Phase 1 Intermediate Design Report
Hudson River PCBs Superfund Site

Attachment I – Evaluation of Potential Ice Effects on Hudson River Remediation – Hudson River – Phase 1 Areas, Near Fort Edward, NY (River Section 1)

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MEMORANDUM

ATTACHMENT I
EVALUATION OF POTENTIAL ICE EFFECTS ON HUDSON RIVER REMEDIATION – HUDSON RIVER – PHASE 1 AREAS, NEAR FORT EDWARD, NY (RIVER SECTION 1)

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BACKGROUND

As part of the effort to remediate sediments in the Hudson River in the reach just downstream of the dam at Hudson Falls, NY (approximately river mile 197) to Thompson Island Dam (approximately river mile 188.6), (Hudson River Phase 1 Remediation Areas), the potential effects of ice on caps that may be employed as part of the planned remediation measures needed to be evaluated. This report discusses the nature of the ice in the Hudson River along Phase 1 areas and associated processes that could conceivably interact with the capping of those sediments. The conclusions below are based on review of data available for the site, on a site visit, on published literature dealing with ice and sediments, and on some 35 years of personal experience examining river and lake ice behavior.

HUDSON RIVER NEAR FORT EDWARD, NY

The Hudson River site of concern is bounded by a large hydroelectric dam at the upstream end of the reach at Hudson Falls, NY (approximately river mile 197) and extending 8 miles downstream to another dam just downstream of Griffin Island (approximately at river mile 188.6). Upstream of the dam at Hudson Falls are other dams. The site of the old Fort Edward Dam (removed about 1973) is at about river mile 194.7. Prior to about the winter of 1982-83 and again in the winter of 1988-89 the flow was partially controlled in the sense that during lower mean flows (below about 6,000 cubic feet per second [cfs]) there were characteristic "weekend drops" in flows (See USGS record for gage 01327750 Hudson River at Fort Edward, NY). Since that time there is no evidence in the hydrograph that there are such intermittent storages and release associated with meeting the demands of hydropower and the hydroelectric dam operates as a "run-of-river" facility and even passes a portion of very high flows (over about 9,000 cfs) over the spillway (Conley, 2005). There is a short, shallow rapids reach downstream of the site of the old Fort Edward Dam, and then the river deepens while simultaneously splitting into two channels around Rogers Island but with most of the flow in the west channel. The west channel at Rogers Island is about 480 feet wide, with maximum depths of the order of 8 to 10 feet, while the east channel is about 200 feet wide, with about the same depth (although shallower at its upstream end). At the downstream end of Rogers Island (located at river mile 193.75), the river becomes a single channel and deepens significantly to a maximum depth of about 13 to 20 feet. Directly east of the downstream end of Rogers Island is Lock 7 of the Champlain Canal. It contributes insignificant flow to the Hudson River and is not operated during the winter. Downstream of Rogers Island and extending to river mile 192, the river varies in width gradually widening from about 400 feet to about 650 feet.

SITE VISIT

A site visit was made on 22 June 2005 and consisted of observations by boat nearly to the upstream end of the west channel at Rogers Island, up to the Fort Edward Yacht Basin on the east channel and downstream to the next dam (Thompson Island Dam) just downstream of Griffin Island at about river mile 188.6. Observations were made from the boat of the vegetation and structures along the shores with the objective of detecting any damage due to ice effects. Operating personnel at the Hudson Falls Dam were also contacted and queried about winter operations. At the time of the site visit, the discharge was about 9,000 cfs. Observations of the reach upstream of Rogers Island to the dam at Hudson Falls were made by occasional access to the top bank of the river by automobile.

CLIMATE AND HYDRAULICS

In terms of winter ice formation, the Hudson River at Fort Edward is in a climatic area where often the ice cover does not always form and persist until break up. Rather, it is cold enough to produce ice possibly as thick as about 20 inches in extremely cold years; but often the ice cover is interrupted by mid-winter thaws, and with those, occasional higher discharges. The average maximum degree-days of freezing, S_F, at Glens Falls (just west of Fort Edward) is 488 °C-days with a standard deviation of 148. The average date of the maximum accumulation of degree days of freezing is 15 March. (See Schmidlin and Dethier, 1985). While historically there have been days during which the minimum air temperature has been as low as -30 °F, these are rare. An examination of the 1961-1990 record at Glens Falls showed few cases during which the January minimum temperature was much colder than -10° F.

