An Assessment of the Applicability of Steady Flow Ice Jam Profile Models

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The purpose of this investigation was to examine the suitability of steady flow, numerical ice jam profile models for studying ice jam characteristics indirectly, through calibration of measured water surface profiles and shear wall data. It had already been illustrated by the authors, in an earlier paper, that certain ice jam parameters are insensitive in the calibration process. Here we explore the significance of unsteady flow to the sensitivity of the numerical model calibration to discharge and composite roughness by measuring discharge, water level, and ice thickness variations during the formation of an ice jam under a steady carrier discharge.

Based on our observations, it is clear that ice jams form under highly unsteady flow conditions, even in cases where the carrier discharge in the stream is relatively constant. In our experiments, measured discharge along the forming jam dropped to values as low as 40% of the steady carrier discharge during ice jam formation. Given the magnitude of this variation for a steady carrier discharge, one must question the applicability of steady flow ice jam profile models for deducing *both* the discharge and composite roughness of ice jams documented in the field.

1. Introduction

Most of the currently available computational tools used for determining the water levels associated with breakup ice jam events (e.g. RIVJAM, ICEJAM, and HEC-RAS) are based on a steady flow approximation despite the fact that ice jam development is an inherently dynamic process. Even if the carrier discharge in a stream is constant, temporal and spatial variations in discharge can be expected during ice jam formation, since water goes into storage as the ice cover thickens and roughens. This raises the question of whether ice jams can be properly modelled using a steady flow assumption, even if they are formed during steady carrier discharge conditions.

The importance of this issue is demonstrated further when one considers the fact that discharge is an unknown for most documented ice jam events. In many cases, the discharge is obtained from the steady flow ice jam profile model itself, and thus becomes an additional calibration parameter. Given the number of other parameters in the calibration, most significantly the under-ice roughness, the question one has to ask is what discharge is the model providing, and is it representative of the carrier discharge in the stream? Also, how representative is the deduced composite roughness in such cases?

In this paper we explore this issue using measured ice jams formed in a laboratory flume under constant inflow conditions. Using observed values of ice thickness, water level and discharge, along with the known properties of our model ice, we explore the applicability of steady flow ice jam profile models using the standard calibration approach adopted for most documented field events.

2. Experimental Apparatus and Procedures

The experiments were carried out in the 30.5 m (metre) long recirculating flume located in the T. Blench Hydraulics Lab at the University of Alberta. This rectangular flume has 0.91 m high side walls and a width of 1.22 m. The bed is sheet metal (though slightly rusted and rough in texture) and the walls are plexiglass. Mannings *n* for the channel, under open water flow conditions, ranges from 0.020 to 0.025.

Discharges up to 80 l/s are supplied to a head tank via a 0.41 m diameter pipe. Flow straighteners in the floor of the head box condition the flume's inflow. At the downstream end of the flume, water levels are controlled with a 0.15 m high rounded weir as well as with a series of adjustable vertical vanes spaced across the channel. The flume can be tilted up to 5 cm, producing a maximum bed slope of 0.00164.

Ice floes were simulated using polyethylene pieces with a specific gravity of 0.92. A mixture of sizes were used ranging from 1.27 x 1.27 x 0.32 (½ x ½ x ⅛ in) up to 5 x 5 x 0.6 cm (2 x 2 x ¼ in). The mixture had a bulk volume of 0.70 m^3, a bulk porosity of 0.46, and a dry angle of repose of 37°.

A 1.9 mm x 1.22 m x 1.22 m sheet of plywood was positioned 25 m downstream of the head box to simulate an intact ice cover in the downstream portion of the flume. Rigid insulation was used downstream of this for the remainder of the flume's length. A wire mesh was fastened to the upstream edge of the plywood to facilitate the control of the thickness and location of the toe of the jam. At the beginning of each experiment a steady discharge was introduced under open water conditions. The plywood sheet and rigid insulation were then lowered onto the water surface, the flow was allowed to stabilize and then a water surface profile was measured.

