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Effect of Toston Dam on upstream ice conditions

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The effect of raising the reservoir level of Toston Dam on the Missouri River on water levels upstream during winter periods with ice is assessed. The analysis used the HEC-2 program with the ice option to estimate water levels under present and future raised dam elevations. Ice thicknesses were estimated using a trial-and-error procedure based on existing ice jam theory. Results of the analysis were validated using field observations from two winters.

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PREFACE

This report was prepared by Dr. George D. Ashton, Research Physical Scientist, Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this study was provided by the U.S. Army Engineer District, Omaha, under the project entitled *Planning Assistance to States.*

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CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM Metric Practice Guide (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	By	To obtain
mile (U.S. survey)	1609.347	meter
foot/second	0.3048000	meter/second
foot^3/second	0.02831685	meter^3/second

Effect of Toston Dam on Upstream Ice Conditions

GEORGE D. ASHTON

BACKGROUND

At the request of the U.S. Army Engineer District, Omaha, and in coordination with the Department of Natural Resources of the State of Montana, a study was conducted to evaluate the effect of raising the winter-period reservoir level at Toston Dam on the Missouri River to an elevation of 3952.6 ft above sea level. At present the dam is operated as an overflow dam with crest elevation of 3941.6 ft during the winter. In summer, flashboards are installed to maintain reservoir levels in the range 3949 to 3952 ft and water is diverted for irrigation. A proposal to install hydropower at the dam would require replacement of the existing flashboard system with radial gates and maintenance of a higher water level at the dam during winter periods. Under this proposed plan of operation, there is concern with the possible effects on the Crow Creek pumping plant located about 2 miles upstream, with possible ice-related flooding of the Burlington Northern railroad track, which extends along the east side of the reservoir, with effects of ice on existing islands in the reservoir, and with ice effects at the dam and proposed hydropower facility. This report addresses those issues.

SITE DESCRIPTION

Figure 1 shows a map of the reservoir. Cross sections of the river were available extending from the Toston Dam (also called Broadwater Dam) to a point just upstream of Lombard. Photography during ice conditions of December 1985 was available and a site visit was made by the writer and DNR personnel in March 1987. During this latter visit no ice was in the river but there were extensive relic ice deposits on the shores. Flows during winter months are typically 2000 to 5000 ft^3/s, but in February of 1963 and December of 1976 flows of 10,000 ft^3/s occurred, although it is not known if ice conditions existed at those times. There seems to be only one report of icing problems experienced by the railroad under the present mode of operation and that occurred somewhere upstream of Lombard. Figure 2 is a plot of the invert elevation of the river from Toston Dam to a point upstream of Lombard and also shows the elevation of the railroad grade to a point 5 miles upstream of the dam. The water surface profiles will be discussed later. Since the cross sections were measured there has been some sedimentation in the reservoir. In the analysis that follows it is assumed that the reservoir has filled with sediment up to an elevation of 3931 ft.

ICE CONDITIONS

The photography of ice conditions in December 1985 and the site visit in March 1987 showed that ice conditions in the reservoir are of the type ordinarily described as "accumulations" of ice largely derived from ice produced upstream, transported to the reservoir and deposited under the action of the river hydraulics. Near the dam, under the action of the lower velocities associated with deeper flows, the ice accumulates initially in a relatively thin cover; this cover progresses upstream and accumulates in a thicker cover under the action of higher velocities. Undoubtedly, some ice is transported beneath the cover and deposited in the deeper part of the reservoir, but the flow tends to maintain some minimal area of flow cross section. The accumulation thickness of the ice cover in the upper reaches of the reservoir can be calculated with some confidence using a theory initially developed in the early 1960s and subsequently refined by Beltaos (1983) and others. These ice cover thicknesses can then be used in conjunction with a hydraulic analysis to determine the expected water levels that occur for various conditions. Some cal-

