated cleaning mechanisms were operating properly, sensor fouling caused loss of turbidity data less than 3 percent of the time with the exception of Middle Fork Vermilion River above Oakwood, Rayse Creek near Waltonville, and Vermilion River near Danville. At these three stations, the fouling was more severe and caused about 10 to 15 percent of turbidity data to be unusable, despite automated cleaning mechanisms that operated properly. During periods of increased streamflow and/or periods of cooler (but above freezing) water temperatures, sensor fouling usually was much less severe and seldom the sole cause of unusable values. Sometimes, the increased streamwater velocities associated with high streamflow or floods effectively cleaned the sensors, by removing biofilm and sediment build-up on and around the sensors. Cooler water temperatures reduced algal-related activity and resulted in reduced biofilm growth on the sensors, and, consequently, reduced the frequency and extent of sensor fouling. Some unusable values were caused by accumulation of sand- and silt-sized sediment lodged on and around the sensors. The specific-conductivity sensor was most vulnerable to sediment fouling, and fouling by sediment build-up caused 12 percent of its data losses.

Operator error

About 72 percent of data losses were caused by operator error, which was the most frequent cause of missing or unusable data values. Two types of operator errors caused nearly all these failures; either the sonde was deployed in a location that was not representative of the stream, or the operator erred during data retrieval or routine field servicing. Data losses caused by poor sonde deployment became apparent during low flow at two stations—the Mazon River near Coal City and the Vermilion River near Danville. In the Mazon River near Coal City during periods of extreme low flow (usually lasting not more than 5–7 days), the water level dropped sufficiently to leave the sonde exposed to the air. For this report, extreme low flow in the Mazon River near Coal City is defined as streamflow less than about 0.5 ft³/s (the 90-percent exceedance streamflow is 1.6 ft³/s). During low flow, Mazon River streamflow was mostly confined to an exposed rock riffle in the center of the stream channel that was from about 0.1 to 0.2 ft deep. Deployment of the Mazon River sonde at or near the riffle was not feasible. The sonde was deployed in a shallow mud-bottomed pool near the right bank, downstream of the riffle, where low-flow stream velocity was slow (less than 0.1 ft/s). The water-quality measurements in the shallow pool likely were not representative of water quality in the riffle zone. The deployment location of the sonde in the Vermilion River near Danville periodically also was not representative of the stream during low flow—defined as less than the 90-percent exceedance flow of 52 ft³/s.

The optimum deployment of a sonde is confounded by the need to satisfy conflicting requirements. The sensors must be at an appropriate stream depth so they are continuously submerged and the location should be representative of the stream overall. Furthermore, the sonde and sensors need to be readily accessible during most streamflow conditions for routine field servicing. These competing requirements are sometimes further complicated by the need to place the sonde within a reasonable distance (generally less than 500 ft) of the streamflow-gaging station, if real-time data-transmission capabilities are required. At the Mazon River station, the sonde was lowered incrementally, as needed, to keep the sensors continuously submerged during the extreme low-flow periods. Lowering the monitor elevation in large increments was not feasible, because the water depth at the deployment location was less than 0.5 ft during the extreme low-flow periods. About 16 percent of all total data loss was caused by the deployment of the sonde in a location that did not adequately represent the stream during low streamflow.

About 58 percent of all data loss was caused by operator errors during field visits and data retrieval, and nearly all these errors occurred in 2003, the final year of data collection. Data losses through operator error were most frequent at the following stations (relative percentage of data loss by indicated station shown in parentheses): Rayse Creek near Waltonville (80 percent), Lusk Creek near Eddyville (68 percent), Middle Fork

Vermilion River above Oakwood (51 percent), and Vermilion River near Danville (41 percent).

Comparison of Continuous Data with Discrete Measurements

Another means of assessing the performance of the monitors is by comparison with independent measurements of the parameters by USGS personnel prior to servicing and by other observers; in this case, IEPA employees during their periodic sampling visits to the stations. The IEPA maintains an ambient water-quality-monitoring program in Illinois (Illinois Environmental Protection Agency, 1989). This program includes 214 (as of 2002) stations across the State in selected representative watersheds; the eight stations where the water-quality monitors were deployed were included in the program. The stations were visited every 6 weeks through the year and water temperature, pH, dissolved oxygen, specific conductivity, and turbidity were measured with calibrated monitors, similar to those deployed for this study but for discrete measurements to accompany the sample analytical data. Field methods for sample collection and measurement of pH, specific conductivity, temperature, dissolved oxygen were comparable to USGS methods (Illinois Environmental Protection Agency, 1989) and the methods for field measurement of turbidity were given in a written procedure (Illinois Environmental Protection Agency, 2002). For the remainder of this report, these discrete measurements will be referred to as discrete independent measurements (DIMs).

The correspondence between DIMS and the sonde-recorded values are shown in figures 3–7. The sonde-recorded values were those nearest in time to the sampling time. To avoid using values recorded during or after a service visit when the sensors were recalibrated, preference was given to the sonde value recorded immediately prior to the sample time. The linear-regression lines, along with the equations and coefficients of determination (R^2), also are shown in figures 3–7. Generally, a strong relation (generally R^2 greater than 0.75) resulted between the DIMs and instantaneous sonde measurements for water temperature. Most values indicate a one-to-one correspondence (fig. 3). The lowest R^2 is 0.93 for the sonde deployed at Vermilion River near Danville. The highest R^2 is 1.0 for the sonde deployed at Illinois River at Valley City.

As previously discussed, each station was selected as representative of a subset of environmental conditions. Because each of the sondes was deployed continuously at a given station for the study duration, except for problems, it is not possible to distinguish specific sonde-related issues from those of the environmental conditions at each station. In other words, the high correspondence between DIMs and sonde values at Illinois River at Valley City (see figures 3–7) could result from the relatively stable and slowly changing nature of the Illinois River at this location, or equally, to the robust and accurate response of the temperature sensor and sonde deployed there.

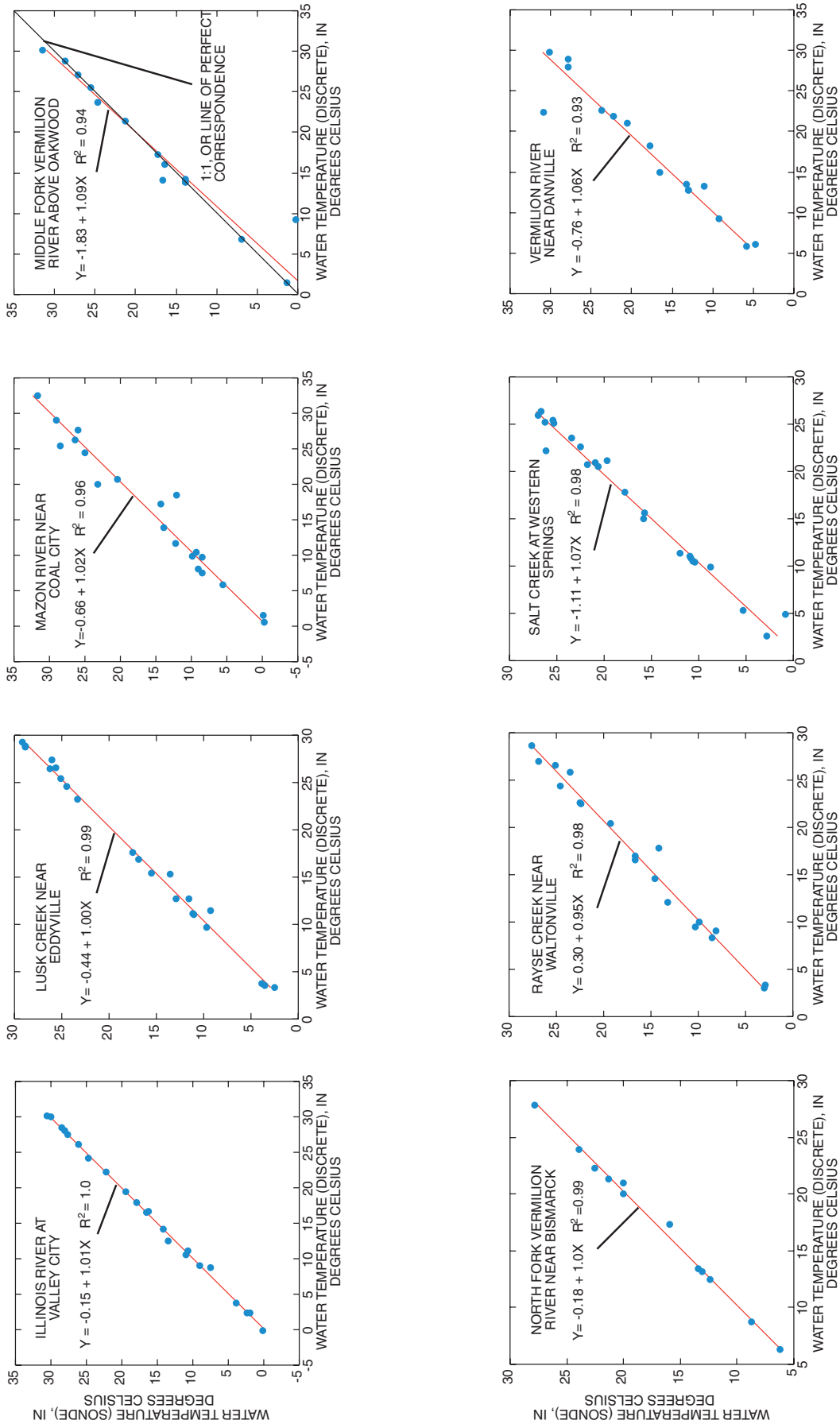


Figure 3. The relation between discrete independent measurements and instantaneous sonde measurements of temperature at eight monitoring stations, Illinois. R² is the coefficient of determination of the regression. 1:1 or line of perfect correspondence (black) only shown where the data and/or regression line will not be obscured.

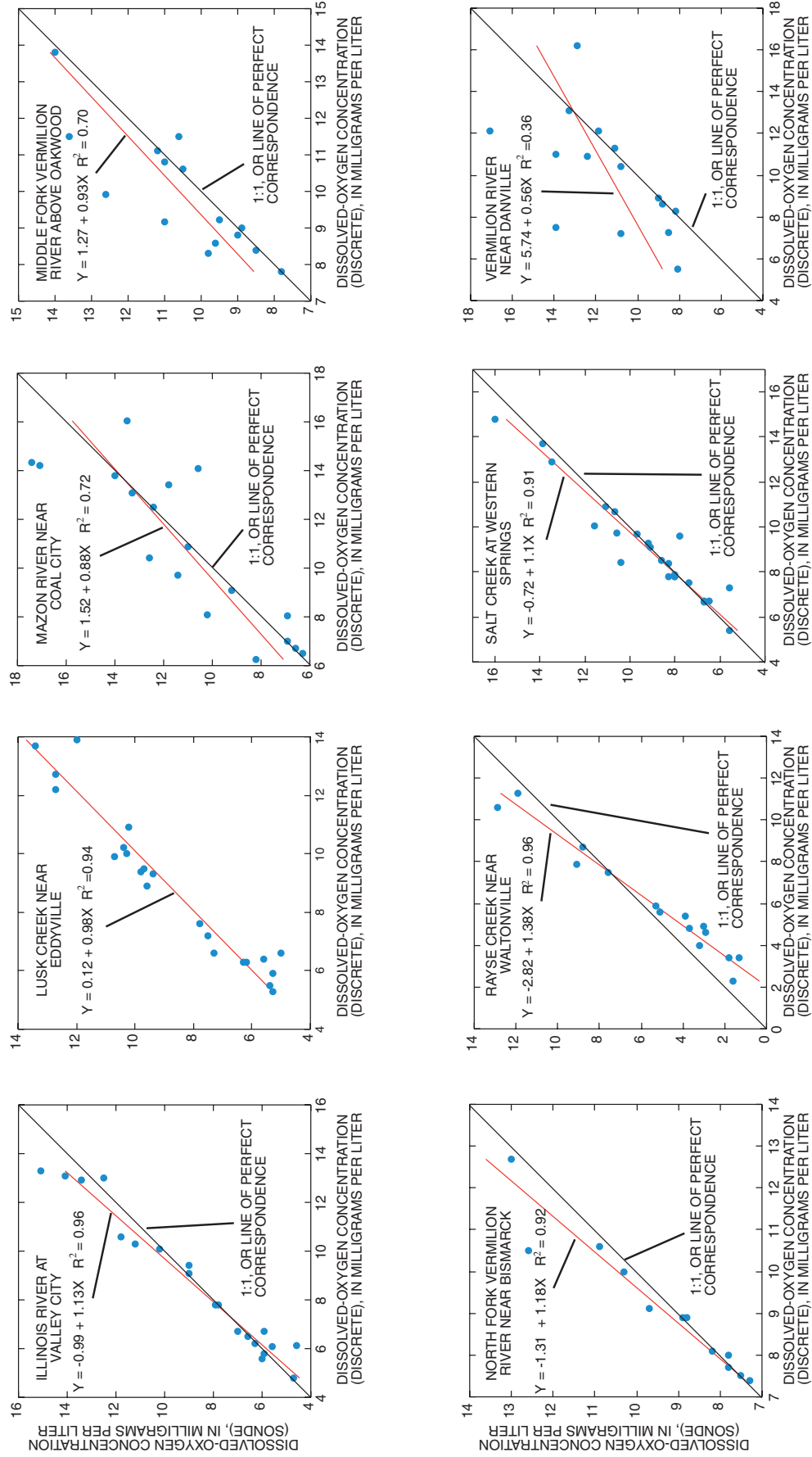


Figure 4. The relation between discrete independent measurements and instantaneous sonde measurements of dissolved oxygen at eight monitoring stations, Illinois. R² is the coefficient of determination of the regression. 1:1 or line of perfect correspondence (black) only shown where the data and/or regression line will not be obscured.

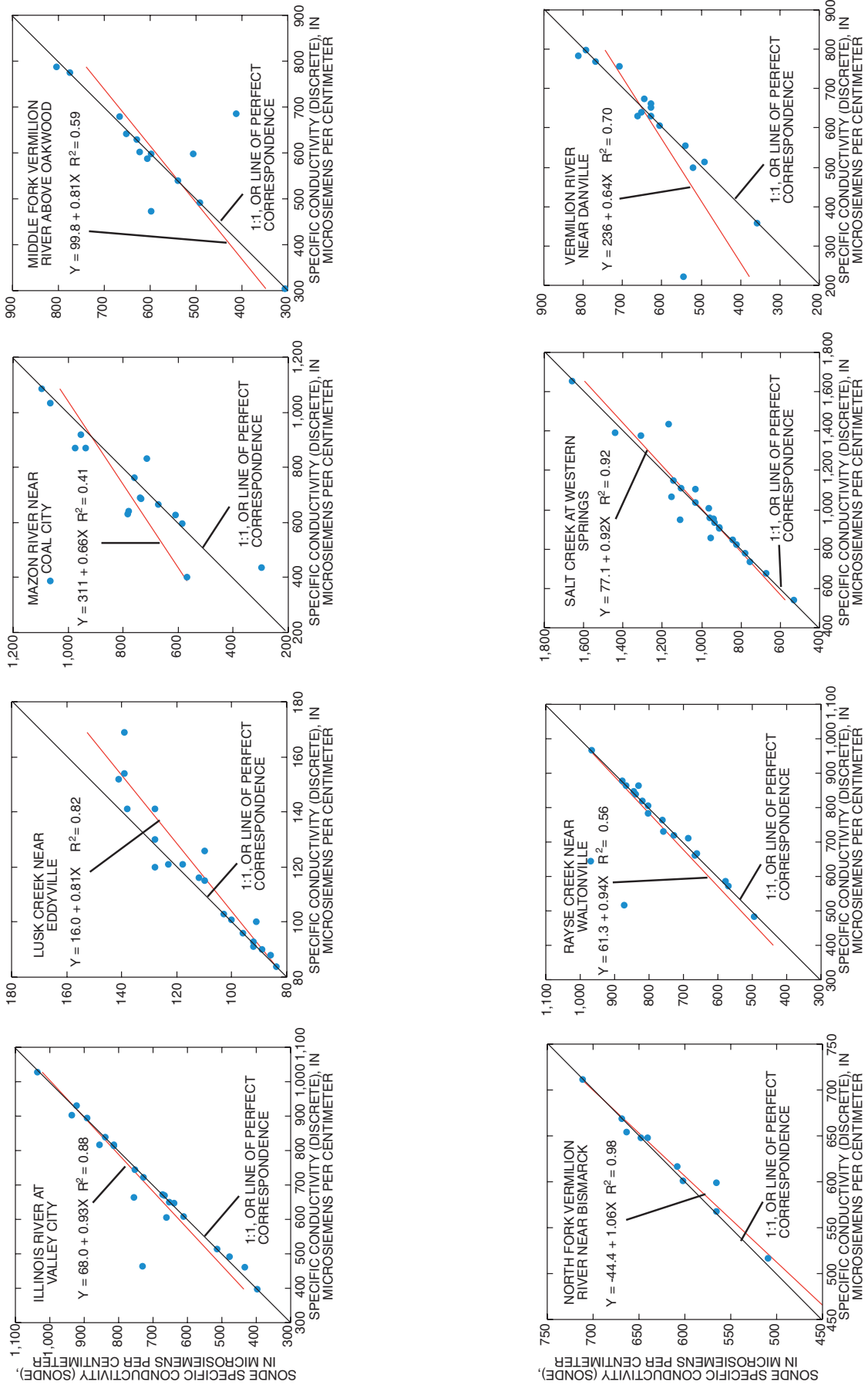


Figure 5. Relation between discrete independent measurements and instantaneous sonde measurements of specific conductivity at eight monitoring stations, Illinois. R² is the coefficient of determination of the regression.

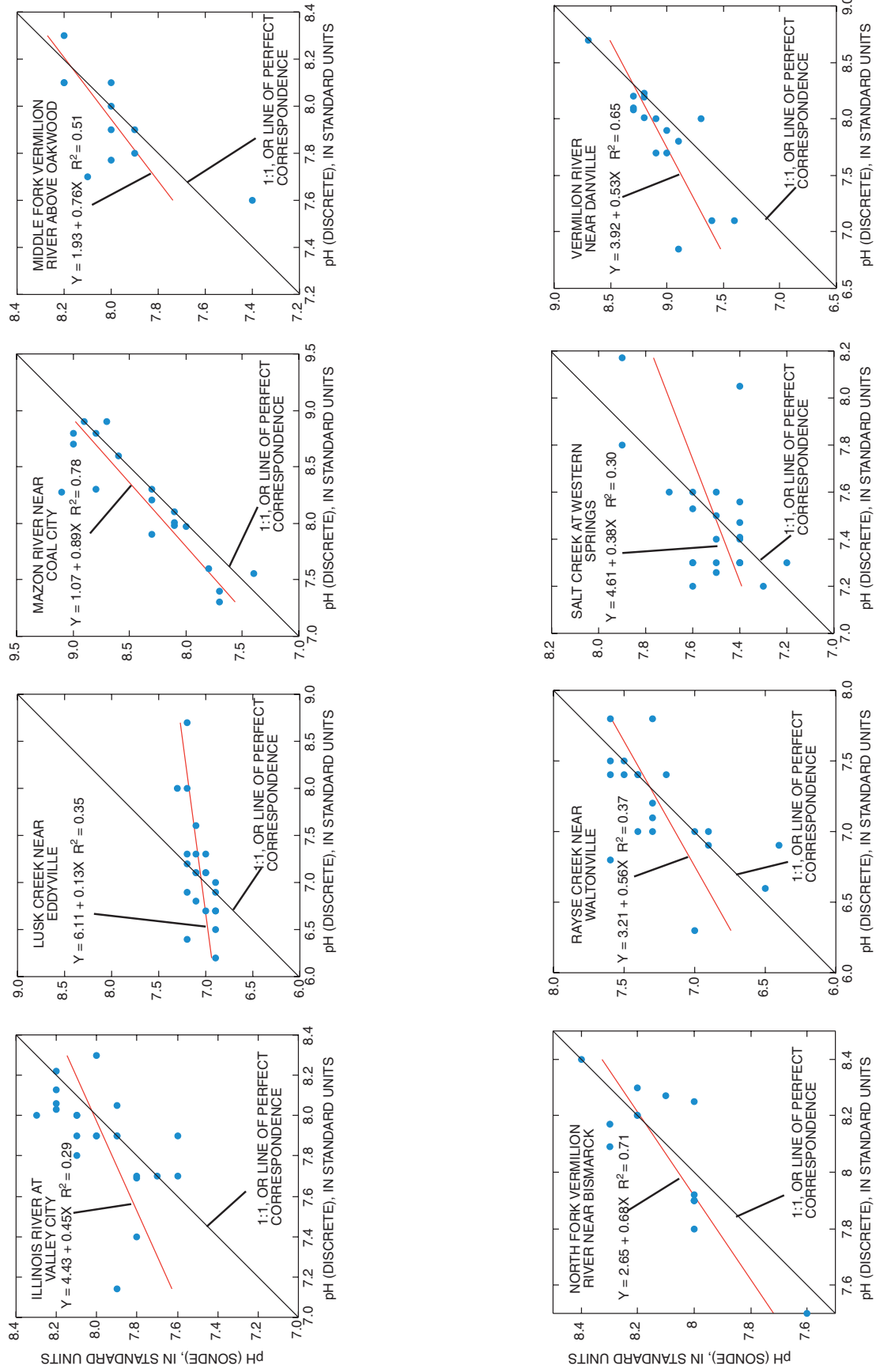


Figure 6. Relation between discrete independent measurements and instantaneous sonde measurements of pH at eight monitoring stations, Illinois. R^2 is the coefficient of determination of the regression.

