# Appendix E

## Effects of Ice on Sediments in LLBdM, Lower Fox River above Appleton, Wisconsin (Ashton 2006)

# Effects of Ice on Sediments in Little Lake Butte des Morts, Lower Fox River above Appleton, Wisconsin

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## Summary of Findings

No evidence was found of ice jamming associated with breakup of the ice cover in OU1 on the Fox River just upstream from Appleton, Wisconsin. There is a possibility of some very limited frazil production and accumulation during very cold periods at the very upstream end of the pool termed Little Lake Butte des Morts, and these accumulations possibly could extend to the upstream region of interest. Other ice processes that conceivably might pose a hazard to capping were examined including the simple blockage of the flow cross section by the ice cover thickness. These blockages only increase the shear stress on the bottom, relative to the same discharge under open water conditions, at low discharges and are much less than the bottom shear stresses at high discharges associated with 100 year return flows. Velocities even at very high flows are less than those associated with ice jamming. The overall conclusion is that ice does not change the selection of capping materials in the regions D and E.

## Background

As part of the effort to remediate sediments in OU1 extending from the Menasha and Neenah channels at the upstream end of the pool to the dam downstream located at Appleton, Wisconsin, there was concern as to the possible effects of ice on sediments and the remediation measures planned. This report discusses the nature of the ice cover at the site and associated processes that could conceivably interact with the sediments or the capping of those sediments in the central region of the Little Lake Butte des Morts extending from downstream of the Menasha channel confluence on downstream to where the Lake narrows approximately 2.5 miles downstream. The conclusions below are based on review of data of stream flows and winter temperatures for the site, on a site visit on 27 October 2006, on published literature dealing with ice and sediments, and on some 35 years of personal experience examining river and lake ice behavior.

The formation of ice in rivers is complex. Nevertheless approximate calculations are made to assess the general behavior of ice at the site to evaluate any possible interactions with sediments.

## Fox River Near OU1 – Appleton, Wisconsin

The Lower Fox River extends from the outlet of Lake Winnebago to its mouth at Green Bay. The flow from Lake Winnebago in winter is dominated by measures taken to control the water level in Lake Winnebago. This includes a winter drawdown beginning in mid-October and extending until the end of February with the intent of providing storage for later runoff into Lake Winnebago. When the drawdown target is achieved the stage at the outlet of Lake Winnebago is held constant until the ice cover in the Lake Winnebago pool breaks up. The stage in Lake Winnebago is then increased beginning about mid-April to provide a navigation stage. More detail on the operating schedules and objectives are contained in USACE (1994).

The region of concern is a reach of river that is similar to a lake (and named "Little Lake Butte des Morts") with through flow until the river narrows about 3 miles downstream. Flows enter into the pool at its upstream end in two channels, the Neenah and the Menasha channel with the flows split between the two channels. The pool formed by the dam downstream at Appleton is quite wide (typically 3000 to 4000 feet) for two miles downstream of the Menasha channel confluence and then narrows to about 1500 feet beginning at the downstream end of the remediation region E2 and further narrows gradually over the last few miles to the dam at Appleton. There is awareness of possible ice problems downstream of Lake Winnebago contained in the operational strategy for the river and to "help prevent frazil ice development, experience has shown that flows must be limited to about 4,000 cfs (113 cms) when the air temperature falls below 25 degrees Fahrenheit, until such time as a complete ice cover has developed on the river." (USACE 1994). Those frazil problems are associated primarily with stretches of the river downstream of the Appleton dam and extending to the outlet at Green Bay. Examination of the detailed flow records at the USGS gaging station at Appleton, WI showed that, at least since 1994, that strategy has been implemented with flows during the freezeup period from 15 December – 31 December no greater than 4420 cfs except for two periods: during the period 14-16 December 1999 when the average daily flow on 15 December was 5,130 cfs; and during 14-18 December 2004 when the average daily flow on 15 December was 5550 cfs. (Note: In December 1999 the air temperature was quite warm until just after 15 December when the flows were reduced; similarly in 2004 the temperatures abruptly decreased just after 18 December when flows were similarly reduced; this is consistent with the intent, namely to maintain flows at about 4,000 cfs during ice formation periods.)

