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CASE STUDY OF A GROUNDED JAM; RESTIGOUCHE R., N.B.

by

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ABSTRACT

The formation, evolution and release of a breakup jam are described and the associated measurements are analyzed and interpreted using existing theories and models. The Restigouche River forms the eastern portion of the boundary between New Brunswisk and Quebec; it is a fair-size stream (width ≈150 m) with a good gradient (slop ≈ 1 m/km). Severe ice jams are known to occur during the ice breakup and a pertinent study was initiated in 1988, jointly by the National Water Research Institute and the N.B. Department of the Environment.

In 1988, the ice began to break in early April and by evening of April 5, an ice jam had formed several kilometers upstream of the town of Matapedia. The jam remained in place for more than three days while water levels remained fairly steady. It was thus possible to carry out accurate and detailed surveys of the water level profile near the toe of the jam. Following release of the jam on April 9, the shear wall height, a crude (but often the only) indication of the thickness of the jam, was measured at several locations. Maximum thickness occurred near the toe of the jam. Using bathymetric data obtained later in the season, along with the ice-jam water levels and shear wall heights, it was possible to reconstruct the configuration of the jam and deduce that it was practically grounded at the toe. The very small area available for unobstructed flow under the jam would indicate an implausibly high velocity, if seepage through the jam were to be neglected. The model "RIVJAM" recently developed at the National Water Research Institute takes seepage into account, and performs the required computations so as to predict the configuration of the jam and the water level profile. Using plausible values for the model coefficients, good agreement between predictions and measurements was obtained. However, this is the only data set where seepage is a major component of the flow and it is desirable to obtain similar data by concentrating on steep or wide rivers where grounding is likely.

RÉSUMÉ

Ce travail décrit la formation, l'évolution et la rupture d'un embâcle de déglacement; à l'aide des modèles et théories actuels, on y analyse et interprète les mesures associées. La Restigouche constitue la partie est de la frontière Québec/Nouveau-Brunswick; c'est un cours d'eau moyen, d'environ 150 m de largeur, avec un bon gradient (pente d'à peu près 1 m/km). Il s'y forme d'importants embâcles pendant le déglacement, et, en 1988, une étude sur le sujet a été entreprise conjointement par l'Institut national de recherche sur les eaux et le ministère de l'Environnement du Nouveau-Brunswick.

En 1988, la glace a commencé à se briser au début d'avril et, le 5 en soirée, un embâcle s'était formé à plusieurs kilomètres en amont de la ville de Matapédia. Il a persisté plus de trois jours, pendant lesquels le niveau de l'eau est resté assez stable. On a donc pu suivre, de façon précise et détaillée, le profil du niveau de l'eau près de la langue de l'embâcle. Après sa rupture le 9 avril, on a mesuré à plusieurs endroits la hauteur de la glace restée échouée, ce qui donne une indication sommaire (mais parfois la seule dont on dispose) de l'épaisseur de l'embâcle. Cette épaisseur était maximale près de la langue de l'embâcle. Avec ces mesures, les données bathymétriques recueillies plus tard dans la saison et les niveaux de l'eau à l'embâcle, on a pu reconstituer la configuration de l'embâcle, ce dont on a déduit qu'il était pratiquement échoué à la langue. En considérant le très faible passage resté libre pour l'écoulement sous l'embâcle, on arrive à des vitesses d'écoulement trop élevées pour qu'on puisse raisonnablement les accepter si l'on exclut l'hypothèse de l'infiltration de l'eau à travers l'embâcle. Le modèle "RIVJAM", récemment mis au point à l'Institut national de recherche sur les eaux, tient compte de l'infiltration et exécute les calculs nécessaires pour prévoir la configuration de l'embâcle et le profil du niveau de l'eau. En utilisant des valeurs plausibles pour les coefficients du modèle, on a obtenu une bonne concordance entre les prévisions et les mesures. C'est cependant le seul jeu de données où l'infiltration est un élément principal de l'écoulement; il est souhaitable de recueillir des données comparables en s'intéressant davantage aux cours d'eau encaissés ou larges où il peut y avoir échouage.

MANAGEMENT PRESPECTIVE

Measurements are presented to document the case of a grounded jam that occurred in the Restigouche River in 1988. To mathematically simulate the configuration of this jam, the model RIVJAM recently developed at NWRI, has been used with encouraging results. More data of this type are required to study the grounding of ice jams, a condition that is related to their persistence and dislodgement.

PERSPECTIVE-GESTION

Ce travail présente les mesures prises pour un embâcle échoué, sur la Restigouche, en 1988. Le modèle RIVJAM, récemment mis au point à l'INRE, a donné des résultats encourageants dans la simulation mathématique de la configuration de l'embâcle. En recueillant d'autres données de ce genre, on pourra étudier l'échouage des embâcles, donc les mécanismes de leur persistance et de leur rupture.

INTRODUCTION

The Restigouche is an interprovincial river, draining parts of Quebec and New Brunswick. The headwaters of the main stem of the Restigouche lie in the Chaleur Uplands. The largest tributaries are the Matapedia, Patapedia, Kedgwick and Upsalquitch rivers. The latter rises in the New Brunswick highlands while the former three rise in the Notre Dame mountains of Quebec.