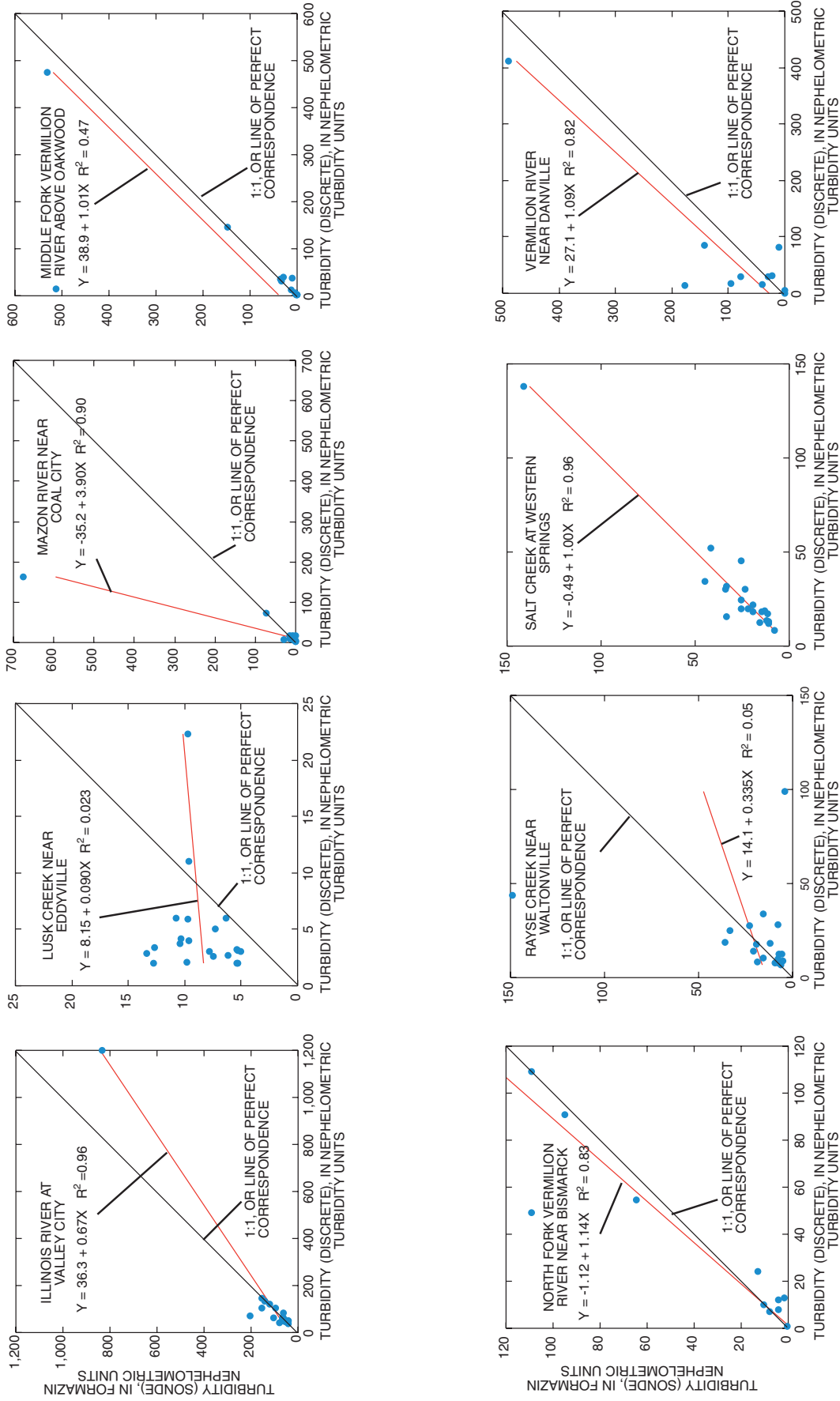


Figure 7. Relation between discrete independent measurements and instantaneous sonde measurements of turbidity at eight monitoring stations, Illinois. R² is the coefficient of determination of the regression. 1:1 or line of perfect correspondence (black) only shown where the data and/or regression line will not be obscured.

Likewise, the relatively low correspondence between DIMS and sonde values at Vermilion River near Danville could be due to the sensor or sonde itself, or to the environmental conditions of the Vermilion River at that location.

The correspondence between DIMs and sonde values for dissolved oxygen, pH, specific conductivity, and turbidity at all eight stations is shown in figures 4–7. In general, the correspondence between DIMs and sonde values is poorer for dissolved oxygen, specific conductivity, pH, and turbidity, than for temperature. The coefficients of determination for these four parameters ranged as low as 0.02 for turbidity at Lusk Creek near Eddyville (the least disturbed watershed) to as high as 0.98 for specific conductivity at North Fork Vermilion River near Bismarck (table 7).

The general sequence (from highest to lowest) of coefficients of determination is

Temperature > Dissolved Oxygen > Specific Conductivity > Turbidity > pH.

This sequence may be misleading. The coefficients of determination for turbidity are higher than pH, in part, because there is a wide range in turbidity values, when compared to temperature or dissolved-oxygen concentration. In all of the datasets, except for North Fork Vermilion River near Bismarck, only one or two values are in the highest range of turbidity and these single values substantially affect the coefficient of determination for the linear regressions on turbidity. For example, turbidity at Mazon River near Coal City (fig. 7 and table 7) has a high coefficient of determination (R^2 of 0.90) even though the regression line deviates substantially from a one-to-one correspondence because of a single value. Further, that single value (data pair) appears to be an outlier (the sonde value or the DIM value) based on visual inspection of the graph.

The relatively poor correspondence between DIM pH and sonde pH may be related to the buffer capacity and, indirectly, on the dissolved-solids concentration of the stream or river. The higher the dissolved solids (indicated by the specific conductivity) and the greater amount of alkalinity, the greater the buffer capacity of the streamwater and, generally, the more stable the pH. Lusk Creek near Eddyville had the lowest specific conductivity and alkalinity (mean specific conductiv-

ity of 122 $\mu\text{S}/\text{cm}$; mean alkalinity of 32 mg/L as CaCO_3). pH electrodes have also been demonstrated to be less accurate in water with specific conductivity less than about 100 $\mu\text{S}/\text{cm}$ (Busenberg and Plummer, 1987). Specific conductivity in Lusk Creek near Eddyville often was less than 100 $\mu\text{S}/\text{cm}$. Gel-filled pH electrodes, such as used in the deployed sondes, may be particularly susceptible to inaccuracy in water of low ionic strength. Lusk Creek near Eddyville has the second lowest correspondence between DIM pH and instantaneous sonde pH. Further, Lusk Creek is the only station where the pHs were consistently near neutral (7.0 standard units). All other monitors recorded pH values generally centered above neutral (pH of 7.5–8.0 or higher), indicating greater alkalinity and buffering capacity than Lusk Creek. Salt Creek at Western Springs has the lowest correspondence between DIM pH and instantaneous sonde pH; however, Salt Creek at Western Springs had the highest specific conductivity. Salt Creek at Western Springs is downstream of about 12 wastewater-treatment plants (WWTP) and during the study period in late summer, fall, and winter, a majority of the streamflow was WWTP effluent. Most WWTPs adjust pH during the treatment process and this could affect the stream pH independent of any natural buffering capacity or alkalinity in the streamwater.

Correspondence between DIM turbidity and instantaneous sonde turbidity is partly a consequence of the timing of sample collection. Generally, samples are collected only during periods of low turbidity—not during the early part of storm runoff. Turbidity data recorded at Vermilion River at Danville from May 5 through May 14, 2002, illustrate stormflow-related turbidity (fig. 8). The maximum turbidity generally occurs during the rising limb of a stormflow peak. Runoff from land surfaces during the early part of a rainstorm has the highest concentration of suspended sediment. Usually, suspended sediment is a major component of turbidity in Illinois streams and rivers. In the short period (hours) following the initial rise of a stormflow peak and later during stable or slowly changing streamflow periods, the turbidity tends to decrease and stabilize and then decrease further to levels before the storm. Rarely are samples taken, or the sondes serviced, during these short increases in turbidity and, there-

Table 7. Coefficients of determination for five parameters at each of eight stations in Illinois.

Station	Temperature	Specific conductivity	Dissolved-oxygen concentration	pH	Turbidity
Illinois River at Valley City	1.0	0.88	0.96	0.29	0.96
Lusk Creek near Eddyville	.99	.82	.93	.35	.02
Mazon River near Coal City	.96	.41	.72	.78	.90
Middle Fork Vermilion River above Oakwood	.93	.59	.70	.71	.47
North Fork Vermilion River near Bismarck	.99	.98	.92	.51	.83
Rayse Creek near Waltonville	.95	.56	.96	.37	.05
Salt Creek at Western Springs	.98	.92	.91	.30	.96
Vermilion River near Danville	.93	.70	.36	.65	.82

fore, the DIMs rarely include the highest stream turbidities. Unfortunately, the high values occur during relatively high flow during storms when a substantial proportion of sediment and possible contaminants attached to sediments flow past the station. Therefore, the lack of data from samples collected during high-turbidity periods represents a substantial uncertainty in measuring the transport of sediments and potential contaminants. The lowest turbidity generally occurs during low-flow conditions when ground-water inflow is the largest component of flow in the stream or river.

The available data on turbidity of natural streams in Illinois are limited. Unlike temperature, dissolved oxygen, and specific conductivity, that have been typically measured over a wide range of historical streamflow conditions at many stations, there are few historical turbidity data and the full range of turbidity values is not well known for many streams. Turbidity has not been convenient to measure until a type of sensor (such as used in this study) was developed in the mid-1990s. Prior to the development of deployable, in-situ sensors, turbidity was chiefly measured in the laboratory with a bench-top instrument. Typically, the requirements of drinking-water clarity were the objectives for these measurements. In fact, the standard USEPA method, 180.1 (U.S. Environmental Protection Agency, 1993), is useful only for the range of 0 to 40 nephelometric turbidity units (NTUs; NTUs are equivalent to FNU, but are measured by a different method). Turbidity in most Illinois streams commonly exceeds 40 NTUs for sub-

stantial periods of time, particularly during storm runoff. The sensors used for this study were not certified for greater than 1,400 FNU. Considerable uncertainty still remains concerning the calibration and reliability of in-situ measurements of turbidity exceeding 1,000 FNU. Because the turbidity at most of the eight stations in this study exceeded 1,400 FNU for at least brief periods during high streamflow, it is not known how these transient high-turbidity periods affect the average turbidity, either on a time-weighted or flow-weighted basis. Development of sensors capable of reliably and reproducibly measuring turbidities much greater than 1,000 FNU (possibly up to 2,000 to 5,000 FNU) and reliable, stable standards for calibration at the upper range may allow the evaluation of the full range of turbidities. Reliable and accurate measurement of stream turbidity greater than 1,000 FNU would potentially allow for development of much more accurate empirical relations between turbidity and suspended solids or suspended sediment (Ziegler, 2002).

Turbidity and suspended sediment in the Illinois River is unusual compared to the other seven streams in the study because of the nature of large high-order rivers, and because the river is a navigable waterway. Barges regularly passed by the Illinois River at Valley City monitor and because of the amount of propulsion required for moving barges, substantial amounts of sediment are re-entrained in the water unrelated to rainfall or runoff and, thus, increased the turbidity in at least part of the river at regular intervals.

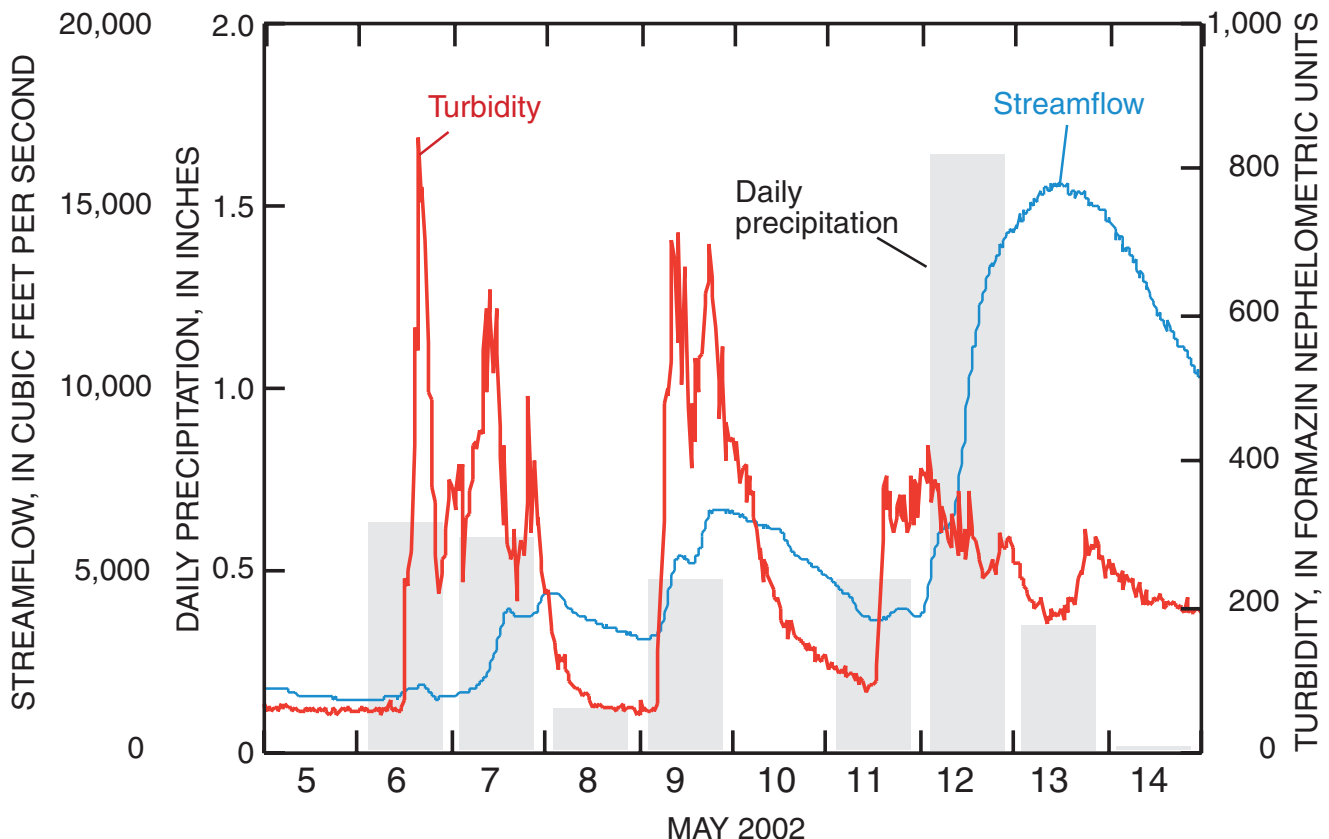


Figure 8. Relations among streamflow, daily precipitation, and turbidity in the Vermilion River near Danville, Illinois, May 5–14, 2002.

ANALYSIS OF WATER-QUALITY DATA

Comparison of laboratory-measured chlorophyll concentrations with the fluorescence (sensor)-measured chlorophyll concentrations indicated that there was no relation between the two datasets. Other characteristics of the sensor-derived chlorophyll concentrations, such as uncharacteristically large hourly or daily variations (sometimes an order of magnitude), indicated that the sensors were not reliably detecting chlorophyll. Based on the data collected for this study, it cannot be determined if the problems with the sensor-derived chlorophyll concentrations data were chiefly with the sensor or monitor, the deployment and calibration protocols, or with the particular environmental conditions at the stations, or a combination of these reasons. These chlorophyll data are not analyzed or discussed further in this report.

The daily maximums, the daily minimums, and the daily range of dissolved oxygen measured with the monitors for the eight stations from July 2001 through September 2003 are shown in figures 9 through 16. Dissolved oxygen is critical to ecosystem health and especially to native fish and other respiring organisms (Allen, 1995). The State of Illinois has set a regulatory minimum of 5 mg/L of dissolved oxygen (this regulatory minimum is shown in the figures 9 through 16) to maintain health of fish and of respiring aquatic organisms. During periods, generally in late summer, even the least developed (least disturbed) watershed—Lusk Creek near Eddyville—recorded dissolved-oxygen concentrations below the regulatory minimum (5 mg/L). Nutrient data collected at this station indicate, that of the eight watersheds monitored in this study, it is the least affected by nutrient runoff (table 8) and should be least likely of the eight watersheds monitored to have oxygen depletion caused by algal bloom die-off. Other watersheds, such as that of the Illinois River at Valley City, had daily oxygen maximum concentrations during short intervals in late summer (hours to days) that did not rise above the 5-mg/L dissolved-oxygen minimum. Rayse Creek near Waltonville has the most variable daily maximums, minimums, and range of dissolved-oxygen concentration.

The patterns of dissolved oxygen and temperature during August 2001 through September 2003 at Salt Creek at Western Springs are shown in figure 17. In general, and for all stations, not just Salt Creek, dissolved-oxygen concentration and temperature through the year are nearly completely out of phase—one reaches its annual minimum when the other reaches its annual maximum. This phase disparity probably results from the following or other factors. First, the solubility of gasses declines with increasing temperature; therefore, at equilibrium and in well-mixed conditions, oxygen in water will decline with increasing temperature. Second, respiration by plants, animals, and bacteria increases with temperature, so, barring other limitations, dissolved oxygen will be used more quickly as water temperature increases. Finally, production of organic matter (particularly algal biomass) increases with temperature. In late summer, algal blooms are most frequent

and the resultant decay of a large mass of algal material can quickly deplete dissolved oxygen in nutrient-enriched streams. Oxygen is constantly replenished in flowing water in contact with the atmosphere; however, biota-driven processes, such as photosynthesis and respiration, can be much faster than physical replenishment. High photosynthetic release of oxygen during sunny periods usually is faster than the rate at which oxygen can diffuse to the surface of the stream and exsolve to the atmosphere. Uptake of oxygen by bacteria and other organisms at night generally is faster than the rate at which oxygen dissolves in water and diffuses to the zone of lower concentration (Hem, 1992).

Daily fluctuations of dissolved-oxygen concentration in response to generation of oxygen by macrophytes and algae during sunny days, and decomposition and respiration by oxygen-using organisms at night are important in all streams and rivers. These daily fluctuations and the overriding effect of stormflow on dissolved oxygen are shown in figure 18 for North Fork Vermilion River near Bismarck during August 2002. The range of daily dissolved oxygen at this station is close to the average for the eight stations monitored during this study. The two storms in the second half of the month (as indicated by the two streamflow peaks on figure 26) show that the storms dampen or eliminate the daily fluctuations and depress the dissolved-oxygen concentrations for days. The lowered dissolved-oxygen concentration at this station does not go below the 5-mg/L regulatory minimum.

The relation between discrete measurements of temperature and discrete dissolved-oxygen measurements in the Illinois River at Valley City is shown in figure 19. There is a strong linear relation between river water temperature and dissolved-oxygen concentration. This station is the only station of the eight monitored with a strong correlation between water temperature and dissolved-oxygen concentration. The river is wide and relatively shallow with a turbidity-limited euphotic zone (probably less than 2-3 ft). Small streams (less than 5,000 ft³/s) have lower turbidity and usually have substantial biomass of periphyton attached to the streambed. The generation of oxygen by the periphyton greatly outstrips the depletion by respiration during sunny days in small streams. The narrow euphotic zone in the Illinois River limits photosynthesis by periphyton and to some extent even the free-floating phytoplankton. Production of oxygen by algae in the Illinois River probably does not greatly outstrip the capacity of the river to equilibrate with atmospheric oxygen; therefore, water temperature could be the main determinant of the amount of dissolved oxygen in the Illinois River at Valley City. Illinois River at Valley City has the smallest range in dissolved oxygen of the eight monitored stations (fig. 9). However, there are periods where the dissolved-oxygen concentration fell below the regulatory 5-mg/L minimum, likely because of decomposition of algal biomass.