The hydraulics of the Hudson River at Fort Edward is also variable. The mean monthly flows during the period of record of the USGS Station 01327750 Hudson River at Fort Edward NY are shown in Table I1 (Period of record 1899-1908 and 1977-2002).

Table I1 – Average and Maximum Monthly Mean Streamflow (cfs) Hudson River at Fort Edward, NY

Month	Average Monthly Mean Streamflow (cfs)	Maximum Monthly Mean Streamflow (cfs)
November	5,092	9,326
December	5,138	10,270
January	4,918	9,766
February	4,696	7,836
March	6,307	10,950

The daily flow record for December through March was also examined for the winters from 1976-77 to 2002-03. While the daily flows were typically in the range of flows shown in Table I1, there were often short duration higher flows during the winter. The seasonal annual daily peak flow observed during the period 15 December to 15 March for each of the 27 years of recent record (winter 1976-77 to winter 2002-03) was extracted from the record and ranked. The ten highest ranked peak daily flows for this period for different years resulted in the following ranking presented in Table I2:

Table I2 – Ranking of Annual Peak Winter Flows During the Period 15 Dec to 15 March

Rank	Highest Daily Peak Flow Period 15 Dec – 15 March (cfs)	Date	Air Temperatures During, Before and After Peak Discharge		
			Average Temperature on Date (˚F)	Before	After
1	33,000	10 Jan 98	35	Warm	Gradually falling
2	26,000	15 March 77	44	Warm	Gradually falling
3	22,000	23 Feb 81	47	Very warm	Gradually falling
4	17,800	1 Jan 85	29	Very warm	Cold to -10 low 9 Jan
5	17,400	10 Jan 78	7	Very warm	17 ˚F average for 5 days
6	16,000	20 Feb 84	40	Warm	Warm
7	15,900	21 Jan 96	18.5	Warm	Gradually falling
8	15,000	25 Dec 90	22.5	Warm	Cool then warm
9	13,000	8 Mar 79	35.5	Warm	Warm
10	13,000	19 Dec 00	Unavailable at time of writing		

While a more detailed statistical analysis was not performed, it is clear that in about 1 year in 10 a daily flow of the order of 20,000 to 30,000 cfs might be expected during the winter period from 15 December to 15 March. These may be compared to an estimated return period of 2 years for a maximum peak daily flow of 23,000 cfs for the entire year and a return period of 10 years for a maximum peak daily flow of 34,500 cfs at the Fort Edward gaging station. The daily air temperatures on the date of the peak and before and after the peak occurrence were examined for the 9 highest ranked discharges and showed very clearly that these winter peaks are almost always associated with warm temperatures (daily averages above 32°F) except for the 17,400 cfs event of 10 January 1978, and the high discharges rarely persist for more than a few days.

ICE JAMMING

Since the dam at Hudson Falls and the dams upstream effectively retain ice upstream, it was not expected that there would be enough ice supply to form an ice jam composed of blocks of ice. In fact, operating personnel at the Hudson Falls dam take no special precautions when ice is arriving from upstream and simply pass the ice through the turbines (telephone conversation with Dan McCarty of the Hudson Falls power plant, 22 June 2005). They also were of the opinion that ice was not associated with short duration high flows during the winter period.

Since ice jams act to scar the trees and vegetation along the shorelines, a large number of trees were examined from the boat during the site visit along the entire reach of interest, with particular attention to those that would be prone to ice damage (exposed and near the banks). No evidence was seen of any tree scarring except possible abrasions near the waterline and these could just as well have been due to abrasion by floating debris. It was concluded that there was no evidence of ice jamming in the reach from at least the upstream end of Rogers Island on downstream to the Thompson Island Dam.

FRAZIL AND ANCHOR ICE FORMATION

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 Figure I1 (originated by Matousek, 1984; and presented with some addition and simplification by Ashton, 1988).

