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Hydraulics and Sediment Transport of a Proposed Ice Control Structure

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The Leesville Dam in East Haddam, Connecticut was lowered by 10 feet in the late 1950s. As a result, ice jams that had previously formed behind the dam, began to occur further downstream, causing damage to private property. The US Army Corps of Engineers have design a series of piers to be constructed upstream of the lowered dam to help promote the formation of ice jams in that location. The focus of this paper is on the hydraulic analysis and sediment transport mechanisms that are predicted to occur in the vicinity and upstream of the piers under open water and ice covered conditions. The Meyer-Peter Muller bed load equation is used for the analysis with modifications to the Manning roughness coefficient to account for the roughness of the ice cover.

I. Introduction

This report was prepared for the US Army Corps of Engineers, Cold Regions Research and Engineering Laboratory (CRREL), Spring 2001. All information regarding the proposed ice control structure by CRREL contained in this report was current at the time of submission; however, specifications and quantities are subject to change pending final design by CRREL.

The purpose of this report is to present the results of the hydraulic and sediment transport analysis performed on the Salmon River in south, central Connecticut. The project site is focused on the section of the river from the confluence with the Connecticut River upstream approximately 7.5 miles to the East Hampton gaging station near Route 16. This study was performed in conjunction with the conceptual design for an ice control structure being conducted by the US Army Corps of Engineers, Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire.

Involved in this study are the hydrology and the hydraulics of the river, which apply to the entire project site. Additionally, the geomorphology, bed material characteristics and sediment transport capabilities are investigated with emphasis on the reach from the Highway 151 Bridge to the steep section of the river upstream from the proposed sedimentation basin. These different facets are analyzed for four different scenarios:

1. Existing conditions
2. With an ice control structure (ICS)
3. With an ice control structure and sedimentation basin (SB)
4. With a sedimentation basin only (no ice control structure).

Results of this study were used to help evaluate the effects of the different scenarios on the sediment transport rates and hydraulics of the river.

II. Background

The Leesville Dam, located at river mile 4.0, has been reported in existence in various forms since 1763 (USACE, 1995). In 1979, construction began to lower the concrete dam by ten feet and create a fish ladder to facilitate fish passage above the dam. The work was complete by 1980. With the dam 10 feet lower, the flood storage capacity was significantly decreased and therefore there was less flood control of both open water and ice flows.

The frequency and magnitude of ice jam occurrences below the dam is reported by local residents to have increased after the dam was lowered. Along with other residents, Mr. Gregory Daigle, has experienced flooding of water and ice on his property, located on the left bank of the Salmon River downstream of the Leesville Dam and upstream of the Highway 151 bridge. Since 1980, he has twice been required to evacuate his residence due to hazards associated with ice jams, the toe of which formed downstream of his property. The lowering of the dam and subsequent loss of flood control may have led to the increase in frequency and magnitude of ice jam formations below the Leesville Dam.

In response to the damaging ice jam events and concerns of the affected residents, the State of Connecticut, Department of Environmental Protection, CT DEP, began investigating ways to alleviate the problems caused by the ice jam formations. As part of this investigation, CRREL was contracted to study the existing conditions and design an ice control structure (ICS) to retain ice as it flows downstream above the Leesville Dam. The ICS is essentially a series of concrete piers, with approximate dimensions of 2 feet wide, 8 feet long and 13 feet high with subsurface footers, constructed across the river channel every 12 feet approximately 200 feet upstream of the Leesville Dam. The ICS is designed to form a barrier across the river and promote ice flows to concentrate and jam on the upstream side of the ICS, rather then progress further downstream as with current conditions.

In addition to the construction of an ICS, the CT DEP is considering constructing a sedimentation basin just upstream of the ICS. A sedimentation basin in this same location was constructed about the same time as the dam was lowered. However, the previous sedimentation basin was filled by the end of 1982, when large amounts of sediments were transported and deposited in the basin.

Both the construction of the ice control structure and the sedimentation basin are evaluated in this project.

III. Purpose of Study

There were two major purposes for performing this study; the first was to perform hydraulic modeling and the second was to perform sediment transport calculations based on the results of the hydraulic model. Both the open water flows as well as the ice covered flows and particularly ice jam events were modeled for the following scenarios:

1. Existing Conditions
2. With Ice Control Structure
3. With Ice Control Structure and Sedimentation Basin
4. With Sedimentation Basin

Hydraulic Engineering Center - River Analysis System (HEC-RAS) v2.2, a Windows based, one-dimensional, steady flow model was used to predict the water surface elevations as well as other hydraulic parameters.

The sediment transport analyses incorporated results from the HEC-RAS study to estimate the amount of sediment that will be transported by the river under different flow conditions and different construction scenarios. The sediment transport calculations were applied to all four scenarios mentioned above and the results are compared for purposes of analysis of the different systems. This process is discussed in detail in Section VII.

IV. Hydrology

It was necessary to evaluate the hydrology of the Salmon River to perform the hydraulic and sediment transport calculations. An established method for determining the values of the return period was created by the Hydrology Committee of the US Water Resources Council and is published in Bulletin 17B “Guidelines for Determining Flood Flow Frequency”. The DOS program FFAN uses the principals of Bulletin 17B to calculate the discharge values for a range of return periods using the Log Pearson Type III Distribution. The annual peak discharge values for the Salmon River were entered into the FFAN program for the years from 1929 – 1999. The results of the FFAN computations are contained in Table 1.

Table 1. Return Period Discharges for the Salmon River below the East Hampton Gaging Station

Return Period (yrs)	Discharge at Confluence with CT River (cfs)
1.1	815
1.25	1,680
2	2,710
5	4,730
10	6,570
50	12,600
100	18,100
500	28,500

The annual peak discharge values were obtained from the Salmon River near East Hampton Gaging Station, #01193500. This is a National Water Conditions station that is reported through the USGS Connecticut Water Resources web site. The location of the gage is fortunate for this study as the gage provides good records of discharge at the upstream end of this project. The gage is located on the left bank of the river at the Route 16 Bridge, 450 feet downstream from the New London-Middlesex County Line. The gage has been in continuous operation since July 1928. A list of the annual peaks values from 1929 to 1999 is contained in Appendix A. The minimum annual peak of 940 cfs occurred on March 26, 1930, and the maximum annual peak of 18,500 cfs occurred on June 6, 1982.

