A RE-EXAMINATION OF SEDIMENT TRANSPORT OBSERVATIONS IN THE LOWER FRASER RIVER

by

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Preface

This study forms part of an investigation of the processes governing channel stability and sedimenation in Fraser River between Hope and Mission. A major task is to develop a long term sediment budget for the repeatedly surveyed reach between Agassiz and Mission. Toward that end, this report gives a thorough review of the available sediment transport observations on the river, which are amongst the most comprehensive available for any river. These have been reconsidered in light of current developments in the analysis of sediment transport measurements, some of which have been made in this study. As a result, some aspects of prior analyses have been substantially revised.

It should be realised, however, that the results presented in this progress report remain to be compared with findings of morphological change along the river, which will be carried out in the final report of this project.

The project is being conducted for the Water Survey of Canada (Environment Canada) in the University of British Columbia, Department of Geography.

Previous progress reports in this series are as follows:

Church, M., McLean, D., Mannerstrom, M. and Evans, D. 1984. Reference materials on sedimentation and morphology of the lower Fraser River. University of British Columbia, Dept. Geography, Fraser River Project Progress Report No. 1, 243 pp.

McLean, D. and Mannerstrom, M. 1985. History of channel instability: lower Fraser River, Hope to Mission. University of British Columbia, Dept. Geography, Fraser River Project Progress Report No. 2, 18 pp + map.

McLean, D. 1985. Lower Fraser River Survey, 1984: Agassiz - Rosedale Bridge to Mission. University of British Columbia, Dept Geography, Fraser River Project Progress Report No. 3, 26 pp.

These reports serve to inform the contractor of progress in the project.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

The main purpose of this report is to present estimates of the annual bedload and suspended load transport rates at Agassiz and Mission. As part of this study, a relatively complete review of the available sediment transport observations was carried out. Particular attention is given to predicting the size distribution of the load and to the problem of distinguishing the wash load and bed material load at each station. The reliability of the available measurements and the precision of the annual load estimates has also been assessed. Some aspects of this work have been published previously (McLean and Tassone, 1985; Mannerstrom and McLean, 1985).

The first sediment transport measurements on the Fraser River were collected by Johnston (1921) at New Westminster. Later on, a systematic programme of measurements was carried out between 1950 and 1952 at Hope (Kidd, 1953). These data were used by Mathews and Shepard (1962) to estimate the long term sedimentation rate at the delta. In 1965 Water Survey of Canada began a comprehensive programme to measure the suspended load and bed load at several locations along the main stem and on some tributaries. Since this time bed load and suspended load have been measured periodically at Port Mann, Mission and Agassiz (Figure 1). Only suspended load data have been collected at Hope. Some early results from these measurements were analysed by Tywoniuk (1972) and by Pretious (1972). More recently the data have been reviewed by Western Canada Hydraulics Laboratories Ltd. (1978) and an overview of the programme was prepared by Kellerhals (1984). However, for the most part, the data have received very little systematic or critical analysis.

2.0 AVAILABLE DATA

2.1 Suspended Load

Daily suspended sediment concentrations and loads have been published by WSC at Hope (1965 - 1979), Agassiz (1966 - 1983) and Mission (1965 - 1983). These daily loads include estimated values for days when samples were not collected. In addition the actual instantaneous measured values are adjusted to estimate the daily averages. The actually observed depth-integrated or point-integrated concentrations and particle size data are also reported. This information is all available on computer tape which made manipulation of the relatively large amount of data very simple. A convenient summary of the available sediment data on the Lower Fraser River is given in Table 1.

2.2 Bed Load

Bed load measurements have been collected at Agassiz since 1968 and at Mission since 1966. Owing to uncertainties in the reliability of the measurements, the data have not been published (except for the bed load size distribution). For this study the data were extracted from the work book files stored at the New Westminster office of Water Survey of Canada. All of the available measurements from Agassiz between 1968 and 1976 were reviewed on a point by point basis. Measurements at Agassiz after 1976 could not be included in the analysis as the data have not yet been reduced by WSC and were not made available. At Mission only data from 1968, 1972, 1974 and 1979 have been fully analysed in this report. The measurements collected in these years provide a good representation of the complete data set and include a large proportion of the high flow observations.

2.3 Channel Hydraulics

Estimates of the hydraulic conditions at the time of the sediment observations were obtained from the hydrometric measurements at Hope, Agassiz and Mission. Discharge measurements have usually been carried out 12 to 15 times each year. At Agassiz these measurements have usually coincided with point-integrated suspended load sampling and bed load sampling. At Mission, the hydrometric measurements have coincided with the point-integrated sampling and some of the bed load measurements. These data have not been published but were made available from the WSC work files.

2.4 Water Temperature

Based on experiences reported from other rivers, it is believed that the range in water temperatures on the Fraser River is sufficiently large to produce a measureable effect on the suspended sediment concentrations (Shen *et al.*, 1978). Water temperatures have been recorded at one week or two week intervals in the winter and virtually daily during the May - August freshet period.

2.5 Bed Material

Between 1965 and 1983 WSC collected 165 bed material samples at Mission with a U.S. BM54 sampler. The samples were collected from five locations across the channel. The BM54 sampler collects only a very small sample (less than 1 kg) so that the individual measurements are too small to adequately represent the coarsest material (16mm - 32 mm) found in the river bed (ISO, 1977; Church _et al_., 1985). However, the composite of all samples collected in a year should provide a reasonably representative measurement. It should also be noted that the BM54 sampler penetrates only the top 50 mm of the bed and therefore provides essentially a surface sample.

Although a few bed material samples were collected by WSC at Agassiz in 1978 and 1979 these samples were too small (less than 10 kg) to estimate the size distribution of the coarse gravel sediments in this reach. For example, published standards for bed material sampling indicate a sample of at least 1500 kg would be required for sediments containing up to 100 mm diameter gravels (ISO, 1977; Church _et al_., 1985). In 1983 and 1984 the author collected bed material samples at 65 sites between Mission and Hope. The size of the individual samples ranged from about 800 kg near Hope (where the coarsest material on the bars reaches 400 mm) to only about 10 kg in the predominantly sand bed reach near Mission. The bed material size distribution near Agassiz was estimated by compositing the results from six 250 kg subsurface samples that were collected from exposed gravel bars adjacent to the measurement site. Additional surface samples were collected at each site using conventional grid sampling techniques. This involved placing a 30 m tape or grid on the bar and measuring the diameter of 100 stones that fell beneath the grid intersections.

2.6 Water Surface Slope

Although some estimates of the water surface slope can be obtained from occasional high water profiles that have been surveyed along the river, regular slope measurements have not been made in the study reach. In addition, the existing hydrometric stations are too far apart to estimate the local slopes near the stations. In 1983 and 1984 surveys were carried out on four occasions to estimate the water surface slope at Mission and Agassiz. The slope at Mission was determined by establishing several temporary staff gauges along the south bank over a distance of 3 km. At Agassiz, the slope was estimated from an 8 km long profile.

2.7 Dune Profiles

Longitudinal echo sounding profiles were repeated on nine separate occasions in 1984 and 1985 to measure the bedform characteristics in the sand bed reach near Mission. The techniques that were used to collect these data were described previously (McLean, 1985). The main purpose of these surveys was to determine the relation between bedform dimensions and flow conditions. On two dates the surveys were repeated several times in the day in order to estimate the migration speed of the dunes.

3.0 RIVER CHARACTERISTICS

3.1 Hydrology

Table 2 summarises some key discharge values from the hydrometric stations at Hope, Agassiz and Mission. Figure 2 presents the variability of the daily flows that have been recorded at Hope. This plot illustrates the dominating effect of the annual snowmelt freshet, with the river very regularly rising in early April and peaking in the first weeks of June.

The drainage area increases by only 870 km^2 between Hope and Agassiz (roughly 0.4% of the area at Hope). However, between Agassiz and Mission the Harrison River and Chilliwack River contribute an additional 10 000 km^2 which corresponds to about 5% of the area at Hope. These tributary inflows typically increase the mean flow by about 18% and the freshet flows by 10 to 15%.

At Hope, where hydrometric measurements have been made since 1912 the annual flow volumes show a pronounced (and statistically significant) serial correlation indicating that runoff in any one year is correlated with the runoff in the preceding year. Figure 3 shows that the long term pattern of runoff in the Fraser River has not remained stationary over the last century and that between 1948 and 1977 the runoff has been persistently higher than the long term average (Slaymaker, 1972). In so large a basin, land use effects are unlikely to have seriously affected sediment yield. Further, it appears that much of the sediment load is derived in the upper basin from along the banks of the main channels during the freshet rise. Assuming then, that the overall rate of sediment supply in the basin has not changed too much over the last century, it is likely that the long term variations in sediment transport follow a similar pattern.

3.2 Channel Characteristics

The morphology of the Lower Fraser River has been described previously (McLean and Mannerstrom, 1984). Between Yale and

Laidlaw the river flows in an irregular single channel and is nearly continuously confined by bedrock, slide debris or Pleistocene terraces. The 50 km reach beween Laidlaw and Vedder River displays a wandering or anastomosed channel pattern with frequent mid-channel islands that subdivide the river into several channels.

The island stratigraphy is often very simple, consisting of gravel and sands overlain by 1 - 3 m of sand or silty sand floodplain deposits. The bed is composed primarily of gravel (typically with a median size of 25 - 30 mm) with 10 - 20% sand. This reach has experienced frequent, irregular channel shifting with bank erosion volumes of roughly 750 000 m^3/year to 1 000 000 m^3/year over the last century (McLean and Mannerstrom, 1984).

Between Sumas Mountain and Mission the channel pattern changes abruptly to a sinuous, single thread, sand bed channel. Echo sounding profiles indicated that dunes usually are found on the river bed near Mission when flows exceed about 4000 m^3/s. At discharges near 8300 m^3/s the dunes reached up to 2.5 m in height (average 1.5 m) and had an average spacing of 25 - 30 m.

3.3 Gauging Site Characteristics

Table 3 summarises the channel dimensions and hydraulic properties at the Hope, Agassiz and Mission hydrometric stations. Figure 4 shows the channel pattern in the vicinity of the stations while the channel cross sections are summarised in Figure 5 and the hydraulic geometry relations are summarised in Figure 6. Figures 7 - 9 show the bed material characteristics of the three sites.

The Hope gauging station is located at the highway bridge crossing where the river is confined by bedrock on the west bank and by the Coquihalla River fan on its eastern side. As a result the river is forced into a sharp bend at the gauging site. Secondary currents and flow impingement along the eastern bank greatly distort the velocity distribution at high flow by causing the point of highest velocity to be depressed far below the water surface (Figure 5). Comparison of repeated gauging measurements shows that the bed scoured up to 7 m during large floods in 1972 and 1974. The secondary currents also induce very strong lateral concentration gradients of suspended sediment across the channel (Figure 10) so that the highest concentrations are found near the inside of the bend (east bank). These factors all tend to make the site less than ideal for measuring sediment transport. On the basis of recommendations by WCHL (1978) sediment observations were discontinued at Hope after 1979.

The Agassiz gauging station is located in a relatively straight reach of the river 300 m downstream of the Agassiz - Rosedale bridge. Over most of the period of observations the Agassiz site has been close to ideal with the velocity and suspended load being distributed very uniformly across the channel (Figures 5 and 10). However, in recent years, gravel bar accretion near the north side of the channel has caused the river to become divided at lower flows. Aside from making future measurements more difficult to collect this bar probably will induce greater variations across the section in channel velocities and sediment transport rates.

At Mission the gauging section is located in a straight reach of the river 340 m upstream of the C.P. railway bridge. This section is very uniform and should be close to ideal for conducting sediment transport observations. One possible complicating factor is that the site is located only 7 km downstream of the limit of the gravel bed reach which ends near Lower Sumas Mountain. Also, at lower flows the Mission site becomes tidally influenced, which causes diurnal variations in discharge and stage. However, during freshet conditions tidal influences are believed to be minor.

4.0 THE SUSPENDED LOAD

4.1 Measurement Procedures

The daily suspended loads reported at Hope, Agassiz and Mission are based on typically 150 to 220 depth-integrated concentration measurements each year at a single vertical. The frequencies of sampling at Agassiz and Mission are summarised in Figures 11 and 12. During the freshet period samples are collected virtually daily. These daily samples (termed K samples) have been taken with sampling equipment permanently mounted on the Hope and Agassiz - Rosedale highway bridges and the C.P. railway bridge at Mission. Concentration values for days when measurements were not taken have been estimated by using a graphical interpolation procedure.

On approximately 10 to 15 days each year depth-integrated measurements have been taken at five verticals to estimate the average concentration in the river. These complete measurements (termed R samples) were made from the highway bridge at Hope and from boats at the Agassiz and Mission gauging stations. By collecting both "K" samples and "R" samples the relation between the average concentration and the single vertical daily sample can be estimated. This ratio is termed the K-factor:

$$K = C_R/C_K$$

The K-factor is used to convert the measured single-vertical daily samples to actual cross section averages. In order to gain some appreciation of the variability of this factor the original K-factor measurements in some years were reviewed. The variation in K factor with discharge at Agassiz and Mission during 1972 is illustrated in Figure 13. At Hope and Agassiz the K-factor appeared to vary randomly over the year with the coefficient of variation of the values ranging from about 0.1 to 0.15.

The K-factor at Mission appears to vary more systematically, becoming noticeably lower at the higher discharges. It is believed that this variation is partly due to the location of the daily sampling station on the Mission bridge. Following discussions with officials from C.P. Rail it was learned that an extensive riprap apron was constructed across the river in the 1960s in order to control persistent scour problems at the bridge piers. As a result the river bed rises abruptly by 2 - 4 m in the vicinity of the bridge centreline. During echo sounding surveys at high flows it was noticed that 2 to 3 m high dunes at the WSC gauging line disappeared as they approached the bridge. It is believed that the material comprising the bedforms was resuspended by the higher velocities and more turbulent conditions at the bridge causing the daily samples to be unusually high.

Particle size analysis has been carried out on the multiple vertical depth-integrated ("R") samples provided the amount of suspended sediment is sufficient for laboratory analysis. Typically this means particle size analysis is not available for flows less than 2000 m^3/s at Hope or Agassiz and 3000 m^3/s at Mission. In the past usually 5 to 10 particle size measurements from "R" samples have been made each year at Agassiz and Mission (Figures 11 and 12).

Point integrated measurements have been carried out at Hope, Agassiz and Mission usually once or twice each year. The measurements are usually carried out at five verticals in the cross section during the summer freshet. Velocity profile data is usually collected along with the point-integrated samples although the velocity measurements are not published.

4.2 Reliability of Suspended Load Data

In this report the term "precision" is properly restricted to indicating the repeatability in a set of ostensibly equivalent observations. Precision is measured in absolute terms as the standard deviation of a sequence of replicate observations, x_i:

(1) $$S_x = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N - 1}}$$

or in relative terms as a coefficient of variation:

(2) $$CV_x = S_x / \bar{x}$$

The most direct means of assessing the precision of the sediment concentration data would be to collect 20 to 30 repeat observations at a single station during a short period of time when the hydraulic conditions remain virtually constant. This approach has been carried out to assess the reliability of the bed load measurements. Less information is available to estimate the reliability of the suspended load data. Therefore the following analysis should be considered as a "first order" estimate.

This study is primarily concerned with estimating the annual sediment load. For the purpose of assessing its precision, the annual load can be expressed as:

(3) $$G_s = K_1 \sum_{i=1}^{N_1} Q_i C_i + K_2 \sum_{i=1}^{N_2} Q_i C_i + K_3 \sum_{i=1}^{N_3} Q_i C_i + \ldots K_j \sum_{i=1}^{N_j} Q_i C_i$$

where K_j is the K factor applied to time interval j
Q_i is the estimated daily discharge
C_i is the measured (or interpolated) daily concentration value determined at a single vertical

The precision of the annual load can be estimated by propagating the errors in K_j, Q_i and C_i through equation (3). For the purposes of this study no distinction is made between the daily measured concentrations and interpolated values. This simplification is not as severe as it first seems since the single vertical measurements are carried out virtually every day during May and June when the greatest proportion of the annual load is transported. With this assumption, the uncertainty in any daily load can be expressed as:

(4) $$CV\ g = \sigma_g/\bar{g} = \sqrt{\left(\sigma_c/\bar{c}\right)^2 + \left(\sigma_Q/\bar{Q}\right)^2}$$

where $\sigma_c/\bar{c}$, $\sigma_Q/\bar{Q}$ and $\sigma_g/\bar{g}$ represent the relative errors in the daily concentrations, discharges and loads respectively.

The total suspended load (based on the measurements at the single sampling vertical) during the interval j when K factor K_j will be applied is:

(5) $$G = K_j \Sigma Q_i C_i$$

The uncertainty in the total can be estimated as the sum of the daily load variances estimated from the single vertical measurements:

$$(6) \qquad \sigma G_{sj} = \sqrt{\sum_{i=1}^{N_1} \sigma g_i^2} = CVg \sqrt{\sum_{i=1}^{N_1} g_i^2}$$

adjusted for the uncertainty of the K-factor between the single vertical and cross section averaged concentrations:

$$(7) \qquad CV\ G_j = \sqrt{\left(\sigma K / \bar{K}\right)^2 + \left(\sigma G_{sj} / \bar{G}_{sj}\right)^2}$$

Finally, the uncertainty in the annual load can be expressed as the sum of the subtotal variances:

$$(8) \qquad \sigma_{G_A} = \sqrt{\sum_{i=1}^{m} (G_j \cdot CV\ G_j)^2}$$

Each subtotal G_j represents the total suspended load transported in the interval when the K-factor K_j is applied. This analysis suggests that the uncertainty in the annual load will depend on:

1. the number of K-factor determinations made each year;
2. the total load transported during the interval between the K-factor determinations;
3. the precision of the daily discharge and concentration measurements;
4. the precision of the individual K-factor determinations.

A first order estimate of the precision of the K-factors was made by computing the standard deviation of the values that were measured in individual years at Hope and Agassiz. The precision of the single vertical daily concentrations was estimated from the replicate daily measurements that were collected in 1968 and 1972 at Hope, Agassiz and Mission. The precision of the daily discharge values was estimated by computing the root mean square deviations from the stage-discharge rating curves at Hope, Agassiz and Mission. It was found that the deviations between individual discharge measurements and the adopted rating curve line seldom exceeded 3% of the measured discharges. Based on these crude estimates of precision the following values were adopted for the error analysis:

CV C = 0.10

CV K = 0.10

CV Q = 0.05

Given these values, the precision of any daily load would be approximately:

$$(0.1^2 + 0.1^2 + 0.05^2)^{0.5} = 0.15$$

The precisions of the annual loads were estimated from (8) using the K-factor estimates and daily loads in 1968 and 1972 at Hope, Agassiz and Mission. The relative error in the annual load (CV G_A) was found to range beween 0.04 and 0.06 at the three stations; i.e. the annual suspended load is measured to within about 5%. It was found that the precision of the annual load was governed mainly by the number of K-factor measurements that were made in the freshet season. This is mainly a result of there being 10 to 20 times more measurements of daily concentrations at the single vertical station as there are complete measurements across the section. The main assumptions of this analysis is that the errors in the discharges, daily single vertical concentrations and K-factors are independent of one another and randomly distributed. An important outcome of these conditions is that errors will tend to be compensating so that the estimate of the annual load will be more precise than any single estimate of a daily load.

There are several sources of systematic error (i.e. bias) that could affect the overall accuracy of the measurements. Previous studies have suggested that the flow at the Hope gauging station is not normal to the metering cross section and that the water discharge and hence sediment loads are overestimated by 5% or more (WCHL, 1978). Such a large systematic error should be easily detected by comparing the discharge records at Agassiz and Hope. This comparison was carried out for the maximum daily discharges, mean June discharge and annual runoff over the period 1967 to 1984. It was found that the discharges at Hope and Agassiz were virtually identical over this period, with the flows at Agassiz being 1% to 2% higher than at Hope on average. This apparent increase is the reverse of what one would expect from the condition suggested by WCHL (1978). Furthermore, approximately half of the 1% to 2% difference in flows can be explained by inflows from Silverhope Creek and other smaller tributaries which contribute a drainage area of 870 km^2 between Hope and Agassiz. These results indicate that discharges are not systematically overestimated at Hope and illustrate that remarkably precise flow measurements can be achieved even when a station is situated at a non-ideal site.

Systematic errors could also arise if there are an insufficient number of measurement verticals at a section to represent the variation in sediment load across the cross section. This problem is most likely to arise at Hope where the bend upstream of the gauge induces very pronounced lateral concentration gradients across the channel (Figure 10).

Finally, it is generally recognised that depth integrated samples will miss a portion of the load near the bed (Ning Chien, 1952; Nordin and Richardson, 1971). Some agencies have devised approximate methods for estimating this "missing load" (Colby, 1957). In this study the original WSC data have been used and no adjustment has been made. As will appear from the interstation comparison below, if there is any such bias in these data, it is effectively consistent at all stations.

4.3 Total Suspended Load Characteristics

Table 4 summarises the annual suspended loads at Hope, Agassiz and Mission between 1966 and 1983. Over the period 1967 - 1979 when measurements were made at all three stations, the mean annual loads were virtually identical. A paired T-test on the annual differences between Hope - Agassiz, Agassiz - Mission and Mission - Hope confirmed that the loads at the three stations are not significantly different statistically.

The average loads at Agassiz and Hope agree to within 1% over the period 1967 to 1979. This difference is close to the expected result if the annual loads were identical at the two sites but could be measured with a precision 5%. This suggests that the error analysis in the preceding section provided a realistic assessment of the measurement results. The annual load comparisons suggest, then, that there has been some duplication of effort in maintaining three stations along this reach.

The data in Table 4 also illustrate that the range in annual loads has been relatively small over the last 18 years, varying between 31 million tonnes/year in 1972 and 8 million tonnes/year in 1983.

The variation in daily transport rates at Agassiz and

Mission over the period of station operation is summarised in the load-duration curves in Figure 14. The maximum observed daily loads have reached 956 000 tonnes/day at Mission and 823 000 tonnes/day at Agassiz.

The seasonal variations in sediment loads are illustrated in Figures 15 and 16 for the measurements at Agassiz and Mission. Virtually identical results were found for the measurements at Hope and Agassiz. Approximately two thirds of the annual load is transported in May and June while the period between October and March accounts for less than 6% of the total.

The fraction of the annual load transported by various discharges was computed from the daily concentration and discharge data at Hope, Agassiz and Mission. Results for Agassiz and Mission are shown in Figures 15 and 16. This analysis shows that the flows contributing the largest fraction of the sediment load are between 8500 - 9000 m^3/s at Mission and 7500 - 8000 m^3/s at Agassiz (or Hope). These discharges correspond to about the 1.5 year flood at each of the sites. By comparison discharges above 10 000 m^3/s (5 year return period at Agassiz or Hope) accounted for only about 12% of the longterm sediment load. It is apparent that over the long term the relatively frequently occuring, moderate freshet flows account for the greatest proportion of the river's annual sediment load while the very high flows occur so infrequently that the actual quantity of sediment contributed is relatively small. This result is in accordance with findings on many other streams (Wolman and Miller, 1960).

The daily and monthly sediment loads display a very characteristic hysteresis over the year as illustrated on the hydrograph in Figure 17 and the sediment rating curves in Figures 18 and 19. These figures show that the sediment load is substantially higher on the rising limb than on the falling limb, indicating that the sediment supply becomes exhausted over the freshet season. This hysteresis has been described previously by Kidd (1953), by Whitfield and Schreier (1981), and many others. In examining the daily sediment load rating curves it is apparent that three distinct periods can be identified:

- an early rising limb period when the sediment loads follow a well defined relation with discharge;
- a supply exhaustion period, which usually begins on the rising limb of the hydrograph. In this period the sediment concentration is virtually independent of discharge and rapidly declines with time;
- a falling limb period where the flows are receding and a second well defined relation exists between sediment concentration and discharge.

This hysteresis greatly complicates the predictions of daily sediment loads.

4.4 Characteristics of the Suspended Sand Load

The size distribution of the suspended load was investigated by analysing the particle size data from the depth integrating multiple vertical measurements (R samples). A preliminary review of the data from the depth integrating single vertical measurements (K samples) showed that it would be difficult to relate these data to the section-averaged results. Therefore "K" sample data were not included in the analysis.

An average of all depth integrated particle size data from

Hope, Agassiz and Mission indicated that the suspended load typically consists 35% of sand, 50% silt and 15% clay during freshet conditions. In this study the main emphasis is directed towards analysing the sand fraction of the load. This is because the clay and silt load can be considered as "wash load" since these fractions are not present within the channel bed. Therefore the sand fraction of the suspended load is the most important component for developing a sediment budget of the river.

The suspended sand load consists primarily of very fine sand (0.063 mm - 0.125 mm) while the coarsest material in suspension seldom exceeds 1 mm.(It is not known whether the relatively small size of the suspended load sampler orifice (4.76 mm) significantly restricts the sampling of coarse material moving in suspension.) The D_{50} size of the sand load averages about 0.12 mm with values ranging from 0.17 to 0.10 mm. Comparison of Figures 20 and 21 shows that seasonal hysteresis is present in the total sand (0.063 - 2 mm) rating curve at Mission, but is much less apparent when the fine sand fraction (0.063 - 0.125 mm) is excluded. This suggests that at least a part of the sand load at Mission is supply limited and can be considered "wash load". In order to verify this finding, the size distribution of the suspended sand load was compared with the bed material size distribution. Figure 22 shows a typical cumulative plot of the suspended load and the bed material at Mission. Figure 23 compares the composite size distribution from all suspended load samples at Mission with the composited bed material distribution . This comparison shows that nearly 50% of the suspended sand load is contributed by the very fine sand fraction (0.063 mm - 0.125 mm). However, this size fraction makes up only about 2% of the bed material. As a result the fine sand load (0.063 mm - 0.125 mm) evidently is not transported in proportion to its presence in the bed but instead can be considered as "wash load". This would account for the noticeable hysteresis that was observed in the total sand rating curves.

In reviewing this finding some consideration was given to the probability that the apparent absence in the 0.063 - 0.125 mm fraction of the bed material samples could reflect the operating characteristics of the U.S. BM54 sampler. However, other large volume samples near Mission also showed similar characteristics as have samples at Port Mann and dredge spoil samples from the lower estuary. Therefore it is reasonable to conclude that in the sand bed reach of the Lower Fraser River the bed material load consists of sediment coarser than 0.125 mm. In practical terms the bed material load at Mission is approximately half of the total sand load.

At Agassiz (Fig. 24) and Hope seasonal hysteresis occurs in all fractions of the suspended sand load . Sand sized material typically constitutes 10 - 15% of the bed material in the gravel bed reach of the river. It is frequently assumed that the finest 10% of the bed material will be transported in suspension as wash load (Einstein, 1950). Therefore both the observed rating curves and the results from past studies suggest that virtually all of the suspended sand load at Hope or Agassiz can be considered "wash load". Its presence in the bed is due to trapping within the interstices of the coarser material.

Unlike the clay and silt fractions which are distributed nearly uniformly throughout the water column, the sand concentrations may be virtually zero near the water surface and may increase to several thousand ppm near the river bed. This feature is most apparent at Mission but it is also found in the gravel bed reach at Agassiz.

The fraction of the total sand load at various depths was calculated from the concurrent velocity profile and point integrating concentration measurements at Mission. The sand load gs transported in any depth increment Δy can be calculated as:

(10) $$gs = Cs(y) \cdot V(y) \cdot \Delta y$$

where Cs(y) is the average sand concentration at depth y
V(y) is the average velocity at depth y

Figure 25 summarises the results from one set of calculations from measurements collected on June 21, 1974 when the discharge at Mission reached 12 600 m^3/s. Results from several observations at Mission showed that under typical freshet conditions about 40% of the sand load is transported within 2 m of the river bed. Considering that the dunes often reach 2 m in height in this reach during freshet conditions it is clear that the distinction beween bed load and suspended load is somewhat artificial in active sand bed rivers. These results also illustrate that it will be difficult to measure the sand load with conventional depth integrating samplers since a large fraction of the load is transported in a very small proportion of the water column. This problem can be partially overcome by separately sampling the sand load near the bottom as is commonly carried out in Dutch practice.

Depth-integrated samplers can only measure to within about 10 cm from the river bed. As a result a small portion of the water column can not be sampled. The high suspended sand concentration gradients near the bed at Mission and Agassiz should introduce a bias in the suspended load measurements so that the sand loads will tend to be systematically underpredicted.

4.5 Annual Sand Loads

One of the main tasks of this study has been to estimate the annual sand loads at Hope, Agassiz and Mission during the period of sediment observation. Two main approaches were followed. First, relations were developed between the percentage of sand in the suspended load and the river discharge (Figure 26). Results of these regressions are summarised in Table 5. The daily sand loads were then computed from the estimated sand fractions (f) and the measured discharges and total concentrations:

$$g = f.C.Q \tag{11}$$

The main advantages of this method are:

1. the sand fraction shows a greater degree of correlation with discharge than either the sand concentration or the total concentration. This was most apparent in the gravel bed reach at Agassiz or Hope where the sand behaves as wash load;

2. the overall variation in the sand fraction is relatively small throughout the freshet, with values typically ranging between 0.3 to 0.45. By comparison sand concentrations may vary over a range of 10 to 20 times. As a result it was considered that the most accurate predictions would be made by computing the relatively insensitive sand fraction and then applying this factor to the actual measured total concentrations.