The region of concern in this report is the central region of the pool. The overall bathymetry (See Foth & Van Dyke Figure 6-2: Post Remedy Water Depth, dated October 2006) is a central deeper portion along the axis of the lake generally about 6 to 10 feet deep. The region of proposed capping (See Foth & Van Dyke Figure 6-1: OU1 Final Optimized Remedy, dated October 2006) involves a proposed 10 inch cap in the central portion about 8000 feet long and a proposed 13 inch cap along the west side of that central portion for about half that length and in water depths of 3 to 6 feet. There is a smaller, narrow area about 2000 feet long near the west side opposite the dredged channel leading to the Menasha lock that will involve capping with a 13 inch deep cap in the areas where the water depth is 3 to 6 feet and two small areas in slightly deeper water where a 10 inch cap is proposed. All of these areas of concern in this report are well away from the shoreline and hence not affected by possible near-shore ice processes.

## OU1 Site Visit

A visit was made to OU1 on 27 October 2006. On the morning of 27 October, the writer, together with Matthew Oberhofer of Foth and Van Dyke, traveled around the river from the mid-pool highway bridge south along the west side, through Neenah and Menasha and then north along the east side and on downstream to the dam at Appleton, Wisconsin. Observations were made of vegetation and structures along the shores with the objective of detecting any damage due to ice effects. None was observed. Notably there were observed extensive small docks for recreational boat mooring, generally consisting of 8 to 12 inch diameter timber piles permanently installed. This is evidence of little or no damage due to ice that would result from major jamming or ice movement. The extended width of the river caused by the dam at Appleton results in the pool above the Appleton Dam characterized as a lake-like environment with relatively slow velocities compared to that in the narrower reaches just upstream of the dam at Appleton and extending on downstream to Green Bay, WI, although even those downstream reaches are a series of pools behind low head dams.

In a previous visit to the Lower Fox River in October 2005 a number of people with experience on the river during winter were interviewed. The overall behavior of the river during winter was characterized by these. Typically the river becomes ice covered in mid-December and melting begins in February to sometimes mid- to late March.

## OU1 Climate and Hydraulics

The Fox River near Green Bay, WI is characterized by a quite cold winter with from as few as 8 to as many as 50 days during which the daily minimum air temperature is below 0°F with a long term average of 24.3 days per winter. Mean monthly temperatures (period 1971-2000) at Green Bay, WI are tabulated below. (Note: The meteorological record for Green Bay is used because of its ready availability and long term record; the site is about 30 miles south of Green Bay).

| December | January | February | March |
|---|---|---|---|
| 21.2°F | 15.6°F | 20.5°F | 31.3°F |

The long term average mean air temperature (average of daily high and lows) decreases to 32°F in late November and increases to 32°F about the last week of March. In terms of freezing degree days (1 freezing degree day is 1°F below 32°F for a day), this means the average freezing degree days accumulated December thru March is 1230 °F – days (684 °C-days). This latter value is useful to estimate the maximum ice thickness to be expected at the end of the winter. An examination of longer term records showed that there have been a few years when it was very cold relative to this long term average; notably in the last 50 years, both 1976 and 1978 experienced very cold winters and the estimated accumulated freezing degree day totals for those winters were about 2200 °F – days (1222 °C – days).

The hydraulics at the site is variable but, as pointed out above, considerably controlled upstream in association with control of the water levels in Lake Winnebago. Average monthly stream flows as measured at Appleton, WI as measured by the USGS for the period 1986- 2005 are

| December | January | February | March |
|---|---|---|---|
| 4060 cfs | 3690 cfs | 3750 cfs | 5050 cfs |

These are fairly constant flows through the winter for a river this far north and are due to the control at the outlet of Lake Winnebago. However, there are excursions of the flow that are quite a bit higher. The daily discharge records at the USGS station at Appleton were examined for the period 15 December to 31 March for the years of record from the winter of 1986-87 through the winter of 2005-2006 and the peak flows during that period extracted.

The maximum peak average daily flows for the period 15-31 December, and for January, February, and March periods over the period of 21 years are:

| 15-31 December | January | February | March |
|---|---|---|---|
| 6860 cfs | 7590 cfs | 7000 cfs | 11,100 cfs |

The five highest ranked peak flows are shown in Table 1 together with the air temperatures experienced before, during and after the peak flow. These are all associated with warm temperatures and little ice production during the period of high flows.

