

RESOLVING ALASKA'S WATER RESOURCES CONFLICTS



INSTITUTE OF WATER RESOURCES/
ENGINEERING EXPERIMENT STATION

University of Alaska-Fairbanks

Fairbanks, Alaska 99775

IWR-108

RESOLVING ALASKA'S
WATER RESOURCES CONFLICTS

Resolving Alaska's Water Resources Conflicts
Linda Perry Dwight
American Water Resources Association

PROCEEDINGS

Linda Perry Dwight, Chairman
Alaska Section
American Water Resources Association

Institute of Water Resources/
Engineering Experiment Station
University of Alaska-Fairbanks
Fairbanks, AK 99775-1760

Report IWR-108

November 1985

Dwight, Linda Perry, Chairman. 1985. Resolving Alaska's water resources conflicts. Proceedings. Alaska Section, American Water Resources Association. Institute of Water Resources/Engineering Experiment Station, University of Alaska-Fairbanks. Report IWR-108. 212 pp.

TABLE OF CONTENTS

	<u>Page</u>
LIMNOLOGY.....	1
The effects of glacial silt on primary production, through altered light regimes and phosphorus levels in Alaska lakes.....	3
Jim A. Edmundson and J.P. Koenings Alaska Department of Fish and Game	
The influences of suspended glacial particles on the macrozooplankton community structure within glacial lakes.....	21
John M. Edmundson and J.P. Koenings Alaska Department of Fish and Game	
Seasonal variation of photosynthetically active radiation in Big Lake, southcentral Alaska.....	37
Timothy G. Rowe U.S. Geological Survey	
Potential for circumventing internal nutrient- recycling in Lucile Lake at Wasilla, Alaska.....	39
Paul F. Woods U.S. Geological Survey	
MINING.....	51
Community structure and longitudinal patterns of benthic invertebrates in a heavy metal contaminated Alaskan river system.....	53
Barry N. Brown and Mark W. Oswood University of Alaska-Fairbanks	
Summary of Alaska particulates criteria review.....	65
Laurence A. Peterson L.A. Peterson & Associates, Inc.	
HYDROELECTRIC POWER DEVELOPMENT.....	75
Lower Bradley River flow regime and its relation to fish.....	77
Larry A. Rundquist, Jean E. Baldrige and Michael R. Joyce Entrix, Inc.	
Applying the consultation process in resolving water resources issues.....	89
William A. Corbus Alaska Electric Light and Power Company and David T. Hoopes R.W. Beck and Associates, Inc.	

TABLE OF CONTENTS (continued)

	<u>Page</u>
HYDROLOGY AND HYDRAULICS.....	97
Glacier runoff in the Upper Susitna and Maclaren River basins, Alaska.....	99
Theodore S. Clarke, Douglas Johnson and William D. Harrison University of Alaska-Fairbanks	
Growth of Wolverine Glacier, Alaska; determined from surface altitude measurements, 1974 and 1985.....	113
Lawrence R. Mayo, Rod S. March and Dennis C. Trabant U.S. Geological Survey	
Fish passage design criteria for culverts.....	123
Douglas L. Kane University of Alaska-Fairbanks and Paula M. Wellen CH ₂ M Hill	
COMMUNITY AND REGIONAL WATER CONFLICTS.....	135
From data to decisions.....	137
Liz Baron Alaska Division of Land and Water Management	
Water-quality characteristics of the Chester Creek basin, Anchorage, Alaska.....	149
Timothy P. Brabets U.S. Geological Survey	
Preferential salt water intrusion in the metamorphic rock aquifer at Indian Cove, southeast Alaska.....	151
Larry L. Dearborn Alaska Division of Geological & Geophysical Surveys	
Recognition and resolution of Eagle River's ground- water conflicts: roles of data and water rights.....	167
James A. Munter Alaska Division of Geological & Geophysical Surveys and Gary J. Prokosch Alaska Division of Land and Water Management	
APPENDIX: PAPERS PRESENTED AT THE 1984 ANNUAL MEETING.....	177
Hydrology of Tsirku River alluvial fan near Haines, Alaska.....	179
Edward F. Bugliosi U.S. Geological Survey	

TABLE OF CONTENTS (continued)

	<u>Page</u>
Sediment transport in the Susitna River basin, 1982-1983.....	191
Stephen W. Lipscomb and James M. Knott U.S. Geological Survey	

LIMNOLOGY

THE EFFECTS OF GLACIAL SILT ON PRIMARY PRODUCTION,
THROUGH ALTERED LIGHT REGIMES AND
PHOSPHORUS LEVELS, IN ALASKA LAKES

by

Jim A. Edmundson
Fisheries Biologist
and
J. P. Koenings
Principal Limnologist
Alaska Department of Fish and Game
FRED Division

ABSTRACT

Suspended silt, derived from glacier melt water, has been found to dominate the phosphorus cycle, and to determine light regimes in glacially influenced lakes. Both parameters are important determinants of autochthonous primary production.

An immediate result of glacier melt water intrusion is an increase in turbidity, a function of varying particle concentrations as well as size distributions. Turbidity levels were found to be inversely related to the light compensation depth thereby defining the extent of the euphotic zone. As a result the euphotic volume, as a percent of the total lake volume, is significantly less in glacial systems compared to the non-turbid systems we examined. Of equal significance to the productivity of glacial lakes is the composition of the silt particles. Fractionation studies have shown that the phosphorus (and iron) contained within the particulate inorganic fraction dominates the cycling of these elements in glacial lakes.

The effects of glacial silt were evident both on primary productivity (carbon uptake rates) and on primary production (chlorophyll a). That is, volumetric measurements of carbon uptake decreased with an increase in glacier melt influence. Moreover, when productivity rates were integrated over the euphotic zone areal productivity was considerably reduced especially at the height of glacial melt water influence. We also observed that summer period chlorophyll a levels were significantly less than those predicted using phosphorus-chlorophyll response (P-C) models derived from clear water lakes. The discrepancies in P-C models were found to be partially explained by the dominance of inorganic particulate phosphorus on the total phosphorus cycle. When only biologically available phosphorus was used as the criterion in P-C models much of the variation was reduced. Finally, a consideration of the ratio of euphotic volume:total volume also proved to be an important factor in P-C expressions and in providing a more meaningful P-C model for use in glacial systems. Thus, the magnitude of glacier melt water intrusion through affects on nutrient cycles and light regimes results in decreased autochthonous production and the increased oligotrophy of glacial lakes.

INTRODUCTION

Autochthonous primary production has been linked to solar radiation (Brylinsky and Mann (1973), and an adequate nutrient supply (Shindler (1978). Brylinsky and Mann (1973) associated productivity more closely with energy related parameters including latitude, temperature, and light penetration. That is, energy variables were correlated more strongly with productivity than with nutrient concentrations. However, phosphorus has also been shown to be an important factor in controlling productivity (Smith, 1979) and as evident by the various phosphorus-chlorophyll relationships proposed by Sakamoto (1966), Dillon and Rigler (1974), Jones and Bachman (1976), and Vollenweider (1976), among others. These factors considered, we observed an increased oligotrophy of glacial systems compared to the clear water lakes with similar morphometric features, climatic conditions, and nutrient ratios. That is, increases in total phosphorus levels were not accompanied by increased chlorophyll concentrations. Thus, we hypothesized that the presence of suspended glacial particles could account for this discrepancy through its effects on both light regimes (energy) and phosphorus (nutrient) supply.

Previous studies have suggested effects of non-algal particles on aquatic production by alteration of light regimes or nutrient concentrations (Hoyer and Jones 1983). Further, Goldman (1960, 1961), indicated that productivity occurring on bright days in near surface layers decreased due to the effects of light inhibition. In turn, he also found that the presence of turbidity lessened this effect, but also tended to decrease areal production due to a decreased euphotic zone. Tizler et al. (1976) also found that turbidity in association with suspended sediments lessened the effect of light inhibition near the surface. More importantly, he found that although sediment loading into Lake Tahoe caused turbidity plumes, productivity within these plumes may have increased as a result of a sediment induced nutrients. Similarly, Verduin (1954) observed increased production within turbid plumes in western Lake Erie, but Rawson (1953) and Oglesby (1977) found decreased production within turbid lakes compared to clear water systems as a consequence of climatic features or light limitation.

Herein, we considered the effect of glacial particles (turbidity) on both the phosphorus economy and upon the light regimes of glacial lakes in order to account for chlorophyll levels at given phosphorus concentrations being an order of magnitude less than that found for less turbid systems. Our approach centered on comparing clear water and glacial lakes as to the nature of particles present (size and concentration) which determines turbidity; and by defining levels of phosphorus associated with inorganic particles which may not be readily metabolized by phytoplankton.

METHODS AND MATERIALS

Turbidity, euphotic zone depth, phosphorus, iron, chlorophyll a (chl a), and mean lake depth were compiled from limnological data collected

through the efforts of the State of Alaska Department of Fish and Game Limnology Program. The field and laboratory methods, and techniques used are described in detail in Koenings et al. (1985) and, thus, materials and methods are discussed here in only general terms.

Turbidity levels, given in nephelometric turbidity units (NTU), were measured using a model DRT-100 (H.F. Instruments) turbidimeter. Representative samples were analyzed for particle size distribution by Marco-Scientific, Ltd., Sunnyvale, California using a model 715 granulometer. Particle numbers were determined visually at X1000 magnification using a Zeiss model 14 compound microscope. Replicate counts of five $2.5 \times 10^{-3} \text{ mm}^2$ grids using a Levy-Hausser counting chamber were made and the particle number calculated per cubic meter. Individual samples were systematically diluted (x1.5, 3, and 6), recounted, and measured for turbidity. Values for euphotic zone depth (EZD) were determined from photosynthetically available radiation measurements obtained using a Protomatic submarine photometer.

The composition of suspended glacial silt particles was determined through fractionation studies. Six lakes representing various lake types i.e., clear water, organically stained, semi-glacial (less turbid), and glacial, were chosen for detailed phosphorus and iron analysis. Samples were collected every three weeks from 1 meter and the mid-hypolimnetic zone using a Van Dorn sampler. Samples were filtered through a Whatman 4.5 cm GF/F filter and a subsample of the filtrate passed through (ultrafiltered) a Millipore CX-10 (10000 MWCO) immersible filter having a nominal pore size of $.05 \mu\text{m}$. The various fractions i.e., unfiltered, filtered, and ultrafiltered were stored frozen until analyzed.

In general, filterable and dissolved reactive phosphorus analyses were determined using the molybdenum-blue method as modified by Eisenreich et al. (1975). Total phosphorus analysis utilized the same method following acid-persulfate digestion. The inorganic (IPP) and organic particulate phosphorus (OPP) fractions were analyzed directly on a seston sample obtained by filtering a known volume (0.5-1.0 l) of lake water through a Whatman 4.5 cm GF/F filter. IPP was extracted using acidified ammonium fluoride and analyzed using the filterable reactive phosphorus method of Strickland and Parsons (1972). The remaining OPP fraction was analyzed using the total phosphorus method after Eisenreich et al. (1975). Values for both colloidal (unreactive and reactive) and dissolved unreactive phosphorus were obtained by difference. Finally, each of the sized fractions were also analyzed for total, total filterable, and dissolved iron (DFe) (Koenings et al. 1985).

The effects of glacial silt on autochthonous primary productivity were examined using various algal transfer and silt addition experiments with carbon-14 radioisotopes (C-14). The method utilized the light-dark bottle technique after Saunders et al. (1962). Replicate clear and lightproof bottles containing 100 ml of lake water were labeled with $5.2 \mu\text{Ci}$ of $\text{NaHC}^{14}\text{O}_3$ and incubated in situ 4-6 hours. Samples were fixed with Lugol's acetate solution and filtered through a Whatman 2.5 cm GF/F filter. Filters were stored frozen in 20 ml polyethylene vials. Prior

to analysis, filters were thawed, acidified, and then dissolved in a toluene based scintillation cocktail. Algal carbon incorporation was quantified using a Packard model 3255 scintillation spectrometer. Volumetric uptake rates (mg C/m^3) were calculated after Saunders et al. (1962), and day rate estimates ($\text{mg C/m}^3/\text{day}$) were determined using the cumulative percent time productivity curve after Vollenweider (1965).

A total of six separate lake samples were collected at various depths from Hidden Lake and Bear Lake, two clear water systems located in the Kenai River drainage basin, and labeled with C-14. The 8 liter bulk samples were then transferred to either Upper Trail Lake or Skilak Lake, both glacially influenced systems located in the same area, and subsamples incubated under the reduced light levels found at comparable depths from which the samples were collected. Replicate sets of bottles of each sample were also incubated in the clear lakes as a control. Due to the proximity of the lakes to one another transportation times were minimal with the actual addition of the isotope occurring only after arrival at the transfer site. Similar algal uptake (C-14) experiments were conducted using glacial lake water from Tustumena Lake, Upper Trail Lake and Skilak Lake, which had varying turbidity levels, incubated under conditions of increased light levels found at comparable depths in the clear water systems. As temperature regimes differ, at equivalent depths, in clear versus turbid lakes all incubations were done during the spring-summer turnover period when the lakes were at the same temperature throughout the euphotic zone.

To examine the effect of turbidity on productivity, as a result of altered light conditions, glacial silt was incrementally added to clear water samples. Glacial silt used in these experiments was extracted by boiling glacial meltwater and then centrifuging. The supernatant was decanted with the remaining concentrated silt removed by pipet, and then added to clear water lake samples reproducing the effect of turbidity. Following the treatment the samples were labeled with C-14 and incubated either at near-surface levels in situ or under laboratory conditions. Laboratory incubation conditions consisted of a constant temperature (15°C) water bath illuminated by 2 Sylvania Gro-Lux lamps which provided a maximum illumination of 30 foot candles.

Chl *a* values used in our P-C regression models were determined by direct analysis using the fluorometric method by Strickland and Parsons (1972) with the modification of dilute acid addition after Reimann (1978). P-C regression analysis was facilitated using STATPRO on an IBM PC-XT.

RESULTS

The Nature of Turbidity and Its Effects on Light Regimes

Mean particle size (PS) within 38 clear and glacial lakes was found to be inversely related to turbidity (NTU) as shown in Figure 1a. A log-log transformation provided the most linear relationship defined as $\text{LOG NTU} = 3.6 - 1.92 \text{ LOG PS}$ with a coefficient of determination (r^2) = 0.76.

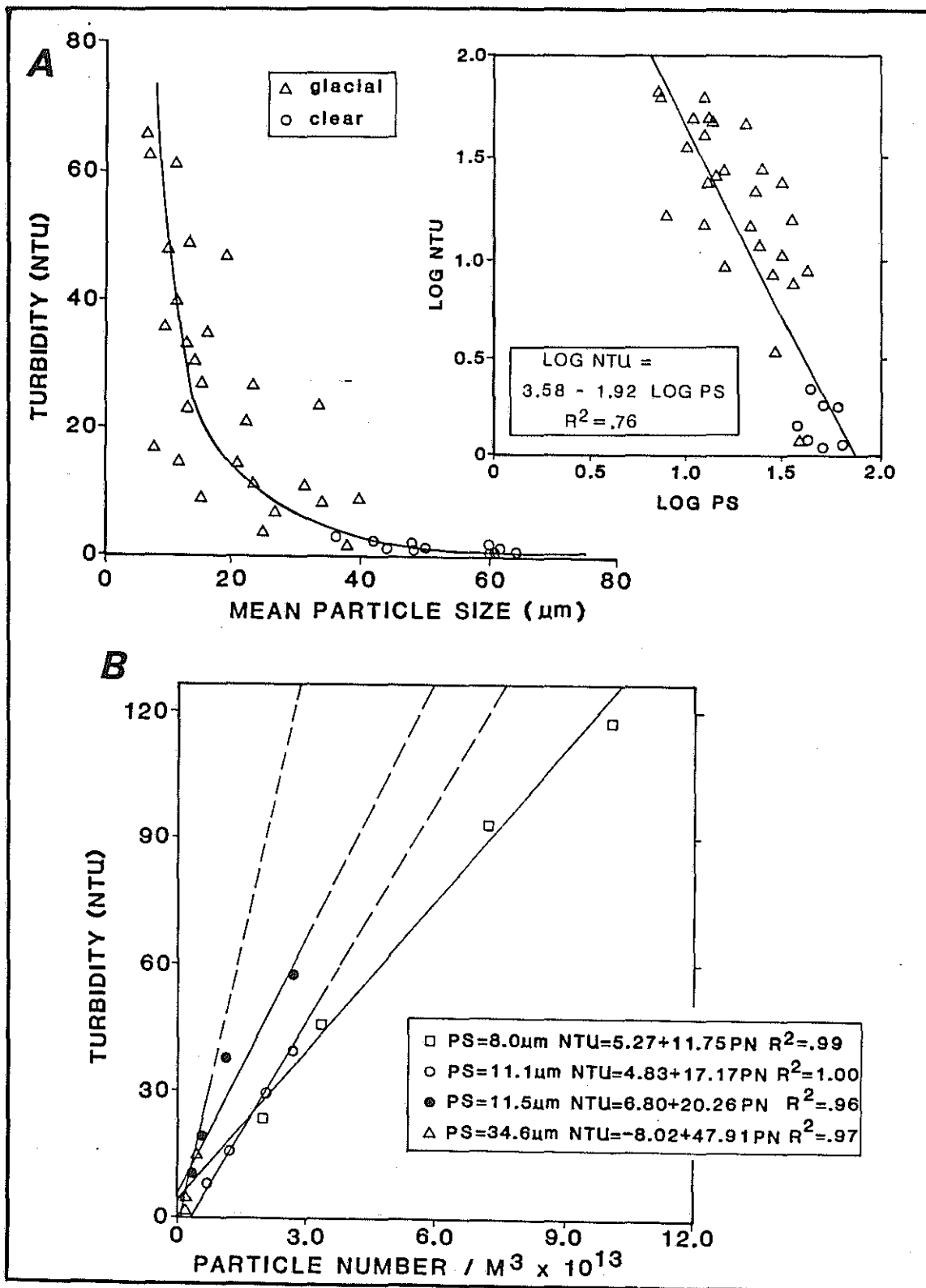


Fig. 1. The relationship of (A) turbidity (NTU) to mean particle size (PS) in microns and (B) the relationship of turbidity to particle number per cubic meter (PN) $\times 10^{13}$ at varying PS.

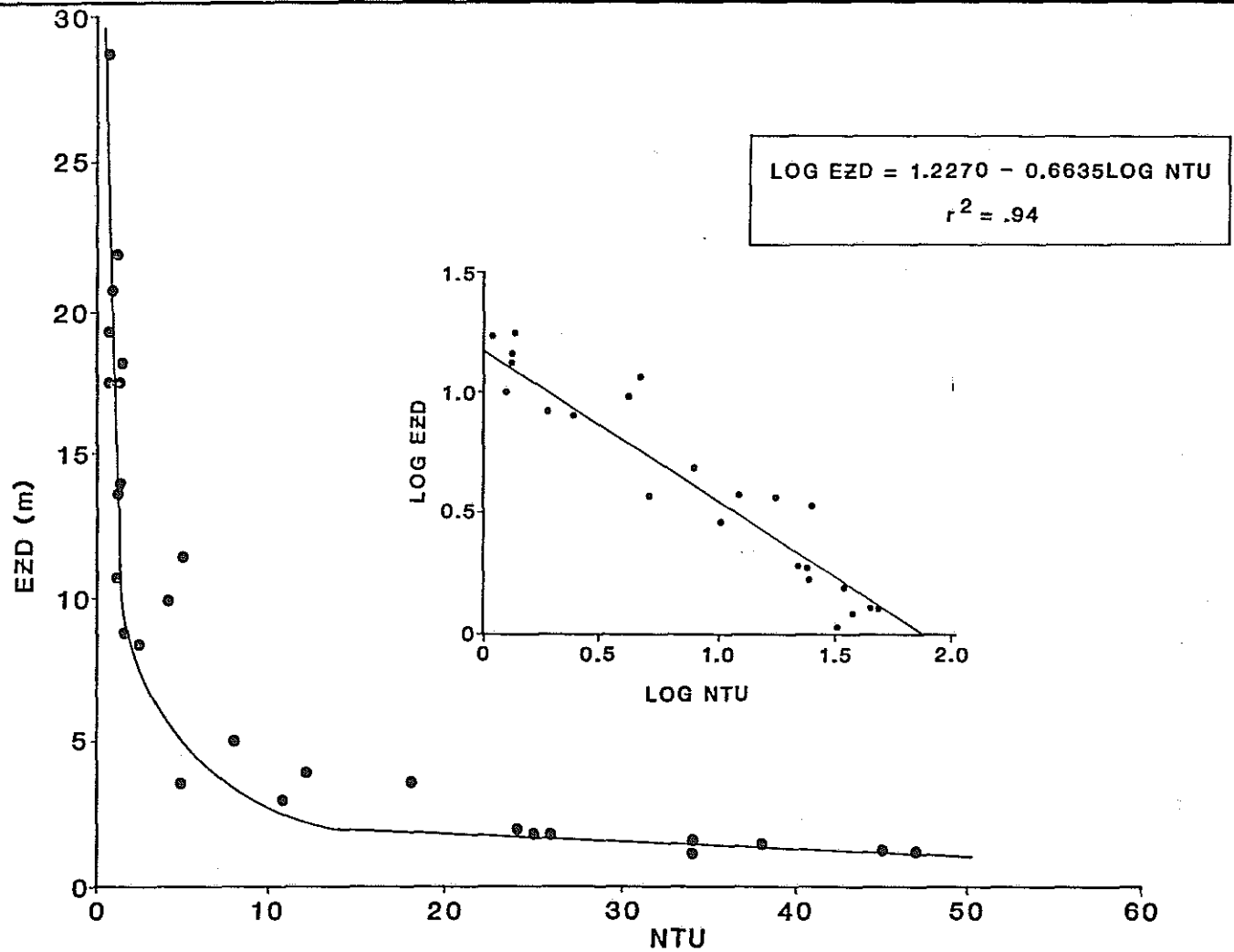


Fig. 2. The relationship of euphotic zone depth (EZD) to turbidity (NTU).

However, there was little overlap observed in PS between the clear and glacial lakes as mean particle size ranged from 6.9-40.3 μm for the glacial lakes and 36.5-64.3 μm for the clear water systems. Hence, we observed that lakes having less turbidity held larger particles, and that a gap between 3 NTU and 6 NTU separated clear from glacial waters. Fig. 1b shows the relationship of particle number per cubic meter (PN) and NTU in four lakes having different mean particle sizes. A decrease in NTU resulted from a decrease in PN by sample dilution. The response remained linear and was significant in each case although the slope values were found to increase with greater PS. Two lakes which had similar values for mean particle size (PS = 11.1 and 11.5) also had similar slopes. Thus, it appears from these data that turbidity is a function of both PS and PN.