The main disadvantage of this method is that the sand loads can be estimated only for the period of sediment observations since measurements of daily total concentrations are required.

The second method for estimating the annual sand loads was to use conventional sediment rating curve techniques. This involved fitting regression equations to the measured sand concentration and discharge data. The annual loads were then computed from the predicted daily sand concentrations and the measured discharges:

(12) $gs = Cs.Q$

This approach has recently been evaluated by Kellerhals Engineering Services (1985) by comparing predicted total suspended sediment loads with published annual loads from the Fraser River at Mission and several other streams.

In the present study two different regression models were used for developing the sand concentration rating curves:

(13) $Cs = aQ^{b}$ (power law)

(14) $Cs = a_0 + a_1Q^{0.5} + a_2Q + a_3Q^{1.5} + a_4Q^2 \ldots$ (polynomial)

Recently it has been noted that conventional power law type regressions will systematically underpredict annual sediment loads (Walling and Webb, 1981). Two methods for removing this bias were considered in this study:

1. applying a bias correction factor using the method of Smillie and Koch (1984);

2. solving the power law coefficients by using a non linear least squares program.

A comparison of these alternative methods has been summarised in a separate report (Church and McLean, 1986).

The significant hysteresis in the daily concentration observed on the Lower Fraser River can introduce errors in predicting annual loads (Whitfield and Schreier, 1981; Kellerhals

Engineering Services, 1985). Therfore it was thought that more reliable estimates of the annual sand loads could be achieved by developing separate seasonal rating curves for the periods January - May and June - December. An overall rating curve for the entire year was also produced to provide a comparison with the seasonal results.

The annual loads were first calculated at Mission since the sand concentrations displayed less scatter at this station than at Agassiz or Hope. Between 1966 and 1982, 51 multiple vertical ("R" sample) suspended sediment measurements were collected between January and May, and 56 measurements were collected between June and December. As discussed previously, the sand concentrations at the Mission single vertical daily sampling site are much higher than the average values measured at the upstream gauging section. Since the relation between these two sets of data was only poorly defined it was decided not to include the single vertical data in the analysis. Figure 20 shows the January - May and June - December data plots as two distinct relations.

Summary statistics from the rating curve regressions are given in Table 6. The fits from the overall rating curve (January - December) were slightly worse than the separate seasonal curves.

Table 7 compares the annual loads predicted by the sand fraction method and the six separate rating curve relations. These results show that the different regression models (polynomial, power law) produced reasonably close agreement, usually within 6 %. The annual loads predicted from the separate seasonal rating curve were consistently higher (by 3 - 8%) than the predictions from the sand fraction method, indicating that there is a systematic source of bias in one of the methods. One potential source of bias in the sand concentration measurements has been described in Kellerhals (1984). In that study it was pointed out that particle size analysis can only be determined for samples with a relatively high concentration (generally above 100 mg/l) so that the sand rating curves will tend to be positively biased. However, since the sand fraction ratio is very insensitive to total concentration, this bias will have less effect on sand load estimates by the sand fraction method.

A second source of bias is related to the freqency of sampling the sand concentrations. In examining the discharges when particle size analysis was carried out it was found that the data are clustered in a narrow discharge range with most of the measurements taken at relatively high flows. This sampling distribution is much different from the total concentration samples which have been collected over a much wider range of flows. The clustering of the sand concentration samples could cause the loads at the lower flows to be overestimated. This hypothesis was tested by comparing published total annual load results with predictions based only on days when particle size analysis was carried out and then on days when all samples were collected. The test showed that rating curves based solely on the days when particle size analysis is carried out will be positively biased. Therefore it was decided that the sand fraction method would produce the most reliable predictions of the annual sand loads and this method was used for estimating the loads at Agassiz and Hope.

Predicted annual sand loads for Hope, Agassiz and Mission are summarised in Table 8. Over the period 1967 - 1979 the sand loads at Hope and Mission averaged about 6.3 million tonnes/year while the load at Agassiz averaged 5.7 million tonnes/year. Comparison of these results with the total suspended loads in Table 4 shows that the annual sand load has reached up to 46.5% of the total load during high freshet years such as 1972 and as little as 24% of the total load in very low runoff years such as 1977 or 1978. However the overall average fraction corresponds to about 35% which is very similar to the estimate based on the individual particle size distribution measurements. Also shown in Table 8 are estimates of the annual load coarser than 0.125 mm. These estimates were computed using exactly the same procedures as in the sand loads. These loads represent the suspended bed material load at Mission and will be discussed in more detail later on.

4.6 Predicting Annual Sediment Loads from Flow Volumes

It would be useful to develop methods for estimating the annual suspended sand load and total load for years when sediment measurements are not available. One approach would be to simply extrapolate the daily total concentration or sand rating curves. An alternative approach is to develop rating curves based on much longer time scales and to predict the annual load directly using the annual flow volume or monthly flows as the independent variables (Kellerhals Engineering Services, 1985). One of the main advantages of this approach is that by considering longer time scales some of the short term variability such as the noticeable hysteresis, will become averaged out. This should result in better correlations betweeen sediment load and discharge and in more precise predictions.

In fact very good correlations are exhibited between annual sediment loads and annual flow volumes at Hope, Agassiz and Mission (Figure 27). In order to test the usefulness of this type of relation the measured annual suspended loads were compared against rating curves based on daily, monthly and annual discharges. For these tests the annual loads were estimated as follows:

(15) $Ga = C\,d\,.(Qi)$ where $Cd = AQ_i^b$ (daily rating curve)

(16) $Ga = A_1Q_{may}^{b_1} + A_2Q_{June}^{b_2} + A_3Q_{July}^{b_3} + \ldots$ (monthly rating curve)

(17) $Ga = AQ_{annual}^{B}$ (annual rating curve)

These comparisons were made using the data at Hope so that load predictions could be made for the years 1950-1952 and compared with the estimates published by Kidd (1953). This comparison would provide a completely independent check on the accuracy of the estimates.

Table 9 summarises the results of the three rating curve regressions. The daily concentration rating curve was based on 1338 measurements between 1966 and 1978. As expected, the standard error of the overall daily concentration regression was very large compared to the monthly or annual relations. For example the standard error of the monthly June loads was found to be only 0.18 (Ln units) compared to 0.77 for the daily regression. Table 10 compares the annual total suspended load predictions from these methods. The best overall estimates of the annual loads were produced by the monthly rating curves (RMS error equalled 2 million tonnes/year or 11% of the mean annual load).

The only year in which the daily rating curves performed significantly better than the monthly or annual relations was in 1950. In this year the annual and monthly rating curves underestimated Kidd's estimate by about 20%. The 1950 flood was the second largest flood in the period of record between 1912-1984. However, both the annual flow volume and mean June discharge were unusually low. Therefore in years when the freshet is unusally "flashy" the daily rating curves might produce the best estimates. It appears, then, that the monthly or annual rating curves are reasonably stable in the long term, except when the freshet is of markedly unusual character. This stability is perhaps the most important characteristic of a correlation that is going to be used for temporal extrapolation.

Multiple regression relations were also developed to see whether the load estimates could be improved by including a number of different flow parameters. These relations were of the form:

(18) $$\text{Log } G = B_0 + B_1 \text{Log } Q_{annual} + B_2 \text{Log } Q_{June} + B_3 \text{Log } Q_{peak}$$

This type of relation improved the prediction of the 1950 load however the overall RMS error from all years was still about the same as that for the monthly regressions. This is because in most years the maximum daily, June mean and annual flow volume are all highly inter-correlated.

Similar regression relations were developed for predicting the annual suspended sand load and total suspended load at

Agassiz and Mission (Table 9). At these stations the annual sand loads were predicted from the annual flow volume and mean June discharge (the peak discharge was found to not significantly improve the correlations):

(19) $$\text{Log } G = B_0 + B_1 \text{Log } Q_{annual} + B_2 \text{Log } Q_{June}$$

It was also found that the best predictions of the annual sand load and total load at Mission were made using flows measured at Hope rather than Mission. This probably is because the Harrison River (which is the main tributary between Hope and Mission) can increase the flows in the Fraser River by 10 to 15% but contributes virtually no additional sediment and is not necessarily in phase with Fraser River flows. This result makes it very simple to predict the past loads at Mission since the flow records at Hope extend back to 1912 while the Mission records extend only to 1965.

Tables 11 and 12 summarise the estimated annual sediment loads at Hope and Mission from 1966 to 1982. The loads have been separated into sand silt and clay fractions. The silt and clay loads were estimated by subtracting the computed total and sand loads and then assuming that the ratio of silt to clay was 3.3:1. This ratio was estimated from the analysis of the depth integrated particle size data.

The precision of the annual load estimates can be measured by the standard error of the regressions. The RMS error for the sand load at Mission, is less than 10% of the mean annual load. The RMS error of the Mission suspended bed material load predictions is about 13.5% of the mean annual load. Figure 28 shows that the agreement between the measured sand loads and the sand loads predicted from the flow volumes is very good.

The sediment load relations developed in this section could be used for estimating the annual load below Mission from flow forecasts that are made in April and May before the peak of the freshet. Such predictions may eventually provide a basis for planning maintenance dredging requirements in the navigable portion of the river below New Westminster.

5.0 THE BEDLOAD

5.1 Measurement Procedure

Between 1968 and 1976 110 measurements were collected at Agassiz with the sampling frequency ranging from 23 measurements/year in 1968 to only 9 in 1976. Unfortunately, only 62 measurements were collected during the freshet season (May-July) when virtually all of the bedload movement takes place. The measurements were collected with a half size VUV sampler (Novak, 1957) and a basket sampler (Ehrenberger, 1931) at the higher flows (generally above 7500 m^3/s). The VUV sampler has an opening width of 225 mm and a height of 115 mm. This pressure difference type sampler is designed so that the water and transported bed material enter the sampler with the same velocity as the undisturbed flow. The WSC basket sampler is based on early Swiss designs from the 1930s and has an opening width of 610 mm, a height of 255 mm and a basket mesh size of 6 mm. Due to the coarse mesh size the finer gravel and sand will not be retained in the sampler.

The sampling times for both the VUV and basket measurements were usually two to three minutes and sample catches usually ranged from a few hundred grams up to 1 or 2 kg in the VUV sampler and up to 10 to 20 kg in the basket sampler.

The Agassiz bedload measurements were collected at six or fewer verticals from a WSC boat on the gauging section line. Typically only two or three repetitive samples were collected at each vertical making a total of 12 to 18 samples in each measurement.

The bedload measurements at Mission were made with a BTMA Arnhem sampler (Schaank, 1937; de Vries, 1973). This sampler is a pressure difference sampler with an intake opening 8.5 cm wide and 5 cm high. The Arnhem sampler was designed for measuring bedload in the Rhine River in the Netherlands where the bed material consists of coarse sand and fine gravel. The samples are collected at five verticals from a WSC boat on the gauging section line upstream of the Mission Railway bridge. Normally 3 to 5 replicate samples are collected at each vertical with individual sample catches ranging from a few grams to a few hundred grams. In some of the early years a complete measurement was often repeated two or three times in the day so that the daily load could be estimated from 50 to 75 samples. In later years the daily load must usually be estimated from about 15 samples.

5.2 Data Adjustment: Sampler Efficiency

None of the daily bedload data has been published by WSC and all of the data in the work files was considered preliminary and subject to revision. Also much more information is available for estimating the efficiency of the samplers at this time than when the data were first collected, Therefore it was decided that all of the bedload data should be re-calculated. These revised estimates were compared against WSC's preliminary values in order to identify any significant discrepancies or calculation errors.

The efficiencies of the basket and VUV samplers were estimated from recent laboratory calibrations performed at the Canada Centre for Inland Waters (Engel, 1982, 1983). These studies, as well as results from previous investigations (Gibbs, 1973), indicated that the efficiency of the basket sampler is about 33% for the hydraulic conditions at Agassiz. However, this efficiency factor does not account for any loss of fine sediment through the coarse mesh of the basket. In all laboratory studies the model bed material was always coarser than the screen size. However at Agassiz a considerable portion of the bedload is finer than the 6 mm wire mesh and was not retained in the sampler. This feature was very apparent when the size distributions of the basket samples were compared with those of the VUV samples. The missing portion of the sample can be estimated approximately by assuming that at high flows the bedload size distribution is similar to the sub-surface bed material size distribution (Einstein, 1971; Parker _et al_., 1982). The bed material samples near Agassiz indicated that about 15% of the sediment was finer than 6 mm. Therefore the overall correction factor adopted in this study was estimated as:

$$K = 1/0.33 \times 1/.085 = 3.5$$

Early studies suggested that the VUV sampler has an efficiency of 60 - 70% (Novak, 1957; Gibbs and Neill, 1973). More recent studies have shown that the efficiency may vary between 60% and 30%, depending on the hydraulic conditions and sampling times (Engel, 1983). For the hydraulic conditions at Agassiz and for sampling times of 2 to 3 minutes the efficiency of the half size VUV sampler was estimated to be about 33% (identical to that of the basket sampler). This estimated efficiency is surprisingly low compared to the results from previous laboratory studies.

The efficiency of the Arnhem sampler was determined from a series of model tests carried out in the 1930s at the ETH laboratories in Zurich (Meyer-Peter, 1937). The efficiency was found to decrease as the sampler filled with sediment varying between 90% and 50%. As a result, the efficiency correction must be applied to each individual bedload sample and an overall factor can not be applied to the total daily load. At the time of this report only the data from 1968, 1972, 1974 and 1979 have been re-computed. This involved manually processing about 2600 individual sample points. Examination of these results indicated that the overall sampling efficiency for the total bed load rate averaged about 70% to 75%, which is very close to previously reported values (Novak, 1957; Hubbel, 1964). In comparison, WSC assumed an overall sampler correction factor of 3.5 (26.8% efficiency) or about 2.5 times the value that would be appropriate for the Arnhem sampler.

5.3 Reliability of the Measurements

Due to the sporadic nature of bed load movement and the physical difficulties involved in sampling, measurements of bed load are usually considered to be less reliable than measurements of suspended load. The problem of bed load sampling reliability has been discussed previously by several researchers (de Vries, 1973; Csoma, 1973; Gibbs and Neill, 1973; Hubbell, 1985). This work has generally involved collecting repetitive samples at a single vertical in the cross section and then comparing the load determined from only a few samples to the actual average load determined from the full set of measurements. The most complete treatment of the problem has been provided by Hamamori (1962) and de Vries (1973) who investigated the fluctuations in bedload rates caused by the passage of dunes and ripples along a sand bed channel. In this work the frequency distribution of the transport rates was determined by the relation:

(20) $$p = 1/4\ g_b/\overline{g}_b(1+\mathrm{Ln}(4\overline{g}_b/g_b))$$

where p is the probability that a single load measurement will be less than a given amount;
$\overline{g}_b$ is the actual average rate.

On the basis of this relation and field measurements from the Rhine, de Vries (1973) recommended that a minimum of 10 samples should be collected at each vertical.

Measurements on the gravel bed portion of the Danube River showed that the probability distribution of transport rates varied across the channel, with the bedload rates being less widely distributed where the transport rates were highest (Csoma, 1973). In this case the Hamamori relation was found not to apply.

Einstein (1937) described the distribution of bedload transport movement by assuming that bedload particles moved in a series of steps and rests, with the rest periods being much longer than movement times. The related problem of describing the distribution of sediment volumes caught in a bedload sampler after a specified sampling time was also considered. The probability density function describing the volume of sediment trapped in a given sampling time was expressed as:

(21) $$P(f) = \exp(-(\sqrt{f} - \sqrt{T})^2 \,.\, T.\ J_1\ (2\sqrt{fT})/(\sqrt{fT} \cdot \exp\ (2\sqrt{fT})$$

where J_1 is a Bessel function of the first order with a complex argument;
f is the volume of sediment trapped in the sampler measured in average collection units;
T is the sampling time measured in average particle rest periods.

This function implies that the distribution of bedload transport rates will depend on the duration of sampling and the intensity of transport, which is in agreement with Csoma's observations. This type of model appears to be more appropriate for estimating the reliability of measurements in gravel rivers.

A preliminary test of this model using repetitive measurements at Agassiz is described by McLean and Tassone (1985). The replicate measurements at Agassiz were made by WSC on June 11, 1985 with the half size VUV sampler at a discharge of approximately 7700 m^3/s. Twenty repeat samples were collected at two verticals and 14 samples were collected at the third vertical. Figure 29 illustrates the large fluctuations in sample catches that were observed and the frequency distribution of the transport rates. The most important feature of these results is that individual measurements could reach up to six times the overall mean transport rate. Furthermore, the distribution of transport rates was very non-symmetrical, with nearly 70% of the samples having loads less than the average and only 30% of the samples having loads greater than the average. These results should make it clear that the normal practice of estimating the mean bedload rate with only two or three samples could result in substantial errors. In reviewing the past measurements at Agassiz it was found that in 30% of the daily measurements between 1968 and 1976 the range in transport rates at a single vertical exceeded the computed average at the vertical by a factor of two. As a result the precision of the computed averages must be very low.

Three sets of repeated bedload measurements have been collected at Mission in 1972 and 1974 under flow conditions that ranged from 10 800 m^3/s to 6570 m^3/s. On these three dates between 20 and 25 bedload samples were collected at a single vertical (Vertical 900) over a period of three to four hours. The variation in transport rates that was observed is summarised in Figure 30.

The 1972 data showed that individual bed load measurements varied between 0.1 and 4 times the average rate estimated from all samples. The frequency distribution of transport rates from the two sets of measurements in 1972 fit the theoretical Hamamori distribution much more closely than the 1974 measurements. The actual distribution of transport rates in sand bed channels will be affected by the bed form characteristics that are present. Unfortunately, longitudinal profiles were not surveyed at the time of the bed load measurements in 1972 or 1974.

Given the distribution of transport rates at a point, the reliability of estimating the true mean bedload rate from an n-sample average can be determined. In this study, the precision of the computed average bedload rates was estimated by using the Monte Carlo simulation technique in conjunction with the measured bedload probability distributions to generate a large number of n-sample averages. The precision of these synthesised measurements was then expressed as a coefficient of variation of the mean rate (standard deviation of the estimated means/mean bedload rate). The calculations were performed with a FORTRAN program that used a random number generator to produce 100 consecutive n-sample averages from the assumed bedload probability distribution (McLean and Tassone, 1985). This approach was first used by de Vries (1973) to estimate the number of measurements required on the sand bed portion of the Rhine River. The results of the simulations using the measured probability distributions at Agassiz and Mission are illustrated in Figure 31. It was found that the precision of the measurements was substantially lower at Agassiz than at Mission. For a three sample average at a vertical the relative error (CV of the mean) was 84% at Agassiz and 50% at Mission. At least 10 repeat samples would be required at Agassiz before the relative error was less than 50%. These values represent the expected error at a single vertical and not the error in total bedload rate at the cross section.

In order to estimate the error in the total bedload rate some information on the spatial variability of the bedload rates across the channel would be required. A field assessment of this problem would require collecting a minimum of 10 samples at 10 to 20 verticals across the section and then comparing the total rate with the estimate from the 5 verticals that are normally used. This exercise has not been carried out. Recently, Hubbel (1985) extended the Monte Carlo approach by allowing the mean transport rate to vary across the channel section so that the error in estimating the total bedload rate from a limited number of verticals and samples could be made. Hubbel considered the case where the bedload rate could have only two possible values and used Hamamori's probability distribution for estimating the variation of transport rates at a point. After reviewing the data at Agassiz and Mission it was considered that it would be more realistic to allow the transport rates to vary continuously across the channel. Several different assumed lateral variations were tested including uniform, triangular, bell-shaped quadratic and bell-shaped exponential. Furthermore, the Einstein probability model was used for computing the frequency distribution of transport rates at a point. The model parameters in Einstein's equation were computed by the method of moments to reproduce the measured bedload transport distributions at Agassiz and Mission. In this second simulation program the precision of the total bedload rate was computed for different sampling strategies by varying the number of verticals in the cross section and the number of repeat samples at each vertical.

The simulations showed that when the spatial variability of the transport rates was less than the temporal variations at a single point then the relative error in the total bedload rate was less than the relative error in the average at any single point. A lower bound estimate for the precision of the total loads can be made by assuming that the actual mean bedload rate is uniform across the channel. For the normal sampling procedures on the Fraser River (5 verticals, 3 samples/vertical) the relative error (CV of the mean) was found to be 40% at Agassiz and 26% at Mission. In examining the measured rates across the sections at Agassiz and Mission it was noted that the maximum rate at a vertical (estimated from 3 samples) seldom exceeded three times the mean rate at the cross section. For the case of a "bell shaped" exponential distribution and a maximum to mean ratio of three, the relative error increased to 58% at Agassiz and 34% at Mission. These values could probably be considered upper bound estimates of the errors in the measured total bed load rates.

The Monte Carlo method was also used to investigate the number of samples or verticals that would be required at Agassiz and Mission to achieve a specified level of precision. The results for some assumed conditions are summarised in Figure 32. These simulations suggest that a moderate increase in sampling effort could have substantially improved the precision of the measurements. In fact, the precision of the Agassiz data could have been increased by nearly a factor of two without having to increase the total number of samples collected between 1968 and 1976. This is because 40% of the measurements were collected in the winter months when the gravel transport rate was effectively zero. This wasted sampling effort could have gone into increasing the number of samples collected during each daily measurement during the freshet season.

5.4 Analysis of Agassiz Bedload Data

Some preliminary interpretation of the bed load data at

Agassiz are contained in Mannerström and McLean (1985). That paper also outlines the efforts that were made to predict the bedload rate from a number of theoretical equations.

Significant gravel transport begins to occur at about 5000 m^3/s. Most VUV bedload samples collected below this flow consisted of sand or granules in the 2 mm to 8 mm size range. The abrupt change from sand transport to gravel transport probably represents the threshold condition for mobilising the local armoured surface layer (Parker et al., 1982). After this condition was exceeded the grain size distribution of the bedload became similar to that of the subsurface bed material.

Figure 33 shows that there is only a poorly defined relation between bedload transport rate and discharge. The error bars on the individual measurements show that a large portion of this scatter may be attributed to the low precision of the bedload measurements. However, it is now generally recognised that in many gravel bed rivers, bed load transport rates may depend on the flow history and the limited supply of mobile sediments along the channel (Church, 1985). As a result a simple equilibrium relation between transport rate and flow hydraulics may not exist.

The wide scatter of bedload transport rates described in this study is not compatible with some previously published results. In WCHL (1978) it was reported that "the bed load data at Agassiz are extraordinarily systematic". This conclusion was based on only a small, selected fraction of the available data and does not represent the actual conditions that are found when all the data are considered. Indeed, given the low precision of the bedload data the chance of finding a systematic relation between bedload rate and discharge would be extraordinarily small.

In examining the bedload discharge plots it was noticed that the data sometimes displayed an apparent seasonal hysteresis. However, the direction of the hysteresis was not consistent from year to year. In some years the rising limb bedload rates were systematically higher than the falling limb rates. In other years the reverse situation was observed. In an attempt to explain some of these effects multiple regression techniques were used in order to include a number of independent variables such as hydraulic parameters (mean velocity, depth), flow parameters (rate of change of discharge, discharge on the day preceding measurement) and suspended sediment parameters (total concentration, sand concentration). Finally the data were split into rising limb/falling limb categories and separate regressions were developed for each group. None of these efforts consistently improved the estimation of the transport rates. We conclude that the seasonally variable behaviour most likely is related to erosional and depositional events along the channel upstream, and follows no consistent fashion.

Therefore the annual bedload rates were estimated on the basis of simple one variable regressions. However, separate rating curves were developed for the loads measured above and below a discharge of 4000 m^3/s. This distinguished the predominantly sand transport at low flows from the predominantly gravel transport at higher flows. Furthermore this separation ensures that the predicted transport rates at the low flows will be based on the VUV measurements while the predictions at high flows will be based primarily on the basket measurements. The two rating curves intersect at a discharge 7000 m^3/s (Figure 33).

Table 12 summarises the annual bedload transport at Agassiz between 1967 and 1968, as estimated from the daily rating curve. The annual bedload rate averaged 170 000 tonnes/year between 1967 - 1982, and ranged from 520 000 tonnes/year in 1972 to 60 000 tonnes/year in 1978. The size distribution of the bedload was assumed to be similar to the size distribution of the volumetric bed material samples taken from the bars near Agassiz. This assumption is reasonable since the bar deposits represent bedload material in storage. Based on this assumption it was estimated that about 15 % of the bedload will consist of sand (primarily in the 0.25 - 1.0 mm size range) and 85 % will consist of gravel (primarily in the 16 - 45 mm range). It remains possible that the VUV sampler traps a minor proportion of suspended sediment near the bed, which may inflate the bedload transport estimates slightly.

The precision of the annual loads was computed from the confidence limits on the bedload rating curve regression lines. The confidence interval on the "true" position of the rating curve can be expresssed as:

$$\bar{y} \pm t_\alpha \text{ SEE } \sqrt{1/n + \frac{(x - \bar{x})^2}{(n-1)\, S_x^2}} \qquad (22)$$

where SEE is the standard error of the regression
t_α is the t-statistic with n-2 degrees of freedom
Since the rating curves were based on power law regressions x and y are the log transforms of the discharge and sediment transport rate.

The one standard error confidence limits on the rating curve line varied from +17.5% to -15% at a flow of 7500 m^3/s and from +30% to -23% at 14 000 m^3/s. The uncertainty in the annual load was estimated as follows:

1. the confidence interval (measured in per cent) on the rating curve estimate E_i was computed for flows ranging from 3000 m^3/s to 15 000 m^3/s;

2. the fraction of the total annual load in each flow interval Q_i was computed to produce a weighting factor, W_i;

3. the relative error in the annual load was then estimated as the sum of the weighted errors in each flow interval, $\Sigma W_i E_i$.

This calculation indicated the estimated annual loads could be specified within $\pm$20% with a one standard error confidence interval or to within $\pm$40% with a two standard error confidence interval. This can be restated by saying there is a 68% chance that the "true" annual bedload rate will be within 20% of the estimated value and a 95% chance that the "true" rate will be within 40% of the estimate. By comparison, the one standard error confidence intervals on the daily bedload measurements ranged from $\pm$40% to $\pm$58% using the Monte Carlo simulations.

Figure 34 shows the fraction of the total bedload transported by different discharges over the period 1967 to 1982. This histogram illustrates that the flows near 8000 m^3/s accounted for the largest fraction of the total bedload transport over the 16 year period. Discharges over 10 000 m^3/s (approximately a 5 year flood) accounted for 24% of the total bedload. Therefore the relatively frequent, moderate flows account for the largest proportion of the total bedload transport. Based on the hydraulic measurements at the gauge site, the shear stress at a flow 8000 m^3/s was found to be only about 50% higher than the critical shear stress required for mobilising the surface armour (Parker et al., 1982). This illustrates that the greatest proportion of the transport rates take place when the bedload movement is weakly established. At conditions near threshold, minor changes in the state of the bed (such as the surface size distribution, extent of imbrication) can induce very large relative changes in the transport rates. Therefore, for most of the annual load, the bedload transport rates will not show a very systematic relation with local hydraulic conditions. This makes it very difficult to predict the transport rates from theoretical formulae (Mannerström and McLean, 1985).

5.5 Analysis of Mission Bedload Data

Figure 35 illustrates individual Mission bedload measurements from 1972 and 1974. A composite diagram based on measurements in 1968, 1972, 1974 and 1979 is shown in Figure 36. The Mission bedload data show considerable scatter; in 1974 the transport rates varied over a factor of five (i.e. ±67%) under virtually constant discharge conditions. This scatter is greater than the expected ±25% to ±40% sampling errors associated with spatial and temporal variations in transport rates discussed in Section 5.3. Furthermore, the available hydraulic measurements show very consistent relations with discharge and display very little scatter (Figure 6). However variations in bedform characteristics, channel resistance, water surface slope and water temperature could all affect the transport rates in a complex manner. Intensive field studies would be required to measure these effects. Nevertheless, the error analysis implies that about half of the scatter on the bedload discharge plots can be associated directly to measurement imprecision.

As a preliminary step in analysing the Mission bedload data, simple power law regressions were carried out on the 1968, 1972, 1974 and 1979 data sets. The sets were also combined to produce an overall rating curve based on 107 data points. The annual bedload rates between 1966 and 1982 were computed by summing the estimated daily loads. The predicted annual loads (based on the overall rating curve) varied between 200 000 tonnes/year in 1972 and only 30 000 tonnes/year in 1979, and averaged about 100 000 tonnes/year. These estimates were found to be substantially lower (by about a factor of 5) than the preliminary figures published for the years 1967-1969 (Tywoniuk, 1972). A portion of this discrepancy is due to the fact that the preliminary WSC estimates were based on an Arnhem sampler efficiency of 0.28, which is 2.5 times lower than the currently recommended value. This still leaves a discrepancy of roughly a factor of 2 that can not be explained. The cause of this discrepancy is still under investigation.