Table 1
Highest Peak Flows December 15-March 31
Period 1986-2006

| | | | Air Temperatures | | |
|---|---|---|---|---|---|
| **Winter** | **Peak Flow (cfs)** | **Date** | **Before** | **During** | **After** |
| 2003-04 | 11100 | 6 Mar | Warm* | Warm | Cool** |
| 1989-90 | 9500 | 21 Mar | Unavailable at time of report | | |
| 1996-97 | 9330 | 29 Mar | Warm | Warm | Very Warm |
| 1988-89 | 8800 | 32 Mar | Unavailable at time of report | | |
| 1997-98 | 8640 | 31 Mar | Very Warm | Warm | Very Warm |

* Warm – average daily air temperatures above 32 °F
** Cool – average daily air temperatures below 32 °F but above 15 °F

Note: At the time of writing detailed air temperatures had not been obtained for the years 1988-1990. However the long term average daily high temperature at the end of March is 45°F and the long term average daily low temperature is 28°F so it is very unlikely that the air temperatures associated with a high discharge would be very cold.

The record was then examined to determine the highest flows that would be experienced during the mid-winter with the results shown in Table 2.

Table 2
Highest Peak Flows December 15-31, January & February
Period 1986-2006

| | | |
|---|---|---|
| December 15-31 | 6860 cfs | 21 December 1992 |
| January | 7590 cfs | 13 January 1987 |
| February | 7000 cfs | 25 February 1994 |

While a more detailed statistical analysis was not performed, it is clear that flows as high as 7500 cfs may be expected during mid-winter and flows as high as 11,100 cfs may be expected in March (although these seem to be associated with warm periods and probably either during or after breakup). It is also possible that a 100 year return period flow of 24,000 cfs could occur near the end of the winter season, but would most likely be associated with quite warm temperatures and significant melting of the ice cover with rise in the hydrograph to such an extreme flow. In this report we will use 12,000 cfs as representative of an extreme flow in association with an ice cover on Little Lake Butte des Morts.

## Flow Velocities

Using the results of hydrodynamic modeling done previously for the site for a design flow of 408 cms (14,400 cfs), the estimated flow velocities at mid-channel for three different flows were determined (by scaling proportional to discharge) for representative reaches beginning in the Menasha channel, just downstream of the region where the flow begins to move northward (beyond the extension of the point of land off the outlet of the Menasha channel, and at the mid-reach from there to the bridge (over E1). The flows chosen for examination were a typical freezeup flow of 4,000 cfs, a high winter flow of 11,100 cfs, and the 100 year return flow of 24,000 cfs. The results are presented in Table 3: (Note: the mapping of velocities available to the author was presented at a resolution of 0.2 m/sec for a discharge of 408 cms (14,408 cfs); nevertheless it is adequate for our purposes here since the resulting velocities are quite low relative to governing threshold velocities for ice behavior). We also note that these are flow velocities during open water conditions and hence are applicable to behavior at the time of onset of the ice cover formation. In a section below the effect of the thick ice cover that exists at the end of the winter season will be discussed.

Table 3
Summary of Maximum Velocities for Different Reaches

| Reach | Typical Freezeup Flow | High Winter Flow | 100 year Return Flow |
|---|---|---|---|
| | (4000 cfs) | (11,100 cfs) | (24,000 cfs) |
| In the Menasha Channel | 0.27 fps | 0.82 fps | 1.6 fps |
| At mid-channel of lake reach where flow begins to move northward | 0.36 fps | 1.08 fps | 2.2 fps |
| Mid-channel over E1 | 0.27 fps | 0.82 fps | 1.6 fps |

We note that except for the “mid-reach of the lake opposite the Menasha channel outlet” the velocities are all less than 2 fps and for discharges up to 11,000 cfs are all less than or equal to 1.08 fps.

## Formation of Frazil, Anchor Ice, and Surface Ice Cover

In very large lakes, and most rivers subject to very cold temperatures, frazil ice can form and be carried to great depths (Frazil is ice in very small crystals formed in supercooled flow (slightly below 0ºC)). In fast flowing rivers, frazil can be distributed through the depth of the flow and attach itself to the bottom sediments. In this form it is termed “anchor” ice. Upon warming slightly or when the buoyancy exceeds the adhesion at the bed, it can rise and sometimes bring a quantity of sediment to which it had adhered. There is considerable experience in assessing the nature and intensity of frazil formation based on mean water velocity and this is well represented by a diagram originated by Matousek (1984) and presented with some addition and simplification by Ashton (1988). From 0 to about 0.2 m/s (0.6 fps) the initial ice formation is in the form of thin sheets on the surface and little frazil formation. From about 0.2 m/s (0.6 fps) to about 0.7 m/s (2.3 fps) a “skim ice run” occurs, again, with little frazil formation. From about 0.7 m/s (2.3 fps) to about 0.95 m/s (3.1 fps) the frazil forms a “layered frazil and slush run” with the ice confined to the near surface of the water. Above about 0.95 m/s (3.1 fps) a “well mixed frazil run” occurs with frazil transported to some or the entire depth of flow. It is this last type of formation that can lead to anchor ice formation on the bed. There is some effect on these boundaries of types of ice formation due to the intensity of cooling with higher cooling rates tending to shift the types of ice formation somewhat towards the more severe types. At about 2 fps and below, the frazil formation is able to accumulate into an initial ice cover and, once stationary, will continue to thicken by thermal growth. Thus frazil produced in high velocity reaches is carried downstream until a lower velocity reach is present at which it forms a solid cover. Further arrival of frazil may be carried under the ice cover and either be further transported beneath the ice cover or deposit out (upwards) beneath the ice cover. In some cases such accumulations may form very thick “hanging dams”. As the deposit thickens, the diminished cross section causes velocities to increase beneath the accumulation. The critical velocity beneath which frazil deposits out from the flow is about 2.0 fps based on observations of frazil deposits in rivers and is consistent with numerical models that use that value as the critical velocity, and with laboratory experiments. Once deposited, the frazil develops some cohesion between particles and, as a consequence, the critical value for erosion is generally taken to be slightly higher and about 2.3 fps.

