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Suspended Sediment Analysis for Three P.E.I. Streams Using Sediment Rating Curves

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ABSTRACT

Caissie, D. and J. Conlon. 1989. Suspended Sediment Analysis for Three P.E.I. Streams Using Sediment Rating Cuves. Can. Tech. Rep. Fish. Aquat. Sci. No. 1704. 16p.

The relation between daily discharge and the suspended sediment concentration was studied using regression analysis for three Prince Edward Island streams. Using the observation from the sampled days, the non linear model was considered for the whole period of observation and annually. The correlation coefficients (R^2) of this study were consistent with the coefficients of previous studies.

RÉSUMÉ

Caissie, D. and J. Conlon. 1989. Suspended Sediment Analysis for Three P.E.I. Streams Using Sediment Rating Cuves. Can. Tech. Rep. Fish. Aquat. Sci. No. 1704. 16p.

L'analyse de régression a été utilisée afin de trouver une relation entre le débit journalier et la concentration des sédiments en suspension de trois ruisseaux à l'Ile-du-Prince-Edouard. Le modèle non linéaire a été considéré en utilisant les données des journées échantillonées sur toute la periode d'observation et annuellement. Les coefficients d'explication (R^2), étaient semblables à ceux des études précédentes.

1. INTRODUCTION

Concurrent with man's increasing activity in drainage basins we often experience declining fish populations in our lakes and rivers. The explanation is frequently associated with pollution in the form of acidic rain, toxic wastes and the decomposition of organic matter. What is not as well documented however is the impact of high levels of inorganic sediment, (particles smaller than 0.83mm., Everest et al. 1987), on aquatic life and, in particular, on salmonid fishes. Inorganic sediment, in high concentrations, can be a harmful pollutant during all freshwater stages of the salmonid life cycle, (Cordone and Kelley, 1964). These sediments may be in suspension (suspended sediment) or they may form a deposit on the gravel bed.

The objectives of this study are to evaluate the suspended sediment characteristics of three river basins in P.E.I., and to select and evaluate a sediment model to enable us to better predict sediment loads and their affect on salmonids.

A sediment rating curve in the form of a mathematical relationship between stream discharge and suspended sediment concentration is developed for each river basin. This will be used to predict sediment concentration for days when only stream discharge data are available.

It is rare to find a river system with a good database on both salmonid populations and sediment loads to study the sediment-salmonid interactions. For this reason we have chosen to analyse the sediment process alone and then to use some of the available literature on sediment-salmonid interactions to study the state of the problem on three PEI streams.

Chapter 2 is devoted to a discussion of the different sediment transport phenomona. Background information on modelling the sediment as a process is also discussed in this chapter. Chapter 3 presents a numerical analysis of three PEI streams using regression analysis. In this chapter the sediment characteristics of each basin are presented along with some information on sediment-salmonid interactions. The last chapter, chapter 4, is devoted to conclusions and recommendations resulting from this study.

2. SEDIMENT TRANSPORT : A REVIEW

Before going into detail on the sediment transport phenomenon, a general description of the forces acting on the particles is appropriate. Basically there are two forces acting on a particle on the stream bottom as shown in Figure 2.1 (Graf, 1984). The first is the drag force (F_D), a horizontal force in the direction of the flow. The second force is the lift force (F_L), an upward vertical force. These random forces are caused by the turbulence of the flow. The inital motion depends on factors such as the size of the particles, the cohesion between them and the amount of turbulence. When the turbulence is high enough that the uplifting force exceeds the weight (W) of the particle, motion results. For cohesive material such as clay, the uplifting force has to overcome not only the weight of the particles but also the cohesive force between them.

The uplifting force acting on the particles, which initiates motion, introduces the concept of critical velocity. Critical velocity is the velocity beyond which the resultant of the drag force and the uplifting force is particle motion. There are three different types of motion (or transport phenomena); bed load transport, suspended sediment transport and saltation.

Saltation can be broadly defined as the movement of particles in a series of short hops or bounces along the bed.

When the particles do not go into suspension but move by "rolling" on the stream's bed, the process is referred to as bed load transport. The bed load transport phenomenon is dependent on discharge, occurring only when discharge is greater than a certain threshold, generally during spring flood events. Such a zero/non-zero process is called an intermittent process or a spell-process.

The last type of motion, the suspended load, describes particle motion initiated by the turbulence forces. Because of their small size the particles can stay in the water column for several hours or several days. The rate at which the particles settle is dependent on their size and settling velocity. This is explained by Stokes' Law (Graf, 1984). The suspended load can come from two different sources; the wash load and the suspended bed material load. The suspended bed material load, which is composed of bed material, is the material that gets into suspension as discharge increases. The wash load comes from erosion of the banks, soil erosion from nearby fields or from any other material which does not originate in the stream. Most of the wash load material is transported by precipitation runoff. The wash load is highly dependent on the topography, the soil type, the ground cover, the form and intensity of precipitation and to some extent the season. All of these parameters determine the sediment supply of the basin. The material from the wash load can be quite different in composition than the suspended bed material load because of its origin.

For basins of high gradient, the erosional process can be important during precipitation. Agricultural activities and roadway practices can also be important contributors to the erosional process of the basin and therefore to the sediment supply. For northern countries like Canada, snow can also be a good sediment transport mechanism as outlined by Julien and Frenette (1985).

If one studies all of the transport phenomena together, then the analysis is on the total load. The total load is the sum of the wash load, suspended bed material load and the bed load. The analysis of the total load can be carried out through a mass balance or a budget analysis of a control volume on a section of the stream. All of the above mentioned tranport phenomena differ in the complexity of the analysis. The suspended sediment load is often used in sediment analysis because it can be obtained through water sampling.

Abrahams and Kellerhals (1973) studied the suspended sediment-discharge relationship (sediment rating curves) for some prairie rivers and they found some correlation coefficients (R^2) varing from 0.56 to 0.87. Having 87% of the variance of the suspended sediment thus explained makes it possible to study suspended sediment through the analysis of discharge. The analysis of discharge is relatively simple and economical. In their study they noted that log transformed data provided a better fit for the sediment-discharge model than non-transformed data.

Hansen and Bray (1987) found some correlation coefficients ranging from 0.33 to 0.61 for annual analysis of the Kennebecasis River in NB. When all of the years of data were analysed together (1970-1979, excluding 1976 when no data were available) they found an overall correlation coefficient of 0.32. Hansen and Bray (1987) also found that partitioning the year into season, month, period of rising stage and period of falling stage did not improve the correlation.

