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MODELLING AN ICE JAM RELEASE SURGE ON THE SAINT JOHN RIVER, NEW BRUNSWICK

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Abstract

Ice jam release surges present a unique challenge to the flood forecaster, since the surge released when an ice jam fails is highly dynamic in nature. The problem is analogous to the classic dam break scenario and should be amenable to analysis by hydraulic flood routing techniques. However, the problem is complicated by data limitations, primarily due to the difficulty in obtaining discharge measurements during the breakup period, and by the complicating influence of ice on the wave propagation.

This paper presents the results of a numerical simulation of the ice jam release which occurred on the Saint John River upstream of Grand Falls in April 1993. The surge propagation analysis was conducted using a one-dimensional finite element implementation of the St. Venant equations, known as the *cdg1-D* unsteady flow model. The model provided fair agreement with available discharge data and the surge propagation speed was well reproduced. However, the model was relatively inaccurate in terms of the predicted stage. This can partly be attributed to the attenuating effects of the sheet ice in the channel downstream of the jam toe, which was not considered in the analysis.

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INTRODUCTION

One of the most dangerous aspects of ice related flooding events involves the surges that are released when an ice jam fails. It is highly desirable to be able to predict the rapid discharge and water level increases which can be anticipated downstream of released ice jams for flood forecasting purposes. However, because of the highly dynamic nature of these flood events, traditional hydrologic flood routing techniques do not apply. In this investigation, the applicability of the hydraulic flood routing approach is examined.

The hydrologic details of the ice related event which occurred at Sainte-Anne-de Madawaska along the Saint John River in 1993, documented by Beltaos, Burrell and Ismail (1994) provide an excellent data set with which to examine the applicability of hydraulic flood routing techniques to ice jam surge release modelling. Data provided by the National Water Research Institute (NWRI), N.B. Power, the New Brunswick Department of the Environment, Gouvernement du Quebec Ministère de l'Environment et de la Faune, and the Water Survey of Canada (WSC) included: channel geometry; a measured ice jam profile; water levels during the release event (measured approximately 5 km below the ice jam toe location); and hourly streamflow data on the Saint John River and four major tributaries along the study reach.

In this study, the *cdg-1D* hydraulic flood routing model was used to model the propagation of the ice jam surge release. This model employs a Petrov-Galerkin finite element method known as the *characteristic-dissipative-Galerkin* scheme (Hicks and Steffler, 1990, 1992) to solve the one-dimensional unsteady open channel flow equations.

DESCRIPTION OF THE STUDY REACH AND THE ICE JAM RELEASE EVENT

Figure 1 shows the study reach of the Saint John River which flows east then southeast along the international boundary between the United States and Canada, from Fort Kent, Maine to the dam at Grand Falls, New Brunswick, a distance of approximately 100 kilometres. Beltaos, Burrell, and Ismail (1994) describe the river as "steep and shallow" in the upper portion and "flat and deep" near St. Leonard. Table 1 presents the location of key sites along the Saint John River in kilometers (measured along the channel centreline) downstream of Fort Kent.

Table 1. Location of key sites along the Saint John River.

Location	**Station (km)**
Fort Kent WSC gauge (01AD002)	1.3
Edmunston WSC gauge (01AD004)	32.6
Ste-Anne-de-Madawaska	62.0
Saint Leonard	74.3
Grand Falls WSC gauge (01AF002)	95.3

The Saint John River has experienced many major flood events which have been documented as far back as 1696 (Kindervater, 1985). The majority (69%) of these were ice related, causing millions of dollars in damage to the communities which lie along the river's banks (Humes and Dublin, 1988). The 1993 ice jam release event on the Saint John River, described by Beltaos, Burrell and Ismail (1994), was particularly well documented. On April 13, the ice jam formed at near Ste-Anne-de-Madawaska (km 69.2). The profiles measured along the jam on April 13 and 14 extended upstream to km 49.2. The high water levels upstream of the jam caused the closure of the Trans Canada Highway at various locations along the banks of the Saint John River, including at Riviere Verte, 15 km upstream of Ste-Anne-de-Madawaska.

