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Breakup Ice Control Structure for the Salmon River in Connecticut

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ABSTRACT

This paper presents a conceptual design for a breakup ice control structure on the Salmon River at East Haddam, Connecticut. Ice jams initiate just downstream of a small neighborhood, where the Salmon River transitions to a flat tidal reach above its confluence with the Connecticut River. Ice jam flood severity has increased since 1979, when a dam located upstream of the community was lowered. The Salmon River watershed is small and relatively steep, responding rapidly to rainfall and snowmelt events. As a result, the ice breakup can be extremely dynamic.

Design development relied on equilibrium ice jam modeling to simulate worst case existing conditions and estimate the performance of structural ice control alternatives under two ice breakup scenarios. The first breakup scenario assumed that a semi-intact ice sheet would rest against the piers and retain a floating equilibrium jam upstream, allowing water discharge to pass beneath. Under a second, and worst case scenario, a grounded jam in direct contact with the piers would divert water flow around the structure via an armored channel in the overbank area. The proposed ice retention structure consists of a row of concrete piers, spaced across the main channel, 60 m (200 ft) upstream of an existing dam.

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INTRODUCTION

The Salmon River is a steep frazil-producing tributary of the tidal portion of the Connecticut River. Much of the 288 km^2 (111 mi^2) catchment is underlain by relatively impermeable glacial till. Intense rainfall produces rapid runoff that can result in extremely dynamic ice breakups on the Salmon River. The Connecticut River backwater extends about 4.8 km (3 mi) up the Salmon River and the tide level on the Connecticut at the time of breakup appears to affect ice jam location.

During 1979 and 1980, the decaying 6.7 m (22 ft) high Leesville Dam, located upstream of the settled area was lowered by 3.0 m (10 ft) for reasons of safety and also for the construction of a fish ladder to encourage the return of Atlantic Salmon (Fig. 1). The reduction in height allowed the breakup ice run to pass over the dam spillway and jam in the bridge opening of the Route 151 embankment, 460 m (1500 ft) downstream. Such an event occurred on 1 February 1982 when the tide was relatively high. On 29 January 1994, at a lower tide level, the ice run proceeded 460 m (1500 ft) beyond the Route 151 bridge and stopped against the intact downstream ice cover. Both events caused significant flooding and ice damage to residential property upstream of the Route 151 embankment.

The 5.6-km (3.5-mi)-long reach upstream of the Leesville Dam lies within state forest land. In this reach, the channel bed is relatively steep, with an average slope of 0.004, and the water surface width varies from 23 to 46 m (75 to 150 ft). Water depth ranges from 0.6 to 1.8 m (2 to 6 ft), and velocity is on the order of 0.9 to 1.2 m/s (3 to 4 ft/s). The East Hampton USGS gage, located at the upstream end of this reach, provides stage and discharge data for the 1949 to present period. The average winter base flow ranges from 1.4 to 5.7 m^3/s (50 to 200 cfs), and a 0.3-m (1-ft) -thick ice cover typically breaks up and moves at a discharge of approximately 28 m^3/s (1000 cfs). Daily peak discharge for both the 1982 and 1994 ice jam events was on the order of 65 m^3/s (2300 cfs). Significant quantities of the sand and gravel also move downstream during high flow events and this material fills much of the 0.8-km (0.5-mi)-long impoundment above the present Leesville Dam.

Following the 1994 ice event, the New England Division of the U S Army Corps of Engineers (USACE) funded the U S Army Cold Regions Research and Engineering Laboratory (CRREL) to investigate the Salmon River ice jam problem and develop a conceptual design for a breakup ice control structure. The study began with a review of historical ice jam events and an ice observation program during the winter of 1994-95. In addition, the study examined factors affecting ice jam frequency and severity such as daily air temperature, rainfall quantity and intensity, Salmon River stage and discharge, and Connecticut River tide level. Numerical models were then used to simulate a worst case existing-conditions ice jam. Further numerical simulations aided in the development of a conceptual design for an ice control structure to be located 60 m (200 ft) upstream of the Leesville Dam. A project report to the New England Division of the Corps (Tuthill et al., 1995) documents the original study.