Pol (1988) studied the Wilmot River in PEI and found some correlation coefficients ranging from 0.36 to 0.65 between the daily mean discharge and daily mean suspended sediment concentration for the years 1972, 1976, 1980 and 1984. He also noted that 88% of the mean total sediment load can be explained by the mean monthly total discharge. Consistent with these referenced studies the sediment rating curve analysis will be carried out in this study.

3. NUMERICAL ANALYSIS

3.1 Study Region

The quantity of material in suspension varies between river systems depending on the soil type and the topography of the basin. This, coupled with intensive land utilisation, is responsible for high suspended sediment load in PEI streams. The understanding of these high suspended sediment loads for PEI is very important for the overall management of inland fisheries. Furthermore, it can be accomplished through the development of a relationship between discharge and suspended sediment concentrations, (or a sediment rating curve). The sediment rating curves can be developed on an annual basis or for all of the years of observation. In this study the two will be considered and compared.

The rivers chosen for this analysis are: Emerald Brook (01CB006), North Brook (01CB005) and Smelt Creek (01CA004) (Figure 3.1). The area encompassing these rivers receives approximately 1100 mm of precipitation annually. The mean daily temperature is 18 °C for July and -7 °C for January (Fisheries and Environment Canada, 1978).

Emerald Brook has a drainage area of 5.59 km^2 and discharges into the Dunk River. North Brook with a drainage area of 12.9 km^2 also discharges into the Dunk River. Smelt Creek, with a drainage area of 17.3 km^2 is tributary to the Gulf of Saint Lawrence. These basins are low gradient, typically less than 1%.

3.2 Sediment-Salmonid Interactions

The following is a brief description of some studies pertaining to sediment-salmonid interactions. For more detailed information the reader is referred to Cordone and Kelley (1961), Chavalier et al. (1984) and Everest et al. (1987)

Sediment-salmonid interaction involves physical, biological and chemical components which often necessitates multidisciplinary studies. Sediment concentration can affect salmonids at different stages of their freshwater life. The effects vary depending on many parameters including: age, species and life stage. It has been shown that sediment in high concentrations can be harmful to fish (Everest et al., 1987). But it has also been shown that sediment in low concentration constitutes a good means of transporting food (Everest et al., 1987). Therefore, the role that sediment plays in the overall aquatic ecosystem is complicated to assess.

Historically, researchers have analysed sediment-salmonid interactions from two different approaches: laboratory and field studies. Some of the field studies describe fish population responses pre- and post- massive sedimentation (Coats et al., 1985). Such studies of massive sedimentation however do not show the cumulative and destructive effects of lesser amounts of sediment being continually deposited in rivers.

Other field studies were carried out by measuring the survival of planted fish in relation to the degree of sedimentation. By studying many factors affecting a fish population, McCrimmon (1954) showed that the amount of sedimentation in riffle areas largely determined the survival of young planted Atlantic salmon (Salmo salar) for Dufferin Creek in Ontario. The significant factor was the increased exposure to predation due to the elimination of shelter which would normally have been available in the riffle.

Everest et al. (1987) found that most studies of bottom sedimentation are carried out by measuring the percentage of sediment in spawning gravels and / or riffle areas to a depth of approximately 10 to 12 cm. The higher the percentage of sediment, the lower the egg-to-fry survival. This can be the result of: "1) suffocation of eggs and alevins, 2) reduced intergravel water flow and dissolved oxygen content, and 3) physical barrier to emergence" (Everest et al., 1987).

It was possible to demonstrate in the laboratory that the suspended sediment reduces the permeability of the gravel; therefore the intergravel water flow and dissolved oxygen are also reduced (Dakin 1965, Wickett 1954). Accompanying this low dissolved oxygen content was either direct mortality or the delay in the development of fish (Cooper 1965).

Hynes (1973) concluded that the upper tolerable level of suspended sediment is 80 mg/l. Any amount greater than this threshold is "...bound to have adverse biological consequences". According to Herbert and Merkins (1961), rainbow trout (Salmo gairdneri) began to die when concentrations of kaolin (a type of clay) reached 90 mg/l. Noggle (1978) found that coho salmon fingerlings (Oncorhynchus kisutch) had difficulty capturing their prey when the suspended sediment concentration was in the range of 300 to 400 mg/l.

Redding et al. (1987) studied suspended sediment concentrations of 2000 to 3000 mg/l on yearling coho salmon and steelhead trout (Salmo gairdneri). They found that concentrations of this level were stressful (as noted by temporarily elevated plasma cortisol concentrations) to the fish and that feeding rates and resistance to disease were reduced. Their conclusion was that the physiological changes were sublethal. An interesting aspect of their study was the duration of the concentration: 0, 3, 9, 24 and 48 hours.

In the present study both the literature data on suspended sediment-salmonid interactions and the data on suspended sediment concentration in rivers will be considered. This will give an indication of the suspended sediment concentration for selected Gulf Region rivers and the possible effects on fish. The 80 mg/l proposed by Hynes (1973) will be used as a guide in this study, and we will assume that all concentrations exceeding this level constitute a stressful environment.

3.3 Suspended Sediment Characteristics

The analysis was carried out using the Environment Canada database on suspended sediment (Environment Canada, 1967..1986). Table 3.1 presents the suspended sediment concentration characteristics for the three basins. The annual load for Emerald Brook ranges from 17.2 to 456 tonnes (excluding 1974 which has only a partial data record), with a mean value of 161 tonnes. The suspended sediment yield, which is the mean annual suspended contribution per unit area, is 29 tonnes/km^2. This quantity also reflects the sediment supply of the basin. The maximum daily suspended sediment (sampled) was measured at 1110 mg/l for Emerald Brook in 1981. North Brook shows an annual load ranging from 56.6 to 931 tonnes (excluding the 1971 partial record), with a mean of 271 tonnes, while Smelt Creek shows an annual load ranging from 62.7 to 376 tonnes (excluding 1967 and 1973 partial records), and a mean of 183 tonnes. The suspended sediment yield was calculated at 21 tonnes/km^2 for North Brook and 11 tonnes/km^2 for Smelt Creek. The maximum daily suspended sediment was measured at 158 mg/l for Smelt Creek while North Brook shows a maximum value of 1720 mg/l. This latter value is in the range of some of the concentrations reported by different researchers on sediment-salmonid interactions discussed in previous chapters.

Smelt Creek has the lowest sediment yield (at 11 tonnes/km^2) of the three analysed basins while Emerald Brook shows the highest sediment yield at 29 tonnes/km^2. From Table 3.1 it can be observed that 19 of the 31 years of suspended sediment record had a maximum daily concentration exceeding the 80 mg/l level identified by Hynes (1973).