The farthest downstream Water Survey of Canada gauge is located near the mouth of Rafting Ground Brook. At this site, the drainage area of the river is 7,740 km^2. The long-term average discharge is 165 m^3/s which, for open water conditions, corresponds to mean depth and width of 1.4 m and 140 m respectively. The local water surface slope is 0.8 m/km. About 10 km downstream is the town of Matapedia situated on the Quebec side by the confluence of the Matapedia River known to have experienced severe ice-jam related problems in the past (Gidas, 1981). Farther downstream, several communities on the New Brunswick side have experienced similar problems, e.g. Flatlands, Tide Head, Atholville and Campbellton (Leger, 1986). Below Matapedia, the Restigouche widens gradually and changes to estuarine character by the time it reaches Chaleur Bay near Dalhousie.

In 1987, a joint research project was initiated by the provincial and federal Environment departments to study ice breakup and jamming processes in the lower Restigouche River. This river was chosen mainly because its hydroclimatic regime differs from that of previously studied rivers in Ontario and New Brunswick. It is only subjected to one breakup event per season (usually in April) and its relatively large slope and width can cause very thick and destructive ice jams. The main objectives of the study are to understand how the breakup event is initiated and ice jams develop, with possible forecasting applications. Figure 1 shows the study reach which, for most of its length, has excellent river access thanks to riverside roads along both banks.

A major ice jam that formed during the 1988 breakup is described herein. Pertinent measurements are interpreted with the aid of a numerical model developed recently at the National Water Research Institute.

THE 1988 ICE BREAKUP EVENT

Mild weather began near the end of March with 20 mm of rainfall during Mar. 25-27. The water level at the gauge site rose from a winter low of 1.3 m on Mar. 25 to 2.1 m on Mar. 30 and held at this stage for the next few days. Another 13 mm of rain fell during Apr. 2-4 and caused additional water level rises leading to breakup.

By the late afternoon of April 5, an ice jam had formed near Babcock Brook, incorporating ice from the Upsalquitch River that had run on April 4. The toe of the jam was 300 m upstream of the Brook mouth while the head was just downstream of the gauge by Rafting Ground Brook (Fig. 1). Downstream of the toe, mostly intact sheet ice cover prevailed with ice blocks accumulated under it. For a distance of 1.5 km, pressure ridges and mounts were evident, diminishing in frequency and height in the downstream direction (Fig. 2). Water levels along this jam were recorded photographically at a few locations and surveyed later during open-water conditions.

Upon return to the site in the morning of April 6, evidence was found that a surge of water had gone by, causing fresh high water marks, exceeding the prevailing water levels by ~0.6 m. Moreover, the water level was now higher than in the previous evening and low sections of the riverside roads were flooded. Aerial reconnaissance revealed that the jam now extended much farther upstream, for a length of ~20 km. The river was open upstream of this jam, at least as far as the Patapedia River, i.e. another 35 km. Large shear walls were present throughout this reach indicating previous ice jamming and release. It thus appears certain that an ice run took place in the early morning hours which is consistent with a local observer's report that the ice was running at a speed of about 20 km/h a little upstream of the Upsalquitch.

In the afternoon and evening of April 6, the water level profile near the toe of the jam was surveyed with a level and this was repeated on April 7. The respective results are shown in Fig. 3 and do not appear to differ significantly, suggesting a steady-state condition. Spot checks on April 8 also indicated little change of water levels. A changing feature during this time was a lead near the toe of the jam that began to open up in the morning of April 6. When first noticed, it was no more than a few metres in size. It gradually grew to much greater width and length, so that by April 9 it had joined a larger lead that had been present since April 5, some 500 m downstream of the toe.

At 08:00 on April 9, evidence was found of overnight jamming and recent release below the main jam so that the sheet ice cover holding it in place was now only ~2 km long. As a result, the water levels at the main jam site were visibly lower. The lead near the toe had extended ~70 m into the ice rubble and the water moved in it at a speed of 2-3 m/s. Ice blocks also moved into the lead, a sign of imminent release which occurred at 09:45. During the release of the jam, water surface velocities near the toe area were estimated by timing the movement of ice floes at 3.2 m/s, close to an estimate obtained from the simple theory of Henderson and Gerard, 1981. After the ice run, the height of shear walls left within the previously jammed reach was measured at several locations. Though crude (Calkins, 1983), this is the only possible estimate of the thickness of a breakup jam. Figure 4 shows these data plotted versus river distance. Noteworthy are (a) the nearly constant-thickness reach (22-27 km), which could be considered an "equilibrium" reach; and (b) the sharp increase in thickness near the toe, followed by a decrease. This is consistent with the plan view of the shear wall, illustrated in Fig. 5.

River bathymetry was measured at several cross-sections, spaced closely near the toe area and farther apart elsewhere. These sections are located at 20.535, 20.635, 20.765, 20.995, 21.090, 21.180, 21.460, 21.615, 21.977, 22.420, 23.590, 24.460, 25.740 and 26.410 km, measured along the river, upstream from an arbitrarily selected datum near Campbellton. The river section at the toe (20.635 km) is shown in Fig. 6, along with the April 6 water level and the jam's approximate lower boundary, based on the local shear wall height. Severe grounding is evident at this site by the considerable reduction of the effective width of the river. More importantly, the area available for unobstructed flow under the jam is only three percent of the total area under the water level (950 m^2).

The available data on water levels, shear wall heights and river bathymetry provide an opportunity to apply the RIVJAM model, a recently developed algorithm that computes the configuration of breakup jams (Beltaos and Wong, 1990).

