SUSITNA HYDROELECTRIC PROJECT

APPENDIX B.8
RESERVOIR SEDIMENTATION

JANUARY 1982

Prepared by:

R&M CONSULTANTS, INC.

Prepared for:

ACRES

ALASKA POWER AUTHORITY

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SUSITNA HYDROELECTRIC PROJECT

APPENDIX B.8
RESERVOIR SEDIMENTATION

JANUARY 1982

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TASK 3 - HYDROLOGY

SUBTASK 3.07 - CLOSEOUT REPORT-RESERVOIR SEDIMENTATION

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1 - PURPOSE AND SCOPE OF STUDY

The purpose of this report is to present the results of analyses of sedimentation within the proposed Watana and Devil Canyon Reservoirs. Analyses of the sedimentation were complicated due to the large percentage of very fine suspended sediment contributed by glaciers in the Susitna River headwaters, possibly making results from the usual analytical techniques to be in error.

The approach to analyzing the reservoir trap efficiency was to first analyze the trap efficiency of the reservoirs based on the capacity-inflow ratio. A literature search was then conducted to determine the trap efficiency of natural glacial lakes and to gather information on their sedimentation processes. Settling column studies of suspended sediment samples from the Susitna River were then conducted to gather empirical data. The information from these three information sources was then assimilated to project the reservoir sedimentation processes.

The annual sediment load entering the reservoirs was estimated using the flow duration sediment rating curve method for the nearest gaging stations and an estimated sediment yield for the area draining directly into the reservoirs. The unit weight and volume of the deposited sediments were estimated using standard techniques.

Modelling of sediment deposition within the reservoirs was considered but was not deemed appropriate or necessary at this time. The settling properties of the very fine "glacial flour" are such that it remains in suspension for long periods of time, affecting the reliability of the model. In addition, the estimated volume of sediment deposited in Watana Reservoir is less than 5% of the total volume of the reservoir. A large proportion of the sediment will be deposited in the dead storage portions of the reservoir due to the slow settling characteristics of the very fine suspended sediments.

Turbidity could not be assessed on a quantitative basis. However, pre-project conditions were assessed, and a qualitative analysis conducted of probable turbidity patterns in the reservoirs and downstream river.

2 - SUMMARY OF RESERVOIR SEDIMENTATION

Trap efficiency estimates based on detention - storage time indicate that 95-100 percent of sediment entering Watana Reservoir would settle, even shortly after filling of the reservoir starts. However, data from Kamloops Lake, British Columbia, a 3 million acre-ft. glacial lake confined in a narrow valley, indicates that up to one-third of the incoming sediment passes through it. Median grain size at the lower end of Kamloops Lake is about 2 microns. For the Susitna River near Cantwell, about 15 percent of the suspended sediment is finer than 2 microns. Preliminary estimates indicate that between 70-95 percent of incoming sediment would be trapped in the reservoir, with particles smaller than 2 microns possibly passing through the reservoir. As Watana Reservoir is longer, deeper, and has a longer retention time than Kamloops Lake, it is possible that even smaller particle sizes may settle in the reservoir. Under the worst case sedimentation condition of 100% trap efficiency, an estimated 472,500 ac-ft. of sediment would be deposited in Watana Reservoir in 100 years.

Devil Canyon Reservoir would have a slightly lower trap efficiency than Watana due to its smaller volume. However, most sediment will be deposited in Watana, the upstream reservoir. Assuming that both reservoirs have a 70% trap efficiency, an estimated 109,000 ac. ft. of sediment would be deposited in Devil Canyon Reservoir in 100 years.

Three interdependent but distinct sedimentation processes occur in glacial lakes. These processes consist of: (a) delta progradation into the lake; (b) sediment density surges down the steep upper slope, depositing material on the lake floor which had previously been on the delta slope; and (c) river plume dispersion, which spreads the fine-grained material throughout the lake. The sediment-laden streamflow will initially spread through the lake either as surface flow, interflow, or underflow, depending on the relative densities of the lake water and the stream water.

Turbidity downstream of the reservoir will decrease sharply during the summer months due to the sediment trapping characteristics of the reservoirs. It is likely that the turbidity of water released in the winter months will be near natural conditions, as suspended sediment in near-surface waters should rapidly settle once the reservoir ice cover forms and essentially quiescent conditions occur.

3 - TRAP EFFICIENCY

Only a portion of the sediment brought into a reservoir is normally trapped and retained, with the balance being transported through and carried out of the reservoir by outflow water. The ability of a reservoir to trap sediment is known as its trap efficiency, and is expressed as the percent of sediment yield (incoming sediment) which is retained in the reservoir.

3.1 - Factors Influencing Trap Efficiency

The trap efficiency of a reservoir depends on the sediment characteristics and the rate of flow through the reservoir. As streamflow enters a reservoir, the cross-sectional area is increased, resulting in a decrease in velocity with a consequent decrease in sediment-transport capacity. The coarse-grained particles are dropped immediately near the head of the back water, with the finer grains remaining in suspension until they are deposited farther into the reservoir or carried out of the reservoir in the outflow water. The percent of total sediment trapped in the reservoir depends on the fall velocity of particles and the rate at which the particles are transported through the reservoir.

The fall velocity of particles in water depends on a number of variables, including the size and shape of the particle, its chemical composition and the viscosity of the water. Electrochemical processes play an important role in determining the fall velocity of fine particles less than 10 microns in diameter, such as clays or glacial flour. In some areas, clays and colloids may aggregate into clusters which have settling properties similar to larger particles, and conversely, highly dispersed particles may stay in suspension for long periods of time and transported out of the reservoir.

Although no mineralogic analyses of suspended sediment from the Susitna River are available, there are mineralogic analyses of suspended sediment from a number of surrounding glacial rivers. Clay minerals (montmorillonite) were absent from all samples except from the Knik - Matanuska Rivers, where less than 2 percent clay minerals were detected (Everts, 1979; Tice, et. al, 1972).

The rate of flow of water through a reservoir determines the detention - storage time. The ratio of reservoir detention - storage time is influenced by the inflow volume with respect to reservoir storage capacity and the outflow rate. Watana Reservoir has a storage volume of 9,650,000 acre-feet, and Devil Canyon Reservoir a volume of 1,092,000 acre-feet. Average annual inflow at Watana and Devil Canyon Reservoirs is 5,880,000 acre-feet and 6,630,000 acre-feet, respectively. Watana Reservoir will release approximately the average annual inflow each year, so that the average annual inflow to Devil Canyon should not differ significantly from pre-project conditions. The ratio of capacity to inflow for the two reservoirs is 1.64 for Watana and 0.16 for Devil Canyon.

The size and location of reservoir outlets also influences the trap efficiency, with bottom outlets more effective in removing the higher sediment concentrations near the bottom. Either multi-level outlets or single outlets at a depth of about 200 feet will be used. Neither type of outlet is near the reservoir bottom. Consequently, the effects of the location of the reservoir outlets will not be further considered in this study.

3.2 - Trap Efficiency Estimates

Although several factors influence trap efficiency, the detention - storage time appears to be the controlling factor in many reservoirs. Brune (1953) developed the generalized trap efficiency envelope curves shown in Figure 3.1, which relate trap efficiency to the storage capacity - inflow ratio. Using the Brune curve, the following range of trap efficiencies were estimated.

Reservoir	Capacity/Inflow	Maximum	Minimum	Median
Watana	1.64	100	95	97
Devil Canyon	0.16	96	84	92

The Brune curve was developed on detention storage time. However, the variation due to differing reservoir shape, operation, and sediment characteristics has not been determined (Gottschalk, 1964). Using the Brune curve, it would appear that about 97 percent of the sediment entering Watana Reservoir would be trapped. Devil Canyon Reservoir would trap about 92 percent of the sediment passing Watana Reservoir and any suspended sediment picked up in the intervening river reach. Consequently, it would appear that very little of the suspended sediment load entering Watana Reservoir would eventually leave Devil Canyon Reservoir. However, some concern has been expressed that the very fine glacial flour would remain in suspension and pass through the reservoir system. This may not be detrimental in the summer, but if it remained in suspension throughout the winter months, winter releases would be turbid instead of clear, as is the natural condition. Consequently, a literature review of sedimentation (App. B) in glacial lakes was conducted to estimate the trap efficiency of glacial lakes. Settling column studies of water samples from the Susitna River were also conducted to determine the sediment deposition rate under quiescent conditions (App. A).

Estimates of sediment trap efficiency at two lakes immediately below glaciers were on the order of 70-75% (Ziegler, 1973; ostrem, 1975). Of more relevance is the estimate of trap efficiency for Kamloops Lake by Pharo and Carmack (1979). Kamloops Lake is somewhat similar in morphometry to Devil Canyon Reservoir. It is 15 miles long by 1.6 miles wide, and has a volume of about 3 million acre-feet. Mean annual flow of the Thompson River entering the lake is about 25,000 cfs. This results in a capacity - inflow ratio of about 0.16, very similar to that of Devil Canyon. Observations of turbidity at the lake inlet and outlet (Figure 3.2) led Pharo and Carmack to estimate that nearly one-third of the incoming sediment is carried through the lake and not deposited, resulting in a trap efficiency of about 67%.

Use of the Brune curve on Kamloops Lake results in trap efficiencies ranging from 84 to 96 percent. This would see to indicate that the sedimentation processes occurring in this deep glacial lake result in a lower sedimentation rate than in those reservoirs analyzed by Brune.

For estimating the volume of sediment deposited in the reservoirs, trap efficiency estimates were in the range of 70-100 percent. A trap efficiency of 70 percent is considered the minimum efficiency, and allows an estimate for the maximum amount of sediment passing through Watana Reservoir and entering Devil Canyon Reservoir. The trap efficiency of 100 percent allows an estimate of the maximum amount of sediment deposited in Watana Resevoir. All bedload is assumed to be deposited.

3.3 - Trap Efficiency during Reservoir Filling

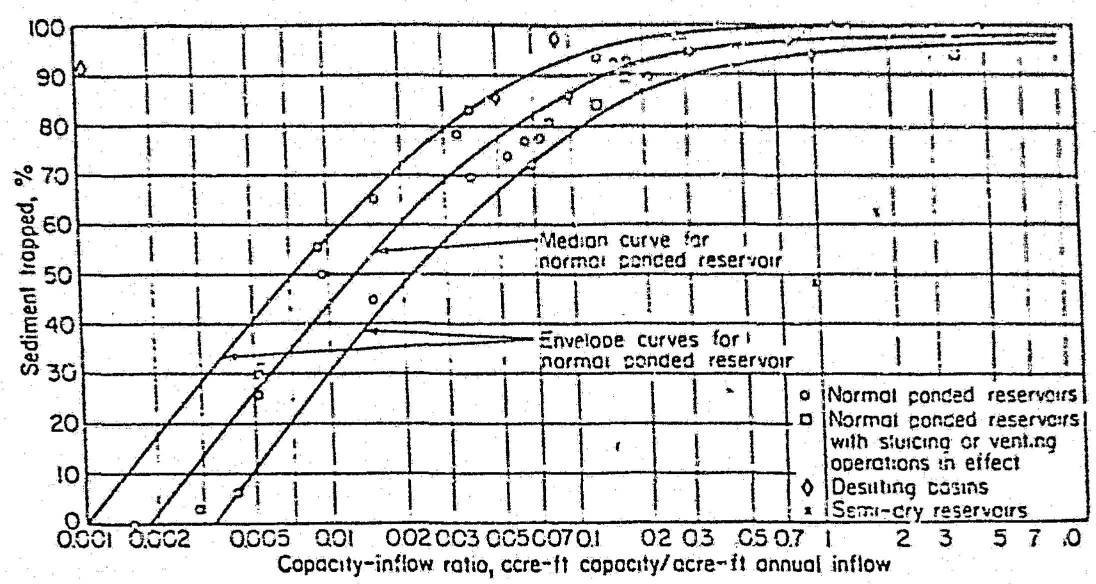
The trap efficiency of a reservoir is sometimes reduced during its filling period due to the reduced storage capacity. An analysis was conducted to estimate the effects at Watana Reservoir. It was assumed that reservoir filling would begin in May. The increase in reservoir storage was estimated using average monthly flows for the Susitna River at Watana.

The Brune curve was used to estimate the trap efficiencies during the filling period. The results are tabulated in Table 3.1. The high flow in May and June fills the reservoir to such a level that trap efficiency rapidly reaches the 95% level. The reservoir would be about 30 miles long within 2 months after filling commences. Consequently, it would appear that sediment deposition during the filling period would be similar to that during full pool.

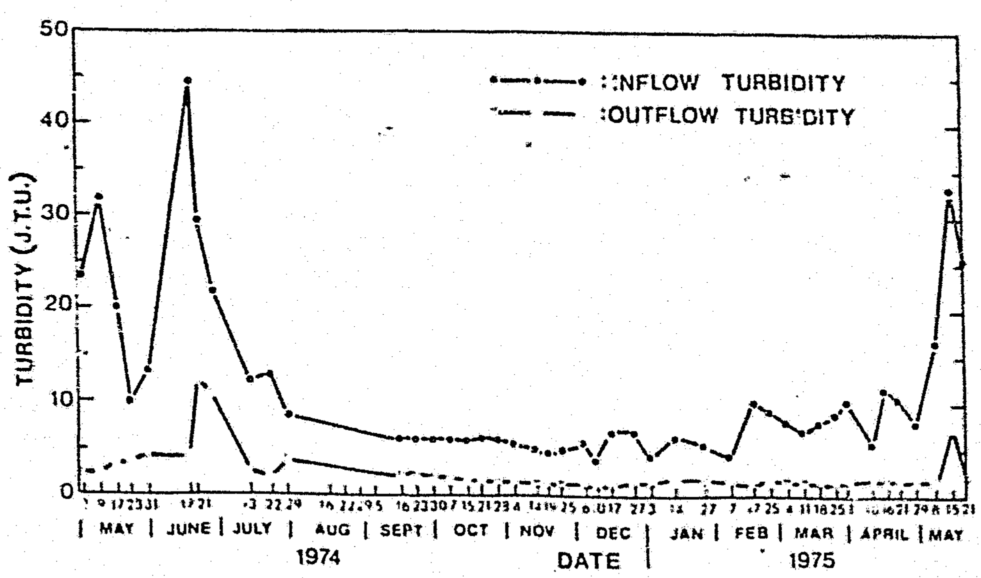
TABLE 3.1

ESTIMATED TRAP EFFICIENCIES DURING RESERVOIR FILLING

End of Month (1st Year)	Flow at Watana (cfs)	Required Flow at Gold Creek	Trap Efficiency (Brune Curve)
May	10,406	6,000	83
June	22,293	7,000	94
1-15 July	20,344	7,000	95
16-31 July	20,344	12,000	95
August	18,012	12,000	96
1-15 September	10,614	12,000	96
16-30 September	10,614	7,000	96



(Brune, 1953)



(Pharo and Carmach, 1979)

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3.1 - TRAP EFFICIENCY CURVES

3.2 - INFLOW & OUTFLOW TURBIDITY LEVELS

KAMLOOPS LAKE, B.C.

FIGURES 3.1, 3.2

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4 - RESERVOIR SEDIMENTATION

4.1 - Sediment Load

Suspended sediment - discharge relationships were established for gaging sites on the Susitna River. The rating curves for stations near the proposed reservoirs are illustrated on Figure 4.1. Using the flow-duration - sediment-rating curve method, the average annual suspended sediment load was estimated for the following four stations.