To summarize, it is expected that there will be frazil formation when the water surface does not have an intact ice cover. This corresponds to regions where the surface velocity is 2 fps or greater. There will be a possibility of anchor ice formation in regions where the flow velocity is greater than about 3 fps. However, as discussed above, the velocities in the Little Lake Butte des Morts are very much lower than the velocity associated with other than thin sheet formation and rapid ice cover formation such as occurs in lakes.

## The Nature of the Ice Formation on Lake Butte des Mortes

With the above guidance, it is possible to describe the nature of ice formation at OU1 associated with the different flows shown in Table 3.

For typical freezeup flows of 4000 cfs, the average velocities in all reaches upstream of the narrow channel just above Appleton are less than 0.5 fps for flows typical of late December during the freeze-up period. We thus expect the ice cover to form rapidly over the entire lake upon the onset of cold air temperatures. The only exceptions to this are the reach further downstream where the river narrows above Appleton and just below the outlets from the Menasha and Neenah channels. The latter will be treated separately below.

The Neenah and Menasha channels derive their flow from Lake Winnebago. The writer does not have measurements of the water temperature in Lake Winnebago, but the typical behavior of water temperatures in similar lakes is as follows: The water first cools to the 4°C temperature associated with the maximum density of water. Further cooling results in cooling of the top surface with a weak density stratification occurring. Generally this temperature stratification is disturbed by wind mixing and the water further cools at depth to temperatures between 1°C and 4°C due to wind mixing until finally there is a more-or-less complete surface ice cover formed that halts further cooling. The result is a temperature beneath the ice that is typically between 0°C and 2°C and this is the water that enters the Menasha and Neenah channels. This water then takes some time (and distance) to further cool to 0°C after which further surface cooling results in ice formation. The result in the case of concern here is that the water entering Little Lake Butte des Morts is probably warmer than the freezing point and there will be a tongue of open water extending out into the lake downstream of the Menasha and Neenah channel outlets. With relatively warm air temperatures the extent of this open water may even extend to the far side of the lake and turn northward; however during very cold periods, the velocities just downstream of the outlet are such that a thin ice cover will form over this “tongue of warm water” and the warm water will be cooled as it passes beneath the ice. Approximate estimates were made of the aerial extents of open water that would result from a 1°C discharge of 4000 cfs from Lake Winnebago into Lake Butte des Morte. At a steady state average air temperature of -5°C (23°F) the corresponding open area would be about 2.25 $km^2$ ; at -10°C (14°F) 1.2 $km^2$ ; and at -15°C (- 5°F) 0.81 $km^2$. These are probably overestimates since at the very low velocities just downstream of the channel outlets, ice will form over slightly above freezing water temperatures. Thus any open water in the otherwise ice covered lake would likely be confined to the immediate areas just downstream of the Menasha and Neenah channel outlets, and during onset of cold spells would become covered with a thin skim of ice that would stop frazil production there.

