

## **Aeration Systems and Winter Streamflow Measurements at Sleepers River, Danville, Vermont**

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### **ABSTRACT**

Research on water, energy and biogeochemical budgets was recently initiated at Sleepers River Research Watershed in rural northeastern Vermont. During the winter of 1990-91, aeration systems, designed to limit the accumulation of ice at streamflow-gaging station controls, were installed in two basins. At gaging-station W-5, which records flow from a 43-square-mile basin, aeration at the broadcrested concrete weir control was not totally effective at eliminating ice. Supplementary manual ice removal was necessary during extremely cold periods. At gaging-station W-3, which records flow from a 3.2-square-mile basin, the aeration system kept the concrete V-notch weir ice-free at temperatures above -18 degrees Celsius. To verify that the controls were free of backwater from ice, winter current-meter discharge measurements were made at open-water cross-sections at both sites. These measurements fell within 5-percent of the established rating curve, thus validating the open-water stage-discharge relation. A valid rating at an open control with an adjacent ice-covered reach provided a unique opportunity to evaluate current-meter measurements under ice. At station W-5, six measurements were made under ice cover at three cross-sections representing different channel geometries. The discharge measurements under ice were within 5 percent of the rated discharge.

### **INTRODUCTION**

Ice formation in stream channels and section controls at streamflow-gaging stations causes backwater and therefore affects stage-discharge ratings. Streamflow records collected during periods of ice formation are less accurate than records obtained during ice-free periods, because of the variable backwater effect. The winter record can be improved if a sufficient number of discharge measurements are made during ice-affected periods. Another approach for improving the reliability of winter discharge data is the reduction or removal of ice cover at gaging-station control structures. Although difficult to achieve, this method can significantly improve the accuracy of the winter record (Wagner, 1990).

Accurate winter streamflow measurement is an important component of the research at Sleepers River. Since their installation in 1958, gaging stations W-5 and W-3, with concrete weir controls, were kept largely ice-free. Ice

buildup was manually removed with ice chisels at weekly, and sometimes daily, intervals. In November 1990, as part of a joint study with the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), the U.S. Geological Survey (USGS) assumed operation of the two gaging stations. Faced with the costly and labor-intensive techniques previously used, the USGS sought other methods of ice management at the gaging-station controls.

The USGS implemented a pilot project to evaluate the effectiveness of an aeration system intended to maintain an ice-free environment at gaging-station controls. The pilot project ran for two winter seasons, 1988-89 and 1989-90, at selected sites in New York and North Dakota (Wagner, 1990). Preliminary results indicate that the technique offers an effective method of preventing ice formation at control structures. Based on the encouraging results of the pilot project, aeration systems were designed and installed at the two gaging stations in the Sleepers River basin.

The concept behind the aeration system, as developed by the pilot project, is that the bubbles released from the diffusers on the streambed cause relatively warm water to rise to the surface (Wagner, 1990). The warm water and the surface disturbances caused by the rising bubbles combine to inhibit ice formation. In order for warm water to rise with the bubbles the gage pool must be thermally stratified. To determine if the pool was thermally stratified, vertical temperature profiles were measured at several locations.

The stage-discharge rating during winter conditions was validated by making open-water current-meter measurements. If the measured discharge was within the normally accepted error of 5 percent, the open-water rating was considered to be verified. The situation of an open control with a valid rating, and an adjacent ice-covered reach, provided a unique opportunity to evaluate current-meter measurements under ice.

To study the accuracy of ice current-meter measurements under ice, a series of discharge measurements was made from ice cover at different cross-sections. The measured discharges were compared to those from the open-water rating curve. Normally, the accuracy of discharge measurements under ice can not be evaluated directly.

## SITE DESCRIPTION

Cross-section control structures at gaging-stations W-5 and W-3 are concrete weirs. Station W-5, located at the outlet of the basin (Figure 1), has a drainage area of 43 mi<sup>2</sup> (112 km<sup>2</sup>). The broadcrested weir control (20:1 slope) is located 30 ft (9 m) downstream from the gage house and stilling well. The normal width of flow at the control during the winter of 1990-91 was 35 to 40 ft (11 to 12 m) and discharges ranged from 30 to 50 ft<sup>3</sup>s<sup>-1</sup> (0.9 to 1.5 m<sup>3</sup>s<sup>-1</sup>). Station W-3 has a drainage area of 3.2 mi<sup>2</sup> (8.3 km<sup>2</sup>). The broadcrested weir control (5:1 slope) is located 20 ft (6 m) downstream from the gage house and stilling well. Flow width at the control during the winter of 1990-91 was normally 8 to 9 ft (2.5 to 3 m) and discharge ranged from 3 to 6 ft<sup>3</sup>s<sup>-1</sup> (0.1 to 0.2 m<sup>3</sup>s<sup>-1</sup>).