The "ice" was fed into the flow from a hopper located at the upstream end of the flume. A piece of rigid plastic was used as a chute to guide the pieces into the flow with a minimum of disturbance. The total time required to deliver the ice pieces to the flume varied from 8 to 10 minutes. Once all of the ice was in, the location of the head of the accumulation was monitored, as was the leading edge of the ice while the ice cover consolidated. Variations in flow depth and ice thickness were monitored with video cameras at stations 10, 20, 23.5 and 29 m downstream of the head tank.. Once the ice cover stabilized (after 1 to 2 hours, typically) water surface and ice thickness profiles were measured. The bottom ice profile was determined by estimating the average thickness across the jam for each measurement section.

Flow rates in the supply line were measured with a magnetic flow meter to an accuracy of ±1 l/s (litres/second), and flow velocities were measured during ice jam formation using Prandtl tubes and pressure transducers. All discharge and velocity measurements were captured digitally using a Pentium computer running the LabView data collection software program. The Prandtl tubes were situated in pairs, positioned on the flume centreline at stations 10, 20 and 29 m downstream of the head tank. Each pair was positioned at 0.2 and 0.8 of the depth, respectively, to obtain the mean velocity on the channel centreline. Numerous steady flow calibration runs were conducted to determine the relationships between the mean centreline velocity and the mean velocity in the channel at each of these three stations for both open water and ice covered conditions (Jahns, 1998). These were obtained by first relating the mean velocity for profiles measured along the channel centreline, to the average channel velocity for the steady flow case, both through measurements of velocity profiles at other points across the section and based on the measured steady discharge. This average velocity for the entire cross section, together with the varying water level and ice thickness documented with the video camera, facilitated the calculation of the discharge.

3. Observations of an Ice Jam Formed under Steady Carrier Discharge Conditions

Figure 1 presents the stabilized water surface and ice thickness profiles measured for an ice jam which formed under a steady carrier discharge of 49 l/s (litres/second). Based on the measured ice jam thickness profile, the *submerged* bulk volume of the jam was 0.67 m^3 which for a specific gravity of 0.92 translates to a total bulk volume of 0.72 m^3. Therefore, the in-situ ice jam porosity was 0.47. The stabilized water levels upstream of the ice jam toe were approximately 1.5 cm above the measured open water levels at the same discharge.

Figure 2 shows the ice thickness and flow velocity variations at Stations 10 m and 20 m during formation of this ice jam. At Station 10 m an accumulation thickness of 6 to 7 cm initially developed. However, it did not persist since the entire ice accumulation shoved on formation, and the head of the ice jam ultimately move 6 m downstream of this point. Of significance here is the fact that a noticeable increase in velocity was observed at both stations once ice was present. Although the depth increased as the ice accumulation developed at these sections, the effective flow area was actually reduced, since the submerged thickness of the ice was greater than this flow increase. Note that at Station 10 m, the velocity dropped once the head of the jam passed downstream and the section was again under open water conditions.

Figure 3 presents the discharges determined for Stations 10 m, and 20 m, along with the constant supply line flow of 49 l/s measured by the magnetic flow meter. As the figure illustrates, the measured discharge at Stations 10 m and 20 m varied considerably during ice jam formation, despite the fact that the carrier discharge was held constant. Initially, the discharge at these sections show a decreasing tendency, as would be expected as water went into storage during formation. The last piece of ice was observed to pass Station 10 m at 12:15 h and, at this time, the flow at Station 10 m returned to a constant value corresponding to the carrier discharge. Unsteady flow persisted at Station 20 m, as the jam continued to consolidate until shortly after 13:00 h. As Figure 3 indicates, essentially steady state conditions were observed at Station 20 m beyond this time.

Based on these observations, it is clear that the jam was formed under highly unsteady flow conditions, despite the fact that the carrier discharge was effectively held constant throughout the entire experiment. During formation of this ice jam the discharge measured at Stations 10 m and 20 m varied significantly, dropping to values as low as 40% of the carrier discharge (minimum observed flow ~30 to 35 l/s). Given the magnitude of this variation for a steady carrier discharge, one must question the applicability of steady flow ice jam profile models for deducing *both* the discharge and composite roughness of ice jams.