The production of frazil in a fast flowing open area through a winter period may be estimated from the cumulative degree-days of freezing. A simple heat balance between the production of frazil and the heat loss to the atmosphere results in

$$\rho \lambda h_f = H_{wa} (T_m - T_a) t$$

where $\rho$ is the density of solid ice, $\lambda$ is the heat of fusion of ice, $h_f$ is the thickness of ice produced over time t when exposed to an air temperature $T_a$ relative to the freezing point $T_m$. The value of $\rho$ is accurately known at 916 kilograms per cubic meter, and $\lambda$ is accurately known at 334,000 Joules per kilogram. Hwa is a heat transfer coefficient between the water surface and the air above. It varies with wind speed with higher wind speeds yielding higher heat transfer rates. Hwa typically varies from 10 Watts per square meter per °C under still air conditions and is about 30 Watts per square meter per °C for moderately windy conditions. Here we will use a more typical average value of 20 Watts per square meter per °C. The product $(T_m - T_a) t$ is the degree-days of freezing. At Green Bay the average cumulative degree-days of freezing December through March is 684 °C – days. Inserting these values into the above equation results in a potential thickness of solid ice production per unit area of 3.84 meters (about 12.5 feet) per unit area of open water surface exposed throughout the winter. The daily temperature records at Green Bay, WI from 1991 to 2005 were examined to find periods of extended consecutive very cold days, since such periods are more directly related to the production of frazil that may be of concern than are the total seasonal cumulative degree-days of freezing. The coldest period found was from 19 December 1998 to 15 January 1999. There were 677 freezing °F –days (376 °C –days) accumulated during this period, so use of the average seasonal accumulation of 684 °C -days is considered conservative in terms of estimating maximum ice production.

The area of open water that conceivably could produce frazil is the Menasha channel from the dam to the island at the mouth of the channel and has a surface area of about 167,000 square meters, although even there the typical velocities during winter are such that skim ice would form on the surface during cold periods (and assuming the withdrawal from Lake Winnebago is at 0°C). This yields a frazil production of 640,000 cubic meters of solid ice and a deposit (assuming a porosity of 0.5) volume of 1,280,000 cubic meters of bulk frazil. The volume available for the deposit is the area approximately 600 meters x 600 meters with a depth of 1 to 2 meters. Assuming the deposit occupies ½ the depth the volume that can be contained before the flow turns northward is about 360,000 cubic meters. Thus some frazil could be deposited downstream of that point. Frazil deposits out when the average flow velocity is about 0.6 m/sec and erodes at a slightly higher velocity of about 0.7 m/sec. Thus it would seem prudent to size the capping material in the region just downstream of the point where the flow turns northward (region D2N) to resist a velocity of 0.7 m/sec. The frazil deposit will not extend further downstream than the D2N region. It is also noted that this is a conservatively high calculation of frazil production since it relies on withdrawal water temperatures from Lake Winnebago of 0°C and that is probably colder than occurs in most, if not all, winters.

## Thickness of the solid ice cover and effect on velocities

The maximum thickness of ice that might be expected at the site is given by a modified Stefan equation of the form $h_i = C\, S_f^{1/2}$ where, if $h_i$ is given in inches and $S_f$ is the degree days of freezing in °F – days, then C is typically about 0.5 to 0.7 for slow flowing rivers and protected still waters. For the average $S_f$ of 684 °C days ( = 1230 °F – days), this results in a thickness of 17.5 to 24.5 inches. For the extreme winters with an accumulated degree days of freezing of 2200 °F – days, this results in a thickness of 23.4 to 32.8 inches. We will use 26 inches as representative of the maximum ice thickness expected.

Thus it is expected that there will be an ice cover formed over most of Little Lake Butte des Morts with a thickness of a little over about 2 feet from mid-winter to just before breakup. The effect of this ice will alter the flow velocities somewhat and also alter the shear stresses exerted by those velocities on the bed materials.

In rivers where the slope of the river is determined by the roughness of the boundaries, the effect of adding an ice cover is to cause a rise in the depth to accommodate the increased flow resistance of the added second boundary. However in lakes, the depth does not increase due to the formation of the ice cover. Little Lake Butte des Morts is much closer to behaving like a lake, particularly in the region of concern (the upper end of the pool formed by the dam at Appleton), and we expect little change in depth to accommodate the throughflow in the reduced cross section caused by the ice cover cross section until the discharges significantly increase over the 4,000 cfs flows associated with the initial ice cover. The overall effect is a tendency to concentrate the flow in the deeper areas of the cross section with resulting somewhat higher velocities there as well as increase in average velocity overall due to the diminished cross section of flow. It is beyond the scope of this report to do a detailed analysis of the altered flow velocity distribution. However some simple considerations provide an estimate of the effects of this cross section blockage by ice on the shear stresses exerted on the bed materials.