A previous hydraulic analysis of the Salmon River was performed by FEMA (Federal Emergency Management Agency) in 1979. The hydrologic analysis for this earlier study was performed using Bulletin 17B procedures and included annual peaks from 1928 to 1978. Twenty annual peaks have been recorded since the previous study, including the maximum peak of 18,500 cfs. This additional information has altered the distribution of the discharges and raised the amount of flow expected for the various return periods. The values used by FEMA are listed in Table 2.

As part of the previous study, FEMA also estimated flow from the tributaries and listed values of discharge in the Salmon River at three different locations: upstream of Pine Brook, upstream from Moodus River, and at the confluence with the Connecticut River. The method used by FEMA to determine the tributary contributions was unavailable for this current study. In order to estimate the values at each of these three locations for the current study, the percentage of additional flow at each of the downstream locations used in the FEMA study was determined and this percent of increase was applied to the initial values estimated by FFAN. Table 3 shows the percentages and the values of discharge for the major return periods used in this study.

Table 2. Return Period Discharges as Determined by FEMA

Return Period (yrs)	Discharge at Confluence with CT River (cfs)
10	7,450
50	13,100
100	16,300
500	24,600

Table 3. FEMA and FFAN Discharge Increases

	Discharges and % Increase from FEMA Study								
	10-year		50-year		100-year		500-year		Average
	Q (cfs)	% Increase	Q (cfs)	% Increase	Q (cfs)	% Increase	Q (cfs)	% Increase	Increase
At Confluence with CT River	7,450	10.2%	13,100	9.9%	16,300	10.4%	24,600	10.2%	10.2%
Upstream from Moodus River	6,690	9.4%	11,800	9.3%	14,600	8.9%	22,100	9.5%	9.3%
Upstream from Pine Brook	6,060	---	10,700	---	13,300	---	20,000	---	---
	FFAN Discharge (cfs) Results Adjusted According to FEMA % Increases								
	1 yr	1.25 yr	2 yr	5 yr	10 yr	50 yr	100 yr	500 yr	
At Confluence with CT River	1,000	2,062	3,326	5,805	8,063	15,464	22,214	34,978	
Upstream from Moodus River	898	1,852	2,988	5,241	7,243	13,890	19,953	31,418	
Upstream from Pine Brook	815	1,680	2,710	4,730	6,570	12,600	18,100	28,500	

The discharge values listed in Table 1 were used as flow data in the HEC-RAS hydraulic model. Additionally, a series of discharges ranging from 490 cfs to 6,000 cfs are also used in the hydraulic analysis. These lower values correspond to the discharge values observed during the ice jam events that were recorded between 1950 and 2000.

The thickness of the ice and the discharge were both recorded for every major ice jam event that occurred on the Salmon River from 1950 to 2000. This information was supplied by CRREL. The values from the largest since jam event of each year are used in this study. There were several years that experienced the same discharge value, in all there are twenty-six unique discharge values that occurred in the fifty years of ice jam observations. This information is used in HEC-RAS to help model the ice jam events.

A total of 34 different discharge values, twenty-six from ice jam events and eight from the return period analysis are modeled for this study using the HEC-RAS program. The next section describes how the hydraulic analyses were performed for this study.

V. Hydraulics

Hydraulic engineering is the application of fluid mechanics in the development of structures, projects and systems involving water resources. This project involves open water flow in the Salmon River in a reach with two major existing structures; the Highway 151 Bridge and the

Leesville Dam; and two proposed structures; the ice control structure and the sedimentation basin. A hydraulic evaluation of the river with the different combinations of the proposed structures was performed using HEC-RAS.

HEC-RAS is a Windows-based, one-dimensional, steady flow model that allows the user to enter various geometry and flow files to model different scenarios.

5.1 HEC-RAS Project Set-up Description

HEC-RAS is into project files, each containing one or more plans (plan files). A plan file in created by selecting a flow file and a geometry file and running a simulation based on information from both files. In one project, the number of flow, geometry and plan data sets is limited to 99 files each.

Each flow file can contain up to 100 different flow values or profiles. However, each geometry file contains only one set of geometry data detailing the configuration of the river system being modeled. Because of this, several different levels of flow or profiles can be analyzed for one geometry set in one plan. The reverse computation, however, is not a modeling option; several geometry scenarios cannot be modeled in one plan for one flow profile. Therefore, each unique set of geometry information requires a unique plan.

For this analysis, eight different projects were created in HEC-RAS. For each flow condition, open flow and ice covered flow, the four different scenarios listed in Section III were each analyzed in a different HEC-RAS project. The information contained in each project is discussed in detail in the following sections.

5.2 HEC-RAS Geometry Files

The geometry files in HEC-RAS basically consist of cross sectional data, reach lengths, and energy loss coefficients such as friction and contraction and expansion losses. Information regarding hydraulic structures such as bridges and weirs is also entered in the geometry files.

In cases of ice cover, an additional section of information is required within the geometry files. The Ice Cover Table requires data such as the ice thickness, the value of Manning’s *n* for the ice, the friction angle, porosity and whether or not a jam exists at each cross section where ice cover is present.

5.2.1 Previous HEC-2 Files

The base line data for the geometry files was taken from the original hydraulic model performed by FEMA in 1979. HEC-2, the original, DOS-based, one-dimensional steady flow model (the predecessor to HEC-RAS) was used by FEMA to conduct the previous study.

Information contained in the GR cards was used to establish the geometry of each cross section on the Salmon River. The geometric data was supplemented with the information contained in the X1, X2, etc cards to complete the data required for the geometry files in HEC-RAS (such as bank locations, reach lengths, and Manning’s *n* values).

5.2.2 Existing Conditions (lowered dam)

The existing conditions vary from the previous FEMA study mainly at the Leesville Dam. The geometric information for the dam, which is modeled as a weir in HEC-RAS, was altered for the existing conditions geometry files to reflect the lowering of the dam by 10 feet. The dam configuration information was obtained from CT DEP construction drawings.