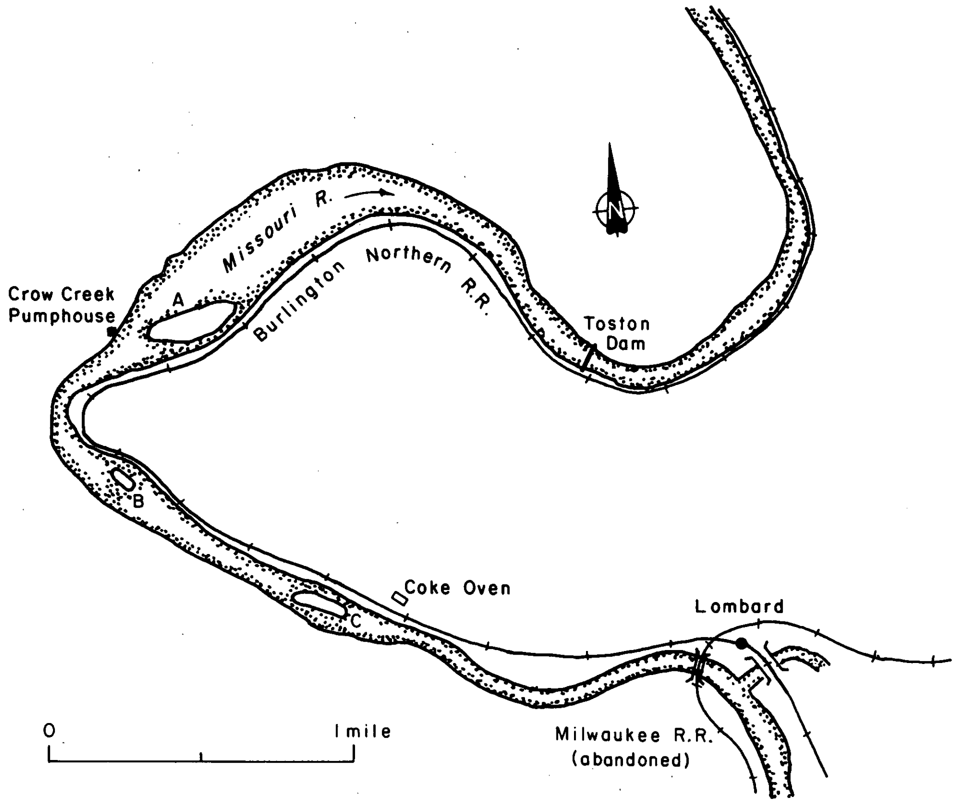

Figure 1. Site map.

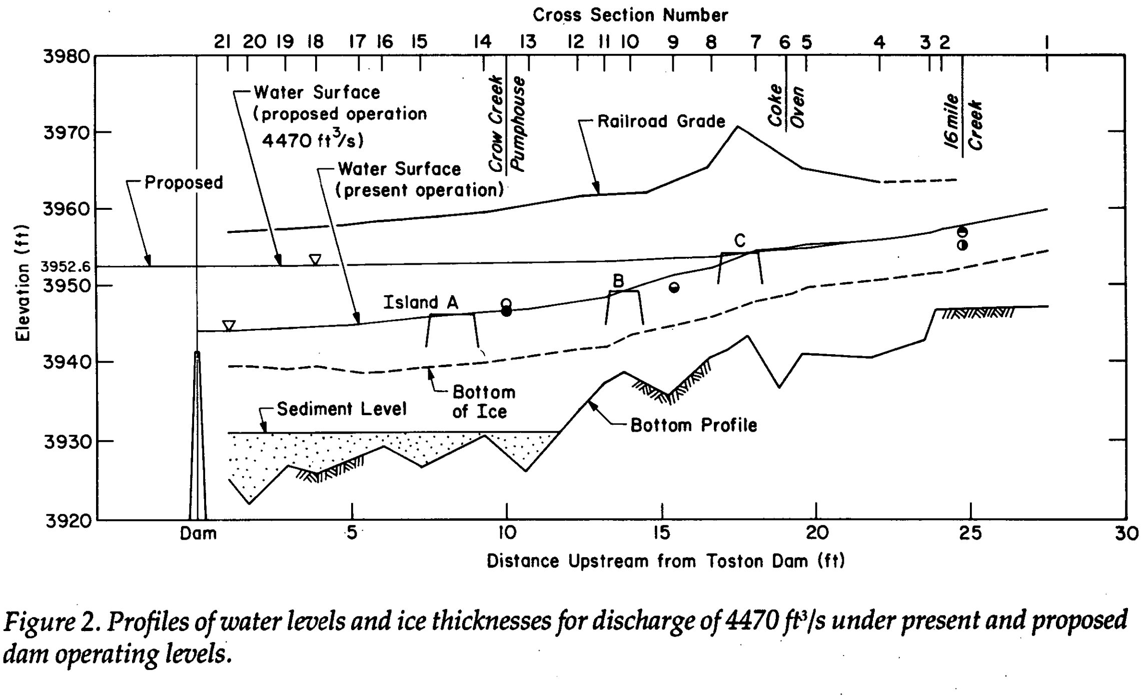

Figure 2. Profiles of water levels and ice thicknesses for discharge of 4470 ft^3/s under present and proposed dam operating levels.

ibration data are available from observations by DNR personnel during December 1985 and by the writer in March 1987.