3.4 Sediment Rating Curves

The sediment characteristics for each basin provide pertinent information on the sediment supply of the basin. To better understand the suspended sediment transport phenomenon as a modelling process, one has to be able to correlate this process with other hydrological parameters. Non-linear regression analysis (Yevjevich, 1972) was carried out between daily suspended sediment concentration (C) and daily discharge (Q). The sediment rating curve is in the form of:

$$C = b\,Q^{m} \qquad (3.1)$$

with b and m being regression constants.

A regression of this form was applied for all of the sample values for each river. Some equations were also developed on an annual basis.

Table 3.2 presents the results for Emerald Brook, where the correlation coefficient ranges from 0.007 to 0.67 annually. An equation developed using all of the sampled days between 1974 to 1981 shows a correlation coefficient of 0.30 . Hansen and Bray (1987) mentioned that even if the R^2 is highly variable from year to year, the exponent (m), which they referred to as the process related variable, is sometimes less variable in time. This was not true for Emerald Brook where the exponent (m) ranged from 0.223 to 1.31. The results on North Brook and Smelt Creek are similar to those for Emerald Brook. The R^2 for North Brook ranges from 0.04 to 0.68 for the annual analysis while the R^2 was 0.36 for the period of record data from 1971 to 1986. The R^2 for Smelt Creek ranges from 0.21 to 0.62 with a value of 0.26 when all of the years of observation are analysed. The exponent (m) for these two rivers is also highly variable with values ranging from 0.286 to 1.77 for North Brook and 0.209 to 0.892 for Smelt Creek.

Five figures are presented to illustrate the observed data in relation to the regression equation. Figure 3.2 presents the relationship between the observed data and the equation for the best R^2 for Emerald Brook which occured in 1978.

Figure 3.3 illustrates the second best R^2 for North Brook, on an annual basis while Figure 3.4 presents a low R^2. The best R^2 for Smelt Creek is presented by Figure 3.5. It can be observed from this figure that the good correlation coefficient is probably due to the limited number of observations. Figure 3.6 presents the analysis of all of the data on Smelt Creek (from 1967 to 1972).

In general, the R^2 varies between a very small value to a maximum value of approximatly 66% for the analysis on an annual basis and for the watercourses considered in the analysis. If all the years of data are considered in one equation for each river, approximatly 30% of the suspended sediment concentration phenomenon can be explained by discharge.

The results of this study are consistent with the study by Hansen and Bray (1987). They found a maximum R^2 of 0.61 for the analysis on an annual basis, and they also noted that 32% of the suspended sediment concentration phenomenon is explained by discharge if all of the observed data are considered.

In order to make use of the sediment rating curves, using only one equation as a predictive tool for suspended sediment modelling, a better understanding of the phenomenon is needed. Indeed, having 30% of the suspended sediment concentration explained by discharge is not very significant, even if statistically (for a certain confidence level) it would appear to be. Partitioning the data annually improves the R^2 for some years but worsens it for others (Table 3.2). This means that the sediment rating curve analysis can be used during the years of high R^2 while some other method will have to be used when R^2 is less.

Using variables other than discharge or including more variables in the regression analysis is one method to better explain the suspended sediment concentration phenomemon. An alternative variable that may influence the suspended sediment is the daily precipitation. The bivariate model including both discharge and precipitation is also another alternative that could be investigated.

The sediment rating curves using regression analysis described above were established for the sampled days only. Figure 3.7 illustrates the time series of both the daily suspended sediment concentration and the daily discharges for 1981 on Emerald Brook. Note that the time series for the suspended sediment concentration consists of both sampled and estimated data. Although the R^2 for 1981 for Emerald Brook was only 0.32, this figure shows a good relationship between the two time series. This same figure also shows very high suspended sediment concentrations during the month of Febuary (1110 mg/l) and November (363 mg/l). During that year the maximum value of 80 mg/l proposed by Hynes (1973) was exceeded twelve times. The duration of these high suspended sediment concentrations is also important (Redding et al. 1987). In March the concentration exceeded 80 mg/l for 8 days (Figure 3.7).

4. CONCLUSIONS AND RECOMMENDATIONS

For the three study streams, suspended sediment concentration could not be analysed with precision using discharge data only. The suspended sediment rating curves (daily suspended sediment concentration vs discharge) for Emerald Brook, North Brook and Smelt Creek had correlation coefficients (R^2) of 0.30, 0.36, and 0.26 respectively, rendering our model inconclusive. Partitioning the data annually did improve the R^2 up to approximatly 60% for some years while for others the correlation coefficient was as low as 0.007. However, care should be taken when data are partitioned annually because a high R^2 is sometimes due to the limited number of observations (as in this case). In terms of confidence intervals, a high correlation coefficient based on only a few observations is no better than many observations with a low R^2.

For future studies relating the suspended sediment to other hydrological parameters, daily precipitation or mean antecedent precipitation could be investigated as the independent variable. Another possible model is the bivariate regression analysis using both the daily discharge and a second variable involving precipitation. Different activities on the drainages basins could also affect the suspended sediment concentration at different times of the year. These activities, such as agricultural and roadway practices, make the analysis more complex and less economical because of the increased number of variables involved.

Joint monitoring programs of both suspended sediment concentration and fish population dynamics are needed to enable us to better understand the two phenomena and their interactions. This could be possible using Environment Canada's sediment survey program in the Gulf Region. Salmonid populations could be measured near one of these stations in order to estabish databases on both sediment loads and salmonid populations. Some attempt might be made to relate the occurrence and duration of high levels of suspended sediment to fish spawning success, benthic production, and changes in habitat availibility.

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TABLE 3.1 Suspended sediment characteristics for Emerald Brook, North Brook and Smelt Creek, Prince Edward Island.

Year	Maximum daily suspended sediment (mg/l)			Suspended sediment load (tonnes)		
	Emerald Bk.	Smelt Ck.	North Bk.	Emerald Bk.	Smelt Ck.	North Bk.
1967		43 [1]			N/A	
1968		38			123	
1969		29			62.7	
1970		30			86.8	
1971		81	226 [2]		264	N/A
1972		76	456		376	931
1973		158 [3]	153		N/A	270
1974	15 [4]		782	N/A		188
1975	16		45	17.2		56.6
1976	111		51	86.1		84.5
1977	137		84	101		134
1978	41		54	70.0		168
1979	342		706	333		772
1980	90		320	60.6		155
1981	1110		240	456		233
1982			64			72.8
1983			131			83.5
1984			120			115
1985			151			83.8
1986			1720			721
MEAN				161	183	271

NOTES:
1 Oct 18 - Dec 31
2 July 17 - Dec 31
3 Feb - Oct (Intermittent Operation)
4 July 13 - Dec 31
N/A Annual load not calculated due to missing data.