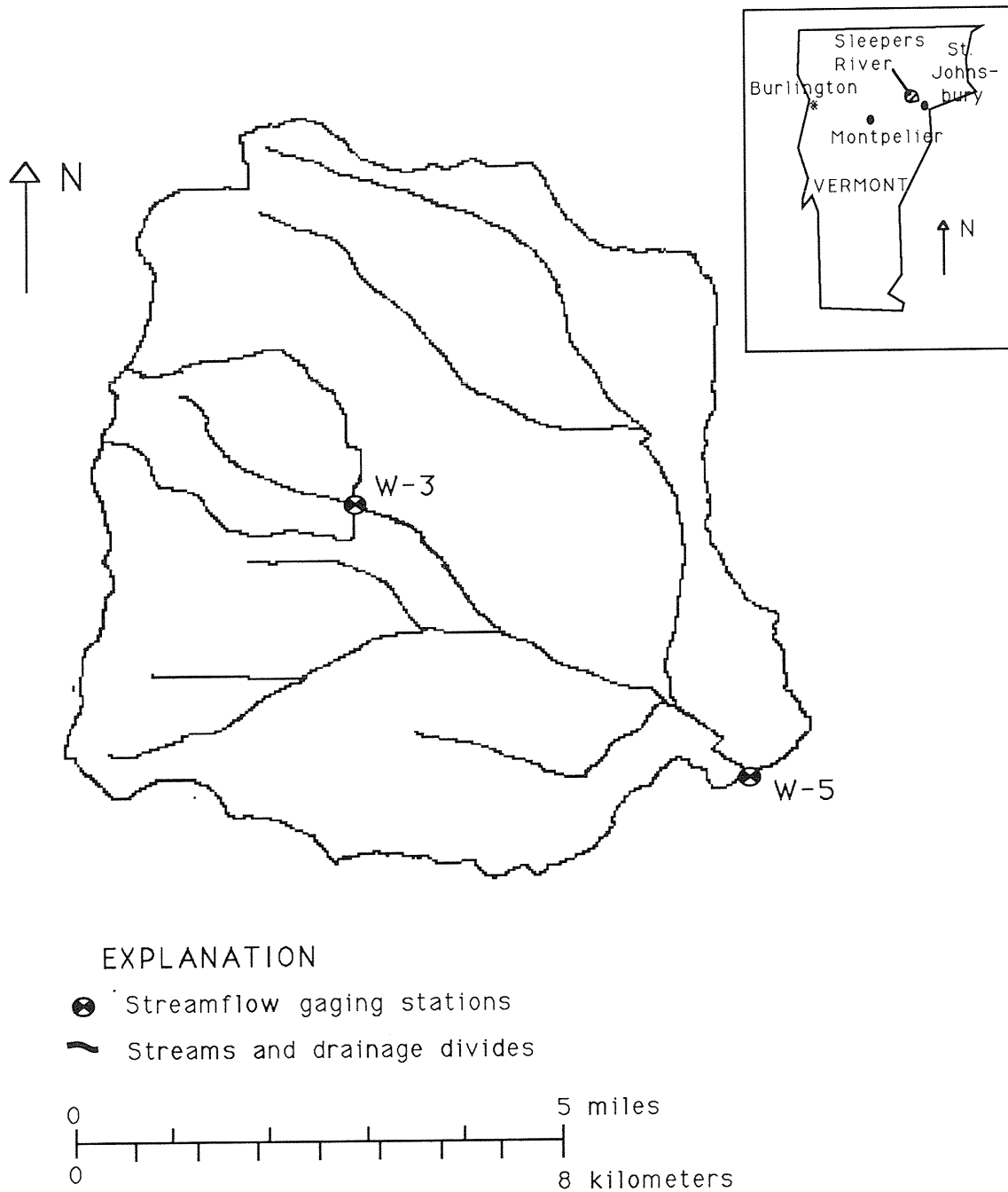


Figure 1. Map of Sleepers River basin, with location of streamflow measurement sites.

