SEDIMENT STATION ANALYSIS

FRASER RIVER NEAR MARGUERITE, BRITISH COLUMBIA

STATION 08MC018

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PREFACE

This report was commissioned by the Water Resources Branch of the Inland Waters Directorate of Environment Canada in Vancouver, through the Department of Supply and Services, under DSS Contract No. KE144-7-4155/01-SS. The Scientific Authority for the project was Mr Ian Stewart, Head, Special Projects, Water Resources Branch, Vancouver.

Sediment station analyses are undertaken for WSC sediment stations after termination of the sampling program or at critical points in the program. The analysis undertaken here for Station 08MC018, Fraser River near Marguerite, is one of several currently being undertaken by WSC across the country.

Analysis of the data and preparation of the report has been assisted considerably by the comments of Bruno Tassone of the Water Resources Branch, Vancouver and by preparation of data files and plots by Joseph McIlhinney, Sediment Survey Section, Water Resources Branch, Ottawa, and this is duly acknowledged.

ABSTRACT

This report provides an analysis of the data collected at the WSC sediment sampling station 08MC018 on the Fraser River, near Marguerite, British Columbia, approximately half way between Prince George and the confluence with the Thompson River at Lytton.

The text of the report and associated figures and tables are presented in Volume I; the data files and related plots are provided in Volume II.

A summary of the findings of the analysis is presented at the beginning of Volume I. The purpose and scope of the report are outlined in the first section of Volume I, and this is followed by statement regarding the goals of the sediment program, and a description of the Fraser River at Marguerite and its associated catchment.

Section 3 describes the type of data collected - discharge, suspended sediment and bed load - and the methods and equipment used for those purposes.

The analysis and interpretation of these data are presented in the main body of the report, Section 4, and deal with the sampling reliability of the data, computations of annual suspended and bed loads, particle size distribution of these loads, and possible sediment sources in the catchment above Marguerite.

An evaluation of the sediment program is provided in Section 5, together with several recommendations for further analysis of existing data, to make them more useful for agencies concerned with the contribution of the upper Fraser River basin to sedimentation in the lower river, delta and estuary.

SEDIMENT TRANSPORT ON THE FRASER RIVER NEAR MARGUERITE: A SUMMARY

1. Annual suspended loads

Suspended sediment loads at 08MC018 have been determined for the period 1971-1986. The annual loads ranged from 5.1 million tonnes (Mt) in 1980 to 20.4 Mt in 1976 (Table 5). The mean for the period is 10.1 Mt, with a standard error of slightly more than 10 percent (Fig. 10). Comparison of discharge data for this period with that from the full period of hydrometric monitoring at this site (1950-1986) indicates that this estimate of mean annual load should be representative of post-1950 conditions. Examination of the longer discharge record from Hope indicates that loads may have been significantly lower in the first part of the century.

2. Seasonal change in suspended load

Monthly suspended loads peak in May, in contrast to the June peak in water discharge (Figs. 12 and 13). Suspended loads in May average 115,000 tonnes per day. The four-month period April to July accounts for 89 percent of the annual suspended load.

3. Suspended sediment concentrations

The previous observations imply that the annual peak in sediment concentration occurs well before that of water discharge (Fig. 17). The four day (continuous) period with the highest sediment concentrations occurs between mid-March and late May (Appendix D3); this contrasts with the similar period for water discharge which occurs between early May and the first week of July. Mean concentrations during the peak four day period ranged from 487 mg/L (1984) to 1670 mg/L (1976). This premature peaking of concentration is the main cause of scatter in the relationship between daily concentration and daily discharge (Fig. 14) which, otherwise, would be quite strong.

4. Particle size characteristics of the suspended load

Particle size data for the suspended load are important to anyone concerned with downstream impacts, whether this be the flux of nutrients or contaminants incorporated in the fine-grained sediment, or dredging of the coarser sand that settles on to the bed of the Lower Fraser. Such data exist for the Marguerite site (Appendix F1, F2), but have not been analyzed by WSC to yield estimates of the annual load by size class. The only data analyzed (Fig. 19) indicate that at low flows virtually all the suspended load is silt and clay; by 2000 m^3/s, the silt-clay component has decreased to about 60%; and by 5000 m^3/s, the sand fraction is at least equal to the silt-clay fraction. Silt dominates the silt-clay fraction. Median particle size of the suspended sediment increases from about 0.02 mm at 2000 m^3/s to about 0.08 mm at 5000 m^3/s.

5. Annual bed loads

No calculations of the annual bed loads have been made except for 1971 (0.8 Mt) and 1953-1971 (1.0 Mt). However, these were based on a regression between bed load rate and water discharge applied to the 1971 sample data. Only seven points were available on this plot, and one of these is suspect (Fig. 18). A new regression based on data collected from 1971 to 1975, inclusive, yields higher transport rates at all flows greater than 3500 m^3/s, and higher annual loads, averaging 1.5 Mt between 1971 and 1982. Uncertainty exists, however, regarding the reliability of the bedload sampling procedure at this station.

6. Bed load and bed material particle size data

Particle size data collected for the bed load (Appendix F3) indicate the sediment to be virtually all gravel, with a median grain size of 23 mm, and with little change apparent from one sampling period to another, except at very low flows when sand size material dominates. The range in grain size is from <0.06 mm to >64 mm. Particle size data have also been obtained for bed material from bar sites (App. F4), using grid-by-number sampling of surface clasts, and bulk sampling of both "surface" and subsurface samples. The mean value for median grain size of subsurface sediment at four sites is 25 mm, not appreciably different from the sampled bed load. The mean value for median gravel (> 8mm) size at these sites was 30 mm (subsurface) and 32-33 mm (surface).

7. Sediment sources

The source of sediment moved by the Fraser past the Marguerite site has not been determined in any detail, except to note that most of it appears to originate in the reach downstream of Hansard, including tributary inflows. The suspended load at Hansard is less than 25% of that at Marguerite, and the annual bed load at Hansard is only 5% of the 1.0 Mt estimated by IPEC (BC Energy Board, 1972) at Marguerite. Though tributaries may contribute much of the extra suspended load, the increase in bed load is probably due more to erosion along the main stem.

8. Reservoir life

The sediment data collected since 1971 confirm that sedimentation would not be a concern in terms of limiting the life of a reservoir built in Moran Canyon. The reservoir considered by the Fraser River Board (1958, 1963) for this site would, under present conditions of sediment transport, survive about 900 years before a volume equal to that of its dead storage had been infilled, and about 1900 years before total storage was lost.

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1. INTRODUCTION

1.1 Purpose of report

The purpose of this report is to review, summarize and present an analysis of the flow and sediment data collected at the station "Fraser River near Marguerite" (08MC018), upstream of Williams Lake, British Columbia. The station is one of six long-term sediment stations on the Fraser River, but one of only two upstream of the confluence of the Thompson River (Fig.1). The other sediment station on the upper Fraser River is that at Hansard (08KA004), upstream of Prince George. A similar report has been prepared for the Hansard station (Zrymiak and Tassone, 1988), and, for ease of comparison, the format of the present report follows that of the Hansard review.

The report has two specific goals. The first, directed primarily to the staff of the Water Survey of Canada, is to assess the effectiveness of the sediment program at 08MC018 in accomplishing its original objectives. The second, aimed more generally at members of the scientific and engineering communities, is to provide a summary of the concentrations, total loads and grain size composition of sediment transported past this station, not only in terms of long-term averages, but also with respect to fluctuations annually, seasonally, monthly and daily.

1.2 Scope of report

The report begins by summarizing the background to the sediment monitoring program at Marguerite (its objectives and history) and by describing the basin, reach and station settings (Section 2).

Section 3 describes the types of data collected, methods of collection (including sampling strategies) and summarizes the quality of the sample data. The section deals with flow data, suspended sediment and bed load, with primary emphasis on suspended matter.

The core of the report (Section 4) then presents an analysis and interpretation of these data.

The concluding section provides an evaluation of the sediment program, aimed primarily at WSC staff (Section 5). The Summary, at the beginning of the report, is oriented more to the external user.

The standard format plots used in Volume I of the report, and which constitute the bulk of the appendices (Vol. II), were produced by the Sediment Survey Section of the Water Resources Branch of the Inland Waters Directorate in Ottawa, and are available for most of the WSC sediment stations.

2. SEDIMENT PROGRAM BACKGROUND

2.1 Objectives of program

The hydrometric station 08MC018 (Fraser River near Marguerite), one of ten active hydrometric stations on the Fraser River, started operations in 1950. It is one of five established on the main stem in the early 1950's, following severe flooding in the lower Fraser basin from snowmelt in 1948.

In the late 1950's, the governments of Canada and British Columbia set up a board to report on the effects of regulation of the Fraser with respect to flood control and power generation (Fraser River Board, 1958; 1963). Among the proposals considered, was one for a dam in the Moran Canyon, 50 km upstream of Lillooet. The associated reservoir would have extended past Marguerite almost to Quesnel.

The sediment station near Marguerite was established in May 1971 by the Water Survey of Canada at the request of BC Energy Board (Southworth, 1971) for the purpose of making a preliminary estimate of the useful life of the proposed Moran Reservoir, and of downstream impacts of the dam closure on the sediment regime and morphology of the Fraser River due to depletion of sediment loads (Dirom, 1979).

The BC Energy Board report was completed in April 1972. It included a preliminary estimate of the life of the reservoir, based on the 1971 data (B.C. Energy Board, 1972, Appendix XV-F). It also contained estimates of degradation downstream from the dam, and of erosion of the Fraser Delta, based on data collected on the Fraser River at Lillooet during 1950-52 by the BC Government (Appendix XV-D:Part B). Because of the paucity of sediment data, the report recommended that the new sediment survey be continued.

Pretious (BC Energy Board, 1972) emphasized the following points in considering downstream impacts of a dam in the Moran Canyon:

(a) degradation of the bed would occur immediately downstream of the dam, but would be limited by rapid armouring of the bed and exposure of rock outcrops;

(b) total sediment inputs to the lower Fraser River would be reduced by about two-thirds, allowing a similar reduction in the magnitude of annual maintenance dredging in the navigation channels of the lower estuary, and improvement of navigation as far upstream as Hope;

(c) the seaward advance of the front of the Fraser River delta would be retarded;

(d) trapping of sand by a dam would have little impact on beaches in the Vancouver area which are not, apparently, being nourished by sand from the Fraser;

(e) river structures (bridge piers, pipeline crossings, etc.) between Chilliwack and New Westminster would not be adversely affected, because the regulation of flow from Moran Dam would lessen scouring of the bed;

(f) undiked islands of the Delta would receive less sediment than at present, and this would have some effect on wildlife habitat.

2.2 History

Preliminary suspended sediment data were obtained at the Marguerite site on three occasions in 1951 and 11 times in 1952 by the BC Government (Kidd and Tredcroft, 1953), but a major sampling program did not begin until 1971. In that year, bed load measurements were made on seven occasions, yielding a reasonably well-defined sediment rating regression between bed load rate and water discharge. Suspended sediment sampling was undertaken from May until December of that year in response to the request from the BC Energy Board.

Following the submission of the BC Energy report, suspended sediment sampling has been undertaken in each month since April, 1972 (except for some low-flow months in some of the winters); the major sampling program was discontinued on April 4, 1987, though some suspended sampling continues on a miscellaneous basis. Samples were collected on 2096 days (averaging 131 days per year) since April, 1971, of which 339 (ignoring dip samples) were subjected to analysis for particle size determination. A bed load sampling program was undertaken between May, 1972 and June, 1979.

2.3 Basin description

The Fraser catchment upstream of the Marguerite station covers an area of 114,000 sq. km., of which 18,000 sq. km occur upstream of the Hansard station. Upstream of Hansard, the Fraser drains the Rocky Mountain trench, composed of lacustrine silts interspersed with outwash sand and gravel, and flanked by steep valley walls comprising folded sedimentrary rocks (Zrymiak and Tassone, 1988).

Downstream of Hansard, the major tributary catchment is the Nechako (42,500 sq. km at Isle Pierre), but most of its drainage network is interrupted by natural and manmade lakes (14,000 sq.

km. of the area at Isle Pierre occurs upstream of the Kenney Dam), so that sediment yields (loads per unit area) will be lower than expected on the basis of relief. The Salmon River, flowing across gentle terrain from the north, is also likely to have a low sediment yield. Of the other large tributary basins, the McGregor draining the Rocky Mtns, the Willow issuing from the Cariboo Mtns, and the West Road River, draining the Interior Plateau, are probably the major tributary sources augmenting the sediment load downstream of Hansard.

2.4 Reach description

Between Prince George and Hope, the Fraser River cuts through the Interior Plateau and then the Coast Range, along a much steeper profile than upstream of Prince George. The average gradient in the vicinity of the Hansard reach is of the order of 17 m per 100 km. In contrast, between Prince George and Marguerite it averages about 64 m per 100 km; it increases again to more than 104 m per 100 km between Marguerite and Hope, as the river becomes largely non-alluvial in cutting through the Coast Range. (These slopes are based on the longitudinal profile of the Fraser provided by the Fraser River Board, 1958.) At Hope, the gradient is reported as 60 m per 100 km (0.00060), decreasing downstream to 0.00048 at Agassiz and 0.00005 at Mission (McLean and Church, 1986).

The topography and channel upstream of Marguerite are shown at 1:250,000 in Fig. 2; the 1:50,000 topographic coverage of the gauging reach is given in Fig. 3; and vertical aerial photograph of the reach in the vicinity of the station is provided in Fig. 4.

Upstream of the Marguerite ferry crossing, the Fraser has an irregular plan geometry comprising several different patterns: narrow, weakly sinuous reaches are separated by a wider, multiple island stretch opposite Buck Ridge, and a more tortuous path around Diamond Island opposite Alexandria. The latter sections appear to represent localized accumulations of mobile bed material. Downstream towards Marguerite, the course begins to straighten, islands and bars gradually disappear, and the channel becomes narrower, presumably corresponding to the further steepening in gradient downstream of Marguerite, already noted.

Unlike at Hansard, the Fraser near Marguerite is primarily a gravel-bed river, not sand-bedded: this is consistent with the increased river gradient just noted. Tassone (1988, pers. comm.) reports that the left bank in the vicinity of the station is composed mostly of clay and is relatively stable. In contrast, the higher right bank comprises gravel, and is subject to erosion.

The station itself is located at the ferry crossing (Fig. 3) and is thus in a short straight part of the reach, just downstream of a mild bend. It would be expected, from this location, that the thalweg would occur on the true left (east) side, shallowing towards the west bank. A gravel bar is in fact visible at low water upstream of the gauging site.

The cross-section, at different times in 1971, is shown in Fig. 5, indicating removal of sediment from the bar area (between mid-channel and the right bank) in the high flows of early summer, followed by a new build-up during the latter part of the year. Although other cross-sectional sounding data do exist at times of regular current-metering at the site, they have not been plotted by WSC. Nonetheless, it is clear that the reach in the vicinity of the measurement section is far from stable, although presumably much more stable than would have been the case upstream of Alexandria. This may be inferred from the stage-discharge rating curves: during the 38 years since the establishment of the hydrometric station, 19 different rating curves, linking discharge to water stage, have been used at the station (Tassone, 1988, pers. comm.).

2.5 Station description

Station 08MC018 is located at latitude 52°31'48" N and 122°26'32" W. The measurement section is 220 m wide; the river depth ranges from 3.5 m at low flows to 10.5 m at high flows.

The hydrometric equipment comprises an A-71 water-level recorder (activated by a servo-manometer pressure sensing system), housed in a shelter on the left bank of the river, just downstream of the cable crossings. There are actually two cable crossings operated by the Ministry of Highways (BC); the upstream one for a powered cable car, and a second one, ten metres downstream, used for the vehicle ferry. The current-metering, needed for the stage-discharge rating curves, is done from the cable car. Suspended sediment sampling was done from the ferry, when in service between spring and late autumn. In the intervening periods, "dip" samples (see below) were taken from the cable car. Bed load samples were taken from the ferry.

2.6 Hydrology of the area

Runoff from the basin is dominated by snowmelt, with daily discharge rising rapidly in April and May of the typical year to a peak in June (Fig. 6); flow declines fairly rapidly during July, then more slowly during the rest of year. Small isolated peaks can occur at any time of the open water period from rainstorms. Maximum daily discharge ranged between 3220 m^3/s on June 22, 1983 and 6510 m^3/s on June 16, 1972. The latter figure is slightly more than double the maximum at Hansard in the same year, occurring on June 14. Mean annual flow in the 1950-1986 period was 1440 m^3/s.

It should be noted that, since October 1952, the flow has been affected by storage and diversion on upstream tributaries.

In particular, the total drainage area of 114,000 sq. km includes 14,000 sq. km. behind the Kenney Dam on the Nechako River.

3. DATA

3.1 Data requirements

The sediment data needed to assess the life expectancy of a possiblé Moran Reservoir are essentially twofold: annual suspended loads and annual bed loads. Data on particle size of the suspended load are also required, however, partly because size affects the settling velocity of the suspended grains (and thus the percentage of the load actually trapped in the reservoir) and partly because it affects the bulk density of the sediment once it has settled to the reservoir floor.

Assessment of the morphological impacts immediately downstream of a reservoir, due to sediment-trapping, requires essentially the same data, though in this context, it is more important to distinguish between the bed material load (moving bed material, irrespective of whether moved along the bed or in suspension at high flows) and the wash load (the fine-grained part of the suspended load that moves through the reach without settling on the bed).

This distinction is important: downstream of a sediment trap, such as a reservoir, the wash load will remain depleted; in contrast, the suspended bed material load will tend to build up again to its upstream concentrations, by scour of the bed, until the river's capacity is once again reached. The distinction is also important because the morphological characteristics of a river reach depend upon the magnitude and grain size of the total bed material load, irrespective of whether that sediment has moved primarily as bedload or temporarily in suspension.

Thus a simple distinction between bed load and suspended load (which are the usual measurement goals in sediment surveys) is inadequate to address impacts of sediment trapping in the reaches immediately downstream. Some attempt is needed to determine how much of the suspended load is actually bed material. This is usually undertaken by particle size comparison of the suspended load and the bed material.

Further downstream, in the lower Fraser, where more of the suspended sediment settles out, especially in the delta mouths, the spatial pattern of sediment deposition is controlled in large part by particle size. In order to predict impacts in this region, particle size data for the total load are clearly an important requirement.

Although the suspended sediment load is one of the primary data requirements at this station, it cannot be measured directly. Rather, values of sediment concentration are determined by sampling, and the sediment load of a given day is calculated as the product of the daily mean water discharge (determined at the hydrometric station) and the daily mean sediment concentration. Much of the data presented in this report will be in the form of concentration values (mg/L), as well as loads (tonnes), however, for the reason that it provides some indication of whether the changes in load are primarily due to changes in water discharge or due to changes in concentration. In addition, in some cases, values of concentration may be of primary interest to fisheries personnel, given that highly turbid stream water is known to have deleterious effects on fish (Berg, 1982).

3.2 Data collected

3.2.1 Flow data

Hydrometric data have been collected at this station on an essentially continuous basis since May 1950, although gaps exist in the record during some of the winters between 1956 and 1964.

Water discharge at the cross-section is computed from a rating curve that relates water flow to river stage (water level). An analogue recording gauge provides a continuous trace of river stage as it fluctuates over time; and a field crew visits the site about six times a year to measure discharge (from velocity, depth of flow and width), enabling revision of the rating curve when necessary. As already noted, 19 versions of the rating curve have been used in the 38-year period, indicative of some degree of instability of the bed. Between 1981 and 1986, for example, at gauge height of 6 metres, discharge increased from 3600 m^3/s to 3880 m^3/s, and the curve was revised four times in this period.

Perhaps more serious than shifts in the rating curve during the open water season are possible errors in estimating discharge under an ice cover and during breakup, when the rating curve is not applicable. Such conditions are indicated in the hydrograph data for each year (Appendix C3) by the letter "B". Examination of those data shows that breakup conditions frequently involve suspended loads of the order of 50,000 tonnes per day, sometimes amounting to 500,000 tonnes during the break up period. The latter represents 5 % of the mean annual suspended load (Section 4.1).

Hydrometric data (daily mean discharges, monthly and annual maximum, mean and minimum flows) for the Fraser River near Marguerite are included in the yearbook "Surface Water Data-British Columbia" published by Environment Canada. A summary of the various flow indices is available in the bi-annual publication entitled "Historical Streamflow Summary - British Columbia".

3.2.2 Sediment data

Sampling of suspended sediment at this location was first undertaken by the Department of Lands and Forests, British Columbia in 1951-52 (Kidd and Tredcroft, 1953). Suspended sediment sampling was conducted from 1971 to 1986 by the Water Survey of Canada, using equipment and procedures described below. Sampling is continuing on a miscellaneous schedule.