TABLE 3.2 Suspended sediment rating curves (C = b Q ^{m}) for Emerald Brook, North Brook and Smelt Creek, Prince Edward Island.

Year(s)	b	m	R^2	b	m	R^2	b	m	R^2
	Emerald Bk.			Smelt Ck.			North Bk.		
1967				11.0	0.892	0.616			
1968				13.6	0.253	0.262			
1969				8.56	0.293	0.253			
1970				9.95	0.354	0.330			
1971				6.18	0.456	0.388	152	1.77	0.388
1972				12.0	0.209	0.212	56.3	0.831	0.621
1973							26.4	0.762	0.438
1974	7.87	0.223	0.007				109	1.28	0.288
1975	14.6	0.480	0.408				11.2	0.286	0.040
1976	31.6	0.650	0.560				10.4	0.305	0.159
1977	76.9	1.31	0.625				76.2	1.57	0.397
1978	18.8	0.779	0.669				19.4	0.978	0.575
1979	262	1.26	0.530				108	1.56	0.542
1980	54.8	0.582	0.322				53.3	1.302	0.337
1981	223	1.11	0.319				48.9	1.25	0.440
1982							9.65	0.439	0.125
1983							50.4	1.73	0.514
1984							19.1	1.31	0.389
1985							28.8	1.05	0.198
1986							61.9	1.24	0.681
1967-72				9.81	0.306	0.261			
1971-86							33.5	1.027	0.355
1974-81	56.2	0.723	0.296						

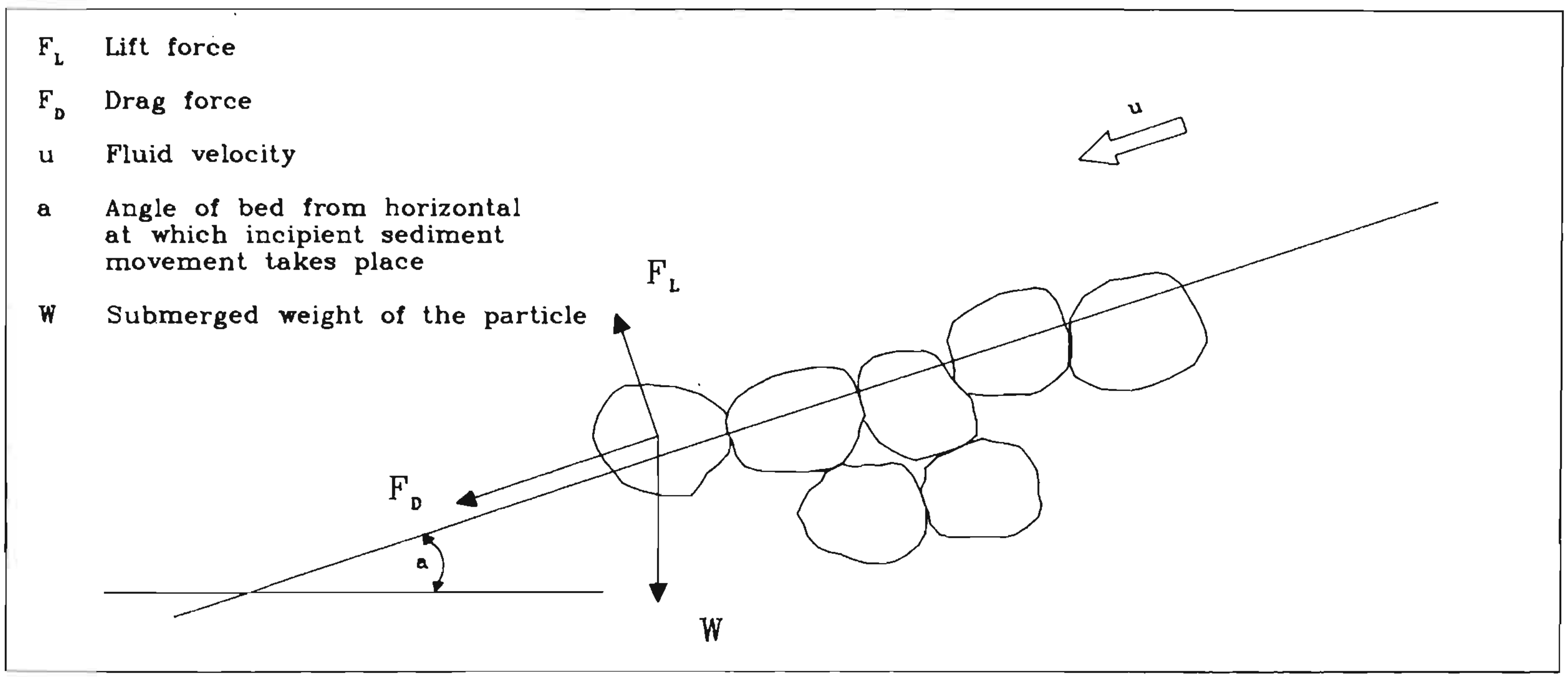

FIGURE 2.1 Illustration of Forces Acting on a Particle on a Stream Bottom (after Graf, 1984)

