COMPARISON OF ACCURACY AND COMPLETENESS OF DATA OBTAINED FROM THREE TYPES OF AUTOMATIC WATER-QUALITY MONITORS

By Max S. Katzenbach

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CONVERSION FACTORS AND ABBREVIATIONS

For the convenience of readers who prefer metric (International System) units to the inch-pound units in this report, values may be converted by use of the following factors:

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)

Temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation:

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

COMPARISON OF ACCURACY AND COMPLETENESS OF DATA OBTAINED FROM THREE TYPES OF AUTOMATIC WATER-QUALITY MONITORS

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ABSTRACT

A comparison of data (specific conductance, dissolved-oxygen concentration, temperature, and pH) collected by the U.S. Geological Survey flowthrough monitor, the U.S. Geological Survey minimonitor, and a self-contained commercial "packaged-sensor" system indicates that the data obtained by means of the flowthrough-monitor system were the most accurate and the most complete of the three systems.

The U.S. Geological Survey flowthrough monitor is powered by 120-volt alternating current and is housed in a heated weatherproof shelter. A pumping system brings water from the stream to sensors clustered in a sample chamber located in the shelter. This instrument measures output from the sensors; data are recorded in binary-coded decimal form on a 16-channel punched-paper tape recorder housed in the shelter.

The U.S. Geological Survey's minimonitor is powered by an external battery and is housed in a weatherproof shelter. This instrument measures output of instream sensors with extension cables having underwater connectors; data are recorded in binary-coded decimal form on a 16-channel punched-paper tape recorder housed in the shelter.

The packaged-sensor system also measures output of sensors housed in a package that is submerged in the stream. It has internal power supply, no moving parts, and does not require a weatherproof shelter; data are stored in solid-state memory.

Minimonitors were installed at four sites in Ohio where U.S. Geological Survey flowthrough monitors were in operation. Two packaged-sensor systems also were assigned to each site and were alternated every two weeks. Detailed records were kept of (1) field measurements, for comparison with monitor-system data from each instrument, and (2) equipment problems that resulted in loss of data. Results of the comparisons show that the flowthrough monitor gave the most accurate and the most complete data.

INTRODUCTION

The U.S. Geological Survey conducts a nationwide program of water-resources surveys, investigations, and research. Over the years, the need for water-quality information has led the U.S. Geological Survey to establish a nationwide network of water-quality data-collection stations on rivers, canals, streams, lakes, and reservoirs. Various systems have been used for automatically measuring and recording water-quality data such as specific conductance, dissolved-oxygen concentration, temperature, and pH.

The two systems currently being used by the U.S. Geological Survey are the flowthrough monitor (fig. 1) and the minimonitor (fig. 2), which gather data electronically, record the data in digital form on perforated tape and (or) transmit the data in real time by Geostationary Operational Environmental Satellite (GOES). In the flowthrough system, water is pumped from the stream to a heated shelter in which a sampling chamber, sensors and associated electronic components, and recording devices are housed. An 110-volt alternating current (AC) power supply is required. The battery-powered minimonitor has sensors that are connected to long cables and submerged in the stream. No AC power or pumping equipment is necessary, and associated electronic components and recording devices can be housed in a smaller, unheated shelter in remote locations. Both systems require maintenance and calibration of sensors in the field.

A more recently developed system makes use of "packaged sensors" (fig. 3). All components in this system--including microprocessor-controlled solid-state data storage, sensors, and power supply--are contained in a sensor package that is submerged in the stream. The sensor package has no external wires and requires no land-based instrumentation or shelter. The system can be maintained and calibrated in an office setting after being exchanged with a spare unit in the field.

In 1985 and 1986, an economic comparison of the minimonitor and the packaged-sensor system was conducted by the U.S. Geological Survey (Katzenbach, 1988). The results show the packaged-sensor system requires less time to install, operate, and maintain than does the minimonitor system.[1] In 1989, at the request of and with support from the U.S. Geological Survey's Hydrologic Instrumentation Facility at Bay St. Louis, Miss., the three concurrent sets of data (flowthrough monitor, minimonitor, and

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[1]Experience shows that the flowthrough-monitor system has a higher installation and operation cost than either the packaged-sensor or minimonitor systems (for example, electricity to run a flowthrough-monitor system can cost as much as $1,000 per year). Maintenance costs for the flowthrough monitor also are slightly higher than those for the other two systems.

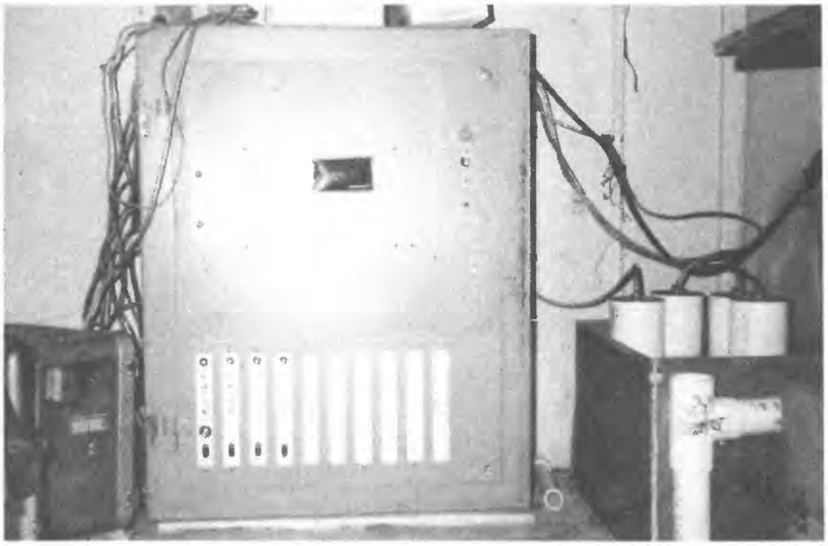

Figure 1.--Flowthrough monitor system.

Figure 2.--Minimonitor system.

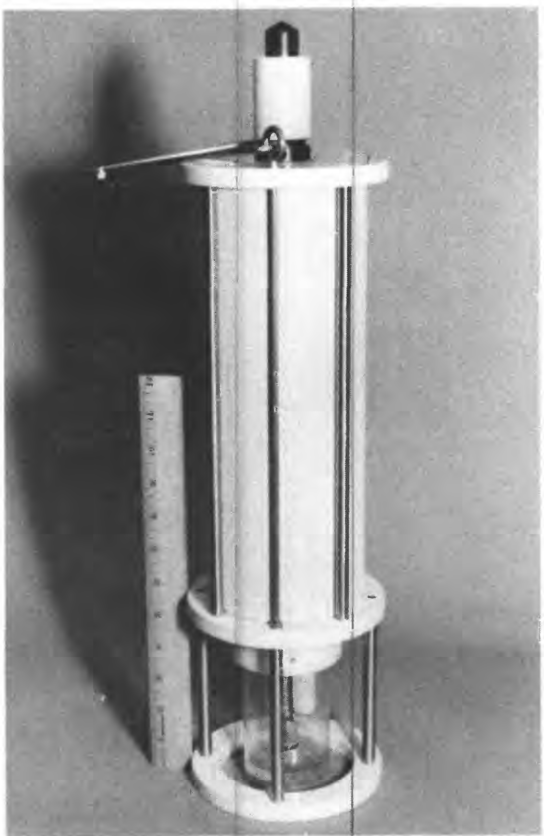

Figure 3.--Packaged-sensor system.

packaged-sensor) collected for the economic comparison were evaluated to determine which set was the most accurate relative to field measurements and which set was the most complete.

Purpose and Scope

This report provides brief descriptions of the flowthrough monitor, minimonitor, and packaged-sensor systems and presents the results of the data comparison. The comparison was based primarily on completeness, consistency, and accuracy of the specific-conductance, dissolved-oxygen-concentration, temperature, and pH data collected. Equipment problems and human error that affected data completeness and accuracy also are discussed.

Minimonitors and packaged-sensor systems were installed at four flowthrough monitor sites in northeastern Ohio (fig. 4; table 1). The water-quality data were collected from October 1985 through September 1986.

Acknowledgment

The author wishes to thank Stuart Garner of Hydrolab, Inc.[2] for his advice and cooperation in solving equipment problems.

DESCRIPTION OF INSTRUMENT SYSTEMS TESTED

Brief descriptions of the flowthrough monitor, minimonitor, and packaged-sensor systems are presented below. Features of the three systems are summarized in table 2.

U.S. Geological Survey Flowthrough-Monitor System

The flowthrough monitor (fig. 1) consists of an AC-powered electronic package controlled by an external clock. At each recording interval, the unit scans, measures, records data in binary-coded digital form on a 16-channel punched-paper tape recorder, and (or) transmits real-time data periodically by GOES. The instrument measures specific conductance, dissolved-oxygen concentration, temperature, and pH with sensors ("probes") located in a sample chamber housed in a weatherproof shelter (fig. 5). Water is continuously pumped from the stream at a rate of 7 to 10 gal/min (gallons per minute) to the sample chamber.

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[2]Use of brand and firm names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

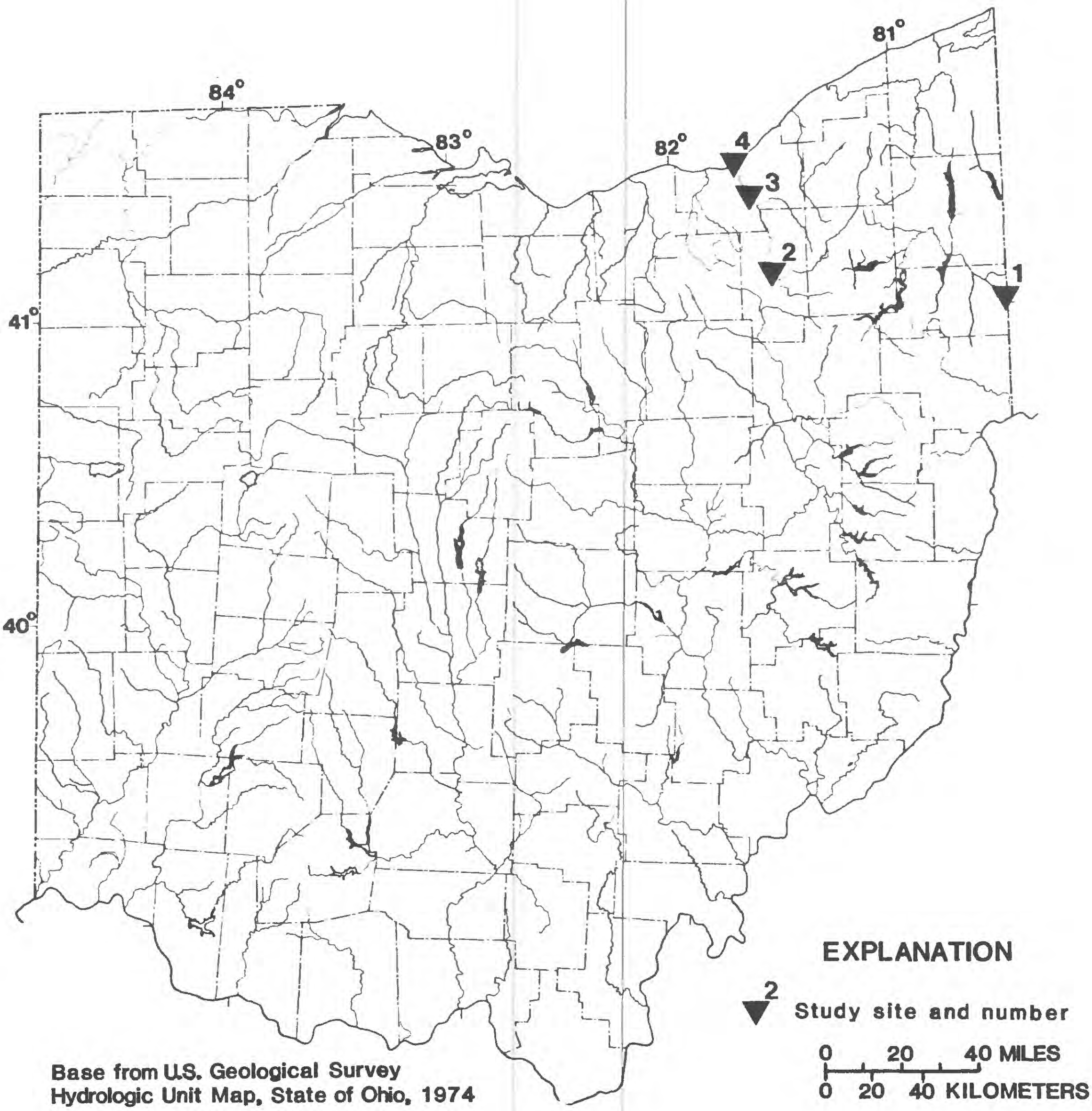

Figure 4.--Location of test sites (see table 1 for additional site data).

Table 1.--Site names and station identification numbers

Site no.	Site name	Type of system	Station ID
1	Mahoning River at Lowellville, Ohio	Flowthrough----	03099510
		Minimonitor----	03099511
		Packaged-sensor	03099512
2	Cuyahoga River at Old Portage, Ohio	Flowthrough----	04206000
		Minimonitor----	04206001
		Packaged-sensor	04206002
3	Cuyahoga River at Independence, Ohio	Flowthrough----	04208000
		Minimonitor----	04208001
		Packaged-sensor	04208002
4	Cuyahoga River at West Third Street Bridge in Cleveland, Ohio	Flowthrough----	04208506
		Minimonitor----	04208507
		Packaged-sensor	04208508

Table 2.--Comparison of instrument features

[I/O, digital input/output data recorder; ATC, automatic temperature compensation; uS/cm, microsiemens per centimeter at 25 °C; mg/L, milligrams per liter; NIST, National Institute of Standards and Technology; v, volts; VDT, video display terminal; N/A, not applicable.]

Instrument features	USGS flow-through monitor	Minimonitor	Packaged-sensor system
Shelter required?----------	Yes	Yes	No
Power----------------------	120v	12v	[a]6v
Pump required?-------------	Yes	No	No
Probes in stream?----------	No	Yes	Yes
Monitor in stream?---------	No	No	Yes
Where is calibration done?-	Field	Field	Office
Internal data memory?------	No	No	Yes
Data output to:------------	I/O	I/O	ASCII into VDT, printer, or computer
		Temperature	
Range----------------------	0-50 °C	0-50 °C	-2 to 50 °C
Sensor type----------------	Platinum resistance element	Platinum resistance element	Linear thermistor
Calibration----------------	Potentiometer (cold & warm solution)	Potentiometer (cold & warm solution)	NBS, factory
Temperature compensation---	N/A	N/A	N/A
		Specific conductance	
Range (uS/cm)--------------	0-3000	0-10,000	0-10,000
Sensor type----------------	4-electrode cell	4-electrode cell	4-electrode cell
Calibration----------------	Potentiometer with sensor immersed in KCl	Potentiometer with sensor immersed in KCl	Keyboard entry with sensor immersed in KCl
Temperature compensation---	Automatic 25 °C reference	Automatic 25 °C reference	Automatic 25 °C reference
		Dissolved oxygen	
Range (mg/L)---------------	0-20	0-20	0-20
Sensor type----------------	Galvanic	Polarographic	Polarographic
Calibration----------------	Potentiometer with sensor in water-saturated air at barometric pressure	Potentiometer with sensor in water-saturated air at barometric pressure	Keyboard entry of barometric water-saturated air at barometric pressure water
Temperature compensation---	ATC	ATC	ATC
Stirrer on dissolved oxygen probe?----------	No	Yes	No
		pH	
Range (units)--------------	0-10	0-10	0-14
Sensor type----------------	Glass-electrode and reference, refillable with replaceable diffusion junction	Combination glass with nonrefillable wood junction	Glass-electrode and reference, refillable with replaceable diffusion junction
Calibration----------------	Potentiometer with probe in; pH 4, 7, or 10	Potentiometer with probe in; pH 7 and 4 or 10	Keyboard entry with probe in pH 7 and 4 or 10
Temperature compensation---	ATC	ATC	ATC

[a]Four "D"-cell disposable batteries

Figure 5.--Flowthrough-monitor shelter and PVC pipes for housing minimonitor and packged sensors.

Specific conductance | Temperature | pH | Dissolved concentration oxygen

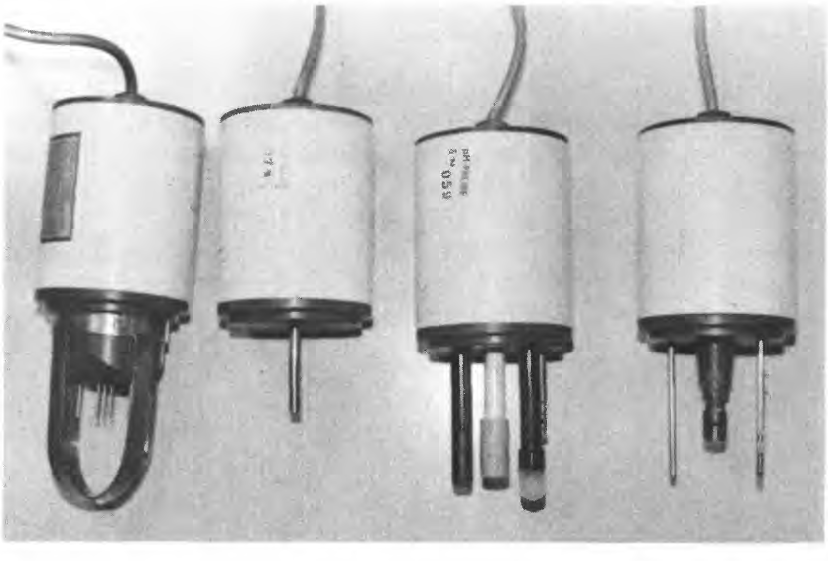

Figure 6.--Flowthrough-monitor sensors.

The flowthrough monitor has an automatic chlorinating system to help keep sensors clean (for example, free of algae and bacterial growth) (Gordon and Katzenbach, 1983, p. 36-41).

Routine Maintenance and Calibration

During a typical site visit for this study, specific-conductance, dissolved-oxygen concentration, temperature, and pH were first read on the flowthrough-monitor panel meter and compared with measurements made with portable field instruments.[3] The flowthrough-monitor sensors were removed from the sample chamber and maintenance was performed in the following manner. The specific-conductance sensor (fig. 6) was serviced by cleaning the electrodes with a soft brush or soaking them in 10-percent hydrochloric acid for a few minutes, if necessary. The dissolved-oxygen sensor (fig. 6) was serviced by cleaning the membrane or replacing the membrane and electrolyte. Generally, the membrane was replaced only when it was damaged or when readings were unstable. Temperature sensors (fig. 6) require no field maintenance other than replacement in case of failure or recalibration if readings exceed allowable error. The pH sensor (fig. 6), which is a combination glass and ceramic-junction reference electrode, was serviced periodically by cleaning the electrode surface with a nonscratching cloth or soft brush.

After servicing, the sensors were returned to their original position in the sample chamber and allowed to stabilize before final data were read from the panel meter. While the sensors were stabilizing, field-instrument measurements again were made and recorded. If the differences between these measurements and the equivalent panel-meter values for each water-quality characteristic were within allowable limits, servicing was complete (Gordon and Katzenbach, 1983, p. 77-79).

Additional maintenance was necessary if the difference between the panel-meter and field-instrument readings was not within allowable limits for one or more characteristics (Gordon and Katzenbach, 1983, p. 80-84). If the problem was determined to be in the calibration, then the instrument was recalibrated with standard solutions. If the problem was a failed or malfunctioning sensor, the sensor was replaced and recalibrated with standard solutions (Gordon and Katzenbach, 1983, p. 44-60).

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[3]The portable dissolved-oxygen meter was calibrated at river temperature of water-saturated air and at barometric pressure at each site, whereas the portable specific-conductance, pH, and temperature meter was calibrated in the office and used in calculating error in the monitor system.

Adjustments or repairs also were made to the pumping system if the sample chamber did not refill at a rate of approximately 7 to 10 gal/min.

Data Output

The data were recorded hourly on 16-channel punched-paper tape and removed at regular intervals for processing. The data were transferred from tape to temporary computer files at the office by means of a Mitron model MDTS-2 data translator. The data were then edited and transferred to permanent computer storage for subsequent analysis.

U.S. Geological Survey Minimonitor System

The minimonitor (fig. 2) consists of a battery-powered electronic package controlled by an internal crystal clock. At each recording interval, the unit scans, measures, records data in binary-coded digital form on a 16-channel punched-paper tape recorder, and (or) transmits real-time data periodically by GOES. The instrument measures specific conductance, dissolved-oxygen concentration, temperature, and pH with sensors submerged in the stream. The sensors typically are submerged in the stream in 6-inch plastic pipe (fig. 5) having 1-inch-diameter holes staggered on 6-inch centers. Extension cables with underwater connectors link the sensors to the electronics package, which is housed in a weatherproof shelter.

Routine Maintenance and Calibration

During a typical site visit for this study, specific-conductance, dissolved-oxygen concentration, temperature, and pH were first read on the minimonitor panel meter and compared with measurements made with portable field instruments. The minimonitor sensors then were removed from the stream, and maintenance was performed in the following manner. The specific-conductance sensor was serviced by removing the shield covering the electrodes (fig. 7) and cleaning them; electrodes periodically were polished with crocus cloth. The sensor shield also was cleaned and replaced. The dissolved-oxygen sensor (fig. 7) was serviced by cleaning the membrane, checking the stirrer assembly, and replacing the membrane and electrolyte if necessary. With few exceptions, the membrane was replaced only when it was damaged or when readings were unstable.

Temperature sensors (fig. 7) require no field maintenance other than replacement in case of failure or recalibration if readings exceed allowable error. The pH sensor (fig. 7), which is a combination of a glass pH electrode and a wood-junction reference electrode, was serviced periodically by cleaning the electrodes' surfaces with a nonscratching cloth or soft brush.

After servicing, the sensors were returned to their original position in the stream and allowed to stablilize before final data were read from the panel meter. While the sensors were stabilizing, field-instrument measurements again were made and recorded. If the difference between these measurements and the equivalent panel-meter values for each water-quality characteristic were within allowable limits, servicing was complete (Gordon and Katzenbach, 1983, p. 84-86).

Additional maintenance was necessary if the difference between the panel-meter and field-instrument readings was not within allowable limits on one or more characteristics (Gordon and Katzenbach, 1983, p. 85-86). If the problem was determined to be in the calibration, then the instrument was recalibrated with standard solutions (Gordon and Katzenbach, 1983, p. 60-74). If the problem was determined to be electronic, the appropriate electronic part was replaced.

Data Output

Data output was the same as for the flowthrough monitor--that is, the data were recorded hourly on 16-channel punched-paper tape and removed at regular intervals for processing. The data were transferred from tape to temporary computer files at the office by means of a Mitron model MDTS-2 data translator. The data were then edited and transferred to permanent computer storage for subsequent analysis.

Packaged-Sensor System

The packaged-sensor system (a Hydrolab Data Sonde, model 2000 series) consists of solid-state electronic circuitry powered by internal batteries and controlled by a quartz clock. It is a self-contained unit that measures specific conductance, dissolved-oxygen concentration, temperature, and pH, without moving parts, land-based instrumentation, or cable attachments for direct readout. A microprocessor controls all necessary measuring circuits, processing, and data storage.

The packaged-sensor system was fully submerged in the stream in a housing of 6-inch plastic pipe (fig. 5) having 1-inch-diameter holes on 6-inch centers.

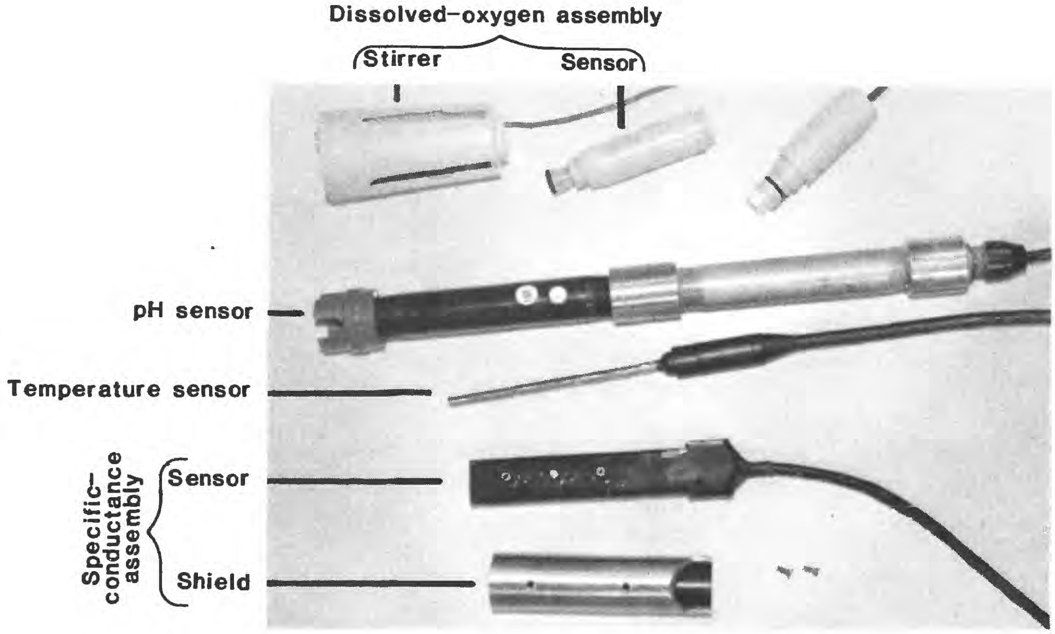

Figure 7.—Minimonitor sensors.

Figure 8.—Packaged-sensor system being replaced in the field.

