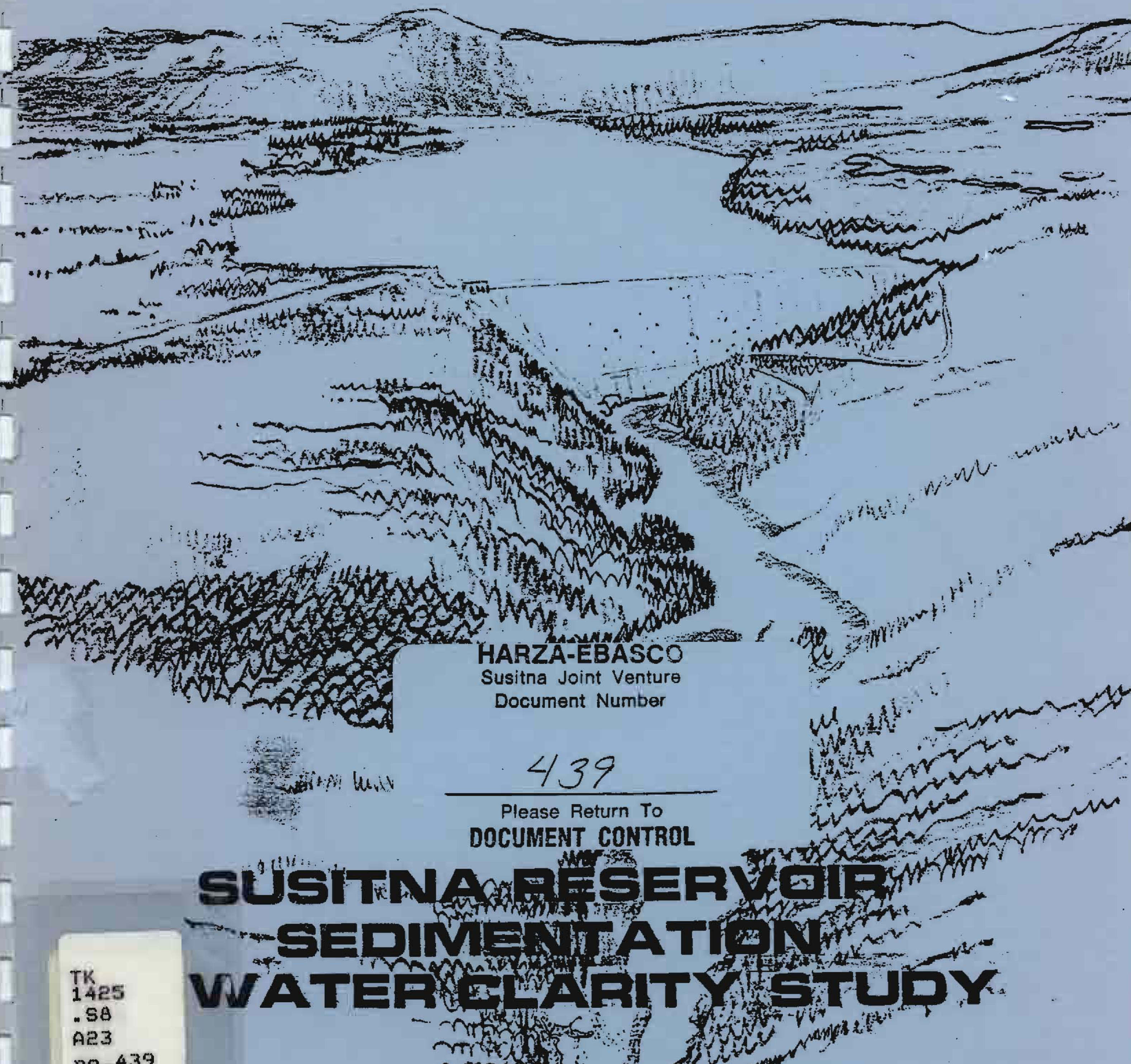

SUSITNA RESERVOIR SEDIMENTATION WATER CLARITY STUDY

Peratrovich, Nottingham & Drage, Inc.
Engineering Consultants

SUSITNA RESERVOIR SEDIMENTATION AND WATER CLARITY STUDY

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SUSITNA RESERVOIR SEDIMENTATION & WATER CLARITY STUDY

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1. PURPOSE AND SCOPE

1.1 Background

This report summarizes the results of the Phase 2 investigations aimed at determining turbidity levels in the proposed Watana reservoir. The Phase 1 studies were completed by R&M Consultants, Inc., (January 1982). These earlier studies developed trap efficiencies for the Watana and Devil Canyon reservoirs. Total sediment accummulation for each of the reservoirs was also estimated. An indication of what downstream river turbidity levels were likely to be was also provided. These studies included a brief description of the delta formation in the reservoir, the likely behavior of glacial flour within the reservoir, and a general discussion on the temperature regime.

The Phase 2 studies which are described here were initiated in order to analyze in more detail additional data obtained on other lake systems throughout the world and to attempt to predict, on a more quantitative basis, likely turbidity levels in the Watana reservoir.

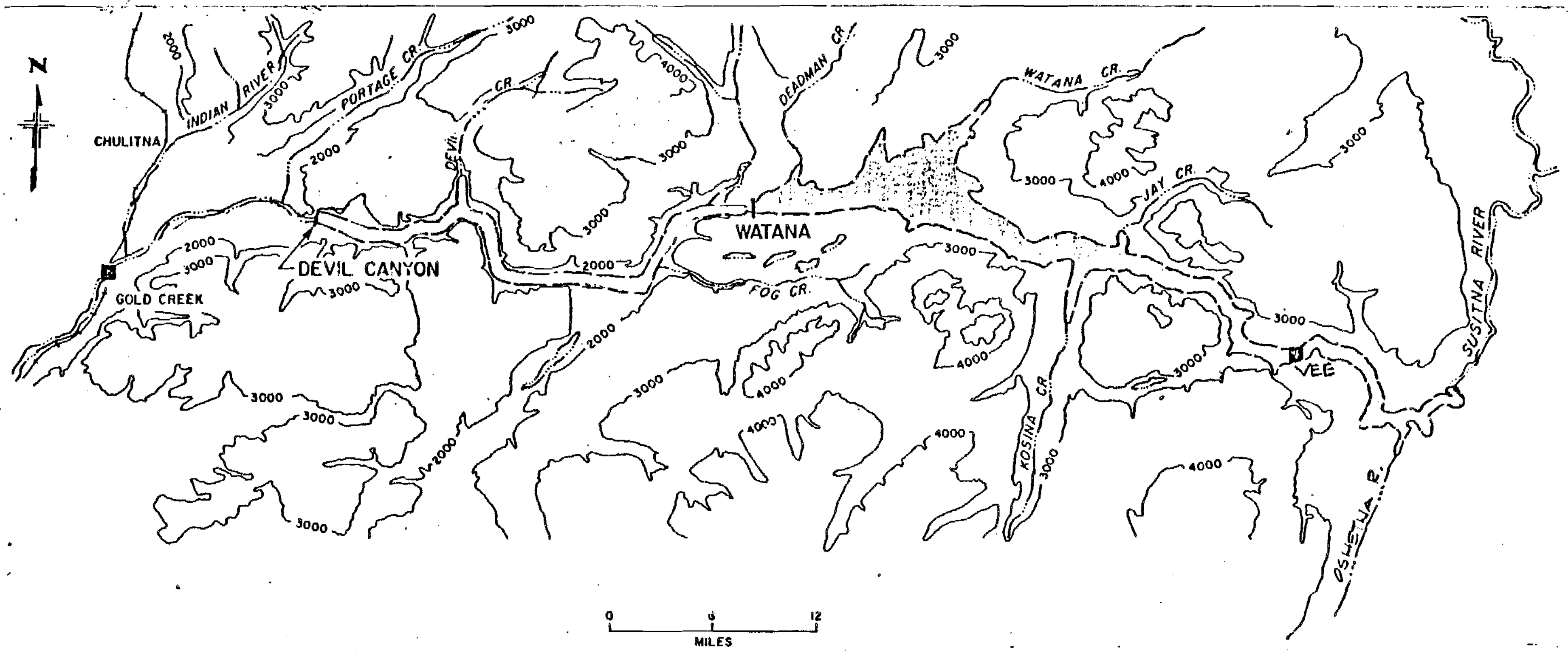
A plan view of the proposed Watana reservoir and the sediment and climatic data stations on the Susitna River used in Phase 2 studies are shown on Figure 1.1.

1.2 Study Objectives

The objective of the study is to estimate the range of sediment concentrations and turbidity levels in the Watana reservoir for the various months of the year. It should be stressed that the objective is not to provide a detailed quantitative estimate, but rather to perform an exploratory type investigation to determine order of magnitude estimates.

1.3 Scope of Work

The scope of work was outlined in a letter to Acres American, Inc., (Acres) dated April 19, 1982. A brief summary of the proposed program follows.



SAMPLING STATIONS	PARAMETER
GOLD CREEK	STREAMFLOW SEDIMENT DISCHARGE WATER TEMPERATURE
WATANA	STREAMFLOW CLIMATE WATER TEMPERATURE
VEE	STREAMFLOW SEDIMENT DISCHARGE

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FIGURE 1.1

(a) Obtain and review all additional data including:

- o climatic data
- o reservoir data
- o sediment data
- o literature survey

(b) Verify the sediment concentration versus turbidity relationship.

(c) Conduct quiescent settling analyses for the reservoir.

(d) Quantify the wind and thermal mixing characteristics of the reservoir.

(e) Estimate ranges of sediment and turbidity values for the reservoir for each month of the year.

Limited input to these studies was derived from the thermal lake modeling conducted by Acres American, Inc. (1982), on the Watana reservoir, and baseline turbidity and sediment concentration data from Eklutna Lake collected by R&M (1982).

1.4 Study Approach

Under quiescent conditions, sediment with particle size greater than about 2 um that flows into the Watana reservoir would practically all settle out. However, the reservoir water is continually subjected to internal mixing induced by meterologic conditions such as wind and temperature, as well as turbulence induced by inflowing and outflowing water. Because of this mixing, many of the smaller particles would not settle, but would remain in suspension and contribute to increased turbidity levels in the reservoir. In addition, turbulence in the water also reintrains sediment that has settled out on the bottom of the shallow portions of the reservoir perimeter, again contributing to increased turbidity levels.

The basic approach to the study involved a semi-quantitive evaluation of the process described above, and consisted of several distinct tasks. These include:

(a) Literature and Data Review

Literature and data relating to other glacial lakes under similar conditions have been reviewed. Any useful information which could be extrapolated to Watana has been abstracted and summarized. This information is then used to support some of the conclusions drawn from the simplified sediment analyses.

(b) Description of the Lake Sedimentation Process

A detailed description of the likely sedimentation process has been developed. It is based on current knowledge of the Watana reservoir and documented descriptions of other similar lakes and reservoirs. This description aided in the determination of sediment types and turbulent mixing analyses.

(c) Description of the Watana Reservoir

All relevant data for the Watana reservoir has been assembled and summarized. These data include a description of the monthly inflows and sediment concentrations, sediment grain size distributions, reservoir storage volumes and releases, and monthly wind and temperature data.

(d) Analysis of Sediment Behavior

The amount of sediment that would settle out under quiescent conditions has been calculated for various sediment inputs, reservoir elevations, and withdrawal rates. Following this, quantitative assessments have been made of wind and temperature induced mixing currents in the reservoir. Use has been made of the thermal modeling conducted by Acres (1982). Approximate turbidity-sediment concentration relationships, previously developed by R&M (January 1982), have been updated using additional Susitna River data, and also used in the analysis.

(e) Prediction of Reservoir Turbidity

Based on the assumption that reservoir mixing velocities of the same order of magnitude as the particle settling velocities would disrupt the settling process, typical ranges of sediment concentrations in the Watana Reservoir, near the outlet, have been estimated. These sediment concentrations are converted to turbidity using the appropriate turbidity sediment concentration relationships.

2. SUMMARY

2.1 Past Studies

The Phase 1 studies conducted by R&M (January 1982) on the Watana reservoir indicated the following:

Typical sediment gradations of Susitna River water in the Watana reservoir area are 15 to 20 percent finer by weight than 2 microns, 25 to 35 percent finer than 10 microns, and 95 to 100 percent finer than 500 microns (0.5 mm). The sediment trap efficiency of the Watana reservoir was estimated to be between 70 and 95 percent with particles less than 2 microns possibly passing through the reservoir. Under worse case sedimentation conditions of 100 percent trap efficiency, an estimated 472,500 acre.ft. of sediment would be deposited in the reservoir over a 100-year period.

Turbidity in the downstream river would decrease significantly during the summer months due to the large amount of sediment trapped by the reservoir. It is likely that the turbidity of water released in the winter months when a stable ice cover exists would be near natural conditions, as suspended sediment in the near-surface water would settle out once the reservoir ice cover reduces surface disturbance and essentially quiescent conditions occur.

2.2 Summary and Conclusions

Due to the complexity of glacial flour sediment behavior in large water bodies, the general shortage of quantitative data, and little direct experience with large glacial feed reservoirs, the conclusions drawn at this time should be considered qualitative. However, the following conclusions are considered defensible and provide order of magnitude quantitative values that should allow project personnel to reevaluate the effects of reservoir water clarity on other physical and biological aspects of the Susitna project.

1. There will be some level of turbidity in the reservoir at all times.

2. It is likely that sediment particles less than 3 to 4 microns will remain in suspension. This constitutes up to 20% of the summer sediment input. Maximum turbidity levels at the outlet are on the order of 50 NTU's, which corresponds to a sediment concentration of 200 to 400 mg/l. Minimum turbidity levels will be in the order of 10 NTU's. This corresponds to a sediment concentration of 30 to 70 mg/l.

3. Order of magnitude turbidity levels at the reservoir outlet during each month appear to be primarily dependent on the travel time it takes sediment slugs, delivered to the reservoir during previous summers, to reach the reservoir outlet. Longitudinal mixing, primarily induced by wind turbulence, will tend to mask the near surface sediment slugs. Quantification of longitudinal mixing has not been directly addressed within the scope of this task.

4. Wind mixing is significant in retaining sediment less than about 12 microns in suspension for the upper 50-foot water layer.

5. Reintrainment of sediment from the shallow depths along the reservoir periphery during severe storms will result in short-term high turbidity levels. This will be particularly evident during the summer refilling process when water levels will rise, resubmerging sediment deposited along the shoreline during the winter.

6. In spite of some limitations, the data gathered from outside sources supports the conclusion that Watana reservoir turbidity levels will be in the range of 10-50 NTU's.

7. Preliminary results from the Eklutna Lake study show summer turbidity levels in the near surface layers to be in the range of 20-40 NTU's. This generally agrees with the range of turbidity values predicted for the Watana reservoir.