## AERATION SYSTEM

### Equipment and Procedure

The aeration system consists of a low-pressure, high-volume electric air pump mounted in the gage house, and a diffusion system that distributes air upstream from the weir. The diffuser system was constructed of 1.0-in (2.5-cm)-inside-diameter black plastic water pipe, with nylon pipe connectors and steel hose clamps.

Plastic material was used because it is economical, durable and easily modified. The drawbacks associated with the plastic pipe are its tendency to curl during installation and its buoyancy when aerated. These problems were overcome by attaching river rocks to the diffuser system to hold it in position. A propane torch, cordless drill, and roto-hammer were essential tools in the assembly process.

The initial aeration diffuser at station W-5 (installation #1) was washed away in late December 1990, during a warming trend that caused significant runoff. Typically, ice cover at this site remains stable throughout the winter; however, during December 1990, conditions similar to spring breakup occurred. Although the diffuser was washed downstream, much of the equipment was retrieved and reused in installation #2. The economic advantage of plastic pipe over galvanized steel or copper pipe was obvious after the washout.

*Site W-5* -- The aeration system at station W-5 (Figure 2) consisted of an air pump mounted in the gage house. A pressure gage and pressure relief valve were attached under the pump. The air line, consisting of black plastic water pipe, was bracketed to the inside of the stilling-well wall and it exited from the intake pipe. A brass check valve was installed in the air line just past the end of the intake. In installation #1 (Figure 2), the air line ran downstream about 20 ft (6 m) to a connection in the middle of the manifold. The 50-ft (15-m)-long manifold was positioned 10 ft (3 m) upstream from and parallel to the weir. The manifold was held in place by a steel cable attached to ledge rock at each bank. Eleven 10-ft (3.0-m)-long diffuser-fingers, extending downstream and perpendicular to the manifold, were spaced at 5.0-ft (1.5-m) intervals. Five 3/64-in, (1.2-mm)-diameter holes were drilled in each diffuser spaced at 2-ft (0.6-m) intervals. The operating pressure of the system with 55 holes was 2 to 3 lb-in<sup>-2</sup> (14 to 21 KPa). The pump capacity limited the number of holes at 50 to 60; beyond this number the pump was unable to maintain adequate air pressure required for effective bubbling.

The replacement aeration diffuser at W-5 (installation #2) was assembled in a linear fashion to minimize time and effort necessary for construction. A continuous air line, without a manifold or diffusers, was positioned in a U-shaped configuration. The air line ran from the gage house and then to each bank, where it was anchored to ledge rock. Installation time was only three hours, minimizing exposure of field personnel to harsh winter conditions. A total of fifty holes were drilled in the two lengths of pipe that paralleled the weir.

Running the air line down inside the stilling well proved successful. Relatively warm air in the pipe normally prevented the well from freezing. During the coldest temperatures (<-18 °C), an auxiliary tank heater was used to ensure that the well did not freeze. The tank heater was necessary only because the gage house at W-5 is situated mostly in the stream and therefore lacked sufficient earth banking to prevent freezing. Other advantages of routing