The coefficient of determination for the linear correlation between temperature and dissolved oxygen at Valley City is 0.90. The highest coefficient of determination at any other station is 0.72 at Lusk Creek near Eddyville. Lusk Creek is

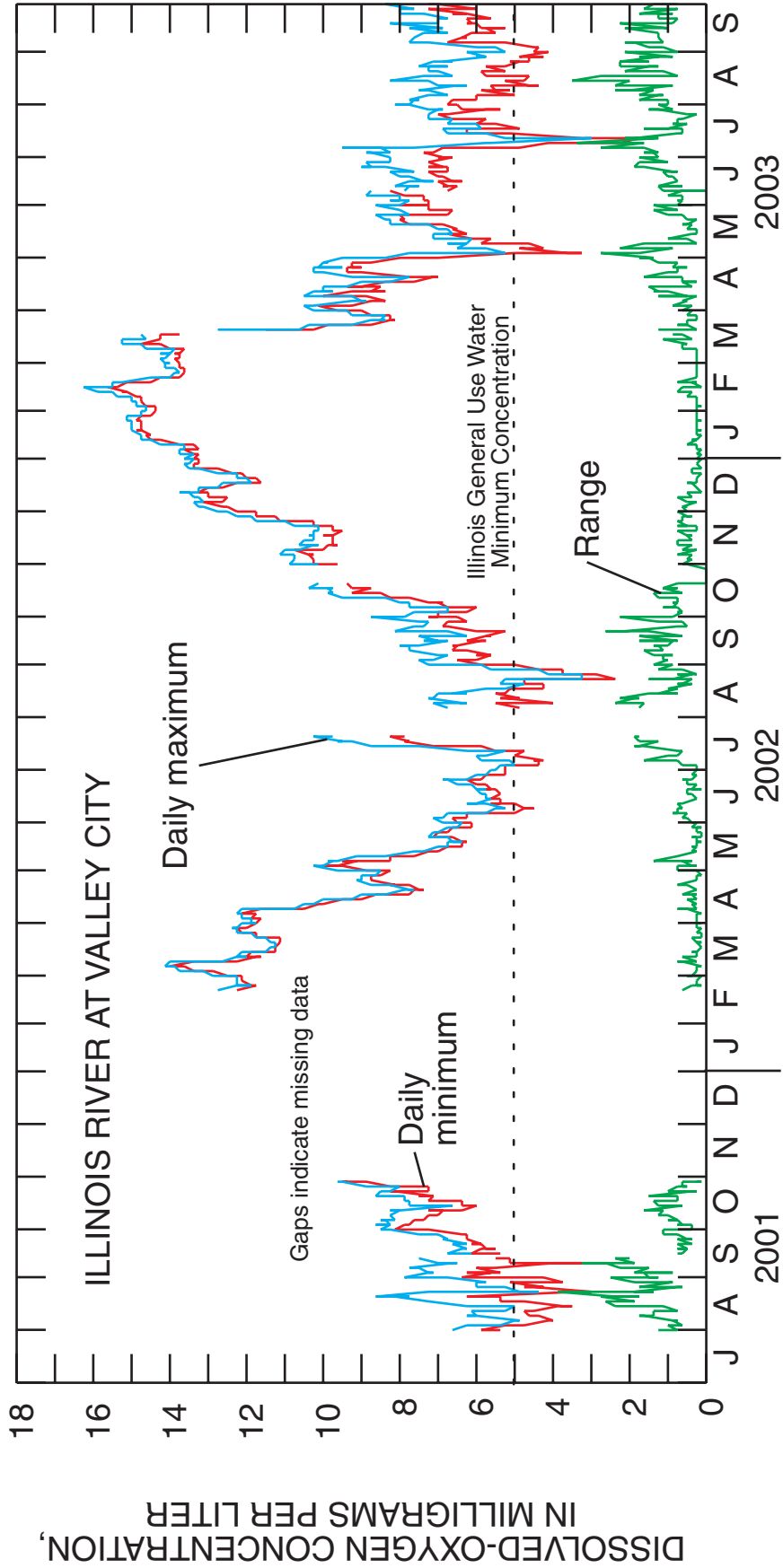


Figure 9. Daily maximum, minimum, and range for dissolved-oxygen concentration at Illinois River at Valley City, Illinois, from August 2001 through September 2003.

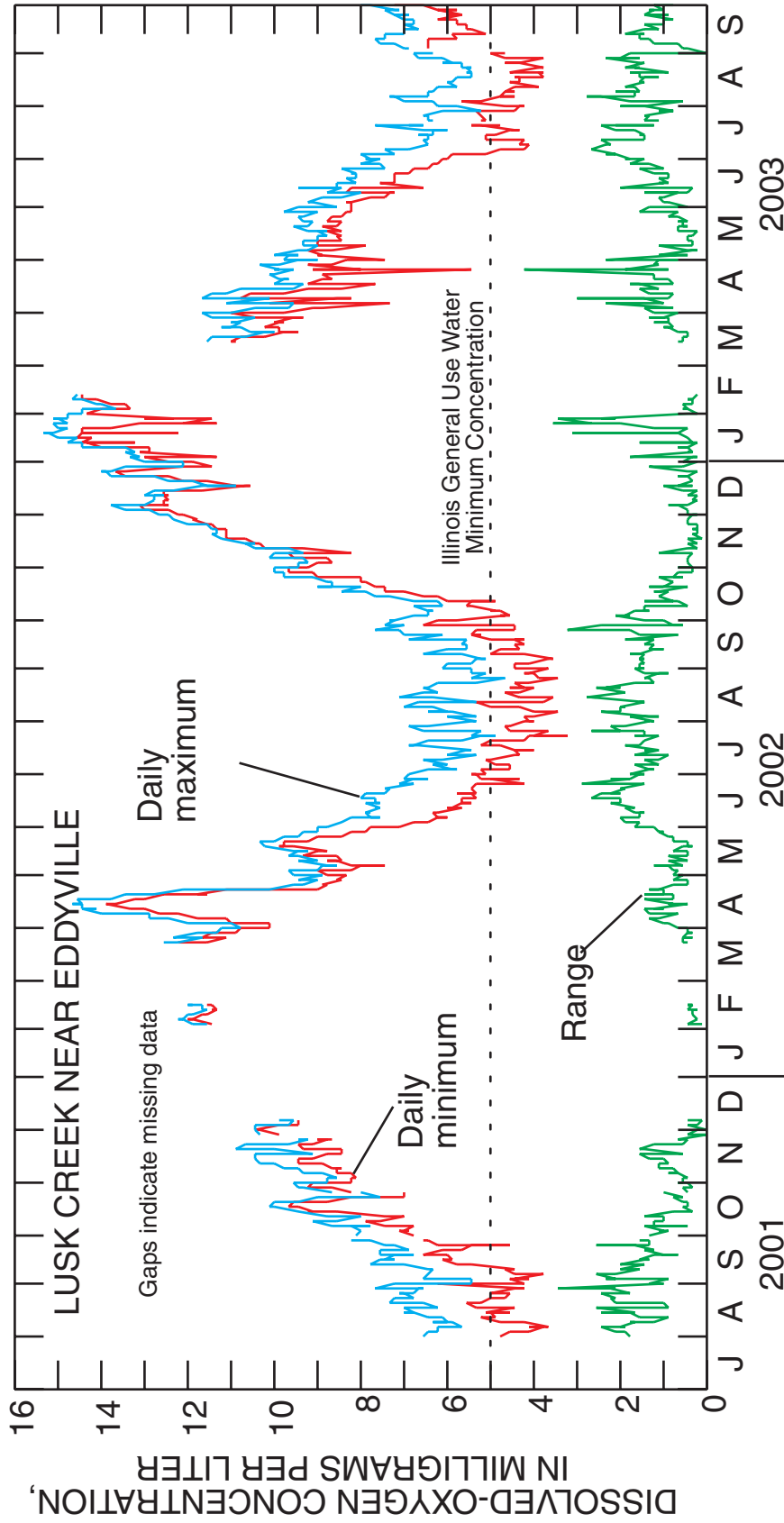


Figure 10. Daily maximum, minimum, and range for dissolved-oxygen concentration at Lusk Creek near Eddyville, Illinois, from August 2001 through September 2003.

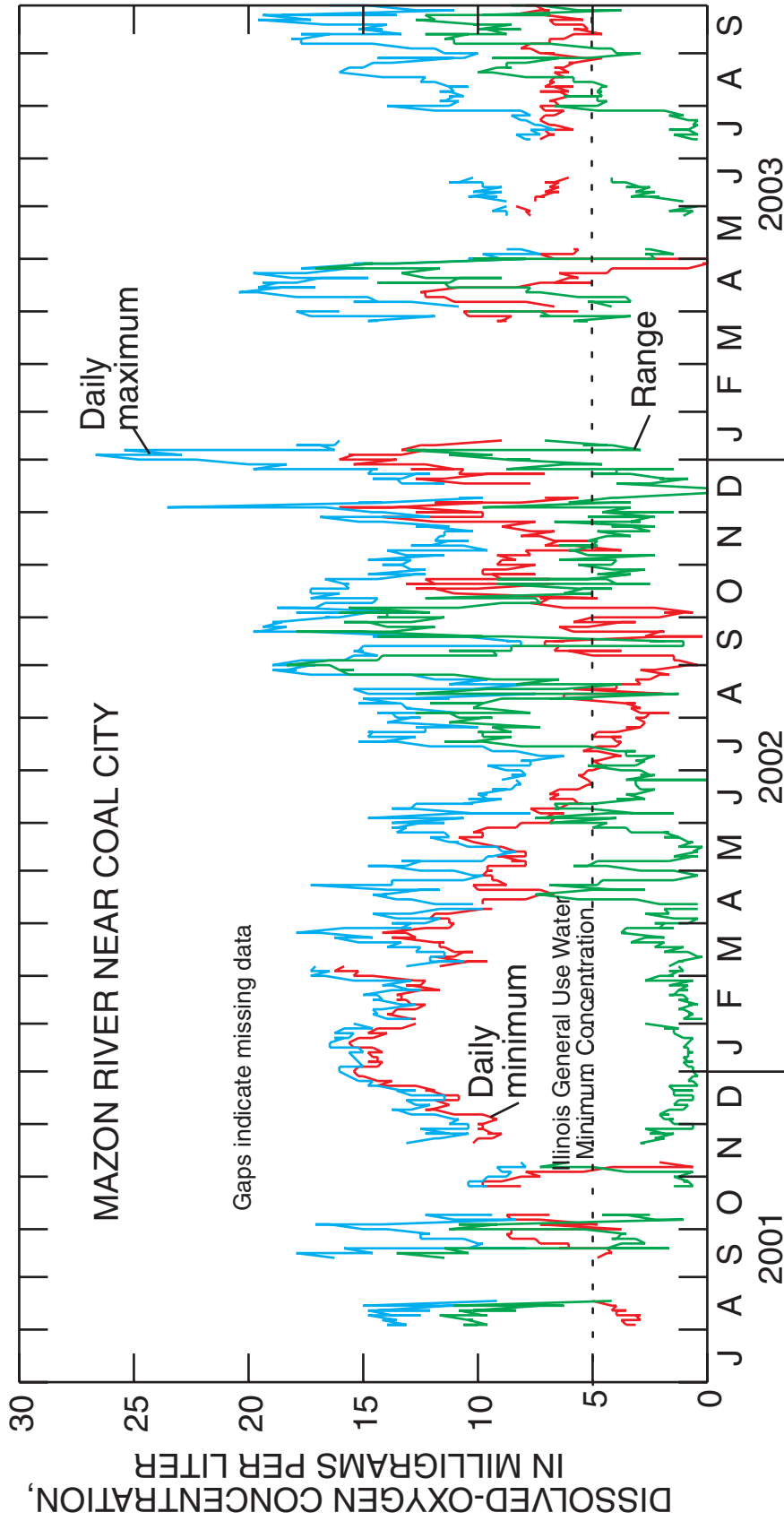


Figure 11. Daily maximum, minimum, and range for dissolved-oxygen concentration at Mazon River near Coal City, Illinois, from August 2001 through September 2003.

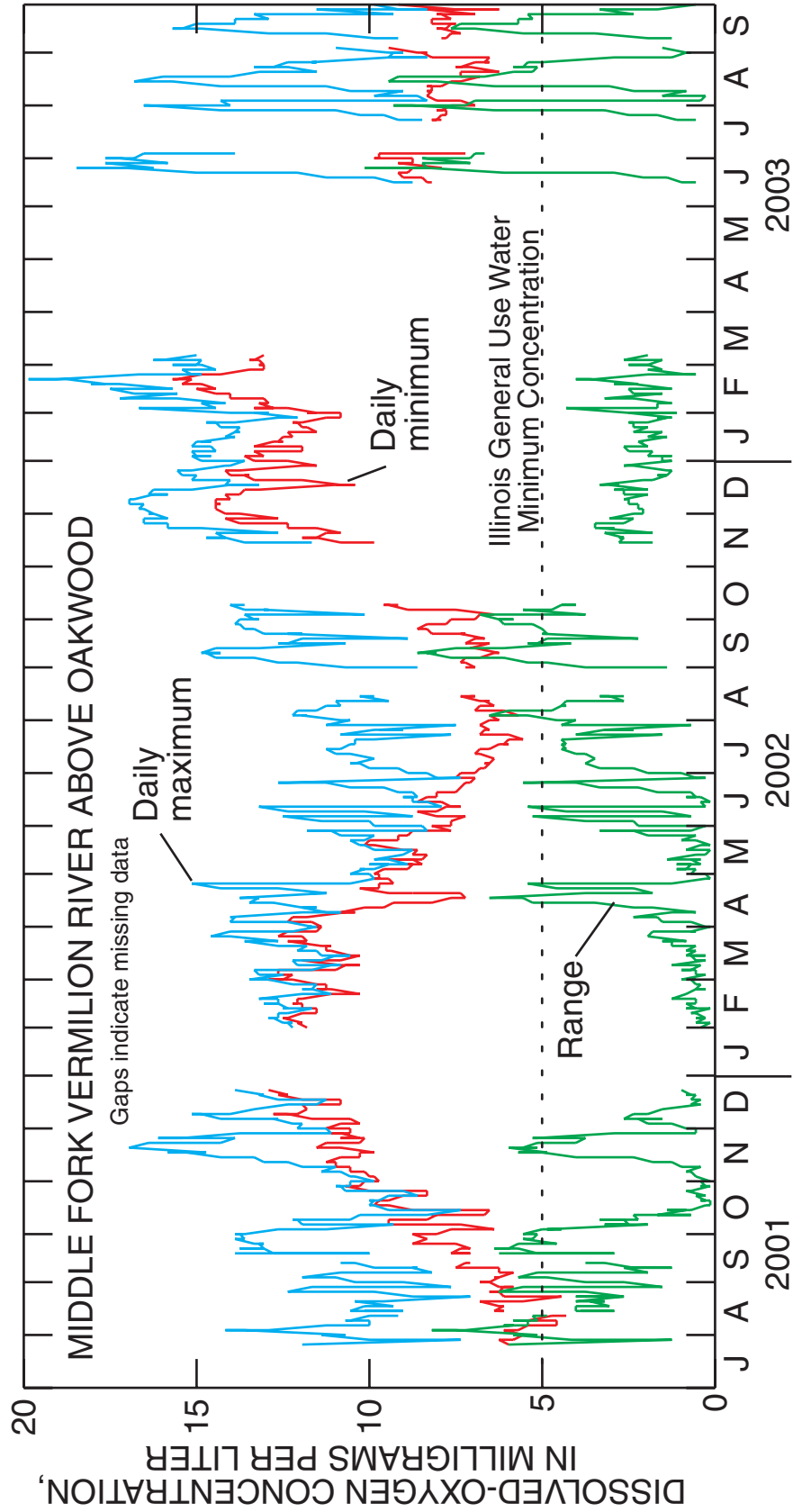


Figure 12. Daily maximum, minimum, and range for dissolved-oxygen concentration at Middle Fork Vermilion River above Oakwood, Illinois, from August 2001 through September 2003.

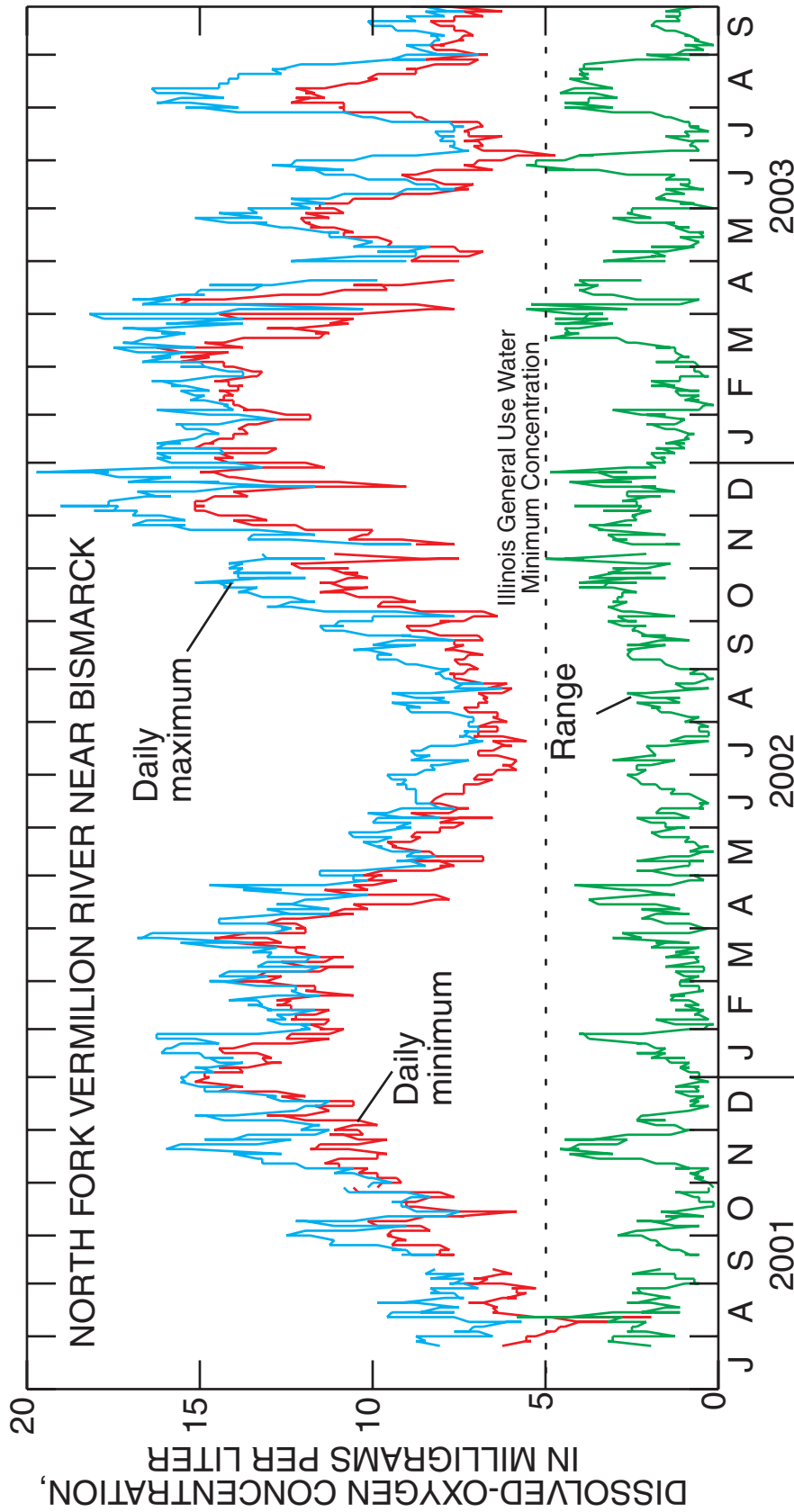


Figure 13. Daily maximum, minimum, and range for dissolved-oxygen concentration at North Fork Vermilion River near Bismarck, Illinois, from August 2001 through September 2003.

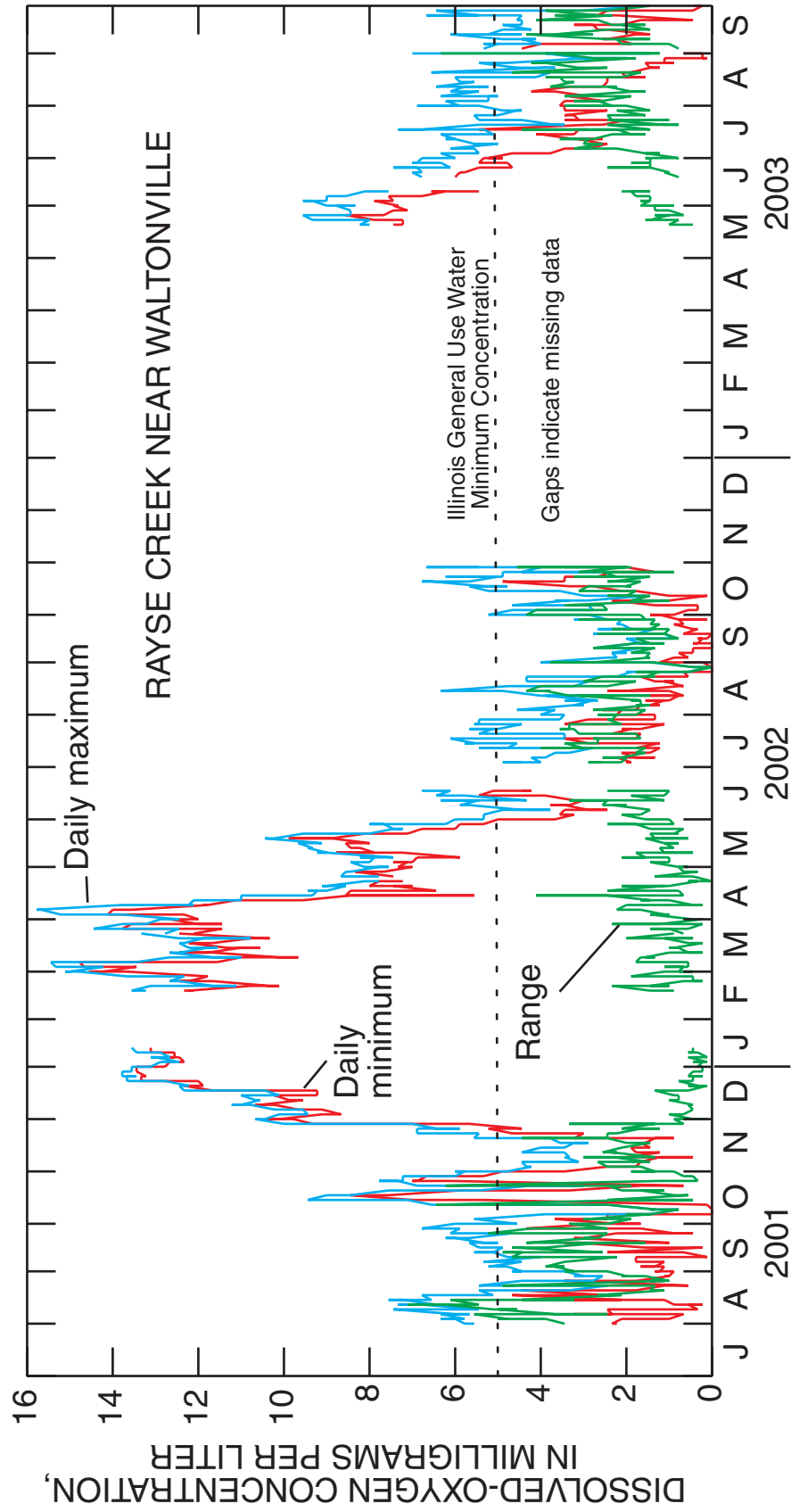


Figure 14. Daily maximum, minimum, and range for dissolved-oxygen concentration at Rayse Creek near Waltonville, Illinois, from August 2001 through September 2003.