ANALYSIS

To determine the water levels associated with ice conditions under both present operations and under the proposed operating conditions, the program HEC-2 was run with the ice cover option. The ice cover option requires specification of the ice cover thickness and ice cover roughness (the latter in the form of a Manning's *n* value for the ice cover). Since the ice cover thickness depends on the hydraulic parameters of discharge, energy slope and width, it was necessary to run the program in a trial-and-error mode until the ice thicknesses calculated from the program output agreed with those used as input. The detailed methodology and theory by which ice thicknesses were calculated and adjusted are described in Appendix A. Essentially, an equilibrium "ice jam" analysis was used, which is known to provide a reasonable upper bound for associated water levels. The final results are obtained in four computer runs described in Table 1.

Table 1. Results of HEC-2 runs.

Run no.	*Discharge (ft^3/s)*	*Elevation at dam (ft)*	*Purpose of run*
24A	4,470	3944.0	Calibration against existing ice data.
25A	4,470	3952.6	Typical ice conditions; hydro operation.
22A	10,000	3945.0	Severe case; present operating mode.
23A	10,000	3952.6	Severe ice conditions; hydro operation.

In Figure 2 the water surface profile calculated for present conditions is plotted together with the available calibration data. (See Appendix B for detailed description of the calibration data points.) The agreement between the calculated results and the calibration points is considered adequate based on past experience with similar data. The ice bottom profile used in the final analysis is also shown. Additionally, the ice thicknesses and levels relative to the three islands are reasonably consistent with the observations of December 1985 and March 1987.

A similar analysis was then done for a water elevation at the dam of 3952.6 ft; the resulting water surface profile is also shown in Figure 2. While detailed results will be discussed below, the main conclusion is that the proposed hydroelectric operation at an elevation of 3952.6 ft has no effect on water levels upstream of section 6, which is located downstream of Lombard, approximately at the location of Coke Oven.

In Figure 3 the results of runs 22A and 23A are compared. Run 22A represents a flow of 10,000 ft^3/s, with ice, under the present mode of operation, while run 23A represents a flow of 10,000 ft^3/s under the proposed hydroelectric operation.

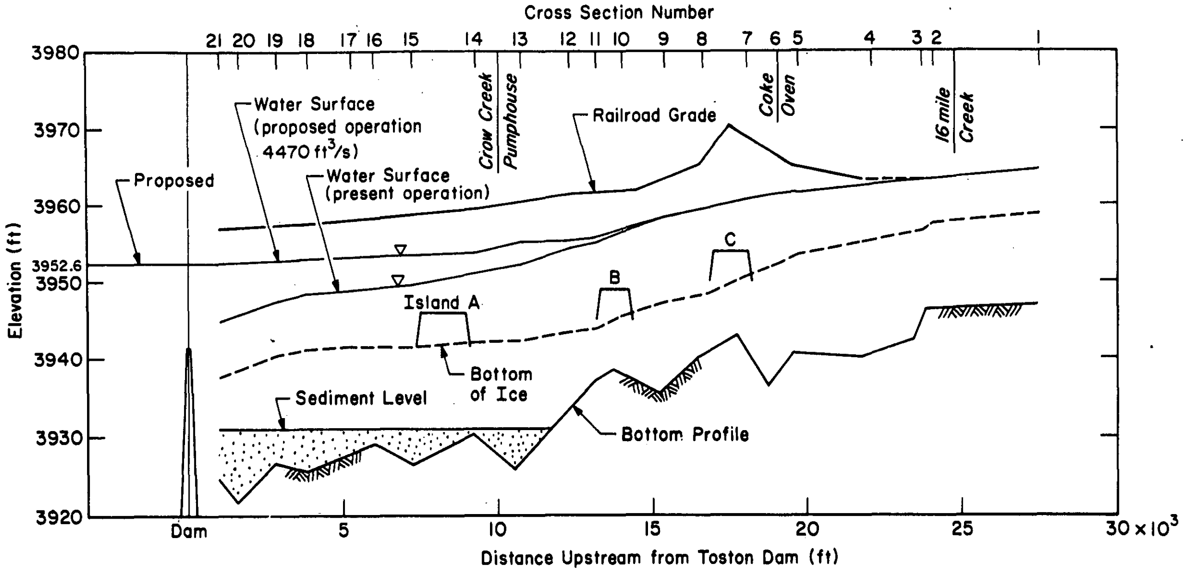

Figure 3. Profiles of water levels and ice thicknesses for a discharge of 10,000 ft^3/s under present and proposed dam operating levels.