BREAKUP ON THE SALMON RIVER

Because it was the most severe event of record, we chose the 28-29 January 1994 ice jam to represent worst case existing conditions. A period of consistently cold air temperature preceded this event during which the accumulated freezing degree days (AFDD) reached 233°C (420°F). This compares to the average AFDD at breakup of 83°C (150°F). Inspection of photographs of ice pieces in the jam lead to an estimate of pre-breakup ice thickness of approximately 0.3 m (1 ft). The first spike in the stage hydrograph at 1600 hr on 28 January 1994 suggests that the ice released at a discharge of about 28 m^3/s (1000 cfs) (Fig. 2). A simulation of the flood wave using the UNET unsteady flow model (USACE 1993) with a 0.3- m (1.0-ft)-thick ice cover suggests that little attenuation occurred as the wave traveled down the relatively straight 5.6-km (3.5-mi)-long reach, from the East Hampton gage to the Leesville Dam (Fig. 2). An eyewitness[3] reported that after the lowering of the dam in 1979, the ice on the pool typically moves over the crest of the Leesville Dam in the form of large broken sheets. These ice pieces then fracture the ice cover below the dam as they move around the island above the Route 151 highway embankment (Fig. 1). According to the same observer, during the 1994 event, the breakup ice run passed through the Route 151 highway embankment, plowing large fractured sheets beneath the downstream cover, until the ice run grounded and stopped.

The HEC-2 gradually varied flow model (USACE, 1990) and the ICETHK equilibrium ice jam model (Wuebben et al., in prep.) simulated the breakup ice jam profile under worst-case existing conditions. From the 1994 event hydrograph (Fig. 2), equilibrium conditions appear to have lasted for a period of 4 to 6 hours, at a more or less steady discharge of 57 m^3/s (2000 cfs). The simulated existing conditions ice jam profile was calibrated to an observed high water mark of 4.3 m (14 ft) MSL, at a location 120 m (400 ft) upstream of the Route 151 embankment. Fig. 3 shows the simulated profile.

Estimated cumulative freezeup and breakup ice volumes for the 1994 winter were compared to assess the benefit of retaining ice above the Leesville Dam. The freezeup ice volume assumed a pre-breakup ice thickness of 0.3 m (1 ft), and the breakup ice volume calculation was based on estimated ice thickness calculated by the ICETHK model. The analysis found that if the upstream ice supply were

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[3] Personal communication with Mr. Greg Daigle, July 1995.

retained at the dam, and the toe of the jam were in its 1994 location, the head of the jam would be approximately 300 m (1000 ft) below the Route 151 embankment, and residential flooding would likely be avoided. The historical record may better indicate the effectiveness of ice retention at the dam though. The infrequency of reported jams before the dam was lowered in 1979 suggests that reliable ice retention at or just above the dam would reduce or eliminate the ice jam flood threat to residential property downstream.

SELECTION OF ICE CONTROL ALTERNATIVE

The study considered several structure locations and types. An ice retention structure located as close as possible to the dam would take best advantage of the solid ice sheet on the pool, and provide a buffer against the surge of ice and water arriving from the steeper upstream reaches. A location at or near the dam would also maximize the ice storage area provided by the pool and its floodplains. We initially examined the alternative of constructing concrete ice piers along the existing dam spillway, a concept has seen success on Canadian rivers. An example is the weir-with-piers structure on the Riviere Ste. Anne, upstream of the town of St. Raymond, Que. (Beltaos 1995). Ice retention behind a row of piers at a location 67 m (200 ft) upstream of the dam was favored over placing piers along the dam for several reasons. First, the channel at this location is wider than at the dam, and the flow area greater. Second, water surface slope and the water velocity beneath the retained ice accumulation are low enough to allow a floating sheet ice cover or stable ice accumulation to exist for the expected range of breakup discharges. Also, construction at the upstream site would not place any additional loads on the existing dam, nor would the ice pile-up interfere with the operation of the fish ladder. Finally, construction costs at the upstream site would likely be less than the cost of altering the dam.