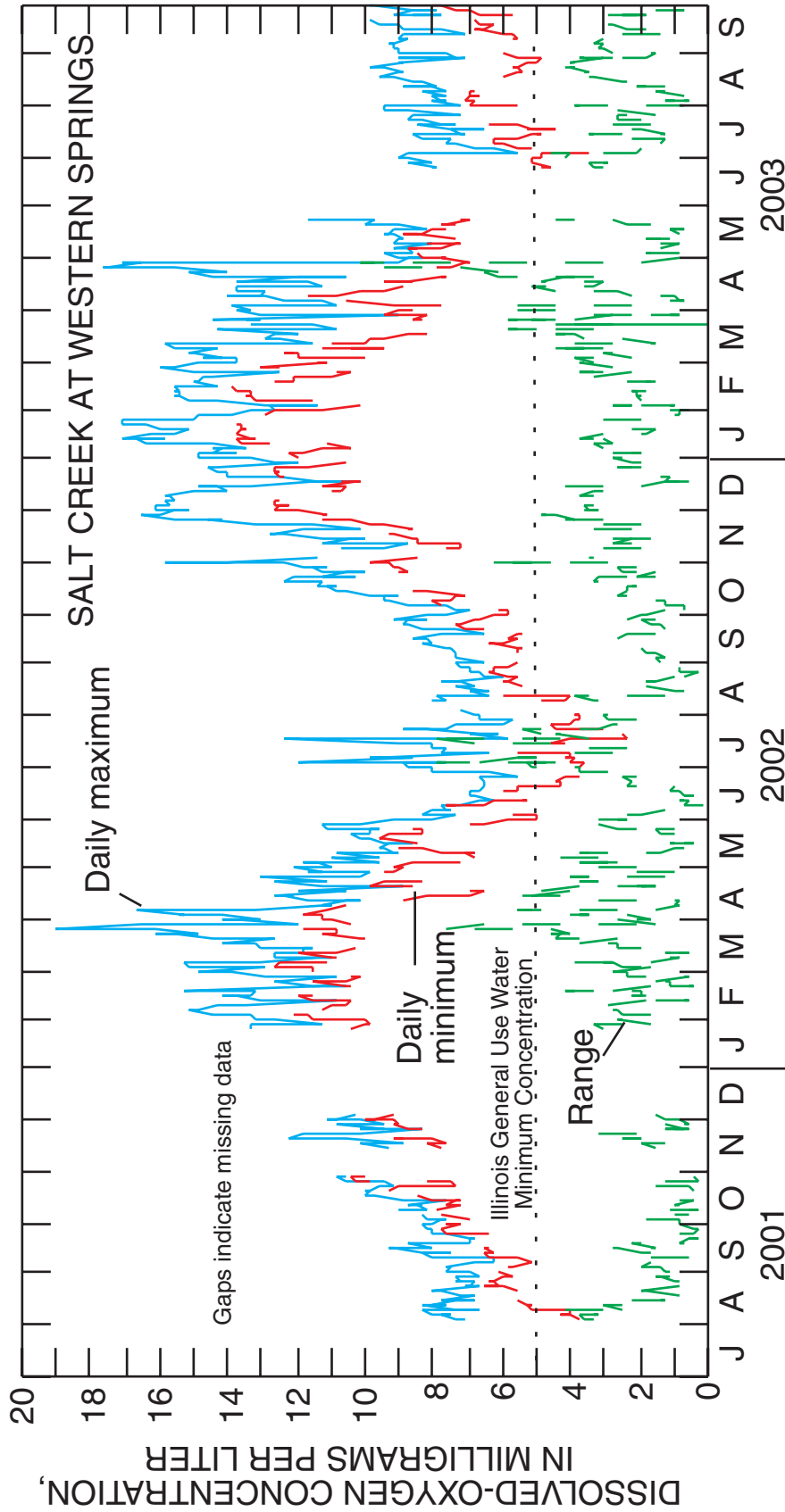


Figure 15. Daily maximum, minimum, and range for dissolved-oxygen concentration at Salt Creek at Western Springs, Illinois, from August 2001 through September 2003.

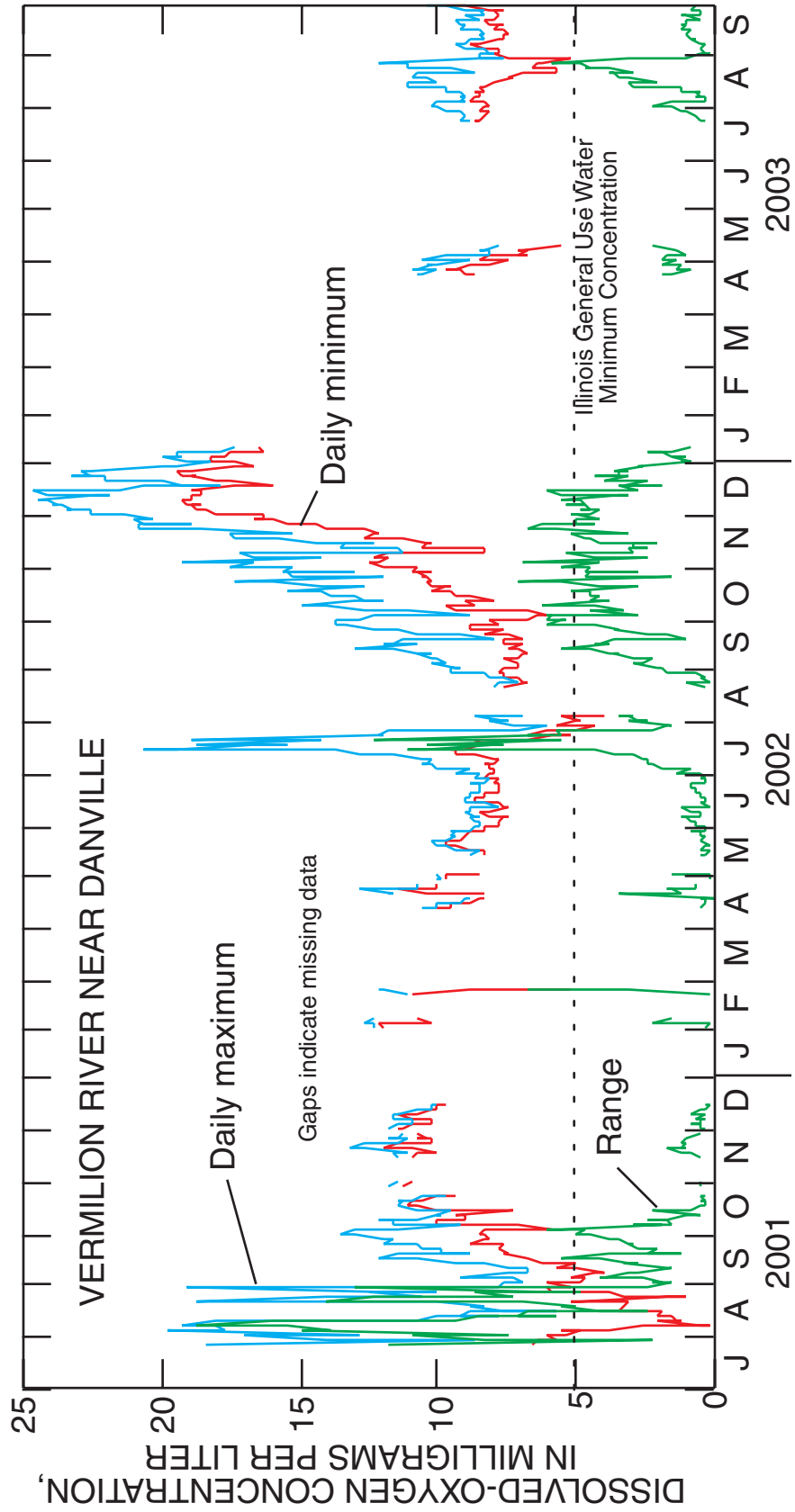


Figure 16. Daily maximum, minimum, and range for dissolved-oxygen concentration at Vermilion River near Danville, Illinois, from August 2001 through September 2003.

the watershed least affected by nutrients in runoff (table 8) of the eight watersheds monitored. Lusk Creek (fig. 10) has the second smallest average daily range in dissolved oxygen of the eight stations monitored. The effect of algal blooms on dissolved oxygen in Lusk Creek should be small relative to other small streams; thus, temperature likely is a major factor affecting dissolved-oxygen concentration in the stream.

The relation between streamflow and specific conductivity is nearly the opposite of that between turbidity and streamflow (fig. 20). Early in the rising limb of a storm hydrograph, specific conductivity drops because of the precipitation directly on the stream and early overland flow from riparian areas of the watershed. The specific conductivity and streamflow for Mazon River near Coal City for the period March 7–27, 2002, shows examples of this phenomenon. In most small streams, (mean annual flow about 500 ft³/s or less), specific conductivity is an indicator of ground-water inflow to the stream because ground water generally has much higher dissolved-solids concentrations than storm runoff in streams. Specific conductivity increases as ground water becomes a larger portion of the streamflow as the flow recedes during late summer, fall, and winter.

Most streams and rivers in Illinois follow the general relation between specific conductivity and streamflow, but the effect often is subdued in some streams because of the relatively high dissolved-solids concentration in streams and rivers relative to precipitation and shallow ground water. Further, streams that have relatively large contributions from WWTPs, such as Salt Creek at Western Springs, have high dissolved-solids concentrations because of the effluent (fig. 21) or from road-salt runoff. The high dissolved-solids concentration of WWTP effluent and consistent discharge to the stream throughout the year and road salt from snow melt create specific-conductivity peaks in the stream that tend to mimic and often overwhelm the increase in specific conductivity caused by ground-water inflow, especially during the winter months (fig. 21).

Since 1972, dissolved-oxygen concentration in Illinois streams has been regulated. The Illinois Pollution Control Board (IPCB) requires that dissolved-oxygen concentration in Illinois General Use (those without special regulations) streams will not be less than 6.0 mg/L for at least 16 hours of any 24-hour period or less than 5.0 mg/L at any time (Illinois Pollution Control Board, 2004). Compliance with this regulation can be difficult to monitor, in part, because there is no definition or restriction regarding the 16-hour period to which the regulation applies. Furthermore, dissolved-oxygen concentration generally reaches its minimum around dawn, when water-quality measurements are rarely collected. This discussion refers primarily to the instantaneous standard (5 mg/L) rather than the 16-hour minimum because most periods of noncompliance in the eight streams of this study involved this standard rather than the 16-hour minimum. Dissolved-oxygen concentration typically fluctuates daily as a result of photosynthesis and algal and other microbial respiration, and relatively low-velocity streams often have larger daily fluctuations compared to faster flowing streams. Some Illinois streams, especially in the southern part of the State, are naturally warmer and, thus, may have lower dissolved-oxygen concentration than cooler streams. The higher stream temperatures often increase the rates of photosynthesis and respiration and, therefore, the range of the daily dissolved-oxygen fluctuations. Most noncompliance with respect to the dissolved-oxygen standard occurs from June through October each year with near-normal weather and rainfall. The dissolved-oxygen concentration from the sondes and the 7-day mean dissolved oxygen for Salt Creek at Western Springs, North Fork Vermilion River near Bismarck, and Lusk Creek near Eddyville are shown in figure 22. The current (2004) dissolved-oxygen standards and example proposed standards also are shown in the figure to compare how these three streams comply when assessed with these standards. These three streams have a wide variety of impairment and environmental conditions and, thus, represent most Illinois streams.

Table 8. Mean total nitrogen and phosphorus concentrations and mean dissolved-oxygen concentration maximums, minimums, and daily range, in milligrams per liter, at the eight stations in Illinois, July 2001 through June 2003.

Station	Mean total nitrogen concentration	Mean total phosphorus concentration	Mean of daily dissolved-oxygen maximums	Mean of daily dissolved-oxygen minimums	Mean of daily range dissolved-oxygen concentration
Illinois River at Valley City	6.6	0.4	9.4	8.6	0.76
Lusk Creek near Eddyville	.45	.02	8.9	7.8	1.2
Mazon River near Coal City	11.4	.09	13.2	8.1	5
Middle Fork Vermilion River above Oakwood	9.2	.11	12.3	9.5	2.9
North Fork Vermilion River near Bismarck	8.2	.16	11.8	9.9	1.8
Rayse Creek near Waltonville	1.9	.24	6.7	4.7	2
Salt Creek at Western Springs	7.4	1.5	10.5	8.1	2.4
Vermilion River near Danville	7.2	.32	12	9.1	2.9

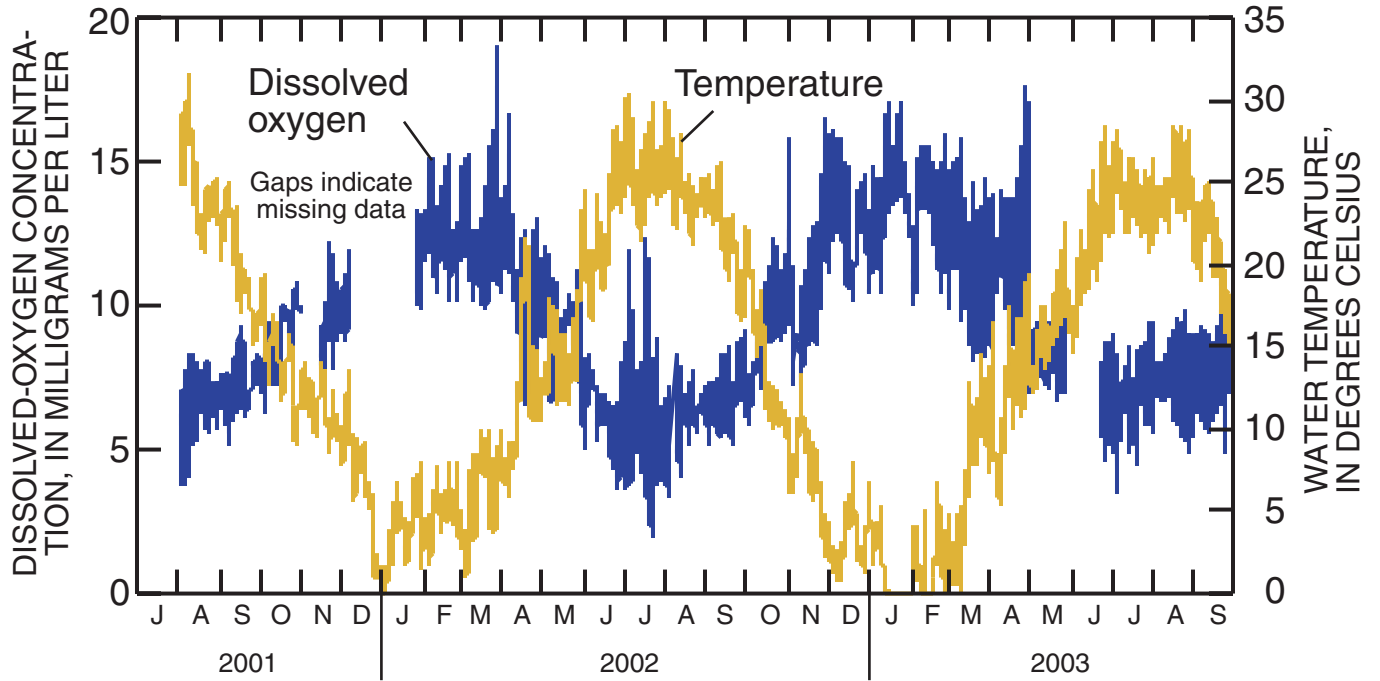


Figure 17. Water temperature and dissolved-oxygen concentration at Salt Creek at Western Springs, Illinois, August 2001 through September 2003.

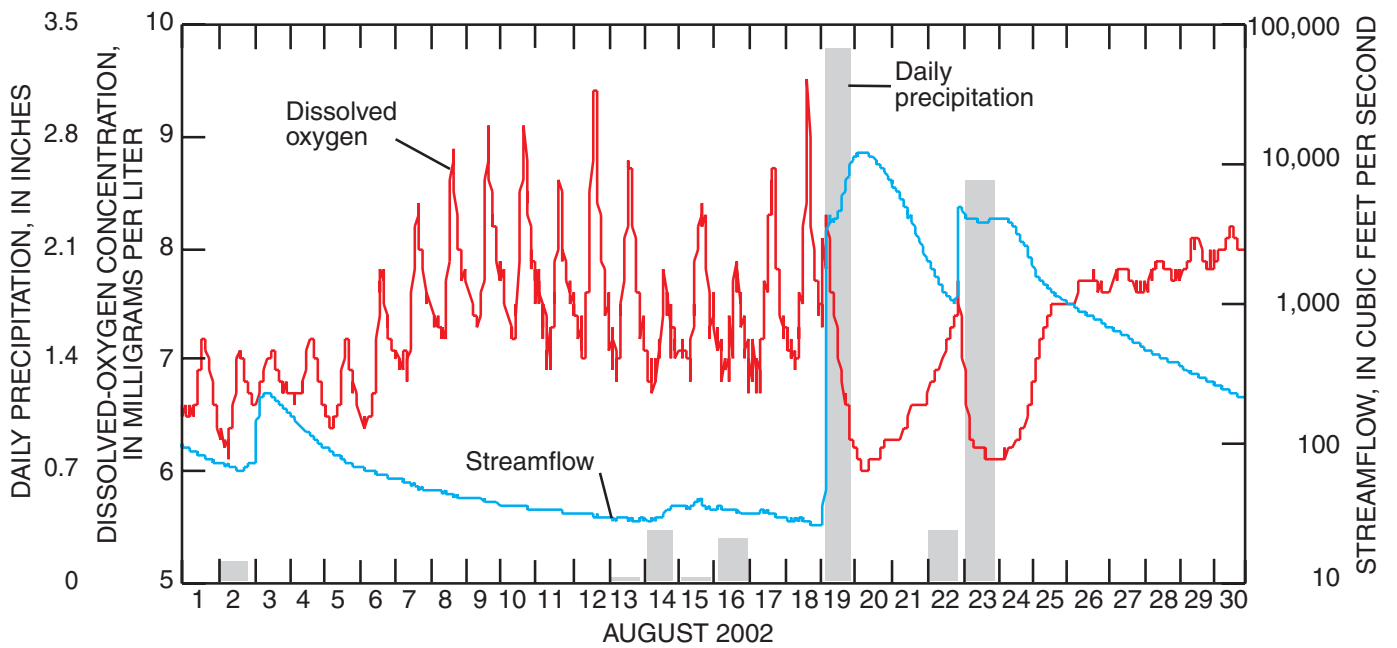


Figure 18. Dissolved-oxygen concentration, daily precipitation, and streamflow at North Fork Vermilion River near Bismarck, Illinois, during August 2002.

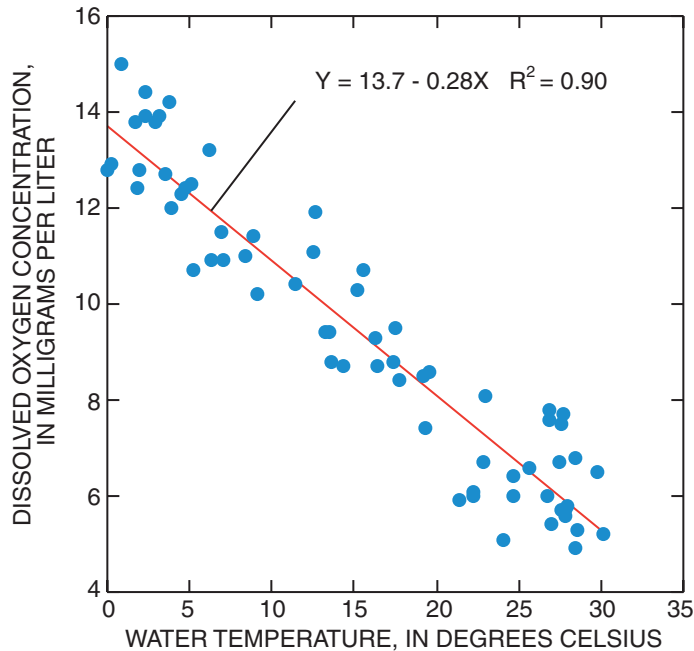


Figure 19. The relation between dissolved-oxygen concentration and water temperature at Illinois River at Valley City, Illinois. R^2 is the coefficient of determination of the regression.