Figure 37 compares the measured instantaneous bed load and suspended bed material load at Mission on days when concurrent samples were collected. This plot shows that the ratio of bed load to suspended bed material load (sand >0.125 mm) varied between about 1% and 4%, and averaged 2%. By comparison, the ratio of estimated annual bed load/ annual bed material load averaged about 3%. These figures illustrate that the bedload makes up a very small fraction of the total bed material load. In fact, the magnitude of the bedload rates is generally less than the expected errors in the measurements of the suspended bed material load. Therefore, the suspended bed material load is by far the most important parameter for evaluating channel sedimentation processes in the sand-bed portion of the river.

Figure 38 shows separate rating curves for the bedload and bed material load at Mission. Also shown are predicted bed material loads from a number of theoretical sediment transport equations. It was found that both the Ackers-White equation and Tofaletti's equation fit the field measurements quite closely (generally within a factor of 0.5 to 2.0 times). These equations have both been calibrated on large sand bed rivers and have been found to perform well (White et al., 1975). Further testing of these theoretical sediment transport equations should be carried out before they are used for estimating bed material loads on the sand bed portion of the lower Fraser River.

6.0 AGASSIZ - MISSION SEDIMENT BUDGET

6.1 Long-term Variations

Tables 11 and 12 summarise the estimated annual suspended load and bedload transport rates by size fraction at Agassiz and Mission. Approximately 150 000 tonnes/year of gravel material (coarser than 2 mm) was transported past Agassiz between 1967 and 1982. The Arnhem bed load samples at Mission showed gravel sediments comprised only 1.5% of the bedload there, which corresponds to gravel transport past Mission of roughly 2000 tonnes/year. Therefore approximately 2.4 million tonnes of gravel sediments were deposited in the Agassiz - Mission reach between 1967 and 1982 and roughly 5 million tonnes has been deposited since 1950.

Comparison of the extensive morphologic surveys that were carried out in 1950 and 1984 (McLean, 1985) should provide independent confirmation of these estimates. The survey comparisons will also indicate the pattern of deposition along the channel.

The mean annual total suspended loads at Hope, Agassiz and Mission all agree within 1% over the period of common record between 1967-1979. T-tests on the annual differences between Hope - Agassiz, Agassiz - Mission and Mission - Hope all confirmed the annual total suspended loads are not statistically different (at $\alpha = 0.1$ significance level).

The estimated annual sand loads at Mission exceeded the Agassiz loads by 550 000 tonnes/year on average between 1967 - 1982. This long term difference was statistically significant at $\alpha = 0.1$. In years characterised by unusually large freshets (such as 1967, 1972, 1974 and 1982), the annual sand load at Mission exceeded the load at Agassiz and Hope by as much as 20 - 40%. These differences are substantially larger than the expected measurement errors. For example, in 1972 the sand load at Mission exceeded the load at Agassiz and Hope by 4 million tonnes. Apparently in some years large quantities of predominantly sand sized sediment can be derived from the Agassiz - Mission reach. Based on the published sediment records from the Chilliwack River at Vedder Crossing it is apparent that the sediment inflows from tributaries between Mission and Agassiz are negligible in comparison to some of the observed increases in annual load at Mission. The source of this sediment is still under investigation.

6.2 Short-term Variations

Comparison of the average monthly load summaries in Figures 15 and 16 indicate that the sand load at Mission in May is characteristically lower than at Agassiz. Conversely, the sand load in June is considerably higher at Mission than at Agassiz. This indicates that substantial quantities of sand are being stored in the Agassiz - Mission reach on the rising limb of the freshet and then are deflated from the reach on the falling limb. These storage changes were examined further by computing the cumulative difference between the total suspended load at Agassiz and Mission, "D(t)", at daily intervals over the year:

(23) $$D(t) = \sum_{i=1}^{t}(g_i\text{Mission} - g_i\text{Agassiz})$$

Figure 39 illustrates the variation of the cumulative differences over the 1968, and 1972 freshets. The 1968 data show that even when the annual loads at Agassiz and Mission are virtually identical, systematic variations in transport rates may take place between stations. On the rising limb of the flood in May the incoming load at Agassiz consistently exceeded the load at Mission while after June 1st the loads at Agassiz were consistently lower than at Mission.

The change from sediment accumulation to sediment depletion coincided with the onset of supply exhaustion at Agassiz. This pattern of sediment accumulation on the rising limb of the flood occurred in virtually every year. In most years a period of sediment depletion took place on the falling limb so that the net change in sediment storage within the reach at the end of the freshet was virtually zero.

Figure 39 also shows the pattern in 1972 when substantial net sediment depletion occurred. This plot shows that the sediment depletion took place on the falling limb of the freshet after a period of initial sediment accumulation.

Examination of similar plots over the full record (not illustrated) makes clear that modest net accumulation occurs in the Agassiz - Mission reach in most years, and is then removed in exceptional floods (1967, 1972, 1974). The individual annual accumulations fell within annual compilation error, but the episodic loss exceeds it. The storage area and exchange mechanisms for this material remain to be determined.

7.0 SUMMARY AND CONCLUSIONS

The main emphasis of this study has been to provide estimates of the annual suspended load and bedload transport along the lower Fraser River. The estimates have been based on the Water Survey of Canada measurements at Hope, Agassiz and Mission during the period 1965 - 1982. Particular attention has been given to assessing the reliability of the measurements and to distinguishing the wash load and bed material load components. Methods for estimating the annual loads have also been developed.

The principle findings from the study are as follows:

1. The annual total suspended loads at Hope, Agassiz and Mission are virtually identical over the period of record. The annual suspended load averaged 17 400 000 tonnes/year during the period 1966-1983.

2. Moderate flows around the 1.5 year return period, account for the greatest proportion of the long term suspended load. More extreme flood flows occur so rarely that the cumulative contribution from these events is relatively minor.

3. In the gravel bed portion of the river at Agasssiz and Hope virtually all of the suspended sand load behaves as wash load. As a result, the suspended sand load is governed primarily by the rate of upstream sediment supply and not by local channel hydraulics.

4. In the sand bed reach at Mission, very fine sand (0.063 - 0.125 mm) makes up nearly 50% of the suspended sand load, but is

virtually absent in most bed material samples. Therefore a portion of the sand load at Mission can be considered as wash load.

5. At Mission the bed material load was found to consist of sand coarser than 0.125 mm and fine gravel. The suspended bed material load makes up only about 19% of the total suspended load.

6. At Mission, approximately 50% of the suspended bed material load is transported within 2 m of the river bed. Since bedforms at Mission frequently reach up to 2 m in height, there is no clear distinction between suspended bed material load and bedload.

7. The loads measured with the Arnhem bedload sampler at Mission comprised only about 2% of the suspended bed material load. The magnitude of the bedload rates is smaller than the expected errors associated with the depth-integrated suspended load measurements. Hence, the suspended load measurements are overwhelmingly dominant in determining bed stability in the sand-bed reach.

8. The annual sand load or bed material load at Mission can be predicted with an RMS error of about 10% from the June monthly flow and annual runoff volume at Hope. The annual runoff volume alone was also found to be a good predictor of the annual suspended load at Mission. The results of this study show that it may be quite feasible to forecast the annual sand load in the navigable portion of the river below New Westminster from routine

runoff forecasts in April or May.

9. Significant gravel transport begins to occur at Agassiz at a discharge of 4000 to 5000 m³/s. In spite of this threshold condition, it was found that moderate flows near the 1.5 year flood return period account for the largest proportion of the long term bedload transport.

10. The annual bedload transport at Agassiz averaged approximately 175 000 tonnes/year between 1967 and 1982. Approximately 85% of this load consisted of gravel sediments coarser than 2 mm.

11. The gravel transport past Mission is about two orders of magnitude smaller than the gravel transport at Agassiz. Approximately 2.4 million tonnes of gravel sediments have been deposited in the Agassiz - Mission reach between 1967 and 1982, and roughly 5 million tonnes have been deposited since 1950.

12. Over the long term, the suspended sand load at Agassiz is approximately equal to the load at Mission. However, in some years the annual sand load at Mission may exceed the Agassiz load by 25 to 40%. In these years substantial quantities of sand must be entrained in the Agassiz - Mission reach, either from bank erosion or channel scour. This emphasises the requirement to have any eventual forecast system for sand delivery to the estuary based on river behaviour at Mission or downstream.

13. Complex, short term changes in sediment storage also occur in the Agassiz - Mission reach. Typically, sediment accumulates

during the rising limb of the flood and then is removed during the falling limb.

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TABLES

TABLE 1

LOWER FRASER RIVER HYDROMETRIC STATION SUMMARY
(HOPE TO MISSION)

STATION	NAME	DRAINAGE AREA (km2)	LOCATION	SUSPENDED LOAD SEDIMENT YIELD	SUSPENDED LOAD TYPE OF OBSERVATION	SUSPENDED LOAD PARTICLE SIZE PI	SUSPENDED LOAD PARTICLE SIZE DI	BED LOAD PARTICLE SIZE	BED MATERIAL PARTICLE SIZE	REMARKS
08MF005	HOPE	217000	49 22 50	1965	MS	1965	1965			REG 52
			121 27 05	1966-69	MC	1967-68	1966-69			
				1970-79	MC	1970-78	1970-78			
08MF035	AGASSIZ	217870	49 12 16	1966	MS	1966				REG 52
			121 46 35	1967-69	MC	1968	1967-69			
				1970-72	MC	1970-72	1970-72	1970		
				1973-79	MC	1973-79	1973-78	1973-79	1978-79	
				1980-82	MC	1981-82	1980-82	1980-82		
08MH024	MISSION	228000	49 07 39	1965	MS	1965	1965		1965	REG 52
			122 18 08	1966-71	MC	1966-68	1966-71		1966-71	
				1972-80	MC	1972-79	1972-80	1973-80	1972-80	
				1981-82	MC	1981-82	1981-82	1981-82	1981-82	

Notes:
- M - manual sampling
- C - continuous operation
- S - seasonal operation
- REG - regulated flow

TABLE 2

DISCHARGE SUMMARY FOR LOWER FRASER RIVER

STATION	WSC REF	PERIOD	DRAINAGE AREA km2	MINIMUM DAILY FLOW m3/s	MEAN ANNUAL FLOW m3/s	MEAN JUNE FLOW m3/s	MEAN ANNUAL FLOOD m3/s	FLOOD OF RECORD m3/s
HOPE	08MF005	1912-1984	217000	340	2730	7030	8766	15200
HOPE	08MF005	1966-1984	217000	527	2826	7215	8586	12900
AGASSIZ	08MF035	1966-1984	217870	470	2880	7180	8760	13100
MISSION	08MH024	1966-1984	228000	648	3410	8140	9790	14400

TABLE 3

CHANNEL CHARACTERISTICS AT GAUGING SITES

STATION	REF	FLOW	Q m3/s	V m/s	d m	W m	S	BED MATERIAL Surface mm		Subsurface mm
HOPE	08MF005	LTM	2830	1.5	7.9	240	.0006	D90	180	128
		mean June	7030	2.8	9.7	258		D75	130	60
		MAF	8766	3.2	10.1	268		D50	100	30
		5yr	10200	3.5	11.1	270		D25	75	7
		10yr	11500	3.7	11.5	270		D10	40	1
		1972 flood	12900	4.0	11.7	275				
AGASSIZ	08MF035	LTM	2880	1.4	4.1	500	.00048	D90	80	80
		mean June	7180	2.3	6.1	509		D75	56	50
		MAF	8760	2.6	6.6	512		D50	42	25
		5yr	10300	2.8	7.1	513		D25	30	8
		10yr	11600	3.0	7.5	515		D10	20	2
		1972 flood	13100	3.2	7.9	516				
MISSION	082H024	LTM	3410	0.7	9.4	518	.00005	D90	8	
		mean June	8140	1.3	12.	530		D75	0.5	
		MAF	9790	1.5	12.6	540		D50	0.38	
		5yr	11500	1.6	13.2	550		D25	0.20	
		10yr	13000	1.7	13.7	552		D10	0.15	
		1972 flood	14400	1.9	14.1	555				

Notes:

LTM = Long term mean discharge
MAF = Mean Annual Flood
Flow statistics for period 1966-1984

TABLE 4

ANNUAL TOTAL SUSPENDED LOADS ON LOWER FRASER RIVER

(loads in tonnes/year)

YEAR	MISSION	AGASSIZ	HOPE
1966	19273000	------	19746000
1967	26071000	25333000	23437000
1968	20927000	21359000	23626000
1969	13928000	12769000	13171000
1970	11499000	12392000	12003000
1971	17531000	18023000	16308000
1972	30954000	28029000	29061000
1973	12220000	13839000	16151000
1974	24938000	24134000	23230000
1975	11975000	11238000	12031000
1976	24883000	25808000	27637000
1977	14535000	12745000	12415000
1978	12297000	10651000	8993000
1979	15008000	14721000	15539000
1980	10908000	9497000	
1981	12366000	12048000	
1982	25562000	23329000	
1983	8093000	8735000	
1966-1983	17387000	-------	-------
1967-1983	17276000	16744000	-------
1966-1979	18289000	-------	18096000
1967-1979	18213000	17772000	17969000

TABLE 5

MISSION SAND FRACTION REGRESSION EQUATION

%SAND = 0.058446*(Q - 2100)**0.7483
R^2 = 0.75
SEE = 0.29 (Ln units)

TABLE 6

MISSION DAILY SAND RATING CURVE RELATIONS

SEASON METHOD	JANUARY - MAY COEFFICENTS	SEE	R^2	JUNE - DECEMBER COEFFICENTS	SEE	R^2	JANUARY - DECEMBER COEFFICENTS	SEE	R^2
power law (no bias adjust)	A= .897E-6 B= 2.127	.301 (ln units)	.867	A= .1407E-5 B = 2.004	.337	.819	A= .2917E-4 B = 1.690	.420	.727
power law (bias adjusted)	A= .9386E-6 B= 2.127	.301 (ln units)	.867	A= .1490E-5 B = 2.004	.337	.819	A= .3187E-4 B = 1.690	.420	.727
polynomial	AO=-.6215E3 A1= .3554E2 A2=-.7976EO A3= .8244E-2 A4= -.2969E-4	25 (arith units)	.856	AO= .1278E3 A1=-.4529E1 A2= .2021E-1 A3= .6000E-3 A4= -.3266E-5	41	.602	AO= .1292E3 A1=-.9268E1 A2=.19495EO A3=-.1316E-2 A4= .3267E-5	42	.590

Notes:

power law rating curve Csand = A*Q**B

polynomial rating curve Csand = AO + A1*Q**0.5 + A2*Q + A3*Q**1.5 + A4*Q**2

TABLE 7

MISSION ANNUAL SAND LOAD PREDICTIONS
(loads in Tonnes/year)

YEAR	SAND FRACTION METHOD	RISING/FALLING LIMB RATING CURVES			ANNUAL RATING CURVE		
		POWER LAW NOT ADJUSTED	POWER LAW BIAS ADJUSTED	POLYNOMIAL	POWER LAW NOT ADJUSTED	POWER LAW BIAS ADJUSTED	POLYNOMIAL
1966	6228600	7187800	7582600	7616700	7850500	8577100	8515300
1967	11078800	11689500	12349400	11045000	12307600	13446800	11436200
1968	7275400	8573600	9049400	8680200	9372600	10240200	9632300
1969	4087500	5728200	6037300	5937700	6112000	6677800	6592300
1970	3411700	4432200	4811400	4680700	3758100	4105900	4009600
1971	5818400	7260700	7653300	7679300	7547600	8246200	8180100
1972	14396000	14822100	15646500	13559700	14750800	16116200	13402600
1973	3374700	4182200	4409200	4447500	4669800	5102100	5139200
1974	9649100	10126600	10694600	10351800	10919900	11930700	10947500
1975	3511200	5137600	5429900	5560100	6220700	6796500	6819700
1976	8857100	10620400	11201400	11065200	11111200	12139700	11891800
1977	3466600	3413000	3598000	3709100	4025600	4398300	4583700
1978	2911800	2980900	3146300	3187900	3731800	4077200	4221100
1979	3754200	3378100	3561700	3722600	3896100	4256700	4401800
1980	2645100	3394400	3575500	3614200	3883800	4243300	4462100
1981	3473700	4221400	4448500	4321800	4765700	5206800	5217400
1982	9246400	8137600	8596000	8523800	9113800	9957400	9555300
mean	6069800	6781500	7164200	6923700	7296300	7971700	7583700

TABLE 8

ANNUAL SUSPENDED SAND LOADS AT HOPE, AGASSIZ AND MISSION

YEAR	HOPE (SAND)	AGASSIZ (SAND)	MISSION (SAND)	MISSION (BED MATERIAL)
		(loads in tonnes/year)		
1966	6994000	-----	6229000	3301000
1967	8253000	8687000	11079000	6937000
1968	7911000	6786000	7275000	4074000
1969	4253000	3735000	4088000	2121000
1970	4085000	3737000	3412000	1773000
1971	5847000	5744000	5818000	3118000
1972	10413000	10196000	14396000	9365000
1973	5474000	4101000	3375000	1687000
1974	8358000	8028000	9649000	5732000
1975	4038000	3378000	3511000	1799000
1976	10326000	8646000	8857000	4892000
1977	4144000	3735000	3467000	1544000
1978	2747000	2973000	2912000	1313000
1979	5451000	4271000	3754000	1721000
1980		2602000	2645000	1204000
1981		3607000	3474000	1724000
1982		7866000	9246000	5167000
1966-1982	-----	-----	6070000	3381000
1967-1982	-----	5506000	6060000	3386000
1967-1979	6254000	5694000	6276000	3545000

TABLE 9

SUMMARY OF SELECTED RATING CURVES FOR PREDICTING ANNUAL SUSPENDED LOADS

STATION	RATING CURVE	EQUATION	COEFFICENTS			N	R^2	SEE
HOPE	daily total conc	C= A*Q**B	A	B				
			.1075E-1	1.179		1338	.55	.769(ln units)
HOPE	monthly total load	Gmonth = A*Qm**B						
	May		.293E-1	1.833		14	.677	.253(ln units)
	June		.608E-2	1.930		15	.804	.183
	July		.278E-2	1.976		15	.848	.195
	Aug		.139E-2	2.073		15	.901	.166
	Sept-Apr		.1356E0	1.586		116	.614	.788
	annual load	Gann = A + B*Qann						
HOPE	total		-1.836E7	405.5		14	.806	2.92E6(arith units)
HOPE	sand		-7.5732E6	154.4		14	.800	1.12E6
AGASSIZ	total		-1.7336E7	377.3		16	.839	2.64E6
AGASSIZ	sand		-7.8610E6	145.8		16	.829	1.06E6
	annual load	Ga = AO + A1*Qpeak + A2*Qannual						
			AO	A1	A2			
HOPE	total		-2.171E7	1.618E2	2.843E2	14	.901	2.01E6
	annual load	Ln Ga = AO + A1*Ln Qann + A2*Ln Qjune						
			AO	A1	A2			
MISSION	sand		-15.73	1.447	1.662	17	.946	.1237(ln units)
MISSION	bed material		-21.68	1.558	2.117	17	.959	.1290

Notes:

- daily and monthly discharges in m3/s
- annual discharges in thousand dam3
- all water discharges measured at Hope

TABLE 10

COMPARISON OF PREDICTED AND MEASURED ANNUAL TOTAL SUSPENDED LOADS AT HOPE

(all loads in tonnes/day)

YEAR	MEASURED LOAD	RATING CURVE PREDICTIONS DAILY RATING CURVE (polynomial)	MONTHLY RATING CURVE (powerlaw)	ANNUAL RATING CURVE (linear)	MULTIPLE REGRESSION RELATION (linear)
1950	20408000	20571000	16257000	16510000	24416000
1951	15252000	14271000	15324000	12170000	13310000
1952	15128000	16408000	16213000	14040000	14508000
1966	19746000	18918000	18751000	19310000	17068000
1967	23437000	24564000	22619000	22027000	22913000
1968	23626000	23432000	21666000	24216000	22057000
1969	13171000	16285000	16304000	16837000	15633000
1970	12003000	11419000	10545000	9335000	12132000
1971	16308000	18637000	19251000	17850000	16821000
1972	29061000	29646000	28683000	25027000	29473000
1973	16151000	14412000	13863000	13512000	13914000
1974	23230000	23763000	23318000	22189000	24890000
1975	12031000	16286000	13890000	15661000	13946000
1976	27637000	28300000	28146000	28676000	27618000
1977	12415000	14621000	14358000	14809000	12480000
1978	8993000	13123000	12018000	12701000	11338000
1979	15539000	13091000	13132000	11200000	13059000
RMS ERROR (ABS)		2380000	2040000	2920000	1680000
RMS ERROR (%)		13	11.2	16.1	9.3
BIAS (ABS)		900000	228000	-500000	0
BIAS (%)		5.6	1.3	-2.7	0

TABLE 11

MISSION TOTAL LOAD SUMMARY

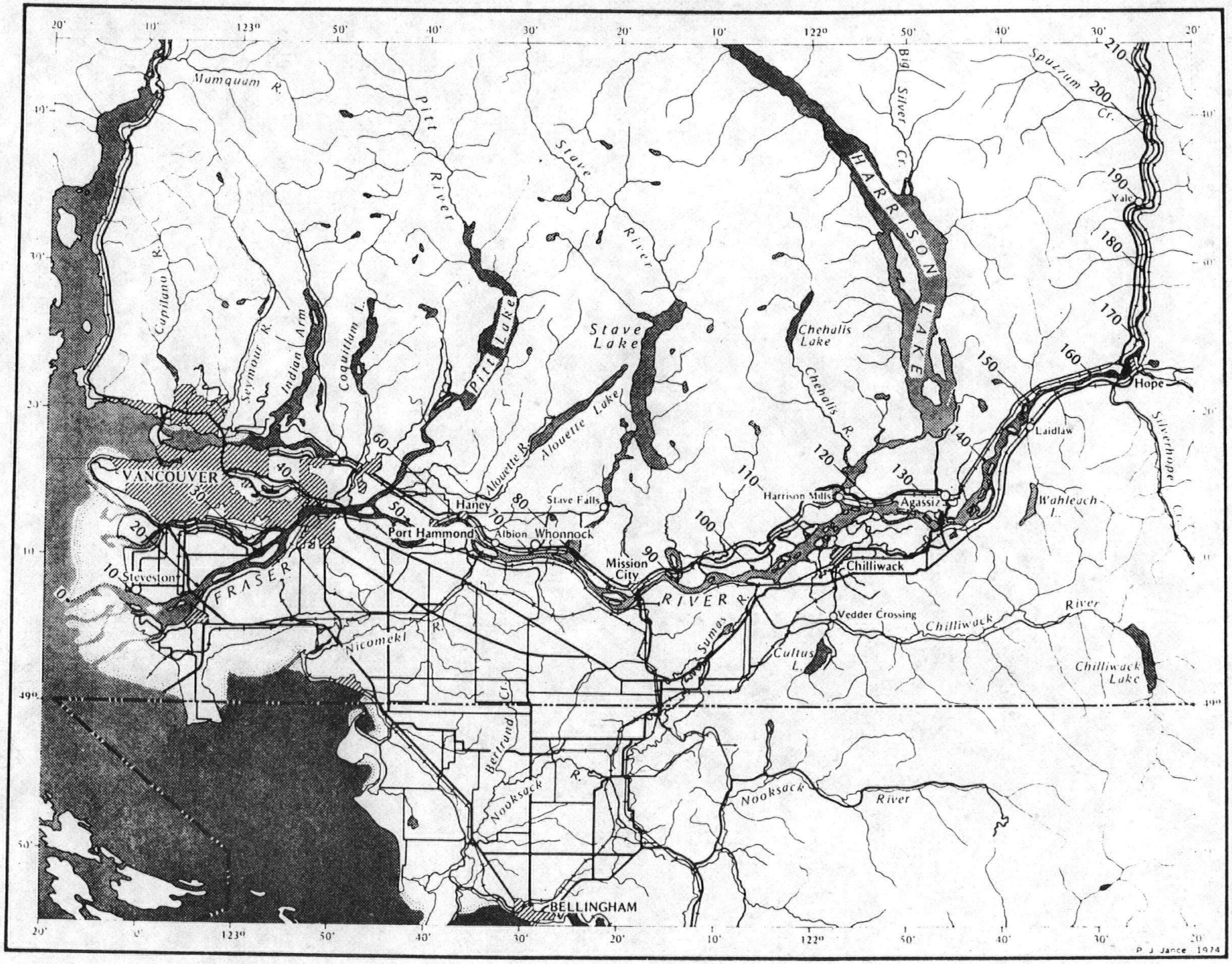
YEAR	SUSPENDED LOAD				BED MATERIAL LOAD		
	TOTAL	CLAY	SILT	SAND	BED LOAD	SUSPENDED	TOTAL
	(all loads in tonnes/year)						
1966	19273000	2959000	10085000	6229000	100000	3301000	3401000
1967	26071000	2574000	12418000	11079000	180000	6937000	7117000
1968	20927000	2944000	10708000	7275000	130000	4074000	4204000
1969	13928000	2316000	7524000	4088000	80000	2121000	2201000
1970	11499000	1874000	6213000	3412000	50000	1773000	1823000
1971	17531000	2602000	9111000	5818000	100000	3118000	3218000
1972	30954000	2424000	14134000	14396000	220000	9365000	9585000
1973	12220000	2122000	6723000	3375000	60000	1687000	1747000
1974	24938000	2983000	12306000	9649000	150000	5732000	5882000
1975	11975000	1992000	6472000	3511000	80000	1799000	1879000
1976	24883000	3426000	12600000	8857000	150000	4892000	5042000
1977	14535000	2840000	8228000	3467000	50000	1544000	1594000
1978	12297000	2412000	6973000	2912000	40000	1313000	1353000
1979	15008000	2820000	8434000	3754000	50000	1721000	1771000
1980	10908000	2045000	6218000	2645000	50000	1204000	1254000
1981	12366000	2168000	6724000	3474000	60000	1724000	1784000
1982	25562000	3435000	12881000	9246000	120000	5167000	5287000
AVERAGE	17934000	2891000	8973000	6070000	100000	3381000	3481000
(% of total)	99.4	16.0	49.8	33.7	0.6	18.7	19.3

TABLE 12

AGASSIZ TOTAL LOAD SUMMARY

YEAR	SUSPENDED LOAD				BED LOAD		
	TOTAL	CLAY	SILT	SAND	TOTAL	SAND	GRAVEL
	(all loads in tonnes/year)						
1967	25333000	4035000	12611000	8687000	310000	47000	263000
1968	21359000	3533000	11040000	6786000	220000	33000	187000
1969	12769000	2190000	6844000	3735000	109000	16000	93000
1970	12392000	2098000	6557000	3737000	86000	13000	73000
1971	18023000	2977000	9302000	5744000	167000	25000	142000
1972	28029000	4323000	13510000	10196000	373000	56000	317000
1973	13839000	2361000	7377000	4101000	108000	16000	92000
1974	24134000	3904000	12202000	8028000	292000	44000	248000
1975	11238000	1905000	5955000	3378000	128000	19000	109000
1976	25808000	4160000	13002000	8646000	300000	45000	255000
1977	12745000	2184000	6826000	3735000	89000	13000	76000
1978	10651000	1861000	5817000	2973000	72000	11000	61000
1979	14721000	2533000	7917000	4271000	86000	13000	73000
1980	9497000	1672000	5223000	2602000	69000	10000	59000
1981	12048000	2046000	6395000	3607000	108000	16000	92000
1982	23329000	3749000	11714000	7866000	265000	40000	225000
AVERAGE	17245000	2846000	8893000	5506000	174000	26000	148000
(% of total)	99.0	16.4	51.0	31.6	1.0	0.15	0.85