Increased levels of turbidity were found to be inversely related to euphotic zone (Fig. 2). A log-log transformation resulted in a linear relationship i.e., $\text{LOG EZD} = 1.23 - 0.66 \text{ LOG NTU}$; $r^2 = 0.94$. Although the relationship shows that a small amount of turbidity substantially decreases EZD this effect was most severely felt at turbidity levels up to 5-10 NTU. That is, turbidity levels <10 NTU still resulted in a continued negative response in EZD; however, the rate of decrease was considerably less. Thus, the inflection point of the curve occurs at turbidity levels of 5-10 NTU which corresponds to a range of EZD of between 6 m-4 m.

Composition of Glacial Silt

We observed total phosphorus and iron concentrations to be strongly correlated ($r^2 = 0.92$ and 0.95 respectively) with turbidity (NTU) as shown in Fig. 3a and 3b. This supports the results of our fractionation experiments which show that in glacial lakes both these elements were contained mostly within the particulate fraction (Fig. 3c and 3d). That is, in the glacial lakes inorganic particulate phosphorus (IPP) comprised from 24%-56% of the total phosphorus compared to only 13%-14% found in the clear and stained lakes. Consequently, organic particulate phosphorus (OPP) comprised 17%-20% of the total phosphorus in the glacial lakes examined compared to 31%-35% found in the clear water and stained lakes. In addition, phosphorus contained within the colloidal fraction (CoP) ranged from 2%-15% in the glacial systems compared to 36%-27% in the clear water and stained lakes. Finally, dissolved phosphorus (DP) ranged from a low 9% of the total phosphorus in a highly turbid system (40 NTU) to 56% in one of the semi-glacial lakes (NTU <10) examined whereas, DP fractions of up to 22% and 25% were found in the clear and stained lakes.

Particulate iron (PFe) comprised from 88%-94% of the total iron present in the glacially influenced systems compared to 31% and 30% found in the clear and stained lakes (Fig. 3d). In contrast, dissolved iron (DFe) dominated the iron cycle within the clear water lake comprising 63% of the total iron compared to less than 2% and 5% in the glacial and stained lakes. Whereas, colloidal iron (CoFe) comprised 65% of the total iron

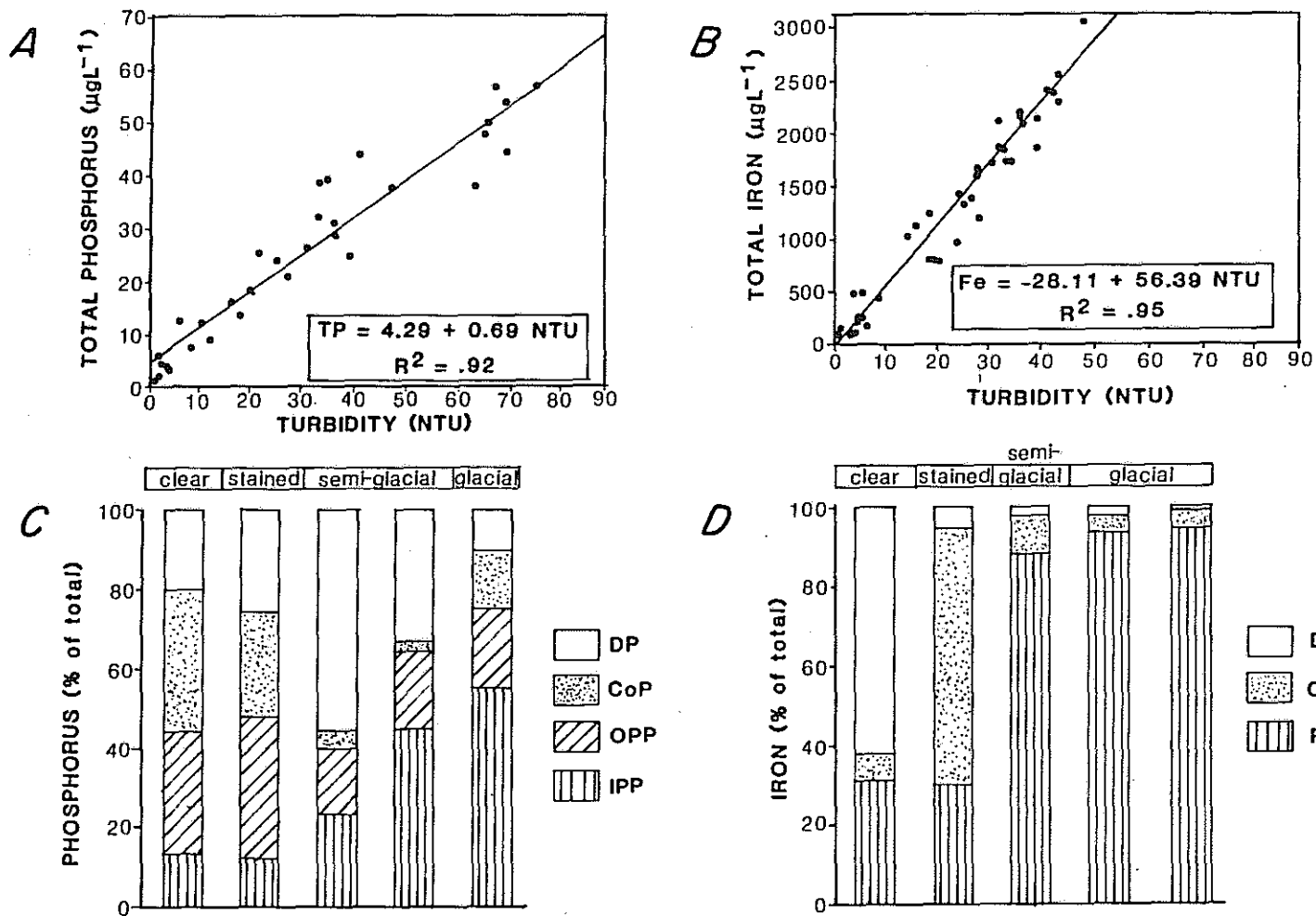


Fig. 3. The relationship of total phosphorus (A) and total iron (B) to turbidity and the various fractions used to characterize total phosphorus (C) and total iron (D) in clear, stained, semi-glacial, and glacial lakes.

present in the stained lake while only 5%-10% comprised the colloidal fraction in the clear and glacial lakes.

The Effect of Altered Light Regimes on Productivity

The results of the carbon-14 transfer experiments (Fig. 4) illustrate the effects of altered light levels on algal uptake. In each clear to glacial lake transfer experiment (clear INC glacial), a decrease in the amount of light resulted in a 52%-100% decrease in day rate productivity. In contrast, the effect of increased light caused by the incubation of glacial lake samples in a clear lake (glacial INC clear) showed the effects of both light stimulation and inhibition on day rate productivity. In five of the six experiments the daily productivity increased from 37%-2375%. However, light inhibition was suspected in one instance when a 5-fold increase in light intensity resulted in a 44% decrease in productivity.

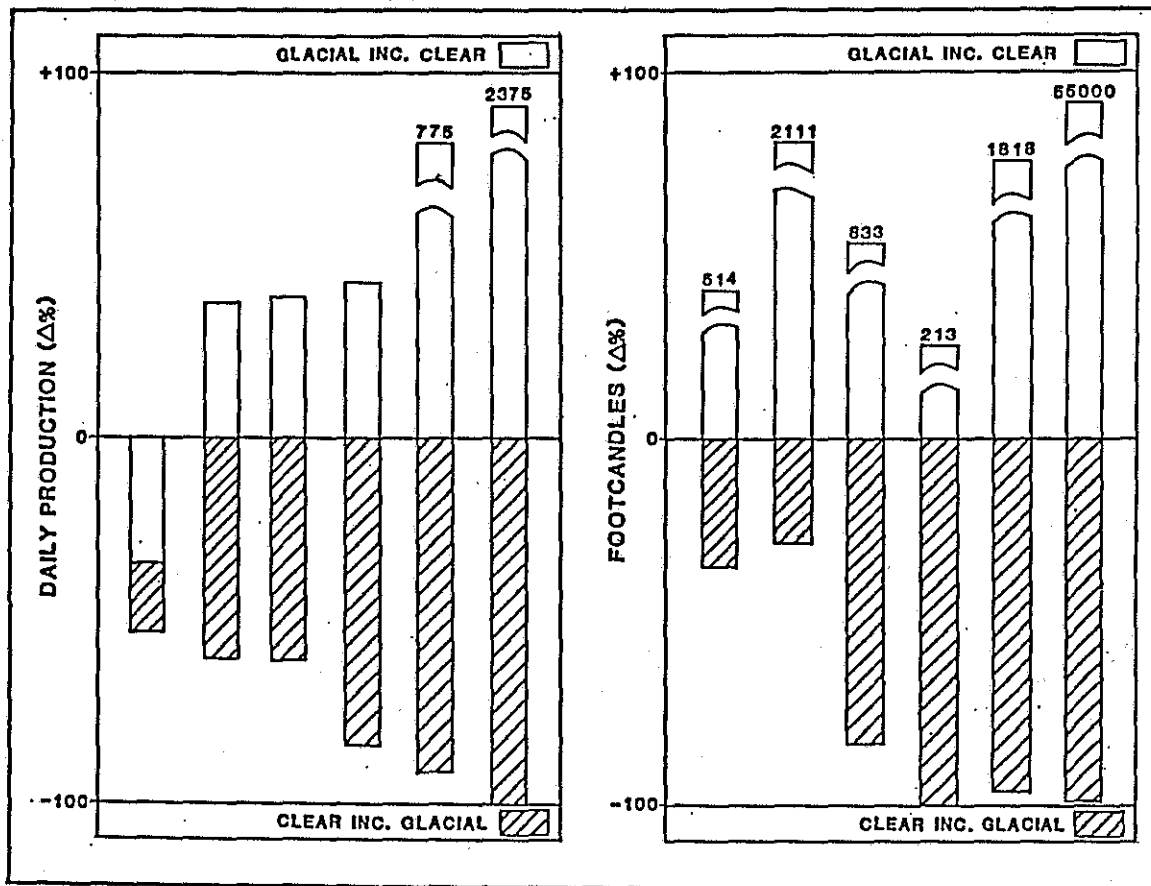


Fig. 4. The results of altering light levels on daily production through algal carbon-14 transfer experiments; incubating glacial water in clear lakes (glacial inc. clear) and incubating clear water in glacial lakes (clear inc. glacial).

In both laboratory and in situ experiments involving the addition of glacial silt (final NTU of 40) to clear lake algal samples prior to incubation, decreases in carbon uptake rate ranged between 50% and 44% for the turbid samples. However, the addition of silt to equivalent clear water samples after photosynthesis had occurred showed no effect on carbon uptake. In fact, we observed a linear response of carbon uptake (CU) over four levels of increased turbidity (NTU) [$CU(mg\ C/m^3d) = 23.7 - 0.185\ NTU$; $r^2 = 0.99$] over the range of turbidity between 0 NTU and 78 NTU. Using the natural lake samples as a control, the carbon uptake rate of equivalent water with glacial silt added decreased at 0.8% per increase in NTU unit. Thus, the decrease in algal uptake rates were attributed to light reductions caused solely by turbidity within the incubation bottles.

The Effect of Glacial Silt on Phosphorus-Chlorophyll (P-C) Response Models

We found that the P-C model $LOG\ chl\ a = -0.75 + 1.03\ LOG\ TP$; $r^2 = 0.79$ derived for Alaskan clear water lakes (Fig. 5) compares with those of Dillon and Rigler (1974), Jones and Bachman (1976), Vollenweider (1976) and Prepas and Trew (1983). However, observed $chl\ a$ levels per equivalent TP for glacial lakes were much less than predicted using the clear water model (Fig. 5a). When $chl\ a$ levels for all glacial lakes were regressed against total phosphorus, we found no relationship ($LOG\ chl\ a = -0.46 + 0.11\ LOG\ TP$; $r^2 = .02$). We did observe, however, that 5 of the data points from glacial lakes overlapped the scatter within lakes used for the clear lake P-C model. These data corresponded to the semi-glacial lake systems. When these were omitted from the glacial P-C data set a linear relationship ($LOG\ chl\ a = -1.55 + 0.88\ LOG\ TP$; $r^2 = 0.65$) was derived (Fig. 5b). The slope was less than that found for the clear lake P-C model indicating that a lower response existed between phosphorus and chlorophyll. In addition, the regression line was shifted downward by a considerable amount (Fig. 5d). Although the data base is small ($n=10$) the regression may provide a useful tool in predicting $chl\ a$ levels in highly turbid lakes, and to justify categorizing glacial systems as a separate lake class.

Total phosphorus (TP) measurements were then corrected for the presence of IPP by regressing TP against corrected total phosphorus (CTP). The resulting equation, for IPP correction, was $CTP = 3.02 + 0.28\ TP$; $r^2 = 0.73$. The slope (0.28) agreed well with the factor (0.30) Verduin et al. (1978) empirically derived to essentially correct for non-biological phosphorus. Our correction for IPP levels resulted in a 47% reduction in predicted $chl\ a$ variation among the semi-glacial lakes with turbidity levels <10 NTU compared to a 70% reduction in glacial lakes with turbidity levels >10 NTU (Table 1). Since IPP only partially explained the variation found in the glacial lake $chl\ a$ response, we considered the euphotic zone as a factor in this discrepancy. We used the P-C expression of Verduin et al. (1978) which used the ratio of euphotic zone depth : mean lake depth to reduce the expression of TP as $chl\ a$. This correction resulted in no further decrease in variation among the semi-glacial lakes, but resulted in an additional 22% decrease in $chl\ a$ variation within the glacial systems (Table 1).

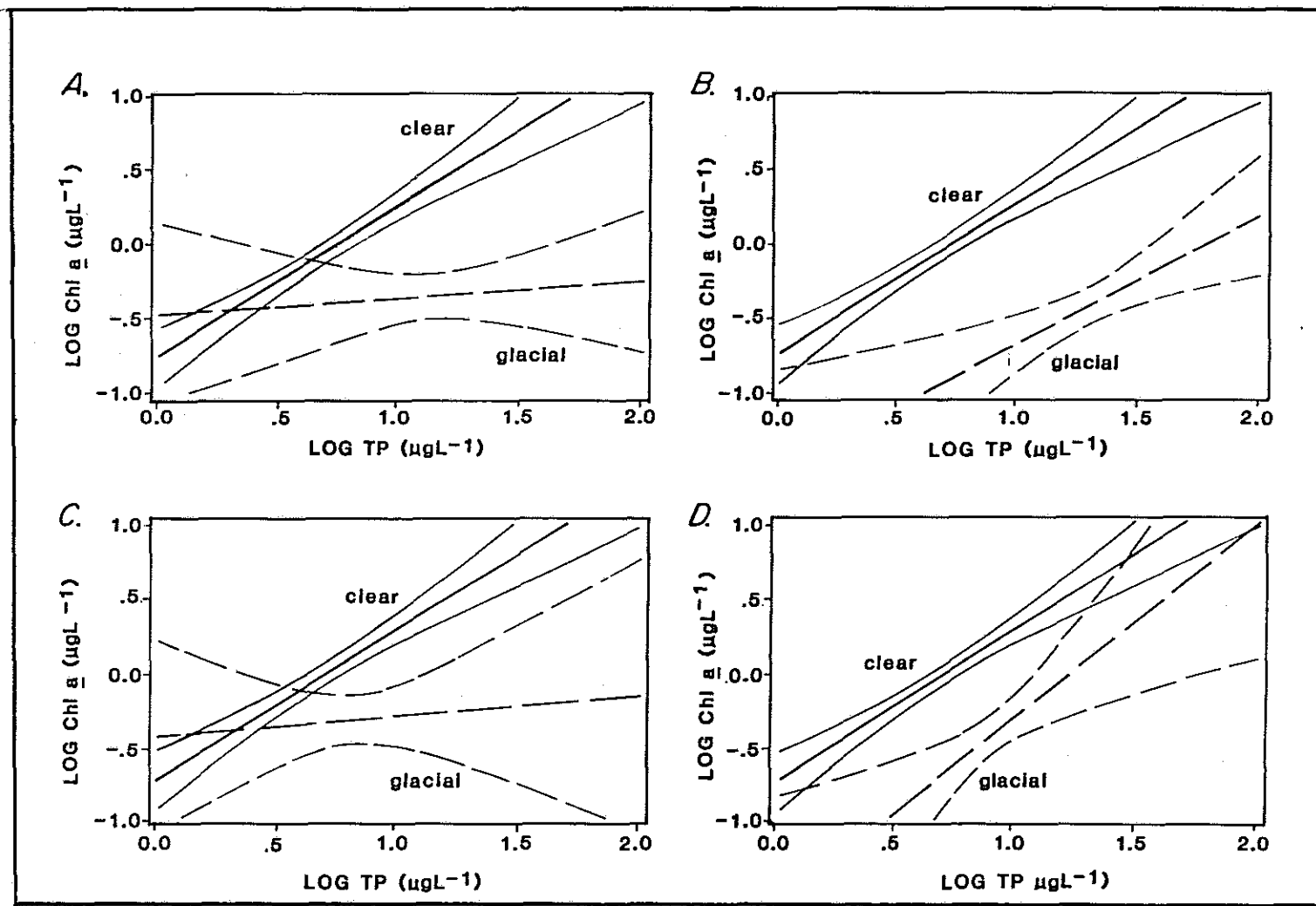


Fig. 5. Phosphorus-chlorophyll (P-C) response models derived for our clear (—) and glacial (---) lakes shown with 95% confidence limits (A), glacial lakes excluding semi-glacial lakes (B), glacial lakes corrected for IPP (C), corrected for IPP without semi-glacial lakes (D).

DISCUSSION

Glacial Silt: Form and Function

A comparison of glacial particles found in differentially turbid lakes reveal features useful to water quality managers. We have shown that turbidity levels in different lakes are a function of both PS and PN. The results indicate that a higher turbidity level is associated with both smaller PS and larger PN. The different values for the slopes (NTU versus PN), derived through sample dilution (Fig. 1b) indicate that realizing a given decrease in NTU at a small PS would require the removal of a larger number of particles than would be necessary for a larger PS. Thus, lakes having higher turbidity levels would more likely remain at a given turbidity, due to the larger number of smaller particles which would tend to stay in suspension. This is opposed to less turbid systems which have relatively larger particles that would be more likely to settle out thereby decreasing turbidity.

As inorganic particles were responsible for much of the turbidity in glacial lakes, we questioned the effect of such a large number of particles on nutrient cycles. For example, iron levels in clear lakes at chemical equilibrium exist in concentrations of less than $20 \mu\text{g L}^{-1}$ (Stumm and Lee, 1960), but the large concentrations of total iron ($2000 \mu\text{g L}^{-1}$) always found in glacial systems indicated an allocthonous source for this element. The fact that total iron correlated with turbidity (Fig. 3b) suggested the source as glacial silt intrusion. We were interested in similar large scale effects on phosphorus levels as we observed correlations between phosphorus, iron, and turbidity (Fig. 3a and 3b). As our fractionation analysis showed that the particulate phase comprised the major fraction of both elements, we determined by chemical analysis that inorganic particulate phosphorus (IPP) comprised a significant amount (24% to 56%) of the total phosphorus (TP) in glacial systems (Fig. 3a). Thus, our fractionation studies confirmed our belief that high levels of inorganic particulate phosphorus (and iron) were derived from glacial silt input i.e., a significant fraction of TP in glacial lakes is comprised of rock phosphorus.

The effects of IPP and light limitation on chl a production were evident upon examination of our phosphorus-chlorophyll response (P-C) models. As Lambou et al. (1982) and Robinson (1957) suggested that the presence of inorganic suspended solids was associated with high levels of non-biologically available phosphorus, we corrected glacial lake total phosphorus estimates for IPP and found that the variation in P-C response was considerably reduced (Fig. 5c and 5d). There remained however, significant variation in chl a response which was not explained by the presence of IPP. Hoyer and Jones (1983) attempted to correct variation in P-C response by considering concentrations of suspended solids (in reality an index of transparency), and Verduin et al. (1978) derived a P-C expression which considered the euphotic zone depth (EZD) to mean depth (Z) ratio as a means to reduce the amount of chl a expressed as phosphorus. We felt that because the EZD in glacial lakes was defined by turbidity levels (Fig. 2) that an EZD correction would prove useful.

Table 1. Variations in chl a from observed values (A) using the clear water phosphorus-chlorophyll (P-C) response model (B), our correction for IPP (C), and the EZD corrected P-C expression (D) of Verduin et al. (1978). Values for both chl a and total phosphorus are seasonal means (May-October) from surface (1m) strata.

Lake-year	Euphotic zone depth (EZD)	Turbidity (NTU)	Observed chl <u>a</u> ($\mu\text{g L}^{-1}$) A	Predicted chl <u>a</u> using clear water P-C model ($\mu\text{g L}^{-1}$) B	Chl <u>a</u> variation ($\mu\text{g L}^{-1}$) B-A	Predicted chl <u>a</u> using IPP corrected P-C model ($\mu\text{g L}^{-1}$) C	Chl <u>a</u> variation ($\mu\text{g L}^{-1}$) C-A	Predicted chl <u>a</u> using EDZ corrected P-C expression ($\mu\text{g L}^{-1}$) D	Chl <u>a</u> variation ($\mu\text{g L}^{-1}$) D-A
1	6.9	3.9	0.2	1.6	+1.4	1.1	+0.9	1.1	+0.9
2	8.6	2.8	0.3	2.6	+2.3	1.6	+1.3	2.0	+1.7
3	8.3	2.9	0.6	1.7	+1.1	1.0	+0.4	1.3	+0.7
4	6.3	4.4	0.6	1.9	+1.3	1.1	+0.5	1.9	+1.3
5	8.1	3.0	1.1	1.2	+0.1	0.9	-0.2	1.2	+0.1
6	7.7	3.3	0.7	1.4	+0.7	0.7	0.0	1.3	+0.6
7	5.2	5.9	0.2	2.8	+2.6	1.5	+1.3	2.0	+1.8
8	9.0	2.6	0.6	0.8	+0.2	0.1	-0.5	0.7	+0.1

9	0.9	46	1.3	8.5	+7.2	2.9	+1.6	0.3	-1.3
10	0.1	46	0.3	6.9	+6.6	1.6	+1.3	0.3	0.0
11	1.1	46	0.9	8.0	+7.1	3.3	+2.4	0.3	+0.6
12	1.3	47	0.6	5.1	+4.5	2.0	+1.4	0.5	+0.1
13	1.6	34	0.3	4.4	+4.1	1.8	+1.5	0.4	-0.1
14	3.8	12	0.2	1.7	+1.5	1.0	+0.8	0.6	+0.4
15	4.0	11	0.4	2.3	+1.9	1.2	+0.8	0.5	+0.1

Applying the Verduin et al. (1978) model to our glacial systems resulted in no improvement over our correction for IPP in lake-year 1-8, but accounted for most of the variation in lake-year 9-15 (Table 1). Lake-year 1-8 were characterized as having turbidity levels <10 NTU and an EZD of from 5-10 m whereas, lake-year 1-15 had turbidity levels >10 NTU and an EZD <5 m.

