General Electric Company
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# THE EROSION PROPERTIES OF COHESIVE SEDIMENTS IN THE UPPER HUDSON RIVER

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CONTENTS


| Section | | Page |
|---|---|---|
| 1 | INTRODUCTION | 1 |
| 2 | COHESIVE SEDIMENT RESUSPENSION PROCESSES | 5 |
| 3 | EROSION POTENTIAL DATA ANALYSIS | 9 |
| | 3.1 Laboratory Study Results | 9 |
| | 3.2 Field Study Results | 10 |
| 4 | SUMMARY | 11 |
| 5 | REFERENCES | 12 |
| APPENDIX A<br>LABORATORY STUDY METHODS AND RESULTS | | 14 |
| | A.1 Sediment Sample Collection | 14 |
| | A.2 Annular Flume Experiments and Results | 14 |
| | A.2.1 Multiple Shear Stress Tests | 17 |
| | A.2.2 Continuous Flow Experiment | 25 |
| | A.3 Data Analysis | 29 |
| APPENDIX B<br>FIELD STUDY METHODS AND RESULTS | | 34 |
| | B.1 Field Study Description and Procedures | 34 |
| | B.2 Data Analysis | 42 |

## FIGURES


| Figure | | Page |
|---|---|---|
| Figure 1-1. | Reach identification for the Upper Hudson River | 3 |
| Figure 2-1. | Comparison of resuspension potential functions for Thompson Island Pool, Fox River and Pawtuxet River. | 7 |
| Figure A-1. | Locations in the Thompson Island Pool of Sediment Samples Used for Flume Experiments. | 15 |
| Figure A-2. | Schematic of the annular flume. | 16 |
| Figure A-3. | Flume data from multiple shear stress tests for sample 1. | 19 |
| Figure A-4. | Flume data from multiple shear stress tests for sample 2. | 20 |
| Figure A-5. | Flume data from multiple shear stress tests for sample 3. | 21 |
| Figure A-6. | Flume data from continuous flow experiment. | 30 |
| Figure A-7. | Effect of bed compaction on resuspension of cohesive sediments deposited in a continuous flow environment. | 32 |
| Figure B-1a. | Locations of in situ resuspension potential stations in the Thompson Island Pool. | 35 |
| Figure B-1b. | Locations of in situ resuspension potential stations in the Thompson Island Pool. | 36 |
| Figure B-2. | Locations of in situ resuspension potential stations from Thompson Island Dam to Troy Dam. | 37 |
| Figure B-3. | Schematic of the shaker. | 38 |


## TABLES


| Table | | Page |
|---|---|---|
| Table 1-1. | Reach average values of $a_0$ | 2 |
| Table A-1. | Flume data from multiple shear stress tests for sample 1 with compaction times of 1, 3 and 14 days | 22 |
| Table A-2. | Flume data from multiple shear stress tests for sample 2 with compaction times of 1, 3 and 14 days | 23 |
| Table A-3. | Flume data from multiple shear stress tests for sample 3 with compaction times of 1, 3 and 14 days | 24 |
| Table A-4. | Flume data from long term compaction test | 26 |
| Table B-1. | Resuspension potential study summary | 39 |
| Table B-2. | Statistical information on $a_0$ values by reach | 43 |

## SECTION 1
## INTRODUCTION

The transport and fate of PCBs in the Upper Hudson River are greatly affected by sediment transport processes. Cohesive sediments are particularly important when considering the transport of PCBs in a riverine system because PCBs are hydrophobic and preferentially adsorb onto fine-grained particles, i.e., clay and silt. Another important factor that must be considered when studying sediment transport processes in a river is that the erosional properties of cohesive sediments (clay and silt) differ greatly from those of non-cohesive sediments (sand and gravel). Understanding and quantifying the long-term fate of PCBs in the Upper Hudson River therefore requires a realistic and accurate description of fine-grained sediment deposition and erosion processes in the river. As a step toward this goal, experimental studies have been conducted and the results analyzed in an effort to describe and quantify the erosion properties of cohesive sediments in this river.

The amount of sediment that can be eroded from a cohesive sediment bed, i.e., a bed primarily composed of clay, silt and organic matter, is generally referred to as *erosion potential* and has units of mass per unit area, e.g., milligrams per square centimeter ($mg/cm^2$). Erosion potential depends upon the properties of the bed and the shear stress applied to the bed, where shear stress is a measure of the force exerted on the bed by flowing water in a river. This information can then be used to estimate sediment erosion during various high flow events (floods). Previous studies of cohesive sediment transport in rivers, e.g., Fox River in Wisconsin (Gailani et al,. 1991) and Pawtuxet River in Rhode Island (Ziegler and Nisbet, 1994), have used laboratory and field data to determine parameter values that represent bed property effects on erosion. The results of these studies clearly indicate the need to obtain river-specific data if accurate predictions of cohesive sediment bed erosion are to be realized.

The river-specific nature of erosion potential prompted General Electric to conduct field and laboratory studies on cohesive sediments from the Upper Hudson River. Data



316774

from these studies have been used to derive relationships between erosion and bed shear stress for each of the eight reaches from Fort Edward to Troy Dam, i.e., the Thompson Island Pool and the pools behind the other seven downstream dams. This information is of importance when considering the fate of PCB-contaminated sediments in this river system.

A formulation that has been shown to accurately and realistically predict erosion potential is presented in Section 2, i.e., Equation (2-1). Laboratory data were used to determine parameter values in Equation (2-1) that are applicable to the Upper Hudson River system. The values of these river-specific parameters are: $m = 0.5$, $T_{d,max} = 7$ days and $\tau_o = 1$ dyne/cm$^2$. Data collected during a field study, using a device called a shaker, were used to calculate values of the reach-specific parameter, $a_o$, for each of the eight reaches in the Upper Hudson River, see Table 1-1 and Figure 1-1. Based upon field study data, setting the exponent n in Equation (2-1) equal to three for all of the reaches is a valid approximation in this riverine system.

Table 1-1. Reach Average Values of $a_o$

| Reach | Mean $a_o$ (mg-day$^{1/2}$/cm$^2$) |
|---|---|
| 8 | 0.071 |
| 7 | 0.079 |
| 6 | 0.135 |
| 5 | 0.116 |
| 4 | 0.340 |
| 3 | 0.140 |
| 2 | 0.067 |
| 1 | 0.192 |

Section 2 of this report reviews experimental research on cohesive sediment resuspension processes and then presents an equation for predicting cohesive sediment erosion that has been successfully used in sediment transport studies on other rivers. An example that highlights the importance of using river-specific data when evaluating the

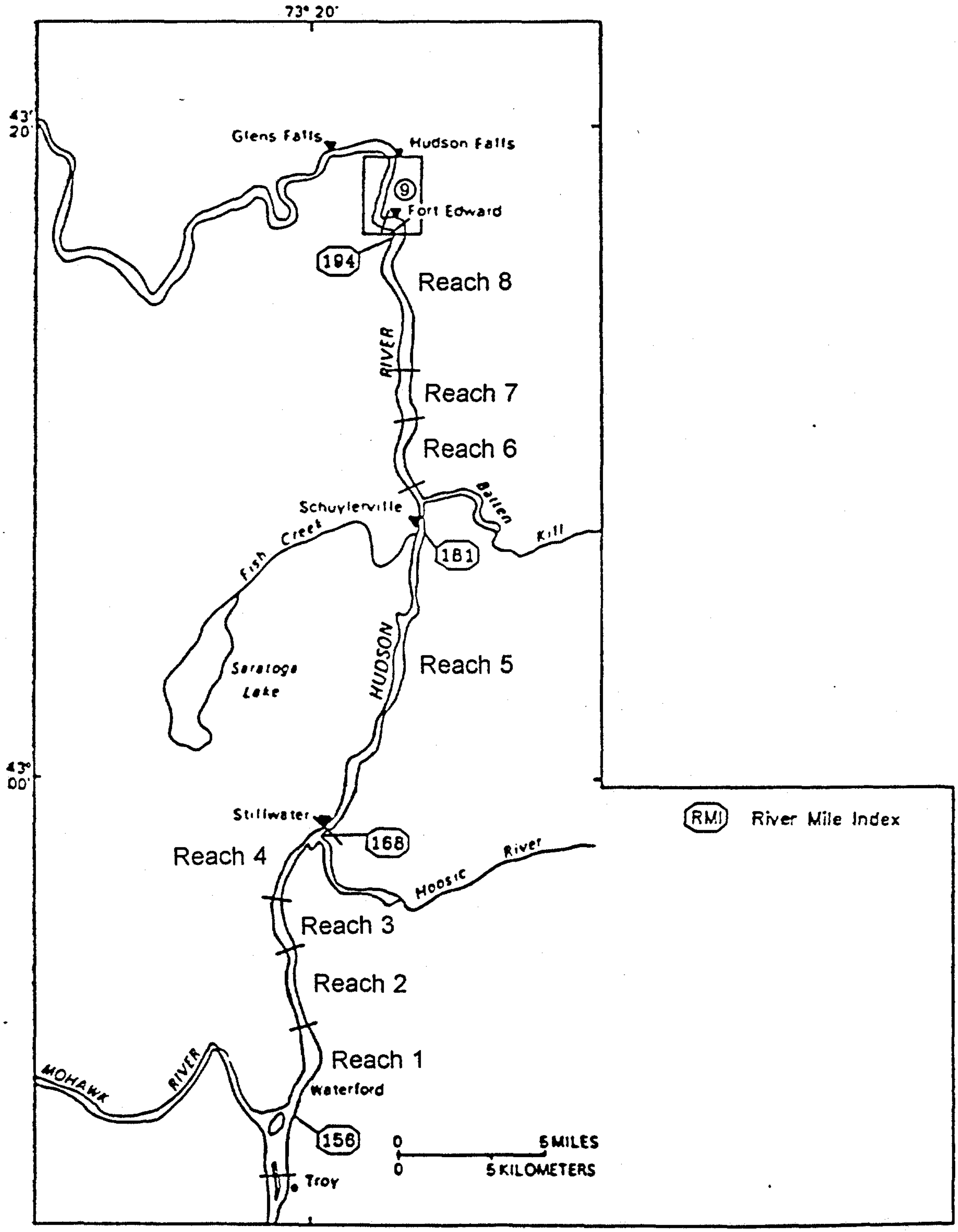


Figure 1-1. Reach identification for the Upper Hudson River.

316776

erosional properties of cohesive sediments in the Upper Hudson River is also included in that section. Section 3 summarizes results of laboratory and field studies conducted on cohesive sediments from the Upper Hudson River. Based upon these experimental data, values of parameters in the resuspension formulation discussed in Section 2 have been determined for Upper Hudson River sediments. This report concludes with a summary of pertinent results.

## SECTION 2
## COHESIVE SEDIMENT RESUSPENSION PROCESSES

Laboratory and field studies on the resuspension properties of fine-grained, cohesive sediments have been conducted by a number of researchers during the last thirty to forty years, with important contributions being made by R.B. Krone (1962), E. Partheniades (1965), A.J. Mehta (1985) and W. Lick (1990). Results of this research have shown that resuspension from a cohesive sediment bed is significantly affected by the wide range of particle sizes, typically varying over two orders of magnitude in the bed of a river, and interparticle cohesion. Compaction effects increase with increasing depth in the bed, as indicated by a decrease in bed porosity with depth, causing surface sediments to be more easily resuspended than sediments buried deeper in the bed. Bed particle size heterogeneity and compaction effects cause bed armoring, which is the observed phenomenon that only a finite amount of sediment can be resuspended from a cohesive sediment bed at a particular bottom shear stress. Cohesive bed armoring has been observed and quantified in various laboratory (Parchure and Mehta, 1985; Tsai and Lick, 1987; Graham et al., 1992) and field studies (Hawley, 1991; Amos et al., 1992). This property of cohesive sediment beds does not extend to a bed composed of non-cohesive, uniform size sediments, e.g., sands, which have a constant erosion rate (Massion, 1982).

