SPECIAL REPORT 96-6

CRREL

Ice Force and Scour Instrumentation for the White River, Vermont

Leonard J. Zabilansky

April 1996

Abstract

In January 1990 a bridge over the White River in White River Junction, Vermont, collapsed during a period of ice breakup. Based on the historic weather and stage data, the bridge had survived more dramatic breakups in previous winters. The ultimate failure was attributed to the progressive deterioration of the foundation due to scour. Twenty years of weather and stage data at the site are presented along with a failure scenario. Instrumentation to measure the ice forces on a bridge pier was incorporated into the design of the replacement bridge. Recognizing scour as the primary cause of failure, the new bridge piers have extensive scour protection. A pier for a bridge 2000 feet upstream of the new bridge was instrumented for scour. The objective was to develop real-time scour monitors that would survive ice and debris and allow correlation between the hydrograph and scour activity. Instrumentation and data acquisition packages for both instrumented bridge piers are presented. The results of the first two years of measurements are presented. Both winters were relatively mild, consequently the breakup loads were low. The maximum dynamic load was 26 kips, which, with a 4-foot-wide panel and 12 inches of ice translates to an ice pressure of 45 psi. The scour measurements were of extreme interest. The bulk of the scour occurred in the initial stages of breakup while the ice sheet was still intact. Apparently to compensate for the fixed ice surface, the mean velocity had to increase as the discharge increased. The faster velocity resulted in more aggressive bed scour. Once the ice sheet broke up and the ice was free floating, the scour activity subsided.

For conversion of SI units to non-SI units of measurement consult ASTM Standard E380-93, *Standard Practice for Use of the International System of Units,* published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

Special Report 96-6

US Army Corps
of Engineers
Cold Regions Research &
Engineering Laboratory

Ice Force and Scour Instrumentation for the White River, Vermont

Leonard J. Zabilansky

April 1996

Prepared for
STATE OF VERMONT
and
FEDERAL HIGHWAY ADMINISTRATION

PREFACE

This report was prepared by Leonard J. Zabilansky, General Engineer, Ice Engineering Research Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

This field instrumentation project is the product of a cooperative effort. The Vermont Agency of Transportation and the Federal Highway Administration funded the project and incorporated the unique design and instrumentation hardware into the construction of the new bridge. The agency's design and construction personnel anticipated the project's special needs and built them into the structure. Instrumentation maintenance and data analysis were funded by the Office of the Chief of Engineers under the Civil Works program, work unit no. 32248, *Ice Effects on Bed and Bank Erosion*. Local concerns were also a major factor in the project's success. Town of Hartford personnel were always ready to assist and provide space for the instrumentation. The Vermont National Bank volunteered a site to park a trailer for the scour instrumentation package.

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Ice Force and Scour Instrumentation for the White River, Vermont

LEONARD J. ZABILANSKY

INTRODUCTION

Design criteria for bridge piers subjected to ice forces that result from ice jams are very conservative. There are currently few alternatives to such a conservative approach, since we lack full-scale field data as well as a clear understanding of ice–structure interaction. In addition the placement of any obstruction such as a bridge pier in a movable riverbed may induce bed scour adjacent to that structure, and this may be accelerated during an ice jamming or flooding event.

Local scour occurs in movable-bed or gravel-bed rivers when the near-bed water velocity increases either because of an increase in discharge during open water flood events or when an ice sheet or ice jam causes the velocity profile to shift toward the bed. As the near-bed velocity increases, the bed starts eroding around bridge pier footings, buried utility crossings, etc., undermining the structure or utility. Once flow conditions start to subside and velocities decrease, fine-grained, non-structured sediment is redeposited in the scour hole, camouflaging its depth. During the next event, this fill is quickly removed and scour resumes.

Because of the redeposition of sediment in the scour hole, sounding rods which are typically used to profile scour do not define the total depth of scour. Irregular geophysical density profiling can define the overall scour boundary but does not allow the correlation of scour depth with particular past events. In particular, it remains unknown which of open water events or ice breakup and ice jam events cause the most severe scour. Documenting the depth of scour during an event has been nearly impossible, and typical post-event documentation usually does not measure the actual maximum depth of scour, nor does it allow correlation of scour with the hydrograph.

The combination of bed scour undermining the pier stability and ice forces can be responsible for bridge collapse, as happened on two occasions in White River Junction, Vermont. This report describes research efforts currently underway to develop instrumentation for in-situ measurements of ice forces on structures and monitoring of bed scour during extreme events, especially during ice breakup.

BACKGROUND

The White River in Vermont drains a relatively small watershed, which, combined with the steep bed slope, results in dramatic ice and flooding events. The town of White River Junction is located at the confluence of the White River with the Connecticut River (Fig. 1). On March 6, 1964, during spring breakup, two spans of the Bridge Street bridge were pushed off the pier by ice forces acting on the superstructure as well as shearing off the upper portion of the stone masonry pier. Since the bridge is a vital transportation link, it was quickly repaired using recycled bridge beams. The beams were approximately 50 ft long, requiring four spans and three piers to fill the gap. Each temporary pier was designed using nine 45-ft Douglas fir timber piles driven in line along the centerline of the pier. The piers were oriented parallel to the flow. From the construction drawings, the tops of the piles appeared to be 29 ft above the riverbed. At the bridge alignment the bedrock is overburdened by 90 ft of gravel, and the 45-ft piles penetrated 16 ft into the gravel bottom. To protect the exposed piles from abrasion by ice and debris, the

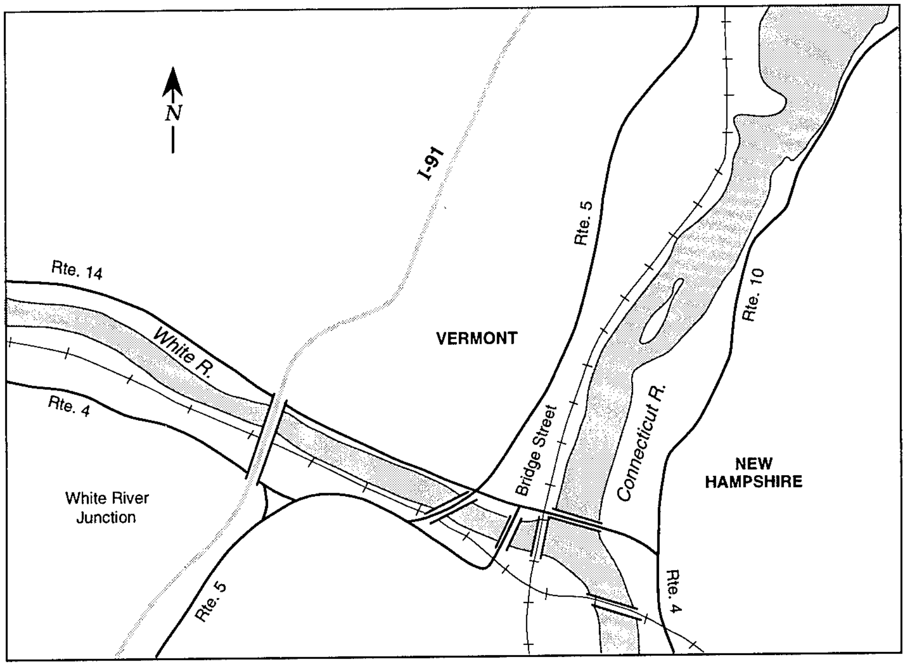


Figure 1. Location of the Bridge Street bridge, White River Junction, Vermont.

portion of the piles above the mud line was encased in concrete (Fig. 2). The concrete was 2.5 ft wide and 44 ft long at the mudline, with a 90° pointed nose.

This temporary bridge lasted until January 26, 1990, when it collapsed during ice breakup. One pier collapsed first, dropping two spans into the river. Fifteen minutes later a second pier failed, dropping a third span into the river (Fig. 3). Historical flow and weather data (App. A) show that the bridge had been subjected to breakups with potentially more ice, due to lower temperatures or higher stage levels or both, than in previous years (Fig. 4). Then why should it have failed? The most likely cause is deterioration of the structural integrity of the foundation due to the cumulative effect of scour. Several post-failure observations indicate that scour around the Bridge Street piers was the primary cause of failure, aggravated by the ice. The local newspaper reported that the bridge "seemed more flexible" to local commuters on the day of the failure. Also heard were comments on how good the fishing was underneath the concrete piers. The concrete used to encase the piles was cast directly on the riverbed, without a cutoff wall or bed protection.

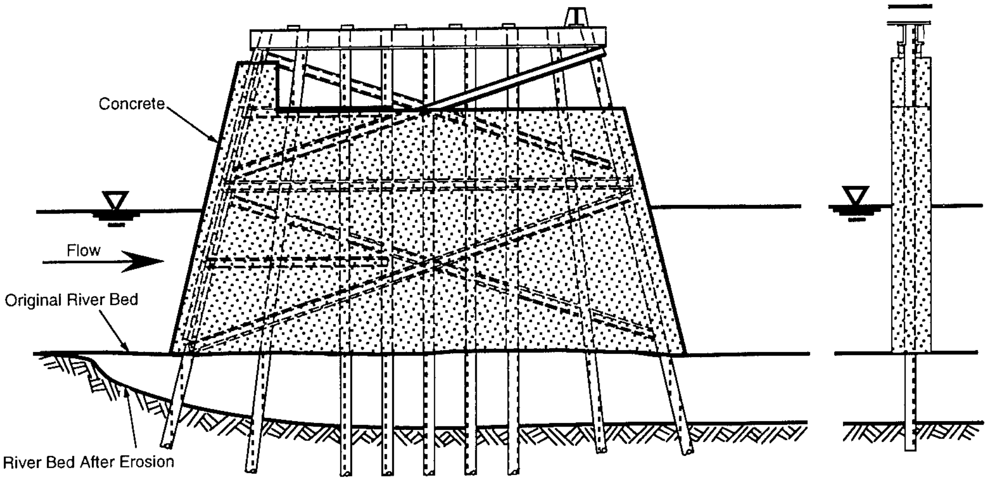
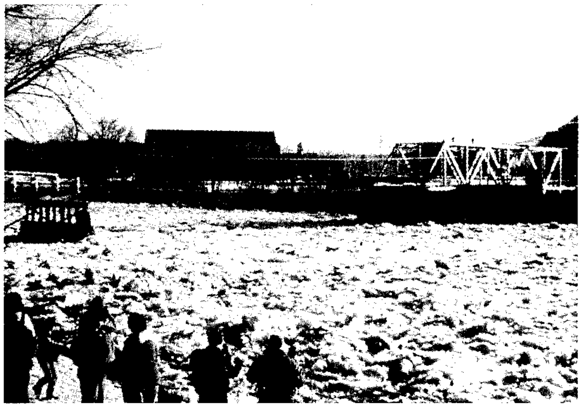


Figure 2. Temporary pier with timber piles and concrete casings.



a. Looking downstream.

b. Looking upstream. The Route 5 bridge is in the background.

Figure 3. Failure of the Bridge Street bridge, January 26, 1990.

Figure 4. Temporary piers subjected to ice forces in 1969.

It is therefore likely that the gravel under the pier was eroded, exposing the piles. Once the current starts swirling around piles, the rate of scour quickly increases.

Other evidence indicating the probability of scour includes:

- A replacement bridge was in the design stage when the temporary bridge failed. The bed elevations obtained in 1989 as part of the soil boring tests were 6–8 in. below the 1964 elevation used in the design of the temporary bridge. This bed elevation is presumed to be the bottom of the concrete casing.
- Public utilities lines (i.e. water and phone lines) immediately downstream of the bridge were exposed during breakup events in the past. The utility lines ultimately failed.
- Foreign material (i.e. logs and metal) was found in the bottom of the excavation for the new pile cap beam 10 ft below the bed. The possibility that this debris was left over from previous construction was ruled out because of the location of the new piers and the construction technique used on previous structures.

Floating ice impacting the nose of a pier generates a shear force and an overturning moment along the axis of the pier. The reaction to the shear force is a function of the cross-sectional area of the foundation elements, i.e. the piles and the concrete. For the White River bridge, the weakest shear element was the piles. For a pile diameter of 12 in. at the mud line and a conservative shear strength of 120 psi (American Institute of Timber Construction 1974), the load capacity of the nine piles was 122 kips. This capacity is three times the predicted load for 12-in.-thick ice and the 100 psi recommended by the AASHTO (1992) design code. Reaction to overturning is developed along the length of the foundation. If the ratio of the water depth to the length of the foundation is less than 1, the pier is usually more than adequate to resist overturning. The water level was well within this criterion on January 24. The thalweg of the White River is skewed to the pier alignment, and it is likely that the piers were subjected to side impacts. In the extreme case (that is, the ice impacting the pier perpendicular to the pier alignment) the pier is not as stable. For simplicity, consider the pier as a column with a side load and the ends restrained by the bridge deck and the foundation. The deck connection was just a bearing pad, which allows free rotation of the pier. The rigidity of the foundation

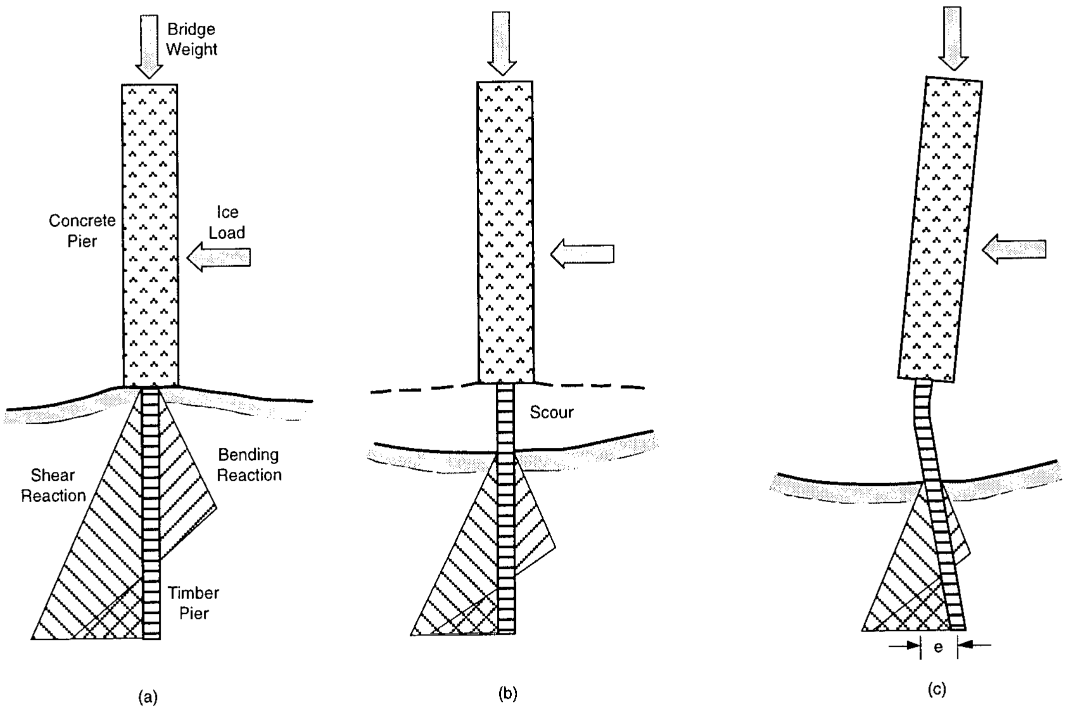


Figure 5. Simplified failure scenario: a) as built, b) reduction in embedded pile length caused by scour, and c) lateral displacement of the pile, making the bridge weight an eccentric load.

depends on the developed lateral and bending stiffness of the piles. Both aspects are a function of the pile's embedded length (Fig. 5a). As built, the piers had sufficient stiffness to resist any lateral movement of the foundation.

Removing gravel, as during a scour event, reduces the pile's embedded length and compromises the structural integrity of the pier. As the length of the exposed pile increased, the relatively slender piles are more prone to flexing. In the extreme case with short penetration, the pile will rotate as a unit within the soil (Fig. 5b). In this condition most of the bridge weight is supported by the point bearing at the tip of the piles. Basically, 10 ft of scour would leave the pier as a block of concrete supported by nine 16-ft stilts. With the relatively low stage during the 1990 breakup, the ice impacted the pier close to the bed, requiring the foundation to take a larger portion of the load. Because of the scour the pier would be more flexible, allowing the pier to deflect sideways as it experiences side impacts. The lateral deflection causes the weight of the bridge to be an eccentric load (Fig. 5c), increasing the bending stresses. The abrupt transition from the timber piles to the piles encased in concrete further aggravates the stress conditions. There is a considerable difference in the stiffness between the two sections, with the wooden piles being more flexible. The increases in stress (i.e. bending and shear) ultimately resulted in the piles snapping at the change in cross section. With the limited lateral support, the piles could easily be deflected or move sideways by the ice loads. The combined shear and bending stresses could easily have exceeded the bending resistance at the transition between the pile and concrete, causing the pier to buckle. This scenario is supported by the snapped timber pile left in the riverbed and in the concrete. The concrete portions of the piers were found on the bottom of the river adjacent to the line of timber piles (Fig. 6).

Figure 6. Piers on the river bottom.

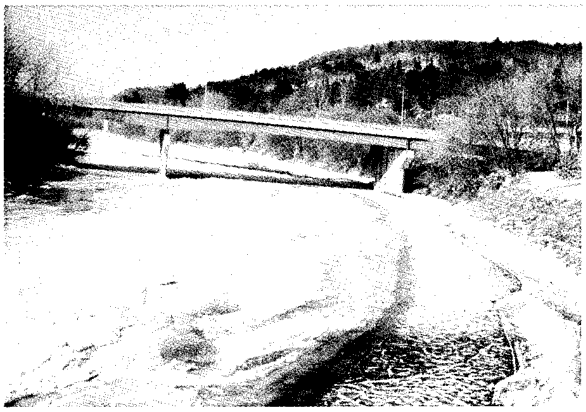


Figure 7. Route 5 bridge, February 1992, showing ice conditions upstream of the instrumented bridge.

The lower reach of the White River has a history of ice jams and scour, which, in addition to being close to CRREL, makes the site ideal for studying ice forces and scour. With the new bridge in the design stage, instrumentation and cable raceways could economically be incorporated into the design with only a slight increase in construction cost. Ideally both the scour and the ice forces should be measured on the same pier. But with scour being recognized as the primary cause of failure of the former bridges, the piers of the new Bridge Street bridge were designed with riprap scour protection, so the installation of instrumentation to measure scour near the new piers would be fruitless. However, approximately 2000 ft upstream of the new bridge, U.S. Route 5 crosses the White River (Fig. 7). Built in the 1960s the piers are not protected by riprap, are easily accessible during low water, and are ideal for evaluating scour instrumentation. The only site limitation is a backwater effect around both bridges from the confluence with the Connecticut River, which is influenced by releases from a 40-mW-peaking hydroelectric dam upstream on the Connecticut River in Wilder, Vermont.

INSTRUMENTATION

The objective of installing the instrumentation is to remotely collect in-situ field measurements of hydraulic parameters that affect or are affected by ice. The focal points of the research efforts are ice forces on structures and ice-induced bed erosion and scour. Instrumentation used to document these phenomena are expected to evolve as our understanding of the processes improves and other parameters affecting the process are identified. Other necessary instrumentation to measure ice thickness and ice velocity using radar technology is also under development at CRREL (Yankielun 1992).

The differences in the focal points (ice forces and scour) are reflected in the types of instrumentation deployed on the two bridges. The two-bridge approach has the added benefit of monitoring the effect that 2000 ft of river and ice has on the system hydraulics.

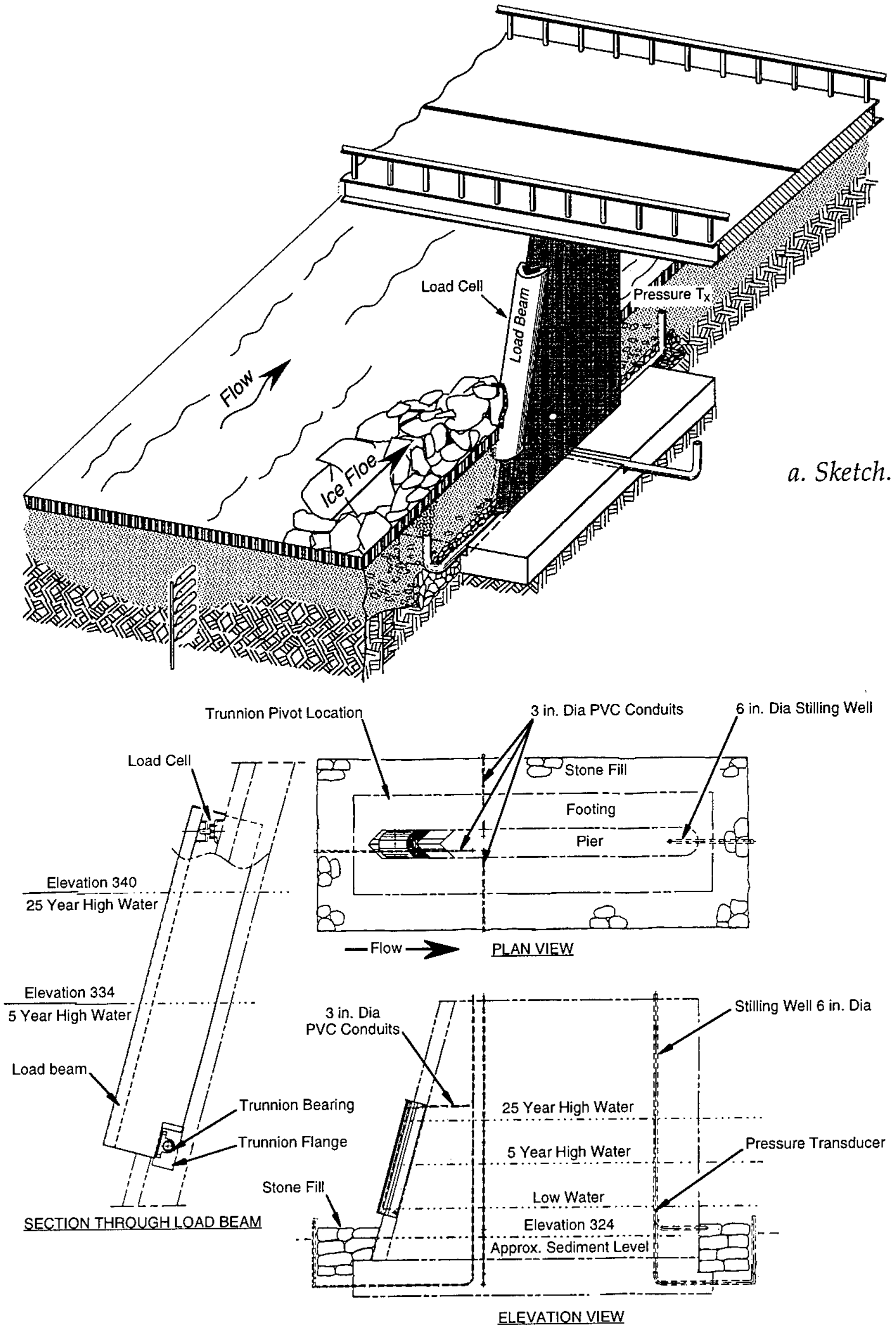
A long-range objective is to develop computer-based data acquisition systems to monitor river hydraulic parameters. The programs are event-driven, with on-site display of the data. This will enable researchers to correlate the measurements with the physical processes. The detail, accuracy and number of parameters incorporated into the data acquisition package are expected to evolve as a function of instrumentation required to enhance our understanding or documentation of the hydraulic and ice force phenomena. Naturally the rate of implementation is subject to funding availability.

Ice forces

There have been several efforts to measure in-situ the forces exerted by ice on bridge piers (Sodhi et al. 1983, Haynes et al. 1991). In such studies, the force measurement instruments had to be retrofitted on existing bridge piers or incorporated into new construction. The construction of the new bridge in White River Junction in 1990 offered another opportunity to include the ice-force monitoring system in the early design stage of the bridge.

Ice force panel

Ice forces are measured using a 4-ft-wide, semicircular beam, attached to the upstream face of the northern bridge pier using a three-point support system (Fig. 8). The beam is a built-up weldment, with the primary elements being two concentric 1/2-in. steel plates that are interconnected using 6-in.-deep channels along the axis of the 16-ft-long beam (Fig. 9). The weldment's cross-section has a high moment of inertia and, when combined with properties of high-strength steel used for fabrication, results in a very rigid structure. Consequently there is little deflection under impact loading. The bottom corners of the beam are connected via pillow block bearings to a common 2.75-in.-diameter stainless-steel pivot shaft passing through the concrete pier just below the low-water level. The top of the beam is supported by a 200-kip strain-gage load cell located on the centerline of the pier. The load cell is designed to be insensitive to bending moments less than 200,000 in.-lb. For redundancy there are two 350-ohm Wheatstone bridge circuits in the load cell. For practical purposes the three-point support can be considered as a simply supported beam. Ice forces are calculated using the measured upper reaction and the corresponding moment arm, i.e., the difference between the water elevation and the elevation of the beam's bottom support pin. Water elevation is measured using a pressure transducer in a stilling well in the downstream end of the bridge pier. The pressure transducer has a 0- to 200-in. range with a corresponding 4- to 20-mA output.



a. Sketch.

b. Schematic.

Figure 8. Instrumented pier on the Bridge Street bridge.

A frequent shortcoming of most ice-force field measuring installations is that there is no simultaneous, continuous measurement of ice thickness. Ice thickness is required to convert the total or global load to an ice pressure. Using units of pressure allows comparisons with other force measurements, and ice thickness can be used as a design criterion. Typically, ice thicknesses are obtained by measuring the ice prior to breakup or measuring the thickness of floes on the side of the channel following the ice run. Neither approach provides the accuracy required to calculate the effective ice pressure. Since the bulk of the ice impacting the White River bridge pier will probably be associated with ice jams with thickness variations, measuring the ice thickness during the ice run is of even greater importance. The technique proposed is to locate the bottom ice surface by using an underwater, up-looking, sonar transducer and to locate the top surface with a downward-looking ultrasonic transducer. The problem is to place the underwater sonar transducer where it will be protected from debris and yet be able to locate the bottom ice surface just before the ice collides with the load beam.