Glacial Silt and Lake Typology

Turbidity has been associated with decreased zooplankton and phytoplankton production (Rawson 1953, Goldman 1960, Oglesby 1977). However, more recent investigations have stressed the specific role of turbidity, caused by suspended non-algal material, in causing much of the variability within P-C relationships (Lambou et al. 1982, Hoyer and Jones 1983, Hunter and Wilhm 1984). While these studies addressed the negative aspects of turbidity, Verduin (1954) and Tizler et al. (1976) both found increased algal production in turbid plumes. In fact, Tizler et al. (1976) concluded that turbidity (caused by sediment loading) would not only lessen the effect of light inhibition, but would also provide needed nutrients counteracting any potential negative effects of light limitation. In turn, we observed a decrease in carbon uptake rates with increased turbidity in both our transfer and silt addition experiments, and increased carbon uptake rates with a decrease in turbidity (Fig. 4). Our results also provide evidence that the productive potential of glacial lake water is large, but can only be realized when sufficient light is made available through the elimination of turbidity. Thus, we suggest that productivity in glacial systems may be a balanced positive/negative response to silt induced nutrient (phosphorus) input and light limitation (turbidity) respectively.

We found that even low levels (5-10 NTU) of turbidity result in significant effects on light regimes (Fig. 2) which can be used to distinguish clear water lakes from glacial lakes. The level of turbidity found to separate clear from glacial lakes by PS analysis also ranged from 3-6 NTU (Fig. 1). Thus, a combination of 3 criteria distinguish glacial from clear water lakes, i.e., EZD <6-4 m, turbidity >5-10 NTU, and PS <20-40 μm . Moreover, according to their response to IPP and EZD corrections, glacial lakes could be separated into two classes by turbidity and/or EZD levels (Table 1). That is, the P-C response in >10 NTU systems could be corrected for by a further consideration of EZD. In fact, it may actually be more appropriate to utilize a separate regression i.e., $\text{LOG chl } \underline{a} = -1.62 + 1.31 \text{ LOG TP} : r^2 = 0.62$ (Fig. 5d). This model describes a P-C trend similar to that found for the clear water lakes, but because of the EZD (light) factor showed a consistently lowered chl \underline{a} response to a given TP level. It is important to note that although >10 NTU glacial lakes may constitute a unique lake type, the chl \underline{a} response to changing TP levels is much the same as in clear water lakes. Overall, primary production is lowered to a new plateau by the presence of suspended glacial silt particles forcing these lakes towards increased oligotrophy. In contrast, lakes within the 5-10 NTU range may be better modeled by a consideration of IPP and a utilization of our clear water P-C response model. This is appropriate because within this 5-10 NTU

level, corresponding to an EZD of 6-4 m, the impact of glacial silt particles on EZD while considerable is not equal to that occurring in lakes with NTU levels >10 where the EDZ is severely compressed. It appears that 5-10 NTU glacial lakes do show reduction in chl a (Table 1) caused by the presence of glacial silt; however, at times of moderate meltwater intrusion tend to mimic non-turbid lakes. Consequently, such systems would have characteristics resembling both clear water and glacial lakes and, thus, constitute an intermediate lake type (semi-glacial). Further P-C model corrections in these type lakes may need to emphasize the importance of morphometric and climatic factors including flushing rate, temperature, and elevation.

REFERENCES

- Brylinski, M. and K. H. Mann. 1973. An analysis of factors governing productivity in lakes and reservoirs. *Limnol. Oceanogr.* 18:1-14.
- Canfield, D. E. Jr., and R. W. Bachman. 1981. Predictions of total phosphorus concentrations, chlorophyll a and Secchi depth in natural and artificial lakes. *Can. J. Fish. Aquat. Sci.* 38:414-423.
- Dillon, P. J., and F. H. Rigler. 1974. The phosphorus-chlorophyll a relationship in lakes. *Limnol. Oceanogr.* 19:767-773.
- Eisenreich, S. J., Bannerman, R. T., and D. E. Armstrong. 1975. A simplified phosphorus analysis technique. *Environ. Letters* 9:43-53.
- Goldman, C. R. 1960. Primary productivity and limiting factors in three lakes of the Alaskan Peninsula. *Ecol. Monogr.* 30:207-230.
- Goldman, C. R. 1961. Primary productivity and limiting factors in Brooks Lake, Alaska. *Verh. Int. Ver. Limnol.* 14:120-124.
- Hoyer, M. V., and J. R. Jones. 1983. Factors affecting the relation between phosphorus and chlorophyll a in midwestern reservoirs. *Can. J. Fish. Aquat. Sci.* 40:192-199.
- Hunter, R. G., and J. Wilhm. 1984. Use of nephelometric turbidity to calculate Carlson's trophic state index in Keystone Lake Oklahoma. *J. Fresh. Ecol.* 2:476-485.
- Jones, J. R., and R. W. Bachman. 1976. Prediction of phosphorus and chlorophyll levels in lakes. *J. Water Pollut. Control Fed.* 48(9):2176-2182.
- Koenings, J. P., Edmundson, J. A., Edmundson, J. M., and G. B. Kyle. 1985. Limnological methods for assessing aquatic production. Alaska Department of Fish and Game. FRED Technical Report Series. (In review).

- Lambou, V. W., Hern, S. C., Taylor, W. D., and L. R. Williams. 1982. Chlorophyll, phosphorus, Secchi disk, and trophic state. *Water Resour. Bull.* 18:807-813.
- Oglesby, R. T. 1977. Phytoplankton summer standing crop and annual productivity as functions of phosphorus loading and various physical factors. *J. Fish. Res. Board Can.* 34:2255-2270.
- Prepas, E. E., and D. O. Trew. 1983. Evaluation of the phosphorus-chlorophyll relationship for lakes off the Precambrian Shield in western Canada. *Can. J. Fish. Aquat. Sci.* 40:27-35.
- Rawson, D. S. 1953. The standing crop of net plankton in lakes. *J. Fish. Res. Bd. Can.*, 10:224-237.
- Reimann, B. 1978. Carotenoid interference in the spectrophotometric determination of chlorophyll degradation products from natural populations of phytoplankton. *Limnol. Oceanogr.* 23:1059-1066.
- Robinson, M. 1957. The effects of suspended material on the reproductive rate of *Daphnia magna*. *Publication of the Institute of Marine Science* 4:265-277.
- Sakamoto, M. 1966. Primary production by phytoplankton community in some Japanese lakes and its dependence on lake depth. *Arch. Hydrobiol.* 62:1-28.
- Saunders, G. W., Trama, F. B., and R. W. Bachmann. 1962. Evaluation of a modified ¹⁴C technique for shipboard estimation of photosynthesis in large lakes. *Univ. Michigan, Great Lakes Res. Div., Spec. Rep. No. 8.* 61 p.
- Schindler, D. W. 1978. Factors regulating phytoplankton production and standing crop in the worlds freshwaters. *Limnol. Oceanogr.* 23:478-486.
- Smith, V. H. 1979. Nutrient dependence of primary productivity in lakes. *Limnol. Oceanogr.* 24:1051-1066.
- Strickland, J. D. H., and T. R. Parsons. 1972. A practical handbook of seawater analysis, 2nd ed. *Fish. Res. Bd. of Canada Bull.* 167:310 p.
- Stumm, W. and G. F. Lee. 1960. The chemistry of aqueous iron. *Schweizerische Zeitschrift fur Hydrologie Revue Suisse d-Hydrologic.* 22:295-319.
- Tizler, M. M., Goldman, C. R., and R. C. Richards. 1976. Influence of sediment inflow on phytoplankton primary productivity in Lake Tahoe (California-Nevada). *Int. Revue Ges. Hydrobiol.* 61:169-181.
- Verduin, J. 1954. Phytoplankton and turbidity in western Lake Erie. *Ecology.* 35:550-561.

- Verduin, J., Williams, L. R., Lambou, V. W., and J. D. Bliss. 1978. A simple equation relating total phosphorus to chlorophyll concentration in lakes. *Verh. Internat. Verein. Limnol.* 20:352.
- Vollenweider, R. A. 1965. Calculation models of phytoplankton - depth curves and some implications regarding day rate estimates in primary production measurements. *Mem. Ist. Ital. Idrobiol. Suppl.* 18:425-457.
- Vollenweider, R. A. 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. *Mem. Ist. Ital. Idrobiol.* 33:53-83.

THE INFLUENCES OF SUSPENDED GLACIAL PARTICLES
ON THE MACRO-ZOOPLANKTON COMMUNITY
STRUCTURE WITHIN GLACIAL LAKES

by

John M. Edmundson
Fishery Biologist
and
J. P. Koenings
Principal Limnologist
Alaska Department of Fish and Game
FRED Division

ABSTRACT

Alaskan lakes exhibiting turbidity levels as low as 5 NTU due to suspended particles ($\geq 1 \mu \leq 20 \mu$) derived from glacier melt-water, support relatively sparse populations of zooplankters; and also show a highly restrictive community composition.

Suspended glacial particles effectively reduce the depth of the euphotic zone (defined by the light compensation point) thereby decreasing areal net primary production. Such lowered primary production results in reduced densities of herbivorous macro-zooplankters which forage on the algal community. We have also found that filter feeding cladocerans e.g. *Bosmina* and *Daphnia* are uniquely absent from the zooplankton community of glacial lakes irregardless of the presence or absence of planktivorous fish. In addition, while primary production and summer temperatures are low both are not beyond the lower limit we have observed for clear water systems that contain robust populations of cladocerans. We provide evidence which suggests that the overlapping size ranges of algal material and glacial silt allows ingestion of the glacial particles by non-discriminating filter feeders. Such an inefficient foraging strategy, especially when particle concentrations are high and algal numbers low, results in the eventual elimination of the species of *Bosmina* and *Daphnia*. Thus, the macro-zooplankton community of glacial lakes consists entirely of the selective herbivore *Diaptomus* and the raptorial feeding *Cyclops*.

INTRODUCTION

Limnological sampling of Alaskan lakes containing suspended glacial silt particles with turbidity levels ranging from 5 to 45 NTU reveal the total absence of the indiscriminate filter feeding cladocerans *Bosmina* sp. and *Daphnia* sp. from the zooplankton community (Koenings et al. 1985). This was puzzling since these species are well represented in several higher altitude clear water lakes that drain into these glacially turbid systems. Summer period water temperatures, primary production, and fish predation pressure cannot explain the absence since nearby clear water

lakes, which overlap these same features, support healthy populations of cladocerans. Our observations led us to question whether suspended glacial silt particles may act directly to eliminate these species. Indeed, McCabe and O'Brien (1983) have shown that *Daphnia pulex* exposed to suspended silt and clay particles suffered decreased filtration, ingestion, and reproductive rates. However, Robinson (1953) found that suspended silt actually stimulated the birth rate of *Daphnia magna*, but only at low concentrations. Regardless of seemingly contradictory results, such studies, along with those of Gerritsen and Porter (1982), suggest that fine particles are actively filtered out of lake water as cladocerans feed. Thus, ingested glacial silt particles may act either to produce sufficient mortality or to interfere with the reproductive process resulting in the total elimination of cladoceran zooplankters.

Controlled lake experiments were performed to show the affect of silt particles on *Daphnia* survival and reproduction over time after transfer from a clear water lake (0 NTU) to the high turbidity environment of a glacial lake (45 NTU); and to determine if and how such exposure could cause sufficient immediate or long term mortality resulting in extinction. Finally, by manipulating food (chl a) and turbidity levels (NTU) in controlled laboratory tests, we determined if suspended silt particles act either as an independent agent or in association with other limiting factors.

METHODS AND MATERIALS

The study area for these experiments is located on the central Kenai Peninsula, Southcentral Alaska. Three lakes were utilized for our field experiments; Johnson Lake a small clear water lake, was the source for *Daphnia galeata mendotae*, whereas Hidden Lake a large clear system, and Tustumena Lake a glacially turbid lake were used as field experiment sites. Inter-lake differences in water quality features, specifically, temperature, pH, conductivity, alkalinity, and chl a were monitored to provide additional information that might aid in our explanation of field and laboratory results.

Daphnia galeata mendotae identified after Pennak (1978) were collected from Johnson Lake using a 0.20 meter diameter plankton net with 153 μm mesh. Individual, non-egg bearing, female *Daphnia* were separated under a microscope and ten individuals placed into each of twenty-four 500 ml polyethylene bottles containing Johnson Lake water strained through 153 μm mesh. Twelve bottles were transported to Hidden Lake, a large clear water lake (NTU of 0.5) containing healthy populations of *Daphnia* and *Bosmina*, to act as a control; and 12 bottles transported to Tustumena Lake, a large glacial lake (NTU of 45) containing only calanoid and cyclopoid copepods. The contents of the polyethylene bottles were emptied into 1 liter plexiglass biochambers (O'Brien and Kettle 1981) one bottle per chamber, to create six sets of duplicate tests per lake. We chose to transfer the zooplankters to two lakes, instead of just to the glacial system, in order to equalize handling stress. The biochambers were then submerged 1 meter below the surface with two biochambers

from each lake being removed every 48 hours. Individual *Daphnia* were examined under a microscope to compare reproductive and survivorship rate between the clear and turbid treatments. Total numbers of survivors and total amount of new production including eggs, developing embryos and newly hatched young were monitored once every 48 hours for 240 hours.

In the laboratory experiments, Johnson Lake water was strained through a 153 μm mesh net and placed into eighteen 1 liter glass jars. Duplicate chambers were used at each of three treatments of turbidity (0, 30, and 60 NTU) and food levels (0.5, 1.0, and 2.0 $\mu\text{g L}^{-1}$ of chl a). Chl a levels for Johnson Lake were determined using the fluorometric method after Koenings et al. (1985). The water treatments were changed every 48 hours to control bacterial growth and to maintain chl a at desired levels throughout the experiment. Turbidity levels were checked and adjusted daily by additions of concentrated silt. To arrive at the chl a treatment levels, each 1 liter jar of Johnson Lake water was filtered through a 4.25 cm GF/F, 0.7 μm filter to the necessary dilution and the filtrate added back to the required unfiltered Johnson Lake water.

To create the various turbidity levels, glacial silt was obtained directly from glacier ice, concentrated by centrifuging the boiled melt water, and removing the concentrated silt with a pipette. The silt was stored frozen in sterile centrifuge tubes with individual tubes being thawed for each experiment. The silt extract was added to the jars to attain the proper NTU levels with turbidity being monitored with a DRT-100 (H. F. Instruments) laboratory turbidimeter. Six non-egg bearing female *Daphnia galeata mendotae* were placed into each of the 1 liter glass jars and the jars placed, to a level just below the lids, into a water bath maintained at the same temperature as Johnson Lake (14°C). Total numbers of *Daphnia* survivors and new production, including eggs, developing embryos and newly hatched young, were recorded every 48 hours for 288 hours.

RESULTS

In-Lake Reproduction and Survivorship Rates

Comparisons of *Daphnia* reproduction and survivorship between the control group under clear water conditions of Hidden Lake and the group exposed to the turbid environment of Tustumena Lake revealed a reduced survivorship and greatly lowered reproduction in the Tustumena group (Fig. 1). Specifically, after 220 hours only 15% of the Tustumena group remained alive while 55% of the control group were still living. Thus, the mortality rate for the Tustumena group equalled 1.9 adults/d, compared to 1.0 adult/d for the clear water group. In addition, the production of eggs and young in Hidden Lake was clearly different as seven times the number of young were found in the clear water chambers compared to those found in chambers exposed to the turbid environment.

The second lake experiment produced an even greater divergence between the clear and turbid treatments (Fig. 2). In this test, all animals

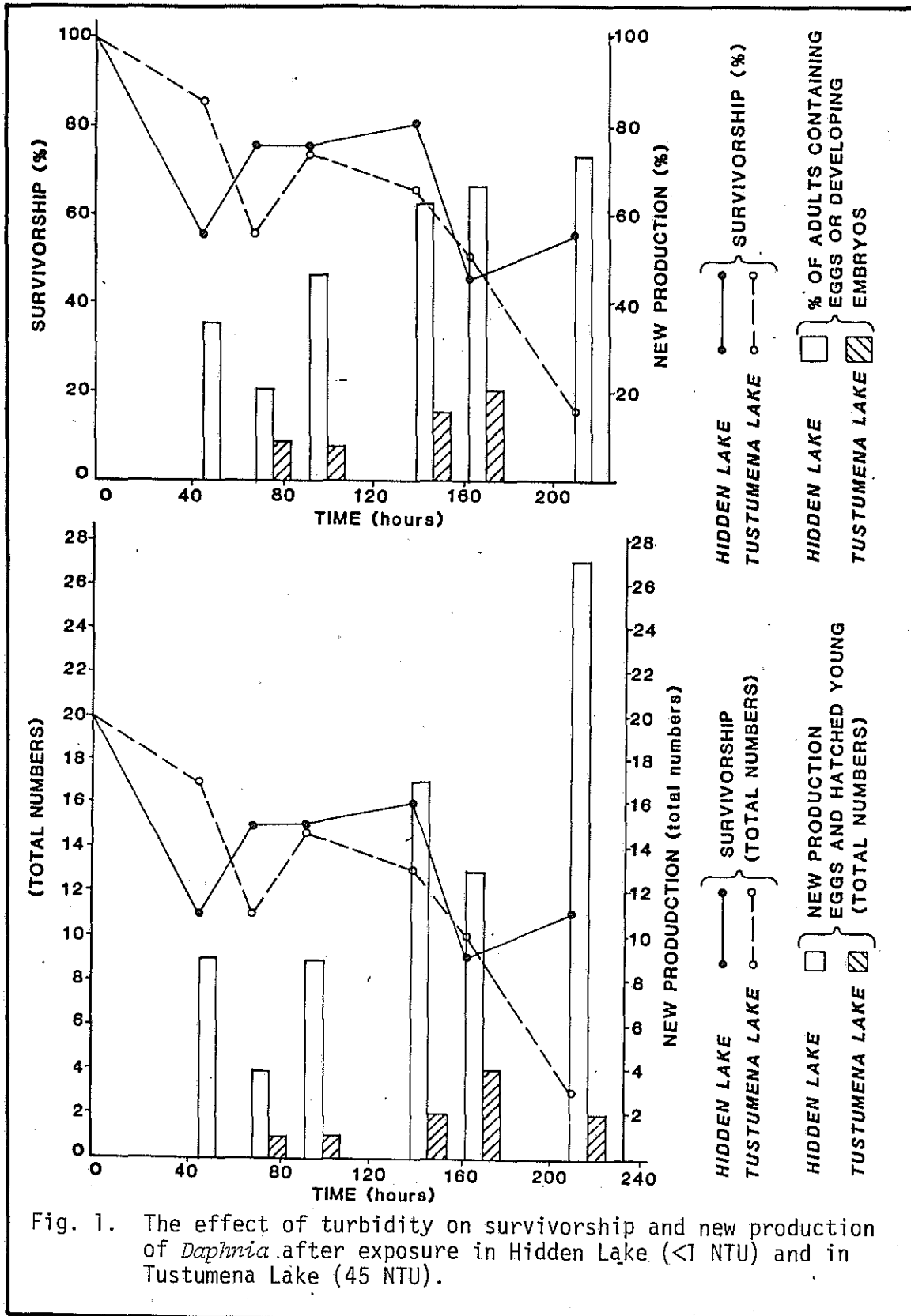


Fig. 1. The effect of turbidity on survivorship and new production of *Daphnia* after exposure in Hidden Lake (<1 NTU) and in Tustumena Lake (45 NTU).