The amount of cohesive sediment resuspended at a specific bottom shear stress depends on the turbulent stress at the sediment-water interface and the state of compaction of the bed (Krone, 1962; Lee et al., 1981; Parchure and Mehta, 1985; Lick and Kang, 1987; Tsai and Lick, 1987; MacIntyre et al., 1990). Analysis of laboratory and field data has indicated that the following relationship is valid (Gailani et al., 1991)

$$\epsilon = \frac{a_o}{T_d^m}\left(\frac{\tau - \tau_o}{\tau_o}\right)^n, \qquad \tau \geq \tau_o \tag{2-1}$$

where $\epsilon$ = net mass of resuspended sediment per unit surface area (mg/cm$^2$); $a_o$ = site-specific constant; $T_d$ = time after deposition in days; m and n are dependent upon the



316778

deposition environment; $\tau$ = bottom shear stress due to currents; and $\tau_0$ = effective critical shear stress.

The resuspension properties of cohesive beds can differ substantially (Gailani et al., 1991; Ziegler and Nisbet, 1994). Variability of erosion characteristics between rivers is reflected in Equation (2-1) parameter values, with data from different rivers indicating that the exponent n can range from two to three and the constant $a_0$ may vary by an order of magnitude. As will be shown in Section 3, laboratory work on Upper Hudson River sediments has suggested that m in Equation (2-1), which accounts for compaction effects, may vary from 0.5 to 2, depending upon deposition environment.

The U.S. Environmental Protection Agency (USEPA) has proposed to use Equation (2-1) in their Upper Hudson River modeling effort, but with parameter values determined from other river systems (Rodgers and Bierman, 1993). This approach may result in significant errors in predictions of cohesive sediment erosion and it should not be considered. Instead, the results of laboratory and field studies on Upper Hudson River cohesive sediments that are presented in this report should be used.

The importance of using river-specific parameters when applying Equation (2-1) to the Upper Hudson River is illustrated by the following example. A comparison of the resuspension potential functions for the Thompson Island Pool, the Fox River in Wisconsin (Gailani et al.. 1991) and Pawtuxet River in Rhode Island (Ziegler and Nisbet, 1994) is shown on Figure 2-1. Data used to develop the erosion potential function for the Thompson Island Pool will be discussed in Section 3. The horizontal axis of the graph is bed shear stress (dynes/$cm^2$) and this quantity is related to river flow rate, i.e., as flow rate increases so does the bed shear stress at a given location. The vertical axis of the graph is erosion potential (mg/$cm^2$).

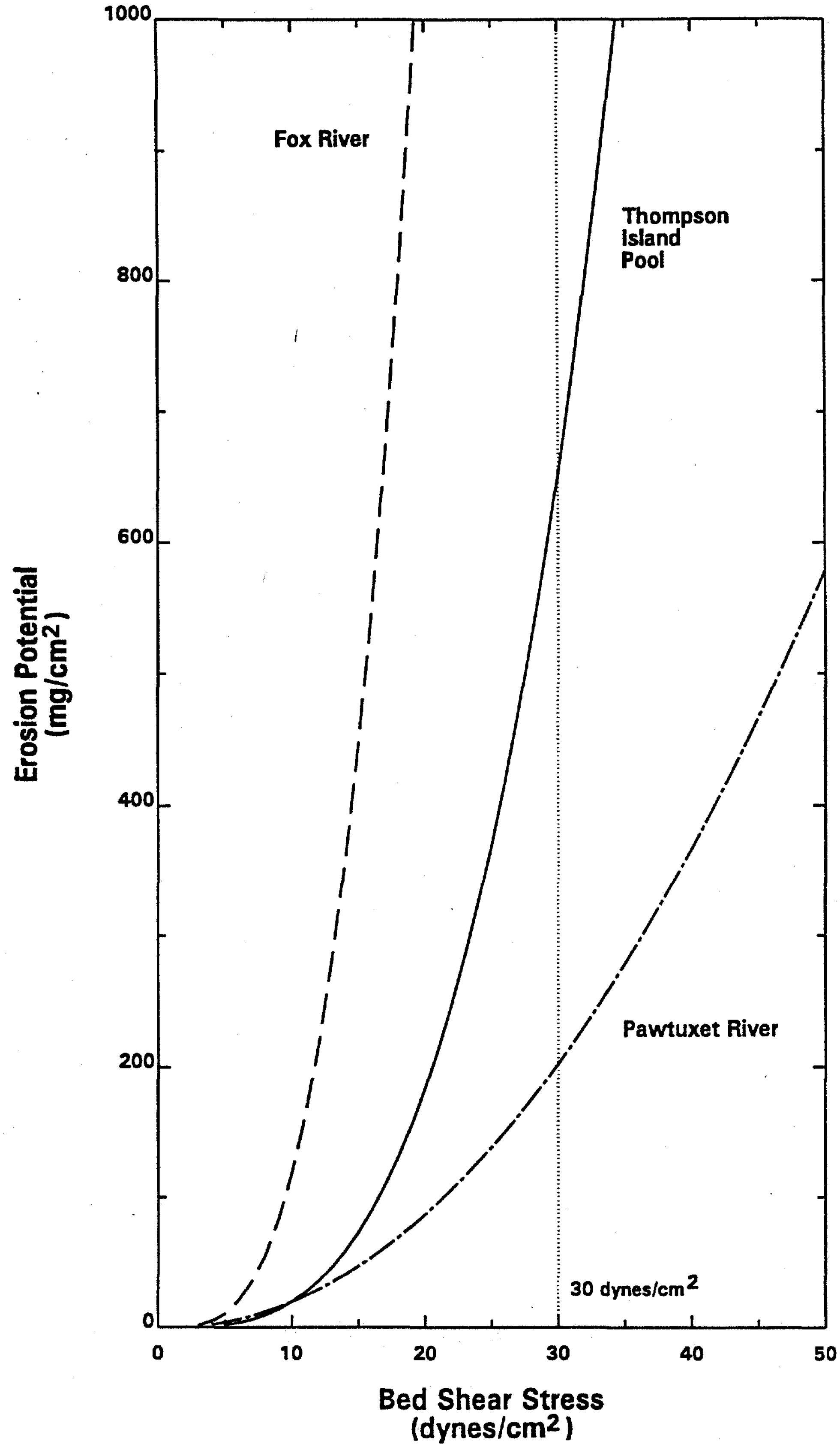


Figure 2-1. Comparison of resuspension potential functions for Thompson Island Pool, Fox River and Pawtuxet River.

The erosion potential functions for the three rivers shown on this figure all have the same functional form; the differences arise from the river-specific characteristics of the cohesive bed. To emphasize the importance of obtaining river-specific erosion potential data, consider the erosion potential predicted in the three different rivers at a bed shear stress of 30 dynes/cm$^2$. This bed shear stress approximately corresponds to the average bed shear stress in the Thompson Island Pool during a high flow event (flood). The predicted erosion potentials are 660, 3980 and 200 mg/cm$^2$, respectively, in the Thompson Island Pool, Fox River and Pawtuxet River. Using data from other riverine systems to predict erosion potential in the Thompson Island Pool could thus generate significant errors. In this case, using Fox River or Pawtuxet River data would result in errors of 600% (high) or -70% (low). Therefore, river-specific resuspension values, developed from Upper Hudson River data, should be used when applying Equation (2-1) if accurate predictions of erosion in this riverine system are to be realized.

# SECTION 3
# EROSION POTENTIAL DATA ANALYSIS

As discussed in Section 2, the resuspension properties of cohesive sediments can vary considerably from one riverine system to another. Hence, parameter values in Equation (2-1), e.g., $a_0$ and n, should be based upon data from field and laboratory studies on cohesive sediments from the Upper Hudson River. This section presents the results of studies on the erosion properties of Upper Hudson River sediments. Laboratory investigations, using an annular flume, were performed to study bed compaction effects on the resuspension of cohesive sediments deposited in a riverine environment and to estimate critical shear stress values. Measurements of in situ resuspension potential throughout the Upper Hudson River were made using established procedures applied in other river systems (Tsai and Lick, 1986; Gailani et al., 1991; Ziegler and Nisbet, 1994). Analyses of the field and laboratory data were also done to determine river-specific values of parameters in Equation (2-1).

## 3.1 Laboratory Study Results

Previous laboratory studies have used an annular flume to investigate various aspects of cohesive sediment resuspension (e.g., Tsai and Lick, 1987; MacIntyre et al., 1990). Annular flume studies were conducted to determine erosional properties of cohesive sediments in the Upper Hudson River. These flume studies were used to derive Upper Hudson River specific values of $T_d$, m and $\tau_0$ in Equation (2-1). The procedure used to determine values of $a_0$ and n in that equation are described in the next sub-section.

Appendix A contains details on laboratory procedures, data presentation and subsequent analysis. The results of the flume studies indicate that the critical shear stress, $\tau_0$, for Upper Hudson River sediments is approximately one dyne/cm$^2$, which is the same value used in other riverine sediment transport studies (Gailani et al., 1991; Ziegler and Nisbet, 1994). The maximum time of deposition, $T_{d,max}$, was found to be approximately seven days. This statement means that all cohesive sediments in the bed with an age of seven days or greater will be assumed to be seven days old when applying Equation (2-1). Finally, results of the annular flume experiments indicated that the exponent m should have a value of 0.5 for cohesive sediment beds formed under continuous flow conditions, as is typically found in rivers.

## 3.2 Field Study Results

A field study was conducted during November, 1990 to measure the in situ resuspension potential of fine-grained, cohesive sediments in the Upper Hudson River. These measurements were made using a portable resuspension device, commonly called a shaker, and a procedure developed by Tsai and Lick (1986). The methods used in this study, a tabulation of the raw data and analysis of these data are presented in Appendix B.

The data analysis indicates that the exponent n in Equation (2-1) is approximately three for all of the eight reaches in the Upper Hudson River. However, the site-specific parameter, $a_0$, is spatially variable and needs to be specified as an average value for each of the eight reaches. The reach mean values of $a_0$ ranged from 0.067 to 0.340 mg-day$^{1/2}$/cm$^2$ and are tabulated in Table B-2.

## SECTION 4
## SUMMARY

A formulation that expresses the mass of sediment resuspended from a cohesive sediment bed as a function of bed shear stress, Equation (2-1), has been successfully applied in sediment transport studies on several river systems and the USEPA has indicated that it will also be used in their modeling effort on the Upper Hudson River. As discussed in Section 2, Equation (2-1) contains river-specific parameters which must be determined from resuspension studies of cohesive sediments in the Upper Hudson River.

This data requirement has been met as a result of laboratory and field studies. The results of these studies, which are discussed in detail in Appendices A and B, indicate that the parameters in Equation (2-1) should have the following values for all of the eight reaches in the Upper Hudson River: $m = 0.5$, $T_{d,max} = 7$ days, $n = 3$ and $\tau_o = 1$ dyne/cm$^2$. The reach-specific constant, $a_0$, needs to be specified as an average value for each of the eight reaches, see Table 1-1.



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## SECTION 5
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# APPENDIX A
# LABORATORY STUDY METHODS AND RESULTS

## A.1 Sediment Sample Collection

Cohesive sediment samples for the laboratory study were collected from three different locations in the Thompson Island Pool (Reach 8), see Figures A-1 and 1-1. Approximately twenty-five gallons of sediment were collected at each site on December 6, 1990. A Ponar grab sampler was used to collect surficial sediments. The sediments were placed in three separate plastic garbage cans and sealed.

Sediment sample 1 was collected in water four to six feet deep about five to fifteen feet from shore. This sediment had a grayish silty appearance and also contained some leaves. Sample 2 appeared to be very muddy and had a gelatinous consistency. This sediment was obtained in five to six feet of water at a distance of forty feet from shore. Sample 3 was taken about ten to fifteen feet east of the island shore in four to nine feet of water. This sample appeared to have a sand content lower than sample 1 but higher than sample 2. Subsequent grain size analysis of the samples showed that samples 1, 2 and 3 had average clay/silt contents of 55, 51 and 21 percent, respectively.