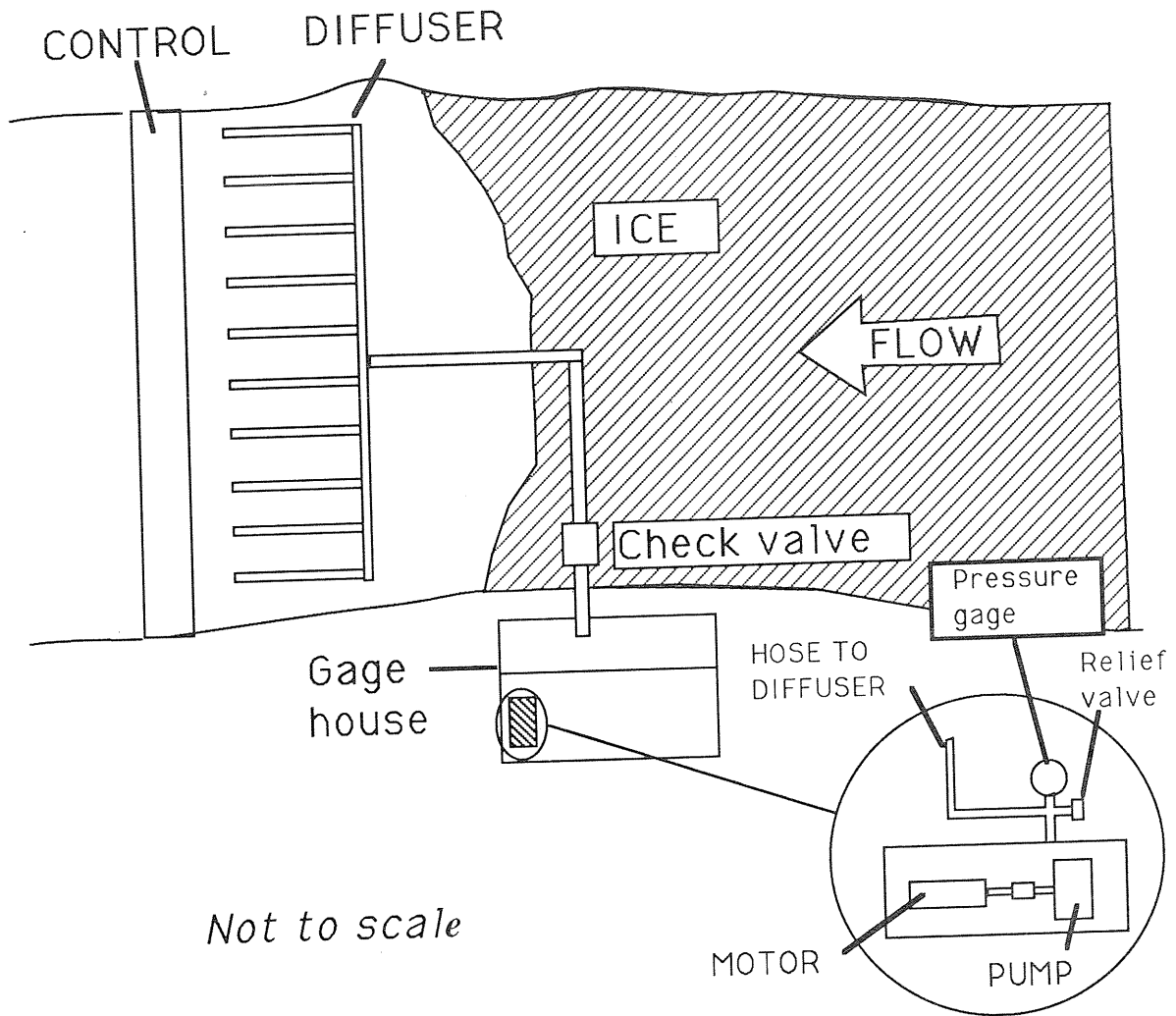


Figure 2. Schematic of aeration system used at station W-5 (diffuser configuration as in installation #1) and station W-3, plan view.

the air line through the stilling well and intake were that vandalism was discouraged and that the potential for water freezing in the air line during system shutdown was reduced.

*Station W-3* -- The aeration system at station W-3 (Figure 2) was similar to the original system (installation #1) at station W-5. The pump assembly was mounted in the gage house and the air line descended into the stilling well and out the intake. The air line connected to the manifold 10 ft (3 m) downstream from the gage. Six 10-ft (3-m)-long diffusers attached to the 10-ft (3-m)-long manifold at 2-ft (0.6-m) spacings. Each diffuser had nine 3/64-in (1.2-mm)-diameter holes at 1-ft (0.3-m) spacings. The manifold line was stabilized by attaching it to metal fence posts. As at station W-5, the assembly was held in place by rock weights. The heated air from the pump together with adequate earth banking kept the stilling well ice-free without an auxiliary heater.

The aeration pump operated reliably throughout the winter after an initial problem was overcome. The gage house at W-3 was tightly sealed and thus provided inadequate ventilation and cooling for the electric pump motor. The unit is thermally protected, so overheating occasionally caused shutdown. The problem was solved by opening a 3.0-in (7.6-cm)-diameter vent in the gage house wall. The vent provided adequate ventilation and the aeration pump operated continuously for the rest of the winter.

## Results

The two systems were evaluated for effectiveness in preventing ice buildup. During weekly site visits, control conditions were recorded in field notes and photographs. Stage hydrographs from graphic recorders were analyzed together with weather records to determine the extent of the ice effects.