SUMMARY

The U.S. Geological Survey (USGS), in cooperation with the Illinois Environmental Protection Agency (IEPA), conducted a study from July 2001 to October 2003 to investigate the applicability of the USEPA nutrient criteria to water quality and environmental conditions in streams in Illinois. The study involved the deployment of multi-parameter continuous water-quality monitors at eight stream or river locations across the State, representing a range of water quality and environmental conditions. The stations are (in alphabetical order):

- Illinois River at Valley City, Illinois;
- Lusk Creek near Eddyville, Illinois;
- Mazon River near Coal City, Illinois;
- Middle Fork Vermilion River above Oakwood, Illinois;
- North Fork Vermilion River near Bismarck, Illinois;
- Rayse Creek near Waltonville, Illinois;
- Salt Creek at Western Springs, Illinois, and;
- Vermilion River near Danville, Illinois

Data on water temperature, dissolved-oxygen concentrations, specific conductivity, pH, and turbidity were collected with these monitors. Data-quality objectives for the study—to

obtain and record fair to excellent data from the multi-parameter monitors for at least 75 percent of the deployment at the eight stations—were achieved. The pilot deployment of eight multi-parameter water-quality continuous monitors generally yielded good to excellent data for five parameters—water temperature, dissolved-oxygen concentration, specific conductivity, pH, and turbidity. Data from sensors for chlorophyll generally did not meet data-quality objectives for this study. The results indicate that the station-visit frequency (from 2 to 6 weeks) was adequate to maintain the accuracy and precision of four of five of the sensors (temperature, specific conductivity, dissolved oxygen, and turbidity). The temperature sensors provided the most accurate and reliable measurements (generally within ± 5 percent of a calibrated thermometer reading). The dissolved-oxygen sensors were the next most reliable during the study and were responsive to changing conditions and accurate at all eight stations. Specific conductivity was the third most accurate and reliable measurement collected from the multi-parameter monitors. Measurements of pH generally met data-quality objectives; however, the pH sensors apparently were the least responsive to changes of the five sensors tested and yielded the least-reliable data. Turbidity sensors collected measurements that met the data-quality objectives below about 1,400 formazin nephelometric units (FNU).

Operator error was the most frequent cause of missing or unusable data values, accounting for 72 percent of overall data losses. Excessive sensor fouling caused about 10 percent of all unusable values. Fouling was most severe during periods of low streamflow and during peak water temperature, often in late summer. Generally, the oxygen and pH sensors were most vulnerable to fouling—about 29 percent of dissolved-oxygen data losses and 11 percent of pH data losses were the result of fouling. Sensor fouling caused loss of turbidity data less than 3 percent of the time with the exception of Middle Fork Vermilion River above Oakwood, Rayse Creek near Waltonville, and Vermilion River near Danville. At these three stations, the fouling was more severe and caused about 10 to 15 percent of turbidity data to be unusable. About 15 percent of oxygen-sensor data losses were caused either by membrane rupture or membrane leakage.

The performance of the monitors also was evaluated by comparison with discrete independent measurements of the parameters by IEPA and USGS sampling personnel during their periodic sampling visits to the stations. Coefficients of determination of linear regressions of the discrete measurements on the instantaneous sonde value are indicators of the correspondence between the two sets of measurements. The correspondence between the discrete temperature measurements and sonde temperature yielded the highest coefficients—0.93 at Lusk Creek near Eddyville to 1.0 at Illinois River at Valley City. The coefficients of determination for dissolved oxygen, specific conductivity, pH, and turbidity ranged as low as 0.02 for turbidity at Lusk Creek near Eddyville (the least disturbed watershed) to as high as 0.98 for specific conductivity at North Fork Vermilion River near Bismarck. The relatively poor correspondence between discrete indepen-

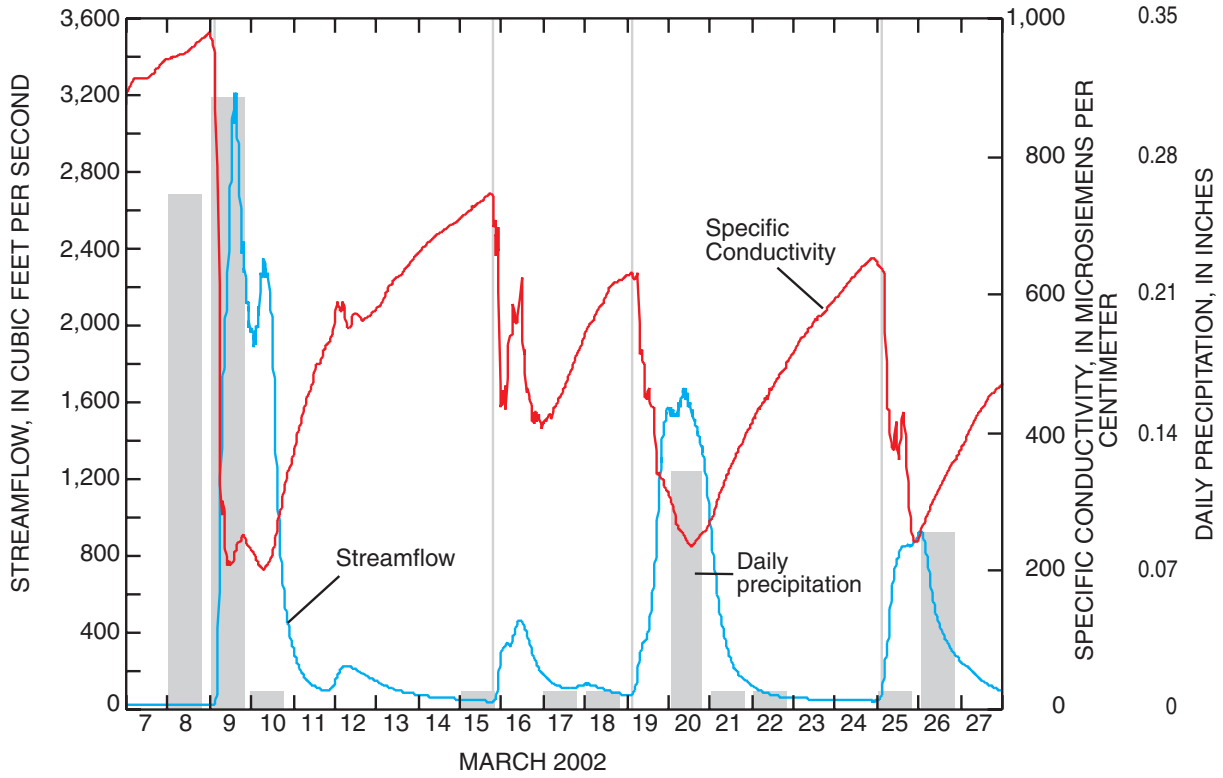


Figure 20. Relations among daily precipitation, streamflow, and specific conductivity in Mazon River near Coal City, Illinois, March 7–27, 2002. Gray lines indicate beginning of stormflow rise.

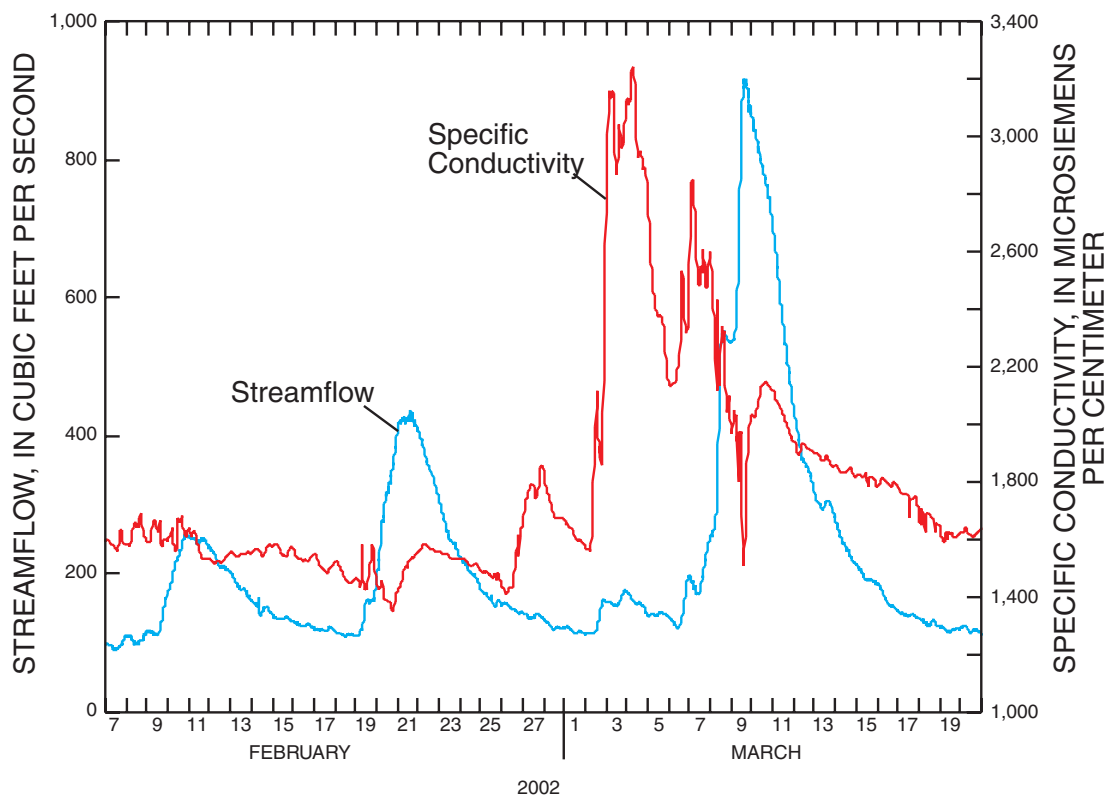


Figure 21. Specific conductivity and streamflow at Salt Creek at Western Springs, Illinois, February 7–March 21, 2002.

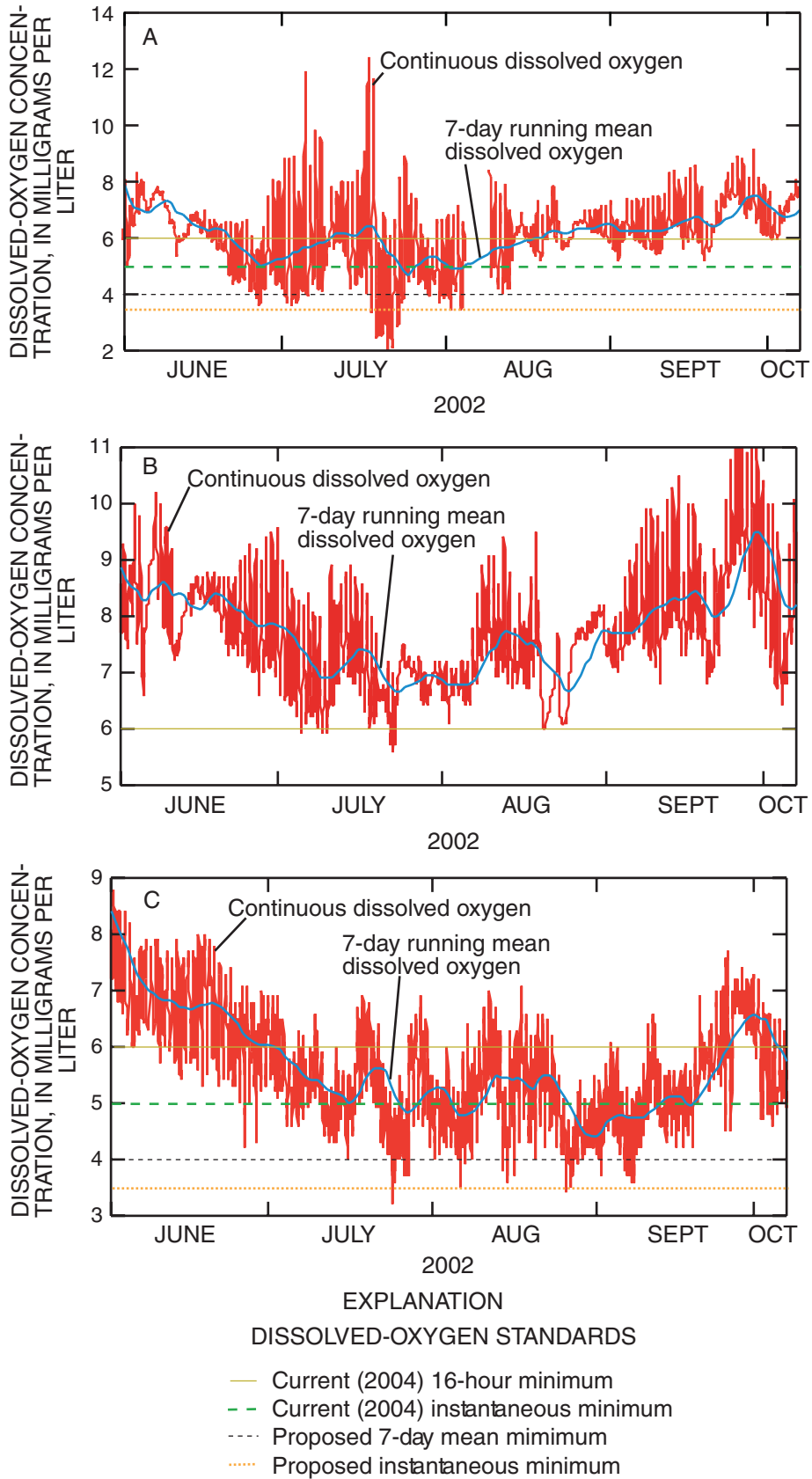


Figure 22. Continuous and 7-day running mean dissolved-oxygen concentrations in three Illinois streams from June 1 through October 7, 2002, (A) at Salt Creek at Western Springs, (B) North Fork Vermilion River above Bismarck, and (C) Lusk Creek near Eddyville, Illinois. Current (2004) dissolved-oxygen standards and example proposed standards are shown for comparison.

dent measurements of pH and sonde pH, relative to the other four parameters, may be related to the buffer capacity and, indirectly, on the dissolved-solids concentration of the stream or river.

Specific conductivity at the eight stations varied widely—from less than 40 microsiemens (μS) at Rayse Creek near Waltonville to greater than 3,500 μS at Salt Creek at Western Springs. In individual streams, specific conductivity often changed quickly (greater than 25 percent in less than 3 hours) and the sensors generally provided good to excellent record of these variations at all stations. The widest range of specific conductivity measurements was in Salt Creek at Western Springs in the Greater Chicago metropolitan area. The pH sensors apparently were the least responsive to changes of the five sensors tested and yielded the least-reliable data. It is not well understood why the pH sensors, in general, were less responsive to in-stream pH variations than the other four sensors. Depending on the data-quality objectives, monitoring of pH may require more intensive field maintenance than was undertaken during this study.

The three factors that limit determination of the accuracy and precision of the turbidity data above 1,400 FNUs are; the upper measurement limit of the sensor (1,400 FNU), the lack of historical turbidity data covering a wide range of streamflow conditions, and the lack of independent turbidity measurements during times when turbidity is expected to be at the maximum. The upper limit on the turbidity sensor is a cause for concern because many peaks in turbidity at most stations exceeded 1,400 FNU. In future deployments, an added effort to collect independent turbidity measurements during periods of maximum turbidity, such as the rising limb of stormflow peaks, would help determine the correspondence between sonde turbidity and the actual turbidity conditions in the stream. More effective calibration of the turbidity sensors during field visits using either high-turbidity (2,000 to 5,000 FNU) standards with sensors that accurately can sense high turbidity also would help ensure the reliability and precision of continuous turbidity monitoring. Continuous collection of turbidity data could be a valuable surrogate for suspended sediment given sufficient data and an empirical relation between turbidity and suspended sediment. Accurately determining the average range of turbidity would be important to water-resources managers in setting effective regulatory limits on turbidity in streams and rivers.

Data collected at all eight stations indicate that a number of factors affect the dissolved-oxygen concentration in the streams and rivers monitored. These factors include: temperature, biological activity, nutrient runoff, and weather (storm runoff). Dissolved-oxygen concentration at the station on the largest stream, Illinois River at Valley City, appeared to be dependent primarily on water temperature. This result may also reflect the limits on algal productivity at this site because of a turbidity-limited euphotic zone or other conditions.

During brief periods usually in late summer, dissolved-oxygen concentrations in half or more of the eight streams and rivers monitored were below the 5-milligrams per liter (mg/L)

minimum established by the Illinois Pollution Control Board to protect aquatic life. These changes result from a combination of factors, such as water temperature, algal production and die off, nutrient runoff, and rainstorms. The importance of each of these factors varies among the streams and rivers. The data collected on dissolved-oxygen concentration in the eight study streams and rivers also indicate that many streams in Illinois, even in relatively undisturbed watersheds, may have periods during which the 5-mg/L dissolved-oxygen concentration minimum criterion is not met. During July 2001 through September 2003, and generally during short late summer intervals, even the daily high dissolved-oxygen concentration did not rise above the minimum at Illinois River at Valley City, Lusk Creek near Eddyville, and Rayse Creek near Waltonville.

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APPENDIX

APPENDIX: Graphs of time series for water-quality parameters at eight streamflow-gaging stations in Illinois and discrete independent measurements for comparison, 2001–03.

The series of 48 graphs on the following pages show the data collected from all sensors of the sondes deployed at the eight selected Illinois streamflow-gaging stations during 2001–03. The multi-parameter continuous water-quality monitors recorded dissolved oxygen, pH, specific conductivity, water temperature, and turbidity. Also shown in the graphs are the precipitation and streamflow at each of the stations. For comparison, the discrete independent measurements are shown in the graphs with associated error bars. The errors bars represent ± 0.3 mg/L for dissolved-oxygen concentration, ± 0.2 standard unit for pH, ± 3 percent of the value for specific conductivity, $\pm 0.2^\circ\text{C}$ for temperature, and ± 5 percent of the value for turbidity. The stations where these data were collected are (in alphabetical order):

Illinois River at Valley City, Illinois

Lusk Creek near Eddyville, Illinois

Mazon River near Coal City, Illinois

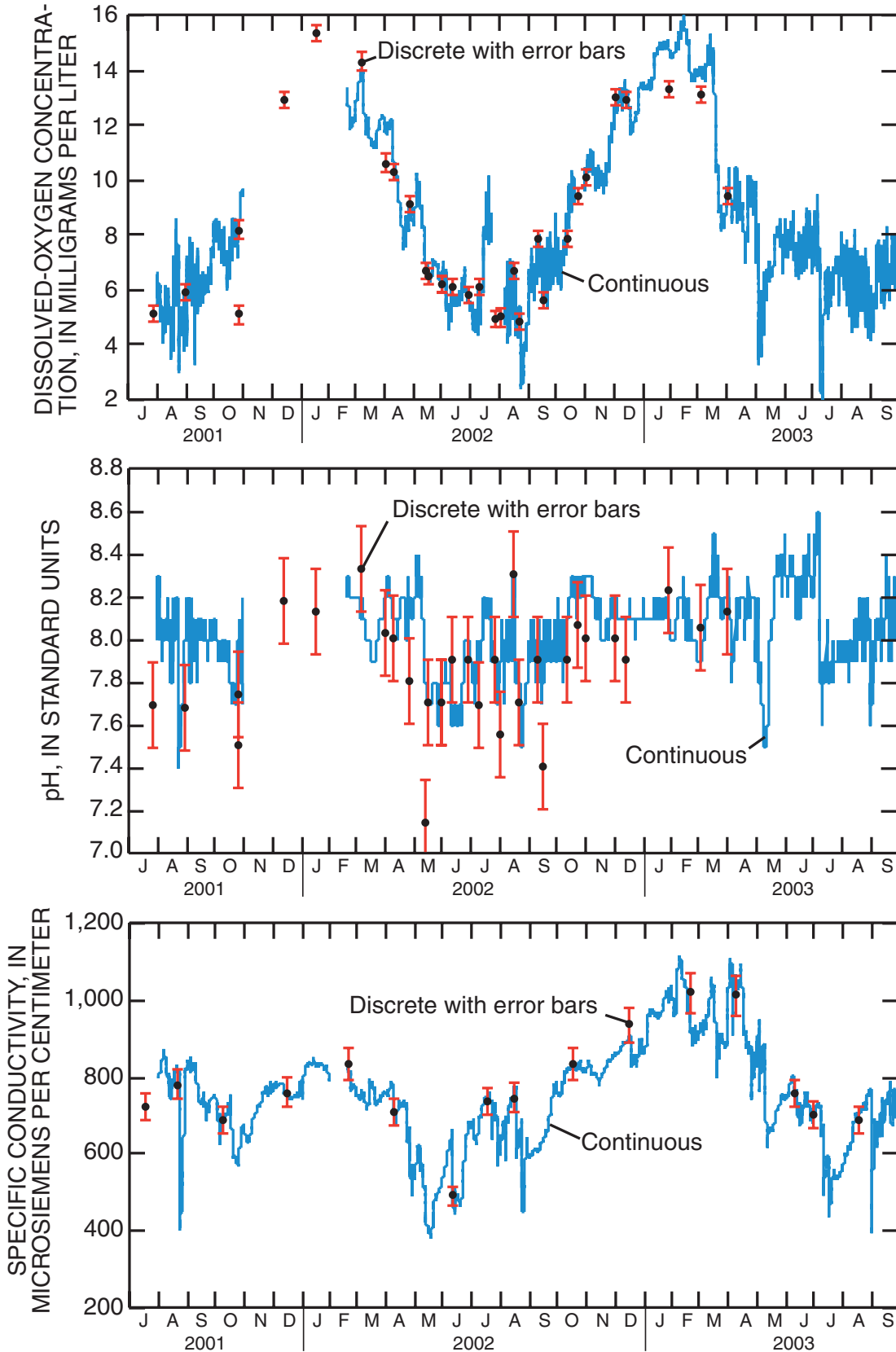
Middle Fork Vermilion River above Oakwood, Illinois