Six additional cross sections, surveyed by CRREL in July 2000, were also used in this geometry set. The cross sections were surveyed to verify the information used in the FEMA study and to provide more detailed information in the vicinity of the Leesville Dam and proposed ice control structure.

5.2.3 With Ice Control Structure

The geometry files for the ice control structure included additional cross sections at the location of the piers. The piers are treated as blocked obstructions in the flow area. For this reason, the upstream and downstream ends of the piers were defined with separate cross sections.

5.2.4 With Ice Control Structure and Sedimentation Basin

For the scenario of the construction of both the ice control structure and a sedimentation basin, additional cross sections were incorporated into the geometry files upstream of the ice control structure. The additional cross section geometry was based on construction drawing for the previous sedimentation basin constructed in 1979 – 1980.

5.2.5 With Sedimentation Basin (no ICS)

The sedimentation basin alone is modeled by removing the blocked obstructions in the cross sections that define the ice control structure. This left essentially the existing conditions with cross sections defining the sedimentation basin.

5.3 HEC-RAS Flow Files

The second major component in a HEC-RAS project file is the flow information. Different flow schemes can be created and stored as separate flow files within each project. This was done for both the open water and ice covered flow conditions for the Salmon River hydraulic study.

One aspect of this project that is unique to coastal rivers is that the lower half of the study site (below the Leesville Dam) is influenced by the tides of Long Island Sound. At high tide the water surface elevation at the confluence of the Connecticut River averages 3.8 feet above sea level. *(Because this project is located near sea level and some bed elevations are actually below sea level, all elevations in the HEC-RAS projects have been increased by 100 feet. This has been done to avoid any computational problems with negative values.)* To be conservative, the elevation of 103.8 feet was used as the downstream known starting water surface elevation for all flow profiles used in this study.

5.3.1 HEC-RAS Flow Files for Open Water

HEC-RAS allows the user to enter up to 100 different flow profiles in one flow file. Several variables can be assigned for each profile; the flow at various locations along the river reach, the reach boundary conditions, the profile names, etc. For the open water condition (no ice cover), there were 34 different discharge values modeled for this study. The determination of these values is discussed in Section IV. All 34 values are contained in one flow file.

5.3.2 HEC-RAS Ice Flow Files

The flow files for the ice flow conditions were created differently than the file created for the open water condition. Because each ice cover requires a unique geometry file, each plan file therefore requires a flow file containing a single profile to correspond to the geometry. There was no data collected for ice jams in 1956, 1971 and 1973. In total, there are twenty-eight individual flow files contained in each project file for the ice cover conditions that represent the range of the discharges recorded during ice jams from 1950 to 2000.

5.4 HEC-RAS Calibration

Normally, a field data collection set consisting of a discharge measurement and cross sectional surveys, with the water surface elevations clearly determined, is used to calibrate a HEC-RAS model. From the collected data, the geometry file for existing conditions is created, as is a flow file corresponding to the measured discharge. The water surface elevations generated by the model are then compared to the actual water surface elevations measured in the field. Adjustments are made to the Manning's *n* values to calibrate the model to best represent actual conditions. Unfortunately, such a data set was not available for the calibration of this model. The alternative methods that were pursued are discussed below.

5.4.1 Open Water Flows

For the open water flows, the only information that is available for comparison and calibration is the set of results from the 1979 hydraulic study performed by FEMA. The dam had not been lowered at the time of this study and therefore, the base line geometry data created from the HEC-2 files is used to calibrate the model.

Flood profiles were created by FEMA showing water surface elevations versus stream distance in miles above the confluence with the Connecticut River for the 10, 50, 100 and 500-year storm. Cross sections F and G from the FEMA flood profiles correspond to the HEC-RAS cross sections 4.429 and 4.923. The water surface elevation at these locations originally determined in this study did not match those modeled by FEMA. Adjustments were made to the configuration of the dam and to the Manning's n values for the bed and overbanks until the water surface elevations of the two studies were close in value.

Since there is no data for the existing conditions (after the dam was lowered) available to calibrate the existing conditions model, the Manning's n values determined for the 1979 conditions were applied to the existing conditions geometry information.

5.4.2 Ice Jam Conditions

Calibration of the ice jams was performed in a similar manner to that of the open flow calibration. During two separate ice jam events, one in 1982 and a second in 1994, the elevation of the top of the water and ice was observed by Mr. Gregory Daigle. Mr. Daigle reported that for both ice jam events, the ice reached the level of his garage floor later determined to be 13 feet MSL or 113 feet for this study.

During the 1982 ice jam, the toe of the jam was reported to be located at the Highway 151 Bridge. This is approximately at river mile 3.6 and cross section 3.679. The pre-breakup ice thickness was 11 inches and the discharge was 2,000 cfs. To calibrate the model, first the necessary information was entered into the Ice Cover Table in the geometry file. Ice cover information includes initial estimates of the Manning's *n* value for the ice, the maximum velocity allowed under the toe of the jam, and the upstream and downstream locations of the jam.

Executing HEC-RAS simulated these conditions and the resulting water surface elevation at cross section 3.790 was compared to the observed value of 113 feet. The first comparison made revealed that the modeled water surface elevation was significantly lower than the observed value. To calibrate the model to more closely represent actual conditions, the values of Manning's *n* for the ice were increased, with higher values near the toe of the jam. Additionally, the maximum velocity allowed below the toe of the jam was also increased. These two factors were adjusted until the model closely matched the observed elevation.

The 1994 jam had a pre-jam ice thickness of 12 inches, a discharge of 2,000 cfs and the toe formed approximately ½ mile downstream from the Highway 151 Bridge. For this event, like the one observed in 1982, the ice again reached the elevation of Mr. Daigle's garage floor, elevation 113 feet. The same process used to calibrate the 1982 ice jam was followed in calibrating the 1994 ice jam event. Again, Manning's *n* values for the ice were increased as well as the maximum velocity under the toe of the jam.