Gaging Station	Average Annual Suspended Sediment Load (tons/year)
Susitna River at Denali	2,965,000
MacLaren River near Paxson	543,000
Susitna River near Cantwell	6,898,000
Susitna River at Gold Creek	7,731,000

The suspended sediment load entering Watana Reservoir from the Susitna River is assumed to be that at the gaging site for the Susitna River near Cantwell, or 6,898,000 tons/year. No bedload data is available for this site. However, the channel is well-armored, and little bedload movement appears possible. Bedload at Susitna River at Gold Creek is estimated to be 1.6 percent of suspended sediment load at 37,200 cfs. Bedload movement in the Tanana River, a braided glacial river north of the Susitna River, is about 1 percent of the suspended sediment load at Fairbanks (Emmett, et.al, 1978). Consequently, bedload entering Watana Reservoir was conservatively estimated as 3 percent of suspended sediment load, or 207,000 tons/year.

The sediment contributed by the tributaries directly to the reservoirs was estimated from the unit sediment runoff per square mile between the gaging sites near Cantwell and at Gold Creek. The difference in annual suspended sediment loads at the two sites was divided by the difference in drainage areas, resulting in a unit sediment load of 412.4 tons/mi.^{2}. Bedload is again assumed to be 3 percent of suspended sediment load. The resulting tributary sediment load is 429,000 tons/year of suspended sediment and 13,000 tons/year of bedload at Watana Reservoir and 260,000 tons/year suspended sediment and 8,000 tons/year bedload at Devil Canyon. The total annual sediment load entering Watana Reservoir is estimated as 7,547,000 tons/year. The estimated trap efficiency of 70 percent for suspended sediment results in an estimated 5,349,000 tons of sediment being deposited per year, with the full 7,547,000 tons/year deposited at 100% trap efficiency.

The total annual sediment load entering Devil Canyon Reservoir consists of the sediment bypassing Watana at 70% trap efficiency, 2,198,000 tons/year, plus the tributary sediment load of 268,000 tons/year, for a total of 2,466,000 tons/year. Using trap efficiencies of 70-100 percent for suspended sediment results in 1,729,000 - 2,198,000 tons/year being trapped in Devil Canyon Reservoir.

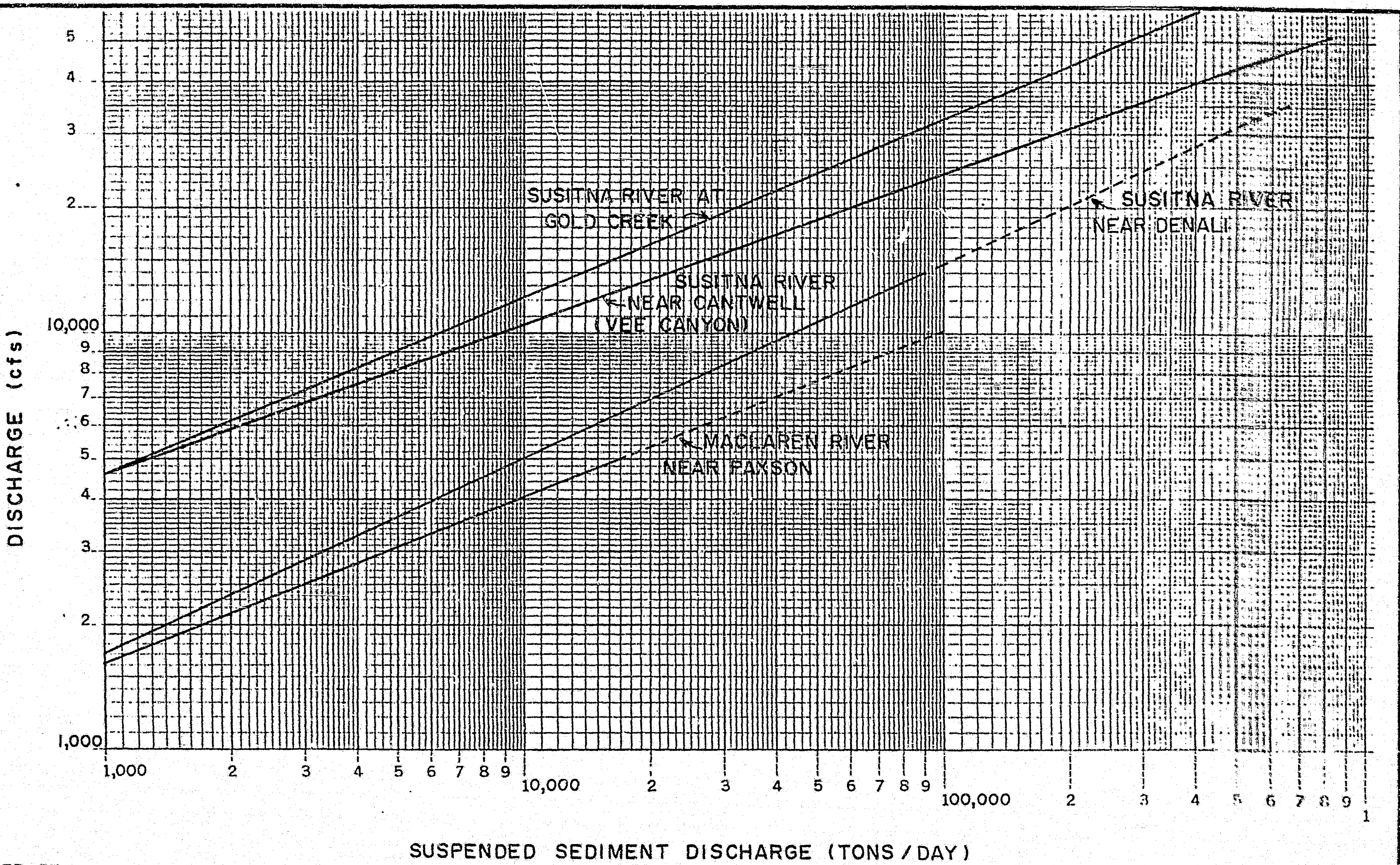
4.2 - Unit Weight of Deposited Sediment

Estimates of the volume of sediment deposited in the reservoirs require the unit weight of the deposited sediment. Published values of the unit weight of deposited sediment vary from 18 to 125 $lb/ft.^3$, depending on the sediment size, depth of deposit, degree of submergence or exposure of the deposit, and length of time the material has been deposited. The initial density for each of seven sediment sizes was estimated using the Trask method. The 50-year and 100-year unit weights were estimated using the Lane and Koelzer method (1958) as modified by Miller (1963). The sediment size analysis developed by the Corps of Engineers (1975) for the Susitna River at Cantwell (Figure 4.2) was utilized to estimate the percentage of each size range of suspended sediment entering Watana Reservoir. The resulting average unit weights for suspended sediment after 50 years and 100 years were estimated at 71.6 and 72.8 $lb/ft.^3$, respectively, assuming the sediment was always submerged or nearly submerged. The unit weight for bedload was assumed to be 97 lb/ft^3.

4.3 - Volume of Sediment Deposits

Using the sediment loads and unit weight previously developed, the following sedimentation volumes were estimated.

	50-Year	100-Year
Watana		
100% trap eff.	240,000 ac-ft.	472,500 ac-ft.
70% trap eff.	170,000 ac-ft.	334,000 ac-ft.
Devil Canyon w/Watana at 70% Trap Efficiency		
100% trap eff.	79,000 ac-ft.	155,000 ac-ft.
70% trap eff.	55,000 ac-ft.	109,000 ac-ft.
Devil Canyon w/Watana at 100% Trap Efficiency		
100% trap eff.	8,600 ac-ft.	16,800 ac-ft.
70% trap eff.	6,100 ac-ft.	6,000 ac-ft.



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SUSPENDED SEDIMENT RATING CURVES
UPPER SUSITNA RIVER BASIN

FIGURE 4.1

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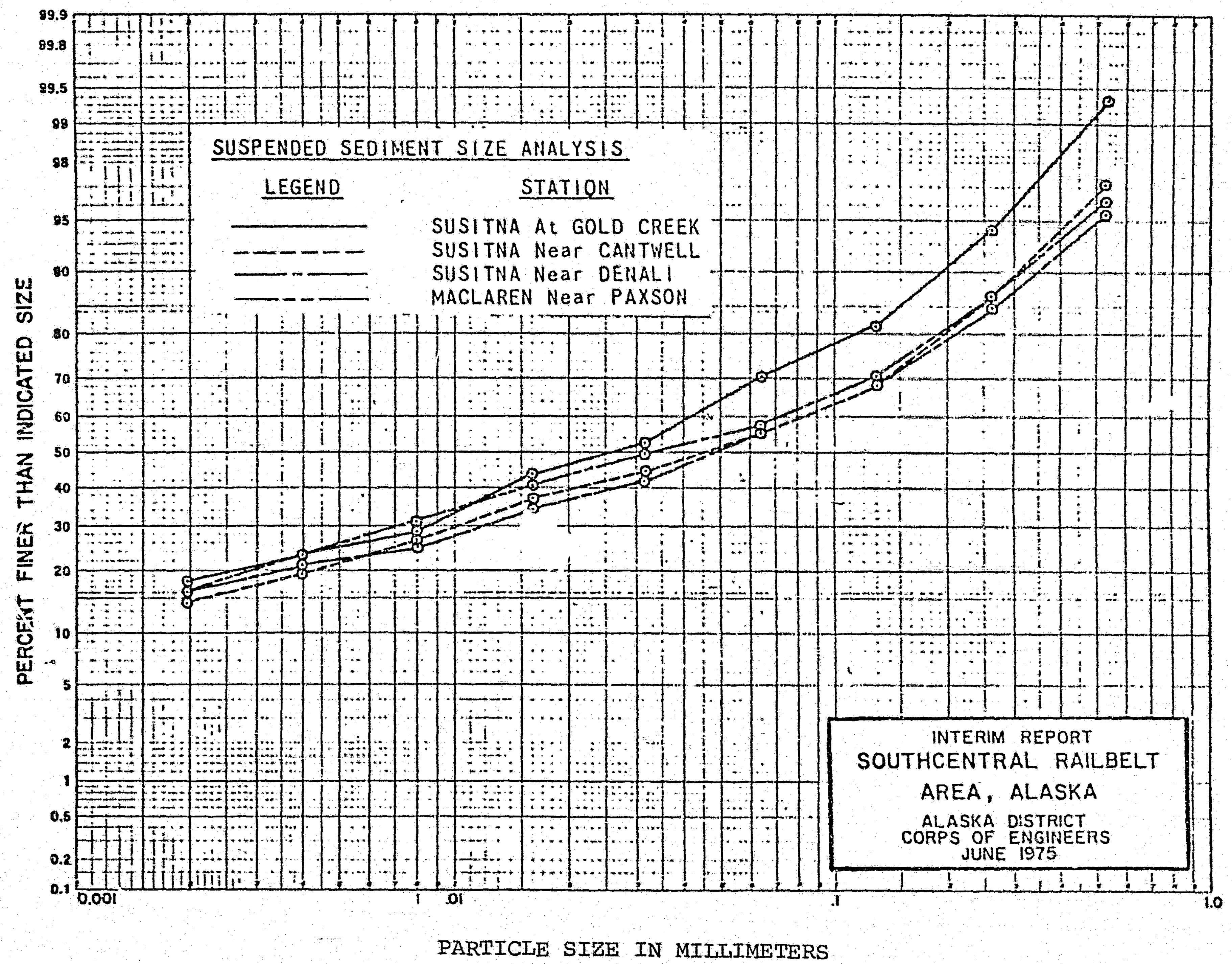

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SUSPENDED SEDIMENT SIZE ANALYSIS

SUSITNA RIVER

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FIGURE 4.2

5 - SEDIMENTATION PROCESSES AND SEDIMENT DISTRIBUTION

Sediment distribution within a lake or reservoir is dependent on several factors, including sediment characteristics, inflow-outflow relations, reservoir shape, and reservoir operation. When a stream enters a reservoir, its velocity drops sharply due to the large increase in cross-sectional area, with a subsequent decrease in the stream's sediment-transport capacity. As the velocity decreases, the coarser particles are deposited initially, forming a delta at the river's mouth. Much of the fine-grained suspended sediment is carried past the delta to be deposited in the deeper parts of the lake.

5.1 - Delta Deposits

As a stream enters a standing water body the channel form and process are altered in the backwater conditions. Bed aggradation and reduced flow velocities extend upstream some distance from the lake. Although most of the fine-grained suspended sediment passes through the backwater zone, much of the bed load is deposited, thus lowering the bed slope and raising the water surface and stream bed elevations. As the delta builds, the front forms a sharp slope break over which the remaining bedload is dumped. As sedimentation continues, the river channel changes to accomodate the changed profile so that sediment continues to be carried to the delta front before being deposited. Examples from Lake Mead on the Colorado River (Lara and Sanders, 1970) and glacial Lake Lillooet, British Columbia (Church and Gilbert, 1975) illustrate the resulting morphology (Figure 5.1). A second process, noted by Pharo and Carmacks (1979) in Kamloops Lake, British Columbia, is that of episodic density surges which redeposit material initially dumped on the delta slope. Sediment density surges differ from the third process, that of river plume dispersion (as overflow, interflow, or underflow), in that density surges are episodic and relatively short-lived compared to the relatively continnous nature of river plume dispersion; sediment density surges involve the redeposition of material already deposited on the delta slope, rather than the uninterrupted extension of river-borne sediment into the lake; and sediment concentrations within sediment density surges dominate the fluid density and drive the downslope flow.

There will be considerable variation in the summer water levels at Watana Reservoir, resulting in a complex delta formation at the head of the reservoir, with the bed elevation trying to re-establish equilibrium.

5.2 - Glacial Lake-Floor Sedimentation

It has been noted by several authors (Embleton and King, 1975; Bryan, 1974) that glacial lake-floor deposits beyond the area of delta growth are predominantly fine, becoming increasingly so as the central or deepest parts of the lake are approached. The very fine material is the glacial rock flour which discolors the water of glacial streams and lakes, and which often requires long periods and quiet water conditions to settle (E.M. Kindle, 1930).

Deep lakes offer the best opportunities for the trapping and deposition of the finest material. In shallow glacial lakes, the existence of more powerful currents prevents the settling of fine material, and often cause it to be washed towards and through the lake outlet, resulting in its loss from the lake.

Glacial lake floor deposits are often laminated, caused by sudden changes of grain size from finest mud to slightly coarser silt between successive thin layers, and often accompanied by a color change between layers. These laminated deposits are known as rhythmites, with an individual pair of one fine and one slightly coarser layer known as a couplet. The thin dark layer of a couplet consists of very fine and partly colloidal material, representing a period of slow deposition under very quiet water conditions, such as when a lake was frozen over in winter with little or no meltwater entering. The light-colored coarser layer indicates a more rapid period of sediment deposition under more disturbed conditions, such as when meltwater is entering the lake and lake currents are spreading silt over the whole lake floor. Some couplets form on an annual basis, and are known as varves. De Geer (1912) indicated that the fine lamina of a couplet was the result of deposition in winter when the lake was frozen and meltwater limited. The abrupt break at the top of the fine lamina represents the spring thaw when new coarser silt enters the lake. Confirmation of this theory has come from pollen studies of rhythmites, and from studies of modern glacial lake-floor deposits, such as that made by W.A. Johnston (1922) on Lake Louise, Alberta. Nonannual rhythmites may also form from sudden fluctuations in discharge, such as from the bursting of an ice-dammed lake upstream, unseasonal warm or cold spells, or periodic storms.