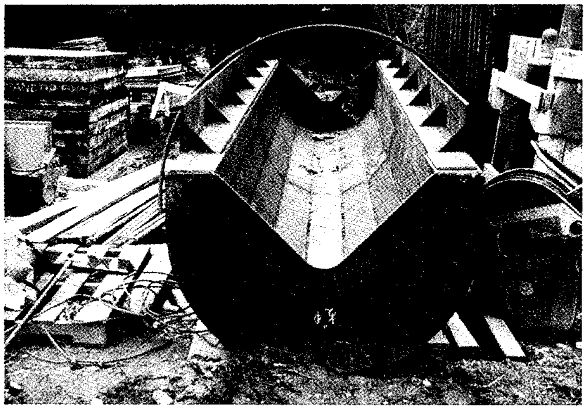


Figure 9. Inner surface of the load beam.

Our approach will be to install the transducer in an instrumentation conduit at the edge of the riprap just upstream of the pier. For protection from floating debris the instrumentation wires will be pulled through a conduit cast in the pier (Fig. 8).

Real-time measurement of the ice thickness using impulse radar technology is being developed at CRREL (Yankielun 1992). The advantage of this approach is that both the transmitter and the receiver can be located on the bridge superstructure, thus avoiding damage from moving ice and floating debris. As this new technology is developed, it will be incorporated into the instrumentation package at the White River site for evaluation and will eventually replace the sonar–ultrasonic system.

Instrumentation conduits have been incorporated into the pier to facilitate easy installation and evaluation of future instrumentation for monitoring ice jams and the bed erosion between the piers. For complete flexibility in locating any of the future bottom-founded instrumentation, access ports for the conduits are on the four sides of the pier at both the mud line and the outer edge of the riprap.

Ice force data acquisition systems

The ice force instruments mounted on the pier are linked to the onshore data acquisition system (DAS) via a 25-shielded-pair instrumentation trunk cable. Instruments on the pier connect to the trunk cable via screw terminal strips housed with a weatherproof box above the pier.

For the first year of operation (1991-92) an analog tape recorder was used to capture the output of both load channels and the water level pressure transducer. Data recording was triggered when the measured load exceeded a preset threshold. Once triggered, analog signals were recorded until the load signal fell below the threshold for more than 5 minutes. In a continuous record mode, a single tape would last 12 hours. The recorded analog data were later digitized for analysis.

For the 1992-93 season a computer-based DAS was installed to monitor the instrumentation in real time (Fig. 10). The controlling software performed three functions: steady-state measurements, dynamic measurements and equipment health monitoring. In steady-state conditions, the ice is stationary and the objective was to document the interaction between water level, air temperature and ice load. To reduce random error, each scan was the average of five readings. If the load or water level changed by a preset margin or at default-time increments, the scan was recorded.

In the dynamic mode the ice is moving and impacting the structure. Dynamic interaction was detected when the output voltage exceeded a threshold. To avoid the limited frequency response of the A/D converter in the HP 3421 data processor, signals were captured on an analog tape recorder. Recording the analog data provided the option of digitizing the breakup data with appropriate fast-rise-time equipment or signal processors or both. To capture intermittent impacts, the tape recorder would record until the output voltage fell below the dynamic threshold for more than 5 minutes.

Several features were incorporated into the data collection system to document the system's performance. Sources of potential

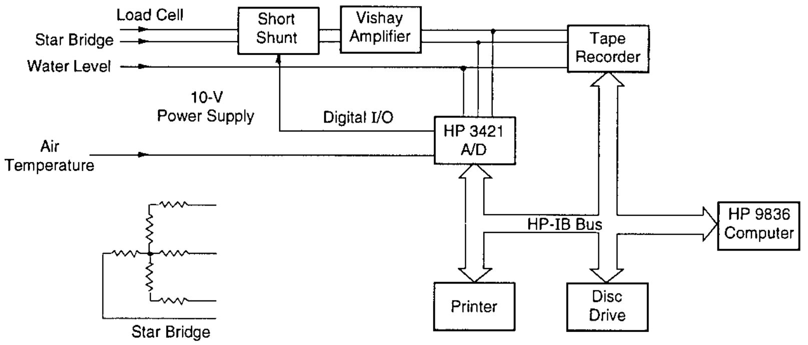


Figure 10. Data acquisition system used for monitoring the ice force instruments.

electrical noise or electrical drift were documented to assure that no artificial loads were introduced into the recorded data. One potential source is common mode noise (electromagnetic interference, or EMI) being picked up by the 500-ft instrumentation trunk cable that connects the instruments on the pier with the onshore DAS. To quantify line noise, a star bridge (Stein 1981) (Fig. 10) was installed as a representative channel starting at the junction box on the bridge. The four 350-ohm resistors used to build the star bridge have the same electrical characteristics as a Wheatstone bridge, therefore the same amplifier response. But with one leg of the four-arm bridge tied in the center, the bridge has zero output. Any measured signal is artificial and action can be taken to eliminate the problem. Another possible source of an artificial load is the drift of the amplifier's electrical zero balance and a change in the amplifier's gain. Fluctuation of the zero translates into an artificial fixed load or shifts the intercept of the linear conversion equation. Amplifier zero was monitored by shorting the input to the amplifier. A change in amplifier gain is similar to changing the slope of the linear conversion equation. Enabling a resistor in parallel with one bridge arm or a shunt, caused a shift in the amplifier's output. The operation of short and shunt relays were controlled by a digital output from the HP 3421. Amplifier checks were conducted prior to opening each 50-point data file and at a preset time daily. The daily short and shunt calibrations were also recorded on the tape recorder as a calibration signal.

By monitoring the analog instrumentation performance, any electrical variation that would otherwise appear as an artificial load is taken into account. Accounting for the precision and bias error reduces the uncertainty in the load measurements.

Erosion and scour instrumentation

Techniques for documenting bed erosion and/or scour vary from simple bottom surface profiles with sounding lines, to elaborate geophysical density profiling. The bottom surface profiles are typically documented after a flood or ice event, and thus the physical processes cannot be correlated to a hydrograph. An objective of this research is to develop real-time scour monitors, enabling correlation between the scour process and the hydrograph. It is critical that the instrumentation perform during breakup and ice-jam periods when scour is most likely to occur. This dictates that the instrumentation be robust and capable of withstanding impact from ice and debris, yet be nonintrusive or "affect" the erosion process. For true versatility the instrumentation has to be independent of a structure for either support or running instrumentation cables. Ideally, scour instrumentation would be installed at several locations to quantify scour due to channel constriction, localized abutment scour and general bed erosion during flooding and icing events.

Scour instrumentation

The technique being developed is based on radio transmitters used to monitor wildlife movement. Being wireless, the active sensors can be located independently of structures. Hence, critical elements, i.e., footings, pipelines etc., can be monitored for scour. Each transmitter has a unique frequency with a superimposed timing pulse. If the transmitter is moving, the timing-pulse rate is fast compared to when the transmitter is stationary. For mechanical protection, the radio transmitter is enclosed in a polyethylene housing ("instrumented fish") as shown in Figure 11. The concept is to tether a series of these transmitters to a vertical mast buried in the riverbed (Fig. 12). On the rising limb of a hydrograph, as the sediment is eroded, successive instrumented fish would be exposed to the current. The front fin of the housing encourages movement of the fish, changing the timing-pulse rate of the transmitter, which is monitored continuously. With the current fish design the water velocity has to be in excess of 4 in./s to trip the activity switch. On the

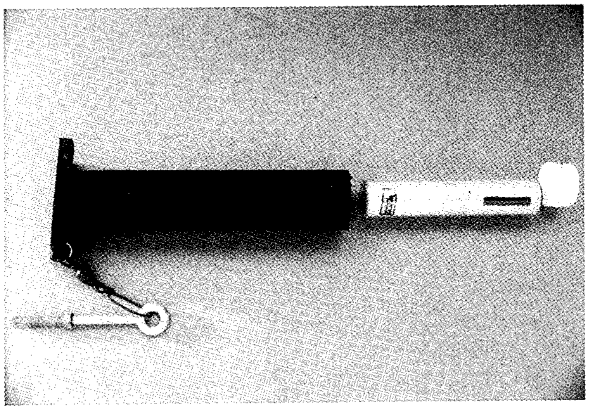


Figure 11. Assembly of the instrumented fish, including an eyebolt, a swivel, a polyethylene housing, a transmitter and an end cap.

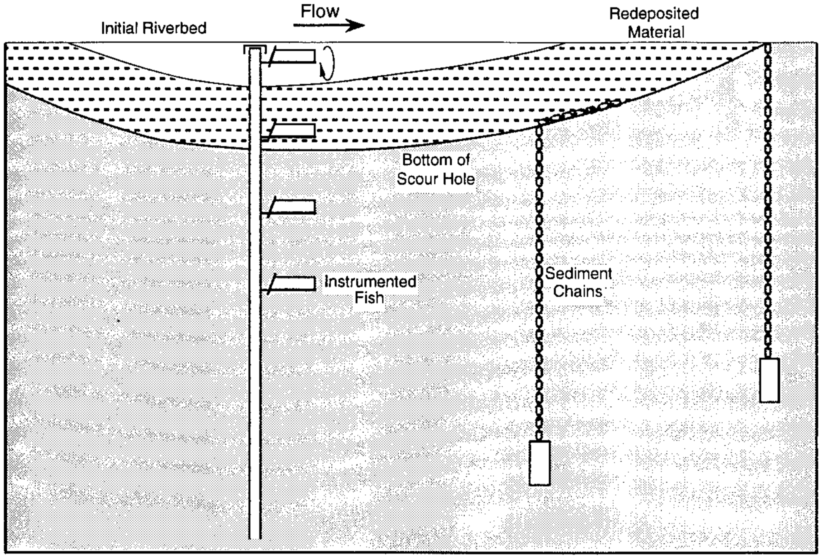


Figure 12. Instrumented fish and sediment chains.

fall of the hydrograph, sediment is re-deposited, the fish is re-buried, and the transmitter returns to a slower pulse rate. The resolution of the erosion rate and volume is a function of the transmitter spacing, which is controlled by the physical size of the transmitter.

Coarse discrete monitoring is acceptable where the active scour layer is significant, e.g., around bridge piers. Where the erosion layer is thin, as the case for general bed or channel constriction, resolution of the bed elevation has to be nearly continuous. Several approaches being evaluated include capacitance, magnetic, sonic or closely spaced point measurements. The difficulty is that these systems typically use an instrumentation wire that is vulnerable to damage from moving ice and debris.

Commercially available continuously active scour monitors will also be evaluated. One commercially available monitor, which attaches to an existing structure, is a Brisco scour monitor. The monitor uses a dropping foot resting on the bed, adjacent to the pier. The elevation of the foot or depth of scour is monitored via a readout unit on the bridge abutment (Fig. 13). One disadvantage of this approach is the need to attach the device to the structure. Hence, the system can only monitor scour adjacent to the structure, and typically the critical element is the footing some distance away from the structure. Also, the need to manually reposition the foot limits the application to monitoring the maximum depth of scour per event.

Passive scour chains (Fig. 12) are often used alone or in conjunction with the active scour systems to establish the total depth of scour. As the soil is eroded, the exposed chains will lie on the bottom and are reburied during sedimentation. When the chains are recovered during low water, the profile of the scour hole and the amount of redeposition can be defined.

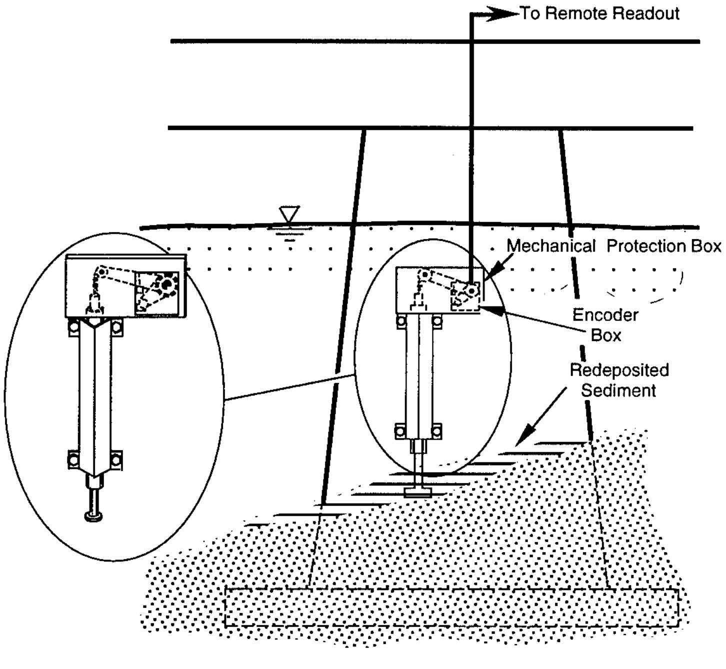


Figure 13. Typical Brisco scour monitor installation.

Peripheral parameters monitored in conjunction with scour are the river stage, air temperature and water temperature. The pressure transducer for river stage and the two water temperature thermistors are attached to near-shore pier right side (Fig. 8).

Bed erosion and scour data acquisition system

Although the hardware for the Route 5 data acquisition system (Fig. 14) is similar to the ice force system, the software is considerably different. The supervisory program running on the HP 9836 performed two functions: monitoring transducers and controlling receiving equipment for the instrumented fish.

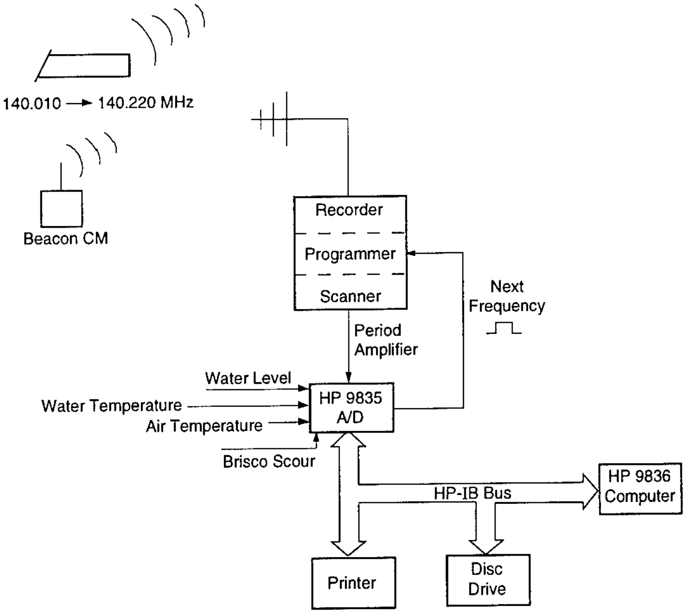


Figure 14. Data acquisition system used for monitoring the scour instruments.

Transducers' output, including water level, and air and water temperatures, was measured and recorded at 15-minute intervals. Accurate field measurements of the air and water temperatures can provide insight into the production and accumulation of frazil ice. These ice crystals are generated in fast-moving water at low air and water temperatures, and the frazil accumulations will affect river hydraulics. To minimize the precision error, the change in the thermistor resistance, which is on the order of 6000 ohms, was read indirectly by measuring the voltage drop across the thermistor (Fig. 15). This approach avoids the problem of detecting a small change in resistance using a large range, dictated by the 6000 ohms full scale. Thermistor resistance is calculated by dividing the voltage drop across the thermistor by the circuit current. To minimize the errors introduced by fluctuation in the circuit current, this current is calculated by dividing the measured voltage drop across the precision resistor by the value of the precision resistor. The calculated thermistor's resistance is then converted to temperature using the Steinhart–Hart equation:

$$1/T = A + B\ln R + C(\ln R)^3 \tag{1}$$

where T = temperature (K)
R = resistance reading of the thermistor
A,B,C = curve-fitting constants.

The coefficients A, B and C are determined by the manufacturer for each thermistor by calibrating the thermistors at three points bracketing 0°C (YSI 1977).

This indirect measurement technique provides a ±0.01°C accuracy on the temperature measurements. Two thermistor probes (Clark 1989) were attached to a cage placed in the channel adjacent to the near-shore pier (Fig. 8). For redundancy, each probe had two thermistors of which one was read by the data acquisition system.

A 6-psi pressure transducer attached to the downstream end of the pier was used to monitor water levels. The transducer was a 350-ohm strain

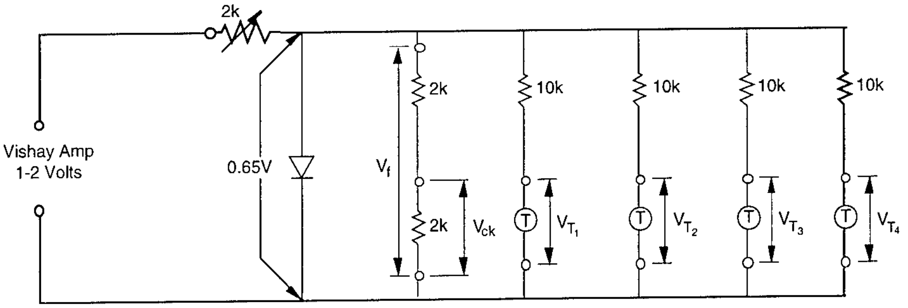


Figure 15. Thermistor string schematic.

gauge configured in a full Wheatstone bridge powered by 10 V DC. The output of the strain gage bridge is a function of the drive voltage. To reduce the precision error, the transducer's drive voltage was read as part of each scan. To reduce random error, each scan was the average of five readings.

Instrumentation to receive and process the signals from the instrumented fish consisted of antenna, receiver, scanner programmer, processor and recorder (Telonics 1991). Transmitted signals are received by a 9-dB directional antenna on shore about 200 ft from the pier. Each instrumented fish transmits at one unique frequency between 140.010 to 140.220 MHz spaced at 10-kHz increments. The receiver, which is tuned to one of the active frequencies by the Telonics scanner programmer, isolates and amplifies the timing pulse signal. Using an adjustable threshold, the recorder would time between signal pulses. For the active state the period was 2 ms, compared to 10 ms for the inactive state.

An analog signal corresponding to the period and amplitude of the time pulse was read by the HP 3421 measurement and process controller. The output voltages for the active and inactive state were 2.5 and 3.5 ± 0.4 V, respectively.

Interrogating the status of the instrumented fish was a multistep process. First, a digital pulse from the HP3421 would step the scanner/programmer to the next preprogrammed frequency. The programmer automatically tuned the receiver to the unique transmit frequency. Software would allow the receiver to settle in on the new frequency for at least three cycles (30 ms) before taking data. Once the active switch was tripped, the faster pulse rate was transmitted for 2 minutes. Readings were taken in a matrix format of five readings per column and six columns wide. To minimize variation of the signal, each column was averaged. To ensure the fish remained in the same state, i.e., active or inactive during the sampling aperture, the averages of the first and last column were compared. If the readings were within 5% of each other, the scan was acceptable and the matrix average was used as a value for the scan. If the scan was outside the tolerance, another complete scan was taken and the error checking process repeated. If an acceptable scan was not achieved in six tries, the sixth reading was flagged as questionable and hard-copy diagnostic data were printed. The programmer would sequence to the next preprogrammed channel using a digital pulse from the 3421 and the process would repeat. Unless there was radio interference or the batteries were weak, the first scan was within the error checking. The status of the fish was read following the transducer readings at 15-minute intervals.

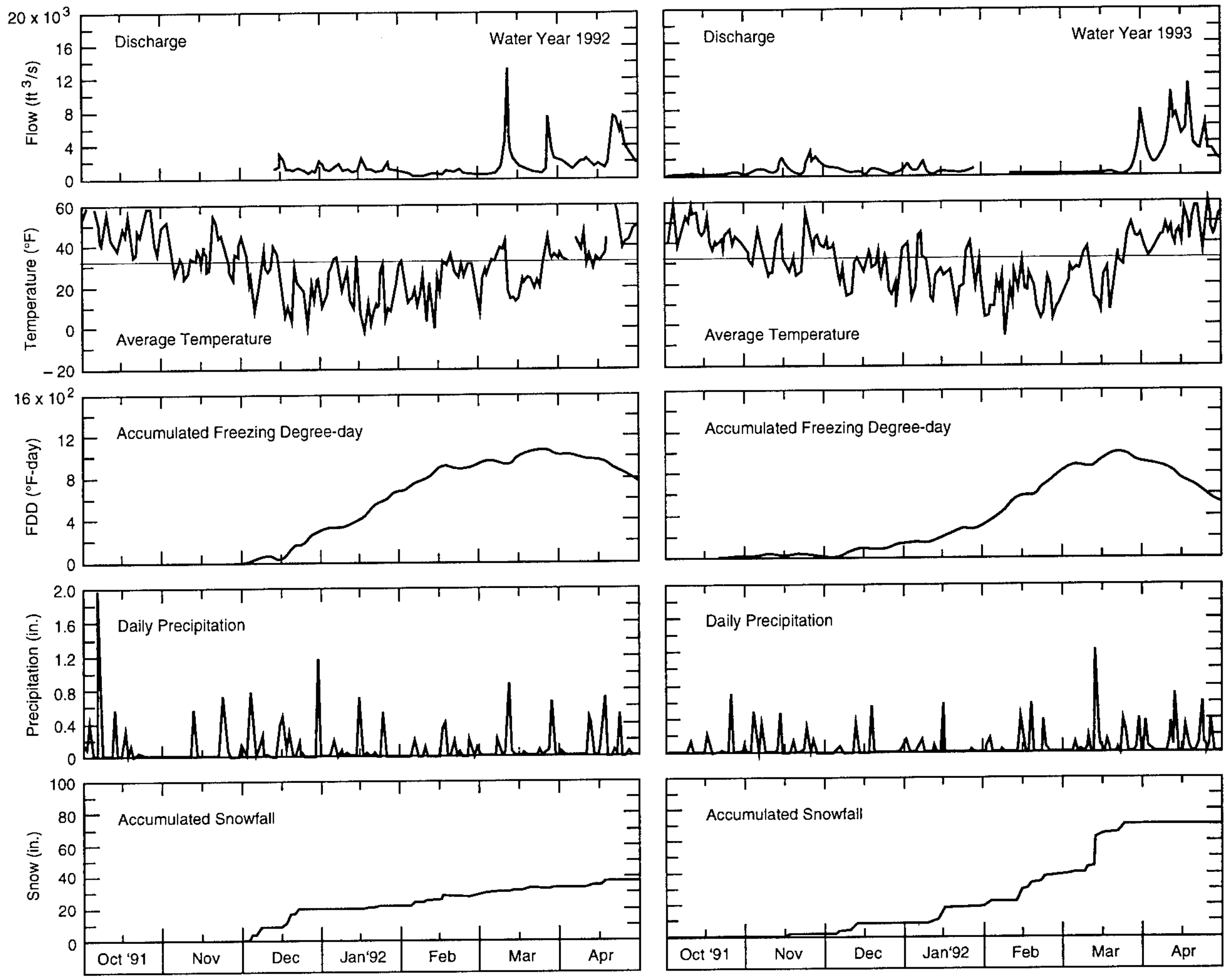
A beacon channel was used to ensure that the data acquisition system and the receiving equipment were aligned and monitoring the same frequency. The beacon had a unique frequency and timing pulse along with a corresponding unique DC voltage. If this unique voltage appeared anywhere in the scan list other than the last channel the entire scan was rejected.

INITIAL RESULTS

Hydrometeorological data

Water discharge records for water years 1992 and 1993, from an existing USGS gaging station in West Hartford, Vermont, are plotted in Figures 16a and b, as well as in Appendix A. The gage is approximately 7 miles upstream of the study area, and these discharge records have not yet been corrected for ice effects. The apparent sudden discharge increases are attributed to an ice jam affecting the gage. An ice cover or ice jam blocks a portion of the flow area and creates a hydraulic drag on the water surface, which reduces the river's conveyance. This loss in capacity results in an increase in stage. Estimating discharge using this higher stage with the open water rating curve results in the calculated discharge being unrealistically high.

The average daily temperatures for the White River region during the 1991-92 and 1992-93 winters are also plotted in Figures 16a and b, respectively. Similar plots for water years 1960–1993 appear in Appendix A. Ice formed during a season is a function of the duration and severity of the temperature. Both factors can be expressed as freezing degree-days (FDD) using the expression $32°-F$, where F is the average daily temperature in degrees Fahrenheit. The volume of ice grown during the winter is reflected in accumulated freezing degree-days $[\Sigma\ (32°-F)]$. In summing the degree-days, if the sum was negative, indicating warm weather, the accumulator was reset to zero. Accumulated freezing degree-days for water years 1960–1993 are included as part of the plot in Appendix A. The AFDDs for the winters of 1991-92 and 1992-93 were 1087 and 1029°F-day, respectively, with both years being approximately 15% warmer than the average AFDD for



a. Water year 1992.

b. Water year 1993.

Figure 16. USGS gage and weather data for West Hartford, Vermont.

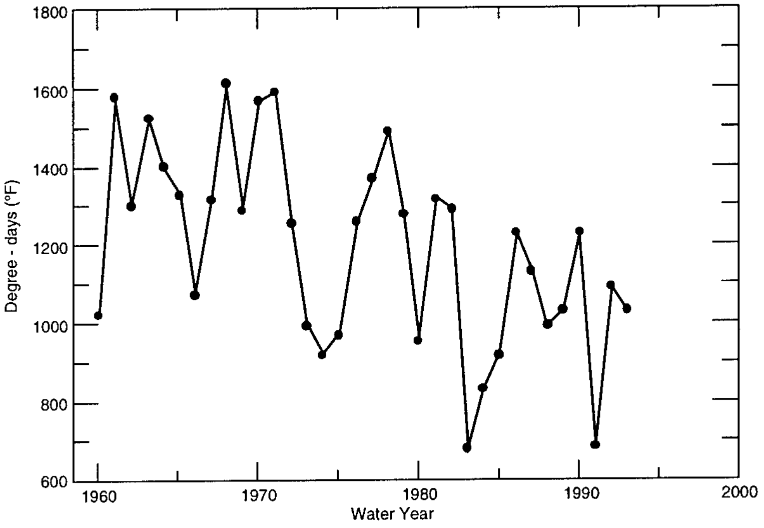


Figure 17. Accumulated freezing degree-days for water years 1960–1993.

the previous 32 years (1969–1991) of 1266°F-day (Fig. 17).

Typically, breakup is initiated by an increase in stage due to runoff from rain and snowmelt. To quantify the potential runoff in the form of snow cover, the accumulated snowfall is plotted in Figure 16, as well as in Appendix A.