*Station W-5* -- Shore ice formed in early December on the quiescent water at the sides of the weir. The diffuser system had no effect on shore-ice formation. Apparently, the dispersed bubble pattern and lack of stream velocity allowed ice to develop. However, the shore ice caused no backwater. The absence of backwater during this period was confirmed by open-water discharge measurements made just upstream from the weir. On extremely cold nights, anchor ice developed on the control, causing considerable backwater. In general, anchor ice caused the largest observed backwater effects during the winter except for periods when overflow and ice breakup occurred. Although anchor ice was a problem in early winter, its occurrence diminished after the formation of complete ice cover upstream from the weir. Furthermore, the accuracy of the winter record was reduced only slightly because anchor ice typically remained on the control for less than 12 hours after its formation. The effectiveness of the bubbler system at reducing backwater improved after the solid surface ice formed upstream from the weir and aeration system. Streamflow velocities in the approach channel were 0.5 to 1.0 ft s<sup>-1</sup> (0.15 to 0.3 m s<sup>-1</sup>). This velocity combined with the surface disturbances caused by the bubbling action tended to inhibit ice formation at the weir section.

To determine if the gage pool was thermally stratified in winter, vertical temperature profiles were measured at several locations. No temperature differences were found along any of the profiles; 0 °C was recorded from the streambed to the surface. Apparently, the gage pool was too well-mixed and shallow (<3.5 ft (1.1 m)) to allow warm water to reside at the bottom. Because relatively warm water was not available in the gage pool, it is apparent

that surface agitation by the bubble action was wholly responsible for inhibition of ice formation. The bubbler system was most effective when the array of bubbles was concentrated in a dense pattern. The weir section at station W-5 is large, and a dense bubble pattern was difficult to maintain. For this reason, the aeration system had to be supplemented by manual ice removal during extremely cold periods.

Ice continued to develop on the weir crest at the edge of water throughout the winter, particularly at temperatures below  $-18\text{ }^{\circ}\text{C}$ . Most of this ice was removed manually by ice chisel during the weekly visits. Backwater attributed to ice formation on the crest of the weir was minimal, as evidenced by the limited drop in stage after the ice was removed. Extensive periods of extreme cold temperatures could result in significant backwater if the ice were not manually cleared. Therefore, the aeration system would be minimally effective during periods of extreme cold at infrequently visited stations similar to W-5. Thus, the climate and stream size at Sleepers River, station W-5 characterize the operating limits of a single-pump aeration system of this type.

*Station W-3* -- The aeration system provided a dense pattern of bubbles that was effective at reducing or eliminating ice buildup in most conditions. A  $100\text{-ft}^2$  ( $9\text{-m}^2$ ) zone above the bubbler system stayed open even during the coldest temperatures. Backwater was observed in early December when anchor ice formed on the weir. Anchor ice did not form after surface ice developed on the gage pool. Minimal backwater occurred during periods of extreme cold, below  $-18\text{ }^{\circ}\text{C}$ , because ice adhered to the top surface of the weir, at the edge of flow. Ice chiseling was only necessary when a column of ice accumulated on the concrete apron just downstream from the weir. This ice column could cause backwater because of the disruption of normal flow through the V-notch.

The bubbling action was effective at inhibiting ice formation despite the negligible stream velocity observed in the gage pool. No thermal stratification occurred in the gage pool. When the air temperature was below freezing, the water temperature throughout the pool was  $0\text{ }^{\circ}\text{C}$ . However, during periods of thaw, the pool temperature rose above freezing to about  $2$  to  $3\text{ }^{\circ}\text{C}$ . At those times, the bubbling action coupled with the warmer water eliminated ice in the weir section and gage pool.

#### VALIDATION OF OPEN-WATER RATING

It was hypothesized that the ice-free zones generated by the aeration systems were sufficient to legitimize the open-water rating. Although on-site observations and analysis of the stage record may suggest the absence of ice effect, two additional factors must be considered: (1) The encroachment by ice at the edge of water may reduce the effective length of the weir, causing backwater; and (2) ice cover on the approach channel can reduce stream velocity, resulting in distortion of the stage-discharge relation. Ice encroachment occurred at both sites when temperatures were below freezing. Changes in the velocity of approach were not a concern at station W-3, because the velocities in the pool were negligible during low flow. At station W-5, approach velocity was a concern because velocities in the gage pool were measurable.