The sediments were allowed to compact and dewater in the garbage cans for approximately two weeks after collection. The sediments were then transferred to plastic containers, which were lined with plastic garbage sacks to prevent leakage, and shipped to the University of California at Santa Barbara (UCSB) on December 28, 1990.

## A.2 Annular Flume Experiments and Results

An annular flume at UCSB was used to study the resuspension properties of the cohesive sediments collected from the Thompson Island Pool. An illustration of the flume is shown on Figure A-2. This flume has been used extensively to study the properties of

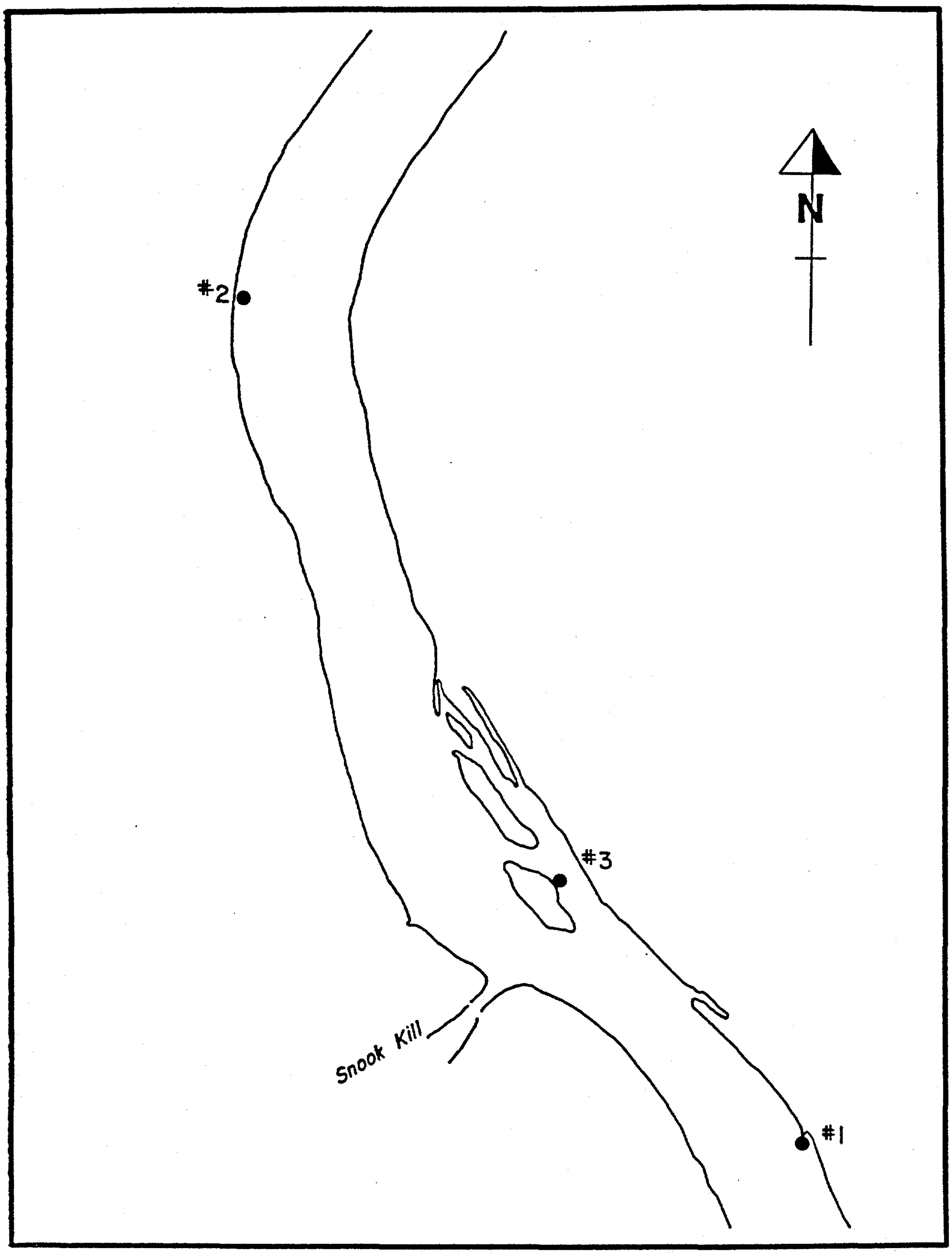


Figure A-1. Locations in the Thompson Island Pool of sediment samples used for flume experiments.

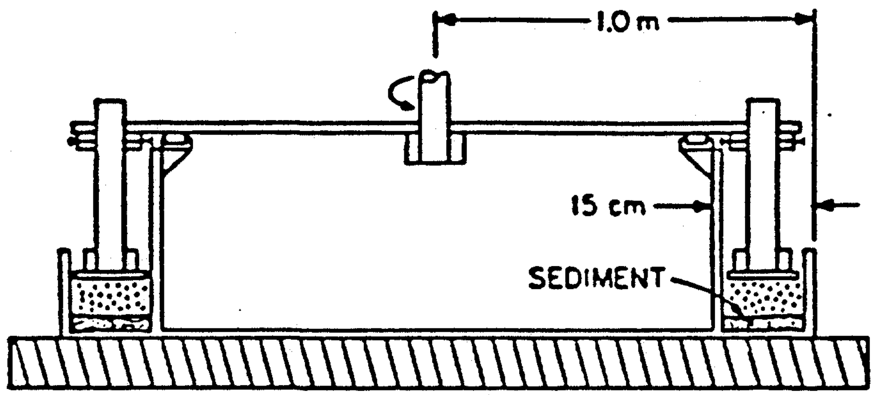


Figure A-2. Schematic of the annular flume.

cohesive sediments from other aquatic systems. Details of flume calibration and operating procedure are discussed in MacIntyre et al., 1990 and Xu, 1991.

The primary objective of the flume experiments was to investigate the effects of bed compaction of sediment resuspension. Two types of experiments were performed to study bed compaction: multiple shear stress tests and a continuous flow test. The procedures and results for these two investigations are presented in the next two sub-sections.

Another goal of these experiments was to estimate the critical shear stress, $\tau_0$, of surficial sediments in the Upper Hudson River. This parameter, which is used in Equation (2-1), is difficult to measure directly. Typically, the value of $\tau_0$ is estimated by observation in the following way. At the beginning of a flume experiment, the applied bed shear stress in the flume is slowly increased from zero until the point at which sediment is first observed to be resuspended from the bed. This shear stress is then estimated to be the critical shear stress for erosion of surficial sediments, which is what is used in Equation (2-1). Results of the flume tests on Thompson Island Pool sediments indicated a critical shear stress of approximately one dyne/cm$^2$.

### A.2.1 Multiple Shear Stress Tests

Multiple shear stress tests were performed on each sediment sample using the following procedure. The flume was filled with sediment to a depth of approximately 6 cm and an overlying water depth of about 7.5 cm. After creating a sediment bed in the flume, the bed was allowed to compact for 1, 3 or 14 days prior to running the experiment. No shear stress was applied to the bed, i.e., the flume was not running, during the compaction period. A total of nine multiple shear stress tests were run; three compaction times were used for each of the three sediment samples.

At the end of the compaction time, the experiment was started by rotating the lid of the flume at a constant speed which corresponded to a bed shear stress of 1 dyne/cm$^2$.

Some sediment was resuspended and the sediment concentration in the flume water increased, rapidly at first and then more slowly until steady-state was reached. The suspended sediment concentration was measured every thirty minutes. After the sediment concentration reached steady-state, which took about two hours, the speed of the lid was increased until a shear stress of 3 dynes/cm$^2$ was reached and more sediment was resuspended. The sediment concentration sampling was continued at thirty minute intervals until steady-state was reached for a shear stress of 3 dynes/cm$^2$. The multiple shear stress test was continued by repeating this procedure for shear stresses of 5, 7, 9 and 11 dynes/cm$^2$.

Generally, no significant problems were encountered during these flume tests. However, gross bed erosion did occur during some of the tests, where gross bed erosion was defined as the formation in the sediment bed of channels with a depth greater than 1 cm. For sample 1 with one day compaction, the bed began to break down at 580 minutes and a shear stress of 11 dynes/cm$^2$. The bed was quite uneven and possibly eroded all the way to the bottom of the flume in spots. The sediment bed became non-uniform at 11 dynes/cm$^2$ for sample 1 with a three day compaction time. The multiple shear stress test for sample 2 had to be stopped at 7 dynes/cm$^2$ for compaction times of one and three days and at 9 dynes/cm$^2$ for fourteen days of compaction. Tests on sample 3 were concluded at 7 dynes/cm$^2$ with one day compaction and at 9 dynes/cm$^2$ for three day compaction. Gross bed erosion was the cause of the test stoppages for samples 2 and 3.

Measured suspended sediment concentrations for the multiple shear stress tests for samples 1, 2 and 3, with compaction times of 1, 3 and 14 days, are listed in Tables A-1, A-2 and A-3, respectively. Graphical plots of the data are presented on Figures A-3, A-4 and A-5.

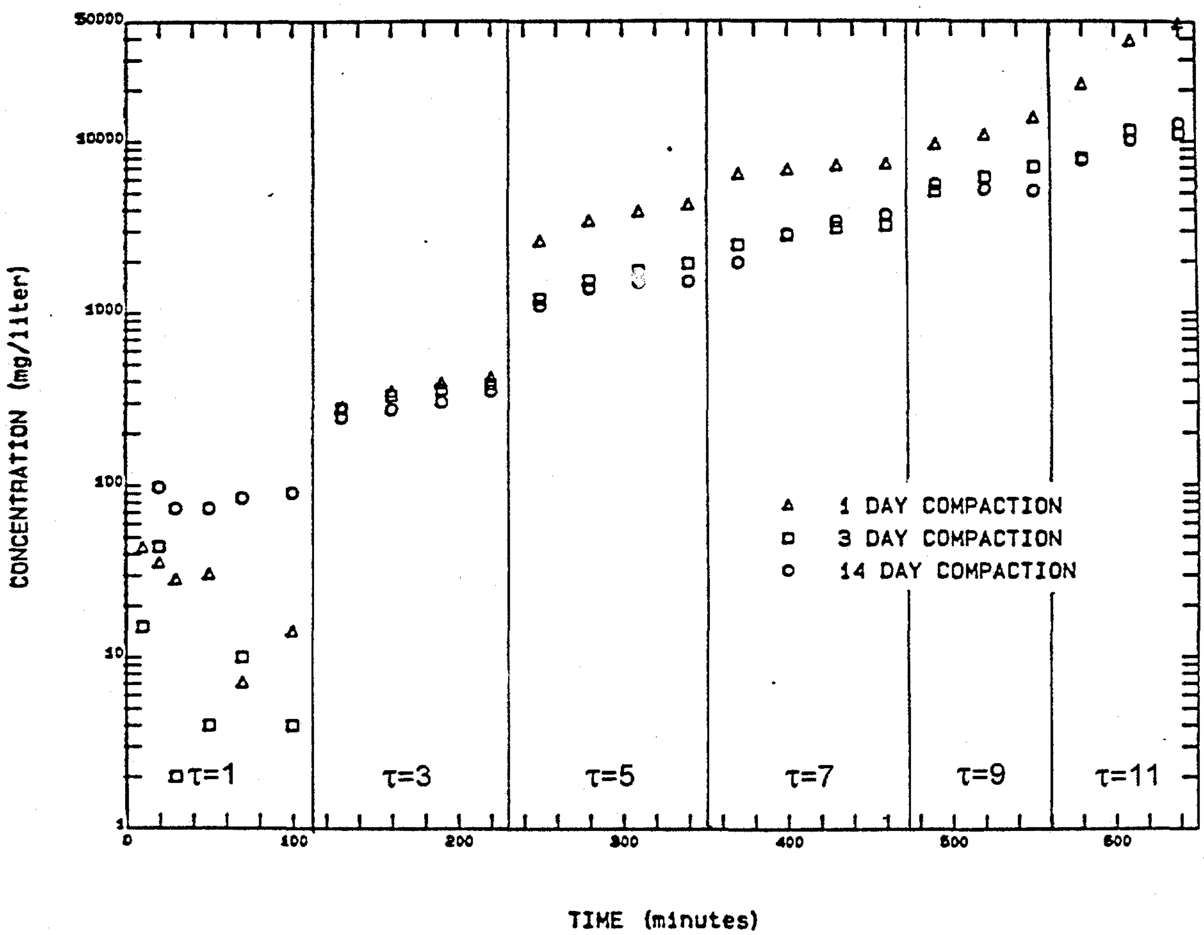


Figure A-3. Flume data from multiple shear stress tests for sample 1.
Shear stress (τ) is in dynes/cm$^2$.