Ice force measurements

The 1992 and 1993 ice-outs were not as dramatic as in previous years (Fig. 4). In 1992, breakup in the lower reaches of the White River was initiated by the heavy rains of March 9–10 (Fig. 16a). The ice concentration during the ice runs was primarily single layer, covering 75–95% of the water surface (Fig. 18). The maximum floe sizes were on the order of 15 ft in diameter, with a norm of 6 ft. Prior to the ice-out, random ice thickness measurements upstream varied from 10 to 18 in. thick, with a norm of 12 in. Because of the open water, ice that impacted the structure typically stopped and then pivoted around the structure. When crushing was observed, it occurred as the floe was stopping and was of short duration.

Figure 19 is a typical ice force record reconstructed using digitized data points. Ice forces are calculated using the simply supported beam equation with the measured reaction load and the calculated moment arm. The water level reading is assumed to be the impact elevation for the ice. An algorithm was used to identify the maximum load associated with each impact. To ignore minor loads associated with localized crushing, the algorithm used the following logical tests. If the current load F_n was greater than the local maximum load ($F_n > F_{max}$), F_n was identified as the new local F_{max}. The end of the impact event was defined by either of two conditions:

- The local load (F_n) was less than 10% of the maximum load encountered during the event ($F_n < 10\% \ F_{max}$), or
- Open water was detected between floes by the load dropping below the 1000-lb threshold.

During the 20-hour period of the ice-out, 8,056 impacts were identified, with the maximum load being 26,071 lb. The impact load frequency distribution is plotted in Figure 20. For a 4-ft-wide beam and a nominal ice thickness of 12 in., the maximum effective pressure was 45 psi.

Figure 18. Ice conditions during breakup, March 10, 1992.

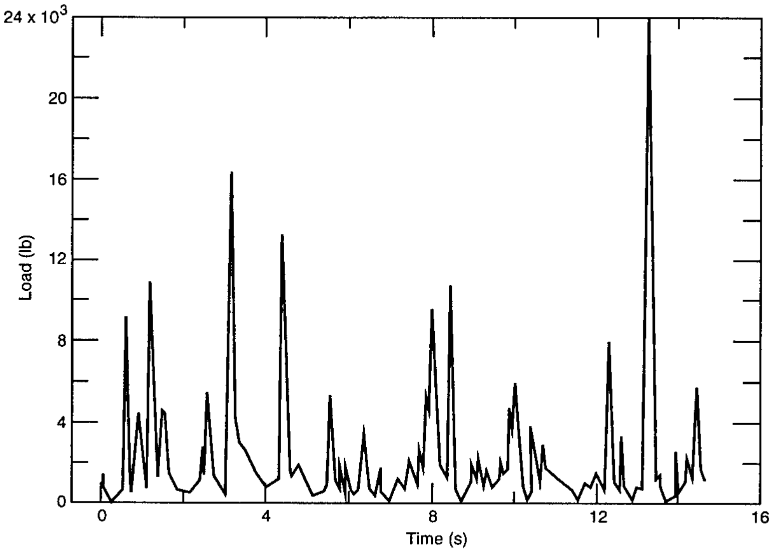


Figure 19. Typical ice force record for the Bridge Street bridge, 1992.

During February 1993 the White River valley received a heavy snowfall. With sunny days and warm nights in March, the snowpack slowly melted, with a slow rise in stage. The slowly rising hydrograph and warm weather allowed the ice sheet to structurally deteriorate or melt in place. The weakened, unstable sheet ultimately collapsed, with very little increase in stage. The limited strength was reflected in the nominal floe sizes on the order of 3 ft in diameter, smaller than the 1992 breakup. During the 1992 breakup a floe impacting the instrument beam was accompanied by a loud percussion. This was not the case of the 1993 breakup, when the ice flushed out of the system with hardly a sound. The force record was nearly constant at 6000 lb, or 10 psi, with a few distinctive impacts in the 60-psi range.

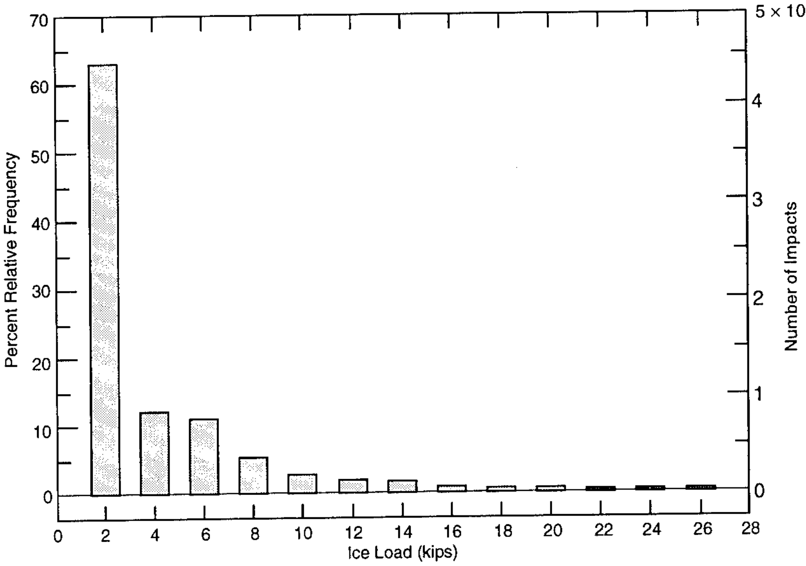


Figure 20. Impact load frequency distribution for 1992.

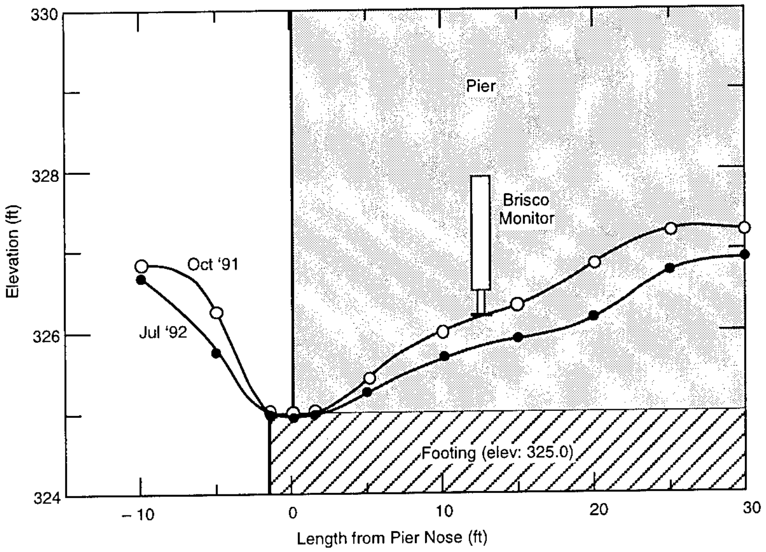


Figure 21. Bed profile adjacent to the Route 5 bridge pier, October 1991 and July 1992.

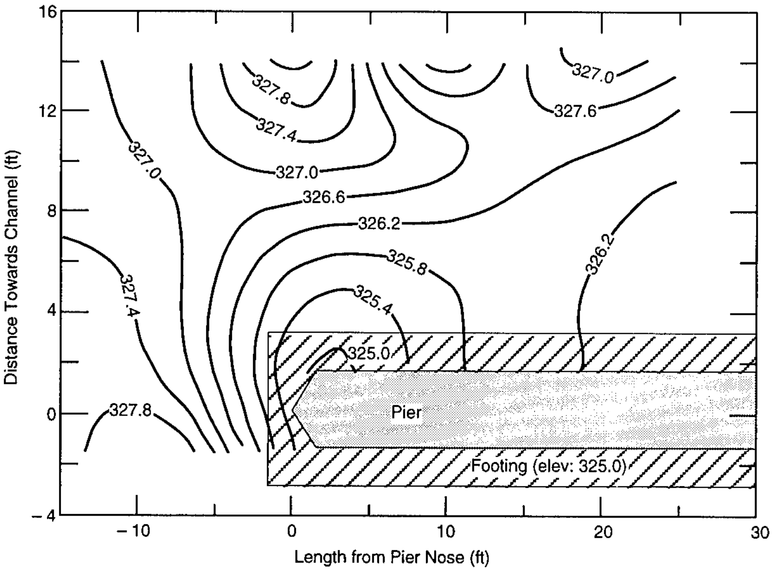
Erosion-scour measurements

In November 1991 a Brisco scour monitor was installed on the channel side of the left pier (Fig. 7) about 14 ft back from the nose. Before the Brisco scour monitor was installed, the bed adjacent to the pier was profiled using a sounding rod (Fig. 21). During the April rains, with no ice in the river, the foot on the Brisco scour monitor dropped 11 in. During low water in August 1992, the river bottom adjacent to the pier was surveyed. The elevation contour lines of the bottom are shown in Figure 22. The profile adjacent to the pier is overlaid on the October 1991 profile (Fig. 21). An interesting point is that 6 in. of material was redeposited into the area of the Brisco scour monitor. Thus, at this single point there was a net loss of 5 in. of bed material. Following the survey, the dropping foot was repositioned at the nominal bed elevation and the electronics were reset. If the loss across the cross section is assumed to be uniform, a considerable amount of material has been removed. The size distribution of the gravel redeposited adjacent to the pier is shown in Figure 23.

In January 1993, fifteen instrumented fish were buried in the gravel upstream of the Route 5 bridge pier. The fish were each attached to one of four masts, at 6-in. vertical spacing on alternate sides of the mast using ball-bearing swivel connectors (Fig. 24). The arrangement of the fish is shown in Figure 25.

Three to five fish were attached to the 1-in.-diameter mast, depending on the location and the anticipated depth of scour around the mast. The overall length of the mast was 8 ft, with the bottom portion used to develop lateral support and anchoring for the upper instrumented section, which could be cantilevered into the flow and exposed to the current and debris. The four masts, or "fish poles," were installed in the riverbed using compressed air and equipment (Fig. 26). The outer driving shell reduced the amount of material that slumped back into the excavation. The inner driving shell was slightly larger in diameter than the mast with attached fish. Because the air probe fluidized the bed, the inner driving shell easily sank into the bed. Material within the driving shell was ejected by using a blast of compressed air at the bottom of the driving shell, with supplemental air from the air probe. With a cavity for the instrument fish, the mast was jetted into the riverbed using the compressed air.

While the instrumented fish were being installed, the following observations were made. First, the upper 2 ft of material in front of the pier was very loose, giving little resistance to the driving shell. At the 2-ft level, there was a hard layer,



22. Elevation contours adjacent to the Route 5 bridge pier, August 1992. The contour lines are at 0.4-ft intervals.

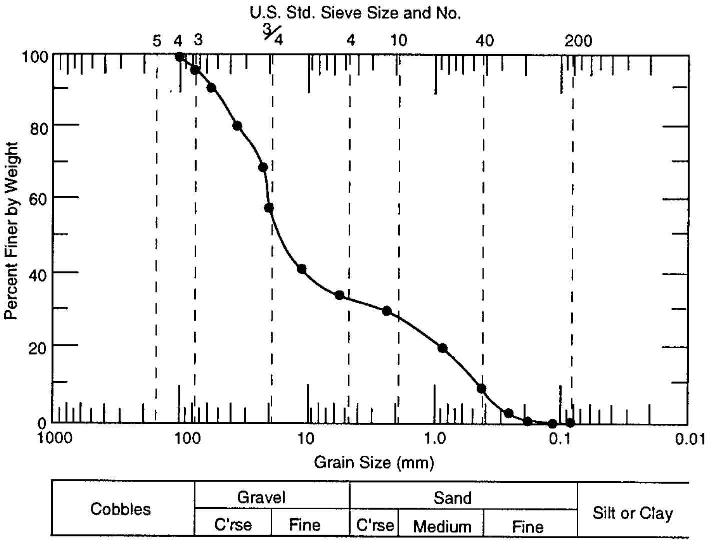


Figure 23. Size distribution of the gravel material redeposited near the Route 5 bridge pier.

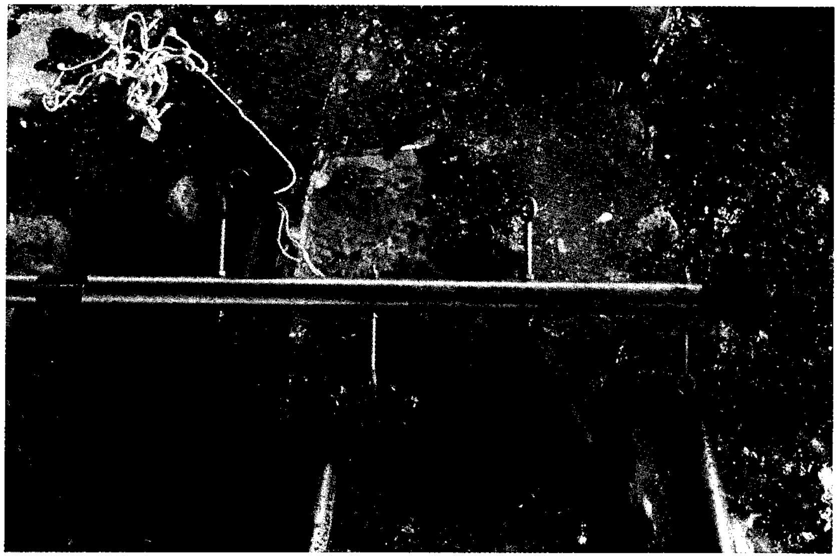
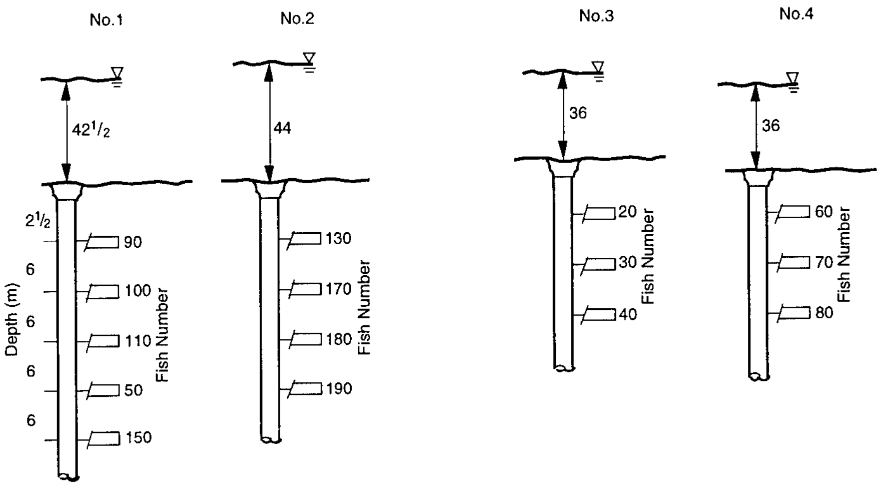
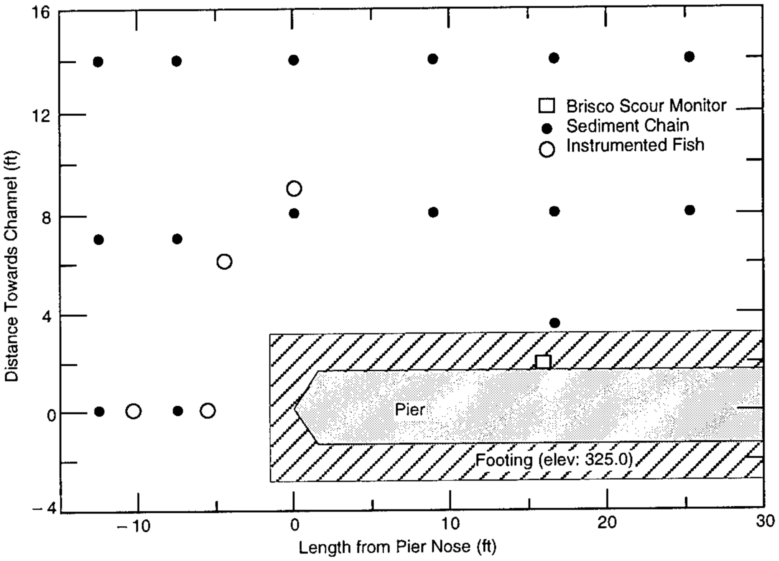


Figure 24. "Fish pole" with attached fish.



a. Elevation view of the fish. The fish are numbered according to their transmitting frequency (in kHz) above the base frequency of 140 MHz.



b. Plan view.

Figure 25. Arrangement of the fish and sediment chains around the Route 5 bridge pier.

which the probe quickly penetrated with a few blows from a sledge hammer. After the hard layer was penetrated, bubbles were coming out of the bed approximately 20 ft upstream of the pier.

An array of 16 sediment chains were installed around the pier (Fig. 25a) to passively document scour depth. A compressed air probe (Fig. 27) and the following procedure made installing the chains very easy:

- The air probe was jetted into the river bottom;
- The access cap on the top of the air probe was removed;
- A weight with an attached 3-ft chain and string was dropped down the air probe; and
- With tension held on the string, the air probe was extracted, leaving the sediment chain protruding just above the surface.

One observation made while monitoring the instrumented fish was the attenuation of the signal due to the frazil ice particles. Following cold nights there was a high concentration of frazil ice in the water, increasing the signal scatter and reducing the amplitude of the received signal. Signal strength also deteriorated but not as severely as the ice sheet thickened. Despite the reduced amplitude and frequency of the received signal, the timing signals indicated that the fish were stationary. The only change in state occurred in the early stage of breakup, when the water level

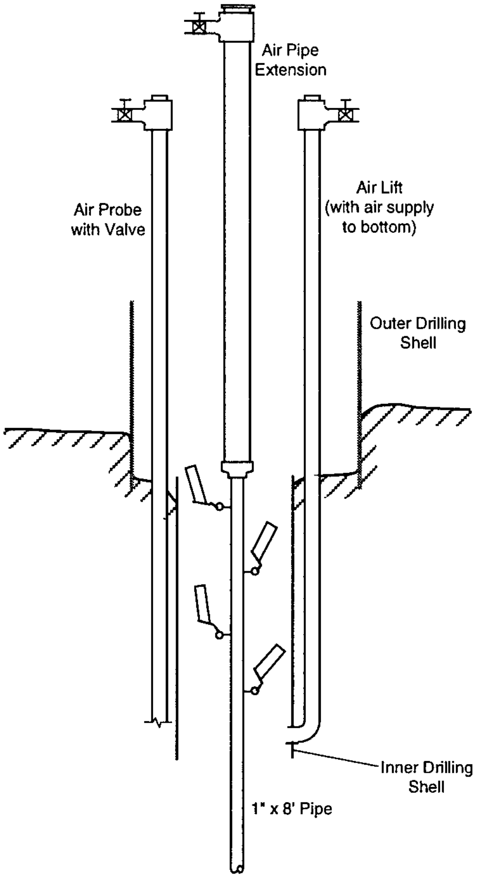


Figure 26. Equipment used to install the fish.

started to rise and the ice sheet was still intact around the pier. During this period, one fish (140.020 MHz) was active for 9 hours before returning to the inactive state. (Except for the top fish on poles 1 and 2 in front of the pier, all remaining fish were stable in their signal strength at the inactive level.) Returning to the inactive state coincides with the ice sheet being broken up and moving freely. Although the ice continued to move by the pier for the next 24 hours there was no additional scour activity.

When the chains and the instrumented fish were recovered in August to evaluate their performance, the top fish on poles 1 and 2 in front of the pier (140.090 and 140.130 MHz) were missing, explaining their erratic response, i.e., not active or inactive.

In the future the support system will be modified to provide better mechanical protection. The installation procedure was also modified to minimize the excessive loading incurred on the swivel connection during installation.

The chains were found in a sand layer that represent a radial cross section along the centerline of the pier (Fig. 28). Extrapolation of the point measurements of scour depth at the chains showed that this 4-in. layer of sand returned to the surface approximately on the same radius as the bubbles observed during installations. Figure 29 shows the contour lines of the scour hole as defined by the sediment chains. The active fish (140.020 MHz) was above the sand layer defined by the chain, confirming that scour did occur. In the process of restoring the riverbed to the "natural" contour, the sediment chains were reset. The instrument fish will be reinstalled using a different mast arrangement for sheltering the fish.

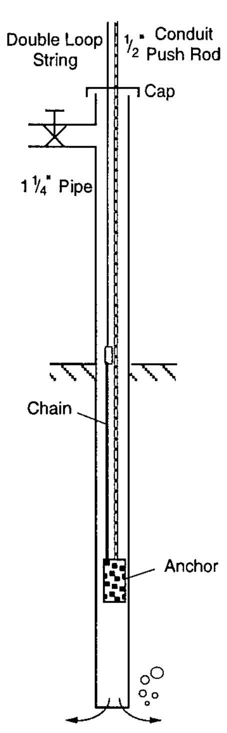


Figure 27. Equipment used to install the scour chains.

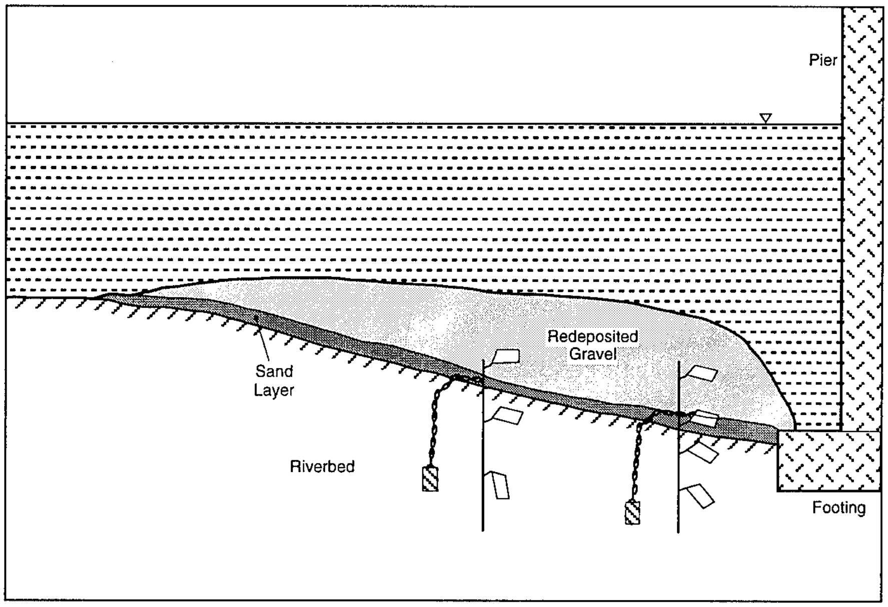


Figure 28. Cross section of the scoured and redeposited gravel wedge.

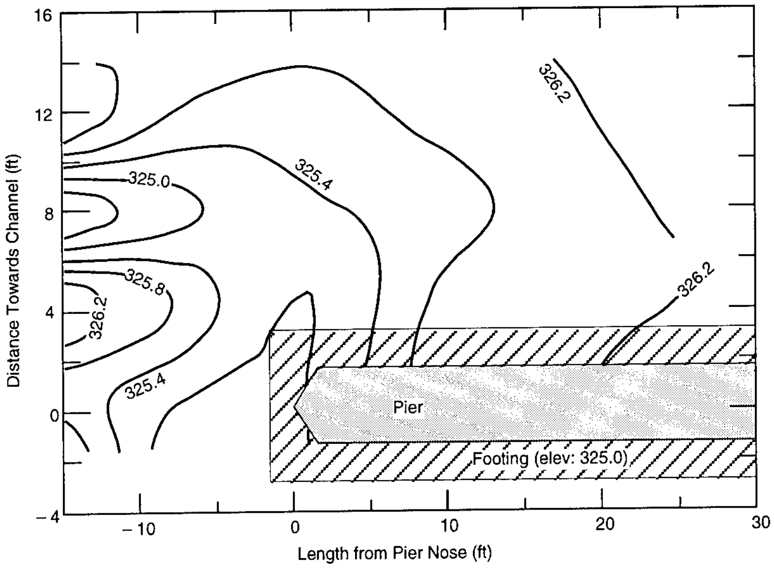


Figure 29. Contours of the scour hole.

DISCUSSION

The global ice loads have been measured with reliable results on the instrumented pier. The low ice strength deduced from these measurements are in line with other measurements of ice strength during spring breakup, when the inner structure of the ice has deteriorated (Michel 1970). The reduced strength is also taken into account in the AASHTO (1992) design code. For spring breakup where the ice floes are "small," the code recommends using 100 psi as a crushing strength. To compensate for incomplete contact between the ice and the structure, the crushing strength can be modified based on the ratio of pier width *b* to ice thickness *t*. Using the 12-in. ice thickness, the corresponding b/t ratio of 4 has a reduction coefficient of 0.8. In essence the design crushing strength is reduced to 80 psi, or twice the crushing strength measured during the 1992 breakup. Based on the 1992 and 1993 measurements this design criterion is conservative.

Real-time measurement of the scour adjacent to but independent of the bridge pier during the spring 1993 breakup is a first. This conclusion is based on only one instrumented fish, but the concept of using motion sensors tethered to a mast for monitoring scour has merit. What is interesting is that the 23 in. of scour measured by the sediment chains had to erode and start to redeposit in the early stages of breakup. This field measurement corroborates the measurements and observations made in the flume studies by Bescha (1983) and Wuebben (1988).

Developing, installing and evaluating real-time scour instruments present real challenges. As prototypes the instrumented fish were successful. Several problems have been identified (i.e., attachment, installation, polyethylene housing, etc.), and the necessary revisions are incorporated into equipment reinstalled prior to the 1994 breakup.

FUTURE RESEARCH

The use of ice thickness measured prior to or following breakup introduces errors in the calculated ice pressure, skewing any comparisons with ice crushing strengths measured in laboratory and field sites. The challenge is to measure the thickness of the ice conglomerate (i.e., single layer, multi-layer, brash, etc.) just prior to impact. The current direction is a refinement of the impulse radar technology. The velocity of the ice floe prior to impact also influences the crushing strength (Sodhi 1992). A radar system that will continuously monitor this aspect of the breakup is currently under development.

Using radio transmitters to monitor scour has real promise. By modifying the mast and fish attachment, we hope to reduce the damage caused by impact from debris and ice. For example, the attachment points will be located downstream on the mast rather than protruding with eyebolts off to the side of the mast, which expose the fish to current and debris. A stiffer mast will shelter the fish from the debris. A future modification would be to use smaller transmitters to allow closer spacing of the instrument fish, improving the resolution of the measurements. The tradeoff is a reduction in service life. The concept of using discrete measurements is acceptable where scour is significant, such as adjacent to bridge piers and abutments. To fully evaluate the impact of river ice and structures on bed erosion, continuous monitoring of the bed elevation is required. Several technologies are being evaluated, but all require an instrumentation cable.