Routine Maintenance and Calibration

The packaged-sensor system (fig. 8) was exchanged with a spare unit at every visit, serviced entirely in the office, and made ready for the next visit. Routine maintenance of the specific-conductance components entailed polishing the six nickel electrodes with crocus cloth and wiping the electrodes clean with alcohol. Maintenance of the dissolved-oxygen sensor (fig. 9) consisted of cleaning the membrane; generally, the membrane and electrolyte needed to be replaced only when calibration was not possible or when the membrane had been damaged. The temperature sensor (fig. 9) which was calibrated at the factory, has no user-serviceable components. Maintenance of the pH sensor (fig. 9) consisted of cleaning the glass electrode and reference electrode with a nonscratching cloth; generally, the reference filling solution (KCl electrolyte) or Teflon junction was replaced if the instrument failed calibration checks. Batteries were replaced each time the packaged-sensor system was serviced in the office.

The packaged sensors were calibrated and programmed in the office by means of a data-management unit (DMU) linked to an external printer-keyboard terminal (fig. 10) or computer terminal. The keyboard operator was prompted by the DMU to immerse the sensors in standard solutions. The unit self-tested and calibrated if the discrepancy between the reading for the standard solution and the value for the standard entered by the field person was within allowable limits[4] as specified by the manufacturer. If the discrepancy exceeded allowable limits, the unit rejected calibration, which indicated either a malfunctioning sensor or an incorrect or contaminated standard solution. If the problem was a malfunctioning sensor, the sensor was replaced and the unit was recalibrated. If the problem was determined to be electronic, the unit was returned to the manufacturer.

If no calibration problems were encountered, the keyboard operator entered a "quit" code. The DMU then would test the packaged-sensor unit's battery and memory, and, finally, would prompt the operator to enter a station identification code and dates and time to begin and end data collection.

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[4] Each of the four water-quality characteristics to be measured (specific conductance, dissolved-oxygen concentration, temperature, and pH) was calibrated in the ranges shown in table 2.

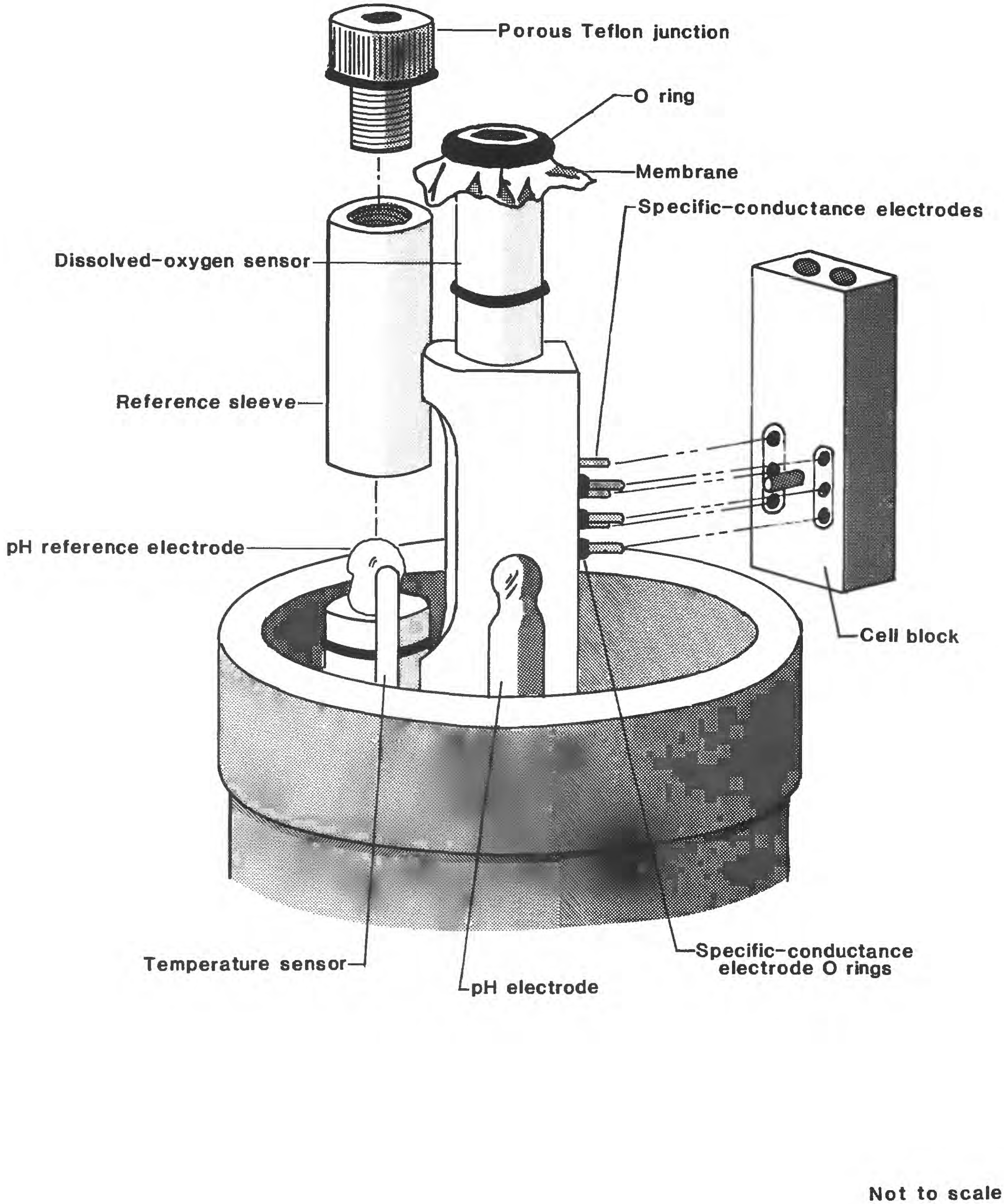

Figure 9.--Exploded diagram of packaged sensors.

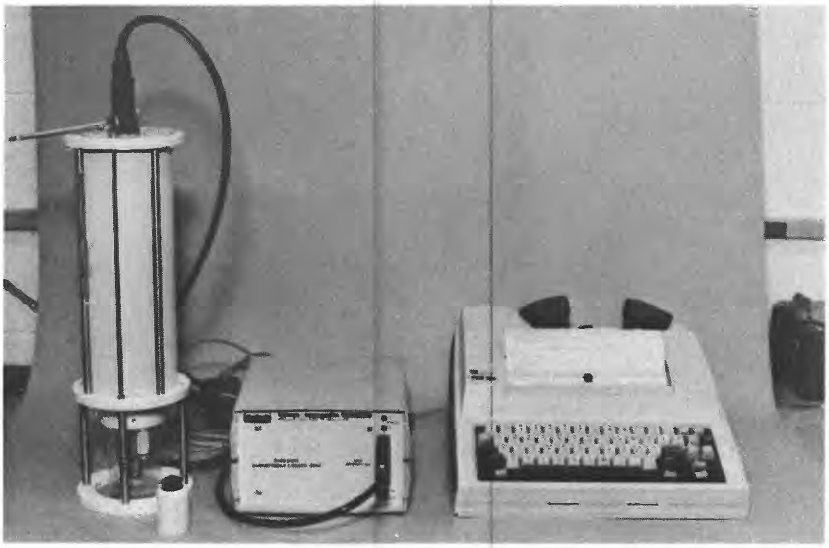

Figure 10.--Packaged-sensor system attached data-management unit and printing keyboard.

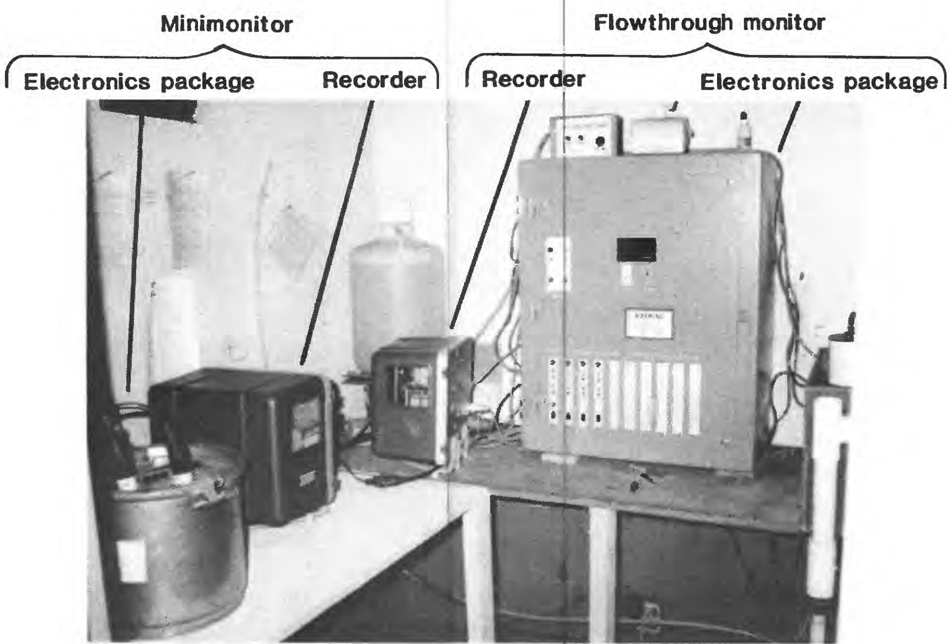

Figure 11.--Minimonitor equipment in typical flowthrough-monitor shelter.

Data Output

Data stored in the packaged-sensor unit's solid-state memory[5] were retrieved in the office during servicing. The output of each unit was organized and formatted by the DMU and, in this study, was transmitted through a modem to a computer located in another U.S. Geological Survey office for temporary storage. The data were then edited and transferred to permanent storage for subsequent analysis.

COMPARISON OF ACCURACY AND COMPLETENESS OF DATA

Four minimonitors and eight packaged-sensor systems were sent from the Hydrologic Instrumentation Facility to the U.S. Geological Survey's District office in Columbus, Ohio, to be tested at four flowthrough-monitor sites in Ohio for 1 year (October 1985 through September 1986). Upon receipt, each system was unpacked, inspected for shipping damage, and set up and calibrated in an office environment.

A minimonitor was installed at each of four sites where flowthrough monitors already were in operation (fig. 11); two packaged-sensor systems also were assigned to each site and alternated every 2 weeks.

Detailed records were kept of data lost and equipment problems. These records, in conjunction with data collected by the three monitor systems and field-measurement instruments, are the basis for the comparisons discussed in the following sections of this report.

Accuracy of Data

The data are summarized in figures 14 through 29 (at back of report). Data collected by field-measurement instruments at each site are used as the standard or reference value. Reference values were compared to the monitor-system values at each site visitation and recorded. Absolute differences were calculated by comparing reference values to monitor values. These absolute differences are illustrated as box plots in figure 12 for all four measurements (specific conductance, dissolved-oxygen concentration, temperature, and pH). The shape of the box plots for all four sets of monitor values indicates the data are right-skewed. This means that there are large values that are far from the mean value. Data sets that are skewed should not be described or tested by statistical tests or statistics that depend upon a normally distributed sample.

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[5]Data were stored every 2 hours during the first part of the evaluation because excessive power consumption resulted in drained batteries. After modification by the manufacturer, data were stored hourly.

A rank transformation was used prior to statistical testing to remove the effect of outliers on the data analysis. An analysis of variance on the ranks (Kruskal-Wallis test) of the absolute values was performed for all four measurement sets (specific conductance, dissolved-oxygen concentration, temperature, and pH). The results of the analysis of variance are presented in table 3. An analysis-of-variance test was performed to determine whether the mean absolute differences are significantly different for each instrument.

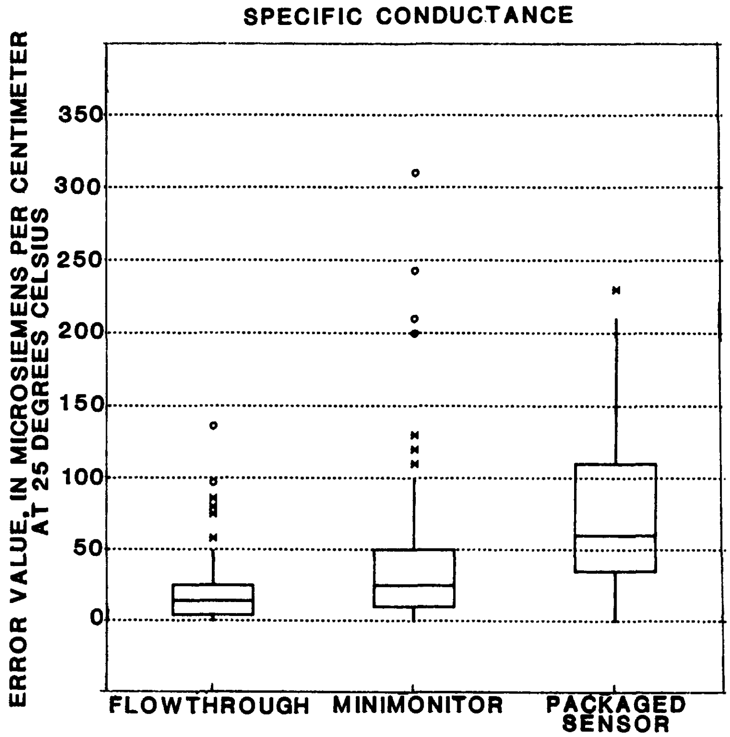
Specific Conductance

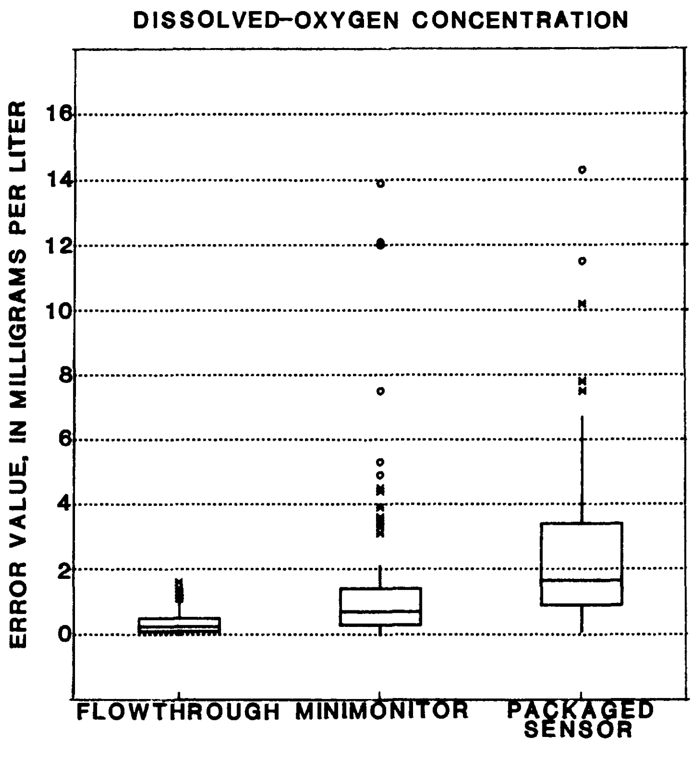
On the basis of the flowthrough-monitor data, the specific conductance of the stream water sampled ranged from 195 to 2,330 µS/cm (microsiemens per centimeter at 25 degrees Celsius) with an average of 655 µS/cm. The flowthrough monitor's calibration range was from 0 to 3,000 µS/cm, whereas the range for the other two systems was from 0 to 10,000 µS/cm. Thus, it was expected that the flowthrough-monitor data would have greater accuracy and precision. The comparison of field-meter values to monitor values is shown in figure 12. Analysis of variance on the absolute differences of data from each system against field-measured values showed that the flowthrough-monitor data from four sites have mean errors ranging from 10 to 25 µS/cm between sites with a mean error of 19 µS/cm for all sites; the minimonitor data have mean errors ranging from 29 to 59 µS/cm between sites with a mean error of 39 µS/cm for all sites; and the packaged-sensor data have mean errors ranging from 54 to 105 µS/cm between sites with a mean error of 76 µS/cm for all sites (table 3).

Dirty sensors had little effect on the data collected by the flowthrough monitors and some effect on the other systems. For the flowthrough monitors, the greatest change in reading due to cleaning of electrodes was 16 µS/cm. No change was noted after cleaning for 60 out of 114 measurements. The average change per cleaning was 2 µS/cm.

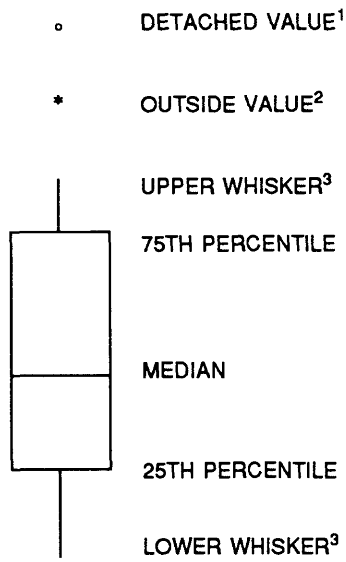
For the minimonitors, the greatest change in reading due to cleaning of electrodes was 310 µS/cm. No change was noted after cleaning for 36 out of 109 measurements. The average change per cleaning was 22 µS/cm.

Because the packaged-sensor units are exchanged rather than cleaned and immediately replaced in the stream, effects of dirty sensors are not easily detected due to lack of a communication link between land surface and sensor package placed in the stream. Moreover, during the first 6 months of the study, the packaged-sensor system had to be calibrated with a standard that exceeded 50 percent full scale (0 to 10,000 µS/cm). The average





EXPLANATION



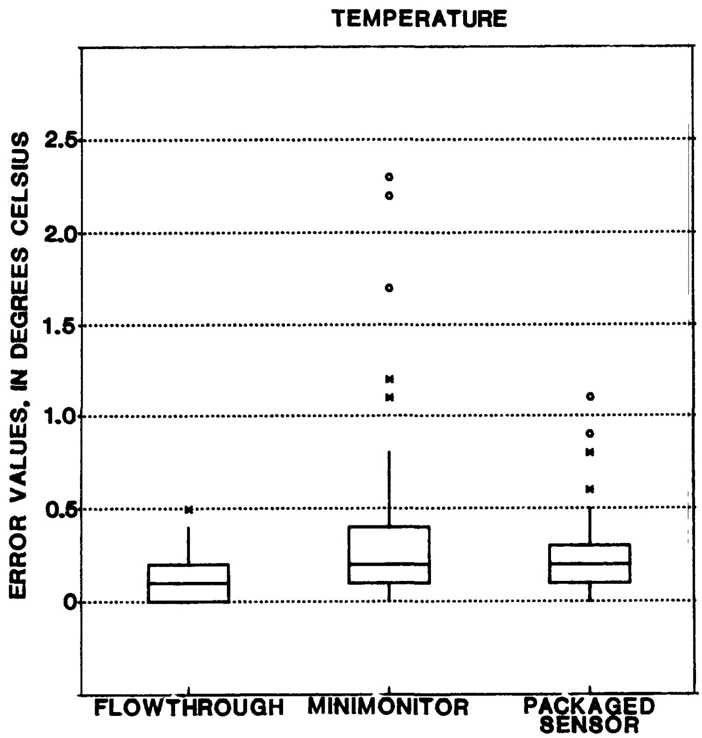
[1]A detached value is defined as a value that is greater than 3 times the interquartile range (beyond the box)

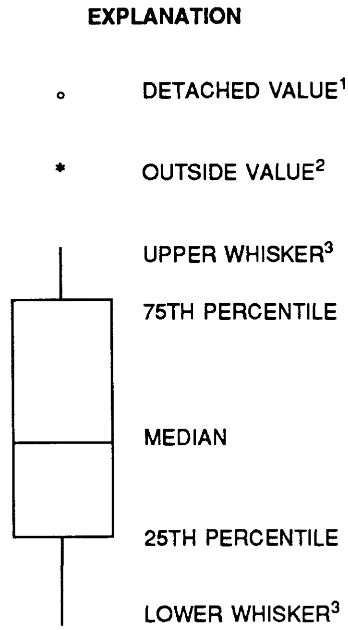
[2]An outside value is defined as >1.5 and ≤3 interquartile ranges from the box

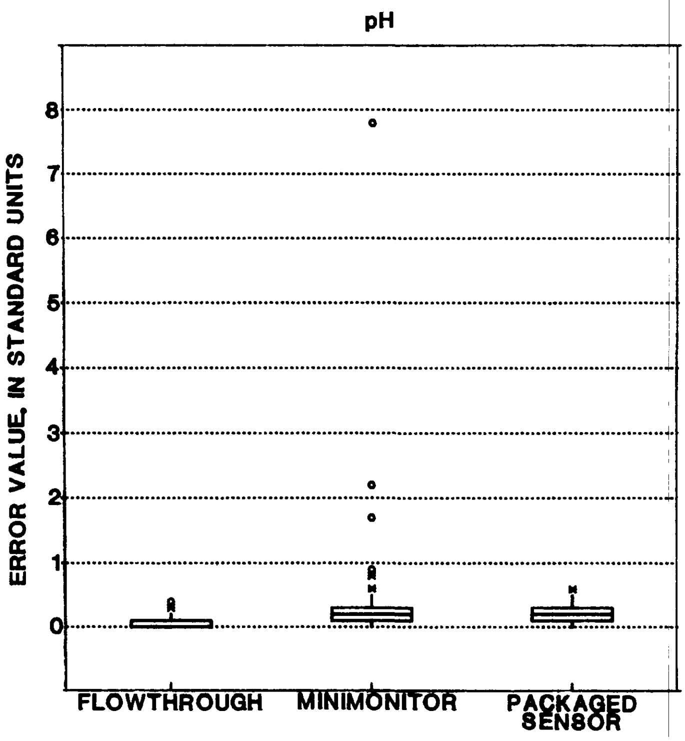
[3]Upper whisker is defined as the largest data point less than or equal to the uper quartile plus 1.5 times the interquartile range. Lower whisker is minus 1.5 times the interquartile range

n = 114 minus the number of data points shown in figure 13

Figure 12.—Absolute differences between field-instrument values and observed monitor values.







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n = 114 minus the number of data points shown in figure 13

Figure 12.—Absolute differences between field-instrument values and observed monitor values—Continued.

Table 3.--Results of the one-way analysis of variance Kruskal-Wallis test on ranked data for the three monitor systems

[N, number of samples]

Data source	N	Mean error	Mean squares	F statistic	Probability of value >F
		Specific Conductance			
Flowthrough monitor------------	114	18.7	82,414	43.28	0.0001
Minimonitor--------------------	109	39.0	1,904		
Packaged-sensor system---------	86	76.4			
		Dissolved Oxygen			
Flowthrough monitor------------	114	.36	124.872	33.16	0.0001
Minimonitor--------------------	105	1.52	3.76		
Packaged-sensor system---------	82	2.63			
		Temperature			
Flowthrough monitor------------	114	.14	.699983	10.06	0.0001
Minimonitor--------------------	110	.30	.0696076		
Packaged-sensor system---------	88	.22			
		pH			
Flowthrough monitor------------	114	.09	1.56918	6.85	0.0012
Minimonitor--------------------	106	.32	.228993		
Packaged-sensor system---------	85	.24			

error for this period for the four sites was 101 µS/cm. After instruments were returned to the manufacturer and modified, the conductance could be calibrated with standards less than 50 percent full scale. The average error for the last 6 months of the study was 52 µS/cm for four sites.

Dissolved-Oxygen Concentration

On the basis of flowthrough-monitor data, the dissolved-oxygen concentration of the stream water sampled ranged from 0.1 to 20.0 mg/L (milligrams per liter), with an average of 8.3 mg/L. The comparison of field-meter values to monitor values is shown in figure 12. Analysis of variance on the absolute differences of data from each system against field-measured values showed that the flowthrough monitors had a mean error for all four sites of less than 0.4 mg/L; the minimonitor had mean errors ranging from 1.1 to 2.0 mg/L between sites, with a mean error of 1.5 mg/L for all sites; and the packaged-sensor system had mean errors of 1.9 to 4.2 mg/L between sites, with a mean error of 2.6 mg/L for all sites (table 3). The minimonitor and packaged-sensor systems had a tendency to read lower than either the flowthrough monitor or the field instruments, especially during the summer months when the sensors became fouled more quickly.

It appears the amount of flow past the membrane and the chlorinating of water to keep sensors clean was the reason for the flowthrough monitor's more accurate data. For the flow-through system, the greatest change in reading due to cleaning of electrodes was 2.4 mg/L. No change was noted for 47 out of 114 readings. The average change per cleaning was 0.4 mg/L.

Because of probe and instrument problems, the number of comparisons was less for the minimonitor. The greatest change in reading due to cleaning was 4.5 mg/L. No change was noted for 7 out of 105 readings. The average change per cleaning was 0.9 mg/L.

Because the packaged-sensor units are exchanged rather than cleaned and immediately replaced in the stream, effects of dirty sensors are not easily detected due to lack of a communication link between land surface and sensor package placed in the stream. In the first 6 months of data collection by the packaged-sensor system, the Teflon membrane was covered by a silicone membrane, and a water-saturated/air calibration method was used. After instruments were returned to the manufacturer for modification, single Teflon membranes were used, and the units were calibrated in a circulating water bath at room temperature (Gordon and Katzenbach, 1983, p. 4-5). The average error for all four sites for the first 6 months was 2.0 mg/L, and for the last 6 months was 2.7 mg/L.

Temperature

On the basis of the flowthrough-monitor data, the temperature of the stream water sampled ranged from 0.0 °C (degrees Celsius) to 30.0 °C with an average of 14.5 °C. The comparison of field-meter values to monitor values is shown in figure 12. Analysis of variance of data from each system against field-measured values showed the flowthrough-monitor data from four sites had a mean error of less than 0.2 °C, and the minimonitors and packaged-sensor systems had mean errors of less than 0.3 °C for all sites (table 3).

pH

On the basis of the flowthrough-monitor data, the observed pH of the streamwater sampled ranged from 7.1 to 9.2, with an average of 7.7. The comparison of field-meter values to monitor values is shown in figure 12. Analysis of variance on the absolute differences of data from each system against field-measured values showed the flowthrough-monitor data from four sites had a mean error of less than 0.1 units; the minimonitor had mean errors ranging from less than 0.2 to less than 0.7 between sites, with a mean error of 0.3 units for all sites; and the packaged-sensor system had a mean error of 0.2 units for all sites (table 3).