Bed load measurements were made between 1971 and 1979 using equipment and procedures described in the next section. These, like the suspended sediment data, include not only transport rates, but also analyses of particle size. No particle size data are available at this site for bed material itself, however, only for sediment in motion.

The suspended sediment data collected at this site have been included in the annual publication "Sediment data - Canadian Rivers" from 1972 to 1983, and subsequently in the yearbook "Sediment data - British Columbia". Bed load data have been published for particle size, but not for annual transport volumes.

3.3 Sediment sampling: Equipment and procedures

3.3.1 Suspended load

Sampling of suspended sediment at a WSC station is generally undertaken by two parties: a visiting WSC technician who samples along five replicate verticals in the cross section, the verticals having been located to partition the river into panels of approximately equal water discharge; and by a local observer who samples, more frequently (usually twice a day at high flows), but at one vertical only, designated as the single sampling vertical.

Such a strategy is necessary in order to maintain a manageable sampling program in terms of sampling frequency, while ensuring that the single sampling vertical is representative of the cross-section as a whole. On average, replicate sampling was done by the technician at the Marguerite site about five times a year (these are designated R samples), while single-vertical sampling (K samples) by the observer was often done twice daily in the high-flow summer months (decreasing slightly during the 16-year period), and decreasing in the low flow months. A summary of the total sampling program is given in Table 1, and Table 2 provides details of the R-sampling program.

At the time of R-sampling, an additional sample is taken on the single sampling vertical, so that the mean concentration for the cross-section can be compared with that of the single vertical. A correction factor (k) is then determined to adjust the concentration at the single vertical to the mean for the cross-section at that moment in time. Variation in the k coefficient through the year is indicated in Table 2, and this may, at first, provide some concern regarding the accuracy of the correction process. In general, however, the pattern of change in k with time is fairly systematic (e.g. Fig. 7) and, on days with K-sampling only, an appropriate value of the k coefficient can be taken from the k-curve for that year with some confidence.

Sampling of suspended sediment at the Marguerite site involved two procedures: "depth-integrated" samples in the main part of the year when flows and concentrations were highest; and "dip" samples in the early and late parts of the year.

Depth-integrated sampling was undertaken from the cable-controlled vehicle ferry. Fig. 5 shows the cross section in 1971, together with the locations of R-sample verticals and that of the single sampling vertical. The location of the latter was fixed (160 m from the right bank) through the 1971-1986 period, but the positions of the R-sample verticals were changed after

1977 because of changes in the cross-sectional geometry, and hence flow distribution. Between 1978 and 1982 the verticals were continually relocated to represent the centre lines of five approximately equal flow panels. From 1983 on, the verticals were fixed at locations only slightly different from those before 1978.

Samples were taken using a P-61 sampler (except for a short period between 1982 and 1984 when a P-63 sampler was used) from a powered D-reel on the ferry. The two samplers were described by Stichling (1969); they are essentially identical. A sampling bottle is contained within a heavy, stream-lined bronze shell. An intake nozzle enables entry of water and sediment at a rate controlled by the local velocity at the intake, and air is expelled through an exhaust passage. The sampler is raised from the stream bed up to the water surface in a period of time short enough to prevent filling of the container. This allows integration of the suspension over the full depth of a sampling vertical, according to the local velocity at each depth in the flow.

It should be recognized that it is physically impossible to sample immediately above the bed: for the P61 instrument this unsampled depth is 0.11 m; for the P63 it is 0.15 m. If dunes are present, the technicians may raise the sampler an additional 0.1 m above the bed. The resulting underestimate of concentration in the vertical is believed to be less than 10% for grains > 0.5 mm, about 5% for 0.125-0.5 mm, and less for finer sizes, based on data from the Mission site (Tassone, 1988, pers. comm.).

During the winter season when the vehicle ferry is not operated (approximately early November to early May), depth-integrated sampling was not possible. Instead, as long as there was no ice cover, the observer continued sampling at the same vertical from a power cable car (on the upstream cable) that is used for passenger traffic. However, in this case, only surface "dip" samples could be taken, using a DH-59 hand-line sampler. Thus, some adjustment is needed to convert the surface concentration to that which would be expected for a depth integrated sample at the single sampling vertical. In order to obtain such a correction factor, dip samples were taken on the single sampling vertical during the summer on some occasions when depth-integrated sampling was also undertaken. This ratio between depth-integrated concentration and dip concentration was used to adjust values for dip concentrations during the winter season. The k-coefficient was then used to adjust the value to a mean for the cross section.

Data pertaining to dip sample corrections are shown in Table 3. It can be seen that concentrations at the end of the year are so low that errors in the dip correction factor would not be important. In contrast, dip concentrations and water discharges in the spring are much higher, and some concern must exist regarding errors in the correction factor then. It should be borne in mind, for example, that the dilution in sediment concentration upwards from the bed to the water surface is strongly influenced by the settling velocity of the sediment (and hence the temperature of the water); dip correction values obtained in the summer may not be strictly applicable in the early spring.

Under ice conditions, when the cable car could not be operated, dip samples were taken through the ice at the left bank and not at the single sampling vertical. Though no clear distinction seems to have been made between these two locations of dip sampling in the summary data, it is assumed that these shore samples corresponded to flow conditions in which concentrations were low, and thus errors due to off-vertical sampling were insignificant. More important would be errors in discharge under ice conditions, noted previously.

3.3.2 Bed load

Sampling of bed load was undertaken by a WSC technician from the cable-controlled vehicle ferry (after the ferry had closed for the day) using two different samplers suspended from a boom and hydraulic reel assembly mounted on a flatbed truck. Samples were taken at the same five verticals in the cross section as used for replicate suspended sediment sampling. A summary of the bed load sampling program, by date, number of samplings etc., is provided in Table 4.

Sampling bed load involves resting a container on the river bed for a short period of time during which water passes through the container, and the associated bed material being moved is collected. The transport rate per unit width of flow is then determined from the entry width of the sampler, the weight of bed material caught, and the duration of sampling.

Because bedload transport varies appreciably over short periods of time, even under steady flow conditions, sampling at each vertical requires many observations (Hubbell, 1987). At Marguerite, at least two and often three specimens of the bed load were taken at one sampling time, but even this is inadequate. Recent data for the Fraser River at Agassiz (similarly gravel-bedded), at flows of 8000 m^3/s, based on replicate measurements at a given vertical with a half-size VUV bedload sampler, confirm this conclusion (McLean and Tassone, 1987). They found that the standard error of a mean bedload rate at a vertical based on only three samplings was 85% of the value of the "true" mean based on 20 samplings. Uncertainty as to the accuracy of the calculated bedload transport rates is the main reason why the data have not been published, in contrast to the suspended sediment data.

Calculation of the total bedload transport rate for the river at the cross-section involves plotting the local transport rate (in, say, tonnes per day per metre width) on a graph against position in the cross-section, interpolating between verticals, and digitizing the total area under the curve to integrate the total daily load, across the full width, in tonnes.

The two samplers used at Marguerite were a basket sampler and the Arnhem sampler. The basket sampler has an opening width of 61 cm and an opening height of 25.4 cm; three screen mesh sizes were available, 6.4 mm, 9.5 mm and 12.7 mm, though the latter was rarely used. It is therefore convenient for assessing most of the gravel bed load, but not sand. Sampling finer sediment involves a finer screen mesh. In turn, this slows down the water flow and induces settling of bed load before it reaches the sampler. To circumvent this problem, the shape of fine-mesh samplers is designed to create a pressure difference between the entrance and exit of the sampler to compensate for the increased mesh resistance. The Arnhem sampler is such a pressure-difference sampler (de Vries, 1973). The one used at Marguerite has an opening width of 9.7 cm and an opening height of 5.1 cm, with a screen mesh of 0.3 mm. Together, the two samplers allow trapping of virtually the full range of particle sizes in the Fraser River bed load at Marguerite. Under low flow conditions, the Arnhem sampler alone suffices. Under higher flows, the basket sampler is used in deeper gravel-carrying flows, and the Arnhem sampler in shallow sand-moving parts of the cross-section.

Neither sampler has a sampling efficiency of 100 percent, i.e., the amount of bed load trapped is less than that which would have moved past that location in the absence of the sampler. Tests on laboratory flumes, however, have shown that for normal sampling durations, the sampling efficiency of the basket sampler is essentially constant at about 33 percent (Engel, 1982, Church et al., 1987); thus sampled loads were increased by a factor of 3.0. This figure refers to grains coarser than the mesh size used. The efficiency of the Arnhem sampler (designed primarily for fine gravel rather than sand) is less certain. Initial work on the lower Fraser River used a correction factor of 3.5 (Water Survey of Canada, 1970), but more recent studies using Fraser River sand have suggested that the figure should be raised to about 4.4 (Church et al., 1987).

3.4 Sediment load computations: methodology

3.4.1 Suspended load

In light of the sampling program just described, there are several stages in the determination of a value for daily mean suspended sediment concentration. These procedures are documented in several publications of the Sediment Survey Section, but need to be summarized here in order that the external user of these data is aware of the methods involved and the possible sources of errors. The procedure for estimating the cross-sectional mean value at any moment in time has already been outlined. The procedure for estimating the daily mean value for the cross-section mean now needs to be considered.

The approach adopted by WSC is one in which intensive sampling over time, especially at periods of high load, allows accurate determination of daily mean loads. These are summed to indicate the annual load. This is repeated over a sufficient number of years that errors in the estimation of the mean annual load are reduced to an acceptable level (Section 4.1). Further sediment sampling is then not necessary and the sediment program can be abandoned. This strategy hinges, of course, on the assumption that the sampling years are representative of the long term condition, and that the long-term condition is stable. This aspect is addressed in Section 4.2.

The WSC approach therefore requires determination of daily mean values for sediment concentration, recognizing that samples are taken only once or twice a day, and on some days not at all. The procedure is as follows. The cross-sectional mean concentration at times of sampling is plotted on a copy of the water level recorder chart at the time of day of the sampling. A "sediment concentration hydrograph" is then constructed by drawing a smooth curve through the concentration points on the water level chart copy (Water Resources Branch, 1983, p. 30) following the pattern of changes in water level. The daily mean concentration for each day is then determined from this restored sediment concentration hydrograph, and multiplied by daily mean discharge to give the suspended sediment load for the day.

At sites where sampling is infrequent, interpolation between sampling days may result in appreciable error. But at sites where intensive sampling is undertaken, such as the Fraser River near Marguerite, this procedure, though subjective, is perhaps the best method of estimating daily mean suspended sediment concentration for the cross-section.

An alternative procedure commonly adopted (but not by the WSC) is to develop a sediment rating curve in which a regression is undertaken of "instantaneous" sediment transport rate (the product of water discharge and cross-section mean sediment concentration) against instantaneous water discharge. In this way, then, sediment loads can be predicted directly from the hydrograph of water discharge. The sediment rating approach will be discussed in Section 4.3: it will be seen that there is considerable scatter in the regression plot.

3.4.2 Bed load

No computations of monthly or annual bed load have been made by WSC, but data do exist to develop a bed load rating curve. This could then be applied to the flow-duration data, and bed loads predicted for each year. The matter is pursued in Section 4.4.

3.5 Sediment sampling: timing

3.5.1 Suspended load

On average, suspended sediment sampling was done on slightly more than 130 days of the year (Table 1), with the most intensive sampling in the heavy load months. In May and June, when loads are highest (Appendix D3), sampling was done at least once daily in the early part of the 16-year period, and even towards the latter part, when overall sampling intensity was less, these months were still being sampled every second day. Thus sampling was undertaken in the periods which mattered most, bearing in mind the procedures used by WSC in the computation of annual load described above. Days of replicate sampling at the five verticals were also concentrated in May and June (Table 2).

The years of highest annual load were 1976, 1972, 1974 and 1982; the 1972 year was the most-intensively sampled of any in the period; while the other three were close to normal in terms of sampling intensity.

3.5.2 Bed load

Sampling for bed load was undertaken from 1971 to 1979; the dates of sampling, and related data, are provided in Table 4. The primary purpose of sampling was to develop a rating equation between instantaneous bed load and water discharge. Thus samplings were conducted throughout the full range of bed material moving discharges (from 677 m^3/s to 5041 m^3/s), though with some emphasis on high flows.

4. ANALYSIS AND INTERPRETATION

4.1 Adequacy of length of record

The main purpose of the sediment program at Marguerite was to estimate the mean annual load of the Fraser River in this location under present day conditions. To that end, a period of time has been sampled from 1971 to 1986, and it is therefore important to assess the adequacy of this sample size in terms of its ability to estimate mean present-day conditions.

A summary of data relating to water discharge at this station is provided in Appendix B: mean monthly and mean annual discharges as reported in the Historical Streamflow Summary for British Columbia (Inland Waters Directorate, 1985); and mean daily discharge for each day of the calendar year during this period (with related dispersion indices).

Data for suspended sediment loads during the period are provided in Appendix C which contains the following information:

C1: the historical summary of annual values;
C2: a summary of monthly suspended loads for all months from May 1971 to December 1986;
C3: values of mean discharge, mean suspended sediment concentration and mean suspended load for each day, for each of the sixteen years;
C4: time charts ("hydrographs") for each year showing the fluctuation in discharge and sediment concentration.

These are the data which have been analyzed to assess the adequacy of the length of sampling period.

The 1971 suspended sediment load of the Fraser River at this site was 8.9 million tonnes (Mt) from May through December; and this could have been used as an estimate of the longterm load in calculating the life of the potential Moran Reservoir at the time of the BC Energy Board report. There was, of course, no reason to believe that this was an accurate estimate of the mean annual suspended load at the site, which is why additional years of sampling were recommended by the BC Energy Board. In the following years, the annual load ranged from a low of 5.1 Mt (1980) to a high of 20.4 Mt (1976), with a mean of 10.1 Mt of suspended sediment. The estimated annual loads are given in Table 5.

As each additional year's load is included in the determination of the mean annual load, the reliability of this sample mean as an estimate of the true mean improves; i.e. its imprecision decreases. This imprecision is normally expressed as the standard error of the sample mean (SEM), and is given mathematically by

$$SEM = \sigma / \sqrt{n}$$

where σ is the best estimate of the standard deviation of individual years.

The smaller is the standard error of the sample mean, the more reliable is the sample mean as an estimate of the true mean. As would be expected, and as the formula indicates, as sample size increases (more years in the sample), the standard error of the sample mean decreases.

Three sets of graphs have been prepared showing how the magnitude of the standard error (as a percentage of the mean) has decreased for mean annual discharge, for mean annual concentration and for mean annual suspended load, as more years of data have been added into the computuations (Figs. 8,9,10). It can be seen that, even though the 1971-1986 mean value for annual suspended load is not radically different from that of 1971 alone, its reliability is much greater: the standard error has decreased from more than 30% to just over 10 percent (Fig. 10). (The curve in the top part of these figures is the expected smooth decrease in the standard error of the mean, based on the standard deviation (s) of <u>all</u> individual yearly values, and assuming that s remains constant as more years of data are included. In actual fact, the addition of each year's data changes the standard deviation of the sample slightly, producing the more irregular decrease in the standard error of the mean over time.

Additional years of sampling would, of course, have improved the reliability of the mean, but, as the related diagram shows, the decrease (labelled "gain") in the standard error (still expressed as a percentage of the mean) decreases with additional sampling, and further improvements would be very small. The present standard error in the mean annual load is higher than that of both the mean annual discharge and the mean annual concentration: this is to be expected given that the load combines discharge and concentration, and thus the errors of both.

In summary, the length of record used for sediment sampling at Marguerite is clearly adequate to provide a reliable estimate of the mean annual suspended load. The decision to curtail further sampling was therefore warranted.

4.2 Representativeness of sampling period

Although the sampling period was long enough, there remains the separate issue of how representative is was of present day conditions.

Some indication of this can be obtained by comparing the discharge in the period 1971-1986 with that in the period for which hydrometric data are available, beginning 1951. As will be seen in Section 4.3, water discharge is a major control on sediment load, so that if the 1971-1986 period is representative in terms of discharge, it can be surmised that the same conclusion probably applies to sediment loads. Unfortunately, although discharge data are available from 1951, gaps in the winter period of record from 1956 to 1964, inclusive, complicate the assessment of annual data during these years.

All statistical analysis of discharge and suspended load data is summarized in Appendix D, which comprises three parts:

D1: annual statistics, viz. total discharge (dam^3), maximum daily discharge (m^3/s), total suspended load (tonnes) and maximum daily suspended load (t/day);

D2: full duration statistics, subdivided by month of the year, e.g. the percentage of time in June during the period of record that daily discharge exceeded 2,000 m^3/s. These data are provided for discharge, sediment concentration and load.

D3: peak period statistics, subdivided by year, e.g, the dates during 1983 corresponding to the highest sediment load in any 4 day period (1% of the year) and the magnitude of that load. This type of data is provided for discharge, concentration and amount of suspended load.

Unfortunately, because of gaps in certain winter periods, the data in Appendix D do not cover the full period 1950-1986, and, in effect, they simply represent a larger sample than the 1971-86 data.

The best use of Appendix D in the present context is found in the peak period statistics (D3). Data are provided for the highest 37 day (continuous) water discharge (10% of the annual period). As can be seen from Fig. 11, the top 10% of daily flows in the year (though not necessarily the highest continuous 37 day flow period) accounts for approximately 60% of the annual load in the average year. Referring to Appendix D3, the mean discharge in the highest 10% flow period during the 16-year period of sampling was 3650 m^3/s; this compares with 3722 m^3/s in the available 31 years of data between 1950 and 1986. The sampling period flow rate is 1.9% less than that of the longer period, an insignificant difference.

Reference to the raw historical flow data of Appendix B1 allows comparison with the full 37 year data between 1950 and 1986. In terms of maximum daily discharge, the mean for the sampling period was 4582 m^3/s, 2.2% less than the mean for the full 37-year period of 4687 m^3/s. On the other hand, reference to the mean discharge during the four month April-July period, shows that the mean for the sampling years was 2709 m^3/s, 4.2% higher than the 2600 m^3/s for the full 37 year period. As Figs 12 and 13 indicate, these four months dominate both the discharge hydrograph and the annual suspended load.

Overall, the general impression is that the sampling period is indeed representative of the longer period for which hydrometric data are available at Marguerite. This was also the conclusion for the post-1971 sampling period at Hansard in comparison with the post-1952 discharge data.

The other question that remains, however, is how representative the 37-year period of hydrometric data at Marguerite is in relation to a longer definition of "present-day" conditions. At Marguerite, there is clearly no way to assess this point. However, flow data have been collected on the Fraser River at Hope, downstream of the Thompson confluence, since 1912, and can be used to make some inference on this point. Church et al. (1987) have examined data for mean annual flow at Hope, and noted that, since 1957, it has been persistently higher than in the period prior to that time. The same observation was made in relation to annual maximum daily flow, the changeover point in that case being 1948. Similar conclusions have been reached for other hydrometric stations in southern British Columbia (Barrett, 1979) and attributed to a change in the atmospheric circulation.

Thus, though the sampling period at Marguerite appears to be representative of post-1948 conditions, the water discharge during the sampling period (and by inference the sediment load) was above average compared to the full post-1912 period. The probability of a decrease in discharge and loads in the future, if meteorological patterns revert to those of the first half of the twentieth century, should not be overlooked.

4.3 Suspended sediment regime

As already noted, sufficient data have been gathered to indicate that the present mean annual suspended load of the Fraser River near Marguerite is close to 10.1 million tonnes. On the other hand, there is no guarantee that discharge conditions in the future will remain the same as in the 16-year sampling period, and it would be useful to establish whether or not suspended loads are capable of prediction from discharge data. In this way, because hydrometric data will continue to be gathered at this station, estimates of suspended load can continue to be made, even though the sediment sampling program has been curtailed. (It must be recognized that major changes in land use would affect the prediction of sediment loads from discharge.) The data for addressing this problem are summarized, graphically, in Appendix E.

The plots in Appendix E are called sediment rating curves: they are graphs of sediment concentration plotted against discharge. The first set of plots refers to annual mean concentration and annual mean discharge for the 16 years. The second set deals with monthly mean values. And the third set focusses on daily mean values, using only those days for which sediment was actually sampled.

Reference to Appendix E1 shows that the relationship between annual mean suspended concentration and annual mean discharge is not strong, and would seem to be unsatisfactory for prediction purposes. The plot of annual suspended load against annual discharge for the 16 years seems to be only slightly better, but the appearance of large scatter is illusory, being influenced by the annotation by year. In fact the coefficient of determination is 77 percent, a reasonably strong correspondence. Church et al. (1985) analyzed the sediment rating curves for Marguerite and other Fraser River stations in some detail (their Appendix 1), and concluded that annual sediment ratings were certainly good enough for estimate of reservoir life or long term regional sediment yields. In fact, applying the annual rating curve for Marguerite (their Table A1.13) to the daily flow data for 1974-1982 provided a mean annual load for the period virtually identical to that determined by the WSC method.