At approximately 09:00h on April 15, 1993 this ice jam released. The surge peak arrived in Saint Leonard, about 5 kilometers downstream of the toe of the jam, 48 minutes after this release. The ice from the jam entered Saint Leonard 35 minutes after the jam release and continued to flow past for 90 minutes. Water levels were documented at Saint Leonard following the release of the jam. As well, two Water Survey of Canada (WSC) gauges on the Saint John River, Fort Kent (WSC 01AD002) and Grand Falls (WSC 01AF002), recorded streamflow during this period. WSC gauges on four major tributaries were also operational during this time.

The channel was free of ice upstream of the ice jam at the time of the release, but this was not the case downstream. On April 13, 1993 sheet ice was observed from the jam toe down to about km 72.5; broken ice from about km 76.5 to km 77.5; and sheet ice again from about km 79.0 to km 83.6. It is believed that no major reductions in ice sheet length occurred between these observations and the time the jam released.

THE HYDRAULIC FLOOD ROUTING MODEL

Ice jam release surges present a unique challenge to the flood forecaster, since traditional hydrologic flood routing techniques are inapplicable in such cases. This is because the surge released when an ice jam fails is highly dynamic in nature. The problem is analogous to the classic dam break scenario (Henderson and Gerard, 1981). However, the applicability of analytical solutions is questionable, since the propagation channel is generally irregular. An alternative is to apply an hydraulic flood routing technique, which essentially involves a numerical solution of the governing unsteady flow equations.

Until recently, hydraulic models were considered unsuitable for flood routing problems because of the high cost of obtaining adequate geometric data over long reaches. In a surge propagation analysis, this problem is exacerbated by the fact that a small spatial discretization is required to resolve the steep wave fronts in the dynamic flow region downstream of release point. Hydraulic flood routing techniques have been successfully applied to route open water floods on the Peace River in northern Alberta, where details of channel geometry were quite limited (Hicks, 1996). This was achieved using the available survey data, supplemented with topographic map data, by neglecting the floodplain and approximating the channel as rectangular. Further studies of more extreme flood events on the Oldman River in southern Alberta (McKay *et al.*, 1996) suggest that this limited geometry approach works well provided floodplain storage effects do not significantly influence flood wave propagation speed. The limited geometry approach has also been applied to ice jam surge release modelling on the Hay River, NWT (Hicks *et al.*, 1995). However, in that case there were no documented ice jam release events available to validate the approach.

The hydraulic flood routing model used in this investigation was based on the St. Venant equations, which were modified to provide a conservation formulation applicable to rectangular channels of varying width (Hicks et al., 1997):

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q \qquad [1]$$

$$\frac{\partial Q}{\partial t}+\frac{\partial QU}{\partial x}+\frac{\partial}{\partial x}\left(\frac{gAH}{2}\right)-\frac{gAH}{2B}\frac{dB}{dx}=gA\left(S_o-S_f\right) \qquad [2]$$

where:

A = cross sectional area perpendicular to flow;
Q = discharge;
q = lateral inflow;
U = cross sectionally averaged longitudinal velocity;
H = depth of flow;
B = width of rectangular cross section;
S_f = longitudinal boundary friction slope;
S_o = longitudinal channel bed slope;
g = acceleration due to gravity;
t = temporal coordinate; and
x = longitudinal coordinate.

These equations were solved using the characteristic-dissipative-Galerkin finite element method (Hicks and Steffler, 1992, 1995).

DATA REQUIREMENTS

Channel Geometry and Resistance

The basic data requirements for this simplified geometry model include details of the effective bed profile, channel widths and hydraulic resistance characteristics of the river. The effective bed level is defined as the bed elevation of an equivalent rectangular section approximating the actual channel geometry. Cross section surveys, supplied by NWRI and N.B. Power, were used to define the effective bed profile by dividing the flow area by the top width for bankfull conditions and then subtracting this average depth from the bankfull water level. Figure 2 shows the effective bed profile determined by this method, with the crosses representing the surveyed cross section locations. The widths of the rectangular approximations were taken as the top width of the surveyed cross section at bankfull conditions.