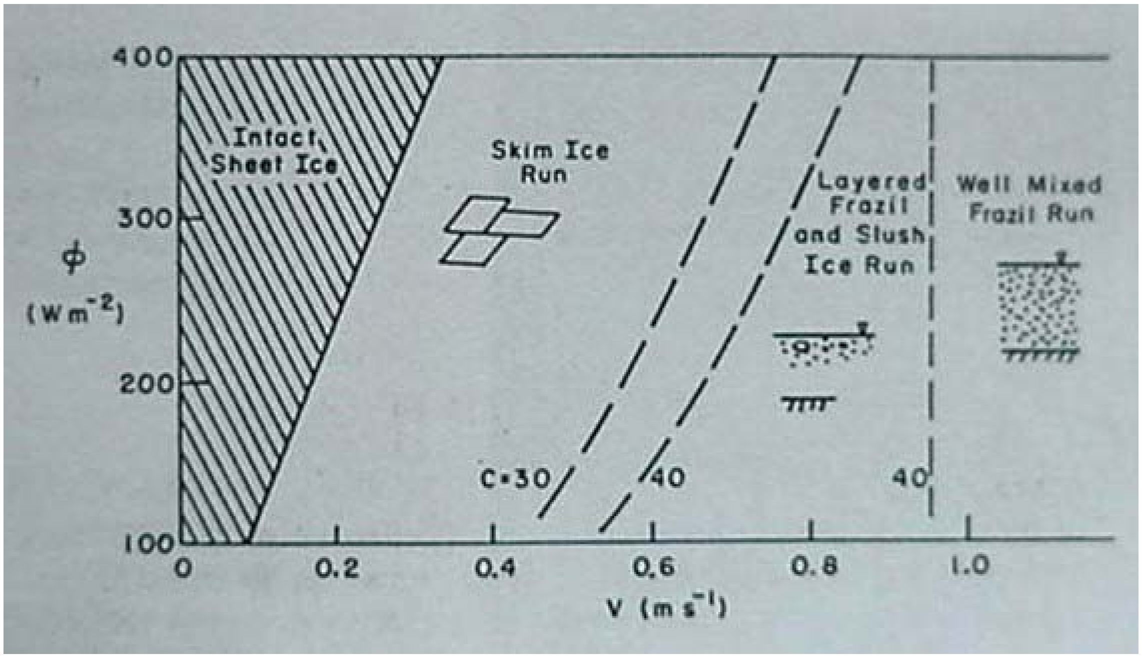

Figure I1. Ice Flow Thresholds (from Matousek, 1984)

In Figure I1 above, the ordinate Φ is the heat loss rate from the open water surface. The boundary between the regime of rapid formation of a sheet ice cover and a frazil run varies from a velocity of 0.1 meter/second (m/s) to 0.3 m/s as the heat loss rate increases from 100 W/m^2 (roughly equivalent to an air temperature of – 5 °C) to 400 W/m^2 (roughly equivalent to an air temperature of – 20 °C). The boundary between the regime of a surface skim ice run and a layered frazil and slush run at the upper surface depends on the Chezy coefficient and the mean velocity. Note that Matousek's field observations were for relatively shallow rivers (~ 0.5 meter and 1 meter depths), and there is no effect of depth explicit in Matousek's diagram. However, larger depth is not expected to be a controlling factor in these calculations. If anything, deeper rivers will exhibit a shift toward the left of the diagram (less depth of frazil entrainment). It is also emphasized that the character of the frazil behavior is that at the onset of frazil formation in an open reach of river.

From 0 to about 0.2 m/s (0.6 feet/second [ft/s]) 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 ft/s) to about 0.7 m/s (2.3 ft/s) a "skim ice run" occurs, again, with little frazil formation. From about 0.7 m/s (2.3 ft/s) to about 0.95 m/s (3.1 ft/s) the frazil forms a "layered frazil and slush run" with the ice confined to the near surface of the water. Finally, as the velocity increases to about 0.95 m/s (or 3.1 ft/s at a Chezy coefficient of about 40), the frazil becomes well mixed over the depth. Above about 0.95 m/s (3.1 ft/s) 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 between 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 ft/s 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. If the velocity is below about 2 ft/s, the ice coverage will progress upstream by accumulation of the arriving ice. If the velocity is above about 2 ft/s, it will be difficult for the ice to progress upstream and the arriving ice will be 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 ft/s 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 the ice particles and, as a consequence, the critical value for erosion is generally taken to be slightly higher and about 2.3 ft/s (0.7 m/s). While these threshold numbers are not exact, they enable characterization of the expected formation of the ice cover.