FIGURES



LOWER FRASER RIVER REGION

Floodplain areas

Distances along Fraser River in Kilometres

Kilometres 10 0 20 30 40 50

Statute Miles 5 0 10 20 30

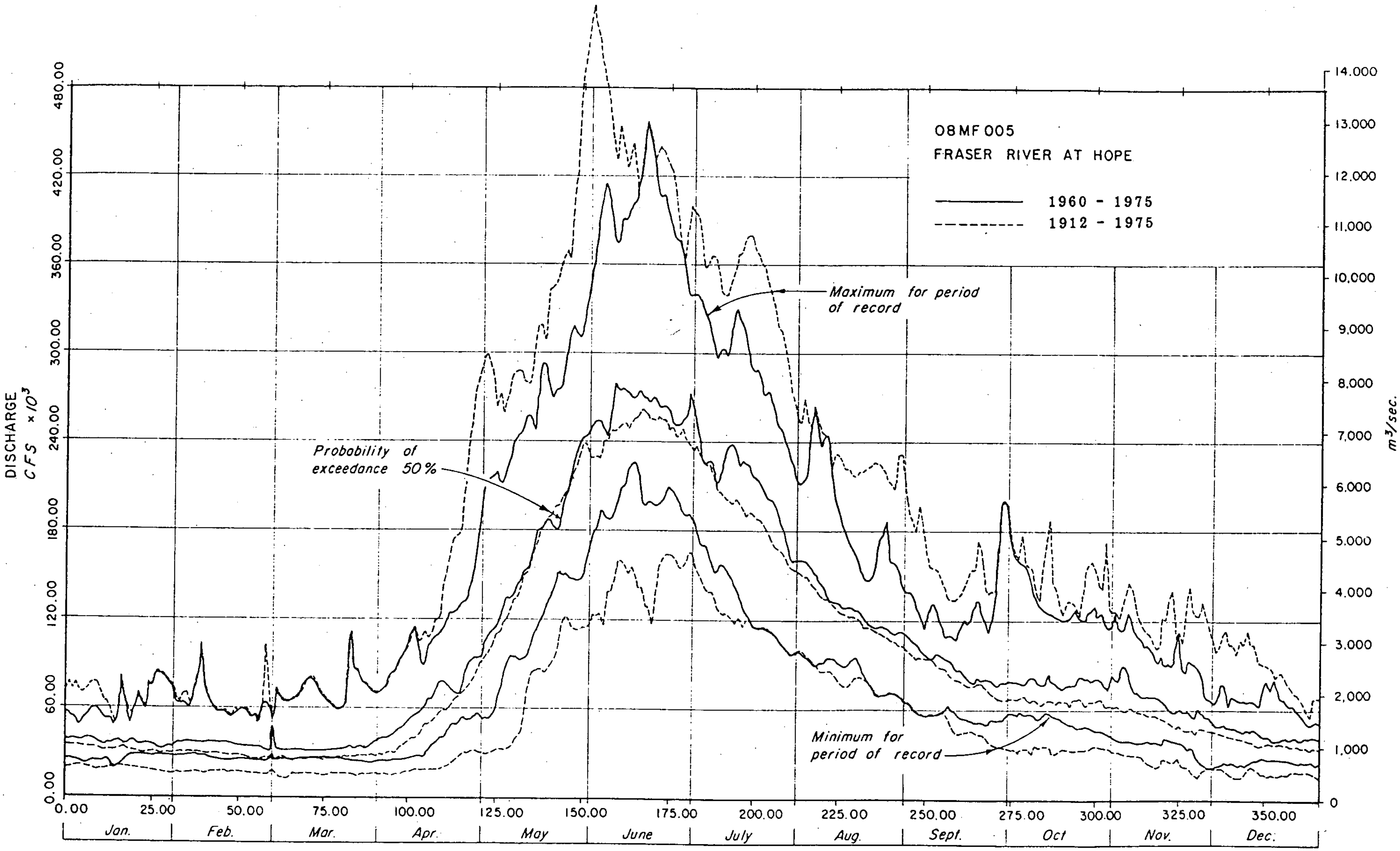


Figure 2 Exceedance probability hydrographs, long term and short term

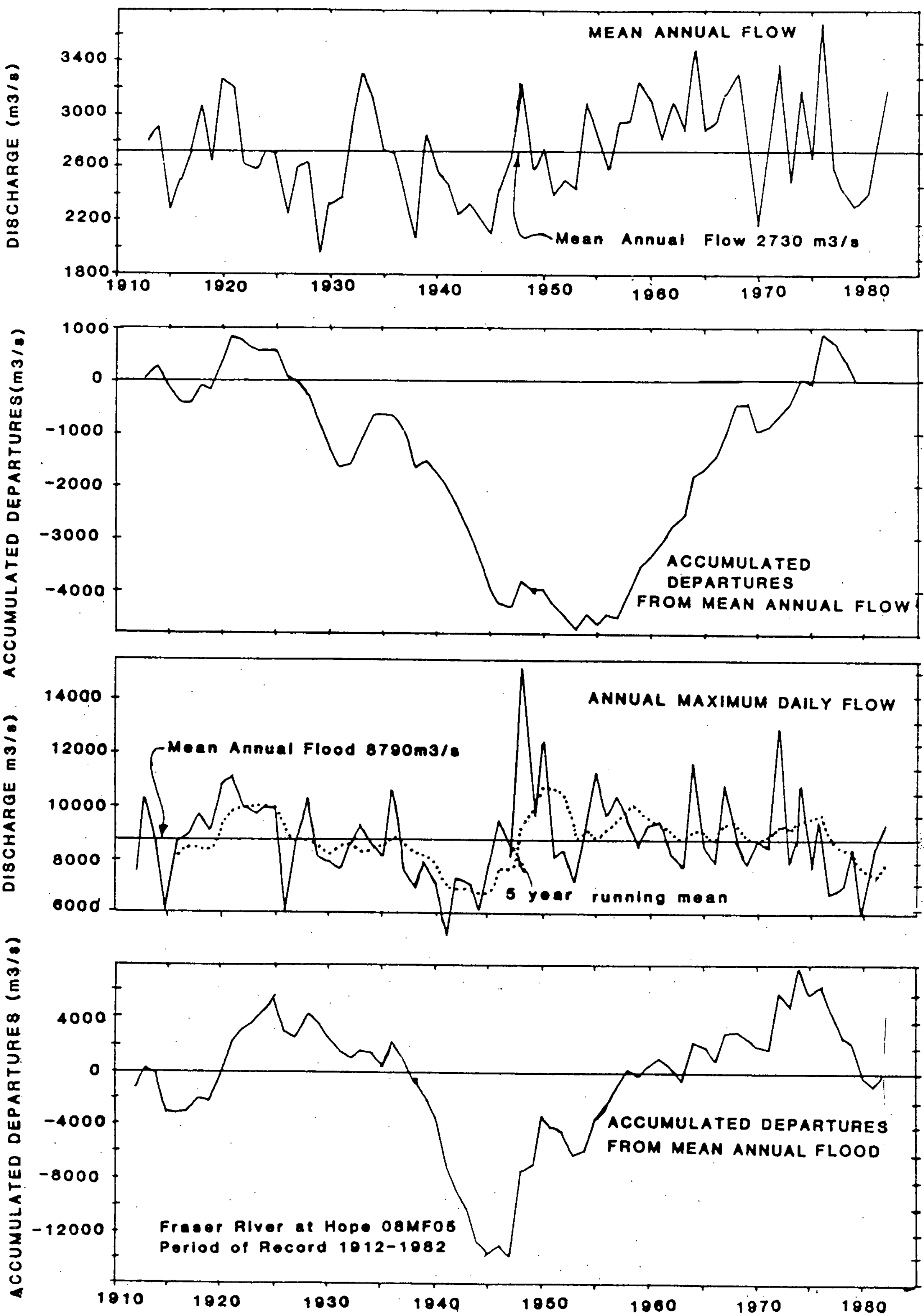


Figure 3 Longterm Flow Variations Fraser River at Hope

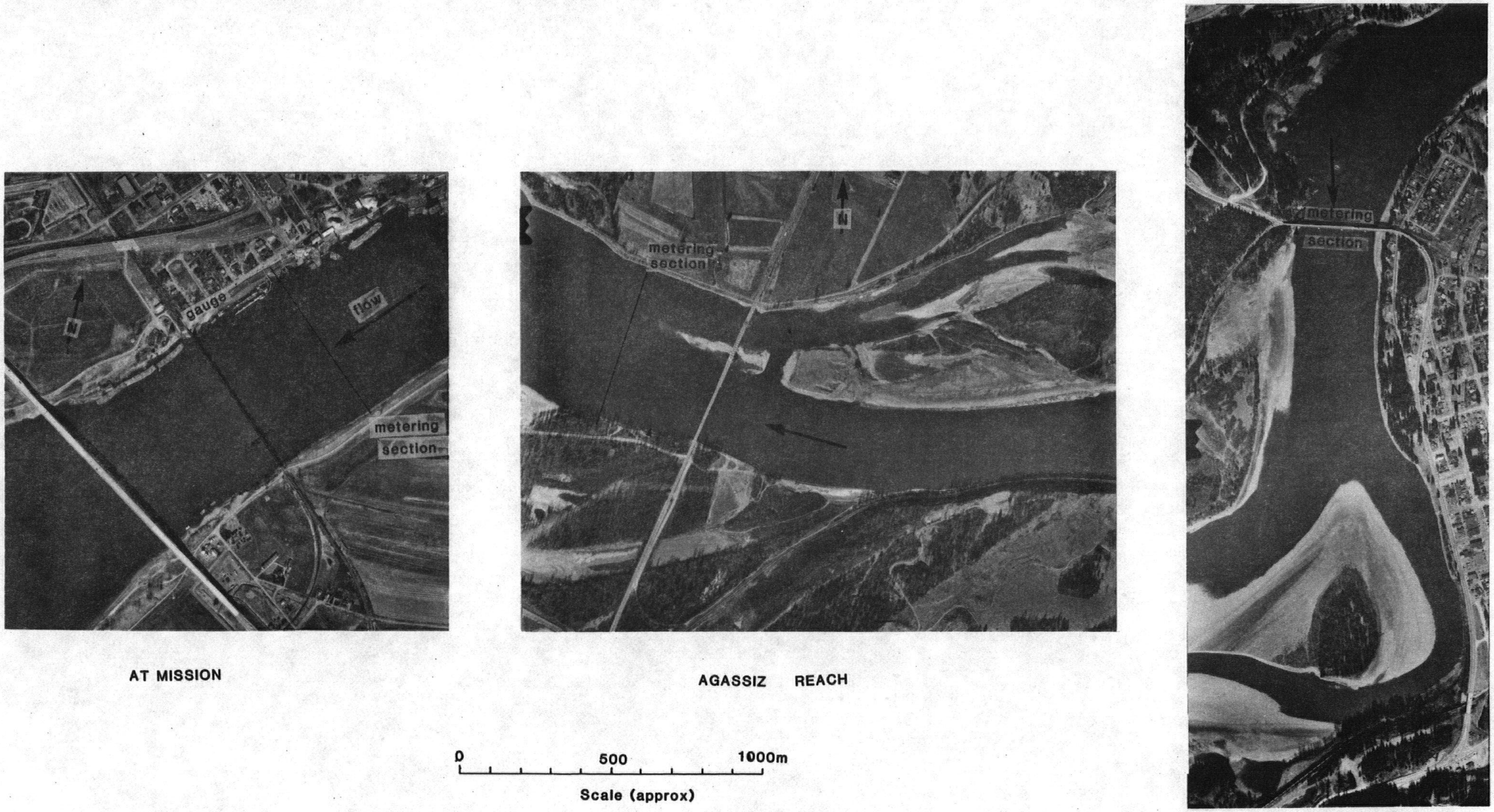


Figure 4 Channel patterns at Lower Fraser River hydrometric stations

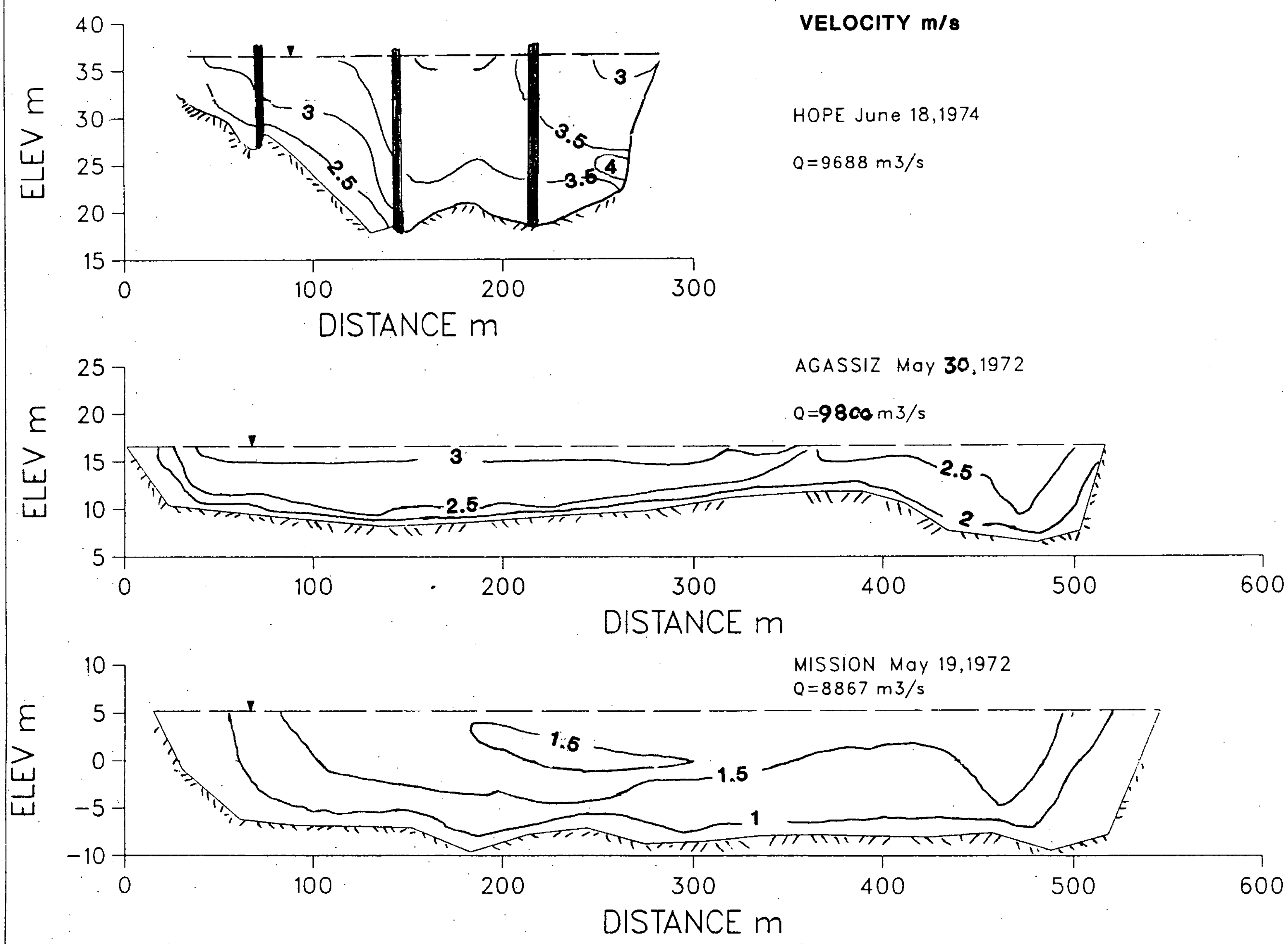
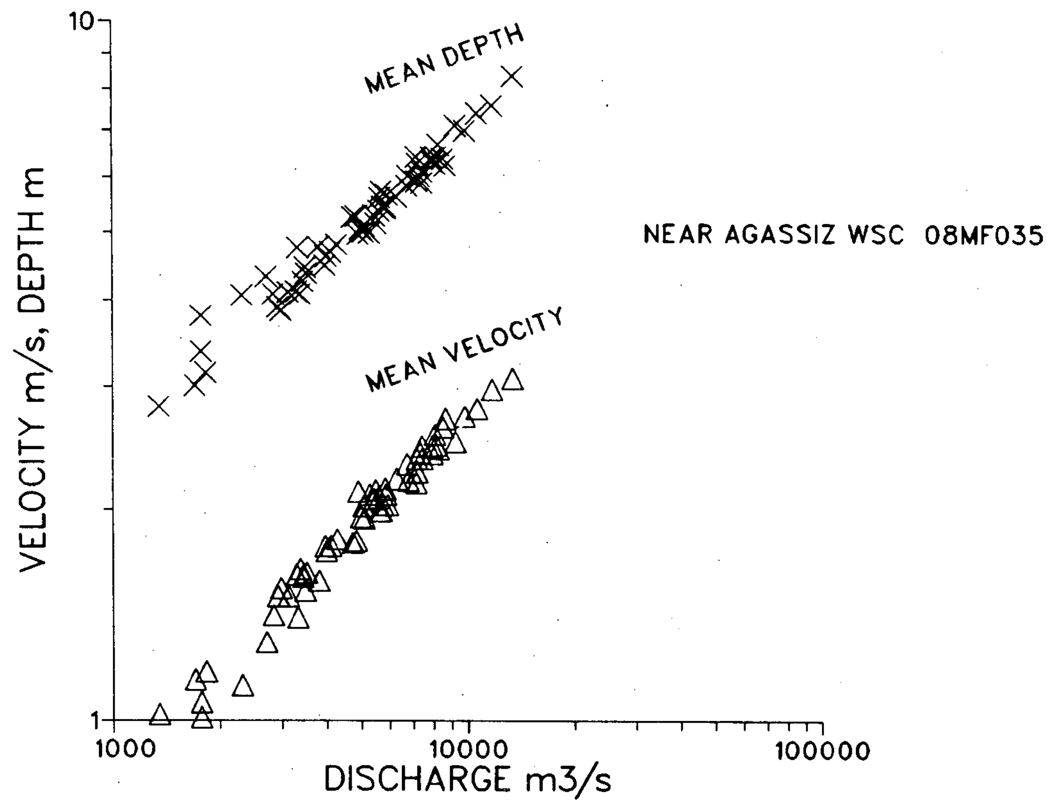


Figure 5 Channel cross sections at hydrometric stations



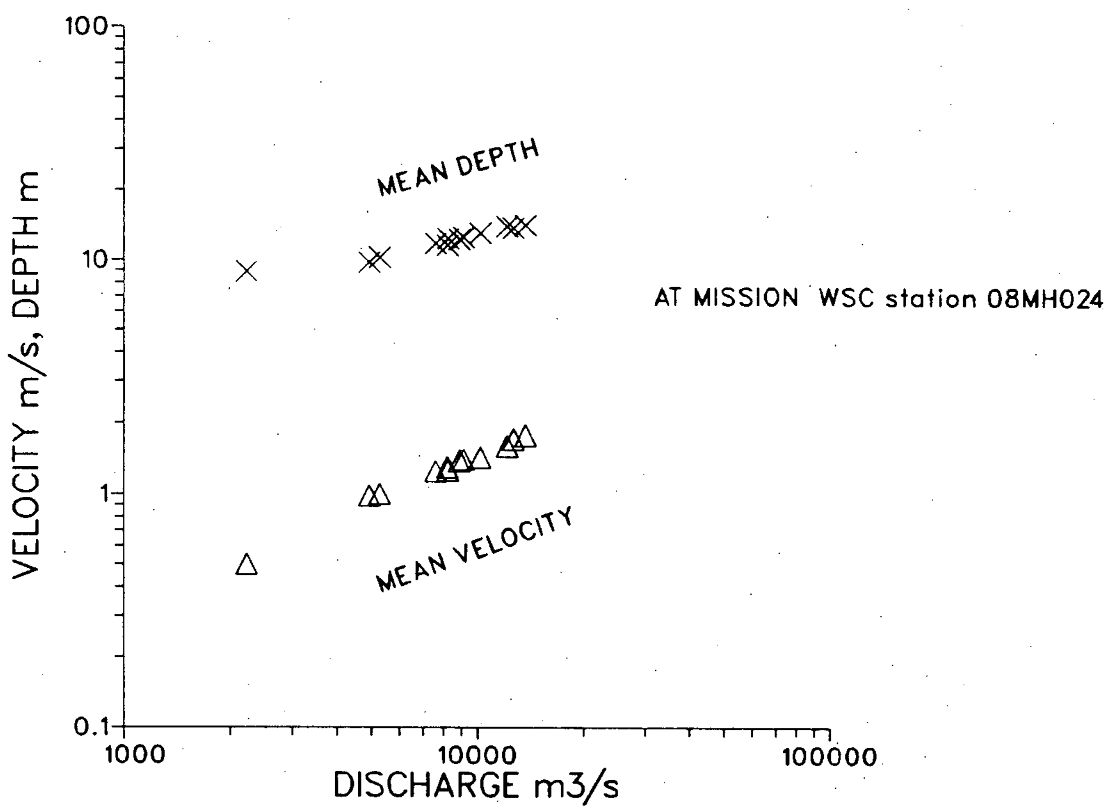


Figure 6 Hydraulic Geometry at Agassiz and Mission Hydrometric Stations.

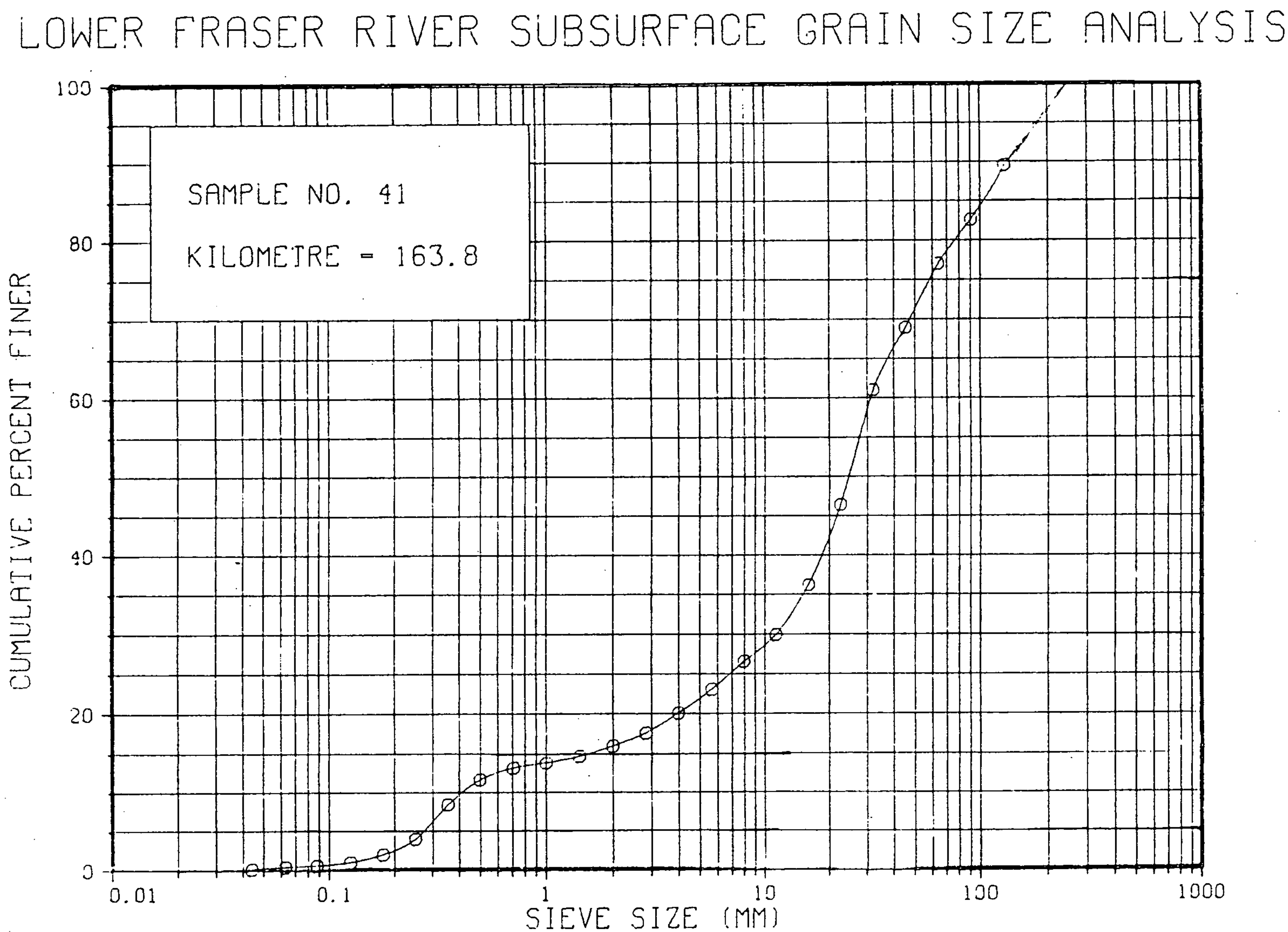


Figure 7. Bed Material Size Distribution near Hope.

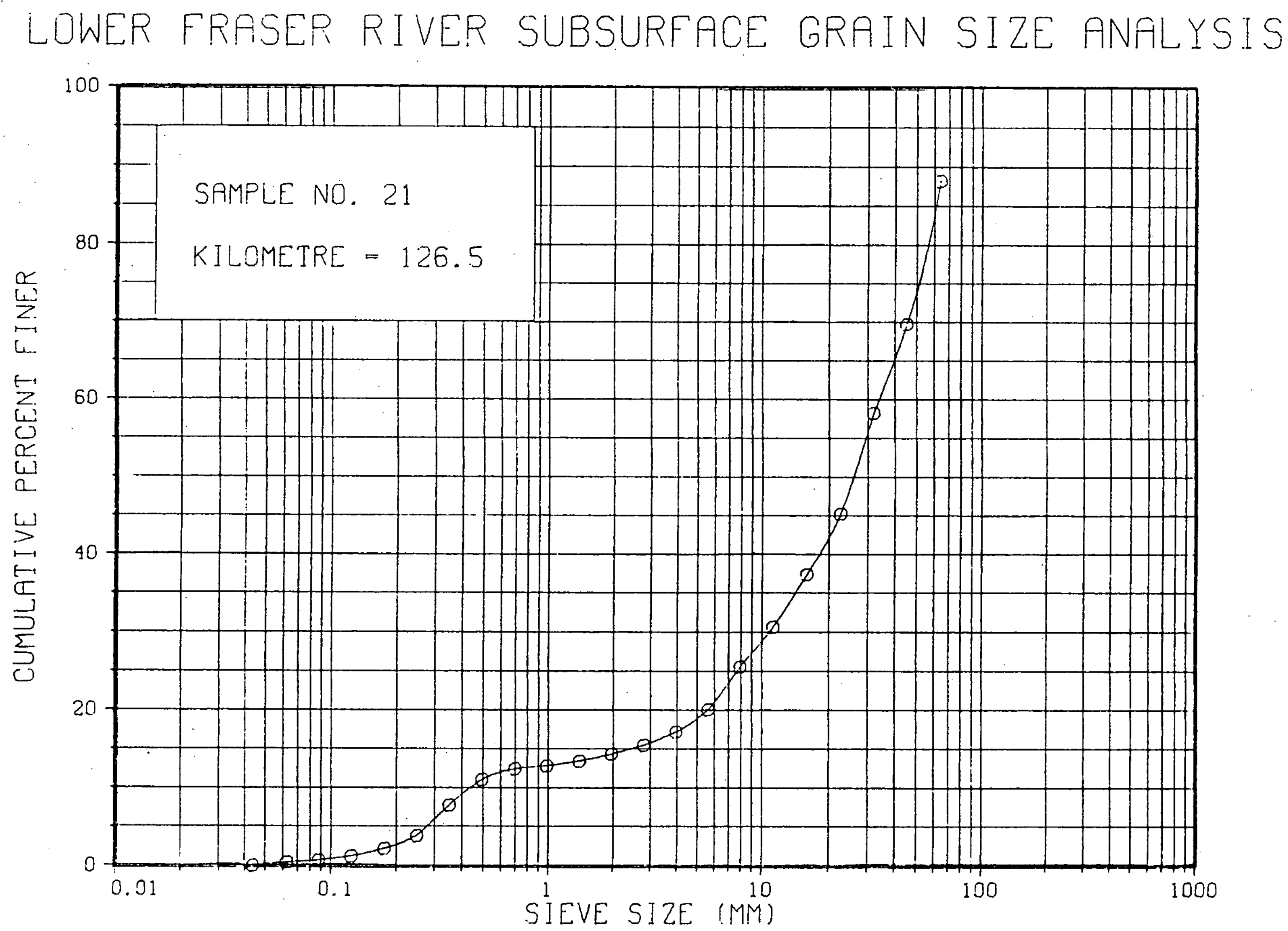
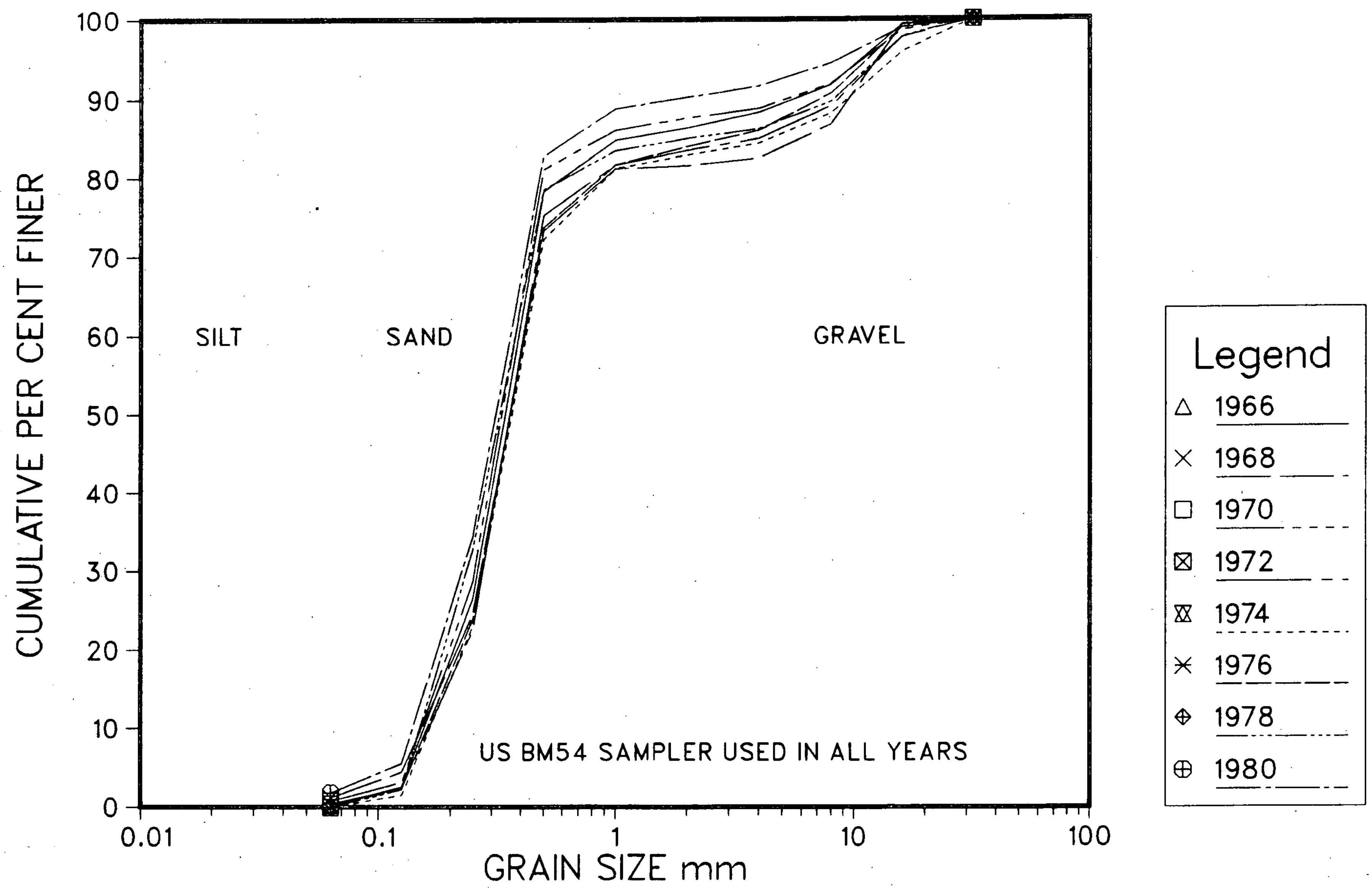


Figure 8. Bed Material Size Distribution near Agassiz.