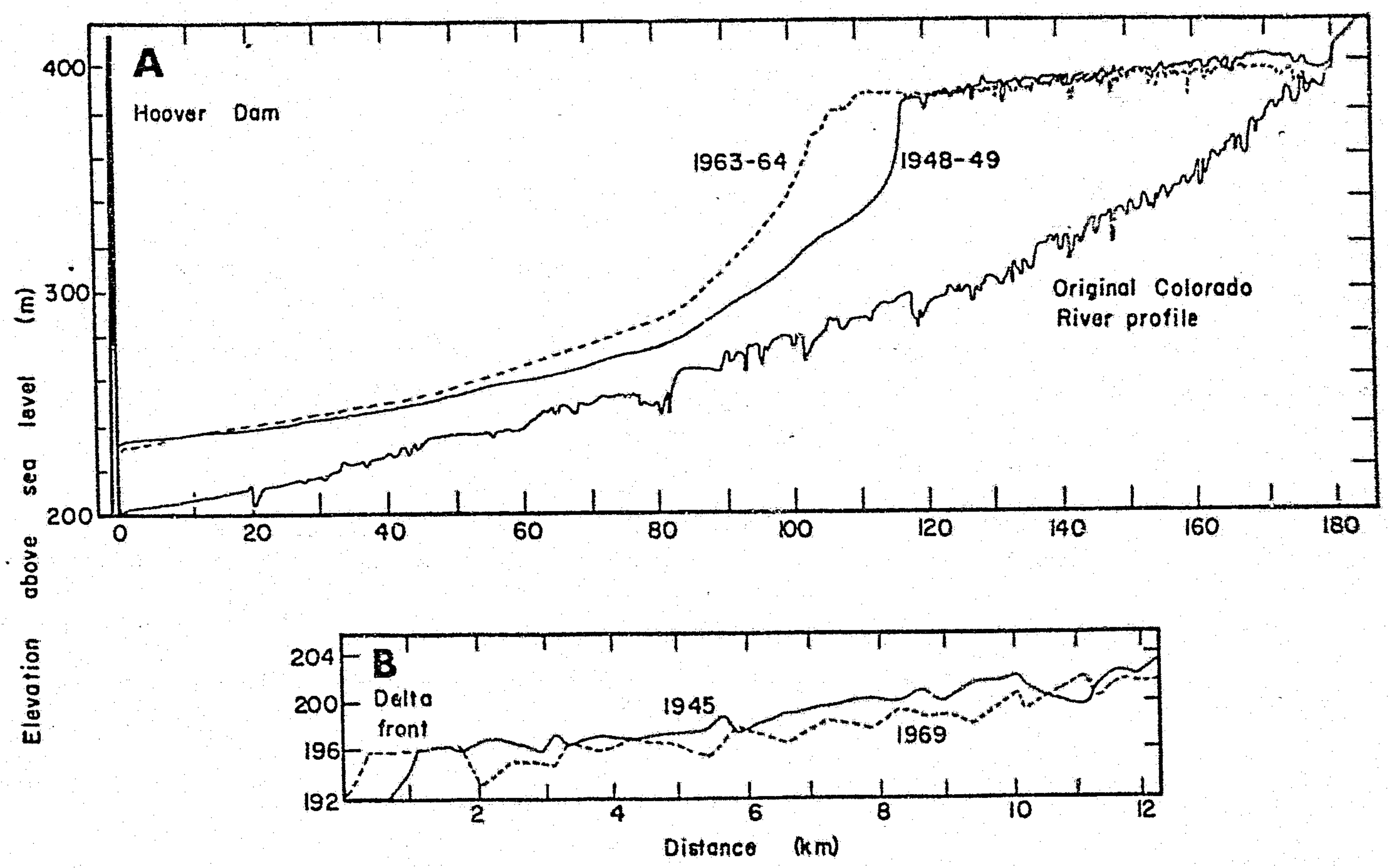
The deposition of the coarser laminae is attributed to turbid underflows and interflows of denser sediment-laden water from glacial meltwater streams. The phenomena of underflow and interflow have been noted in numerous studies of sedimentation in glacial lakes (Emerson, 1898; Kuenen, 1951; Mathews, 1956; Gilbert, 1973; Bryan, 1974 a, b; Theakstone, 1976; Ziegler, 1973; Østream, 1975; Gustavson, 1975; Pharo and Carmack, 1979). The frequency, duration, and intensity of the underflows and interflows have been attributed to stream temperature and sediment load, temperature and suspended sediment distribution in the lake, and lake bathymetry, especially near the stream mouth.

The uninterrupted downlake transport of the silt and clay - sized material was noted as being due to the interflow process in Kamloops Lake (Pharo and Carmack, 1979). During summer the lake surface waters warm more rapidly than those of the incoming river. The river water first moves to the plunge line, where it sinks and flows down along the slope of the delta as a turbulent gravity current. The plume entrains lake water as it sinks, causing convergence at the lake surface and resulting in a color change at the plunge line. When the plume reaches a depth where its density is approximately equal to that of the lake water, the river plume with its large suspended load leaves the bottom slope and spreads horizontally along lines of equal density (temperature), as illustrated in Figure 5.2. The interflow is indicated by the tongue of turbid water extending from the face of the river delta at a depth of about 20 m. The flow parallels isothermal surfaces, and is modified by the Coriolis force so that the river plume is directed towards the right hand shoreline in the direction of flow. The preferential movement to the right-hand side was evidenced by both higher turbidity readings and coarser sediments along the right-hand shore of the lake. A schematic of the three interdependent but distinct processes controlling sediment transport and deposition within Kamloops Lake is shown in Figure 5.3.

As previously noted, glacial lake-floor sediments become increasingly fine as the central or deepest parts of the lake are reached. Grain size distribution in Kamloops Lake varied from 0.5 mm near the lake inlet to 0.002 mm (2 microns) near the lake outlet. Accumulation rates decreased with distance from the delta, with rates of 8.00 cm/year adjacent to the delta decreasing to 0.35 cm/year near the lake outlet. Not all sediment was deposited in Kamloops Lake. Measurement of inflow and outflow turbidity levels indicated that nearly one third of the incoming sediment was not deposited, with the percentage varying with time. As illustrated in Figure 3.2, turbidity at the lake outlet increased following periods of very high turbidity levels at the inlet.

5.3 - Glacial Lake Temperatures

Deep glacial lakes commonly show temperature stratification (Mathews, 1956; Gilbert, 1973; Pharo and Carmack, 1979, Gustavson, 1975), although stratification is often relatively weak. Bradley Lake, Alaska, (Figure 5.4) demonstrated a weak thermocline in late July, 1980, but was virtually isothermal by late September, and demonstrated a reverse thermocline during winter months (Corps of Engineers, unpublished data). Temperature data for Kluane Lake (Bryan, 1974b) are also illustrated in Figure 5.4. Selected thermal profiles from Malaspina Lake, Alaska, are illustrated in Figure 5.5 (Gustavson, 1975), as are bathythermograms showin the destruction and reforming of the thermocline in Lillooet Lake (Gilbert, 1973) during periods of strong underflow. Garibaldi Lake, British Columbia, also demonstrates a thermocline in the summer months, as seen on Figure 5.6 (Mathews, 1956).



Profiles of (A) Colorado River at Lake Mead (after Lara and Sanders, 1970, p. 155) and (B) Lillooet River at Lillooet Lake, showing that the greatest accumulation on an established delta occurs at the delta front and on the foreset beds. Lake Mead data reproduced by courtesy of the *United States Bureau of Reclamation.*

(Church and Gilbert, 1975)

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DELTA FORMATION

LAKE MEAD AND LILLOOET LAKE

FIGURE 5.1

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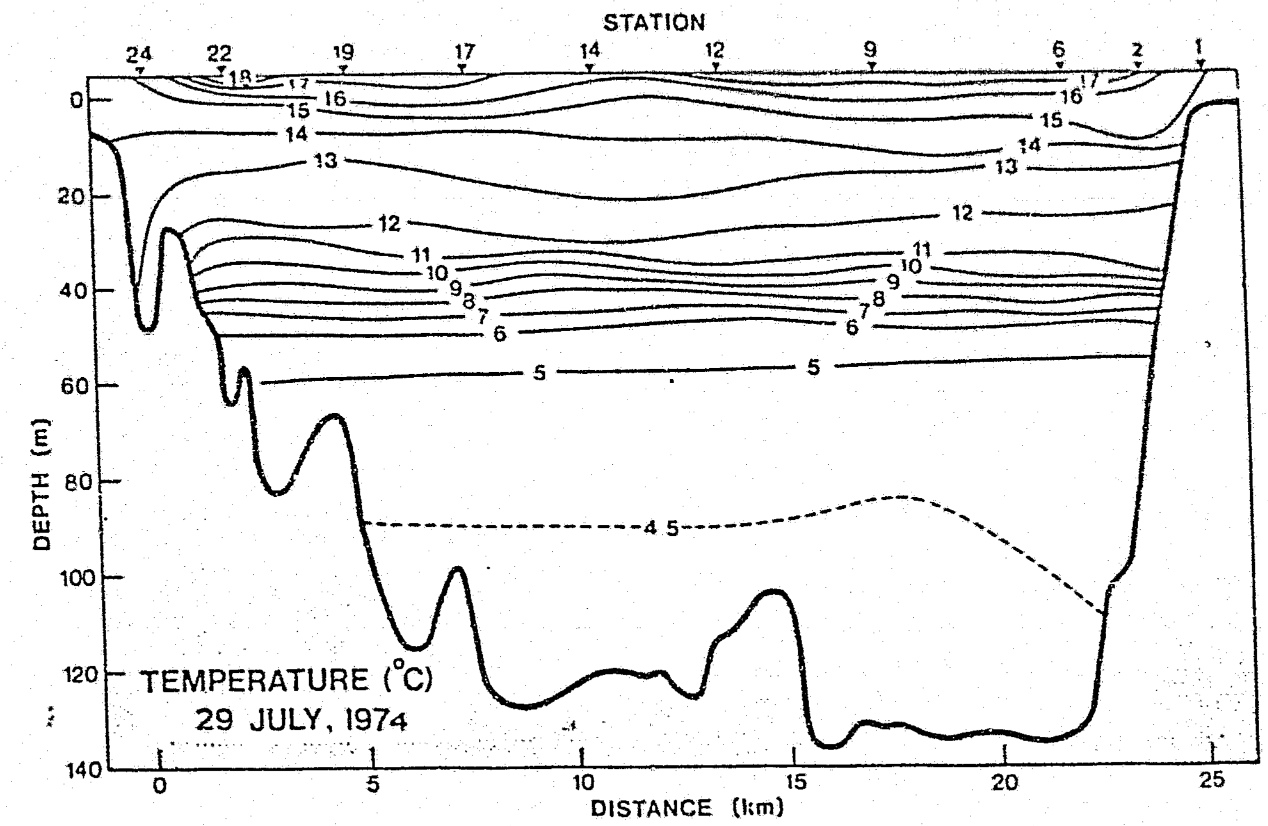

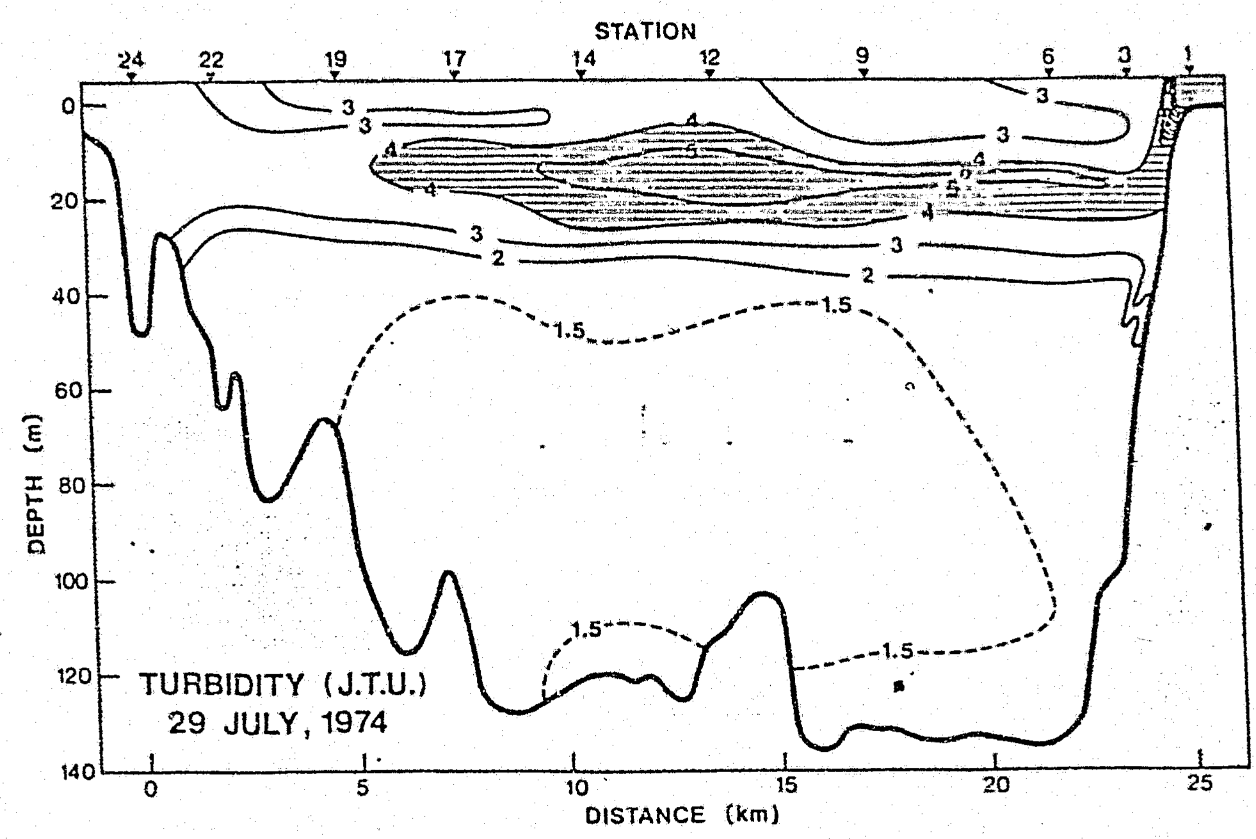

(Plan and Carmachs, 1979)

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TEMPERATURE & TURBIDITY ISOLINES

KAMLOOPS LAKE

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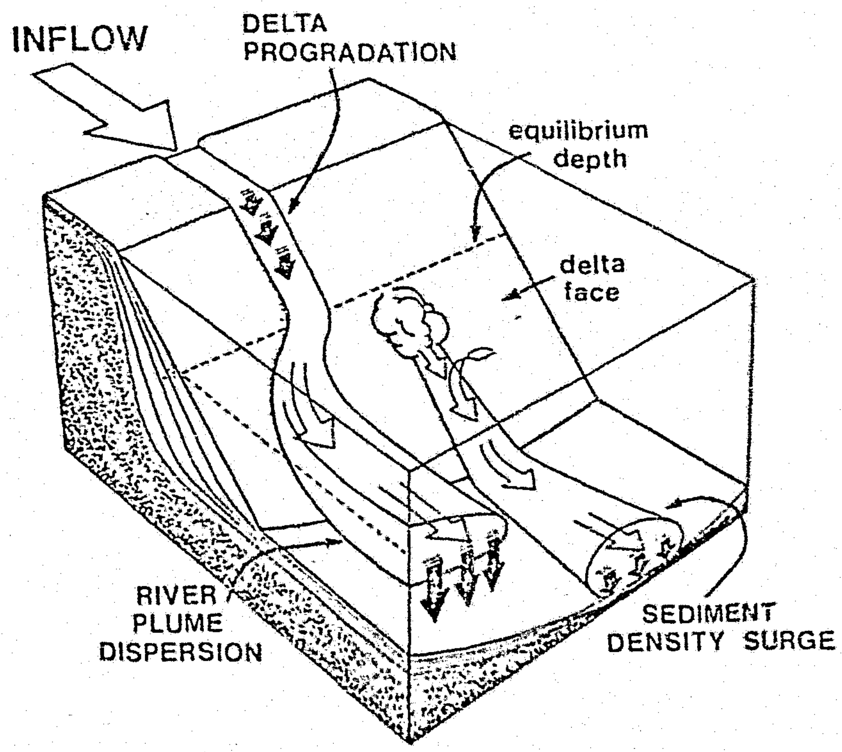
FIGURE 5.2



NOTE:
BLACK ARROWS DENOTE SEDIMENTATION
LIGHT ARROWS DENOTE FLUID MOTION

Schematic illustration of sediment transport and deposition mechanisms associated with a river entering a lake assumed to be temperature stratified. The equilibrium depth is that at which the inflowing river water has the same density as the lake water, and at which the river water flows down the lake.