The design of the proposed structure could be as simple as a line of steel piles or concrete piers placed at intervals across the channel width. Steel pile structures were used successfully on rivers in the Czech Republic (Brachtl, 1974) and concrete pier structures retain breakup ice runs in Quebec and Ontario (Cumming-Cockburn Associates, Ltd., 1986 a & b). Rock filled timber cribs, similar to those on the Narraguagus River at Cherryfield, ME (Perham, 1983) could also provide a simple, low cost ice retention alternative. This paper presents a conceptual design for a concrete pier ice control structure. Included are structure location and layout, pier spacing and height, as well as the expected ice and hydraulic loads on the structure.

The design considers two ice breakup scenarios. The first assumes that an ice control structure retains a relatively intact sheet ice cover on the lower pool during the course of breakup, with a jam forming upstream of the sheet. The second scenario assumes that the ice sheet on the lower pond is fractured into relatively small pieces by the breakup surge, and the structure must retain a floating equilibrium ice accumulation. We also addressed the possibility of a grounded ice jam behind the piers.

For the first scenario, water drag on the underside of the broken sheet ice cover and the downslope component of the ice cover weight were calculated in order to determine the total downstream force exerted by the ice on the structure. Foltyn and Tuthill (1996) and U S Army (1982) describe ice loading calculation methods. A sharp bend at a rock ledge outcrop 290 m (950 ft) upstream of the structure was considered the upstream limit of the ice cover contributing to the loading. Upstream of this point, the downstream forces on the ice accumulation are assumed to be resisted by ice-on-bank friction. For the 290-m (950-ft)-long ice covered reach, assuming 0.46-m (1.5-ft)-thick sheet ice with a Manning's roughness of 0.02, and a HEC-2 calculated water surface slope of 0.0017, the predicted ice loading on the structure is 9.2 kN/m (630 lb/ft) of river width. The maximum force exerted by the 0.46-m (1.5-ft)-thick sheet ice on an individual pier is found by multiplying the 4.3 m (14 ft) pier spacing by 9.2 kN/m (630 lb/ft), or 39 kN (8820 lb). Assuming a pier face width of 0.6 m (2.0 ft) and a center to center spacing of 4.3 m (14 ft), this calculated ice force results in a stress on the pier faces of about 128 kPa (20 psi). This estimated stress is significantly less than the crushing strength for ice which typically lies within the 690 to 2800 kPa (100 to 400 psi) range (U S Army 1982). These results suggest that the sheet ice cover behind the structure will not fail in crushing, or extrude past the piers under a static load due to water shear and gravity alone.

In the event that the breakup surge completely fractures the ice cover on the pool, the structure would need to be capable of retaining a stable equilibrium ice accumulation. Such an accumulation was modeled by HEC-2 with ICETHK using a discharge of 65 m^3/s (2300 cfs) (See Fig 4 for a profile). Once upstream of the structure, hydraulic conditions appear favorable for the existence of a stable floating ice accumulation with an equilibrium thickness of about 2.1 m (7 ft). The ice thickness calculation was based on a water surface slope of 0.0028, an ice accumulation Manning's roughness of 0.06, and an internal strength coefficient (μ) of 1.17. Under-ice water velocity is on the order of 0.9 m/s (3 ft/s), so significant erosion of the ice accumulation would not be expected. At the structure itself, the ice accumulation will likely exceed equilibrium thickness, producing water current velocities in excess of the calculated values. This points to the need for to bed protection in the vicinity of the piers. The calculated ice loading on the piers resulting from gravity and water drag acting on a 290-m (950-ft)-long section of the above described equilibrium accumulation would be about 17 kN/m (1140 lb/ft) of river width. This is roughly double the estimated ice loading produced by large broken sheets. If the downstream forces are great enough, the jam may ground at its toe. The previous analyses assumed that the ice accumulation was floating for its entire length, allowing water discharge to pass beneath. The possibility of a grounded jam occurring cannot be ruled out, however. The next section outlines provisions for flow around the grounded portion of the jam.