4. Analysis of an Ice Jam Formed under Steady Carrier Discharge Conditions

The three steady flow ice jam models most commonly used in current North American practice are; the RIVJAM model, developed by Beltaos and Wong at the National Water Research Institute, Ontario, Canada (Beltaos and Wong, 1986; Beltaos, 1988, 1993); the ICEJAM model, which was developed by Flato and Gerard at the University of Alberta, Edmonton, Canada (Flato and Gerard, 1986; Flato, 1988), and the U.S. Army Corps of Engineers HEC-RAS model which was recently adapted to include an ice jam modelling option (Daly, 1998). Each of these models solve an ice jam stability equation in conjunction with a one-dimensional, steady, gradually varied flow equation and all have the capacity to compute profiles for equilibrium and non-equilibrium ice jams. Healy and Hicks (1998) provide an in-depth examination and comparison of the ICEJAM and RIVJAM models, including details of the analytical equations solved, the numerical solution approaches, the required boundary conditions, and the relative sensitivity of the models' calibration parameters. The solution algorithm used in the HEC-RAS is based upon the same approach as adopted by the ICEJAM model (Daly, 1998); readers are referred to the HEC-RAS model manual for further information on its implementation.

In our initial investigation we limited our analysis to application of the ICEJAM model which calculates the thickness and water surface profiles for a cohesionless, wide channel ice jam with a floating toe (Flato and Gerard, 1986). For this floating toe scenario, the "seepage" through the interstitial spaces in the ice cover is neglected. In contrast, the RIVJAM model does incorporate seepage analysis in the ice jam profile calculation.

The discharge during formation was found to drop to approximately 35 l/s under a constant carrier discharge of 49 l/s. Using the known porosity of the jam (0.47), typical values of μ and K_x (1 and 10, respectively), and the measured ice thickness at the head of the jam, the ICEJAM model was calibrated to provide the best visual fit to the observed water surface profile for both of these discharges, with roughness as the only unknown parameter.

Figure 4 presents a comparison these calibrated ice jam profiles with the observed values. For a discharge of 49 l/s, Mannings composite roughness was calibrated to $n_{composite} = 0.023$, while for a discharge of 35 l/s the roughness was calibrated to $n_{composite} = 0.048$. In fact, a slightly better fit to the observed data was obtained with the lower discharge and a higher roughness, though the other calibration might be considered better if ice thickness were an unknown (as is often the case in real-world situations). In either case, one can see that dramatically different calibrations can produce reasonable calibrations to a measured water surface profile. The computed ice thickness values were less than the observed values for both calibrations. Attempts to rectify this discrepancy by adjusting the other ice jam parameters (specifically, μ and K_x) did not produce significantly different results; in fact, this lack of sensitivity to these other parameters was expected (Healy and Hicks, 1998). The computed profiles were also not found to be sensitive to the input porosity (within physically reasonable limits).

We also conducted a steady gradually varied flow analysis of the stabilized jam, using the known ice thickness profile presented in Figure 1 and the corresponding steady post-event discharge of 49 l/s. The composite roughness under the ice jam was found to be $n_{composite} = 0.020$ in this case, which agrees well with the value obtained at the same discharge with the ice jam model. In this context, one must question the added value of conducting the analysis with an ice jam profile model, given the lack of sensitivity of the other ice jam parameters.

We also attempted calibrations with the RIVJAM model, using the measured toe thickness for the downstream boundary condition. However, the model did not produce physically reasonable profiles in this case (divergence of the top and bottom of ice profiles occurred). Further experimental and numerical simulations are planned to explore this issue.

5. Summary and Recommendations

We have measured the spatial and temporal variation in discharge occurring during ice jam formation in a model flume using polyethylene pieces to simulate the ice floes. During the simulation, the carrier discharge was maintained at a constant (steady) flow rate, yet variations in discharge within the ice affected flow were as large at 40% of this carrier discharge as the ice jam consolidated on formation.

A steady ice jam profile model (ICEJAM) was calibrated to provide the best visual fit to the stabilized ice jam profile for two discharges (the carrier discharge and the minimum observed flow) with roughness as the only unknown parameter. These two calibrations produced comparable quality results, yet resulted in dramatically different calibrated composite roughness values ($n_{composite} = 0.023$ versus 0.048). Based on this, one must question the validity of any ice jam calibration conducted with a steady flow ice jam profile model, unless an independent determination of carrier discharge has been obtained.