When the entire flow is supercooled, and the velocities are high enough, frazil particles may come in contact with the bed and adhere to the bed material. In this form the frazil is termed "anchor ice." Further thickening of the anchor ice may occur over time, and typically large masses rise to the surface with only slight warming of the flow, usually on a daily basis.

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 ft/s or greater. There will be a possibility of anchor ice formation in regions where the flow velocity is greater than about 3 ft/s.

OCCURRENCE OF FRAZIL, ANCHOR ICE, AND SURFACE ICE COVER AT SITE

With the above guidance, it is possible to describe the nature of ice formation at the site using charts of the velocity associated with different discharges. Charts were available that mapped the mean velocities associated with a discharge of 23,000 cfs (corresponding to the 2-year return period of annual peak flows) into surface areas with velocities 0 to 1 ft/s, 1 to 2 ft/s, 2 to 3 ft/s, 3 to 4 ft/s, and 4 to 5 ft/s. While not exactly precise, these same areas correspond to, respectively 0 to 0.5 ft/s, 0.5 to 1 ft/s, 1 to 1.5 ft/s, 1.5 to 2 ft/s, and 2 to 2.5 ft/s for a flow of 11,500 cfs, and half of those, in turn, for a flow of 5,750 ft/s. We will refer to these values as the "high winter flow" case, the "medium winter flow" case and the "typical winter flow" case.

Using the guidance developed above we can now describe the probable nature of the formation of ice cover for each of the three cases by examining the charts of the 2-year return period mapping of velocities. The analysis below assumes that air temperatures are quite cold during the cases. Particularly for the "high flow case" this was only true for the flow ranked 5 of 17,400 cfs on 10 January 1978.

“High Flow” Case

In the “high flow case” (23,000 cfs), there will likely be extensive open water extending downstream from the Hudson Falls dam to just upstream of Rogers Island. Along the east channel by Rogers Island flow velocities are typically 2-3 ft/s in mid-channel and we would expect border ice to form and some open water in the mid-channel. We would not expect anchor ice to form here. In the west channel, velocities higher than 3 ft/s extend along most of the reach although the region of occurrence tapers from nearly full width at the upstream end to a narrow band at the lower end of the west channel. Here we expect a persistent open mid-channel area and the possibility of limited anchor ice formation dominantly along the upper half of the reach. Just downstream of Rogers Island the velocities again rise to the 3 to 4 ft/s range and we would expect an open area in the ice cover but extending only a short distance (0.4 mile or so) to where the velocities decrease to 2 to 3 ft/s. Here there will be some border ice formation but it is expected the central portions will remain open over most of the reach. However, the velocities are less than 3 ft/s so we don’t expect any anchor ice formation. It is also noted that these high discharge cases are generally associated with mid-winter thaws and the water temperature (and air temperatures) may be such as to preclude significant ice formation. It is also noted that, in general, these high discharge cases are of short duration, of the order of a few days and generally less.

“Medium Flow” Case

This case (11,500 cfs) corresponds to periods during the winter when the flow is unusually high relative to the long-term average but somewhat less than the extreme peak flows. In this case, there will again be some open water extending downstream from the Hudson Falls dam to just upstream of Rogers Island. Along the east channel by Rogers Island flow velocities are typically 1 to 1.5 ft/s in mid-channel and we would expect border ice to form and rapid formation of a more-or-less complete ice cover with the possibility of some open water in the mid-channel during initial formation. There will be no frazil formation once the ice cover is established since the ice cover blocks heat loss from the flow. In the west channel, velocities higher than 1.5 ft/s extend along most of the reach although tapering from nearly full width at the upstream end to a narrow band at the lower end of the west channel. Here we again expect rapid formation of a complete ice cover perhaps with a persistent narrow open mid-channel area. Just downstream of Rogers Island the velocities again rise to the 1.5 to 2 ft/s range and we would expect slower formation of a complete ice cover but only extending a short distance (0.4 mile or so) to where the velocities decrease to 1 to 1.5 ft/s. We thus expect frazil formation to only occur upstream of Rogers Island, except for a very short initial period of cold temperatures while the surface frazil accumulates to form the first cover.