(Pharo and Carmachs, 1979)

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SCHEMATIC OF SEDIMENTATION PROCESSES

KAMLOOPS LAKE

FIGURE 5.3

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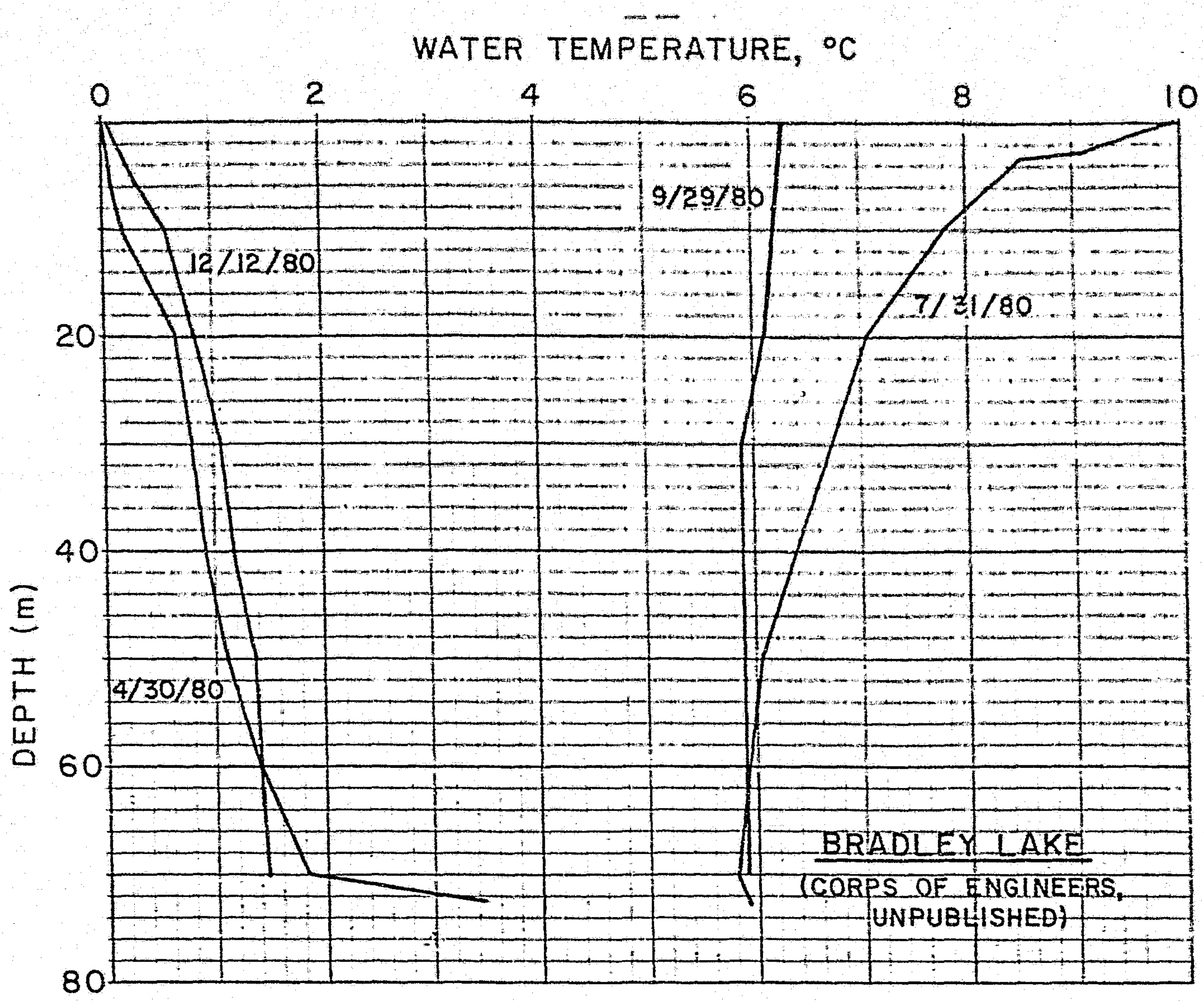

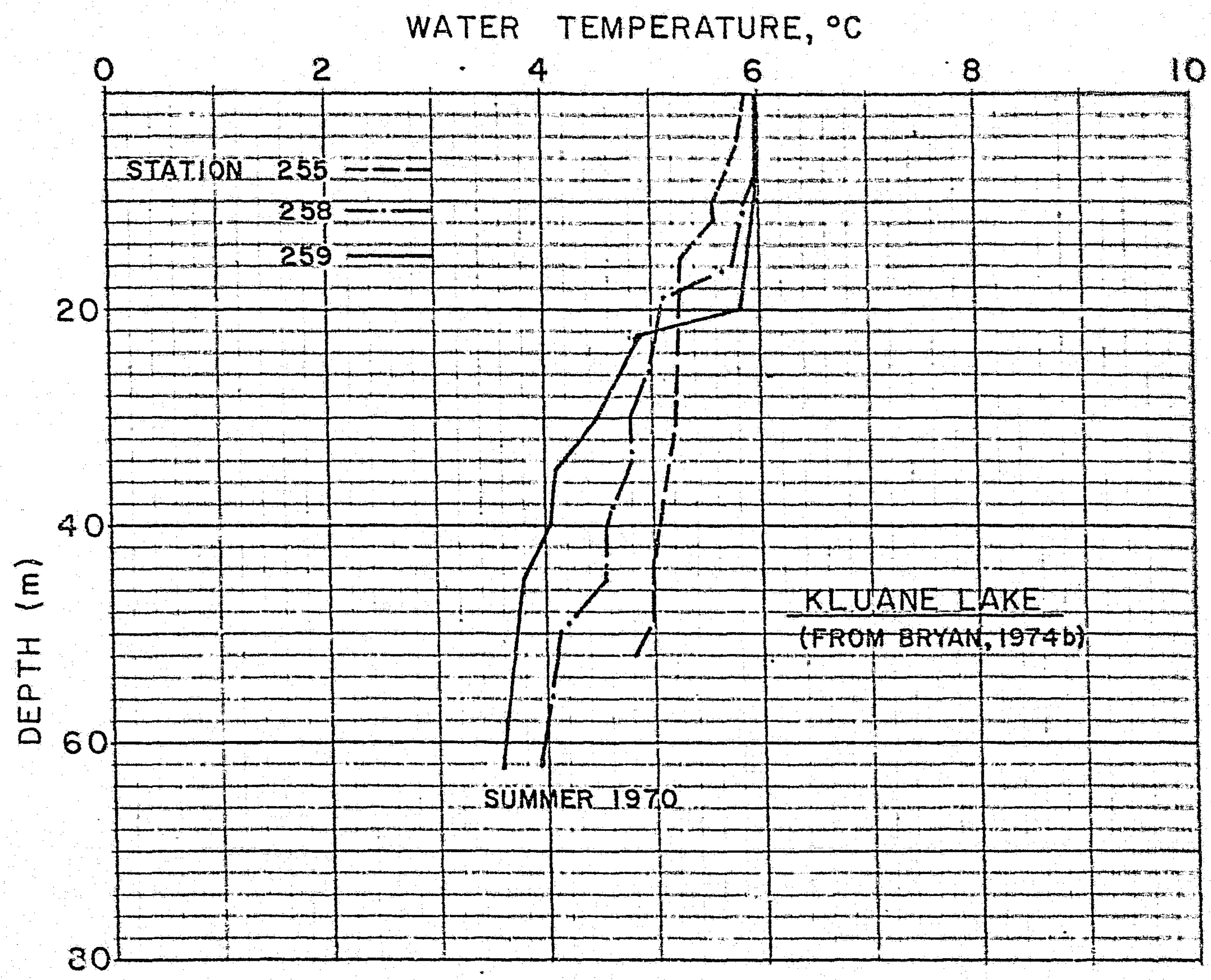

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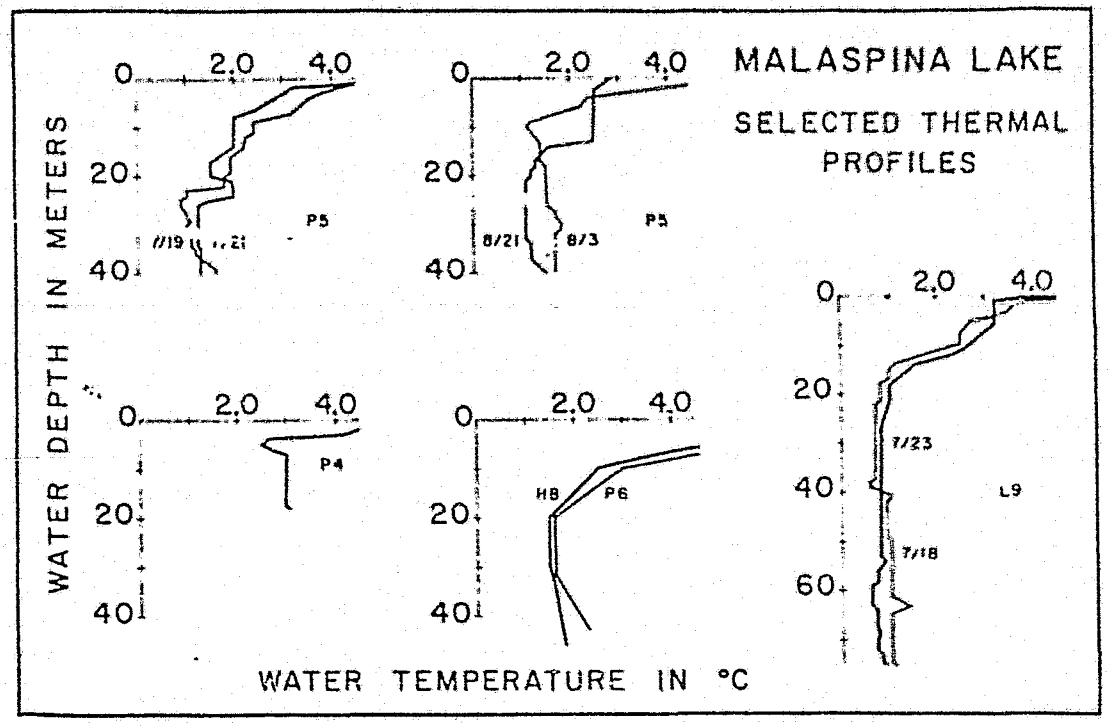
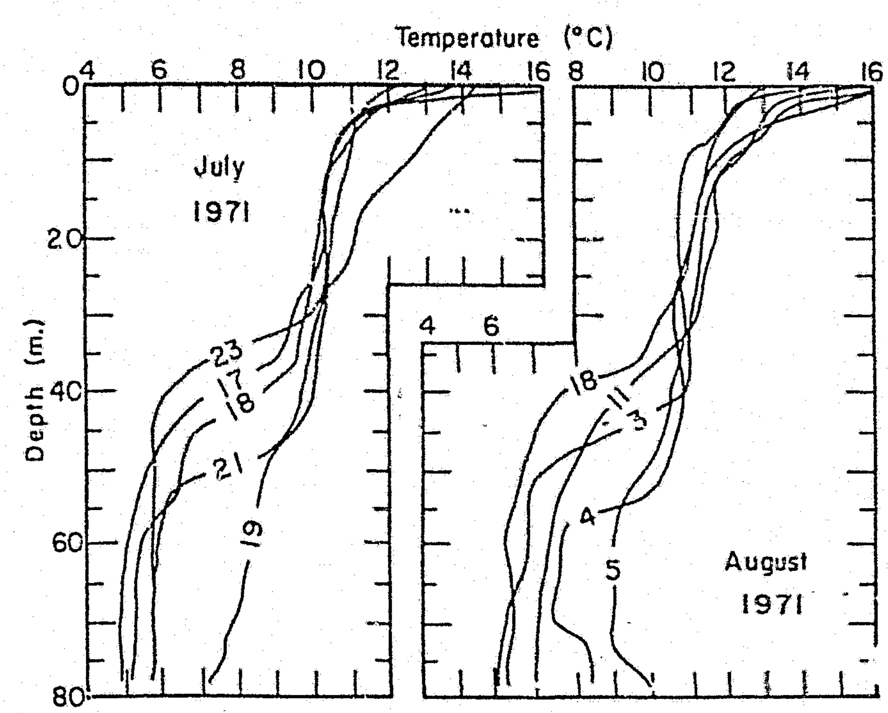
WATER TEMPERATURE PROFILES
BRADLEY LAKE, ALASKA AND
KLUANE LAKE, YUKON TERRITORY

FIGURE 54



Water temperature throughout Malaspina Lake decreases with depth. [illegible] (P5) [illegible] instrument station (fig. 3) where thermal profile was recorded. Two profiles [illegible] identified by date (7/21) on which they were recorded. Profiles measured in [illegible]

(Gustavson, 1975)



Bathythermograms showing the destruction and reforming of the thermal structure of Lillooet Lake associated with two periods of strong interflow and underflow. Numbers refer to dates of the observations in July and August 1971.

(Gilbert, 1973)

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TEMPERATURE PROFILES, MALASPINA LAKE, ALASKA, & DURING STRONG UNDERFLOW, LILLOOET LAKE, B.C.