On the other hand, estimation of loads for individual years by the annual rating is not as satisfactory, and attention should therefore be turned to the feasibility of using - for any given year - the sediment rating curve <u>for that year</u> based on daily mean, or monthly mean, values, applied to the flow duration data. In the event that sediment sampling is completely abandoned, but discharge-monitoring continued, application of the <u>long-term</u> sediment rating curve to the discharge data for a given year would provide a means of estimating loads in future years.

The composite plot for all <u>daily</u> mean values in the period (Fig 14) shows considerable scatter. However, there is no real segregation on the plot according to the year of data, suggesting that the regression line itself (the sediment rating) has remained relatively stable during this time period. This is generally confirmed by examination of the individual regression equations for each year (marked at the base of the figures in Appendix E3), although (as previously noted by Church et al. (1985), Table A1.16) the regression slopes for 1978 and 1980 are significantly gentler than the rest, while 1971 is somewhat steeper. The overall stability of the sediment rating is also supported by the plot of cumulative annual suspended load versus cumulative annual discharge (Fig 15) which, apart from minor oscillations, shows no real departure from a linear trend during the period.

The major problem with the daily sediment rating curve is clearly the fact that, for the same discharge, sediment concentrations vary appreciably according to the month of the year. This point is evident on most of the annual time charts of discharge and concentration in Appendix C4. It is also shown consistently on the sediment rating plots for 1971 through to 1986; and is nicely summarized on the plot of monthly mean concentrations against monthly mean discharge (Fig. 16). The points for March and April regularly show the highest positive residuals, followed by points for May and June. Points for days in other months tend to fall below the regression line. The implication is that sediment is more available, or more readily entrained, in the early parts of the year (Fig. 17). Whatever the reason, superior predictions of the load in any year of sampling (and any future year without sampling) would be obtained by using separate regressions for each month of the year.

Church et al. (1985, Appendix 1) tackled this problem in a slightly different manner, using a "shifting" rating curve, i.e., the relationship $c=aQ^b$ is assumed valid, and b is a constant through the year, but the value of "a" varies from one sampling day to another. For days without sampling, the value of "a" is obtained by linear interpolation between the nearest sampling days, and the value of c estimated accordingly. The results for Marguerite (their Table A1.15) showed good agreement with the WSC loads for the years 1971 to 1982, based on only 10 to 20 sampling days, and substantially better than the ordinary rating curve (fixed "a") with the same number of samplings. The results offer a new, more efficient method of monitoring short term sediment loads (monthly, annual) over a long period of time. However, the method is obviously not applicable to future years if the sampling program at a station is completely abandoned, and predictions would have to be based on the long-term sediment rating already available, stratifying the data by month of the year to improve accuracy.

Finally, it should be remembered that logarithmic regressions provide biased estimates of the untransformed dependent variable. In other words, although the <u>logarithmic</u> residuals approximately "balance" the least squares line, after anti-logging the <u>actual</u> residuals above the curve are much greater than those below it (Ferguson, 1986). Suspended loads would thus be underestimated by the conventional rating approach; they would need to be increased by an amount dependent upon the standard error of estimate of the logarithmic rating equation (Smillie and Koch, 1984; Ferguson, 1986).

International Power and Engineering Consultants Limited used the 1971 Marguerite sediment rating data to estimate what the mean annual suspended load at the site would have been in the years 1953-1971 (BC Energy Board, App. XV-F). Their estimate was 15.0 Mt. No comparable prediction has been made using the 1971-1986 regression data, but the IPEC estimate is 50% higher than the 1971-1986 suspended load computed by the WSC procedure (Section 3.4.1). Reference to App. E3, and to Church et al. (1985, Fig.A1.2, Table A1.16), shows that, for flows greater than about 2500 m^3/s, the 1971 regression line is well above average, in fact the highest in the 1971-1986 period. Thus the 1971 sediment year, while representative in terms of its annual suspended load, was unrepresentative in terms of its sediment rating. The continued sampling at this site by WSC can therefore be considered useful in terms of substantially revising the estimate of mean annual suspended load put forward by IPEC.

Though the primary purpose of suspended sediment sampling at Marguerite was computation of mean annual suspended load, other aspects of suspended sediment transport are of interest. Pretious (1979), for example, emphasized the problem of sediment accumulation in fishways in the Fraser River canyons during freshets. Similarly, fisheries managers may be interested in knowing the amount of time in a certain month of a year that the sediment concentration exceeds a particular level deemed deleterious to fish stock. Such duration data, whether they be for the full duration or only peak periods, are provided in Appendix D for reference purposes.

4.4 Bed load transport

A prelimary estimate of bed load transport was made by Peterson (1971) based on the first year's sampling at Marguerite. No additional calculations have been made by WSC since that time, given the uncertainties already noted. The following analysis must also be viewed with caution for the same reasons.

The 1971 estimate was based on a regression between bedload transport rate during the seven sampling periods in that year and the corresponding water discharge. The coefficient of determination was 0.92. The regression was then applied to the mean water discharge of each day, thus providing an estimate of each day's bed load. The total amount predicted during the period January 1 to November 13 was of the order of 800,000 tonnes. Suspended sediment data for the same period are not available, but the total suspended load for the period May 1 to December 31, 1971 amounted to 8,920,000 tonnes, indicating that bed load accounted for about 8 % of the total load in that year.

The 1971 bedload rating line was applied to the discharge data for 1953-1971 by IPEC for the BC Energy Board (1972) to indicate a probable long-term average annual bed load of 1.02 Mt.

Bed load transport rates at times of sampling between 1971 and 1975, together with water discharge, are shown in Table 4. Sample data for the years 1976-1979 have not been integrated by WSC to give total cross-section rates. In any case they would be of limited value, being based only on the Arnhem sampler, even though flows at the time of sampling would have been transporting gravel (Table 4). The data are plotted in Fig. 18 and compared with the 1971 data; separate regression lines are provided for the two sets of data, as well as for the composite set. Only those days for which sampling of gravel (using the basket sampler) was undertaken are plotted: on four of these occasions, the Arnhem sampler was not used, but these were at high discharges. The unpublished values of load for 1972-1975 have been multiplied by 3.0, before plotting, to adjust for sampling efficiency, as done by WSC for 1971.

The graph (which shows rather more scatter than the 1971 data) suggests that the 1971 line was strongly influenced by one particular sampling day: November 9th. As a consequence, it would have overestimated loads at flows less than 3500 m^3/s, while underestimating them at higher discharges. Examination of the raw data for November 9th indicates that, although sampling was done at five verticals, sediment was caught at one vertical only. Moreover, the three samplings at this vertical, all done for 3 minutes, produced bedload catches of 37, 123, and 4357 gm, indicating that the total load for the full channel width was probably overestimated because of one abnormally high sampling yield.

It is difficult to evaluate the effect of this error, in the 1971 regression, on the estimates made for the long-term average bed load, without applying the new regression to the full discharge data set again: overestimates in using the 1971 equation at low flows are to some extent countered by underestimates at high flows. It is true that the 1971 equation would have produced consistent <u>under</u>estimates because it was not corrected to eliminate the bias when converting from logarithmic regressions back to the non-logarithmic values Ferguson (1986), but the correction needed is very small because of the little scatter in the 1971 data. The 1971 regression ($r^2=0.92$), converted directly to power function form and corrected for bias, is:

$$L = 2.36 \times 10^{-7} \quad Q^{3.00}$$

for bedload (L) in tonnes per day and discharge (Q) in m^3/s. The overall regression for the 1971-1975 years, after excluding the November 9th point, has a coefficient of determination of 0.74 and yields, after correction for bias:

$$L = 5.91 \times 10^{-13} \, Q^{4.61}$$

The two equations have been applied to the daily flow data for the years 1971-1982 (Tassone, 1988, pers. comm.) and the results summarized in Table 8. The revised mean load for the period of 1.5 Mt per year is 50% greater than that based on the 1971 data alone.

For comparison, the bed load estimated in this way at Hansard was only 53,000 tonnes, substantially less than the IPEC estimate at Marguerite of about 1 Mt, and the new estimate of 1.5 Mt. The ratio of bed load at Marguerite and Hansard (28:1) is much higher than the ratio of the suspended loads (4.4:1). Bearing in mind the steeper river gradient at Marguerite, an increase in bed load is not unexpected, but the magnitude of the increase is surprising. Downstream of Marguerite, McLean and Church (1986) estimated the mean annual bed load at Agassiz (for gravel size sediment) to be 0.174 Mt, which is almost an order of magnitude less. The discrepancy is surprising given the apparent similarity in the channel at the two sites: slope at Agassiz is given as 0.00048, and median size of bed material is reported as 42 mm at the surface and 25 mm beneath.

A detailed analysis to ascertain the reason for the much higher bedload at Marguerite, compared to Agassiz, is beyond the scope of this station analysis. A few points should, however, be noted. Firstly, the mean gradient between Prince George and Marguerite (0.00064), though comparable with that at Hope, is steeper than that at Agassiz. Some aggradation between Hope and Agassiz must therefore be anticipated, though the preliminary analysis by McLean and Mannerstrom (1985) indicates this to be minimal. Secondly, considerable abrasion of coarse gravel would be expected in the gorge downstream of Marguerite, depleting the gravel load, and augmenting the finer fractions. Data from New Zealand (Adams, 1980) indicate rapid losses of gravel mass even in fully alluvial gravel rivers.

Thirdly, there remains the possibility that one, or both, of the bedload figures is in error. In the case of Marguerite, the precision of the bedload rating curve (as indicated by the r_2 value of 0.74) is reasonably good, but systematic errors might exist which inflate the catches. Tassone (1988, pers. comm.), for example, believes that sampling from the cableway may have led to scooping of extra bed material during sampler retrieval. Examination of the raw data files also indicates considerable uncertainty in the interpolation of local transport rates between sampled verticals across the channel: in many cases, especially at high discharges, peak local bedload transport was inferred to occur between sampling verticals at a rate substantially above the rates at the nearest verticals. This would have contributed to a systematic overestimation of total bedload through the cross section, and thus biased the bedload rating curve upwards.

4.5 Particle size

4.5.1. Suspended sediment

The particle size distribution of the suspended sediment is relevant in assessing trap efficiency of any proposed Moran Reservoir, consolidation of the trapped sediment, and, particularly, in assessing implications of the depletion in sediment supply to the lower Fraser River.

Particle size data are available for 339 depth-integrated samples at this station. Of these, 37 refer to mean values for the cross-section, obtained by averaging the distributions collected at the five verticals during R-sampling periods. The rest of the data originate from the single sampling vertical.

The data collection is summarized, by year, in Table 6. The purpose of the R-samples is to provide a calibration for the single-vertical data. Unfortunately, the R-samples obtained in the earlier years were not taken at times when samples from the single sampling vertical were analyzed for particle size distribution. Their value is therefore limited. Data which refer to more or less concurrent R and K-sampling (within one or two hours and at essentially the same discharge) are summarized in Table 7.

It can be seen from this table that there is a consistent tendency for the daily K sample to be coarser than the average for the cross-section. The table indicates that these K samples also have higher concentrations than the corresponding R samples, so that this subset of data is consistent with the total data set in which the k-coefficient (Section 3.3.1) was generally less than unity, especially at high flows. The higher concentrations at the single sampling vertical seem to be primarily due to extra sand: concentrations of silt and clay are not systematically different between the K and R-samples. Thus while the single sampling vertical is representative of the wash load, it has higher sand concentrations, presumably because it was located on the shallower bar area (Fig. 5): in the thalweg, it is unlikely that there would be much bed material fine enough to move in suspension.

At flows above 2610 m^3/s, the R-samples in Table 7 average only 0.80 of the percentage sand in the K-samples, and average only 0.84 of the total suspended concentration. This k-coefficient is comparable with those previously noted for the high flow season in Table 2, and suggests that the subset is reasonably representative. In other words, the percentage sand fraction in the K-sample data should be reduced by multiplying by 0.8 to make it more representative of the cross section as a whole.

The summary data for particle size distribution are included in Appendix F. The salient points for suspended sediment are as follows:

a. median particle size for the K-samples ranges from 0.02 mm at low flows to 0.2 mm at high discharges;

b. percentages of silt-clay in K-samples range from almost 100 % at low flows to less than 40 % at high discharges;

c. clay size sediment (<4 µm) generally accounts for about 20 % only of the silt-clay fraction, though no anlaysis has been done of the variation in this percentage;

d. data for mean values of percentage clay, silt, sand are of limited value, unless based on separate computations of annual load for the three classes, which have not been calculated;

e. mean values for the sand fraction during the months of May and July, i.e. before and after the hydrograph peak, during 1971-1974 (in which sufficient samples were taken to allow comparison) are 41% and 38%, respectively, compared to mean monthly discharges of 3422 and 3065 m^3/s, indicating little change between the rising and falling limbs of the main spring flood;

f. samples analyzed for particle size have been collected in flows ranging from 1000 m^3/s to 7000 m^3/s, i.e. through the full range of sediment-transporting flows;

4.5.2 Bed load

Particle size data were collected for bed load samples on 35 days between 1971 and 1979 as indicated in Table 4.

The resultant data are shown in Appendix F, though the WSC printout does not include 1971 and 1972, and omits some other dates on which samples were taken. Appendix F provides, for a given day, separate particle size distributions for the Arnhem and basket samples. Each represents the mean grading curve based on samples collected at several verticals (up to five); although raw data are available for the particle size distribution of the individual verticals, in combining them to obtain a mean value, the verticals were not weighted according to the local transport rate, i.e. the data are simple means.

The data of the last four years, when only Arnhem samples were collected, are of limited use. The Arnhem sampler is designed to sample medium and coarse sand and fine gravel. In the late seventies, it was used in gravel-moving conditions with maximum particle sizes in the range 32 to 64 mm. These grading curves should therefore be ignored.

The data for the basket samples were remarkably consistent with median particle diameter ranging - with one exception - from 19.6 mm to 27.0 mm, averaging 23 mm. The exception was a high value of 37.8 mm (1974 May 15 at 0430 hrs). However, this represents the data from a single sample at a single vertical, and contrasts with the mean basket sample 45 minutes later based on five samples drawn from two verticals.

The data for the pre-1976 Arnhem samples indicate an average median grain size of 0.33 mm. The average value of median particle diameter for the sand fraction of the suspended load has not been computed, but the data indicate a range from 0.09 mm to 0.45 mm. Much of the sandy bed material clearly moves in suspension, and given that the sand fraction of the sampled suspended load averages about 40 % during May-July, some concern must be raised about the magnitude of the unsampled sediment load. This term was introduced by Colby (1957) to denote that part of the suspended load that cannot be sampled because the sampler, in traversing a sediment vertical, cannot access that part of the flow closest to the bed. There is no simple means of estimating this without velocity data at the time and point of sampling (see Colby, 1957); it must simply be recognized that the indicated loads are minimum estimates, although, as previously noted, it is believed by WSC that the degree of underestimation is small.

In terms of the particle size of the overall bed load, some attempt must be to assess the relative proportions moving as sand and as gravel. Indeed, in terms of downstream impacts, this is just as important, if not more so, than the particle size distribution within the two categories. The existing data have not been analyzed by WSC to determine these proportions, but some indication is obtained by comparing the relative contributions of the Arnhem samples and the basket samples to the total bed load. Even this is difficult without first integrating the local bedload transport rates (for the two samplers separately) over the cross-section. On the other hand, comparison of basket data with Arnhem data in 1971 indicates that the local transport rate in the basket samplings exceeded those of the Arnhem sampler by one or two orders of magnitude. And, except for the low flow sampling of 14 September, 1971 (1586 m^3/s), the sand bed load would seem to have accounted for less than 1 % of the total bed load. In other words, virtually all of the sand moving at this site moves in suspension; and almost all of the bed load is gravel.

4.5.3. Bed material

No particle size data for bed material were originally available at this site (see Addendum), but, in the context of the original purpose of the program, this is probably unimportant.

In terms of reservoir life, what matters is particle size of the moving sediment. In terms of downstream impacts, what matters is the bed material at sites downstream, both immediately downstream of a possible dam, and further downstream in the lower Fraser and delta areas. Impacts downstream would then depend on the annual loads at Marguerite of those size fractions which constitute bed material at downstream locations. What is important at Marguerite, therefore, is information regarding the particle size distribution of the suspended and bed load. This information is available.

On the other hand, in other contexts (e.g. fisheries) it would be useful to have data on particle size of bed material at Marguerite (and its variation through the cross-section) in order to characterize local habitat. Such data would also be useful in any testing of bed load formulae at this site.

4.6 Reservoir life

IPEC (in BC Energy Board, 1972) indicated the capacity of the Moran Reservoir to be 6900 million cubic metres of dead storage and 7900 million cubic metres of live storage. They assumed that the trap efficiency of the reservoir would be 100 percent; that all of the trapped sediment would be deposited within the confines of the reservoir; that the total sediment load would average 16 Mt per year; and that the sediment would consolidate to a bulk density of 1.3 t/m^3 in the case of the suspended load, while bed load would accumulate at 1.5 t/m^3. Their calculations indicated that dead storage would be filled by sediment in 600 years; and that total storage would be depleted in 1300 years.

Based on the same assumptions, but using a revised total sediment load of 11 Mt per year as estimated for 1971-1986, the life expectancy would be increased as follows: a volume equivalent to dead storage would be lost in about 900 years, and a volume equal to total storage would fill with sediment in about 1900 years.

None of the assumptions can be claimed to be completely accurate (and certainly there is no reason to believe that the load will stay at 11 Mt per year in the next millenium), but the data clearly support the view that loss of storage capacity by sedimentation is not a serious issue here.

4.7 Sediment sources

Identification of sediment sources is difficult given the paucity of relevant data. Comparison with the suspended load for the Fraser River at Hansard indicates that during the period 1976-1980 (the only years at Hansard with full sampling through the year) the annual suspended load at Hansard averaged only 2.31 Mt, compared to 10.3 Mt per year at Marguerite, during the same period. It is true that the specific yield (annual load per unit area) is not appreciably different between the two sites: 128 t/km^2 at Hansard and 103 t/km^2 at Marguerite (ignoring the area above the Kenney Dam). On the other hand, a large portion of the basin above Marguerite is relatively gentle plateau, in contrast to the basin at Hansard.

Examination of topographic conditions upstream of Marguerite would suggest that much of the remaining 77% probably originated in the steep catchment of the McGregor River. On the other hand, as indicated in Section 4.4, the bed load at Marguerite is also substantially greater than that at Hansard. It is unlikely that much of this extra bed load originated in the McGregor catchment, given that a large part of it is gravel, and that the gradient of the Fraser River downstream of the McGregor confluence continues to be very gentle (Section 2.4).

By inference it would seem that much of the sediment load at Marguerite originates in the tributary rivers of the Interior Plateau (particularly the West Road River) and from the channel boundary of the Fraser River, itself, downstream of Prince George. Pretious, writing for the BC Energy Board (1972), came to a similar conclusion: "from Prince George to Hope, the Fraser River cuts ... through deep glacial deposits of unconsolidated gravel, sand, silt and clay. In this stretch, the river probably picks up most of its sediment load." The substantial input of suspended sediment between Hansard and Marguerite, and the difficulty of quantifying these sources, should be borne in mind in any development of intervening tributaries, such as the Nechako. The only tributary sediment station in the Fraser basin in the Interior Plateau is the new one on the Chilko River near Redstone (08MA001), and it would be useful to undertake a preliminary examination of its data in order to assess its load and yield.

5. PROGRAM EVALUATION

5.1 Estimate of mean annual suspended load

The primary purpose of the Marguerite sediment program was estimation of present day sediment loads in the vicinity of the possible Moran Reservoir. The data collected for suspended sediment to date are quite sufficient for that purpose, and necessitate a revision of estimates made by the BC Energy Board (1972).

The mean annual suspended load between 1971 and 1986 was 10.1 Mt, with a standard error of slightly greater than 10 percent. The 1971-1986 years appear to be representative of the post-1950 conditions, based on a comparison of discharge data in the 16-year sampling period with the 37-year period of hydrometric monitoring at the station. On the other hand, analysis of hydrometric data at Hope indicates that discharges in the post-1950 period have been significantly higher than in the first half of the century; hence the WSC estimate may be too high for the long-term rate.