2.3 Recommendations

Should more reliable and accurate estimates of turbidity levels be required, futher work is warranted to firm up predictions of sediment concentration and turbidity in the Watana reservoir. Some of the major weaknesses in the current data base and analytical approach include the lack of knowledge of the electrochemical behavior of the sediment, the role of phytoplankton and its effect on turbidity, and the simplistic nature of the analysis of the sedimentation process. To overcome these deficiencies, the following study program is recommended:

(a) Conduct more detailed laboratory settling tests on river sediment samples.

(b) Develop more reliable relationships between turbidities and sediment concentration incorporating the effects of phytoplankton growths should this be regarded important, and incorporating results from USGS summer field program to measure sediment discharge.

(c) Apply a two-dimensional model to analyze the longitudinal distribution of sediments deposition in the reservoir. The model should incorporate the values of mixing velocities derived from the Acres (1982) thermal modeling using a diffusion type analogy. It is important to incorporate a relatively long sequence (several years) of representative inflow and sediment concentration data in these studies. This will facilitate a more accurate determination of turbidity ranges likely to occur in the reservoir.

3. REVIEW OF AVAILABLE LITERATURE

Under Phase I of the current reservoir sedimentation study, investigations have been ongoing to retrieve any unpublished data or reports from those references included in the Reservoir Sedimentation Report (January, 1982) and to search out any additional information from sources worldwide.

Appendix B includes a bibliography of all additional reports of data obtained from the literature search. It has been separated into two parts; the first containing references from New Zealand Lake studies, the second listing additional general references on reservoir sedimentation or the behavior of fine particles in a water body. Efforts have been made not to duplicate those publications referenced in the earlier reservoir sedimentation study (R&M, January, 1982).

Compilation of information from these sources has been an on-going process. Contacts in New Zealand have provided the most relevant information for Susitna. Table 3.1 summarizes the available basin and reservoir/lake characteristics for major study sites.

Lakes Tekapo, Pukaki and Ohau lie in adjacent mountain valleys at slightly different altitudes. Each basin is a long, narrow glacial trough exposed to strong winds, primarily from the northwest, blowing down the valleys. Thermal stratification is weakly developed and deep, and all lakes have a low chemical content of the water (specific conductance at 25°C of 5.0-7.0 umhos/cm).

In general, the lakes are clearest in autumn as precipitation in the upper basins falls as snow and inflow to the lakes is reduced. Turbidity increases in the late spring as the snow melt period begins and flow increases. Inflow to the lakes then carries a heavy silt load. The mean SECCHI disc readings for one year were: Lake Ohau - 9.36m (30.7 ft.), Lake Tekapo - 4.99m (16.37 ft.), and Lake Pukaki - 0.57m (1.87 ft.). The maximum readings were 21.74m (71.31 ft.), 7.0m (23.0 ft.), and 1.0m (3.28 ft.) respectively.

The literature reports that the differences in turbidity indicated by the SECCHI disc readings are related to silt content, rather than to algal production affecting light penetration.

The variations in extinction depth appear to be due in part to the percent of each drainage basin covered by glaciers.

However, at this time, limitations on the data preclude making direct comparisons between the behavior of fine sediments in the proposed Watana reservoir and existing New Zealand lakes. Additional supporting data on climatic characteristics, ice regime, incoming sediment size distribution, and seasonal turbidity or extinction depth for each lake are needed to complete the analysis.

TABLE 3.1
COMPARISON OF BASIN CHARACTERISTICS

BASIN CHARACTERISTICS	WATANA	EKLUTNA	PUKAKI	NEW ZEALAND TEKAPO	OHAU
Drainage Area (mi^2)	5,180	119	545	565	463
Glacier Area (mi^2)	290	6.2	73	16.6	8.0
% of Drainage Area	5.9	5.2	13.4	2.9	1.7
Annual Inflow (ac.ft.)	5,750,263	234,300	1,557,442	989,990	917,548
RESERVOIR/LAKE CHARACTERISTICS					
Length (miles)	48	7	14	15.5	10.5
Maximum Depth (feet)	680	200	230	395	423
Mean Depth (feet)	360	-	154	226	243
Maximum Width (miles)	5	0.7	-	-	-
Mean Width (miles)	1.5	0.6	5.0	3.7	3.2
Surface Area (acres)	37,800	3,420	24,460	21,500	13,340
Elevation of Water Surface (feet)	2,185	871	1,624	2,322	1,696
Capacity, Total (ac. ft.)	9,500,000	414,000	3,780,400	4,866,180	3,260,340
Average	8,330,000	-	-	-	-
Live	4,210,000 *	213,271	-	-	-
Average	3,040,000	-	-	-	-
Maximum Drawdown (feet)	140	60	-	-	-
Live Storage/Total Storage	0.44	0.52	-	-	-
Total Storage/Surface Area	251	121	155	226	244
Length/Average Depth	704	-	480	362	228
Drawdown/Depth	0.21	0.30	-	-	-
Length/Average Width	32	11.7	2.8	4.2	3.3
Mean Water Residence Time	635	646	418	847	612

4. SEDIMENTATION PROCESS

4.1 General

Sediment inflow to the Watana reservoir is derived mainly from the glaciers located in the upper portions of the drainage basin. The sediment size generally varies from less than 2 microns (0.002 mm) to 1 mm. As the river flows into the reservoir, the coarse fraction of sediment will settle out in the upper reaches and form a delta deposit. The finer particles will continue to flow into the reservoir where some will settle. Some of the fine particles will not settle, others will be reintrained and ultimately will be discharged from the reservoir through the powerhouse or over the spillway.

Under quiescent conditions, as the water flows through the reservoir, shear stress will be generated around the sides and along the bottom and density strata boundaries. These will generate some turbulence within the reservoir which will keep some of the smaller particles in suspension.

Under actual conditions, a large reservoir such as Watana does not experience these quiescent conditions. Continuous mixing processes are generated by climatic influences on the lake's surface and by inflowig and outflowing currents. These processes create a substantial amount of additional turbulence within the reservoir which would tend to keep the smaller fraction of the sediment in suspension.

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The following sections describe the above-mentioned processes in more detail. Much of the information has been obtained from the work done by Imberger and Patterson (1981).

4.2 Sediment Settling Characteristics

4.2.1 Settling Velocities for Spherical Particles

The behavior and rate of a particle settling in a fluid is not only dependent on the fluid flow, but also on the characteristics of the sediment particles. Fluid flow governs whether the sediment particle will be entrained, transported, or eventually deposited. In time and space, the eventual deposition of very fine particles is also dependent on the physical characteristics of the sediment. Size of the sediment particle is the most important property. However, the specific weight and shape of the particle along with the electrochemical characteristics of the fluid medium and concentration of sediment in the fluid, directly affect the sediment fall velocity.

The classical relationship that defines the physics of a sphere falling within a quiescent fluid medium is Stokes Law.

$$w = \frac{gd^2}{18}\left(\frac{\gamma_s - \gamma}{\mu}\right)$$

w = settling velocity

g = acc. of gravity

d = particle diameter

μ = kinematic viscosity

γ_s = sp. wt. of sediment

γ = sp. wt. of liquid

The above equation assumes the drag coefficient on the particles is constant and is therefore only valid for particle Reynolds numbers of less than 0.1.

Table 4.1 lists the settling velocities calculated for particle sizes ranging from 0.5 micron to 1 mm. Values for the .1 mm to 1 mm range (100 to 1000 microns) were obtained from curves for spherical particles given by W.N. Graf (1971). All the above values have been

TABLE 4.1

PARTICLE SETTLING RATES

Particle Diameter mm	Particle Diameter microns	Settling Velocity of Spherical Particles (S.G = 2.5, T = 40^{o}F) fps	Particle Reynolds No. (R) of Spherical Particles	Assumed Settling Velocity of Glacial Particles fps
1		3.1×10^{-1}	61	2.7×10^{-1}
0.5		1.5×10^{-1}	14	1.3×10^{-1}
0.2		4.9×10^{-2}	2	4.3×10^{-2}
0.1	100	1.6×10^{-2}	0.3	1.4×10^{-2}
	50	4.4×10^{-3}	<.1	3.8×10^{-3}
	20	6.9×10^{-4}	"	6.0×10^{-4}
	10	1.7×10^{-4}	"	1.5×10^{-4}
	5	4.3×10^{-5}	"	3.7×10^{-5}
	2	6.9×10^{-6}	"	6.0×10^{-6}
	1	1.7×10^{-6}	"	1.5×10^{-6}
	.5	4.3×10^{-7}	"	3.7×10^{-7}

Note: (1) Values for $R > .1$ based on curves in Reference (7) by W.H. Graf (1971).

(2) Values for $R < .1$ based on Stokes equation

(3) Settling velocities of glacial sediment particles are based on 1/1.15 x velocity of spherical particles.

calculated for a temperature of $40^{o}F$ and assumed particle specific gravity of 2.5.[1]

Figure 4.1 shows the depth of settling with time in the upper active layer for 2, 5, and 10 micron size particles using the settling velocities listed in Table 4.1.

The above analytic technique is for an ideal situation that would reveal the maximum settling velocities that could be expected. As previously discussed, even under quiescent conditions, the rate of settlement would be less due to the influence of other physical properties on the particle fall velocity.

4.2.2 Effect of Particle Shape on Settling Velocity

Sediment grains are rarely spherical in shape and vary from a rod-shaped particle to a disc-shaped particle. Glacial sediments tend towards a platy-type shape, but the shape is dependent on the parent mineral and process of decomposition.

Preliminary results from shape analysis of Susitna River sediments show that finer sediments tend towards a platy-type shape due to the relatively high percentage of mica and feldspar.

A study conducted by McNown, et al, (1951), determined the settling velocities for various machine-shaped particles and related the resistance factor 'K' to the shape factor 'SF', as shown on Figure 4.2. These tests were run for Reynolds numbers less than 0.1, which are representative of particles less than sand size. The curves represent theoretical results for ellipsoids (McNown & Malaika, 1950). The numbers beside each data point give the shape factor (b/c), and the shapes used are indicated in the Figure.

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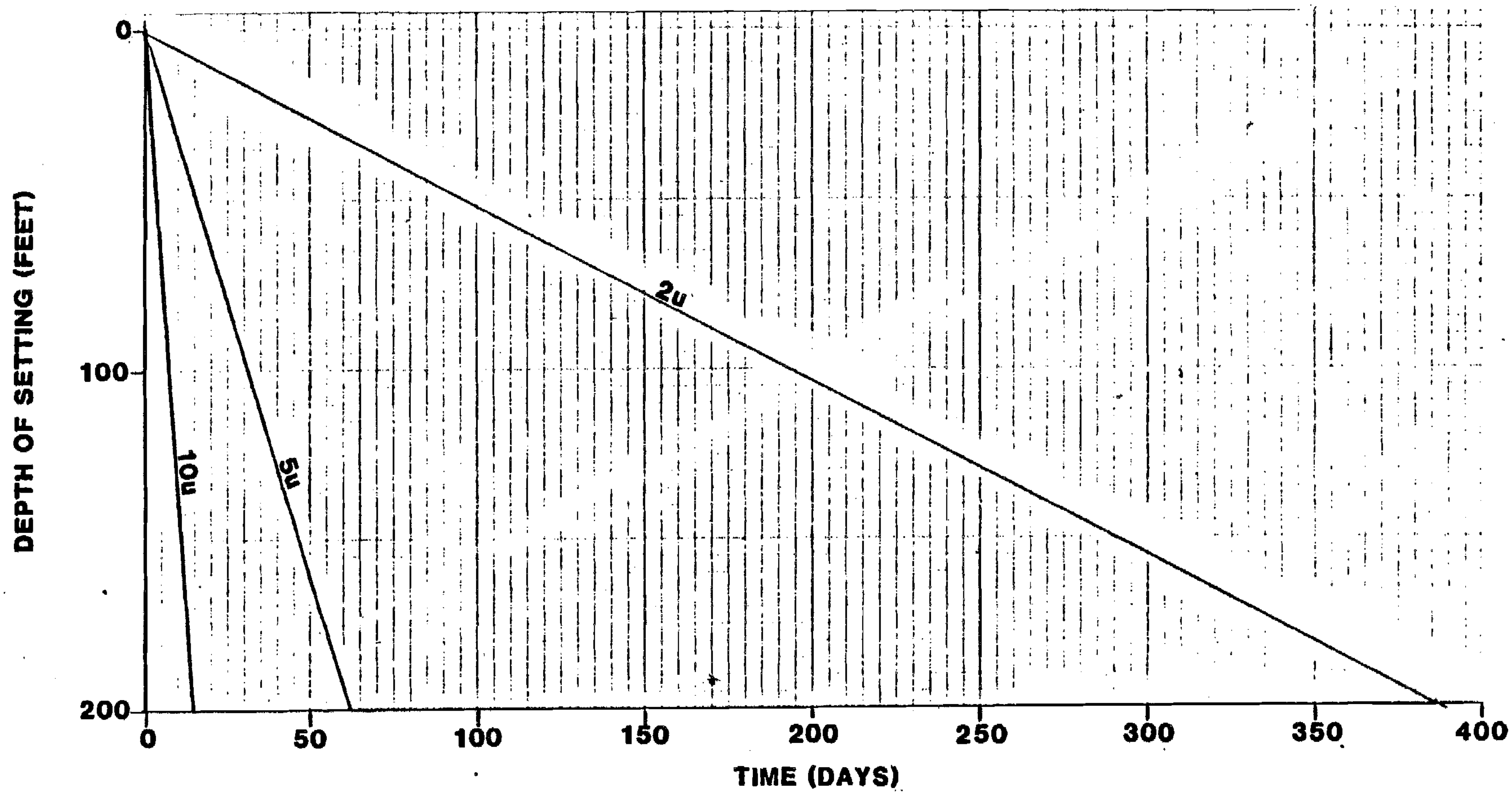
[1]Recent petrographic lab data indicates that Susitna River Sediment may have a higher mean specific gravity.