While it would be necessary to have a field observed water surface elevation for each ice jam event to properly calibrate each geometry file, this information was not available. Instead, the calibration values used for the 1982 and 1994 ice jams are used as a basis for all other ice jam models. Generally, the maximum velocity under the toe of the jam is designated between 10 and 15 feet per second, and the Manning's *n* values near the toe of the jam are between 0.08 and 0.15. It should be noted that the HEC-RAS program estimates the value of Manning's *n* for the ice if the user does not set this value as "fixed". HEC-RAS uses empirical data determined by Nezhikovskiy to estimate the *n* values. Therefore, for most cross sections upstream or downstream of the toe of the jam, the Manning's *n* value is entered in the Ice Cover Table, however, this is only an estimate that HEC-RAS uses to determine the most appropriate *n* value.

Once the calibration phase was complete, the model was executed for all four geometric scenarios for both open water and ice covered flows.

5.5 HEC-RAS Model for Open Water Conditions

With the geometry and flow files created, the plans were assigned the appropriate files and the model simulations were executed. All of the "runs" or model simulations for this project were modeled with sub-critical flow.

5.6 HEC-RAS Operation for Ice Jam Model

The simulation of the ice jams is not as simple as the simulation of open water. To start, the entire river from the confluence to the East Hampton stream gage was modeled as having an ice cover of the thickness measured for each individual jam. Each ice jam event required a separate geometry file with information regarding the jam entered in the Ice Cover Table. This also meant that each plan created for each geometry file required a flow file containing only the discharge associated with the individual ice jam event.

5.6.1 Existing conditions

For the existing conditions, two jams are modeled. The lower jam has a toe at the Highway 151 Bridge and the upper jam is toed at the upstream side of the Leesville Dam. At the time of this study, HEC-RAS did not have the capability to model the flow of ice moving over a weir. Therefore, what may actually be one long jam starting at the bridge, was modeled as two separate jams. However, due to the way the computations were performed, this did not limit the volume of ice that HEC-RAS will calculate in the lower jam.

The upstream ends of the jams are required to be designated in the Ice Cover Table. For existing conditions, the upstream end of the lower jam was designated as the cross section just downstream of the dam. The most upstream cross section in the entire geometry set was designated as the upstream end of the upper jam.

5.6.2 With Ice Control Structure

In theory, the ice control structure will cause all ice flows to stop at the piers. This being the case, the volume of ice available to form a jam downstream is then limited to only the volume of ice covering the river below the dam prior to the ice jam event. This volume was determined by multiplying the top width of each cross section by the thickness of the ice. The average area between consecutive cross sectionals is then determined and multiplied by the length between the two cross sections. This computation was performed for all cross sections between the upstream end of the Highway 151 Bridge and the cross section just downstream of the dam. The volumes between each set of cross sections were summed to determine the total volume available for the downstream jam; this is the “known” volume.

In HEC-RAS, however, there currently is no simple way to simulate a limited volume of ice. In order to do this, the user must artificially limit the volume by changing the location of the upstream end of the jam as well as changing the thickness of the ice (near the upstream end of the jam), and if necessary, altering some of the Manning’s *n* values of the ice. After each change to the Ice Cover Table, the simulation of the revised plan was executed and the total ice volume in the jam was evaluated (this value is listed in the Ice Cover Output Table). If the volume modeled was not close to the original volume calculated, more adjustments were made to the Ice Cover Table. This is a trial and error process that was complicated by the fact that HEC-RAS performs the water portion of the calculations from downstream to upstream and the ice jam calculations from upstream to downstream. It is feasible for the user to change the upstream ice thickness by 0.1 foot and observe relatively little change in the total volume of ice for one run, then change the thickness by another 0.1 foot and have the total volume change by orders of magnitude from the previously calculated volume. An approximation of the volume within five percent of the “known” volume was deemed acceptable for this study.

The upper ice jam, with the toe located at the ICS, was modeled as in the existing conditions. No special adjustments were required for the upper jam.

5.6.3 With Ice Control Structure and Sedimentation Basin

The same process of trial and error, comparing the known ice volume to the calculated ice volume below the dam and ICE was repeated for the scenario of an ICS and with a sedimentation basin scenario. Again, a total calculated volume within five percent of the known volume was accepted as a fair simulation of actual events.

5.6.4 With Sedimentation Basin (no ICS)

Without the construction of the ICS, there is no mechanism to limit the ice from flowing over the dam and adding to the volume of a downstream ice jam. This scenario was modeled with two ice jams as discussed for the existing conditions, using the geometry defining the sedimentation basin upstream of the dam.

5.7 HEC-RAS Summary

Eight different scenarios were modeled in HEC-RAS for this project. Four different geometric scenarios were modeled using two different flow regimes; open water and ice cover. The open water project organization was fairly simple with one flow file and one geometry file for each project scenario. The ice cover models were far more complicated as each different ice jam event required an individual geometry file and therefore an accompanying individual flow file and plan file.

VI. Sediment Transport

The factors influencing the movement of sediment in rivers are numerous and interact in many different and complicated ways. Estimating the amount of movement is far from an exact science. At this point in the evolution of sediment transport equations, the results are estimates only. Many equations are based on empirical data gained in laboratory studies. Applying these equations to actual river conditions can yield results that may be within 50% to 1000% of actual values.

In addition, very little information has been obtained regarding sediment transport under ice. Field studies and sampling efforts are limited due to the difficult and often dangerous conditions that exist when sampling would need to take place.

Some laboratory experiments have been conducted using material other than ice to simulate the affects of a boundary on the top of the water surface as well as the bed. One such study was performed using plywood instead of ice (Ettema, 1999). The general conclusions drawn from these efforts were that under ice cover conditions, typically the water depth increases and velocity decreases, resulting in less sediment transport under ice.

For this study on the Salmon River, there were no measurements of sediment transport obtained in the field. The information available in regards to the ice conditions was the ice thickness and discharge of flow during ice jams from 1950 – 2000. This information was used to model the flow and ice jam conditions to estimate the hydraulic parameters that affect the sediment transport. Additional factors that influence the sediment transport rate in a river aside from the hydraulics are the geomorphology and bed material characteristics.