Estimates of the long-term suspended load at the site were previously made by International Power And Engineering Consultants Limited and E.S. Pretious for the BC Energy Board (1972). The latter suggested a figure between 12 and 17.4 million tonnes, based on data from Lillooet in 1951 and 1952, and compared with sediment data from Hope for 1950-1952 and 1966-1968. The figure is higher than the 10.1 Mt estimated here for the Fraser River at Marguerite, but this would be expected given the inputs from other sources in the intervening reach.

The estimate by IPEC (15.0 Mt/yr) was based on the 1971 regression between daily load and water discharge, applied to the 1953-1971 discharge record at Marguerite. The overestimate appears to be partly due to the fact that the sediment rating equation for 1971 was, by chance, the steepest in the 1971-1986 period, overestimating loads at high discharges.

5.2 Estimate of mean annual bed load

Only limited data are available for annual bed load. Water Survey of Canada estimated the 1971 load to be slightly in excess of 0.8 Mt. IPEC (BC Energy Board, 1972) applied the 1971 regression between bed load transport rate and discharge to the 1953-1971 flow data and obtained a value of 1.02 Mt, not radically different.

The 1971 regression was based on only seven points (the lowest of which is extremely dubious) and almost certainly underestimates the regression slope. The new data set of 22 points (excluding the suspicious 1971 point) provides a radically different regression for which flows greater than 3500 m^3/s yield higher bed loads. At 5,000 m^3/s, the 1971 underestimate is 50%: 30,000 tonnes per day, compared to 60,000 t/d. The new regression has been applied to the flow data for years between 1971 and 1982, and indicates annual loads ranging from 0.18 Mt to 4.0 Mt, averaging 1.5 Mt. This is almost ten times the annual gravel load downstream at Agassiz. However, various facets of the bedload sampling program indicate that the Marguerite values are almost certainly overestimates, by amounts that are difficult to assess, of the real bedload yields.

5.3 Estimate of reservoir life

The revised estimate of annual sediment loads implies that loss of reservoir storage due to sedimentation would occur even more slowly than the rate estimated by the BC Energy Board (1972). Using the same assumptions made in that report, but with a revised mean annual load of 11 Mt for combined bed and suspended material, a volume equal to dead storage would not be lost through sedimentation for 900 years, and it would take about 1900 years to deplete the total storage volume. On the other hand, if actual annual bed loads are as large as indicated by the rating analysis, major regime changes would take place upstream of any reservoir, with rapid delta growth and aggradation upriver.

5.4 Sources of sediment

Only 20-25 percent of the suspended load at Marguerite, and only 5 percent of the indicated bed load, originates from the Fraser River upstream of Hansard. No data have been analyzed to quantify the sources of the sediment added between Hansard and Marguerite. Some data are available, however, for suspended loads at other stations in the upper Fraser Basin, and these should be examined for that purpose. Most of the bed load is probably derived from the steepened part of the main stem of the Fraser itself, downstream of Prince George, but no data exist which would allow verification of that conjecture.

5.5 Assessment of downstream impacts

Assessing downstream impacts requires detailed knowledge of sediment and hydraulic conditions at the various downstream sites of concern; it is beyond the scope of this review. Nonetheless some comment is necessary regarding the adequacy of the data from Marguerite for this task.

In addition to annual sediment loads, the essential information needed from this site is the breakdown of the load into different size fractions. The navigation channels of the Main Arm and the North Arm of the Fraser Delta, for example, are primarily coarse sand, of which about 2.3 Mt were dredged annually in the early seventies (BC Energy Board, 1972; App. XV-D, Part B). Assessment of the impact of possible sediment trapping in a reservoir at Moran would thus require data on annual loads of this specific size fraction.

Sufficient particle size data are available at the Marguerite site for these various purposes, but they have not been analysed by WSC to produce loads by size fractions. Casual inspection of the data (Fig. 18) indicates that, at high loads, sand (0.063 mm - 2.0 mm) may account for up to 50% of the suspended load (after correcting for the bias at the sampling vertical), but probably nearer to 40%, or slightly less, overall. This would amount to an annual load of the order of 4 Mt for the sand fraction.

Sediment transport and bed material in the lower Fraser River between Hope and Port Mann have been investigated in detail by Church et al. (e.g., 1987). At the Mission site they indicate an annual suspended sand load between 1966 and 1982 of 6.25 million tonnes. The implication is that a considerable part of the sand load of the lower Fraser originates upstream of Marguerite, and it would be worthwhile to undertake a separate calculation of the annual load of the coarse sand fraction to define this contribution more accurately.

Similar partition of the rest of the suspended load at 08MC018 into fine sand, silt and clay would be useful (in relation to impacts further downstream, in backwater areas, and offshore), but may not be as simple to undertake. This will depend on how systematically the percentage of the sediment in these size fractions changes with discharge. The finer fractions may show much more scatter in their relationship with discharge.

5.6 Recommendations

(a) There are four recommendations made below. The first two should be addressed in the near future.

5.6.1. Sampling of bed material for grain size analysis

A bed material sampling program at the site would need to precede any field bedload program. Even if additional bedload investigations are not undertaken, however, a bed material sampling program would be useful in assessing how much of the bed material actually moves as bed load and in suspension. Comparison of sediment transport and channel conditions with sites on the lower Fraser, e.g. Hope and Agassiz, is hampered at the present time by the absence of such data. (See Addendum)

Ideally samples would be taken at the verticals previously used for bed load sampling, and at different times of the year, bearing in mind the seasonal pattern of scour and fill shown in Fig. 5. Whether this is practical will depend on availability of bed material sampling equipment.

5.6.2. Verification of bed load transport data

Given the high bedload volumes indicated for Marguerite by the bedload rating curve (28 times greater than at Hansard and 9 times greater than at Agassiz), and given the morphological impacts that would result from trapping of such a large load by any dam near this site, there is clearly a need to assess the accuracy of the bedload data more fully than has been possible in this report.

In particular, most of the analysis undertaken here has been based on calculated results taken from WSC files; there would seem to be some justification for a closer analysis of the raw data involved in these calculations, paying special attention to issues such as errors at individual sampling verticals and interpolation between such verticals. Sampling equipment and sampling procedures should also be reviewed for possible sources of error.

Depending on the results of the above analysis, it might be necessary to carry out a field test of the bedload rating by undertaking a short, but thorough, bedload sampling program at this site during high flow. Sampling on two or three days, with flows greater than 3,500 m^3/s, would not be sufficient to construct a new bedload rating curve, but would provide an important check on the existing rating.

By limiting sampling to just a few occasions, scope is allowed for detailed replication at a vertical (up to about 12 times, rather than 2 or 3) and an increase in the number of verticals (up to about 8, in effect, doubling the number of "active" verticals). Sampling from a boat, rather than the ferry, may be necessary to eliminate concerns regarding bed material scoop on retrieval of the sample.

(b) The following two recommendations do not require immediate consideration but should be addressed prior to any largescale development in the basin.

5.6.3. Determination of annual suspended loads for individual grain size classes

In light of the previous comments dealing with downstream impacts (5.5), it is clear that separate estimates of the annual suspended loads of the various size fractions (coarse sand; medium and fine sand; silt; and clay) would be very useful to agencies working on the lower Fraser. Such information on annual loads by particle size class would be invaluable in assessing sedimentation rates in different environments downstream and offshore, and in estimating fluxes of both nutrients and contaminants (which adsorb preferentially to the fine fractions) to the lower Fraser river area.

Sufficient data exist to undertake such an analysis; and the cost of such work would be minimal compared to the effort already undertaken in the Marguerite sampling program. Even if a dam is not built in the Moran Canyon, knowledge of the contribution of the upper Fraser basin to the the annual loads of different classes of sediment in the lower Fraser is basic to any proper management of the Fraser River catchment.

5.6.4. Regional assessment of suspended loads in the upper Fraser River basin

The marked increase in annual suspended load between Hansard (2.3 Mt) and Marguerite (10.1 Mt), in a relatively short length of the Fraser River, warrants further study to identify the sources of this sediment. Admittedly the load per unit area of catchment is essentially the same at the two stations, yet this itself is surprising, given the contrast in relief of the two catchments. The large number of lakes in much of the basin above Marguerite, and the gentle plateau terrain, would seem to imply that much of the load at Marguerite originates in localized river reaches.

Given the large contribution of the Fraser River at Marguerite to the load of the lower river, identification of these sources would seem to be important prior to any largescale development, land use change or inter-basin water diversion in the catchment upstream of Marguerite.

Limited data already exist in fact for several other stations on the main stem of the river upstream of Hope, and it would be useful to undertake a synthesis of these data. The data concerned were collected in the early 1950's by the Water Rights Branch of the BC Dept. of Lands and Forests at Quesnel, Big Bar

Creek and Lillooet (which do not have WSC sediment programs) as well as Marguerite and Hope (for which WSC sediment data are available). Though data are available for only 3 years, their long-term effectiveness could be improved by comparison with the data for Marguerite and Hope, for which long-term records exist, as already noted. More recent data (e.g. WSC sites on the Chilko River) should be included where available.

Such a synthesis would, clearly, not compare in scope or detail with that of the Lower Fraser (Church et al., 1987), but would provide a useful identification of sediment sources on this important part of the main stem, and would assist in planning any future studies of sediment delivery from the upper Fraser Basin, and any new sediment stations there.

5.7 Conclusion

The sediment data collection program at Marguerite has met the original program objectives, and the decision to reduce the program in 1986 was justified.

The importance of the station at Marguerite is, however, probably greater than indicated in the original terms of reference for the sampling program begun in 1971, i.e. in connection with a possible dam in the Moran Canyon. Its real significance, today, lies in the data that it provides in the context of sedimentation in the lower Fraser River. How much of the sand dredged from the navigation channel originates in the upper basin? How much of the nutrient and contaminant loads originate there? What are the sources, within the upper basin, of this sediment load?

To some extent, the data collected by WSC have not been processed sufficiently to answer these questions, yet enough data are generally available for that purpose. This is the reason for the recommendations made above.

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ADDENDUM: BED MATERIAL GRAIN SIZE DATA

In response to Recommendation 5.6.1 (p. 46), a bed material sampling program was undertaken by staff of WSC at six sites on the Fraser River near Marguerite (Fig. 20) on 5-6 October 1988.

Sampling was done on exposed parts of the bed in three areas: an island bar at the bend exit zone just upstream of the ferry (Site 2 at bar head; Site 1 at bar tail); at the upstream end of a lateral bar attached to the right bank of the channel downstream of the ferry (Site 5 near bank; Site 6 near to water's edge); and at the head of an island bar approximately 9 km downstream of the ferry (Site 3 near water's edge; Site 4 near left bank).

Photographs taken at the time of sampling (Figs. 21, 22) show that the bar-tail Site 1 was veneered with considerable fine sediment (< 2 mm) unlike the bar-head Site 2. Sites 5 and 6 had little fine sediment at the surface. The surface gravel at Sites 3 and 4 also contained little fine sediment; oblique photographs of this downstream island bar indicate, however, a much darker tone on the bar tail (unsampled) suggestive of fines.

Two main methods of sampling were undertaken at all four sites on the island bars:

(a) sampling of surface gravel (> 8 mm) using a grid by number (GBN) approach (Yuzyk, 1986, p.22);

(b) bulk sampling of subsurface sediment (bulk by weight:BBW) as described by Yuzyk (1986, p.17).

The two methods have been shown theoretically to yield comparable results (Kellerhals and Bray, 1971).

The GBN method involved measurement of b-axis length on 100 clasts. At Sites 1 to 4, this was done over a distance of 15 m at 15 cm intervals. At Sites 5 and 6, sampling was done over a distance of 15 m also, but using two parallel tapes (1 m apart) with clasts picked at 30 cm intervals on the tape.

The BBW method for the subsurface sediment involved scraping off the surface layer to a depth equal to the length of the largest clast found on the surface. About 100-150 kg dry mass were removed in this way, and a similar amount was taken from the subsurface. This was bulk sieved in the field down to the 8 mm sieve. The material passing the 8 mm sieve was returned to the laboratory for sieve analysis down to 0.062 mm.

At Sites 1,2 and 4, similar sieve analysis was done on the scraped surface sample. These BBW surface data are particularly important because they allow direct comparison with the subsurface data. Comparison of the GBN surface particle data with the BBW subsurface data is difficult because the former refer to clasts spread over a length of bar 15 m long, while the subsurface sample was taken from an area less than one metre square. Thus comparison of the two sets of BBW data allows some inference regarding the degree of armouring and paving of the gravel bed; the GBN data, while they cannot be used for this purpose, probably provide a better estimate of average gravel conditions in the bar area than does the "point" BBW sample.

It should be emphasized that the scraped surface sample was not an "areal" sample (Yuzyk, 1986, p.28) and thus should not be corrected for the bias associated with areal sampling. It is also not a true surface sample because it contains some clasts not actually exposed at the bar surface.

The resultant data are summarized graphically in Appendix F4. There are four plots:

F4.1: size distribution of the three surface bulk samples;
F4.2: size distribution of the four subsurface samples;
F4.3: size distribution of the surface gravel GBN sample;
F4.4: comparison of size distribution curves for the gravel only (>8 mm) as represented by both GBN and BBW surface data and BBW subsurface data.

The data for the four island bar sites are summarized in the two tables below.

	Median gravel size (mm)		
	Surface		Subsurface
	GBN	BBW	BBW
1	26	27	24
2	34	38	31
3	38		33
4	28	35	33
Mean	32	33	30

TABLE A1 GRAVEL DATA (>8mm)

	Percent less than 1 mm	
	Surface	Subsurface
1	14	14
2	5	14
3		11
4	5	14

TABLE A2 AMOUNT OF FINE SEDIMENT

The following points are worth noting:

1. The values for percentage by weight finer than 1 mm in the subsurface bulk samples (Table A2) are quite consistent and indicate, for Sites 2 and 4, a definite armouring of the surface (in the sense of Bray and Church, 1980) due to the winnowing of fines. The higher content of fines indicated at the surface of Site 1 is consistent with the visual observations noted above.

2. The suspended sediment data (described earlier in the report) show that grains occur in suspension up to a size of 1 mm. The implication is that, at high flows, about 14% of the bed sediment moves in suspension, the rest being transported as bed load.

3. Comparison of the two methods of sampling surface gravel (Table A1) indicates a tendency for the BBW sample to be slightly coarser than the GBN sample, though this is only really significant at Site 4. There are several possible explanations for such a difference, but none can be discussed seriously given the small number of comparisons, and the fact that the two methods sampled different geographic populations.

4. Comparison of the surface and subsurface BBW samples (Table A1) indicates, in all cases, that gravel is coarser at the surface than at depth, though this is only pronounced in the case of Site 2. (The GBN data for Site 4 do not conform with this pattern.) The evidence suggests that the sampled bed area of the Fraser is slightly "paved" (in the sense of Bray and Church, 1980) as well as being distinctly armoured. This conclusion does not necessarily apply to deeper parts of the channel.

5. Data for clast size of gravel bed load caught by basket samplers at the ferry crossing were presented in Section 4.5.2; they indicated a median clast size in the range 20 mm to 27 mm in

different flow conditions. The sampled bed load was thus slightly finer than the bulk gravel collected during the bed material sampling program, but it should be borne in mind that the basket bed load data included 8%-11% finer than 8 mm. Restricting attention to the >8 mm size range indicates that bed load (at flows greater than 3000 m3/s) and bed material are, within the limits of sampling, essentially similar.

Sampling of surface gravel using the GBN method, but without any bulk sampling, was undertaken at Sites 5 and 6. The gravel in this lateral bar was shown to be much coarser than on the two island bars: median b-axes were 60 mm (Site 5) and 69 mm (Site 6) compared to the 26mm-38 mm range on the island bar sites. It is possible that some of this coarser gravel is derived from the channel bank.

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LIST OF TABLES

Number of days sampled for suspended sediment

	J	F	M	A	M	J	J	A	S	O	N	D	Total
1971					31	30	31	31	25	27	28	4	207
1972				30	31	30	31	31	30	31	22		236
1973			4	5	31	30	29	31	19	10	9	7	175
1974	1	1		11	31	30	30	19	3	6			132
1975	2	1	2	4	27	28	24	11	4	5	4	5	117
1976	2	1	5	8	26	16	8	17	20	14	5	4	126
1977	4	4	5	4	20	16	7	22	22	4	5	4	117
1978			6	10	21	22	21			5		4	89
1979	1	1	1	9	27	18	9	10	19	3	4	3	105
1980		1	5	13	17	19	13	15	18	7	5	5	118
1981	2	5	4	17	22	20	18	12	13	5	7	5	130
1982	2		1	8	20	17	14	12	11	5	5	5	100
1983	4	6	12	20	20	21	15	16	13	11	3	5	146
1984	7	5	6	9	15	13	13	13	10	7	1	3	102
1985			6	11	15	13	13	6	6	6	4	2	82
1986	5	5	4	10	14	17	18	15	11	6	5	4	114
Total	30	30	61	169	368	340	294	261	224	152	107	60	2096

TABLE 1

Annual summary of suspended sediment sampling program

Year	Number of R samples	min k value	max k value	date of minimum
1971	7	0.79	1.11	Jun 17
1972	7	0.68	1.13	Jun 18
1973	7	0.83	1.33	Jun 15
1974	6	0.82	1.06	Jun 14
1975	6	0.83	1.04	Jun 26
1976	6	0.74	1.02	May 26
1977	4	0.88	0.98	Sep 27
1978				
1979	4	0.93	0.96	May 18
1980	4	0.86	1.07	Jun 25
1981	7	0.86	1.08	May 27
1982	4	0.80	1.04	Jun 1
1983	5	0.92	1.18	Jun 1
1984	5	0.79	0.98	Jun 19
1985	3	0.84	0.97	Jun 11
1986	5	0.86	1.04	Sep 19

TABLE 2

Annual summary of R-sampling program

Year	Early season Max load t/day (thous)	Early season last sampling	Summer DI/Dip min	Summer DI/Dip max	Late season first sampling	Late season Max load t/day (thous)
1973			1.42	1.81		
1975			1.44	1.59		
1977			1.14	1.75		
1980	126	May 28	1.15	1.32	Nov 22	10.9
1981			0.98	1.30		
1982			1.06	1.28		
1983			1.01	1.60		
1984	80	May 24	1.05	2.20	Oct 21	2.9
1985	150	Apr 30	1.09	1.96	Nov 6	1.7
1986	104	Apr 21	0.9	1.56	Nov 10	1.4

TABLE 3

Annual summary of dip sampling program

Date	Discharge m3/s	Number of verticals Arnhem	basket	Total	Total number of samples	Bedload t/day	Particle size done ?
71.05.19	3143	1	4	5	8	7108	
71.06.07	3794	2	3	5	12	3517	B
71.06.17	4559	2	2	4	9	19142	B
71.06.28	2874	2	3	5	12	7965	A,B
71.07.22	2671	2	3	5	11	5189	B
71.09.14	1586	4	2	5	13	255	A,B
71.11.09	677	4	2	5	11	93	B
72.05.08	2637	1	5	5	13	4759	B
72.05.25	4956	0	5	5	11	51722	B
72.06.05	5041	0	5	5	13	22359	
72.06.21	4843	0	5	5	13	42294	
72.08.09	2436	0	5	5	15	110	
72.10.05	1481	5	0	5	11		
73.05.30	3200	2	3	5	12	959	A,B
73.06.11	4163	2	3	5	11	12873	A,B
73.06.25	3880	2	3	5	11	14804	A,B
73.07.17	2467	2	3	5	11	735	A,B
73.08.22	1266	5	0	5	10		
73.10.11	1025	5	0	5	10		A
74.04.24	2237	2	3	5	10	4904	A,B
74.05.15	3398	2	3	5	11	3733	A,B
74.06.18	4672	2	3	5	11	110477	A,B
74.07.04	4078	2	3	5	10	40472	A,B
74.08.16	1696	5	0	5	10		A
75.05.08	1940	5	0	5	10		
75.06.12	2537	5	0	5	10		A
75.06.26	3200	2	3	5	10	5036	A,B
75.07.17	3115	2	3	5	10	3968	B
75.08.07	1801	5	0	5	10		
75.10.06	875	5	0	5	11		
76.04.28	2217	5	0	5	10		A
76.05.26	3795	5	0	5	10		A
76.06.16	4305	5	0	5	11		A
76.08.10	3880	5	0	5	10		A
76.10.05	1473	5	0	5	10		
77.05.05	3280	5	0	5	10		A
77.06.13	3280	5	0	5	11		A
77.06.23	4050	5	0	5	10		A
77.08.11	2210	5	0	5	11		A
77.09.22	1090	1	0	1	3		
78.04.27	1570	5	0	5	15		A
78.06.08	3280	5	0	5	15		A
78.06.29	2100	5	0	5	15		A
79.04.30	2450	5	0	5	15		A
79.05.17	2810	5	0	5	15		A
79.06.21	3520	5	0	5	10		A