When the flow is 4 feet deep and ice cover 2 feet thick the effective flow area is reduced by a factor of 2 and increases the flow velocity by a factor of 2. When 6 feet deep the flow area is decreased by 1/3 and the velocity increases by a factor of 1.5. These increased velocities, however exert a shear stress on both the underside of the ice cover and the bottom materials more or less equally so that $\tau_{bi} = \tau_i = \tau/2$, where $\tau_{bi}$ is the shear stress on the bed during period of thick ice cover, $\tau_i$ is the shear stress on the bottom materials during period of thick ice cover and $\tau$ is the total of the shear stresses exerted by the flow. Assuming the shear stress is more or less proportional to the square of the mean velocity, the shear stress on the bottom will increase relative to the open water value (for the same discharge) when the ratio of ice thickness to depth is greater than about 0.3 and the shear stress on the bottom will be less relative to the open water value when the ratio of ice thickness to depth is less than about 0.3. For an ice thickness near mid to end of winter of 2 feet this corresponds to a depth of 6.67 feet. Thus, all other things being equal, we may expect an increase in shear stresses on the bottom materials (relative to the open water case at the same discharge) when the open water depth is less than 6.67 feet and a decrease when the water depth is greater than 6.67 feet. This is somewhat offset by the shifting of the flow from shallower areas to deeper areas of the cross section and also by the rise in water level associated with accommodating the flow (Note: most of the water level rise relative to open water conditions is expected to occur in the narrower reach just upstream of the dam at Appleton but that backwater effect will extend upstream through the wider pool considered here).

Cross sections at approximately the location of D2 and at E3S were plotted with an ice cover present assuming little elevation of the water surface due to the ice presence (see Figures 1 and 2) and approximate flow areas calculated for open water and ice-covered (2 feet thick) conditions and resulted in amplification of mean velocities at D2 by about a factor of 2 and amplification of mean velocities at E3S by about a factor of 1.5. Following the same logic as presented above, at D2 we would expect shear stresses on the bottom to increase by about a factor of 2 (approximately $2^2/2 = 2$) and at E3S shear stresses to increase slightly by about a factor of 1.125 (approximately $1.5^2/2 = 1.125$), both relative to open water flows at the same discharge. However while this blockage effect increases the shear stresses on the bottom over those for open water conditions at the same discharge, they are still lower than the shear stresses associated with higher open water discharges about 2 or 3 times the winter discharge of about 4 to 5000 cfs.

As the discharge increases, the flow transitions from a lake-with-slow-through-flow to a river-like behavior. In rivers the depth increases to accommodate the flow. An approximate calculation was made of the increase in depth to accommodate a flow of 12,000 cfs with a resulting increase in depth of about 0.5 feet. For this case the amplification of mean velocities at D2 changes somewhat to $1.84^2/2 = 1.69$ and at E3S shear stresses to decrease by about a factor of $1.09^2/2 = 0.59$. Finally at even higher flows the shear stress is more or less equally distributed to the underside of the ice cover and the bottom and the bottom thus experiences ½ the shear stress associated with the equivalent open surface discharge.

The capping materials are selected to resist the shear stresses associated with a 100 year return period flow of about 24,000 cfs. These shear stresses in OU1 are above those that are amplified by the blockage effect at low discharges and hence the net effect of the blockage on the selection of capping materials is moot.

# References

Ashton, G. D. 1988. Intake design for ice conditions, Chapter 2 In: P. Novak (editor) Advances in Hydraulic Engineering, Vol. 5, p. 107-138, Elsevier Applied Science, London, 1988.)

Foth & Van Dyke, Figure 6-1 OU1 FINAL OPTIMIZED REMEDY, dated October 2006.

Foth & Van Dyke, Figure 6-2 POST REMEDY WATER DEPTH, dated October 2006.