North Fork Vermilion River near Bismarck, Illinois

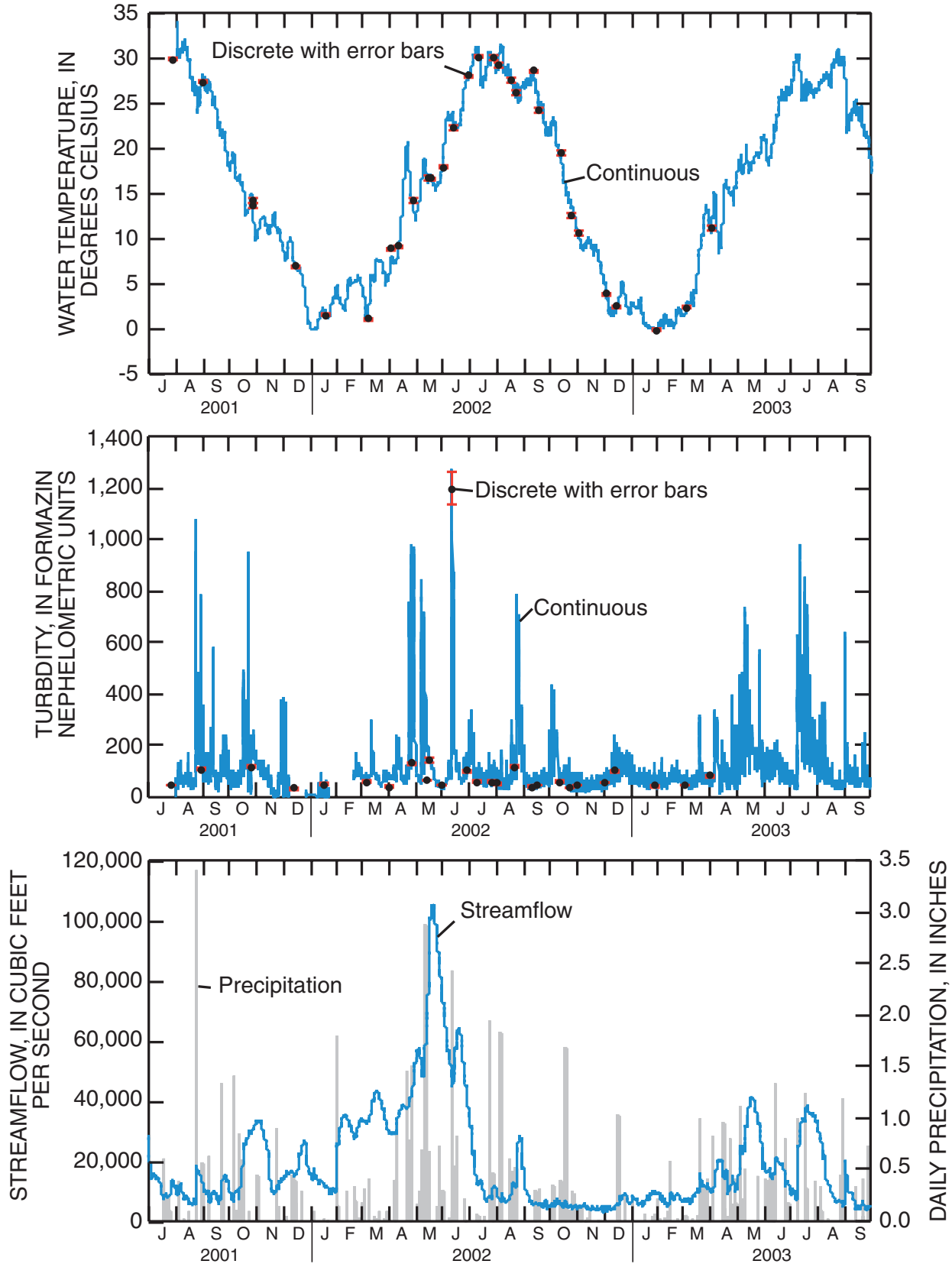
Rayse Creek near Waltonville, Illinois

Salt Creek at Western Springs, Illinois

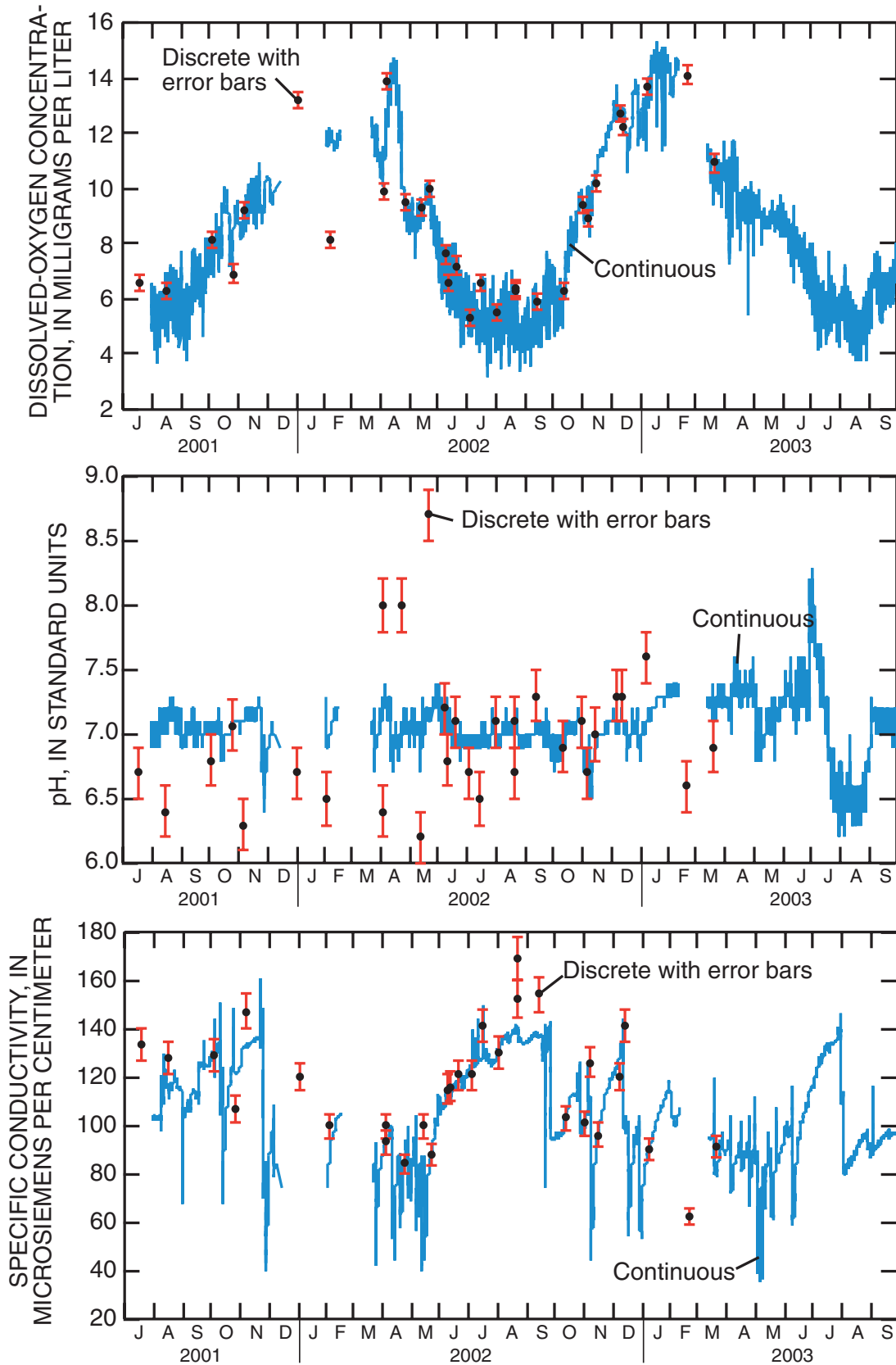
Vermilion River near Danville, Illinois



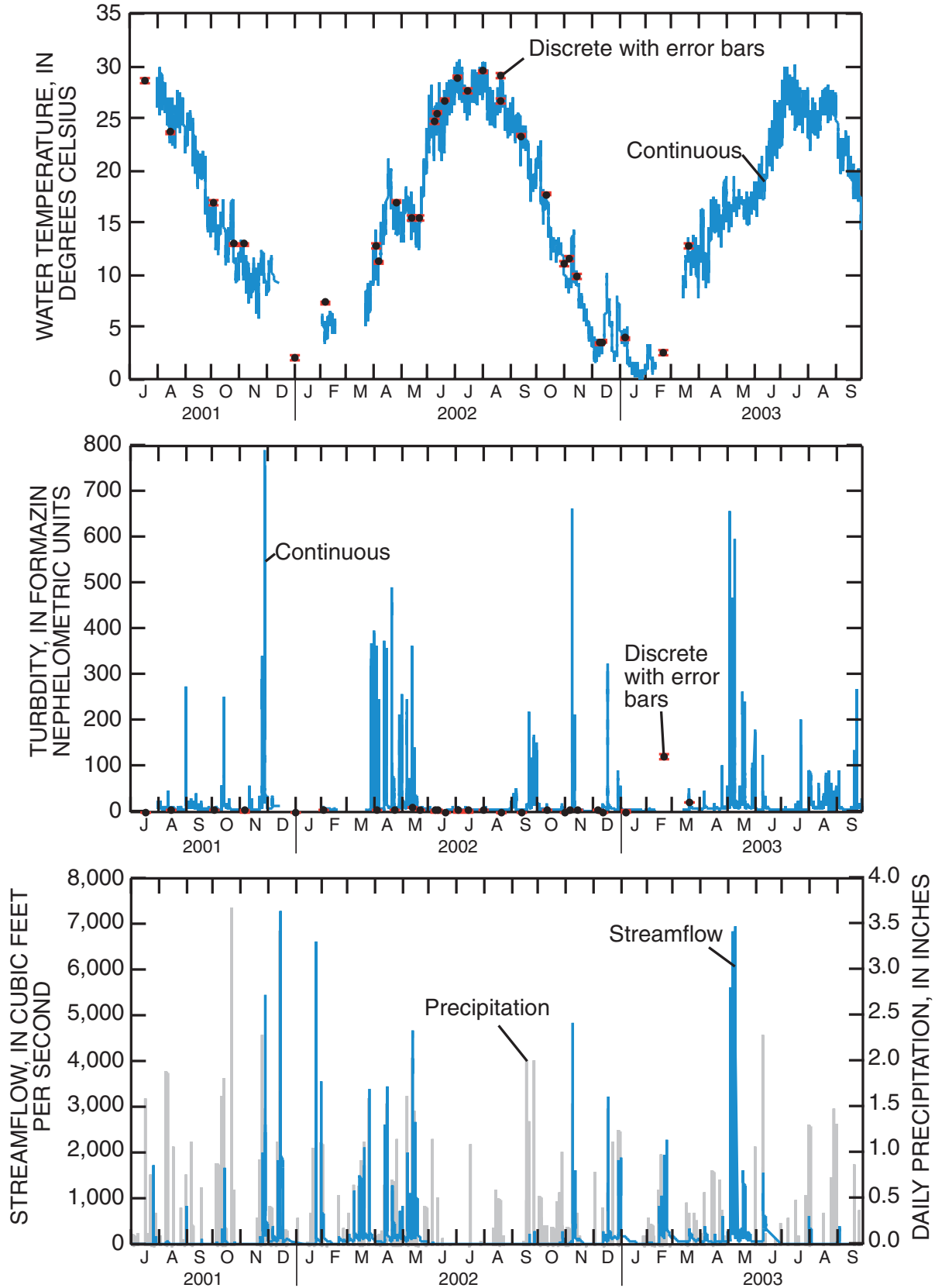
Dissolved-oxygen concentration, pH, and specific conductivity in the Illinois River at Valley City from July 1, 2001, to September 30, 2003. Blue solid lines are data from the sensors on the continuous in-situ monitor and the black dots with red error bars are the discrete measurements made by U.S. Geological Survey and Illinois Environmental Protection Agency personnel. Gaps in the blue line indicate periods of missing data.



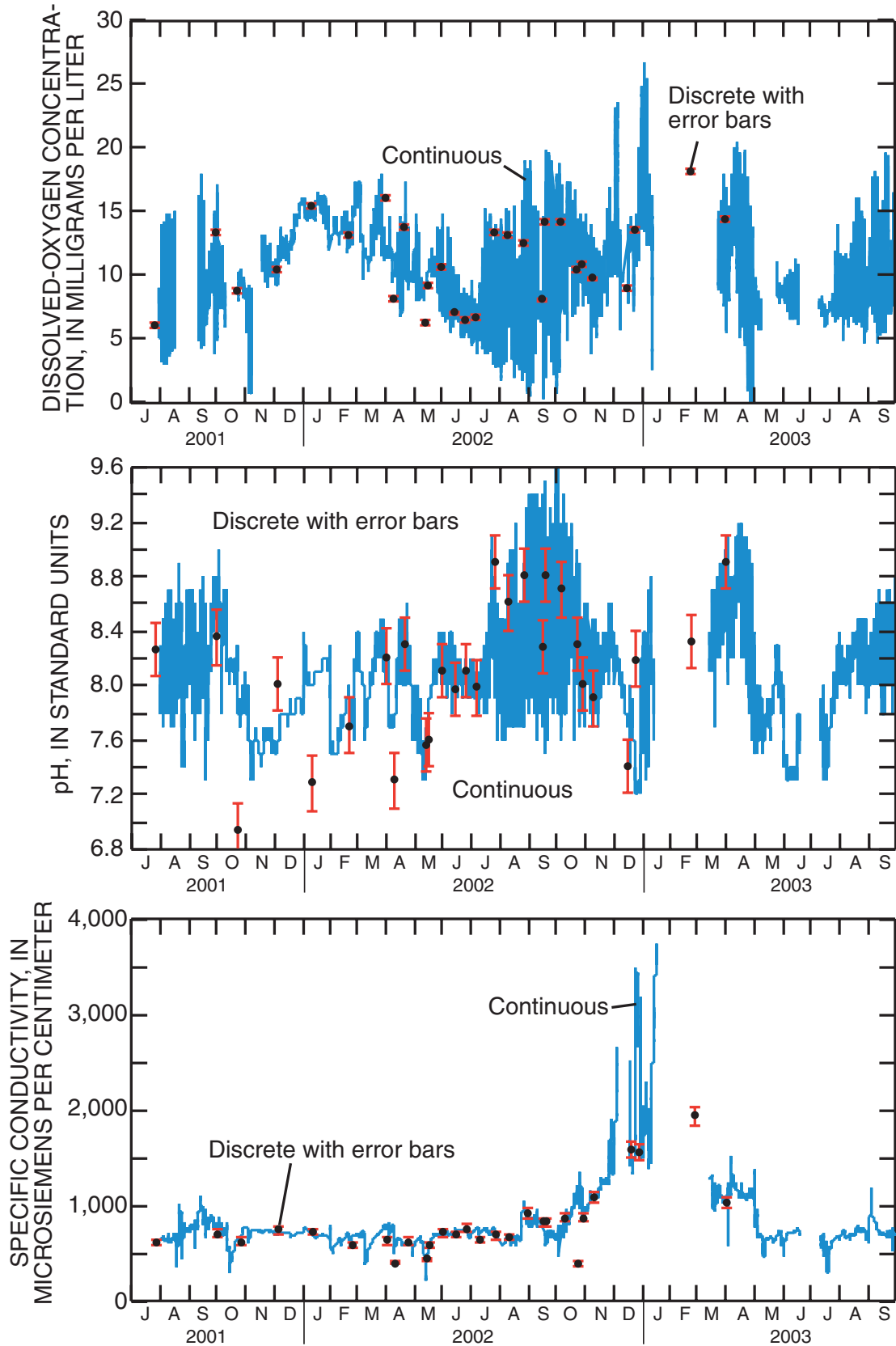
Water temperature, turbidity, and streamflow in the Illinois River at Valley City and precipitation at Beardstown from July 1, 2001, to September 30, 2003. Blue solid lines are data from the sensors on the continuous in-situ instrument and the black dots with red error bars are the discrete measurements made by U.S. Geological Survey and Illinois Environmental Protection Agency personnel. Gaps in the blue line indicate periods of missing data.



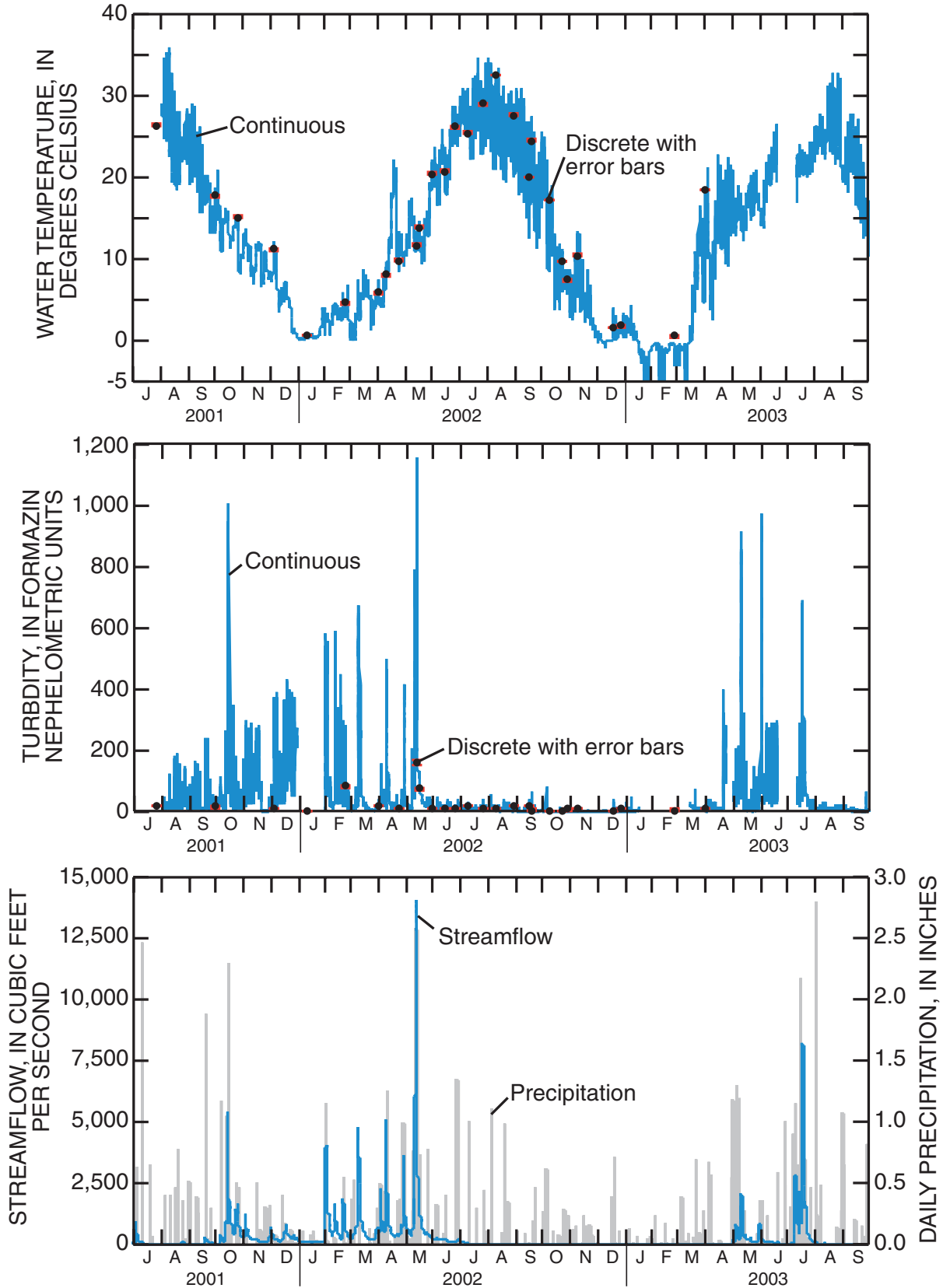
Dissolved-oxygen concentration, pH, and specific conductivity in Lusk Creek near Eddyville from July 1, 2001, to September 30, 2003. Blue solid lines are data from the sensors on the continuous in-situ instrument and the black dots with red error bars are the discrete measurements made by U.S. Geological Survey and Illinois Environmental Protection Agency personnel. Gaps in the blue line indicate periods of missing data.