NUMERICAL SIMULATION

The RIVJAM Model

This is a modified, more robust version of a model developed earlier to investigate the configuration of ice jams near their toe (Beltaos and Wong, 1986a). It is based on the flow continuity and momentum equations and the stability conditions of "wide" jams (Pariset et al, 1966). The latter is expressed as (Beltaos, 1988):

$$\frac{dt_s}{dx} = \frac{s_i/(1-s_i)}{(1-p)K_x}\left\{S_w\left(1+\beta_2\frac{h}{t_s}\right) - \frac{\mu(1-s_i)}{s_i}\frac{t_s}{B}\right\} \qquad (1)$$

in which t_s = submerged portion of jam's thickness; x = downstream distance; S_w = water surface slope; h = average depth of flow under the jam; B = channel width at the bottom level of the jam; s_i = specific gravity of ice; p = porosity of the jam; K_x = ratio of longitudinal to vertical stresses within the jam; μ = coefficient related to the internal friction of the jam, as originally defined by Pariset at al (1966); and $\beta_2 = f_i/2f_o$ with f_i = friction factor of the jam's underside and f_o = composite friction factor for the flow under the jam. If a jam is long enough, dt_s/dx will approach zero far upstream of the toe, hence leading to "equilibrium" conditions where jam thickness and flow depth are approximately uniform. Accordingly, if the LHS of Eq. 1 is set equal to zero, the equilibrium thickness of the jam can be calculated simply via a relationship that is equivalent to that of Pariset et al (1966).

In the past, it has been generally assumed that the seepage flow through the voids of the jam is negligible so that the entire discharge must flow under the jam. Near the toe of a jam, however, this assumption produces flow velocities far in excess of the "erosion limit" which makes it difficult to predict the local jam profile (e.g. see Flato, 1988). A good example is Fig. 6 where, if no seepage is allowed for, the flow velocity would have to be 10 m/s! RIVJAM accounts for seepage using the relationship

$$Q_s = \lambda A_J \sqrt{S_w} \qquad (2)$$

in which Q_s = discharge through the voids of the jam; A_J = wetted area of the jam, and λ = seepage coefficient in m/s; the average seepage velocity is equal to $\lambda \sqrt{S_w}/p$. As a jam thickens near the toe, both A_J and S_w increase so that an increasing portion of the total discharge, Q_T, flows as seepage. In this manner, the flow velocity underneath the jam does not increase appreciably.

The momentum equation is expressed simply as:

$$S_w \simeq (\tau_i + \tau_b)/\rho g h \qquad (3)$$

in which τ_i, τ_b = flow shear stresses applied on the ice and bed respectively; ρ = density of water; and g = gravitational acceleration.

Equations 1-3, along with appropriate hydraulic resistance considerations, lead to two differential equations with two unknowns which can be solved numerically (Beltaos and Wong, 1990). Computation may proceed either upstream or downstream, starting at a site where the water level and the jam thickness are specified.

<u>Coefficients</u>

Several coefficients must be specified in order to run the model. They relate to ice and water properties; hydraulic resistance and seepage characteristics of the jam; and material properties of the jam, assumed to behave as a floating granular mass.

The coefficient, f_o, which relates the average shear stress [$=0.5(\tau_i + \tau_b)$] to the average flow velocity is empirically expressed as:

$$f_o = c t_s^{m_1} h^{-m_2} \qquad (4)$$

in which various choices of the constants c, m_1, m_2 represent different assumptions concerning resistance. For example, $m_1 = m_2 = 0$ implies that f_o = const = c while $m_1 = 0$, $m_2 = 1/3$ implies n_o = const = $0.10\sqrt{c}$(n_o = Manning roughness coefficient). Where $m_1 > 0$, an effect of jam thickness on resistance is implied, as has been found empirically (Nezhikhovskiy, 1964; Beltaos, 1988). By examining data on equilibrium jams, Beltaos and Wong (1986a) deduced $c \simeq 0.5$ and $m_1 = m_2 = 1.2$. The coefficient β_2 ($= f_i/2f_o$) is assumed to be constant along a jam for simplicity, even though this is not necessarily true. Often, β_2 is fixed at 0.50 but could vary between 0.3 and 0.8 (Beltaos, 1983). User-imposed limits can be applied to f_o in cases where Eq. 4 gives implausibly high or low values, e.g. near the toe or head of the jam.

Equation 1 indicates that it is the product of K_x and 1-p that governs the solution rather than the individual values of K_x and p. Since p is not known by measurement, it can be fixed at the commonly quoted value of 0.40 and K_x be allowed to vary so as to reproduce the appropriate value of K_x (1-p). The only field-based determination of K_x gave $K_x (1-p) \simeq 6$, so that $K_x \simeq 10$ (Beltaos, 1988). The coefficient μ has an average value of 1.2 - 1.3 but could be as low as 0.8 and as high as 2.0.

The coefficient λ is not known under natural conditions. Existing theories suggest that $\lambda \propto \sqrt{h_i}$ (h_i = thickness of ice blocks in a jam). Extrapolation of laboratory data (Beltaos and Wong, 1986b) to the present case of $h_i \simeq 0.6$ m gives $\lambda \simeq 1.4$ m/s.

