US Army Corps of Engineers®

Ice Engineering

U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire

Ice-Affected Flood Frequency

Virtually every hydraulic structure design or other type of study involving rivers requires the development of a frequency analysis, in which river discharge is plotted against exceedance probability. These curves allow the quantitative selection of design life for structures such as bridges or levees, and are required for risk-based analyses. When combined with stage-discharge and stage-damage curves, damage estimates and other economic analyses can be made. Stage-frequency curves also are often the basis for regulatory floodplain delineations such as those presented in flood insurance studies.

Guidance is available for the preparation of discharge-frequency curves for open-water conditions at gaged sites (e.g., Water Resources Council 1982, Hydrologic Engineering Center 1992).

Because ice jams often cause high stages at relatively low discharges, the traditional discharge-frequency curve is not appropriate and a stage-frequency curve must be constructed. Developing an ice-affected stage-frequency curve can be difficult. Gages subject to ice jams may experience damage that renders them useless (Fig. 1).

Ice jams are unstable at high discharges, and therefore may affect only a portion of the stage-frequency curve. Some stages reported to be ice-affected may actually be open-water stages. Length of record, the major obstacle encountered in open-water flood frequency analyses at gaged sites (Greis 1983), is exacerbated for ice-related events, which generally occur much less frequently than open-water events and consequently have even smaller sample sizes.

A recent study by the U.S. Army Corps of Engineers St. Paul District (USACE 1999a,b) provides a good example of developing ice-affected stage frequency along a river reach. Following the large flood of 1997, it was necessary to update the flood insurance studies for the communities of Wahpeton, North Dakota, and Breckenridge, Minnesota, to include the effects of ice, upstream flood control reservoirs, and an upstream breakout-flow area (i.e., above certain elevations, overland flow will bypass the gage).

The analysis presented here addresses the development of ice-affected stage frequency. The methodology employed is within the general guidance for ice-affected flooding as provided by the Federal Emergency Management Agency (FEMA 1995). Specific guidance was provided by the Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire, and the Corps of Engineers Hydrologic Engineering Center (HEC), Davis, California.

Site description

The Red River of the North is formed by the confluence of the Bois de Sioux River and the Otter Tail River in the communities of Wahpeton, North Dakota, and Breckenridge, Minnesota. The local effective drainage area downstream of two flood control reservoirs (White Rock Dam and Orwell Dam) is 1020

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Figure 1. Gage house for USGS Gage No. 01010000, St. John River at Ninemile Bridge, Maine, following April 1991 ice jam. Note remaining ice debris, right.