DEPTH OF PARTICLE SETTLING OVER TIME UNDER QUIESCENT CONDITIONS

FIGURE 4.1

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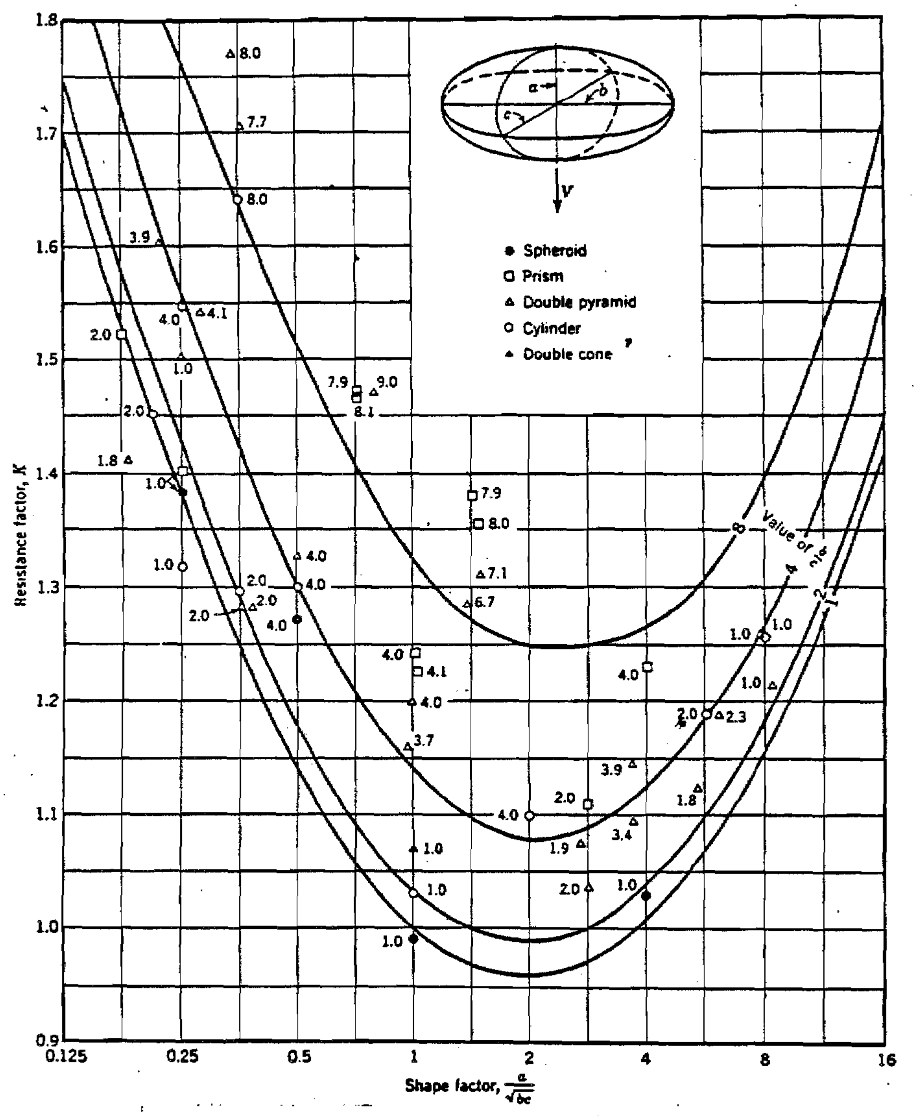


COMPARISON OF THEORETICAL VALUES OF K FOR ELLIPSOIDS AND OBSERVED VALUES FOR ELLIPSOIDS AND SEVERAL OTHER SHAPES FOR REYNOLDS NUMBERS LESS THAN 0.1 (McNOWN,et al., 1951)

VANONI, V.A. (1975) SEDIMENTATION ENGINEERING

There is little difference between the theoretical values for perfect ellipsoids and the observed values for ellipsoids and other shaped particles. The values of 'K' based on the two ratios, $a/\sqrt{bc}$ and b/c are within 10 percent of the theoretical value for ellipsoids, thus indicating that the axis ratios represent the principal hydrodynamic features of the particle shape. These curves can then be used to estimate settling velocities of nonuniform shaped particles occurring in nature. The value for 'K' is equal to the ratio of the fall velocity of a sphere with the same volume and weight as the particle to the fall velocity of the particle. For example, comparing a 20-micron sphere with an ellipsoid particle that has the same specific gravity, volume, and a shape factor of b/c = 4 would produce a resistance factor of 1.15 for the ellipsoid. This means that an ellipsoid with the ratio of dimensions presented above would have a fall velocity of 15 percent less than an equivalent spheroid.

In the particle size range being investigated here, there are few particles that approach a spherical shape. As yet, no information is available on the actual particle shapes. For purposes of this study, therefore, it has been assumed that a resistance factor of 1.15 applies. Table 4.1 lists the corresponding settling velocities for these assumed glacial sediment particles.

4.2.3 Effect of Sediment Concentration on Settlement Velocity

The previous discussion addressed a single particle settling in a clear infinite fluid. Influence of other particles falling within the water column could retard or accelerate the settling rate of a single particle. If the particle was one of an isolated group of similar particles, the settling rate of the particle group and hence, the single particle would tend to increase. This situation approaches that of flocculation. However, in the natural system that is continuously being supplied by sediment, it is likely that a variable spectra of sediment sizes would be found in the water column. When this occurs, the interference between neighboring particles will tend to reduce their fall velocity, which is often referred to as hindered settling.

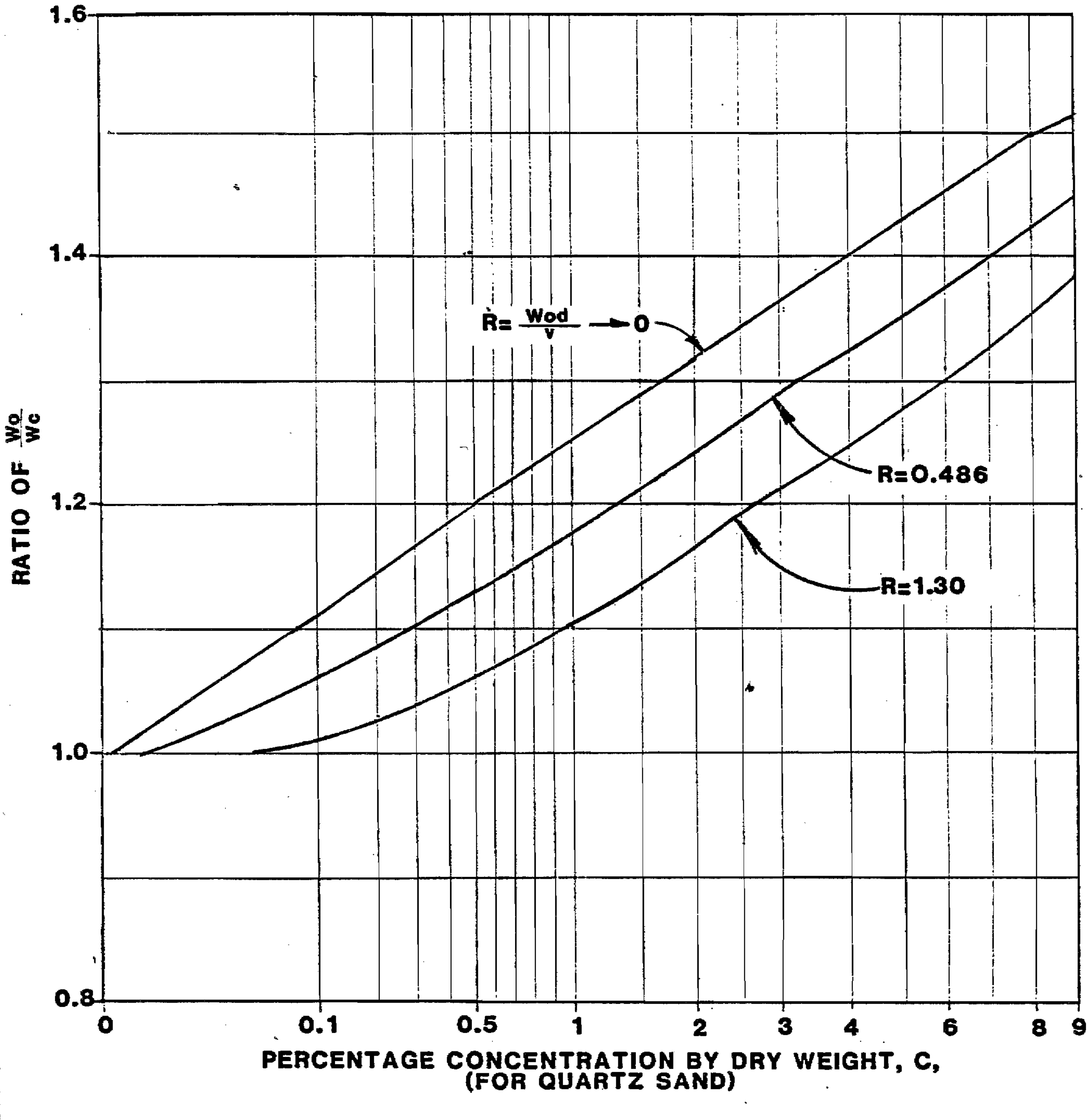
McNown and Lin (1952) studied theoretically and experimentally this phenomena, generating a relationship between the ratio of clear water settling velocity (W_o) and the particle velocity in a fluid with a given sediment concentration (W_c). The curves shown in Figure 4.2 are for an approximate theory based on the Oseen modification of Stoke's theory for the motion of a sphere in a viscous liquid at a low velocity. The curves apply for Reynolds numbers less than 2, which is representative of most of the particle size range being considered for this project. In referencing Figure 4.3, the influence of sediment concentration on the fall velocity can be significant when the sediment concentration is around 0.1 percent or 1000 mg/l. Susitna River suspended sediment concentrations measured at Gold Creek generally fall between 500 mg/l and 2000 mg/l when the discharge is greater than 20,000 cfs. Concentrations within the reservoir, however, are expected to be significantly lower.

As an example, if the inflow to the reservoir has a sediment concentration of 1000 ppm, it would be expected that the settling rate would be retarded by about 10 percent. The solid lines on Figure 4.3 are representative for different particle Reynolds number. For particle sizes of 50 microns or less, the Reynolds number is less than 0.1, therefore, the upper curve should be used for the Susitna Project.

As the sediment concentrations within the lake generally will be significantly lower than 1000 mg/l, the impact on settling velocities will therefore be much less than 10 percent. For purposes of these studies, therefore, the effect of sediment concentration on settling velocity has been neglected.

4.2.4 Effects of Flocculation on Settling Rates

If the mineralogy of the particles and the water chemistry are compatible, electrochemical forces will tend to hold particles together once they come in contact. Contact of particles and the potential subsequent formation of an agglomeration, or floc, can be



EFFECT OF CONCENTRATION ON FALL VELOCITY OF UNIFORM QUARTZ SPHERES (McNOWN AND LIN, 1952)

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induced by internal mixing of the fluid or by particles with higher fall velocities overtaking and capturing slower particles. Once two or more particles combine, the floc will settle at a higher rate than any of the individual particles of the floc falling alone. Low levels of turbulent mixing will tend to aid the formation of the floc; higher levels will break the floc apart. There is therefore a limit to the floc size depending on the level of turbulence within the system and electromagnetic forces. When the relatively turbulent river water initially enters the relatively quiescent reservoir water, the sediment particles will be dispersed in the water column. During this initial period, the greatest opportunity for heavier particles to encounter and adhere a smaller particle will occur. With time, the particles will tend to stratify in similar particle sized bands and therefore decrease the number of particle encounters.

To date, no studies have been done on the flocculating characteristics of the sediment in the Susitna River. However, metal shadowed micrographs of sediment samples from the Susitna River near Chase show a significant amount of agglomeration. Petrographic analysis revealed that these were composed of denser materials (pyrite, iron oxides, illenite) agglomerated onto lighter minerals (quartz, feldspar). More thorough investigation of the processes of agglomeration and flocculation would be needed to assess the impact of these processes on sediment behavior, particularly settling rates. For purposes of these studies, the effect of flocculation or agglomeration have therefore been neglected.

4.3 Quiescent Settling in the Reservoir Basin

The approach used for estimating quiescent settling involved application of a reservoir sedimentation computer model. The model, DEPOSITS, has been developed by A. Ward (1979) for the design of sedimentation ponds. It describes the sediment transport and deposition process in a reservoir as a function of the basin geometry, inflow hydrograph, the inflow sediment graph, the sediment characteristics, the outlet structures and the hydraulic behavior of flow within the basin. The model determines basin trap efficiency, loss in storage due to sediment accummulation and effluent suspended sediment concentrations. The model has been verified with data from several different ponds and reservoirs located throughout the nation, but not with a basin that has significant glacial flow and sediment contribution.

In the model, flow within the basin is idealized by plug flow concepts. Plug flow assumes no mixing between plugs and routes the flow on a first in, first out basis with each plug representing an equal time increment. Settling of the sediment particles is described by Stoke's Law of Settling. The reservoir bed is considered a perfect absorber of sediment and resuspension or saltation of the particles is disregarded. The model accounts for the variation in sediment concentration with depth by subdividing each plug into four layers. Selective withdrawal, at the basin outlet, from these layers is provided for in the model.

The basic inputs to the model include:

1) Inflow hydrography
2) Viscosity of the flow
3) Stage-area curve for the basin
4) Stage-discharge curve for the basin
5) Stage-discharge distribution curve
6) Degree of dead storage or short-circulating
7) Sediment inflow graph or load
8) Particle size distribution and specific gravity of the suspended sediment

For purposes of these studies, the model has been modified to accept specified discharge values rather than a stage discharge curve.

Because it ignores dispersive mixing within the reservoir, the model will tend to underestimate the minimum discharge concentrations and overestimate the maximum outflow concentrations. This must be taken into account when interpreting the results of the model runs.

A second approach has been used to check on the results of the model runs. It is described by H.T. Rouse (1948) and is based on work done by Camp (1943). This approach is briefly outlined below.

The Watana reservoir is a relatively long (48 miles) and narrow (1 1/2 miles basin). For purposes of sediment deposition calculations, it can therefore by treated as a channel. Water flows into the upstream end, passes through the channel-shaped basin, and flows out at the downstream end. Storage changes take place which result in differences in the inflow and outflow rates. As the sediment particles pass through the reservoir, they gradually settle out. The velocity of flow through the basin generates shear stress along the boundaries, and hence, turbulence within the reservoir. This turbulence tends to reduce the rate of settling, particularly of the small particles.

Camp (1943) evaluated the turbulent transport function for two-dimensional flow. He assumed the water velocity is the same at every point in the channel and that the mixing coefficient is also the same at all points. The functional relationship he developed is as follows:

$$\frac{(qs)e}{(qs)i} = \frac{w}{t/p}, \frac{wL}{Vy}$$

in which

(qs)e = quantity of sediment of given particle size in effluent

(qs)i = quantity of sediment of given particle size in influent

w = fall velocity of the given particle size

$$t/p = \text{shear velocity} \quad \frac{Vn \quad g}{1.49y^{1/6}}$$

y = basin depth

n = Manning's roughness coefficient

L = basin length

V = mean velocity of flow in basin

This function has been evaluated analytically and verified experimentally. It is shown on Figure 4.4.