Channel resistance is the only calibration parameter in the hydraulic flood routing model. However, in this particular case, it was of importance primarily to the determination of initial conditions, since the ice jam propagation took place over a very short reach in which dynamic effects were dominant. Based on information supplied by N.B. Power, Mannings *n* was taken as 0.025 upstream of Edmunston and 0.020 in the reach downstream of Edmunston.

Boundary Conditions

Two boundary conditions and all lateral inflows must be specified in order to solve the non-linear partial differential equations used in the hydraulic flood routing model. One boundary condition must be specified at each end, as the flow in the modelled reach of the Saint John River is subcritical. In general, the upstream boundary condition is a discharge hydrograph. The downstream boundary condition may be a stage or discharge hydrograph, or a stage-discharge rating curve.

Since a measured ice jam was to be superimposed on the flow to generate the surge being modelled in this study, the upstream boundary had to extend far enough upstream to ensure that the modelled reach included the backwater reach upstream of the jam. Since the inflow must be know at this upstream boundary, it was taken at the WSC gauge on the Saint John River near Fort Kent, approximately 30 km upstream of the influence of the ice jam backwater.

The downstream boundary was taken at Grand Falls (95.3 km). The boundary condition at this location assumed a constant stage, estimated from the stage hydrograph measured at the WSC gauge at Grand Falls. This approach was taken since variations in this water level were limited during the simulation period, and the model was not found to be sensitive to the range of values observed.

Hourly streamflow data were available for four of the tributaries which flow into the Saint John River within the study reach: the Madawaska River; the Iroquois River, the Green River (Riviere Verte) and Grande River. The inflow locations are illustrated on the profile in Figure 2. Numerous other tributaries contributing to the flow could not be quantified with the available information and this is considered one of the significant limitations of the modelling effort.

Initial Conditions

The initial conditions (stage and discharge) must be specified at every computational node prior to beginning an unsteady flow simulation. For the Saint John River case study these initial conditions were established in three steps. The first involved using the *cdg1-D* model to calculate a gradually varied flow profile for constant incoming and tributary inflows, based on the flows observed at the time hourly data was first available (April 14, 1993 at 16:00 h). Once the steady flow conditions were determined for this time, the discharge hydrograph at Fort Kent and the variable tributary inflows were routed until the point in time when the jam released, estimated to be at 09:00 h in April 15, 1993. Figure 2 illustrated the computed water surface profile at this time. The ice jam profile measured on April 14 was then superimposed on this profile, thus establishing the antecedent conditions for the ice jam surge release. The backwater profile shown in Figure 2 (obtained using the steady, gradually varied flow model, HEC-2) was also superimposed on the computed flow profile. Thus, the initial stage profile used in the surge propagation model was only based on the *cdg1-D* simulation results upstream of Edmunston and downstream of the jam toe, as illustrated in Figure 2. It is important to note that the initial discharge conditions specified throughout the entire reach were based on the *cdg1-D* model output at 09:00 h in April 15, 1993. This is considered a reasonable assumption as the ice jam profile did not vary significantly during the period preceding the release.

Verification Data

In addition the input data required to define the problem for the numerical model, it is essential to have hydrographs at points along the channel downstream in order to appraise the model's performance. Ideally this verification would include stage and discharge hydrographs at more than one point, in order to assess both the propagation speed and amplitude accuracy of the modelled wave. In this investigation, the receiving channel was relatively short in length, extending only to Grand Falls approximately 25 km downstream of the jam toe. Water levels were measured at the bridge in St. Leonard as the surge passed and estimated inflows to the Grand Falls plant were provided by N.B. Power.

MODEL RESULTS

The ice jam surge propagation simulation initiated at 09:00 h on April 15, 1993 with the ice jam profile described above. Inflows were varied during the routing period, based on the hourly data at the Fort Kent gauge and the four tributaries. It was assumed from the start of the simulation that the ice in the jam provided no resistance to the flow. No account was taken of the ice downstream of the jam in the surge propagation analysis.