### Validation Procedure

Validating the established rating at station W-5 was difficult because of the absence of an open-water cross section. Winter discharge measurements are less reliable than measurements made during open-water conditions because of ice cover. For this reason, an open-water section was prepared artificially by removing surface ice to create a 14-ft (4-m)-wide opening across the channel. An initial investigation of the velocity profiles at four test verticals indicated that the normal flow pattern was disrupted by the ice cover bordering the open section. The open-water section was insufficiently long in the direction of flow to allow flow velocities to recover from the effect of surface ice. To determine the mean velocity at a subsection, it was necessary to use the vertical-velocity curve method (Rantz, 1982). Only one open-water measurement was made at station W-5 because of the difficulties in preparing the section and making the measurement.

To validate the open water rating at station W-3, a series of winter current-meter discharge measurements were made at an open water cross-section upstream from the gage. This measurement section remained ice-free most of the winter and provided a convenient site to conduct measurements by the wading method.

### Results

The discharge determined from the single winter open-water measurement at station W-5 was 4.5 percent less than the rated discharge (Figure 3). Because this value is within the normally accepted 5-percent error for streamflow measurements, the winter open-water measurement was considered to fall on the rating. Although only one open-water measurement was made at station W-5, six winter open-water measurements validated the established stage-discharge rating at station W-3. The six measurements each fell within the acceptable 5-percent error range (Figure 4).

### ICE DISCHARGE MEASUREMENTS -- SITE W-5

Discharge measurements made from ice cover typically are less reliable than open-water measurements. Four important problems are associated with winter measurements: 1) Determining the effective width of flow is made difficult by the possibility of damaging the ice auger if it is accidentally drilled into the bank. 2) Determining the effective depth of flow in the vertical sections is made difficult by the presence of frazil or slush ice. 3) If the current meter freezes or fills with frazil ice, it can underregister velocities. 4) It is difficult to detect and adjust for flow that is not perpendicular to the cross section.

Most problems associated with winter discharge measurements can be avoided if the measurements are made under favorable conditions. The cross-sections used for this series of measurements were well-defined. Therefore, the effective width and depth were determined accurately. Slush and frazil ice did not accumulate on the meter. The measurements were made during moderate weather conditions. On cold days, the current meter was immersed in hot water to eliminate icing.



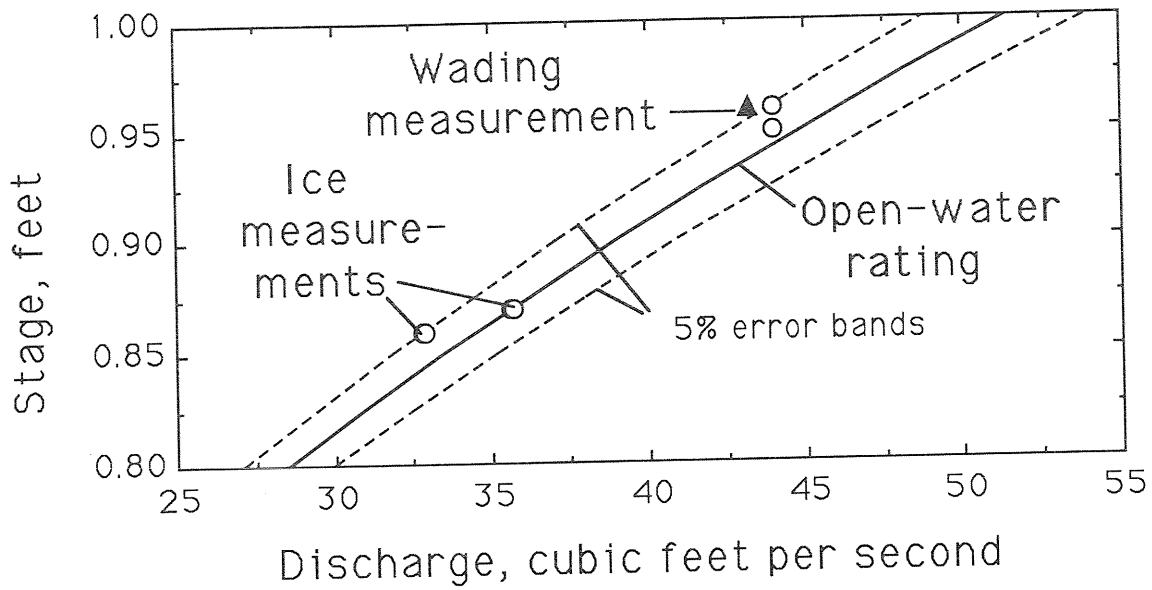


Figure 3. Stage-discharge rating at station W-5, with 5-percent error bands, 6 winter ice measurements, and one wading measurement.