CONCEPTUAL ICE CONTROL STRUCTURE DESIGN

This section presents a conceptual design for a concrete pier ice control structure that would retain an ice accumulation that is either floating over its entire length or grounded at its toe. For the floating toe case, water discharge would pass under the ice and between the piers. For the grounded toe case, relief flow would pass through the toe and around the structure on the left floodplain, as shown in Fig. 5. The preliminary design assumes a pier face width of 0.66 m (2 ft), and a length of 2.4 m (8 ft) in the streamwise direction. The pier top elevation is 5.5 m (18 ft) MSL, and individual pier heights range from 1.5 to 4.0 m (5 to 13 ft) above the existing bed depending on location. Fig. 5 shows the existing channel topography upstream of the dam with a plan view of the pier configuration. Eight piers are required to span the main channel, with a center-to-center spacing of 4.3 m (14 ft) and a gap width of 3.7 (12 ft). Fig. 6 shows a cross-section at the structure with typical freezeup and breakup water levels of 3.7 and 5.0 m (12.3 and 16.4 ft) respectively.

The choice of a 3.7 (12 ft) gap widths was based on the observed success of similar existing structures. This spacing is slightly conservative compared to the structure on the Riviere Ste. Anne at St. Raymond, Que., where concrete piers are spaced at 6 m (20 ft) intervals, along the crest of the weir. The breakup structure on the Lamoille River in Hardwick Vt. successfully retains a grounded ice jam behind granite blocks with a 4.3 m (14 ft) gap width (Lever et al., 1996).

If the jam grounds in the main channel, or thickens to the point that a major portion of the channel area is ice filled, the left overbank area would provide flow relief. Fig. 5 shows a 120 m (400-ft) -long gravel bar, with a top elevation of approximately 4.6 m (15 ft), which separates the main river channel from a smaller natural channel along the left-hand edge of the floodplain. Assuming a breakup equilibrium ice accumulation occurs behind the structure, as shown in Fig. 4, the gravel bar itself might prevent ice pieces from entering the relief channel. If the accumulation behind the structure is greater than the equilibrium ice thickness however, higher water levels would result. Representing an extreme case, a HEC-2 simulation at 65 m^3/s (2300 cfs), with 3 m (10 ft) thick ice in the main channel and open water in the left floodplain produced a water level of 5.2 m (16.9 ft) immediately upstream of the structure and 5.5 m (18.1 ft) at river km 6.55 (mi 4.07), 30 m (100 ft) upstream. With the right channel blocked by ice, all flow is shifted to the left-hand channel where the simulated average water velocity is 1.6 m/s (5.2 ft/s).

Although it is possible that the existing elevation of the crest of the gravel bar by itself would be sufficient to keep ice pieces from entering the flow relief channel, a line of concrete blocks or boulders placed along the crest of the gravel bar would provide additional insurance. The arrangement shown in Fig. 5 would prevent main channel ice from entering the flow bypass channel. The boulder tops would need to be about 1 m (3.3 ft) above the existing grade of the gravel be to be level with the tops of the concrete piers.

Fig. 5 shows areas where bed protection would potentially be needed during high flow events with ice. Assuming that the individual piers rest on a continuous concrete apron, beds of riprap extending approximately 3 m (10 ft) upstream and downstream of the apron, would provide additional scour protection. The left overbank would also need scour protection, both along the left side of the flow relief channel and possibly along the crest of the gravel bar.

CONCLUSIONS

The conceptual design described in this paper takes advantage of an existing dam, and combines aspects of two different types of existing breakup ice control structures. The first is a weir-with-piers type structure designed to retain a floating ice accumulation, while passing water discharge beneath the ice and over the weir. The second structure type consists of a row of piers designed to initiate a grounded ice jam in the main channel and pass much of the water flow around the structure. The structure proposed for the Salmon River in Connecticut differs from the first type only in that the piers are located a short distance upstream of the dam rather than along its crest. The ice/hydraulic analysis done in this study suggest that the piers would retain a stable, floating ice accumulation under most anticipated ice breakup scenarios. In the event that the toe of the retained ice accumulation does ground, the proposed structure would perform in a similar way to the second structure type. In this case, water discharge would flow around the grounded portion of the jam via a gravel bar area to the left of the piers.