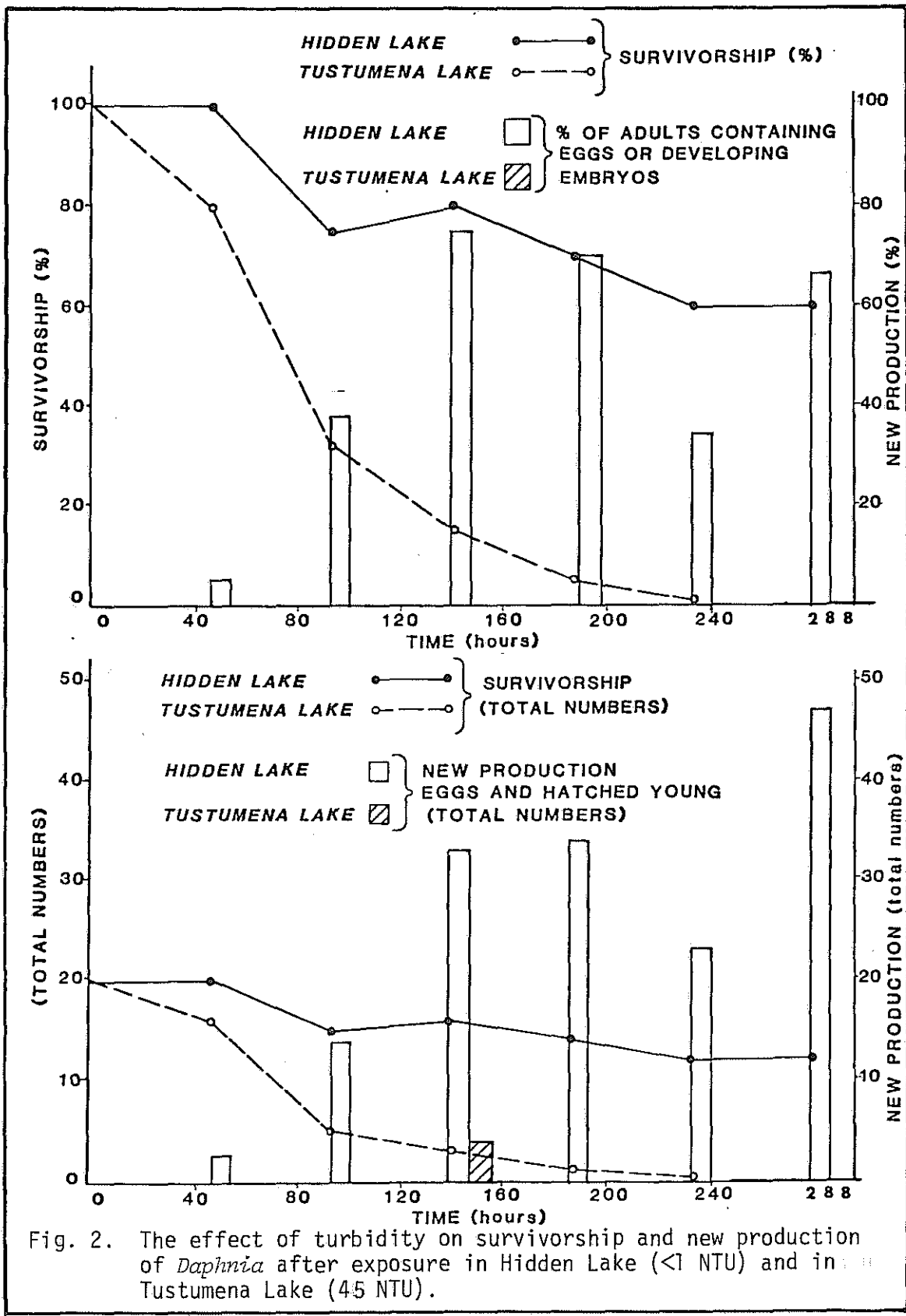


Fig. 2. The effect of turbidity on survivorship and new production of *Daphnia* after exposure in Hidden Lake (<1 NTU) and in Tustumena Lake (4.5 NTU).

within the Tustumena group had died after 240 hours compared with only 40% for the Hidden Lake control group. In this experiment the mortality of the turbid group equalled 2.0 adults/d compared to 0.7 adults/d for the clear water group. However, a major wind storm on Tustumena Lake may have affected our results as wave action may have exacerbated mortality. Nonetheless, the control group also exhibited a 12 fold increase in new production over those in the Tustumena group. These results showed that mortality rates from exposure to the suspended glacial silt particles was increased, but need not be immediate; and that the most severe impact appeared to occur on the reproductive potential of *Daphnia*. Additionally, examination of individual animals under a microscope equipped with a video camera and monitor revealed the ability of *Daphnia* to rapidly filter, ingest, and pass silt particles through the gut. We determined filtering rates to be 0.31 ml/animal-hour or 8.3×10^6 particles/animal-hour. This suggests that ingestion of silt particles along with algal material of overlapping size ranges may interfere with the energy requirements of individual *Daphnia*, increasing mortality and disrupting reproduction.

Reproduction and Survivorship Under Manipulated Food and NTU Regimes (I)

In these experiments, we prepared three different food levels (0.5, 1.0, and $2.0 \mu\text{g L}^{-1}$ of chl *a*) using varying ratios of filtered/unfiltered Johnson Lake water. In addition, we simulated three separate turbidity levels (0, 30, and 60 NTU) by adding varying values of concentrated glacier silt to each of the three food levels. Finally, all treatments were replicated resulting in 18 chambers (3 food levels x 3 turbidities x 2 replicates).

Unexpectedly, we observed that under all food regimes *Daphnia* reproduction and survivorship fared best under turbid conditions, usually at the highest turbidity level (60 NTU), while clear water conditions (0 NTU) proved least successful (Fig. 3 and 4). Specifically, at 60 NTU a total of 235 young were produced across all food levels compared to 140 young at 30 NTU and to 85 young at 0 NTU (Fig. 3). In addition, at the end of the 60 NTU experiment 26 adults out of the original 36 were still alive for a mortality rate of 0.8 adults/d compared to 1.4 adults/d at 30 NTU, and 1.5 adults/d at 0 NTU. When we compared turbidity treatments within equivalent food levels, we found that recruitment for the $0.5 \mu\text{g L}^{-1}$ chl *a* level equalled 130 young compared to 175 young at $1.0 \mu\text{g L}^{-1}$ and 155 young at $2.0 \mu\text{g L}^{-1}$ (Fig. 4). Overall, mortality rates at the lower food level equalled 1.5 adults/d compared to 1.3 adults/d at the intermediate food regime, and 0.9 adults/d at the higher food level. In general, reduced food levels seemed to reduce survivorship, and to a more limited extent recruitment, whereas increased turbidity appeared to drastically increase reproductive success while at the same time reducing mortality.

These results, although conflicting with field test results, do show that *Daphnia* can survive and reproduce, in fact thrive, in a high turbidity environment. Thus silt, by itself, cannot be held responsible for the absence of cladocerans from the zooplankton community. However, we grew

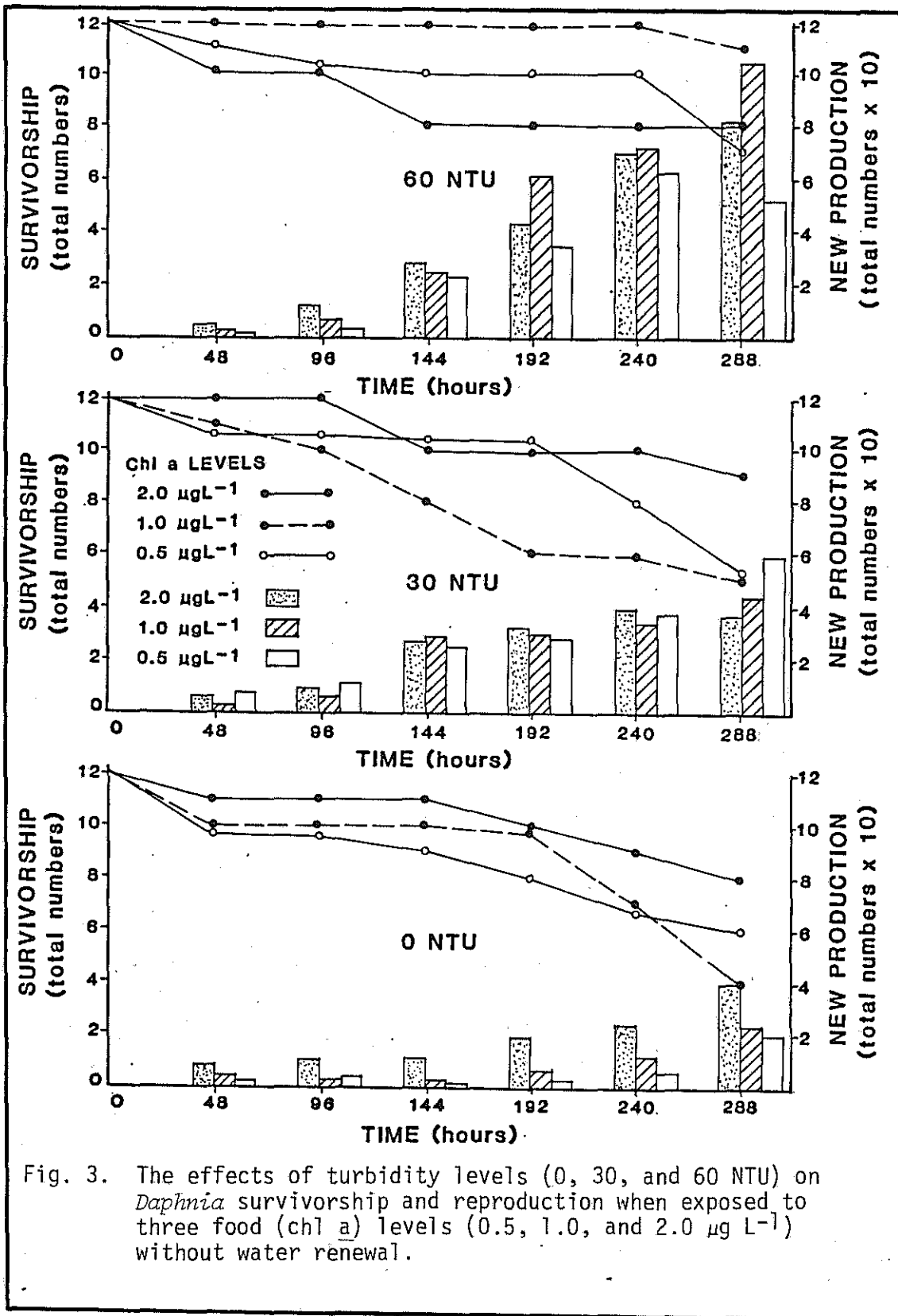
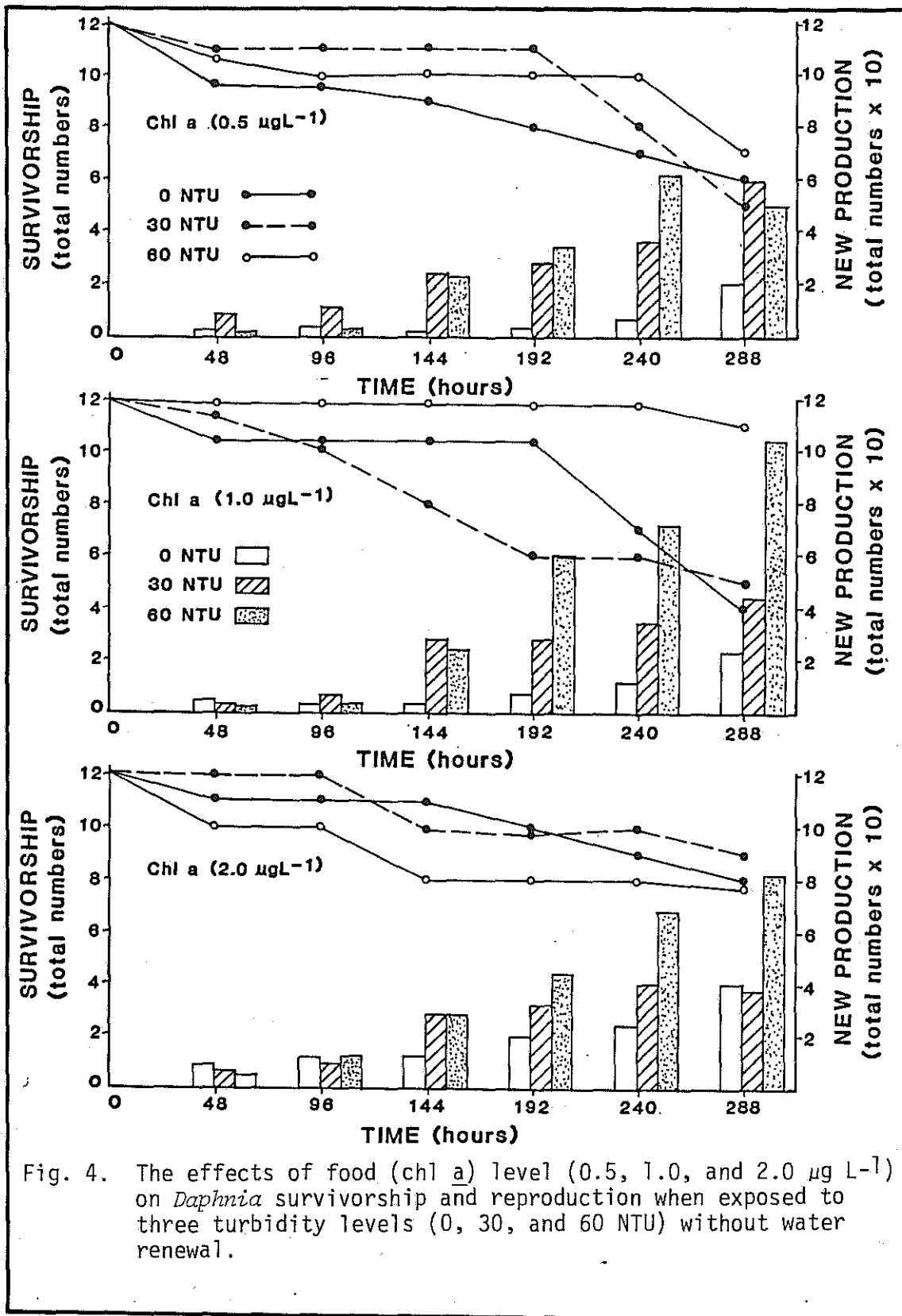


Fig. 3. The effects of turbidity levels (0, 30, and 60 NTU) on *Daphnia* survivorship and reproduction when exposed to three food (chl *a*) levels (0.5, 1.0, and 2.0 µg L⁻¹) without water renewal.



curious about both the lack of a constant reproductive response to different food levels within an NTU treatment (Fig. 3), and the fairly consistent positive benefit on recruitment of increased turbidity within and across food levels (Fig. 4). We theorized that the deposition and accumulation of fecal pellets, composed of ingested silt particles, at the bottom of the glass jars was furnishing an inoculum for bacterial growth. This provided an unlimited food source for *Daphnia* exposed to turbidity water. As bacterial population growth is roughly proportional to the amount of exposed surface (Robinson 1957), this would explain why recruitment failed to respond proportionally to the originally established chl a levels. That is, the different algal food levels were masked by an overwhelming bacterial food supply as the higher turbidity levels provided a greater medium for bacterial growth (Arruda et al. 1983). Indirectly then, increasing turbidity levels provided the best environment for *Daphnia* survival and reproduction.

Reproduction and Survivorship Under Manipulated Food and NTU Regimes (II)

To eliminate the problem of suspected bacterial contamination, the experiment was repeated with the added precaution of changing the water, resetting food and turbidity levels, every 48 hours. This process would also simulate, but not equal the continuous water exchange conditions which exists in the submerged biochambers during the lake experiments where the water exchange rate equalled 12 l/hr.

Across the turbidity levels, we found both survivorship and recruitment for the combined food (chl a) levels to be relatively unaffected as turbidity increased (Fig. 5). At 60 NTU the overall mortality equalled 0.8 adults/d compared to 0.8 adult/d at 30 NTU and 0.6 adult/d at 0 NTU. Moreover, at 60 NTU production of young *Daphnia* equalled five animals whereas production at 30 NTU equalled nine young, and at 0 NTU increased slightly to 14 animals. However, within each turbidity level, we found a major drop in both survivorship and recruitment as food levels decreased (Fig. 5). For example, at 60 NTU the mortality at $2.0 \mu\text{g L}^{-1}$ chl a equalled 0.3 animals/d compared to 0.8 animals/d at $1.0 \mu\text{g L}^{-1}$ chl a and 1.5 animals/d $0.5 \mu\text{g L}^{-1}$ chl a.

Across food levels (chl a), we found the greatest survivorship and production for combined turbidity levels to be at the highest food level of $2.0 \mu\text{g L}^{-1}$ chl a (Fig. 6). The overall mortality rate at $0.5 \mu\text{g L}^{-1}$ chl a equalled 1.8 animals/d compared to 0.7 animals/d at $1.0 \mu\text{g L}^{-1}$ chl a and only 0.4 animals/d at $2.0 \mu\text{g L}^{-1}$ chl a. Greater food levels also promoted recruitment as numbers of young increased from 0 at low chl a concentrations to three young at intermediate food levels, and then to 29 young at the highest food level. Within a given food level survival was not greatly affected by increased turbidities except at the lowest chl a level. For example, at $1.0 \mu\text{g L}^{-1}$ chl a, the mortality rates for 30 NTU and 60 NTU treatments were equal as were the mortality rates of 60 NTU and 0 NTU at $2.0 \mu\text{g L}^{-1}$ chl a. The major exception to this occurred within the lowest food level where mortalities seemed to be exacerbated by increased levels of glacial silt. Finally, recruitment of young was not observed at $0.5 \mu\text{g L}^{-1}$ chl a regardless of

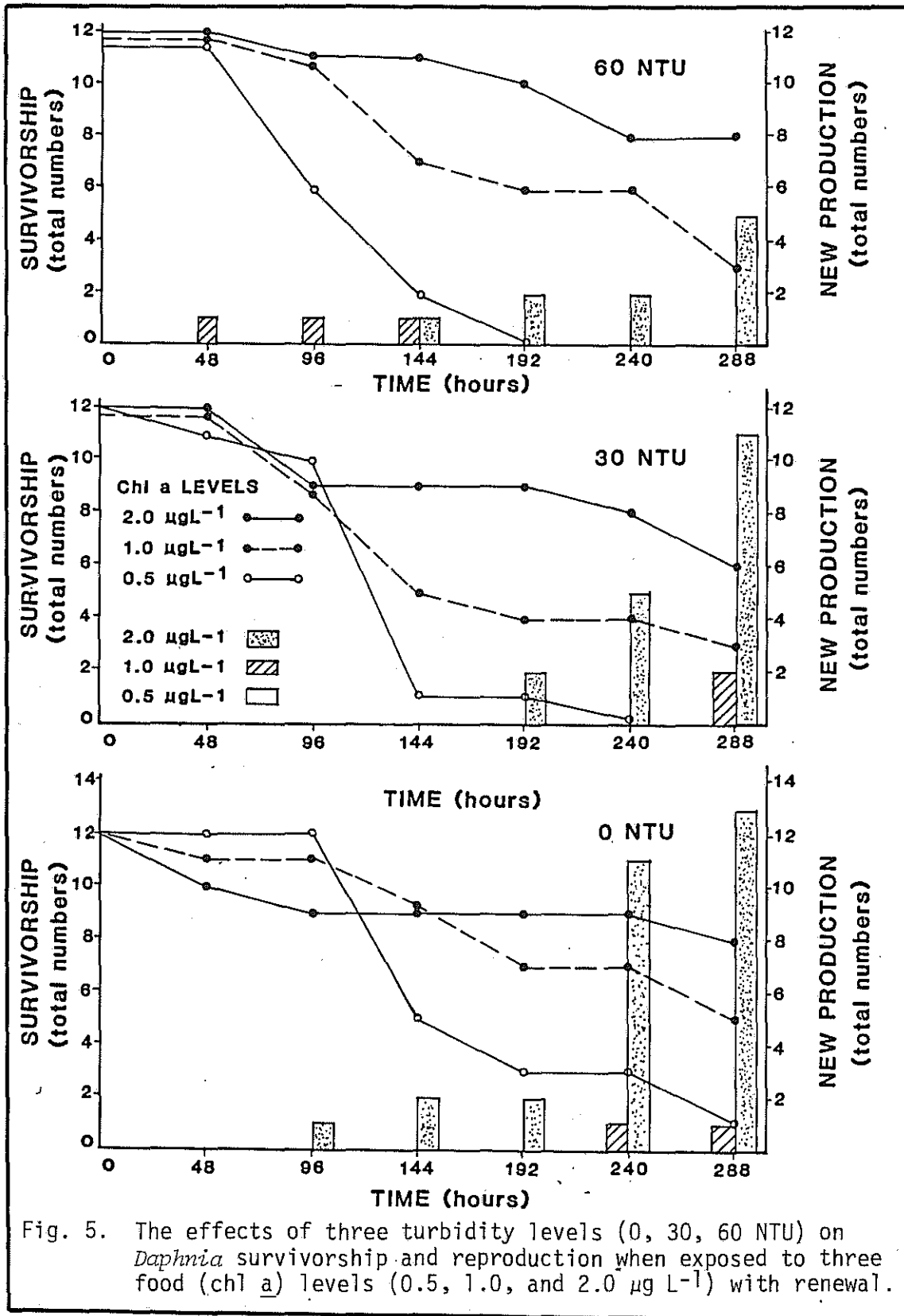
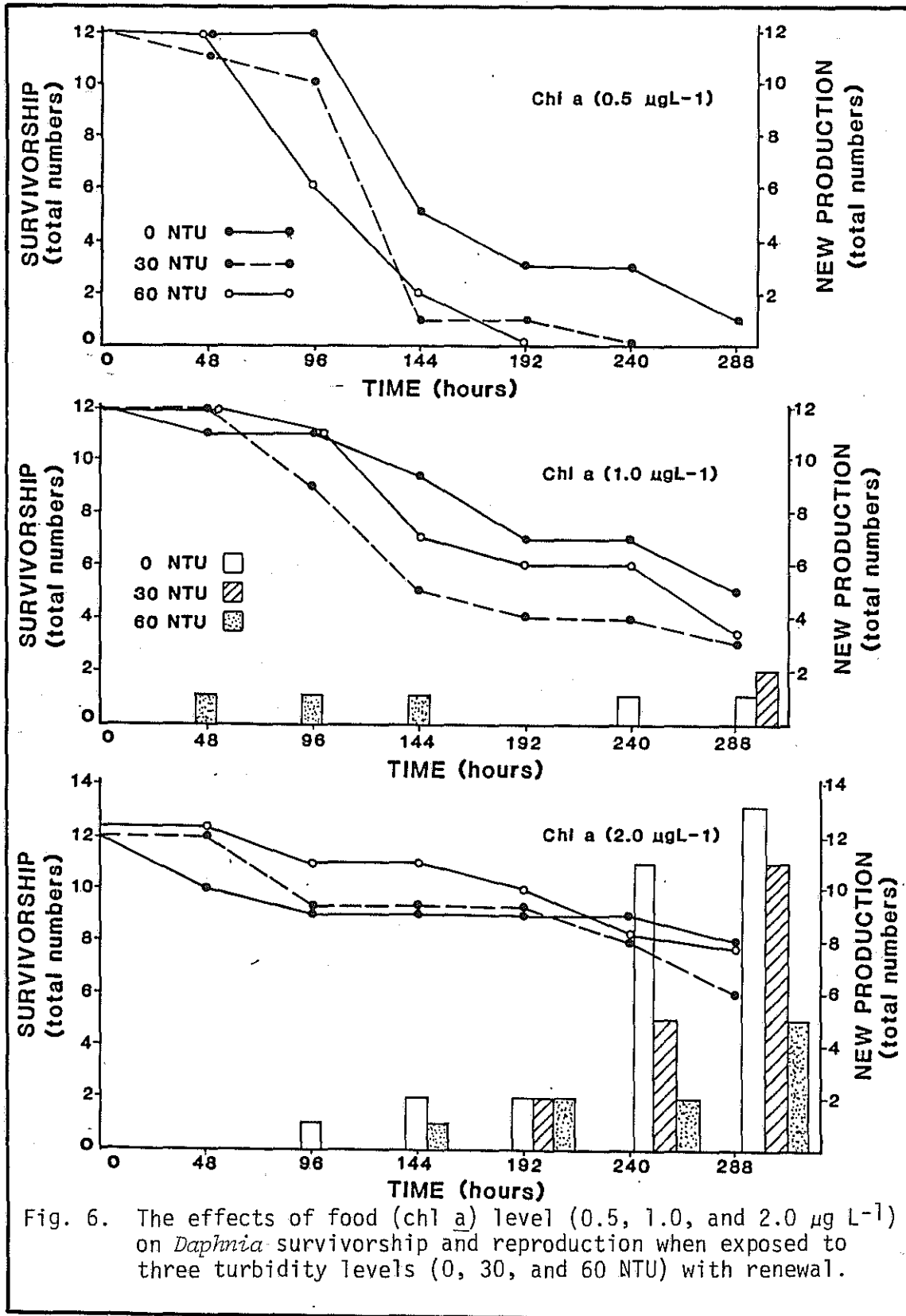


Fig. 5. The effects of three turbidity levels (0, 30, 60 NTU) on *Daphnia* survivorship and reproduction when exposed to three food (chl *a*) levels (0.5, 1.0, and 2.0 µg L⁻¹) with renewal.



turbidity level whereas at $1.0 \mu\text{g L}^{-1}$ chl a we saw new production only in the 0 NTU and 30 NTU treatments, and at $2.0 \mu\text{g L}^{-1}$ chl a recruitment occurred at all turbidities. At this higher food level increasing turbidity levels slowed recruitment as five young were produced at 60 NTU followed by 11 young at 30 NTU, and 13 young at 0 NTU.