Application to Restigouche River Jam

The water levels obtained on April 6 and 7 and the shear wall heights measured after the release of the jam provide an excellent opportunity to study the characteristics of jams near the grounding condition. Numerous runs of RIVJAM were made and good performance (Fig. 7) was obtained with the following set of parameters: p = 0.40; c = 0.40; $m_1 = m_2 = 1.0$; $\beta_2 = 0.50$; $K_x = 12.0$; $\mu = 0.80$; $\lambda = 2.5$ m/s. This set was not defined by rigorous optimization but by varying the parameters within plausible ranges until a "satisfactory" prediction was obtained. The latter was based on three criteria, (a) accurate reproduction of the measured water levels near the toe of the jam; (b) approximate reproduction of ice jam thickness as deduced from shear wall heights; and (c) prediction of an equilibrium, or constant-thickness, condition starting some distance above the toe which should have been the case, given the considerable length of the jam on April 6.

An additional application of the model can be made by considering the few approximate water levels for April 5 that were obtained from photographs. The main interest here is to check whether RIVJAM can predict the location of the head of this short, non-equilibrium jam. Figure 8 indicates that the predicted location is within 200 m (about a river width) of the observed. It was necessary, however, to increase c to 0.60 (from 0.40) which is plausible because jams are expected to become smoother with time by thermal erosion. The flow discharges used for April 5 and 6 were respectively 315 and 330 m^3/s, both consistent with prevailing hydro-meteorologic conditions.

DISCUSSION

The two applications of RIVJAM to the April 5 and April 6 ice jams have been encouraging because the values of the coefficients used to obtain good predictions are plausible. There is one discrepancy, however, and it results from the model value of 2.5 m/s for λ. As mentioned earlier, extrapolation of laboratory results would, in this case, indicate $\lambda \simeq 1.4$ m/s. This is based on existing theories which require that λ vary in proportion to the square-root of particle (or ice block) size. However, re-analysis of available data on flow through rockfill suggests that λ grows with particle size faster than implied by the square-root relationship (Beltaos, unpublished). This means that λ could well be more than 1.4 m/s in nature, though it is not known whether 2.5 m/s is reasonable. Clearly, more studies of very thick or grounded jams are needed. Relatively steep and wide rivers with good water's edge access, such as the Restigouche, are the most suitable.

An important aspect that cannot be quantified at present, pertains to the conditions downstream of the toe. Our measurements of April 6 and 7 indicate water levels that are higher than those estimated for flow under sheet ice cover without any ice block accumulation underneath (Fig. 3). It follows that between the toe of the jam and the end of under-ice accumulation, there should be a transitional reach in which the thickness of the accumulation decreases from a maximum at the toe to zero. In the present case, it is not possible to adequately describe this transition because our surveys did not extend far enough downstream.

The abrupt change in water surface slope at the toe suggests a change in hydraulic conditions, likely related to the open lead mentioned earlier. It is estimated that this lead could carry most of the discharge at the relatively mild slope downstream of the toe (~0.0015 as opposed to ~0.02). It is not known why these leads form but they are very common and seem to be significant with respect to the eventual release of the jam. The fact that the jam remains stable even long after the lead has attained appreciable dimensions is also not well understood but could perhaps be explained by the development of cohesion with time by freeze-bonding (e.g. see Schaefer and Ettema, 1986). Eventually the lead becomes so wide that the local strength of the jam is exceeded and the ice rubble moves into the lead, followed by a general surge of ice and water.

SUMMARY AND CONCLUSIONS

A grounded jam that formed in the Restigouche River during the 1988 breakup has been described along with pertinent measurements and data interpretation. It was found that if seepage flow through the voids of the jam is considered, it is possible to predict the configuration of the jam near the toe. This can be accomplished using a numerical algorithm, such as RIVJAM, that solves the appropriate differential equations. On the other hand, if seepage had been neglected, extremely high flow velocities, far exceeding the jam erosion limit, would have to be postulated.

In general, the various coefficients and parameters used in the model were in agreement with previous findings elsewhere. However, the seepage coefficient was about twice what would have been projected from laboratory experiments. This could be due to a size effect but more information is needed before any conclusions can be made. Wide and steep rivers like the Restigouche are suitable for this purpose because they are subject to formation of very thick or grounded jams.

Downstream of the toe of the jam, an open lead developed and progressively grew in size during the 3-1/2 days that the jam was in place. The final release of the jam was preceded by ice discharges into the lead, muc has been observed elsewhere. More detailed information is needed with regard to the reach downstream of the toe in order to understand the conditions of release.

ACKNOWLEDGMENTS

W. Moody of NWRI conducted the hydraulic surveys following the breakup event, including channel bathymetry, water surface slopes and ice jam elevation surveys from photos. R. Lane of Water Survey of Canada, Fredericton, assisted in establishing data recording and accessing devices in the gauge shed and in obtaining ice thicknesses during the winter. W. Waite assisted in setting up hydro-meteorologic instruments in the study area and provided specialized weather forecasts for the lower Restigouche reach. L. Irvine, our local

observer, made pre-breakup and breakup observations and provided helpful advice for subsequent hydraulic surveys.