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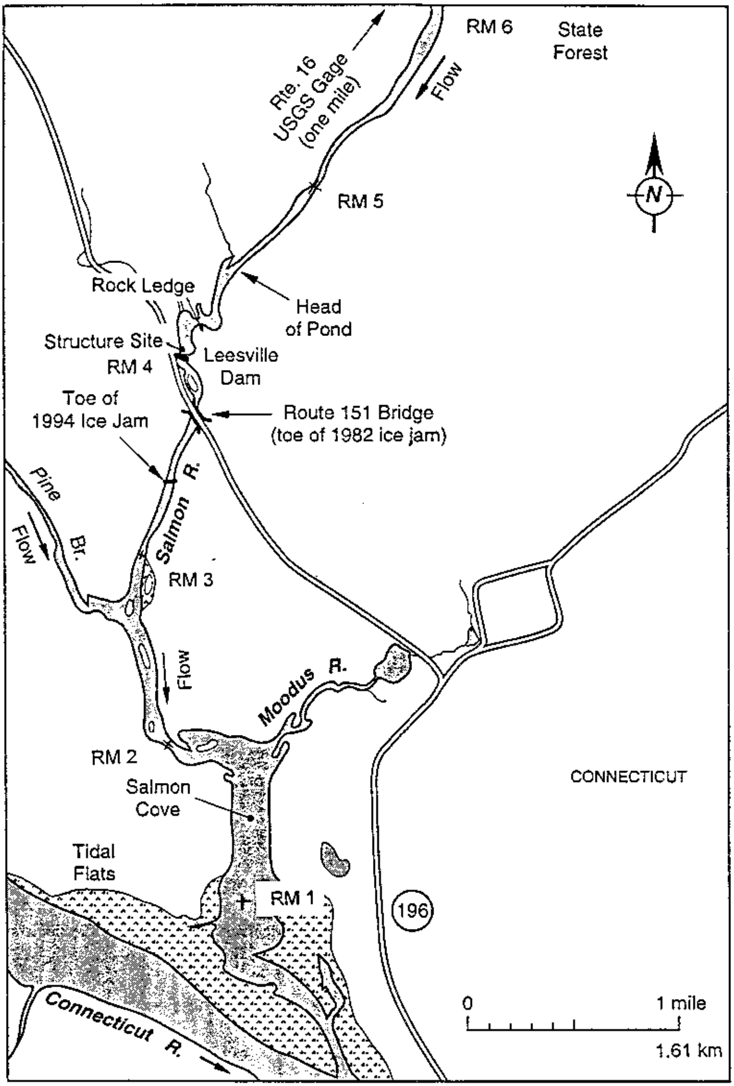

Fig. 1 Map of study area, Salmon River, Connecticut.

