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Ice Jams, Contaminated Sediment, Dam Removal, and Bridge Scour on the Clark Fork River, Montana

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The Milltown Dam, at the confluence of the Clark Fork and Blackfoot Rivers in Montana lies at the downstream end of nation's largest Superfund Project. Since its construction in 1906, several hundred thousand tons of metal-contaminated sediment from upstream mining activities, primarily copper, have accumulated in the dam impoundment. A large amount of this sediment was scoured during a 1996 ice jam event on Clark Fork and Blackfoot Rivers and transported downstream. The EPA remediation plan calls for phased removal and off-site disposal of much of the contaminated sediment, and removal the Milltown Dam and a smaller mill dam upstream on the Blackfoot River. As much as possible, the river channels will be restored to their pre-project natural morphology. This study examined ice impacts associated with the restoration plan, specifically where ice jams and related ice jam scour might occur with and without the dams in place. Also addressed was the effect of dam removal on potential ice-related scour around the piers of five bridges that cross the Blackfoot River just upstream of the Milltown Dam.

1. Introduction

The Milltown Dam, built in 1906 on the Clark Fork River, lies just downstream from the confluence of the Blackfoot River about 7 miles east of Missoula, MT (Figs. 1 and 2). Since construction, some 7 million cubic yards of sediment have accumulated in the dam's mile-long impoundment. Much of this is material is contaminated with metals (As, Cd, Cu, Pb and Zn) as a result of the historic mining activities upstream at Butte and Anaconda. Since 1982, the EPA has listed the Milltown Reservoir-Clark Fork River on the National Priorities List, and it is now part of the nation's largest Superfund site. Extensive investigations have led to a remedial action plan consisting of phased removal of the Milltown Dam and the contaminated sediments in its impoundment. Ultimately, the dam decommissioning may result in a drop in bed elevation of up to 30 ft. The small timber crib Stimson Dam, located one mile upstream on the Blackfoot River, was removed in 2005 to allow fish passage and improve safety.

The Clark Fork and Blackfoot Rivers experience infrequent ice events, the most severe in recent history occurring on February 9-10, 1996. On February 9, a massive ice run on the Blackfoot River had jammed about 1/3 of a mile upstream of the Stimson Dam (Figs. 3 and 4). On February 10, a massive breakup ice run on the Clark Fork passed through the Milltown Dam impoundment. This ice event scoured large amounts of fine-grained metal-contaminated sediment and deposited them downstream (Moore and Landrigan, 1999).

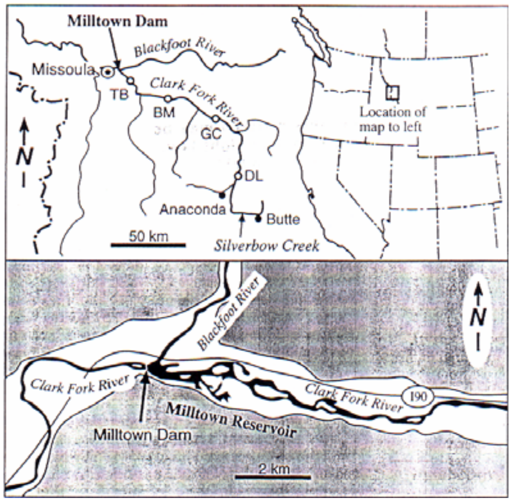

Fig. 1. Map of study area (from Moore and Landrigan, 1999)

Fig. 2. Clark Fork-Blackfoot confluence and Milltown Dam in 2005.

Our study assessed the impact of the Milltown Dam removal on the ice regime of the Clark Fork and Blackfoot Rivers. Of particular interest was the displacement of ice jams from their traditional locations upstream of the Milltown Dam impoundment to downstream sites, and possible ice-related scour in the vicinity of the piers of the five bridges that cross the lower Blackfoot River. Major tasks included 1) characterizing the existing ice regime through historical review and field observation; 2) hydraulic modeling of ice cover formation and breakup for the pre- and post-dam removal cases, 3) evaluation of the potential for post-dam removal ice jam scour around the bridge piers on the lower Blackfoot; and 4) identification of possible ice mitigation measures.