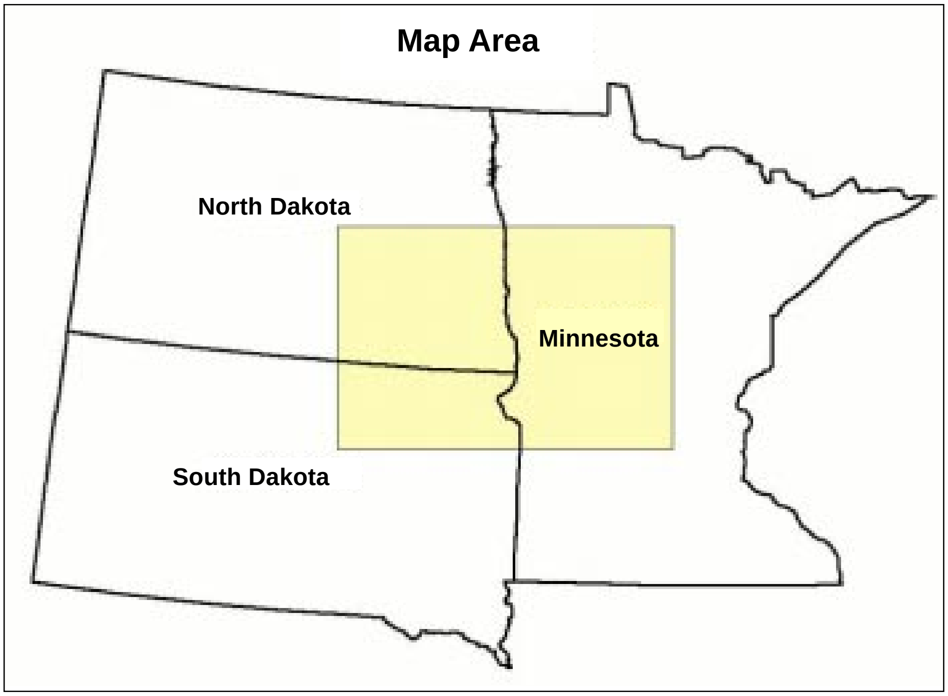

Figure 2. Location of study area.

square miles. A general location map is shown in Figure 2.

Gaged streamflow data is provided by USGS Gage No. 05051500, Red River of the North at Wahpeton. The gage is located 800 ft downstream from the confluence of the Bois de Sioux River and the Otter Tail River at River Mile 548.6. The period of record dates from April 1942 with observed flow measurements that are considered fair. The maximum instantaneous peak stage of 19.42 ft was influenced by backwater from ice and occurred on 6 April 1997. The hydrograph of the 1997 event is shown on the stage-discharge curve at the gage (Fig. 3). The rising limb of the hydrograph generally follows the ice-affected annual peaks until some point above about 8000 cfs, after which it rises to the peak stage of 962.5 ft along an apparent open-water curve. The falling limb follows the same open-water curve.

Stage frequency at gage

Because of the significant number of ice-affected floods in the study area, flood frequency analysis based on peak annual instantaneous discharges alone was not considered appropriate. Of the 56 years of available streamflow records (1942–1997) for the Red River of the North at Wahpeton, half of the annual peak stages were ice-affected and half were associated with open-water discharges. Using the mixed-population approach, an accepted method of analyzing stages arising from different causes, the two populations were separated according to the season (ice-affected vs. open-water) and not arbitrary calendar months, as is sometimes done. In the mixed-population method, the annual peak ice-affected stage frequency and annual peak open-water stage frequency are combined using

$$P_c = P_1 + P_2 - (P_1)(P_2) \qquad (1)$$

where P_c is the probability of a selected elevation being equaled or exceeded from either an ice-affected flood event or an open-water flood event, P_1 is the probability of that elevation being equaled or exceeded from an ice-affected flood event, and P_2 is the probability of that elevation being equaled or exceeded from an open-water flood event.

The mixed population method requires that peak stages be determined for each season for every year of record. It can be difficult to locate such information for ice-affected gages, and ice peaks for years in which the annual peak was not ice-affected must often be synthesized. Fortunately, in this case a detailed search of archived USGS records revealed ice peaks for the years in which the annual peak occurred during the open water season. The ice-