6.1 Geomorphology

The geomorphology in this area is varied and highly influenced by human activities. The Salmon River upstream of the proposed sedimentation basin location is a steep, armored channel (upper reach). The slope in this section averages 23 feet per mile; the bed material size averages 40.7 mm, and is comprised mainly of well-graded gravel with some sand. The river valley is narrow with steep, heavily vegetated side slopes in this section, as seen in this picture. The sinuosity is 1.02, where a value of 1.00 represents a completely straight river.

At RM 4.92, as the river approaches the upstream end of the proposed sedimentation basin, the slope decreases significantly to approximately 4 feet per mile. There are scattered overbank floodplains located in this section as the valley widens slightly in this area and becomes slightly more sinuous.

Three small tributary creeks confluence with the Salmon River in this reach. At the confluence of the creeks, there are areas of significant deposition, which have created small overbank floodplains. The photo on the right was taken from the right bank looking upstream to the area where the tributaries confluence with the Salmon River on the right bank. Note the sand bar that has been deposited in this location.

Just upstream of the dam exists a depositional section with mainly fines and sands deposited in the previously constructed sediment basin. This area is now a large pool. Large outcrops of bedrock exist both upstream and downstream of the dam. A large cobble / gravel bar has formed on the left side of the channel on the inside of a slight bend just upstream of the dam. A small side channel exists on the left edge of the bar.

Downstream of the Leesville Dam, large boulders and bedrock outcrops constrict the channel on the left. A well-established island exists between the Leesville Dam and the Highway 151 Bridge. The Daigle property is on the left bank of the left channel that flows around the island. The Salmon River makes a sharp bend at the Highway 151 Bridge, which is approximately at a 45° angle to the flow of the water.

6.2 Bed Material Characteristics

The characteristics of the bed material are essential in estimating the amount of sediment that can be transported by the river. On a field trip conducted July 14, 2000, eight different bed material locations were sampled. Seven were physical samples analyzed at the CRREL lab in Hanover, NH. The results of the laboratory analysis are contained in Appendix C. The eighth sample was a Wolman count performed the day of the field trip. Figure #1 depicts the locations of where the samples were taken from the river. Because this study focuses on the effects of the ICS and sedimentation basin on sediment transport in the Salmon River, the samples were taken above the Leesville Dam. Table 4 summarizes the results of the sample analysis.

Samples # 6 and #7 are typical of the bed material in the upstream portion of the project as described in the geomorphology section. The D_{50} for these samples are 48.1 mm and 33.4 mm respectively. The C_c values are 2.93 and 2.58 and the C_u values are 17.20 and 19.43. These values represent well-graded gravel.

In the middle reach above the dam, sample #5 was taken from a section of eroding left bank. This material is much smaller, D_{50} = 0.34 mm and consists of poorly graded sand. Sample #5 is typical of the material in the overbank flood plains.

A total of five samples were taken in the lower reach, all approximately 470 feet upstream of the Leesville Dam. The material sampled in the pooled water (Samples #1, 2, and 2A) consists mainly of poorly graded sand with gravel, with an average D_{50} = 0.94mm. This composite sample was chosen for the analysis of the sediment transport as it represents the material that has been deposited in the location of the previous sediment basin. It is also the size of the material easily available for transport from depositional overbank areas and overland flow in the upstream reaches.

Table 4. Bed Material Characteristics

Sample #	D_{50} (mm)	D_m (mm)	C_c	C_u	Description
1	1.11	4.95	0.69	3.86	Poorly graded sand with gravel
2	0.95	4.19	0.76	2.90	Poorly graded sand with gravel
2A	0.76	2.99	0.87	2.75	Poorly graded sand with gravel
3	6.31	11.30	0.59	13.68	Poorly graded gravel with sand
4	39.63	45.12	1.08	3.00	Poorly graded gravel
5	0.34	0.61	1.01	2.82	Poorly graded sand
6	48.07	45.26	2.93	17.20	Well graded gravel
7	33.43	40.81	2.58	19.43	Well graded gravel with sand

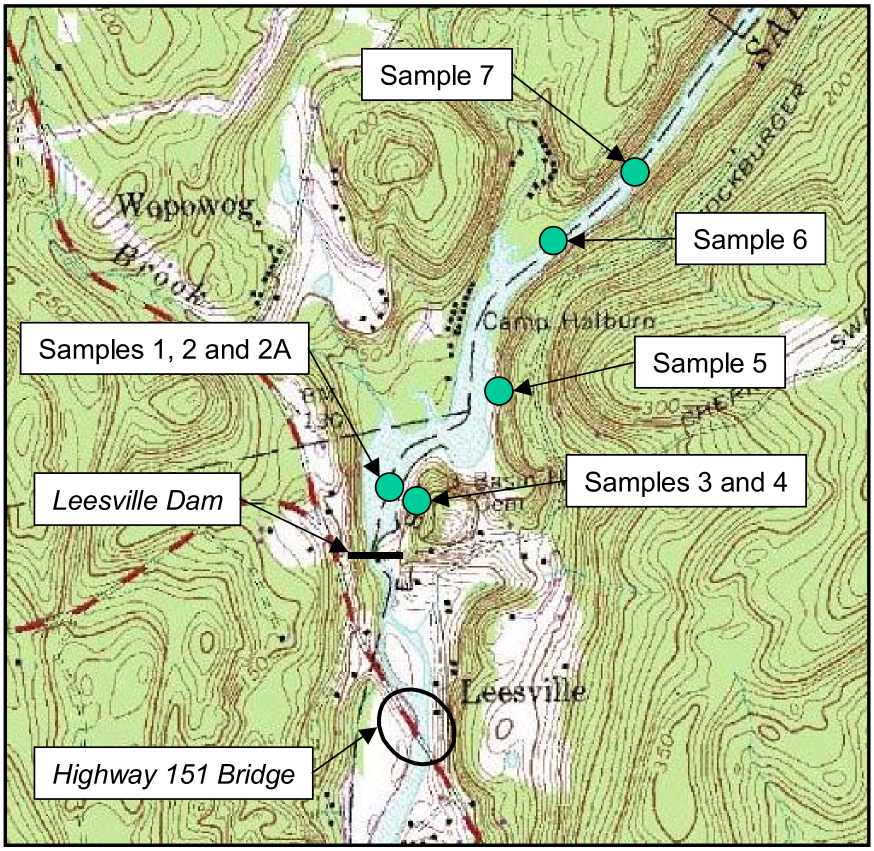

Figure 1. Vicinity Map with Sample Locations

6.3 Lane's Relationship

An important relationship to consider in the evaluation of this project is Lane's Relationship (Simons and Senturk, 1992).