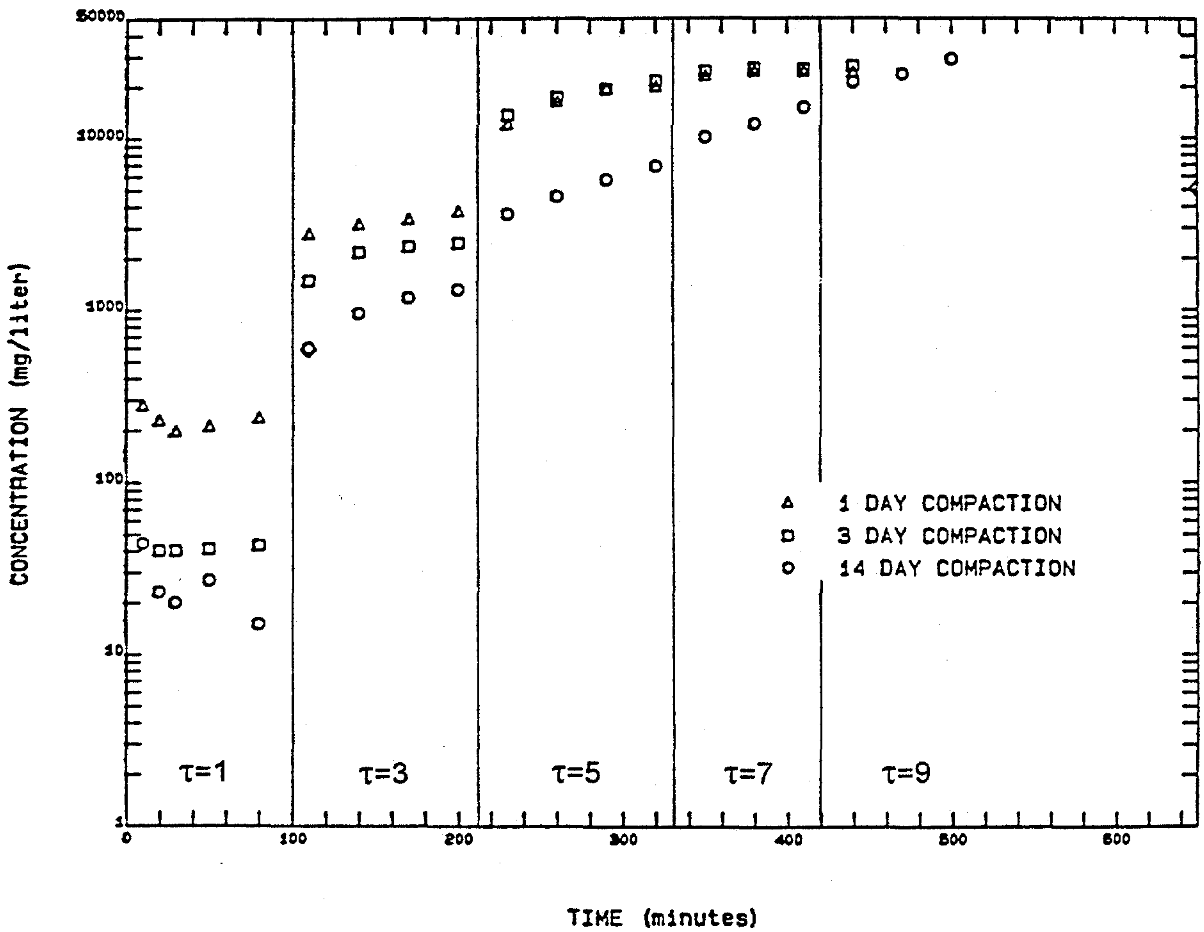


Figure A-4. Flume data from multiple shear stress tests for sample 2.
Shear stress (τ) is in dynes/cm$^2$.

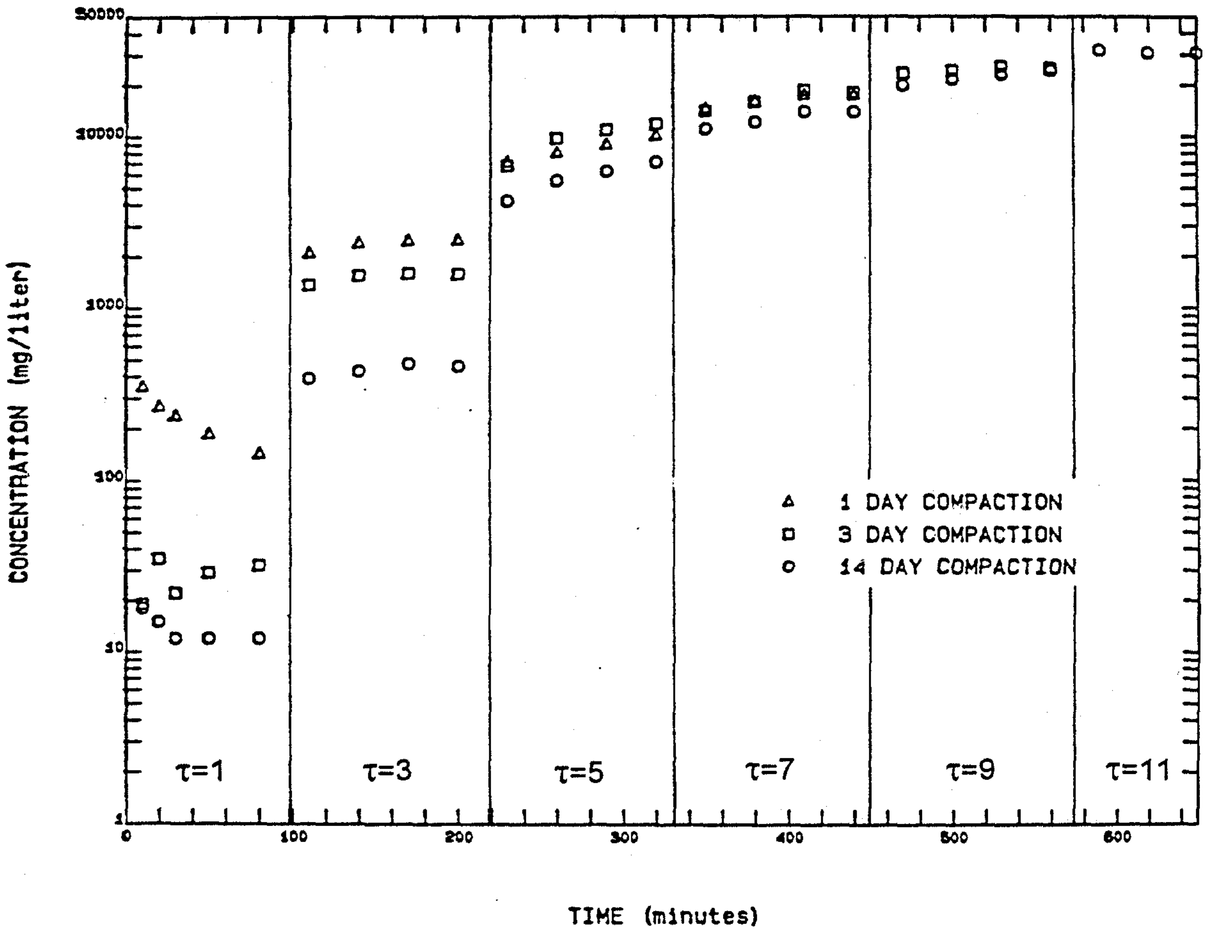


Figure A-5. Flume data from multiple shear stress tests for sample 3. Shear stress ($\tau$) is in dynes/cm$^2$.

| TABLE A-1. FLUME DATA FROM MULTIPLE SHEAR STRESS TESTS FOR SAMPLE 1 WITH COMPACTION TIMES OF 1, 3 AND 14 DAYS | | | | |
|---|---|---|---|---|
| Shear Stress ($dynes/cm^2$) | Run time (minutes) | Concentration (mg/l) | | |
| | | 1 day | 3 days | 14 days |
| 1 | 10 | 43 | 15 | -- |
| | 20 | 35 | 44 | 97 |
| | 30 | 28 | 2 | 73 |
| | 50 | 30 | 4 | 73 |
| | 70 | 7 | 10 | 84 |
| | 100 | 14 | 4 | 90 |
| 3 | 130 | 282 | 278 | 246 |
| | 160 | 344 | 330 | 274 |
| | 190 | 384 | 358 | 302 |
| | 220 | 414 | 384 | 350 |
| 5 | 250 | 2,596 | 1,204 | 1,102 |
| | 280 | 3,404 | 1,546 | 1,388 |
| | 310 | 3,852 | 1,760 | 1,510 |
| | 340 | 4,210 | 1,940 | 1,522 |
| 7 | 370 | 6,340 | 2,496 | 1,964 |
| | 400 | 6,720 | 2,830 | 2,876 |
| | 430 | 7,100 | 3,135 | 3,404 |
| | 460 | 7,270 | 3,235 | 3,725 |
| 9 | 490 | 9,440 | 5,110 | 5,590 |
| | 520 | 10,760 | 6,180 | 5,260 |
| | 550 | 13,540 | 7,100 | 5,140 |
| 11 | 580 | 21,280 | 7,960 | 7,700 |
| | 610 | 38,080 | 11,560 | 10,160 |
| | 640 | 48,400 | 11,120 | 12,780 |

| TABLE A-2. FLUME DATA FROM MULTIPLE SHEAR STRESS TESTS FOR SAMPLE 2 WITH COMPACTION TIMES OF 1, 3 AND 14 DAYS | | | | |
|---|---|---|---|---|
| Shear Stress (dynes/cm$^2$) | Run Time (minutes) | Concentration (mg/l) | | |
| | | 1 day | 3 days | 14 days |
| 1 | 10 | 277 | -- | 44 |
| | 20 | 226 | 40 | 23 |
| | 30 | 196 | 40 | 20 |
| | 50 | 210 | 41 | 27 |
| | 80 | 234 | 43 | 15 |
| 3 | 110 | 2,774 | 1,490 | 606 |
| | 140 | 3,158 | 2,190 | 960 |
| | 170 | 3,373 | 2,363 | 1,183 |
| | 200 | 3,740 | 2,467 | 1,320 |
| 5 | 230 | 11,927 | 13,640 | 3,640 |
| | 260 | 16,220 | 17,280 | 4,595 |
| | 290 | 19,220 | 19,420 | 5,740 |
| | 320 | 19,850 | 21,590 | 6,880 |
| 7 | 350 | 22,900 | 24,570 | 10,160 |
| | 380 | 24,310 | 25,670 | 12,120 |
| | 410 | 24,190 | 25,340 | 15,110 |
| 9 | 440 | 23,980 | 26,340 | 21,260 |
| | 460 | -- | -- | 23,760 |
| | 490 | -- | -- | 29,020 |

| TABLE A-3. FLUME DATA FROM MULTIPLE SHEAR STRESS TESTS FOR SAMPLE 3 WITH COMPACTION TIMES OF 1, 3 AND 14 DAYS | | | | |
|---|---|---|---|---|
| Shear Stress (dynes/cm$^2$) | Run Time (minutes) | Concentration (mg/l) | | |
| | | 1 day | 3 day | 14 days |
| 1 | 10 | 350 | 19 | 18 |
| | 20 | 269 | 35 | 15 |
| | 30 | 237 | 22 | 12 |
| | 50 | 186 | 29 | 12 |
| | 80 | 143 | 32 | 12 |
| 3 | 110 | 2,100 | 1,368 | 390 |
| | 140 | 2,400 | 1,556 | 430 |
| | 170 | 2,476 | 1,596 | 474 |
| | 200 | 2,488 | 1,578 | 458 |
| 5 | 230 | 7,053 | 6,760 | 4,216 |
| | 260 | 8,033 | 9,750 | 5,520 |
| | 290 | 8,960 | 10,915 | 6,255 |
| | 320 | 10,067 | 11,795 | 7,065 |
| 7 | 350 | 14,450 | 14,067 | 11,040 |
| | 380 | 15,970 | 15,853 | 12,053 |
| | 410 | 17,140 | 18,527 | 13,907 |
| | 440 | 17,330 | 17,960 | 13,880 |
| 9 | 470 | -- | 23,380 | 19,900 |
| | 500 | -- | 24,180 | 21,640 |
| | 530 | -- | 25,520 | 23,140 |
| | 560 | -- | 25,140 | 24,320 |
| 11 | 590 | -- | -- | 31,930 |
| | 620 | -- | -- | 30,920 |
| | 650 | -- | -- | 30,950 |
| | 680 | -- | -- | 30,710 |