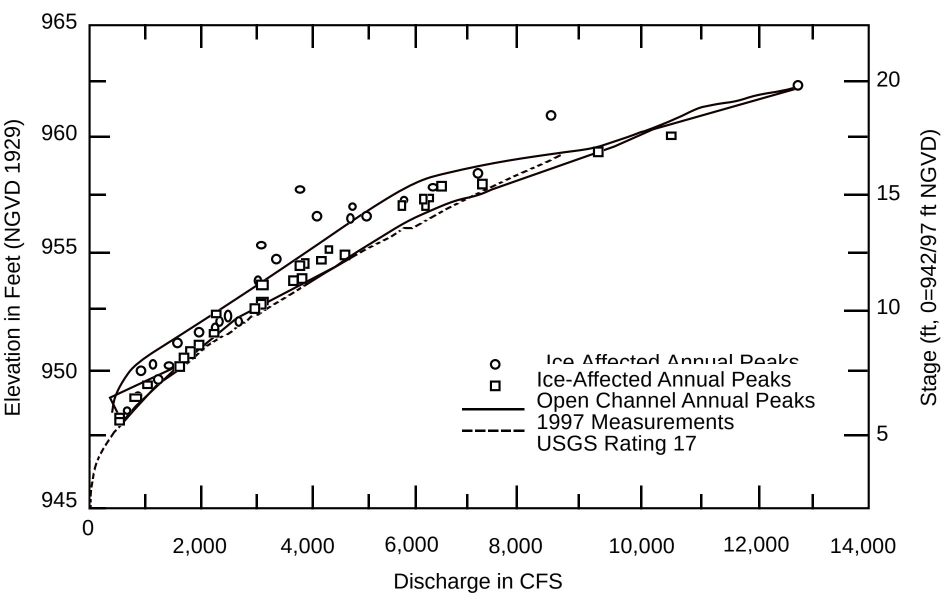

Figure 3. Elevation-discharge data for USGS Gage 05051500, Red River of the North at Wahpeton, North Dakota, showing ice-affected and annual peaks along with data for the 1997 event and the current rating curve (#17).

Table 1. Stage frequency for the Red River of the North at Wahpeton.

Elevation (ft)	*Exceedence probability*		
	Ice-affected	*Open-water*	*Combined*
964.8			0.002*
964.1			0.003*
963.0	0.0045	0.0025	0.0070
962.0	0.0080	0.0050	0.0130
961.0	0.0150	0.0100	0.0250
960.0	0.0250	0.0170	0.0416
959.0	0.0430	0.0300	0.0717
958.0	0.0700	0.0550	0.1212

*Elevations for the 0.2% and 0.3% exceedence frequency events were defined by the all-season peak discharge-frequency relationship using the open-water elevation-discharge rating curve.

affected stage-frequency curve was developed at the USGS gage based on the 56 years of stage data available. Annual peak ice-affected elevations were graphically plotted using median plotting positions. The 1997 peak ice-affected elevation of 962.4 ft was plotted as the highest flood elevation since the historic spring flood of 1897 (peak elevation 960 ft) and has a median plotting position of 0.69% based on a 101-year historic period from 1897 to 1997.

The open-water stage-frequency curve was based on an annual series peak open-water discharge-frequency curve over a 56-year period. An open-water elevation-discharge rating curve developed at the USGS gage was used in combination with the adopted open-water discharge-frequency curve to graphically develop an annual peak open-water stage-frequency curve.

The combined-population stage-frequency curve was developed at the gage by combining the independent frequency curves for the ice-affected elevations and open-water elevations using eq 1. Because of expected ice instability at high discharges, the upper end of the frequency curve (0.2% and 0.3% exceedence frequency elevations) was defined from the annual all-season peak discharge-frequency curve. The adopted combined-population stage-frequency curve for the Red River of the North at the USGS gage is shown in Figure 4 along with the frequency curves for ice-affected elevations and open-water elevations. Table 1 provides a summary of exceedence probabilities for selected elevations for the ice-affected population, open-water population, and the combined population for the Red River of the North at the USGS gage.

Stage frequency along study reach

Stage-frequency curves were computed at cross-section locations for floods with selected recurrence intervals of 10, 50, 100, and 500 years. These in turn were used to establish the 100- and 500-year floodplain boundaries and the 100-year floodway throughout the study area.

The HEC-2 step-backwater computer program (USACE 1990) was used to generate water surface elevations for selected recurrence intervals for both open-water conditions and ice-affected conditions at all cross sections throughout the study area. The HEC-2 model was calibrated using the historical flood profiles of the Red River of the North, Otter Tail, and Bois de Sioux Rivers. Water surface profiles at selected recurrence intervals for open-water conditions were computed using the starting water surface elevations from the stage-discharge rating curve.

Water surface profiles were computed for ice-affected conditions with the USACE computer program NEWTHK, a version of ICETHK (Tuthill et al. 1998) that interfaces with HEC-2 in an iterative manner. NEWTHK, which has algorithms for ice jam stability analysis (Tuthill and Mamone 1998), allows the modeler to determine the potential severity of ice jamming to an area. Data necessary for the ice portion of the hydraulic analysis were obtained from field observations at Wahpeton and Breckenridge beginning in 1990. The ice type varies somewhat from year to year but is basically strong and competent. The typical ice thickness of 18 in. was used in the study. A Manning's *n* of 0.026 for the underside of the ice cover was assumed. The discharges used in developing the ice-affected water surface profiles were determined from the ice-affected stage-discharge curve (Fig. 3) for the stages on the stage frequency associated with the selected recurrence intervals. Using these discharges, ice-affected stages at upstream reaches were determined using NEWTHK.