We also conducted a steady gradually varied flow analysis of the stabilized jam, using the known ice thickness profile and the corresponding steady post-event discharge of 49 l/s. The composite roughness under the ice jam was found to be $n_{composite} = 0.020$ in this case, which agrees well with the value obtained at the same discharge with the ice jam model. In this context, one must question the necessity for using a steady ice jam profile model to deduce ice jam roughness characteristics when shear wall data is available, given the lack of sensitivity of the other ice jam parameters.

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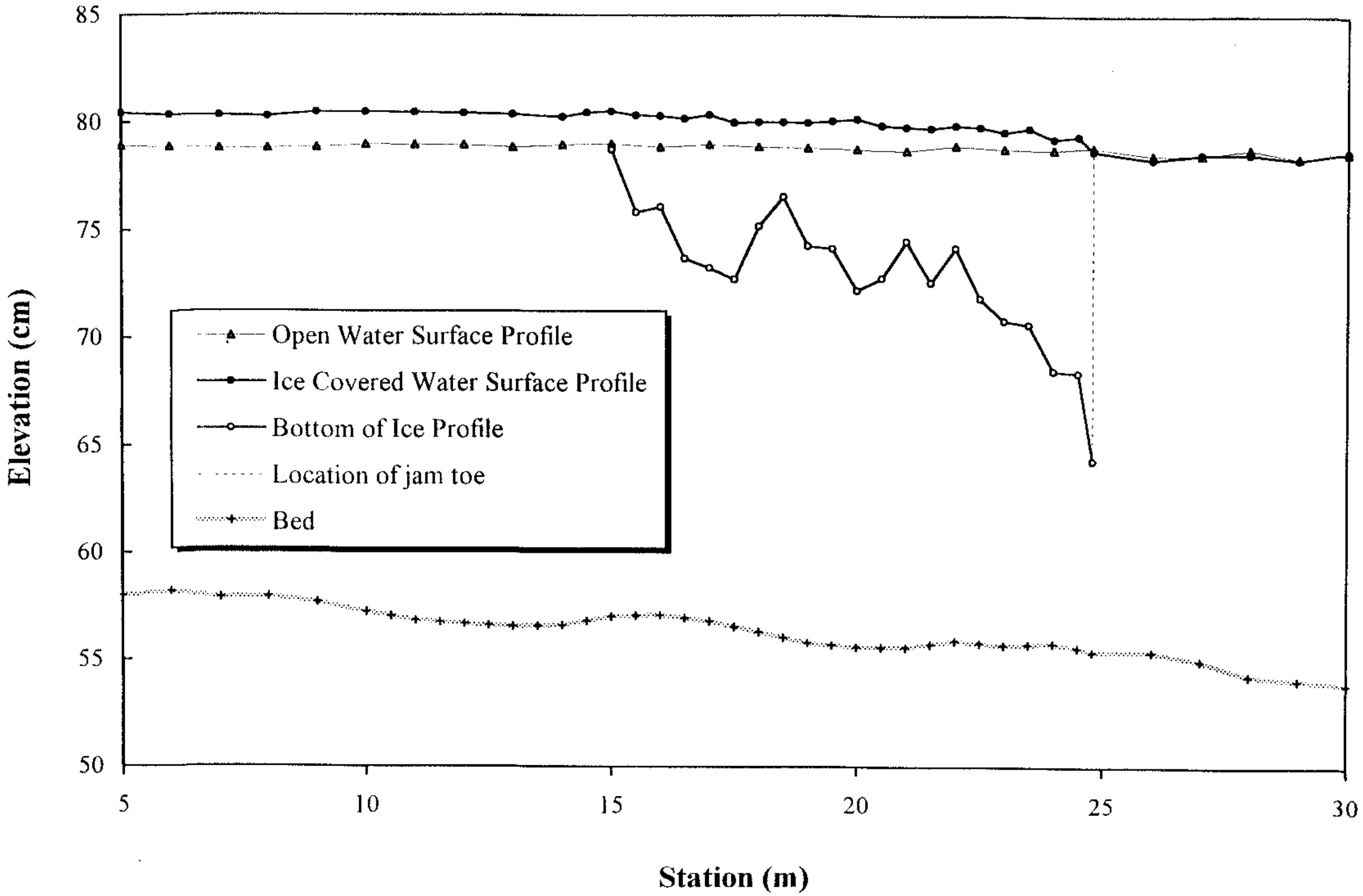

Figure 1. Measured open water and ice jam profiles for carrier discharge of 49 l/s.