FIGURE 9 MISSION BED MATERIAL



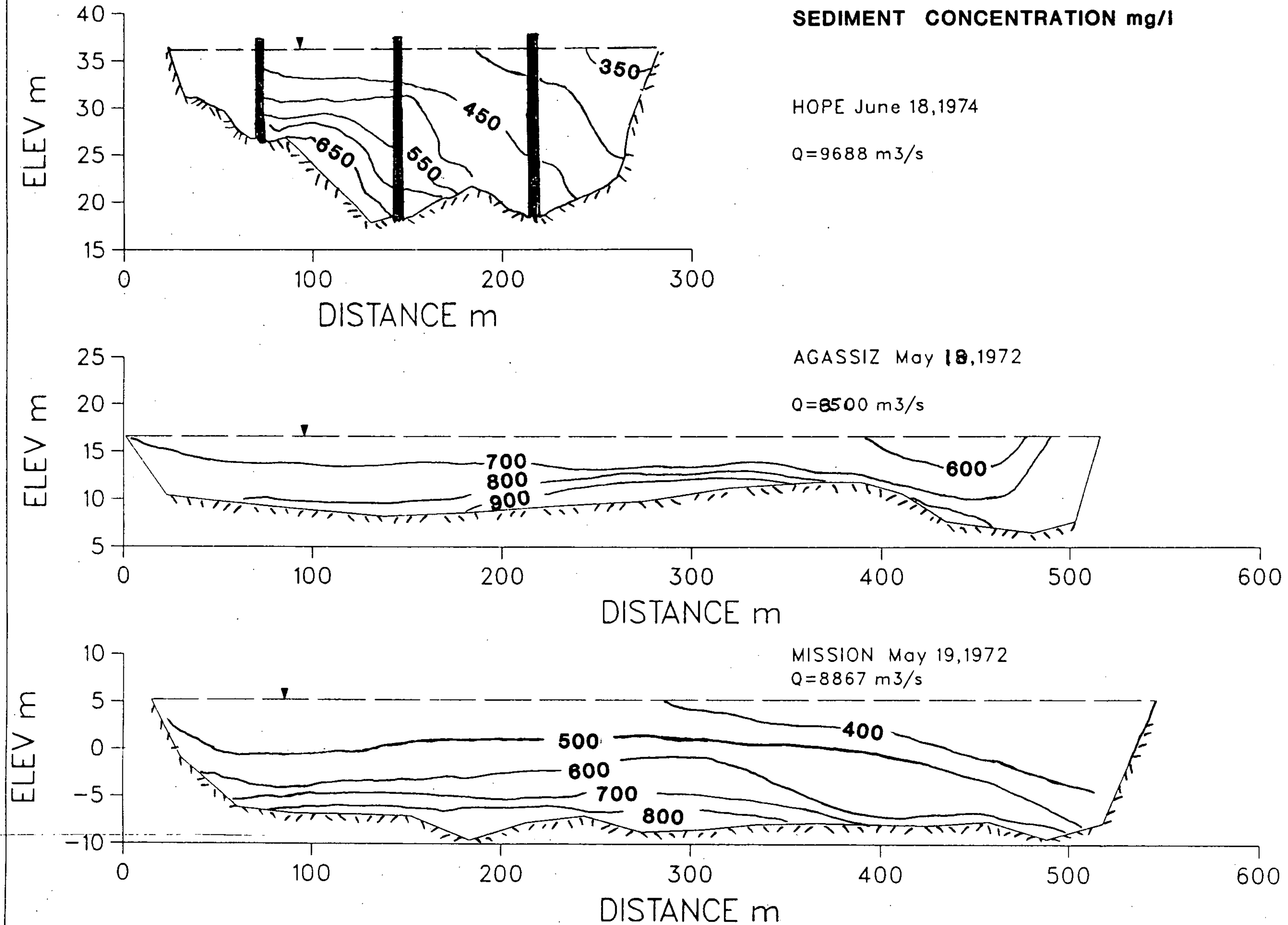


Figure 10 Distribution of suspended sediment concentration at gauging sections

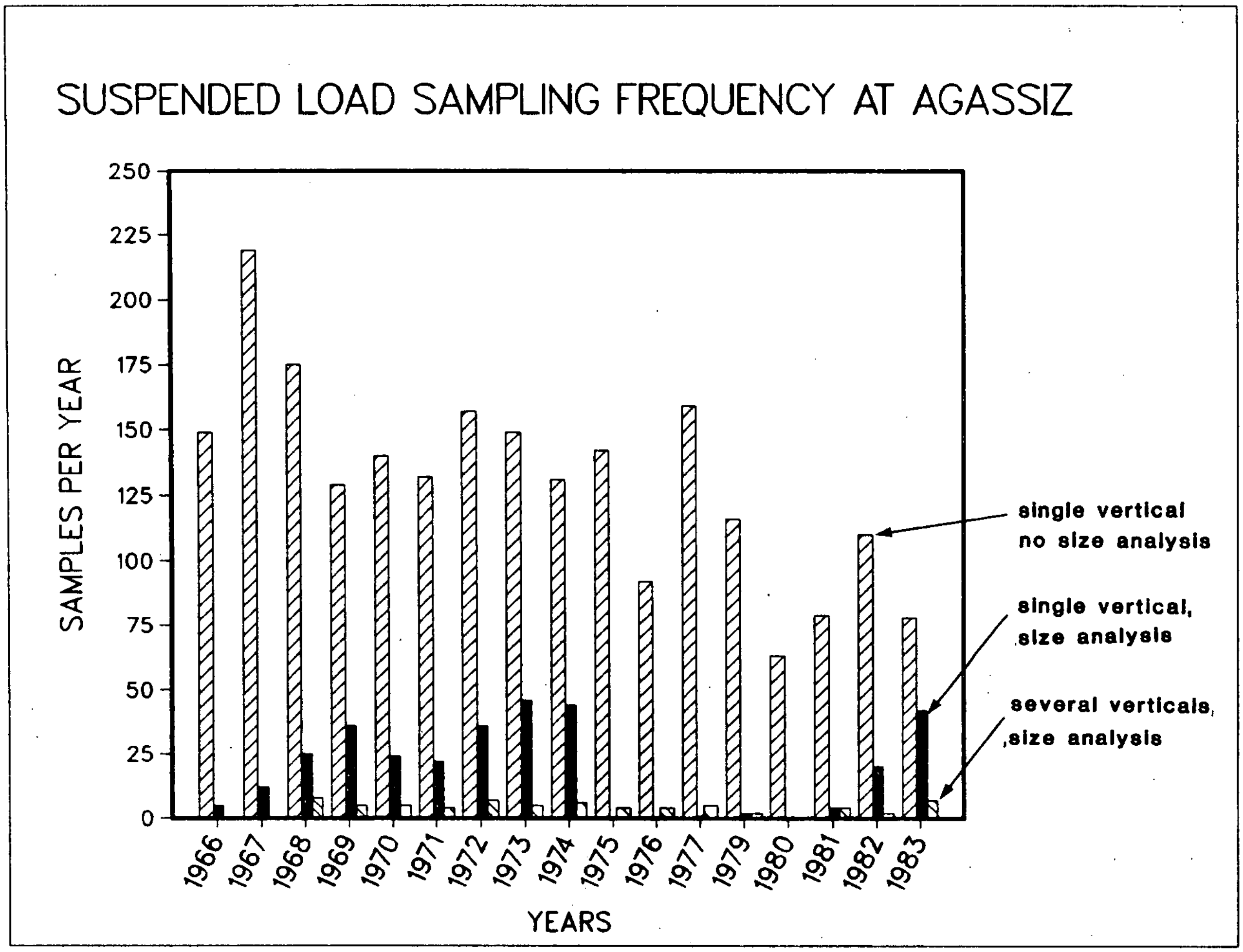


FIGURE 11. Suspended Load Sampling Frequency at Agassiz.

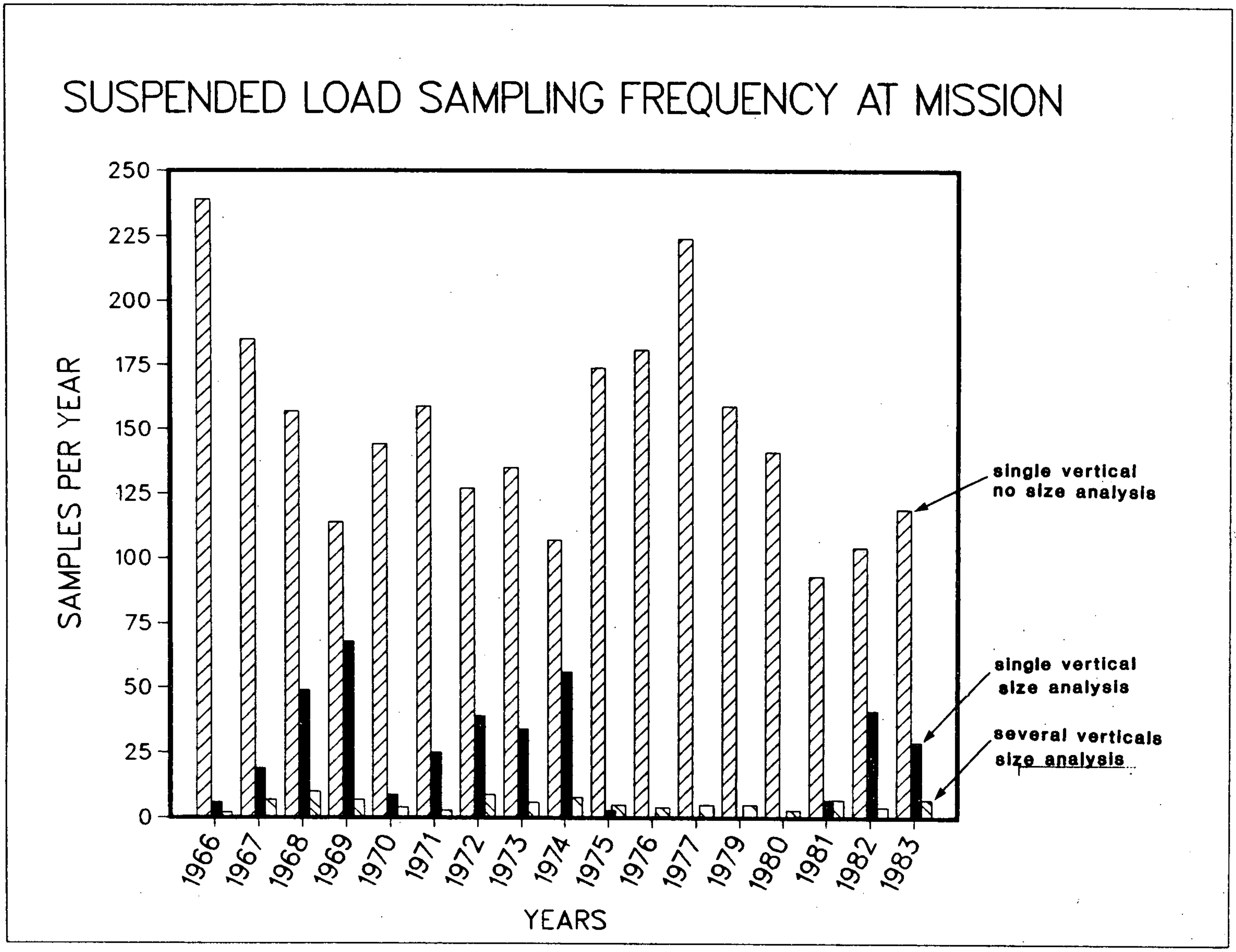


FIGURE 12. Suspended Load Sampling Frequency at Mission.

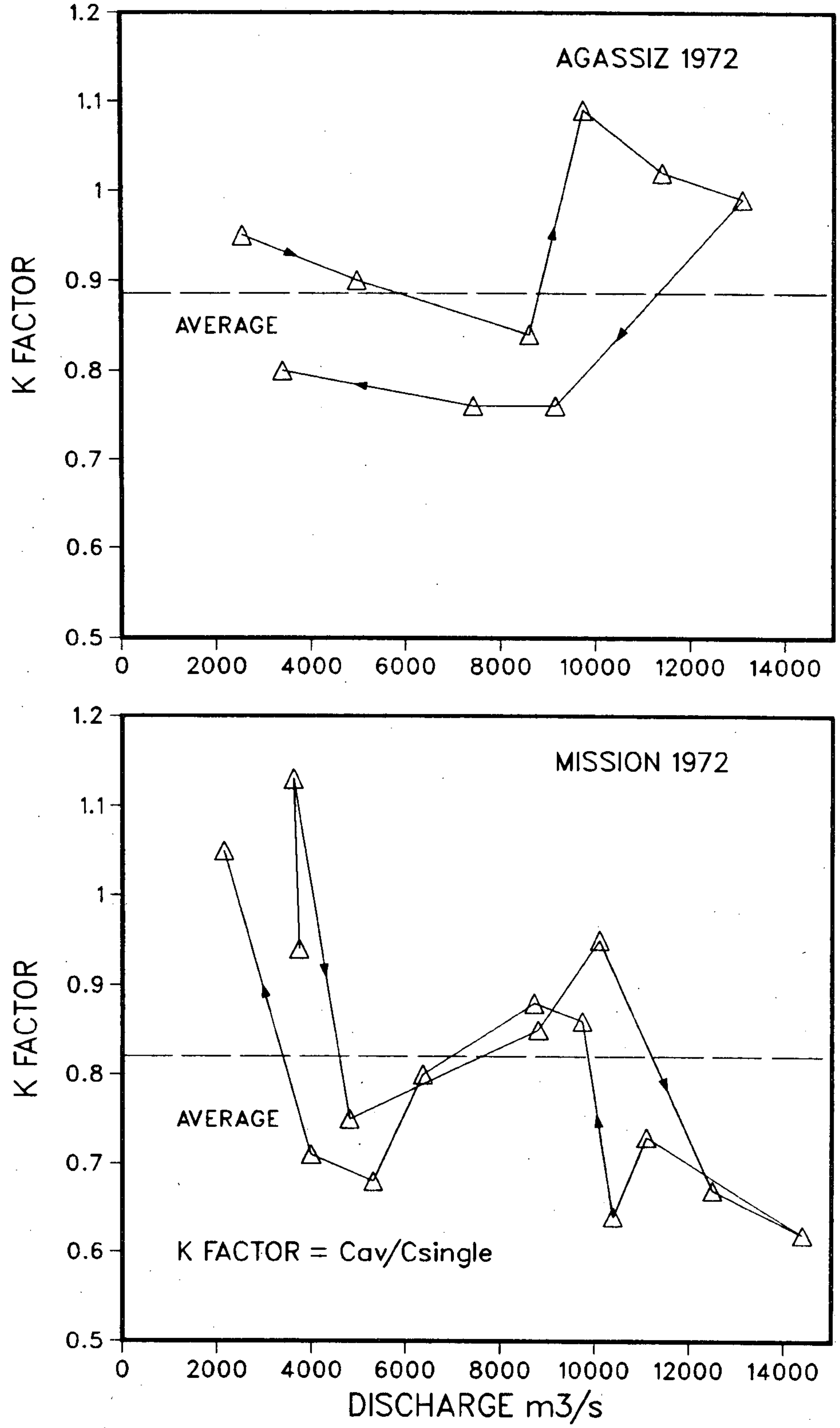
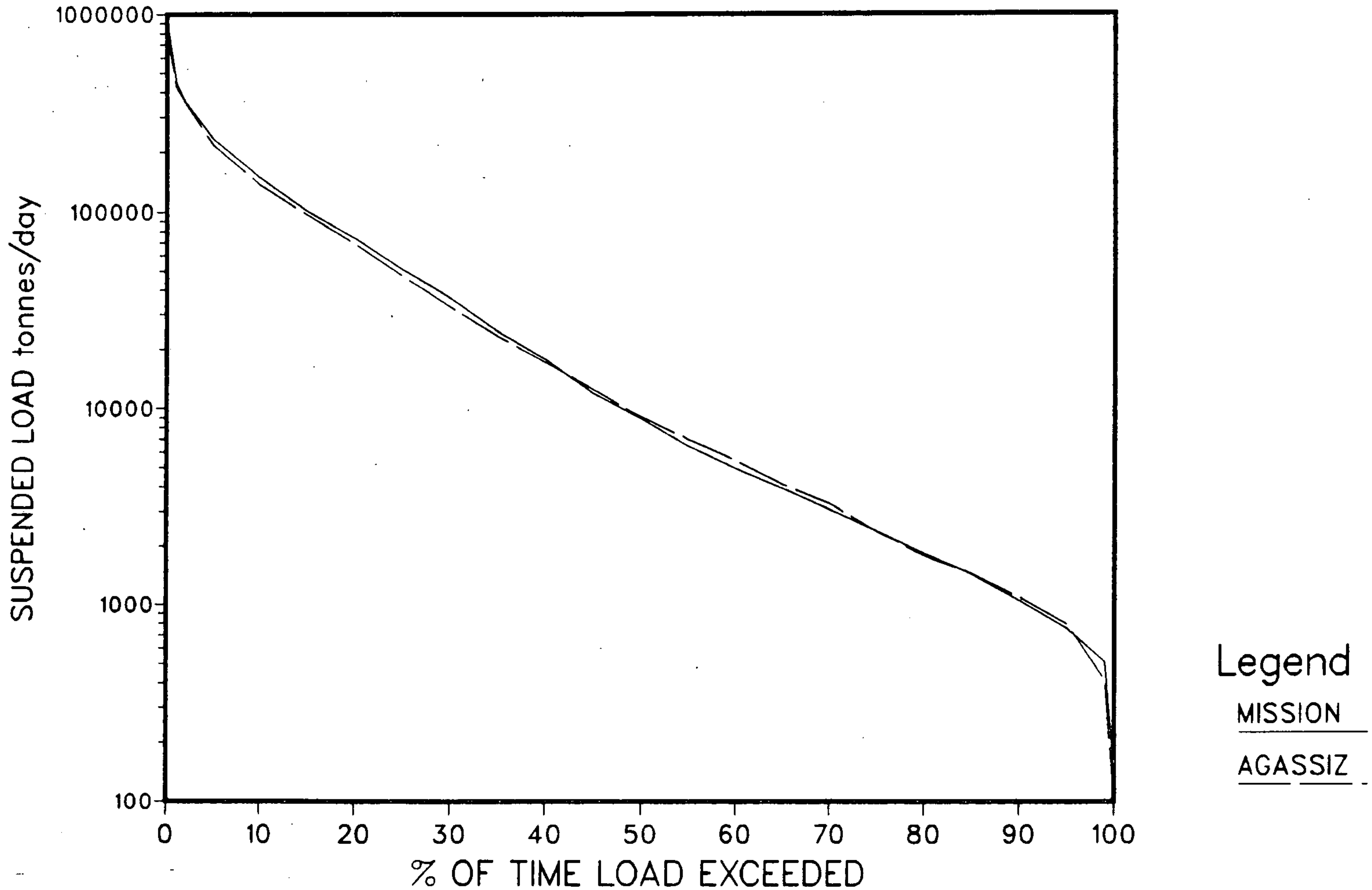


FIGURE 13. K-Factor Variation at Agassiz and Mission.

FIGURE 14

SUSPENDED LOAD DURATIONS – MISSION & AGASSIZ



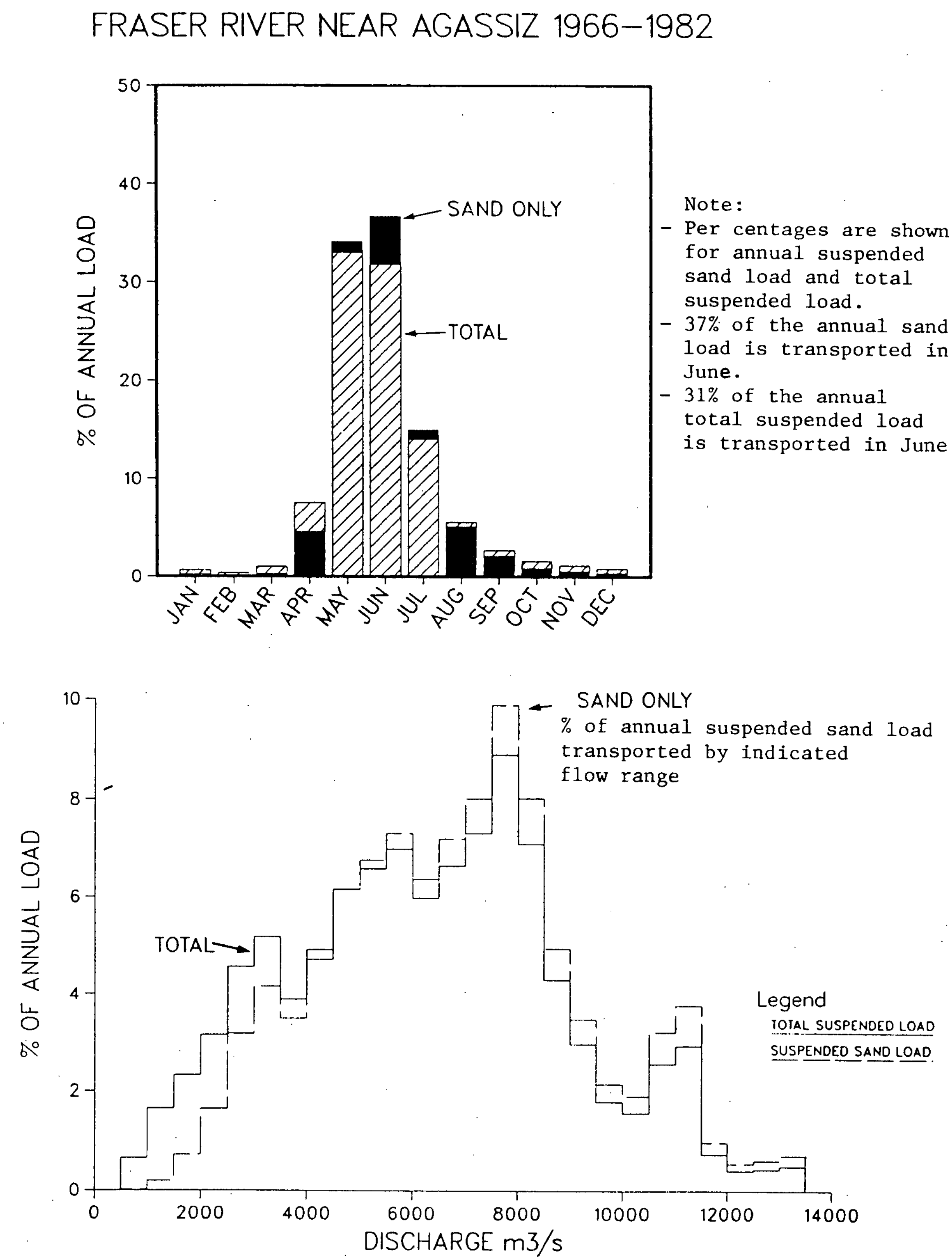
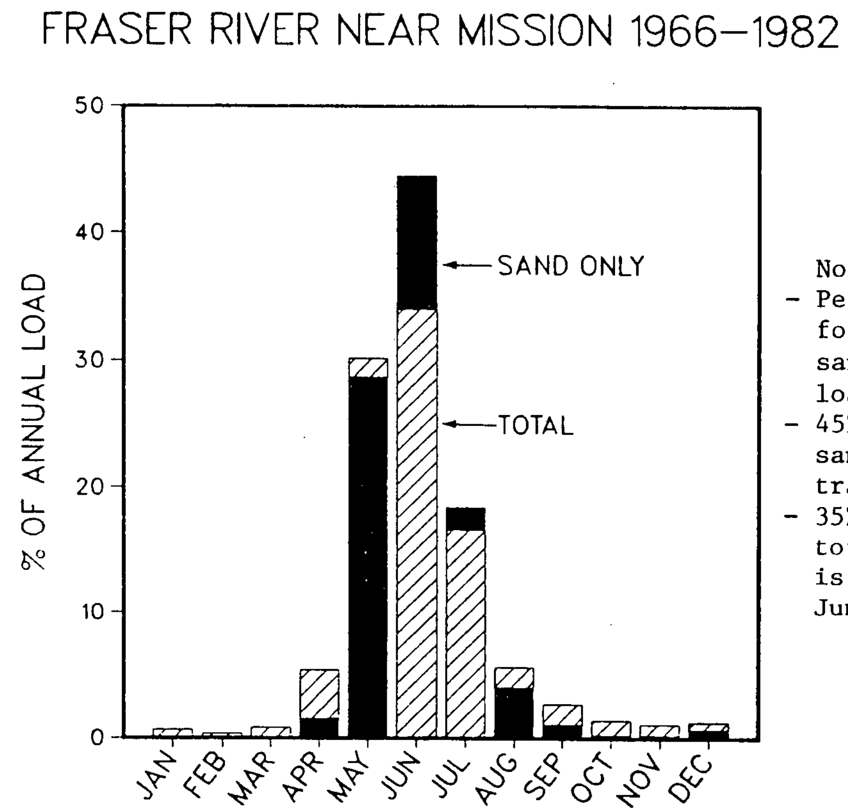


Figure 15. Variation of Daily Suspended Load by Season and Discharge



Note:
- Per Centages are shown for annual suspended sand load and total load.
- 45% of the annual sand load is transported in June.
- 35% of the annual total suspended load is transported in June.

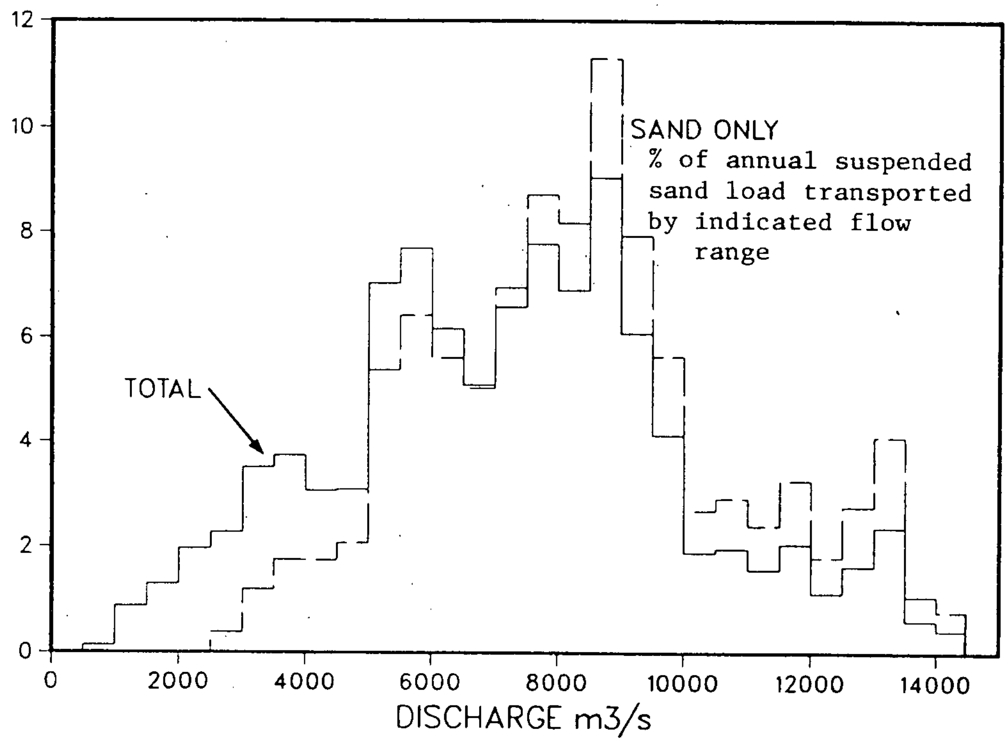


Figure 16. Variation of Daily Suspended Load by Season and Discharge at Mission.