A denotes Arnhem sampler; B denotes basket sampler

TABLE 4

Annual summary of bedload sampling program

Year	Annual flow million dam3	Annual load (Mt)	Annual mean concentration (mg/L)
1951	38.0		
1952	41.8		
1953	37.7		
1954	47.3		
1955	43.3		
1965	50.2		
1966	50.5		
1967	55.5		
1968	55.1		
1969	43.0		
1970	41.1		
1971	45.2		
1972	55.6		
1973	44.0		
1974	51.0	14.5	154
1975	41.3	7.3	123
1976	65.1	20.4	199
1977	50.2	9.5	129
1978	36.8	5.6	115
1979	40.7	10.8	125
1980	37.9	5.1	95
1981	41.0	8.1	118
1982	49.2	13.9	165
1983	36.5	5.3	101
1984	43.1	7.6	121
1985	41.1	10.6	148
1986	41.7	10.1	122

TABLE 5

Annual summary of data, 1951-1986

Number of days sampled for particle size analysis

	Suspended load			Bed load		
	Total	K	R	Total	basket	Arnhem
1971	31	28	3	6	6	2
1972	43	39	4	2	2	0
1973	42	38	4	5	4	5
1974	38	38	4	5	5	4
1975	2	0	2	3	1	3
1976	3	0	3	4	0	4
1977	1	0	1	4	0	4
1978	3	2	1	3	0	3
1979	31	27	4	1	0	1
1980	4	4	0			
1981	26	24	2			
1982	24	22	2			
1983	31	29	2			
1984	10	8	2			
1985	28	16	2			
1986	23	22	1			

TABLE 6

Annual summary of particle size sampling program

Date	Discharge m3/s	median grain size (um)		% sand		concentration (mg/L)	
		K	R	K	R	K	R
81.05.01	1710	10	12	10	14	196	194
81.05.27	4310	68	53	52	46	959	821
82.05.19	4520	65	39	51	38	1460	1080
83.05.31	2610	37	34	37	35	544	507
84.06.11	3250			47	41	540	489
84.06.19	3560			47	32	380	286
85.05.23	4450			50	45	888	850
85.06.11	3420			41	28	233	198

TABLE 7

Comparison of particle size data for K and R samples

Year	Load (Mt)	
	1971 eqn	1971-1975 eqn
1971	0.84	0.95
1972	1.90	3.94
1973	0.80	0.98
1974	1.41	2.15
1975	0.60	0.57
1976	2.22	4.01
1977	0.94	1.06
1978	0.31	0.18
1979	0.95	1.36
1980	0.39	0.26
1981	0.55	0.57
1982	1.32	1.92
Mean	1.02	1.50

TABLE 8

Predicted annual bed loads, 1971-1982, using bedload rating equations

LIST OF FIGURES

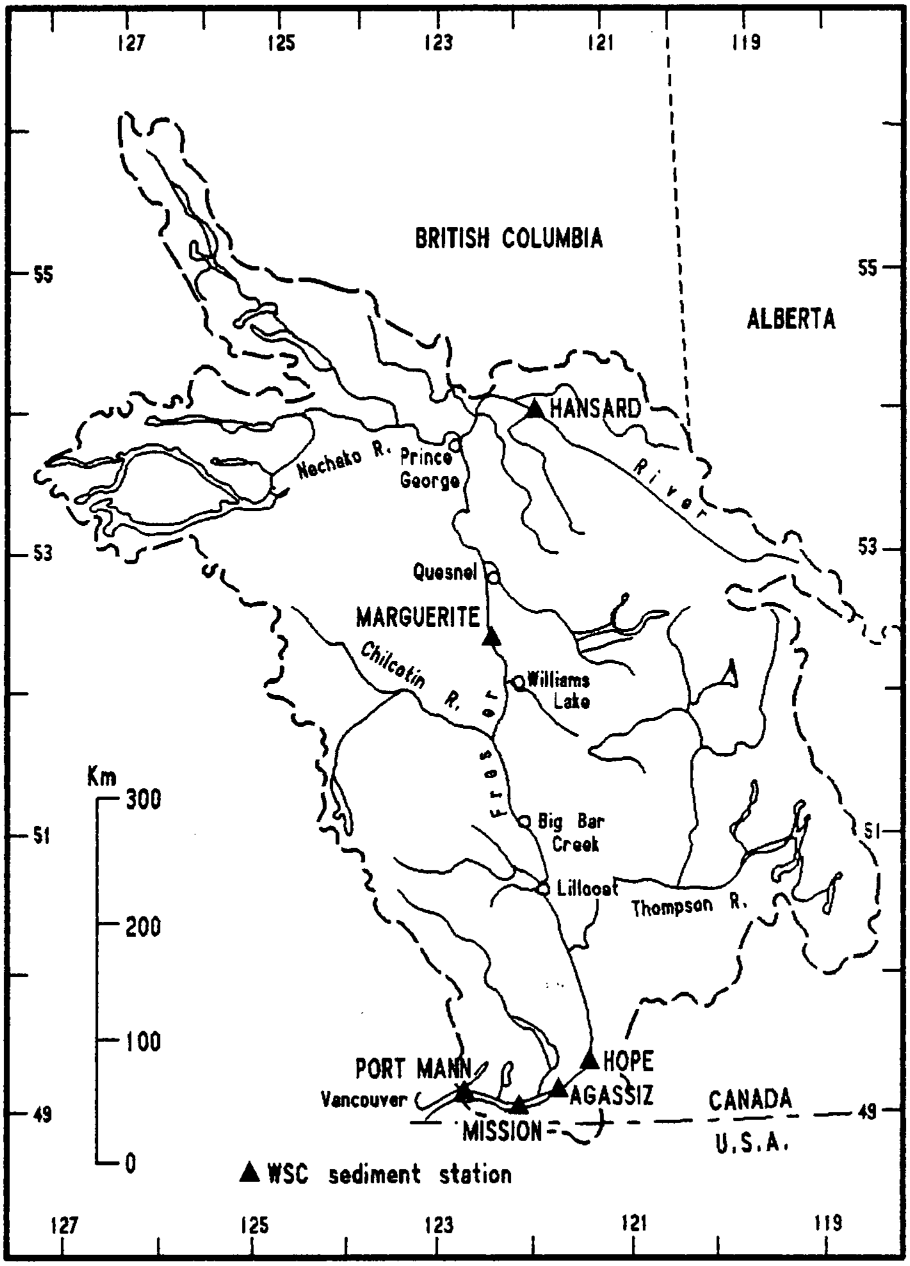
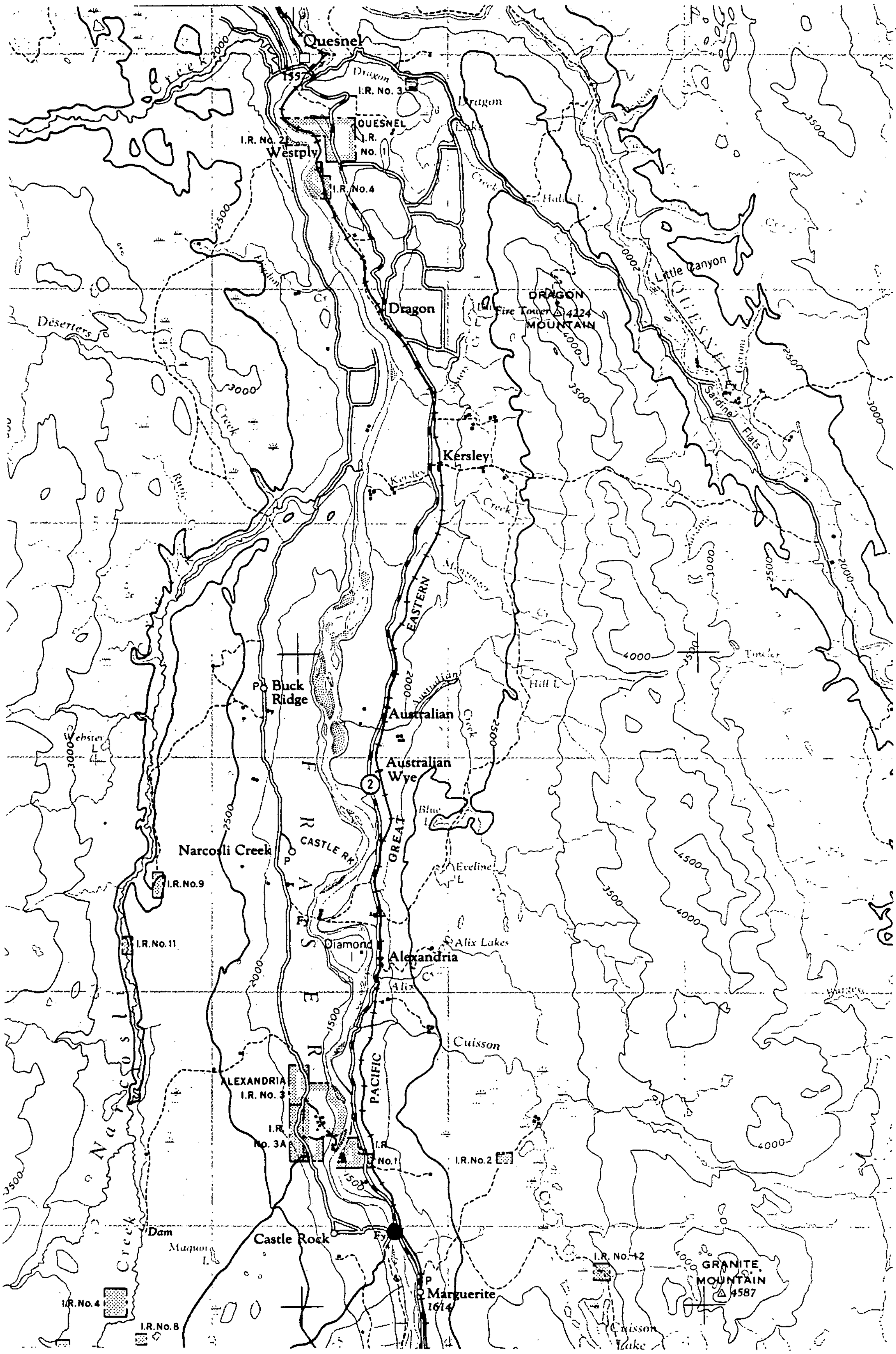
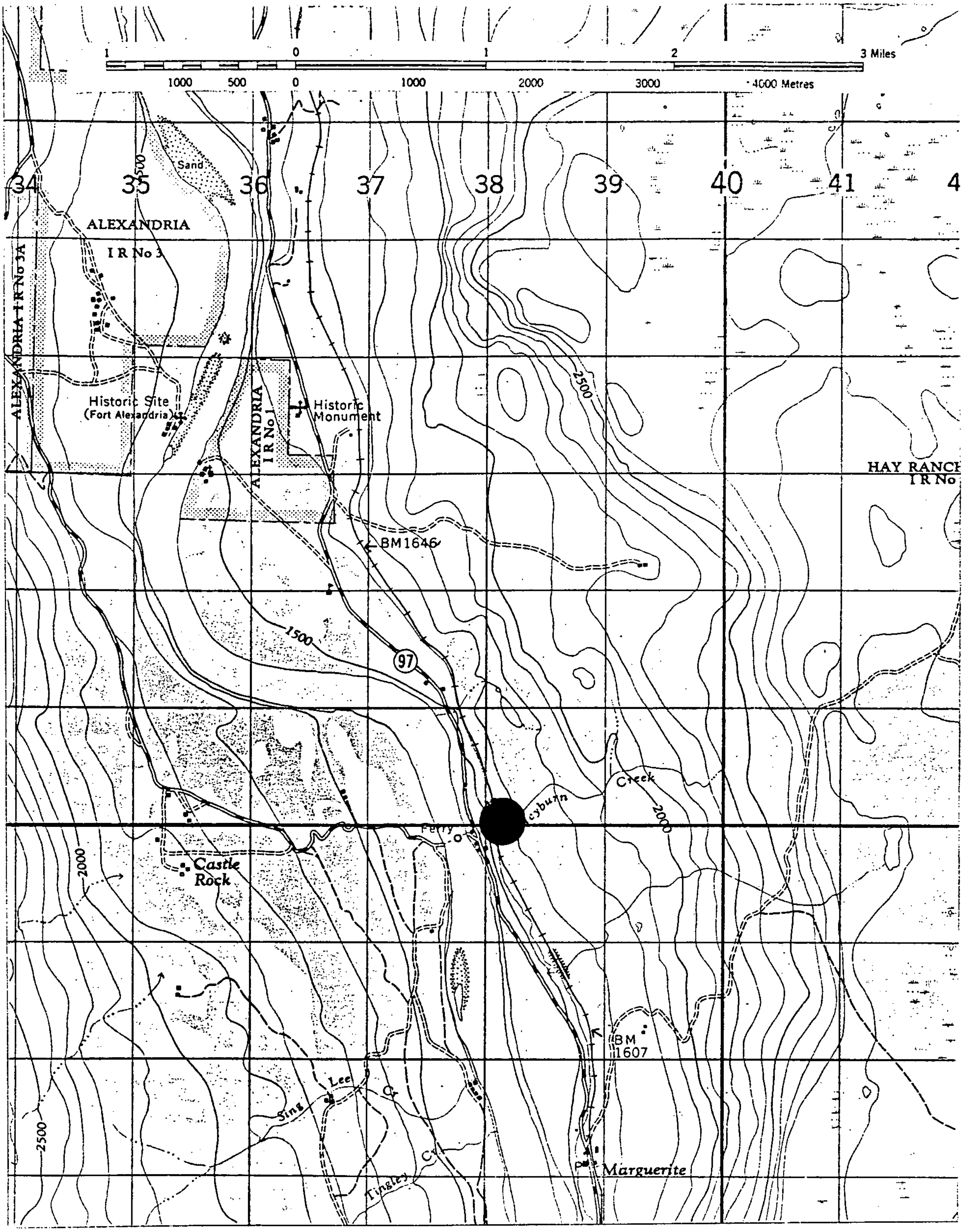


FIGURE 1

FRASER RIVER BASIN



2. The Quesnel-Marguerite reach (1:250,000)



3. The Marguerite Ferry Crossing reach (1:50,000)

4. Aerial photograph of the Ferry Crossing reach (1:15,000)
Flow towards bottom of page.

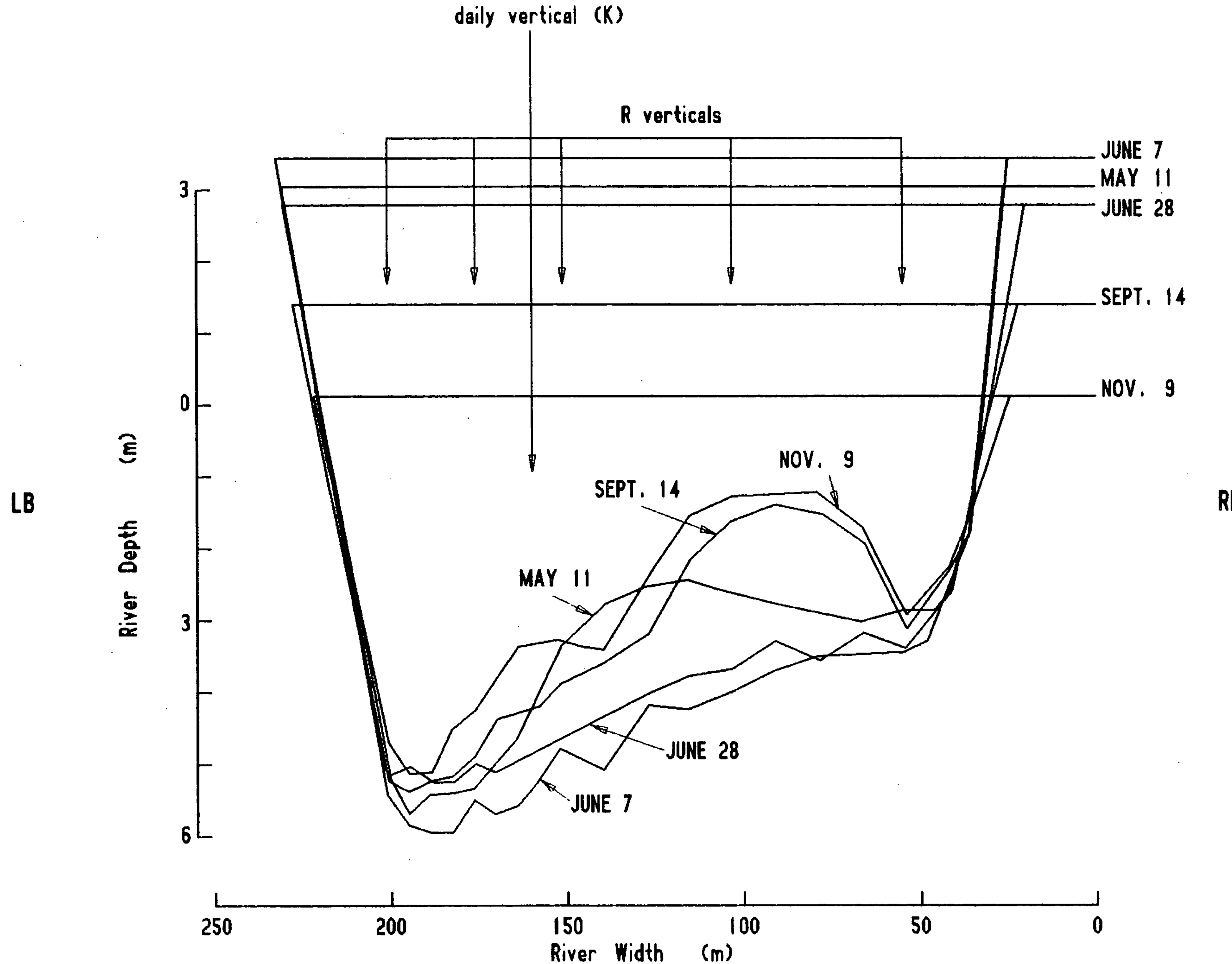
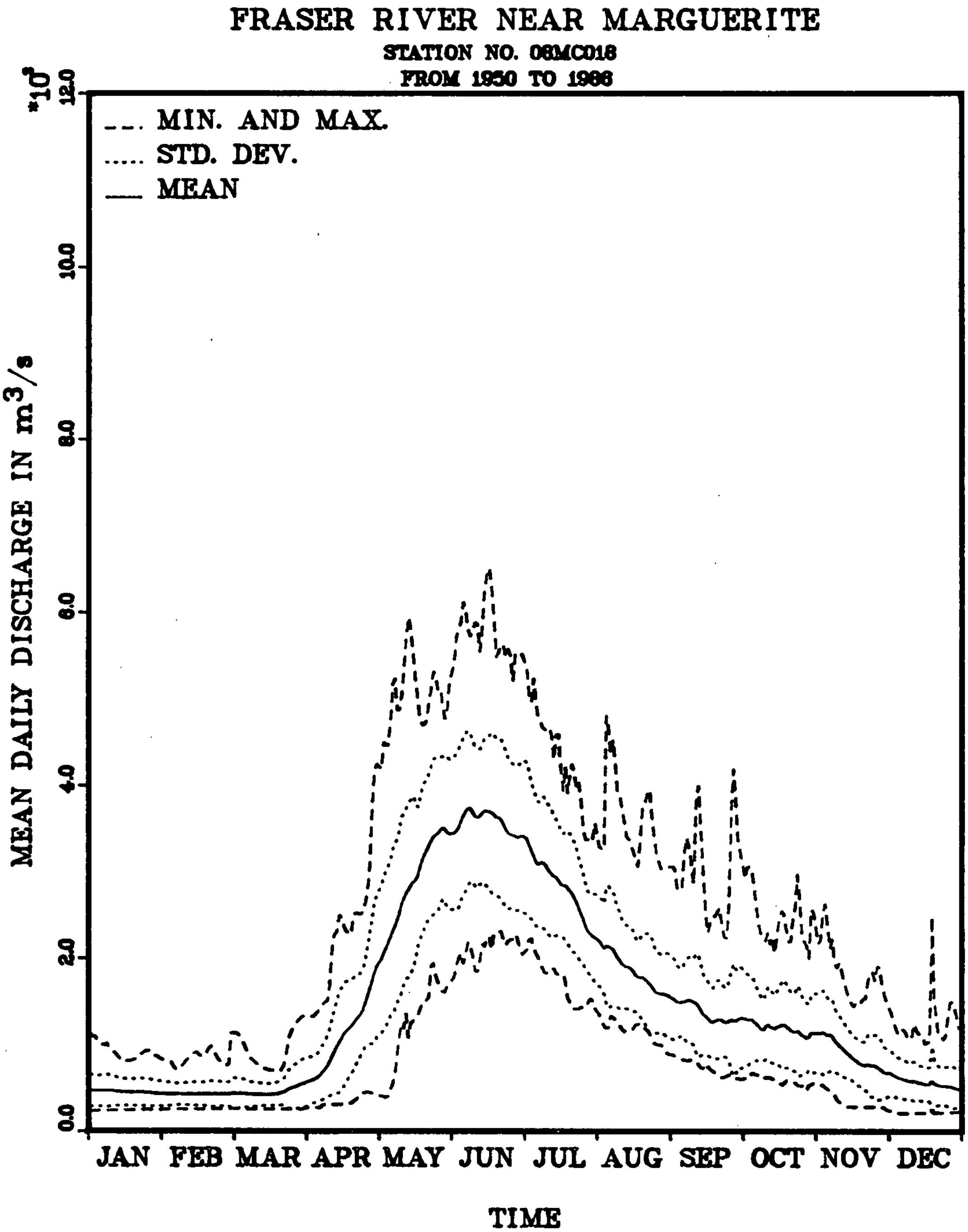