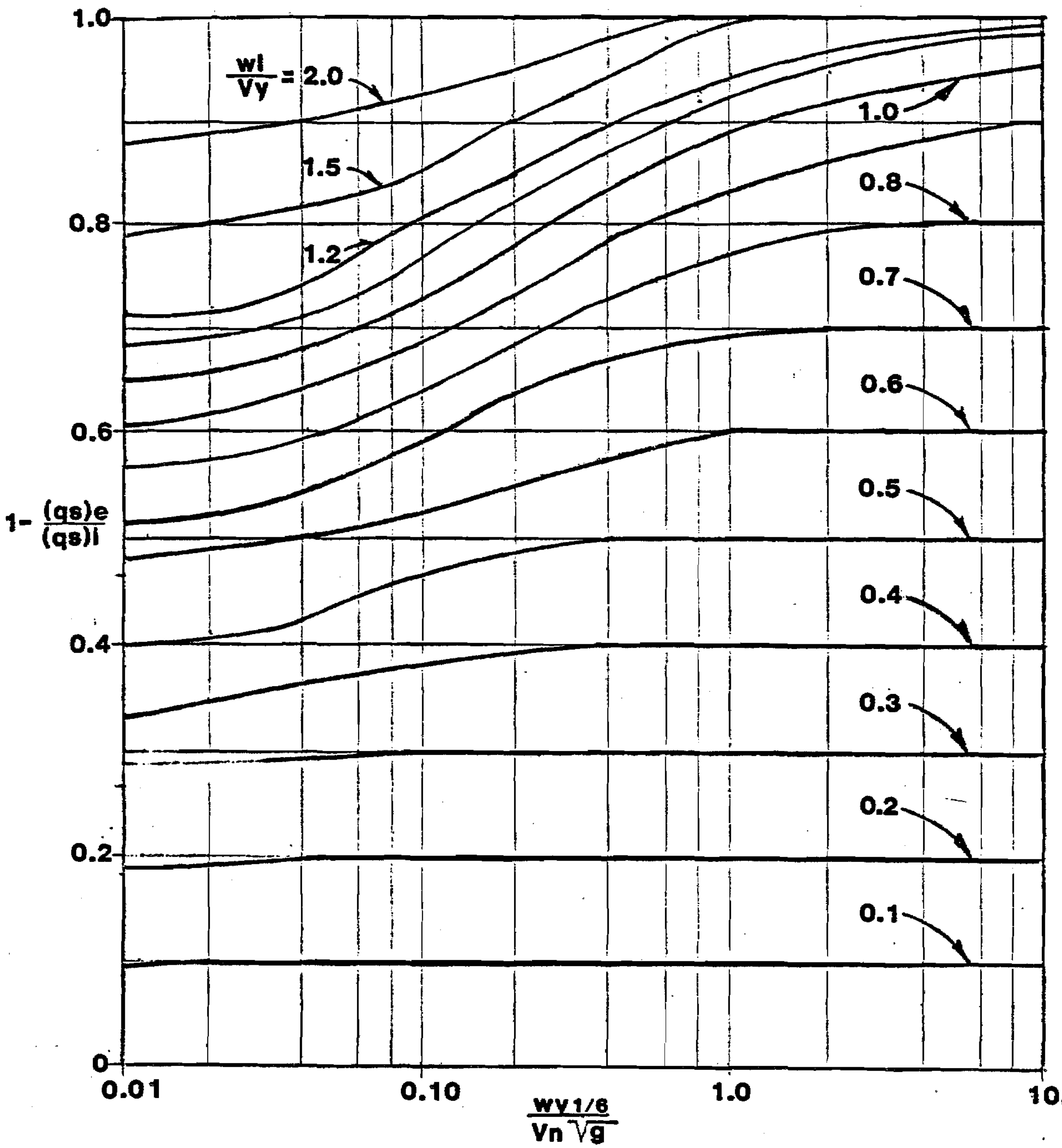
4.4 Reservoir Mixing Process

As outlined by Imberger and Patterson in Fisher et al (1979), the major mixing processes occurring in the Watana reservoir are meterologic conditions and the inflowing and outflowing water. These processes all tend to generate turbulent eddies within the reservoir which continually stir the sediment in the water. The basic processes are discussed below.

4.4.1 The Annual Cycle

The annual thermal regime of the reservoir is currently being studied by Acres (1982). Based on preliminary results from these studies, as well as earlier thermal modeling also conducted by Acres (1982), the reservoir's thermal regime appears to be relatively stable as compared to more moderate climate reservoirs and lakes.

During the winter months (November through April), most of the water in the reservoir would be at 4°C (40°F). In the upper layers, temperatures would drop to 0°C (32°F). During the spring and summer warming period (May through July), surface temperatures would gradually increase to approximately 9 to 10°C (48-50°F). The reservoir would be reasonably well stratified with a thermocline located up to 50 meters (165 feet) below the surface. Water temperatures below depths of approximately 100 meters (328 feet) would remain at 4°C. During the cooling periods (August through October), the surface water would cool down. Overturning would take place in the upper 100 meters as the surface temperatures reach 4°C. During this period, the upstream 10-mile reach of the reservoir which has depths less than 100 meters would probably be subjected to complete overturning.



SEDIMENT-REMOVAL FUNCTION FOR SETTLING BASINS

ROUSE, H. (ed.), 1950, ENGINEERING HYDRAULICS will tend to flow into the near surface layers of the reservoir which are the same temperature. During the spring warming period, from May to June, the river water would warm at a quicker rate than the reservoir surface, and, therefore, continue to flow into the upper layers of the reservoir. During the July to September period, river water would start to cool more rapidly than the reservoir water. Flow into the reservoir would gradually tend to enter at lower layers; and towards September, the flow would be entering the reservoir in the vicinity of the thermocline. As the lake water cools, the river inflow would gradually move back to the surface layers.

Based on the above discussion, it is evident that the sediment entering the reservoir will flow in near the surface most of the year. The exception is during the late summer and fall months when it would tend to flow into deeper layers near the thermocline. During this period, the overturning that occurs in the upper layers of the reservoir would provide some mixing of the sediment particles in these layers and somewhat reduce the amount of sediment that settles out.

R&M (1982) is currently conducting studies on Eklutna Lake, located approximately 100 air miles to the south of Watana, in support of ongoing model efforts. These studies indicate that Eklutna Lake is subject to complete overturning during the fall period. In addition, sufficient mixing forces over the length of the lake surface result in little variation in surface turbidity levels, regardless of the distance from inflowing streams. Maximum turbidity is not always recorded at the surface. Turbidity plumes below the surface have been traced in the lake.

The observed behavior at Eklutna Lake and predicted behavior of the Watana reservoir still need to be confirmed. The two are not necessarily consistent in all respects. Data for a full annual cycle at Eklutna Lake will be needed to strengthen assumptions and conclusions about the similarity in behavior of the two systems.

4.4.2 Particle Mixing in the Epilimnion

The major mixing forces active in the upper layers of the reservoir, Fisher et al, 1979, include:

- o penetrative convection
- o wind induced mixing
- o mixing induced by inflowing or outflowing water

These are discussed in more detail below.

(a) Penetrative Convection

The epilimnion would be subjected to diurnal temperature fluctuations due to daytime heating and nighttime cooling. The depth of penetration of the short wave radiation depends on the water clarity, but in the absence of wind there is always an identifiable temperature rise and stratification layers during the sunlight hours. As night falls and radiative heat losses begin to dominate the thermal exchange at the surface, the surface layer cools and convective motions mix the upper layers. Often these convective motions proceed until they reach the mature thermocline where they begin to erode the stable temperature structure.

(b) Mixing Due to Weak Winds

A wind blowing over a lake exerts a stress on the water surface that causes waves to form, break, and transfer momentum to the water. The wave motion, especially when waves are breaking, produces turbulence in the upper layer. This turbulence then interacts with the mean shear in the upper few meters to produce further turbulent kinetic energy. Often this interaction produces a secondary motion as well as a mean windward drift. Such secondary motions are called Langmuir cells and they are distinguishable to an observer by the characteristic slick pattern associated with the regions of convergence. The net turbulent kinetic energy produced in these upper few meters is then exported to the lower parts of the epilimnion during turbulent diffusion or by the advective motion associated with the Langmuir circulation.

In addition to this stirring of the surface water layers, the wind will also cause the water to accelerate so that after a short time the whole epilimnion will have a mean motion with a velocity. The shear associated with this mean motion may then further contribute to the production of turbulent mixing.

(c) Reservoir Behavior Under Severe Wind Conditions

So far, the discussion of wind mixing in the epilimnion has not taken into account the motion of the water in the reservoir. The wind stress will initiate motion and move the water in the epilimnion in the direction of the wind. If the water surface is to remain nearly horizontal, as it does, then the water in the hypolimnion must counter this flow and move in the reverse direction. A shear will develop across the thermocline which will increase with time until the thermocline has tilted sufficiently to set up a hydrostatic pressure gradient which just balances the surface stress. At this stage the motion changes from a whole basin circulation to two closed gyres, one each in the epilimnion and the hypolimnion, and the shear at the interface will decrease to a very small value. All the work done by the wind is then either dissipated internally or used to deepen the epilimnion. The set up time is proportional to the seiching period of the thermocline which may be as much as two or three days, giving the wind stress ample opportunity to develop an appreciable shear across the thermocline.

4.4.3 Vertical Mixing in the Hypolimnion

Observations in large lakes using measured distribution of natural or artificial traces indicate that vertical diffusive mixing in the hypolimnion ranges from molecular diffusion to values up to 10^{-4} to 10^{-5} in m^2/sec (10^{-6} to 10^{-7} $ft.^2$/sec.) (Fisher et al 1979, and Hamblin, 1982). In addition to this, sometimes relatively rigorous mixing occurs. The only apparent explanation for this is that although overall there is not sufficient kinetic energy to cause mixing, there are portions of the lake at any particular time where the energy density has been increased by some type of concentrating mechanisms, allowing a local breakdown in the mixing of the structure. The mixing is thus patchy and intermittent and quickly collapses under the action of buoyancy. Upon collapse, the mixed patches elongate and interleave with themselves and their surroundings, leading to steplike vertical density structures.

4.4.4 Outflow and Inflow Dynamics

Local mixing is generated in the zone where the inflow and outflow occurs. Depending on the magnitude of the discharge, the outflow may draw water from several layers within the reservoir. The velocity field induced by the withdrawal will generate additional turbulent mixing. However, for a reservoir as large and as long as Watana, this mixing influence is expected to be limited to a small local area near the power intakes.

A river entering a reservoir nearly always will be at a different temperature, and thus density, than the surface water in the reservoir. Upon entering the reservoir, it will thus push the stagnant lake water ahead of itself only until buoyancy forces, due to the density differences, have become sufficient to arrest the inflow. At that point, the inflowing water will either flow over the surface of the lake if it is warmer, or plunge and flow submerged if it is colder. There are three distinct mixing regimes associated with the inflow.

First, there is mixing associated with the plunge line. Second, in the case of the underflowing situation, the bottom roughness often leads to mixing, called entrainment, at the interface between the reservoir water and the inflow. Third, whenever the density of the inflowing water equals that opposite in the reservoir, then the inflowing water will leave the bottom and intrude horizontally into the reservoir. These intrusions may also occur along the surface if the density of the inflowing water is less than that of the surface water.

4.5 Reintrainment of Sediment

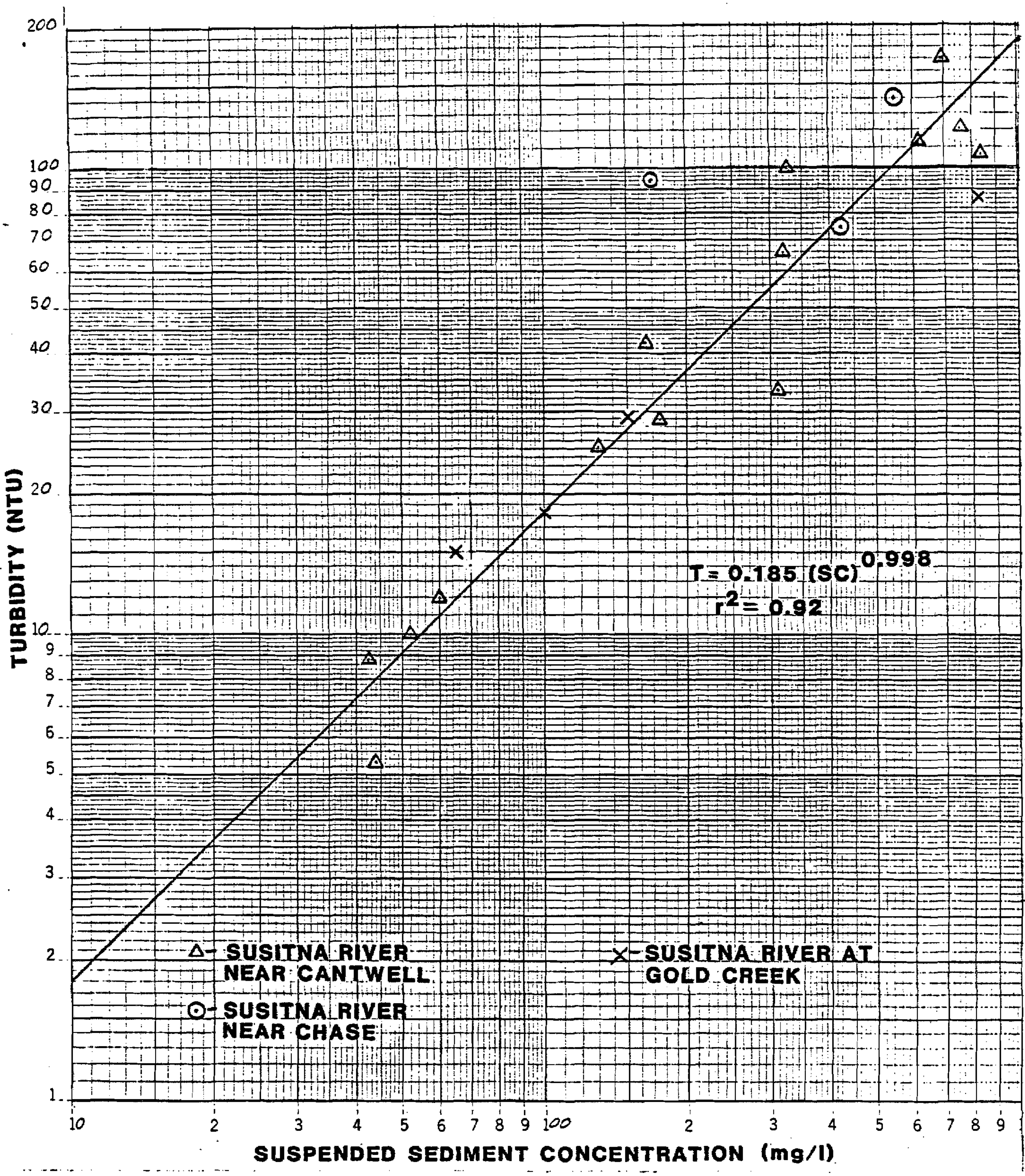
Along the shoresline of the reservoir, the convective and wind mixing effects will reach the bottom sediment. Some of these sediments will be resuspended and reintrained in the water. The maximum particle size and, hence, the amount of sediment that will be reintrained will depend on the strength of the mixing currents. During high wind periods, this reintrainment can contribute substantially to turbidity in the reservoir along the shore.