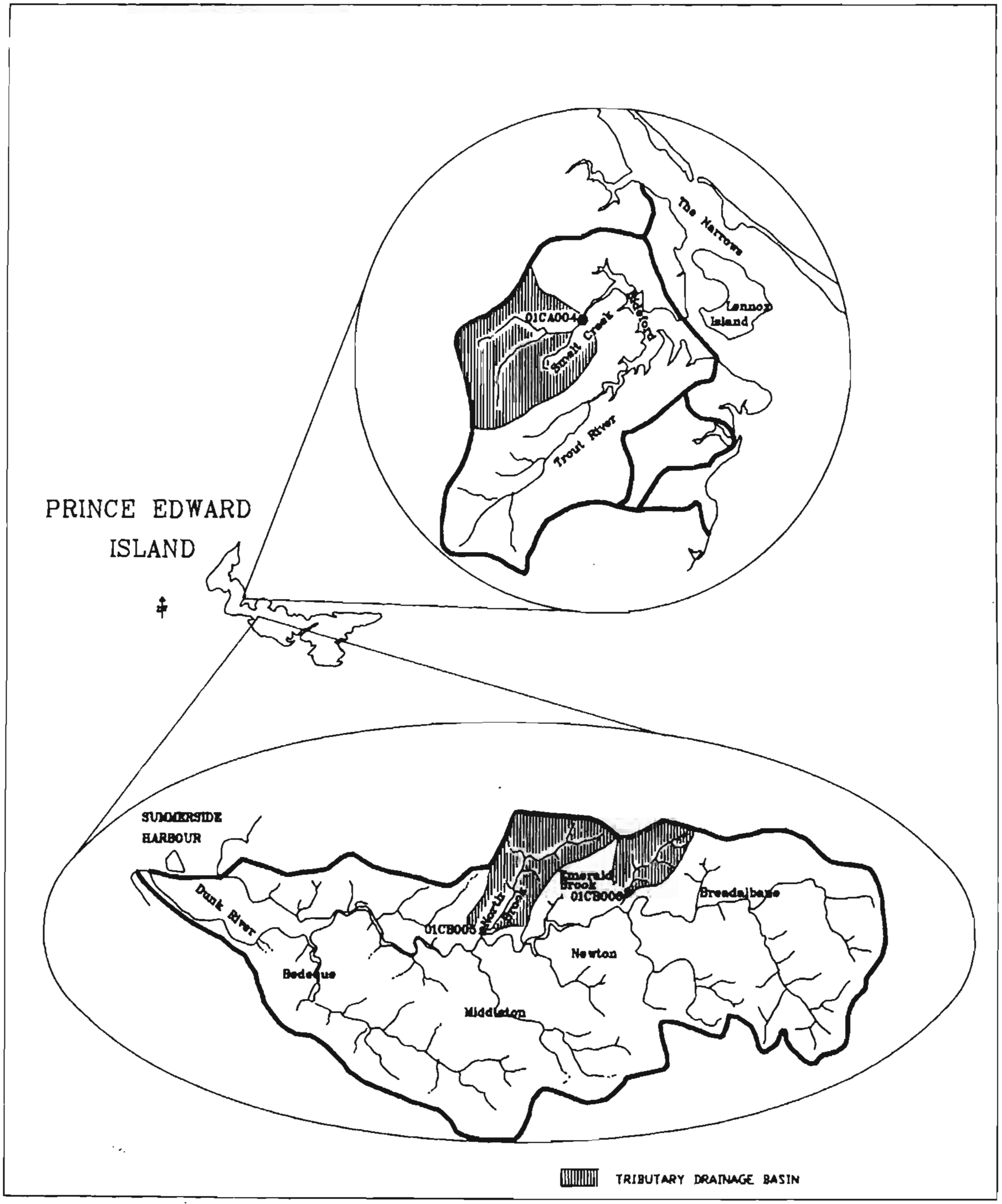

FIGURE 3.1 Map Showing Location of Sediment Sampling Stations and Tributary Drainage Basins

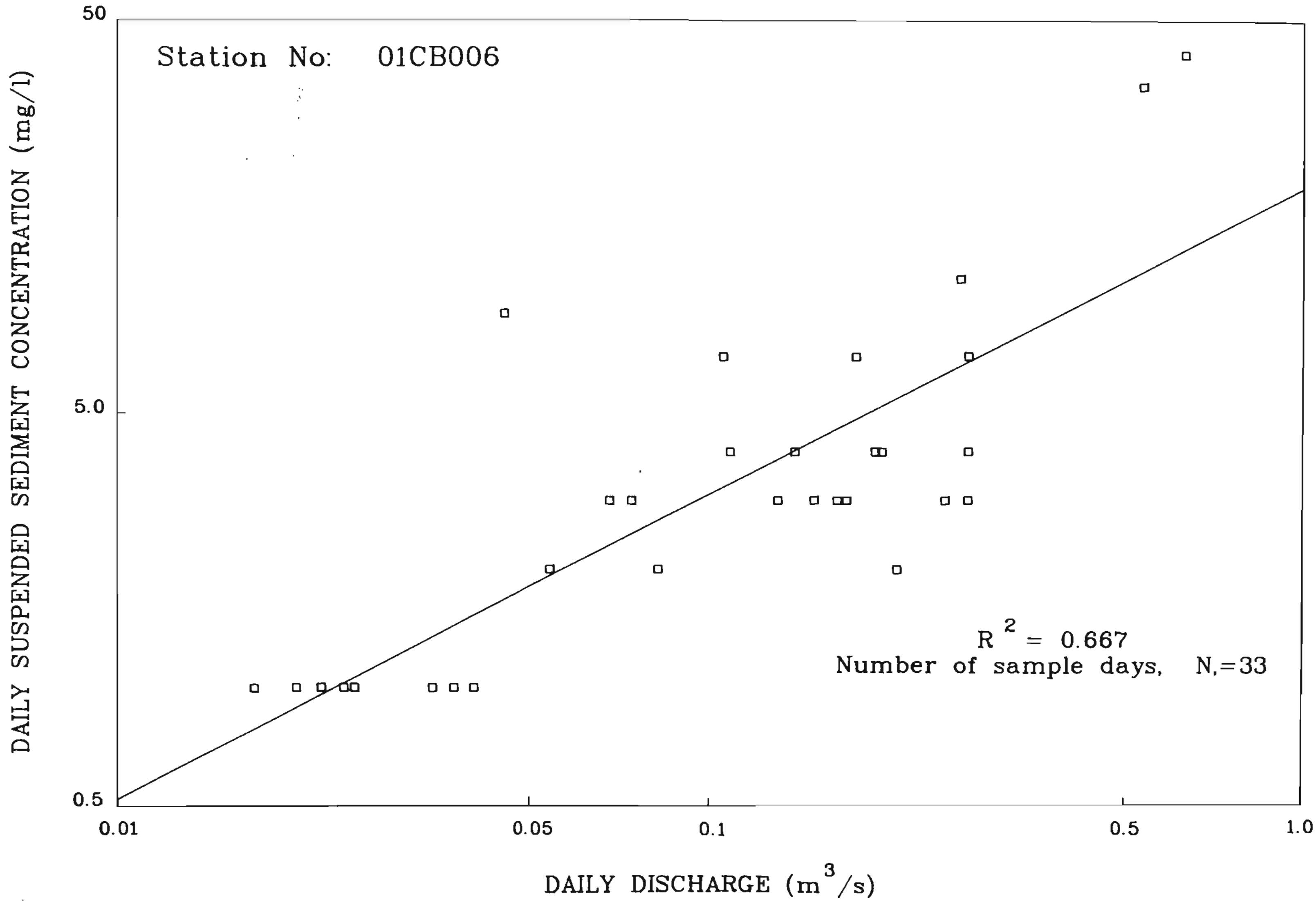

FIGURE 3.2 Suspended Sediment Rating Curve for Emerald Brook (1978)