2. History of Ice Jams on the Clark Fork and Blackfoot Rivers near Missoula

Although significant ice jams were reported for 1974 and 1984, the February 1996 event stands out as the most severe by a large margin. In the preceding three weeks, extreme cold caused thick ice covers on the Blackfoot and Clark Fork Rivers. A maritime weather system brought rapid thawing to the region, releasing over 40 miles of ice on the Blackfoot. The massive Blackfoot ice run grounded and stopped about 1.5 miles upstream of the Milltown Dam to form a three-mile-long, 12 to 18-ft thick jam (Figs. 3 and 5). A number of smaller ice jams also occurred as a breakup front progressed downstream on the Clark Fork, ultimately fracturing its way through the 1-ft-thick sheet ice cover on the Milltown Dam pool on February 10. During the next several days, continued high flows and much more ice passed through the Clark Fork portion of the pool. The likely scour mechanism in 1996 appears to have been ice impact and ice gouging of the channel bed and banks rather than hydraulic scour caused by high velocity flow beneath a stationary ice (Tuthill et al. 2005).

Fig. 3. Blackfoot River ice jam, Feb. 1996.

3. Frequency and Severity of Ice Events

A hindcasting analysis based on historic hydro-meteorological data from 1929 to 2002 (Tuthill et al. 2005) identified possible ice events that may have gone unrecorded. Based on the known historic events of 1996, 1984 and 1974, causal factors for ice jams include a pre-breakup ice thickness of 10 inches or greater and an increase from base flow to peak flow equal to or greater than 1400 cfs. For each winter, maximum ice thickness (t_i) was calculated from accumulated freezing degree-days (*AFDD*). Increases in discharge and ice thicknesses were ranked and assigned probabilities. Assuming that increase in discharge (ΔQ) and ice thickness (t_i) are independent variables, the exceedance probability of an historic or hindcast event can be estimated by multiplying the two probabilities. By this approach, the calculated frequency of a 1996-like event recurring was less than 0.1 percent.

4. Hydraulic Modeling

We used the HEC-RAS model (US Army, 2000) to analyze ice formation and breakup processes under existing and post-project conditions. The modeled reach included 20 miles of the Clark Fork plus 7 miles of the Blackfoot River from the Bonner Gage downstream to the mouth. The model was modified to simulate post-project channel geometry by removing the Milltown and Stimson Dams and adjusting the channel width and minimum bed elevation to conform to a preliminary restored channel design by Westwater Consultants et. al (2005). The restored channels had bottom widths of 200 ft above the confluence and 250 ft downstream. The restored Blackfoot channel followed the existing straight alignment while, for the Clark Fork restored channel, a sinuosity of 20% was assumed.

In the freezeup case, HEC-RAS was used to calculate average channel velocities for typical early winter discharge levels. Simple water velocity criteria then identified likely areas of thermally-grown sheet ice, frazil ice accumulations, and areas where open water is likely to persist throughout the winter. The analysis found that, with the exception of the dam impoundment area, juxtaposed and shoved frazil floes could be expected at most locations within the study reach. Based on the historic AFDD analysis, the sheet ice thickness on the pools was assumed to be 1 ft. The equilibrium frazil transport theories of Shen and Wang (1995) predicted some frazil deposition beneath the impoundment ice covers, but in terms of overall ice volume, this additional frazil volume was not significant.   For the post-project case, the water velocity criteria suggest frazil ice covers would extend through the restored river channels, resulting in a slight increase in the total calculated ice volume on the two rivers upstream of the former dam location.

The February 1996 event served as a worst-case scenario in terms of discharge and ice supply for the breakup ice jam modeling. Breakup jams for the existing conditions were modeled at the upper end of the former Stimson Dam pool on the Blackfoot and at the upstream end of the Clark Fork portion of the Milltown Dam reservoir. Fig. 4 shows simulated ice jam locations and Fig. 5 shows the simulated profile on the 1996 ice jam on the lower Blackfoot River). Because HEC-RAS does not predict ice jam location, several possible post-project jam sites (Fig. 4) were tested on the Clark Fork: the first in a bend 3.5 miles downstream of the confluence and the second at an island 3200 ft downstream of the confluence. A third breakup jam was simulated 10 miles below the confluence in downtown Missoula where multiple bridges and grade control structures cross the river. At these three sites, calculated water velocities beneath the ice jam toe areas were at or above 4 ft/s, suggesting that stable ice jams could probably not exist, and the breakup ice run would likely pass through without jamming.