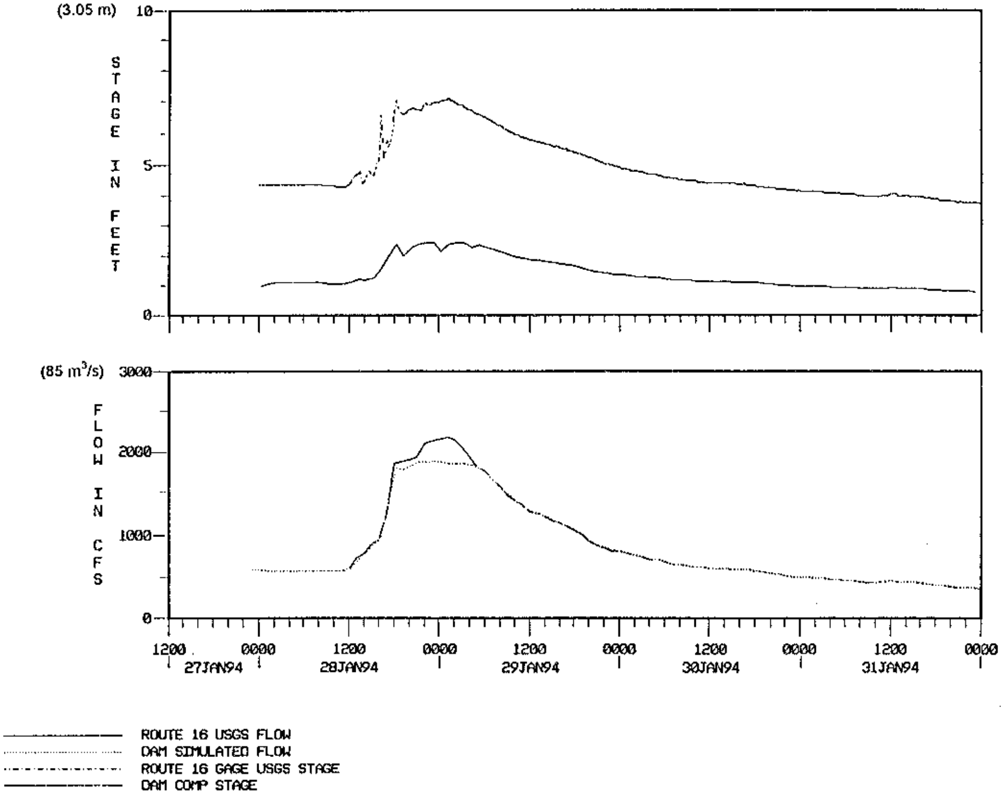

Fig. 2 Stage and discharge hydrographs for the 1994 ice jam event.