4.6 Turbidity Versus Sediment Concentration

Biological activity in the lake is dependent on light penetration, which in turn, is a function of the concentration of suspended matter. A relationship is therefore required to convert predicted lake sediment concentrations to turbidity.

R&M (1982) developed a regression equation relating to turbidity in NTU's to sediment concentration in mg/l. The data was derived from measurements at the Gold Creek and Vee stations. Subsequent to these studies, additional data have become available at the Susitna River station near Chase. A new regression equation has been developed combining all the available data and is shown in Figure 4.5.

Much of the subsequent analysis in this report is based on this turbidity-sediment concentration relationship because of limitations on



TURBIDITY vs SUSPENDED SEDIMENT CONCENTRATION

other available data. It is important to incorporate all additional data from the USGS 1982 field sampling program as it becomes available. Weekly measurement of turbidity and sediment concentration in the Susitna River near Chase will provide data to verify the relationship presented here. These results can then be modified to account for the variation in behavior in lakes and rivers.

5. WATANA RESERVOIR SYSTEM

5.1 Climate

Wind-induced mixing is one of the principal mixing processes occurring in the Watana reservoir. Winds blowing over the reservoir surface produce turbulence in the upper layers and can initiate water motion in the direction of the wind.

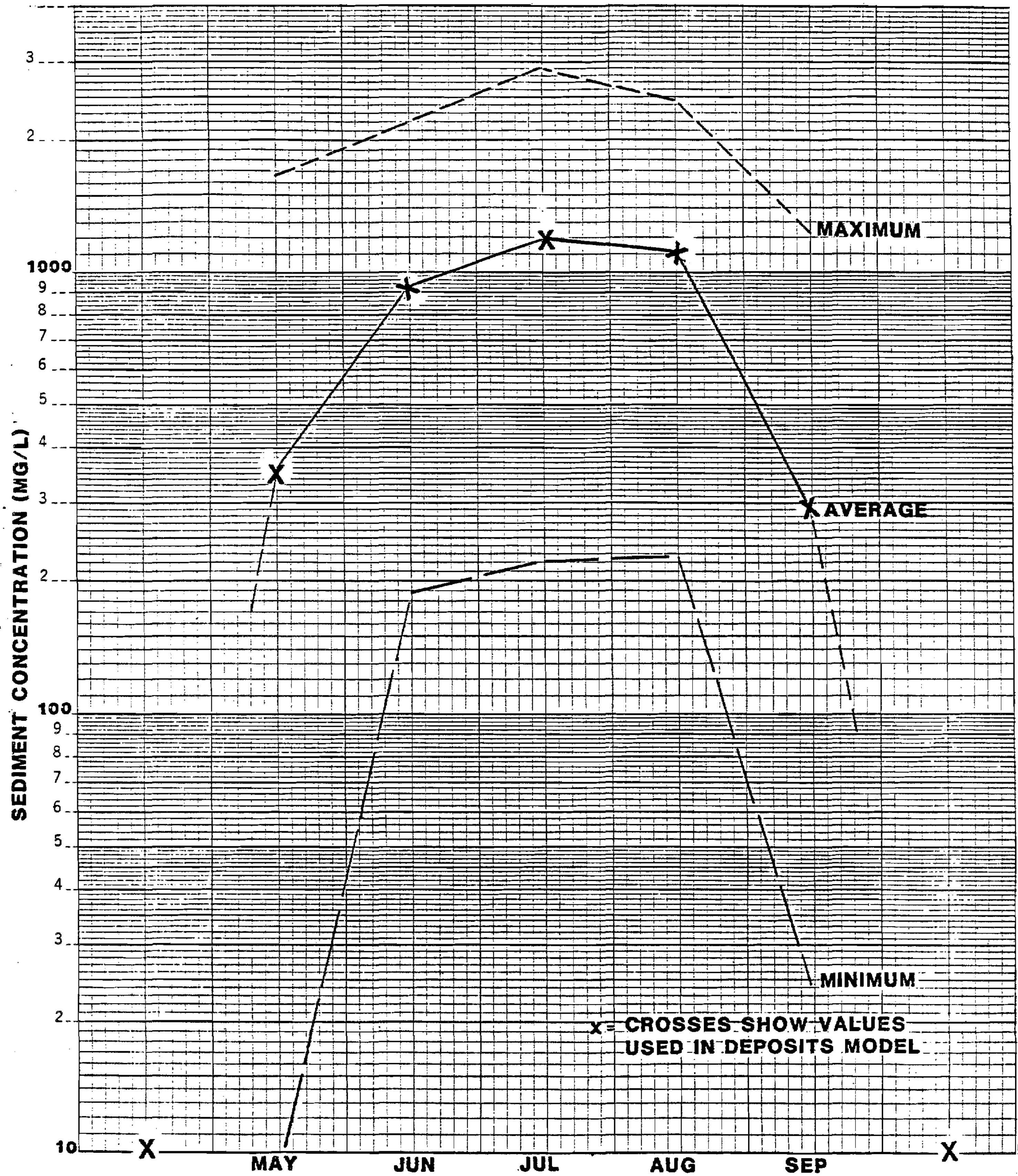
To carry out detailed wind analysis, data from three weather stations in the Susitna Basin were reviewed. Data on wind magnitude and direction from the Watana weather station were selected for use in analysis. This station most nearly represents conditions at the reservoir and also has the most complete record.

5.2 Hydrology

Case C intermediate flow and power conditions, presented in Volume 4, Appendix A, of the Susitna Feasibility Report, has been used to provide baseline hydrology information for determining monthly reservoir operating conditions.

5.3 Sediment Regime

Data from several sources has been compiled to define the sediment regime in the Susitna River near the proposed dam site. Historical data from the USGS on sediment concentration and particle size distribution has been summarized on a monthly basis for input into the DEPOSITS model using data collected at the Gold Creek Station. Figures 5.1 and 5.2 present average monthly sediment concentration with maximum and minimum values, and average monthly particle size distribution. The crosses on both figures indicate values used in the DEPOSITS model.



SUSITNA RIVER AT GOLD CREEK
SEDIMENT CONCENTRATION-SUMMER VALUES ONLY (1952-1981)*

* DOES NOT INCLUDE 1981 USGS DATA

FIGURE 5-1

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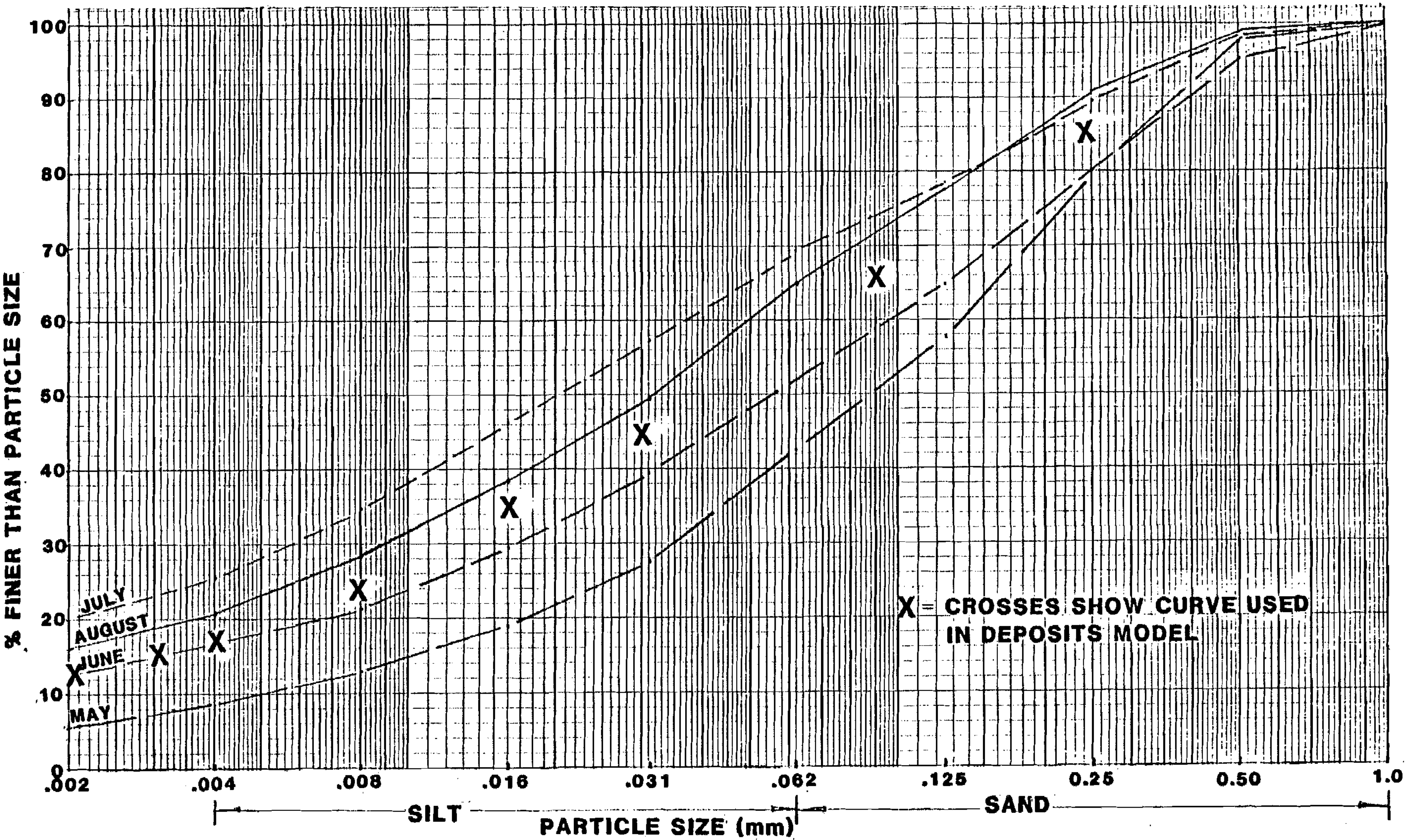

SUSITNA RIVER AT GOLD CREEK
AVERAGE MONTHLY PARTICLE SIZE DISTRIBUTION

FIGURE 5.2

PERATROVICH, NOTTINGHAM & DRAGE, INC.
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During the summer of 1982, an extensive sediment sampling program was carried out by the R&M Consultants, Inc., and the USGS, to improve understanding of the existing sediment regime. Samples collected on a weekly basis through the summer months included turbidity, sediment concentration, and bedload. Analysis of the turbidity samples is complete, however, sediment concentration and bedload sample analyses have not been completed at this time. When these results become available, they should be incorporated into the statistical analysis of turbidity versus sediment concentration to add strength to the correlation.

For this report, existing turbidity versus concentration values for the Susitna River at Cantwell (Vee), at Gold Creek, and near Chase have all been combined to revise the regression line presented in the earlier report. Figure 4.4 shows the new regression line used to convert predicted sediment concentration in the reservoir to turbidity.

5.4 Reservoir

Information on daily inflow to reservoir and projected powerhouse flows used in determining monthly water retention time, flow-through velocities, and live storage for the reservoir have been taken from the Susitna Feasibility Report, Volume 4, Appendix A. Table 5.1 shows the resulting monthly values of the above mentioned parameters used in this report for modelling and analysis.

TABLE 5.1
WATANA RESERVOIR CHARACTERISTICS

MONTH	INFLOW(cfs) AVG.	INFLOW(cfs) MAX.	INFLOW(cfs) MIN.	POWERHOUSE FLOW (cfs)	AVERAGE FLOW (cfs)	WATER SURFACE AT END OF MONTH (ft.) AVG.	WATER SURFACE AT END OF MONTH (ft.) MAX.	WATER SURFACE AT END OF MONTH (ft.) MIN.	STORAGE (ac.ft.) LIVE	STORAGE (ac.ft.) TOTAL	VELOCITY (fps) LIVE	VELOCITY (fps) TOTAL	RETENTION TIME (yrs) LIVE	RETENTION TIME (yrs) TOTAL	RESERVOIR LENGTH AT END OF MONTH
OCTOBER	4513.1	6458.0	2403.1	7370.5	5941.8	2177	2185.6	2122.5	3.98×10^6	9.27×10^6	.009	.004	.93	2.15	49.3 miles
NOVEMBER	2052.4	3525.0	1020.9	8723.6	5388.0	2166	2173.2	2112.6	3.67×10^6	8.97×10^6	.009	.004	.94	2.30	48.4
DECEMBER	1404.8	2258.5	709.3	11135.4	6270.1	2150	2155.9	2097.3	3.22×10^6	8.51×10^6	.011	.004	.71	1.87	47.2
JANUARY	1157.3	1779.9	619.2	9535.0	5346.1	2133	2138.2	2081.2	2.75×10^6	8.04×10^6	.011	.004	0.71	2.08	46.9 miles
FEBRUARY	978.9	1560.4	602.1	9150.3	5064.6	2119	2122.0	2068.5	2.35×10^6	7.64×10^6	.012	.004	0.64	2.08	46.6 miles
MARCH	898.3	1560.4	569.1	6865.4	3881.9	2107	2110.0	2054.5	2.01×10^6	7.30×10^6	.011	.003	0.71	2.60	46.4
APRIL	1112.6	1965.0	609.2	6176.9	3664.7	2097	2100.0	2045.3	1.73×10^6	7.02×10^6	.012	.003	0.65	2.64	46.2
MAY	10397.6	15973.1	2857.2	5767.5	8082.5	2106	2119.1	2045.2	1.99×10^6	7.28×10^6	0.023	0.006	0.34	1.24	46.4 miles
JUNE	22912.9	42841.9	13233.4	6099.7	14506.3	2139	2164.7	2075.9	2.91×10^6	8.21×10^6	0.028	0.010	0.28	0.78	47.0 miles
JULY	20778.0	28767.4	14843.5	5483.7	13130.9	2166	2190.0	2109.0	3.67×10^6	8.97×10^6	0.021	0.009	0.39	0.94	48.4 miles
AUGUST	18431.4	31435.0	7771.9	9329.3	13880.3	2181	2190.0	2130.3	4.10×10^6	9.39×10^6	0.020	0.009	0.41	0.93	49.7 miles
SEPTEMBER	10670.4	17205.5	4260.0	10158.7	10414.5	2182	2190.0	2126.8	4.13×10^6	9.41×10^6	0.015	0.007	0.55	1.25	49.8 miles
AVERAGE	7942 (cfs)	42841.9 (cfs)	569.1 (cfs)	7983 (cfs)	7741.5 (cfs)	2150 (ft.)	2190 (ft.)	2045.2 (ft.)	3.04×10^6 (ac.ft.)	8.33×10^6 (ac.ft.)	0.015 (fps)	0.006 (fps)	0.60 (yrs.)	1.74 (yrs.)	47.7 miles

6. ANALYSIS OF SEDIMENT BEHAVIOR

6.1 Quiescent Settling

a. DEPOSITS Model

In order to allow for an initital start-up period, the model was run for a period of four average years. The resultant steady state discharge sediment concentrations are summarized in Table 6.1. The discharge values range from approximately 0 to 60 mg/l for the upper portion of a dead storage area of 900,000 acre-ft., and range from 0 to 100 mg/l for the upper portion of a dead storage area of 5,290,000 acre-ft.