“Typical Flow” Case

This case (5,750 cfs) corresponds to periods during the winter when the flow is near the long term average. In this case, there will again be some open water extending downstream from the Hudson Falls dam to just upstream of Rogers Island. Along the east channel by Rogers Island flow velocities are typically 0.5 to 0.75 ft/s in mid-channel and we would expect rapid formation of a more-or-less complete ice cover initially composed of skim ice. There will be no frazil formation once the ice cover is established since the ice cover blocks heat loss from the flow. In the west channel maximum velocities are in the 1 ft/s range. Here we again expect rapid formation of a complete ice cover. Just downstream of Rogers Island the velocities again rise to the 0.75 to 1 ft/s range and we would expect slower formation of a complete ice cover but only extending a short distance (0.4 mile or so) to where the velocities decrease to 0.5 to 0.75 ft/s. We thus again expect frazil formation to only occur upstream of Rogers Island, except for a very short initial period of cold temperatures while the surface frazil accumulates to form the first cover.

Summary of cases

In all cases, it is expected that the river surface will remain partially open from the Hudson Falls dam to just upstream of Rogers Island. This is the region of significant frazil formation and almost assuredly some anchor ice formation, although the region of possible anchor ice production is not currently targeted for remediation. Downstream there will be very little, if any, anchor ice formation and only very limited frazil formation at the beginning of the period of ice formation while the ice cover is being established. An ice cover effectively prevents frazil formation by blocking the heat transfer from the water to the air above the ice cover. Thus the dominant production of frazil that is carried downstream as far as Rogers Island occurs in the rapids region extending from the site of the old Fort Edward dam to just upstream of Rogers Island.

Production of frazil ice in the rapids reach

The production of frazil in the rapids reach 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 ρ is the density of solid ice, λ 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 ρ is accurately known at 916 kilograms per cubic meter, and λ is accurately known at 334,000 Joules per kilogram. H_{wa} 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. H_{wa} 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 Glens Falls the average cumulative degree-days of freezing is 488 °C – days with a standard deviation of 148. However, the manner in which these degree-days of freezing are accumulated include the period at the beginning of the season before the water temperature has cooled to the freezing point. For this reason, it is considered appropriate to use the average value to provide an estimate of frazil production. Inserting these values into the above equation results in a potential thickness of solid ice production per unit area of 2.74 meters (about 9 feet) per unit area of open water surface exposed throughout the winter. The rapids reach is about 1000 feet long and 600 feet wide. Thus the resulting potential frazil production is a volume of 200,000 cubic yards of solid ice. When deposited the frazil has porosity of the order of 0.5 so the total bulk volume of frazil produced is estimated to be about 400,000 cubic yards.

Deposition of frazil downstream of the rapids reach

The frazil produced in the rapids reach will be carried downstream and, just as sediment deposits out in slower velocity reaches, so does the frazil deposit (upwards) beneath the downstream ice cover. It does this rather quickly and accumulates in thickness until the resulting diminished flow area beneath the deposit has increased the velocity to about 2 ft/s, at which point it is carried further downstream until the velocity again decreases. The process may be visualized as an extending (upside down) delta. The upstream sections will accumulate first and the deposit will gradually extend itself downstream. It is possible to do a time – stepping simulation of this deposition process, but for present purposes we simply calculated the flow volume beginning at river mile 194.4 and extending to river mile 193.5. The cumulative flow volume over this reach was found to be approximately 1,100,000 cubic yards. Thus the frazil production of 400,000 cubic yards (bulk volume) can be contained in a deposit occupying only 36 % of the flow volume. We thus expect the majority of the thick frazil deposits to be upstream of river mile 193.5 (just downstream of Rogers Island).

The same limiting velocity beneath which frazil deposits out from the flow also means that bottom sediments whose critical erosion velocity is above that, will not be scoured by the flow. It is prudent to use the critical velocity for those considerations as the somewhat higher value associated with erosion of frazil (2.3 ft/s) since there clearly could be cases where increasing flows will take some time to erode the frazil deposit.

ANCHOR ICE FORMATION

Anchor ice is frazil ice that has been carried to the bottom of a stream or river and attaches to the bottom material (and, after initial covering, to itself). Once attached, the crystals may subsequently grow quite a bit larger than those seen in the bulk flow. It is most readily observed in shallow mountain streams and may build up to considerable thicknesses, but it also occurs in deep rivers and in lakes where the mixing arises from wind and wave action.