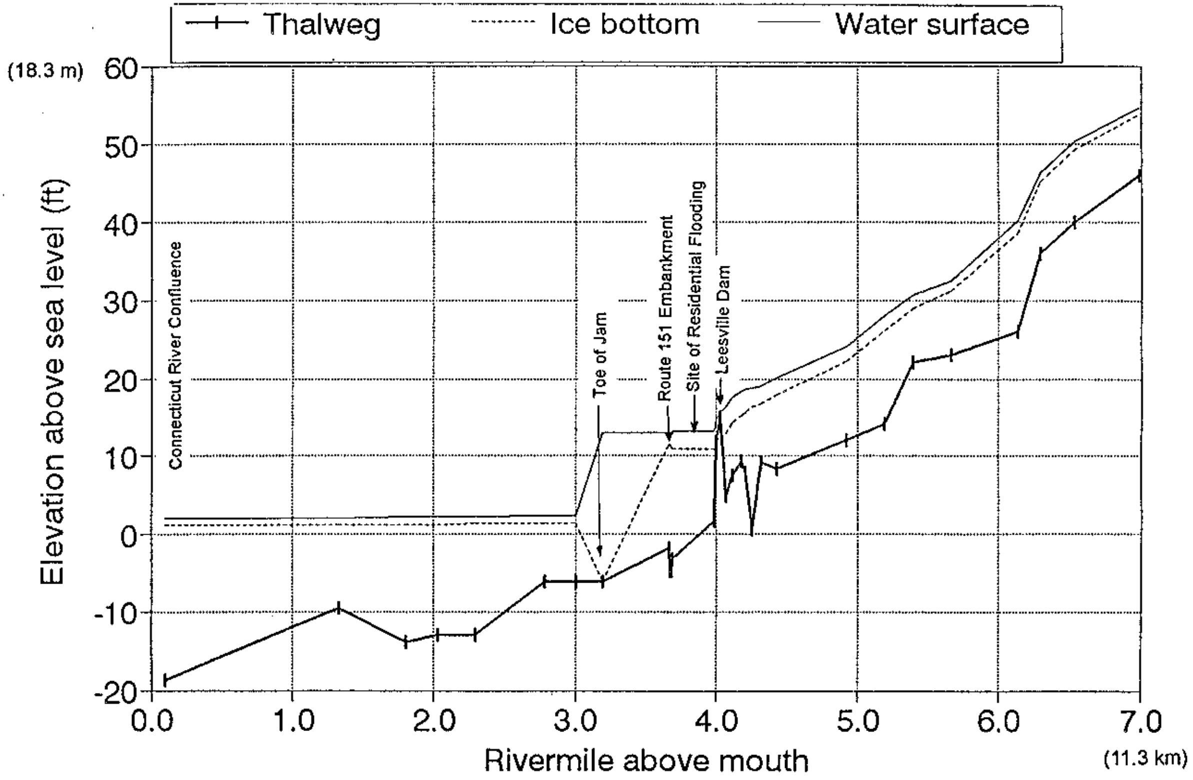

Fig. 3 Profile of the January 28-29, 1994 ice jam, simulated by HEC-2 and ICETHK.

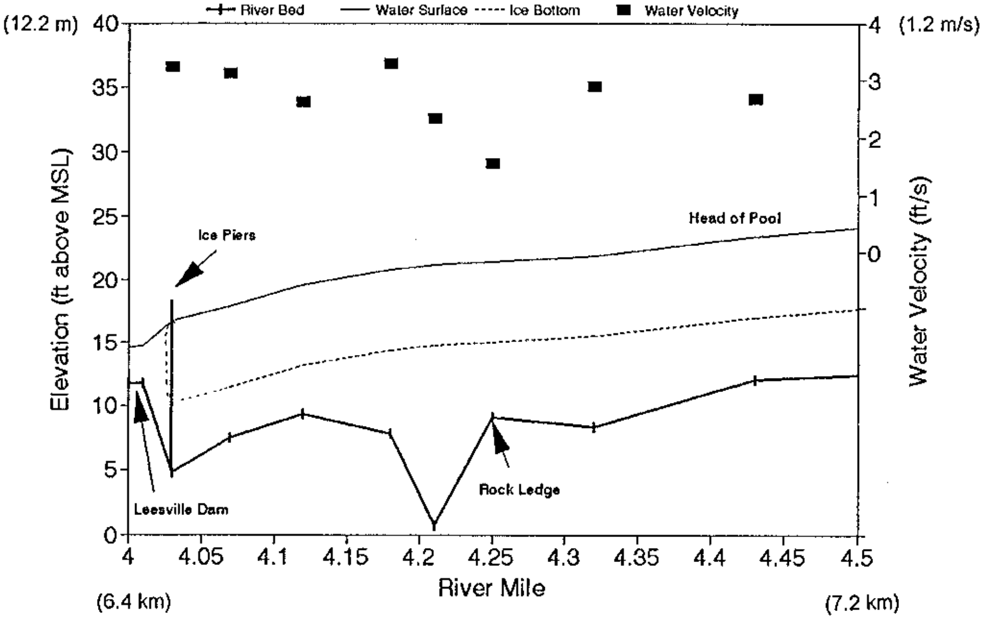

Fig. 4 Profile of equilibrium ice accumulation retained upstream of the Leesville Dam.