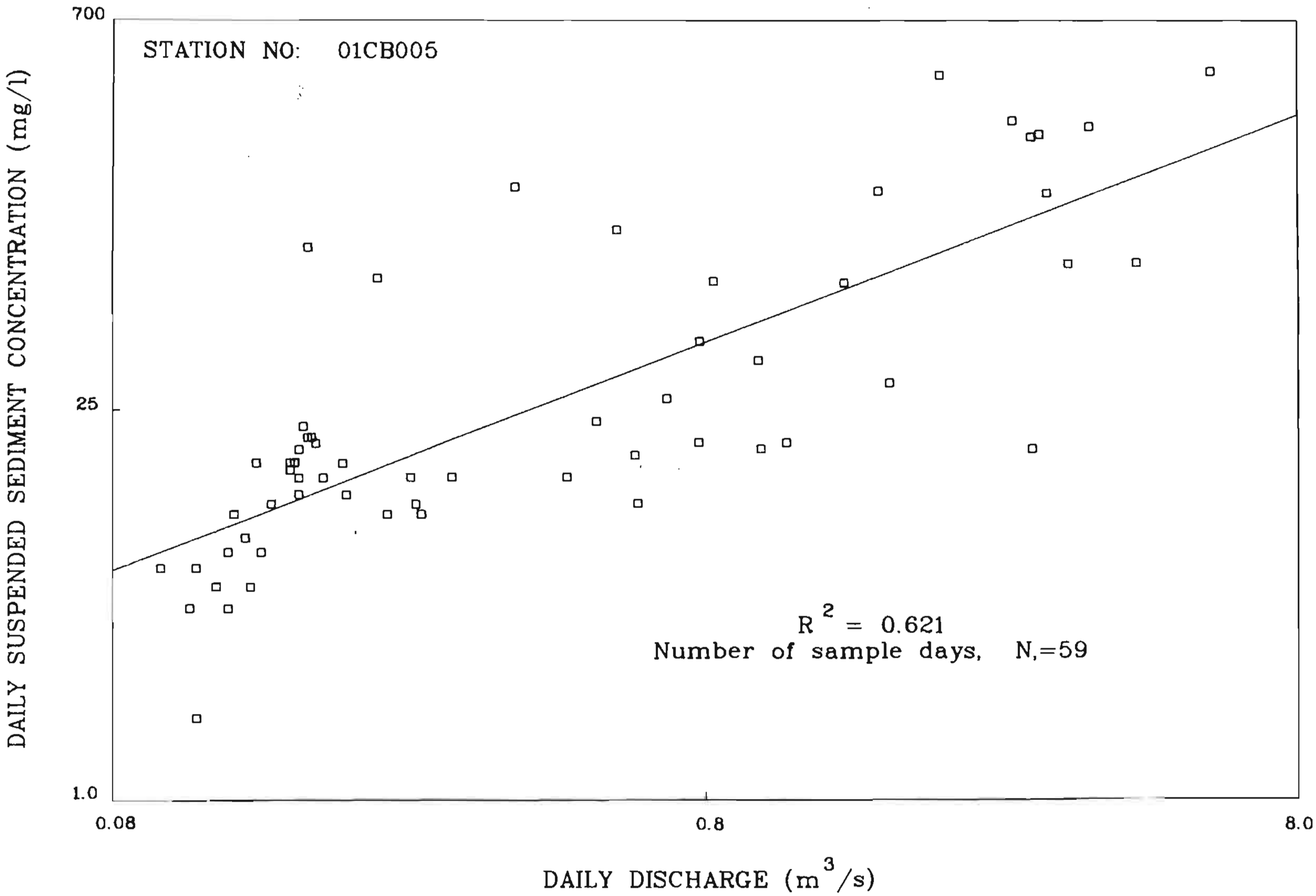

FIGURE 3.3 Suspended Sediment Rating Curve for North Brook (1972)