### A.2.2 Continuous Flow Experiment

The multiple shear stress tests were performed on sediment beds in the flume that were compacted under zero flow conditions. Other flume research (Xu, 1991) has indicated that the flow environment under which bed compaction takes place affects the resuspension potential of fine-grained, cohesive sediments. A continuous flow, such as in a river, appears to slow the rate at which compaction effects modify the resuspension properties of cohesive sediments, when compared with similar sediments that undergo compaction in a quasi-quiescent flow, i.e., a lake. In an attempt to quantify these effects, a multiple shear stress test was conducted on a sediment bed that had been subjected to compaction under continuous flow conditions.

The sediment bed in the continuous flow experiment was prepared in the same manner as the previous multiple shear stress tests and sediment from sample location 2 was used. After initial formation of the bed, the flume was run continuously for 47 days, from July 20, 1991 until September 5, 1991, at a shear stress of about 1 dyne/cm$^2$. A short, medium-strength resuspension event was simulated on days 7, 21, 28 and 35 by increasing the shear stress to 5 dynes/cm$^2$ for two hours, after which the shear stress was decreased to 1 dyne/cm$^2$. On day 42, a complete multiple shear stress test was conducted, as described in Section A.2.1, with the exception that the maximum shear stress was 13 dynes/cm$^2$. The shear stress was then decreased to 1 dyne/cm$^2$ for five additional days and then a final 5 dyne/cm$^2$ shear test was conducted on day 47. The sediment concentration in the flume was measured daily during constant 1 dyne/cm$^2$ flow conditions. During the 5 dyne/cm$^2$ and multiple shear stress tests, water column concentrations were measured at thirty minute intervals. The sediment concentration data for this experiment are listed in Table A-4.

TABLE A-4. FLUME DATA FROM LONG TERM COMPACTION TEST

| Date | Sheer Stress (dynes/cm$^2$) | Run Time (minutes) | Concentration (mg/l) |
|---|---|---|---|
| 7/21/91 | 1 | | 66 |
| 7/22/92 | 1 | | 120 |
| 7/23/91 | 1 | | 164 |
| 7/24/91 | 1 | | 172 |
| 7/25/91 | 1 | | 292 |
| 7/26/91 | 1 | | 246 |
| 7/27/91 | 1 | | 312 |
| | 5 | 15 | 4,085 |
| | 5 | 30 | 5,440 |
| | 5 | 60 | 7,480 |
| | 5 | 90 | 8,267 |
| | 5 | 120 | 9,153 |
| 7/28/91 | 1 | | 194 |
| 7/29/91 | 1 | | 148 |
| 7/30/91 | 1 | | 112 |
| 7/31/91 | 1 | | 154 |
| 8/01/91 | 1 | | 206 |
| 8/02/91 | 1 | | 160 |
| 8/04/91 | 1 | | 152 |
| 8/05/91 | 1 | | 118 |
| 8/06/91 | 1 | | 166 |
| 8/07/91 | 1 | | 158 |
| 8/08/91 | 1 | | 174 |
| 8/09/91 | 1 | | 72 |
| 8/10/91 | 1 | | 44 |
| | 5 | 15 | 1,383 |
| | 5 | 30 | 1,547 |
| | 5 | 60 | 1,767 |
| | 5 | 90 | 1,827 |
| | 5 | 120 | 1,947 |
| 8/11/91 | 1 | | 396 |



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| TABLE A-4. FLUME DATA FROM LONG TERM COMPACTION TEST (continued) | | | |
|---|---|---|---|
| Date | Sheer Stress (dynes/$cm^2$) | Run Time (minutes) | Concentration (mg/l) |
| 8/12/91 | 1 | | 290 |
| 8/13/91 | 1 | | 234 |
| 8/14/91 | 1 | | 242 |
| 8/15/91 | 1 | | 162 |
| 8/16/91 | 1 | | 160 |
| 8/17/91 | 1 | | 134 |
| | 5 | 15 | 1,700 |
| | 5 | 30 | 1,807 |
| | 5 | 60 | 1,970 |
| | 5 | 90 | 2,010 |
| | 5 | 120 | 2,103 |
| 8/18/91 | 1 | | 270 |
| 8/20/91 | 1 | | 194 |
| 8/21/91 | 1 | | 144 |
| 8/22/91 | 1 | | 140 |
| 8/23/91 | 1 | | 66 |
| 8/24/91 | 1 | | 18 |
| | 5 | 15 | 1,623 |
| | 5 | 30 | 1,693 |
| | 5 | 60 | 1,913 |
| | 5 | 90 | 1,927 |
| | 5 | 120 | 1,957 |
| 8/25/91 | 1 | | 98 |
| 8/26/91 | 1 | | 82 |
| 8/27/91 | 1 | | 112 |
| 8/28/91 | 1 | | 78 |
| 8/29/91 | 1 | | 96 |
| 8/30/91 | 1 | | 52 |
| 8/31/91 | 1 | | 60 |
| | 3 | 15 | 515 |
| | 3 | 30 | 590 |
| | 3 | 60 | 657 |

| TABLE A-4. FLUME DATA FROM LONG TERM COMPACTION TEST (continued) | | | |
|---|---|---|---|
| Date | Sheer Stress (dynes/cm$^2$) | Run Time (minutes) | Concentration (mg/l) |
| | 3 | 90 | 750 |
| | 3 | 120 | 777 |
| | 5 | 150 | 1,443 |
| | 5 | 180 | 1,600 |
| | 5 | 210 | 1,650 |
| | 5 | 240 | 1,740 |
| | 7 | 270 | 2,100 |
| | 7 | 300 | 2,155 |
| | 7 | 330 | 2,260 |
| | 7 | 360 | 2,250 |
| | 9 | 390 | 2,813 |
| | 9 | 420 | 3,113 |
| | 9 | 450 | 3,300 |
| | 9 | 480 | 3,373 |
| | 11 | 510 | 4,407 |
| | 11 | 540 | 4,780 |
| | 11 | 570 | 5,133 |
| | 11 | 600 | 5,333 |
| | 13 | 630 | 6,707 |
| | 13 | 660 | 7,187 |
| | 13 | 690 | 8,513 |
| | 13 | 820 | 9,213 |
| 9/3/91 | 1 | | 198 |
| 9/5/91 | 5 | 15 | 1,623 |
| | 5 | 30 | 1,703 |
| | 5 | 60 | 1,773 |
| | 5 | 90 | 1,927 |
| | 5 | 120 | 1,920 |

No equipment malfunctions occurred during this experiment. Visual observations of the sediment bed in the flume indicated the presence of many small, thin worms, less than 1 cm in length, working the surface of the bed. The worms dug burrows into the bed and their heads protruded out of the bed to feed. This bioturbation formed a loose, thin layer of sediment approximately 0.2 cm thick.

No gross bed erosion occurred during the multiple shear stress at day 42, which was significantly different than the previous multiple shear stress tests during which the bed typically became unstable at about 9 dynes/cm$^2$. The bed remained level, even at 11 dynes/cm$^2$. However, during the 13 dynes/cm$^2$ portion of the test, the bed became wavy and unstable. Examination of the bed after completion of the experiment indicated that the bed had a gelatinous consistency which was nearly uniform from top to bottom.

## A.3 Data Analysis

The flume experiments described in Section A.2 produced data that can provide insight into the effects of compaction under continuous flow conditions. Sediment concentrations measured in the flume are directly related to the mass of sediment resuspended from the bed, so this data can be used to evaluate erosional effects due to compaction. The $T_d^{-m}$ term in Equation (2-1) accounts for compaction effects; the mass of sediment resuspended decreases with increasing time after deposition, which is correlated with bed compaction. However, two questions about the $T_d^{-m}$ term must be answered before applying Equation (2-1). First, at what time after deposition do compaction effects on resuspension of surficial sediments become negligible? Second, what is the value of the exponent m?

The continuous flow experiment results can be used to approximately answer the first question. Previous research has suggested that the effects of compaction on the resuspension of surficial cohesive sediments become insignificant approximately seven to fourteen days after deposition (Tsai and Lick, 1987; MacIntyre et al., 1990). Results of the continuous flow experiment indicate that bed compaction effects become negligible at seven days or less after deposition. This finding can be demonstrated by examining a time history plot of the water column sediment concentration data during the 47 day test period, see Figure A-6.