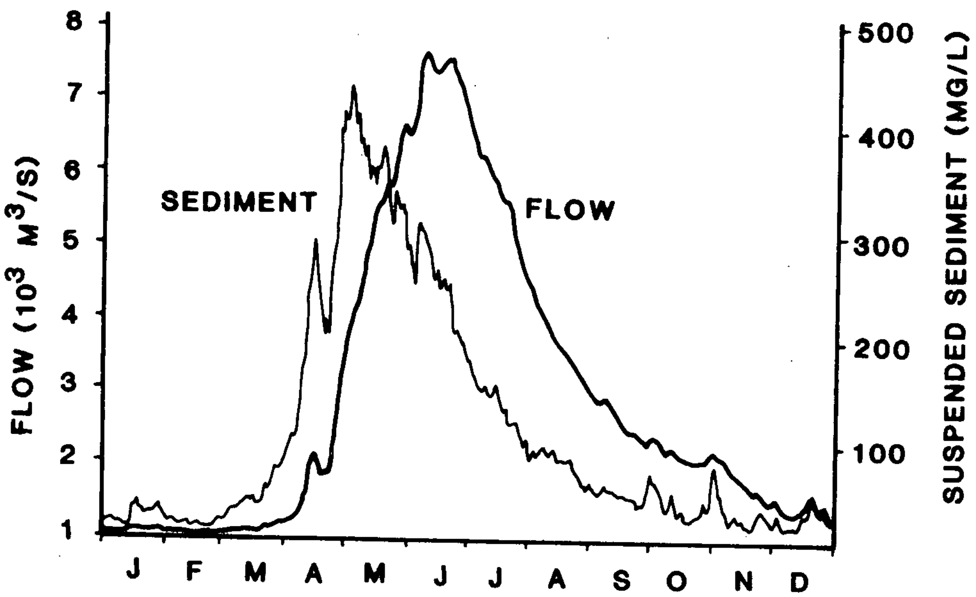


FIGURE 17. Average Annual Variation in Discharge and Suspended Sediment Concentration at Agassiz, 1967 - 1982.

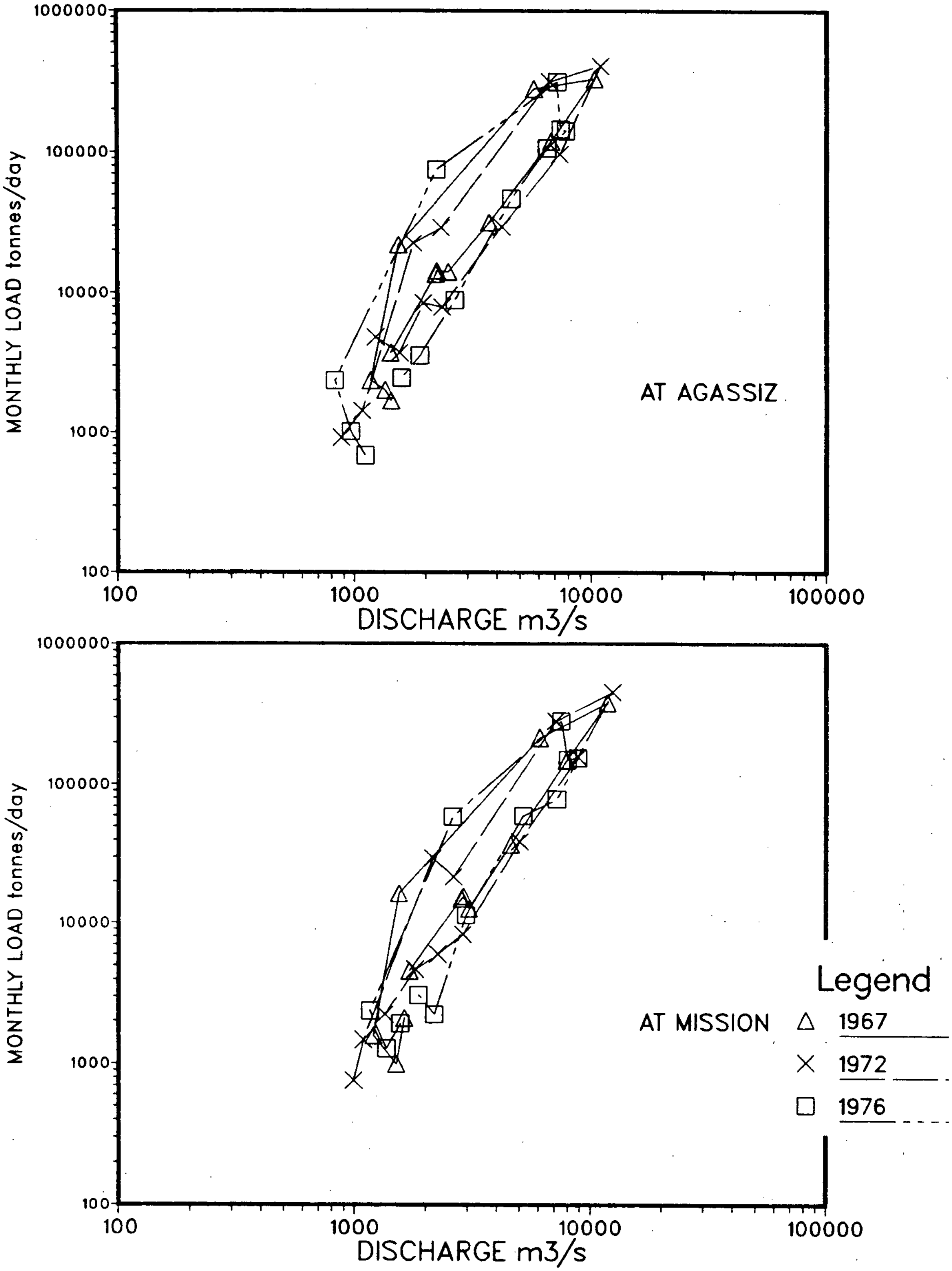


Figure 18. Variation in Monthly Suspended Sediment Loads at Agassiz and Mission.

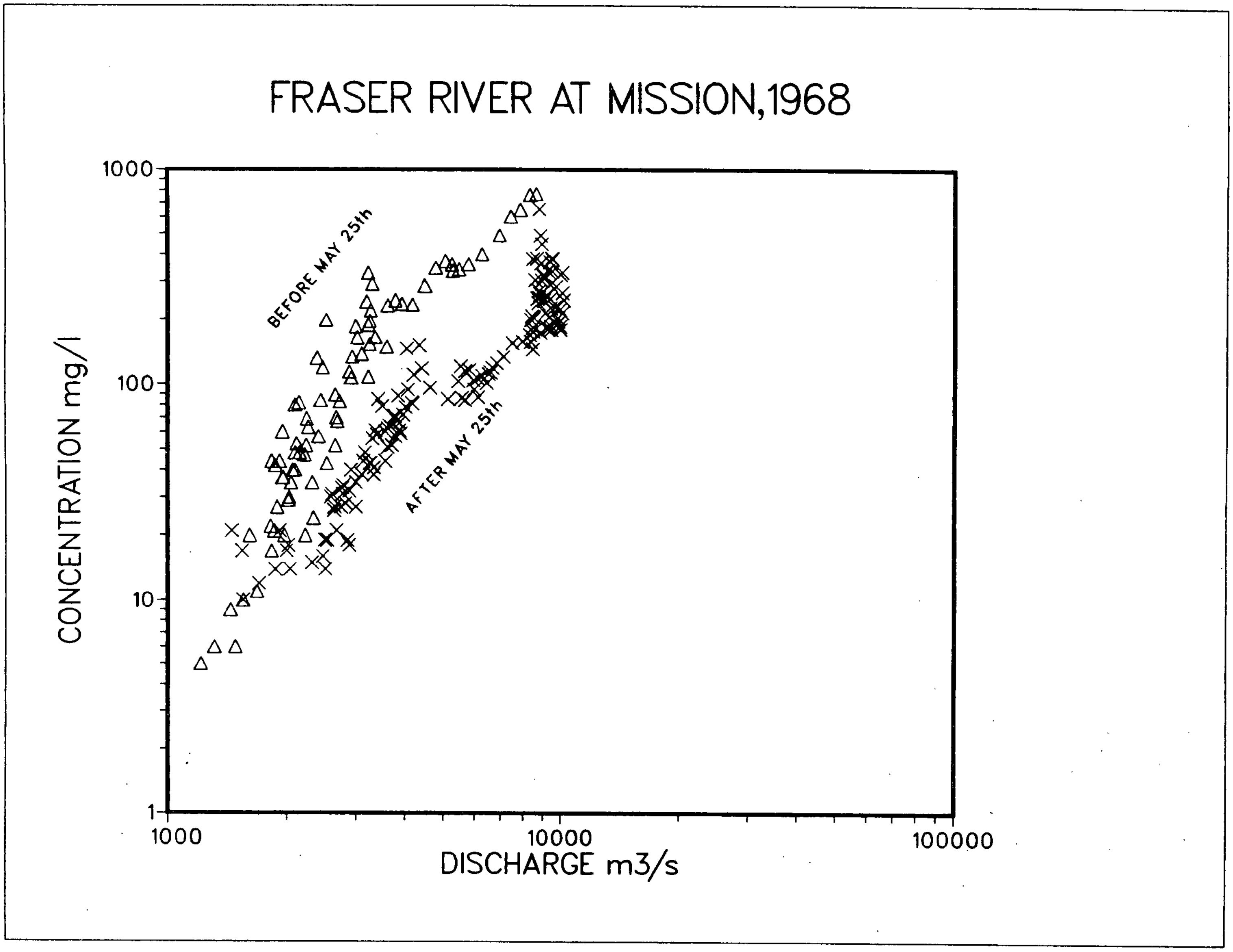


Figure 19. Seasonal Hysteresis in daily Suspended Sediment Concentration at Mission.

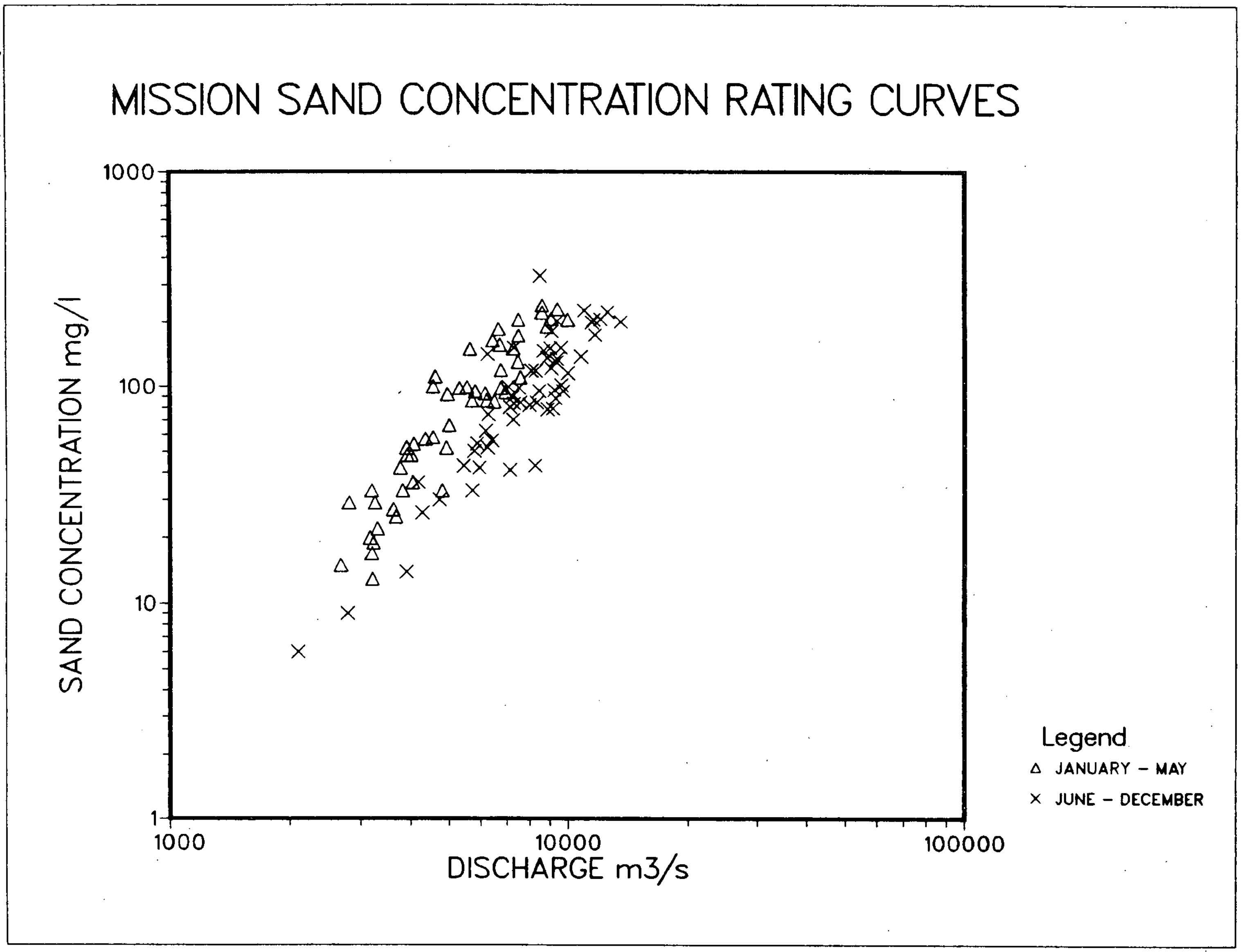


Figure 20. Mission Sand Concentration Rating Curves.

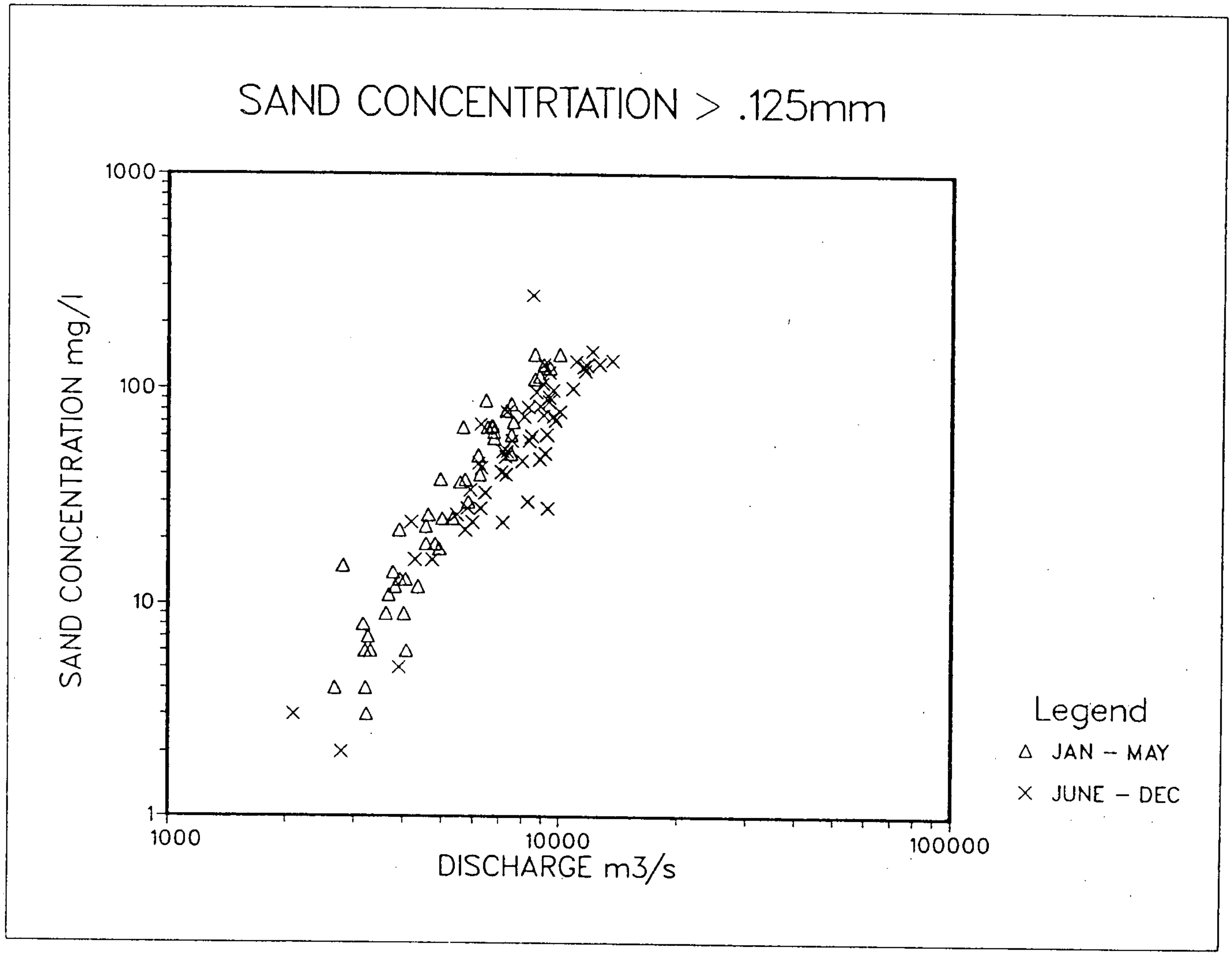


Figure 21. Mission Suspended Bed Material Rating Curve.

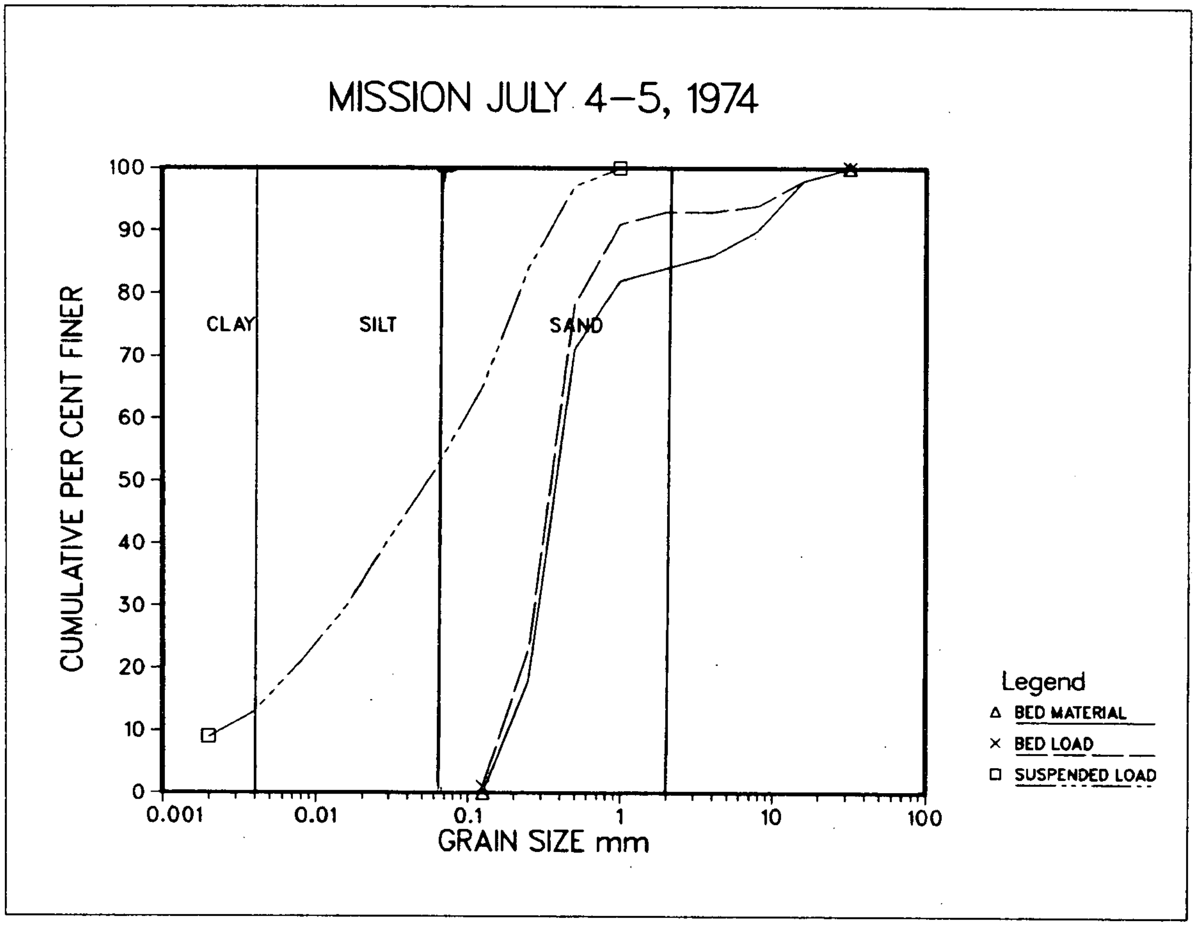


Figure 22. Comparison of Typical Bed Material, Bed Load and Suspended Load Size Distributions at Mission.

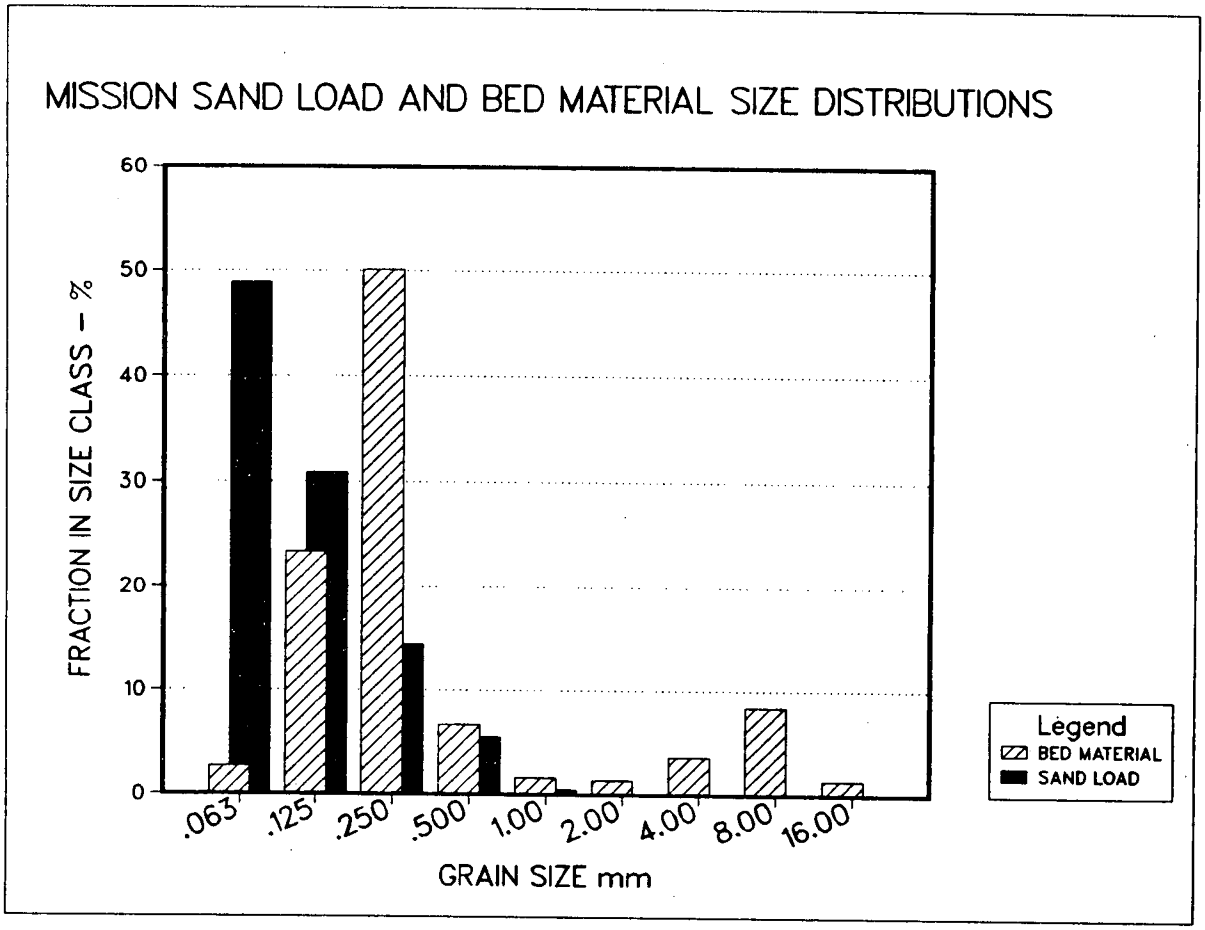
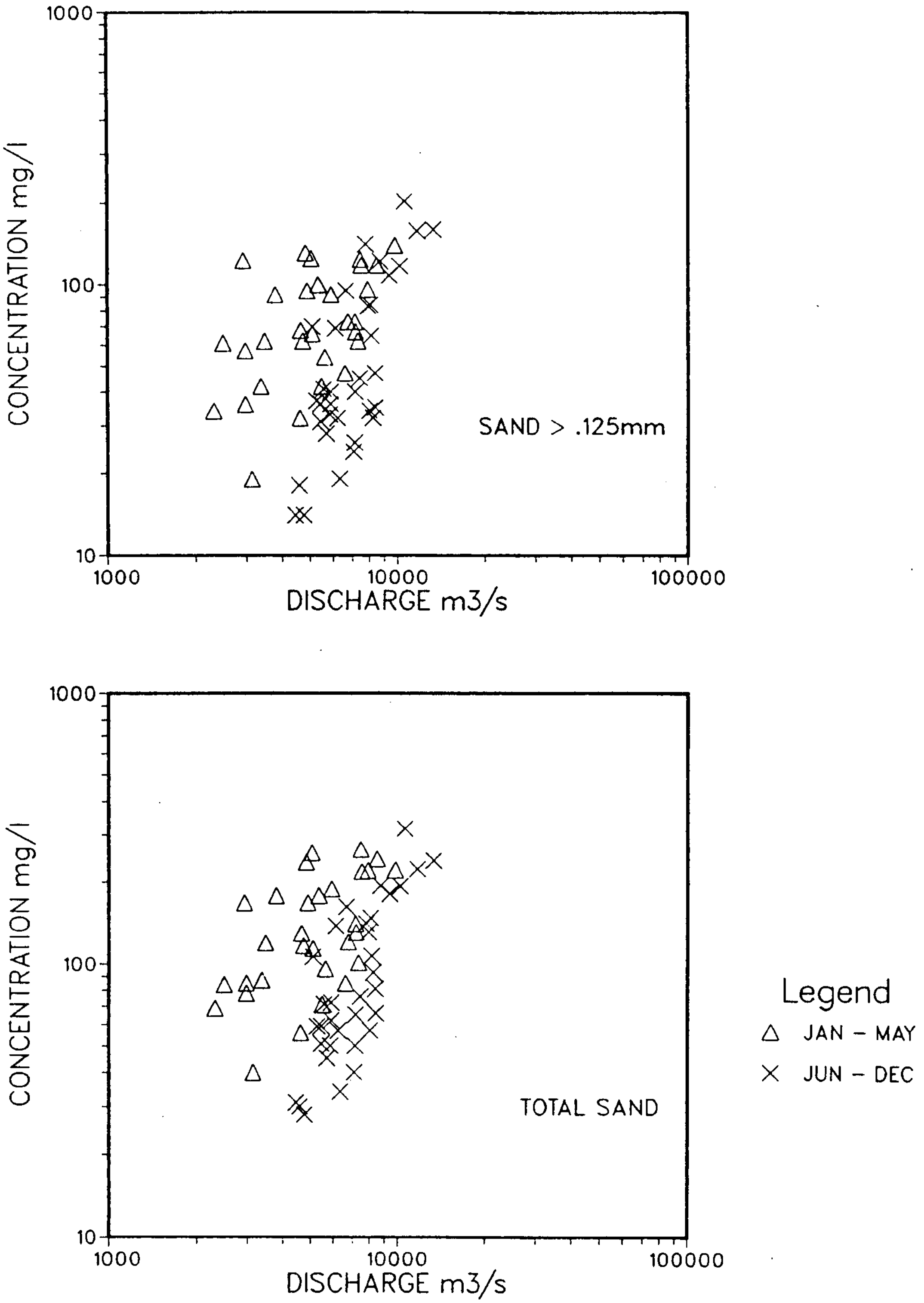


Figure 23. Mission Suspended Sand Load and Bed Material Size Distributions.