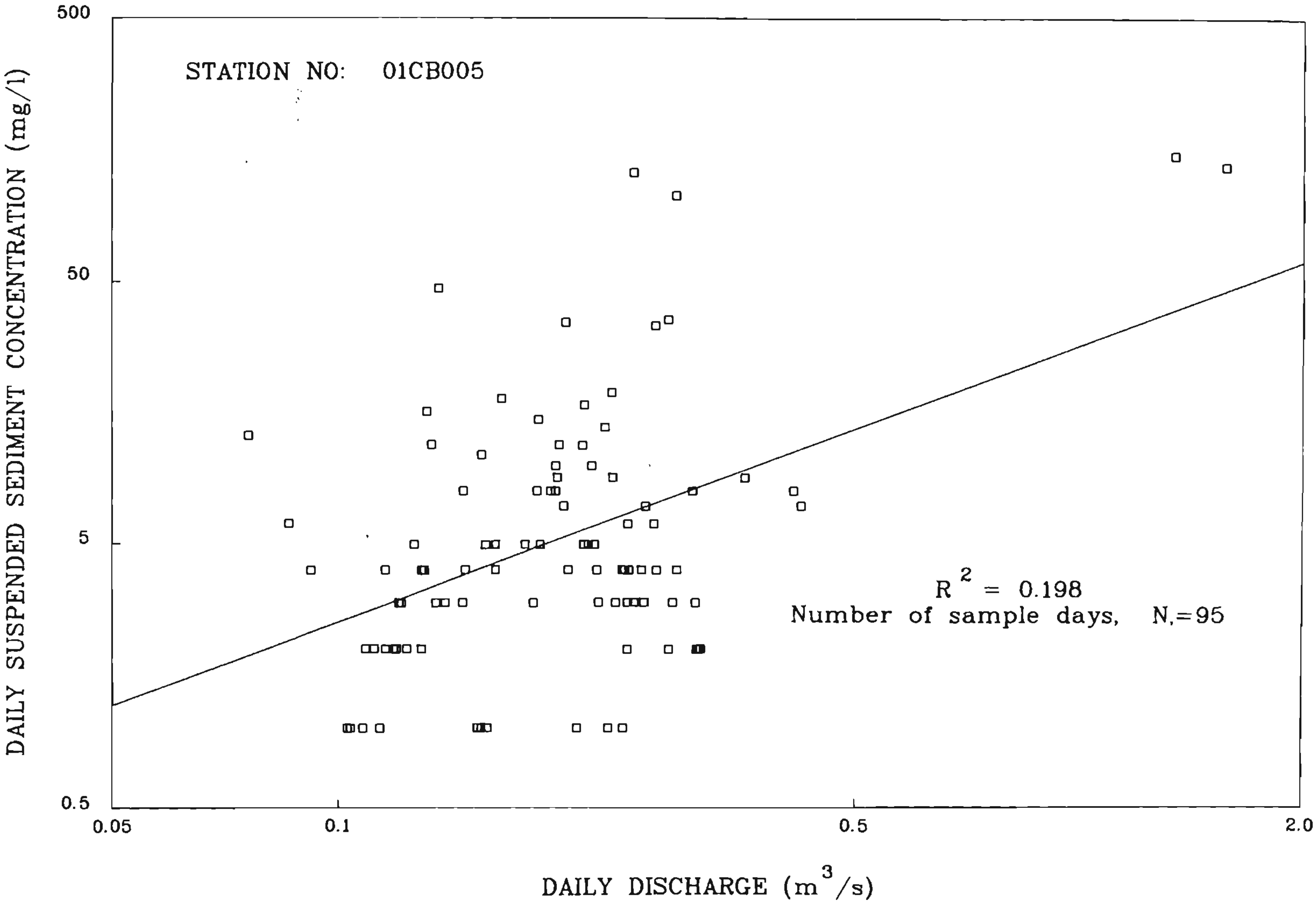

FIGURE 3.4 Suspended Sediment Rating Curve for North Brook (1985)

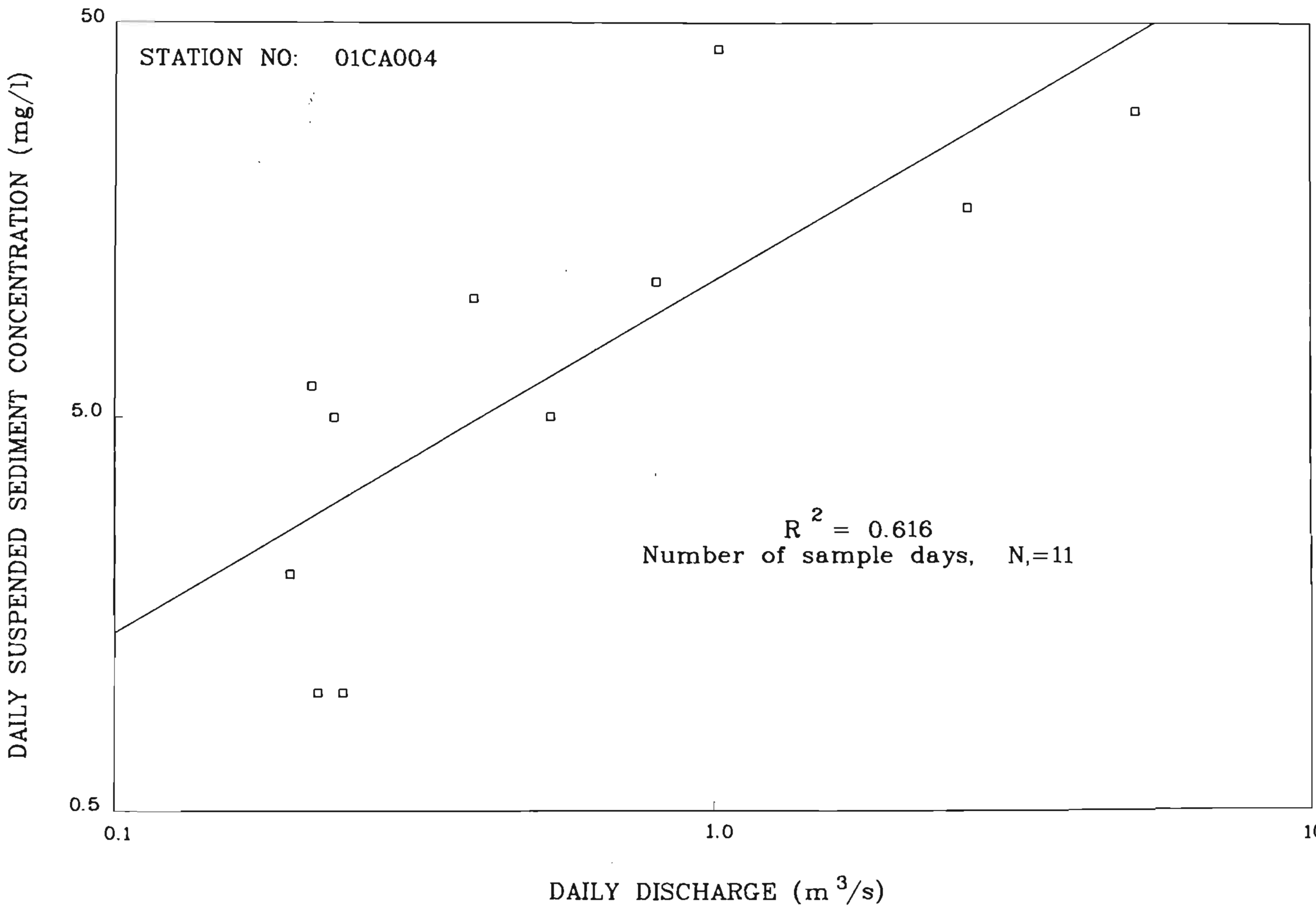

FIGURE 3.5 Suspended Sediment Rating Curve for Smelt Creek (1967)