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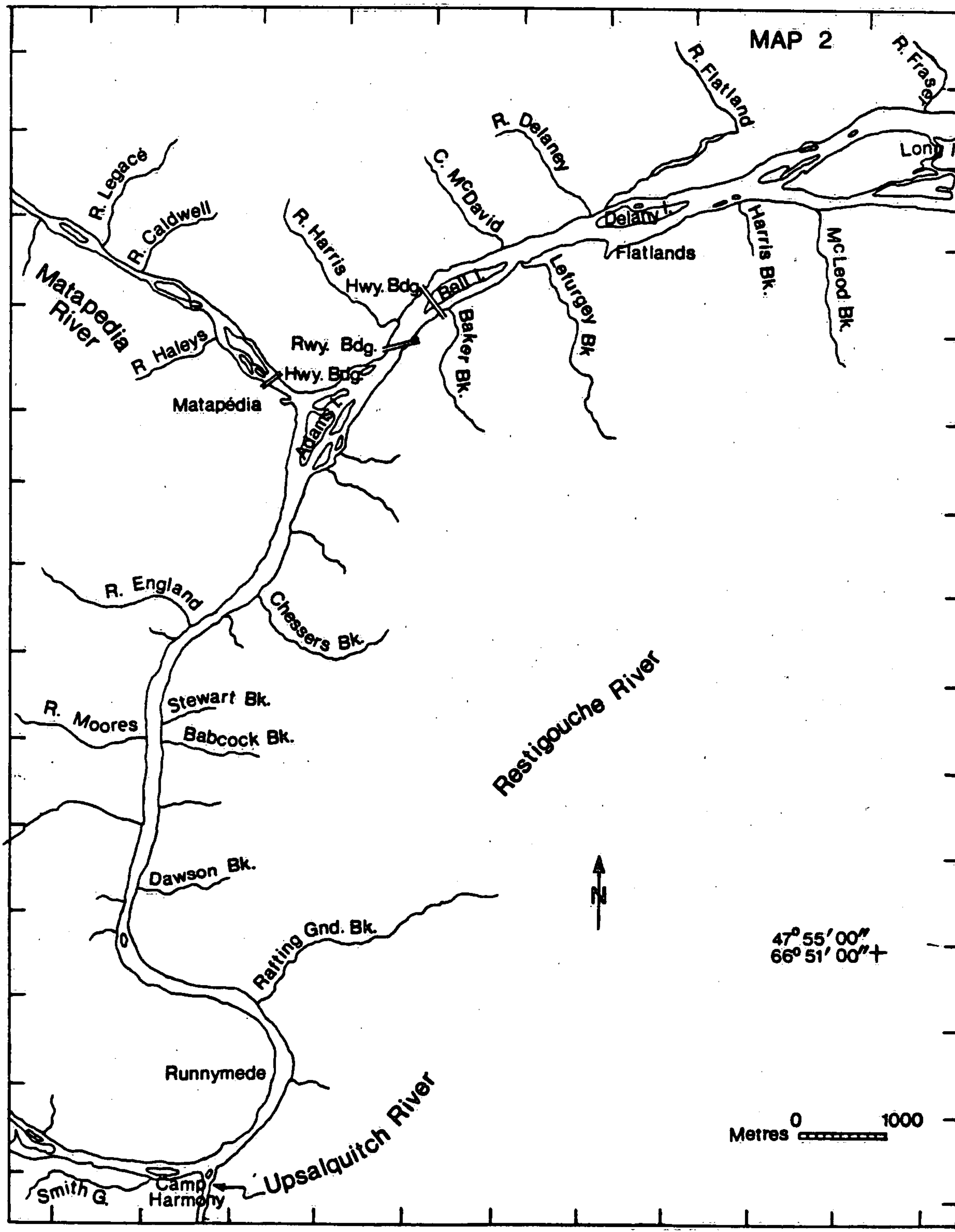


Fig. 1. Planview of study reach.

(a) looking upstream from near toe; note high water level threatening road.

(b) looking downstream from near toe; note pressure ridges and evidence of crushing action between ice slabs.

Fig. 2. Photos of jam, p.m., April 5.