5. Ice-Related Bridge Scour Analysis

Although previous analyses (Tuthill et al. 2005) indicate that ice jams are unlikely in the restored Blackfoot channel, the possibility of ice jam scour was examined since five bridges cross this reach, the most important being the two lanes of Interstate 90. Bed shear was calculated using the depth-slope product, for both a hypothetical ice jam case, and also the 100-year open water flood for comparison. Bed shear was also calculated using steps outlined by Beltaos (2001), which is based on water velocity and drag on the ice underside. Hydraulic and ice parameters such as water surface slope, average depth and average channel velocity are taken from the HEC-RAS simulation with a possible breakup ice jam starting 3200 ft downstream of the confluence and extending upstream beneath the bridges (Fig. 6). Both methods assume a floating ice cover of uniform thickness across the river width and no ice grounding.

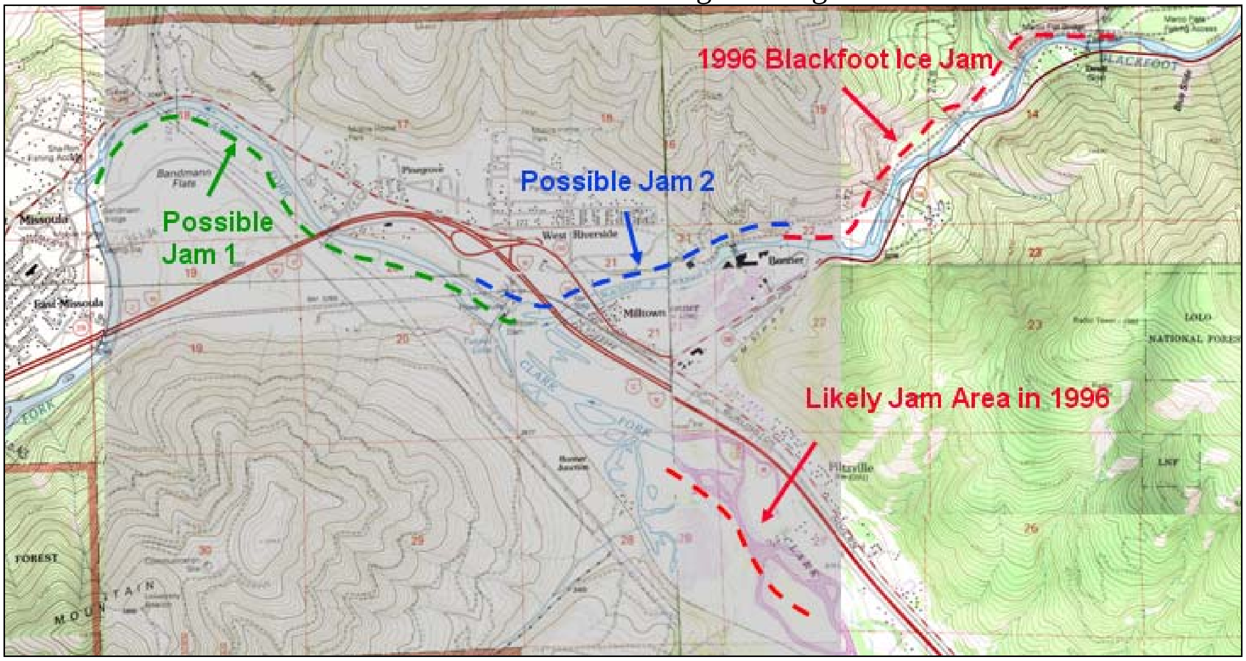

Fig. 4. Map showing simulated 1996 ice jams and possible post-project ice jam locations.