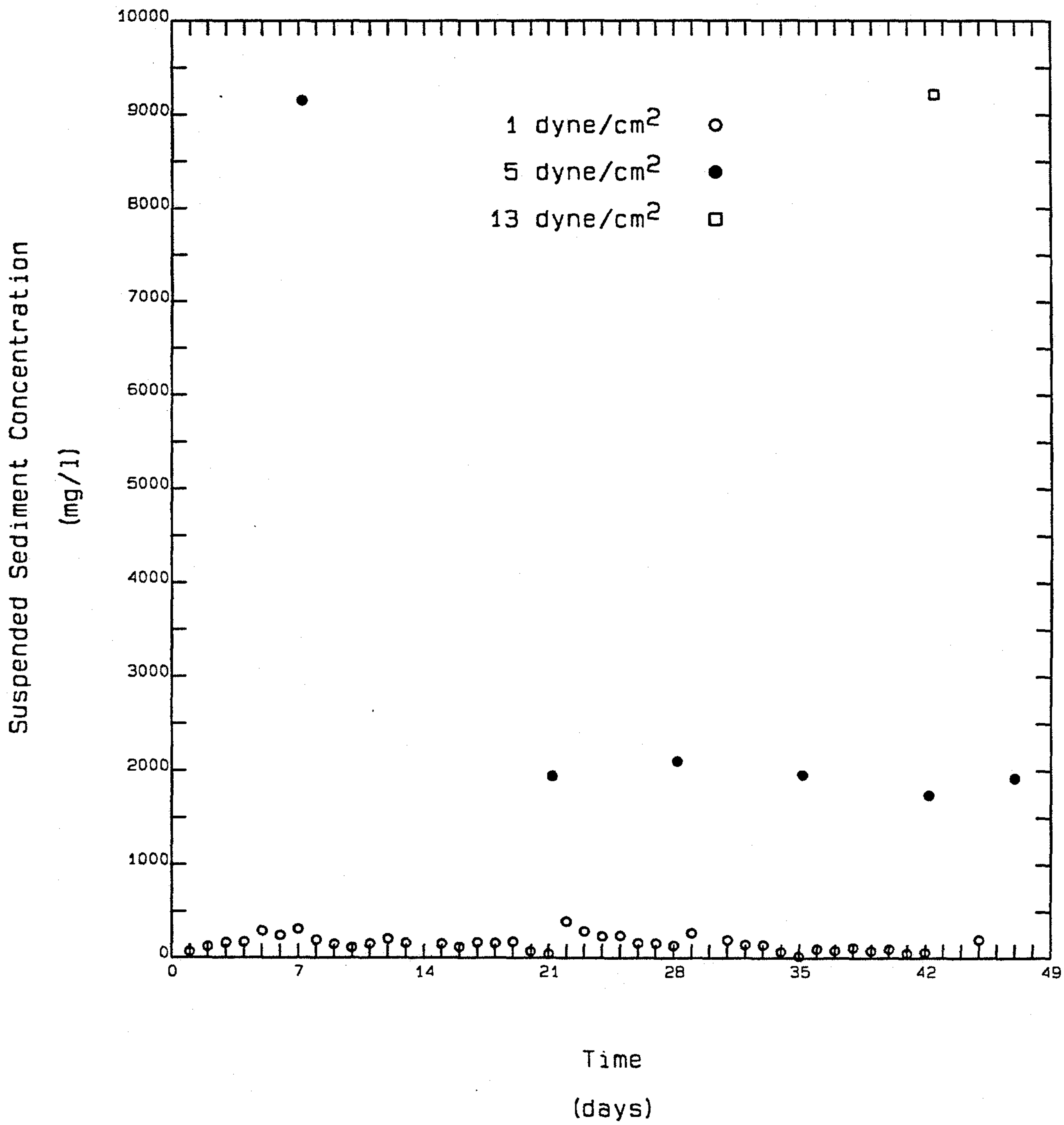


Figure A-6. Flume data from continuous flow experiment.

First, note that the sediment concentration at the 5 dyne/cm$^2$ shear stress test on day 7 is much higher than measured values at the same shear stress on days 14, 21, 28, 35, 42 and 47. After day 7, the sediment concentration for an applied shear stress of 5 dynes/cm$^2$ is very repeatable ($\pm$9% and coefficient of variation = 0.07). This result shows that the bed created in the flume has changed characteristics after the first 5 dyne/cm$^2$ resuspension event. As a result of the day 7 resuspension event, the sediment in the flume has changed from a bed created under static conditions to a bed formed in a depositional environment under continuous flow conditions.

The 5 dyne/cm$^2$ resuspension events on days 21, 28, 35, 42 and 47 had times of deposition of 14, 7, 7, 7 and 5 days, respectively. However, all five events had approximately the same mass of sediment resuspended in the flume. This result indicates that the effects of compaction on resuspension were about the same for sediments deposited for 5 , 7 or 14 days. Based on these data, a valid assumption when applying Equation (2-1) is that the maximum time of deposition, $T_{d,max}$ , of a cohesive sediment bed in a riverine environment is seven days. This statement means that all sediments in the bed with an age of seven days or greater can be assumed to be seven days old when using Equation (2-1). These results are consistent with experimental work done by Lick et al. (1995) on the effects of consolidation on resuspension of fine-grained sediments from the Fox, Saginaw and Buffalo Rivers.

Earlier flume studies on sediments deposited in a quiescent environment have shown that exponent m in Equation (2-1) has a value of approximately two (Tsai and Lick, 1987). To determine if this value is appropriate for river sediments, the multiple shear stress data was plotted as a function of compaction time, see Figure A-7. The data on this plot has been normalized with respect to shear stress, i.e.,



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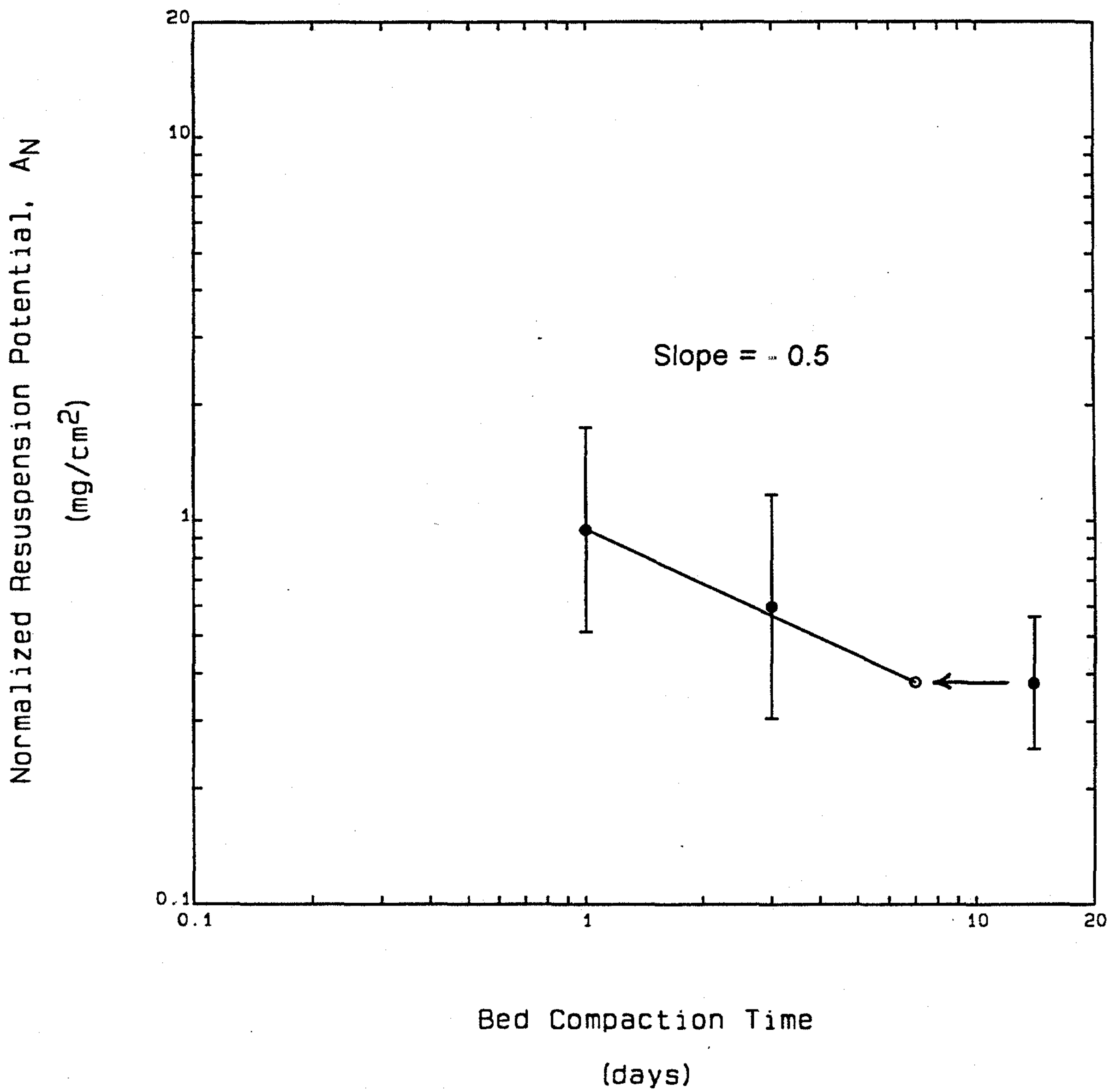


Figure A-7. Effect of bed compaction on resuspension of cohesive sediments deposited in a continuous flow environment.

$$A_N = \frac{a_o}{T_d^m} = \epsilon_M \left(\frac{\tau - \tau_o}{\tau_o}\right)^{-n} \qquad \text{(A-1)}$$

where $A_N$ = normalized resuspension potential (mg/cm$^2$) and $\epsilon_M$ = measured mass of eroded sediment per unit area (mg/cm$^2$). This normalization allows resuspension data obtained at different shear stresses to be compared. Furthermore, the slope of a log linear regression line, for $A_N$ as a function of $T_d$, corresponds to the exponent m, which can be seen from a log transform of $A_N$,

$$\log A_N = \log a_o - m \log T_d \qquad \text{(A-2)}$$

Using the finding from the continuous flow experiment that compaction effects are negligible after about seven days of deposition, the assumption can be made that the log mean of the fourteen day data from the multiple shear stress test is approximately equal to what would have been measured at seven days. Transferring the fourteen-day log mean value to seven days on Figure A-7 and then performing a linear regression analysis through the log means at 1, 3 and 7 days results in a slope of -0.5, or m = 0.5. Regressing a line through the 1,3 and 14 day log mean values would result in m = 0.35. Lick et al. (1995) reported values of m (which was denoted as n in that paper) ranging between 0.8 and 1.1 for Fox, Saginaw and Buffalo River sediments, providing further validation of the present analysis.

## APPENDIX B
## FIELD STUDY METHODS AND RESULTS

### B.1 Field Study Description and Procedures

A field study was conducted during November, 1990 to measure the in situ resuspension potential of fine-grained, cohesive sediments in the Upper Hudson River. Surficial sediment cores were collected at twenty locations in the Thompson Island Pool (Reach 8), see Figure B-1. Samples were also collected at eight locations (two sampling sites per location) in the seven reaches downstream of the Thompson Island Pool, see Figure B-2. The cores were collected from shallow, nearshore areas where the sediment bed is primarily composed of cohesive sediments with varying amounts of fine sand. A five-inch diameter push core was used to collect the samples, which were typically six to eight inches long.

The cores were transported to shore within one hour of collection for testing in a portable resuspension device, commonly called a shaker, see Figure B-3. The procedure described in Tsai and Lick (1986) was used to measure the in situ resuspension potential of the collected cores in the following manner. Three surficial cores were collected at each sampling location and each of the three cores was tested at a different effective shear stress. Generally, the cores at each site were tested at shear stresses of 5, 9 and 11 dynes/cm$^2$. However, twelve of the sampling locations in the Thompson Island Pool were tested at shear stresses of 5, 7 and 9 dynes/cm$^2$. The in situ resuspension potential data resulting from this study are tabulated in Table B-1.