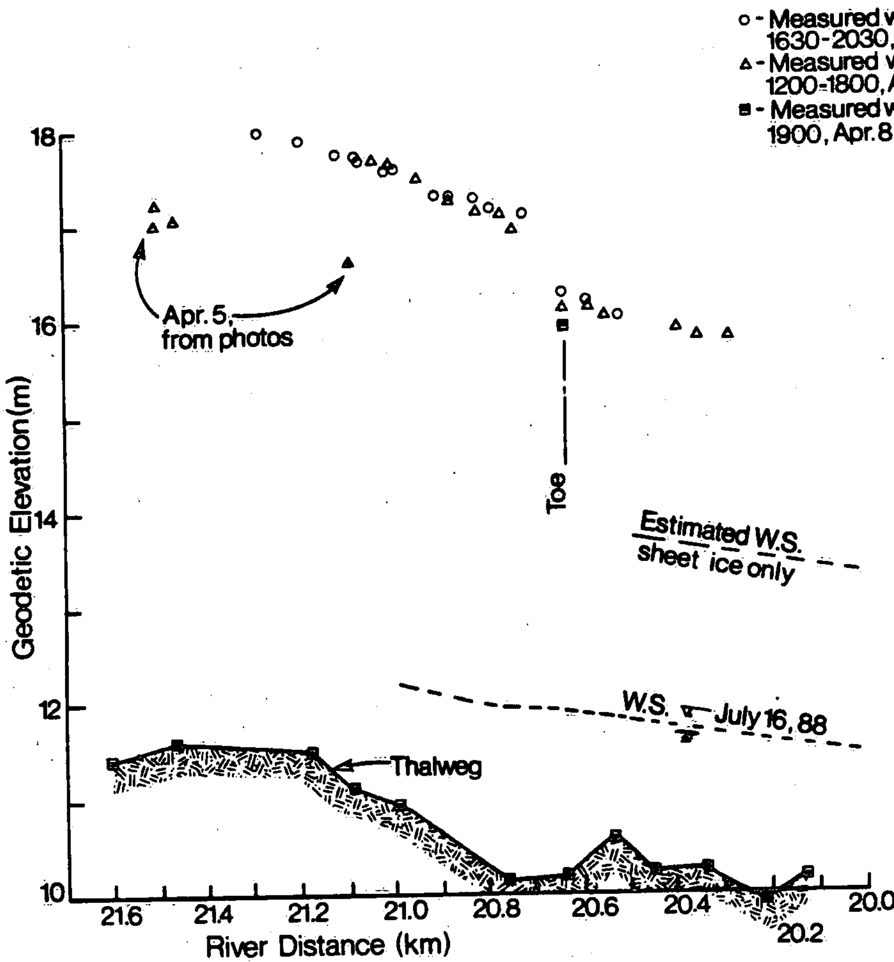


Fig. 3. River profile and measured water levels near the toe of the jam.

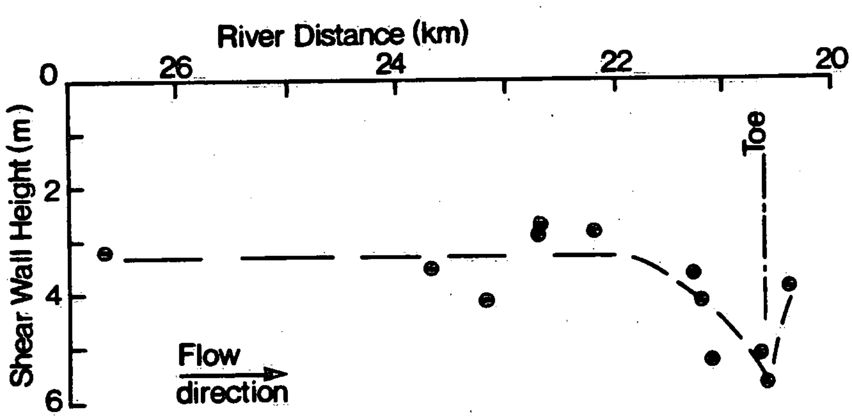
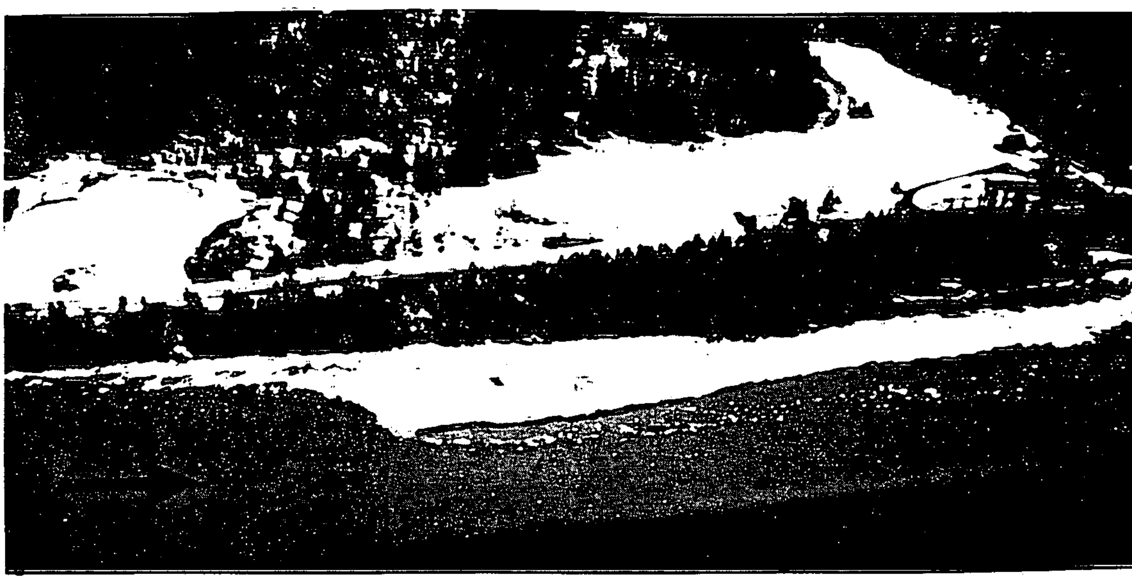


Fig. 4. Shear wall heights measured along the jammed reach.

(a) shear wall near Upsalquitch confluence; est. height above water level ~ 2 m.



(b) aerial view of grounded ice jam remnants at the (former) toe; note planar geometry indicating rapid increase of jam thickness upstream of the toe and gradual decline downstream.

Fig. 5. Post-release photos.