FIGURE 5.5

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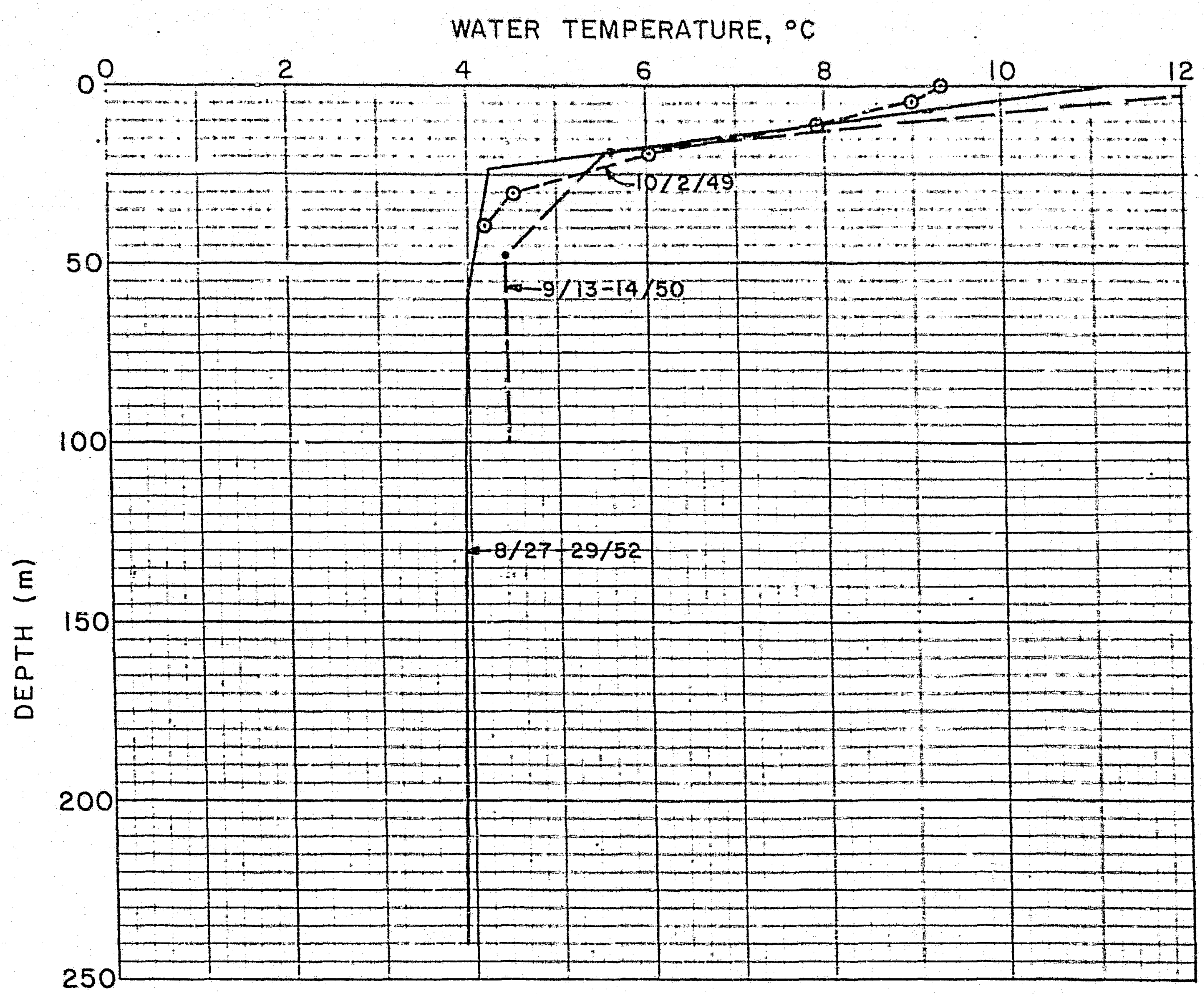

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WATER TEMPERATURE PROFILES
GARIBALDI LAKE, BRITISH COLUMBIA

FIGURE 5.6

ACRES

6 - RESERVOIR AND DOWNSTREAM TURBIDITY

The reservoirs will have a significant impact on the turbidity of the Susitna River between Devil Canyon and the Susitna-Chulitna confluence, with the river being considerably less turbid in the summer and possibly more turbid in the winter. A rigid quantitative analysis is not possible with the available data. However, a qualitative analysis discussing the interrelated factors will shed some light on the probable post-project turbidity in the reservoir and downstream of Devil Canyon.

6.1 - Pre-Project Turbidity

Turbidity data for the Susitna River were reviewed for the Gold Creek and Vee Canyon sites. The U.S. Geological Survey gathered turbidity data during 1974, 1975 and 1976, with turbidity visually measured in Jackson Turbidity Units (JTU). R&M Consultants measured turbidity using photoelectric detectors during 1980 and 1981 at both the Gold Creek and Vee Canyon sites, with the data presented in nephelometric turbidity units (NTU). The units are approximately equivalent, but due to the subjective nature of visual observations, nephelometric means are generally considered more accurate, especially in the lower ranges of turbidity (less than 40 NTU's).

The nephelometric turbidity data was logorithmically plotted against vertically integrated samples of suspended sediment concentration for the Gold Creek and Vee Canyon sites. The plots, regression equations and correlation coefficients for both sites are shown on Figure 6.1. Best fits for the data were obtained by the general equation $T = a[ss]^b$, where T is turbidity, ss is suspended sediment concentration in mg/l, and a and b are coefficients. Sediment concentration and turbidity have a very high correlation. Available USGS data were also analyzed to obtain relationships for discharge and suspended sediment concentration for the above two gaging sites. The following relationships were derived for turbidity, suspended sediment concentration, and discharge.

Susitna River near Cantwell

$$T = 0.3568(ss)^{.8607}, \quad n = 9, \; r^2 = 0.98$$
$$ss = 0.0000553\, Q^{1.70}, \quad n = 37, \; r^2 = 0.703$$

Susitna River at Gold Creek

$$T = 0.2496(ss)^{.9551}, \quad n = 6, \; r^2 = 0.95$$
$$ss = 0.000673\, Q^{1.381}, \quad n = 332, \; r^2 = 0.585$$

The poor correlation coefficients between suspended sediment concentration and discharge are to be expected on glacial rivers, where glaciers contribute irregular amounts of sediment.

Even though the determine coefficients are rather poor, the regression equations are still useful in determining the seasonal variation in turbidity. The turbidity-suspended sediment concentration equations and the suspended sediment concentration - discharge euqations were used together with the mean daily flow summary hydrographs for the two sites to estimate the monthly pattern of turbidity. The summary hydrographs used are found in the Corps of Engineers Interim Feasibility Report (1975). The resulting estimated average annual turbidity patterns are shown on Figure 6.2. The actual turbidity patterns show much greater variation in a single year due to the larger variations in suspended sediment concentration.

6.2 - Factors Effecting Turbidity

Reservoir sedimentation processes described in Section 5.2 are the main processes affecting reservoir turbidity. The sediment-laden river will enter the reservoir as either overflow, interflow, or underflow, depending on its density relative to that of the reservoir waters. Once it reaches its equilibrium density level, the inflowing river plume spreads horizontally along lines of equal density. The flow parallels isothermal surfaces, and is modified by the Coriolis force so that the river plume is directed towards the right hand shoreline in the direction of flow.

The turbidity at the reservoir outlet is also dependent on the residence time of inflowing waters in the reservoirs. Watana Reservoir has mean annual bulk residence time (volume/mean annual streamflow) of 600 days, with Devil Canyon having a mean annual bulk residence time of 60 days. However, the bulk residence time varies with flow, with the bulk residence time decreasing to about 110 days for the mean annual flood entering Watana. The residence times for summer flows are affected by the relative reservoir level. As the reservoirs will be filling during the early high flow periods, the residence time would be somewhat increased above 110 days for the breakup flood.

The long residence times indicate that an ice cover would form before much of the late summer flow passes through the reservoirs. Settling column studies (Appendix A) indicated that suspended sediment rapidly settled out under quiescent conditions, with turbidity also rapidly decreasing (Figure 6.3). Once an ice cover forms, essentially quiescent conditions will exist in the reservoirs, with wind action no longer disturbing the surface, and inflow dropping to minimal levels. Consequently, relatively rapid sedimentation should commence once an ice cover forms, with surface waters rapidly clearing beneath the ice. The turbidity of inflowing waters is also quite low during this period, thus contributing little additional sediment.

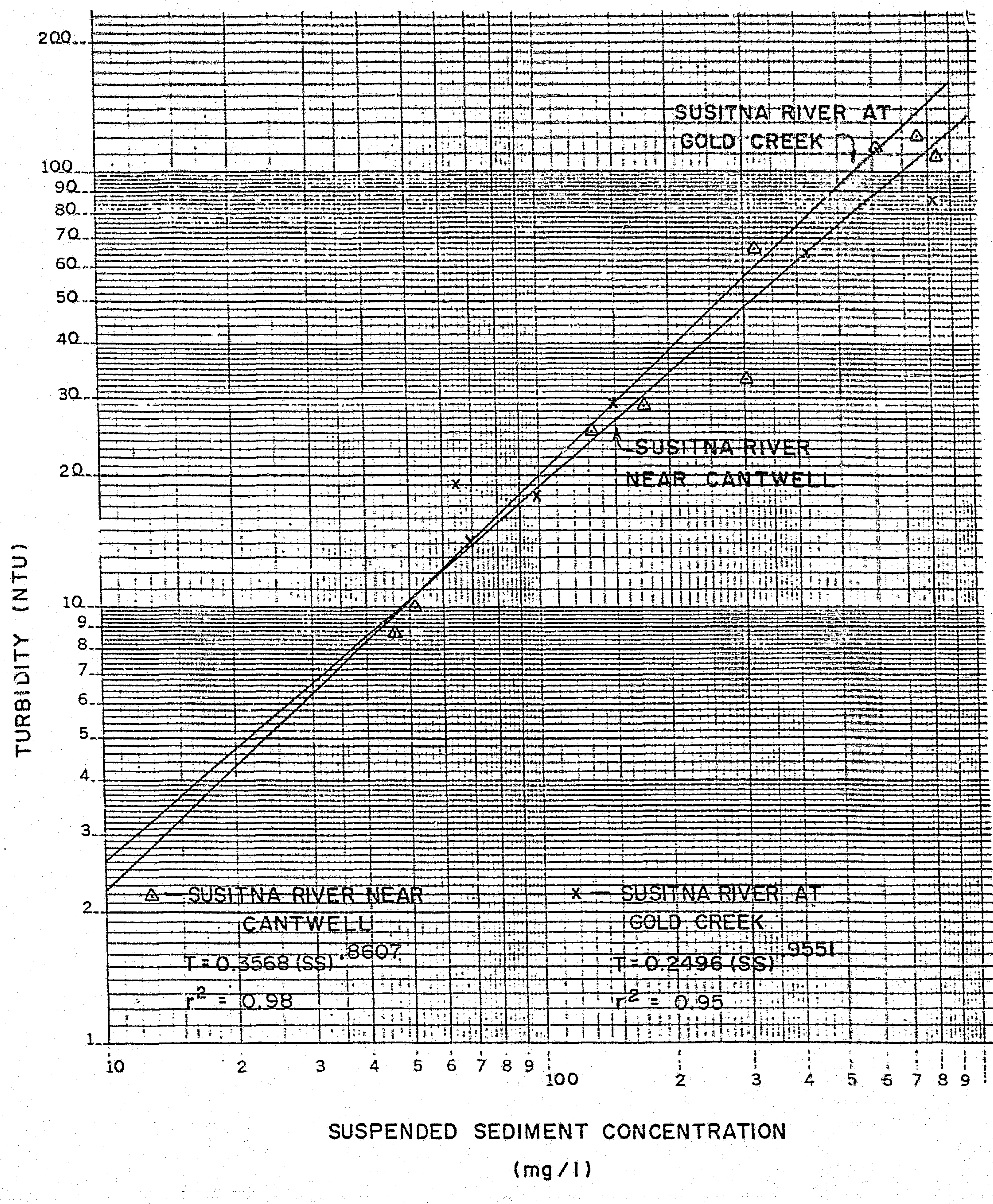
6.3 - Post-Project Turbidity

A discussion of the timing of certain events occurring within the reservoirs and Upper Susitna River will serve to help describe the changes in the turbidity pattern. Breakup normally occurs in late April or early May on the Susitna River. Suspended sediment concentrations and turbidity sharply increase in May, and remain high into September, as the glaciers are contributing significant amounts of sediment during their melt period. However, the ice cover on the reservoirs will remain longer than ice now remains on the river, as the lake ice will not be flushed out of the system by breakup but will instead melt in place. Consequently, relatively quiescent conditions will occur through most of the lake until the ice cover has significantly decreased, which will probably not occur until late May or early June. Even though turbid water will enter the reservoir in early May, an increase in turbidity in outlet waters should not occur until early to mid-June.

During the summer months, turbidity will increase as suspended sediment concentrations increase at the reservoir inlet. Pulses of sediment may pass through the reservoir when very large sediment concentrations enter the reservoir, such as during a large flood, but they will be sharply dampered. The pattern will probably be similar to that shown at Kanloops Lake on Figure 3.2, except that the decrease should be even larger in the Susitna River system due to relatively larger size of the reservoirs (longer residence time).

Downstream turbidity can not be accurately quantitied, but tentative estimates indicate that is possible that it will not exceed maximum values of 35-45 NTU during peak flows, and will normally be in the 10-20 NTU range during summer months, based on cursory estimates from flow suspended sediment concentrations, trap efficiency, and reservoir outflow. Reservoir turbidity will decrease in the downstream direction as the larger sediment sizes settle out.

In September and October, inflowing turbidity levels to the reservoir are significantly less than summer values, as the glaciers contribute less meltwater and sediment. Ice cover on the reservoirs will normally start to form about the third week in October. Once the ice cover forms, essentially quiescent conditions occur, and turbidity in the upper levels of the reservoir should rapidly decrease.



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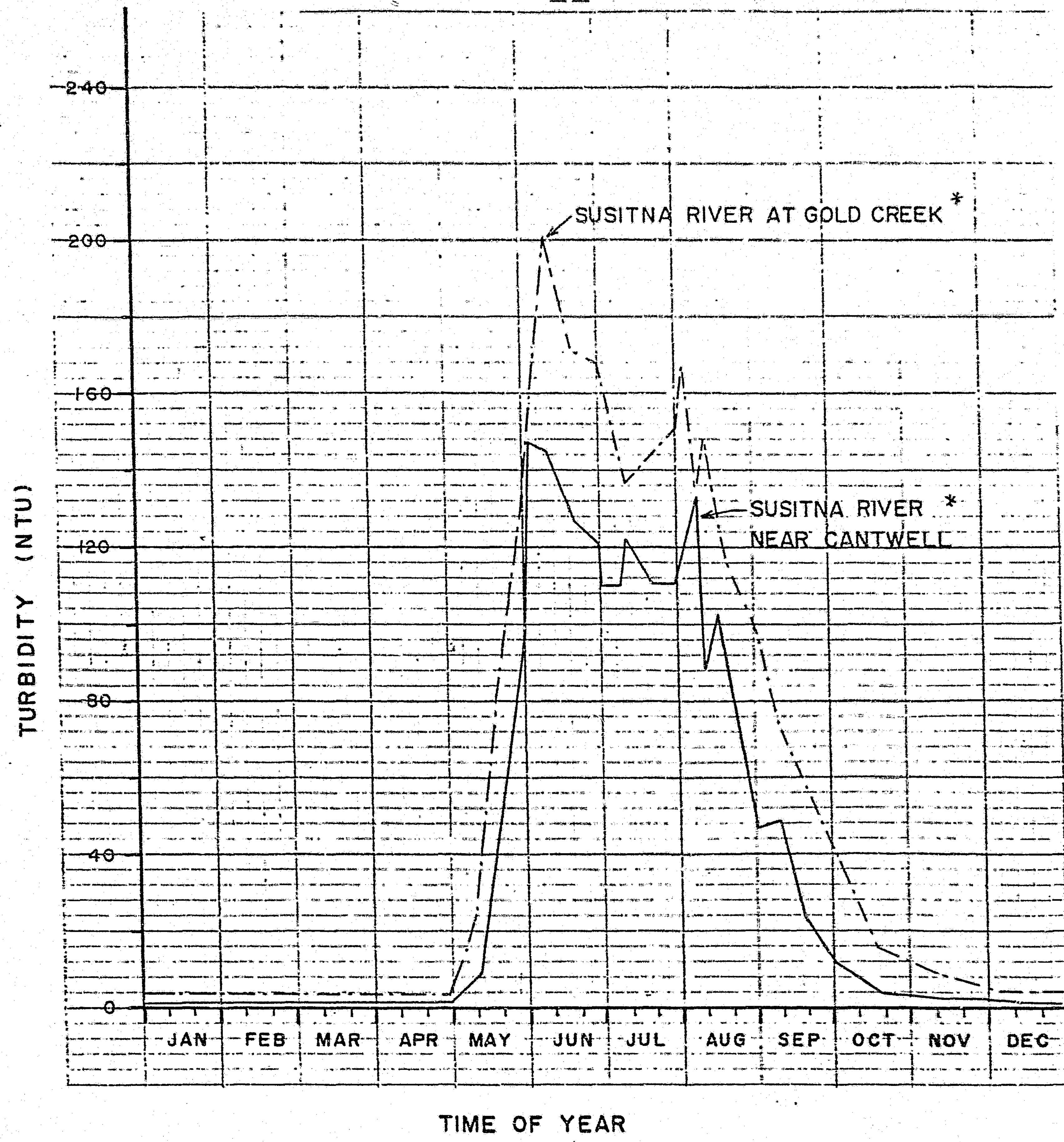
TURBIDITY VS. SUSPENDED SEDIMENT CONCENTRATION

FIGURE 6.1



* Curves are estimates based on the mean daily flow summary hydrographs and from regression equations relating discharge, suspended sediment concentration, and turbidity. Turbidity in a single year displays greater daily variation.