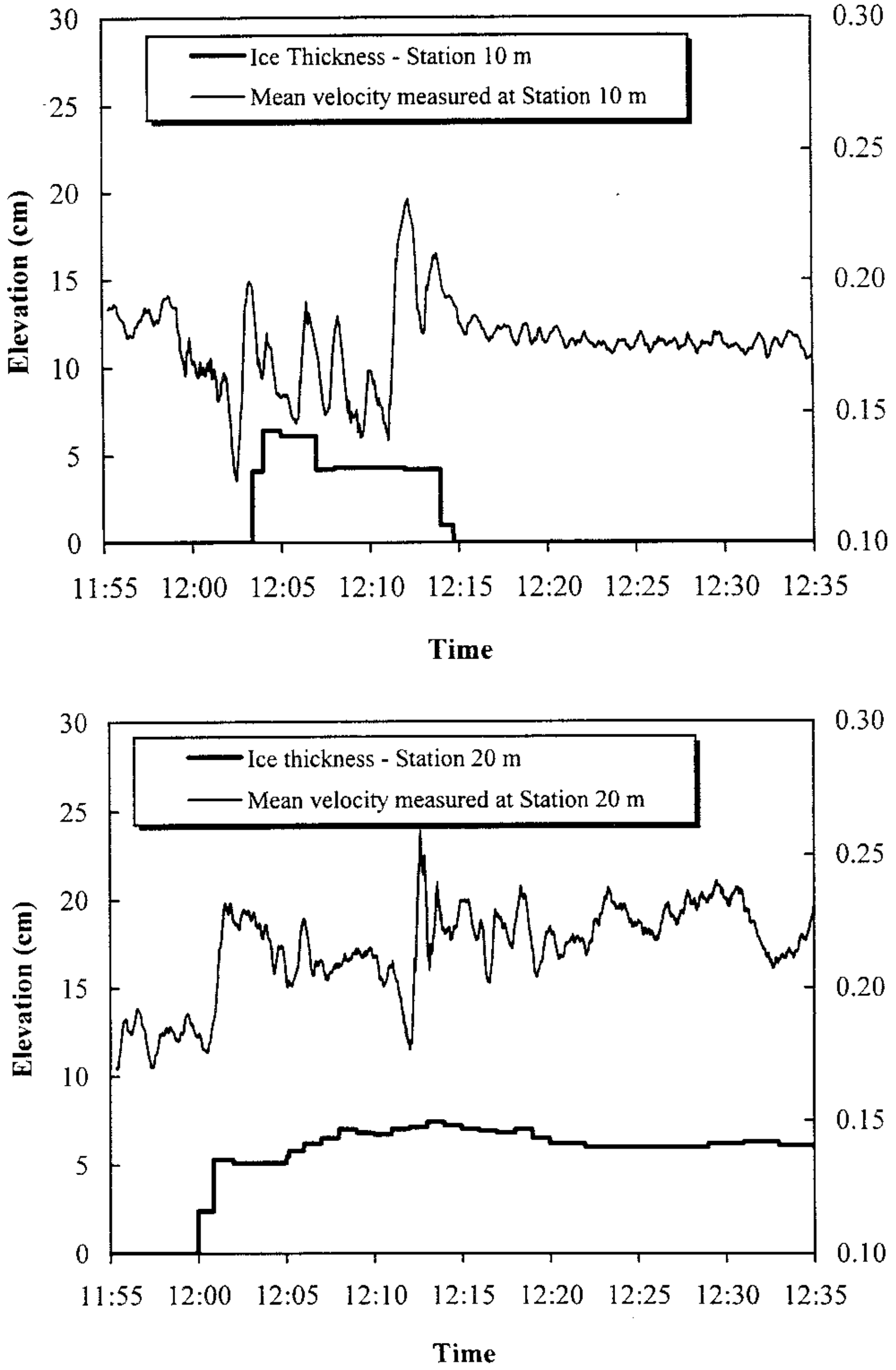

Figure 2. Mean velocities and ice thicknesses measured during ice jam formation.