An additional run was done assuming all the volume below elevation 2,050 feet to be dead storage. In this run, the discharge was assumed to occur uniformly over the full depth of the active storage zone, i.e. above 2,050 feet. The results are similar to those using a dead storage value of 5,290,000 acre-feet. As mentioned in Section 4.3, the program neglects dispersive mixing. The range of values stated using all the different dead storage areas is therefore probably over estimated.

The amount of dead storage selected represents a range from a minimum value of approximately 10 percent of the total storage to maximum level equal to the annual average difference between total and live storage as reported in Table 5.1.

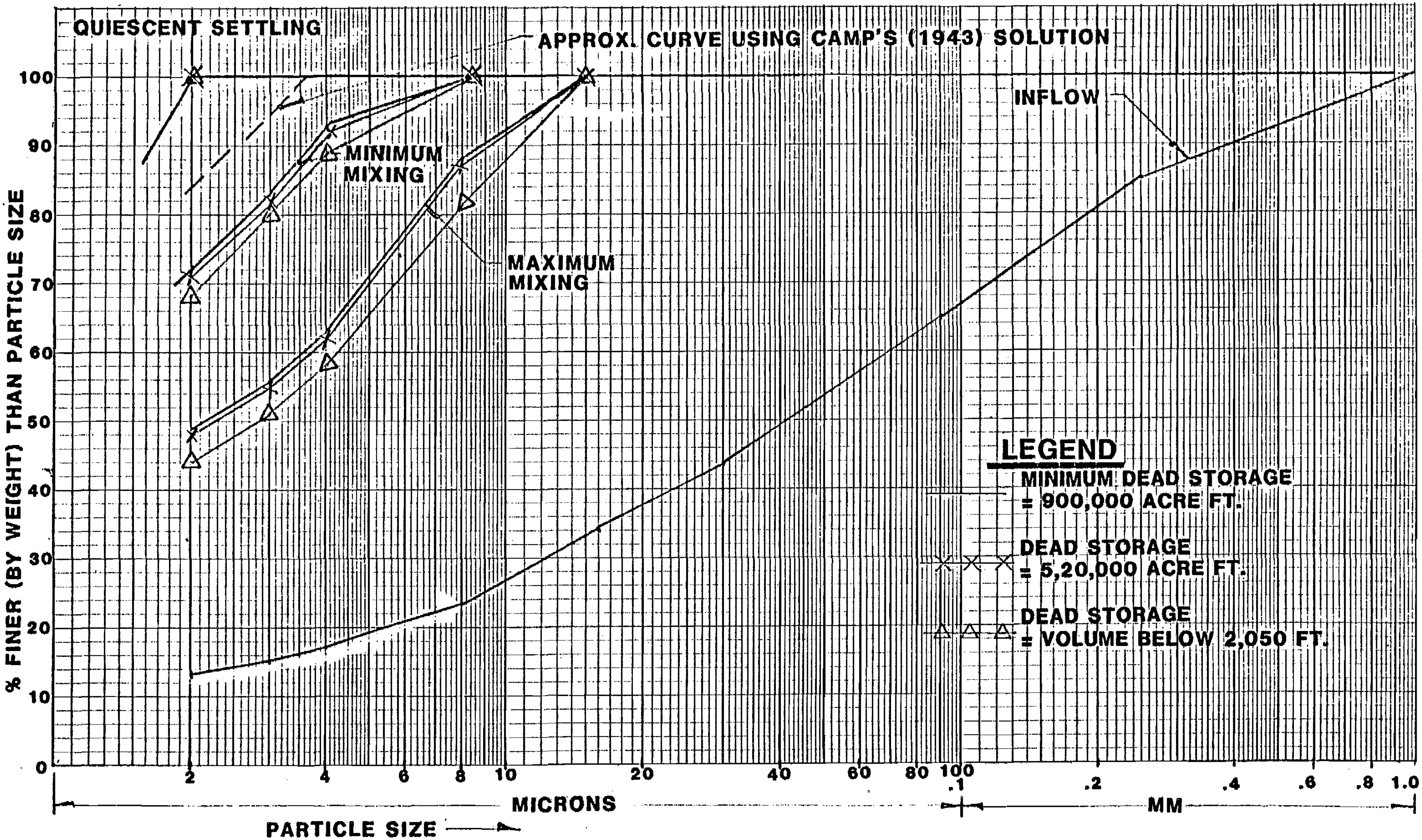
The trap efficiency predicted by these model runs ranges from 94 to 96 percent, depending on the dead storage area. The inflow and predicted outflow sediment gradation curves are shown in Figure 6.1. It can be seen that only particles with diameters of 2 microns or less travel through the reservoir under quiescent conditions.

As the model does not take into account horizontal mixing, and because it is difficult to predict the actual amount of dead storage, it is not possible to estimate the time variation of sediment concentrations at the discharge point.

TABLE 6.1
RESULTS OF "DEPOSITS" MODEL RUNS
SEDIMENT CONCENTRATION (mg/l)

SIMULATION CASE	DEAD STORAGE VOLUME ACRE.FT.	INFLOW PEAK	INFLOW SUMMER AVERAGE	OUTFLOW MAXIMUM	OUTFLOW AVERAGE	OUTFLOW MINIMUM	TRAP EFFICIENCY (%)
Quiescent	900,000	1197	773	61	30	0	96
	5,290,000	1197	773	95	56	2	94
	Volume below 2050*	1197	773	94	54	5	94
Minimum	900,000	1197	773	211	84	2	93
Mixing	5,290,000	1197	773	213	121	2	87
	Volume below 2050*	1197	773	224	134	12	86
Maximum	900,000	1197	773	316	124	3	90
Mixing	5,290,000	1197	773	316	179	2	81
	Volume below 2050*	1197	773	345	206	18	78

Note: * Assume uniform withdrawal over depths at discharge end of reservoir. All other runs assume withdrawal is limited to upper 25% of depth at discharge end of reservoir.



PARTICLE SIZE DISTRUBUTIONS PREDICTED BY DEPOSITS MODEL

FIGURE 6.1

b. Camp Curves

The relationship shown in Figure 4.4 was also used to calculate the amount of sediment that would settle out in the Watana reservoir. The monthly sediment size gradation curves shown in Figures 5.2 and the corresponding settling velocities contained in Table 4.1 were used. The integration of the total amount of sediment which settles out was carried out using particle sizes of 0.5, 0.1 mm, 50, 10, 5, and 1 micron. Monthly reservoir velocities were calculated by the following equation:

$$V = \frac{QL}{Vol}$$

Where:

V = average longitudinal velocity through the reservoir (ft./s)

Q = average monthly outflow ($ft.^3/s$)

K = length of reservoir (ft.)

Vol = average monthly reservoir volume ($ft.^3$)

Reservoir volumes were obtained from Table 5.1, and an average reservoir length of 48 miles was used. Reservoir depths were calculated by subtracting the average monthly reservoir stage from the minimum active zone elevation of 1,950 feet, which is approximately 50 feet below the power intake elevation.

The results of these analyses for the summer months are summarized in Table 6.2. They demonstrate that a large proportion of the sediment would settle out and that only particles of diameter of less than 3 to 4 microns would leave the reservoir.

These results agree reasonably well with the DEPOSITS computer model results. The following sections describe how these results should be modified to give a more realistic indication of sediment concentration by incorporating the turbulent mixing in the reservoir.

TABLE 6.2

RESULTS OF QUIESCENT SETTLING ANALYSES
FOR THE WATANA RESERVOIR

Month	Percentage of Sediment Inflow Running Through the Reservoir - %	Approximate Maximum Size of Sediment Particle Running Through The Reservoir (microns)
May	4	3
June	10	4
July	21	3
August	16	4
September	17	3

6.2 Induced Mixing

Two approaches were adopted in quantitatively evaluating the mixing induced by wind, thermal input, and the inflow and outflow. The first approach involved evaluating the effect of wind wave action only. For each month of the year, the total period in which wave heights exceed critical values was evaluated. The critical wave heights were those which induce an orbital current of 2×10^{-4} ft./s at depths of 25 and 50 feet respectively.

The second approach involved using the results of the Acres (1982) thermal modeling of Watana Reservoir. The program was modified to print out the shear velocities associated with wind and thermal mixing in the epilimnion and with mixing induced by inflow and outflow in the hypolimnion. The two approaches are discussed in more detail below.

6.2.1 Wind-Induced Mixing

The main objective of this analysis was to determine the impact of oscillating wind-induced currents on small suspended particles. A particle settling velocity of 2×10^{-4} ft./s was arbitrarily selected for this study. It corresponds to a particle size of approximately 12 microns (see Table 4.1).

Equations for calculating oscillating wave velocities at depth for a given wave height and period have been developed by the U.S. Army Coastal Engineering Research Center (1977). These equations were orbital velocities of 2×10^{-4} ft./s at depths of 25 and 50 feet respectively. Effective wind fetches were calculated for the reservoir for each 22 1/2 degree directional component. Using this information in conjunction with the equations developed by the U.S. Army Coastal Engineering Research Center (1981) for determining fetch limited wave height and periods, and the critical wave heights calculated previously, the corresponding critical wave speeds were calculated. These winds speeds were calculated for each directional component for each month during 1981, and for critical velocities occurring at 25- and 50-foot depths respectively. Using these wind speeds and the results of the monthly wind speed direction duration analyses, the percentage of time the critical wind speed is exceeding in each month was calculated. For these analyses a water depth of 600 feet was used.

The results of the analyses for the open water period are summarized in Tables 6.3 and 6.4. The percentage durations reflect the integrated duration of winds from all directions during that month. As can be seen, significant mixing to a depth of 25 feet occurs between 35 and 55 percent of the time during the summer months except during the month of August, when the prevailing winds were from the north. A significant reduction in mixing occurs at the 50-foot level.

The wave orbital velocities above the indicated depths increase over the value of 2×10^{-4} as one gets closer to the water surface. This means that in the shallower layers, particles with settling velocities much larger than 12 microns will be held in suspension by the wave action.

The results of those analyses indicate that under certain conditions, particles as large as 12 microns could pass through the reservoir. It is important to remember that these analyses are based on 1981 recorded data and do not necessarily reflect average monthly conditions.

6.2.2 Wind and Thermal Mixing

The dynamic reservoir simulation model, DYRESM, is a one-dimensional (vertical) numerical model for the prediction of temperature and salinity in lakes and reservoirs. It is a comprehensive model, and attempts to model all the mixing mechanisms within the reservoir.

The model is provided with 6 hourly averaged input data, including air and inflowing water temperature, long and short wave radiation, and

TABLE 6.3

DURATION OF WAVE MIXING TO 25-FOOT DEPTHS

Month	% of Month During Which Wind Waves Generate Orbital Velocity Exceeding 2×10^{-4} ft/s
May	40
June	41
July	35
August	8
September	30
October	35
November	55

TABLE 6.4

DURATION OF WAVE MIXING TO 50-FOOT DEPTHS

Month	% of Month During Which Wind Waves Generate Orbital Velocity Exceeding 2×10^{-4} ft/s
May	4
June	2
July	1
August	0
September	1
October	0
November	12

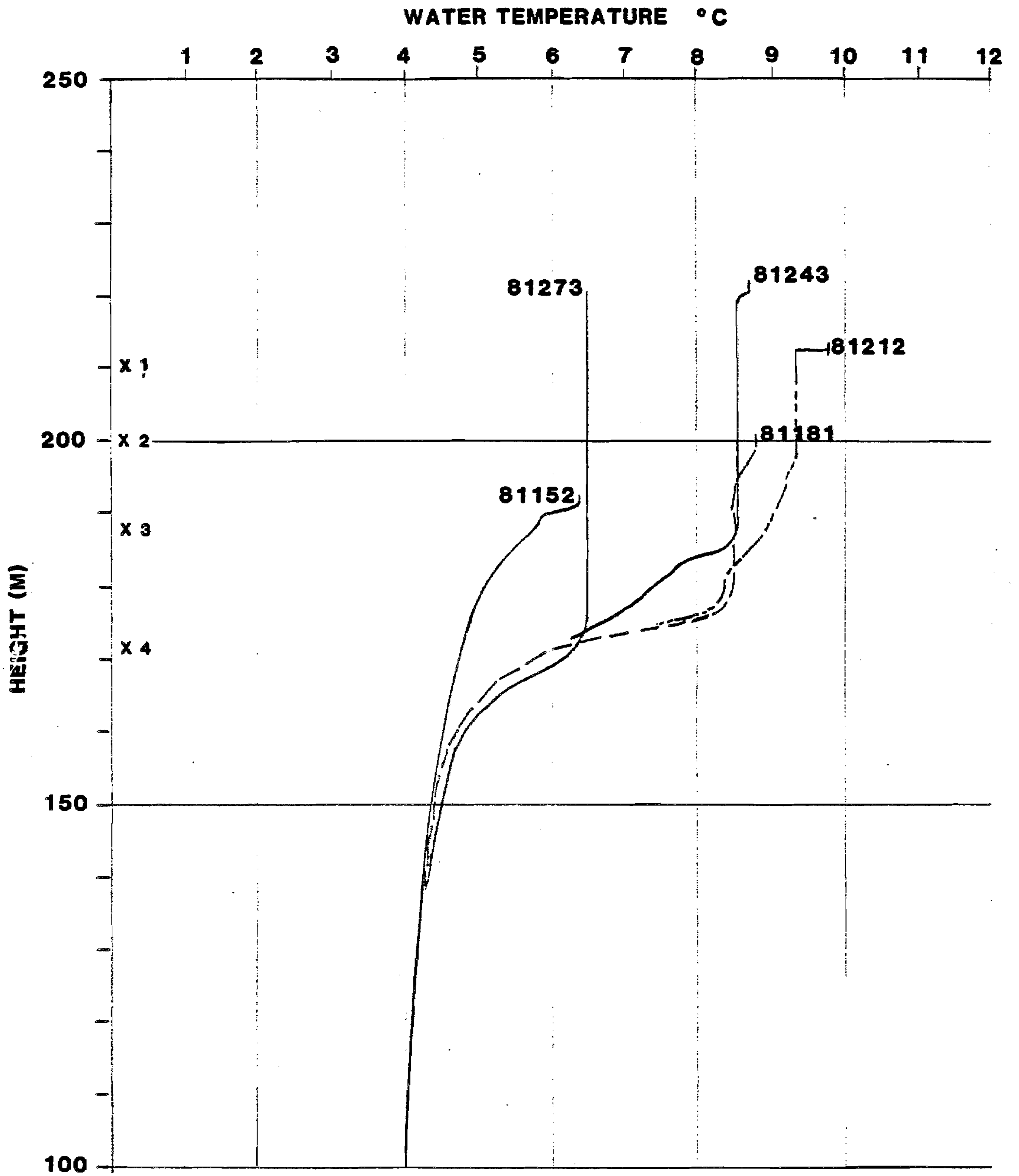
evaporation. Withdrawal rates and changes in reservoir storage are also specified. The model then simulates the vertical mixing due to the meterologic forcing functions and turbulence introduced by the inflowing and outflowing water. It is vertically layered and calculates the temperature and salinity for each layer at the end of each computational period. A detailed description of the model is given by Imberger and Patterson (1981). Acres (1982) applied the model to the Watana Reservoir for the May to October 1981 period. The temperature profiles predicted by the model are shown in Figure 6.2. Modifications have been made to the model in order to calculate and print out the shear velocities induced by the mixing process. In the epilimnion, the root mean square shear velocity of the velocities, induced by convective penetration and by wind shear, and the associated depth of mixing are calculated. This shear velocity is assumed to be constant with depth over the calculated depth of mixing.