Completeness of Data

Completeness of data reflects the number of equipment problems associated with each system during the test period. Most of the problems that occurred during the test were minor, and some of the data loss was due to malfunction of the recording equipment. A complete history of equipment problems and data lost for each system at each of the four sites is presented in tables 4, 5, and 6 (at back of report).

Flowthrough-Monitor System

The flowthrough monitors had very few equipment problems or data loss during the test period (table 4 and fig. 13). Data were lost once because of a malfunctioning pump, once because a recorder was wired wrong, and once because of dissolved-oxygen sensor failure. Several times the entire dissolved-oxygen sensor was replaced (Gordon and Katzenbach, 1983, p. 82) rather than just the membrane when dissolved-oxygen values were outside allowable tolerances (Gordon and Katzenbach, 1983, p. 78).

Minimonitor System

Problems with the minimonitors occurred sporadically throughout the test period (table 5 and fig. 13), although more data loss occurred during the first half of the period, owing to an insufficient supply of spare parts. There were two failures each for specific conductance and temperature sensors. Problems with the dissolved-oxygen sensors were primarily confined to dirty or damaged membranes; however, at least four dissolved-oxygen sensors appear to have failed, as well as four stirrer assemblies. Problems with the pH sensors were numerous, and the malfunctioning sensors were replaced whenever spares were available. In addition, nine recorders had to be replaced during the test period, three that failed to advance tape and six that punched erroneous data. In one instance, high water washed away a sensor housing and the sensors inside. Other problems included a monitor that was not left in operating mode, a punch tape that was not secured to the take-up spool, interruptions in data collection when minimonitors were returned to the Hydrologic Instrumentation Facility for modification, and data loss because the field person could not diagnose an electronic problem.

Packaged-Sensor Systems

In general, fewer equipment problems with the packaged-sensor systems occurred near the end of the test period than at the beginning (table 6 and fig. 13). Early in the project, short periods of record were lost because excessive power consumption resulted in drained batteries. After modifications were made to correct for excessive power consumption, only two periods of record were lost. These losses were caused by one malfunctioning unit that would calibrate but not store data. The high-water event that caused loss of minimonitor sensors also removed the packaged-sensor housing, which caused loss of data and damage to the unit. Packaged-sensor data were lost only twice due to errors. In one case, temperature was the only parameter programmed into the unit. In the other case, pH was omitted during programming of the unit.

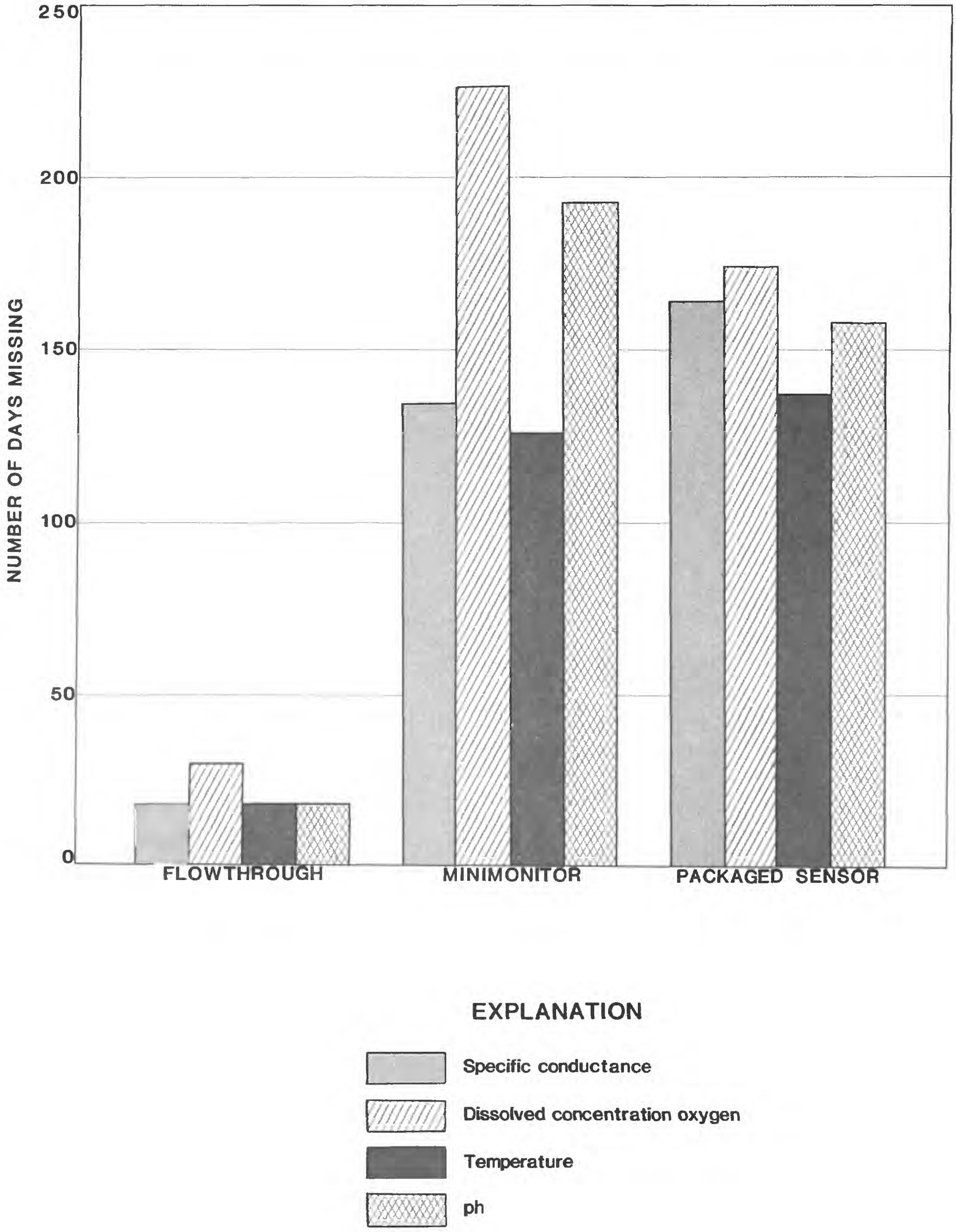


Figure 13.—Number of days of missing data.

CONCLUSIONS

Review of the data presented herein leads to the following conclusions.

1. Data collected with the flowthrough monitor were the most accurate overall for each water-quality characteristic measured, probably because (a) the chlorinating system kept sensors cleaner, and (b) the pumping system distributed an even flow of water to the sensor tank, especially across the dissolved-oxygen membrane.

2. Evaluation of the accuracy of the minimonitors and packaged-sensor systems shows that the minimonitor data generally were the more accurate for specific conductance and dissolved-oxygen concentration, whereas the packaged-sensor data generally were the more accurate for temperature and pH.

3. Data from the flowthrough-monitor systems were the most complete because the flowthrough monitors had the fewest equipment failures.

4. Data from the packaged-sensor systems were the least complete during the first 6 months of the test; however, after modifications were made to the equipment, the packaged-sensor data appear to exceed the minimonitor data in completeness because of fewer equipment failures.

5. Although not currently being used by the U.S. Geological Survey, the packaged-sensor system shows potential for meeting Survey data-collection requirements, except perhaps for dissolved-oxygen data.

REFERENCES CITED

Gordon, A. B., and Katzenbach, M. S., 1983, Guidelines for use of water quality monitors: U.S. Geological Survey Open-File Report 83-681, 94 p.

Katzenbach, M. S., 1988, Economic comparison of two types of automatic water-quality monitors: U.S. Geological Survey Water-Resources Investigations Report 87-4232, 24 p.

(p. 28 follows)

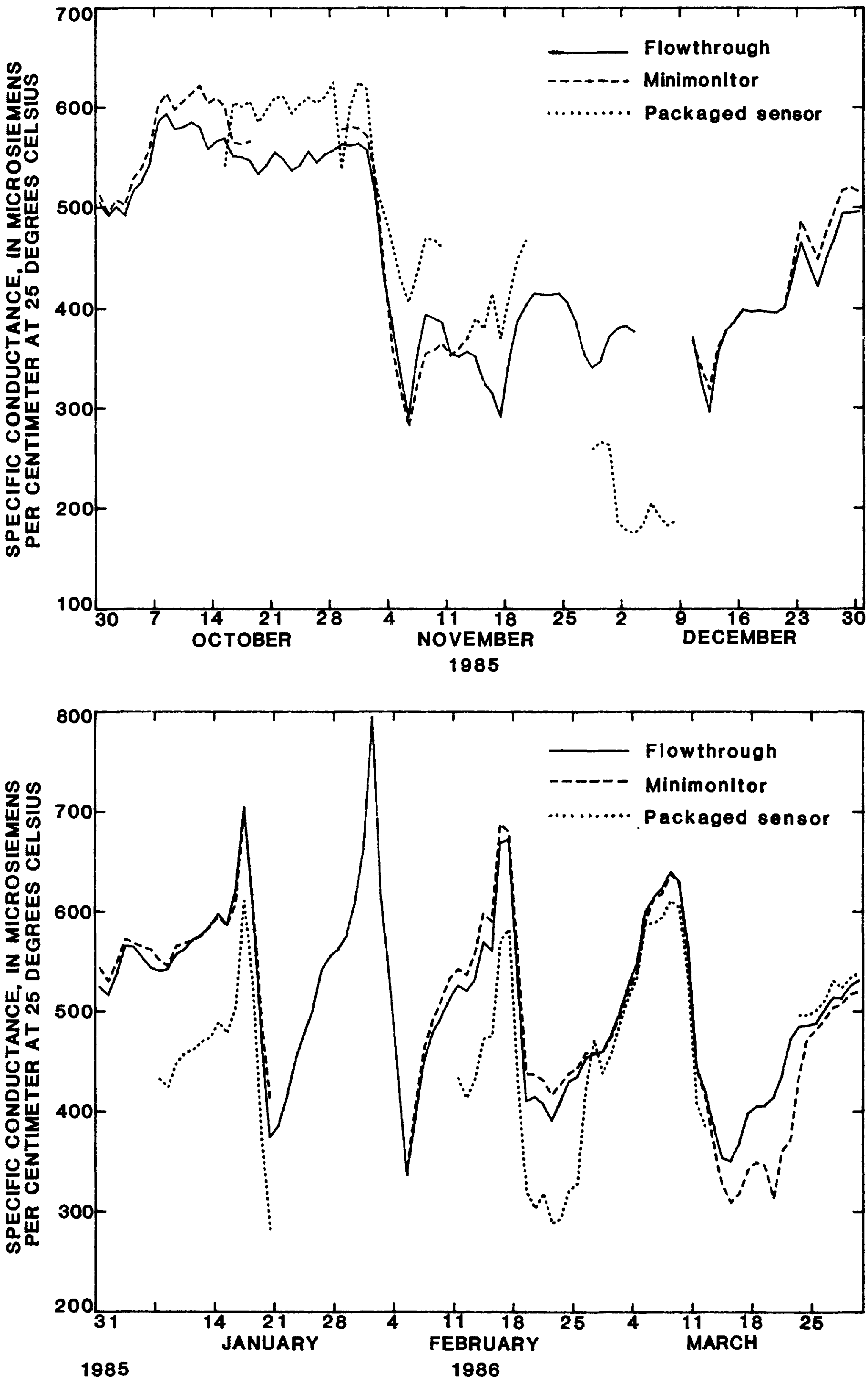
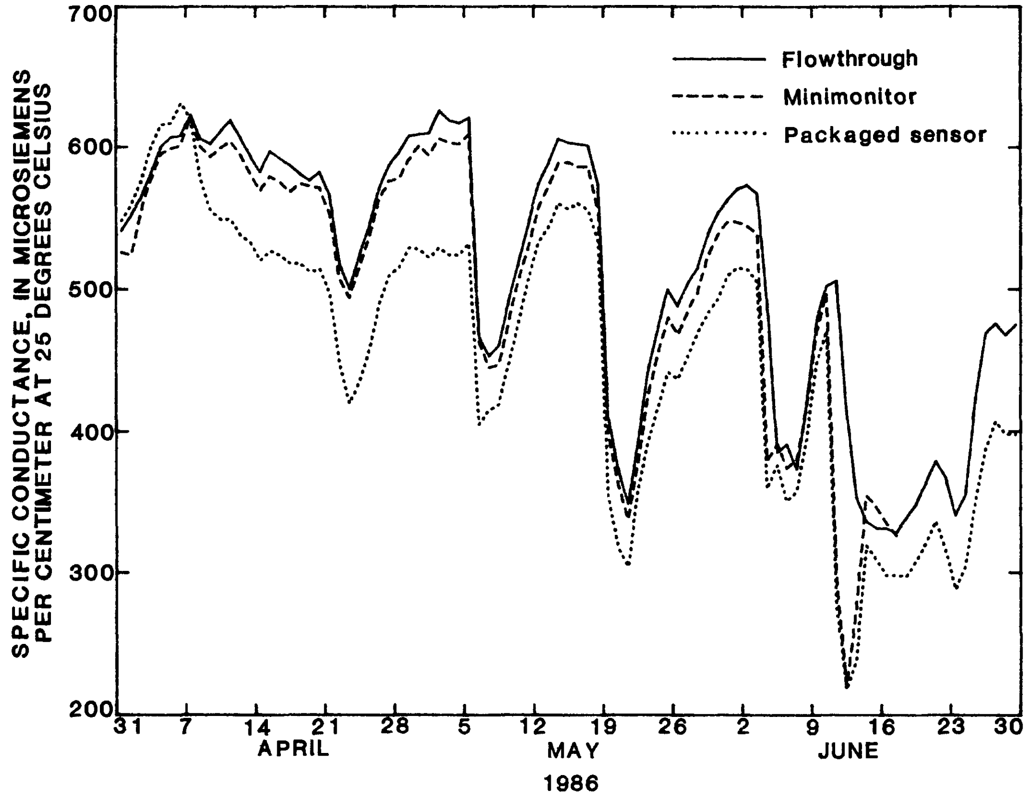


Figure 14.—Daily mean values for specific-conductance data collected by flowthrough, minimonitor, and packaged-sensor systems, site 1.



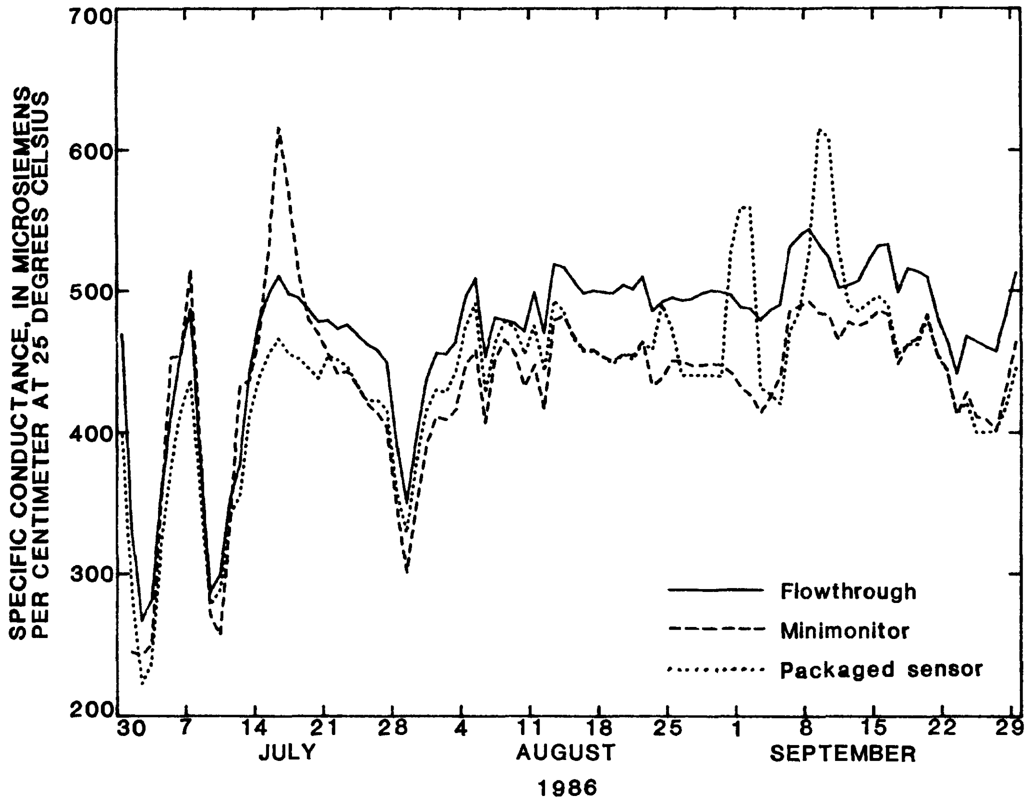


Figure 14.--Daily mean values for specific-conductance data collected by flowthrough, minimonitor, and packaged-sensor system, site 1--Continued.

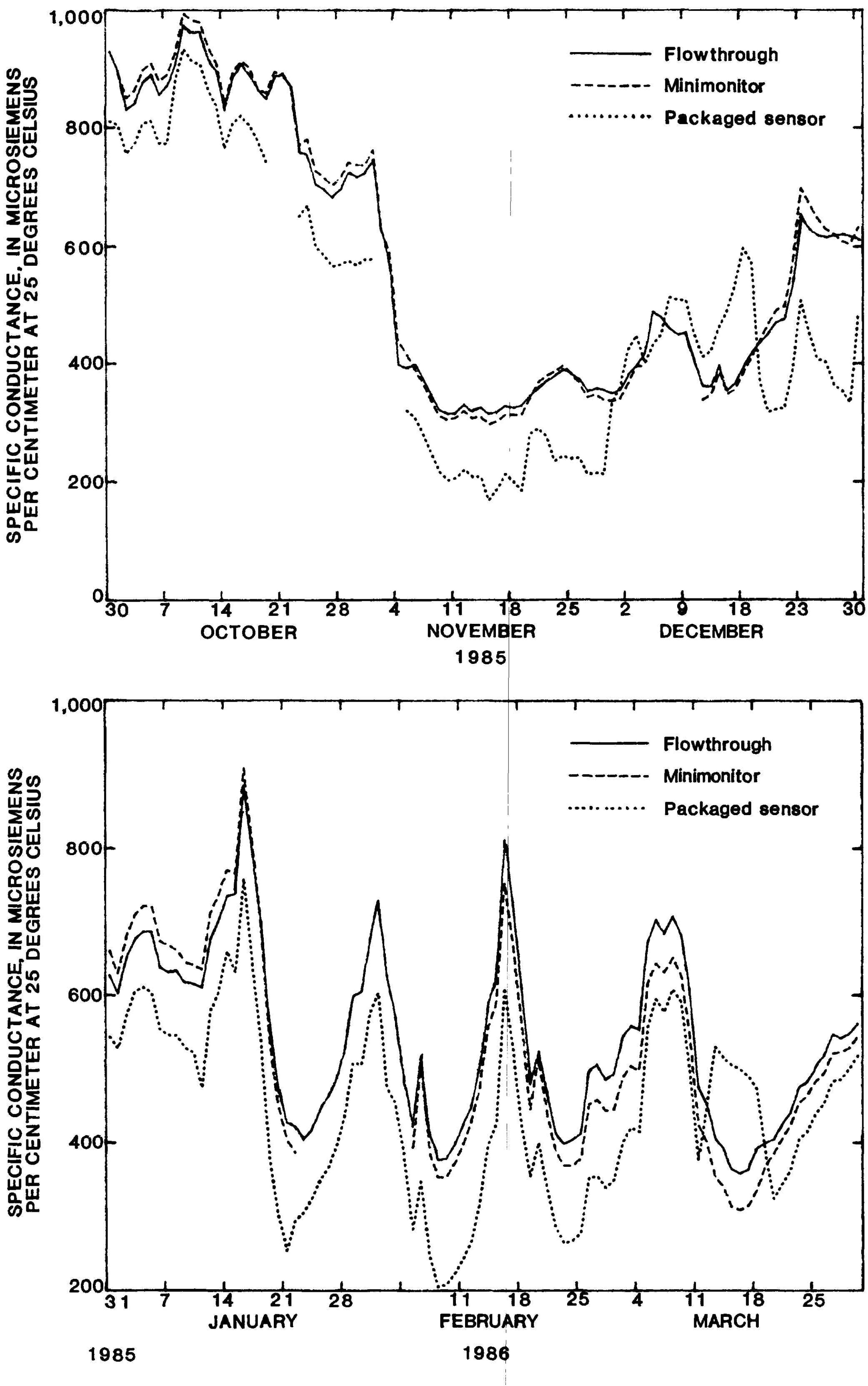
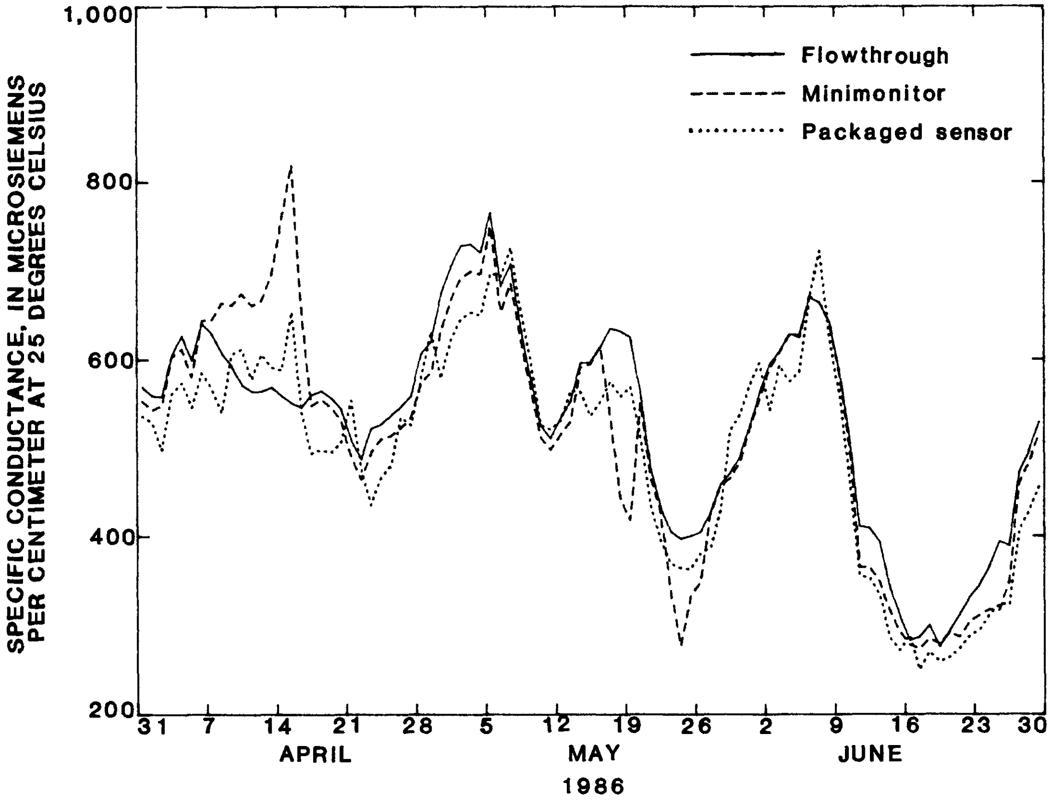


Figure 15.—Daily mean values for specific-conductance data collected by flowthrough, minimonitor, and packaged-sensor systems, site 2.



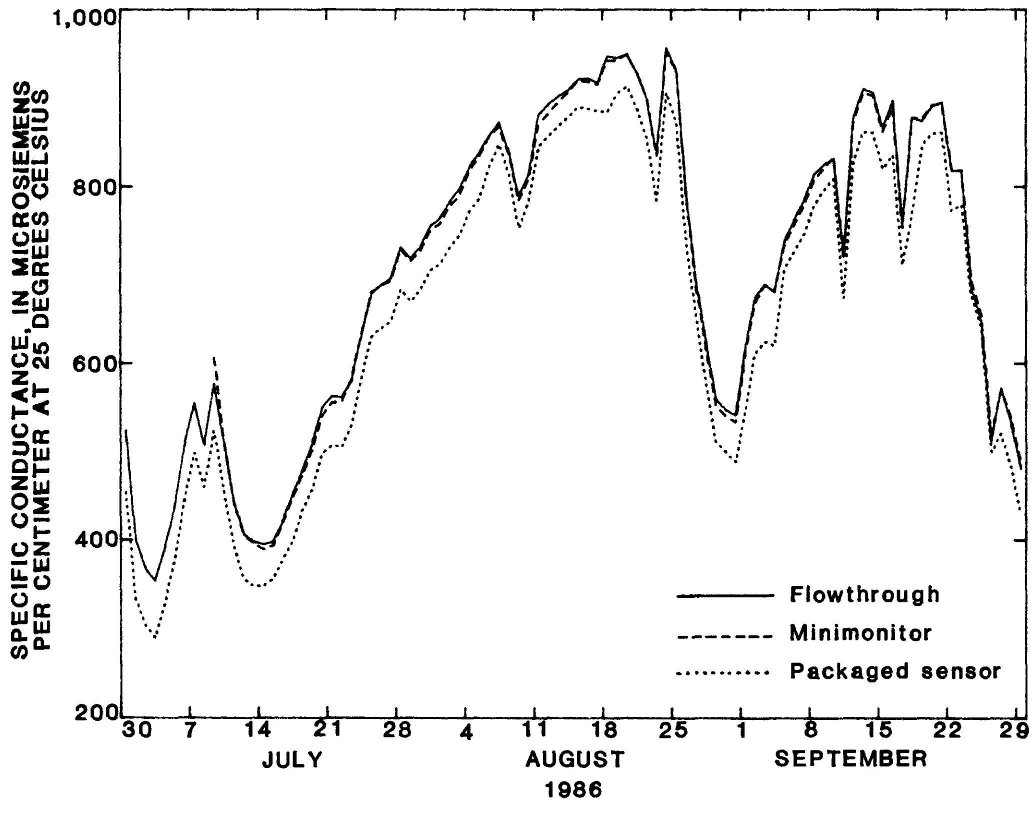


Figure 15.--Daily mean values for specific-conductance data collected by flowthrough, minimonitor, and packaged-sensor systems, site 2--Continued.