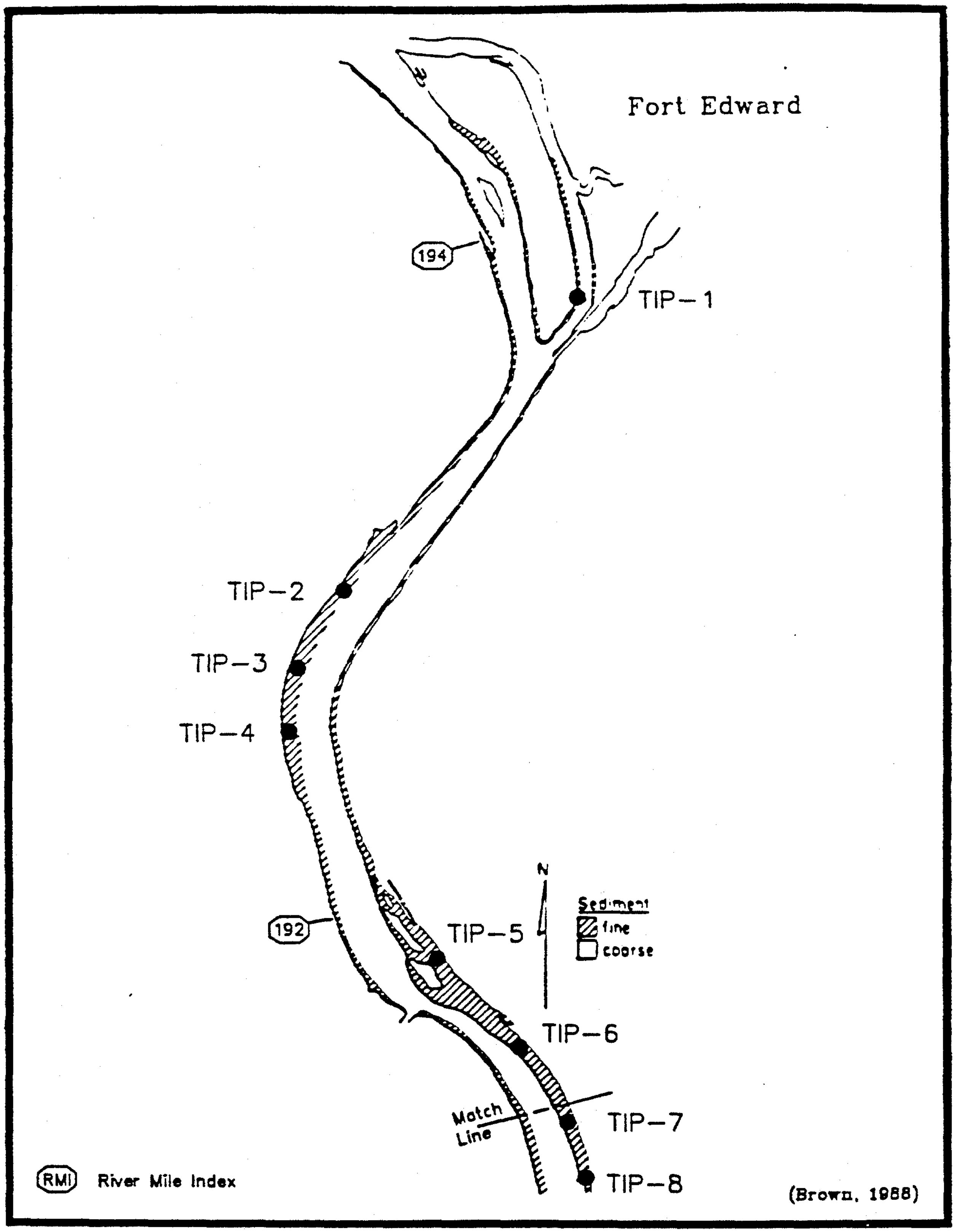


Figure B-1a. Locations of in situ resuspension potential stations in the Thompson Island Pool.

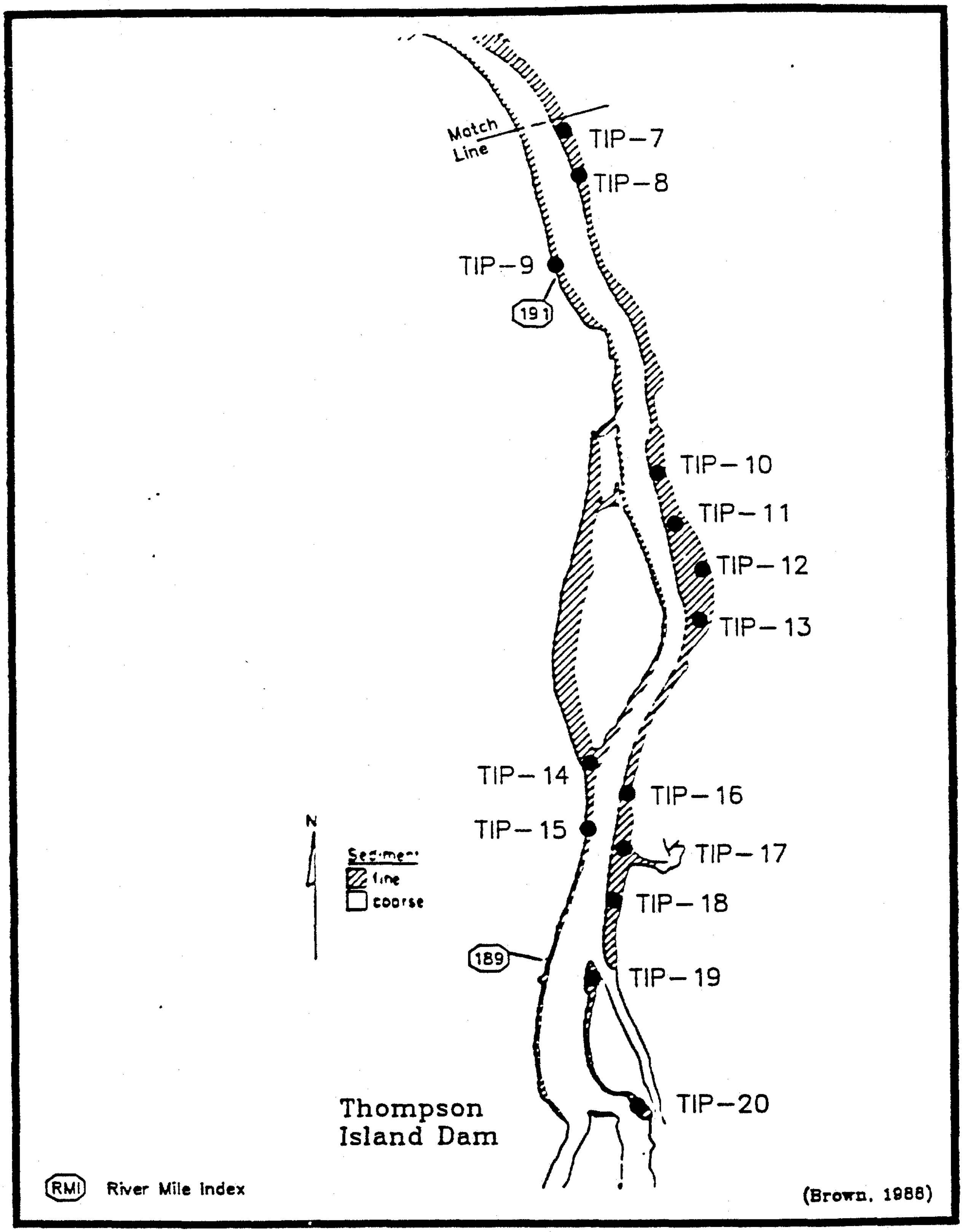


Figure B-1b. Locations of in situ resuspension potential stations in the Thompson Island Pool.

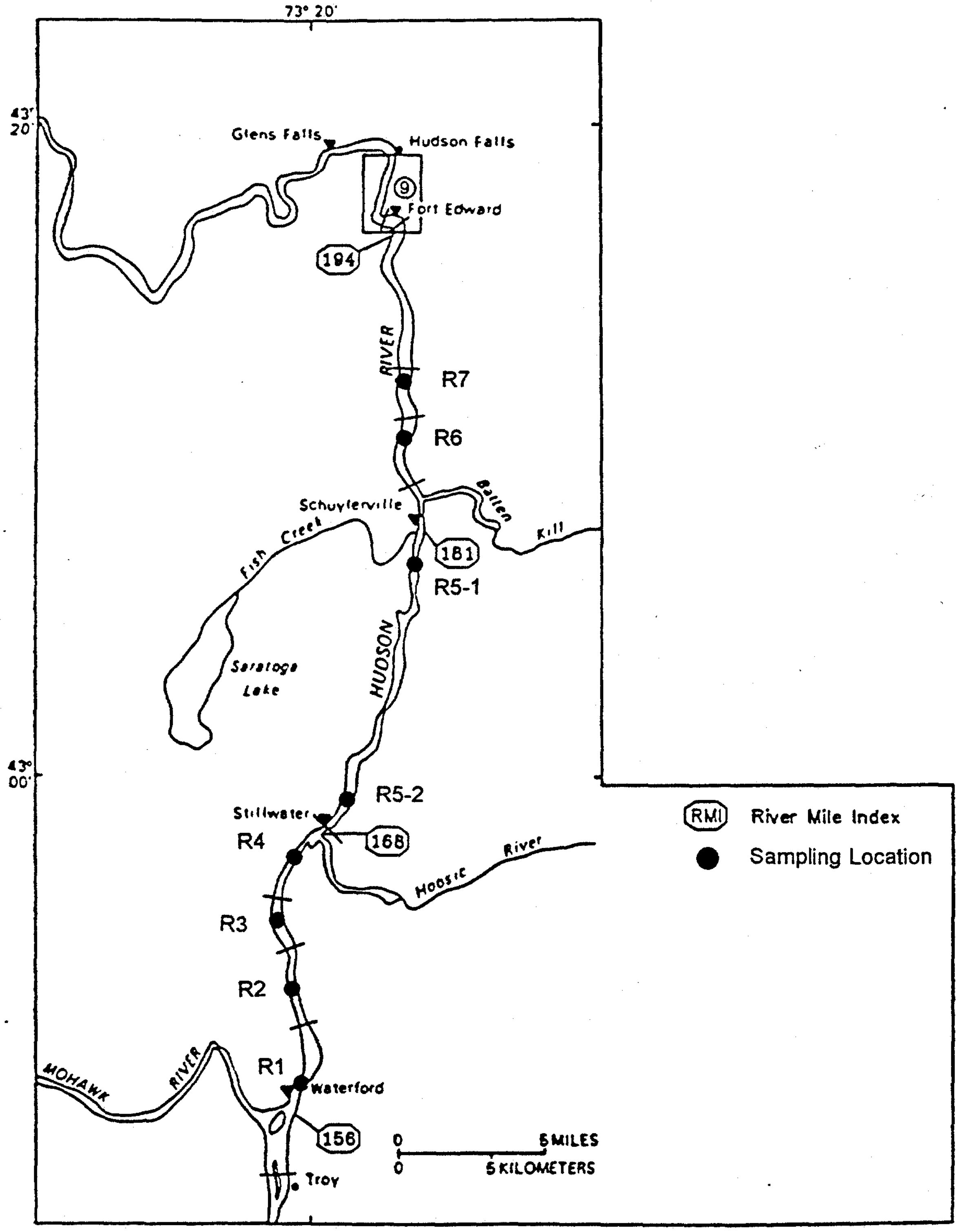


Figure B-2. Locations of in situ resuspension potential stations from Thompson Island Dam to Troy Dam .