Water velocity enters into the existing equations for scour (Richardson et al. 1993) and is a parameter that needs to be measured. Rather than subjecting delicate velocity probes to debris for direct velocity measurements, the approach is indirect measurement. By measuring stage, a corresponding discharge can be obtained from a discharge rating curve, and a mean velocity can be calculated. However, this approach is only valid when the ice is free-floating and not restricting the flow. Further, this does not account for velocity fluctuations due to surges as water is put into or released from storage by the ice.

CONCLUSION

An instrumentation package has been developed for measuring and monitoring ice forces on a bridge pier and for monitoring the development of bed scour due to ice and open-water floods.

A beam for measuring forces was installed on a pier of the newly constructed Bridge Street bridge over the White River in White River Junction, Vermont, in the fall of 1991. The 1992 and 1993 ice breakups were uncharacteristically mild but proved, nevertheless, that the ice force beam and data acquisition system were functioning and capable of detecting ice impact loads on the bridge pier. The measured loads were within the design guidelines established by AASHTO.

The scour-monitoring system was installed in January 1993 around a pier of the Route 5 bridge, some 2000 ft upstream from the Bridge Street bridge. In addition to traditional scour chains, it consists of active scour sensors, including a Brisco sensor and a matrix of "instrumented fish" attached at incremental depth to a vertical mast buried in the riverbed. A mortality radio transmitter enclosed in each fish is capable of detecting movement when a fish becomes exposed as scour progresses. Reburial of the fish occurs as sediment refills the scour hole as the flow velocity subsides. Therefore, these fish do not require resetting after each scour event.

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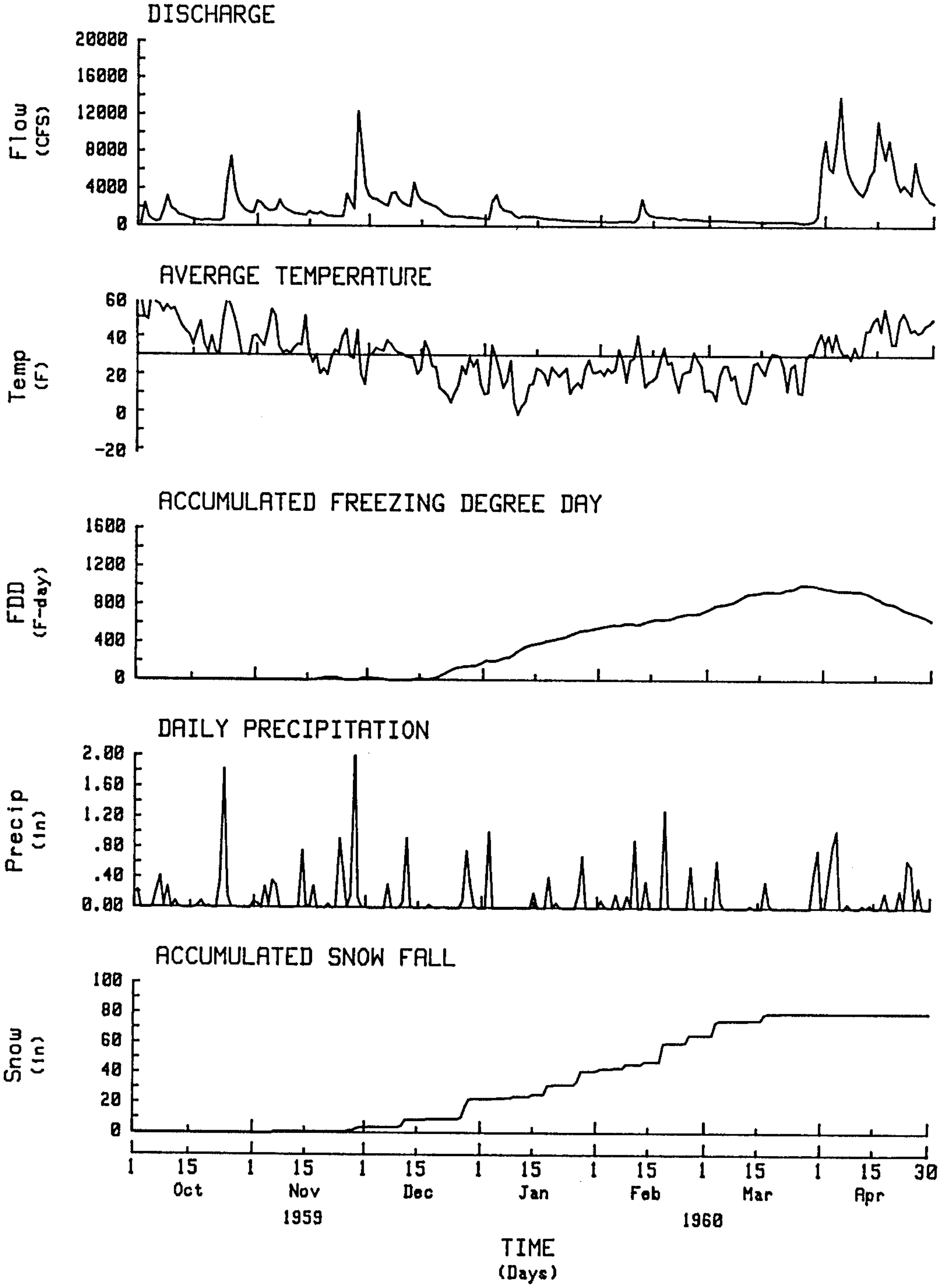
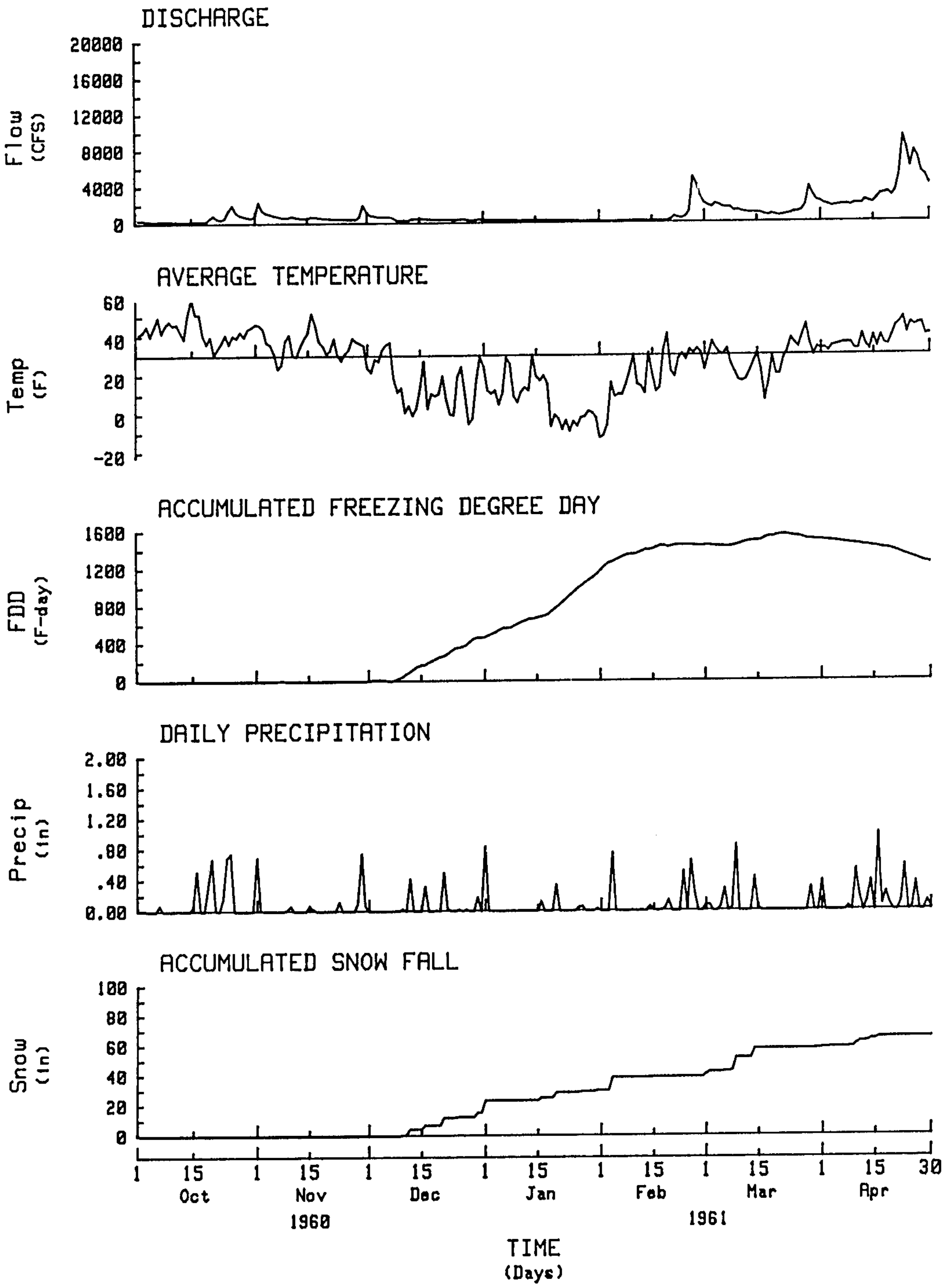
APPENDIX A. DISCHARGE AND WEATHER DATA FOR THE WHITE RIVER AREA

The discharge data are from the USGS gage, West Hartford, Vermont. The weather data are from the National Weather Bureau for the White River Junction region. The primary reporting station is the Lebanon (New Hampshire) Regional Airport. The secondary reporting station is in Hanover, New Hampshire.