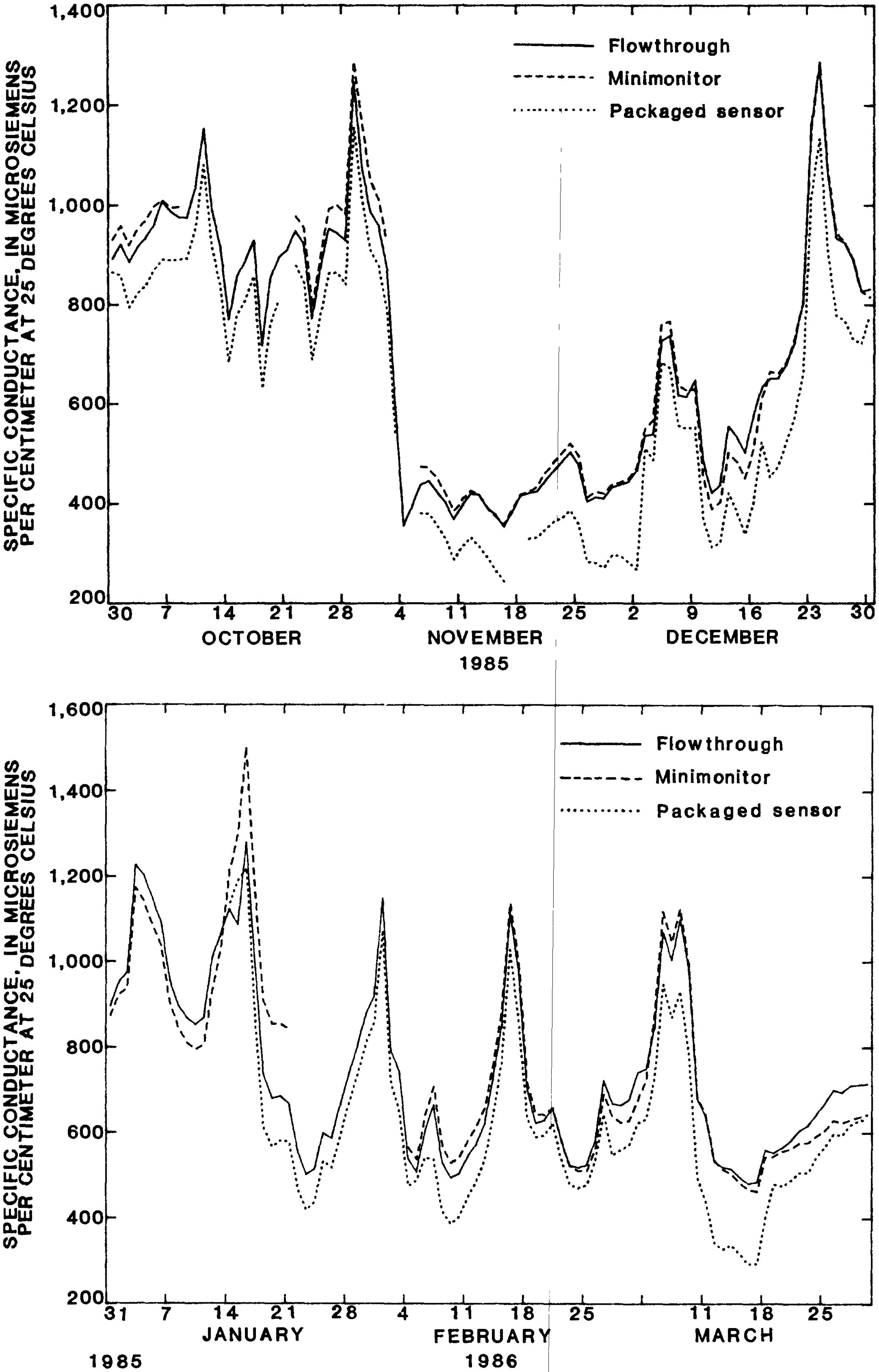
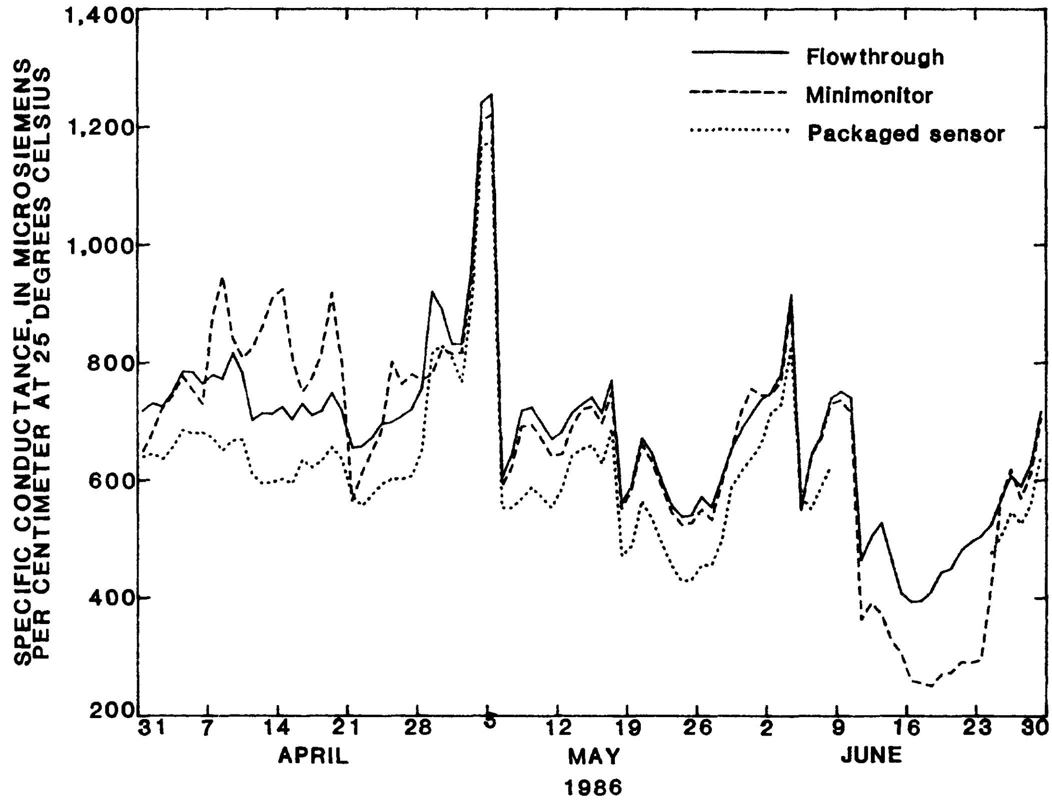


Figure 16.--Daily mean values for specific-conductance data collected by flowthrough, minimonitor, and packaged-sensor systems, site 3.



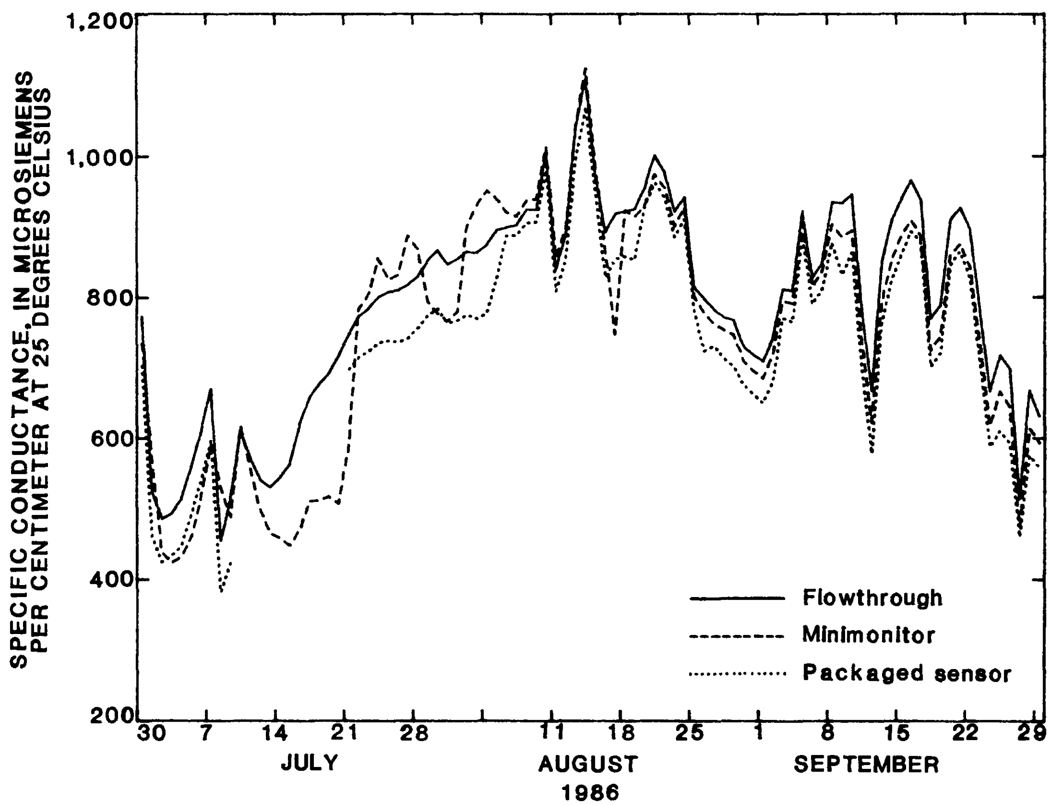
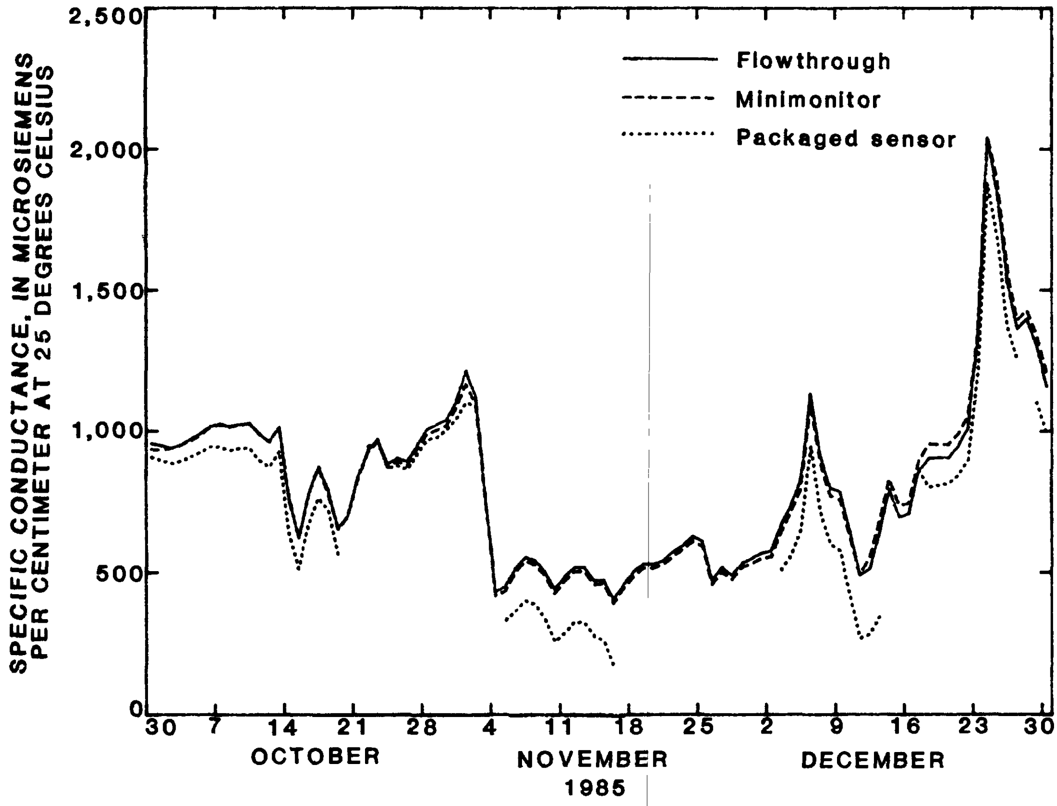


Figure 16.--Daily mean values for specific-conductance data collected by flowthrough, minimonitor, and packaged-sensor systems, site 3--Continued.



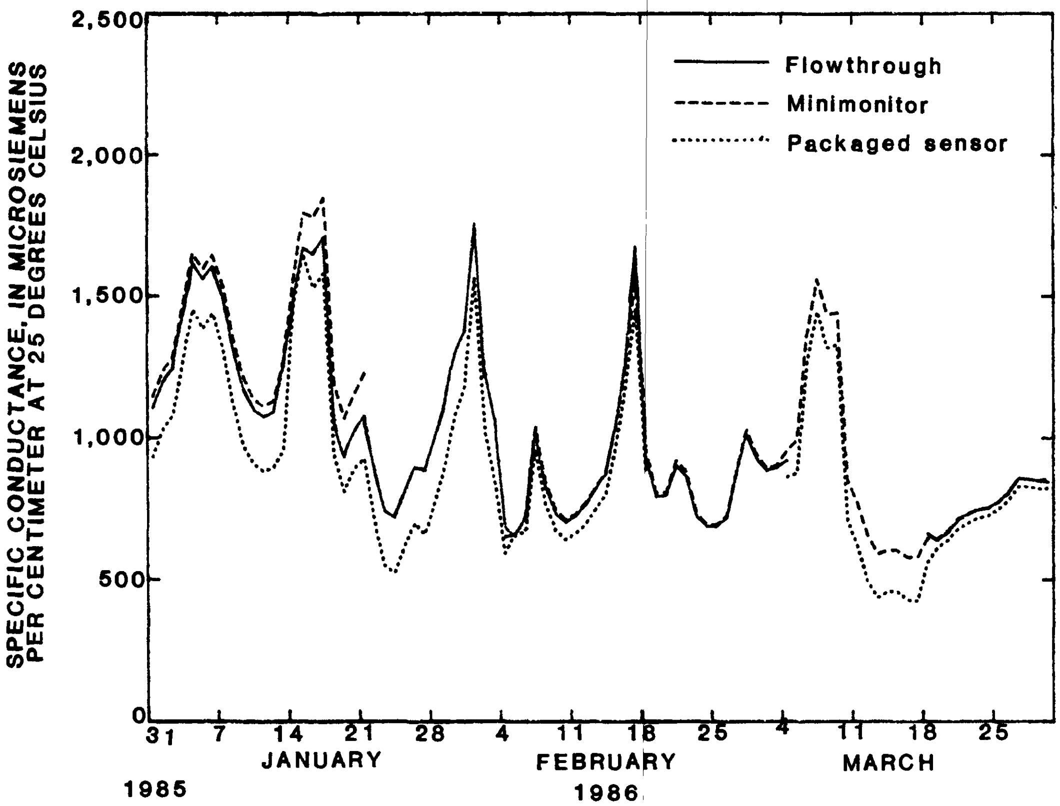
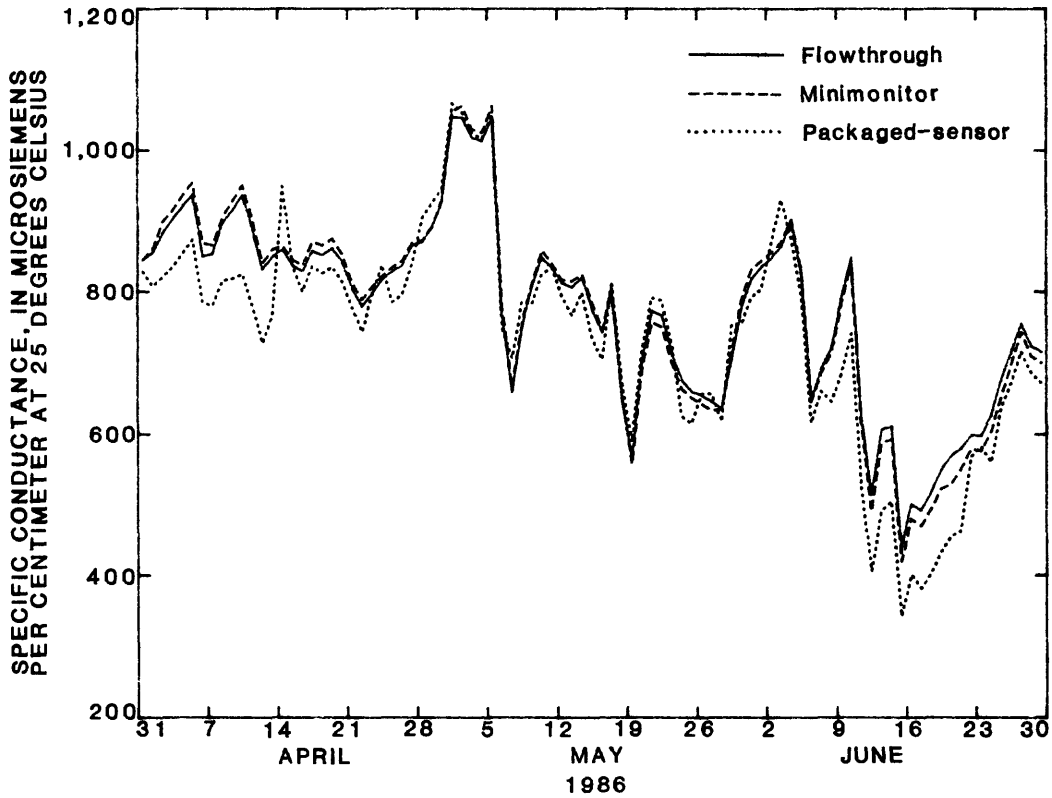


Figure 17.--Daily mean values for specific-conductance data collected by flowthrough, minimonitor, and packaged-sensor systems, site 4.



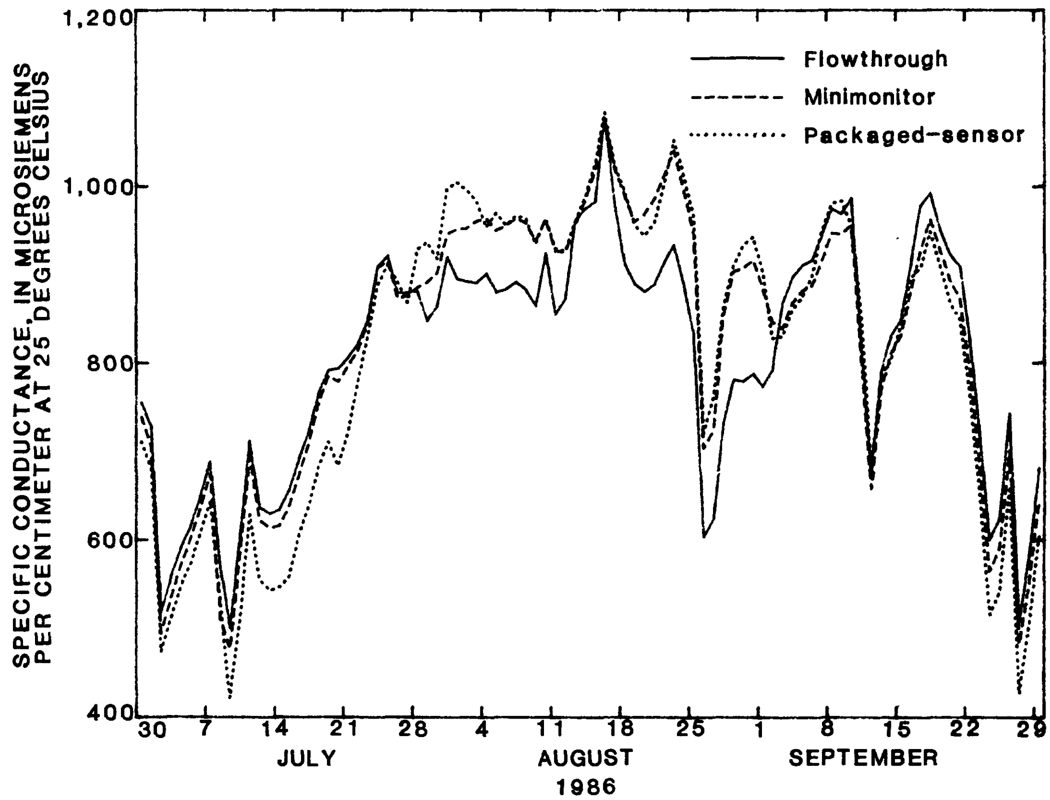


Figure 17.--Daily mean values for specific-conductance data collected by flowthrough, minimonitor, and packaged-sensor systms, site 4--Continued.

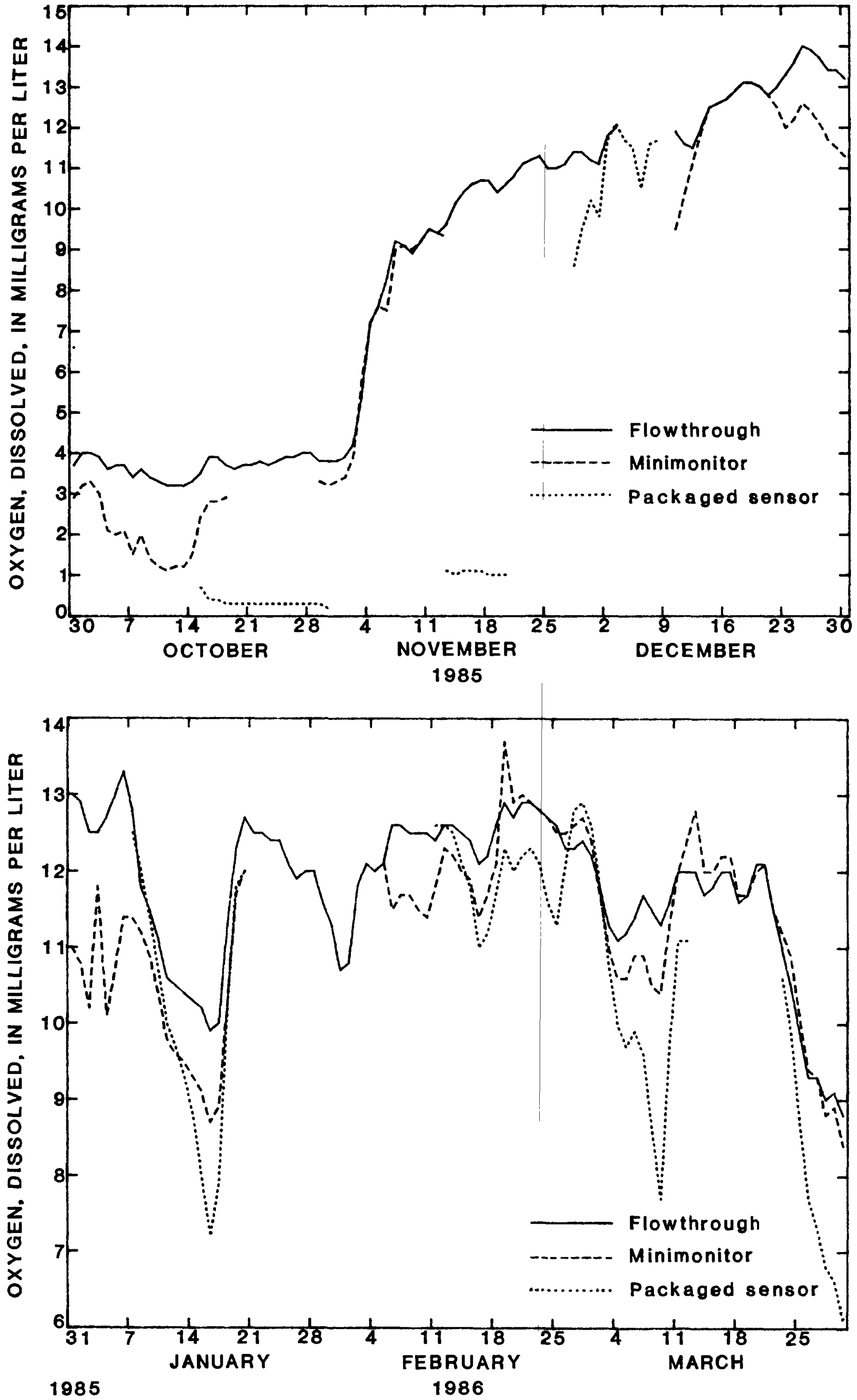


Figure 18.--Daily mean values for dissolved-oxygen data collected by flowthrough, minimonitor, and packaged-sensor systems, site 1.