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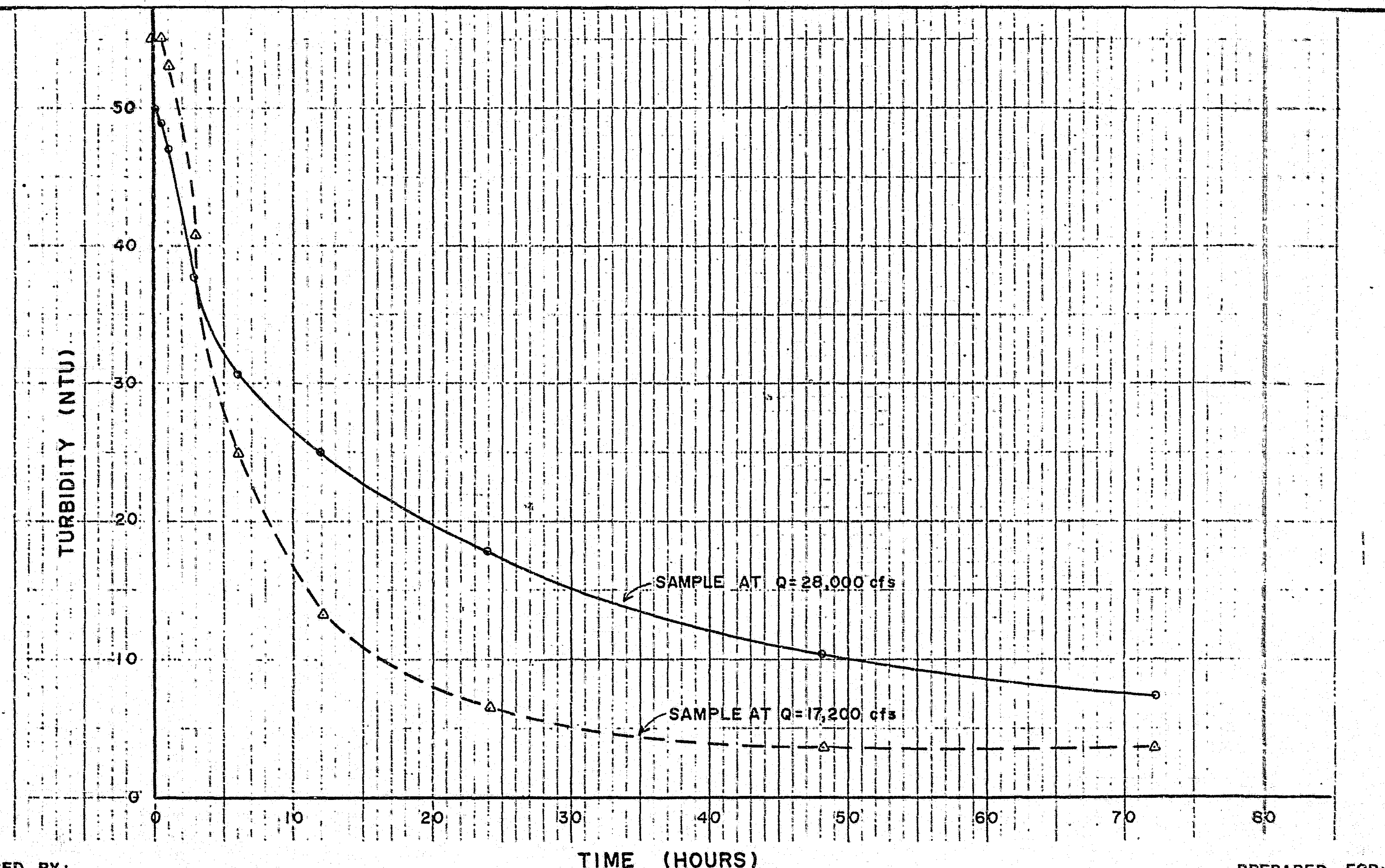
AVERAGE ANNUAL TURBIDITY PATTERN
SUSITNA RIVER

FIGURE 6.2



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TURBIDITY VS TIME

SUSITNA RIVER

SETTLING COLUMN STUDY

FIGURE 6.3

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7 - PROJECTED RESERVOIR SEDIMENTATION

Trap efficiency estimates using the Brune curve indicate 90-100 percent of the incoming sediment will be trapped in the reservoirs, even shortly after reservoir filling, but sedimentation studies at glacial lakes indicate that fine glacial sediment may pass through the lake. Delta formation at the head of the reservoir will be constantly adjusting to the changing water level. Sediment passes through the channels on the delta to be deposited over the lip of the delta. Depending on the relative densities of the lake water and the river, the sediment-laden water will either enter the lake as overflow, interflow, or underflow (turbidity current). It is probable that the turbid summer flows of the Susitna River will initially dive below the surface, seeking an equilibrium density layer. The settling process will then commence somewhere below the surface.

Estimates of the total amount of deposition of fine flacial sediment in the reservoirs are somewhat uncertain. Glacial lakes immediately below glaciers have trap efficiencies of 70-75%. Kamloops Lake, B.C., retains about 66% of the incoming sediment. Sediment concentration at the outlet of Kamloops Lake increased during periods of high sediment inflow, which would correspond to high stream flows. Kamloops Lake is a natural lake, so retention time of high flows decreases to about 20 days during the spring freshet. However, Watana Reservoir has significant active storage capacity. During the May - July period the reservoir will normally be filling, so that outflow will be much less than inflow. The increased residence time due to refilling of the reservoir would tend to allow more of the sediment to settle. Once the reservoir is full, there may be periods of increased turbidity downstream following periods of very high streamflow, similar to that evidenced at Kamloops Lake on Figure 3.2. The median grain size at the lower end of Kamloops Lake was 0.002 mm, and appeared to be uniformly distributed across the lower end of the lake. The suspended sediment size analysis for stations on the upper Susitna River (Corps of Engineers, 1975), shown on Figure 4.2, indicates that about 15 percent of the suspended sediment entering Watana Reservoir (Susitna River near Cantwell gaging station) is smaller than 2 microns (.002 mm). The trap efficiency of Watana Reservoir is estimated be between 70 - 97 percent, with only the material finer than 2 microns possibly passing through the reservoir.

The minimum assumed trap efficiency for Devil Canyon Reservoir is 70 percent, based on data from other lakes. However, it is possible that the trap efficiency may be much lower, as only fine material with very slow settling rates would pass through Watana Reservoir.

Based on the results of the settling column studies, (App. A) much of the suspended sediment still in suspension when an ice cover forms would settle, as quiescent conditions would soon be prevalent.

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APPENDIX A

SETTLING COLUMN STUDIES

SETTLING COLUMN STUDIES

Settling column studies were conducted to obtain data on the settling rates of suspended sediment and on time based turbidity levels of Susitna River water after it enters standing water.

Procedure

Two 55 gallon water samples were obtained from the Susitna River near Watana damsite. These samples were taken in an area of turbulent flow using a pump whose inlet depth was varied to allow depth integrated sampling. The samples were retrieved at the following flow rates and water temperatures.

Sample #1	July 29, 1981 at 3:00 p.m.	28,000 c.f.s.	50°F
Sample #2	Sept. 3, 1981 at 5:00 p.m.	17,200 c.f.s.	46°F

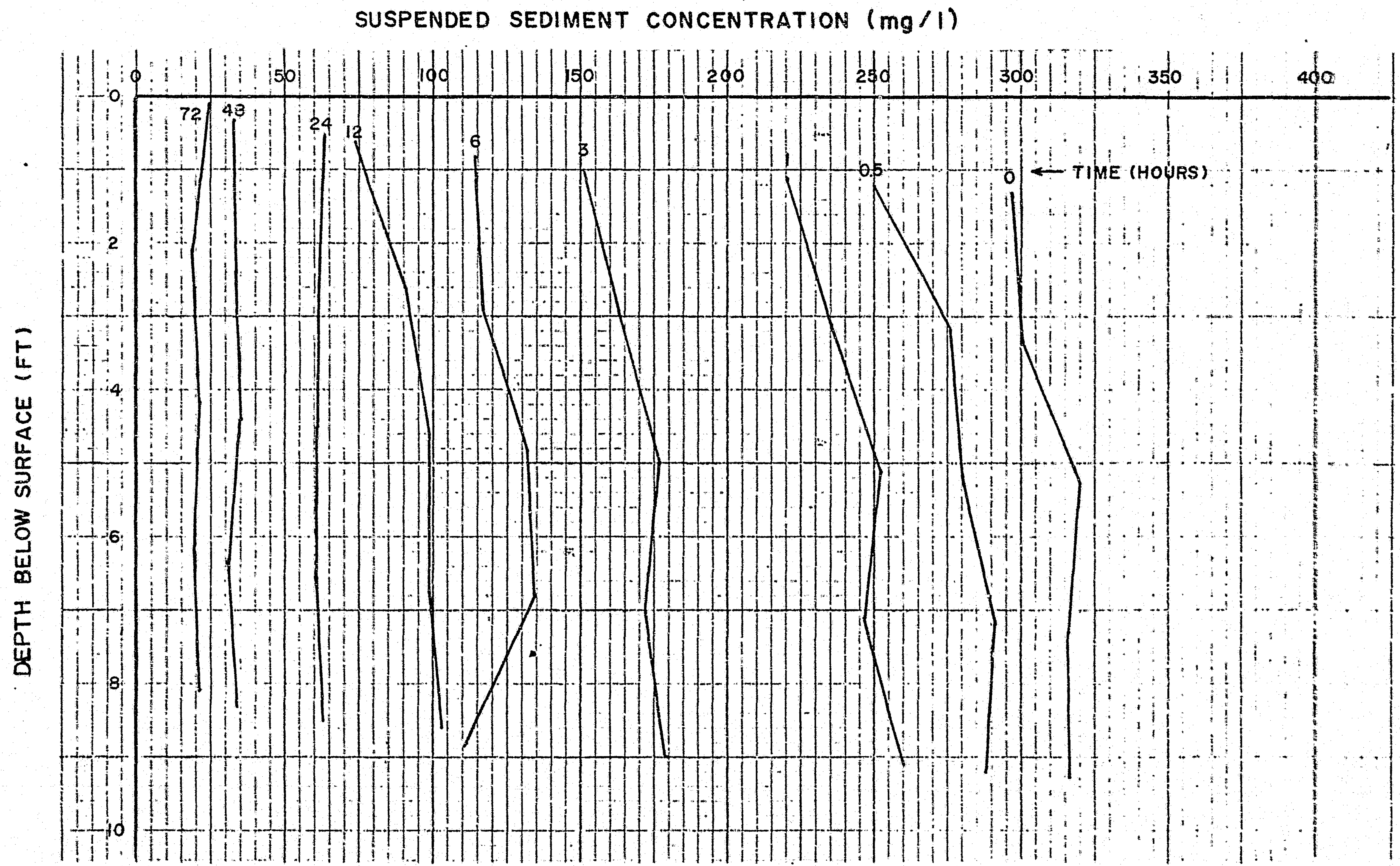
The samples were placed in the settling columns, thoroughly mixed and initial (time zero) samples taken from ports which were located at 0.5, 2.5, 4.5, 6.5 and 8.5 feet from the bottom of the column. The depth of water in the columns varied during testing as water was removed for testing. In column 1 the average depth of water was 9.2 feet and in column 2 the average depth was 8.9 feet.

Samples were taken at 0, 0.5, 1, 3, 6, 12, 24, 48 and 72 hour intervals and analyzed for turbidity (N.T.U.) and total suspended solids (T.S.S. in mg./liter). Air and water temperatures at these times were also recorded.

Results

Results of the settling column studies are illustrated for suspended solids in Figures A.1 and A.2. In 72 hours, total suspended sediment concentration decreased by 93% in the 28,000 cfs sample and by 98% in the 17,200 cfs sample. Little density stratification was noted in the 28,000 cfs sample during the settling period, but was more noticeable in the 1-6 hour period for the 17,200 cfs sample.

Turbidity levels showed a similar decrease. The composite average for each time period is shown on Figure 6.3. There was little variation in turbidity with depth. As would be expected from the suspended sediment results, turbidity decreased significantly, with reductions of 85 percent for the 28,000 cfs sample and 94 percent for the 17,200 cfs sample.



SAMPLE COLLECTED ON 29 JULY 1981, 1 MILE ABOVE WATANA DAM SITE
WATER TEMPERATURE (7/29/81) = 50° F

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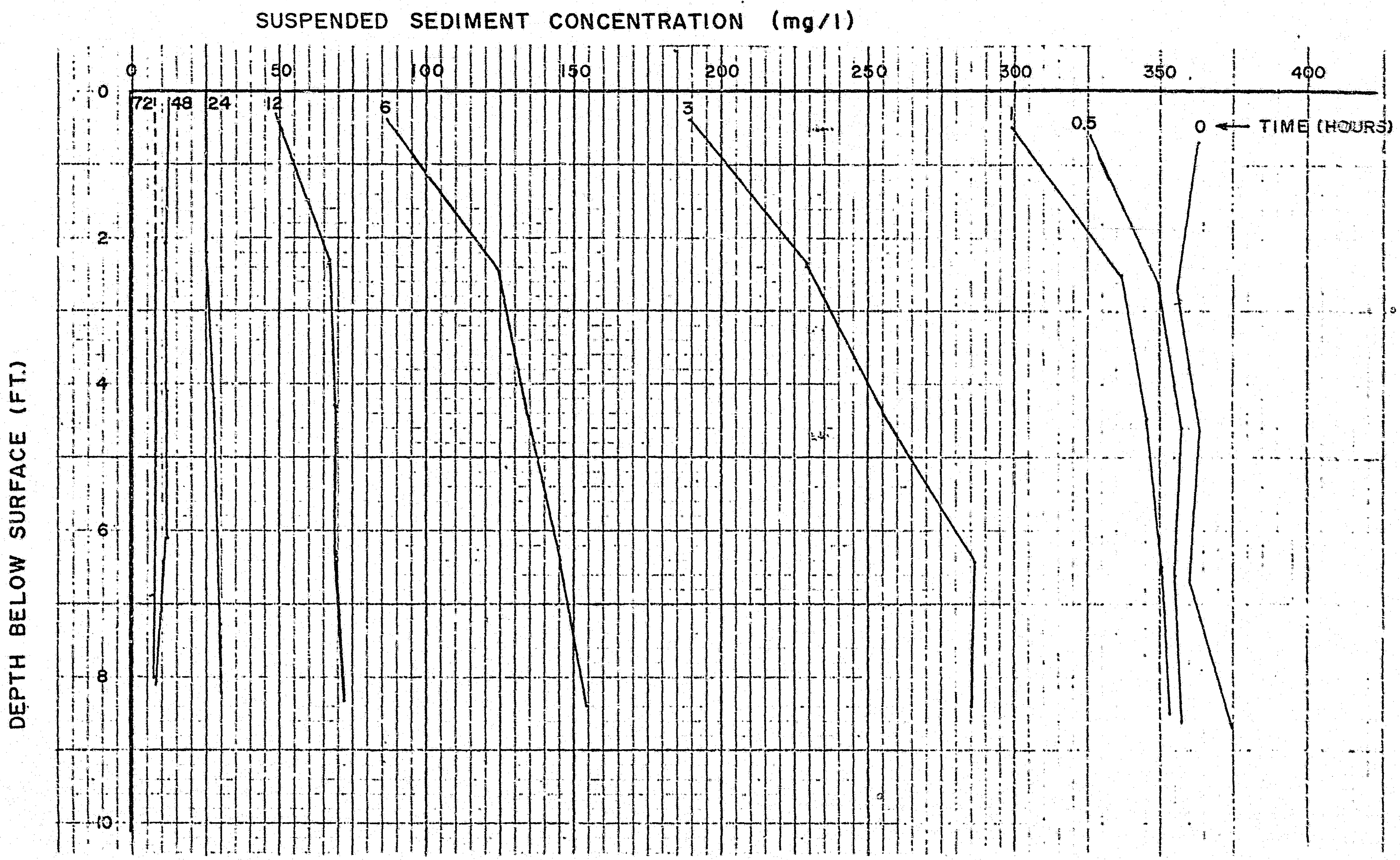
SUSPENDED SEDIMENT CONCENTRATION VS TIME & DEPTH
SETTLING COLUMN STUDY
28,000 CFS SAMPLE