$$QS_o \propto Q_s D_m \qquad [1]$$

In this statement of proportional equilibrium, Q is the discharge in the river, S_o is the slope of the river bed, Q_s is the sediment discharge and D_m is the median grain size diameter. Based on this equation, when a variable on one side is altered, the remaining variables adjust to re-establish equilibrium conditions. If the discharge increases and the slope and median grain size diameter remain the same, then Q_s will increase. Likewise, if the slope of the river bed is increased and the discharge remains the same, either the sediment discharge or median grain size diameter will increase accordingly. This establishment of equilibrium may have been a contributing factor to the rapid rate at which the previous sedimentation basin was filled with deposited material. When the dam was lowered by 10 feet, the slope of the river bed upstream increased. A response of the river may have been an increase in sediment discharge. This coupled with the fact that the largest discharge on record occurred shortly after the construction of the sediment basin may explain why the basin filled in so quickly.

6.4 Sediment Transport Theory

6.4.1 Brief History of Sediment Transport

The movement of sediment in water has been investigated for centuries and longer although not always in scientific terms. However, it was not until the end of the nineteenth and beginning of the twentieth centuries that serious progress was made toward developing equations that applied specifically to the movement of sediment in water. In the second half of the last century, a multitude of equations have been derived, many are empirical, based on laboratory flume studies. Unfortunately, for all of the progress that has been made, the existing equations are still limited in applicability and precision.

6.4.2 Limitations

Most of the existing equations are based on experiments that were conducted in sand-bed flumes and channels with limited ranges of sediments sizes and small discharges. Information from such studies, typically conducted under steady, uniform flow conditions, was used to make broad assumptions in developing the equations. Other equations are based on theory with statistical information used to determine exponents.

When these laboratory-based equations are applied to large rivers with varying sediment sizes and flow conditions, an estimate of transport rate is the best that can be expected.

6.4.3 Available Equations

Some of the sediment transport equations currently available are the Einstein Bed-Load Function, the Modified Einstein Method, the Meyer-Peter, Muller Equation, the Colby Equation, Bishop Method and the Laursen Method, just to name a few. Most of the equations can be broken down into a form such as $Q_s = A(Q-Q_c)^B$ or $Q_s = A(\tau - \tau_c)^B$, where A and B are parameters related to flow and sediment characteristics and $Q – Q_c$ and $\tau - \tau_c$ are conditions of exceedance. The values represented by Q and τ are the power or force available to move the sediment and Q_c and τ_c represent the critical amount of force or power required to initiate the movement of the sediment. When the difference between the two is positive, sediment transport will occur.

It is important in choosing an equation that the basis used to derive the equation is one that most closely fits the conditions to be modeled. The Meyer-Peter Muller equation is based on experiments with sand particles of uniform sizes, sand particles of mixed sizes (such as found in samples 1, 2, 2A and 5), and natural gravel (such as found in samples 3, 4, 6 and 7). As described in on text, “To estimate the transport capacity of steeper streams with coarse bed material, the Meyer-Peter Muller bed load transport equation is often cited and relied upon in engineering and environmental analysis.” (Simons and Senturk, 1992)

6.5 Meyer-Peter Mueller Equation

To estimate the sediment transport rates and evaluate the impact of the ice control structure and sedimentation basin, a sediment transport equation was needed. The Meyer-Peter Muller (MPM) equation was selected for the Salmon River project. This equation applies best to the sandy and gravel conditions determined to exist in the study area of the Salmon River.

The Meyer-Peter Muller Equation (Simons and Senturk, 1992) is written as:

$$g_b = \left[\frac{\left(\gamma_w R \left(\frac{k}{k'} \right)^{3/2} S \right) - \left(0.047 (\gamma_s - \gamma_w) D_m \right)}{0.25 \rho^{1/3} (\gamma_s - \gamma_w)^{2/3}} \right]^{3/2} \qquad [2]$$

where g_b = sediment transport rate in lbs/(ft-sec)

γ_w = specific weight of water = 62.4 lbs/ft^3

γ_s = specific weight of the sediment = 2.65 *62.4 = 165.4 lbs/ft^3

k = 1 / n where n is the Manning's roughness value

k' = 26/(d$_{90}$)$^{1/6}$ where d$_{90}$ is in meters

D_m = median grain size diameter of the bed material

R = hydraulic radius

ρ = density of the water in slugs/ft^3

This can be simply represented as

$$g_b = \int (\tau - \tau_c) \qquad [3]$$

where τ represents the shear stress on the bed and τ_c is the critical shear stress required to cause incipient motion. When the shear stress on the bed,

$$\gamma_w R \left(\frac{k}{k'} \right)^{3/2} S \qquad [4]$$

exceeds the critical shear stress,

$$0.047 (\gamma_s - \gamma_w) D_m , \qquad [5]$$

sediment transport will occur.

Meyer-Peter and Muller performed laboratories experiments based on uniform sand sizes, mixed sand sized, natural gravel, lignite and baryta, to determine the parameters and exponents of the equation, $\int$, that comprise the details of the equations.

In this equation, values of γ_s, γ_w, and ρ are all constants for this application. Variables needed to solve the equation are $R, K, S, D_m,$ and D_{90}. Values for the hydraulic parameters of R, K and S are obtained from the results of the one-dimensional hydraulic water model, HEC-RAS.

The bed material characteristics are determined from samples of the bed material taken during a field trip to the Salmon River. Table 4 summarizes the sample information.