DISCUSSION

Results from our initial laboratory experiments (I), which presumably allowed the build up of bacteria, suggests that cladocerans can inhabit lake environments of high turbidity provided there is a high level of available food. These findings are consistent with observations from reservoirs located in agricultural watersheds in southwestern and southeastern United States. Arruda et al. (1983) have suggested that high turbidity, together with conditions of warmer water temperatures and high primary production, may actually be beneficial by furnishing a site for bacterial growth and, thus, provide an additional food source for foraging cladocerans. Particles derived from melting glaciers, however, have little opportunity to form such associations especially in colder, unproductive Alaskan lakes so that ingestion in nature provides little benefit (Stockner, per. comm. 1983).

Clogging of filtering appendages was also considered as a cause for the absence of cladoceran zooplankters, but was rejected as microscopic examination showed the ability of *Daphnia* to filter, ingest, and pass ingested silt particles through the gut. Individuals were also observed to use the abdominal claw to remove unwanted particles from the food groove, and were never observed to become clogged. Predation by planktivorous fish was also eliminated as a process of sufficient intensity to cause the total elimination of cladocerans from turbid glacial systems. McCabe and O'Brien (1983) have surmised that suspended silt particles provide protection from fish predation by reducing the visibility of cladocerans. Such protection apparently overrode any deleterious effects of reduced filtration, ingestion, and reproduction rates. If this were true for Alaskan glacial lakes, we would expect to find thriving cladoceran populations. In addition, we have observed cladocerans to be absent from glacial lakes regardless of the presence or absence of foraging planktivorous fish. Also, clear water lakes of the same region that have dense populations of planktivorous fish i.e., sockeye salmon fry, support large numbers of cladocerans. We suggest that in nature the harmful effects of suspended glacial particles outweigh the beneficial affects of reduced predation, and are a factor in limiting cladoceran populations.

Our field experiments demonstrate that *Daphnia* suffers lowered recruitment and survival in glacial water (NTU of 45) compared to that observed in a clear water (NTU of <1) environment. Since chl a levels ranged from $0.4 \mu\text{g L}^{-1}$ to $1.0 \mu\text{g L}^{-1}$ in the clear lake and from $0.5 \mu\text{g L}^{-1}$ to $2.5 \mu\text{g L}^{-1}$ in the glacial lake during the experiment, algal biomass levels were not responsible for the increased mortality within the glacial lake. However, we realized that algal quality as well as quantity is an important factor in zooplankton nutrition (Porter 1975,

Table 1. Comparison of zooplankton community composition (May-November) between glacial (>5 NTU) and non-turbid (<5 NTU) lakes. Represented lakes are examples taken from a more complete data set, glacial (n=18): non-turbid (n=78) that includes lakes throughout Southcentral and Southeast Alaska. Relative densities are represented by: absent (-), <33% (+), >34%<66% (++) , and >67% (+++).

Taxa/Lake	Glacial (>5 NTU) lakes							Non-turbid (<5 NTU) lakes							
	Tustumena	Kenai	Crescent	Grant	Ptarmigan	Crescent	Miners	Kushtaka	Bear	Upper Russian	Hidden	Packers	Lesiure	Karluk	Badger
<u>Cladocera:</u>															
<i>Boemina</i> sp.	-	-	-	-	-	-	-	-	++	+	+	+	+++	+	+
<i>Daphnia</i> sp.	-	-	-	-	-	-	-	-	++	+	+	+	+	+	+
<i>Holopedium gibberum</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+
<i>Alona</i> sp.	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
<i>Polyphemus pediculus</i>	-	-	-	-	-	-	-	-	++	-	-	-	-	-	+
<u>Copepoda:</u>															
<i>Cyclops</i> sp.	+	++	+	++	++	+++	++	++	-	+++	+	+	+	+++	+++
<i>Diaptomus</i> sp.	+	+	-	-	++	-	-	-	-	-	+	++	+	+	+
<i>Epsichura</i> sp.	-	-	-	-	-	-	-	-	+	-	+	+	-	-	-
<u>Rotifera:</u>															
<i>Kellicottia longispina</i>	+	+	+	+	+	+	+	+	+	+	++	-	-	-	+
<i>Aoplanchna</i> sp.	-	-	+++	+	-	-	-	+	-	-	-	-	-	-	-
<i>Keratella</i> sp.	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-
<i>Conochiloides</i> sp.	-	-	-	-	-	-	-	-	-	+	+	-	-	-	-

1977). Thus, decreased algal availability may have caused the increased mortality and failed recruitment in our biochambers incubated in glacial water. This in turn would mean that all glacial lakes are populated by species of inedible phytoplankton as none are capable of supporting cladoceran zooplankters (Table 1). As unlikely as this may be, we tested the effect of increased turbidity (using the same silt stock for each turbidity treatment) by using different ratios of filtered and unfiltered Johnson Lake water. Thus, the cladocerans were exposed to equivalent conditions except for varying levels of the same glacial silt and/or chl a. Given these conditions, our results again showed that glacial silt itself was not responsible for increased mortality (Fig. 3). Glacial silt exacerbated *Daphnia* mortality and lessened recruitment only as chl a levels dropped to around $0.5 \mu\text{g L}^{-1}$ (Fig. 4 and 5). At this decreased level of algal biomass mortality followed turbidity increases, a trend which lessened as the chl a levels increased. As seasonal mean chl a levels in glacial lakes ($n=15$) equal $0.4 \mu\text{g L}^{-1}$ (Edmundson and Koenings 1985), glacial silt may act to exclude populations of cladocerans through reducing autochthonous primary production.

The primary affect of suspended glacial particles on *Daphnia* appears to be an interruption of the reproductive process. In Alaskan lakes, suspended glacial silt particles become a limiting factor for the survival and reproduction of cladocerans by decreasing light penetration, reducing euphotic volume, and thus decreasing net primary production. When food levels are low and silt concentrations high, the nonselective foraging strategy of cladocerans results in glacial particles being ingested together with algal material of overlapping size range. The net result is that cladocerans may be able to acquire sufficient energy for short term survival, but successful reproduction is curtailed (McCabe and O'Brien, 1983). Indeed, our results from tiered food levels suggest that the first major effect of reducing algal biomass from $2.0 \mu\text{g L}^{-1}$ chl a to $1.0 \mu\text{g L}^{-1}$ chl a was a drastic reduction in recruitment (Fig. 6). A further drop in chl a to $0.5 \mu\text{g L}^{-1}$ results in drastically increased mortality especially at the higher turbidity levels. This supports the contention of Richman and Dodson (1983) that under extremely low food abundances calanoids not cladocerans dominate the zooplankton community because calanoids ingest a lower number of select food particles per unit time which requires less energy. The inefficient filtering process of cladocerans, however, requires a great deal of energy because a large amount of water must be filtered to collect a small amount of food. In addition, cladocerans rely on a parthenogenic reproductive strategy, rapidly producing many broods of young during the summer months to take advantage of abundant food supplies and to combat huge losses due to predation. Under abundant food conditions this strategy works well, especially so for inefficient filter feeders extremely vulnerable to predation. We suggest that effects of suspended silt on cladoceran populations, from interference with this type of reproductive strategy, are more deleterious than for calanoid copepods that expend less energy in support of a slower paced sexual reproduction strategy. The net result (Table 1) is that cladocerans are unable to obtain the required energy for successful survival and reproduction, leaving glacial lakes in Alaska populated by the selective herbivore *Diaptomus* and the raptorial feeding *Cyclops*.

REFERENCES

- Arruda, J. A., Margolf, R. G., and R. T. Faulk. 1983. The role of suspended sediments in the nutrition of zooplankton in turbid reservoirs. *Ecology*. 64:1225-1235.
- Edmundson, J. A. and J. P. Koenings. 1985. The effects of glacial silt on primary production, through altered light regimes and phosphorus levels, in Alaskan lakes.
- Gerritson, J. and K. Porter. 1982. The role of surface chemistry in filter feeding by zooplankton. *Science* 216: 1225-1227.
- Koenings, J. P., Kyle, G. B., and R. D. Burkett. 1985. Limnology and fisheries evidence for rearing limitation of sockeye production in Crescent Lake, Southcentral Alaska, (1979-1982). Alaska Department of Fish and Game, FRED Technical Report Series. (In press).
- Koenings, J. P., Edmundson, J. A., Edmundson, J. M., and G. B. Kyle. 1985. Limnological methods for assessing aquatic production. Alaska Department of Fish and Game. FRED Technical Report Series. (In review).
- McCabe, G. D. and J. W. O'Brien. 1983. The effects of suspended silt on feeding and reproduction of *Daphnia pulex*. *American Midland Naturalist* 110:324-337.
- O'Brien, J. W. and D. Kettle. 1981. A zooplankton bioassay chamber for lab and field use. *Journal of Plankton Research*. 3:561-566.
- Pennak, R. W. 1978. *Freshwater invertebrates of the United States*. Second edition. John Wiley and Sons. New York. 803 p.
- Porter, K. G. 1975. Viable gut passage of gelatinous green algae ingested by *Daphnia*. *Verh. Int. Verin. Limnol.* 19:2840-50.
- Porter, K. G. 1977. The plant-animal interface in fresh water ecosystems. *Amer. Sci.* 65:159-170.
- Richman, S. and S. Dodson. 1983. The effect of food quality on feeding and respiration by *Daphnia* and *Diaptomus*. *Limnol. Oceanogr.* 28:948-956.
- Robinson, M. 1956. The effects of suspended materials on the reproduction rate of *Daphnia magna*. *Publ. Inst. Mar. Sci. Univ. Texas.* 4:265-277.
- Stockner, J. G. 1983. Personal communication. Department of Fisheries and Oceans, Fisheries Research Branch, West Vancouver Laboratory, 4160 Marine Drive, West Vancouver, British Columbia V7N 1N6.

SEASONAL VARIATION OF PHOTOSYNTHETICALLY ACTIVE RADIATION
IN BIG LAKE, SOUTH-CENTRAL ALASKA

by Timothy G. Rowe¹

ABSTRACT

The depth distribution of PAR (photosynthetically active radiation) was measured in Big Lake, south-central Alaska, during 1983-84 as part of a study of primary productivity. The quantity of PAR incident upon the lake surface was recorded hourly. A spherical quantum sensor measured the vertical distribution of PAR within the lake on a bi-weekly basis from May through October and on a monthly basis from November through April.

The PAR, in Einsteins per square meter per day, received daily at the lake surface varied with season and meteorological conditions and ranged from 0.1 to 57.1 over the two-year period. The depth distribution of PAR in the lake and the depth of euphotic zone were strongly affected by variations in incident PAR, by reflection from the lake surface and by the extinction within the water column. In summer about 5-10 percent of the incident PAR was reflected, whereas in the winter about 90 percent was reflected by a cover of snow and ice.

¹ Hydrologist, U.S. Geological Survey WRD, 1209 Orca Street, Anchorage, AK 99501.

POTENTIAL FOR CIRCUMVENTING INTERNAL
NUTRIENT-RECYCLING IN LUCILE LAKE AT WASILLA, ALASKA

by Paul F. Woods¹

ABSTRACT

The water quality of Lucile Lake, a shallow (mean depth of 1.7 meters), 146.3 square hectometer urban lake is adversely affected by nuisance growths of submersed aquatic macrophytes and severe depletion of dissolved oxygen under winter ice cover. Harvesting of aquatic macrophytes has been used to remove nutrients and organic material from lakes and to disrupt macrophytic uptake of nutrients from lake sediments. Limnological data collected in the summer of 1984 were used to evaluate the hypothetical response of Lucile Lake to a proposed program of macrophyte harvest. Of the following three in-lake nutrient pools--lake water, submersed aquatic macrophytes, and lake sediments--the lake sediments contained 99.1 percent of the total phosphorus and 97.4 percent of the total ammonia plus organic nitrogen. Therefore, macrophyte harvest alone does not appear capable of substantially reducing the nutrient content of Lucile Lake. Circumventing internal nutrient-recycling in Lucile Lake may require removal of both the macrophytes and the upper layer of lake sediments.

INTRODUCTION

The rapid expansion of population in the Palmer-Wasilla area of southcentral Alaska in recent years has resulted in increased residential development around and recreational use of the area's numerous lakes. The shorelines of many lakes are now occupied by numerous residences. Most of the domestic wastewater from these residences is disposed of via individual on-site septic systems. Nutrients contained in this wastewater can enter nearby lakes through the shallow groundwater system. This may eventually degrade the affected lake's water quality via cultural eutrophication, the process by which an increased nutrient supply leads to large increases in biological productivity. The various symptoms of cultural eutrophication include nuisance growths of aquatic macrophytes and severe depletion of dissolved oxygen within a lake.

Lucile Lake, within the city of Wasilla (fig. 1) has been declared as culturally eutrophied because it has nuisance growths of aquatic macrophytes and severe depletion of dissolved oxygen under winter ice cover (Alaska Department of Environmental Conservation, 1983). Lucile Lake occupies a shallow depression in low-relief terrain and has a surface area of 146.3 hm² and a volume of 253.0 hm³. The lake's mean depth (volume ÷ area) is 1.7 m and its maximum depth is about 6.5 m. Ice as thick as 1 m covers the lake from mid-October into May. No defined streams enter the lake but numerous springs occur along its northeast margin. The lake is drained by Lucile Creek which eventually enters Big Lake, a major recreational lake about 20 km to the west.

¹Hydrologist, U.S. Geological Survey, Water Resources Division, 1209 Orca Street, Anchorage, Alaska, 99501

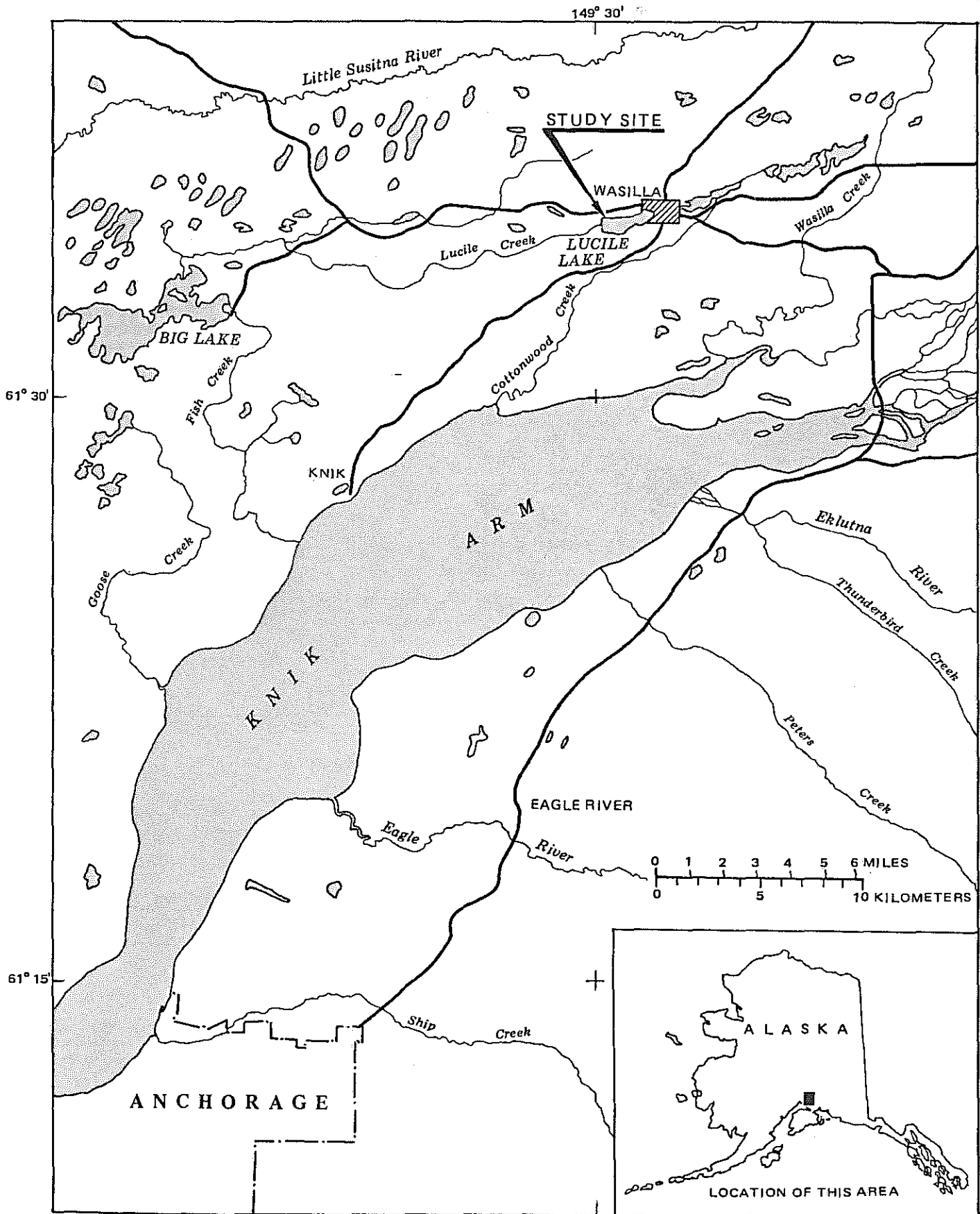


Figure 1. -- Location of Lucile Lake in Wasilla.

The city of Wasilla (1984 population estimate of 3,548) has responded to Lucile Lake's water-quality problems by undertaking construction of a municipal sewer system that will include service to the approximately 100 residences that occupy the lake's 6.8 km shoreline. Existing individual on-site septic tanks will be replaced with new ones that pump wastewater into the municipal system's collector network. Existing leachfields will be abandoned in place.

When completed in late 1986, the municipal sewer system will likely reduce nutrient inflows to Lucile Lake. The lake, however, may be able to recycle nutrients internally because of its extensive population of aquatic macrophytes. Submersed aquatic macrophytes, such as those in Lucile Lake, obtain significant quantities of nutrients through their root systems (Hutchinson, 1975). Nutrients thus obtained from the lake sediments are translocated through the plant and are eventually released into the water column during senescence and decay of the plant. The plant's tissues ultimately are incorporated into the lake sediments and thus serve as a nutrient source for subsequent plant growth. Over time, this cyclic process builds a nutrient-rich layer of sediment which reduces the depth of the lake.

Lucile Lake's nuisance growths of aquatic macrophytes led the city of Wasilla to enter into a cooperative water-quality study with the U.S Geological Survey to determine if removal of the macrophytes could substantially reduce the amount of nutrients within the lake. The study design concentrated on estimating the distribution of nutrients among three major in-lake compartments - lake water, lake sediments, and submersed aquatic macrophytes-- as well as limnological sampling to assess water-quality conditions during the active-growth season of the aquatic macrophytes.

METHODS

A limnological sampling station was located at the deepest part of the lake (fig. 2) and was sampled from May 7 through September 25, 1984 on an approximately biweekly schedule. The water column was profiled for temperature, dissolved-oxygen concentration, and photosynthetically active radiation (PAR). The PAR data were obtained with a spherical sensor and were used to determine the depth of the euphotic zone. In this study the euphotic zone is defined as the depth at which in-situ PAR is one percent of the PAR incident upon the lake's surface. Water column transparency was measured with a 20 cm Secchi disc. Water samples were collected from 1 m beneath the surface and 1 m above the bottom. Methods described in Skougstad and others (1979) were used to analyze the water samples for the following constituents: total phosphorus, dissolved orthophosphorus, total ammonia plus organic nitrogen, dissolved ammonia, and total nitrite plus nitrate. Chlorophyll a samples were taken at 1-m intervals within the water column and were analyzed fluorometrically with correction for pheophytin per Wetzel and Likens (1979).