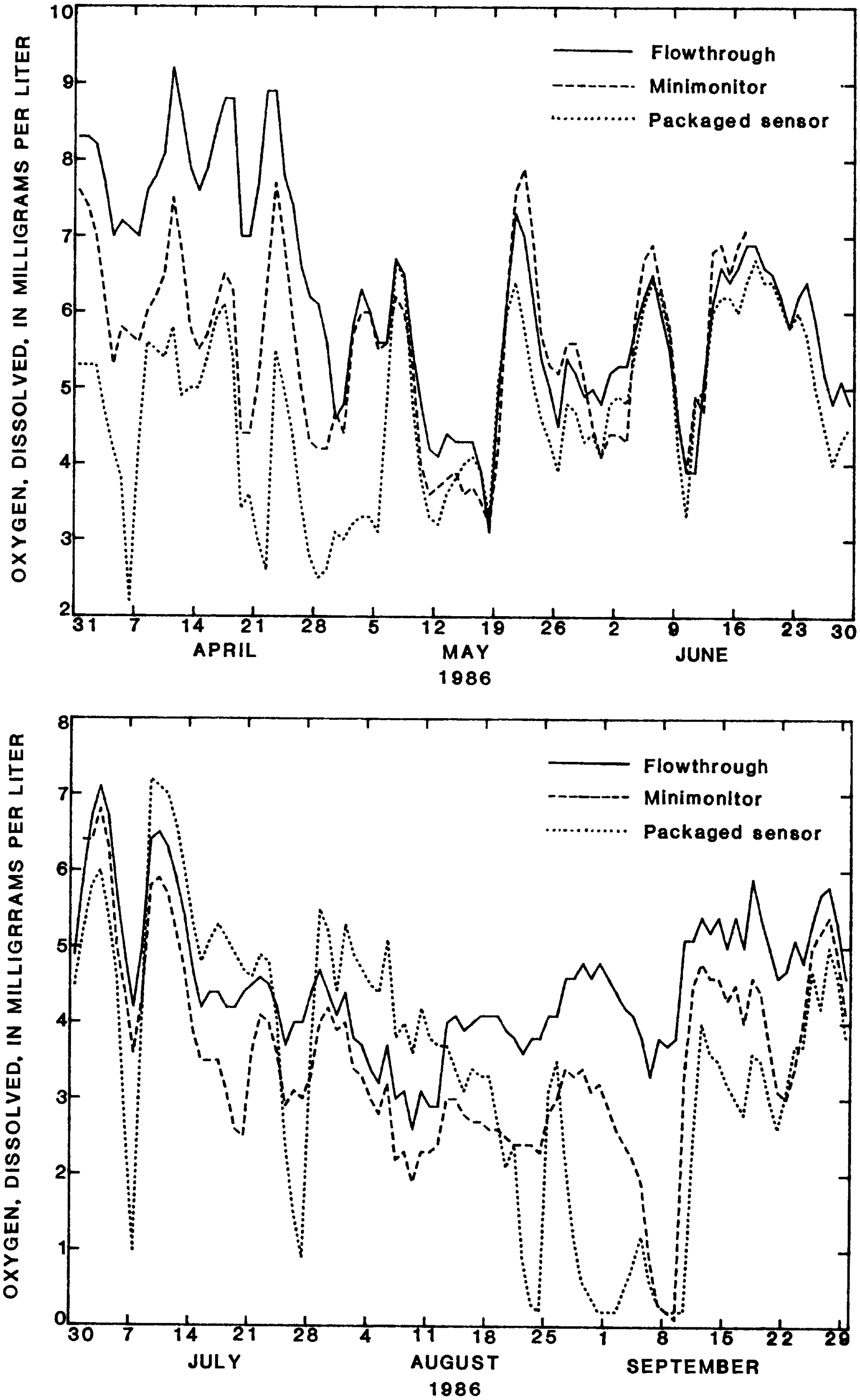


Figure 18.--Daily mean values for dissolved-oxygen data collected by flowthrough, minimontor, and packaged-sensor systems, site 1--Continued.

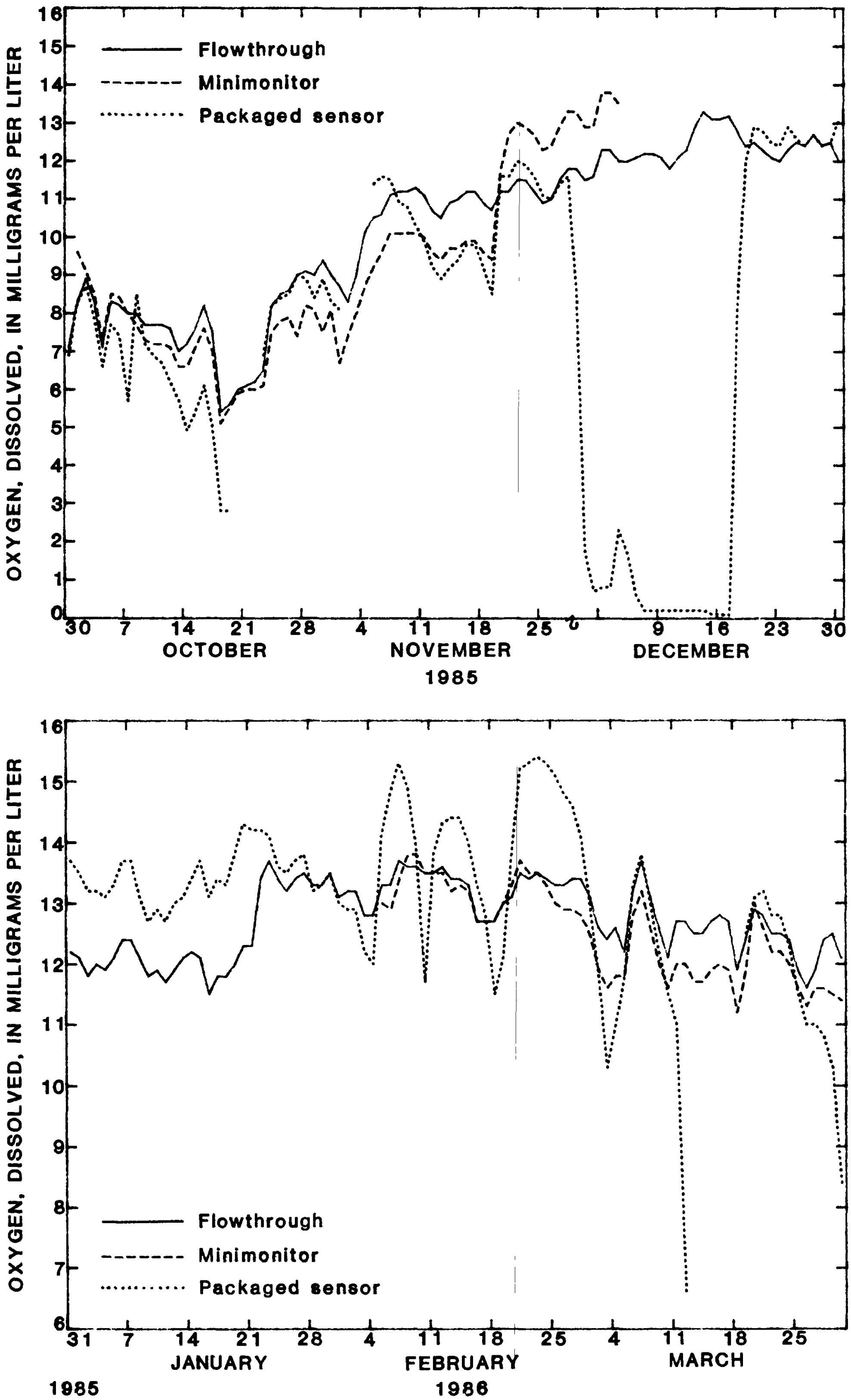


Figure 19.--Daily mean values for dissolved-oxygen data collected by flowthrough, minimonitor, and packaged-sensor systems, site 2.

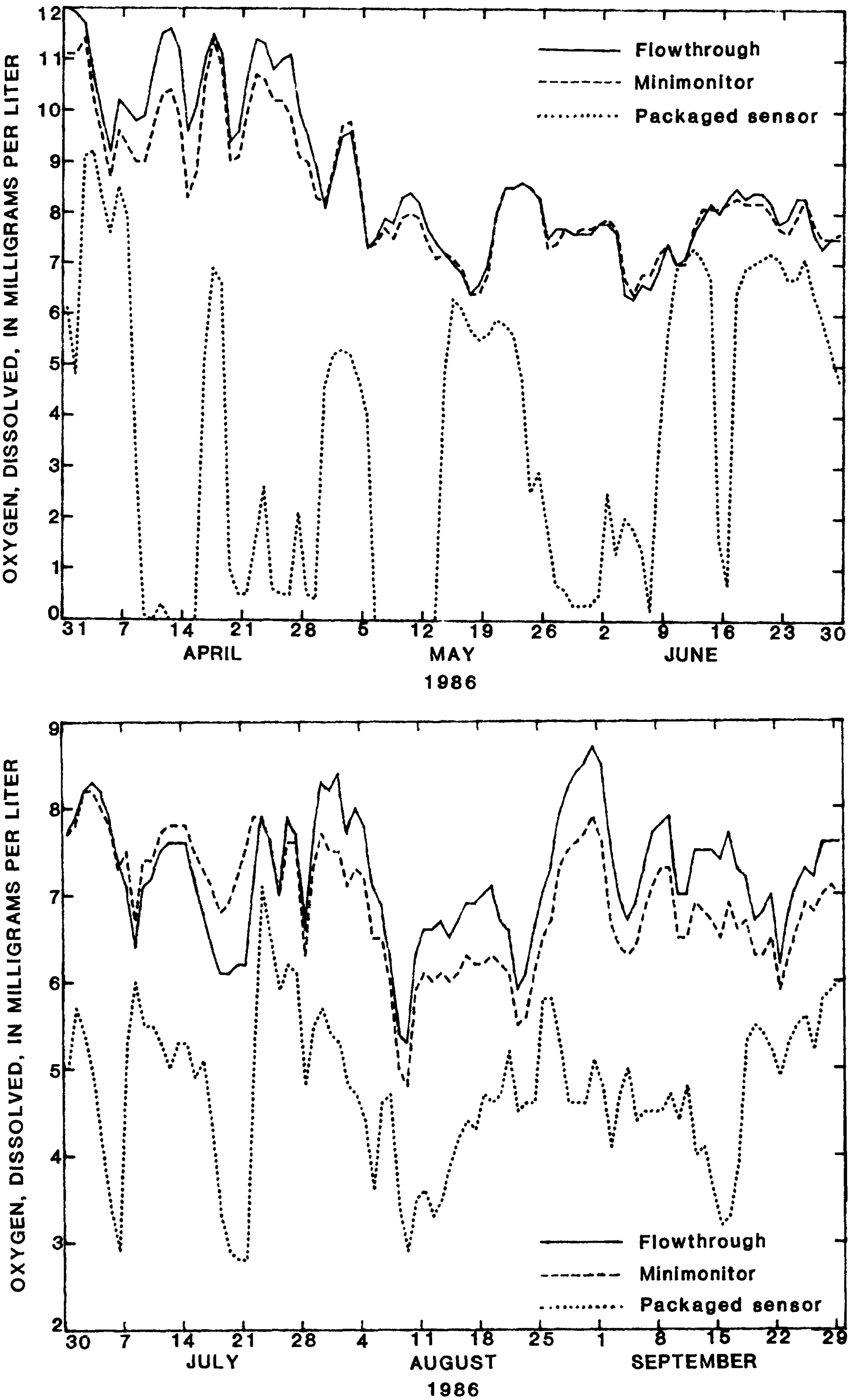


Figure 19.--Daily mean values for dissolved-oxygen data collected by flowthrough, minimonitor, and packaged-sensor systems, site 2--Continued.

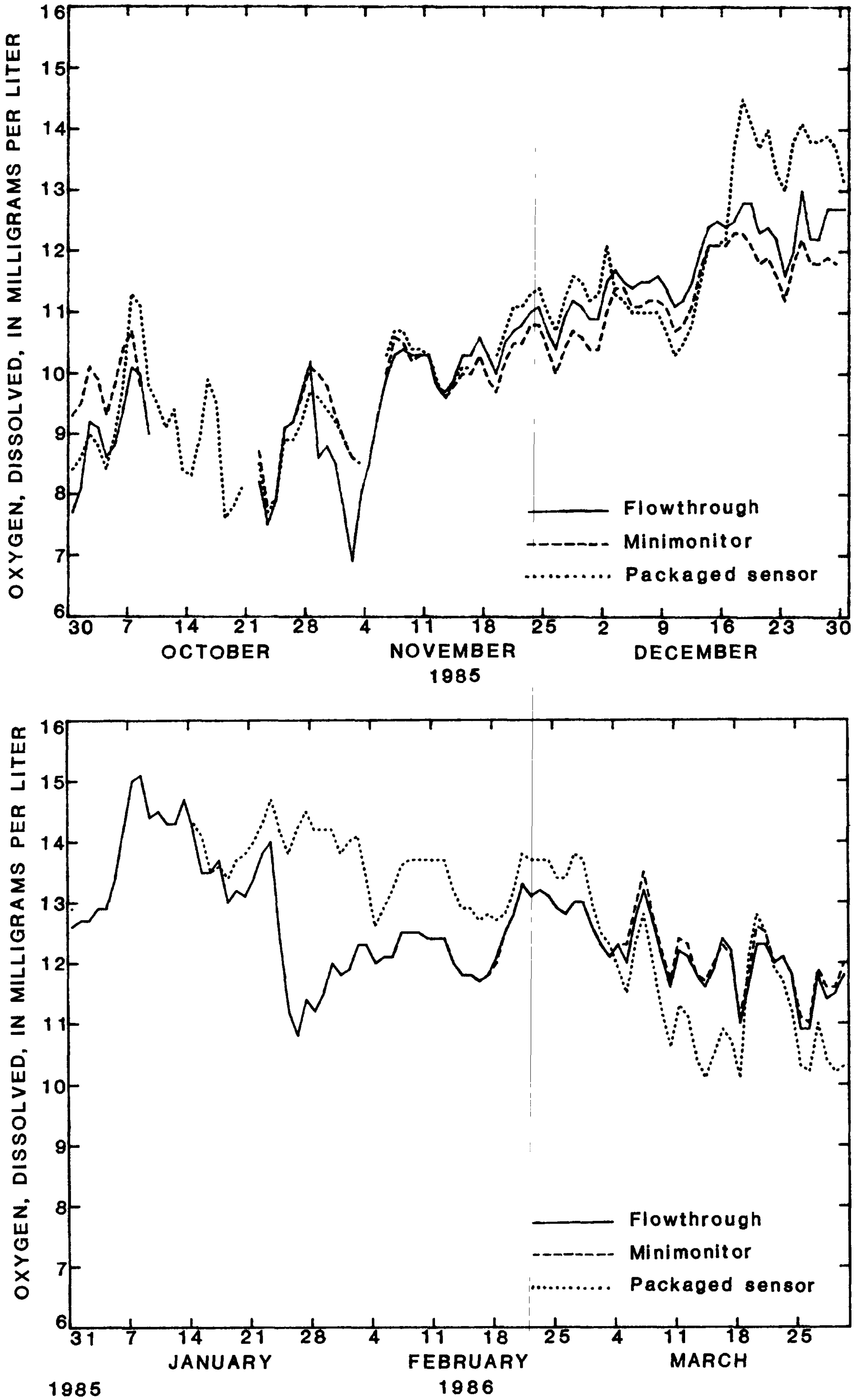


Figure 20.--Daily mean values for dissolved-oxygen data collected by flowthrough, minimonitor, and packaged-sensor systems, site 3.

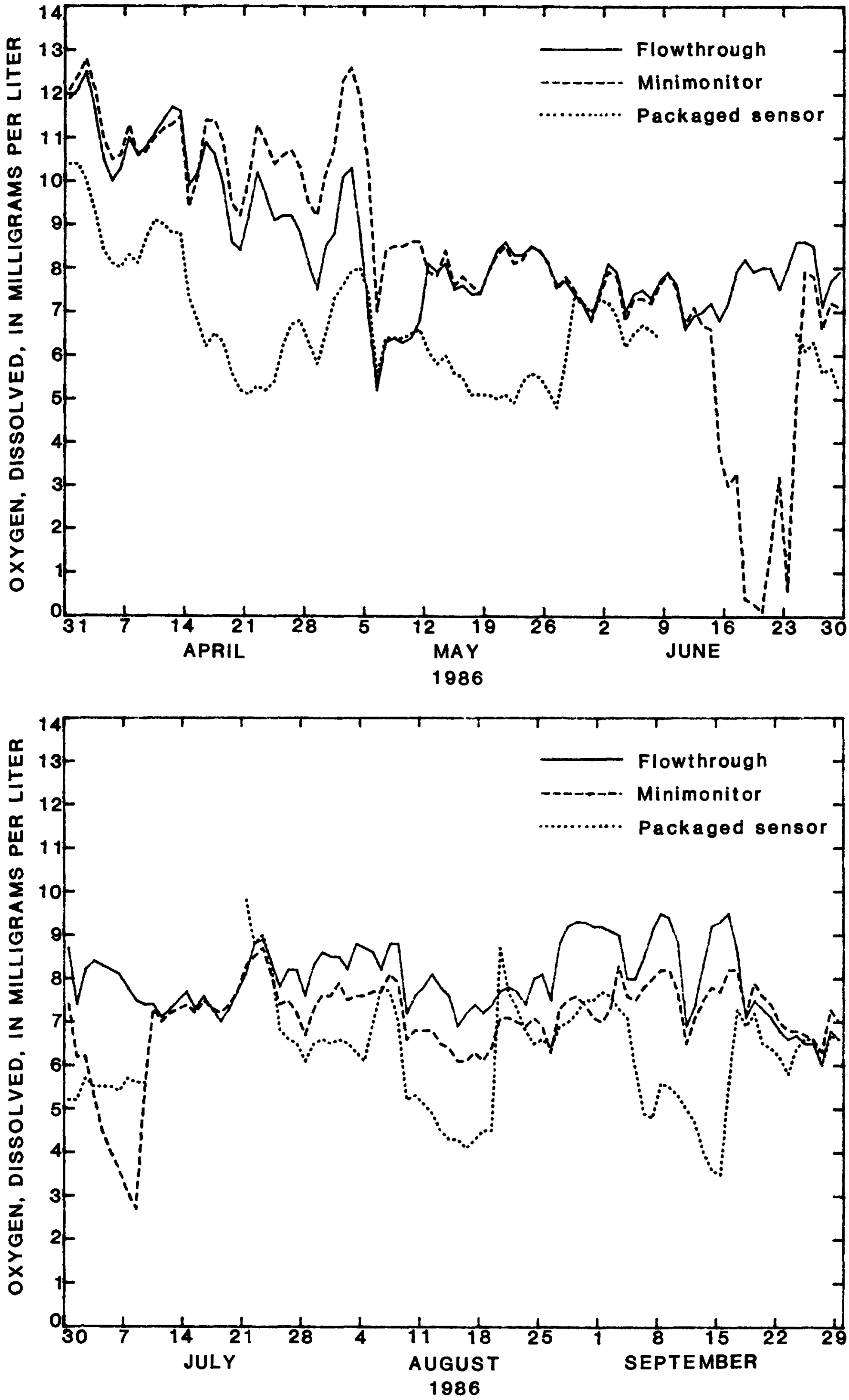


Figure 20.--Daily mean values for dissolved-oxygen data collected by flowthrough, minimonitor, and packaged-sensor systems, site 3--Continued.

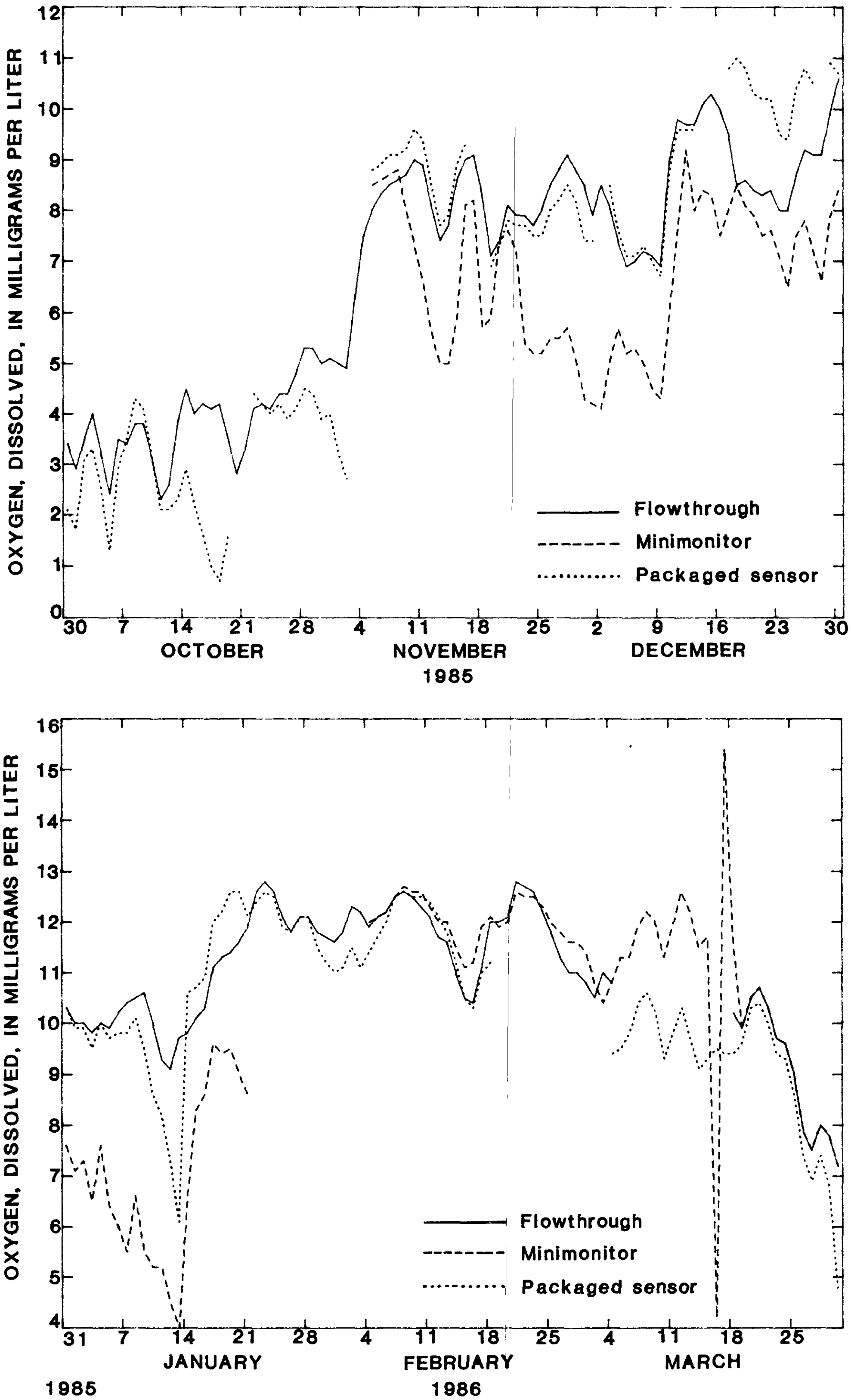


Figure 21.--Daily mean values for dissolved-oxygen data collected by flowthrough, minionitor, and packaged-sensor systems, site 4.

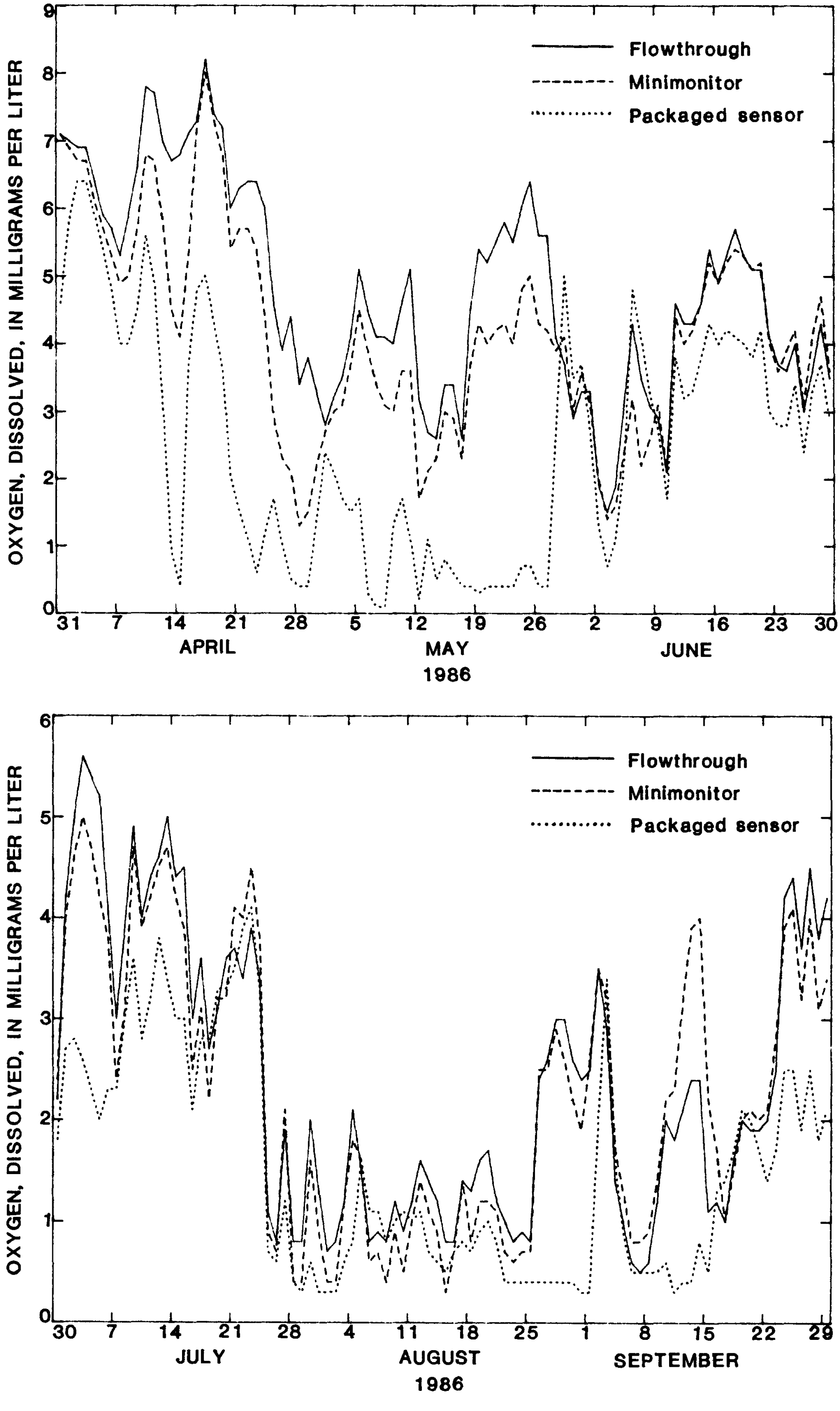


Figure 21.—Daily mean values for dissolved-oxygen data collected by flowthrough, minimonitor, and packaged-sensor systems, site 4—Continued.