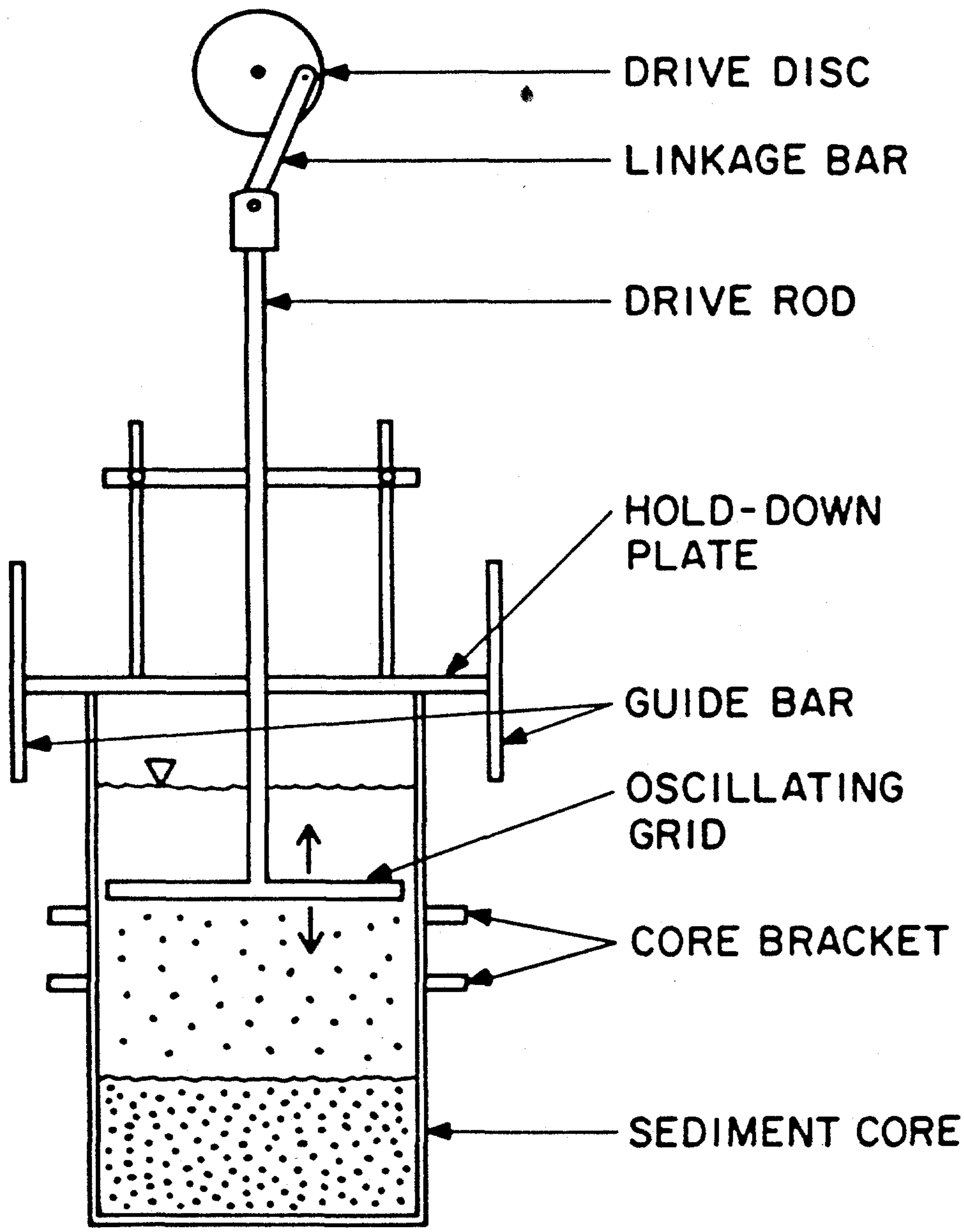


Figure B-3. Schematic of the shaker.

TABLE B-1. RESUSPENSION POTENTIAL STUDY SUMMARY

| Station | Depth (Ft.) | Resuspension Potential (mg/cm$^2$) $\tau=5$ | $\tau=7$ | $\tau=9$ | $\tau=11$ | Sediment Description |
|---|---|---|---|---|---|---|
| TIP-1 | 5 | 0.11 | - | 3.76 | 13.24 | Fine sand to silt, grass and weeds growing on bottom, very compact, difficult to core, most of the bottom was hard but not gravel. |
| TIP-2 | 5 | 0.41 | - | 2.05 | 7.20 | Mixture of silt and sand with more silt on surface and more sand under surface. Some organic on surface, but not as much as TIP-4. ~80 percent sand in these cores. |
| TIP-3 | 5 | 1.06 | - | 3.70 | 13.91 | Very soft fine sand to silt, lots of organic flocs on surface, resuspends very easily, cores taken on outer bend of river, very shallow area, lots of sediment deposition. |
| TIP-4 | 8 | 0.29 | - | 5.57 | 16.97 | Soft mud, very silty, organic debris on surface, cohesive like a gel, lot of zooplankton, some sand mixed in. |
| TIP-5 | 6 | 0.68 | - | 3.54 | 8.95 | Very silty, soft, lots of organic debris, not as much flocculation, a lot of fine sand mixed in, a few roots and some zooplankton. |
| TIP-6 | 10 | 0.35 | - | 4.33 | 22.18 | Silt, some fine sand, lots of organics, fibers, loose flocs. |
| TIP-7 | 8 | 0.64 | - | 9.7 | 12.96 | Silt, some organics and fiber. |
| TIP-8 | 5 | 0.06 | - | 3.71 | 0.47 | Coarse sand, difficult to core, some gravel and organic debris, very little organic debris. |
| TIP-9 | 14 | 0.21 | 7.05 | 11.02 | - | Soft mud, a lot of roots, loose flocs. |
| TIP-10 | 7 | 1.82 | 10.26 | 12.21 | - | Soft mud, loose flocs, some zooplankton and wood fiber, easy to resuspend, sediment bed is patchy mud/gravel. |
| TIP-11 | 9 | 4.26 | 5.23 | 8.74 | - | Soft mud, loose flocs. |

| TABLE B-1. RESUSPENSION POTENTIAL STUDY SUMMARY (continued) | | | | | | |
|---|---|---|---|---|---|---|
| | | Resuspension Potential (mg/cm$^2$) | | | | |
| Station | Depth (Ft.) | $\tau=5$ | $\tau=7$ | $\tau=9$ | $\tau=11$ | Sediment Description |
| TIP-12 | 7 | 2.52 | 13.79 | 15.70 | - | Very soft mud, loose flocs, small amount of fibers and wood, some zooplankton. |
| TIP-13 | 11 | 2.37 | 14.29 | 12.52 | - | Soft mud, some bottom plants, zooplankton, some wood chips and fiber. Sediment bed has steep slope from shore and changes rapidly from mud to gravel. |
| TIP-14 | 6 | 3.48 | 8.44 | 21.37 | - | Soft mud, loose flocs. |
| TIP-15 | 5 | 1.28 | 5.46 | 10.23 | - | Soft mud, loose flocs, wood fibers, lots of organics, some zooplankton. |
| TIP-16 | 5 | 1.23 | 2.93 | 22.67 | - | Soft mud, loose flocs, lots of zooplankton and worms, some wood fiber, resuspends very easily. |
| TIP-17 | 11 | 3.24 | 6.60 | 28.84 | - | Soft mud, loose flocs, some wood fiber, small amount of dead grass, resuspends very easily. |
| TIP-18 | 8 | 1.14 | 12.68 | 9.74 | - | Soft mud, loose flocs, easily resuspended, organic fibers perhaps which the flocs attach to; some organic debris, wood fibers and roots. |
| TIP-19 | 7 | 8.30 | 14.39 | 25.25 | - | Soft mud with loose flocs, lots of organic debris including wood chips, fiber and dead weeds, very easily resuspended. |
| TIP-20 | 8 | 0.40 | 0.99 | 8.32 | - | Soft mud, flocs, some wood fiber, tuberous roots throughout cores, low amount of resuspension, cores surface layers were very irregular due to roots, sediment was fairly compact at bottom of core. |
| R7-E | 6 | 5.78 | - | 6.54 | 43.99 | Fine sand, silty surface with some organic growth, some flocculation on surface, clay in lower portion of core. Some snails on surface. Clay has grey color. |

| TABLE B-1. RESUSPENSION POTENTIAL STUDY SUMMARY (continued) | | | | | | |
|---|---|---|---|---|---|---|
| | | Resuspension Potential (mg/cm$^2$) | | | | |
| Station | Depth (Ft.) | $\tau=5$ | $\tau=7$ | $\tau=9$ | $\tau=11$ | Sediment Description |
| R7-W | 12 | 1.16 | - | 2.36 | 9.29 | Fine sand, not much flocculation, very little organic or growth. Very uniform core, fine sand with a little silt. No zooplankton, but some very small clams below the surface. Sand has reddish brown color. |
| R6-E | 10 | 3.16 | - | 8.00 | 13.66 | Loose flocs on surface, silt mixed with sand in upper inch, clay below that. |
| R6-W | 7 | 8.85 | - | 19.63 | - | Clay to silt, loose flocs, not much debris or organics, some small roots on surface, very soft. |
| R5-1E | 7 | 0.88 | - | 6.80 | 60.78 | Fine sand, leaf debris, dead weeds. |
| R5-1W | 7 | 1.26 | - | 12.49 | 44.57 | Clay to silt, leaf debris, dead weeds, a little organics. |
| R5-2E | 5 | 4.87 | - | 25.44 | 47.81 | Sandy, very fine, silt mixed in, very little organic debris. |
| R5-2W | - | 4.12 | - | 36.24 | 38.54 | Fine sand and silt, fairly soft, no organic debris, not much flocculation on surface. |
| R4-E | 5 | 19.40 | - | 62.52 | 56.91 | Fine sand with clay, fairly compact, not much organic debris. |
| R4-W | - | 11.76 | - | 30.99 | 44.42 | Fine sand and clay with a lot of organic debris mixed in. |
| R3-E | 7 | 6.16 | - | 29.59 | 44.00 | Fine sand with some fine silt or clay mixed in, not much organic debris. |
| R3-W | 7 | 1.16 | - | 27.73 | 48.59 | Fine sand with some clay. Lots of zooplankton and little shrimp, some organic debris and weeds growing. |
| R2-E | 5 | 1.57 | - | 23.80 | 43.17 | Fine sand in top layer with a light colored clay on the bottom layer. |
| R2-W | 6 | 0.40 | - | 2.31 | 23.03 | Sand and silt, not much organic on the surface, very little flocculation. |
| R1-E | 6 | 12.04 | - | 20.35 | 94.91 | Fine sand and silt. |
| R1-W | 7 | 1.69 | - | 13.25 | 59.17 | Sand and silt mixed together. |

## B.2 Data Analysis

The objective of the field study was to obtain data that could be used to determine values of $a_0$ and n in Equation (2-1) that are appropriate for cohesive sediments in the Upper Hudson River. Studies in other rivers have shown that the exponent n can range from two to three (Gailani et al., 1991; Ziegler and Nisbet, 1994). Examination of the resuspension potential data from the eight reaches of the Upper Hudson River indicated that setting n equal to three for all of the reaches was a valid approximation.

The only remaining parameter in Equation (2-1) that must be determined is the site-specific constant, $a_0$. The flume experiments described in Appendix A were used to set values of $\tau_0$, m and $T_{d,max}$. The assumption will be made that the depositional age of collected cores was seven days, i.e., $T_d = T_{d,max,}$ in using the resuspension data to determine $a_0$ in Equation (2-1). This assumption is valid because the cores were collected at a time when negligible deposition had occurred during the previous three to four weeks. Thus, the value of $a_0$ for each of the collected cores was calculated using a manipulated version of Equation (2-1)

$$a_o = T_{d,max}^{m} \left(\frac{\tau - \tau_o}{\tau_o}\right)^{-n} \epsilon_M = 2.65 \ (\tau - 1)^{-3} \ \epsilon_M \qquad \text{(B-1)}$$

where $T_{d,max}^{m} = 7^{0.5} = 2.65$ and $\epsilon_M$ = measured resuspension potential for a particular core (mg/cm$^2$).

As in any riverine system, variability in cohesive bed composition resulted in $a_0$ values ranging over nearly two orders of magnitude for the cores tested in the Upper Hudson River. The goal then was to determine the mean value of $a_0$ that was representative of cohesive sediments throughout the system; system average values have been used successfully in other sediment transport studies (Gailani et al., 1991; Ziegler and Nisbet, 1994). However, significant variation of $a_0$ between the various reaches of the Upper Hudson River made it necessary to determine the mean value of $a_0$ for each reach instead of calculating a global average for the entire system. The reach average $a_0$ values for the Upper Hudson River are presented in Table B-2. Note that cores from two stations in the Thompson Island Pool (TIP-8 and TIP-19) were not included in the averaging process because the $a_0$ values for the cores at those locations appeared to be outliers. Examination of the visual description of these cores supports this decision.

TABLE B-2. STATISTICAL INFORMATION ON $a_0$ VALUES BY REACH

| Reach | Mean $a_0$ (mg-day$^{1/2}$/cm$^2$) | Standard Deviation | Sample Size |
|---|---|---|---|
| 8 | 0.071 | 0.062 | 54 |
| 7 | 0.079 | 0.087 | 6 |
| 6 | 0.135 | 0.135 | 5 |
| 5 | 0.116 | 0.058 | 12 |
| 4 | 0.340 | 0.266 | 6 |
| 3 | 0.140 | 0.067 | 6 |
| 2 | 0.067 | 0.047 | 6 |
| 1 | 0.192 | 0.165 | 6 |