FIGURE 5
FRASER RIVER NEAR MARGUERITE: CHANNEL GEOMETRY, 1971



6. Annual hydrograph of mean, minimum and maximum daily discharges

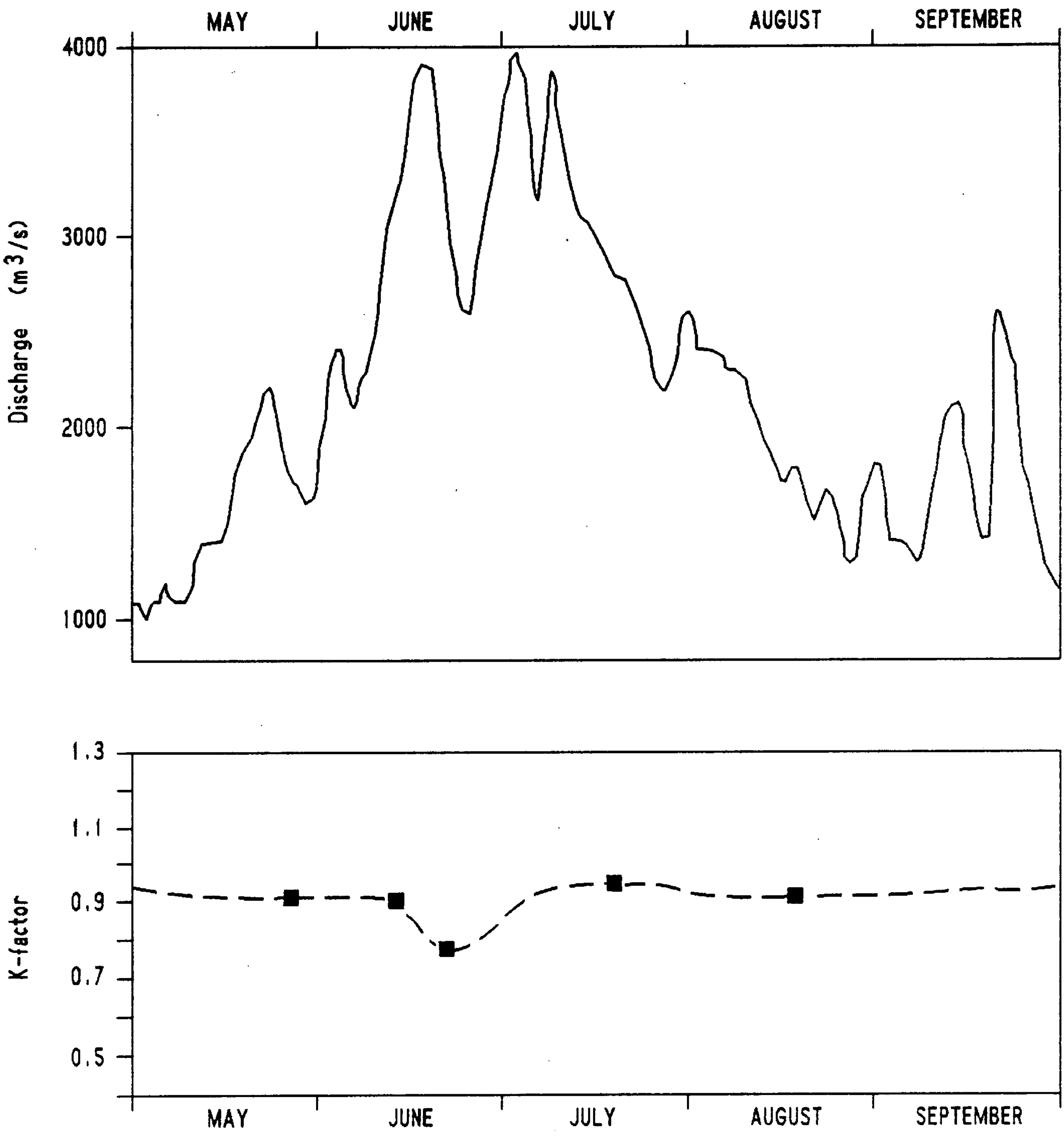
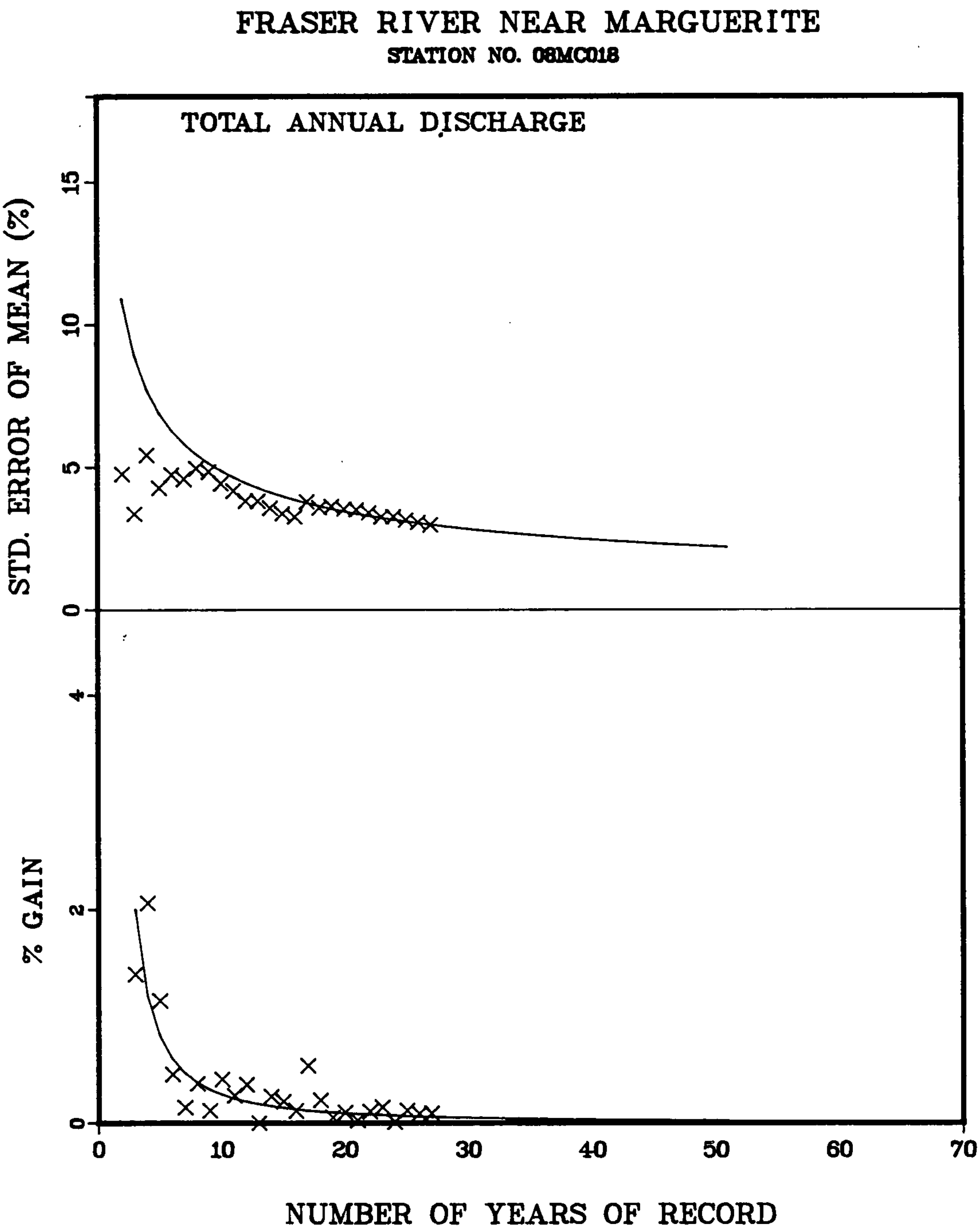
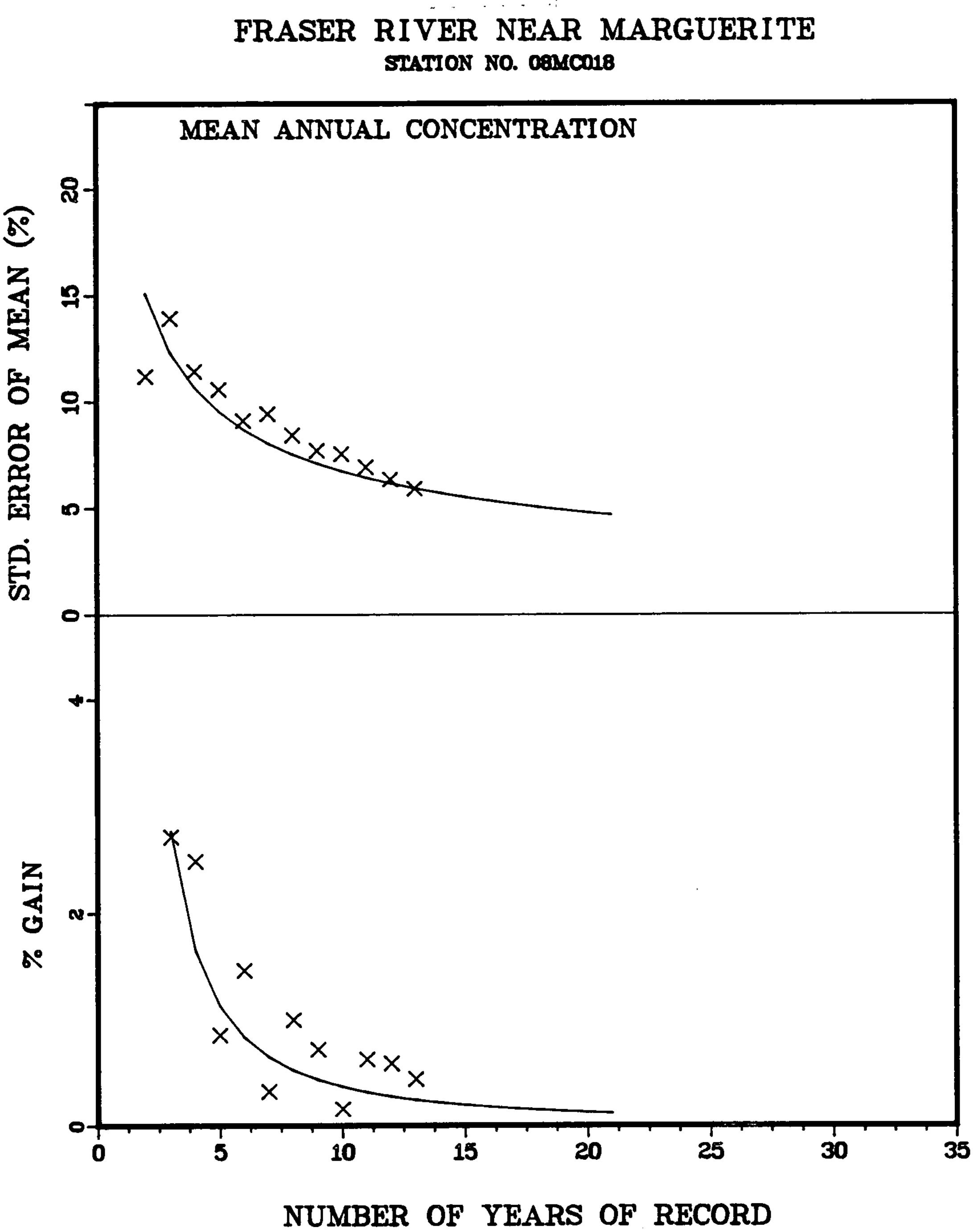


FIGURE 7

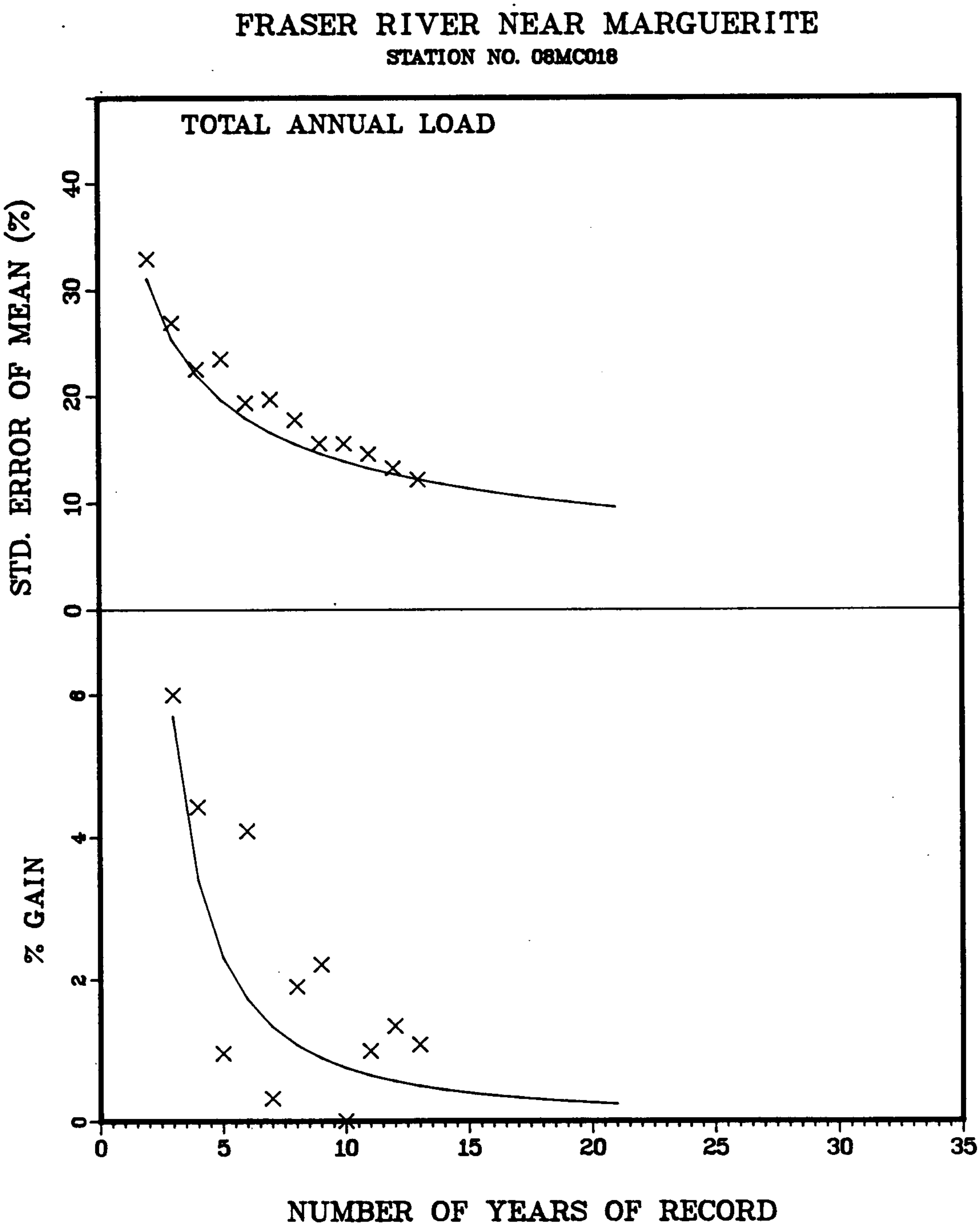
VALUES OF THE K-FACTOR AT FRASER RIVER NEAR MARGUERITE IN RELATION TO HYDROGRAPH, MAY-SEPTEMBER 1984



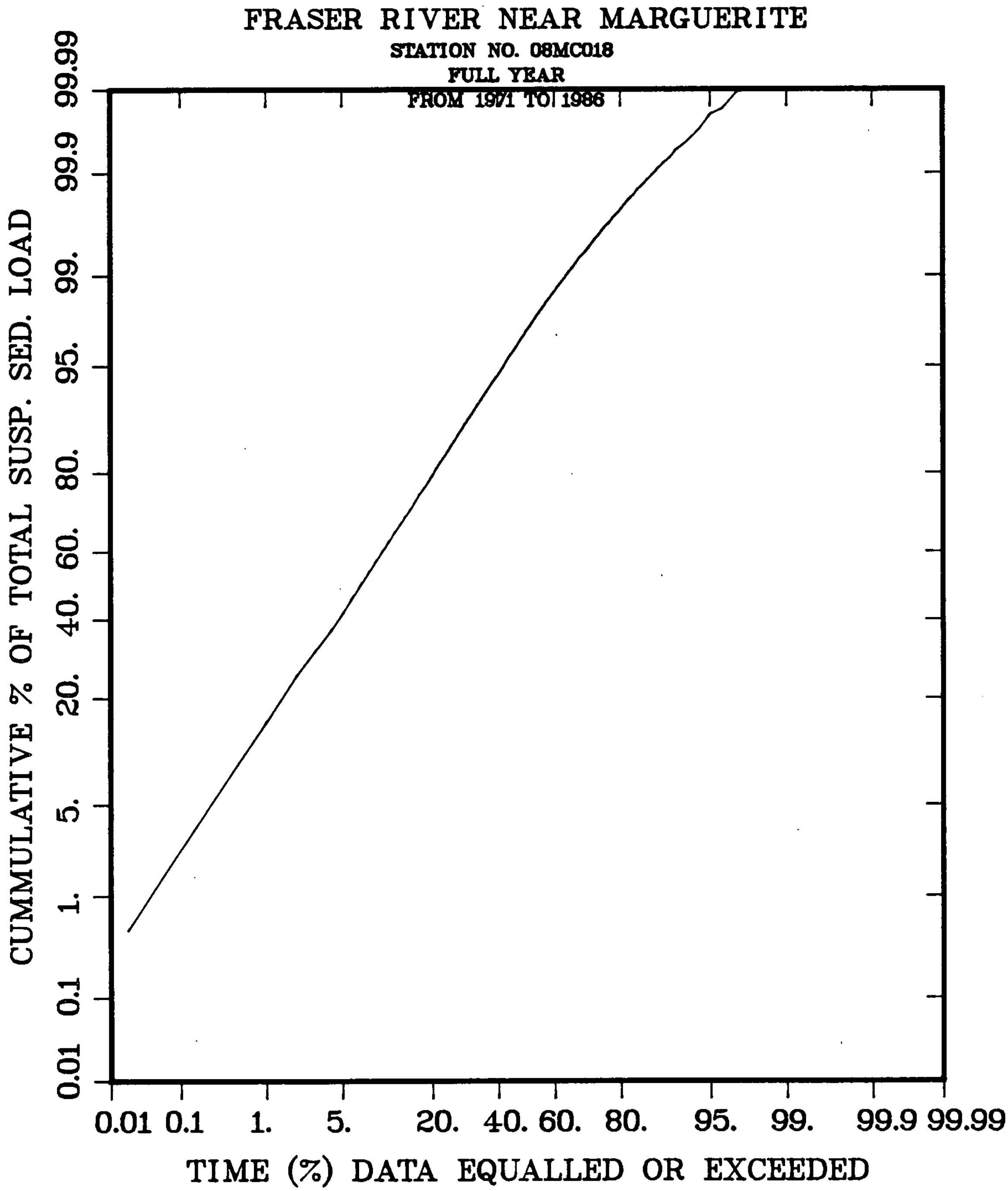
8. Improvement of standard error of mean total annual discharge (top) and decrease in percentage improvement (bottom) with increasing number of years of record.