The distribution of submersed aquatic macrophytes was determined from aerial and in-lake surveys. A dredge was used in mid-August at 14 sites (fig. 2) to obtain macrophyte samples for determination of taxonomic composition and nutrient concentration. These sites were selected to obtain data representative of the distribution of macrophytes. The macrophytes were identified using standard taxonomic references (Steward and others, 1963; Hotchkiss, 1972). Methods

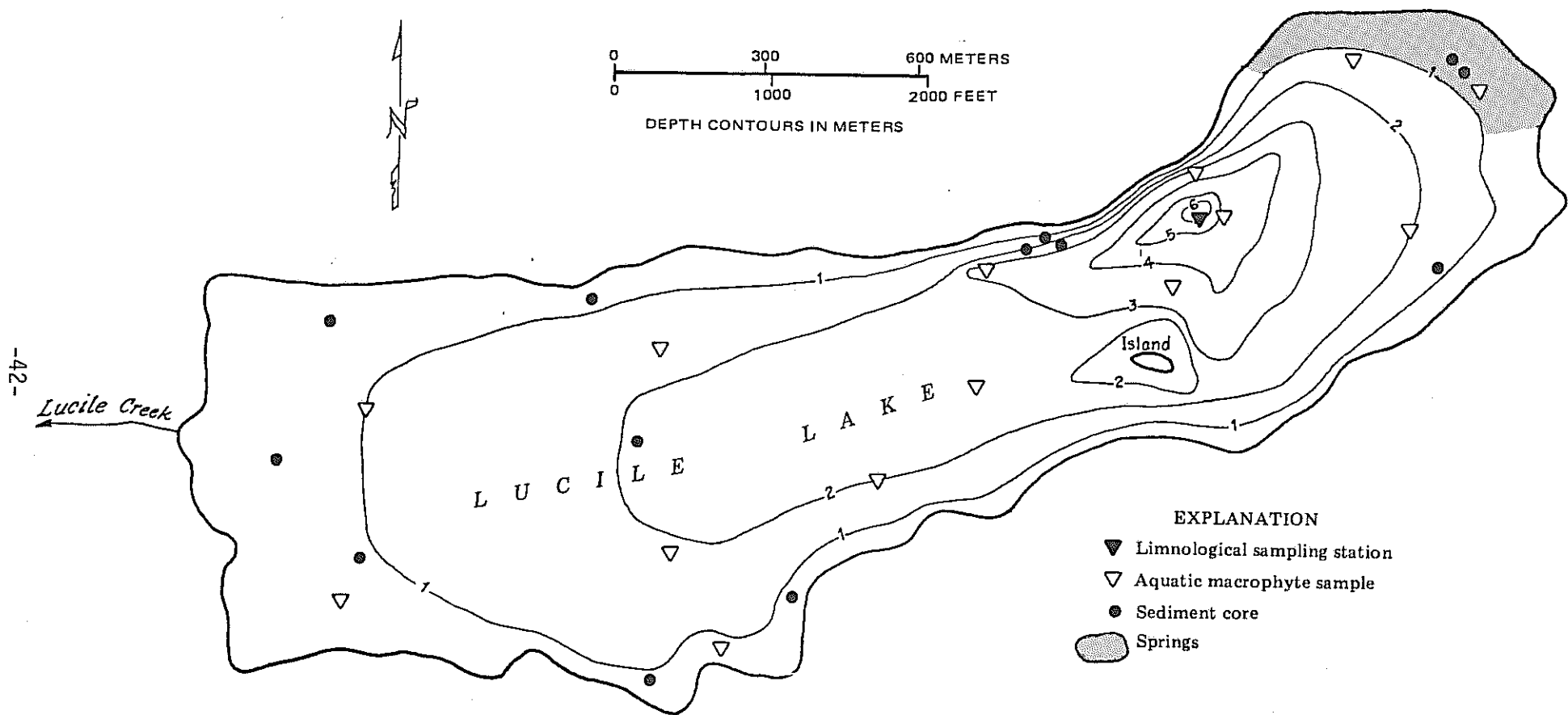


Figure 2. -- Location of data-collection sites.

described in American Public Health Association and others (1981) were used to obtain wet, oven-dry, and ash-free dry weights of the macrophyte samples. Subsamples of the oven-dried materials were analyzed for total phosphorus and total ammonia plus organic nitrogen per methods in Koenings and others (1985).

Thirteen sediment cores were obtained in mid-August (fig. 2). A plastic tube 36 mm in diameter was driven 0.75 m into the lake bottom, sealed, and then extracted. Lake water lying above the sediment core was pumped out of the tube before dumping the 0.75-m long core into a tared sample container. The core's weight was recorded and then a subsample was removed for later analysis for total phosphorus and total ammonia plus organic nitrogen per methods in Koenings and others (1985). The reported nutrient concentration, in mg kg^{-1} , represents a water-sediment mixture because interstitial water was not removed from the sediment core.

The aquatic macrophytes and sediment cores were quantitatively sampled to permit expansion of these data into lake-wide values. The nutrient content of each in-lake compartment --lake water, lake sediments, and aquatic macrophytes --was calculated using lake morphometric data and the results of nutrient analyses. The nutrient content results pertain only to conditions in mid-August, a time at which the aquatic macrophytes appeared to have attained their maximum biomass for the year.

RESULTS AND DISCUSSION

The temperature of Lucile Lake increased rapidly after its ice cover melted on May 3; by May 21 the vertical distribution of temperature was 13 to 15 °C. The maximum surface temperature of 19.8 °C was measured on July 9 when the upper 3.75 m of the lake were warmer than 19 °C. The lake began to cool in late August and by late September had reached 10 °C throughout the water column. The ten temperature profiles taken during this study indicated a lack of thermal stratification except for a slight temperature gradient that developed below 4 m from late June to early July. The general lack of thermal stratification was attributed to the lake's shallow depth and its frequent exposure to strong winds which are common in the Palmer-Wasilla area.

Throughout the study the upper 3 m of the lake had dissolved-oxygen concentrations in excess of 9 mg L^{-1} . From mid-July to mid-August, the dissolved-oxygen concentrations near the lake bottom fell to between 1 and 2 mg L^{-1} and indicated that deoxygenation exceeded reaeration even in the absence of strong thermal stratification. Cooling and circulation within the lake after mid-August resulted in a well-oxygenated water column. The upper few meters were often supersaturated with dissolved oxygen as a consequence of photosynthetic production of oxygen by submersed aquatic macrophytes and their attached periphyton. Percentage saturation reached a high of 134 percent within the upper 4 m on May 21; values as low as 10 percent occurred near the lake bottom from mid-July to mid-August. The dissolved-oxygen profiles in Lucile Lake during the summer of 1984 contrasted sharply with profiles made on January 11, 1985 over the deepest part of the lake. Under a 0.57 m ice cover the lake was devoid of dissolved oxygen beneath the 2.75 m depth (T.G. Rowe, U.S. Geological Survey, written commun., 1985). A history of severe dissolved-oxygen depletion in the lake under winter ice cover has also been noted by the Alaska Department of Environmental Conservation (1983).

The frequent occurrence of oxygen supersaturation during the study was due in part to the highly transparent water column which allowed deep penetration of photosynthetically active radiation. The euphotic zone extended to the deepest portion of the lake on all sampling trips, even those on overcast, rainy days. Secchi disc transparencies ranged from 3.1 to 5.5 m (mean = 3.8 m, n = 9) with the shallowest reading on July 23.

Distinct patterns over depth or time were not apparent for concentrations of chlorophyll a which ranged from 2.3 to 6.3 ug L⁻¹ (mean = 4.0 ug L⁻¹, n = 50). Nutrient samples near the bottom tended to have slightly higher concentrations of total phosphorus and dissolved ammonia than did the near-surface samples but otherwise they did not show distinct patterns over depth or time (table 1). A complete listing of the chlorophyll and nutrient data are contained in U.S. Geological Survey (1985).

TABLE 1. Means and ranges of lake-water nutrient concentrations sampled in Lucile Lake.

Nutrient	Concentrations of near-surface samples (micrograms per liter)		Concentrations of near-bottom samples (micrograms per liter)	
	Mean ^a	Range	Mean ^a	Range
Total phosphorus	9.2	5 - 21	11.6	6 - 31
Dissolved orthophosphorus	b	5 - 13	b	<2 - 15
Total ammonia plus organic nitrogen	710	400 - 1600	680	300 - 1400
Dissolved ammonia	32.1	8 - 80	62.3	11 - 264
Total nitrite plus nitrate	c	<10 - 28	d	<10 - 28

^aNumber of samples is 10 for each nutrient

^bFour concentrations were <2 ug L⁻¹

^cSeven concentrations were <10 ug L⁻¹

^dNine concentrations were <10 ug L⁻¹

The mean concentrations of total phosphorus and chlorophyll a and the mean Secchi disc transparency are indicative of oligotrophic lakes, according to trophic state classifications listed in Taylor and others (1980). This oligotrophic classification differs from the eutrophic classification assigned to Lucile Lake by the Alaska Department of Environmental Conservation (1983). Their eutrophic classification was based on the lake's nuisance growths of aquatic macrophytes and the severe depletion of dissolved oxygen. One explanation for this discrepancy is that the extensive populations of macrophytes reduce lake-water concentrations of total phosphorus and chlorophyll a to oligotrophic levels. Macrophytes are capable of competing with phytoplankton for nutrients such as nitrogen and phosphorus (Blažka and others, 1980) and thus may have re-

stricted the development of phytoplankton (represented by chlorophyll a) in Lucile Lake. The resultant low concentrations of chlorophyll a increased the lake's transparency, which yielded oligotrophic values for Secchi disc measurements. Total phosphorus concentrations may also have been reduced via adsorption to and precipitation with calcium carbonate, commonly referred to as marl. Macrophytes were heavily coated with marl during the summer of 1984 and indicated that epilimnetic decalcification was occurring.

The submersed aquatic macrophytes in Lucile Lake were identified as muskgrass (*Chara* spp.), whitestem pondweed (*Potamogeton praelongus*), sago pondweed (*P. pectinatus*), and northern watermilfoil (*Myriophyllum exalbescens*). The lake's 146.3 square hectometer area was occupied in the following percentage distribution (fig. 3): muskgrass alone, 62.1; combination of both pondweeds and watermilfoil, 8.9; the four macrophytes growing together, 4.5; and no macrophytes present, 24.5. Water less than 1 m deep generally was devoid of macrophytes except in the northeast margin where the springs are located. The absence of macrophytes was attributed to freezing of the root zone along the lake's near shore margin. Lake areas between 1 and 3 m in depth were almost exclusively occupied by muskgrass. In early May the muskgrass extended approximately 0.3 m above the bottom, but by mid-August it had nearly reached the lake's surface even in 3-m deep water.

The mean concentrations of total phosphorus and total ammonia plus organic nitrogen in the macrophyte samples are listed in table 2. The highest concentrations were present in the mixture of both pondweeds with the watermilfoil. The muskgrass had the smallest concentration for both nutrients but it had a substantially higher mean oven-dry weight than the other two macrophyte assemblages.

TABLE 2. Mean oven-dry weight and nutrient concentration of aquatic macrophyte samples. [Number of samples in parentheses]

Macrophyte assemblage	Mean oven-dry weight (gram per square meter)	Mean nutrient concentration (milligram per gram)	
		Total phosphorus	Total ammonia plus organic nitrogen
Muskgrass	1560.6 (7)	0.59 (8)	9.71 (8)
Whitestem and sago pondweed plus northern watermilfoil	461.3 (4)	2.96 (4)	24.29 (4)
Mixture of the four macrophytes	557.8 (2)	.74 (2)	11.08 (2)

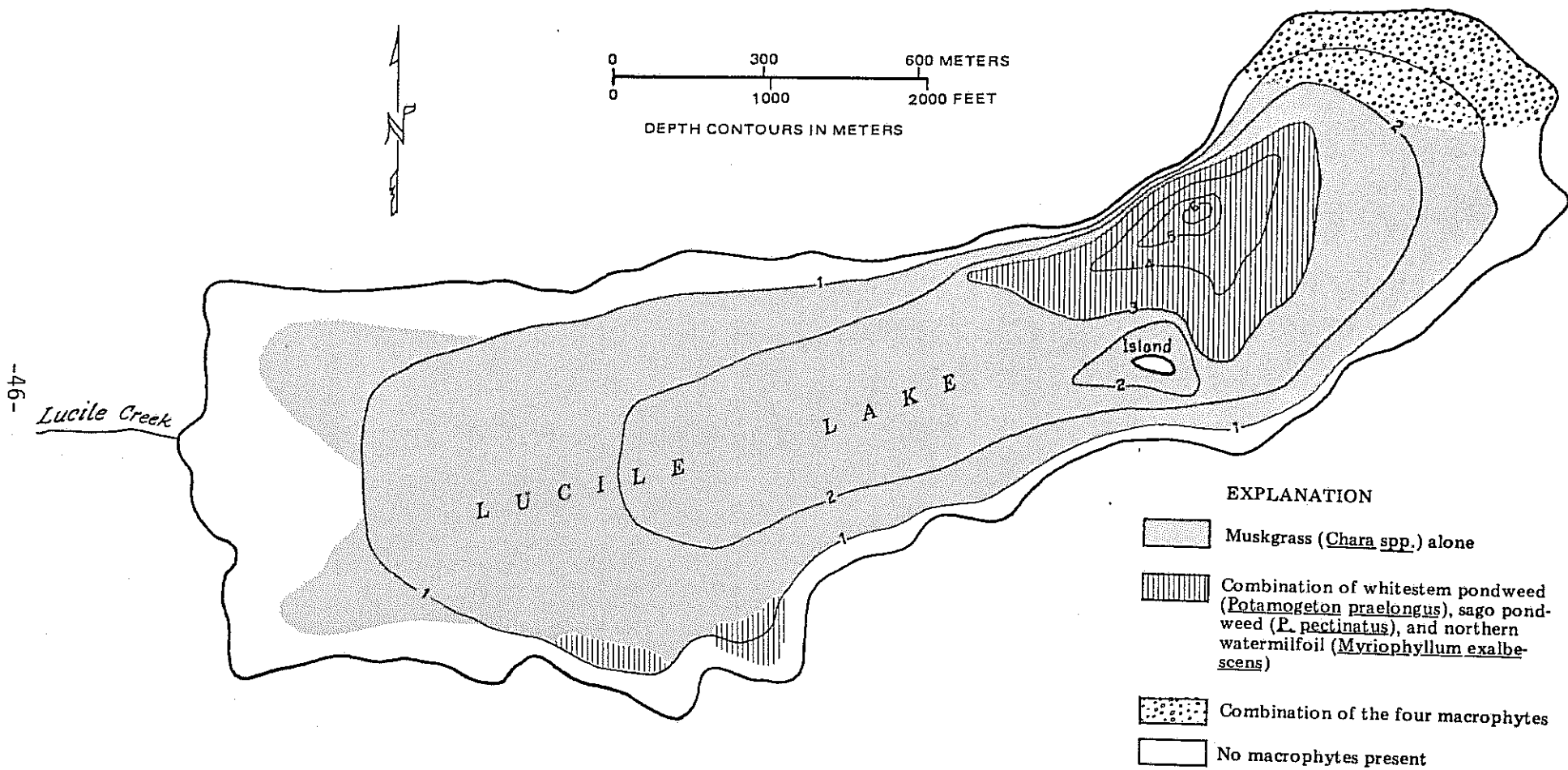


Figure 3. -- Distribution of submersed aquatic macrophytes.

The 13 sediment cores had a mean total phosphorus concentration of 140.0 mg kg⁻¹ and a mean total ammonia plus organic nitrogen concentration of 772.8 mg kg⁻¹. The mean weight of the 36-mm diameter by 0.75-m long sediment cores was expanded to a square meter basis and yielded an areal weight of 565.6 kg m⁻². The product of this mean areal weight and the mean nutrient concentrations resulted in an areal nutrient content of 79.2 g m⁻² for total phosphorus and 437.1 g m⁻² for total ammonia plus organic nitrogen.

The lake-wide content of nutrients, in megagrams, during mid-August within the three compartments -- lake water, lake sediments, and aquatic macrophytes -- is listed in table 3. Of the three compartments, the lake sediments contained 99.08 percent of the total phosphorus and 97.35 percent of the total ammonia plus organic nitrogen. The aquatic macrophytes contained 0.89 percent and 2.39 percent, respectively, of the total phosphorus and total ammonia plus organic nitrogen. The small amounts of both nutrients contributed by the 253.0 hm³ of lake water were based on average lake-wide nutrient concentrations of 15.75 ug L total phosphorus and 675 ug L⁻¹ total ammonia plus organic nitrogen which were sampled on August 6.

TABLE 3. Lake-wide content of nutrients within the lake water, sediments, and aquatic macrophytes of Lucile Lake during mid-August.

In-lake compartment	Total phosphorus content (megagram)	Total ammonia plus organic nitrogen content (megagram)
Lake water ^a	40	1,710
Lake sediments ^b	116,000	640,000
Aquatic macrophytes ^c	1,040	15,700
Total	117,080	657,410

^aBased on lake-wide mean concentration

^bBased on water-sediment mixture

^cBased on nutrient concentration of oven-dried samples

Macrophyte harvesting has been found to be a useful method for lake restoration (Cooke, 1983) in that nutrients and organic matter are removed from the lake and macrophytic uptake of nutrients from the sediments is curtailed. These benefits may be short-lived, however, because aquatic macrophytes can regrow rapidly (Reimer, 1984; Cooke, 1983; U.S. Environmental Protection Agency, 1981) and thereby require repeated harvests within a growing season and in subsequent years. Macrophyte harvests have also been followed by blooms of phytoplankton (King and Burton, 1981), presumably as a result of reduced competition for nutrients and photosynthetically active radiation between macrophytes and phytoplankton.

Harvesting Lucile Lake's submersed aquatic macrophytes would temporarily reduce the macrophyte biomass in the lake but harvesting would do little to circumvent internal nutrient-recycling because much of the lake is anaerobic under its winter ice cover. During the winter, the lake's sediments can be expected to release nutrients into the water column. These sediment-derived nutrients will then be available to fuel phytoplankton and macrophyte growth during the following spring and summer. The oxygen demand caused by autumn senescence and decomposition of macrophytes would also be reduced after harvesting; however, the lake's dissolved-oxygen problems would not be reduced significantly because of the lake's shallowness and nutrient-rich sediments. Several Matanuska-Susitna Borough lakes that are also shallow but devoid of nuisance growths of aquatic macrophytes have been found to have severe depletion of dissolved oxygen under winter ice cover (Woods, in preparation). The limnological complexity of Lucile Lake and its hypothetical response to macrophyte harvest lends support to Cooke's (1983) conclusion that much additional research is needed before macrophyte harvesting can be successfully applied over the wide range of lakes with macrophyte problems.

In conclusion, it appears that macrophyte harvesting is incapable of substantially reducing the in-lake nutrient content of Lucile Lake over the long term because of the small contribution of aquatic macrophytes to the nutrient pool and to the propensity for aquatic macrophytes to regrow rapidly after harvesting. The nuisance growths of aquatic macrophytes and the nutrient-rich sediments allow continuation of internal nutrient-recycling in the lake. Unless this internal nutrient recycling is curtailed the reduction of nutrient inflows to the lake expected from the City of Wasilla's municipal sewer system may not be realized. Other methods of lake restoration such as desiccation and freezing of aquatic macrophytes via lake level drawdown (Cooke, 1980) coupled with sediment removal (Peterson, 1981) may offer a more feasible, long-term solution to Lucile Lake's water-quality problems because these methods can circumvent internal-nutrient recycling.

REFERENCES CITED

- Alaska Dept. of Environmental Conservation. 1983. Lakes Lucile and Wasilla water quality report, Wasilla, Alaska February 1-3, 1983. Working Paper. Juneau, AK. 40 pp.
- American Public Health Association, American Water Works Association, and Water Pollution Control Federation. 1981. Standard methods for the examination of water and wastewater (15th ed.). Washington D.C. American Public Health Association. 1134 pp.
- Blazka, P., T. Backiel and F.B. Taub. 1980. Trophic relationships and efficiencies. Pages 393-410 in E.D. Lecren and R.H. Lowe-McConnell, (eds). The functioning of freshwater ecosystems. Cambridge University Press, Cambridge.
- Cooke, G.D. 1980. Lake level drawdown as a macrophyte control technique. Water Resources Bulletin. 16(2): 317-322.

- _____, 1983. Review of lake restoration techniques and an evaluation of harvesting and herbicides. Pages 257-266 in U.S. Environmental Protection Agency, Lake restoration, protection, and management. EPA 440/5-83-001.
- Hotchkiss, Neil. 1972. Common marsh plants of the United States and Canada. Dover Publications, New York, 124 pp.
- Hutchinson, G.E. 1975. A treatise on limnology -- Volume III, Limnological botany. J. Wiley & Sons, New York. 660 pp.
- King, D.L. and T.M. Burton. 1981. The efficacy of weed harvesting for lake restoration. Pages 158-161 in U.S. Environmental Protection Agency, Restoration of lakes and inland waters. EPA 440/5-81-010.
- Koenings, J.P., J.A. Edmundson, J.M. Edmundson, and G.B. Kyle. 1985. Limnological methods for assessing aquatic production. Alaska Department of Fish and Game. Division of Fisheries Rehabilitation, Enhancement, and Development. Technical Report. (In press.)
- Peterson, S.A. 1981. Sediment removal as a lake restoration technique. U.S. Environmental Protection Agency. EPA 600/3-81-013. 55 pp.
- Reimer, D.N. 1984. Introduction to freshwater vegetation, AVI Publishing Co., Westport, Conn. 207 pp.
- Skougstad, M.W., M.J. Fishman, L.C. Friedman, D.E. Erdmann, and S.S. Duncan. 1979. Methods for determination of inorganic substances in water and fluvial sediments. U.S. Geological Survey Techniques of Water Resources Investigations. Book 5, Chapter A1. 626 pp.
- Steward, A.N., L.R.J. Dennis, and H.M. Gilkey. 1963. Aquatic plants of the Pacific Northwest. Oregon State University Press, Corvallis. 261 pp.
- Taylor, W.D. V.W. Lambou, L.R. Williams, and S.C. Hern. 1980. Trophic state of lakes and reservoirs: U.S. Environmental Protection Agency. Environmental Monitoring and Support Laboratory. Technical Report E-80-3. 30 pp.
- U.S. Environmental Protection Agency. 1981. Clean lakes program guidance manual. EPA-440/5-81-003. 103 pp. + app.
- U.S. Geological Survey. 1985. Water resources data, Alaska, water year 1984. U.S. Geological Survey Water-Data Report AK-84-1. [In press].
- Wetzel, R.G., and G.E. Likens. 1979. Limnological analyses. W.B. Saunders, Philadelphia. 357 pp.
- Woods, P.F. (In preparation.) Limnology and the survival and growth rates of rainbow trout in nine lakes, Matanuska-Susitna Borough, Alaska. U.S. Geological Survey Water-Resources Investigation Report.