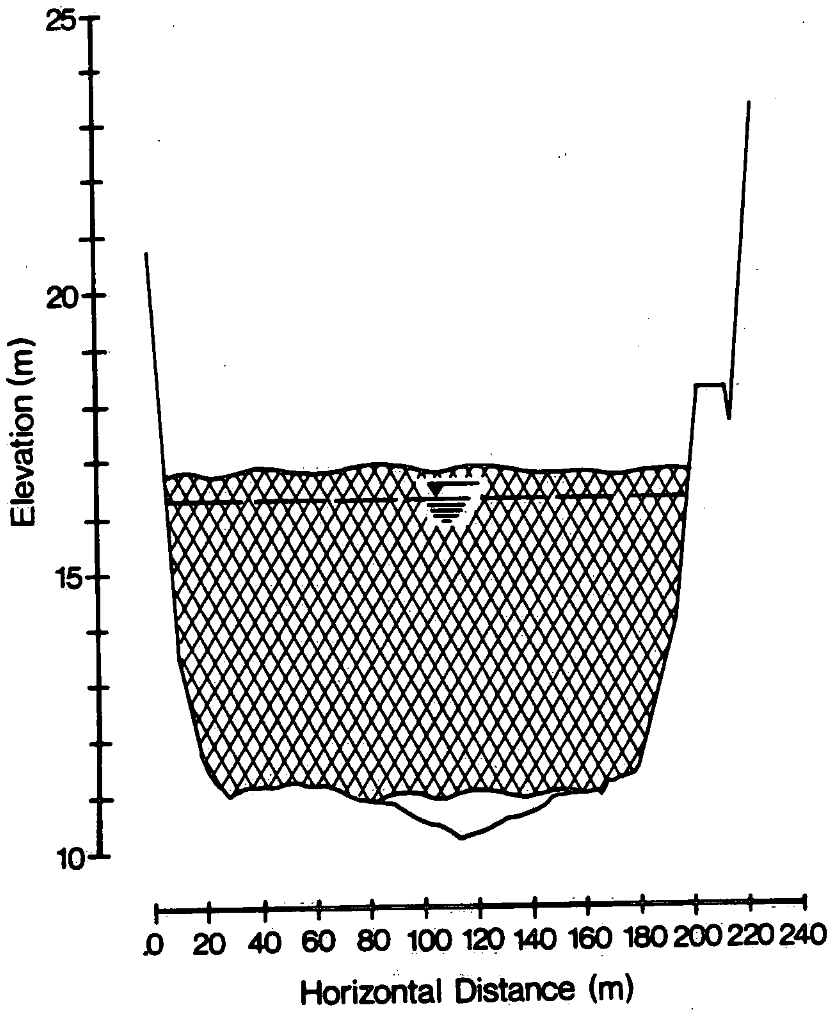


Fig. 6. River cross-section at the toe of the jam; note practically grounded condition.