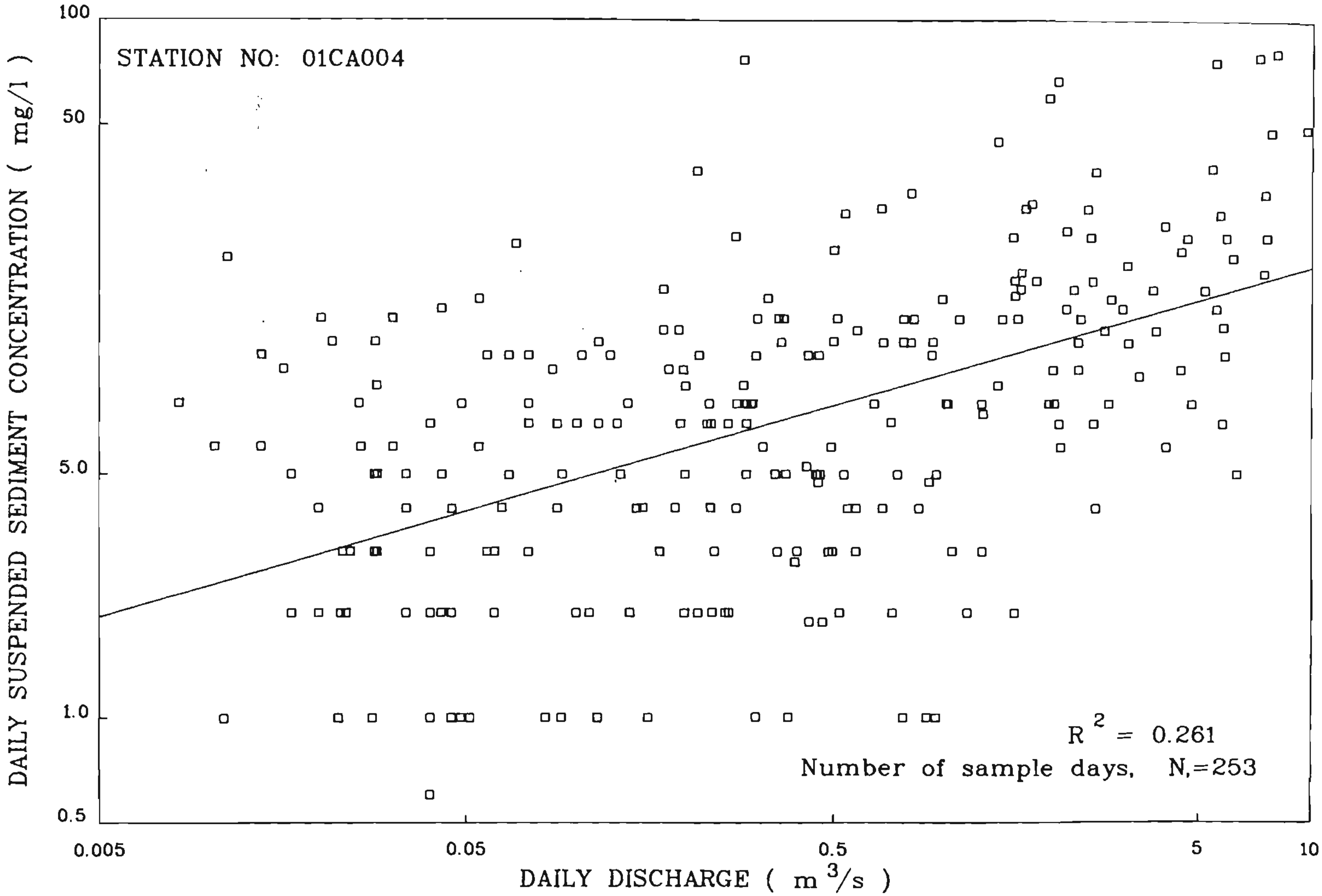

FIGURE 3.6 Suspended Sediment Rating Curve for Smelt Creek (1967–1972)

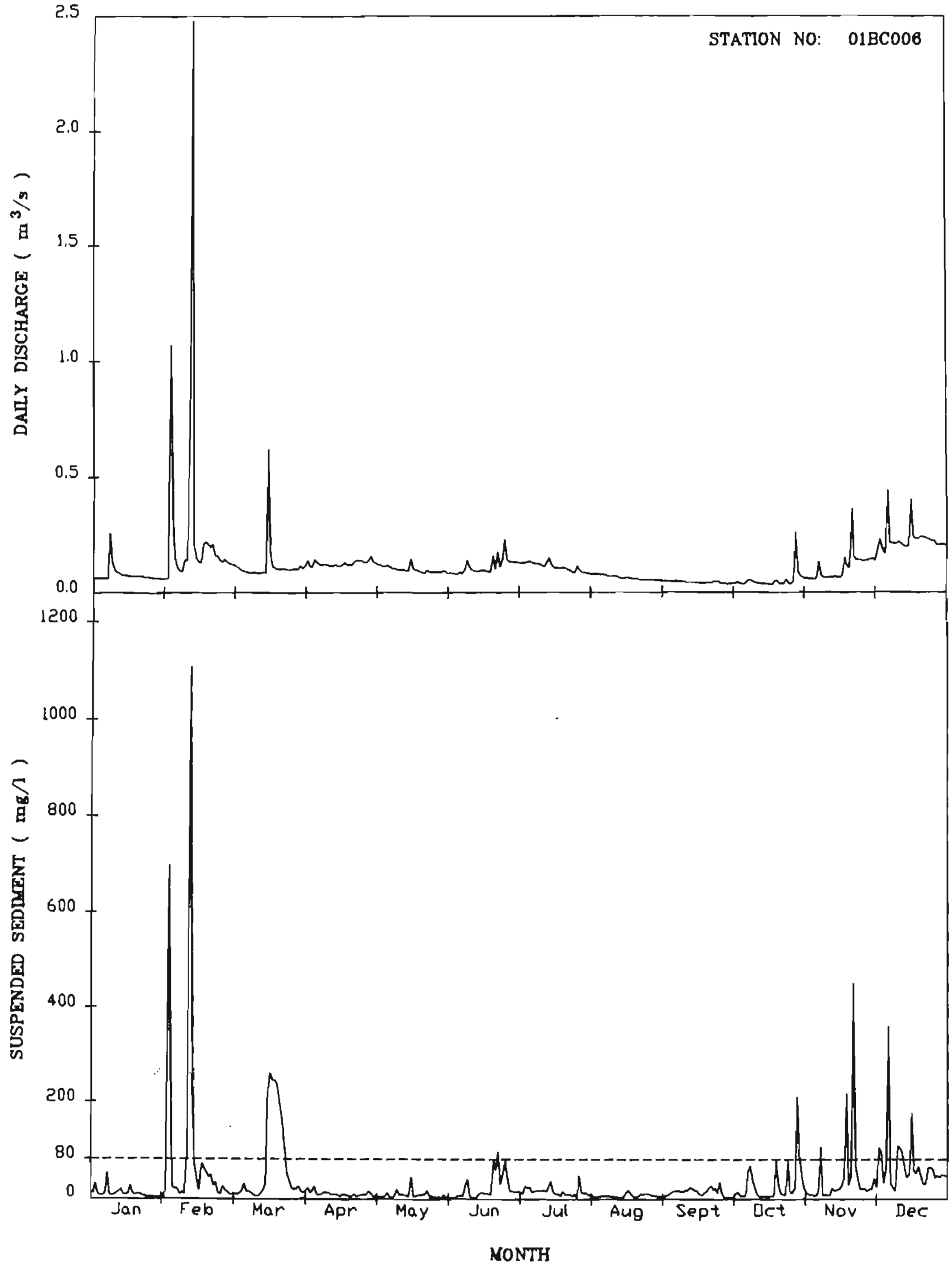

FIGURE 3.7 Daily Discharge and Suspended Sediment Time Series for Emerald Brook (1981)