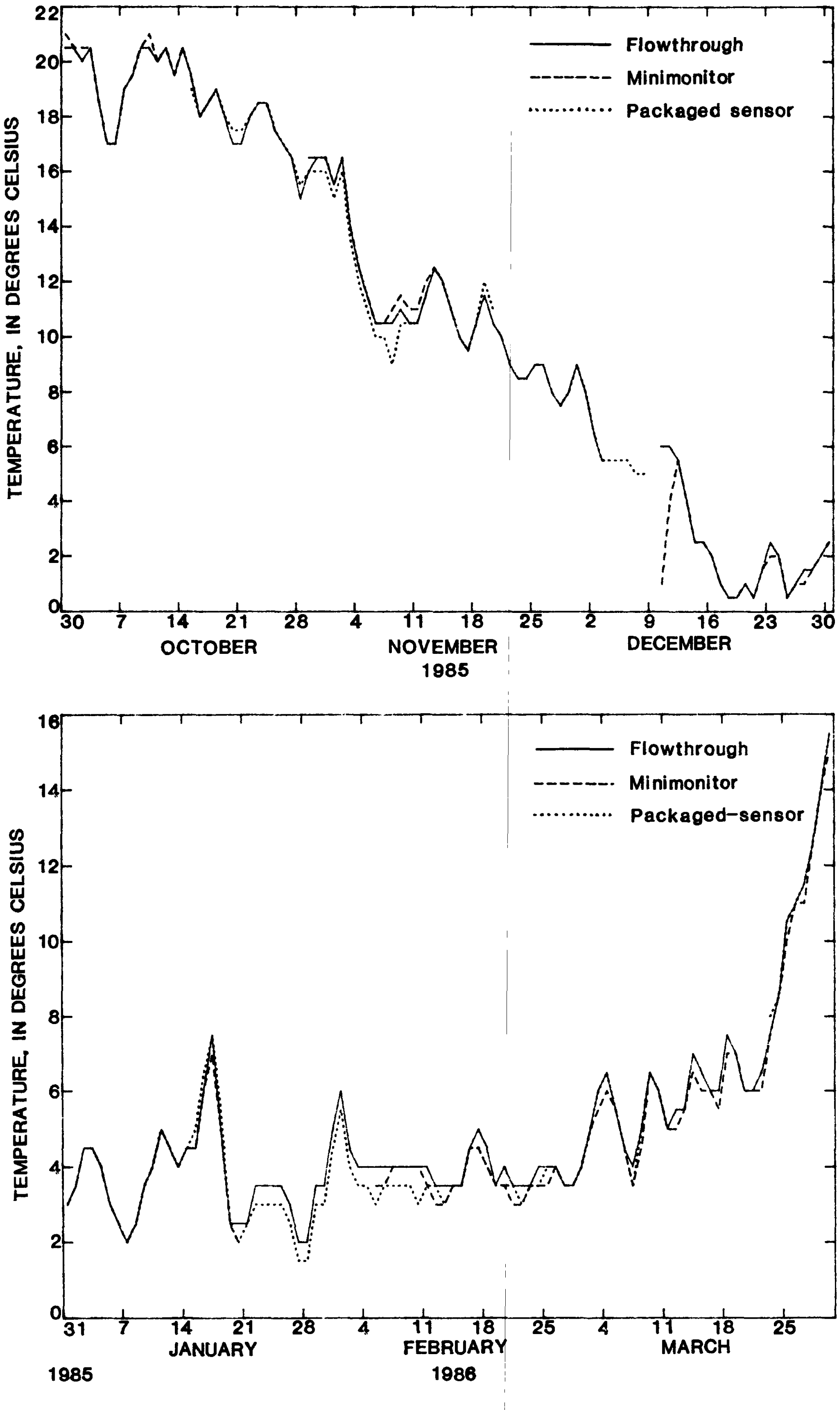
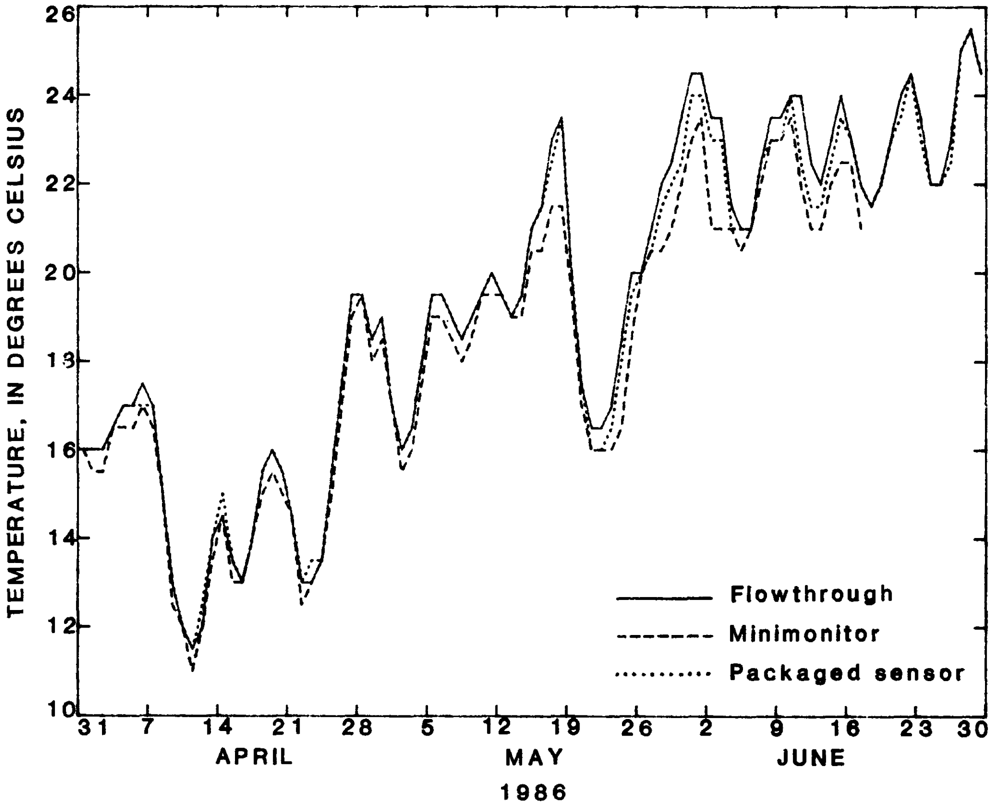


Figure 22.—Daily mean values for water-temperature data collected by flowthrough, minimonitor, and packaged-sensor systems, site 1.



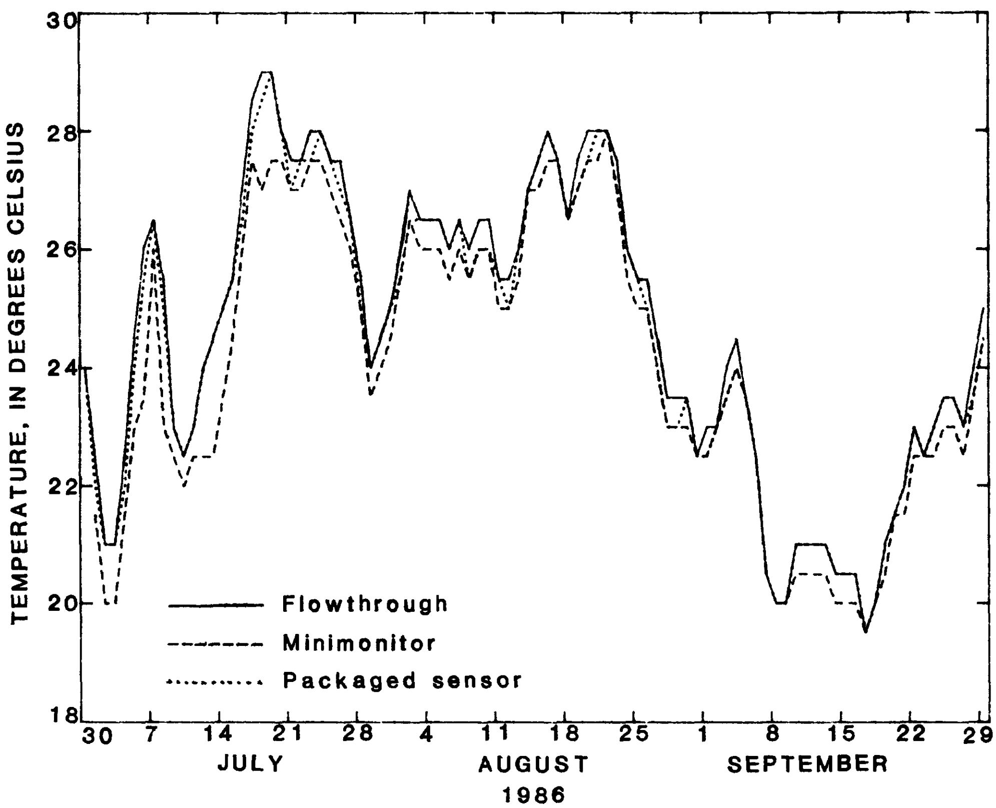


Figure 22.--Daily mean values for water-temperature data collected by flowthrough, minimonitor, and packaged-sensor systems, site 1--Continued.

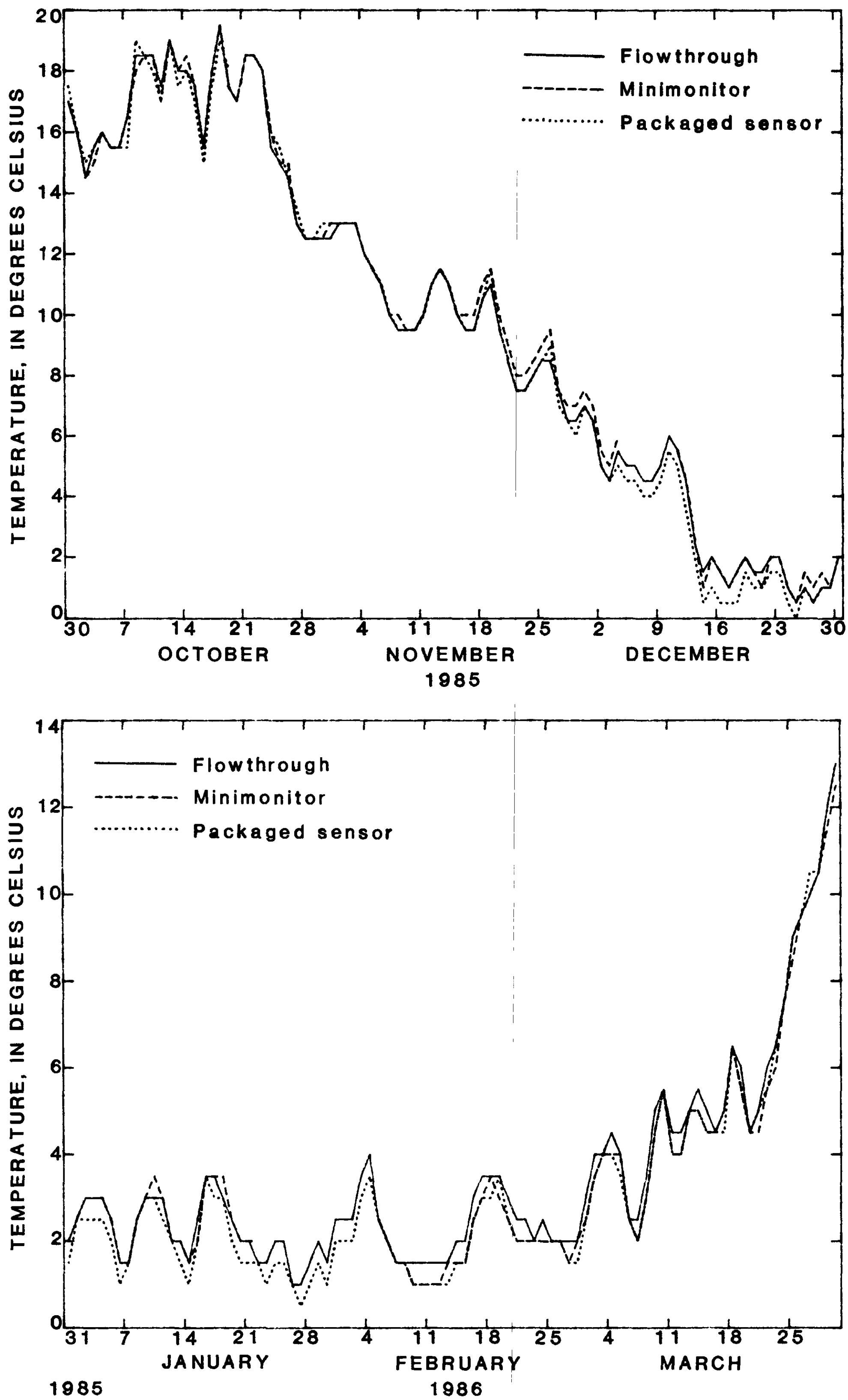
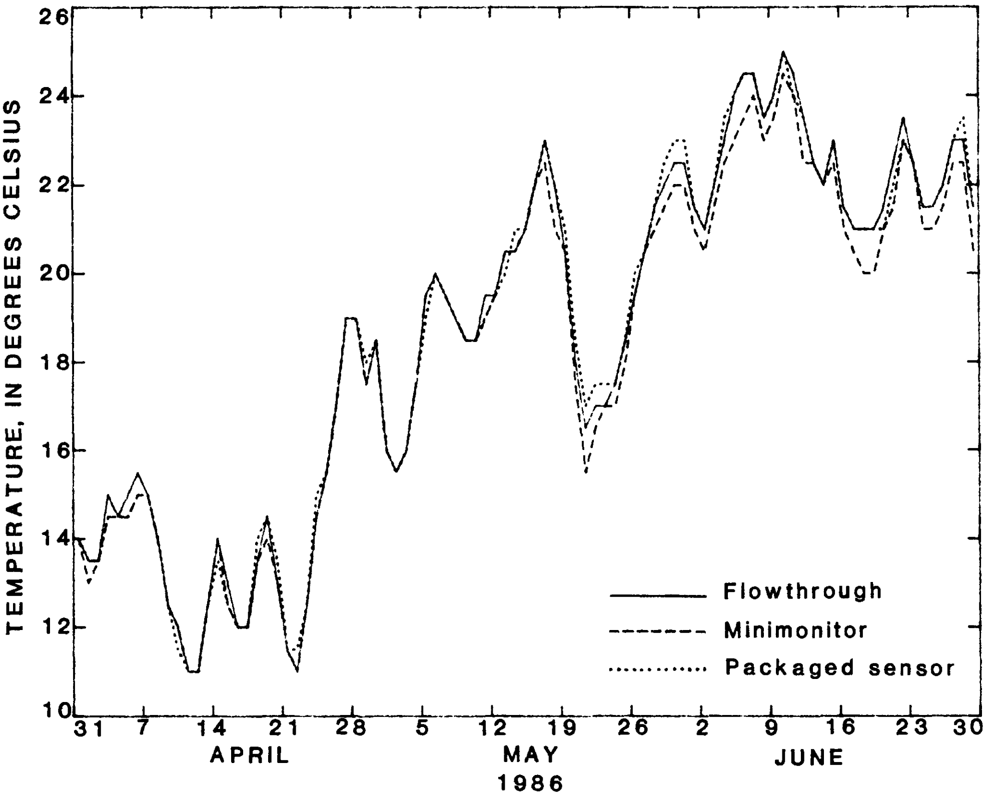


Figure 23.--Daily mean values for water-temperature data collected by flowthrough, minimonitor, and packaged-sensor systems, site 2.



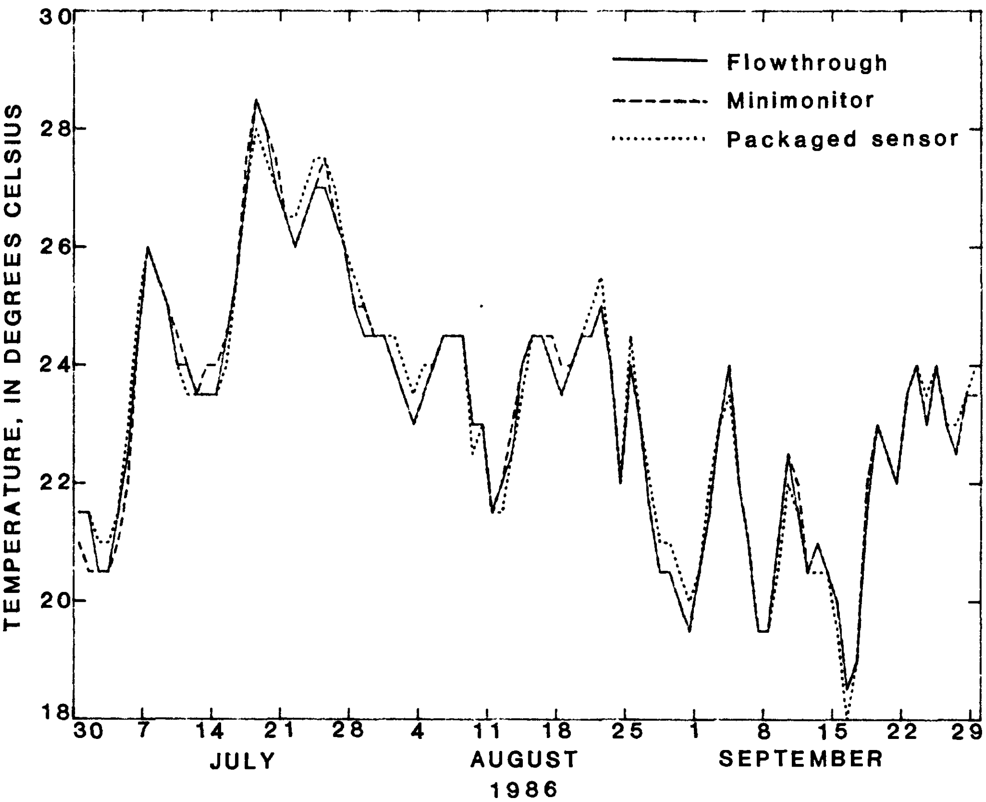


Figure 23.--Daily mean values for water-temperature data collected by flowthrough, minimonitor, and packaged-sensor systems, site 2--Continued.

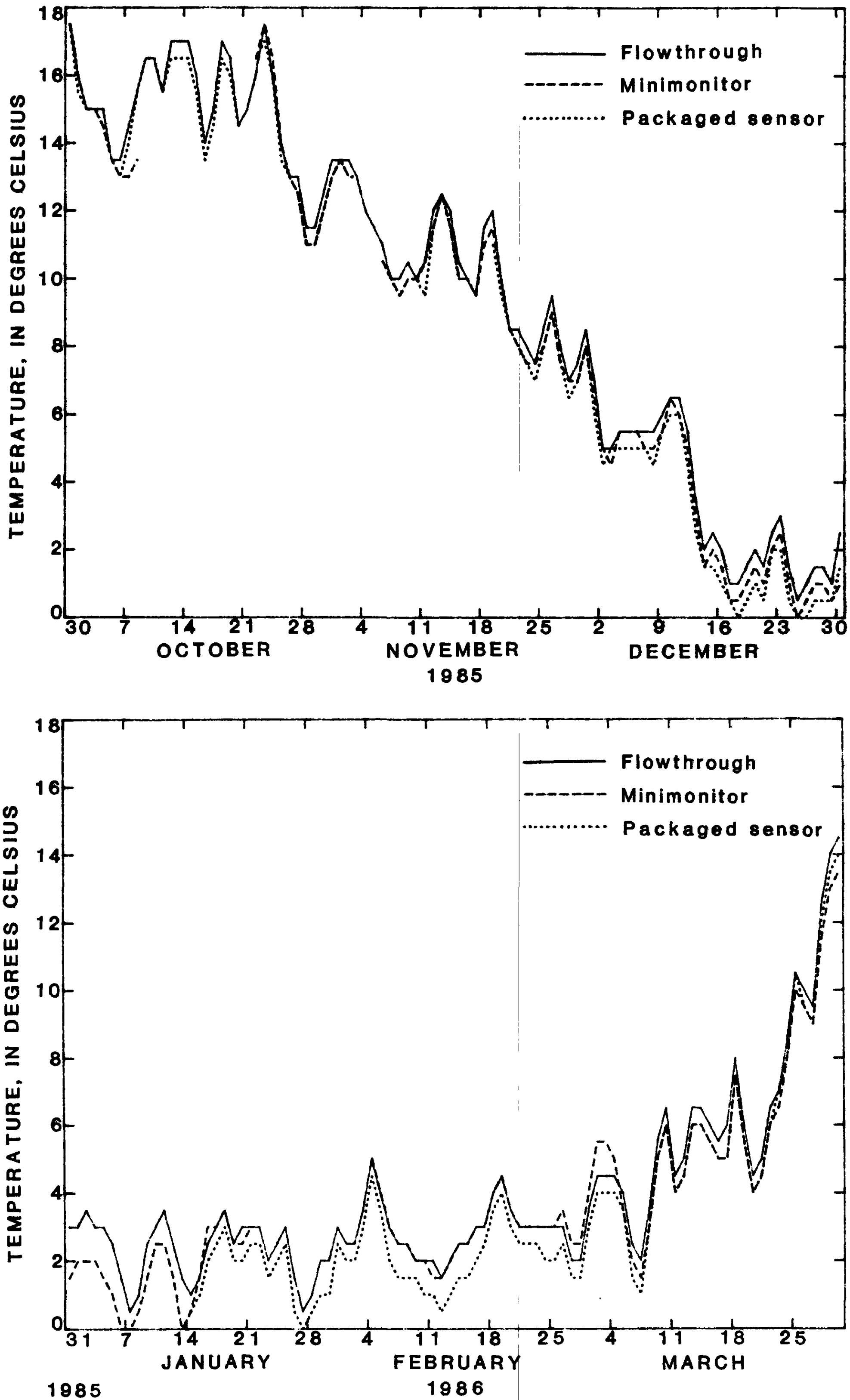


Figure 24.--Daily mean values for water-temperature data collected by flowthrough, minimonitor, and packaged-sensor systems, site 3.

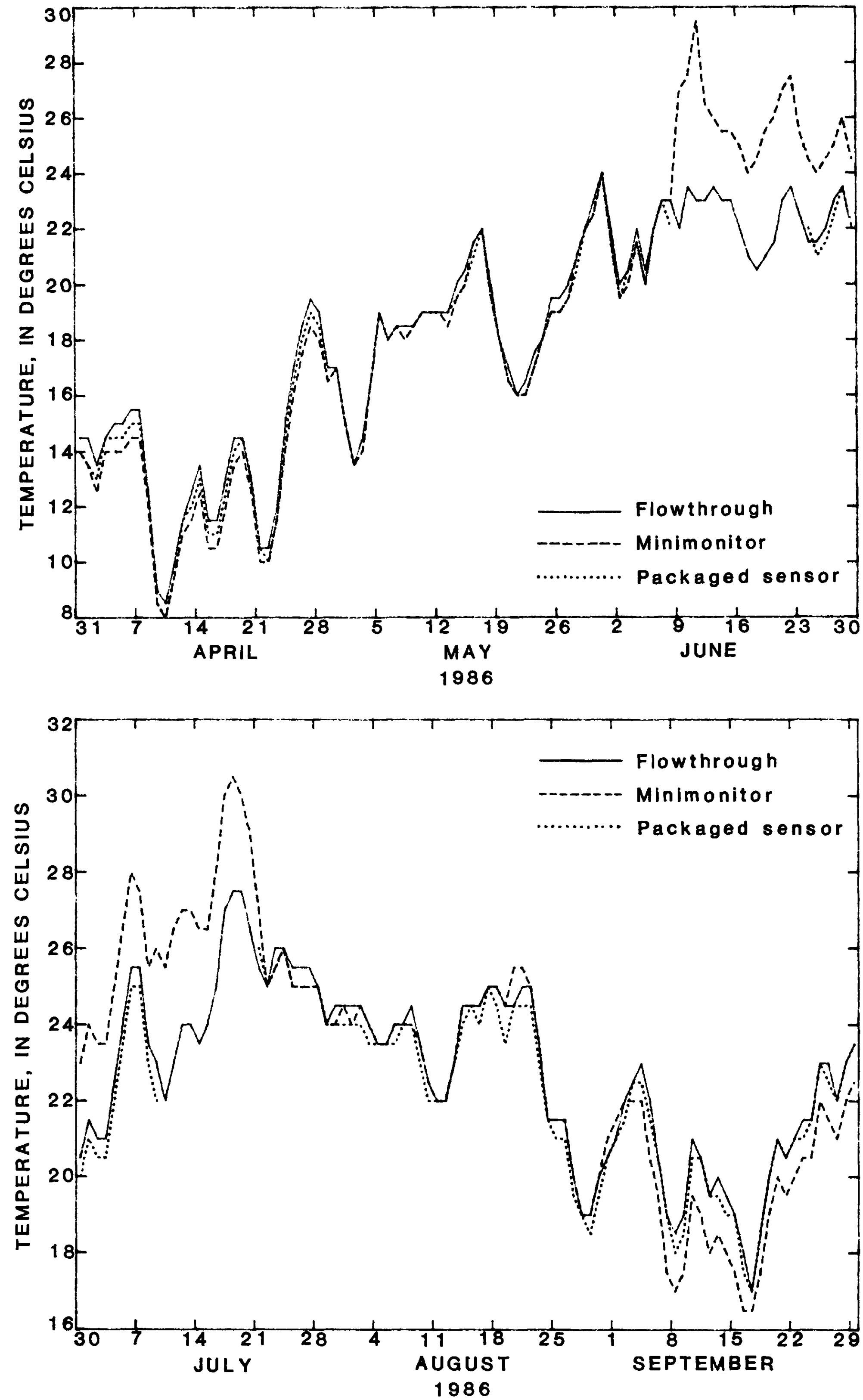


Figure 24.--Daily mean values for water-temperature data collected by flowthrough, minimonitor, and packaged-sensor systems, site 3--Continued.