MINING

COMMUNITY STRUCTURE AND LONGITUDINAL PATTERNS OF BENTHIC
INVERTEBRATES IN A HEAVY METAL CONTAMINATED ALASKAN RIVER SYSTEM

by Barry N. Brown¹ and Mark W. Oswood²

ABSTRACT

Community structure of stream invertebrates was investigated in a heavy metal contaminated watershed in Denali National Park Alaska. Three sites were located on Stampede Cr., with one station above an antimony mine (active 1916-1970) and two stations below. An additional site was located on the Clearwater Fork of the Toklat River downstream of the Stampede Cr. confluence. Quantitative samples of benthic invertebrates and associated coarse (> 1 mm) detritus were obtained in late June (early spring), late July (summer), and late August (early fall). Gut analyses allowed categorization of insects to functional feeding groups. Water temperatures increased and detrital storage generally decreased downstream. Abundance of shredders and total organisms was positively correlated with abundance of coarse detritus. Longitudinal changes in functional group composition were consistent with the River Continuum hypothesis. Heavy metal contamination appeared to differentially affect taxonomic and functional groups. Grazers and predators were severely underrepresented directly downstream of the mine. Most shredders (e.g. *Podmosta*, *Zapada*) declined downstream from the headwater stream, while *Nemoura* increased directly downstream of the mine, causing a net increase in shredder biomass immediately downstream of the mine. We hypothesize that heavy metal induced depression of primary producers (and associated grazer food webs) is occurring.

INTRODUCTION

Need for Study

Streams and rivers are often receptacles for byproducts of human activities. Heavy metals are among the more dangerous of these pollutants since they may be toxic at very low concentrations and are not biodegradable. Sources of heavy metals include a variety of industrial processes, atmospheric fallout of airborne pollutants, and terrestrial sources such as leaching of solid and mining wastes. Heavy metal pollution is of direct concern to human health when contaminated waters are a source of drinking water and of indirect concern through toxic effects on food chains. Forstner and Wittman (1981) and Moore and Ramamoorthy (1984) have recently reviewed heavy metal pollution in

¹ Graduate Research Assistant, Department of Biology, Fisheries and Wildlife, University of Alaska, Fairbanks, Alaska 99775

² Associate Professor, Institute of Arctic Biology, University of Alaska, Fairbanks, Alaska 99775-0180

aquatic ecosystems. Our study examines the effects of chronic heavy metal pollution on the ecology of a stream/river system in Denali National Park, Alaska.

The structural and functional characteristics of stream communities change along the course of a river as a result of continuously changing physical conditions (Vannote et al., 1980). This River Continuum Concept is a major paradigm of lotic ecology in which the entire stream to river complex is viewed as one ecosystem composed of a series of communities along a continuum. However, applicability of the River Continuum Concept to regions other than temperate North America is under question (Winterbourn et al. 1981). Our study sites ranged from a first order headwater stream to a fifth order river. We examined ecological changes along this longitudinal profile with regard to predictions of the River Continuum Concept.

Site Description and History

This study is located in the Kantishna Hills, a range of low mountains less than 1600 m in elevation in the north central portion of Denali National Park. Three of our study sites are on Stampede Creek, one above the Stampede Antimony Mine and two below, and one study site is on the Clearwater Fork of the Toklat River directly below its confluence with Stampede Creek. Other studies of the Kantishna Hills area have described the geology and mineral deposits (Bundtzen, 1981), the heavy metals in streams and rivers (West, 1982; West and Deschu, 1984), and the abundance and distribution of fish (Meyer and Kavanagh, 1983).

The Stampede Antimony Mine and the surrounding watersheds became part of the park by the 1980 Alaska National Interest Lands Conservation Act which expanded the boundaries of Denali National Park and Preserve. Since the discovery of placer gold in 1905 the Kantishna Hills has been an active mining area also noted for lode deposits of antimony, copper, gold, lead, silver, and zinc. Development work on the Stampede antimony deposit began in 1916 but active mining began in 1936 and antimony shipments from the mine peaked during World War II when the Stampede Mine was Alaska's largest antimony producer (Bundtzen, 1978). Antimony production continued until 1970, and in the late 1970's the mine and buildings were donated by mine owner, Earl Pilgrim to the University of Alaska, Fairbanks. There has been gold placer mining activity along Stampede Creek in the early 1900's and again during 1947 to 1949 (Meyer and Kavanagh, 1983). Other sporadic disturbances to the stream were from construction activities and road building associated with the antimony mine. Clearwater Fork has no gold placer claims but may have had some placer mining in the early 1900's and definitely had some on three tributaries (Meyer and Kavanagh, 1983).

Stampede Creek starts out as a small headwater stream and becomes a second order stream as it flows 4.6 km to its confluence with Clearwater Fork. Clearwater Fork is a large fifth order river. Site 1 is 0.4 km above the Stampede Mine and has never had any mining activities or disturbances. It is a well shaded headwater stream with a closed

riparian canopy of willow, alder and some black spruce. The stream channel is narrow (1-3 m wide) with a steep gradient. The substrate is mostly boulder and rubble with some gravel, sand, silt and woody material. Sites 2 and 3 are 0.5 km and 1.0 km respectively below the mine on Stampede Creek and both have been subjected to mining activities and disturbances. The sites are shallow, with primarily rubble and gravel substrates and little canopy. Site 4 is located on the Clearwater Fork of the Toklat River just downstream of the confluence of Stampede Creek. The channel is wide (> 30m) and consists mostly of rapids with few pools. Substrate materials are largely boulders, rubble and gravel.

Determinations of heavy metal concentrations were made at the same site locations on Stampede Creek and the Clearwater Fork by West (1982) and West and Deschu (1984). One sample was taken at each site on 5 August 1982, 7 July 1983 and 26 August 1983. West (1982) and West and Deschu (1984) compared heavy metal concentrations of individual samples with three water quality standards: Alaska Drinking Water Maximum Contaminant, U.S.E.P.A. Water Quality Criteria for Human Health, and U.S.E.P.A. Criteria for Protection of Freshwater Aquatic Life. Heavy metal concentrations of individual samples exceeded one or more of these water quality criteria for the following metals: antimony, copper, iron, manganese, nickel, cadmium, arsenic, mercury and zinc. The very small sample size of these studies does not allow examination of variance associated with sampling, storage and determination procedures, seasonality or stream flow, and a much more extensive investigation would be required to relate such variability to water quality criteria. Nonetheless, mineralization and mining is clearly associated with heavy metal contamination at Stampede Creek and the Clearwater Fork.

We further analyzed the data of West (1982) and West and Deschu (1984) by comparing total (unfiltered) heavy metal concentrations among the four sample sites using the Kruskal-Wallis test (a non-parametric one-way analysis of variance). Three metals showed significant differences between sample sites (Table 1): antimony, manganese and selenium. Both antimony and manganese showed a longitudinal pattern consistent with derivation from the mine, i.e., an increase in concentration directly below the mine followed by a downstream decrease. Selenium shows the highest concentration at site 1 (above the mine) with declining downstream concentrations apparently indicating a localized source of selenium in the upper valley.

TABLE 1. Mean (n=3) concentrations of heavy metals showing significant ($P < 0.05$) differences between sample sites. All values in mg/l. Based upon data from West (1982) and West and Deschu (1984).

	Site 1	Site 2	Site 3	Site 4
Antimony	.037	.207	.186	.058
Manganese	.0077	.0468	.0203	.0203
Selenium	.0014	.0009	.0005	.0005

METHODS

Benthic samples from six randomly selected locations were taken at each study site in late June (early spring—soon after breakup with large ice shelves still covering part of site 1), late July (summer), and late August (early fall - with input from riparian vegetation at all sites) in 1981. A Portable Invertebrate Box Sampler was used for benthic sampling. For sampling deep water (up to 0.8 m) a collapsible sheet metal extension was attached to the sides of the box sampler. The box sampler enclosed a substrate area of 0.1/m². The substrate was stirred up by hand to a depth of approximately 10 cm until all dislodged invertebrates and detrital particles were swept by the current into the net and no particles were visible in the enclosed water column. On the first sampling date, nested 80 µm and 360 µm mesh nets were used on the box sampler. Few additional organisms were captured by the 80 µm net and on the other two sampling dates a 360 µm mesh net alone was used. Samples were preserved immediately in the field with Kahle's solution.

All samples were transferred to 95% ethanol and identified to the lowest practical taxonomic level. Each taxon was counted and biovolume estimated by volumetric displacement of ethanol in a pipette as described in Cowan et al. (1983). Gut analyses were performed on subsamples of each major taxon (for methods see Cowan et al., 1983) and all taxa were assigned to functional feeding groups (Cummins and Klug, 1979) based on the results of our gut analyses or designations by Merritt and Cummins (1984). In this study we use the following functional groups: shredders (feed by shredding coarse plant detritus), collector-gatherers (feed by collecting depositional fine detritus), grazers (feed by scraping periphyton), filter feeders (feed by filtering suspended particles) and predators (feed by engulfing prey).

The ash-free dry weight of the coarse particulate organic matter (CPOM) contained in each sample was determined by first removing woody refractory material (e.g. twigs and roots). Then the sample was gently rinsed repeatedly through a 1 mm sieve. The fractionated material was dried at 50°C for 48 hours, cooled, weighed, then burned in a muffle furnace at 500°C for 12 hours and then cooled and reweighed. Differences in numerical abundance or biovolume of benthic organisms between sites was tested using a non-parametric one-way analysis of variance (Kruskal-Wallis test). Sample size (n) for all tests was 24 (4 sample sites x 6 samples/site/date). Data from each of the three sampling times (seasons) were analyzed separately.

RESULTS

Longitudinal distributions of the major shredder taxa are shown in Figure 1. All of them are nemourid stoneflies with Podmosta and Zapada most abundant at site 1 and mostly Nemoura at site 2. The average shredder biovolume was highest at site 2 for spring and fall and at site 1 for summer.

The two major grazers are shown in Figure 2. *Gymnopsis*, a black fly was only found at sites 1 and 2, and showed a significant increase at site 1 in fall and summer. *Baetis*, a mayfly was found at all sites except site 2 and showed a significant increase at site 4. *Pseudocloeon*, a mayfly and Glossosomatidae, a type of caddisfly, the only other grazers, were only found at site 4. Grazers were absent at site 2 and in extremely low abundance at site 3. The only filter feeder found was *Prosimulium*, a black fly which occurred at all sites and generally increased downstream.

The major collector-gatherer taxa are shown in Figure 3. Capniidae and *Ameletus* were most abundant at site 1, and Taeniopterygidae, *Cinygmula* and *Epeorus* at site 4. The biovolume of collector-gatherers appeared to be minimal at sites 2 and 3 directly downstream from the mine.

The major predator taxa are shown in Figure 4. Perlodidae were most abundant at site 4 and *Dicranota* at site 1. Chloroperlidae were very abundant at sites 1 and 4 and uncommon at sites 2 and 3 while

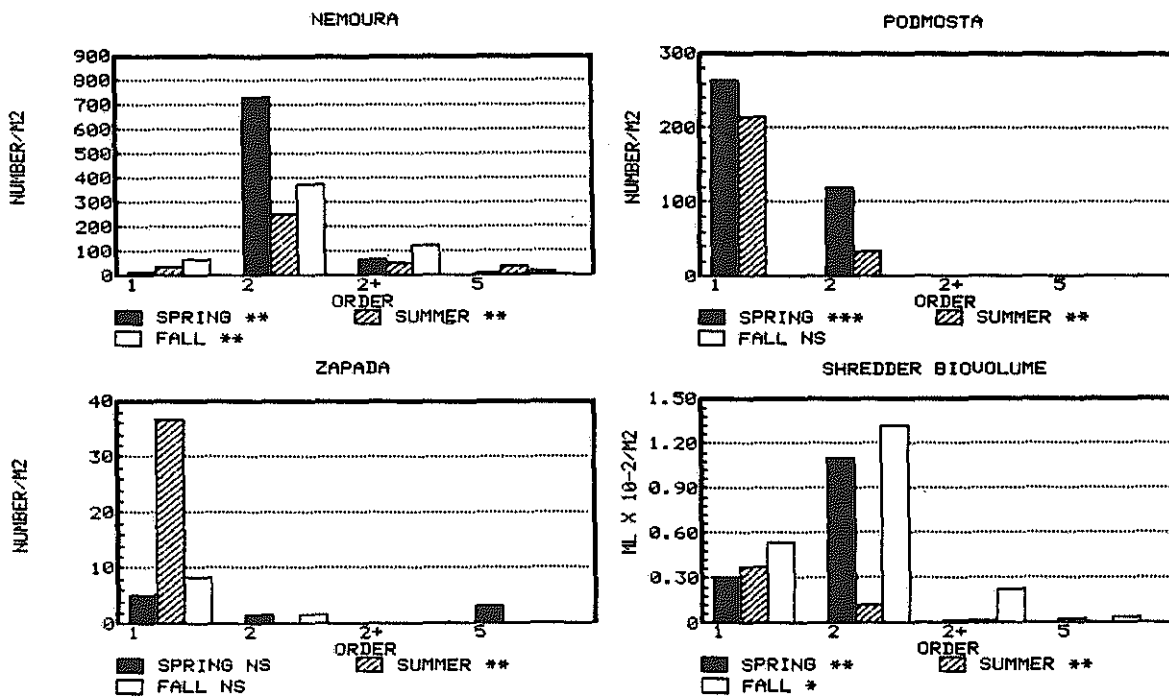


FIGURE 1. Longitudinal distribution of shredders. Order 1, 2, 2+ and 5 correspond to sites 1-4. Significance of differences between sites indicated by: NS=not significant ($P>0.05$), $*=P<0.05$, $**=P<0.001$ and $***=P<0.001$.

Empididae exhibited the opposite pattern, being very abundant at sites 2 and 3 and much less so at sites 1 and 4. Predator biovolume was significantly higher at site 1 for all seasons. Predators were essentially absent at sites 2 and 3.

The standing crop of coarse detritus (CPOM) at each site for each season and as a seasonal average is shown in Table 2. Spring and fall showed similar patterns with site 1 having the highest amount and a general progressive decrease from sites 2-4. During summer, site 4 had a large increase in coarse detritus and the seasonal average reflects this increase with site 4 having a larger value than sites 2 and 3.

The biovolume and numerical abundance of total benthic invertebrates at each site for each season is shown in Table 2. Site 2 had a significantly higher biovolume for spring and fall, with site 1 close behind and the other two sites much lower. Site 1 had a significantly higher biovolume for summer with the other three sites much less. Macroinvertebrate densities were highest at site 2 in spring and highest at site 1 in summer and fall.

There was a significant ($P < 0.05$) positive correlation between the amount of coarse detritus and shredder biovolume in each sample and between the amount of coarse detritus and total biovolume of all benthic invertebrates at all seasons and for a seasonal average. Correlation coefficients range from 0.39 to 0.97.

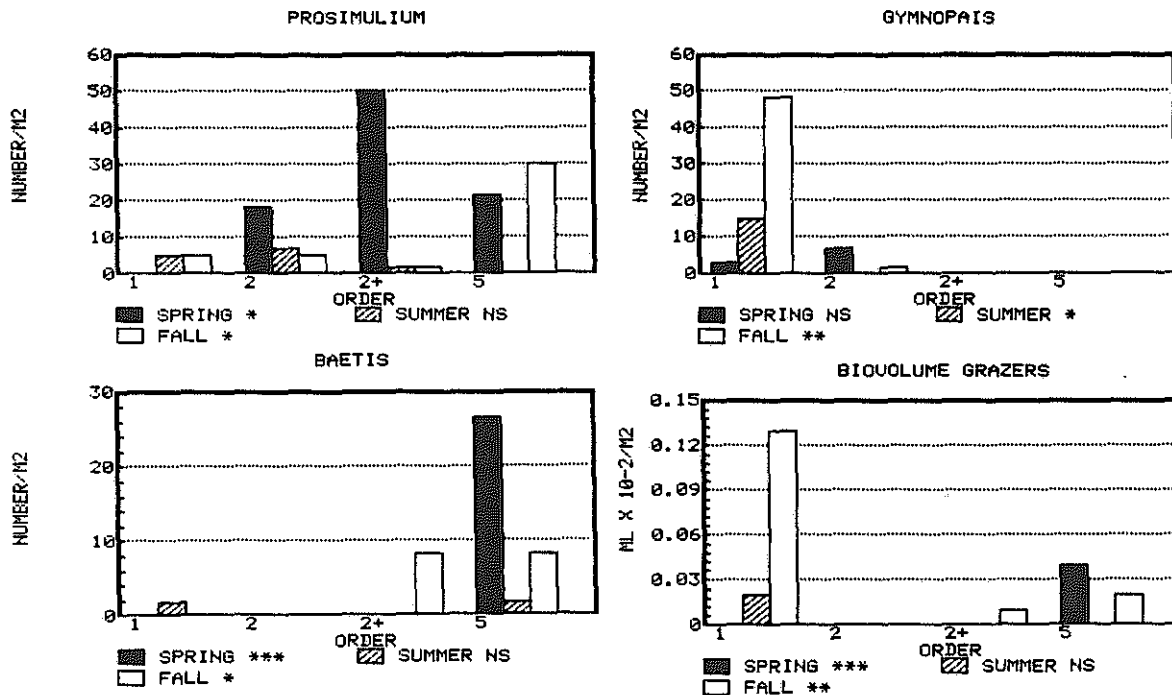


FIGURE 2. Longitudinal distribution of grazers (*Gymnopsis* and *Baetis*) and filter-feeders (*Prosimulium*). Symbols as in Figure 1.

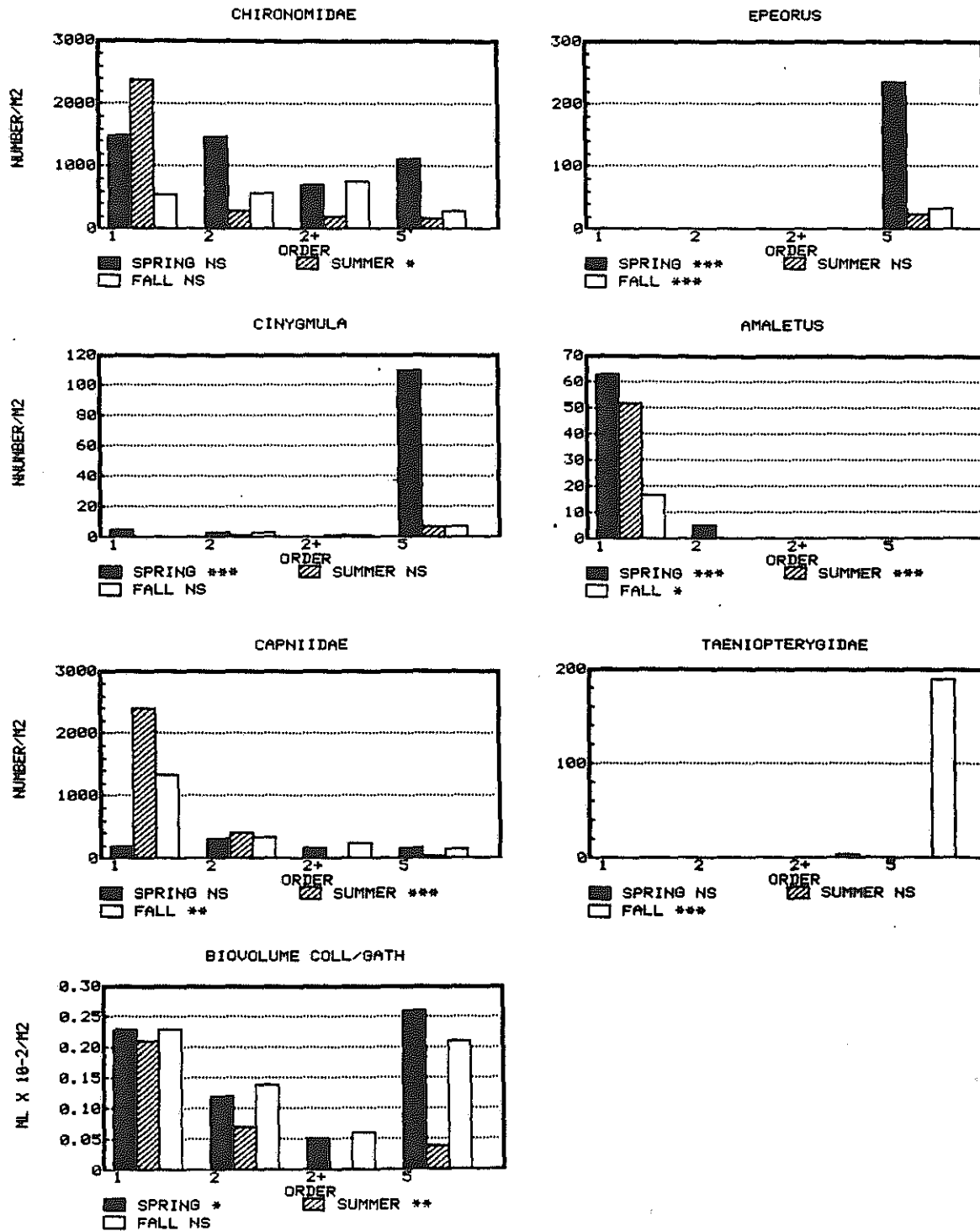


FIGURE 3. Longitudinal distribution of collector-gatherers. Symbols as in Figure 1.