FIGURE 24

AGASSIZ SAND CONCENTRATION RATING CURVES



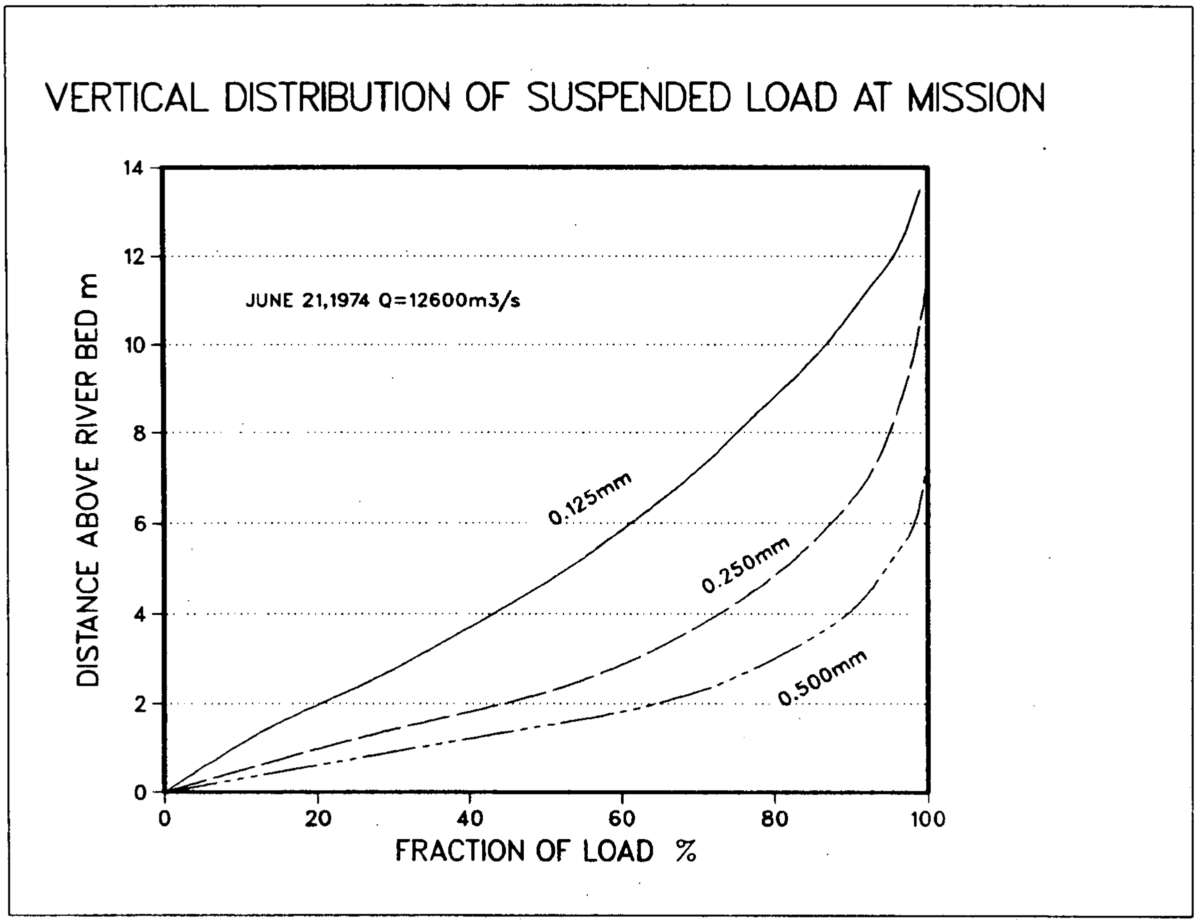


Figure 25. Vertical Distribution of Suspended Load at Mission.

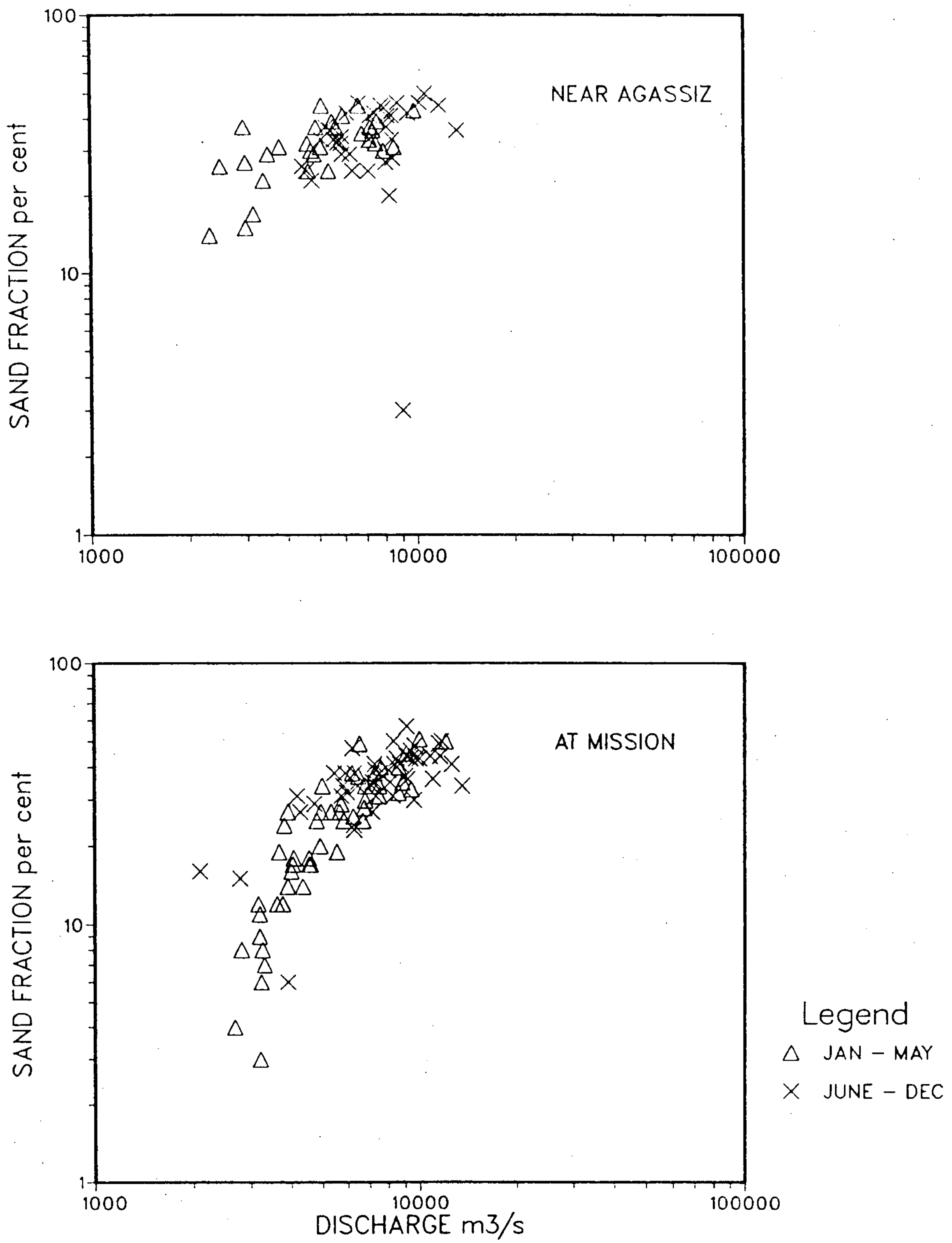
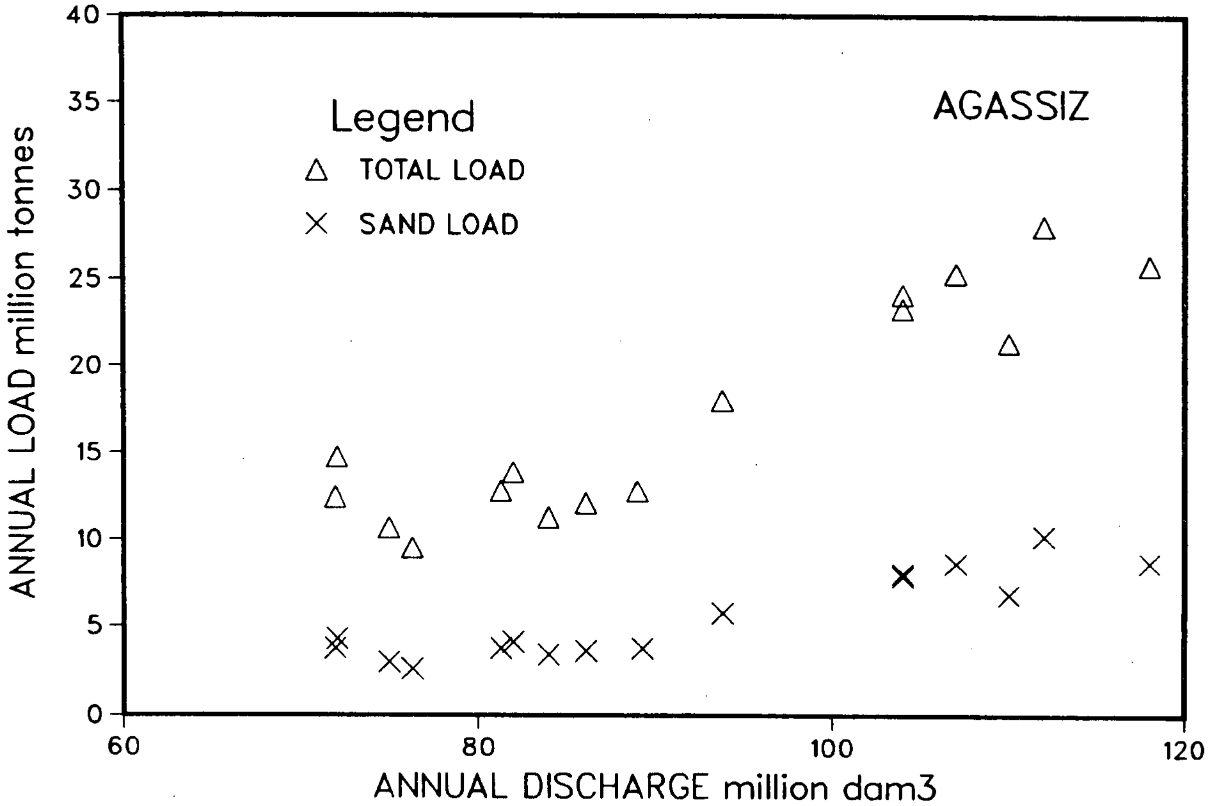


Figure 26. Relation between Sand Fraction of the Suspended Load and Discharge at Mission and Agassiz.



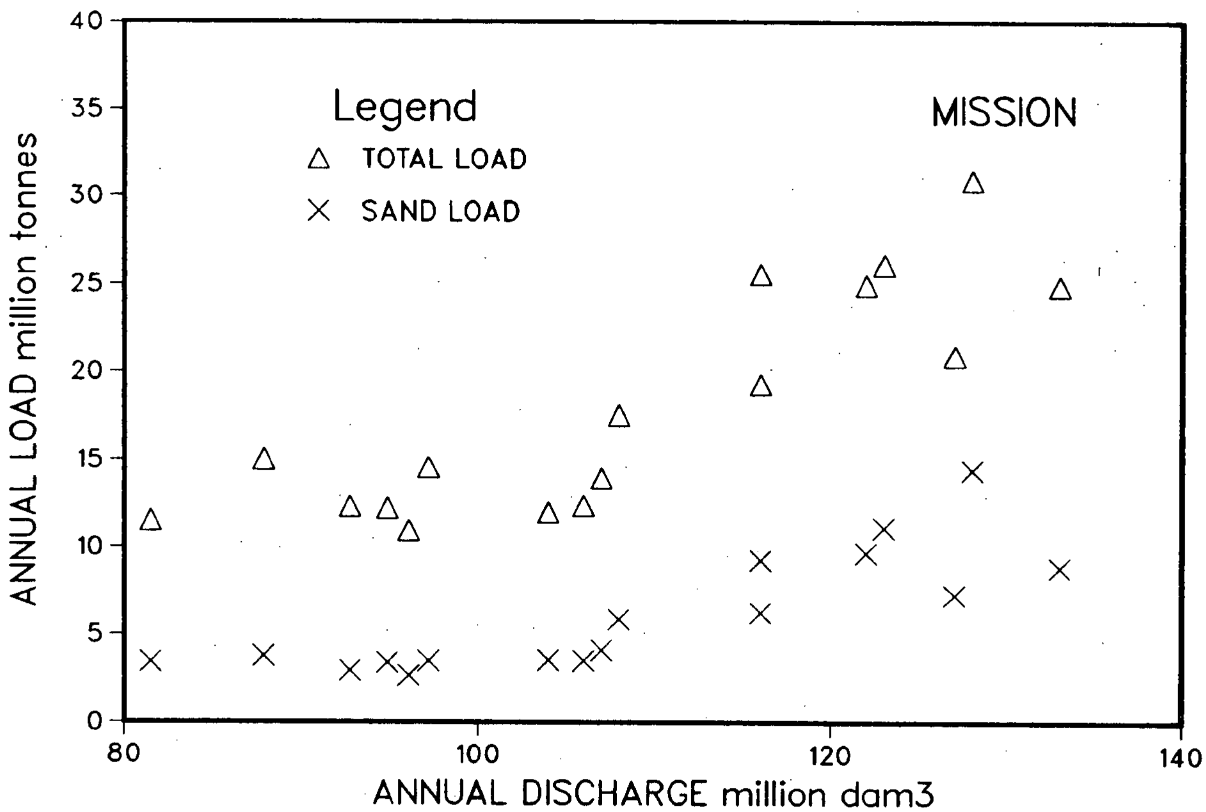


Figure 27. Relation between Annual Suspended Load and Flow Volume

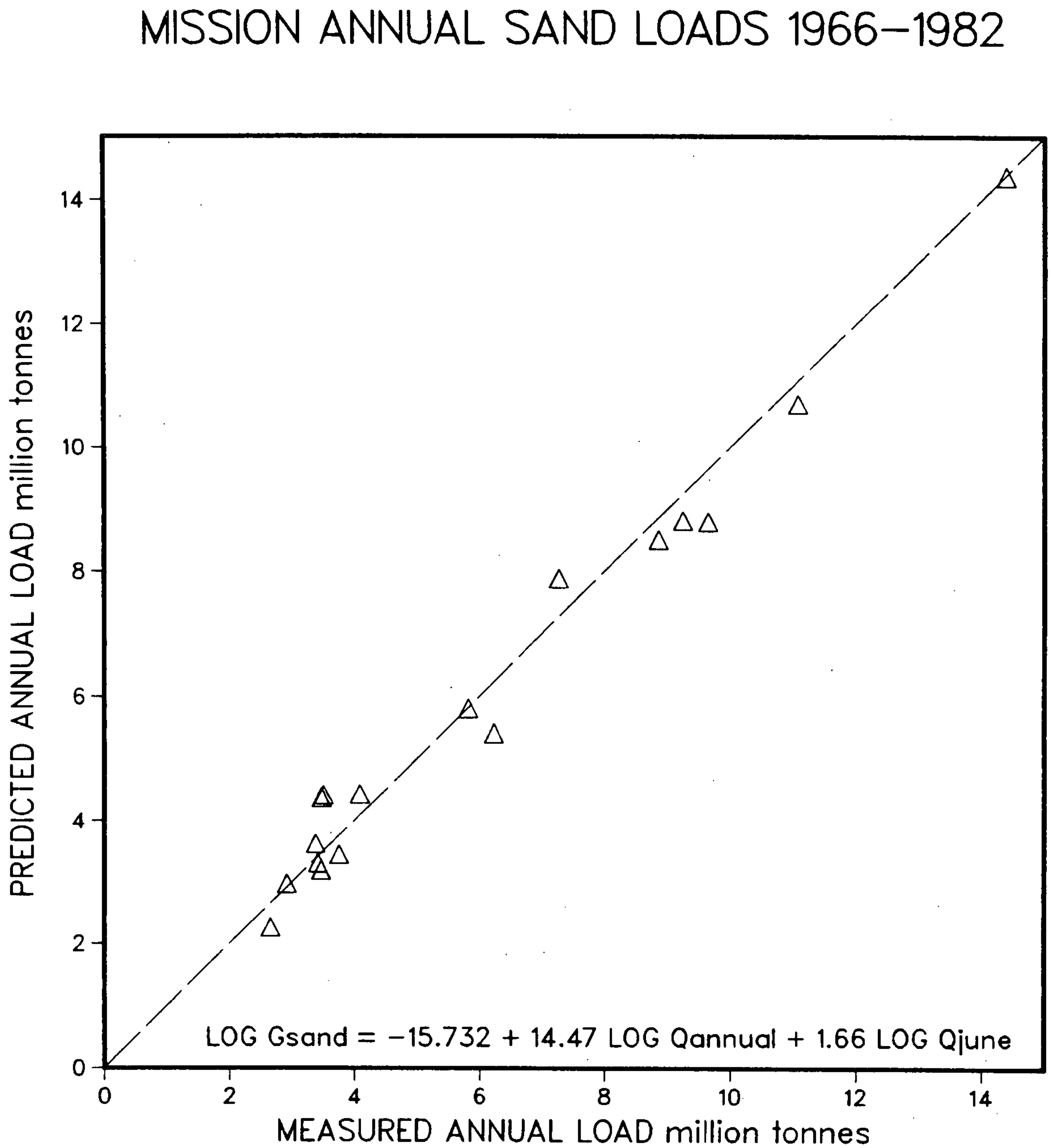


Figure 28. Comparison of Measured and Predicted Annual Sand Loads.

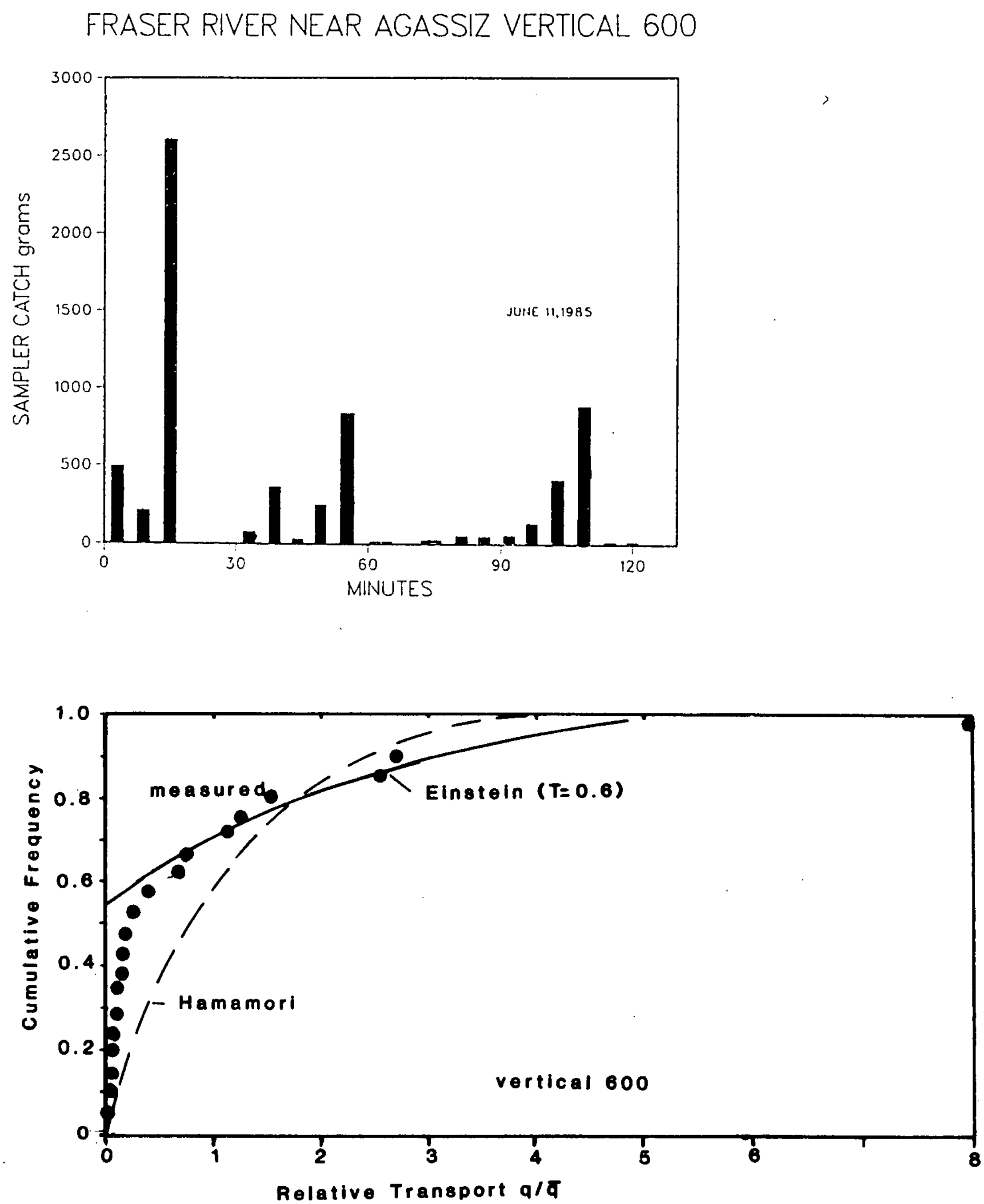


Figure 29. Variation in Bed Load Sample Catches at Agassiz.

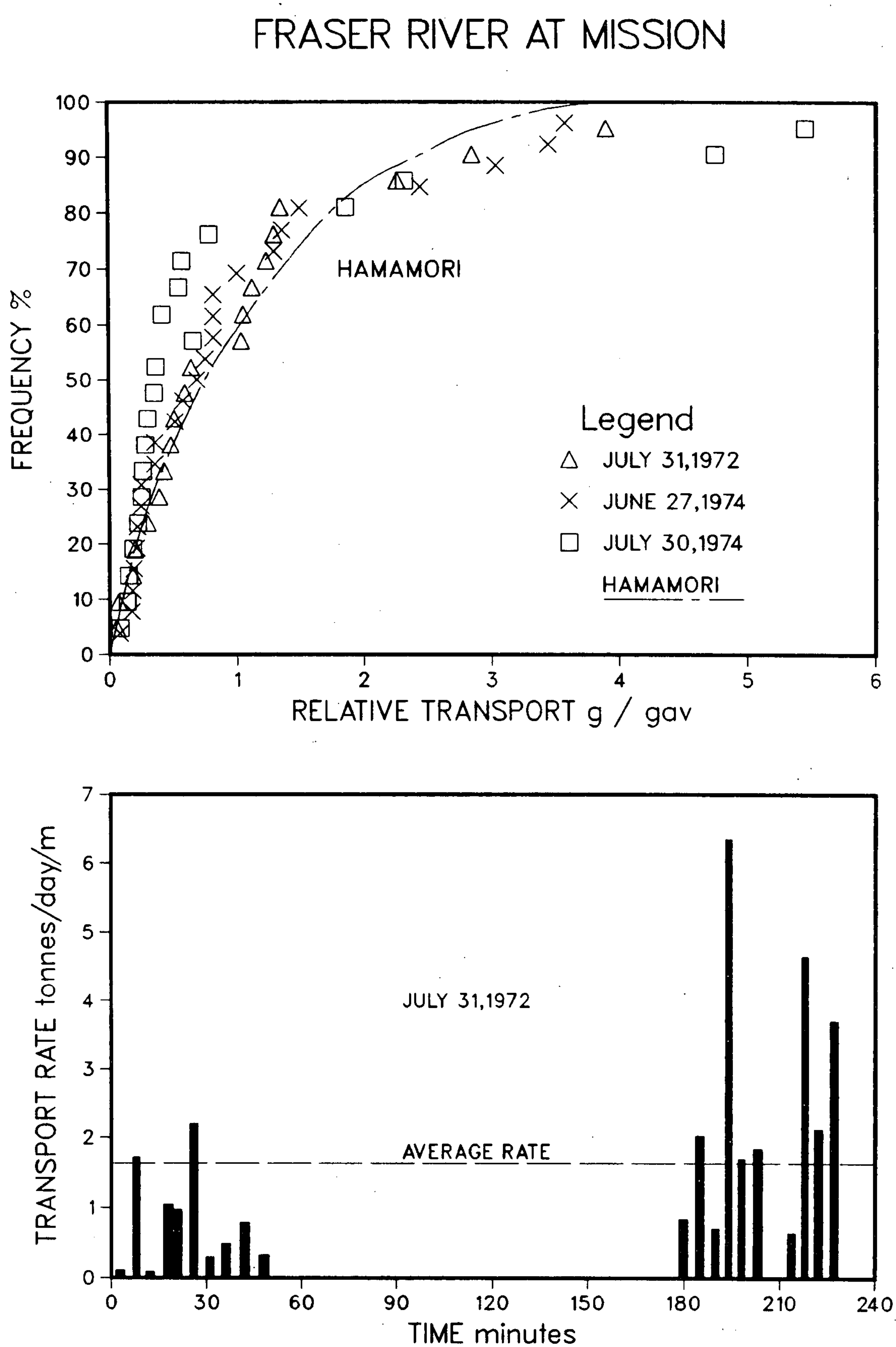


Figure 30. Variation in Measured Bed Load Rates at Mission.

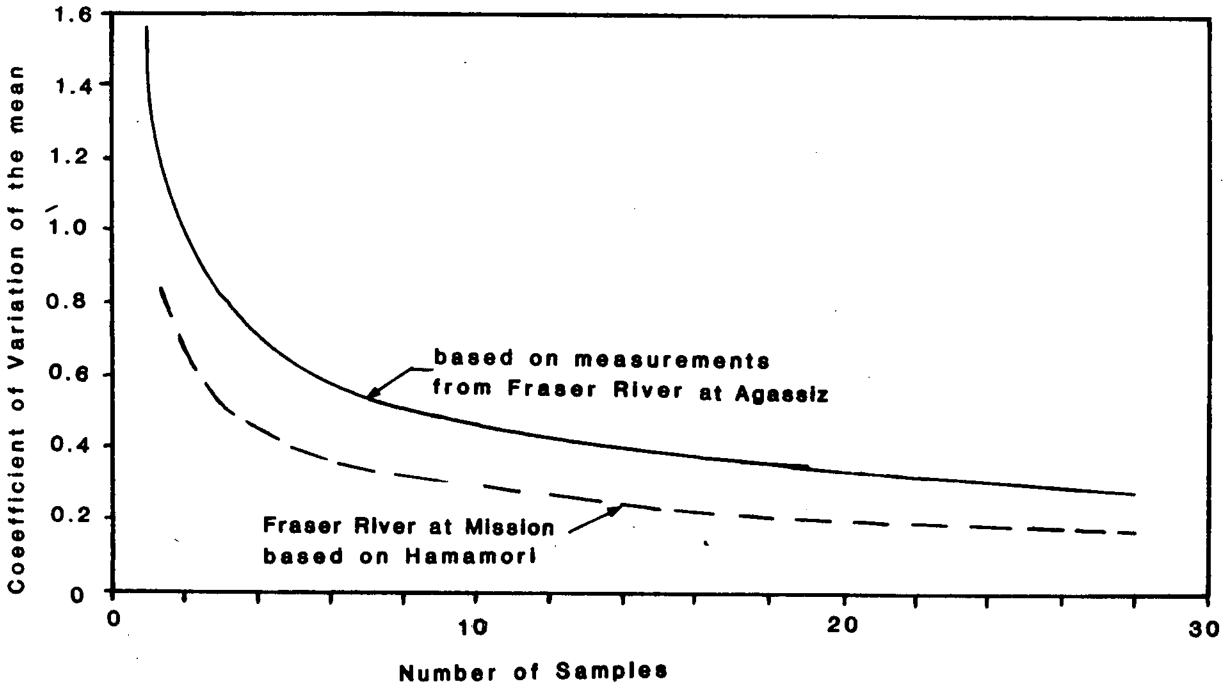


Figure 31. Precision of n-Sample Bed Load Measurements at a Single Vertical at Agassiz and Mission.