FIGURE A-1



SAMPLE COLLECTED ON 3 SEPT. 1981, 1 MILE ABOVE WATANA DAM SITE
WATER TEMPERATURE (9/3/81) = 46°F

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SUSPENDED SEDIMENT CONCENTRATION VS TIME & DEPTH
SETTLING COLUMN STUDY
17,200 CFS SAMPLE

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FIGURE A-2

APPENDIX B

ANNOTATED BIBLIOGRAPHY
OF
SEDIMENTATION PROCESSES
IN
GLACIAL LAKES AND RIVERS

INTRODUCTION

A literature search was conducted to obtain information on glacial lake trap efficiency of suspended sediments, with emphasis on materials smaller than 50 microns. Relevant information will provide a basis for predicting the fate of suspended sediments entering the reservoirs of the proposed Susitna Hydroelectric Project.

The bibliography contains annotations for 36 references with relevant information and a listing of 31 additional references with no specific information. There is information on depositional processes when proglacial rivers enter standing water bodies (Church and Gilbert 1975; Carmack, Gray, Pharo, and Daley 1979; Embleton and King 1975; Gilbert 1973, 1975; Gilbert and Shaw 1981; Hamlin and Carmack 1978; Pharo and Carmack 1979; Smith 1978; Sturm and Matter 1978), with details on particle size distribution for two ancient lake environments (Ashley 1975; Shaw 1975). However, research reveals that reconstructing modern depositional environments from analyses of ancient environments may be misleading, as distance from source and shore and depth of lake are not as significant as density, wind-induced currents, and stratification (Bryan 1974a, b). Furthermore, misinterpretation of depositional events can lead to overestimation of the time involved in deposition (Shaw, Gilbert, and Archer 1978). A method is presented for determining sedimentation rates by radioactive fallout (Ashley 1979). One study on a modern lake shows that suspended sediment concentrations affect density stratification (Gustavson 1975b). Two studies (Ostrem 1975; Theakstone 1976) address lake trap efficiency and distance of deposition from the source.

The literature search included a review of University of Alaska theses and publications of the University of Alaska's Institute of Water Resources and Geophysical Institute, the U.S. Geological Survey, and the U.S. Army Corps of Engineers' Cold Regions Research and Engineering Laboratory (CRREL). A computer search was conducted on the CRREL Bibliography and on Selected Water Resources Abstracts.

PART I - RELEVANT INFORMATION

1. Arnborg, L., H.J. Walker, and J. Peippo. 1967. Suspended load in the Colville River, Alaska, 1962. Geografiska Annaler. 49A (2-4):131-144.

   Discussion of suspended sediment data collected during one year (1962) for hydrologic-morphologic study of the Colville River delta. Three aspects of suspended load considered were: quantity transported in water; size of particles in suspension; and total quantity transported in a given period of time. As unit volume increases, median grain size and total load carried increases. Grain size analyses for samples representative of selected locations, depths, and times are presented. The amount and size of suspended material increased with depth at one location.

2. Ashley, G.M. 1975. Rhythmic sedimentation in glacial Lake Hitchcock, Massachusetts-Connecticut. Pages 304-320 in A.V. Jopling and B.C. McDonald, eds. Glaciofluvial and glacio-lacustrine sedimentation. Society of Economic Paleontologists and Mineralogists, Tulsa, OK. Special Publication 23.

   Discussion of seasonal silt and clay deposition (varves) in an ancient environment. Suspended sediment concentration affects water density far more than temperature in glacial lakes. The settling velocity of a 60 silt grain in 4°C water undisturbed by currents is 0.05 cm/second. Therefore, such a grain would settle 50 m in 1.15 days. However, silt was found in all winter clay layers, and could indicate that lake currents were present, preventing settling, or sediment was introduced year-round. Mean grain size of silt layers depends on location in the lake whereas grain size distribution of clay layers is uniform. Grain size analyses are presented, but there is no specific information on the distance traveled across the lake prior to deposition.

3. Ashley, G.M. 1979. Sedimentology of a tidal lake, Pitt Lake, British Columbia, Canada. Pages 327-345 in Ch. Schluchter, ed. Moraines and Varves. Proceedings of an INQUA Symposium of Genesis and Lithology of Quaternary Deposits, Zurich, September 10-20, 1978. A.A. Balkema, Rotterdam.

   Sedimentation rates were determined by ^{137}Cs dating techniques. Grain size analyses were determined for 190 samples and mean grain size distribution was mapped. Annual sediment accumulation equalled 150± 20 x 10^3 tons, of which 50% was coarser than 50.

4. Ashley, G.M., and L.E. Moritz. 1979. Determination of lacustrine sedimentation rates by radioactive fallout (^{137}Cs), Pitt Lake, British Columbia. Canadian Journal of Earth Sciences. 16(4):965-970.

Discussion of techniques for determining modern lacustrine sedimentation rates.

5. Borland, W.M. 1961. Sediment transport of glacier-fed streams in Alaska. Journal of Geophysical Research. 66(10):3347-3350.

Developed empirical formula for sediment yield rates for glacial drainage basins based on glacier area, total drainage area, and length of watercourse. No differentiation by particle size. Used five years of U.S. Geological Survey suspended sediment data from Denali and Gold Creek stations to test formula.

6. Bryan, M.L. 1974a. Sedimentation in Kluane Lake. Pages 151-154 in V.C. Bushnell and M.G. Marcus, eds. Ice Field Ranges Research Project Scientific Results, Vol 4. American Geographical Society, New York, NY, and Arctic Institute of North America, Montreal, Canada.

Study of bathymetry, thermal structure, and sediment distribution in Kluane Lake, 1968. A weak thermocline developed in July and August, which was occasionally destroyed by storm-induced mixing. The lake is ice-covered for eight months, and receives sediment from the Slims River for four months. Statistical parameters of grain size analyses are presented. Sedimentation is affected by density, by wind-induced lake currents, and by stratification as well as by bathymetry, distance from shore and input, point and sediment composition. Highly turbid, cold glacial waters may be sufficiently dense to flow across the lake bottom regardless of thermal stratification. When the Slims River warms, it flows over the lake.

7. Bryan, M.L. 1974b. Sublacustrine morphology and deposition, Kluane Lake, Yukon Territory. Pages 171-187 in V.C. Bushnell and M.B. Marcus, eds. Icefield Ranges Research Project Scientific Results, Vol 4. American Geographical Society, New York, NY, and Arctic Institute of North American, Montreal, Canada.

Discussion of processes affecting sedimentation in lakes from glacial streams. Bathymetric mapping of Kluane Lake in 1968 and 1970 revealed growth of the Slims River delta. Cartographic and statistical analyses of bottom sediments are presented. Finest sediments farthest from the Slims River

were not in the deepest portion of the lake. Distance from source, depth of lake, and distance from shore are not significant in controlling deposition. Reconstructing depositional environments based on sediment size analysis may be misleading.

8. Carmack, E.C., C.B.J. Gray, C.H. Pharo, and R.J. Daley. 1979. Importance of lakeriver interaction on the physical limnology of the Kamloops Lake/Thompson River system Limnology and Oceangraphy. 24(4):634-644.

   Discussion of physical effects of large river entering a deep, intermontane lake. No information of particle size analysis.

9. Church, M., and R. Gilbert. 1975. Proglacial fluvial and lacustrine environments. Pages 22-100 in A.V. Jopling and B.C. McDonald, eds. Glaciofluvial and glaciolacustrine sedimentation. Society of Economic Paleontologists and Mineralogists. Tulsa, OK. Special Publication 23.

   Discussion of deposition when proglacial rivers enter standing water bodies. Significant events are: aggradation on the bed due to deposition of bed load extends upstream from the lake, along with reduced flow velocities; development of a high angle delta, with transport of sediment to the delta lip; movement of coarse material over the lip and down into the lake in turbidity flows (bottom flow); movement of river water down the delta front to lake water of equal density (interflow); movement of river water onto the surface of the lake if density is less than the lake (surface flow); deposition of fine-grained material and formation of varves, of which the silt (summer) portion is deposited by turbidity currents, and the clay (winter) portion by the turbidity current after stagnation, and then by slow, continuous settling from suspension. Turbidity underflow is not a continuous event in the melt season. Varve formation cannot be directly correlated to mean annual discharge, because a single large flood can create a turbidity flow. Turbidity flows resulting in more rapid deposition depend on discharge, river and lake water temperature, thermal structure of the lake, quantity of sediment suspended in the lake from previous events, and river and lake dissolved sediment concentrations. No specific information on particle size is presented.

10. Embleton, C., and C.A.M. King. 1975. Glacial geomorphology. John Wiley and Sons, New York, NY. pp. 532-558.

    Review of general principles affecting sediment deposition in lacustrine environments with examples. Lake floor deposits become increasingly fine toward center or deepest parts of

lakes, requiring quiet water and long settling periods. Turbidity currents formed by cold, silt-laden stream water are important in distributing sediment across the lake floor. Rhythmites (laminated deposits) develop in cold freshwater lakes receiving intermittent streamflow, and in some cases form on an annual basis (varves). They can also form from sudden fluctuations in discharge (bursting of an ice-dammed lake upstream), unseasonal warm or cold spells, or periodic storms.

11. Everts, C.H. 1976. Sediment discharge by glacier-fed rivers in Alaska. Pages 907-923 in Rivers '76. Vol. 2. Symposium on Inland Waterways for Navigation, Flood Control and Water Diversions. 3rd Annual Symposium, Colorado State University, Fort Collins, CO. Waterways, Harbors and Coastal Engineering Div., American Society of Civil Engineers, New York, NY.

    Investigation of glacial sediments discharged into the coastal zone (Knik, Matanuska). Size distribution, composition, and settling characteristics of glacial sediment are important characteristics in determining where the sediment will be transported and deposited when it reaches the marine environment. Based on particle size distribution analyses, it appears that fine-grained particles pass completely through the river system. Ice margin lakes fringing glaciers are depositories for coarse sediments. Clay minerals were absent, which is significant because clay particles form aggregates with other fine-grained particles and settle more rapidly. This absence may be common in other glacial areas because of negligible chemical weathering in the source areas.

12. Fahnestock, R.K. 1963. Morphology and hydrology of a glacial stream: White River, Mount Rainier, Washington. U.S. Geological Survey. Professional Paper 422A. 70 pp.

    Investigation of formation of a valley train by a proglacial stream. Particle size analyses of deposited material showed silts and clays were washed out of stream deposits. Analysis of suspended load indicated that silt and clay stay in suspension and are carried out of the study area into Puget Sound.

13. Fahnestock, R.K. 1969. Morphology of the Slims River. Pages 161-172 in V.C. Bushnell and R.H. Ragle, eds. Ice Field Ranges Research Project Scientific Results, Vol. 1. American Geographical Society, New York, NY, and Arctic Institute of North America, Montreal, Canada.

    Investigation of the Slims River, a proglacial stream flowing 14 miles from Kaslawulsh Glacier to Kluane Lake. The river is modifying a valley train deposited when the glacier was up

against a terminal moraine. It is regrading, ie, adjusting to a decrease in load at the source by cutting in the upper reaches and depositing in the lower reaches. The Slims River is also affected by downstream changes in the base level, which is controlled by the extension of the delta into Kluane Lake and the variation in lake level. As the volume growth rate of the delta is not known, the sediment transport rate cannot be estimated. Suspended sediment is predominantly silt and clay. No data on particle size distribution.

14. Gaddis, B. 1974. Suspended-sediment transport relationships for four Alaskan glacier streams. M.S. Thesis. University of Alaska, Fairbanks, AK. 102 pp.

    Investigation of suspended sediment transport relationships in glacial streams at Gulkana, Maclaren, Eklutna, and Wolverine glaciers. Data on mean particle size is presented for four glacial streams for one season at sites near the terminus. Sediment availability depends on amount of sediment, distance travelled downstream, and mechanical nature of sediment entrainment (no specific information on entrainment).

15. Gilbert, R. 1973. Processes of underflow and sediment transport in a British Columbia mountain lake. Pages 493-507 in Fluvial Processes and Sedimentation. Proceedings of the 9th Hydrology Sympasuim, University of Alberta, Edmanton. Canada, May 8-9. Subcommittee on Hydrology, Associate Committee on Geodesy and Geophysics, National Research Council of Canada.

    Description of processes involved in formation of varved sediment deposits in proglacial lakes, primarily underflow and interflow. Underflow increases with increase of water and suspended sediment inflow. Cores obtained to determine thickness and comparision of varves. No information on particle size distribution.

16. Gilbert, R. 1975. Sedimentation in Lillooet Lake, British Columbia. Canadian Journal of Earth Sciences. 12(10):1697-1711.

    Lillooet Lake receives sediment from a 3,580 sq km drainage basin, of which 7% is glacier-covered. Interflow and underflow distribute sediment through the lake in summer when the lake is stratified. Factors affecting distribution are: density characteristics of the lake and inflowing water, as determined by temperature and suspended sediment concentrations; currents induced by wind and inflow; thermal structure of the lake water, which determines the nature of circulation patterns and allows interflow along the thermocline; diurnal and seasonal fluctuations in inflowing waters and sediment;

and the large annual volume of inflow (4.5 times greater than the lake volume on the average). Interflow carries sediment at the base of the epilimnion to the distal end of the lake in one to two days. No specific information on particle size.

17. Gilbert, R., and J. Shaw. 1981. Sedimentation in proglacial Sunwapta Lake, Alberta. Canadian Journal of Earth Sciences. 18(1):81-93.

    Examination of hydrologic and limnologic conditions of Sunwapta Lake, a small, proglacial lake in the Canadian Rockies. Sediment input was measured and sedimentation rates were calculated. Sediments of small, shallow lakes with large and highly variable inflows are expected to demonstrate lateral and vertical variability, whereas those in large proglacial lakes are more predictable due to modification by large, stable water masses.

18. Gustavson, T.C. 1975a. Bathymetry and sediment distribution in proglacial Malaspina Lake, Alaska. Journal of Sedimentary Petrology. 45:450-461.