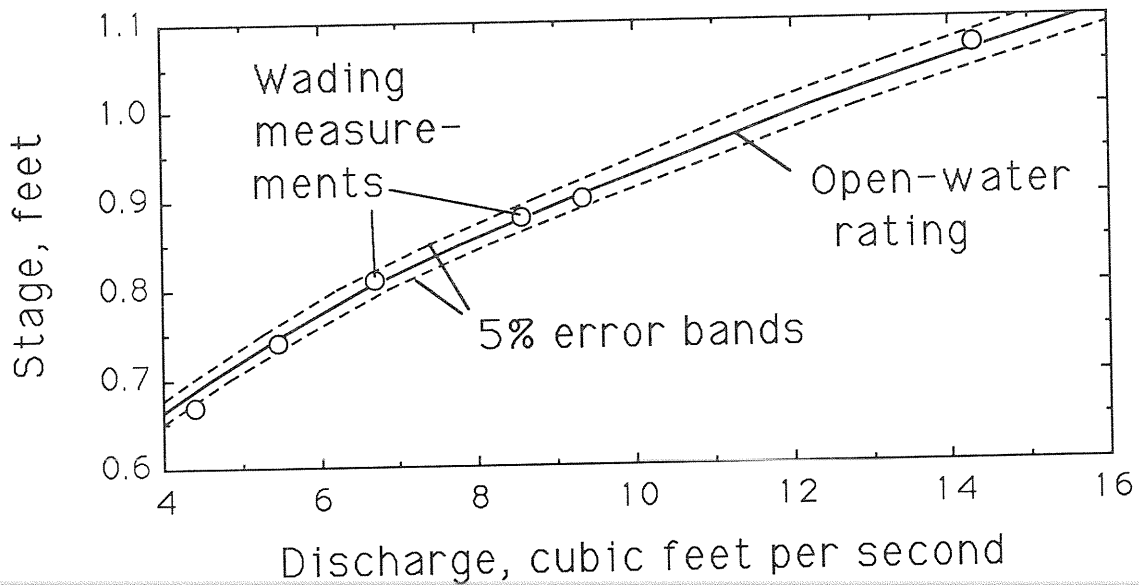


Figure 4. Stage-discharge rating at station W-3, with 5-percent error bands and 6 wading measurements.

### Equipment and Procedure

At station W-5, a valid rating at an open control with an ice-covered reach provided a unique opportunity to evaluate current-meter measurements under ice. A total of six discharge measurements were made under ice at three cross-sections representing different channel geometries. The ice current-meter used for five of the measurements was the Price AA (metal bucket wheel) with a Water Survey of Canada-type yoke, mounted on a rod. For one measurement a prototype USGS ice current-meter was used. This meter had a Price AA metal bucket wheel, optical head, and digitizer mounted on a rod. Discharge measurements under ice cover were made following the guidelines of Buchanan and Somers (1969). At least 24 holes were drilled at each cross section.

No discharge measurements from ice cover were made at station W-3 because an open-water section was available most of the winter. Therefore, the rating at W-3 was validated by wading measurements only.

### Results

All six discharge measurements under ice at station W-5 plot within 5 percent of the open-water rating; values range from -4.9 to -1.1 percent (Figure 3). The apparent negative bias in the results may reflect minimal backwater caused by ice effect. Also, the current meter used for this study may underregister velocities in depths less than 1.5 ft (0.46 m) because of interference caused by the boundary effect (Rantz, 1982). The results show that discharge measurements made under ice cover at station W-5 during favorable conditions meet the 5-percent accuracy criterion.

### CONCLUSIONS

The aeration systems tested were effective at reducing, but not eliminating, ice accumulation at streamflow gaging-station controls. These systems can significantly improve the accuracy of the winter streamflow record in cold regions. Validation of the established rating at the ice-free weir control was accomplished by open-water current-meter measurements. These discharge measurements verified the open-water rating curve. The accuracy of ice current-meter measurements was determined by comparing the measured discharges against the rating curve. Six measurements fell within 5-percent of the rating; values ranged from -4.9 to -1.1-percent, and therefore met the accuracy criterion for acceptable discharge measurements.

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