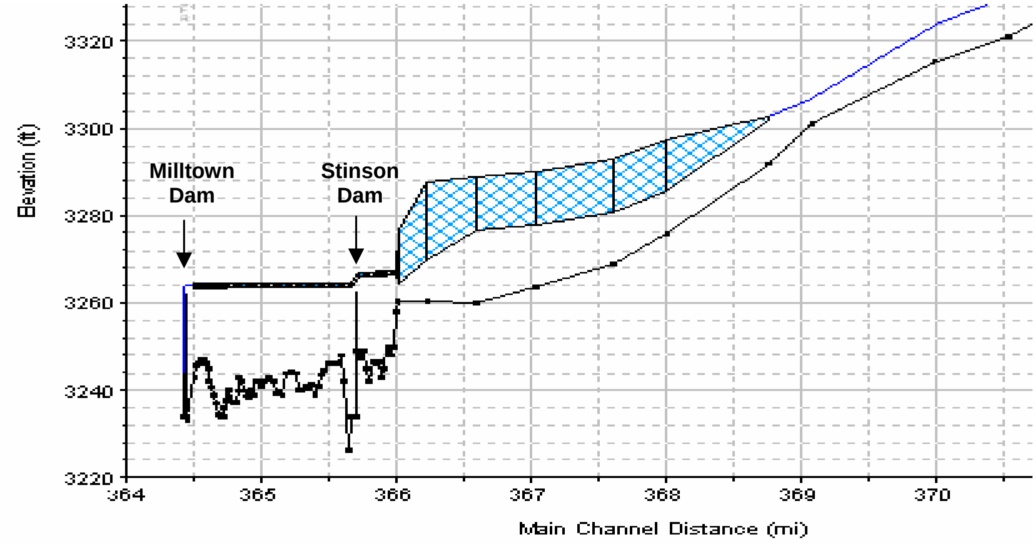

Fig. 5. HEC-RAS-Simulated profile of the 1996 ice jam on the lower Blackfoot River with existing-conditions.

Using the two-layer flow hypothesis, for uniform flow beneath an ice accumulation, bed shear, t_b , can be calculated using depth-slope product (e.g., Chow 1959):

$$\tau_b = \gamma R_b S \qquad \text{(Eq. 1)}$$

where γ is the unit weight of water, R_b is the portion of the hydraulic radius affected by river bed roughness , and S is the water surface slope. The HEC-RAS ice option uses this approach to partition the under ice hydraulic radius R into ice affected and bed affected components R_i and R_b, based on ratios of the ice or bed roughness to the composite ice roughness, raised to the 3/2 power (U. S. Army, 1998).

For the open water case at the 100-year discharge (24,000 cfs), an 18-ft flow depth, and a water surface slope of 0.00256, Eq. 1 gives an average bed shear of 2.8 psf. For the ice-hydraulic conditions of the HEC-RAS simulated jam 3200 ft downstream of the confluence, slope = 0.0025, a coarse gravel bed (D_{84} = 75 mm), an under-ice depth of 6 ft, and a Manning's ice roughness of 0.06, Eq. 1 gives a bed shear of 0.45 psf.

The Beltaos (2001) approach calculates a bed friction factor f_b adjusted for flow beneath an ice jam, which is then used in the Darcy-Weisbach equation to calculate bed shear:

$$\tau_b = \frac{1}{8} f_b \rho U^2 \qquad \text{(Eq. 2)}$$

where $f_b = 0.118$, ρ is water density and U is average under-ice water velocity (3 ft/s). By Eq. 2, the estimated under-ice bed shear in the vicinity of the I-90 piers is 0.25 psf, about half the under-ice bed shear calculated by the depth-slope product, and one-tenth the 100-year flood bed shear estimate by Eq. 1.

Assuming clear water scour conditions, recommended values of limiting shear stress for coarse gravel (D_{50} = 50 mm) and sandy silt (D_{50} = 1 mm) found in the site are about 0.8 and 0.04 psf respectively (Zipparo and Hasen, 1992). Based on this information, the sandy silt would be expected to erode under the predicted 0.25-0.45 psf bed shear beneath the simulated 6-ft-thick breakup ice accumulation, while the gravel bed would resist erosion under these conditions. The silt and some of the gravel would be expected to erode during open water season high flow events as well.