As pointed out above, the only location where anchor ice is expected to form is in the high velocity reach in the rapids upstream of Rogers Island. This area is not currently targeted for remediation.

Occasionally anchor ice has been known to entrain the sediment to which it is attached into the flow when the ice releases from the bottom. The author has seen small-fist-sized rocks in floating ice covers that undoubtedly were the result of such a process but when seen, these have been widely dispersed and represent only insignificant transport. The magnitude of such sediment transport may be appreciated by a simple hydrostatic force balance. The buoyant upward force of the ice mass is $(\rho_w - \rho_i)(1 - p)\, h_i$ where ρ_w is the density of water, ρ_i is the density of solid ice, p is the porosity and h_i is the thickness of the anchor ice accumulation. The resisting downward force is $(\rho_w - \rho_s)(1 - p)\, h_s$ where ρ_s is the density of the sediments and h_s is the thickness of sediment which is in equilibrium with the attached ice mass. Assuming similar porosities and a specific gravity of the sediment particles of 2.67 (silica) the ratio of h_i to h_s is (2.67-1.0)/(1.0 – 0.916) = 19.9. In short, the thickness of sediment possibly entrained by an anchor ice deposit is 1/20 the thickness of the deposit. This assumes, of course, that the sediment has enough cohesion to support the sediment beneath the ice-sediment interface. This author doubts that anchor ice deposits ever exceed about a foot or so in thickness at the site, and in any case, are confined to the rapids area, which is not subject to remediation.

FREEZING TO BOTTOM IN SHALLOW WATER

In shallow water regions of the site, we are concerned with those regions where the water is shallower than the maximum thickness of ice that can form over the winter. In such areas, the freezing process may continue into the bed beneath, and upon rise of the water level with increasing discharge, the material (i.e., sediment or capping material) frozen to the bottom of the ice cover may be lifted and transported with the ice cover. This would apply, of course, to regions where the ice cover is sufficiently buoyant to overcome the weight of the sediment frozen to the bottom. After breakup of rivers, ice pieces with a thin layer of sediment on the bottom are often seen. It is believed that this is a very minor sediment transport mechanism and probably offset by sedimentation in such shallow areas during the remainder of the year.

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 488 °C days (= 878 °F – days), this results in a thickness of 14.8 to 20.7 inches. If the average plus one standard deviation of degree days of freezing is used, this results in maximum ice thicknesses of 16.9 to 23.7 inches. Thus, the mechanism described above is applicable to regions where the water depth is 2 feet or less under average or typical discharges during the winter. Following the same buoyancy calculation as used in estimating the sediment that could be lifted by anchor ice (see above) only now the ice has a zero porosity results in the maximum thickness that could be lifted of about 1/10 the ice thickness. While such a thickness seems theoretically possible and would result in a capping material of about 2-inch size, the author doubts that it need be that large to protect the bed. Additionally, most of the regions of the river where the ice can attain such maximum thicknesses are in protected areas and the ice is more likely to melt in place. This seems to be the case in this reach of the Hudson River. Examination of the topography of the bottom from river mile 194.5 to river mile 189.5 showed only one significant area of such shallow water, namely the slough west of Griffin Island. There the velocity is nearly zero and the ice will melt in place.

SUMMARY OF FINDINGS

No evidence was found of jamming in the reach extending from river mile 194.5 (just upstream of Rogers Island) to river mile 188.6 (Thompson Island Dam). The general character of the ice formation in this reach of river is one of rapid formation of a more-or-less complete ice cover with the onset of cold temperatures. There very likely will be some open water areas upstream of Rogers Island, particularly in a rapids reach just downstream of the dam at Hudson Falls and near the site of the old Fort Edward dam. Here it is possible for anchor ice to form during very cold periods but is not in areas planned for remediation. There will also be some sustained frazil production possible in these open areas during cold periods of the winter. An estimate of the frazil production through a winter season was made and the volume produced can be accommodated by a deposit beneath the ice cover that would likely not extend downstream further than the lower end of Rogers Island at river mile 193.75. These frazil deposits are easily eroded and should not result in scour of sediments that are resistant to velocities of about 2.3 ft/s. There is a theoretical possibility of the ice cover freezing to the bed in shallow protected areas less than about 20 to 24 inches deep, and with rising flows moving the sediment frozen to the bottom. However, this is considered a minor sediment transport mechanism.

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