The analysis and methodology employed were the same as for the earlier described runs at the lower, more typical winter discharges. These runs represent severe winter flow conditions and, if they were to occur with ice, would cause very high water levels, particularly at the upper end of the reach under consideration. However, as with the earlier, more typical winter cases, the effect of raising the water level to 3952.6 ft extends upstream only to the vicinity of Coke Oven. Upstream of that point Toston Dam exerts no influence on water levels associated with ice conditions at this high discharge.

There is some question as to whether the ice cover can accumulate and progress upstream as far as section 6 when the flow is 10,000 ft^3/s. A brief attempt to determine if the ice cover could accumulate sufficiently downstream to reduce the velocity by "staging" in the vicinity of sections 9 to 6 was made: the velocities at the upstream end of an accumulated ice cover were too great to allow upstream progression. In such cases the arriving ice is simply carried with the flow on downstream.

ICE EFFECTS ON ADJACENT RAILROAD

No significant effects were found for the railroad adjacent to the reservoir as a consequence of the proposed hydroelectric operation. At typical winter flows of 4470 ft^3/s, some drainage culverts may be flooded by the higher pool elevation but these will still function in the sense of allowing flows back and forth through those culverts. Upstream of section 6, ice conditions are unaffected by the water level maintained at Toston Dam for these typical winter flows. At the extreme flow conditions of 10,000 ft^3/s and with ice conditions, the water and ice levels upstream of section 3 are similarly unaffected by operation of Toston Dam at the proposed higher elevation of 3952.6 ft. However, under these severe flow and ice conditions, the water levels upstream of section 3 approach or exceed the grade of the railroad. The point to be made is that those conditions, while possibly damaging to the railroad, are not aggravated by the proposed hydroelectric operation. Whether these extreme conditions in fact occur can best be assessed from past experience, and evidence of past flooding attributable to ice is meager.

ICE EFFECTS ON CROW CREEK PUMPING PLANT

The Crow Creek pumping plant is located on the left bank of the reservoir, approximately 10,000 ft upstream of Toston Dam. At present the pumping plant floor level is at elevation 3952.0 ft, which is 0.6 ft lower than the proposed water surface elevation at Toston Dam. Backwater effects ascribable to ice conditions will result in water surface levels at the Crow Creek pump house of elevations 3952.8 and 3954.0 ft for the proposed operation at winter discharges of 4470 and 10,000 ft^3/s respectively. At these levels the pump house floor will be flooded, the intake and trash rack completely submerged, and the surrounding service yard flooded and covered with ice. The character of the ice accumulation here is not expected to result in large ice loads and, in fact, the trash rack has not appeared to have been adversely affected by ice at lower levels during past winters. It is recommended, however, that the pump units and surrounding service yard be raised to elevation 3955 ft to provide some freeboard and to prevent nuisance ice from adversely affecting the pumphouse. No added protection is felt to be necessary for the trash rack and intake if the pumping plant is not operated during the winter.

ICE EFFECTS ON ISLANDS IN RESERVOIR POOL

Examination of available cross sections, aerial photography taken in August 1979, and the site visits of December 1985 and March 1987 indicate that there are three islands that may be affected by the proposed hydroelectric operation. Island A is just downstream of Crow Creek pumphouse; island B is upstream of Crow Creek pumphouse; island C is about 2 miles downstream of Lombard and just downstream of Coke Oven (Fig. 1). During the site visit in March 1987 all of these islands had deposits of frazil ice along their shores and often extensive deposits on the surrounding flats that were not covered by vegetation.

At present, ice-affected backwater from Toston Dam causes these islands to experience wintertime water levels nearly as high or as high as the summer levels when flashboards are installed. At the proposed operationlevel of 3952.6 ft, island A will be submerged more or less year-round and the vegetation will most likely be affected—the ice effects will be in the form of frazil deposits over all of the island. If the island vegetation can survive the year-round higher water levels, ice is not expected to aggravate it further. Island B currently experiences ice along its shores, but no significant ice in its interior. At the proposed operating level of 3952.6 ft, there will be additional submergence during winter and there will be frazil deposits over most of the island. The velocities are not high here and this, combined with the character of the ice (small fragments or frazil), suggests no serious damage caused by ice movement. Again, if the vegetation survives the higher water levels, it is expected that ice will not further aggravate the situation. Island C is located at about the point where water levels with ice are little affected by the choice of operating level at Toston Dam. This island currently experiences frazil ice deposits about 6 ft thick about its periphery. These will continue, but should not be much different from what happens at present. No adverse effect is expected as a result of the increased water levels proposed for winter operation.