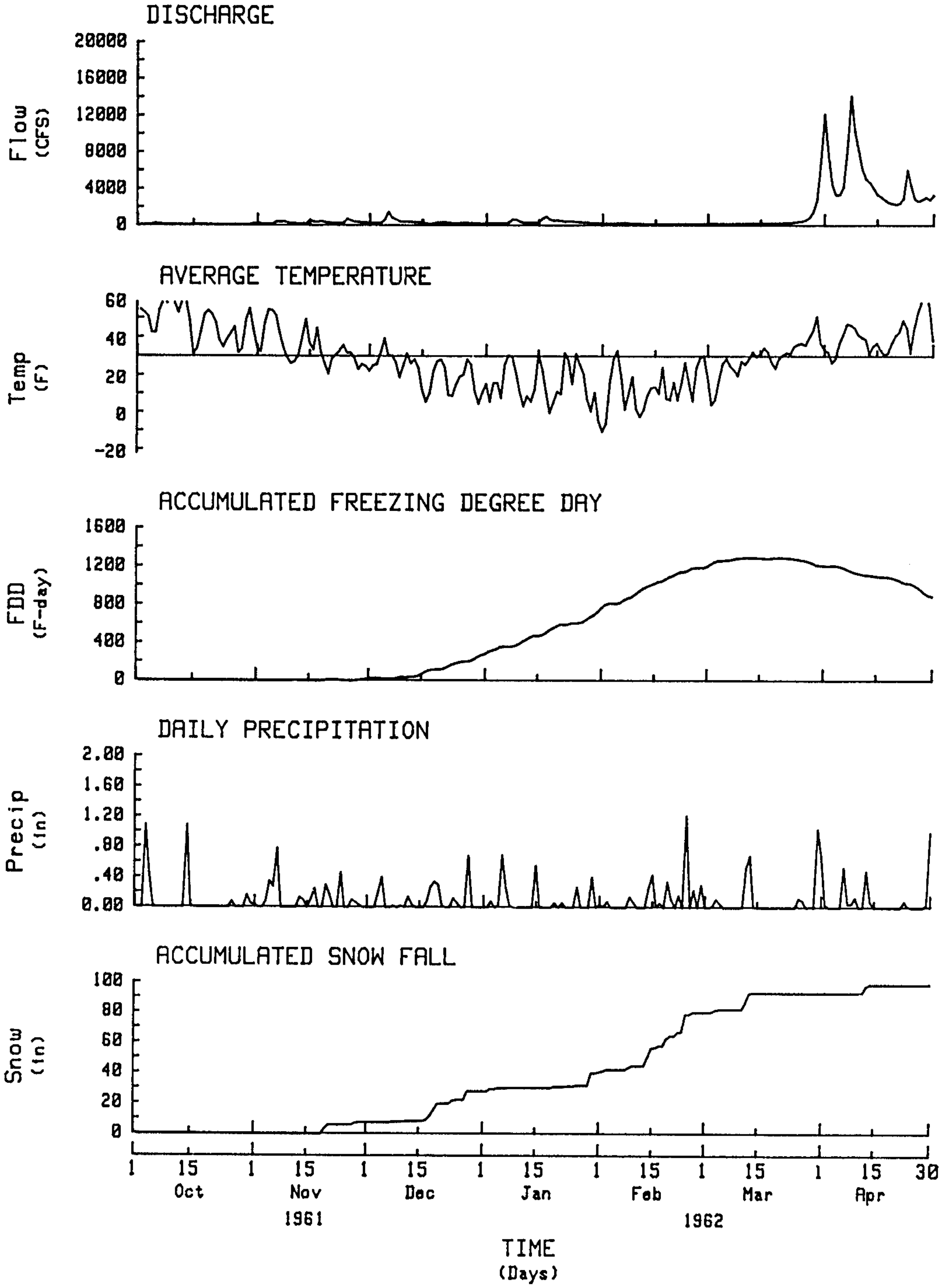
WATER YEAR 1960



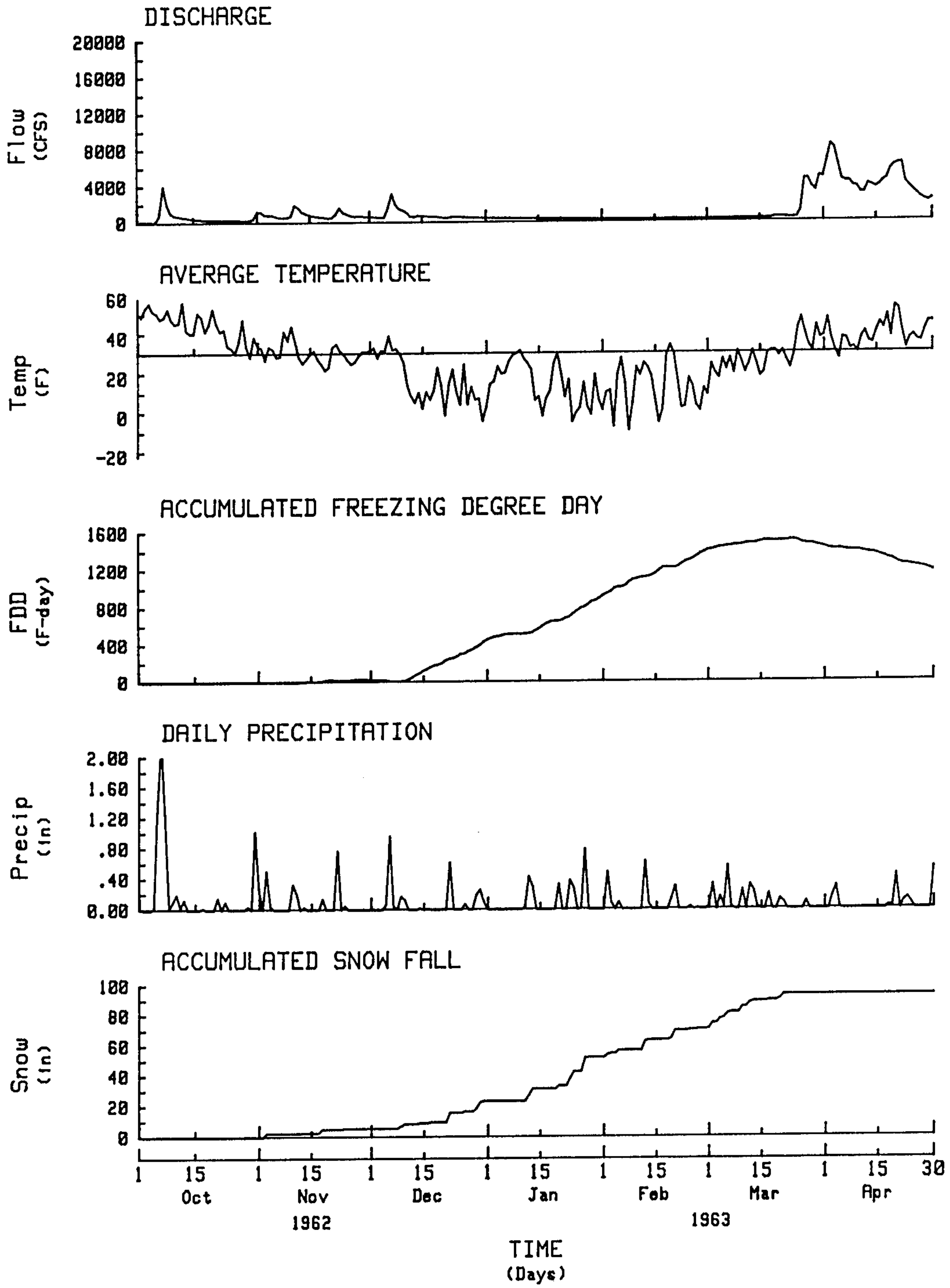
WATER YEAR 1961



WATER YEAR 1962



WATER YEAR 1963


DISCHARGE

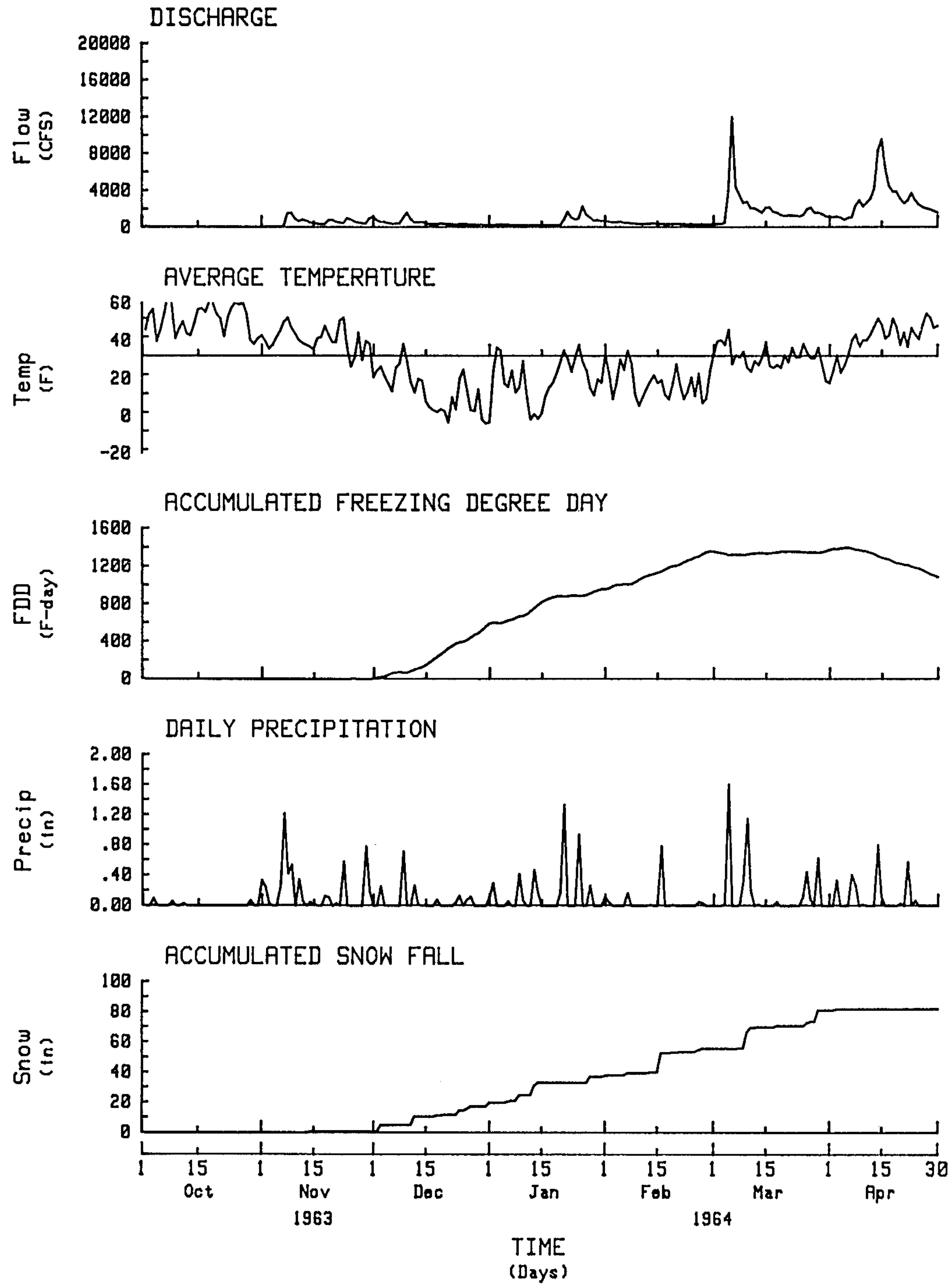
AVERAGE TEMPERATURE

ACCUMULATED FREEZING DEGREE DAY

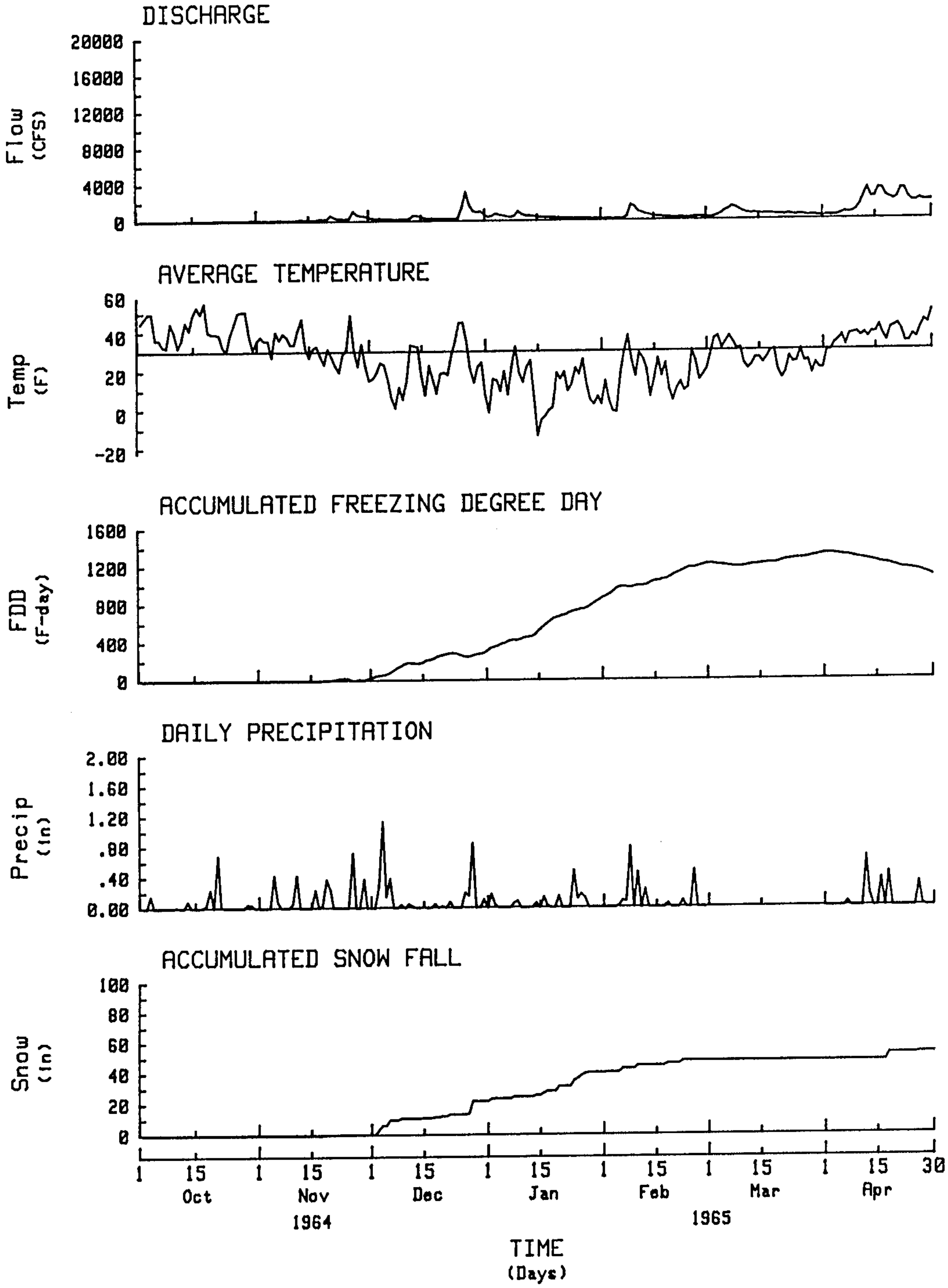
DAILY PRECIPITATION

ACCUMULATED SNOW FALL

WATER YEAR 1964



WATER YEAR 1965



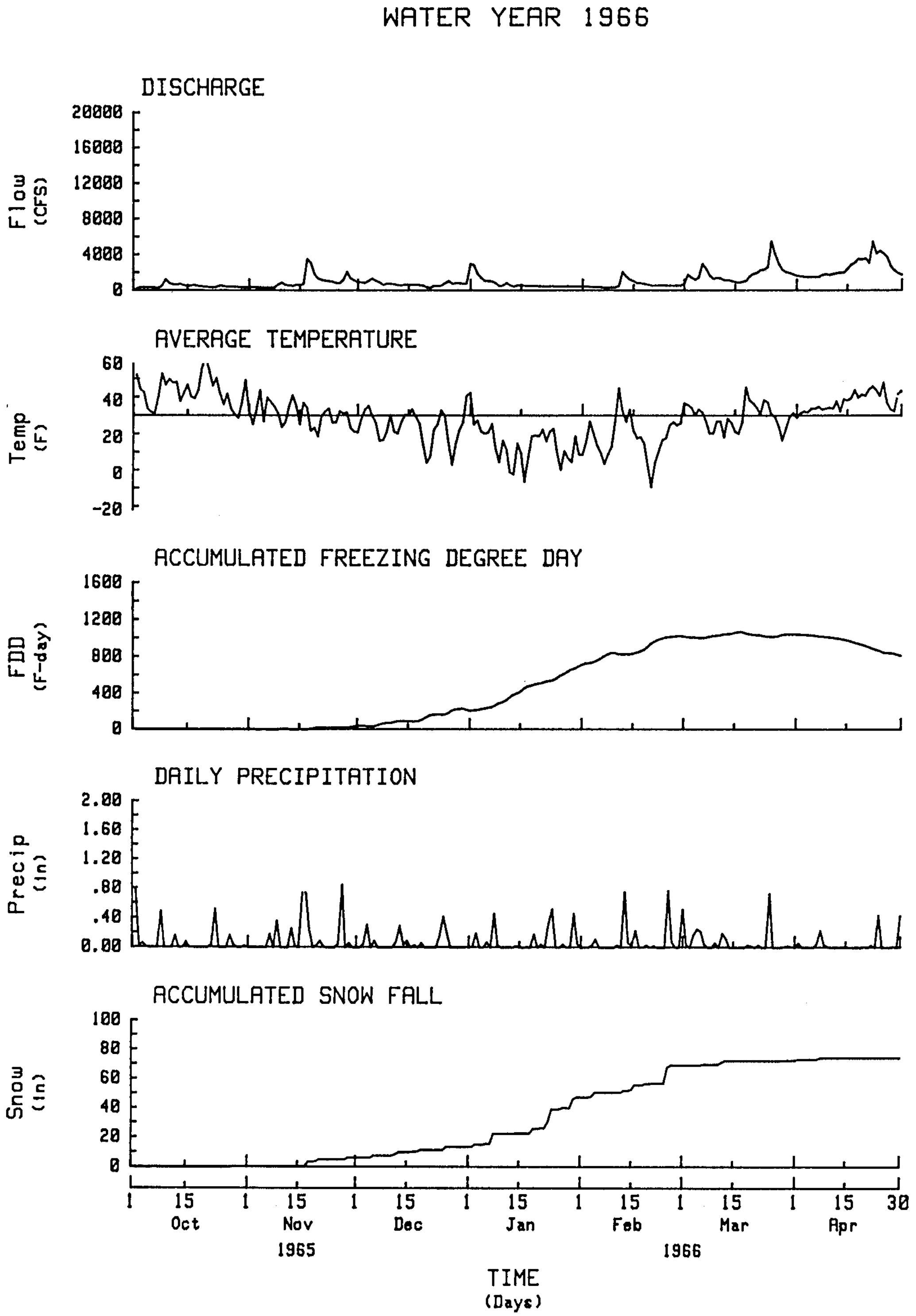
DISCHARGE

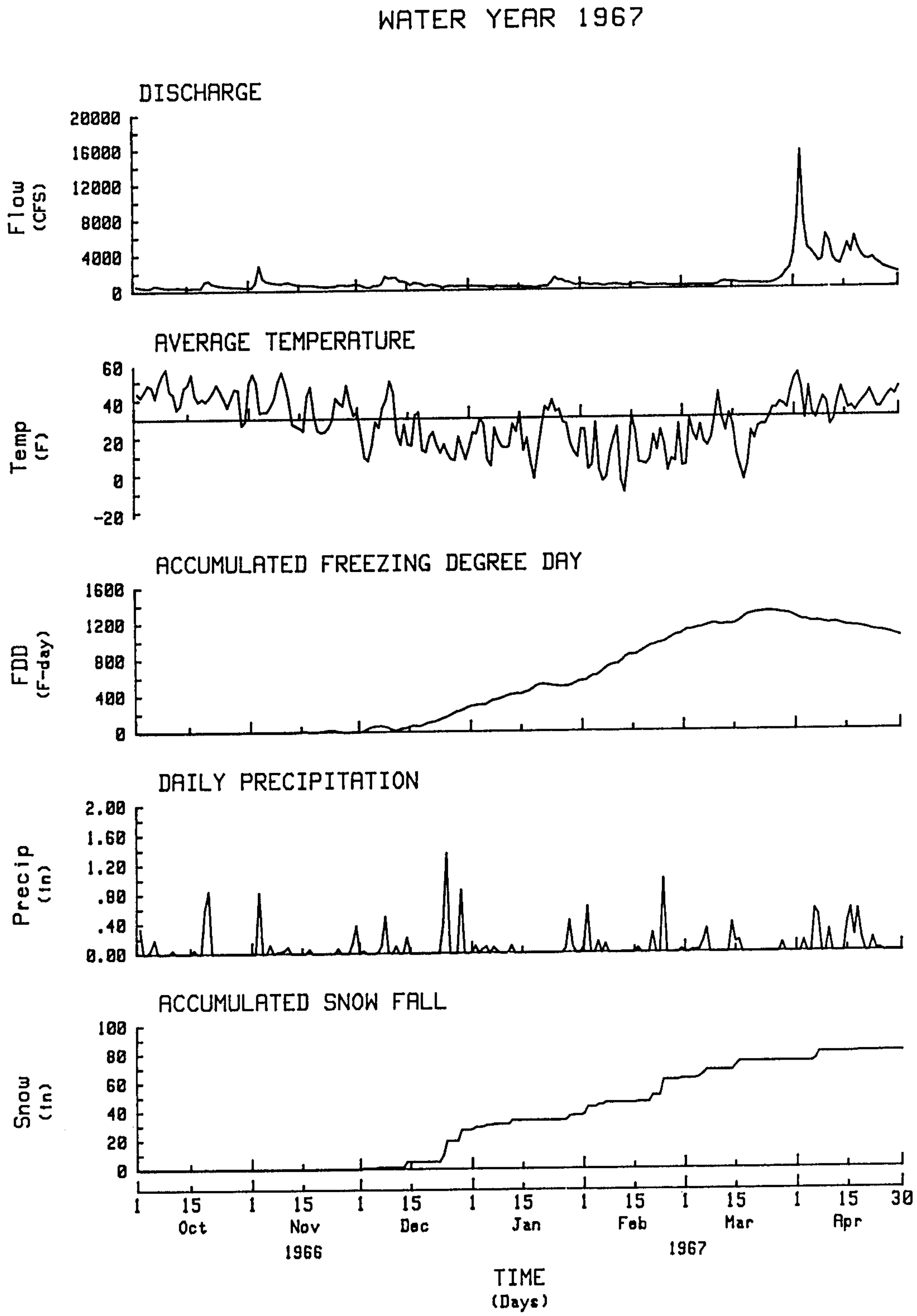
AVERAGE TEMPERATURE

ACCUMULATED FREEZING DEGREE DAY

DAILY PRECIPITATION

ACCUMULATED SNOW FALL


WATER YEAR 1966
DISCHARGE
Flow (CFS)
20000
16000
12000
8000
4000
0
AVERAGE TEMPERATURE
Temp (F)
60
40
20
0
-20
ACCUMULATED FREEZING DEGREE DAY
FDD (F-day)
1600
1200
800
400
0
DAILY PRECIPITATION
Precip (in)
2.00
1.60
1.20
.80
.40
0.00
ACCUMULATED SNOW FALL
Snow (in)
100
80
60
40
20
0
1
15
Oct
1
15
Nov
1965
1
15
Dec
1
15
Jan
1
15
Feb
1966
1
15
Mar
1
15
Apr
30
TIME
(Days)



WATER YEAR 1967

DISCHARGE

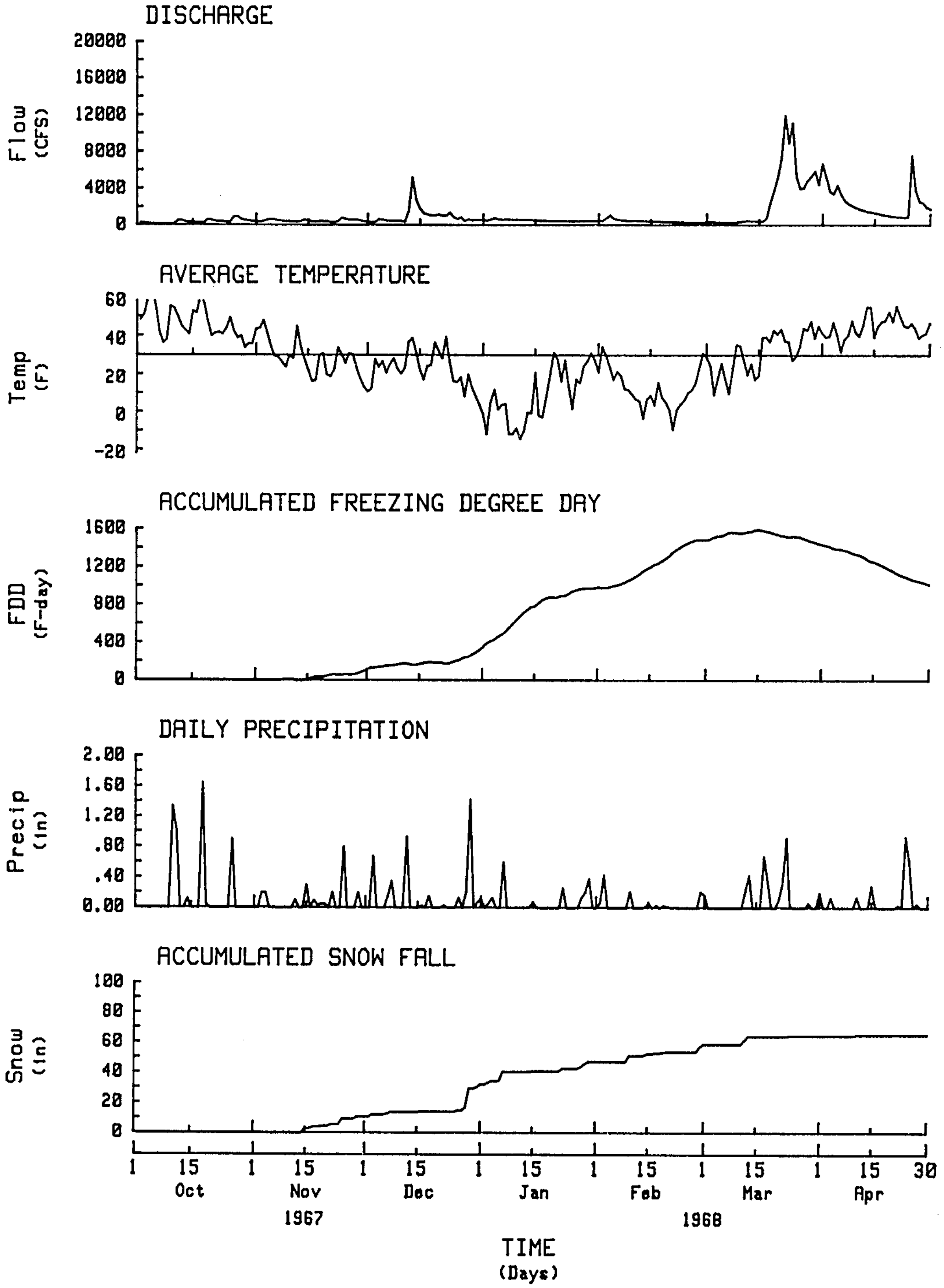
AVERAGE TEMPERATURE

ACCUMULATED FREEZING DEGREE DAY

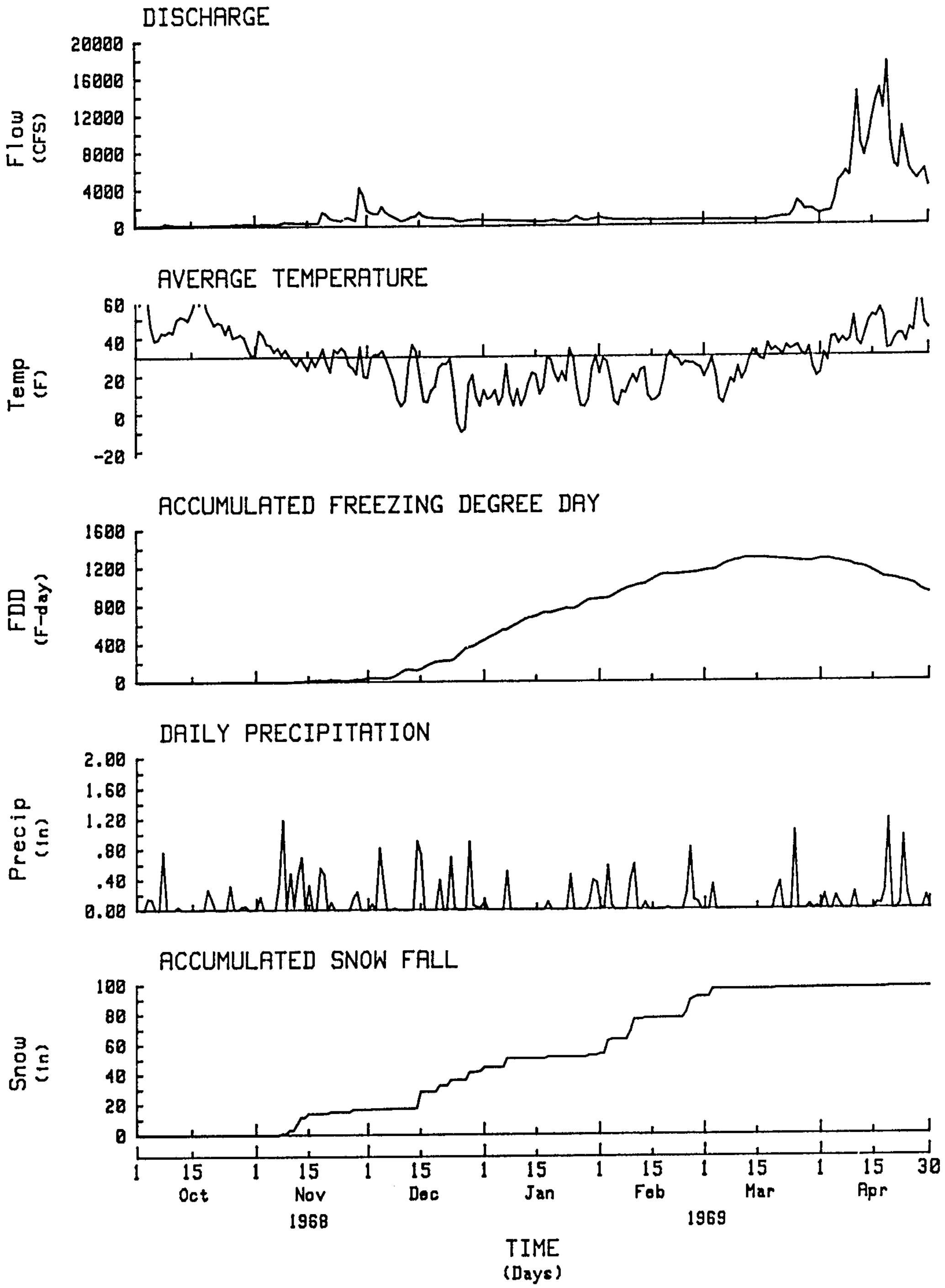
DAILY PRECIPITATION

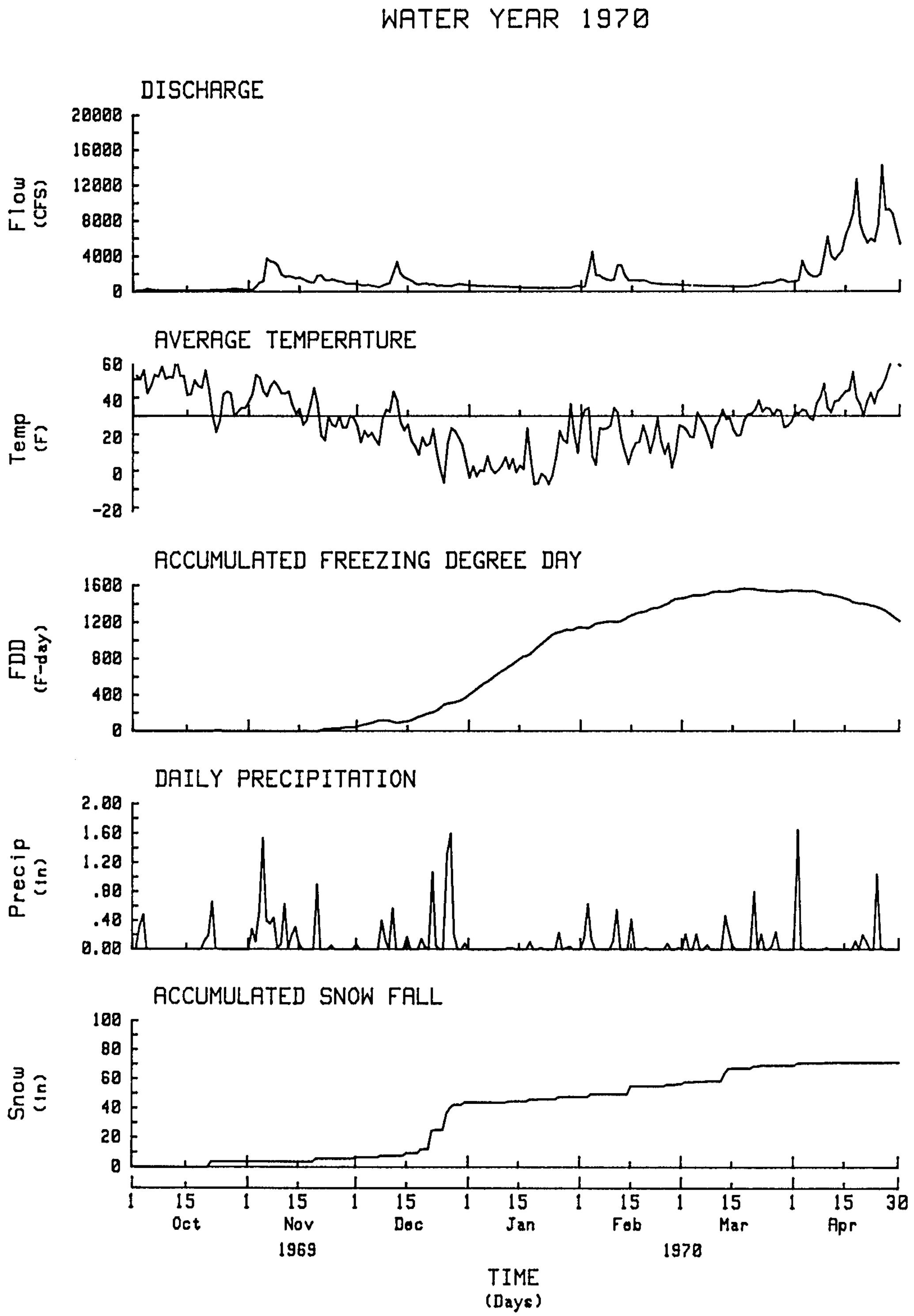
ACCUMULATED SNOW FALL

WATER YEAR 1968

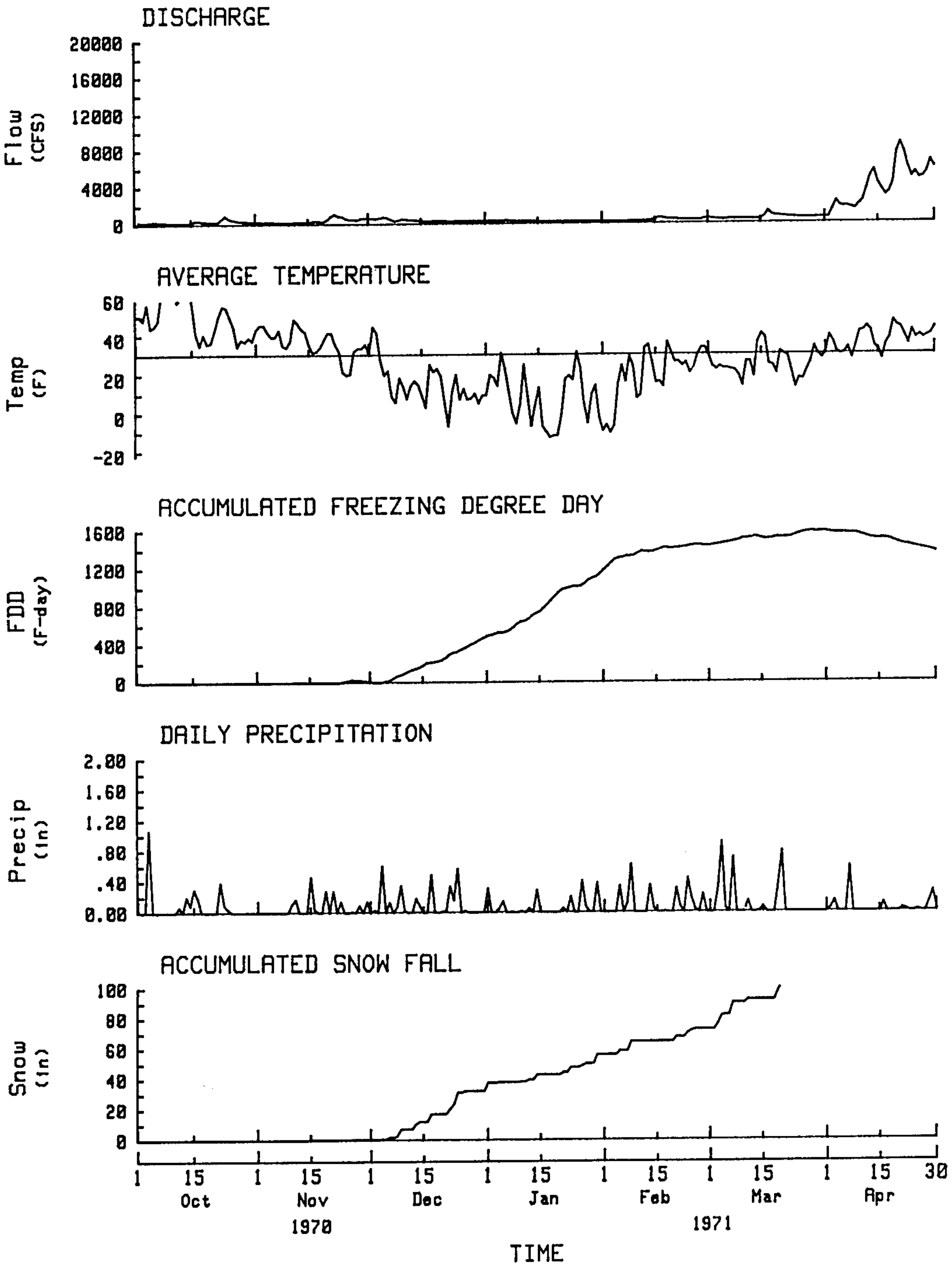


WATER YEAR 1969

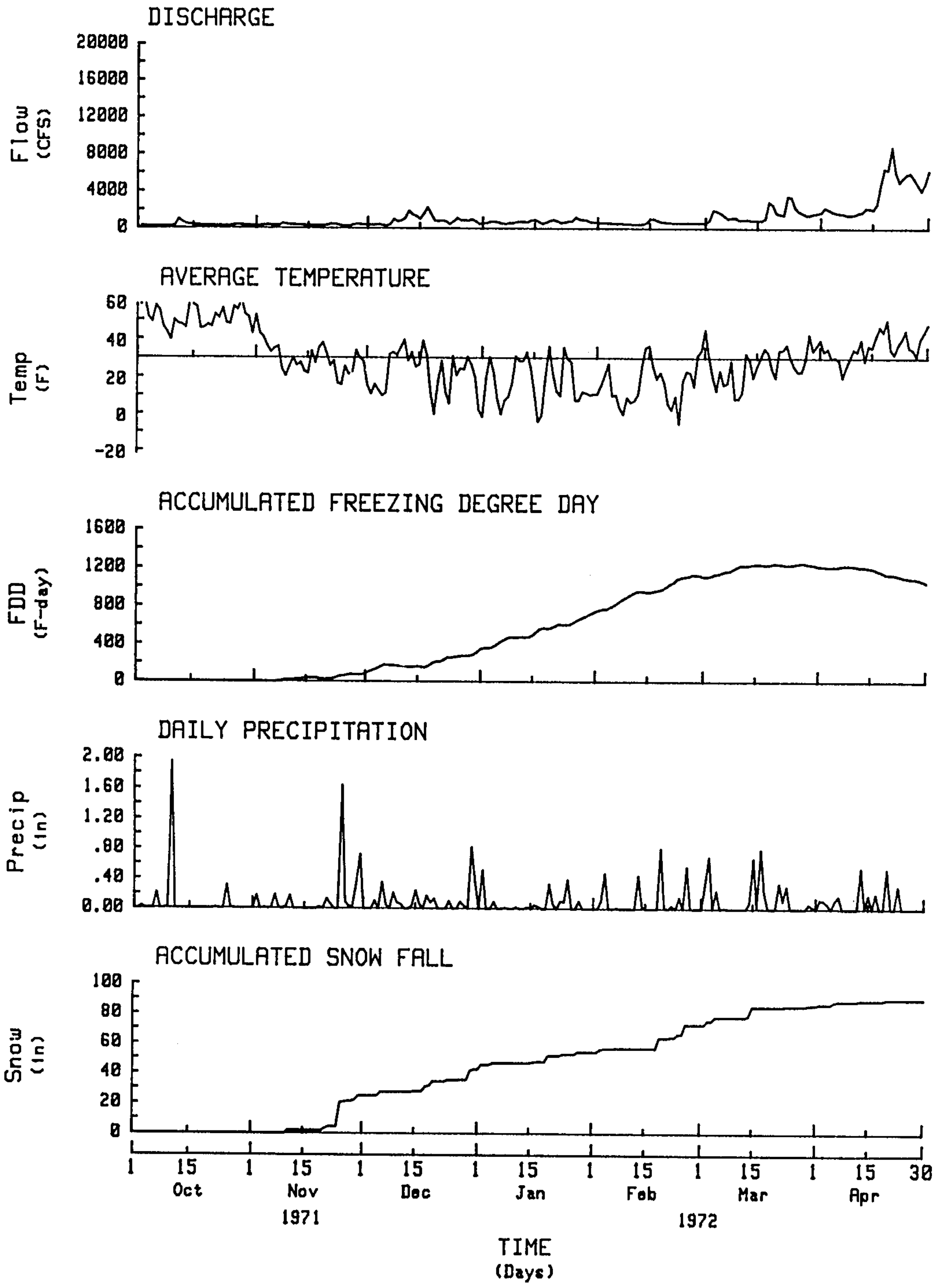



WATER YEAR 1970
DISCHARGE
Flow (CFS)
20000
16000
12000
8000
4000
0
AVERAGE TEMPERATURE
Temp (F)
60
40
20
0
-20
ACCUMULATED FREEZING DEGREE DAY
FDD (F-day)
1600
1200
800
400
0
DAILY PRECIPITATION
Precip (in)
2.00
1.60
1.20
.80
.40
0.00
ACCUMULATED SNOW FALL
Snow (in)
100
80
60
40
20
0
1
15
1
15
1
15
1
15
1
15
1
15
1
15
30
Oct
Nov
Dec
Jan
Feb
Mar
Apr
1969
1970
TIME
(Days)