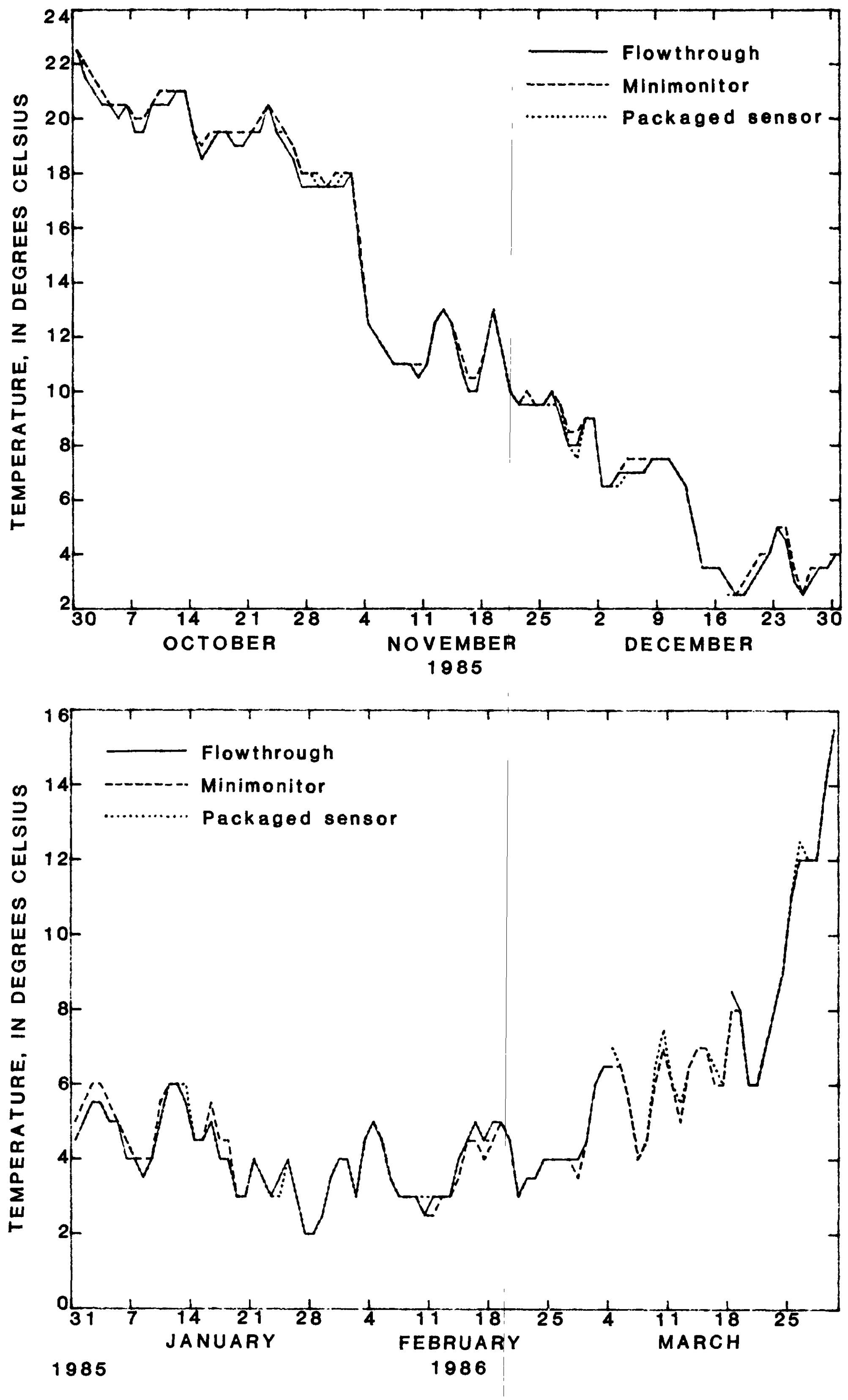


Figure 25.--Daily mean values for water-temperature data collected by flowthrough, minimonitor, and packaged-sensor systems, site 4.

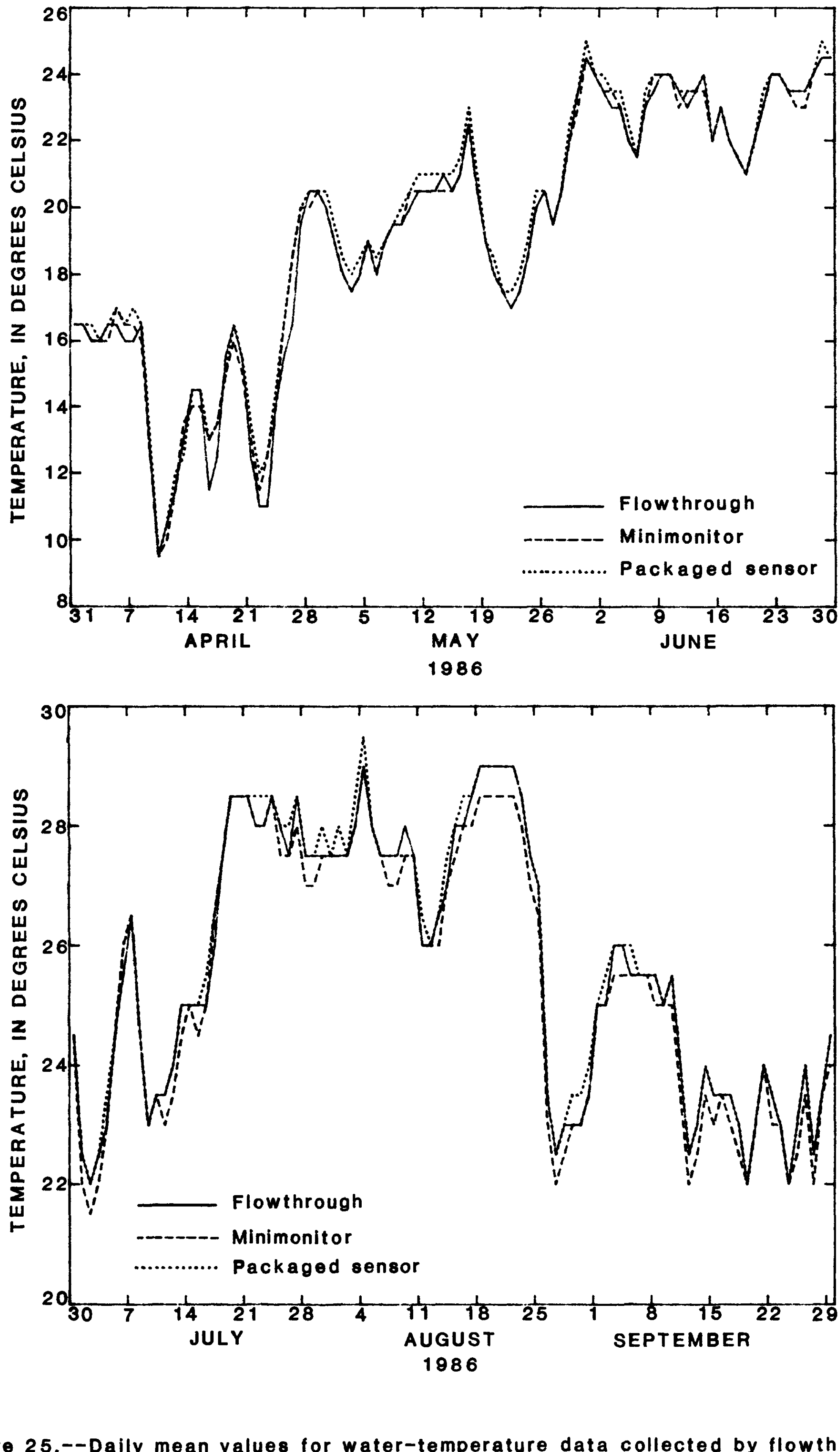


Figure 25.--Daily mean values for water-temperature data collected by flowthrough, minimonitor, and packaged-sensor systems, site 4--Continued.

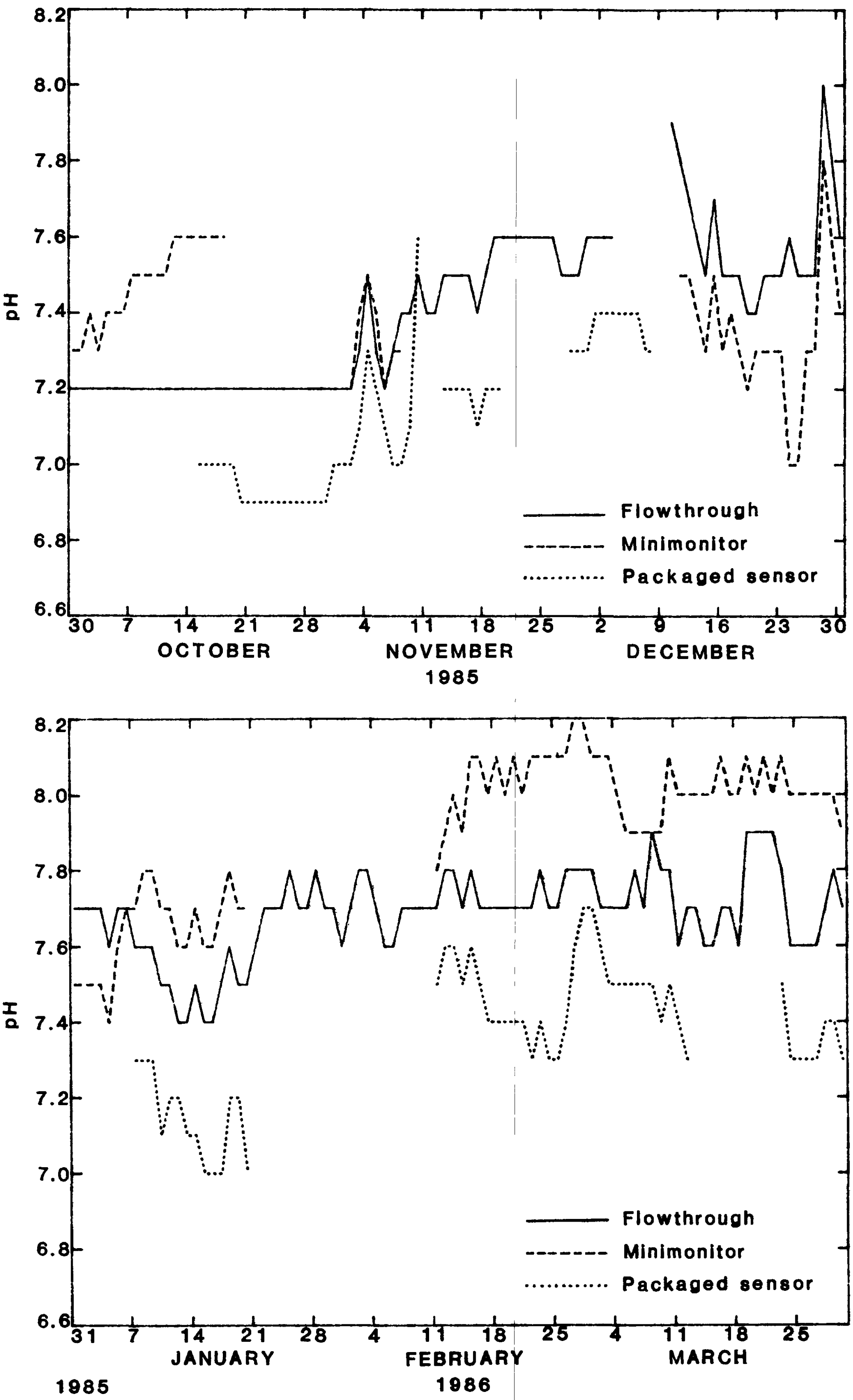
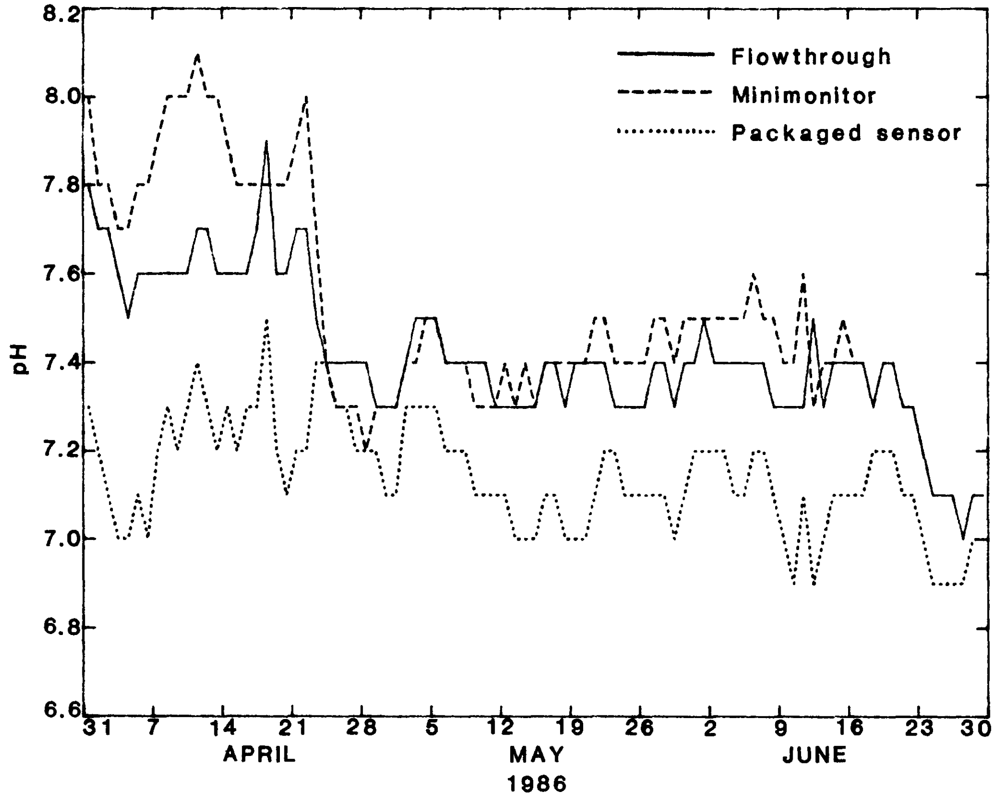


Figure 26.--Daily mean values for pH data collected by flowthrough, minimonitor, and packaged-sensor systems, site 1.



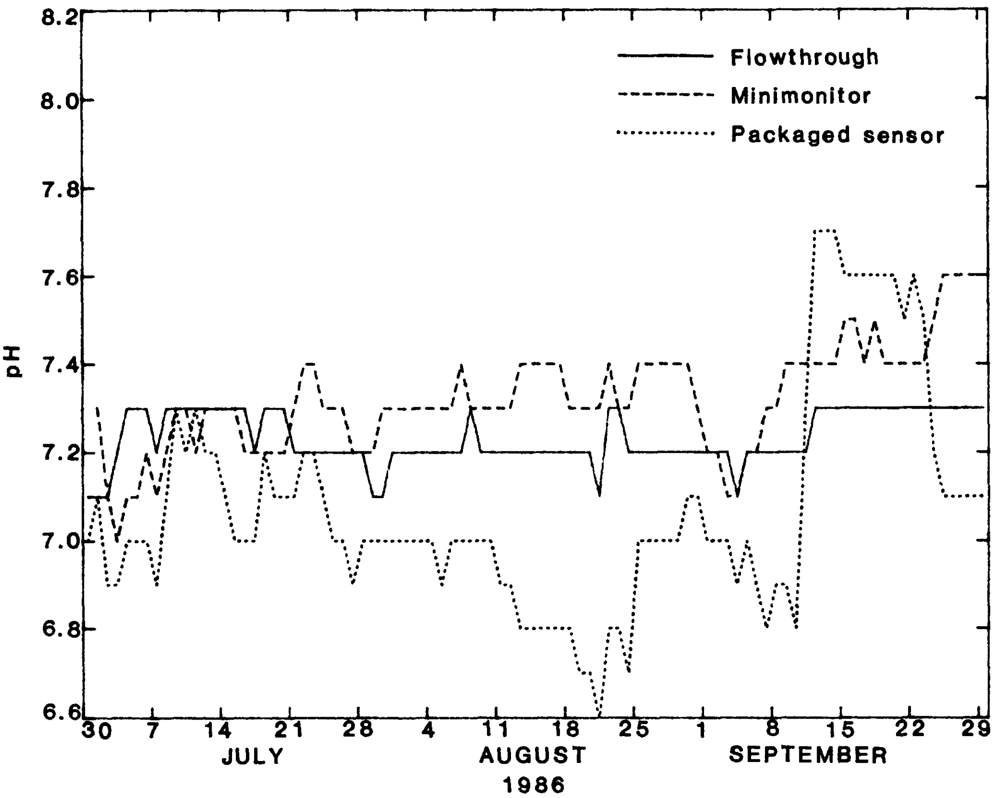


Figure 26.--Daily mean values for pH data collected by flowthrough, minimonitor, and packaged-sensor sytsems, site 1--Continued.

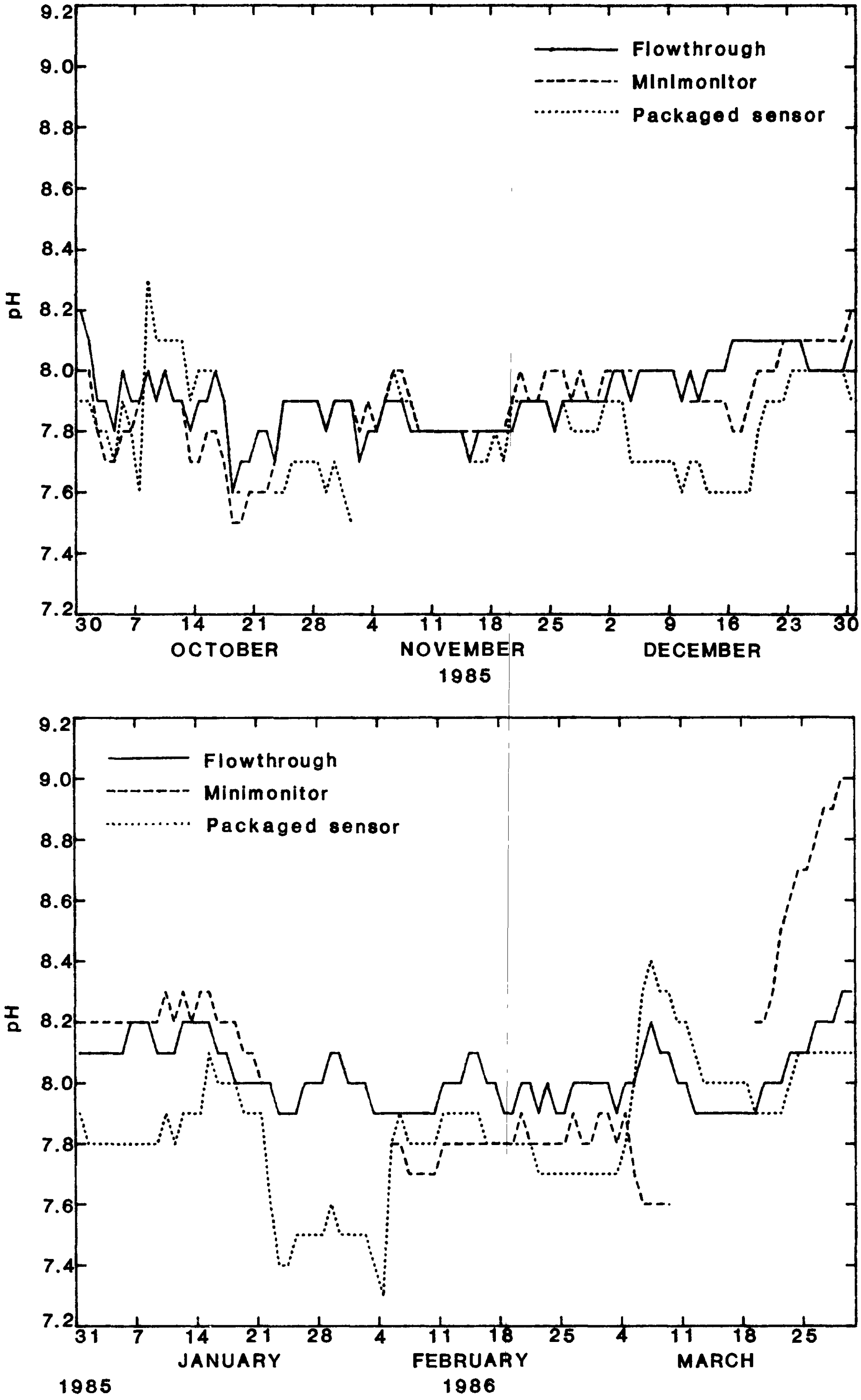
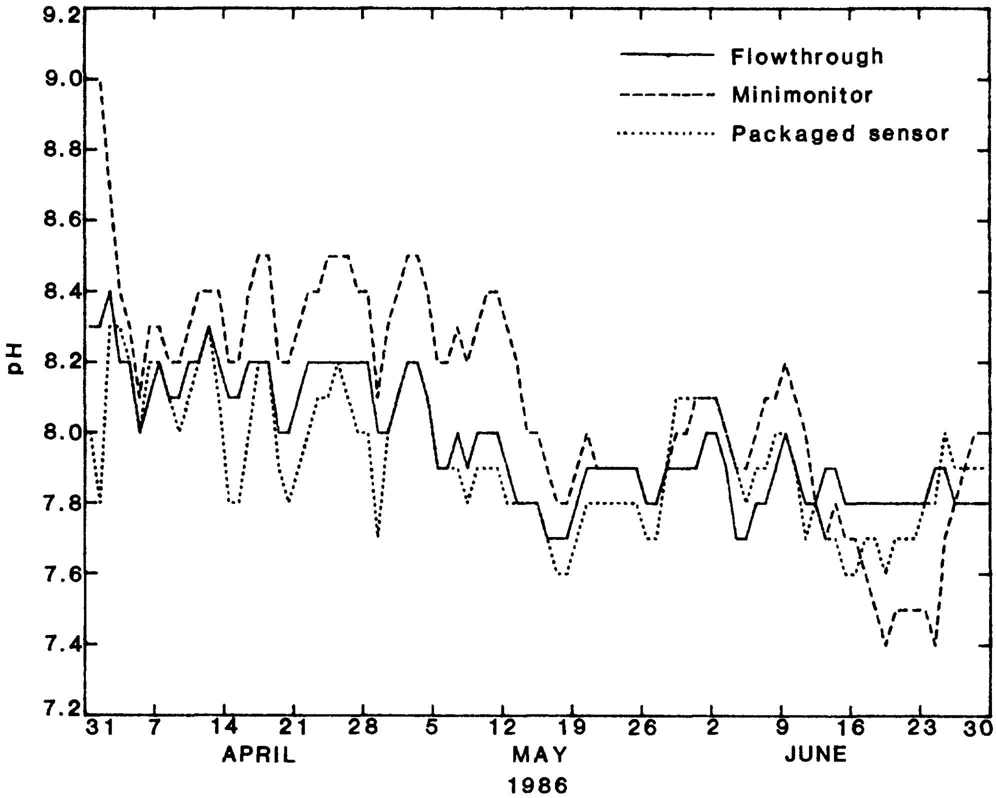


Figure 27.--Daily mean values for pH data collected by flowthrough, minimonitor, and packaged-sensor systems, site 2.



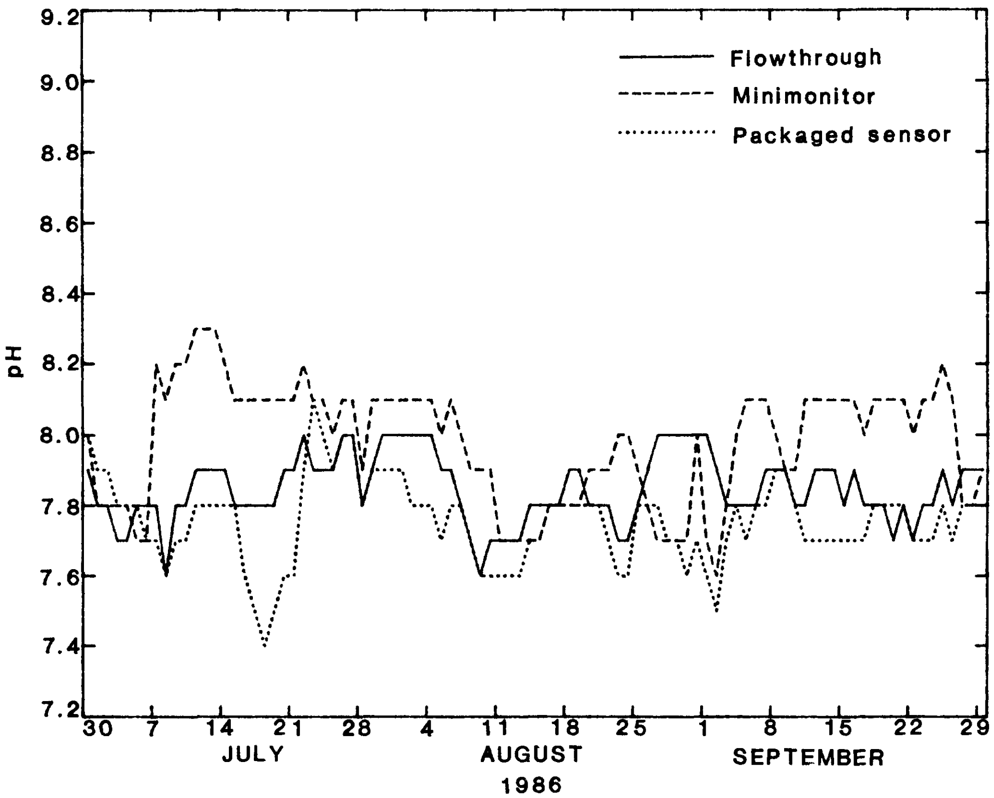


Figure 27.--Daily mean values for pH data collected by flowthrough, minimonitor, and packaged-sensor systems, site 2--Continued.