Figure 3 presents the simulation results in comparison with the available data. Water levels at St. Leonard are presented in Figure 3 (a) where it is seen that the predicted peak height is about 1 m higher than the observed values. The high peak stage predicted by the model may be due, in part, to neglecting the peak attenuation effects of the sheet ice in the downstream channel (which was still in place at the time the ice jam released). The approximate geometry used must also be considered a factor. Based on the wave propagation velocity, it was determined that the wave remained dynamic all the way to Grand Falls. This was reflected in the fact that the modelled peak stage was found to be insensitive to variations in input channel resistance.

Figure 3 (b) presents the computed discharge hydrographs at various locations along the channel. Results are comparable to the estimated inflow to the Grand Fall plant (provided by N.B. Power).

It is significant to note that the modelled flow was dropping prior to the ice jam release, while the estimated Grand Falls inflow was larger and increasing. This implies that the ungauged inflows were significant, which means that the simulation results would be even higher if all of the tributaries had been measured and included in the analysis.

Despite the relatively poor performance in terms of stage accuracy, the model did display good wave speed accuracy. The computed peak discharge of 6000 m^3/s passed St. Leonard 41 minutes after the jam released, which compares favourably with the observations. As Figure 3 (b) illustrates, the peak arrival at Grand Falls was consistent with the observations there, as well.

Despite the limitations in the data and in the model itself, this surge propagation simulation still provides some interesting information about the release of such natural flow impoundments. As Figure 4 (a) illustrates, the discharge profile initially has two peaks (e.g. results at $t = 30$ s and 2.5 min) which quickly combine into one wave as the stored water is mobilized. At $t = 5$ min, though the peak discharge has increased from 2000 m^3/s to more than 7000 m^3/s, the water surface profile (shown in Figure 4(b)) has changed only slightly. This effect has been observed in ice jam surge release simulations conducted by the first author for other case studies, and may explain the dramatically increased velocities which have been observed in open water leads downstream of ice jams immediately prior to jam release (Beltaos, 1995). Another interesting feature of Figure 4 is the fact that the peak discharge remains upstream of the jam toe, and propagates upstream while the surge front propagates downstream.

CONCLUSIONS

The purpose of the investigation was to determine the feasibility of applying hydraulic flood routing techniques to ice jam surge release modelling. Based on the event modelled here, the results are considered instructive, providing information on the applicability of the limited geometry approach, and suggesting the importance of including ice effects in the analysis. In addition, some insight has been gained into the nature of the release, in terms of the discharge profile characteristics.

The ice jam surge release model provided fair agreement with available discharge data and the propagation speed was well reproduced. However, the model was relatively inaccurate in terms of the predicted stage. This is consistent with the finding of earlier investigations using the limited geometry model and can likely also be attributed in part to the effect of the ice cover in the downstream channel, which was not considered in the model.

Finally, it is hoped that this modelling effort will assist in providing some guidelines for the collection of field data during future events. In particular, it is important to assess the relative importance of ungauged tributary inflows and attempt to quantify those which are significant. It is also important to document ice conditions upstream and downstream of the ice jam both prior to and during the surge propagation, in order to facilitate consideration of these effects in any modelling effort.