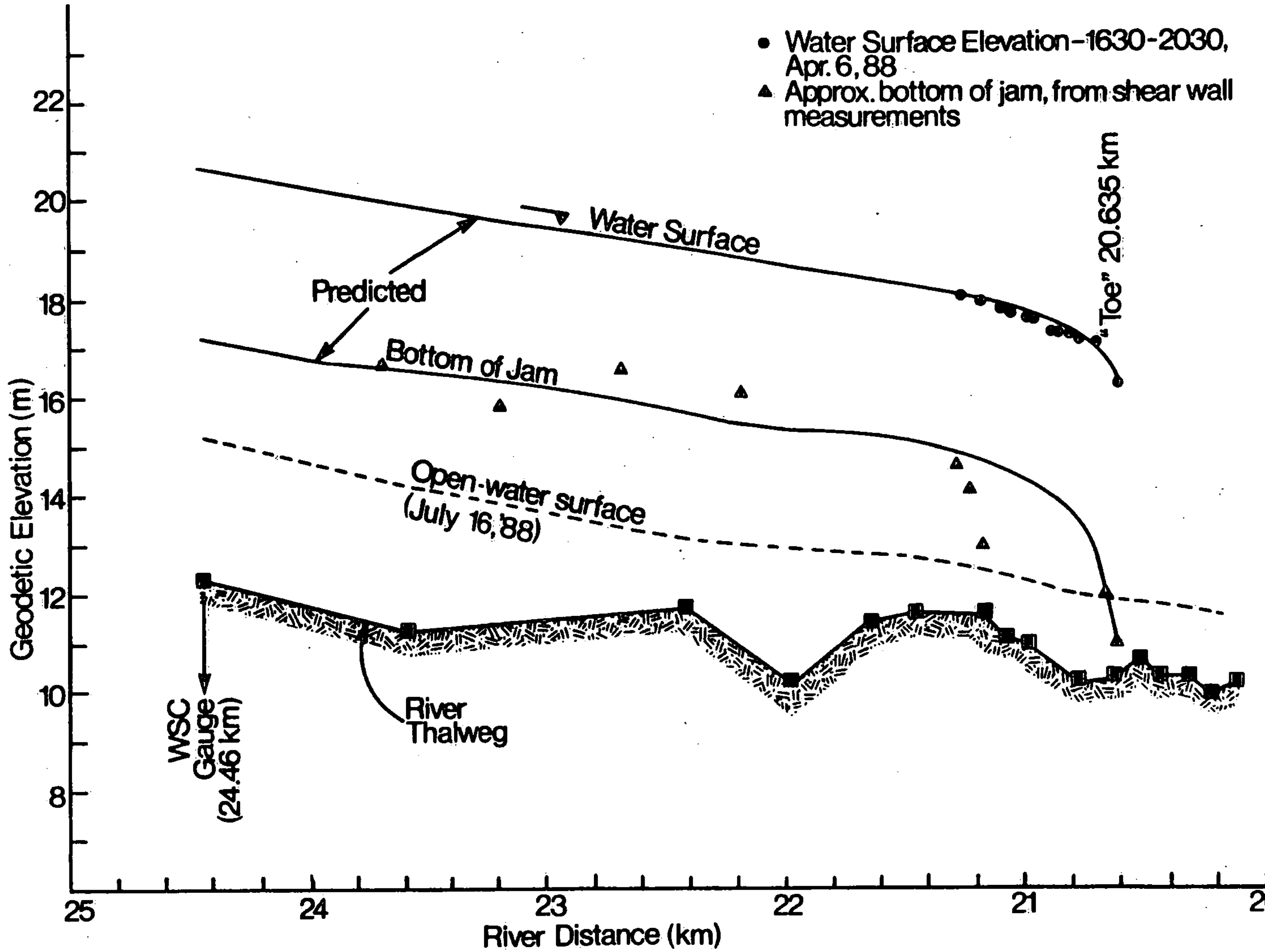


Fig. 7. Comparison between RIVJAM predictions and measurements for the April 6 water level survey; note "equilibrium" condition predicted to start a few river widths above the toe.

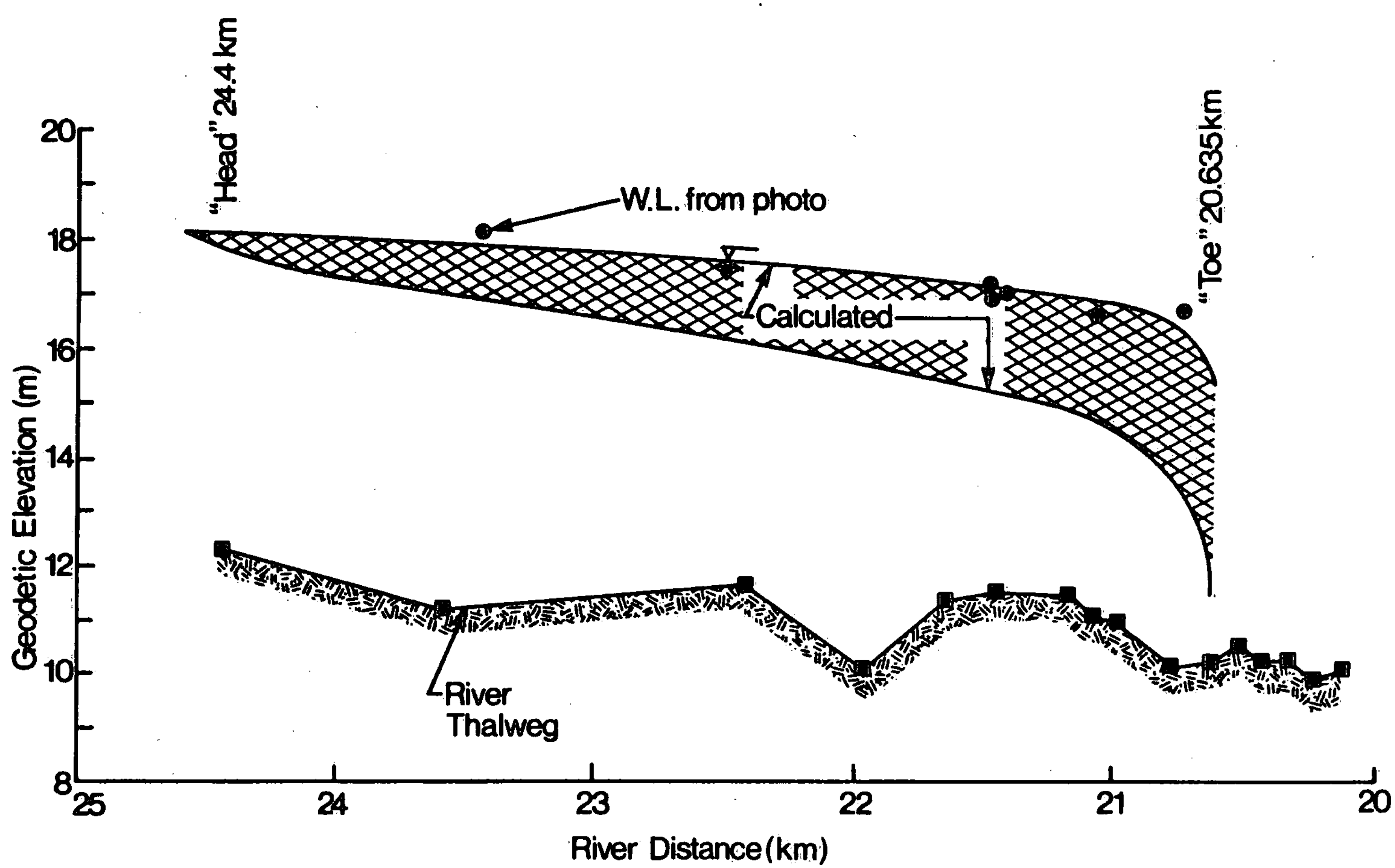


Fig. 8. Comparison between RIVJAM predictions and measurements for the short jam on April 5; the water levels are crude (from photos) but head location is predicted to within a river width.