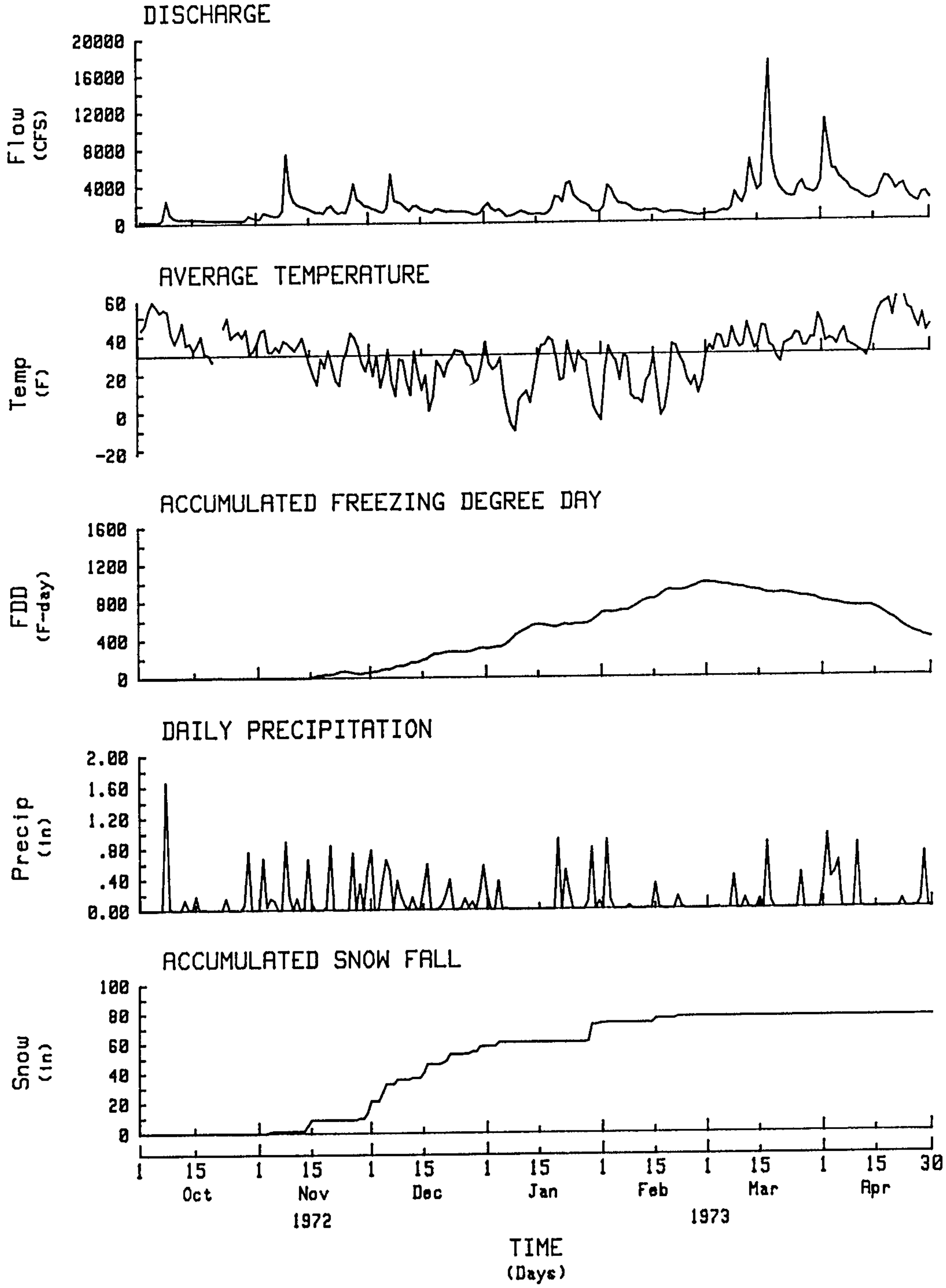
WATER YEAR 1971



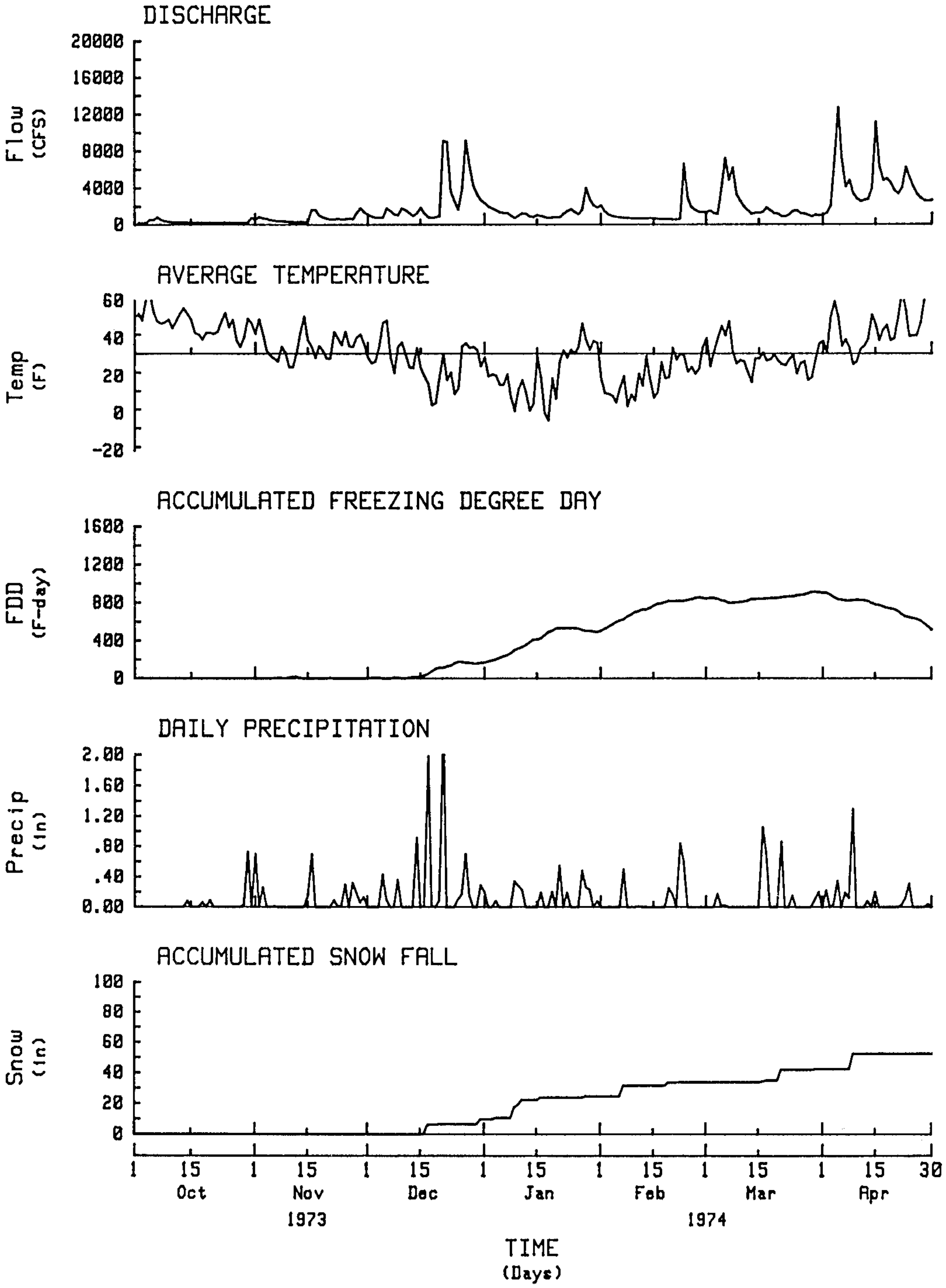
WATER YEAR 1972



WATER YEAR 1973



WATER YEAR 1974



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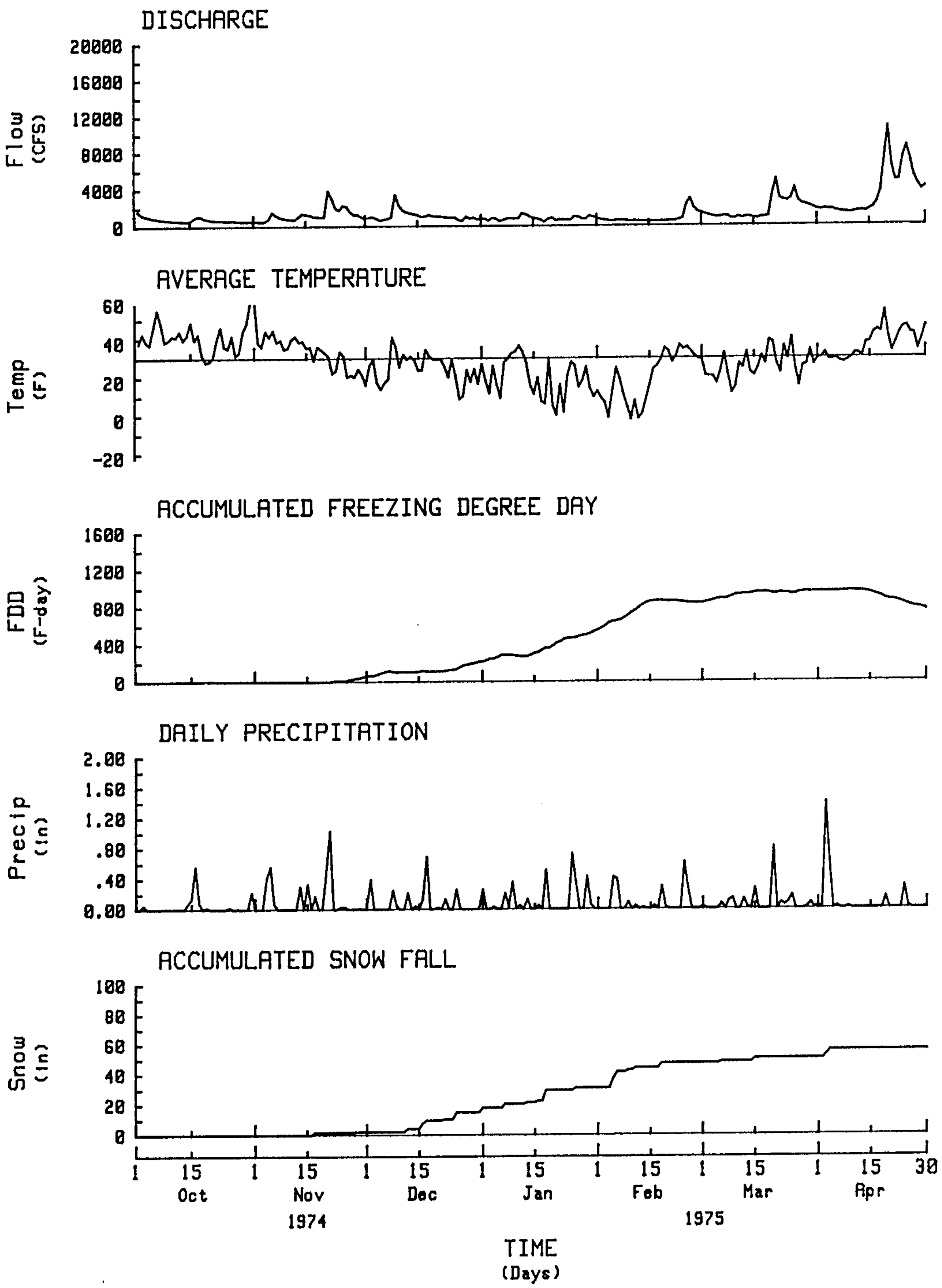
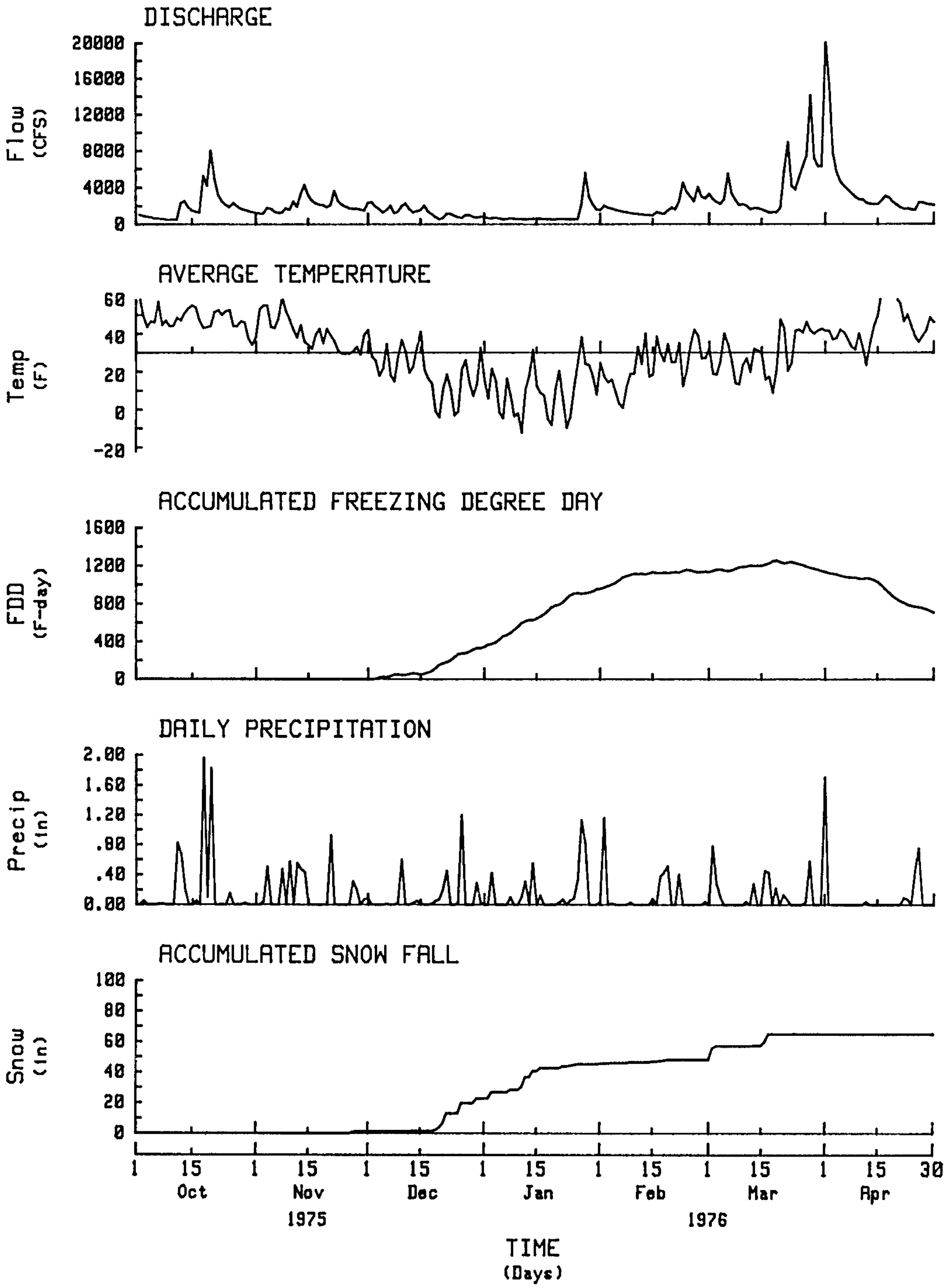
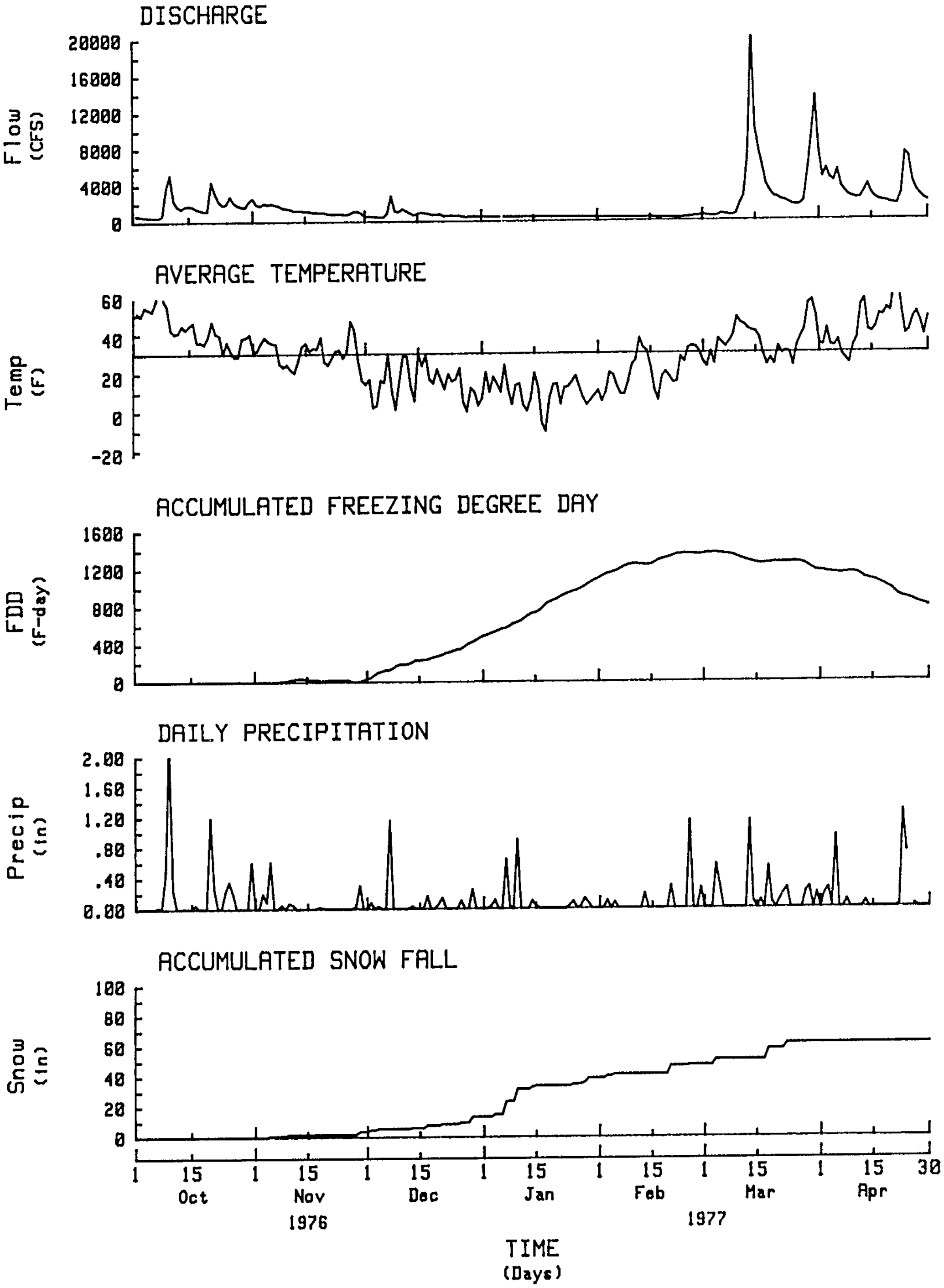