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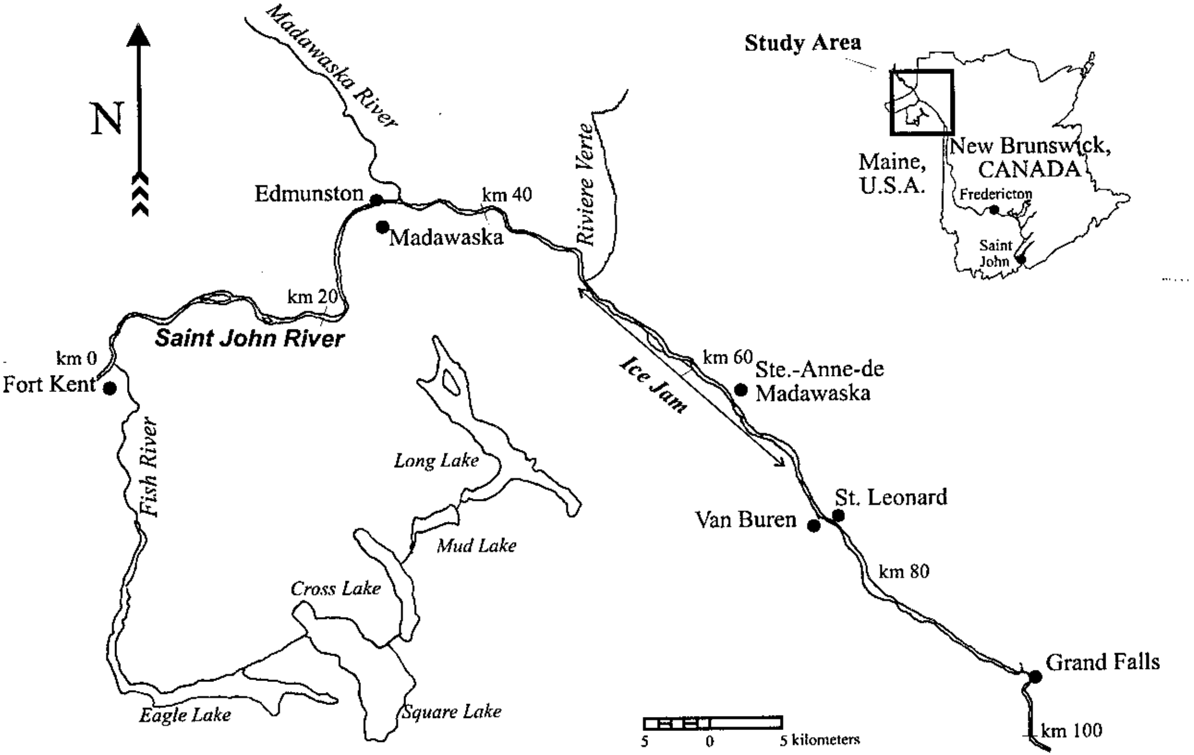

Figure 1. Location sketch for the Saint John River study reach.