Mixing in the hypolimnion is controlled by molecular diffusion and the buoyancy frequency between the various reservoir layers, wind shear transferred from the epilimnion, and the inflowing and outflowing currents. The latter terms generally are several orders of magnitude greater than molecular diffusion. The program prints out these velocities for each of the reservoir layers for each calculation time period.

When interpreting the results, it should be remembered that the model is one-dimensional, and that all the mixing parameters are averaged within each layer over the entire width and length of the reservoir.

6.3 Sediment Reintrainment

As outlined in Section 4.5, reintrainment of particles around the edges of the reservoir will occur, particularly during windy periods. Figure 6.3 illustrates the relationship between the mixing depth and the percentage of the reservoir area in which water depths are less than the mixing depth. This curve gives some indication of how much of the lake surface would be subject to reintrainment. The 25-foot mixing depth calculated in



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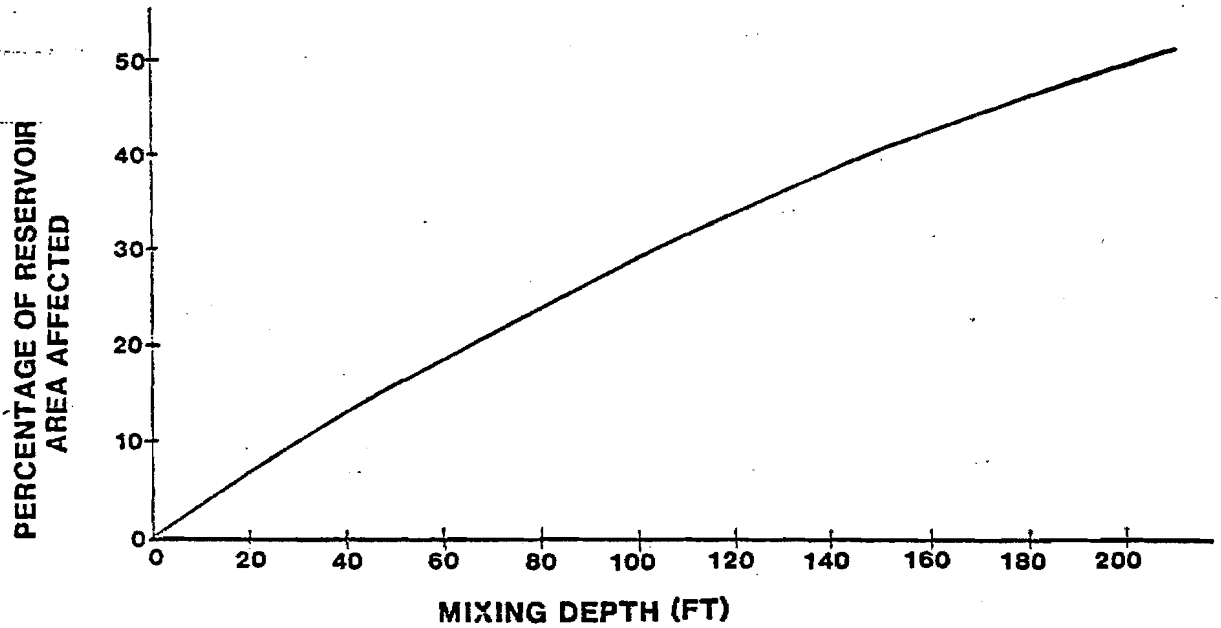
SUSITNA HEP
RESERVOIR TEMPERATURE MODEL
WATANA
FROM ACRES AMERICAN, INC.

FIGURE 6.2

NOTE: CURVE VALID FOR RESERVOIR WATER LEVELS BETWEEN 2050 AND 2200 FEET



RELATIONSHIP BETWEEN MIXING DEPTH AND PERCENTAGE OF RESERVOIR AREA AFFECTED BY MIXING

PERATROVICH, NOTTINGHAM & DRAGE, INC.
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FIGURE 6.3

Section 6.2 indicates that approximately 8 percent of the reservoir surface area would be subjected to reintrainment of particles of sizes 12 microns and less, between 35 and 55 percent of the time during the summer months (to be confirmed by reference to thermal model output).

Based on the above, it can be concluded that reintrainment would occur, but that it would not present a major problem except during severe storm events when the wave mixing depth exceeds 25 feet.

The results of the preliminary runs conducted on Watana using DYRESM model summarized in Tables 6.5 and 6.6 indicate that under maximum wind conditions, the shear velocity in the epilimnion and hypolimnion are generally below 3×10^{-3} and 1.5×10^{-4} ft./s respectively. During calm periods, these can drop to just above 3×10^{-4} and 3×10^{-5} respectively. The epilimnion values bracket the order of magnitude numbers calculated using the wave equations as described in Section 6.2.1.

It should be noted that DYRESM Model runs to date have only been conducted for the open water period. No data is available on the mixing that occurs during the ice cover months. It is, however, not expected to be very dissimilar to the values quoted above for the hypolimnion during calm periods.

The DEPOSITS Model was updated to allow for the reduction in the calculated settling velocities due to shear velocities. The effective settling velocity was assumed equal to the quiescent settling velocity minus the shear velocity. The upper quarter depth of the water plugs in the model were subjected to the epilimnion shear velocity an the lower three quarters to the hypolimnion velocity. As before, the inflow was assumed to be well mixed over the full reservoir depth and all discharge was taken from the top one-quarter depth.

The results of these model runs are shown on Table 6.1. They indicate that discharge sediment concentrations could range from below 50 mg/l during quiescent conditions to over 300 mg/l during windy periods.

TABLE 6.5

ROOT MEAN SQUARE SHEAR VELOCITY OF VELOCITIES
INDUCED BY CONVECTIVE PENETRATION
AND WIND SHEAR

Month	Average (fps)	Maximum	Minimum
June	1.6×10^{-3}	2.6×10^{-3}	4.1×10^{-4}
July	1.4×10^{-3}	3.0×10^{-3}	5.0×10^{-4}
August	1.9×10^{-3}	3.7×10^{-3}	3.3×10^{-3}

TABLE 6.6

HYPOLIMNION MIXING SCALE

Month	Average (fps)	Maximum	Minimum
June	1.0×10^{-4}	2.3×10^{-4}	5.8×10^{-5}
July	6.3×10^{-5}	1.1×10^{-4}	5.3×10^{-5}
August	1.1×10^{-4}	2.0×10^{-4}	5.3×10^{-5}

As mentioned earlier, considerable care must be taken when interpreting these results, as longitudinal dispersion in the reservoir is not taken into account. Also, these values are only representative of conditions near the dam. Higher concentrations could occur towards the upstream reaches.

7. PROJECTED RESERVOIR TURBIDITY

All the anaytical work described above is based on limited data and very idealistic models. In determining reservoir mixing velocities, the reservoir has been treated as a one-dimensional body of water. This is a severe limitation when one considers that the body of water is 48 miles long and averages 1 1/2 miles wide.

In this section, an attempt is made to project expected reservoir turbidities under post-project conditions. Because of the analytical limitations outlined above, these projections must be regarded as tentative order of magnitude estimates only. The values reported apply to conditions averaged over the reservoir, and no attempt is made to distinguish between conditions at the upstream and downstream ends respectively.

The first step in evaluating reservoir turbidity involves projecting likely sediment concentrations in the lake by adjusting the values predicted by the quiescent settling calculations for wind- and thermal-induced mixing. The second step involves converting these concentrations to turbidity using the curves presented in Section 4.6.

7.1 Projected Sediment Concentrations

It is assumed that sediment particles within the reservoir will tend to remain in suspension provided the mixing velocities are equal to or greater than the particle settling velocities. This approach tends to overestimate the sediment concentration in the reservoir, as some settling will still occur even when the mixing velocity equals the particle settling velocity.

7.2 Projected Turbidity Levels

Using the suspended sediment concentration versus turbidity relationships given in Figure 4.4, the projected lake turbidities would be in the range of 10-50 NTU's.

List of References for Sections 1, 2, 4, 6 and 7

(1) R&M Consultants, Inc., "Subtask 3.07 - Closeout Report - Reservoir Sedimentation," January 1982.

(2) Acres American, Inc. - New Report - Results of Temperature Modeling.

(3) R&M Consultants, Inc. - New Report - Results of Eklutna Data Collection Program.

(4) Fisher, H.B., et al, "Mixing in Inland and Coastal Waters," Academic Press, 1979.

(5) Imberger, J., and J.C. Patterson, "A Dynamic Reservoir Simulation Model - Dyresm: 5," Transport Models for Inland and Coastal Waters, Academic Press, Inc., 1981.

(6) Simons, D.B., and F. Senturk, "Sediment Transport Technology," Water Reservoir Publications, Fort Collins, Colorado, 1977.

(7) Graf, W.N., "Hydraulics of Sediment Transport," McGraw-Hill Book Company, 1971.

(8) McNown, et al. (1951)

(9) McNown & Malaika, (1950)

(10) McNown and Lin, (1952)

(11) Camp, T.R., "The Effects of Turbulence on Retarding Settling," Proceedings Second Hydraulics Conference, University of Iowa, Studies in Engineering, Bulletin 27, 1943.

(12) Rouse, N.T., "Engineering Hydraulics," John Wiles and Sons, Inc., 1949.

(13) Acres American, Inc. - New Report on Thermal Modeling of Watana, 1982.

(14) Acres American, Inc., "Susitna Hydroelectric Project - Feasibility Report, Volume 4 - Appendix A, Hydrological Studies," Alaska Power Authority, 1982.

(15) R&M Consultants, Inc., - New Report on Data Collected From the Eklutna Lake, 1982.

(16) Hartman, C.W., and P.R. Johnson, "Environmental Atlas of Alaska," University of Alaska, April 1978.

(17) Hamblin, P., Personal Communication, Canada lake for inland Water, Burlington to Ontario, September 1982.

(18) U.S. Army Coastal Engineering Research Center "Shore Protection Manual - Volume 1," Department of the Army Corps of Engineers, 1977.

(19) U.S. Army Coastal Engineering Research Center "Coastal Engineerig Technical Note - Revised Method for Wave Forecasting in Deep Water," CETN-1-7 3/1981.

(20) Ward, Al, Maan, T., Tapp, J., "The DEPOSITS Sedimentation Pond Design Manual," Institute for Mixing and Mineral Research, Kentucky Center for Energy Research Laboratory, University of Kentucky, Lexington, Kentucky, 1979.

APPENDIX A

BIBLIOGRAPHY OF ADDITIONAL INFORMATION SOURCES

PART I
NEW ZEALAND LAKE STUDIES

Brodie, J.W., and J. Irwin, 1970, "Morphology and Sedimentation in Wakatipu, New Zealand," New Zealand Journal of Marine and Freshwater Research, 4 (4): 479-96.

Study of the morphology of the lake floor has shown a system of current channels developed by movement of underflows related to flood discharges of inflowing rivers, or turbidity currents generated by slumping of previously deposited slope sediments. For Lake Wakatipu, the surface waters are reported to be clear at all times due the continuous sinking of turbid inflowing water.

Irwin, J., 1968, "Observations of Temperatures in Some Rotorua District Lakes," New Zealand Journal of Marine and Freshwater Research, 2(4): 591-605.

Irwin, J, 1971, "Exploratory Limnological Studies of Lake Manapouri, South Island, New Zealand," New Zealand Journal of Marine and Freshwater Research, 5(1): 164-77.

Lake Manapouri develops thermal stratification by mid-summer and continues into late fall. Near isothermal conditions exist in late winter. Water temperatures below 200m is between 7.8° and 8.0°C throughout the year. Surface temperature varies between 16.25°C in summer (January-March) and 8.0°C in winter (August - September). Tritium values suggest mixing has taken place to at least 400m.

Irwin, J, 1972, "Sediments of Lake Pukaki, South Island, New Zealand," New Zealand Journal of Marine and Freshwater Research, 6(4): 482-91.

Through most of the lake, excluding the delta slope, 80-90% of bottom sediments are less than 8 microns. At great depths there is little variation in spring and summer core samples.

No information is given in the report on incoming suspended sediment size distribution or climatic conditions for the lake. However, the lake is reported to be turbid throughout the year with average depth of disc disappearances of 0.5 meters.

Irwin, J., 1974, "Water Clarity Records From Twenty-Two New Zealand Lakes," New Zealand Journal of Marine and Freshwater Research, 8(1): 223-7.

Four lake types were studied:

1) associated with glacial activity
2) associated with volcanic activity
3) formed by wind
4) formed by landslide

Water clarity values are greatest in lakes of glacial origin, as these are generally the largest and deepest. However, values are affected by glacial silt. Smaller and shallower lakes formed by wind and volcanic activity have lower water clarity values.

Irwin, J., 1978, "Bottom Sediments of Lake Tekapo Compared With Adjacent Lakes Pukaki and Ohau, South Island, New Zealand," New Zealand Journal of Marine and Freshwater Research, 12(3): 245-250.

After travelling 1.3 km into the lake, 25 % of bottom sediments are less than 4 microns in size. However, water clarity values are low for this deep, glacially fed lake. Average depth of disappearance of the secchi disc was 4.9m in May 1971 and 1.6m in April 1974.

