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Distributed function analysis of ice jam flood frequency

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ABSTRACT

River ice jams can cause extreme flood events with major socio-economic and ecological impacts. A major practical question is how to quantify and assess ice-jam flood risk. Ideally, this question can be answered by means of historical ice-influenced water level peaks. More commonly, however, the available historical information is scarce and determination of ice-jam flood frequencies or probabilities must rely on a synthetic method. After noting that empirical evidence does not support the assumption of discrete stage outcomes, which is central to the existing methodology, a new synthetic method is developed. It hinges on the fact that the peak stage can take on any value between discharge-dependent envelopes and is thence called the distributed-function method, or DFM, and successfully tested by means of four case studies. It is shown further that the DFM produces more realistic results relative to those of the existing approach. Practical limitations are common to both methods and arise primarily from the need to use the peak runoff discharge, rather than the unknown value that prevails at the time of the peak stage. Resulting errors in probability estimates are evaluated in an extreme case and shown to be both conservative and tolerable. Analysis of additional case studies is recommended as a means of enhancing the utility of the DFM.

1. Introduction

Ice jam floods commonly occur during the transitional periods of freezeup and breakup, which mark the beginning and the end of an ice cover season. In temperate regions, they may also occur in mid-winter, during so-called "mid-winter thaws" that can lead to highly dynamic breakups. Jams often extend for many kilometres along a river and can attain aggregate thicknesses of several metres. To pass the incoming flow, the water level has to rise considerably in order to accommodate both the keel of the jam (~nine-tenths of thickness) and the extreme hydraulic resistance of its underside (Manning coefficients up to ~0.1). Flooding is often the result, even if the prevailing river flow is moderate relative to that of open-water floods. This effect is aptly illustrated in Fig. 1: the stage of the 40-year return period open-water flood, which represents a sizeable flow, is equaled or exceeded 5 times more frequently (once in ~8 years) when ice jams are present.

Ice jam floods can be devastating in terms of social disruption (e.g. mass evacuation, loss of human life) and damage to property and infrastructure (e.g. homes, buildings, ships, bridges, roads, railway lines). They also have major ecological impacts, which can be both beneficial (e.g. replenishment of floodplain ecosystems with river water and sediment) and detrimental (e.g. fish mortality, loss of spawning grounds). Detailed information on the socio-economic and ecological impacts of ice jams is presented in several publications, for example, Carlson et al. (1989); Gerard and Davar (1995); Prowse (2000); Brakenridge et al. (2001); Morse and Hicks (2005).

Evaluating the risk of ice-jam flooding is an essential step in regulating floodplain development, identifying effective ice-jam mitigation measures, and assessing the economic and ecological impacts of regulation or de-regulation, and of climate change. As with open-water flooding, the risk at a particular location is quantified by developing a stage-frequency (or stage-probability) relationship. However, ice-influenced flood events are not readily amenable to traditional stage-frequency analyses. The complex hydro-meteorological and structural processes that lead to ice jam formation, progression, and release are highly site-specific. Therefore, parametric regional equations such as those developed for open-water floods do not apply. Moreover, historical-data gaps are much more pronounced for ice-related events because hydrometric gauges are often damaged by ice, usually when an ice jam forms nearby. Not only does this shorten the stage record, but the missing data include those associated with extreme events. Often, flood risk assessment is required at sites where there are few or no historical data on past ice-influenced peaks. In such instances, the only alternative is to develop synthetic flood-frequency relationships (White and Beltaos, 2008).

The main objective of this paper is to present a new method for generating synthetic relationships, based on the empirical observation that any stage between flow-dependent lower and upper bounds is possible. Background on different types of ice jams and their flooding potential is presented in the following section. The presently-used approach for synthetic frequency analysis is outlined next and the

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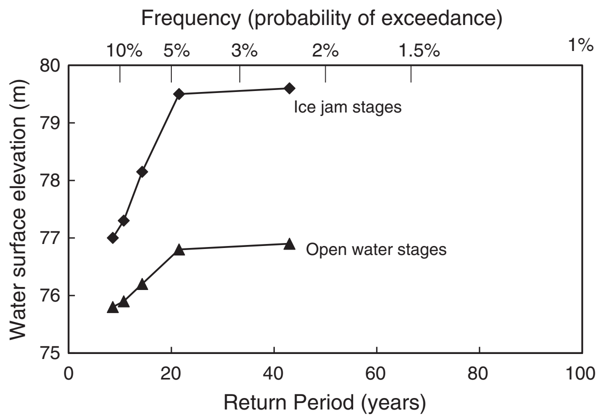

Fig. 1. Comparison of stage-frequency curves for ice-jam and open-water floods; Saint John River at Perth-Andover, Canada (Beltaos and Burrell, 2002).

associated assumptions evaluated in the context of current knowledge of ice jam processes. The distributed function method (DFM) is subsequently introduced and mathematical expressions are developed to calculate ice jam flood stage probability, based on established hydraulic concepts. Case studies that illustrate the efficacy of the DFM are followed by a discussion of limitations and future research.