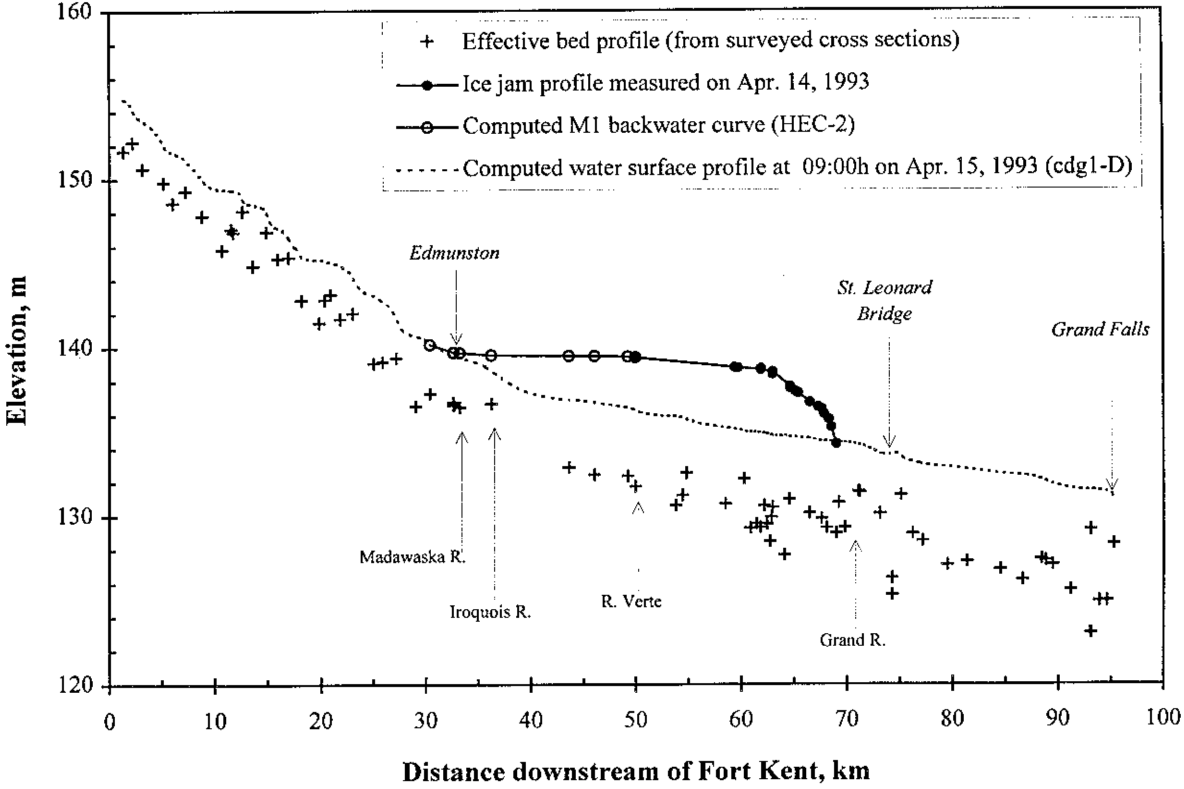

Figure 2. Effective bed profile and water levels used for the ice jam surge release simulation.