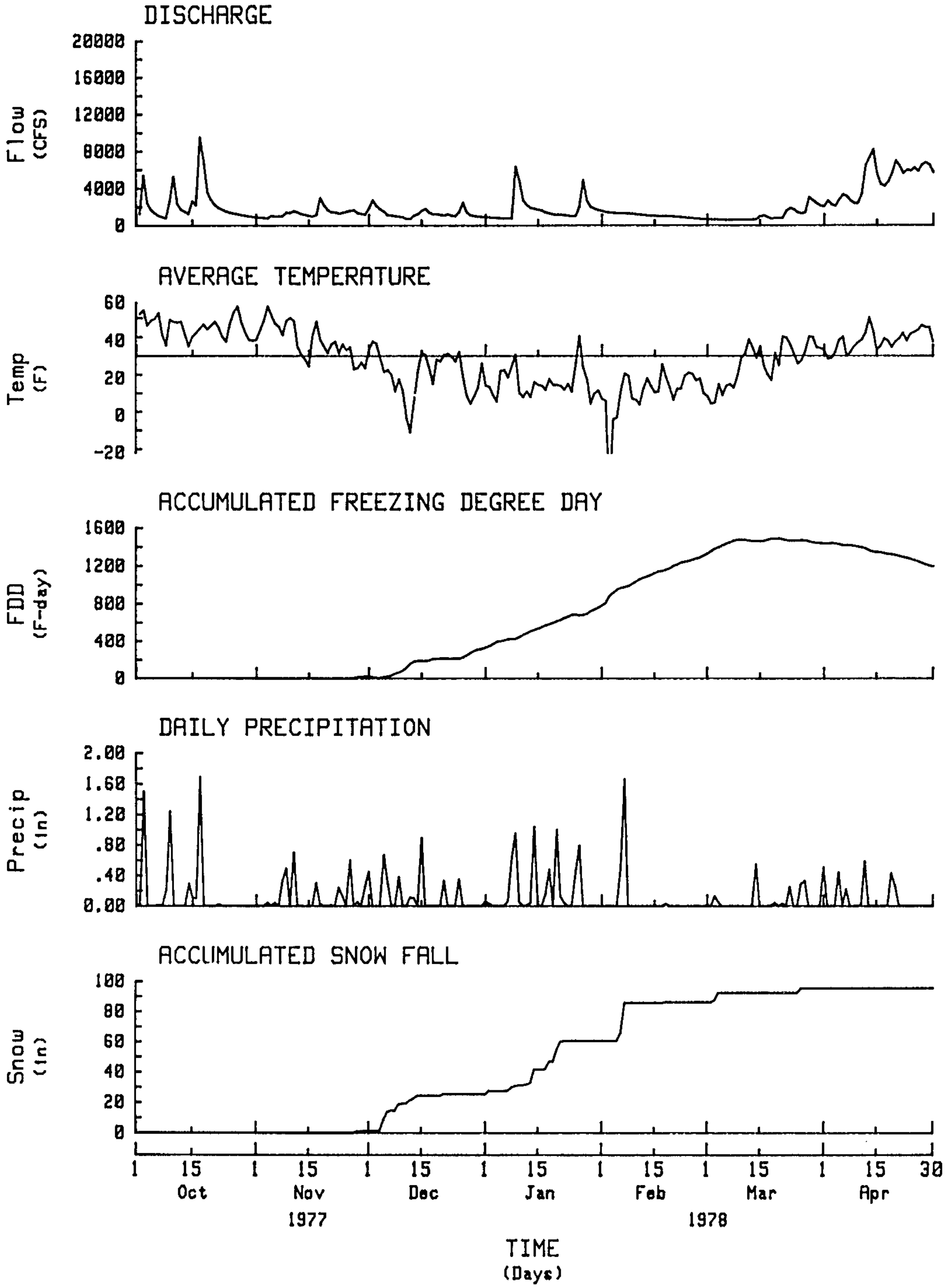
WATER YEAR 1976



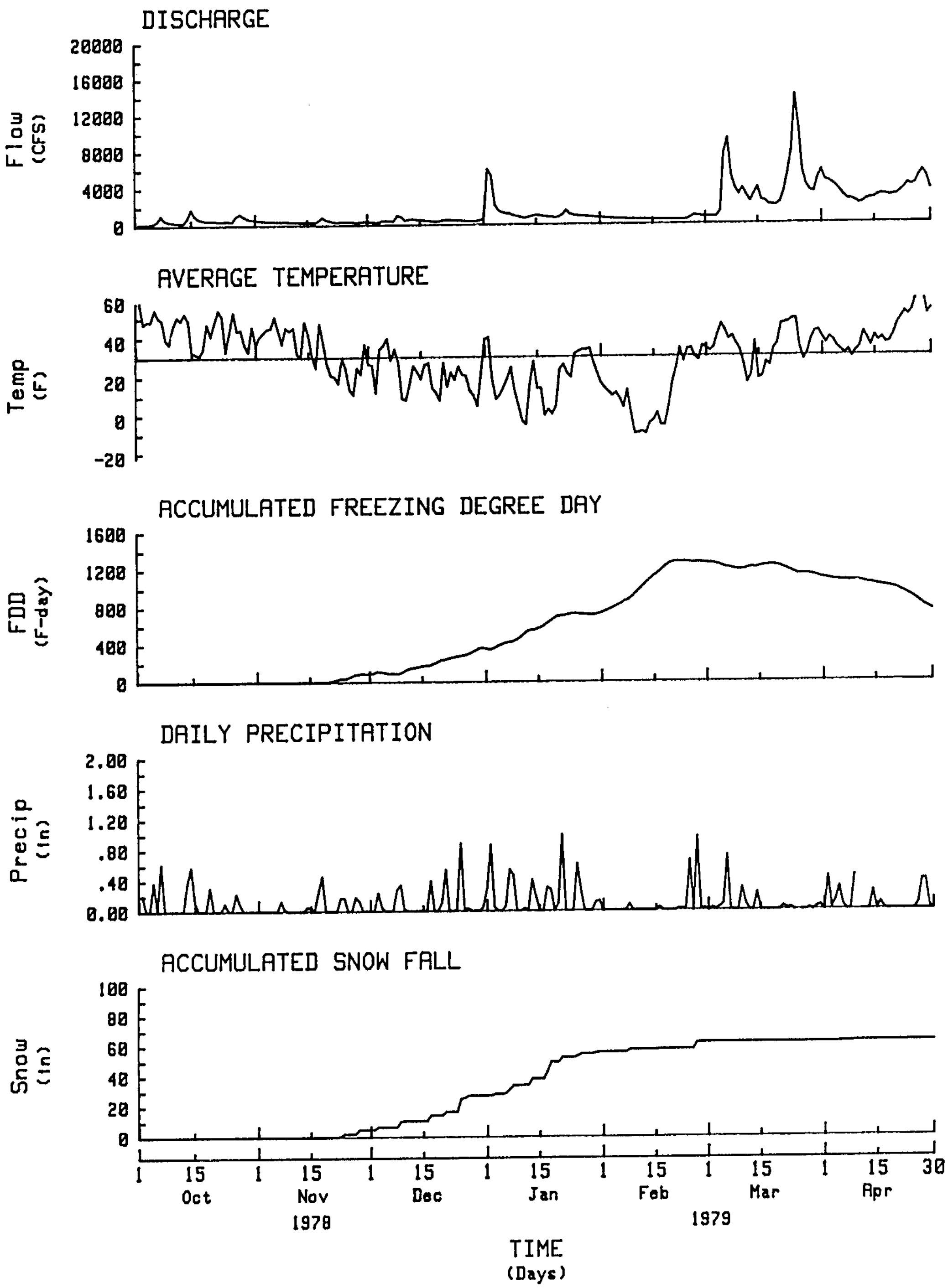
WATER YEAR 1977



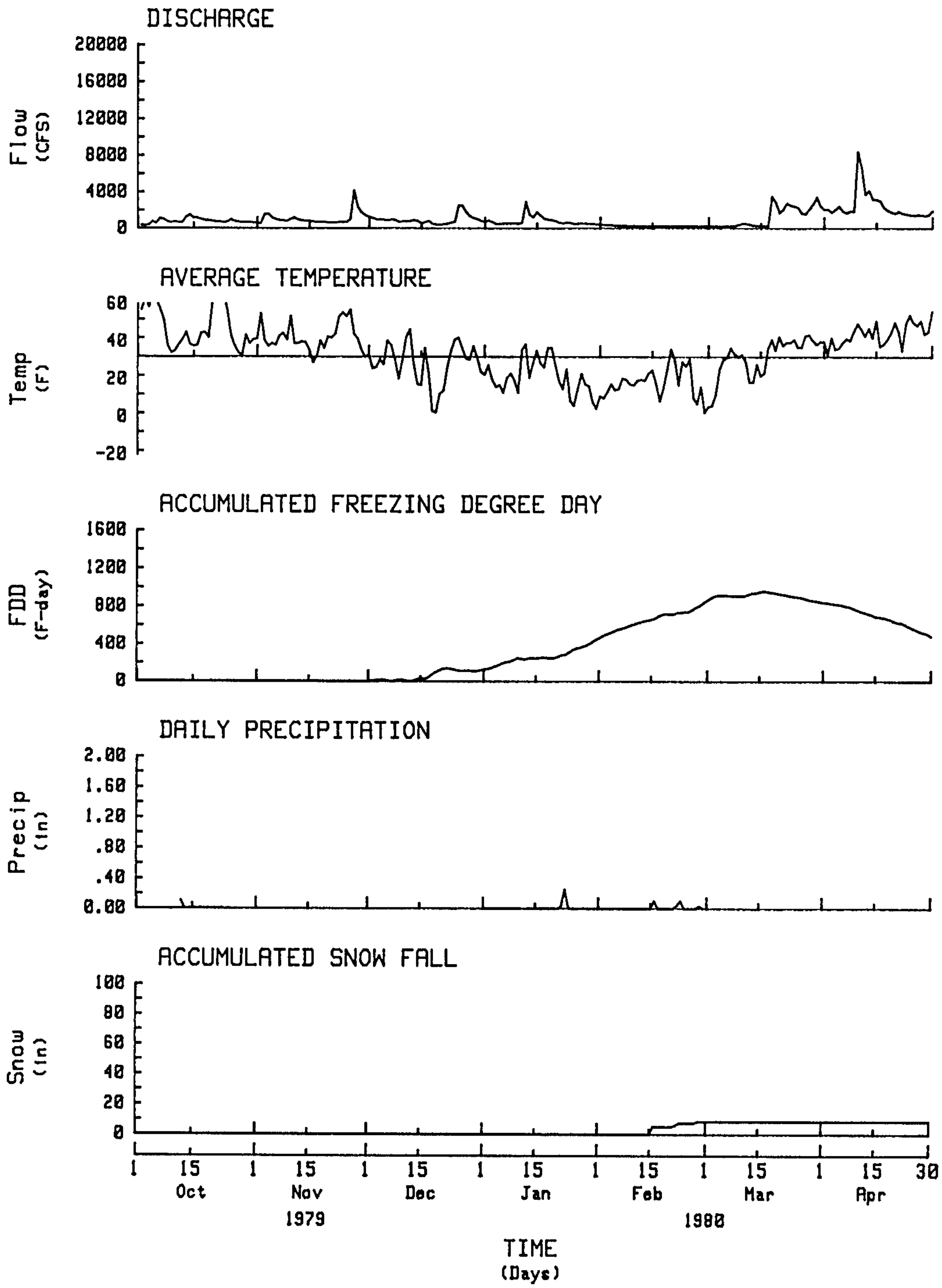
WATER YEAR 1978



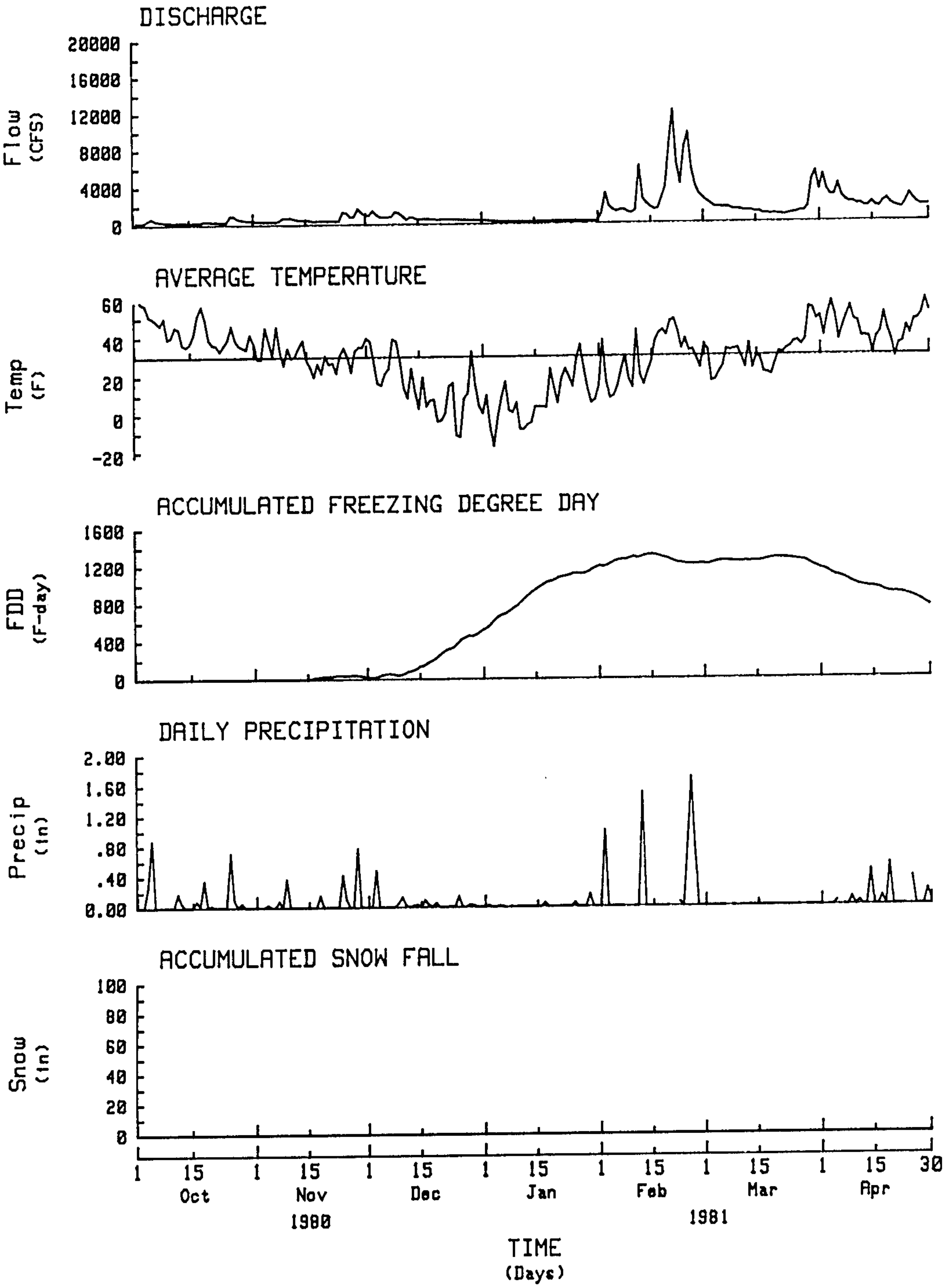
WATER YEAR 1979

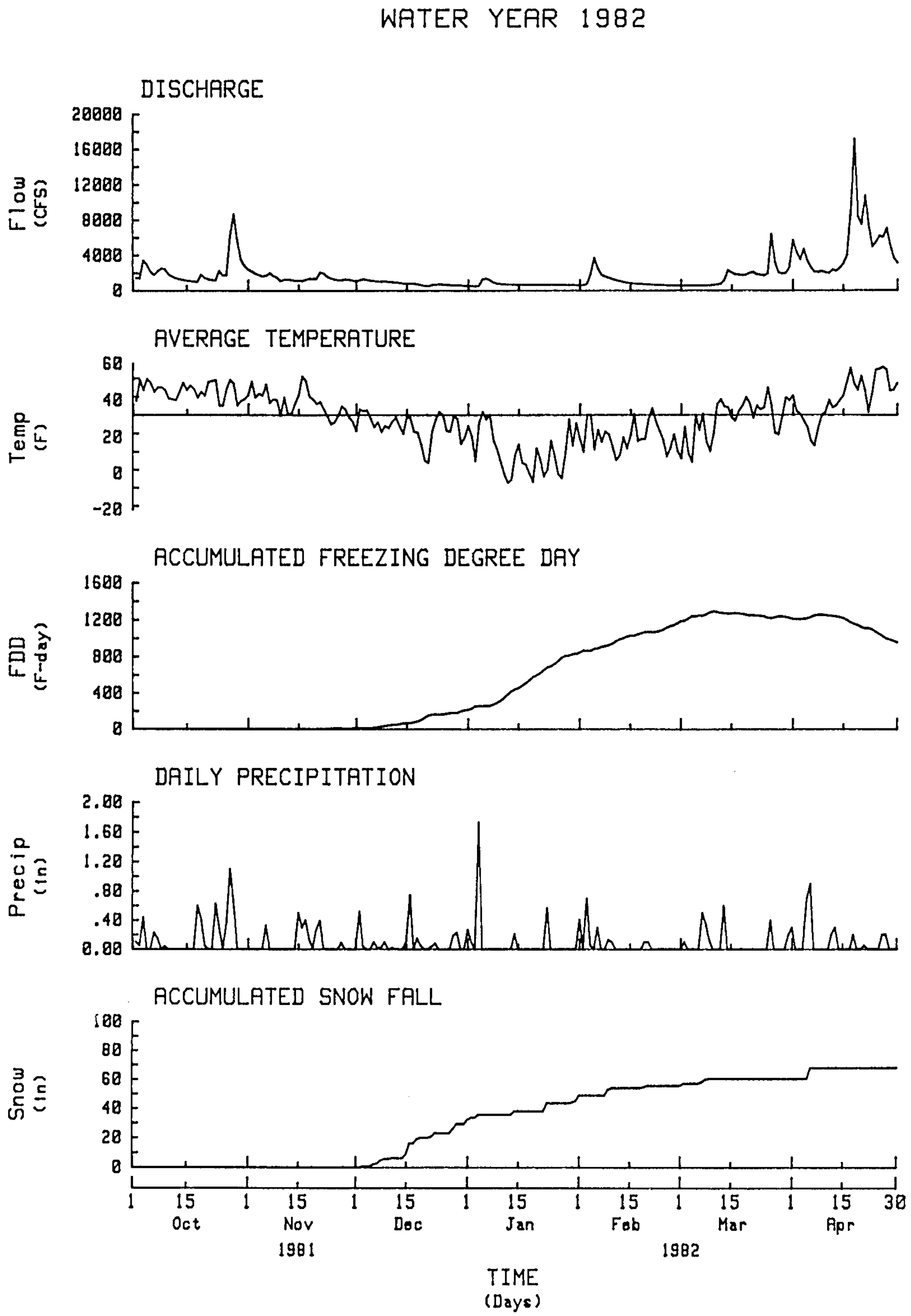


WATER YEAR 1980

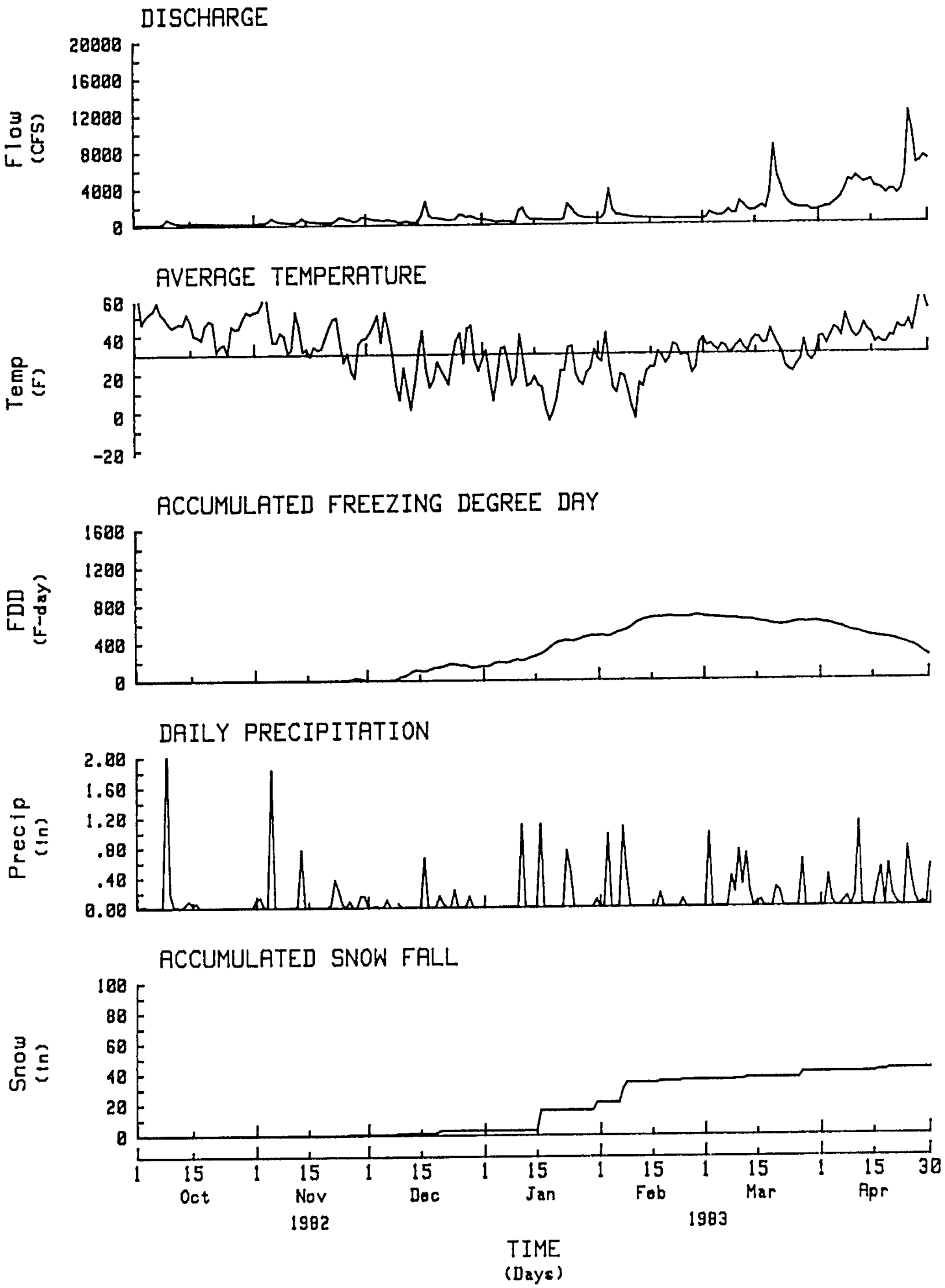


WATER YEAR 1981

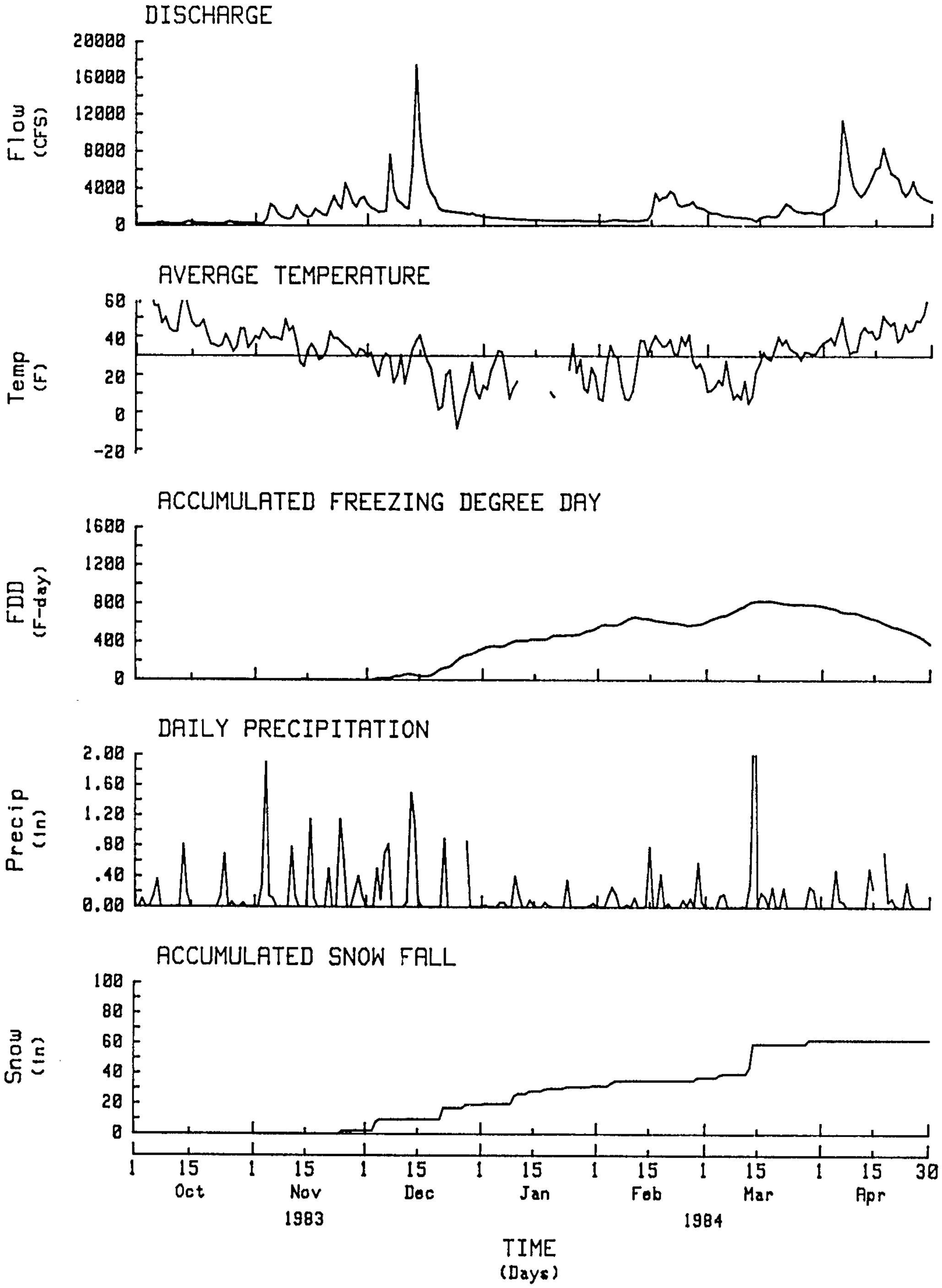



WATER YEAR 1982
DISCHARGE
Flow (CFS)
20000
16000
12000
8000
4000
0
AVERAGE TEMPERATURE
Temp (F)
60
40
20
0
-20
ACCUMULATED FREEZING DEGREE DAY
FDD (F-day)
1600
1200
800
400
0
DAILY PRECIPITATION
Precip (in)
2.00
1.60
1.20
.80
.40
0.00
ACCUMULATED SNOW FALL
Snow (in)
100
80
60
40
20
0
1
15
Oct
1
15
Nov
1981
1
15
Dec
1
15
Jan
1
15
Feb
1
15
Mar
1982
1
15
Apr
30
TIME
(Days)