See next abstract

19. Gustavson, T.C. 1975b. Sedimentation and physical limnology in proglacial Malaspina Lake, southeastern Alaska. Pages 249-263 in A.V. Jopling and B.C. McDonald, eds. Glaciofluvial and glaciolacustrine sedimentation. Society of Economic Paleontologists and Mineralogists, Tulsa, OK. Special Publication 23.

    Underflow, interflow, and overflow water entered Malaspina Lake, and the type of flow is dependent on the relative suspended sediment content of the lake water and the inflowing melt water. The 18-km long lake is density stratified (increasing suspended sediment concentration with depth) but not thermally stratified. No specific information on particle size or trap efficiency is presented.

20. Guymon, G.L. 1974. Regional sediment yield analysis of Alaska streams. Journal of the Hydraulics Div. of the American Society of Civil Engineers. 100(HY1):41-51.

    Analyzed Borland's (1961) formula. Considered particle size, but used an average particle size in the formula. However, concluded that particle size affects application of the formula.

21. Hamblin, P.F., and E.C. Carmack. 1978. River-induced currents in a fjord lake. Journal of Geophysical Research. 83(C2):885-889.

Discussion of dynamics of strong flowing river entering a long, narrow lake (Kamloops Lake, B.C.). River-induced currents influence circulation patterns in a fjord lake. No specific information on sedimentation rates or particle size analysis.

22. Hobbie, J.E. 1973. Arctic limnology: a review. Pages 127-168 in M.E. Britton, ed. Alaskan arctic tundra. Arctic Institute of North America. Technical Paper 25.

Review of properties of lake in northern tundra regions. Thermal cycle of deep arctic lakes is highly variable, and stratification is uncommon, occurring only in warm, calm weather after lake waters rise to 4°C. Deep lakes maintain circulation even when ice covered. Deeper lakes are relatively turbid as a result of glacial flour from streams draining active glaciers. Lake Peters is fed by glacial streams and drains via a 1-km long, 15-m deep channel into Lake Schrader in the Brooks Range. Both are 50-60 m deep. Lake Peters acts as a settling basin. When dense glacial water enters Lake Peters in June, it sinks to the bottom, and the lake fills upward with turbid water.

23. Mathews, W.H. 1956. Physical limnology and sedimentation in a glacial lake. Bulletin of the Geological Society of America. 67:537-552.

Garibaldi Lake, British Columbia, receives sediment from two glacial streams with relatively low sediment content. Particle size and composition of bottom deposit analyses revealed slow transport to site of deposition and slow rate of deposition for clays. No information on amount of sediment passing through system.

24. Ostrem, G. 1975. Sediment transport in glacial meltwater streams. Pages 101-122 in A.V. Jopling and B.C. McDonald, eds. Glaciofluvial and glaciolacustrine sedimentation. Society of Economic Paleontologists and Mineralogists, Tulsa, OK. Special Publication 23.

Recognized problems of utilizing glacial waters for hydroelectric projects, specifically in reservoirs and turbines. Grain size analyses of cores of varved sediments showed that summer layers consisted of coarser material than winter layers (based on 20 micron grain size variation). X-ray diffraction analyses showed that summer deposits contained more quartz (rapid sedimentation), and winter deposits, more mica (slower sedimentation). For one 1,800-m long proglacial lake over 29 years, about 70 percent of the total suspended sediment input was deposited.

25. Ostrem, G., T. Ziegler, and S.R. Ekman. 1970. A study of sediment transport in Norwegian glacial rivers, 1969. Institute of Water Resources, Dept. of Hydrology, Oslo, Norway. Report 6/70. Report for Norwegian Water Resources and Electricity Board. Translated from Norwegian by H. Carstens. 1973. Institute of Water Resources, University of Alaska, Fairbanks, AK. Report 35. 1 vol.

Investigations were conducted on water discharge and sediment volume measurements in glacial rivers above and at the outlet of glacial lakes to calculate the sedimentation of fine material on the bottom of the lakes. Volume of material available for transport is probably largest at the beginning of the season. No data on particle size.

26. Pharo, C.H., and E.D. Carmack. 1979. Sedimentation processes in a short residence-time intermontane lake, Kamloops Lake, British Columbia. Sedimentology. 26:523-541.

Sediment transport and deposition in the lake is controlled by three interdependent processes: delta progradation at the lake-river confluence; sediment density surges originating along the delta face, which result in turbidite sequences lakeward from the base of the delta; and dispersal by the interflowing river plume, which, due to Coriolis effects, results in a higher sedimentation rate and greater fraction of coarser material along the right-hand of the lake in the direction of flow. Suspended sediment concentrations are high above the thermocline where higher turbulence, maintained by wind mixing and river inter interflow, reduces settling velocities. Particles settle rapidly once they enter the hypolimnion.

27. Ritchie, J.C., J.R. McHenry, and A.C. Gill. 1973. Dating recent reservoir sediments. Limnology and Oceanography. 18:254-283.

Discussion of radioactive ^{137}Cs dating. Method could be used to date sediment in reserviors that have not been surveyed.

28. Shaw, J. 1975. Sedimentary successions in Pleistocene ice-marginal lakes. Pages 281-302 in A.V. Jopling and B.C. McDonald, eds. Glaciofluvial and glaciolacustrine sedimentation. Society of Economic Paleontologists and Mineralogists, Tulsa, OK. Special Publication 23.

Discussion of sedimentation in proximal portion of a glacial lake based on interpretation on the ancient environment. Mean grain size values were determined for sections of each facies from o to 80. No information on transport of fine materials.

29. Shaw, J. 1977. Sedimentation in an alpine lake during deglaciation, Okanagan Valley, British Columbia, Canada. Geografiska Annaler. 59(A):221-240.

Ancient lake sediments were examined to develop a model of alpine lake sedimentation based on changing depositional processes with time and distance from the ice margin.

30. Shaw, J., R. Gilbert, and J.J.J. Archer. 1978. Proglacial lacustrine sedimentation during winter. Arctic and Alpine Research. 10(4):689-699.

Discussion of deposition of coarse-grained sediments during winter in Lillooet Lake. Misinterpretation can lead to overestimation of time seqences of deposition.

31. Slatt, R.M. 1970. Sedimentological and geochemical aspects of sediment and water from ten Alaskan valley glaciers. Ph.D. Thesis. University of Alaska, Fairbanks, AK. 125 pp. Studied five groups of glaciers with different bedrock lithologies; Worthington and Matanuska; Castner and Fels; Gulkana and College; Rendu and Reed; and Carroll and Norris. Particle size analyses and mineralogy of superglacial and suspended stream sediments are presented. The environment of transport has a much greater effect on grain size than the nature of the starting material.

32. Slatt, R.M. 1971. Texture of ice-cored deposits from ten Alaskan valley glaciers. Journal of Sedimentary Petrology. 41(3):828-834.

Revised and condensed portions of Ph.D. thesis (see above).

33. Smith, N.D. 1978. Sedimentation processes and patterns in a glacier-fed lake with low sediment input. Canadian Journal of Earth Sciences. 15(5):714-756. Snow melt and glacial melt waters carrying relatively low suspended sediment concentrations enter Hector Lake in the eastern Rocky Mountains, Alberta. When stratified, water and fine sediments enter the lake as interflow and overflow. Grain size analyses were conducted on 42 cores. Deposition varies left to right as well as distally due to katabatic winds generating downlake currents in the epilimnion that are deflected southward (rightward) by the Coriolis force.

34. Sturm, M., and A. Matter. 1978. Turbidites and varves in Lake Brienz (Switzerland): deposition of clastic detritus by density currents. Pages 147-168 in A. Matter and M.E. Tucker, eds. Modern and ancient lake sediments. International Association of Sedimentologists. Special Publication 2.

Discussion of sediment transport and deposition by overflow, interflow, and underflow in a long, narrow, deep basin with rivers entering at each end. Fine-grained sediments supplied by overflows and interflows settle continuously during summer thermal stratification. Most of the fine-grained particles remain in suspension at the thermocline because the vertical density gradient is more dependent on temperature than on an increase in density due to suspended particles. During fall turnover, the remaining sediment trapped at the thermocline settles.

35. Theakstone, W.H. 1976. Glacial lake sedimentation, Austerdalsisen, Norway. Sedimentology. 23(5):671-688.

A lake completely filled with glacial sediments, over which braided stream deposits formed. A new proglacial lake then formed. Discussion of bedding and composition of ancient lake sediments. Initially, deposition was very slow in deep (80 m) water. In another lake 300 m from a glacier, about 75 percent of the sediment transported in suspension is retained in the basin, but the amount retained in one day is highly variable. The daily summer values exceeded the minimum by 200 times (data not presented).

36. Tice, A.R., L.W. Gatto, and D.M. Anderson. 1972. The mineralogy of suspended sediment in some Alaskan glacial streams and lakes. Cold Regions Research and Engineering Laboratory Corps of Engineers, U.S. Army, Hanover, NH. Research Report 305. 10 pp.

Investigation of the role of chemical weathering of bedrock in cold regions determined that no chemical changes occurred in fine suspended material. Suspended-sediment samples were obtained for X-ray diffraction analyses from galcial outwash streams and lakes in seven areas (Chackachamna, Palmer-Matanuska, Moose Pass-Portage, Valdez, Juneau, Mt. McKinley National Park, and Black Rapids).

PART II- NO SPECIFIC INFORMATION

1. Agterberg. F.P., and I. Banerjee. 1969. Stochastic model for the deposition of varves in glacial Lake Barlow-Ojibway, Ontario, Canada. Canadian Journal of Earth Sciences. 6:625-652

2. Banerjee, I., and B.C. McDonald. 1975. Nature of esker sedimentation. Pages 132-154 in A.V. Jopling and B.C. McDonald, eds. Glaciofluvial and glaciolacustrine sedimentation. Society of Economic Paleontologists and Mineralogists, Tulsa, OK. Special Publication 23.

3. Boothroyd, J.C. and G.M Ashley. 1975. Processes, bar morphology, and sedimentary structures on braided outwash fans, northeastern Gulf of Alaska. Pages 193-222 in A.V. Jopling and B.C. McDonald, eds. Glaciofluvial and glaciolacustrine sedimentation. Society of Economic Paleontologists and Mineralogists, Tulsa, OK. Special Publication 23.

4. Bradley, W.H. 1965. Vertical density currents. Science. 150(3702):1423-1428.

5. Clague, J.J. 1975. Sedimentology and paleohydrology of late Wisconsinan outwash, Rocky Mountain trench, southeastern British Columbia. Pages 223-237 in A.V. Jopling and B.C. McDonald, eds. Glaciofluvial and glaciolacustrine sedimentation. Society of Economic Paleontologists and Mineralogists, Tulsa, OK. Special Publication 23.

6. Everts, C.H. and H.E. Moore. 1976. Shoaling rates and related data from Knik Arm near Anchorage, Alaska. Coastal Engineering Research Center, Corps of Engineers, U.S. Army, Fort Belvoir, VA. Technical Paper 76-1. 84 pp.

7. Gilbert, R. 1971. Observations on ice-dammed Summit Lake, British Columbia, Canada. Journal of Glaciology. 10(60):351-356.

8. Gustavason, T.C., G.M. Ashley, and J.C. Boothroyd. 1975. Depositional sequences in glaciolacustrine deltas. Pages 264-280 in A.V. Jopling and B.C. McDonald, eds. Glaciofluvial and glaciolacustrine sedimentation. Society of Economic Paleontologists and Mineralogists, Tulsa, OK. Special Publication 23.

9. Guymon, G.L. 1974. Sediment relations of selected Alaskan glacier-fed streams. Institute of Water Resources, University of Alaska, Fairbanks, AK. Report 51. 17 pp.

10. Hobbie, J.E., ed. 1980. Limnology of tundra ponds: Barrow, Alaska. Dowden, Hutchinson and Ross, Inc., Stroudsburg, PA. US/IBP Synthesis Series 13. 514 pp.

11. Howarth, P.J., and R.J. Price. 1969. The proglacial lakes of Breidamerdurjokull and Fjallsjokull, Iceland. Geographical Journal. 135:573-581.

12. Jopling, A.V. 1975. Early studies on stratified drift. Pages 4-21 in A.V. Jopling and B.C. McDonald, eds. Glaciofluvial and glaciolacustrine sedimentation. Society of Economic Paleontologists and Mineralogists, Tulsa, OK. Special Publication 23.

13. Kindle, E.M. 1930. Sedimentation in a glacial lake. Journal of Geology. 38(1):81-87.

14. Lawson, D.E. 1977. Sedimentation in the terminus region of the Matanuska Glacier, Alaska. Ph.D. Thesis. University of Illinois, Urbana-Champaign, IL. 287 pp.

15. Long, W.E. 1972. Glacial processes and their relationship to streamflow; Flute Glacier, Alaska. Institute of Water Resources, University of Alaska, Fairbanks, AK. Report 18. 1 vol.

16. Ludlam, S.D. 1967. Sedimentation in Cayuga Lake, New York. Limnology and Oceanography. 12(4):618-632.

17. McDonald, B.C., and W.W. Shilts. 1975. Interpretation of faults in glaciofluvial sediments. Pages 123-131 in A.V. Jopling and B.C. McDonald, eds. Glaciofluvial and glaciolacustrine sedimentation. Society of Economic Paleontologists and Mineralogists, Tulsa, OK. Special Publication 23.

18. Moores, E.A. 1962. Configuration of the surface velocity profile of Gulkana Glacier, central Alaska Range, Alaska. M.S. Thesis. University of Alaska, Fairbanks, AK. 47pp.

19. Moravek, J.R. 1973. Some further observations on the behavior of an ice-dammed self-draining lake, Glacier Bay, Alaska, USA. Journal of Glaciology. 12(66):505-507.

20. Reger, R.D. 1964. Recent glacial history of Gulkana and College Glaciers, central Alaska Range, Alaska. M.S. Thesis. University of Alaska, Fairbanks, AK. 75 pp.

21. Rust, B.R. 1975. Fabric and structure in glaciofluvial gravels. Pages 238-248 in A.V. Jopling and B.C. McDonald, eds. Glaciofluvial and glaciolacustrine sedimentation. Society of Economic Paleontologists and Mineralogists, Tulsa, OK. Special Publication 23.

22. Rust, B.R., and R. Romanelli. 1975. Late quaternary subaqueous outwash deposits near Ottawa, Canada. Pages 177-192 in A.V. Jopling and B.C. McDonald, eds. Glaciofluvial and glaciolacustrine sedimentation. Society of Economic Paleontologists and Mineralogists, Tulsa, OK. Special Publication 23.

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26. Shira, D.L. 1978. Hydroelectric powerplant siting in glacial areas of Alaska. Pages 59-76 in Applied Techniques for Cold Environments, Vol. 1. Proceedings of the Cold Regions Specialty Conference, Anchorage, AK, May 17-19. American Society of Civil Engineers, New York, NY.

27. Slatt, R.M., and C.M. Hoskin. 1968. Water and sediment in the Norris Glacier outwash area, upper Taku Inlet, southeastern Alaska. Journal of Sedimentary Petrology. 38(2):434-456.

28. Stone, K.H. 1963. Alaskan ice-dammed lakes. Association of American Geographers: Annals. 52:332-349.

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31. Yould, E.P., and T. Osterkamp. 1978. Cold regions considerations relative to development of the Susitna hydroelectric project. Pages 887-895 in Applied Techniques for

Cold Environments, Vol.2. Proceedings of the Cold Regions Specialty Conference, Anchorage, AK, May 17-19. American Society of Civil Engineers, New York, NY.