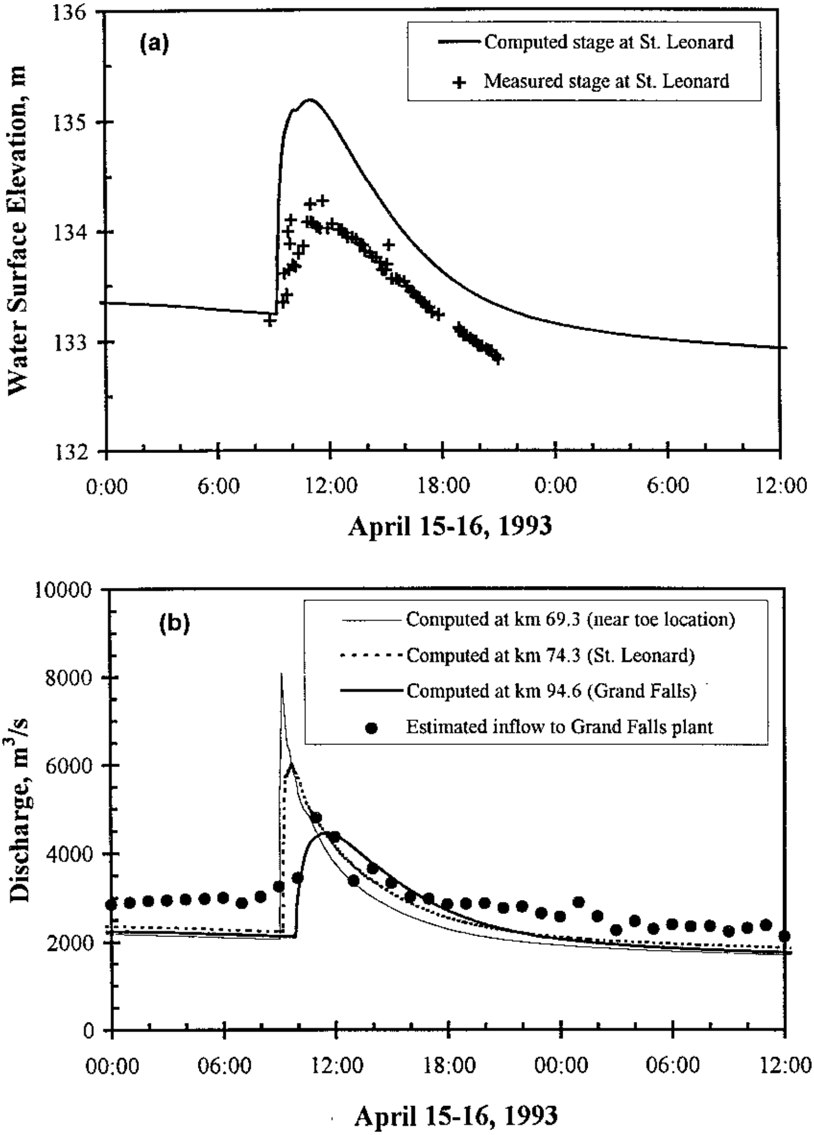

Figure 3. Comparison of measured and computed flows and stages.

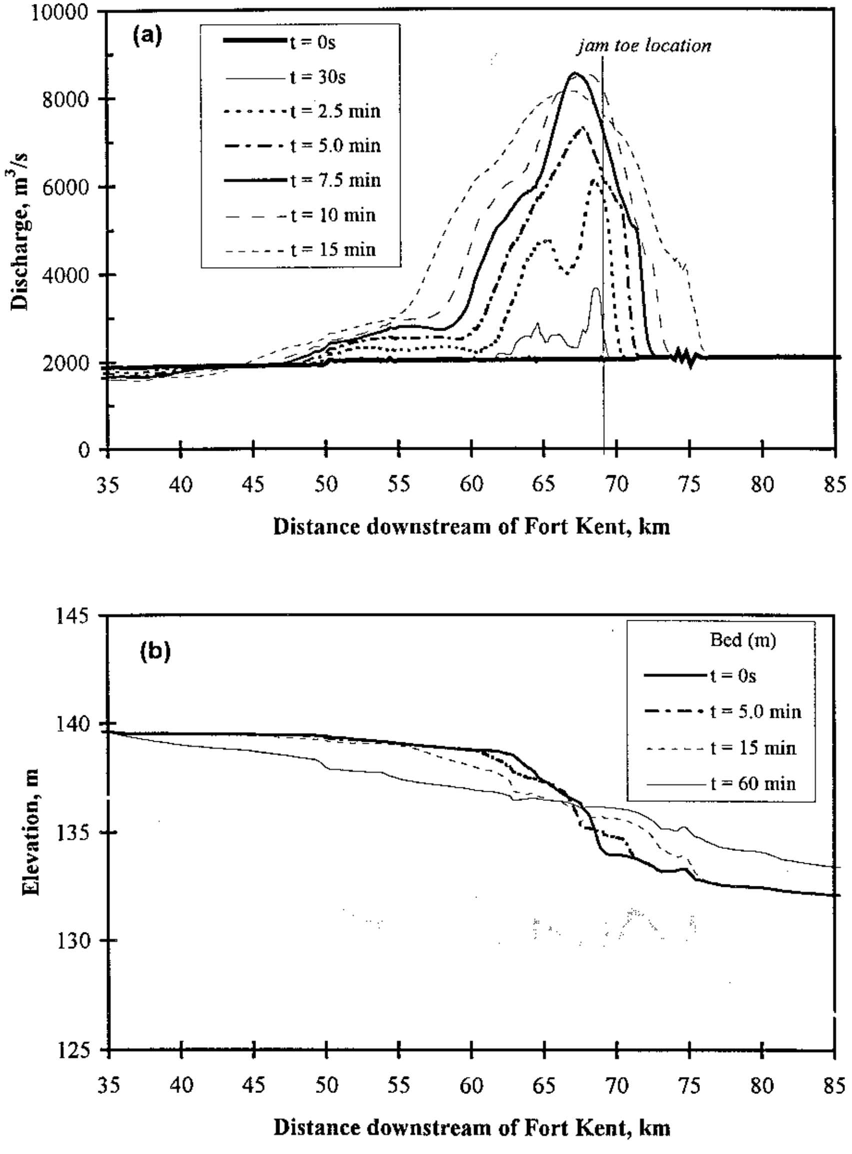

Figure 4. Computed discharge and water level profiles.