Irwin, J., 1978, "Seasonal Water Temperatures of Lakes Rotoiti and Rotoroa: South Island, New Zealand," New Zealand Oceanographic Institute Records, 4(2): 9-15.

Irwin, J., and R.A. Heath, 1972, "Winter Temperature Structure in Lake Atiamuri and Ohakuri, New Zealand," New Zealand Journal of Marine and Freshwater Research, 6(4): 492-496.

Irwin, J., and V. Hilary Jolly, 1970, "Seasonal and Areal Temperature Variation in Lake Wakatipu (Note)," New Zealand Journal of Marine and Freshwater Research, 4(2): 210-6

Irwin, J., and R.A. Pickrill, in press, "Water Temperature and Turbidity in Glacial-Fed Lake Tekapo," New Zealand Journal of Marine and Freshwater Research

Surveys of lake temperature and turbidity suggest a seasonal cycle of lake-river interactions. Waters are clearest in early spring. Inflowing water either interflows or underflows down-slope to the deepest basin. Coriolis force deflects inflowing water to the east. Lake water stratifies as summer progresses. Significant diurnal fluctuations result from water travelling through wide braided delta channel. Turbid water, at 5 times the lake concentration, enters the lake as interflow. Winter is associated with near isothermal lake water at $8^{o}C$ but the lake remains turbid. Cold inflowing water ($2-3^{o}C$) underflows to deepest basin.

Jolly, V.H., 1975, "Thermal conditions," New Zealand Lakes, V.H. Jolly and J.M.A. Brown, eds., Auckland University Press/Oxford University Press, p. 90-105.

Important thermal regime characteristics for the New Zealand lakes investigated show:

1) The coldest temperatures occur from the end of June to mid-August and full circulation for stratified lakes when hotomictic would be at least three months.

2) Warmest temperatures are found from mid-December to mid-March, but usually in January or February.

3) Thermoclines, particularily in large deep lakes, form late in the warming period because of strong winds and develop very deep epilimnia.

4) Many relatively deep lakes do not permanently stratify, because of the turbulent waves created by winds blowing over long fetches.

5) The annual temperature range is not as great as that observed in most lakes in similar latitudes due to mild oceanic climate.

Jowett, I.G., and D.M. Hicks, 1981, "Surface Suspended and Bedload Sediment - Clutha River System," Journal of Hydrology, 20(2): 121-130.

Pickrill, R.A., 1980, "Beach and Nearshore Morphology and Sedimentation in Fiordland, New Zealand: A Comparison Between Fiords and Glacial Lakes," New Zealand Journal of Geology and Geophysics, 23: 469-480.

Pickrill, R.A., and J. Irwin, in press, "Sedimentation in Deep Glacier-Fed Lake, Lake Tekapo, New Zealand," Sedimentology

Major controlling processes of sedimentation in Lake Tekapo:

1) Single dominant inflow at head of lake has resulted in delta progradation.

2) Underflows appear to be predominant inflow mechanism during spring freshets and floods.

3) Small changes in bed morphology can produce large changes in sedimentation rates over short distances. Morphology controls the direction and distance travelled by underflows.

4) Across lake variaton in sedimentation rates are controlled by Coriolis force deflecting inflowing water.

5) Seasonal cycle of sed. input controls temporal variations in sedimentation rate and texture.

6) Lake level fluctuations redistribute coarse sediment downslope.

7) Rotational slumping redeposits delta sediments down lake.

Pickrill, R.A., J. Irwin, and B.S. Shakespeare, 1981, "Circulation and Sedimentation in a Tidal-Influenced Fjord Lake: Lake McKerrow, New Zealand," Estuarine, Coastal and Shelf Science, 12: 23-37.

Stout, V.M., 1978, "Effects of Different Silt Loads and of Hydro-Electric Developments on Four Large Lakes," Verh International Verein Limnol, 20: 1182-1185.

Brief review of key basin and lake characteristics for Lakes Tekapo, Pukaki, Ohau, and Benmore including physical features, mean and maximum SECCHI disc readings, and kinds of phytoplankton present.

Stout, V.M., 1981, "Some Year to Year Fluctuations in a Natural and in an Artificial Lake, South Island, New Zealand," Verh International Verein Limnol, 21: 699-702.

Both chlorophyll a content and zooplankton populations have retained similar seasonal patterns. However, turbidity of the water in both lakes during spring and summer months has shown significant changes from year to year due to climatic variations.

Thompson, S.M., 1978, "Clutha Power Development - Siltation of Hydro-Electric Lakes, August, 1976," Environmental Impact Report on Design and Construction Proposals, New Zealand Ministry of Works and Development.

Report describes siltation problems in the Clutha River, processes causing the problems and possible remedies.

Appendix 2 describes the method used to determine the grain size distribution in the total load of the river from the distribution of sediment grain sizes on the lake bed.

PART II

GENERAL INFORMATION

Baxter, R.M., and P. Glaude, 1980, "Environmental Effects of Dams and Impoundments in Canada: Experience and Prospects," Can. Bull. Fish Aquat. Sci., 205: 34 p.

Brylinsky, M., and K.H. Mann, 1973, "An Analysis of Factors Governing Productivity in Lakes and Reservoirs," Limnology and Oceanography, 18(1): 1-14.

Data collected from 43 lakes and 12 reservoirs from the tropics to the arctic showed that variables related to solar energy input have a greater influence on production than those related to nutrient concentration. Morphological factors have little influence on productivity per unit area.

Csanady, G.T., 1978, "Water Circulation and Dispersal Mechanisms," Abraham Lerman, ed., Lakes: Chemistry, Geology and Physics, Springer-Verlag Press, New York, Pages 21-64

Conceptual model developed to describe lake hydrodynamics including special cases for long and narrow basins with discussions on such things as effect of bottom friction and coriolis force, coastal jets, and spontaneous thermocline movements near shore.

Elder, Rex A., and Walter O. Wunderlich, 1972, "Inflow Density Currents in TVA Reservoirs," Paper 7, International Symposium on Stratified Flows, Novosibirsk.

Irwin, J., 1975, "Morphology and Classification," V.H. Jolly and J.M.A. Brown, eds., " New Zealand Lakes, Auckland University Press/Oxford University Press, Pages 25-56.

Kellerhals, R., M. Church, and L.B. Davies, 1979, "Morphological Effects of Interbasin River Diversions," Can. Jour. Civ. Eng., 6: 18-31.

Kellerhals, R., and D. Gill, 1973, "Observed and Potential Downstream Effects of Large Storage Projects in Northern Canada," Proceedings of 11th International Congress on Large Dams, Madrid, 1973, Pages 731-753.

Kinnunen, Kari A.I., 1981, "Problems Connected with Modeling Artificial Lakes in Finland," Unpublished Report, National Board of Waters, Finland.

Kinnunen, Kari A.I., B. Nyholm, and J.S. Niemi, 1981, "Ecological Model of a Subarctic Lake," Verh. Internat. Verein. Limnol., 21: 102-108.

- Variation of EPAECO model calibrated for temperature with ice cover and effect of wind mixing on Finland Lake Paijanne.
- Max. surface temp. in early August ($\sim 18^{o}C$).
- Thermocline at 10-20m below surface-average max. depth at 30m in mid-September.
- Becomes isothermal by early-mid November. Stays isothermal until mid-May.
- Effect of wind especially important in early summer when stratif. period starts. Without wind consideration simulated temperature stratification is too steep.

Kinnunen, Kari A.I., J.S. Niemi, T. Frisk, T. Kyla-Harakka, 1981, "Water Quality Modeling at the National Board of Waters, Finland," Unpublished Report, National Board of Waters, Helsinki, Finland.

- Evolution of the FINNECO model from the EPAECO model.
- New model includes: mixing effect of wind
  precipitation of phosphorous
  new temp. correction
  ice formation routine
  denitrification process

- o Investigation of some river water quality models.

Kjeldsen, O., 1981, "Sediment Transport Studies in Norwegian Glacial Streams, 1980," Report 4-81, Norwegian Water Resources and Electricity Board, Oslo, Norway.

Kjeldson, O., and G. Østrem, 1977, "Sediment Transport Studies in Norwegian Glacial Streams, 1975," Report 3-77, Norwegian Water Resources and Electricity Board, Oslo, Norway.

Kuenen, Ph.H., 1968, "Settling Convection and Grain-Size Analysis," Journal of Sed. Petrology, 38: 817-831.

Lambert, A., and K.J. Hsu, 1979, "Non-Annual Cycles of Varve-Like Sedimentation in Walenese, Switzerland," Sedimentology, 26: 453-461.

- o multiple layers deposited in lake bed represent continuous-fed turbidity currents generated by hyperpycnal inflow during river-flood stages.

- o Currents with bottom velocities up to 50 cm/sec. were detected during summertime even when the lake is thermally stratified.

Lambert, A., and S.M. Luthi, 1977, "Lake Circulation Induced by Density Currents: An Experimental Approach," Sedimentology, 24: 735-741.

Saltwater was continuously fed into a tank of freshwater to model turbidity underflows caused by flood-stage discharge.

In most cases the height of lake water dragged along by the underflow is about equal to the underflow thickness. Maximum return velocity occurs in the lower (denser) parts of a lake basin.

Lee, Dong-Yong, W. Lick, and S.W. Kang, 1981, "The Entrainment and Deposition of Fine-Grained Sediments in Lake Erie," J. of Great Lakes Research, 7(3) 224-233.

- Provides quantitative data on the entrainment rates. Variations depend on shear stress, water content and type of sediment (size and mineralogy). Vertical variation in thin surficial layer active in deposition - entrainment produce different entrainment rates.

- effect of benthic organism not considered.

- Main cause of entrainment is oscillating wave action.

- Report does not include settling, flocculation, and mechanical degradation in calculations of sediment transport in a lake.

Lerman, A., Devendra Lal, and Michael F. Dacey, 1974, "Stoke's Settling and Chemical Reactivity of Suspended Particles in Natural Waters," R. Gibbs, ed., Suspended Solids in Water, Plenum Press, New York, Pages 17-44.

Organization for Economic Cooperation and Development, 1979, Joint Activity on Multi-Purpose Hydraulic Projects: The Planning of the Vuotos Reservoir, National Board of Waters, Finland.

Østrem, G., T. Ziegler, S.R. Ekmkan, H.C. Olsen, J. Andersson, and B. Lunden, 1971, Studies of Sediment Transport at Norwegian Glacier Streams, Stockholm University, Department of Physical Geography, Report 12, 133 pp.

Ragotzkie, R.A., 1974, "Vertical Motions Along the North Shore of Lake Superior," Proceedings from the 17th Conference on Great Lakes Research, Pages 456-461.

Slow net upward motion has been documented in Lake Superior. Vertical motion extending from as deep as 190 meters to near surface levels with vertical velocities up to 30 meters per day have been observed during the period of thermal stratification.

Ritchie, J.C., Frank Schiebe, and J. Roger McHenry, 1976, "Estimating Suspended Sediment Loads from Measurements of Reflected Solar Radiation," H.L. Gotterman, ed., Proceedings of the 1st Symposium on Interaction between Sediments and Freshwater, Amsterdam, 1976.

Data from temperate region lake has shown that a quantitative relationship exists between surface suspended sediments and reflected solar radiation. Most significant in the wave lengths between 700-800 mm. Concentration of surface suspended sediment can be used to estimate total suspended sediment concentration in a vertical water column.

Scott, Kevin, M., 1982, "Erosion and Sedimentation in the Kenai River, Alaska," Geological Survey Prof. Paper 1235, 34 pp.

- Sediment concentration generally lower primarily due to storage in lakes.

- Give sediment concentration for Kenai River at Soldotna and Kenai River at Cooper Landing.
  - No turbidity measurements reported.
  - No turbidity-sediment concentration correlation presented.

Shuter, N., K. Stortz, G. Oman, M. Sydor, 1978, "Turbidity Dispersion in Lake Superior Through Use of Landsat Data," Journal of Great Lakes Research, 4(3-4): 359-360.

Sly, P.G., 1978, "Sedimentary Processes in Lakes," Abraham Lerman, ed., Lakes: Chemistry, Geology and Physics, Springer-Verlag Press, New York, Pages 65-89.

- Review and discussion of various factors influencing sedimentary processes in lakes including, but not limited to, lake morphology, characteristics of inflowing sediment, and climatic settling.

Stortz, K., R. Clapper, and M. Sydor, 1976, "Turbidity Sources in Lake Superior," Journal of Great Lakes Research, 2(2): 393-401.

- Strong correlation found between average turbidity and average suspended load of red clay in turbidity plumes.

- Major source of turbidity due to shoreline erosion by wind driven waves during ice free season.

- Most of scattered light observed arises from fines less than 3µ (=25% of bank material).

- For maximum sediment concentration observed in plume = 20 mg/l $T_{(NTU)}$ 18.5 based on correlation

$$S = 1.3 \times T - 4.0$$

- Sediment resuspension in winter with partial ice cover

$$= 10^6 \text{ metric tons}$$

- During severe storms: range = 5 x 10^5 metric tons of eroded material/storm.

  Suggest 50% of lake turbidity comes from these storms.

Sturm, M., 1979, "Origin and Composition of Elastic Varves," Ch. Schluchter, ed., Moraines and Varves-Origin, Genesis and Classification, A.A. Balkema, Rotterdam, Pages 281-285.

Sturm, M., ____________, "Depositional and Erosional Sedimentary Features in a Turbidity Current Controlled Basin (Lake Brienz)," IXth International Congress on Sedimentology, 5(2): 385-390.

Sturm, M., and A. Matter, 1972, "The Electro-Osmotic Guillotine, A New Device for Core Cutting," Journal of Sedimentary Petrology, 42(4): 987-989.

Sundborg, Ake, 1980, "Symposium Theme No. IV: Reservoir Sedimentation," Proceedings of the International Symposium on River Sedimentation, Beijing, China, March 24-29, 1980, Pages 1325-1333.

Sundborg, Ake, 1981, "Environmental Problems of Reservoir Development with Special Regard to Conditions in Sweden," Proceedings of the International Symposium of Reservoir Ecology and Management, Quebec, June 1981, Pages 63-72.

Thomas, R.L., 1968, A Note on the Relationship of Grain Size, Clay Content, Quartz and Organic Carbon in Some Lake Erie and Lake Ontario Sediments

Wunderlich, Walter O., ______, "The Dynamics of Density-Stratified Reservoirs, Gordon E. Hall, ed., Reservoir Fisheries and Limnology, Special Publication No. 8, Pages 219-231.

Data from Tennessee Valley Authority field investigations are used to illustrate dynamic reservoir processes and their influence on water quality. Water movement into, within, and out of, the reservoir in the presence of density stratification are described.