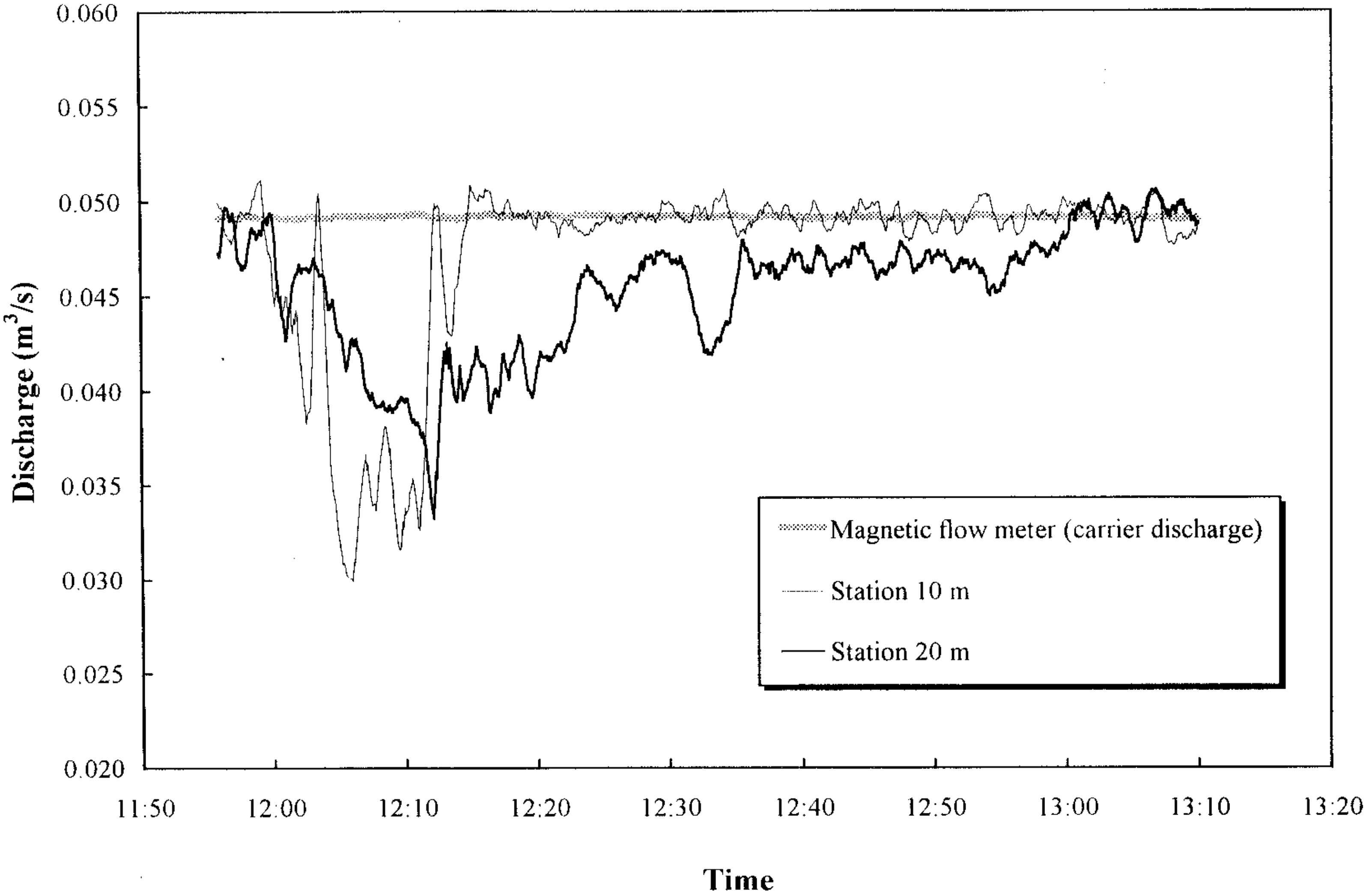

Figure 3. Discharges measured during ice jam formation (60 second moving average shown).