6.5.1 Open Water Flow

Thirty-four different values of flow and the associated hydraulic parameters were investigated for sediment transport under open water conditions. The flow values correspond to the 1, 1.25, 2, 5, 10, 50, 100 and 500-year return events. In addition, for the sake of comparison to the under-ice condition, all values of flow that were observed during ice jam events are also investigated. The parameters used in the MPM equation were generated directly from the results of the HEC-RAS model.

6.5.2 Ice Flow

At this time, there is no sediment transport equation design to be applied to transport under ice cover conditions. In an attempt to estimate sediment transport rates, modifications to the parameters in the MPM equation were required in order to account for the presence of the ice cover in estimating sediment transport. The hydraulic radius, normally determined by dividing the flow area by the wetted perimeter, is affected by the presence of a second boundary at the surface of the flow, in the form of the ice cover. However, it would not be representative in determining the hydraulic radius to include the entire surface of the ice cover with the wetted perimeter in the MPM equation. This would significantly decrease the hydraulic radius, in turn decreasing the amount of shear force available to move the sediment. The presence of the ice however does affect the hydraulic radius and does need to be accounted for in the calculations (White, 1999). This is done using the equation

$$R_i = \left(\frac{n_i}{n_c}\right)^{3/2} \frac{y_i}{2} \qquad [6]$$

Where n_i is the Manning's roughness value for the ice cover and n_c is the combined Manning's roughness value of n_i and n_b (the roughness value for the bed). The equation

$$n_c = \left[\frac{n_i^{3/2} + n_b^{3/2}}{2}\right]^{2/3} \qquad [7]$$

is used to determine the value of the combined Manning's roughness (White, 1999).

In addition to altering the value of the hydraulic radius in the MPM equation, the k value is also adjusted to account for the ice presence. Where $k = 1/n$, (normally n_b), the value of n_c is substituted for n.

6.5.3 Applications with HEC-RAS Results

The hydraulic data such as the discharge, flow area, energy grade line slope and flow depth determined in the HEC-RAS models was exported from HEC-RAS and imported into an Excel spreadsheet. The information was imported for all cross sections between 5.0832 on the upstream end to 4.003 on the downstream end. Cross section 5.0832 is located in the upper reach where the slope is fairly steep and the hydraulic conditions are such that this will be the area with the highest sediment transport rate. As such, this was established as the upper end of the sediment transport analysis reach. Cross section 4.003 is just upstream of the Leesville Dam. The proposed sedimentation basin and the ice control structure are both located between these two cross sections.

The estimated bed load transport rate at each cross section was determined for each of the flows in each of the eight scenarios. The Meyer-Peter Muller equation (MPM) relies on the median grain size diameter of the bed material to estimate the bed load transport rate. Sample #2, which represents the average material available for transport in the upstream reaches, was selected for comparisons of transport rates based on the MPM estimates.

6.6 Comparison of Results

The discharge during ice jam conditions during the fifty-year study period averaged 1,400 cfs. This falls between the 1.1 year and 1.25 year return period storm for the Salmon River. In open water conditions, movement is expected to begin at flows from 500 cfs to 1500 cfs depending on the size of the sediment. However, less movement is expected for the under-ice condition than for the open water conditions with the same discharge.

There is not significant movement in the bed at the lower flows that typically occur during the winter. Very little scour is expected in the upstream reach (gravel bed) and therefore very little deposition is expected behind the ICS during the winter months.

However, the results of the analysis indicate that scour will occur under the ice in two general locations in the lower sections. In the area of the ice control structure, the Manning's roughness values are high as are velocities. This combination lends itself to higher sediment transport rates. These rates however are dependent upon the median diameter size of the bed material, the smaller the material, the higher the rate of scour. Riprap is recommended around the ice control structure, upstream, downstream and between the piers.

The second location of potential scour is in areas of the jam where the ice collects and becomes very thick. This too causes higher velocities and Manning's *n* values. The thickness of the jam can vary from downstream to upstream when modeled in HEC-RAS. Slight variations to the Ice Cover Table will result in differing locations of thickness as well. Due to this, the MPM equation indicates higher rates of sediment transport in the sometimes random locations of thicker ice. This makes evaluations based on predicted bed load somewhat difficult, as the results do not necessarily follow any trends. As an example, Figure 2 depicts sediment load versus discharge at one specific cross section, 5.0832. As expected for open water, as the discharge increases in this fairly uniform cross section with steep overbanks, so too does the bed load rate. The R^2 value for the trend line of open water flow verses bed load rate is 0.992, indicating a very close correlation. However, for two cases of ice jams (one with existing conditions, the second with ice control structure and sedimentation basin) the same correlation is not observed. The R^2 values are 0.26 and 0.25 respectively. The values of bed load transport rate are essentially the same for each ice covered condition at the lower flow values, but the influence of the ice jam thickness is observed at higher discharges where bed load rates vary drastically.

Figure 3 also demonstrates the variability of bed load estimates when an ice jam is modeled. This figure represents sediment transport rates estimated for a median diameter size of 4.2 mm (Sample #2) at a flow of 6,000 cfs from cross section 4.003 to 5.0832. The two ice jam scenarios (existing and with ICS / with SB) show a wide range of variability, especially in the area near the ICS and toe of the jam. The open water flow however has low values of bed load transport rate in the wide sedimentation based, as expected, and the values increase upstream as the channel narrows and steepens.

The majority of sediment transport is expected to occur during the spring runoff when peak flows are expected. A likely scenario is that mostly sand sized sediment will be transported from the overbank areas and overland flow on an average year and deposited in the sedimentation basin. During larger spring runoff years with a 50- or 100-year flow, some of the larger bed material that exists upstream will be transported and deposited in the basin. During the winter ice jams, some of this deposition will be scoured in areas near the ice control structure or where the ice jam is very thick.

The existing channel in the area of the sedimentation basin is wide and the slope is very flat. These are conditions more conducive to deposition rather then scour. Because of this, there is not a significant change in estimated bed load rates between the existing and proposed sedimentation basin condition. However, the ice control structure will create faster moving water due to blocked areas of flow and causes the Manning's roughness to increase. These two factors cause the sediment transport rates to increase in the vicinity of the ICS.