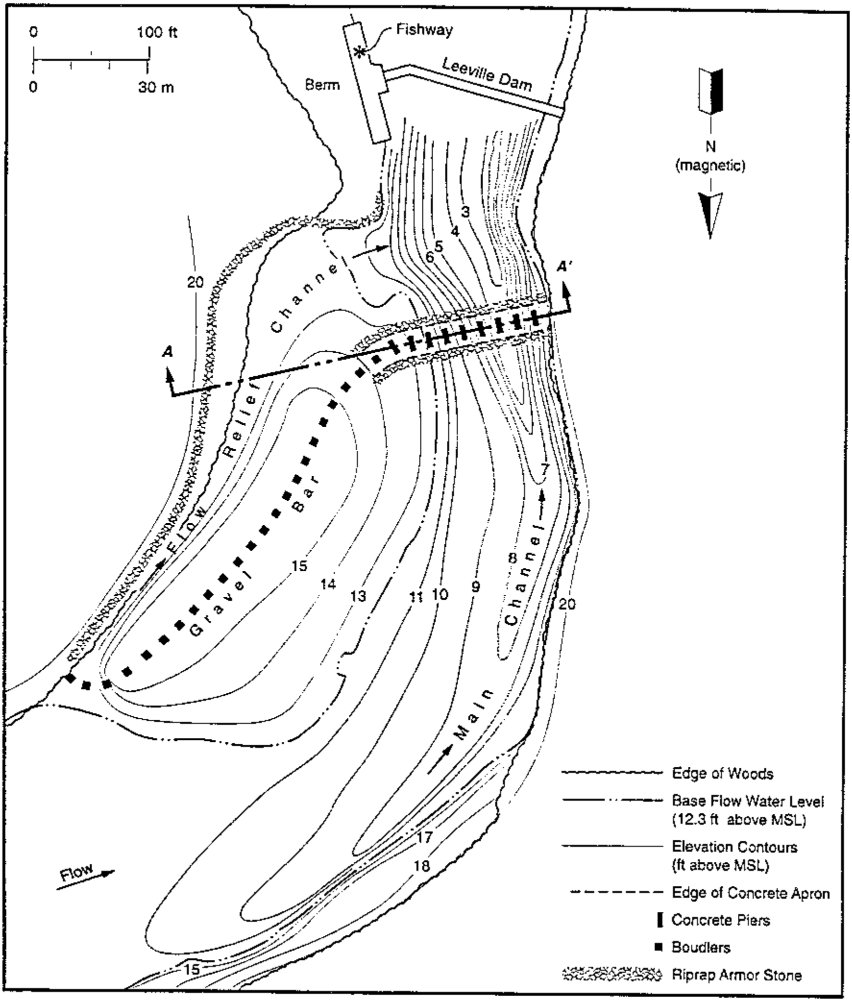

Fig. 5 Map of pond area upstream of the Leesville Dam showing channel topography and location of proposed concrete pier ice control structure.

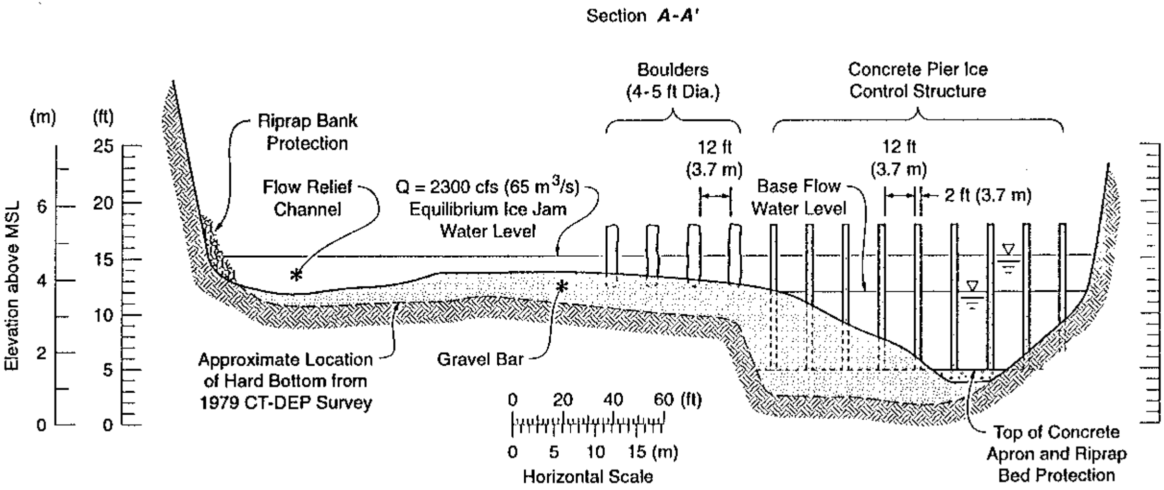

Fig. 6 Elevation view of proposed concrete pier ice control structure.