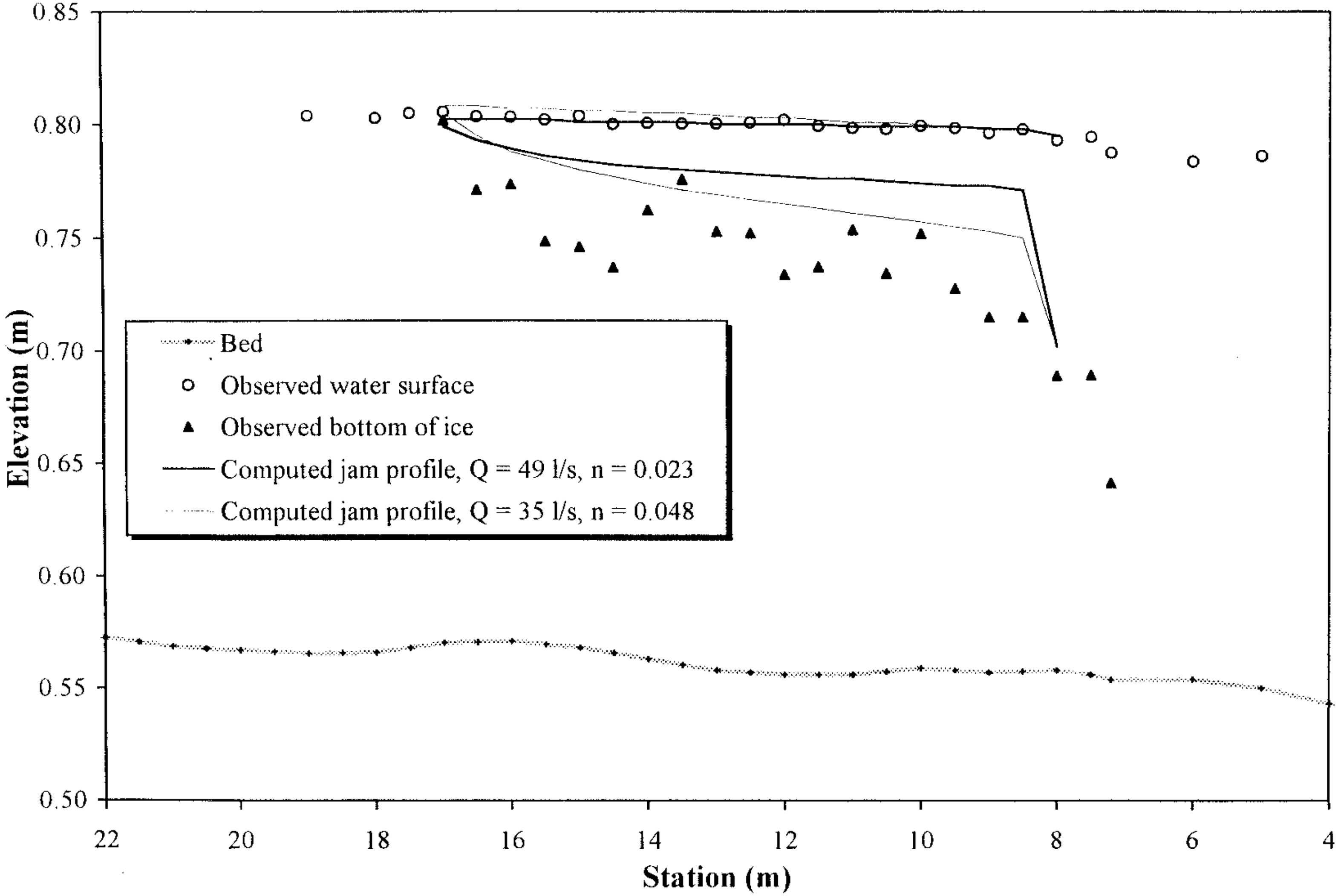

Figure 4. Ice jam profiles as computed using the ICEJAM model.