VII. Summary

The Salmon River was modeled from the confluence with the Connecticut River upstream approximately 7.5 miles to the East Hampton gaging station. HEC-RAS, a one-dimensional, steady flow, modeling program was used to model both open flow and ice jam conditions. Four different scenarios were modeled for each flow condition, existing, with the ice control structure, with the ice control structure and sedimentation basin, and with the sedimentation basin alone.

Results from the HEC-RAS study were used to estimate sediment transport rates for the various scenarios. The results indicate that only small amounts of sediment will be transported under the ice, mainly due to the low flows that are typical during the winter. Some scour is expected however at the ice control structure and in areas of the jam where the ice is very thick. Most likely, the majority of sediment will be transported during the spring peak hydrograph and deposited in the basin at that time. Some localized scour will then transport some sediment further downstream during ice jam conditions.

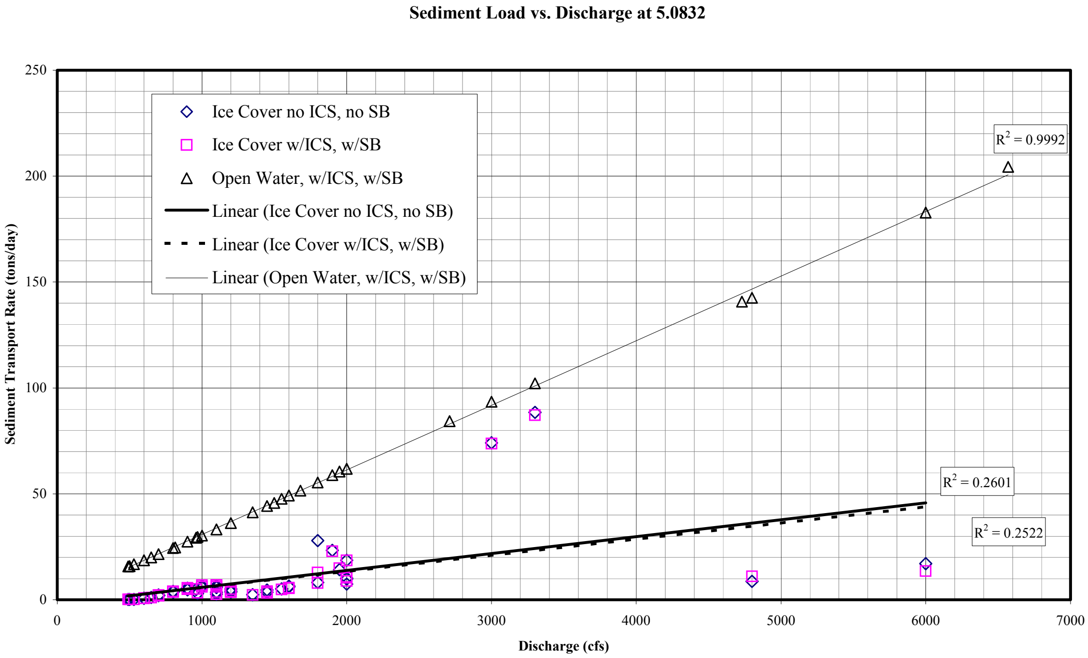

Figure 2. Sediment Load vs. Discharge at Cross Section 5.0832

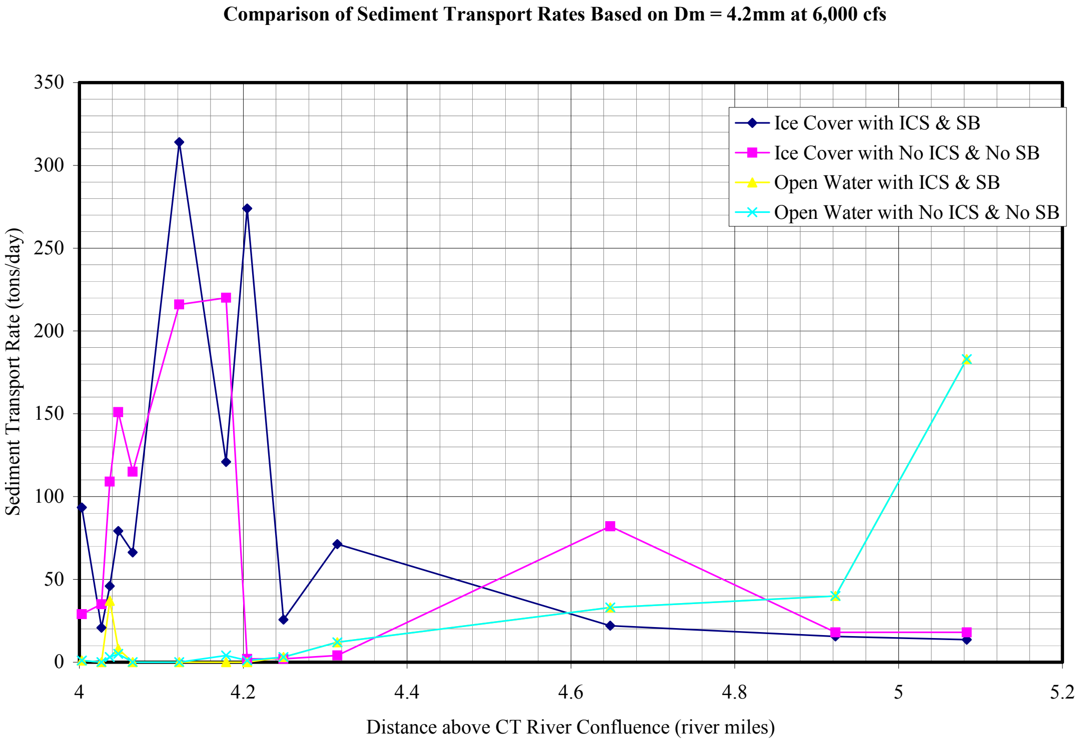

Figure 3. Sediment Load vs Distance for Q = 6,000 cfs

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