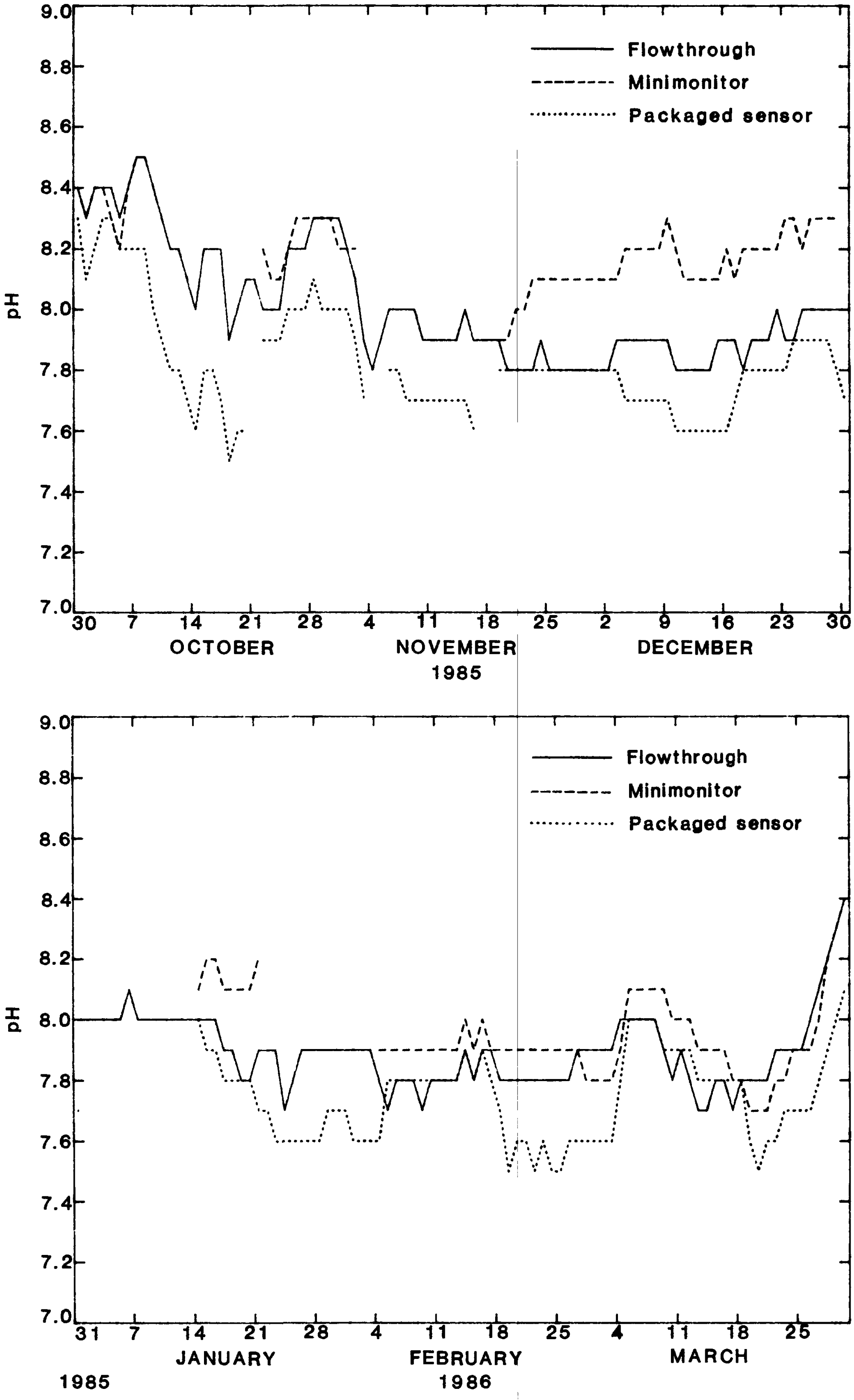
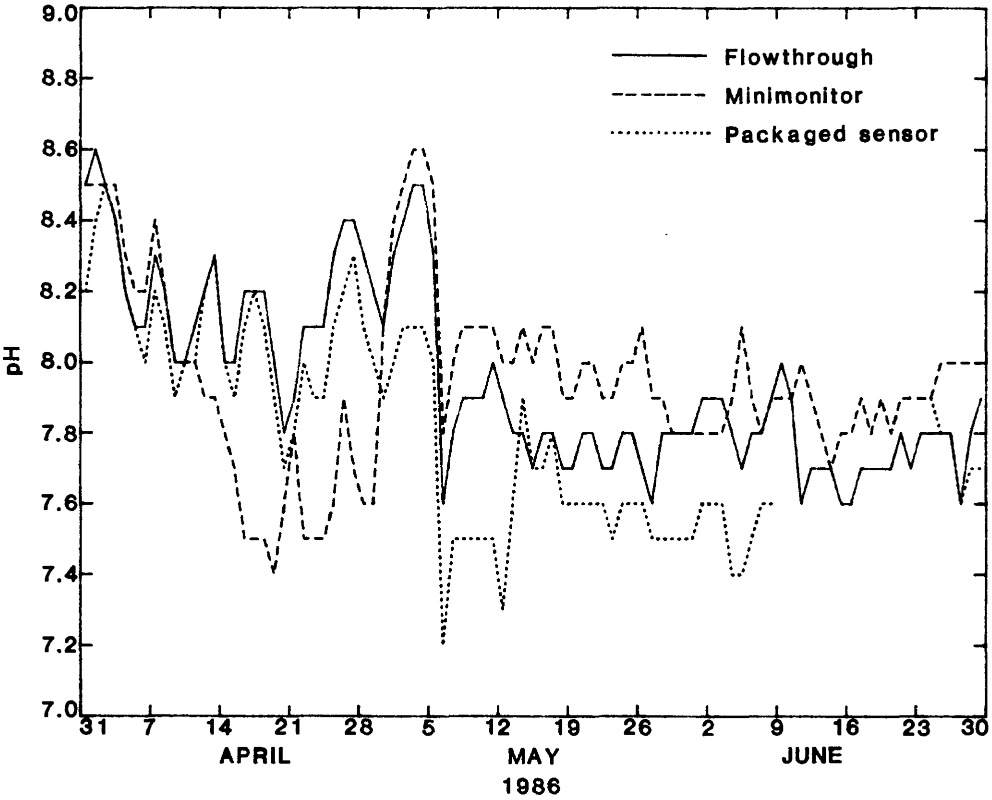


Figure 28.--Daily mean values for pH data collected by flowthrough, minimonitor, and packaged-sensor systems, site 3.



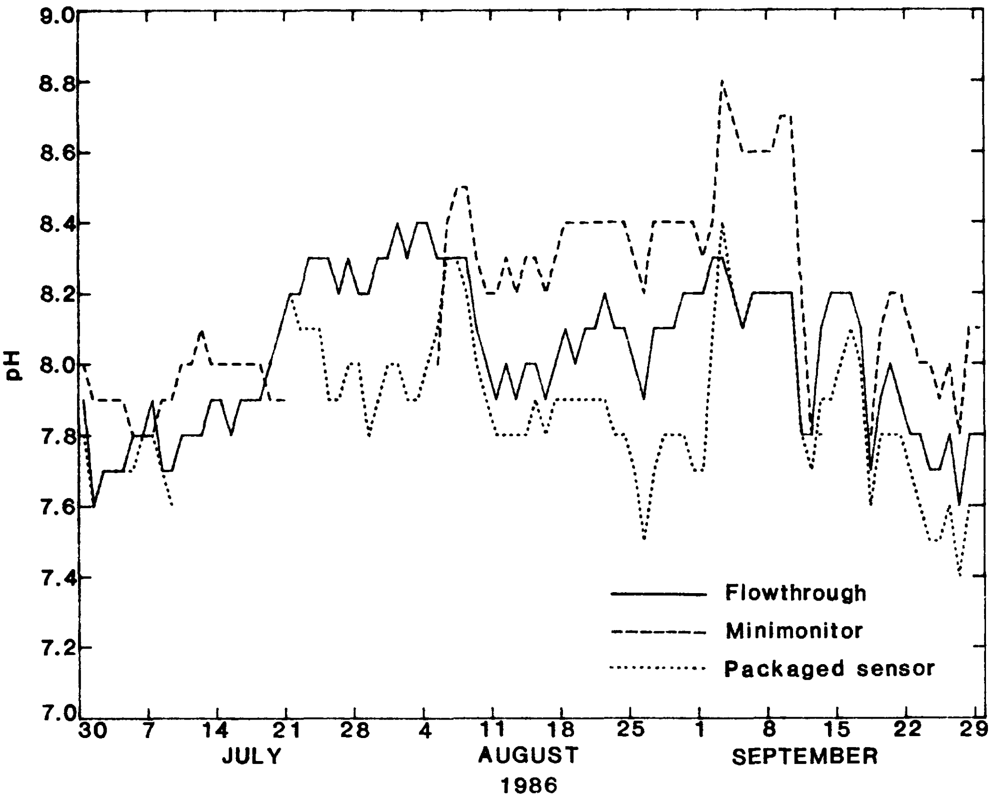


Figure 28.--Daily mean values for pH data collected by flowthrough, minimonitor, and packaged-sensor systems, site 3--Continued.

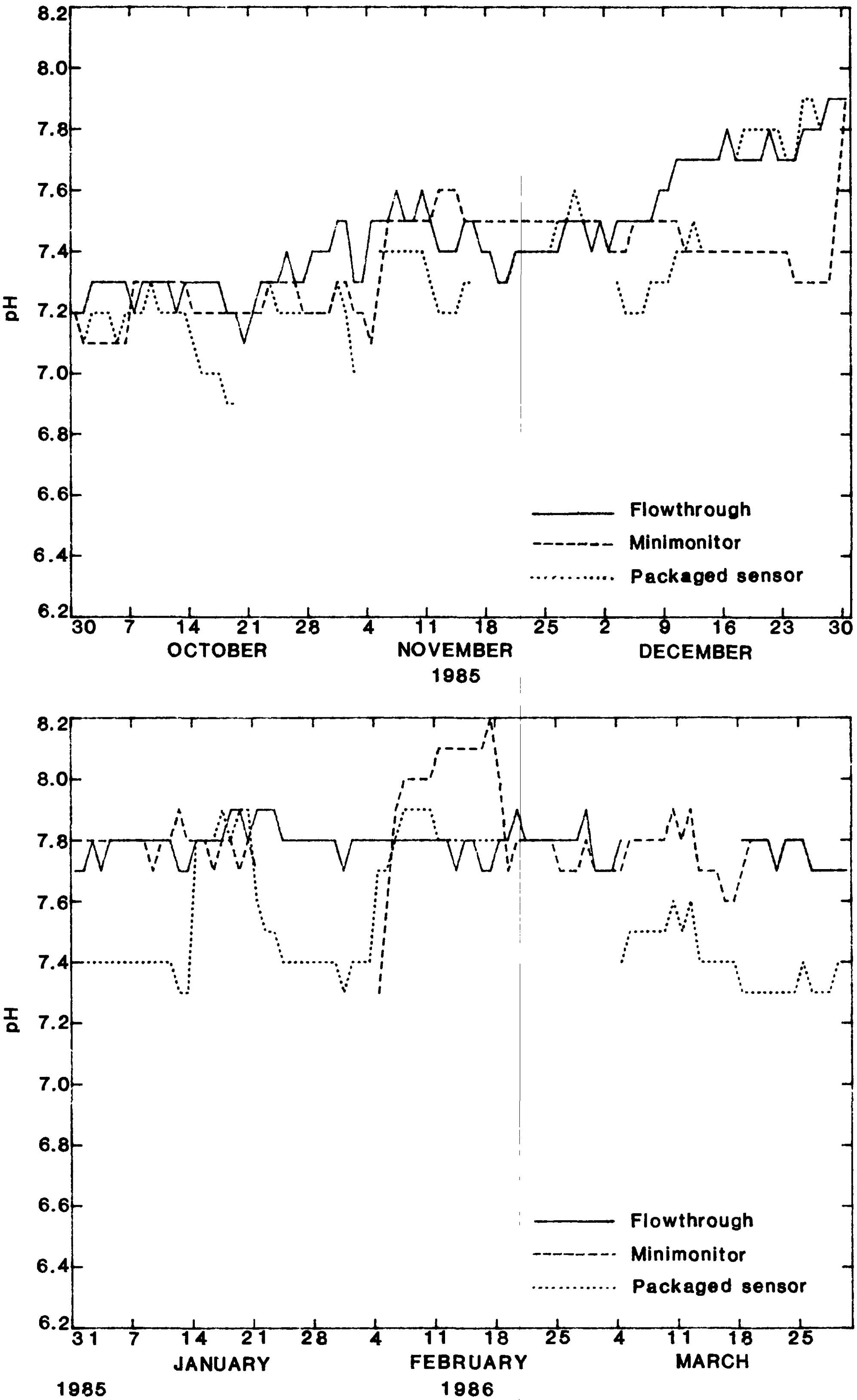


Figure 29.--Daily mean values for pH data collected by flowthrough, minimonitor, and packaged-sensor systems, site 4.

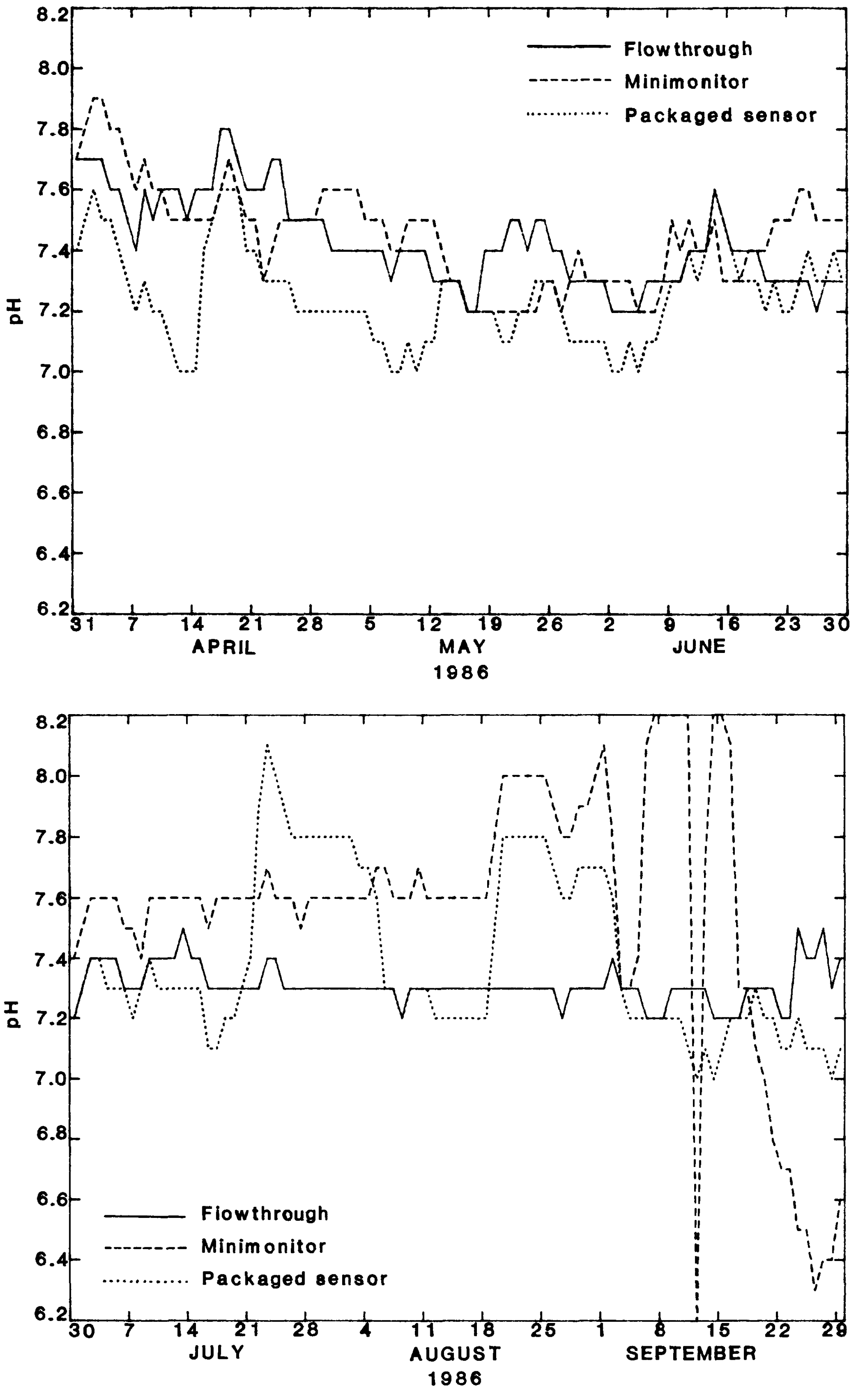


Figure 29.--Daily mean values for pH data collected by flowthrough, minimonitor, and packaged-sensor systems, site 4--Continued.

Table 4.--History of equipment problems, flowthrough systems

Site number and date	Figure showing data plot	Any data loss?	Measured characteristic affected: Specific conductance	Dissolved oxygen	Temperature	pH	Remarks
Site 1							
11/4	18	No		X			Replaced sensor.
12/3 to 12/11	a	Yes	X	X	X	X	Replaced pump.
12/23 to 1/6	26	No				X	Defective sensor (replaced glass electrode).
7/30	18	No		X			Replaced sensor.
9/11 to 9/25	18	No------	------	------	------	------	Chlorinator line broken.
Site 2							
10/1 to 9/30	b	No------	------	------	------	------	Normal routine maintenance.
Site 3							
10/11 to 10/22	20	Yes		X			Sensor failure.
12/8	20	No		X			Replaced sensor.
2/19	20	No		X			Replaced sensor.
5/1	20	No		X			Replaced sensor.
Site 4							
12/30	c	No------	------	------	------	------	Recorder dropping 0200 (replaced).
3/5	c	No------	------	------	------	------	Recorder replaced (punches slow).
3/15 to 3/19	c	Yes	X	X	X	X	Replaced recorder (wired wrong).
4/16 to 5/1	c	No------	------	------	------	------	Recorder dropping 0040 (replaced).
9/3	21	No		X			Replaced sensor.

[a]Figures 14, 18, 22, and 26.
[b]Figures 15, 19, 23, and 27.
[c]Figures 17, 21, 25, and 29.

Table 5.--History of equipment problems, minimonitor systems

Site number and date	Figure showing data plot	Any data loss?	Measured characteristic affected: Specific conductance	Dissolved oxygen	Temperature	pH	Remarks
Site 1							
10/20 to 10/29	a	Yes	X	X	X	X	Tape stuck in punch block (recorder replaced).
11/10 to 12/11	a	Yes	X	X	X	X	High water removed sensor-protector pipes, damaged sensors and mux board.
11/29	a	No					Replaced recorder.
12/11 to 1/6	a	No					Recorder dropping 0100 (replaced).
1/6	18	No		X			Replaced sensor.
1/22 to 2/6	a	Yes	X	X	X	X	Removed minimonitor for modification by HIF.
2/6	18	No		X			Replaced sensor.
2/6 to 2/12	26	Yes				X	Defective sensor; no spare.
4/24	18	No		X			Replaced sensor.
5/22 to 6/5	a	No					Recorder dropping 0400 (replaced).
6/5 to 7/22	a	No					Recorder dropping 0010 (replaced).
6/18 to 7/2	a	Yes	X	X	X	X	Removed monitor; power fuse kept blowing (defective capacitor on pH board).
9/11	18	No		X			Replaced membrane and solution.
Site 2							
10/1 to 10/3	b	Yes	X	X	X	X	Tape would not advance (recorder replaced).
10/8 to 12/5	19	No		X			Replaced sensor.
12/6 to 12/11	b	Yes	X	X	X	X	Tape put on wrong (field-person error).
12/13 to 1/23	19	Yes		X			Defective card; no spare (replaced stirrer assembly and probe).
1/24 to 2/6	b	Yes	X	X	X	X	Removed monitor for modification by HIF.
3/10 to 3/20	27	Yes				X	Defective pH sensor (replaced).
4/17	19	No		X			Replaced sensor.
6/26 to 7/8	b	No					Recorder dropping 0020 (replaced).
6/29 to 7/8	15	Yes	X				Defective conductance sensor (replaced).

Table 5.--History of equipment problems, minimonitor systems--Continued

Site number and date	Figure showing data plot	Any data loss?	Measured characteristic affected: Specific conductance	Dissolved oxygen	Temperature	pH	Remarks
Site 3							
10/10 to 10/22--	c	Yes	X	X	X	X	Switch on "hold".
11/4 to 11/7----	c	Yes	X	X	X	X	Tape stuck in punch block (recorder replaced).
11/7 to 11/20---	28	Yes				X	Sensor did not work after being cleaned and put back in water (had water inside); no spare on 11/7.
11/20-----------	28	Yes				X	Replaced pH probe.
11/7 to 11/25---	c	No------------------------------------					Recorder dropping punches (replaced).
12/30 to 1/15---	20	Yes				X	Defective pH sensor (replaced).
12/30 to 1/22---	20	Yes		X			Defective dissolved-oxygen stirrer assembly and sensor.
1/22 to 2/5-----	c	Yes	X	X	X	X	Removed monitor for modification by HIF.
2/5-------------	20			X			Replaced stirrer assembly and sensor.
3/5-------------	24	No			X		Defective temperature sensor (replaced).
7/10------------	20	No		X			Replaced sensor.
7/22 to 8/6-----	28	Yes				X	Defective sensor; spare also defective.
7/22------------	24	No			X		Replaced sensor.
8/20------------	16	No	X				Replaced defective sensor after cleaning.
9/14 to 9/17----	28	Yes				X	Defective sensor (no spare).
9/17------------	20	No		X			Replaced sensor.
9/19------------	28	Yes				X	Replaced sensor.

Table 5.--History of equipment problems, minimonitor systems--Continued

Site number and date	Figure showing data plot	Any data loss?	Measured characteristic affected: Specific conductance	Dissolved oxygen	Temperature	pH	Remarks
Site 4							
10/1 to 10/23---	21	Yes		X			Defective sensor and stirrer assembly; no spare.
11/16-----------		Yes					Replaced sensor and stirrer assembly.
12/4 to 12/12---	21	No		X			Stirrer not working (defective card); replaced.
12/18 to 12/30--	21	No		X			Stirrer not working (defective card); replaced.
1/15------------	21	No		X			Stirrer not working (defective card); replaced.
1/22------------	21	No		X			Stirrer very slow; defective motor. May have caused all card failures.
1/22 to 2/5-----	d	Yes	X	X	X	X	Removed for modification by HIF.
2/5-------------	21	No		X			Replaced sensor and stirrer assembly.
2/5-------------	29	No				X	Defective sensor (replaced).
3/19------------	21	No		X			Dissolved-oxygen sensor had water inside (sent with wrong O-ring; replaced).
9/3-------------	21	No		X			Replaced sensor.
9/3-------------	29	No				X	Defective sensor (replaced).

[a] Figures 4, 8, 22, and 26.
[b] Figures 15, 19, 23, and 27.
[c] Figures 16, 20, 24, and 28.
[d] Figures 17, 21, 25, and 29.

Table 6.--History of equipment problems, packaged-sensor systems

Site number and date	Figure showing data plot	Any data loss?	Measured characteristic affected: Specific conductance	Dissolved oxygen	Temperature	pH	Remarks
Site 1							
10/2 to 10/15--	b	Yes	X	X	X	X	No data stored (instrument failure).
10/6 to 10/29--	22	Yes		X			No data stored (sensor failure).
11/12-13, 22-28	b	Yes	X	X	X	X	Batteries had run down.
12/10 to 12/12-	b	Yes	X	X	X	X	Batteries had run down.
12/12 to 1/7---	b	Yes	X	X	X	X	High water took out pipe.
1/22 to 2/11--	14,18,26	Yes	X	X		X	Only temperature was programmed in.
3/14 to 3/23---	b	Yes	X	X	X	X	No data stored (instrument failure).
4/24 to 9/30---	b	No	X	X	X	X	Modified instruments, removed silicone membrane (4/24 to 9/30), water-bath calibration[a] (5/22 to 9/30).
Site 2							
10/21 to 10/23-	c	Yes	X	X	X	X	Batteries had run down.
11/3 to 11/5---	c	Yes	X	X	X	X	Batteries had run down.
3/14 to 3/19---	19	Yes		X			Sensor failure.
2/20 to 9/30---	c	No	X	X	X	X	Modified instruments, removed silicone membrane (3/18 to 9/30), water-bath calibration[a] (5/15 to 9/30).
Site 3							
10/22----------	d	Yes	X	X	X	X	Batteries had run down.
11/5-6, 18-19--	d	Yes	X	X	X	X	Batteries had run down.
1/2 to 1/14----	d	Yes	X	X	X	X	Instrument failed (sent in for repair).
6/9 to 6/24----	d	Yes	X	X	X	X	No data stored; instrument failed.
7/11 to 7/21---	d	Yes	X	X	X	X	No data stored; instrument failed.
4/16 to 9/30---	d	No	X	X	X	X	Modified instruments[a], removed silicone membrane (4/15 to 9/30), water-bath calibration[a] (5/14 to 9/30).

Table 6.--History of equipment problems, packaged-sensor systems--Continued

Site number and date	Figure showing data plot	Any data loss?	Measured characteristic affected: Specific conductance	Dissolved oxygen	Temperature	pH	Remarks
Site 4							
10/21 to 10/22-	e	Yes	X	X	X	X	Batteries had run down.
11/4-5, 18-19--	e	Yes	X	X	X	X	Batteries had run down.
11/18 to 12/2--	21,25	Yes	X			X	Did not program in (field-person error).
12/3, 15-17, 29	e	Yes	X	X	X	X	Batteries had run down.
2/20 to 3/4----	e	Yes	X	X	X	X	No data stored.
4/16 to 9/30---	e	No	X	X	X	X	Modified instruments, removed silicone membrane (4/16 to 9/30), water-bath calibration[a] (5/14 to 9/39).

[a] When packaged-sensor units were first installed, battery life was insufficient for 2-hour data storage for the required 2-week period between site visits. After modifications by the manufacturer, data could be stored at 1-hour intervals for the required 2 weeks. Dissolved-oxygen sensors for the packaged-sensor units initially came with silicone-rubber membrane on top of standard 1-mil Teflon membranes. After the modifications mentioned above, use of only the standard membranes was recommended by the manufacturer. The dissolved-oxygen sensor was first calibrated in air; however, calibration using a circulating water bath was substituted later in the test period.

[b] Figures 14, 18, 22, and 26.

[c] Figures 15, 19, 23, and 27.

[d] Figures 16, 20, 24, and 28.

[e] Figures 17, 21, 25, and 29.