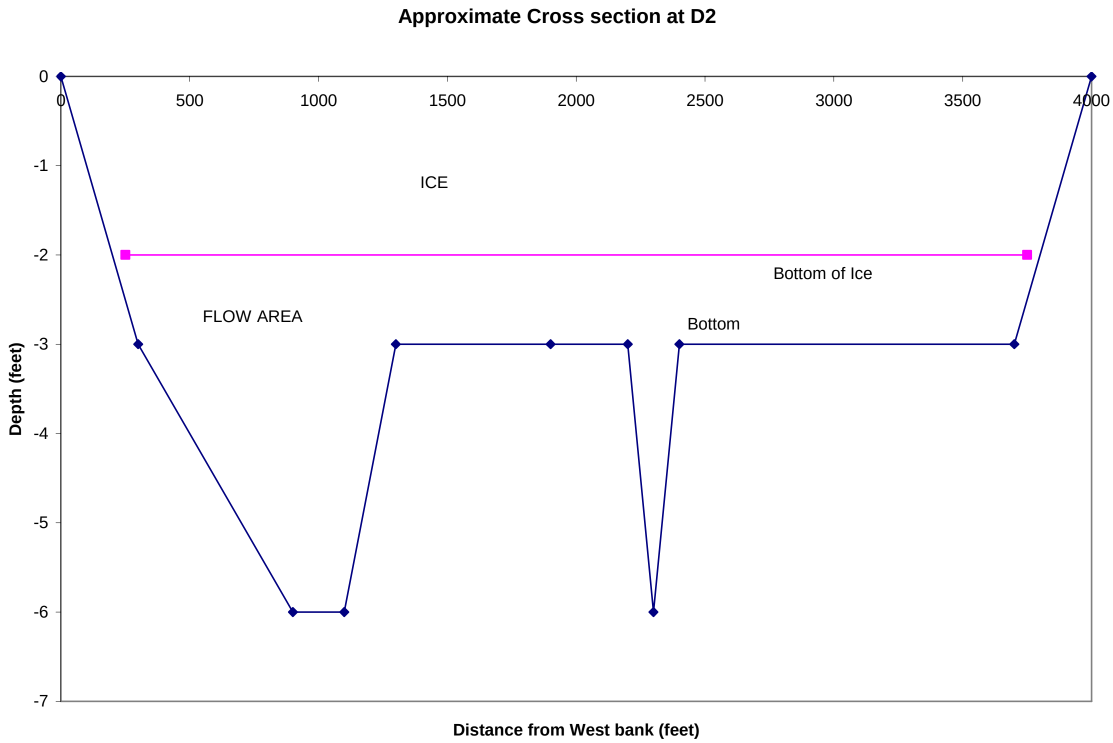
Matousek, V. 1984. Types of ice run and conditions for their formation. Proceedings IAHR Ice Symposium 1984, Hamburg, Vol. I, pp. 315-28.

RETEC Figure 2-5: Maximum velocity rate estimated for flow condition of 408 cms at Rapid Croche Dam: Little Lake Butte des Morts, dated 01/03/03.

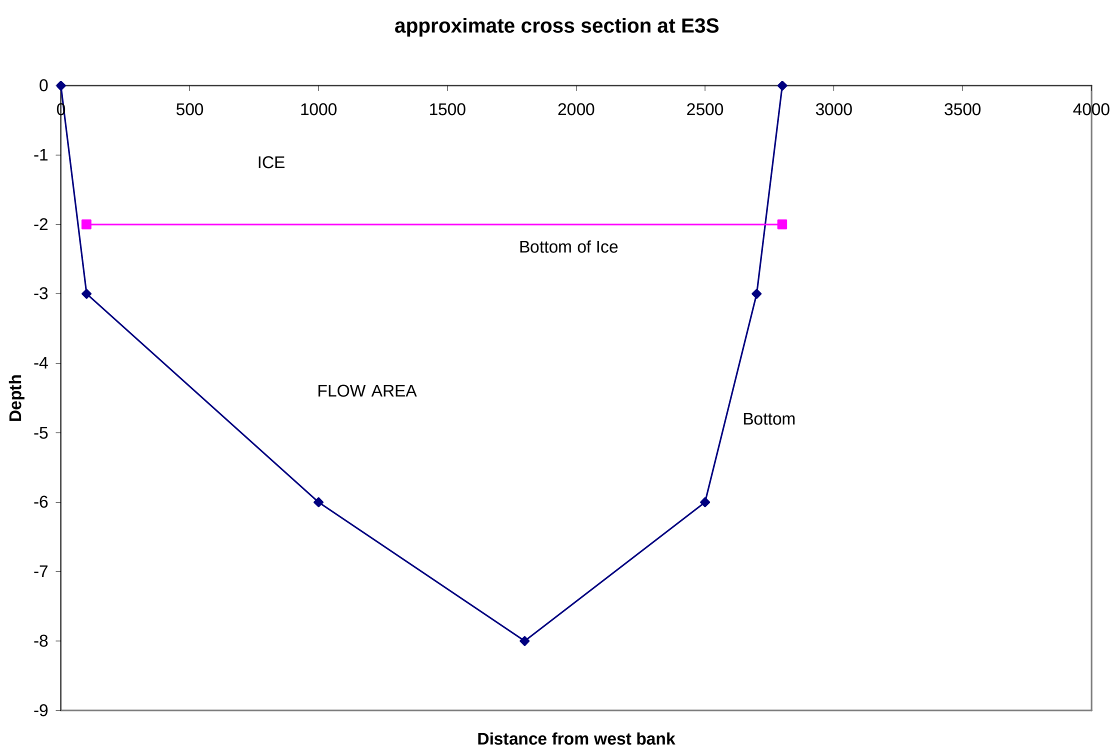
U.S. Army Corps of Engineers Detroit District. 1994. Lake Winnebago Fox-Wolf River Basin (pamphlet), 16 p.