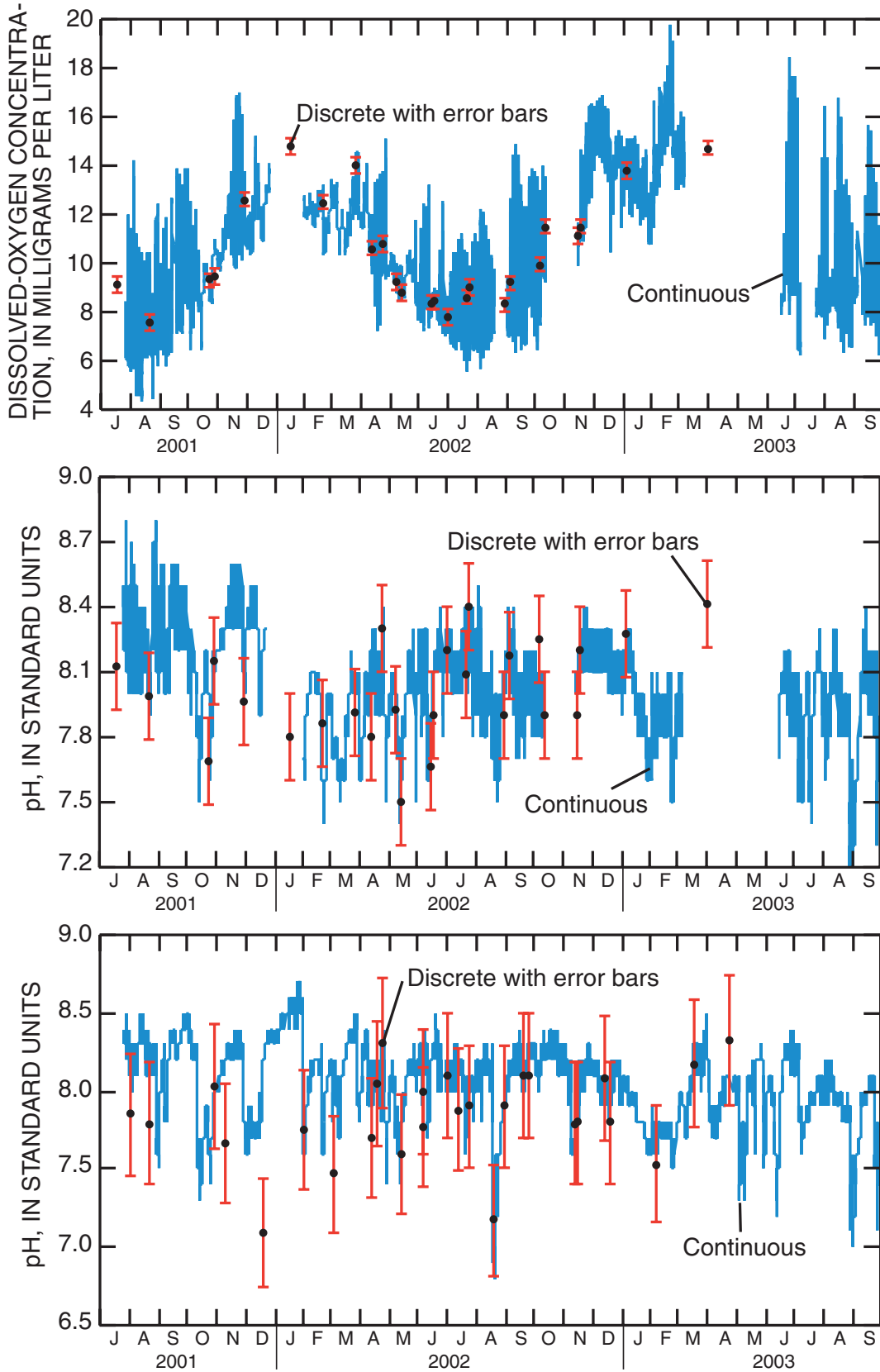
Water temperature, turbidity, and streamflow in Lusk Creek near Eddyville and precipitation at Harrisburg from July 1, 2001, to September 30, 2003. Blue solid lines are data from the sensors on the continuous in-situ instrument and the black dots with red error bars are the discrete measurements made by U.S. Geological Survey and Illinois Environmental Protection Agency personnel. Gaps in the blue line indicate periods of missing data.



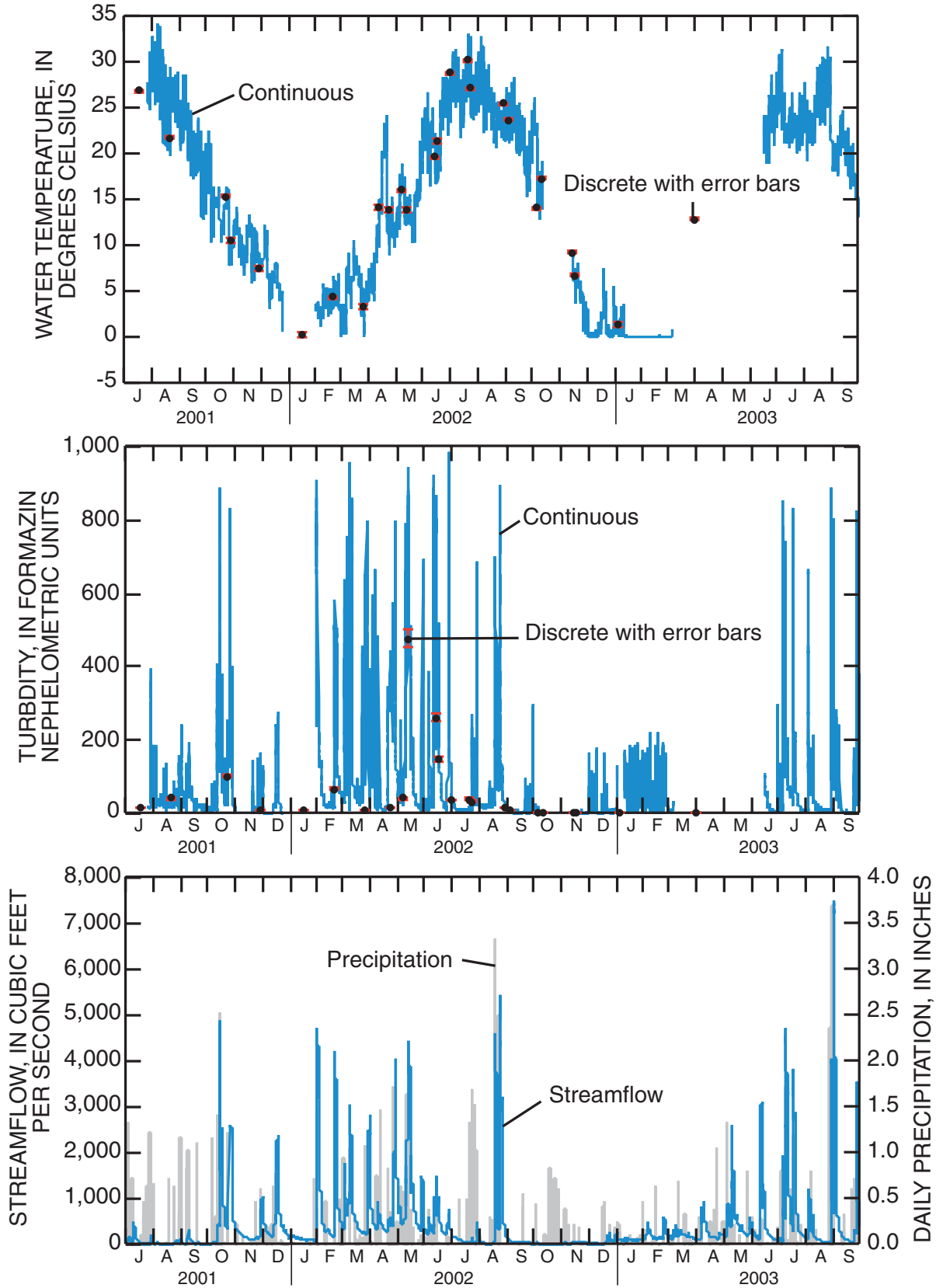
Dissolved-oxygen concentration, pH, and specific conductivity in Mazon River near Coal City from July 1, 2001, to September 30, 2003. Blue solid lines are data from the sensors on the continuous in-situ instrument and the black dots with red error bars are the discrete measurements made by U.S. Geological Survey and Illinois Environmental Protection Agency personnel. Gaps in the blue line indicate periods of missing data.



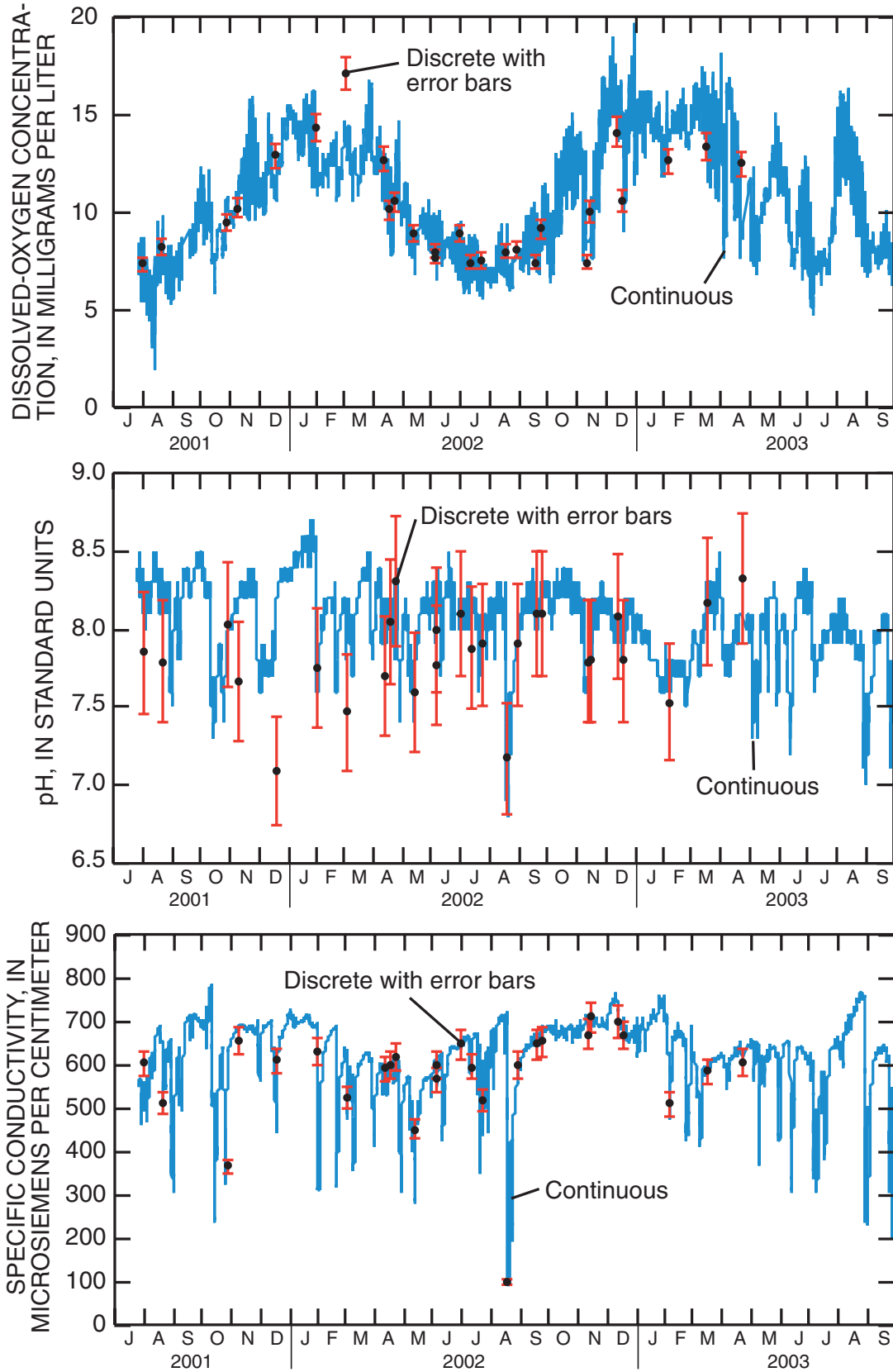
Water temperature, turbidity, and streamflow in Mazon River near Coal City and precipitation at Morris from July 1, 2001, to September 30, 2003. Blue solid lines are data from the sensors on the continuous in-situ instrument and the black dots with red error bars are the discrete measurements made by U.S. Geological Survey and Illinois Environmental Protection Agency personnel. Gaps in the blue line indicate periods of missing data.



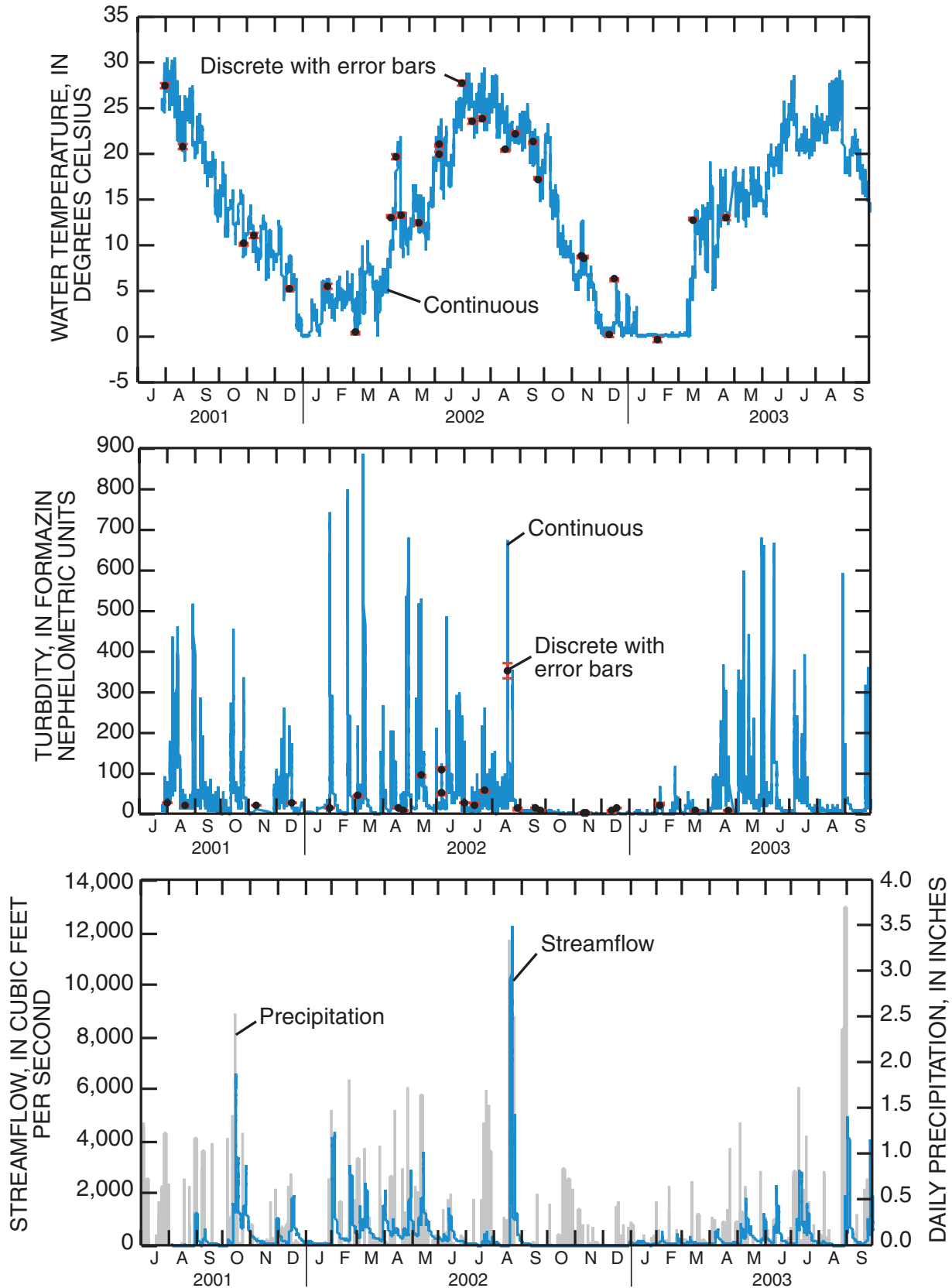
Dissolved-oxygen concentration, pH, and specific conductivity in Middle Fork Vermilion River above Oakwood from July 1, 2001, to September 30, 2003. Blue solid lines are data from the sensors on the continuous in-situ instrument and the black dots with red error bars are the discrete measurements made by U.S. Geological Survey and Illinois Environmental Protection Agency personnel. Gaps in the blue line indicate periods of missing data.



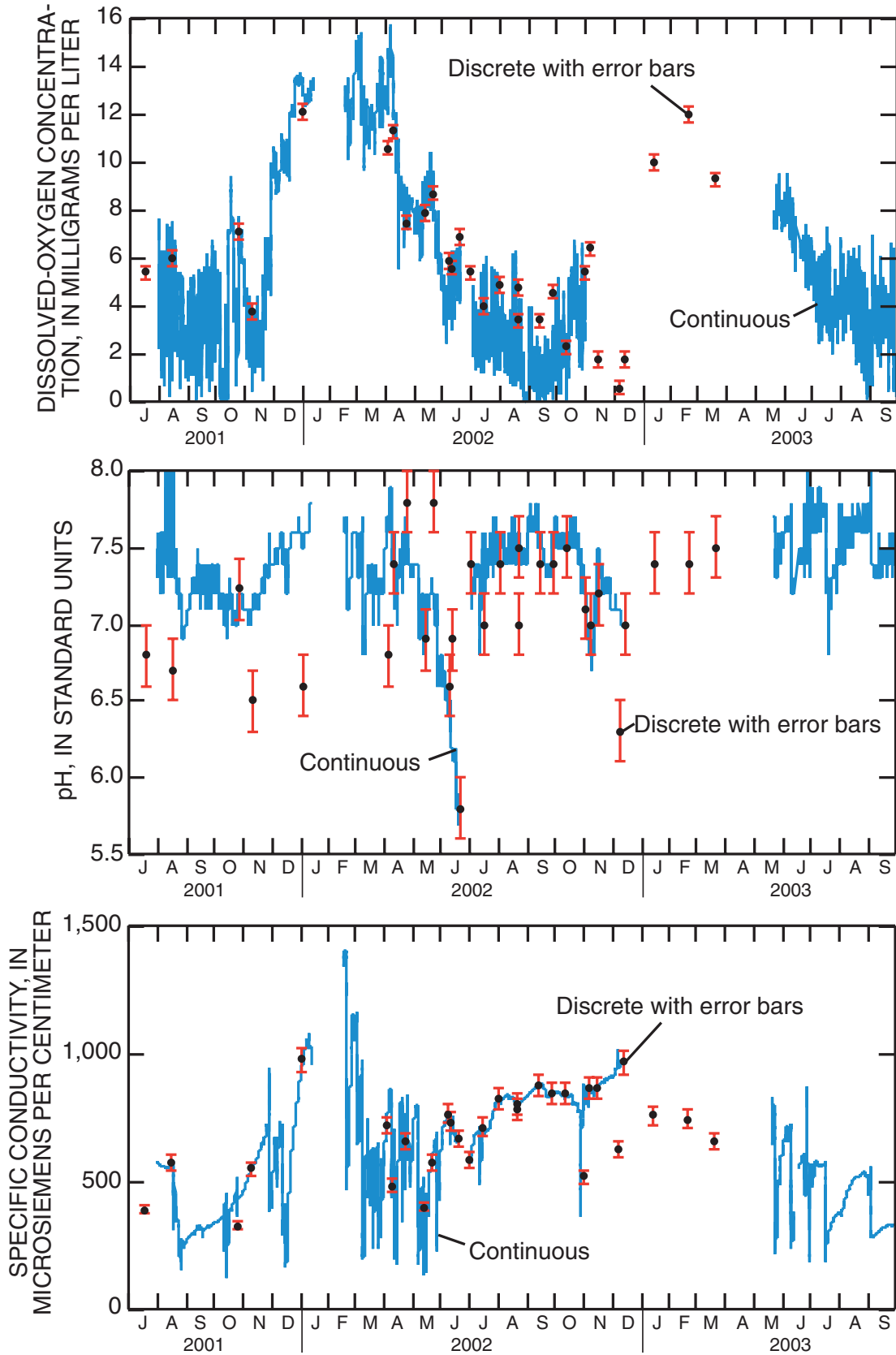
Water temperature, turbidity, and streamflow in Middle Fork Vermilion River above Oakwood and precipitation at Danville from July 1, 2001, to September 30, 2003. Blue solid lines are data from the sensors on the continuous in-situ instrument and the black dots with red error bars are the discrete measurements made by U.S. Geological Survey and Illinois Environmental Protection Agency personnel. Gaps in the blue line indicate periods of missing data.