The calibrated HEC-2 was checked against the stage-discharge hydrograph recorded during the spring flood of 1997 (Fig. 4) to determine how well the calculated water surface elevations compared to the observed values at the USGS

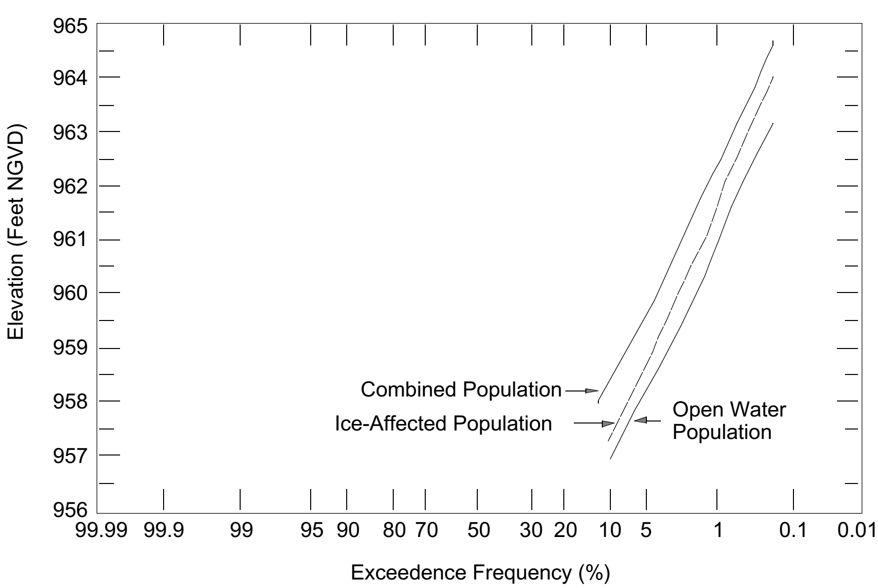

Figure 4. Stage-frequency curves for the Red River of the North at Wahpeton.

gage. Over the entire range of ice-cover measurements and up to the peak stage, on the rising (ice-affected) and falling (open-water) limbs of the hydrograph, the computed and observed values were within 0.2 ft.

For each cross-section location, frequency relationships were developed for both the ice-affected and open-water populations by graphically fitting curves to the elevations generated by the HEC-2 model for floods of eight different recurrence intervals (5, 10, 20, 50, 100, 125, 200, and 500 years). The combined-population stage-frequency curve at each of the selected cross-section locations was then determined using eq 1.

Summary

Engineers accustomed to developing discharge-frequency curves along rivers are often confused when confronted with the need to perform an ice-affected frequency analysis, because stage frequency must be considered. This case study provides an example of developing such information using a mixed-population analysis under ideal conditions (i.e., a USGS gage with long-term records is located nearby, peak stages are about equally divided between open-water and ice-affected stages, and ice-affected peak stages can be identified for each year of record). These are the essential steps in such an analysis:

1. Determine open-water stage frequency for all years of record.
2. Determine ice-affected stage frequency for all years of record.
3. Combine data from steps 1 and 2 for selected stages to develop an all-season stage-frequency curve.
4. Perform open-water backwater analysis using discharges determined from the open-water stage-discharge and stage-frequency curves for selected recurrence intervals (use calibrated HEC-2 or HEC-RAS).
5. Perform ice-affected backwater analysis using discharges determined from the ice-affected stage-discharge and stage-frequency curves for selected recurrence intervals (use calibrated NEWTHK, ICETHK, or HEC-RAS).
6. Combine the results of steps 4 and 5 for selected stages at the selected cross sections to develop an all-season stage-frequency curve.

The same general approach may be utilized under non-ideal conditions. However, additional steps such as synthesis of ice-affected peak stages for every year of record could be required because annual ice peaks are not often available.

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