ICE EFFECTS ON BRIDGES AT UPSTREAM END OF RESERVOIR

The Burlington Northern bridge over 16-Mile Creek at Lombard is beyond the ice-affected backwater effect caused by the proposed higher pool level at Toston Dam. Thus, there should be no adverse effects of ice on this bridge caused by the higher operating levels of Toston Dam. It should be noted, however, that extreme events in winter may result in ice and water levels that approach the railroad grade line at Lombard regardless of the level of operation of Toston Dam. However, the character of the ice is such that it is not expected to result in severe forces, but rather will be in the form of loose masses of ice in water at the higher levels. Similarly, the abandoned CMSPRR bridge across the river will not be adversely affected by ice associated with the proposed higher water levels at Toston Dam since the bridge is beyond the backwater effects of the higher level of operation.

ICE EFFECTS AT DAM AND PROPOSED HYDROPOWER FACILITY

The deeper flows just upstream of the dam result in low velocities and as a result the initial ice cover forms as a relatively thin cover that rapidly stabilizes into a solid ice cover. Undoubtedly, frazil and ice fragments arriving from upstream are carried under the upstream edge of this upstream-progressing cover and deposit beneath it. These deposits partially block the cross section, thus increasing the head loss and cause a backwater effect that eventually raises the water levels upstream, slows the velocities, and allows the ice cover to progress further upstream. In the language of ice jam development this process is called "staging."

With the higher operating levels proposed, this same process of staging will occur but will start further upstream. Frazil ice will still be carried beneath the cover and deposited but some frazil will be present in the flow withdrawn by the hydropower facility.

It is beyond the scope of this study to address all elements of ice engineering related to hydropower facilities in rivers. However, the effects of ice on the dam and gates and on the intake are briefly considered here.

The ice cover that will exist at the pool level of 3952.6 ft will be similar in nature to that currently existing with the overflow spillway, i.e., a thin, solidly frozen ice cover with frazil deposits beneath. The gates will be subjected to some ice forces since the ice will freeze to the upstream side. Some measure must be taken to assure that the gates can be operated when ice is frozen to them so that high flows can be passed. The seal design and possible structural loads from freezing of ice to the skin plates should be considered.

The intake may be blocked by frazil deposits on trashrack bars. The most critical period is at the beginning of the winter season when the reservoir is open and frazil in the supercooled water arrives at the intake. The velocities at typical flows of about 5000 ft^3/s are, however, sufficiently low that the frazil will rapidly form a protective ice cover extending at least 2 miles upstream. Supercooled water passing under this ice cover will gradually warm to the freezing point and the arriving frazil-laden flow at the intake will be in the passive mode. Creation of a pool with slow velocities is generally the preferred means of mitigating ice problems at intakes. The proposed higher operating level implements exactly this strategy.

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APPENDIX A: ICE THICKNESS CALCULATIONS

Use of a gradually varied steady flow hydraulic analysis such as the HEC-2 program with the ice option requires specification of the ice cover thickness. The ice cover thickness is determined by the flow but also affects the flow, so that to obtain the correct water levels a trial-and-error procedure must be used. There are two aspects in the adjustment of ice thicknesses that must be considered. At each cross section the thickness must be adjusted to agree with that determined by the slope, width and flow rate. However, ice thicknesses must be adjusted downstream so as to affect the slope of the water surface at the upstream point. This latter procedure represents the staging process that actually occurs as the ice cover progresses upstream. Criteria that guide the adjustments are to maintain velocities under the ice cover at about 2 or 3 ft/s. Thus, the final ice thicknesses represent two processes, the initial thickening and upstream progression of the ice cover in accordance with a theory described in more detail below, and a deposition of ice at downstream sections so as to raise water levels upstream, thus reducing the slope and associated velocities at the upstream edge of the ice cover to allow it to progress upstream. At the end of the trial-and-error procedure, the following general criteria are the objective: the ice cover must be at least as great as that indicated by the final slope, width and discharge, but not so thick as to cause under-ice velocities greater than 2 to 3 ft/s.