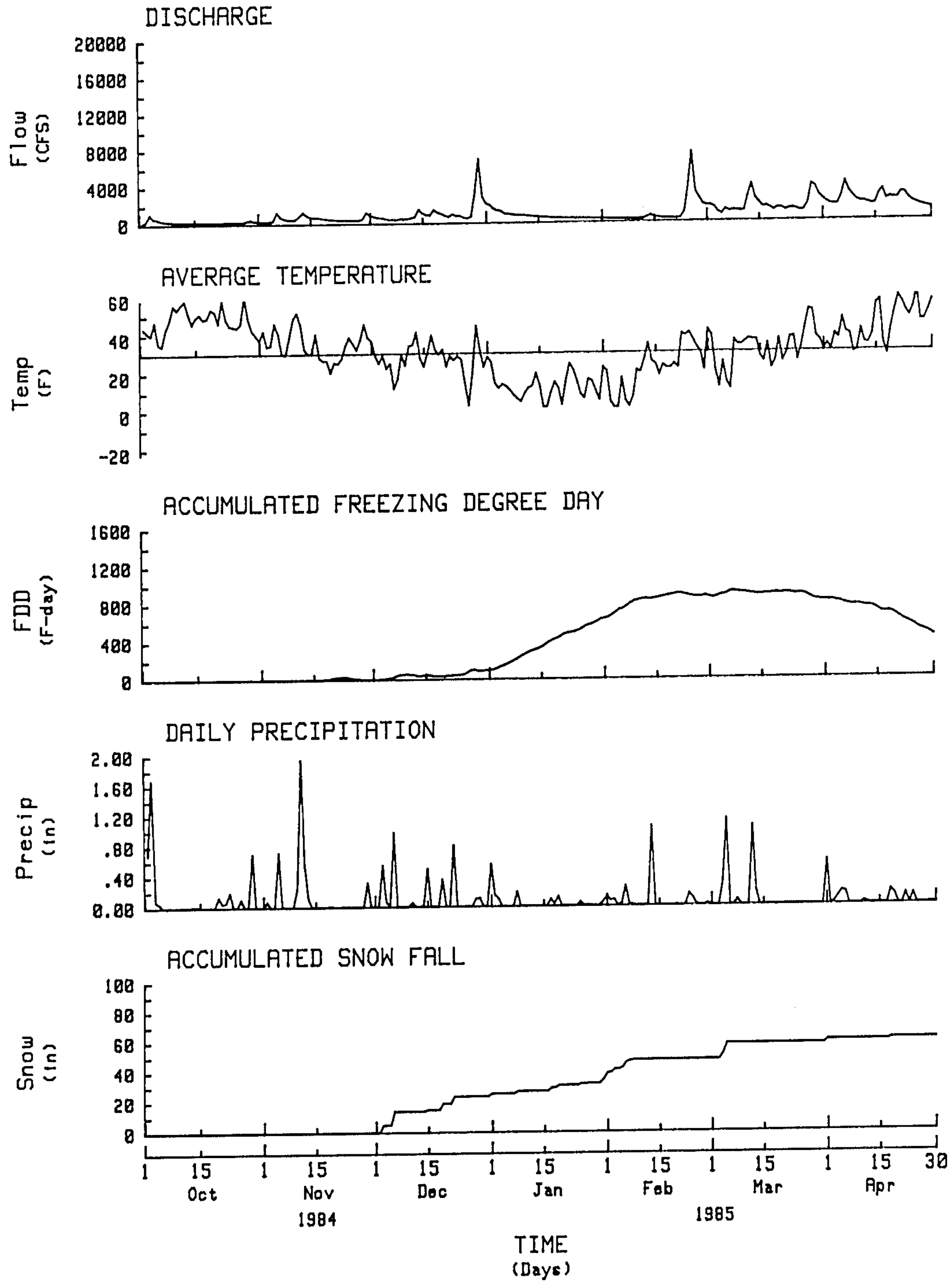
WATER YEAR 1983



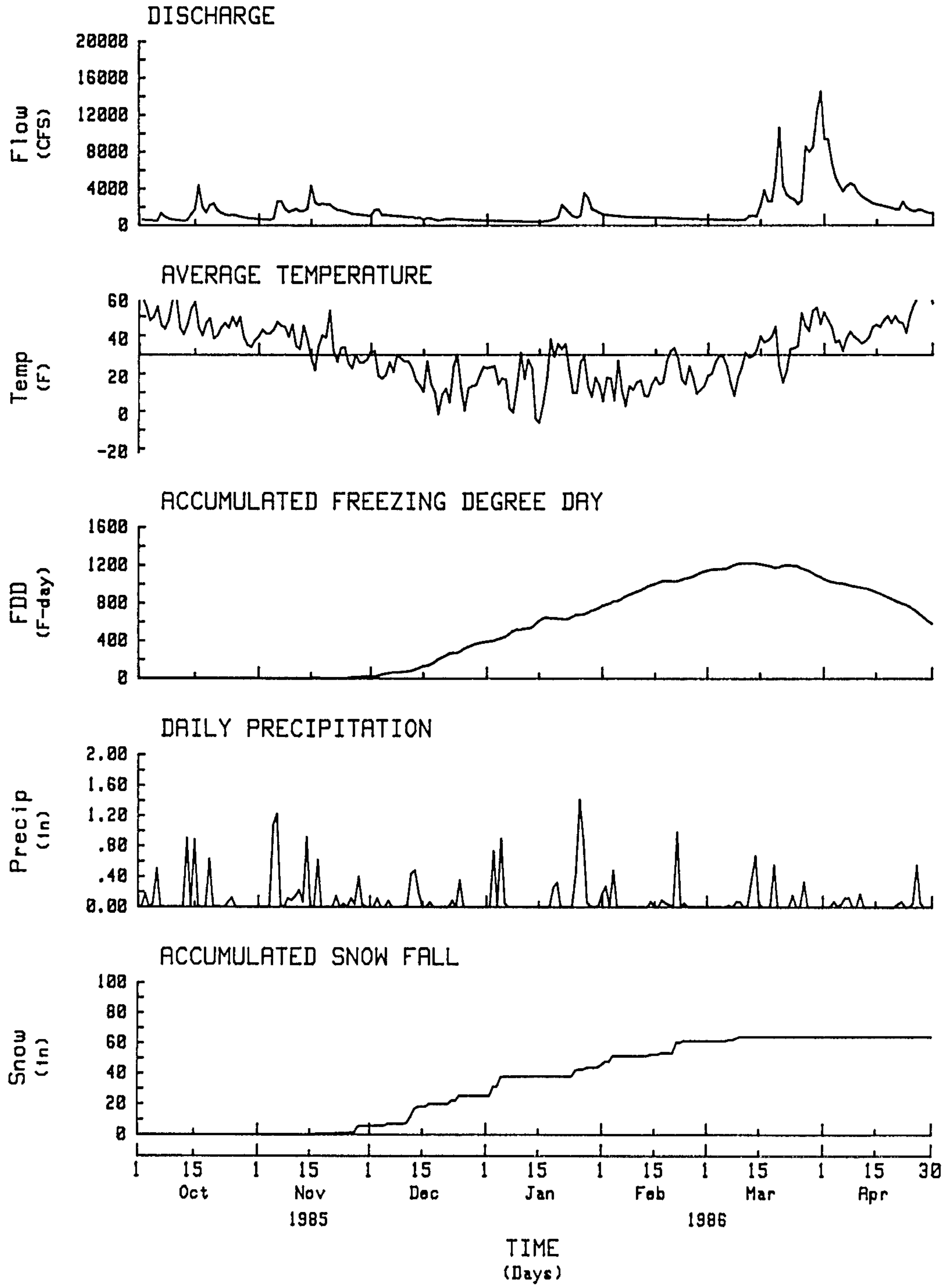
WATER YEAR 1984



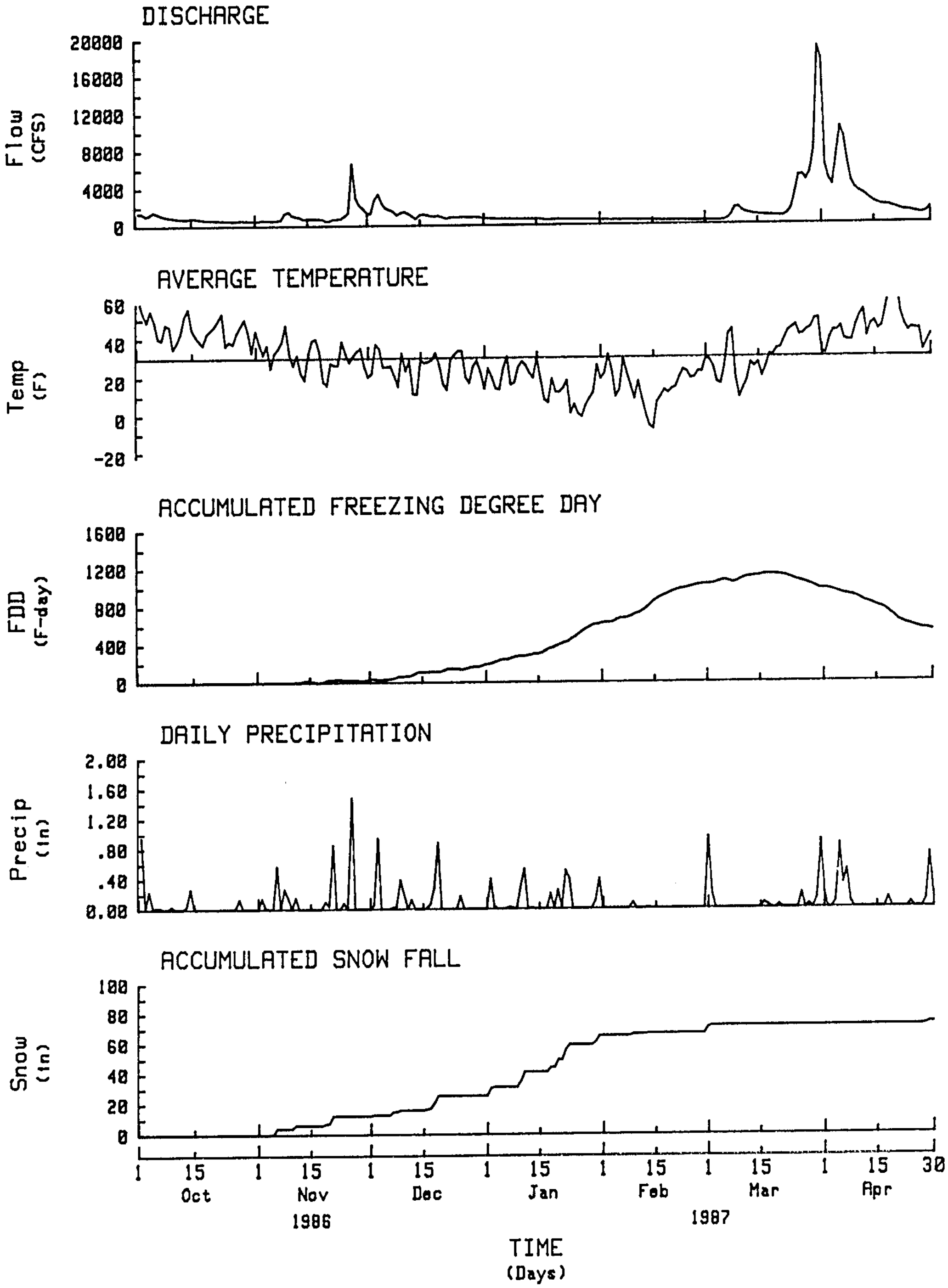
WATER YEAR 1985



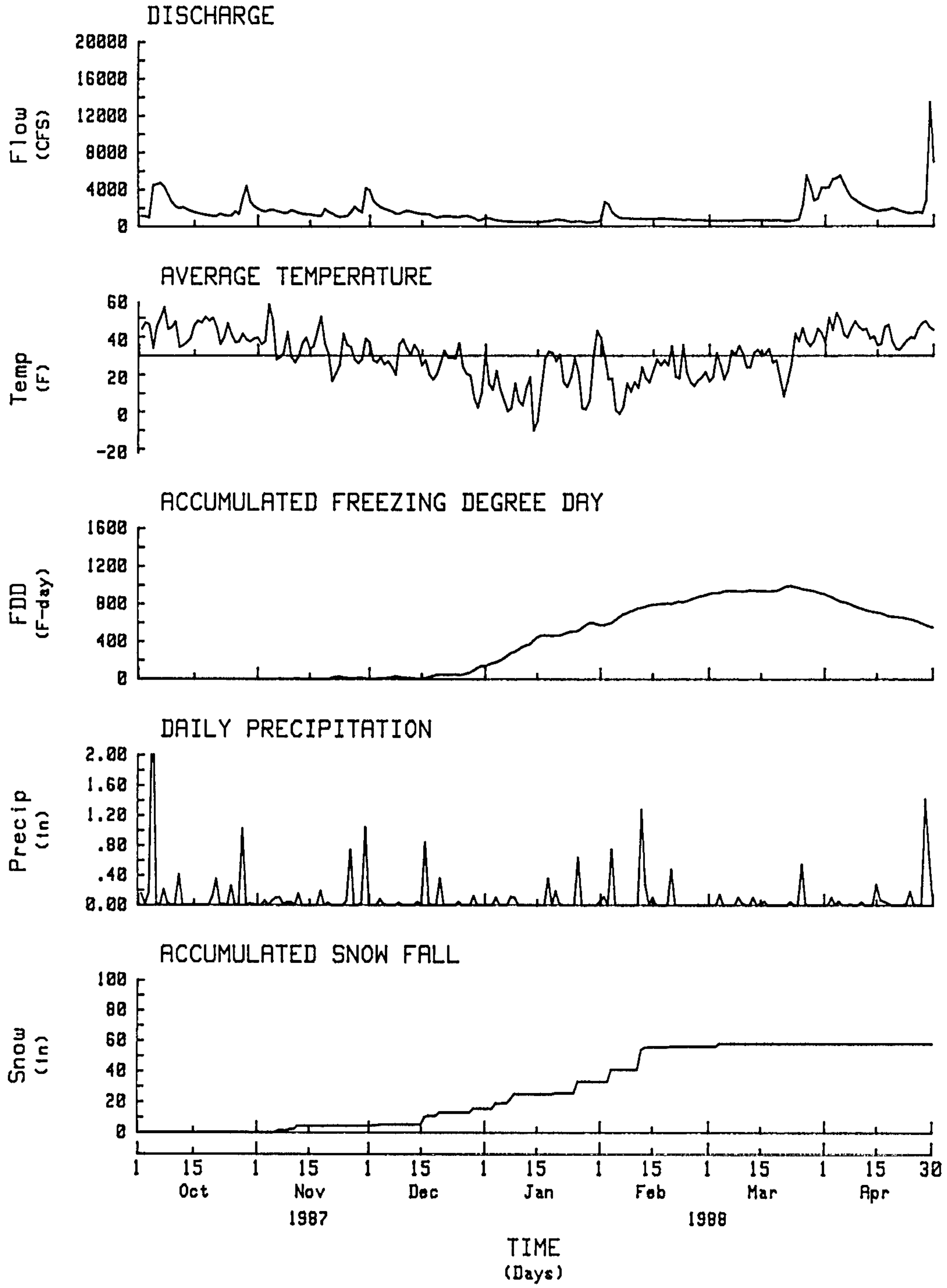
WATER YEAR 1986



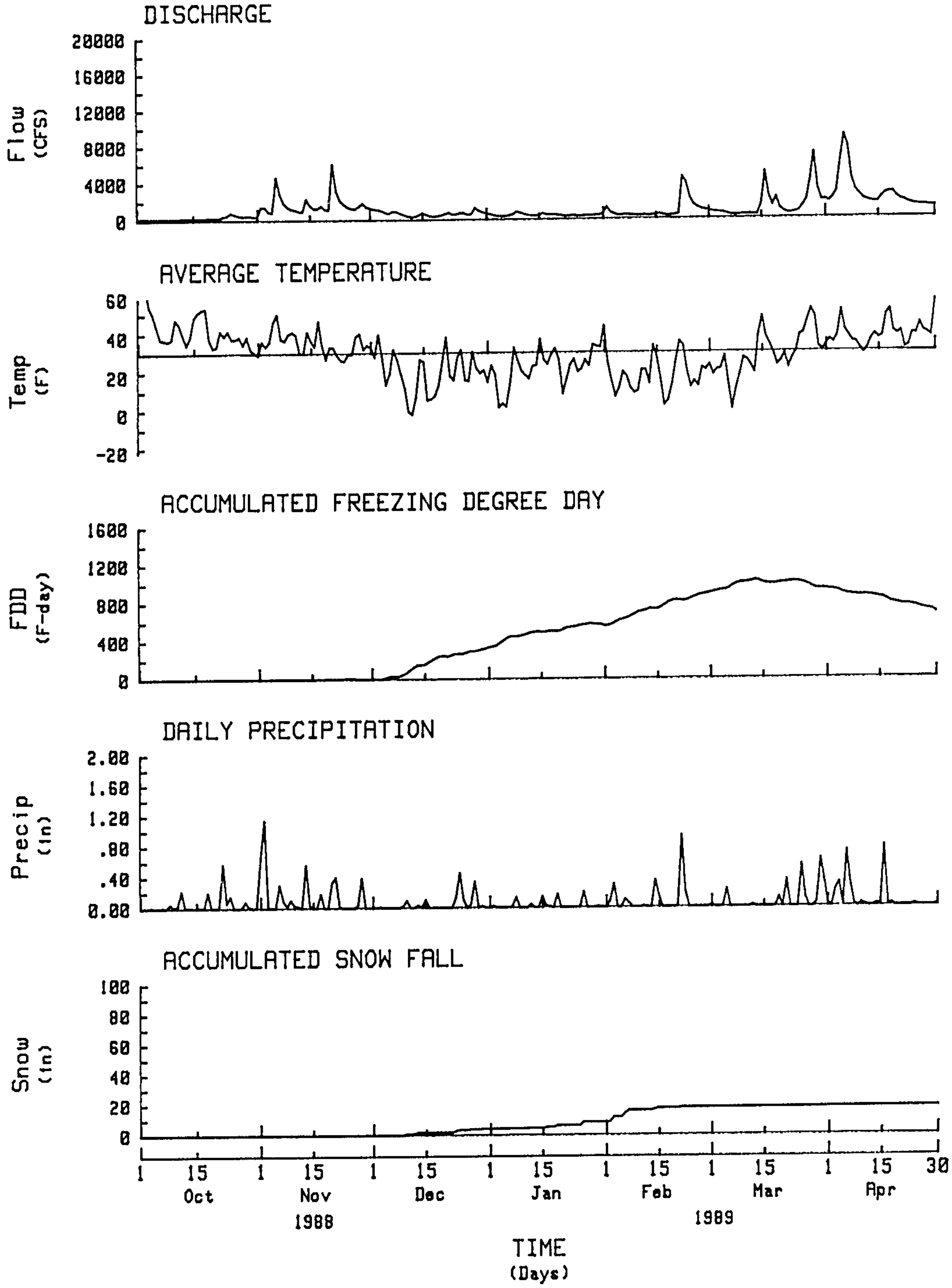
WATER YEAR 1987



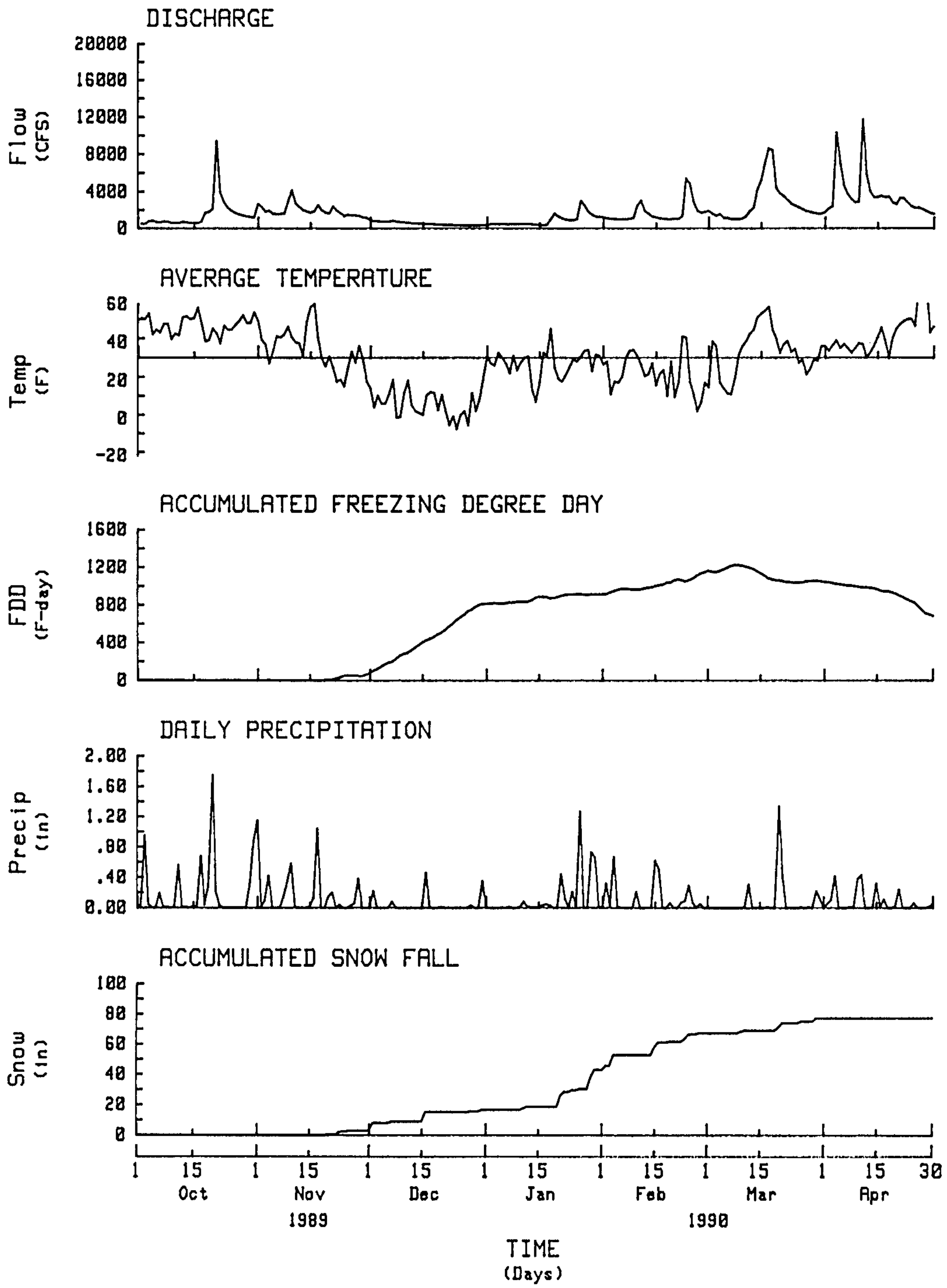
WATER YEAR 1988



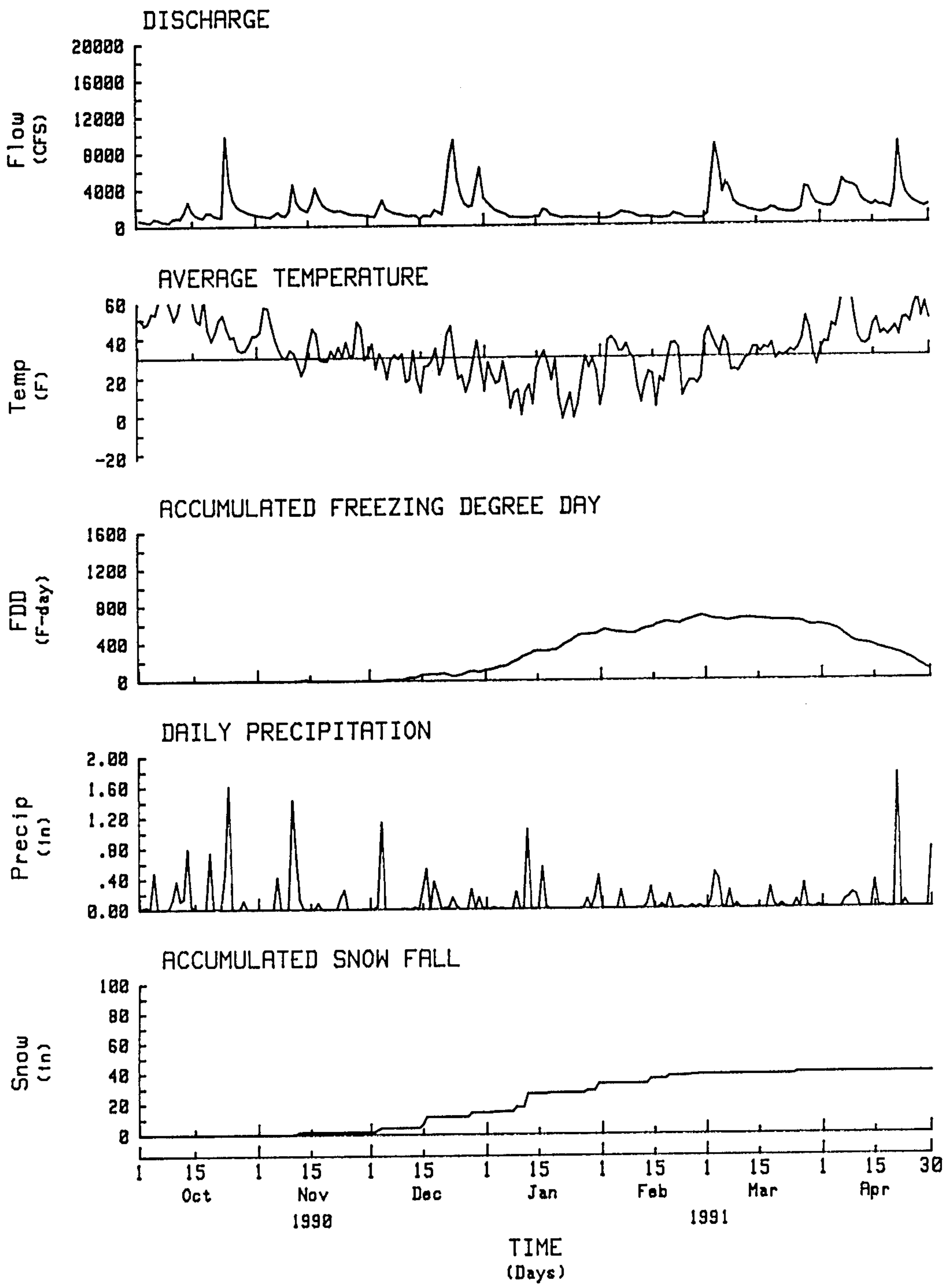
WATER YEAR 1989



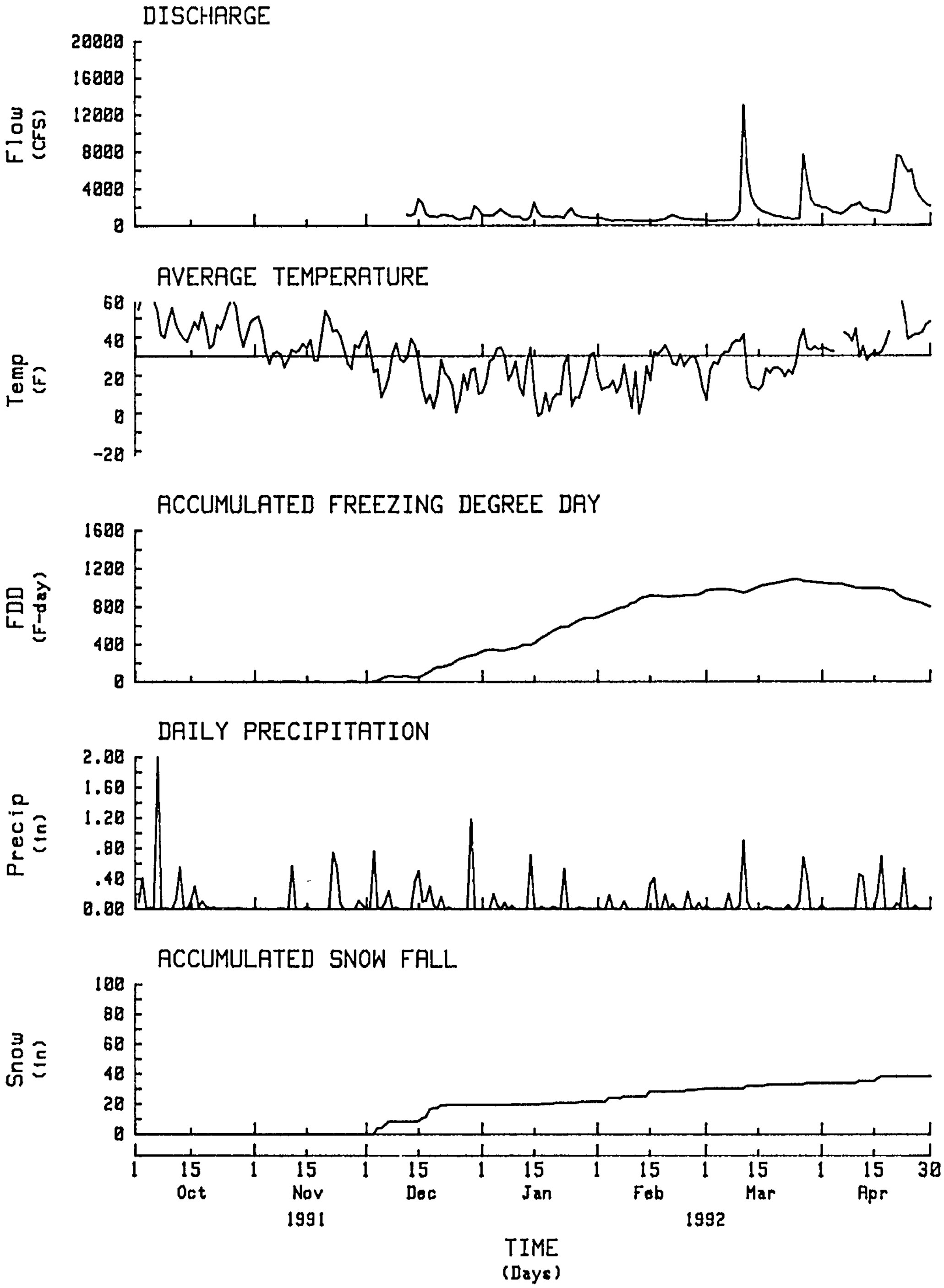
WATER YEAR 1990



WATER YEAR 1991



Water Year 1992



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13. ABSTRACT (*Maximum 200 words*)

In January 1990 a bridge over the White River in White River Junction, Vermont, collapsed during a period of ice breakup. Based on the historic weather and stage data, the bridge had survived more dramatic breakups in previous winters. The ultimate failure was attributed to the progressive deterioration of the foundation due to scour. Twenty years of weather and stage data at the site are presented along with a failure scenario. Instrumentation to measure the ice forces on a bridge pier was incorporated into the design of the replacement bridge. Recognizing scour as the primary cause of failure, the new bridge piers have extensive scour protection. A pier for a bridge 2000 feet upstream of the new bridge was instrumented for scour. The objective was to develop real-time scour monitors that would survive ice and debris and allow correlation between the hydrograph and scour activity. Instrumentation and data acquisition packages for both instrumented bridge piers are presented. The results of the first two years of measurements are presented. Both winters were relatively mild, consequently the breakup loads were low. The maximum dynamic load was 26 kips, which, with a 4-foot-wide panel and 12 inches of ice translates to an ice pressure of 45 psi. The scour measurements were of extreme interest. The bulk of the scour occurred in the initial stages of breakup while the ice sheet was still intact. Apparently to compensate for the fixed ice surface, the mean velocity had to increase as the discharge increased. The faster velocity resulted in more aggressive bed scour. Once the ice sheet broke up and the ice was free floating, the scour activity subsided.

14. SUBJECT TERMS

Ice forces   Scour   White River

15. NUMBER OF PAGES
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