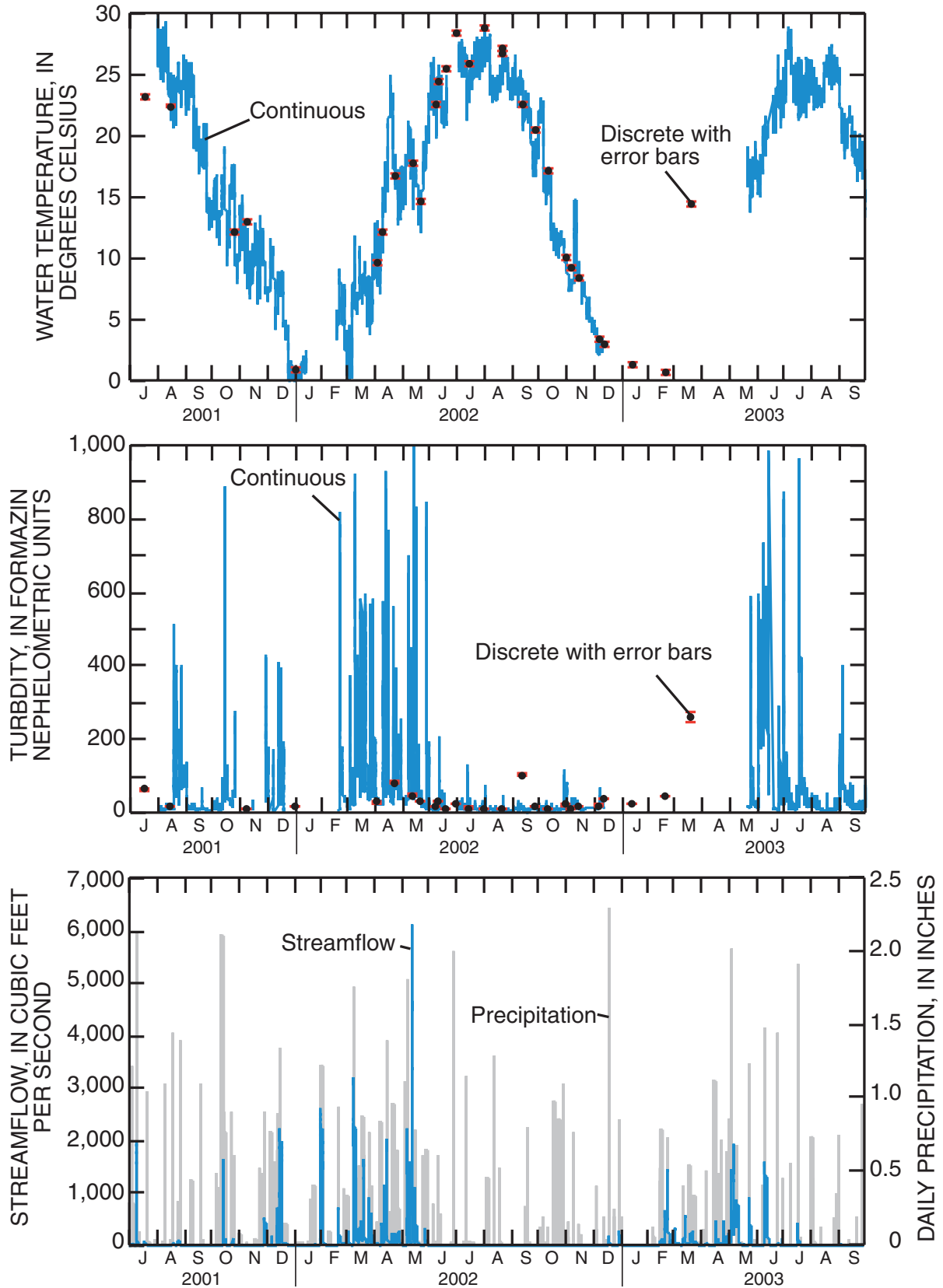
Dissolved-oxygen concentration, pH, and specific conductivity in North Fork Vermilion River near Bismarck from July 1, 2001, to September 30, 2003. Blue solid lines are data from the sensors on the continuous in-situ instrument and the black dots with red error bars are the discrete measurements made by U.S. Geological Survey and Illinois Environmental Protection Agency personnel. Gaps in the blue line indicate periods of missing data.



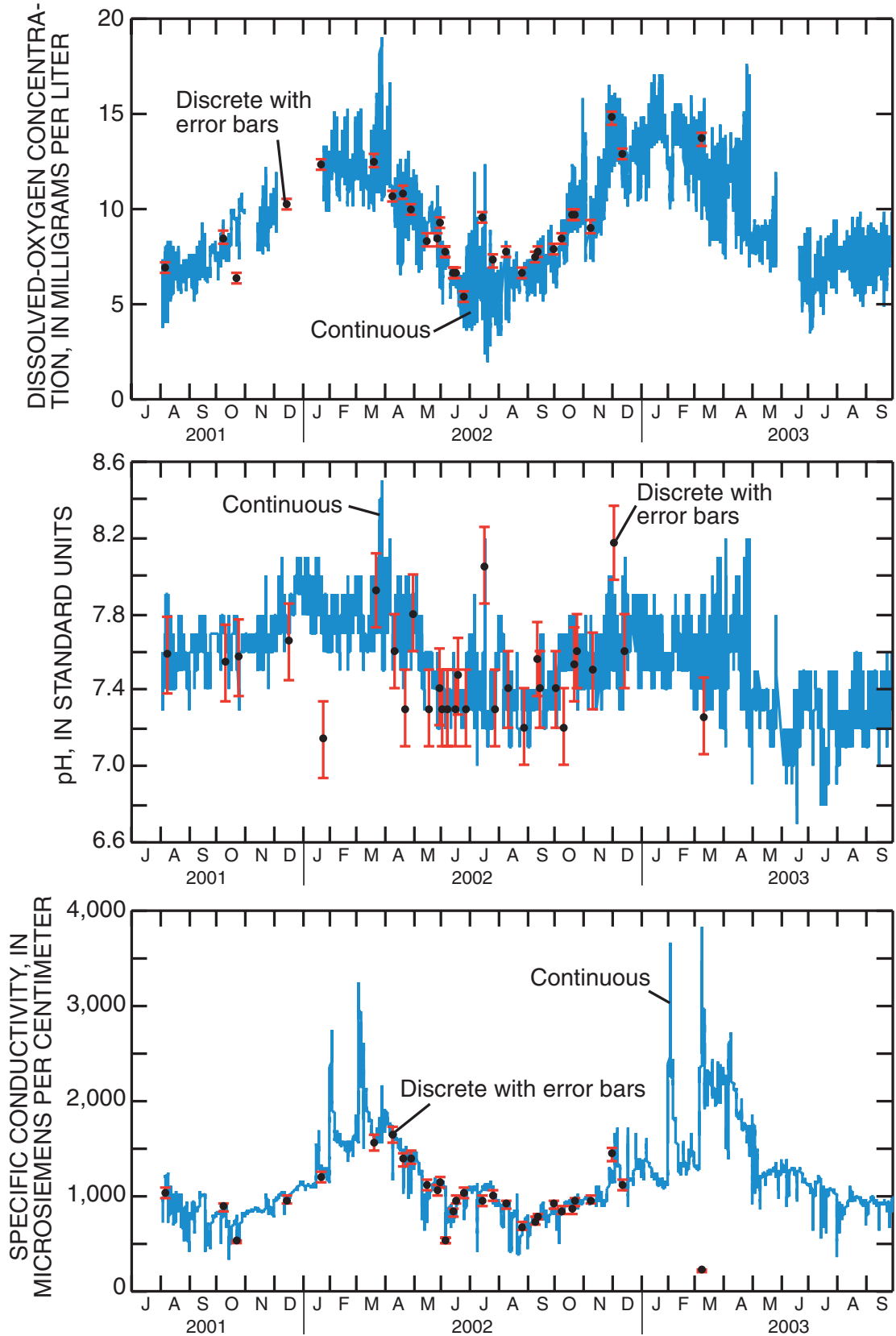
Water temperature, turbidity, and streamflow in North Fork Vermilion River near Bismarck and precipitation at Danville from July 1, 2001, to September 30, 2003. Blue solid lines are data from the sensors on the continuous in-situ instrument and the black dots with red error bars are the discrete measurements made by U.S. Geological Survey and Illinois Environmental Protection Agency personnel. Gaps in the blue line indicate periods of missing data.



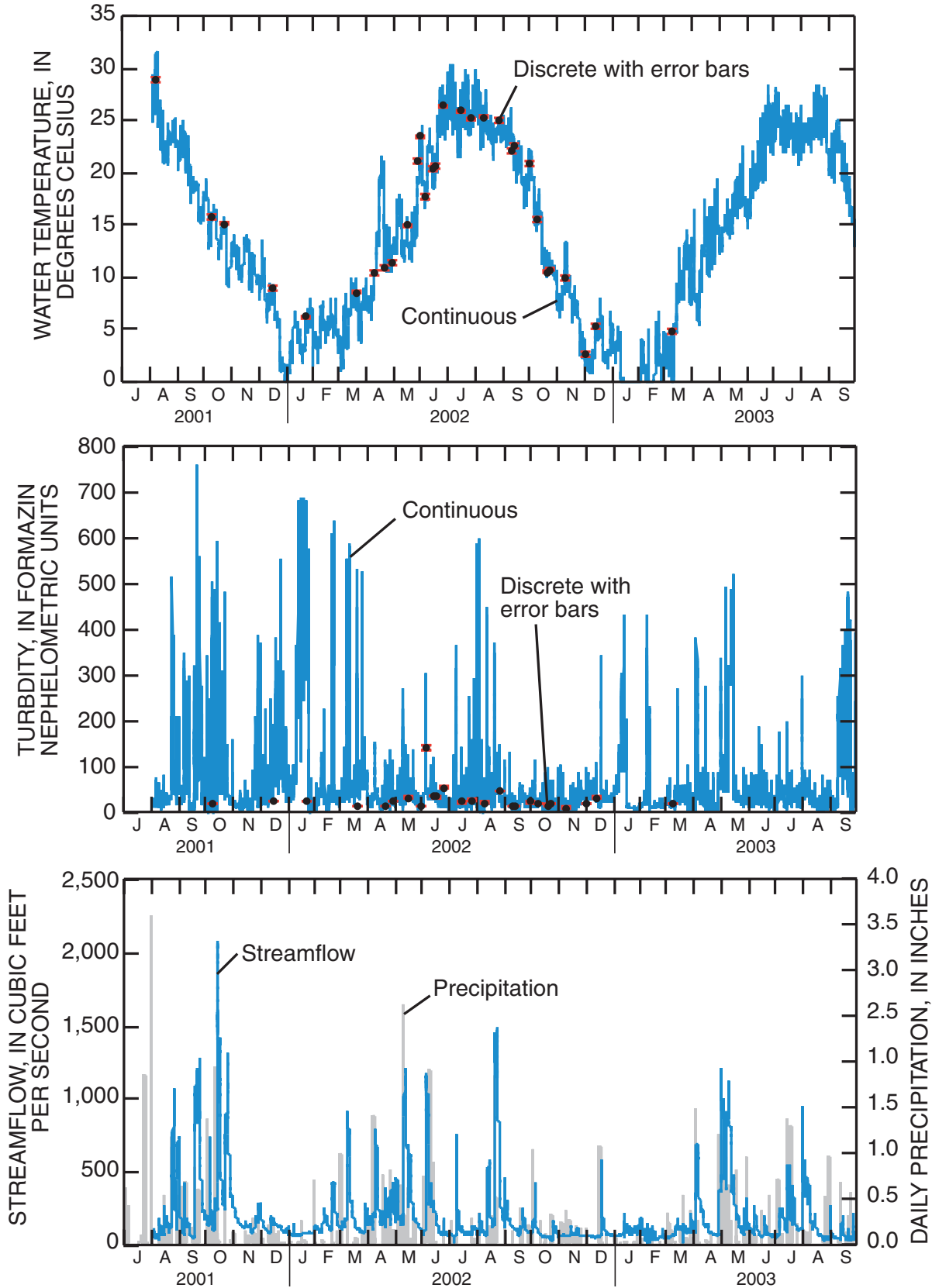
Dissolved-oxygen concentration, pH, and specific conductivity in Rayce Creek near Waltonville from July 1, 2001, to September 30, 2003. Blue solid lines are data from the sensors on the continuous in-situ instrument and the black dots with red error bars are the discrete measurements made by U.S. Geological Survey and Illinois Environmental Protection Agency personnel. Gaps in the blue line indicate periods of missing data.



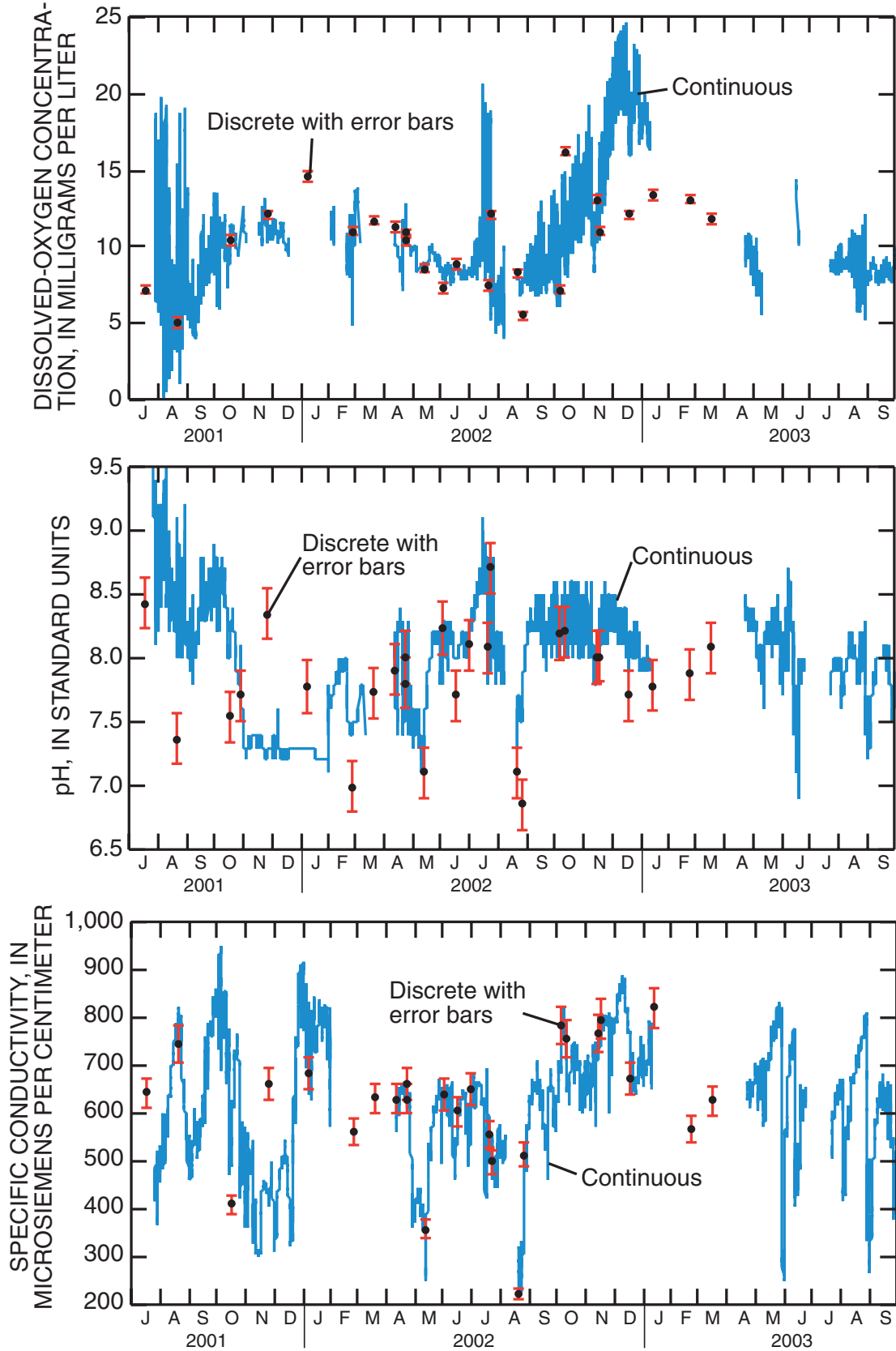
Water temperature, turbidity, and streamflow in Rayse Creek near Waltonville and precipitation at Waltonville from July 1, 2001, to September 30, 2003. Blue solid lines are data from the sensors on the continuous in-situ instrument and the black dots with red error bars are the discrete measurements made by U.S. Geological Survey and Illinois Environmental Protection Agency personnel. Gaps in the blue line indicate periods of missing data.



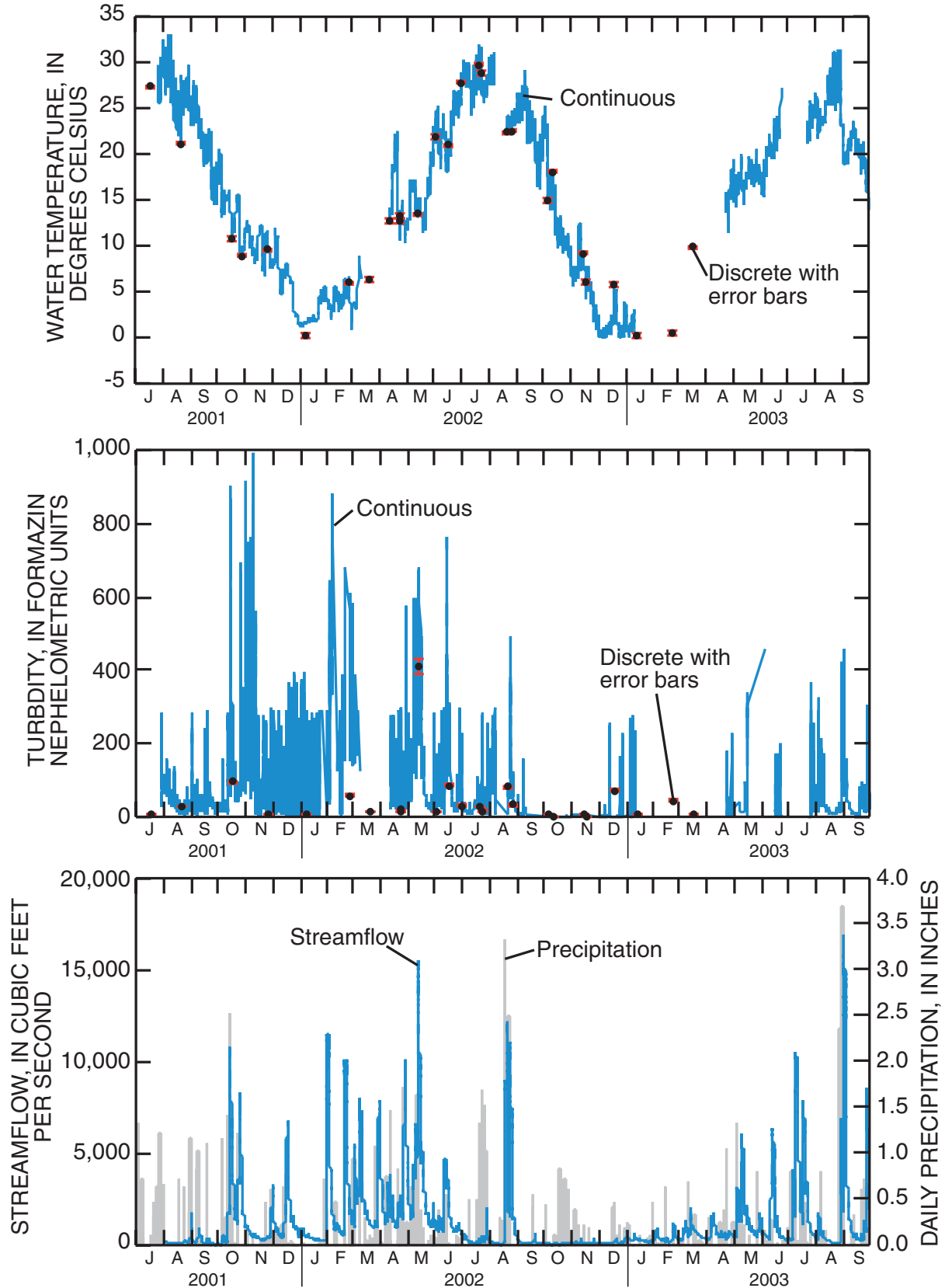
Dissolved-oxygen concentration, pH, and specific conductivity in Salt Creek at Western Springs from July 1, 2001, to September 30, 2003. Blue solid lines are data from the sensors on the continuous in-situ instrument and the black dots with red error bars are the discrete measurements made by U.S. Geological Survey and Illinois Environmental Protection Agency personnel. Gaps in the blue line indicate periods of missing data.



Water temperature, turbidity, and streamflow in Salt Creek at Western Springs and precipitation at Midway Airport from July 1, 2001, to September 30, 2003. Blue solid lines are data from the sensors on the continuous in-situ instrument and the black dots with red error bars are the discrete measurements made by U.S. Geological Survey and Illinois Environmental Protection Agency personnel. Gaps in the blue line indicate periods of missing data.



Dissolved-oxygen concentration, pH, and specific conductivity in Vermilion River near Danville from July 1, 2001, to September 30, 2003. Blue solid lines are data from the sensors on the continuous in-situ instrument and the black dots with red error bars are the discrete measurements made by U.S. Geological Survey and Illinois Environmental Protection Agency personnel. Gaps in the blue line indicate periods of missing data.



Water temperature, turbidity, and streamflow in Vermilion River near Danville and precipitation at Danville from July 1, 2001, to September 30, 2003. Blue solid lines are data from the sensors on the continuous in-situ instrument and the black dots with red error bars are the discrete measurements made by U.S. Geological Survey and Illinois Environmental Protection Agency personnel. Gaps in the blue line indicate periods of missing data.

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