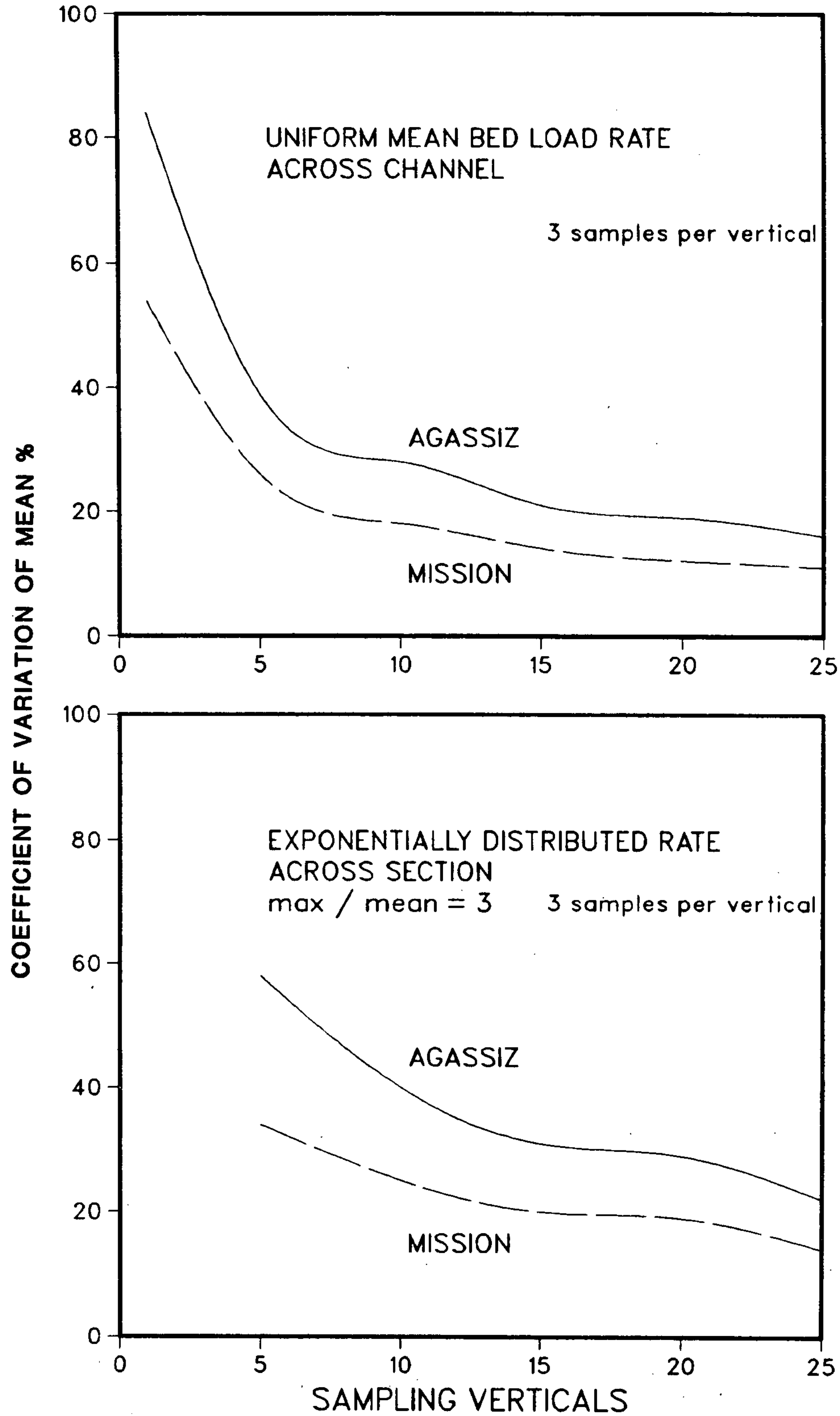


Figure 32. Precision of the Total Bed Load Rate at Agassiz and Mission

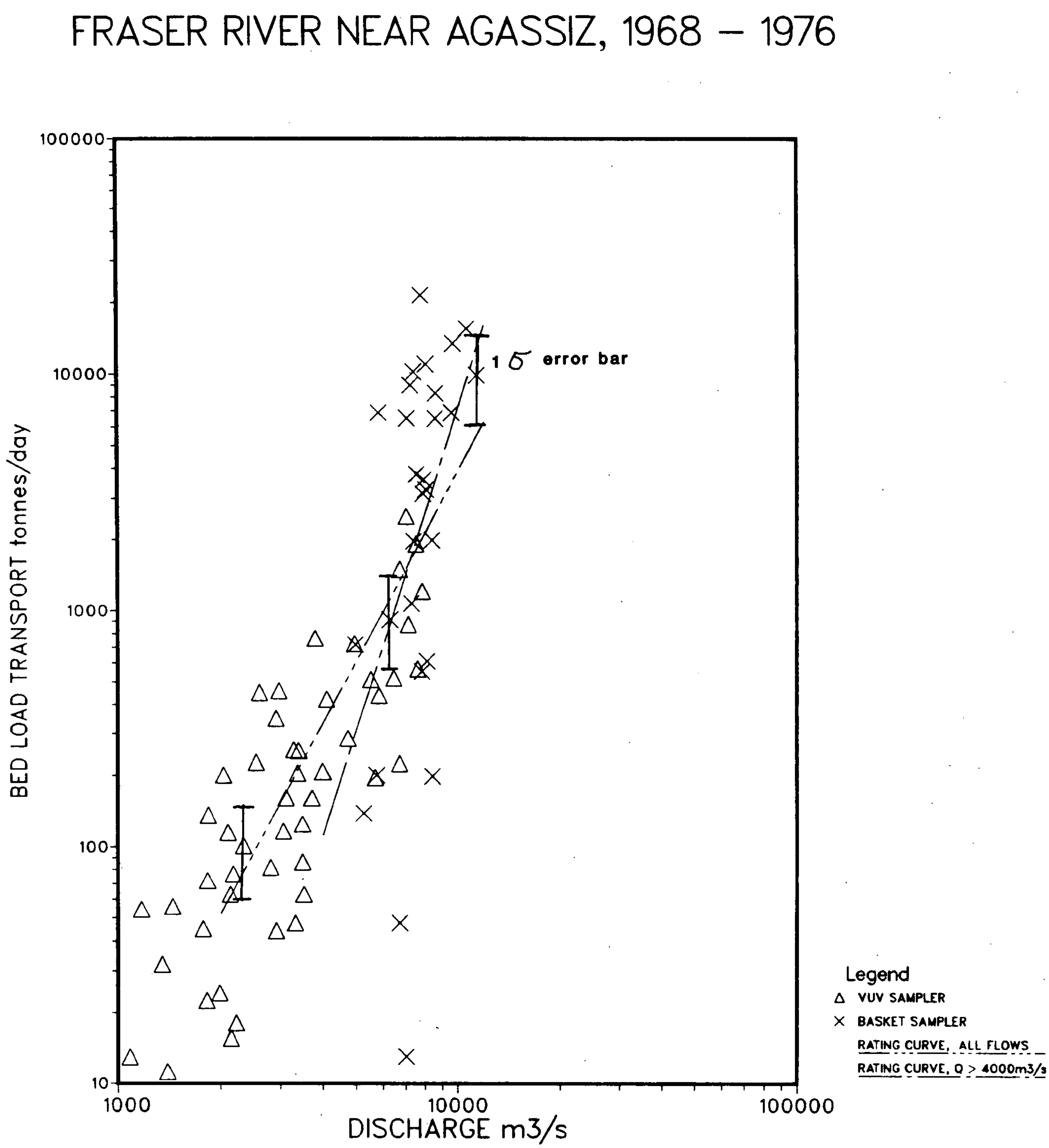


Figure 33. Bed Load Rating Curve at Agassiz, 1968 - 1976.

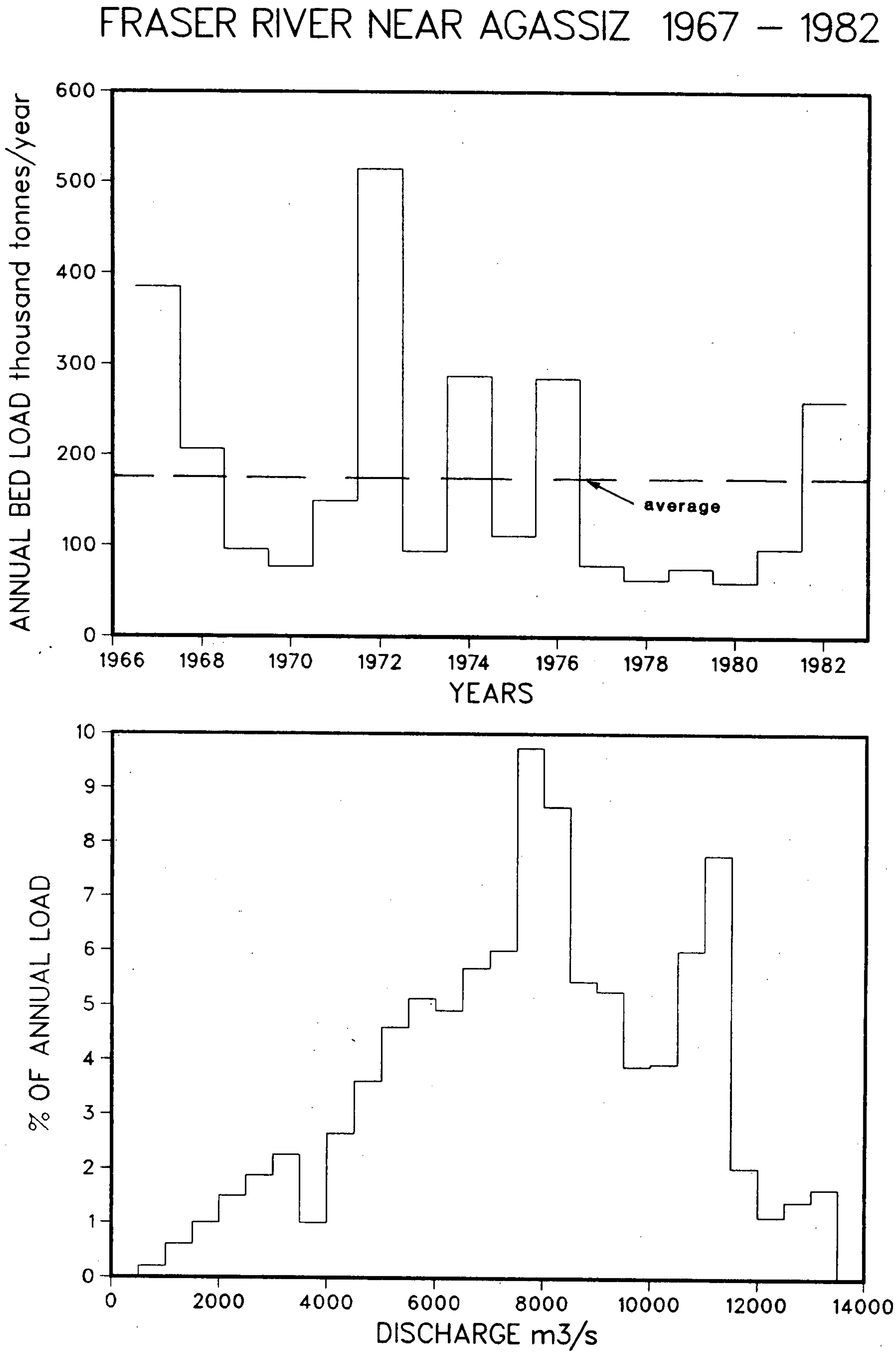
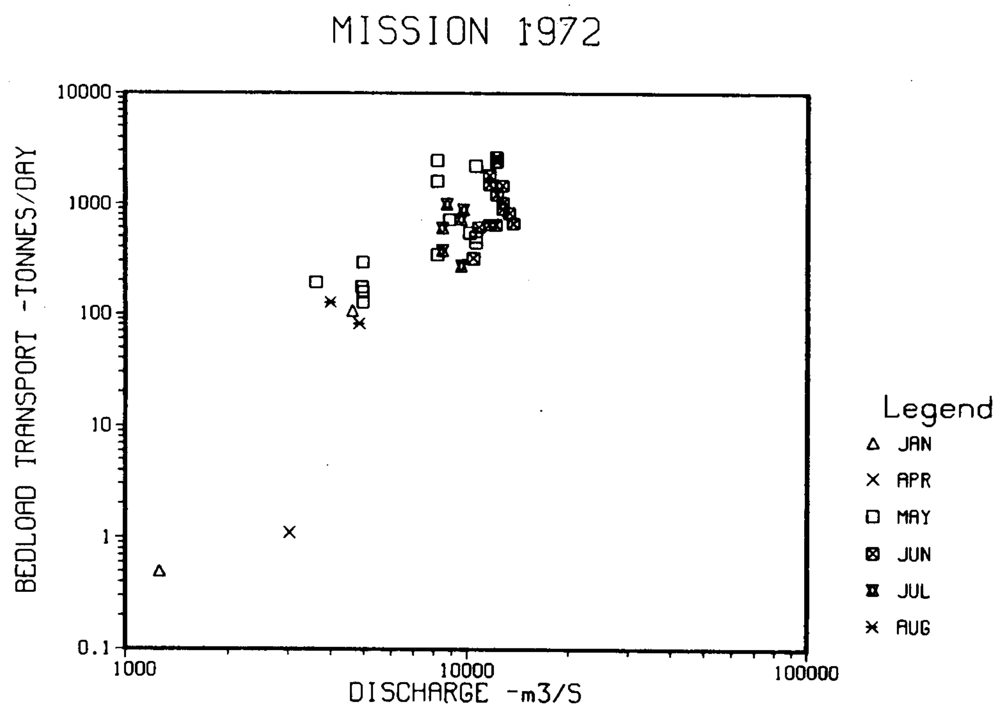


Figure 34. Variation of Bed Load at Agassiz .



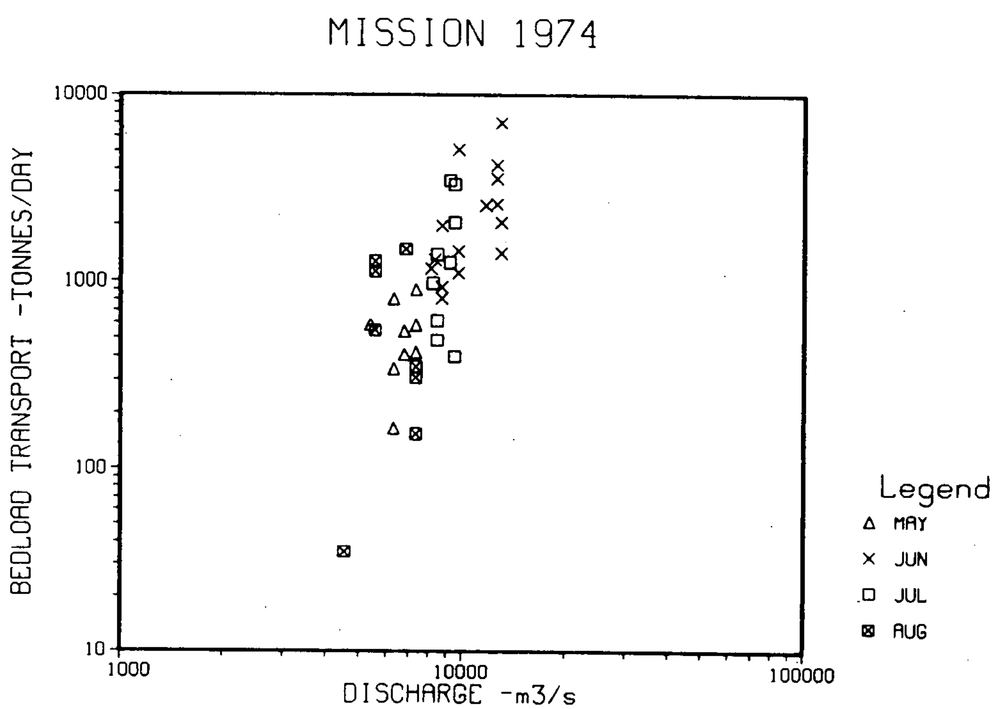


Figure 35. Mission Bed Load - Discharge Relations, 1972 and 1974.

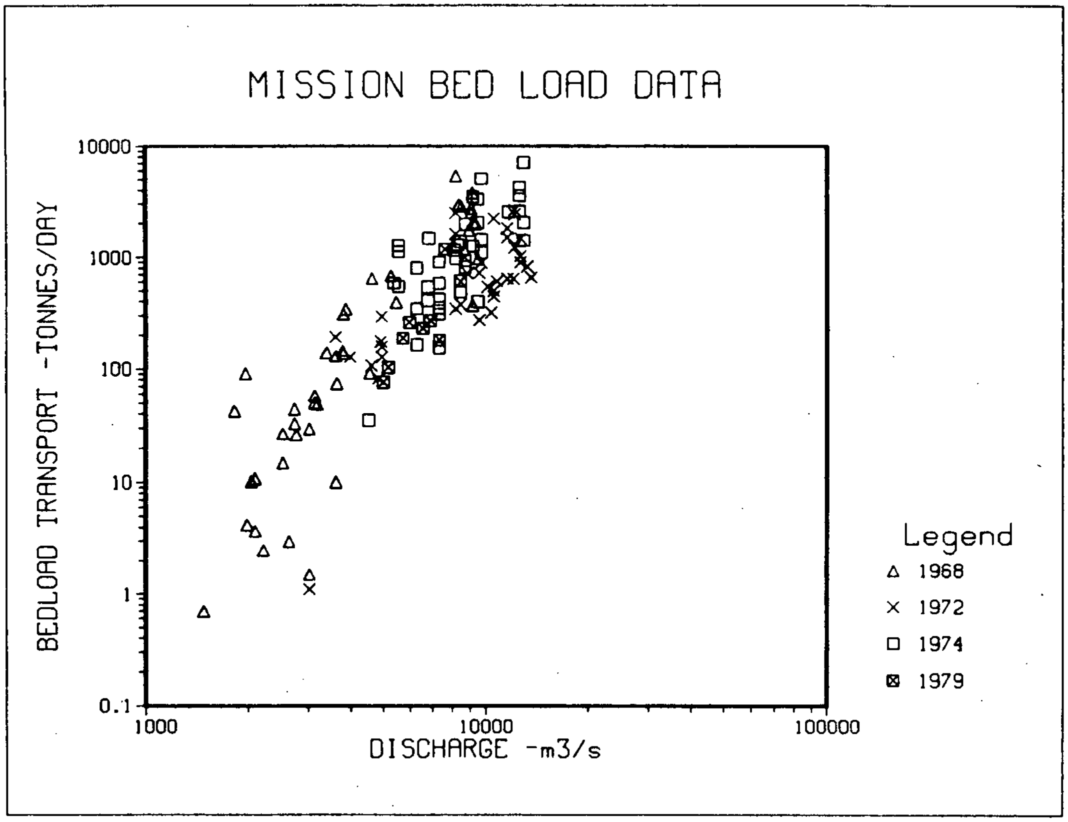
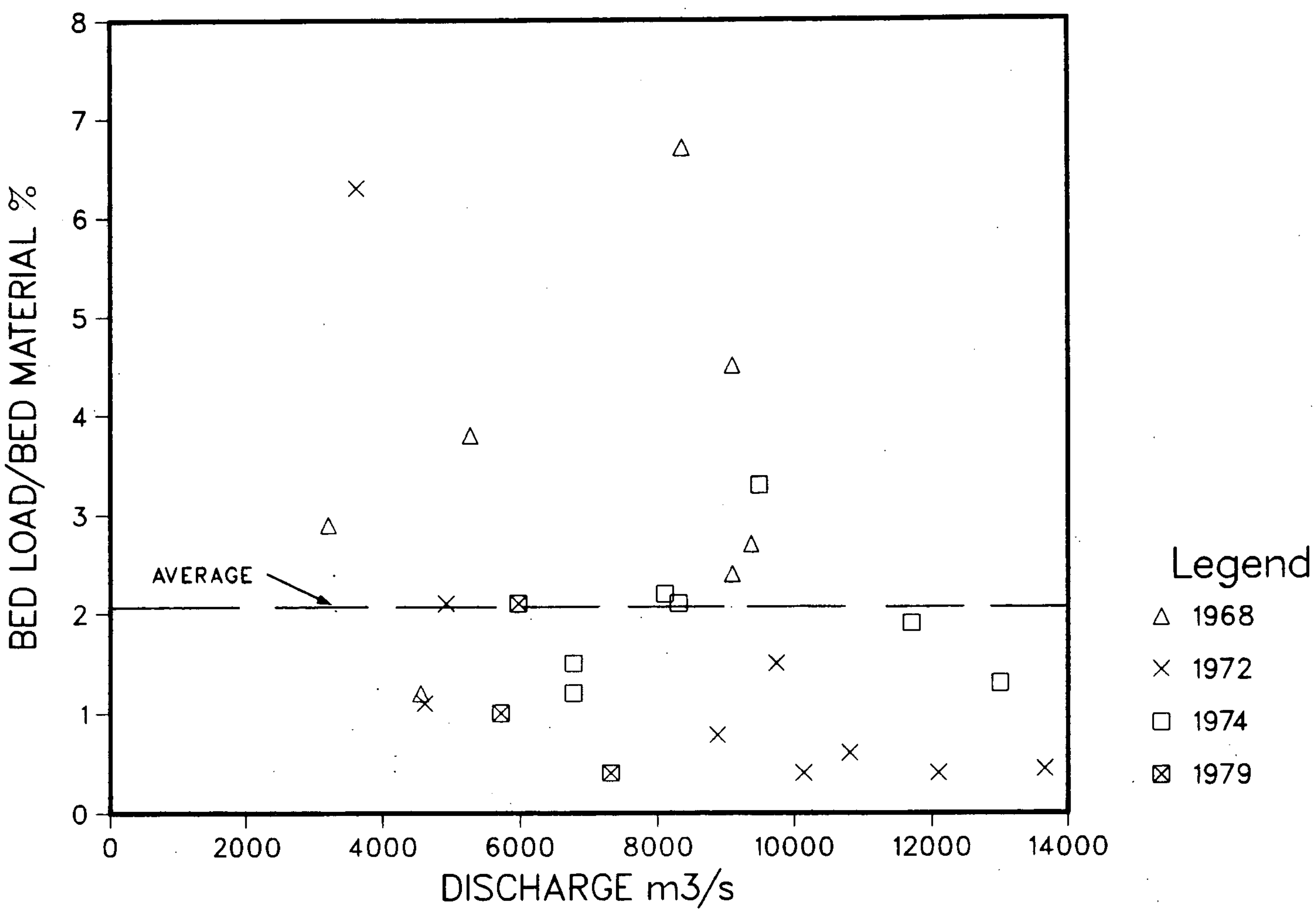


Figure 36. Mission Bed Load Rating Curve.

FIGURE 37

BED LOAD / BED MATERIAL LOAD RATIO AT MISSION



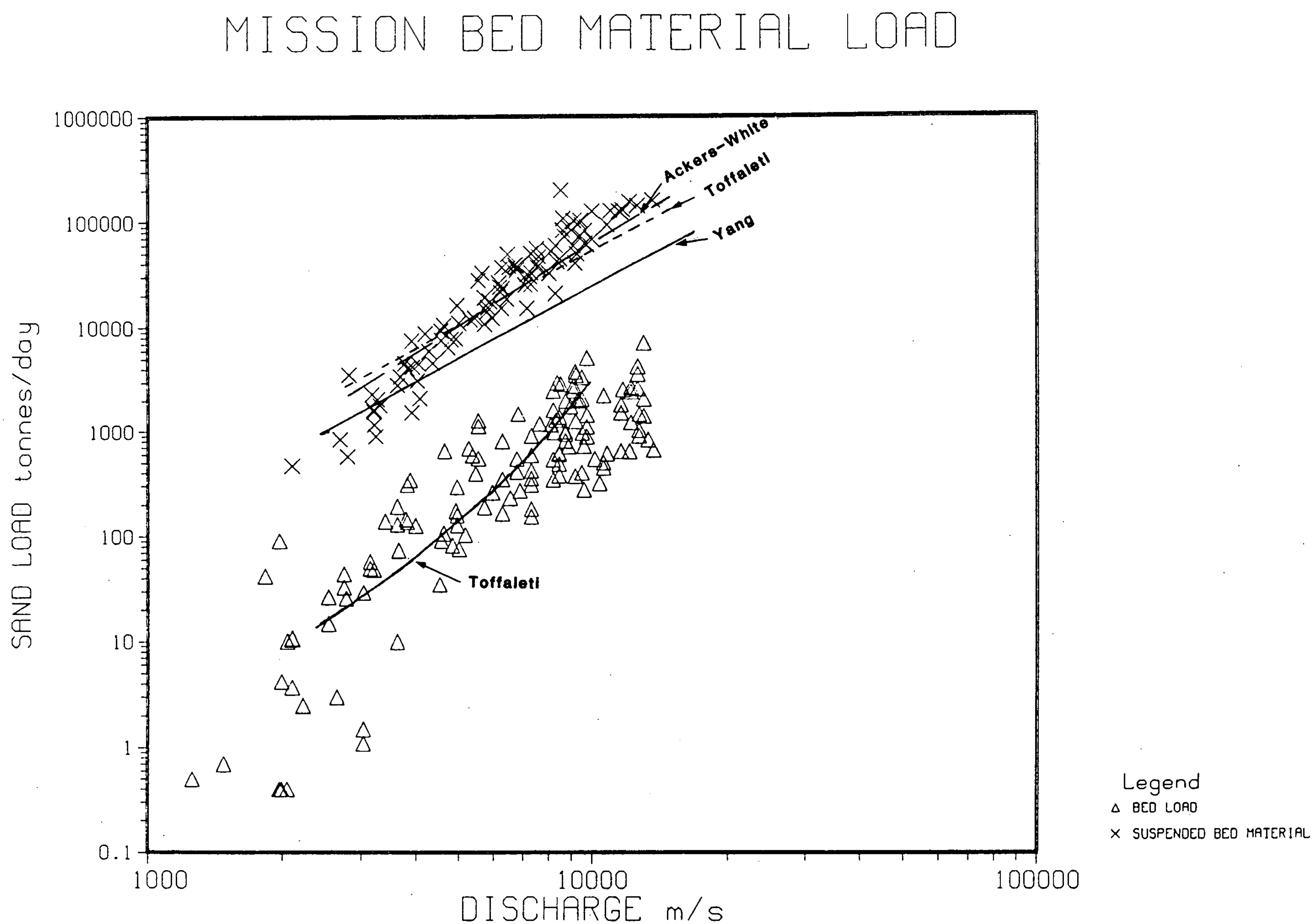


Figure 38 Comparison Bed Load and Suspended Bed Material Load

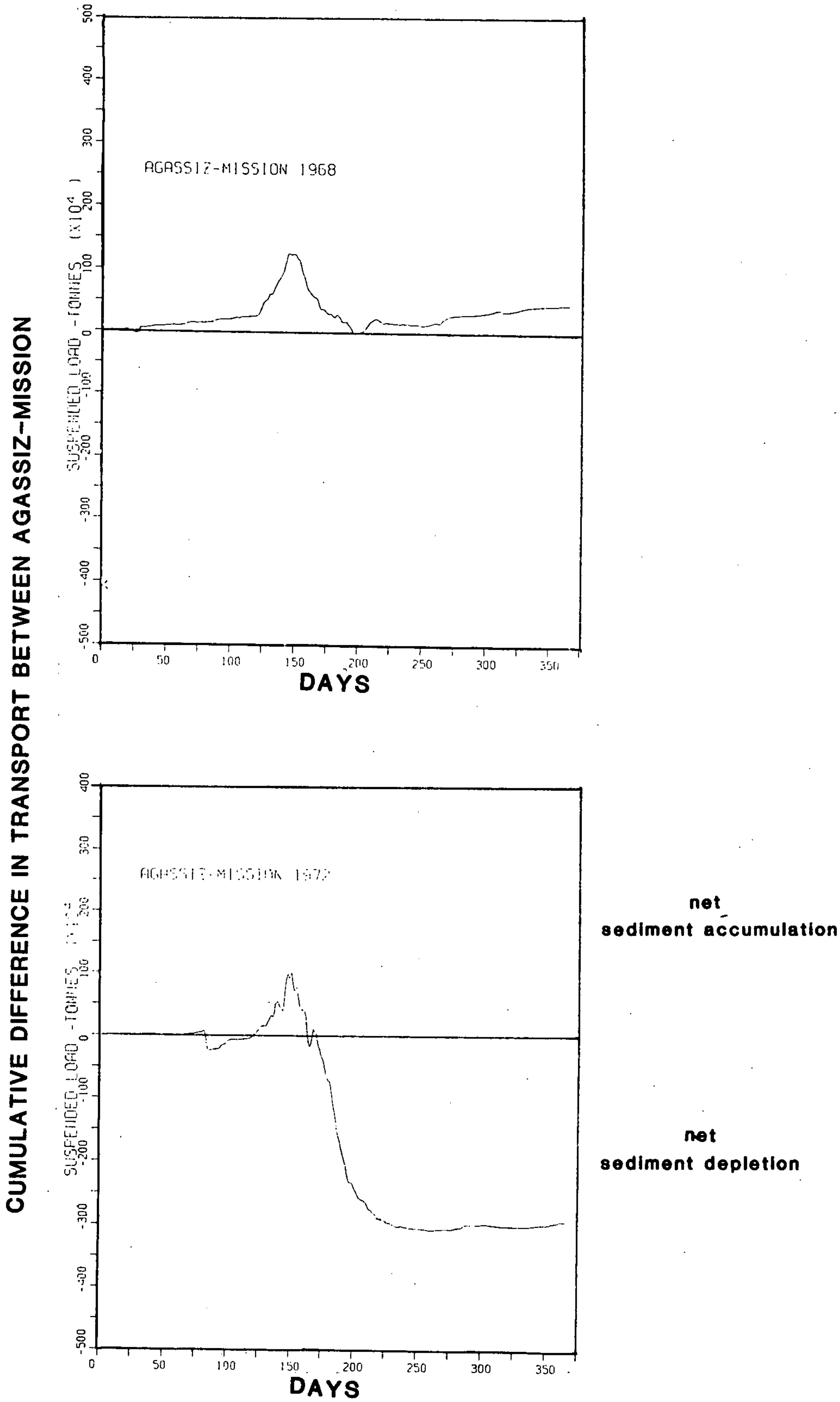


Figure 39. Cumulative Differences between Suspended Loads at Agassiz and Mission.