The thickness of the ice cover that accumulates under the action of the hydraulic forces was calculated using a theory originally put forth by Pariset and Hausser (1961) and subsequently refined and evaluated by Pariset et al. (1966) and more recently by Beltaos (1983). The Beltaos formulation for ice jam thickness is

$$t = \frac{WS}{2\mu(1-s_i)}\left\{1+\left[1+\frac{(2f_o)^{1/3}\mu(1-s_i)}{s_i}\left(\frac{f_i}{f_o}\right)\left[\frac{(Q/W)^2}{gS/WS}\right]^{1/3}\right]^{1/2}\right\}$$

where t = ice cover thickness
W = width of flow
S = slope of energy gradient
Q = discharge
g = gravity
μ = a cohesion coefficient
s_i = specific gravity of ice
f_i = Darcy–Weisbach friction factor for ice undersurface
f_o = composite friction factor for ice-covered flow.

For the present analysis, values of $g = 9.807\ \mathrm{m/s^2}$, $s_i = 0.92$, $\mu = 1.2$, and $f_i = 1.25 f_o$ were used. f_o is affected by the discharge Q, width W, and slope S, and an empirical approximation to existing data of the form

$$f_o = 3.16\,\frac{W^{5/6} g^{1/6} S^{2/3}}{Q^{1/3}}$$

was used. Substituting this expression into the equation for t, and after some algebra, results in

$$t = 5.208\ WS\left[1+\left(1+0.128\,\frac{Q^{0.555}}{W^{1.389}\,S^{1.111}}\right)^{1/2}\right]$$

where meter-second units are used for t, W and Q.

The procedure used in the present study was approximately as follows. HEC-2 was run with the ice cover option, but with a 0.1-ft thickness throughout and $n = 0.035$. This provides the effect of adding the second boundary (the ice cover) to the flow resistance effects. By use of these slopes and widths, ice was then deposited at downstream points so as to decrease upstream slopes consistent with the concept of ice front progression. The procedure was repeated until the results of runs yielded thicknesses that reasonably agreed with known thicknesses.

APPENDIX B: CALIBRATION DATA

The following data were available to aid in calibrating the profiles of ice and water levels during present winter operation with ice.

During the site visit of December 1985, which had a freezeup flow of 4280 ft^3/s, the water elevation at a Burlington Northern drainage culvert across from Crow Creek pumphouse was estimated at 3946.5 ft (see photo 19 in DNRC [1985)]). This culvert is approximately at section 13.

During the site visit of December 1985 by DNRC personnel, photo 4 was taken with a man standing on the ice beneath the railroad bridge over 16-Mile Creek at Lombard (DNRC 1985). Assuming 3 ft from railroad grade to the bottom of the bridge girder, 5 ft from bottom of the girder to the top of the ice, and a railroad grade at 3963.0 ft yields the top of the ice at 3963.0 – 8.0 = 3955.0 ft.

During the site visit by DNRC personnel and the writer on 5 March 1987, there was no ice in the river. However, there were extensive relic ice deposits on and along the shores that are representative of ice levels at the time of freezeup. Flows at freezeup are estimated from USGS records to be between 4000 and 5000 ft^3/s.

At Crow Creek pump house, relic ice deposits at the intake extended to a point 4.33 ft below its top. The top of the ice elevation is then 3952.0 – 4.33 = 3947.67 ft. After correcting for a freeboard of 3.0 ft, the ice thickness gives a water surface elevation of 3947.4 ft.

Relic ice at the railroad bridge over 16-Mile Creek at Lombard was estimated to be 6 ft below the railroad grade. The top of the ice is then 3963.0 –6.0 ft. Corresponding water level, assuming 4-ft-thick ice, is 3856.7 ft. At the mouth of 16-Mile Creek the relic ice was 6 ft above open water. The open water at a flow of 3000 ft^3/s was analyzed to have an elevation of 3950.7 ft. The corresponding top of ice elevation is 3956.7 ft, which, after accounting for freeboard, corroborates the earlier estimate within 0.5 ft.

At a location downstream of Coke Oven and approximately at section 9, relic ice was 5 ft above the open water surface. Assuming the water surface elevation at Toston Dam was 3944.0 ft and 0.4 ft of backwater gives a top of the ice elevation 3944.0 + 0.4 + 5.0 = 3949.4 ft.

The above calibration data are plotted in Figure 2. The analysis of flow levels with ice agrees quite closely with the data at Crow Creek pump house but overpredicts somewhat the water levels at section 9 and at the 16-Mile Creek bridge. This is to be expected since the analysis used is generally considered to give an upper boundary on water levels.