2. Types and flooding potential of ice jams

There are several kinds of ice jams, depending on their formation mode, season of occurrence, spatial extent, and state of evolution (Beltaos, 1995a). At freeze-up, cold weather cools the river water to produce frazil slush and pans; while at breakup, warm weather and increased runoff lead to fracture of the winter ice cover. In both cases ice slush, ice pans, and ice blocks are being transported on or near the water surface. If this flux is arrested for any reason (e.g. an existing ice cover) or the ice transport capacity of the river is reduced locally (congestion), an ice jam may form.

Once initiated, jams propagate upstream in ways that are dictated by flow and channel conditions as well as by internal strength of the accumulation of ice slush and floes. Depending on the manner of their evolution, jams can be of the *surface* or *thickened* kind. The former has minimal potential for damage, but is a common means of winter ice cover formation via freezing of the interstitial water. The season of occurrence is an important element in ice jam classification. Intuitively, one may be inclined to assume that freezeup jams occur in the fall and breakup ones in the spring. This is true in many cases, but there is also the possibility of mid-winter jamming, resulting from brief thaws accompanied by rainfall. The resulting runoff is often large enough to initiate breakup, followed by renewed freezeup when the cold weather resumes. In certain regions, mid-winter jams can be even more extreme than spring jams (Beltaos et al., 2003; Burrell and Tang, 2009). Owing to larger flows, breakup jams have typically greater flooding potential than freezeup ones, but freezeup jams can also cause problems (e.g. Beltaos et al., 2007a, 2007b; Weyrick et al., 2007).

Thickened jams include *the narrow/wide - channel* variety (Pariset et al., 1966) as well as the *hanging dam*. The wide-channel jam is more common at breakup than at freezeup and forms by collapse and shoving of ice-floe accumulations until it attains a sufficient thickness to withstand the applied external forces. These forces arise from the flow shear stress and the jam's own weight and are resisted by the internal strength of the rubble that comprises the jam, which is mobilized by the net buoyancy of the ice accumulation. In contrast to wide-channel jams, narrow-channel jams (rare during breakup) have a thickness that is controlled by the hydraulic conditions at their head (or upstream end). The thickness is just sufficient for the net buoyancy of the jam to withstand submergence by the local hydrodynamic forces and overturning moments. A hanging dam is an accumulation of frazil slush that forms by transport and deposition under an existing ice cover. Hanging dams form typically at freezeup and are too thick to shove, sometimes attaining extreme dimensions in deep river sections (Beltaos and Dean, 1981; Michel and Drouin, 1981).

Ice jams have also been classified according to whether they are evolving or have attained a “steady state” (Beltaos, 1995a). Truly steady-state conditions rarely occur in rivers but the temporal changes of various parameters are often small enough to permit the assumption of steady state for prediction purposes. For steady-state jams, an *equilibrium* reach may be established if there is sufficient ice supply. Here, jam thickness and water depth remain more or less constant, apart from fluctuations due to natural stream irregularities (Beltaos, 1995b). The water surface slope becomes equal to the open water surface slope, provided the flow is free to assume a relatively uniform condition, i.e. there are no significant flow control influences. Once an equilibrium reach has formed, further supply of ice to the jam results in a mere lengthening of the equilibrium reach without changing the maximum water depth or the lengths of the transitional reaches leading to the head and toe (downstream end) of the jam, respectively.

Ice-influenced peak water levels for freezeup and breakup generally increase with discharge, but exhibit large scatter, signifying that they are generated by jams of different severity, which may or may not fully affect the site where the water level is measured. The highest stages are caused by equilibrium jams and can be calculated by means of well-established predictive methodology (Beltaos, 1995b; Beltaos and Burrell, 2010; Carson et al., 2011).

3. Discrete-function approach for synthetic stage-frequency analysis

Where the available historical stage data are sparse, it may be possible to generate the stage-frequency relationship indirectly (Gerard, 1989). Indirect approaches combine flow frequency estimates with two synthetic stage-flow rating functions for ice-affected conditions. These rating functions respectively represent an upper limit and a lower limit, such that stage can either equal a discharge-dependent upper value or a discharge-dependent lower value. Consequently, the existing methodology is herein termed the “discrete-function” approach.

Historical flow data are far more readily available than peak ice-influenced stages because the spatial variability of flow is much smaller than that of ice-jam water levels. As a result, the flow at an ungauged site may often be deduced from records of upstream and downstream hydrometric gauges, or even from regional estimates, whereas ice-jam stage data cannot be meaningfully transposed. Once the frequency of peak ice-influenced flows (Q_m) is established, the frequency of corresponding stages can be determined by introducing the empirically assessed local probability of jam occurrence in any one year, P(J). In what follows, the word “frequency” will be largely displaced by the word “probability”, since the mathematical developments that lead to frequency estimates involve probabilities of various outcomes. The two concepts are equivalent, though frequency is commonly expressed in terms of average return period, such as once every 2 years (probability = 0.5), once in 100 years (probability = 0.01), etc.

According to Gerard and Calkins (1984), the probability, P_i, of a peak ice-influenced stage, H_m, being less than a value H in any one year, can be calculated as:

$$P_i(H) \equiv P(H_m < H) = P(J)P(H/J) + P(NJ)P(H/NJ) \quad (1)$$

in which P(H/J) and P(H/NJ) respectively represent the probabilities that river stage will remain less than H, given that a jam will, or will