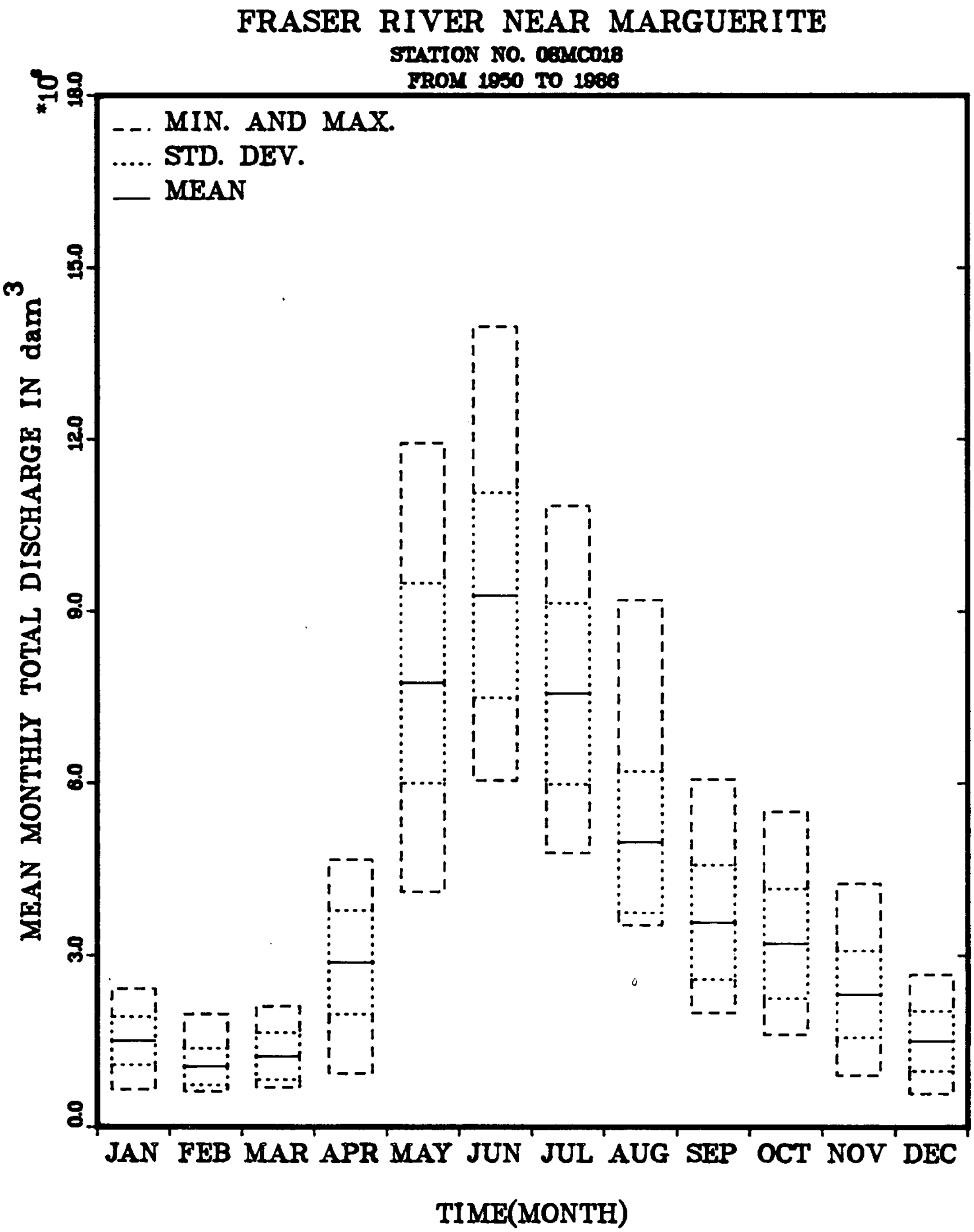
9. Improvement of standard error of mean average annual concentration (top) and decrease in percentage improvement (bottom) with increasing number of years of record.



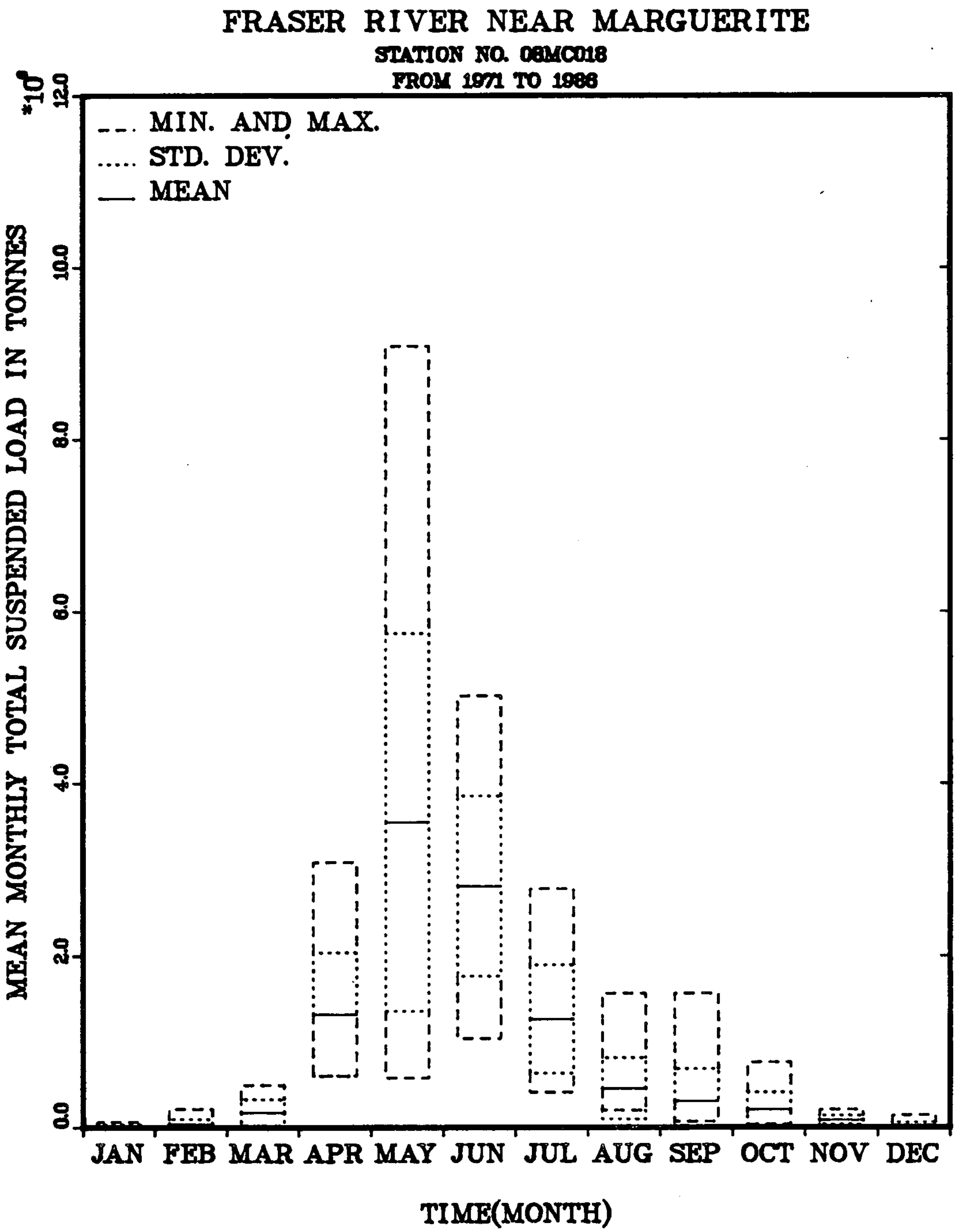
10. Improvement of standard error of mean total annual load (top) and decrease in percentage improvement (bottom) with increasing number of years of record.



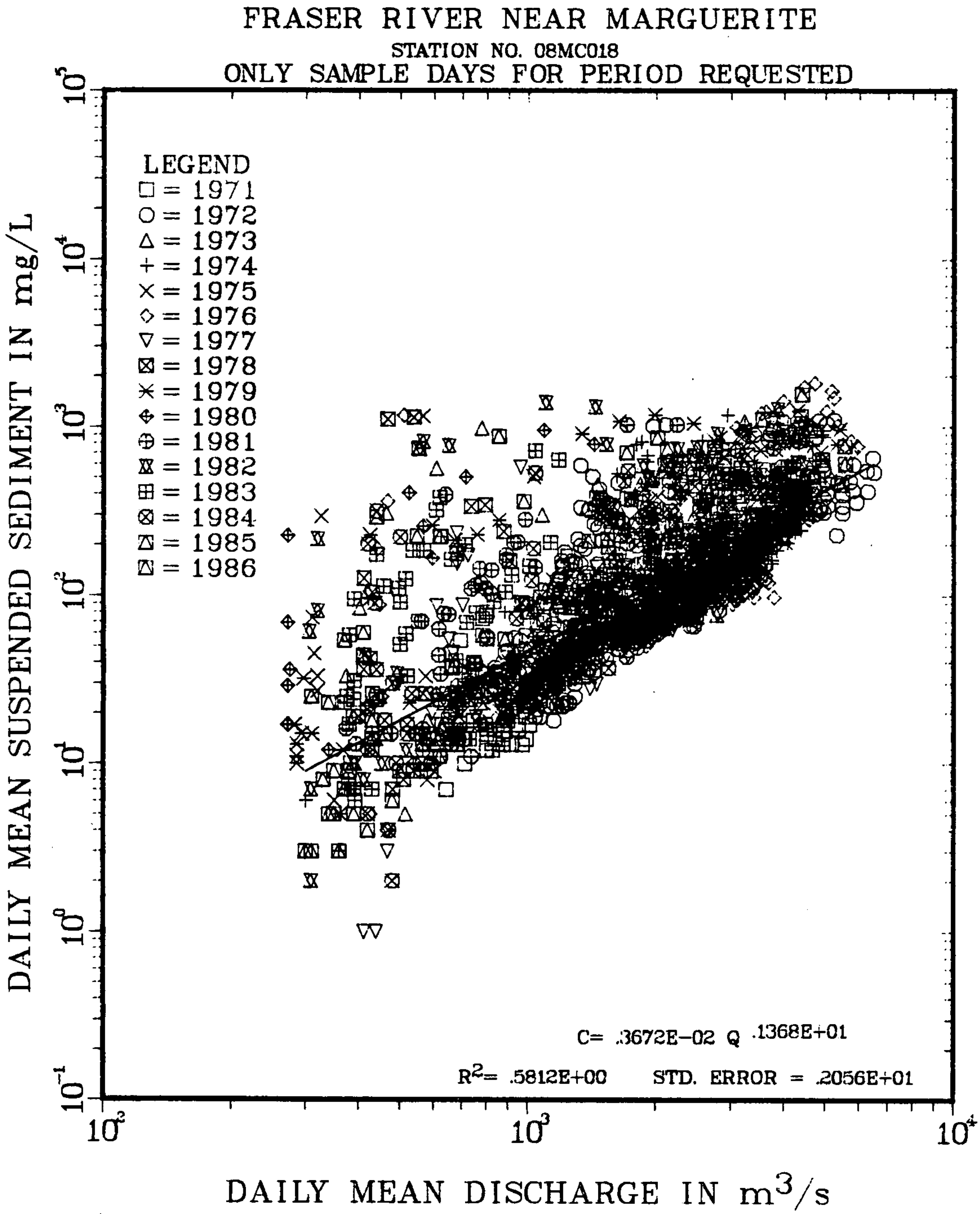
11. Percentage of total annual suspended load transported plotted as a function of time.



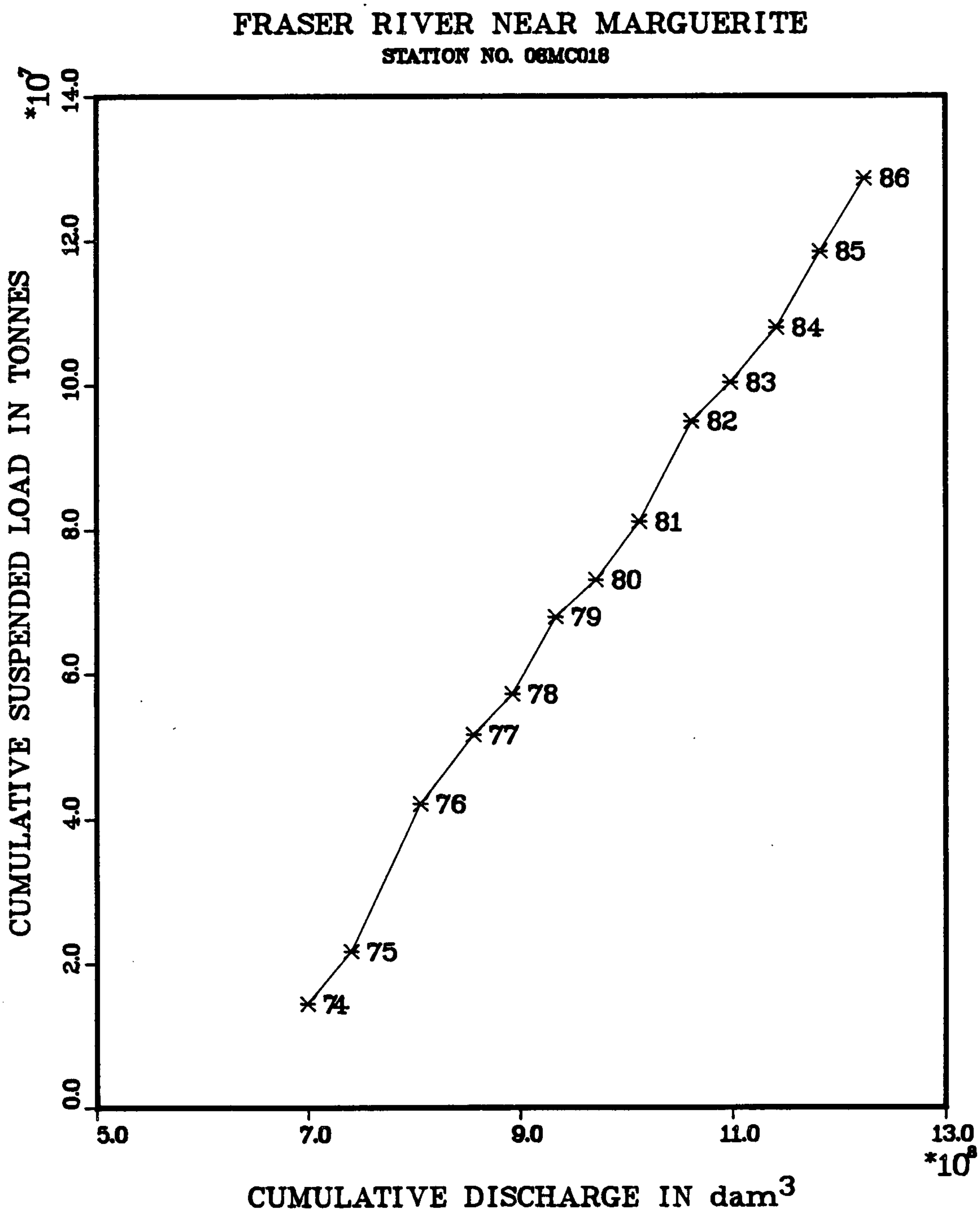
12. Seasonal change in monthly total water discharge.



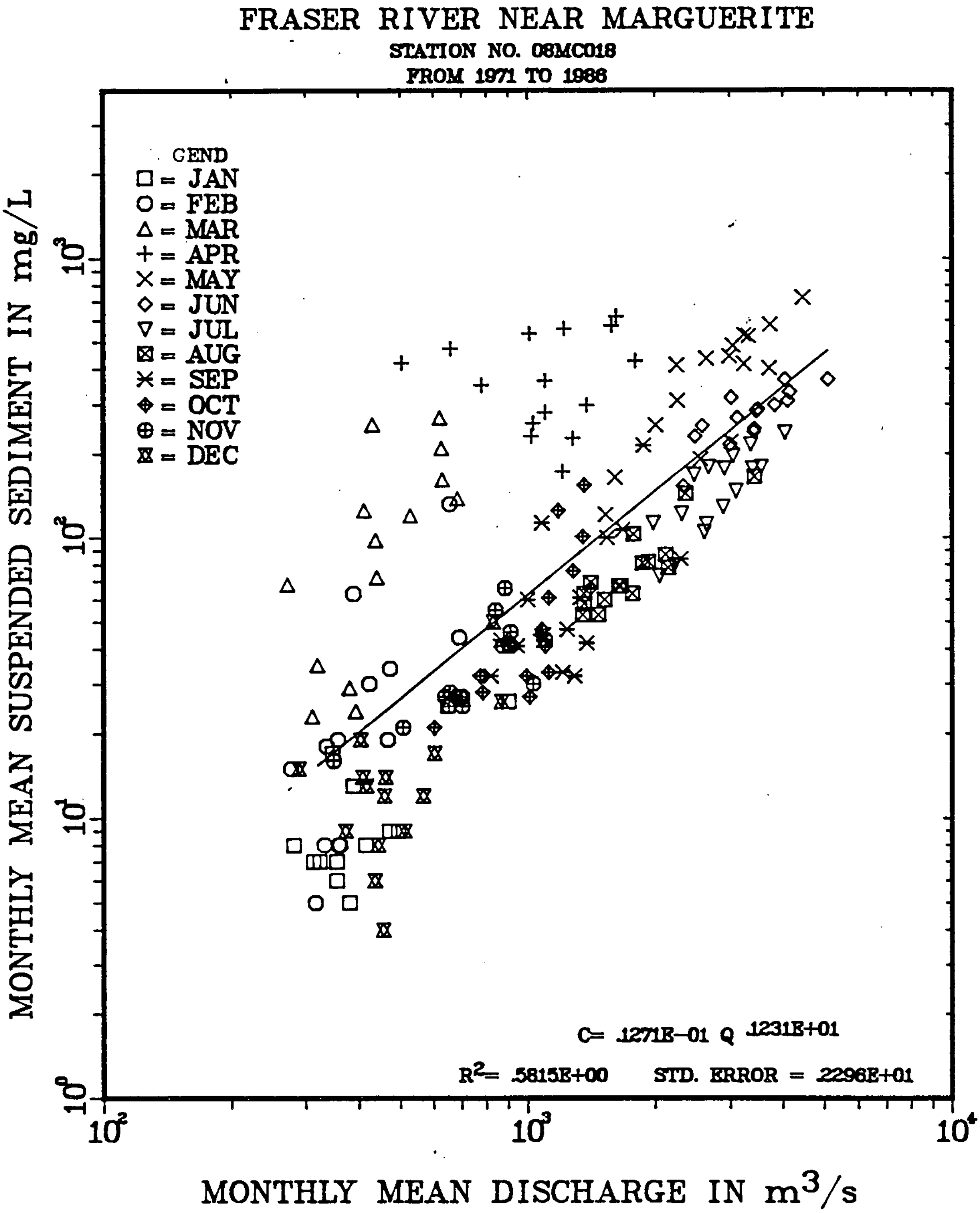
13. Seasonal change in monthly total suspended load.



14. Sediment rating diagram of daily mean concentration against daily mean discharge, 1971-1986, with data points classifed by year.



15. Double mass curve of suspended load and water discharge.



16. Sediment rating diagram of monthly mean concentration against monthly mean discharge, 1971-1986, with data points classified by month.