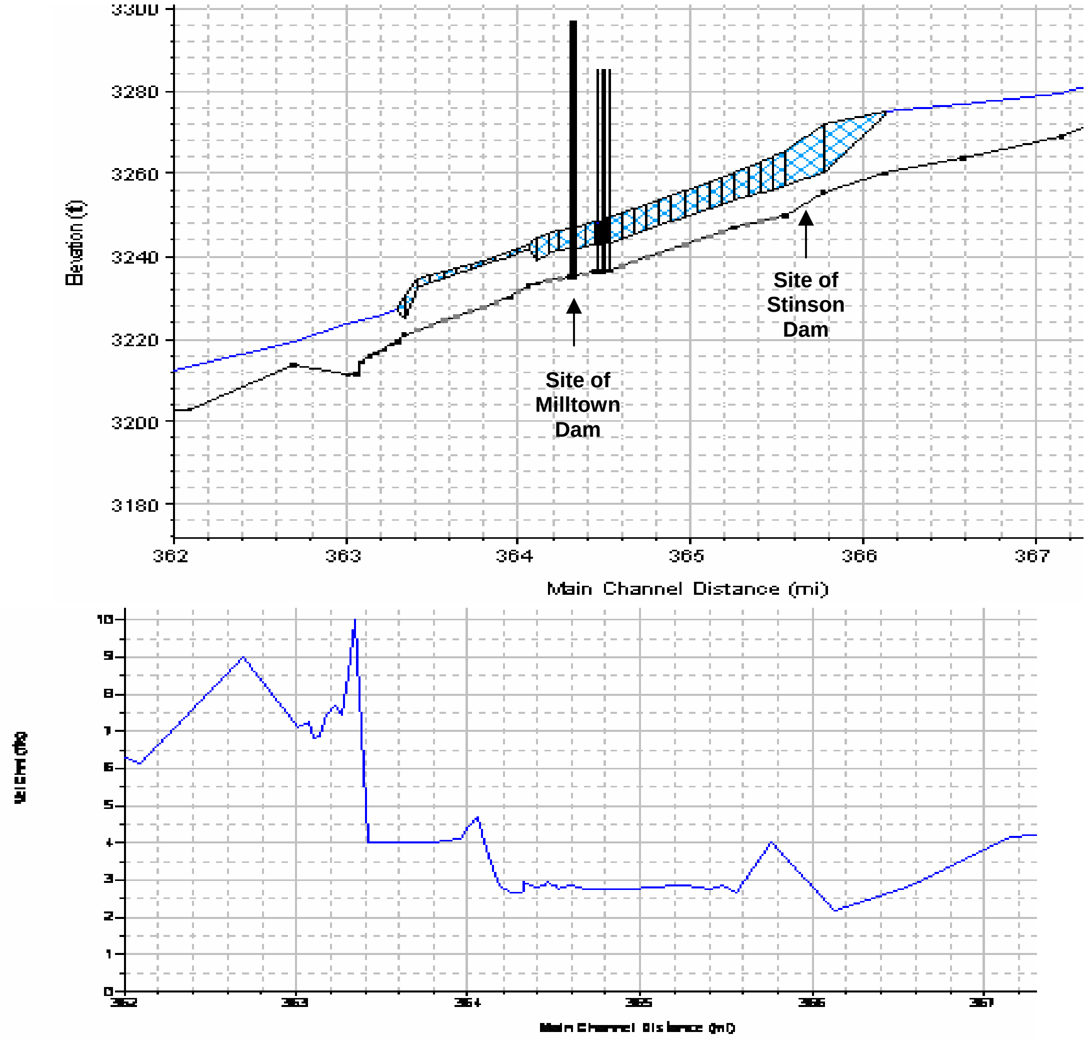

Fig. 6. Simulated ice jam in restored Blackfoot channel (top) and average under-ice water velocity (bottom).

6. Possible Ice Mitigation Measures

Although it is not expected that the removal of the Milltown and Stimson Dams will significantly increase ice jams and ice-related problems on the lower Clark Fork, it is possible that ice run on the Blackfoot River could continue downstream and jam in the vicinity of the five bridges. instead of stopping where it did in 1996, This scenario would increase the potential for under-ice scour in this section of river. The simplest mitigation strategy would be to design the bed protection to withstand the expected under-ice bed shear stresses in the vicinity of the bridges. Based on the above results, it appears that, the armor required for the 100-year open water event will be adequate for protecting the bed during a severe breakup ice jam event.

A more conservative approach would be to construct grade control and possibly ice-retention piers to ensure that the Blackfoot breakup ice run stops at its traditional location about 1.5 miles upstream of the confluence. Monitoring post-project conditions would help determine if ice retention piers are needed in addition to other mitigation measures. It may be that the Blackfoot ice run will continue to stop in its traditional location with no additional structures, since the causal factors such as the sharp bend along Highway 200 and some of the gravel deposits at the head of the former Stimson Dam impoundment will remain after the dams are removed and the channel restored.

7. Conclusions

A phased dam removal planned as part of a larger project to remediate contaminated sediments in the Clark Fork River, Montana, required an innovative approach to evaluate ice impacts. A historical search of ice records provided information about several serious ice events. This data, combined with historical hydro-meteorological information, was used in developing HEC-RAS models of simulated ice jams under different conditions. Both freezeup conditions and breakup ice jams were modeled. The results of the ice-hydraulic modeling were used to assess potential ice jam impacts upstream and downstream from the Milltown Dam after its removal. Impacts included potential scour in the vicinity of five bridges on the Blackfoot River just upstream from the Milltown Dam. The results indicate that bed and bank protection designed to meet 100-yr open water conditions would be sufficient to mitigate against scour for expected ice conditions.

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