U.S. Army Corps of Engineers, Table 3-12: Lower Fox River Stream Velocity Estimates, date unknown.

## Figure 1




## Figure 2



# Follow-up Agency Questions and Responses to November 8, 2006 Ice Scour Report

This is in response to questions on ice scour.

**Question No. 1:** Is ice jamming at the old railroad trestle and at the 441 bridge possible. Include the appropriate discussion of this in the plan.

**Response to Question No. 1:** *Ice jamming at the old railroad trestle is highly unlikely. The maximum likely velocity there for a very high winter flow of 11,100 cfs is only about 0.82 fps (See Table 3 of original report). It is generally considered that the threshold velocity at which ice pieces are swept under an ice cover and begin forming a jam is about 2 fps. Thus ice pieces may lodge against the trestle but will remain at the surface and no jam would form. At the 441 bridge the velocities are even lower and estimated at less than 0.5 fps for the same conditions. Again, large floating ice sheets may lodge against the piers but would not submerge to form a jam.*

**Question No. 2:** During cold years where thick ice can accumulate, shear velocities can more than double for areas 6.67 feet and shallower. Address this possibility.

**Response to Question No. 2:** *The observation that "shear velocities can more than double for areas 6.67 feet and shallower" was stated in the original report. It was meant to refer to "areas" where the overall cross section is of average depth of 6.67 feet and shallower. To elaborate on cases where the average depth is shallower than 6.67 feet a more detailed analysis was made of Section D2 where the average depth under open water conditions is about 3.3 feet. As part of that analysis the effect of shifting of the flow from shallower areas to deeper areas (due to higher resistance to flow of shallower areas of the cross section) is also addressed.*

*A detailed analysis of the redistribution of the flow due to creating locally shallower flow passages was not carried out in the original report since the resulting shear stresses from the analysis presented in the report were considerably less than those experienced by the bed at the 100 year open water flow discharge of about 24,000 cfs.*

*However, to address the Comment 2 above in more detail, an analysis of the redistribution of the flow for section D2 was carried out by dividing the cross section into four portions labeled Sections A, B, C and D in the Figure 1 below (adapted from Figure 1 of the original report). The results are also presented in Table I below. This cross section was selected since it well illustrates the redistribution of the flow from shallower to deeper areas and represents a cross section with extensive relatively shallow depths. In Table I the open water velocities are denoted by Vow and the ice covered velocities by Vic.*

# Table 1

## Calculations Based on a Total Discharge of 5000 cfs and 26 inch Thick Ice Cover

(submerged depth of 24 inches)

| | Section A | Section B | Section C | Section D | Total X Section |
|---|---|---|---|---|---|
| Average velocity Open water case | 0.41 fps | 0.36 fps | 0.44 fps | 0.34 fps | 0.38 fps |
| Average velocity Ice covered case | 1.1 fps | 0.78 fps | 1.23 fps | 0.66 fps | 0.96 fps |
| $V_{ic}$ / $V_{ow}$ | 2.68 | 2.17 | 2.80 | 1.94 | 2.53 |
| Ratio of shear stresses on bottom $V_{ic}$ / $V_{ow}^2/2$ | 3.59 | 2.35 | 3.92 | 1.88 | 3.2 |

From the Table, it is seen that the amplification of velocities and shear stresses are greater in the deeper parts of the flow than the shallower portions due to the flow redistribution effects.

Note also that the shear stresses on the bottom for the open water 100 year case of 24,000 cfs would be greater than the reference value of shear stress for a 5000 cfs open water flow by approximately $(24000/5000)^2$ ~= 23 based on the simple concept that shear stresses are more or less proportional to the square of the average velocity. A similar ratio of $(24000/11000)^2$ ~= 4.8 results for the very extreme winter discharge of 11,000 cfs, although historically such high winter discharges were always associated with warm weather and there would undoubtedly be a great deal of melting of the ice cover as this flow occurred. Additionally such high flows would also result in the reach changing from a lake-with-through-flow to a more river-like flow situation and result in elevation of water levels to accommodate the flow and a consequent reduction in the amplification effect calculated in Table I where no such elevation was allowed.

# Figure 1

## (adapted from Figure 1 of original report)