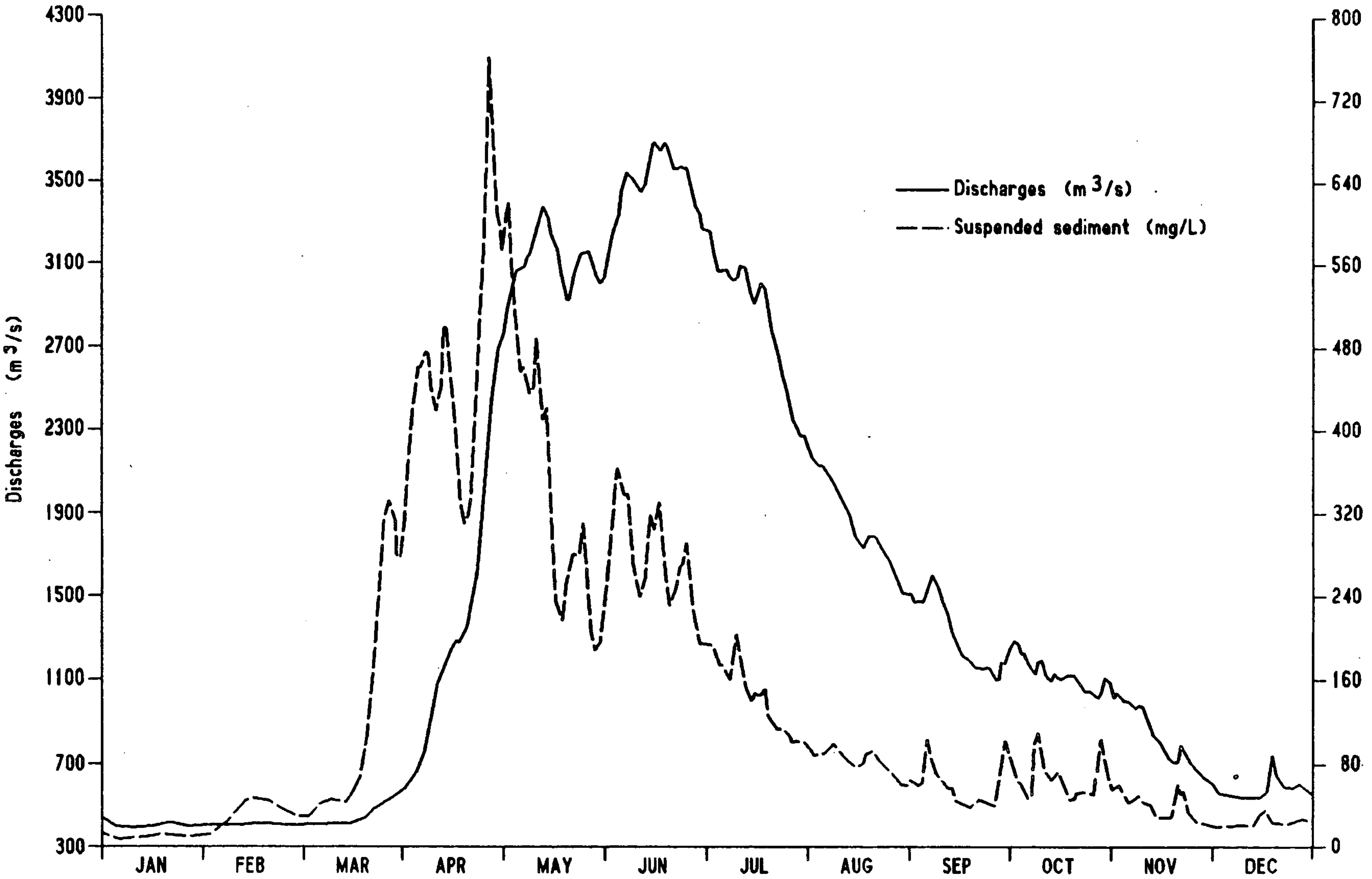
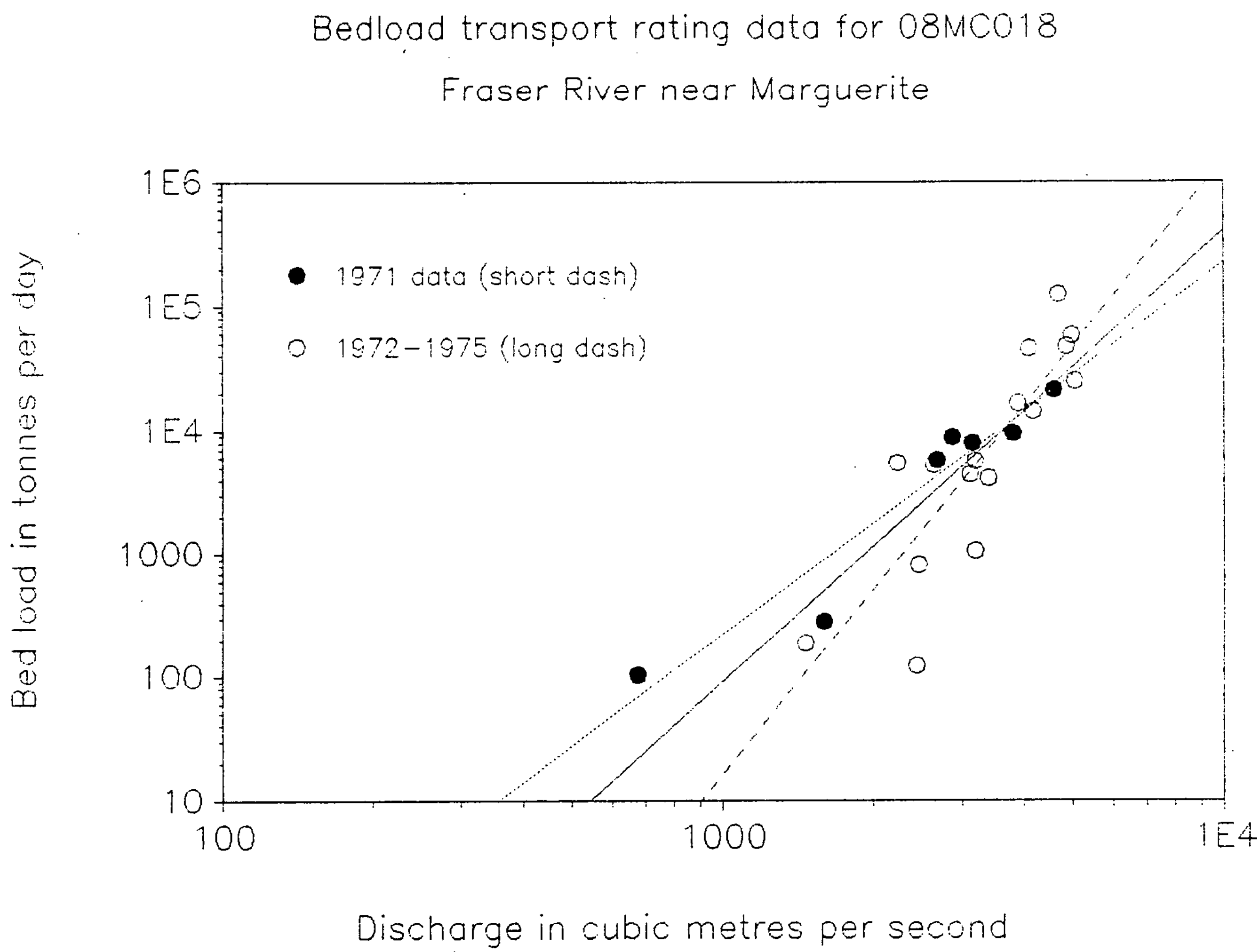
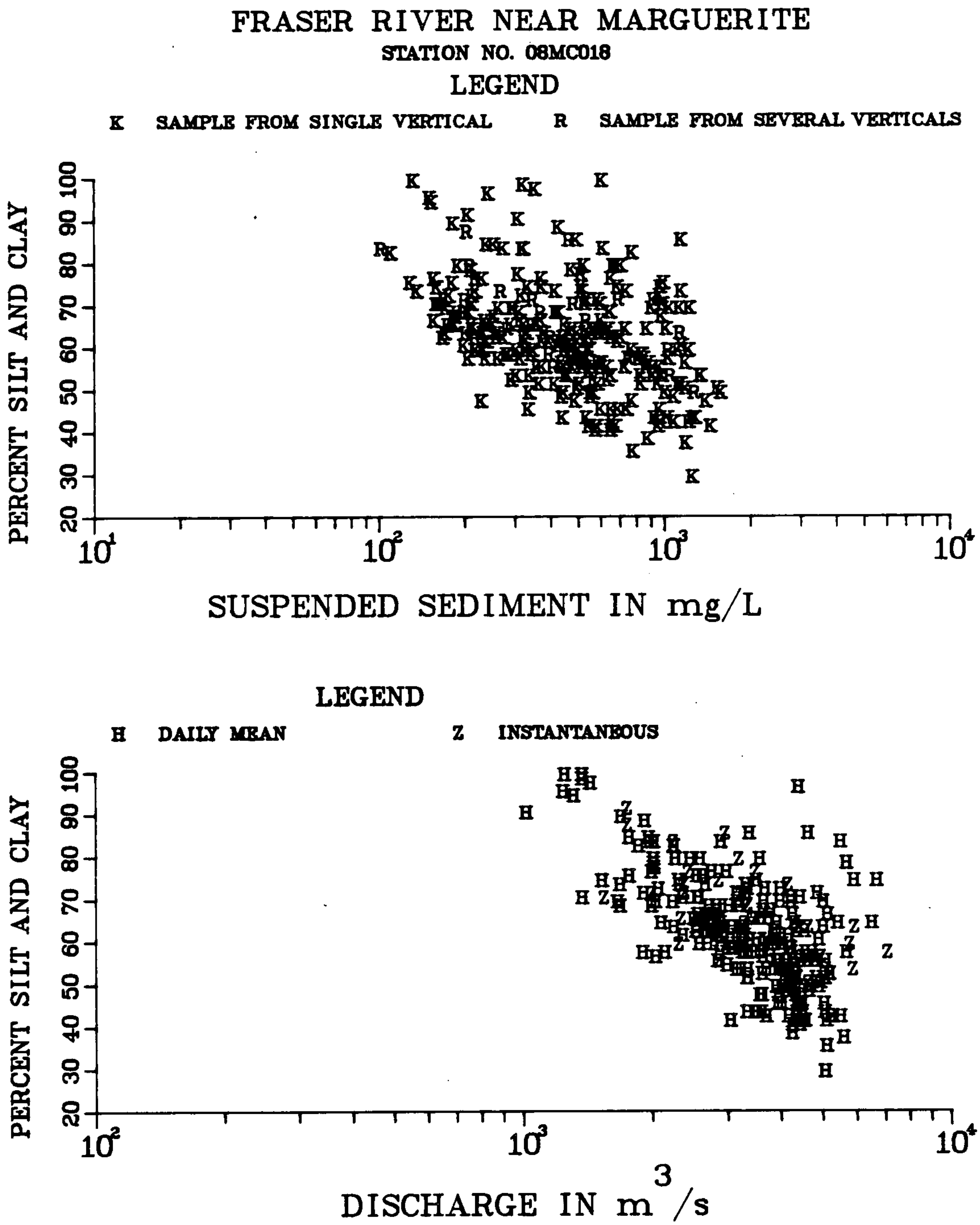


FIG. 17 MEAN DAILY VALUES, 1971-1980: DISCHARGE AND SEDIMENT CONCENTRATION



18. Bed load rating diagram.



19. Percentage silt-clay in suspended load in relation to suspended sediment concentration (top) and water discharge (bottom).

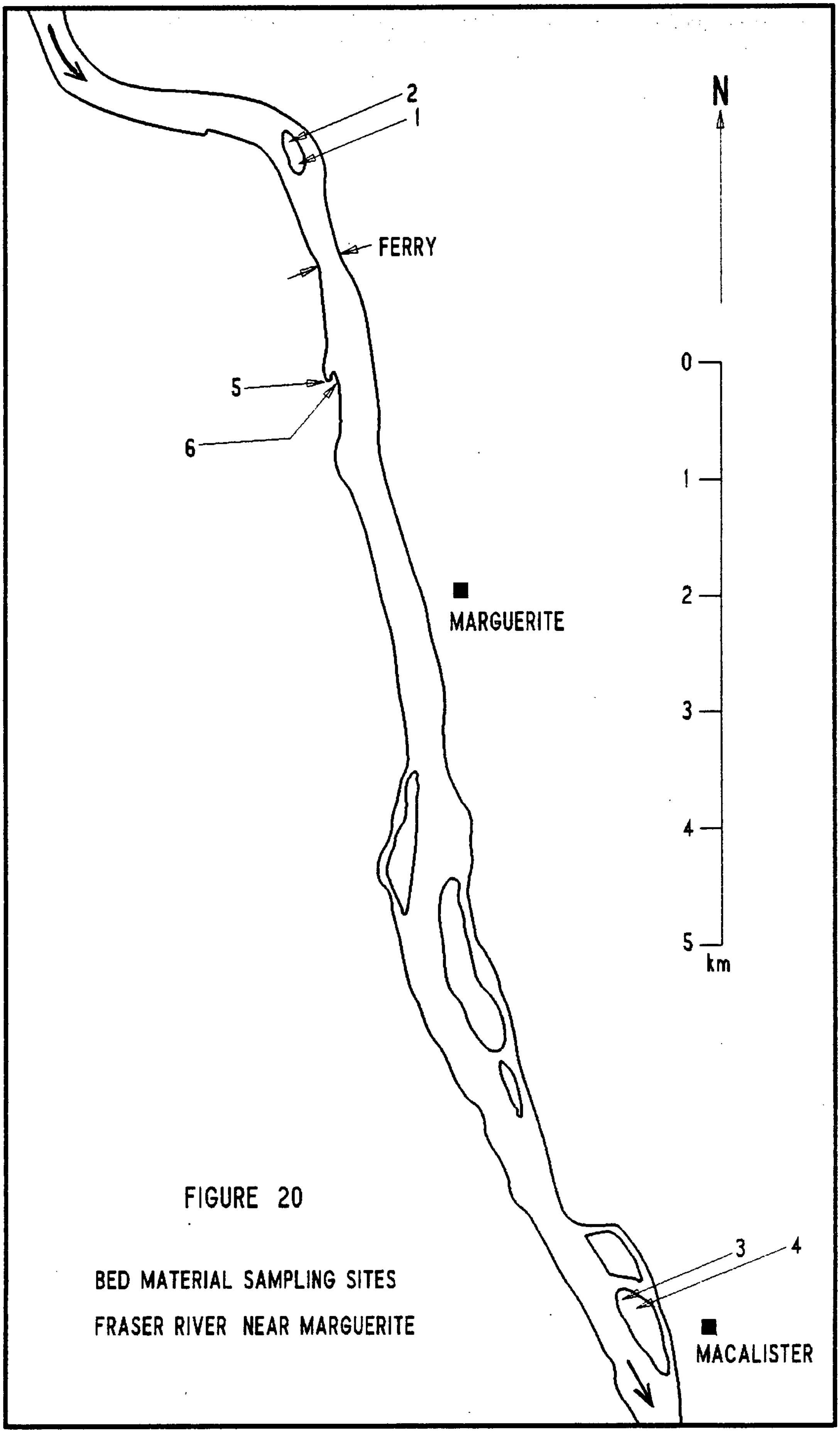


FIGURE 20

BED MATERIAL SAMPLING SITES
FRASER RIVER NEAR MARGUERITE

FIG. 21 BED MATERIAL SAMPLING SITE 1 (BAR TAIL) SHOWING INFILLING OF SURFACE FINES

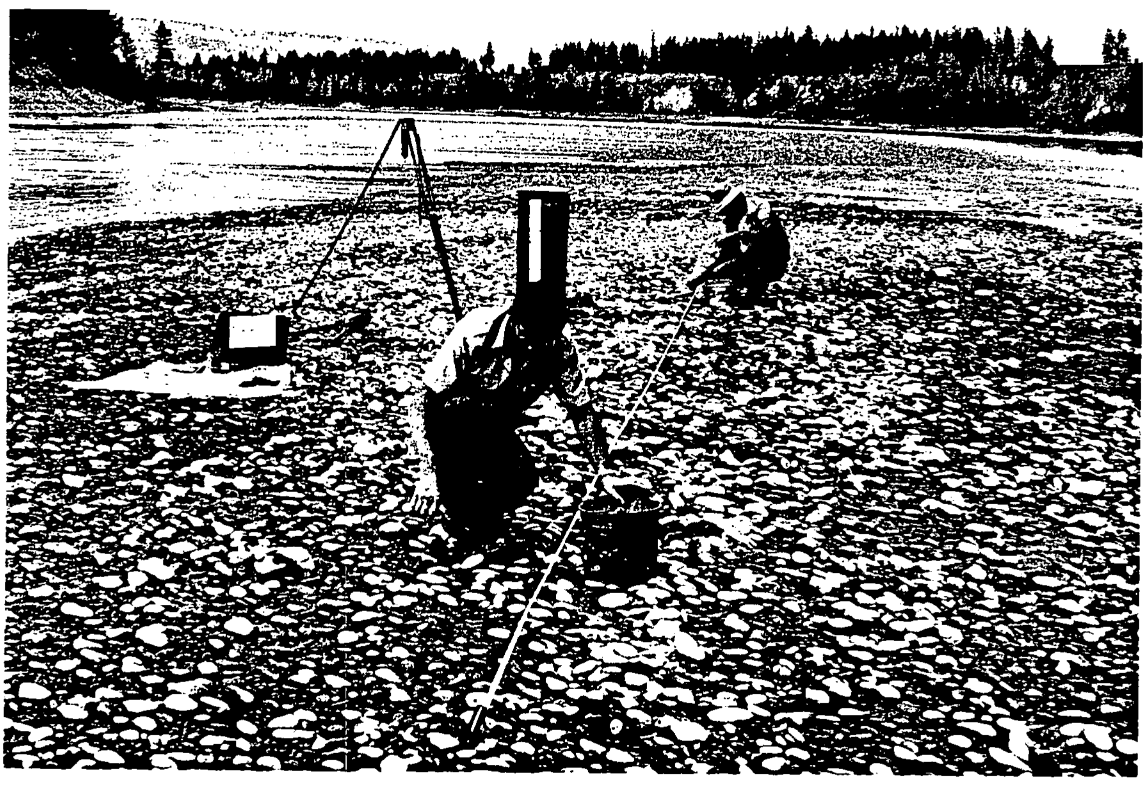


FIG. 22 BED MATERIAL SAMPLING SITE 2 (BAR HEAD) LOOKING UPSTREAM

APPENDIX A

EXTRACTS FROM ANNUAL SEDIMENT DATA PUBLICATION

OF THE WATER RESOURCES BRANCH

Pages vi-x and xv-xvii of
"Sediment Data, British Columbia, 1985"
published 1987 by
Water Survey of Canada
Water Resources Branch
Inland Waters Directorate
Environment Canada
Ottawa

(Available upon Request)

APPENDIX B

SUMMARY OF HYDROMETRIC DATA

B1 : Mean discharges for each month and year, 1950 to 1986. (1 page)

B2 : Annual extremes of discharge for each year in the period 1950 to 1986. (same page)

B3 : Mean daily discharge for each of the 365 days in the period 1950-1986, with related dispersion indices. (6 pages)

(Available upon Request)

APPENDIX C

SUMMARY OF SUSPENDED SEDIMENT LOAD DATA

C1 : Annual mean and extremes: 1971-1985 (1 page)

C2 : Total loads for each month and year, 1971-1986. (1 page)

C3 : Daily mean discharge, concentration and load for each day, 1971-1986 (62 pages)

C4 : Annual "hydrographs" of discharge and concentration, 1971-1986 (16 pages)

(Available upon Request)

APPENDIX D

DURATION DATA FOR DISCHARGE, CONCENTRATION AND LOAD

D1 : Annual statistics and recurrence intervals

(a) annual total discharge (dam^3)
(b) annual maximum discharge (m^3/s)
(c) annual total suspended load (tonnes)
(d) annual maximum suspended load (t/day)

(12 pages)

D2 : Full duration statistics (for each month of the average year) and duration curve for the full period.

(a) discharge (m^3/s)
(b) concentration (mg/L)
(c) load (tonnes)
(d) yield (tonnes per sq. km.)

(12 pages)

D3 : Peak period statistics (for each year of the study period) and plots of year-to-year changes in these statistics.

(a) total discharge (dam^3)
(b) concentration (mg/L)
(c) load (tonnes)

(6 pages)

(Available upon Request)

APPENDIX E

SEDIMENT RATING DIAGRAMS : SUSPENDED LOAD

E1 : Annual plots

- mean concentration (mg/L) versus mean water discharge (m^3/s)
- total load (tonnes) versus total discharge (dam^3)

(2 pages)

E2 : Monthly plots

- monthly mean concentration (mg/L) versus monthly mean water discharge (m^3/s)
- monthly total load (tonnes) versus monthly total water discharge (dam^3)

There are two versions of the first chart: data points classified according to month (one graph); and data points classified according to year (two graphs).

(4 pages)

E3 : Daily plots

daily mean concentration (mg/L) versus daily mean water discharge (m^3/s) for sampled days only; there is one plot for each year, with data points classified according to month.

(16 pages)

(Available upon Request)

APPENDIX F

PARTICLE SIZE DATA

F1 : Depth-integrated suspended sediment

- Statistics for particle size distribution of each sample analyzed, 1971-1983. (7 pages)
- Composite plot of particle size distribution of these samples (1 page)

F2 : Instantaneous suspended sediment

Statistics for particle size distribution for "instantaneous" samples, 1984-1986. (15 pages)

F3 : Bed load data

- Statistics for particle size distribution of each bed-load sample analyzed, 1973-1979. (1 page)
- Composite plot of these samples (1 page)

F4 : Bed material data

- Size distribution of "surface" bulk samples
- Size distribution of subsurface bulk samples
- Size distribution of surface gravel GBN samples
- Comparison of surface and subsurface gravel

(Available upon Request)