The relative distribution of functional groups between the four sites is shown in Figure 5. Shredders dominated sites 1-3 and showed a sharp decline at site 4. Collector-gatherers show a sharp increase at site 4. Grazers are in low proportion at sites 1 and 4 and essentially

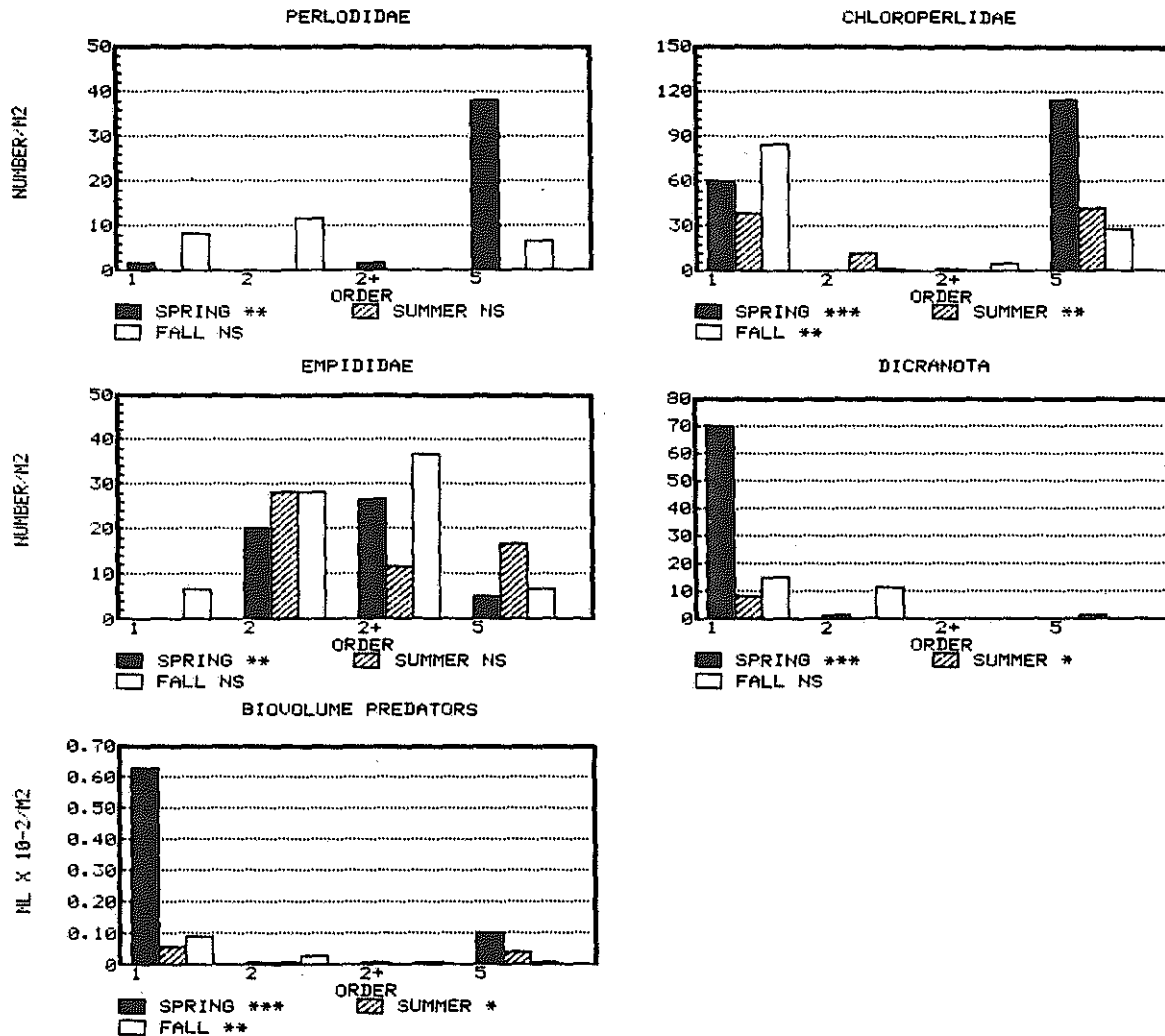


FIGURE 4. Longitudinal distribution of predators. Symbols as in Figure 1.

absent at sites 2 and 3. Predators occur in modest proportion at sites 1 and 4, show a sharp decline at site 3, and are essentially absent at site 2. Chironomidae are considered apart from the functional groups and are represented at all sites with a peak at site 3.

DISCUSSION

The River Continuum Concept (Vannote et al., 1980) suggests that shredders are expected to be codominant with collector-gatherers in the headwaters, and to rapidly diminish in importance downstream as the detrital base shifts from mainly coarse particles to fine particles. Collector-gatherers are expected to increase in importance downstream becoming the predominant macroinvertebrate component in large rivers. Our results (Figure 5) show a shift from dominance by shredders to dominance by collector-gatherers between site 3 (2nd order) and site 4

TABLE 2. Detritus (CPOM, > 1mm) and macroinvertebrate abundance at study sites.

	Site 1	Site 2	Site 3	Site 4
(A) CPOM (gm AFDW·m ⁻²)				
Spring	12.90	10.37	2.19	3.05
Summer	33.44	5.52	5.15	24.77
Fall	16.10	10.99	8.37	2.56
Average	20.81	8.96	5.24	10.12
(B) Macroinvertebrate Densities (#·m ⁻²)				
Spring	2200.00	2728.33	1193.33	2166.67
Summer	5221.67	1066.67	301.67	403.33
Fall	2223.33	1868.33	1395.00	1003.33
Average	3215.00	1888.00	963.00	1191.00
(C) Macroinvertebrate Biovolumes (ml·10 ⁻² ·m ⁻²)				
Spring	1.21	1.36	0.11	0.51
Summer	0.84	0.22	0.04	0.10
Fall	1.28	1.62	0.41	0.35
Average	1.11	1.07	0.19	0.32

(5th order). Grazers are expected to increase in importance downstream as primary productivity increases with increased light penetration (reaching a maximum in mid-sized rivers). Our results do not reflect this pattern for grazers. Grazers are similar in importance at site 1 and site 4 while essentially absent at site 2 and site 3. Filter feeders should become more abundant downstream as fine detritus increases. As is common in interior Alaskan streams, Simuliidae are the only filter feeders. *Prosimulium*, the only filter feeder found in this study, generally increases in abundance with increasing stream size (Figure 2). Predators are expected to change little in relative dominance with stream size. They exhibit this pattern if site 1 is compared to site 4, but at site 2 they are essentially absent and at site 3 they are greatly reduced.

Despite elevated concentrations of many heavy metals, there is surprisingly little difference in numbers or biovolume of benthic invertebrates between site 1 with the least contamination and site 2 with the most (Table 2).

Hynes (1963), stated that a characteristic feature of toxic pollution in stream communities is the differential elimination of taxonomic and functional (feeding) groups. Several taxa (*Chloroperlidae*, *Gymnopais*, *Ameletus*, *Baetis*) show a sharp decrease in abundance at site 2 compared to the other sites. *Nemoura* shows a sharp increase in abundance at site 2 which causes the shredders to show maximum density at site 2. Standing crop of coarse detritus is much lower at site 2 compared to site 1 (Table 2) but perhaps *Nemoura* is more tolerant of heavy metals than its closest competitors (the other nemourid shredders *Zapada* and *Podmosta*) which drop sharply in abundance between site 1 and site 2. Alternatively, perhaps the sharp decrease in predators at site 2 led to the increased abundance of *Nemoura*.

% FUNCTIONAL GROUPS BIOVOL

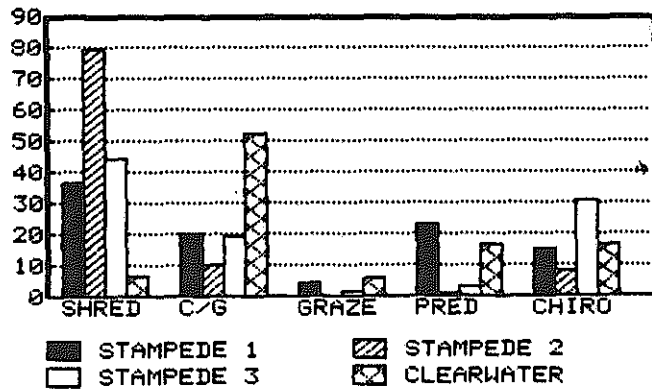


FIGURE 5. Relative changes in functional group composition at the study sites.

Grazers are essentially absent from site 2 and in very low proportion at site 3 compared to site 1 and site 4. We found few grazer taxa in this system. Throughout the course of this study, no periphyton was observed at any sites, and gut analyses found no non-diatom algae in any guts anywhere and only trace amounts of diatoms in any guts from organisms at site 2 although at other sites some organisms had large amounts. We hypothesize that heavy metals are inhibiting primary producers.

Predators show a similar pattern to grazers. They are essentially absent from site 2 and in very low proportion at site 3. Lack of prey does not appear to be a problem judging from benthic invertebrate numbers or biovolume (Table 2). Sheehan (1980) found that the proportion of predators was the most predictive parameter along a copper polluted stream gradient, with percent abundance of predators dropping radically in response to copper pollution. It appears that heavy metal pollution has substantially affected the predicted longitudinal changes in benthic community structure in this stream system.

ACKNOWLEDGEMENTS

We thank Anne Jones for field assistance and Cathy Cowan for laboratory assistance. We thank Fred Dean and Cooperative Parks Study Unit, UAF, for assistance with logistical arrangements, and the Mineral Engineering Dept., UAF, and Biology, Fisheries and Wildlife Dept., UAF, for providing financial assistance, and the Institute of Arctic Biology, UAF, for providing manuscript preparation. We thank Robin West and Nancy Deschu for sharing their data with us and Jackie LaPerriere and John Irons III for review of the manuscript.

REFERENCES

- Bundtzen, T.K. 1978. A history of mining in the Kantishna Hills. The Alaska Journal. Spring:151-161.
- Bundtzen, T.K. 1981. Geology and mineral deposits of the Kantishna Hills, Mt. McKinley Quadrangle, Alaska. M.S. Thesis. University of Alaska, Fairbanks, AK. 238 pp.
- Cowan, C.A., M.W. Oswood, C.A. Buttimore and P.W. Flanagan. 1983. Processing and macroinvertebrate colonization of detritus in an Alaskan subarctic stream. Holarctic Ecology. 6:340-348.
- Cummins, K.W. and M.S. Klug. 1979. Feeding ecology of stream invertebrates. Annual Review of Ecology and Systematics. 10:147-172.
- Forstner, V. and G.T.W. Wittmann. 1981. Metal pollution in the aquatic environment. Springer-Verlag, New York, NY. 468 pp.
- Hynes, H.B.N. 1963. The biology of polluted waters. Liverpool University Press, England. 202 pp.
- Merritt, R.W. and K.W. Cummins, eds. 1984. An introduction to the aquatic insects, second edition. Kendall/Hunt Publishing Company, Dubuque, IA. 722 pp.
- Meyer, S.C. and R.C. Kavanagh. 1983. Fish resources and the effects of mining activities in the Kantishna Hills, Denali National Park, 1982. U.S. Dept. of Interior National Park Service, Alaska. 150 pp.
- Moore, J.W. and S. Ramamoorthy. 1984. Heavy metals in natural waters. Springer-Verlag, New York, N.Y. 268 pp.
- Sheehan, P.J. 1980. The ecotoxicology of copper and zinc: studies on a stream macroinvertebrate community. Ph.D. Dissertation. University of California, Davis, CA.
- Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell and C.E. Cushing. 1980. The River Continuum Concept. Canadian Journal of Fisheries and Aquatic Science. 37:130-137.
- West, R.L. 1982. Kantishna Hills heavy metals investigation. U.S. Fish and Wildlife Service, Fairbanks, Alaska. 34 pp.
- West, R.L. and N.A. Deschu. 1984. Kantishna Hills heavy metals investigations Denali National Park, 1983. U.S. Fish and Wildlife Service, Fairbanks, AK. 42 pp.
- Winterbourn, M.J., J.S. Rounick and B. Cowie. 1981. Are New Zealand stream ecosystems really different? New Zealand Journal of Marine and Freshwater Research. 15:321-328.

SUMMARY OF ALASKA PARTICULATES CRITERIA REVIEW

by Laurence A. Peterson ^{1/}

ABSTRACT

This paper evaluates the effectiveness of existing Alaska particulates criteria and recommends necessary changes to these criteria. The paper assesses both fresh and marine water particulates criteria and considers some of the criteria for the various water uses protected by Alaska standards. These uses include water supply, recreation, and the growth and propagation of fish, shellfish, and other aquatic life.

INTRODUCTION

The federal Water Pollution Control Act as amended in 1972, Public Law 92-500, was modified and renamed the Clean Water Act in 1977. This Act required all states to adopt standards of quality to protect their waters for specific uses. In Alaska, the water quality standards are the responsibility of the Department of Environmental Conservation (ADEC). Except in a few special cases, fresh and marine surface waters in Alaska must meet all standards designed to protect water quality for the uses shown below. The exceptions are noted in the 1985 water quality standards which indicate that all water bodies in Alaska except the lower Chena River and Nolan Creek and all its tributaries excluding Acme Creek are classified for all uses.

Freshwater Uses

- + Drinking water supply
- + Agriculture (irrigation and stock watering)
- + Aquaculture
- + Industry (mining, pulp milling, etc.)
- + Contact recreation (swimming, wading, bathing, etc.)
- + Secondary recreation (boating, hiking, camping, etc.)
- + Growth and propagation of fish, shellfish, and other aquatic life

Saltwater Uses

- + Seafood processing
- + Harvesting of clams or other aquatic life
- + Aquaculture
- + Industry (other than seafood processing)
- + Contact recreation (swimming, wading, bathing, etc.)
- + Secondary recreation (boating, hiking, camping, etc.)
- + Growth and propagation of fish, shellfish, and other aquatic life

^{1/} President, L.A. Peterson & Associates, Inc.
118 Slater Drive
Fairbanks, Alaska 99701

Associated with each use are criteria for different water quality parameters. For example, drinking water supply criteria specify limits on bacterial contamination, color, temperature, turbidity, and sediment, as well as other parameters. The water quality standards consist of the most stringent criteria associated with each water use.

Particulates include fine sediment in the water column and on the substrate. Typical measurements of particulate levels include total suspended solids, turbidity, settleable solids, and the percentage accumulation of fine sediment in gravel beds.

ADEC currently uses two categories to limit particulates, turbidity and sediment, and both categories have numerical and narrative criteria. In general, the turbidity criteria for the various protected uses range from a 5 to 25 nephelometric turbidity unit (NTU) increase above natural conditions. The sediment criteria are more subjective and include such statements as "No increase in concentration of sediment, including settleable solids, above natural conditions" and "No imposed sediment loads that will interfere with established water supply treatment levels."

The objectives of this paper are to summarize:

- (1) Particulate measurement techniques;
- (2) Compare Alaska particulates criteria to criteria used in other states;
- (3) Particulates requirements for water supply, recreation, and biota; and,
- (4) Proposed changes to existing Alaska particulates criteria.

Information in this paper is summarized from "Alaska Particulates Criteria Review," a report of a project funded by the ADEC and performed by L.A. Peterson & Associates, Inc. Readers interested in more detail regarding particulates criteria are encouraged to review that report. References are not cited in this summary paper, but appear in "Alaska Particulates Criteria Review."

MEASUREMENT TECHNIQUES

Particulate levels in water are measured by numerous direct and indirect techniques. Direct measurements include parameters such as total suspended solids, settleable solids, and the amount of fine sediments on streambeds and lake bottoms. Four different techniques for measuring total suspended solids are reported in the literature. The most widely accepted technique involves filtering, drying, and weighing. Centrifugation has been used to concentrate samples followed by drying and weighing, but there are disadvantages to this technique. One disadvantage occurs with fine-grained material having organic matter associated with it since organic matter can have a density similar to

water, thereby making it very difficult to separate. Centrifugation is also inapplicable for dilute water having less than about 10 mg/L suspended solids. Radioactive absorption has also been used because the absorption of radiation is proportional to the mass present and therefore a direct measurement of the concentration of suspended sediment. Suspended organic matter has been determined in the marine environment by direct counting of particles under a microscope. However, this technique is time consuming, making it impractical whenever a large number of sample analyses are required.

Settleable solids are directly measured by securing a 1 liter sample, allowing 45 minutes of settling followed by rotating the Imhoff cone or stirring around the sides of the cone, followed by another 15 minutes of settling before reading the volume of settled material. A gravimetric technique for settleable solids can be employed. However, this technique is time consuming and requires all the equipment used in the suspended solids test. The volumetric test can be performed easily in the field. Hence, it is the recommended procedure for settleable solids.

The volume of fines in substrate samples are determined by obtaining a sample using a substrate sampler, such as a corer or a dredge. The sample is then subjected to a grain size analysis. Like other sampling techniques, different substrate samplers have advantages and disadvantages when sampling different sized substrate material.

Indirect measurements of particulates are related to light penetration and are essentially an indication of the concentration of particulates. These measurements include turbidity and transmissivity, or its inverse, light extinction. Parameters calculated from light transmission measurements include the depth at which 1 percent of available surface light is found in the water and the associated light extinction coefficient.

Indirect measurements quantify optical absorption and/or light scattering. Nephelometric turbidity measures the 90 degree angle scattering of light by suspended particles, whereas the beam transmittance meter measures the attenuation of light by scattering and absorption. The Secchi disk is a simple kind of irradiance "meter" whose values have been correlated with turbidity and light extinction coefficients.

An alternative method for directly counting suspended organic matter in the marine environment has been employed. The volume concentration of particulate matter of different size was measured using a conductometric particle counter or Coulter counter and the abundance of particles was measured with a nephelometer. A fluorimetric determination of pigments (by luminescence) in phytoplankton cells was then used to determine the amount of organic matter. This of course accounts for only live or dead algae, which in the marine environment probably accounts for a high percentage of organic matter.

COMPARISON OF ALASKA CRITERIA TO OTHER STATES

Approximately 30 percent of the states (17) employ general narrative criteria defining turbidity limits. These narrative criteria range from general "antidegradation" statements to broad guidelines that prohibit turbidity levels which would impact other uses. The remaining 70 percent (33 states) have at least some protected water uses with quantitative criteria for instream turbidity. Very few states have established quantitative turbidity criteria for all water uses.

Evaluation of 20 states having quantitative turbidity criteria and cold-water systems similar to Alaska reveals that their turbidity criteria for recreation, and fish and wildlife propagation are numerically equal to or, in many cases, more stringent than Alaska criteria for these same uses. The turbidity criteria for lakes are also comparable.

Of the 22 states with marine or estuarine waters along their borders, 14 have specific criteria for turbidity in marine or tidal waters. Of these 14 states, seven employ quantitative criteria. Existing Alaska turbidity criteria apply to the seven different water use categories used to protect marine water. Some of these criteria are quantitative, while others are narrative.

None of the states have quantitative criteria for settleable solids levels. Only four states other than Alaska -- Nevada, New Jersey, South Dakota, and West Virginia -- currently have numeric criteria for suspended solids. Of the remaining states, 17 have general narrative statements addressing these parameters. Alaska is the only state with criteria controlling the accumulation of sediments as a maximum percentage by weight of spawning bed gravels.

PARTICULATES REQUIREMENTS FOR WATER SUPPLIES

The amount of particulates allowable in raw water supplies depends on the type and degree of treatment used to produce finished water. An excellent source of water requiring only disinfection would have a turbidity of 0 to 10 units. A good source of water supply requiring usual treatment would have a turbidity of 10 to 250 units. For disinfection purposes, raw drinking water sources should be limited to 5 turbidity units, and finished water should have a maximum limit of 1 turbidity unit where the water enters the distribution system. Most people find water with 5 or more turbidity units objectionable.

The water quality requirements for particulates varies among industrial uses. At one extreme, rayon manufacture requires water with only 0.3 turbidity units, whereas water used for cooling can have up to 50 turbidity units. Most other industrial uses require maximum turbidity levels within this range. Placer mining is one industry where water containing turbidity or suspended solids levels significantly higher than 50 units may be acceptable.

Criteria established for evaluating and identifying water treatment needs for fish hatcheries include limits on suspended solids. The suggested limit for suspended solids for incubating eggs is 3 mg/L and for rearing and holding the limit is 25 mg/L in the absence of other pollutants.

PARTICULATES REQUIREMENTS FOR RECREATION

The noticeable threshold for water contact recreation is 10 turbidity units and the limiting threshold is 50 units. The suggested maximum turbidity limit for Canadian contact recreational water quality is 50 turbidity units and the minimum Secchi disk visibility depth is 1.2 meters. The noticeable threshold for boating and aesthetic uses is 20 turbidity units. There is apparently no level found in surface water that is likely to impede these uses, although many people prefer clear water conditions. Fishing success is reduced where turbidity is greater than about 25 units.

PARTICULATES REQUIREMENTS FOR BIOTA

A large body of experimental data exist regarding the effects of fine sediment deposition on salmonid eggs in natural and laboratory stream gravels. By comparison, only limited numerical data are available regarding the effects of sediment on fish emergence time and population changes. The percentage of fines and level of spawning gravel embeddedness are critical factors to developing eggs and emerging fry. In general, salmon, trout, and char egg survival and emergence success are adversely affected when the fraction of fine sediment exceeds 20 percent. Although the critical particle size is highly variable among species, sediment smaller than 3 mm in diameter appears to be the most deleterious to fish egg survival, emergence success, and productivity. A number of investigators emphasize the deleterious effect of particles smaller than 1 mm in spawning gravels. In addition, it is generally recognized that deposited sediments smother fish eggs and benthic macroinvertebrates by blanketing the substrate.

The adverse impacts of a wide range of suspended solids and turbidity levels have been reported for a diversity of aquatic plants, macroinvertebrates, and various stages of fish development. Research has been conducted under a variety of environmental conditions for different lengths of time and the results are often expressed in different units of measure. In many instances, the data presented in one investigation either do not support or cannot be readily compared to the results of other investigations. An organism's level of sensitivity to suspended solids is dictated by its age, species, relative mobility, feeding and reproductive habits, the season, the size and nature of the sediment, the duration of exposure, the general health and stress level of the individual, and the degree and duration to which the individual was previously exposed. Furthermore, an individual's level of susceptibility depends to some degree upon its origin. For instance, one investigator indicates that hatchery-raised coho salmon are considerably

more sensitive to suspended solids than are wild coho. Moreover, the results derived from laboratory experiments do not necessarily reflect field conditions because of the stress factors involved and because many organisms possess innate adaptation capabilities in response to changes in their environment. These variables are not always considered in the literature. It is relatively common to find the results from one particular study cited in three or more literature reviews. Upon reviewing the original document, it appears that some of the data have been presented without discussing other pertinent factors. Consequently, it is difficult to draw definitive conclusions concerning the impact of a specific suspended solids concentration or turbidity level on a particular species or age class of organism. With these limitations in mind, the following summary statements are made concerning the effects of suspended solids and turbidity on freshwater aquatic organisms.

Lethal suspended solids concentrations vary widely depending on the species and duration of exposure. Adult Arctic grayling can survive high concentrations (10,000 mg/L) of suspended solids but not extremely high concentrations (250,000 mg/L) for a few days. High levels of turbidity (up to 8200 NTU) appear to have no adverse effect on adult grayling survival. Rainbow trout are capable of withstanding 30 to 90 ppm of certain types of suspended solids for several months but suffer significant mortality (50 percent) at levels greater than 100 mg/L for several weeks. At extremely high levels of suspended solids (160,000 mg/L), rainbow trout suffer total mortality in 1 day. Total egg mortality may occur at much lower concentrations (less than or equal to 2500 mg/L) in less than a week. Chum salmon egg survival is decreased by about half when suspended solids levels are increased from 97 to 111 mg/L. The amount of sediment required to cause 50 percent mortality in juvenile coho salmon in 4 days is much higher in November (35,000 ppm) than in August (1200 ppm).

In general, salmonid feeding, growth, reproduction, and behavior are not significantly affected by turbidity levels less than 25 NTU or suspended solids concentrations less than 50 mg/L. An exception is the cutthroat trout, which ceases feeding at 35 ppm suspended solids. With one exception, there is no indication that suspended solids concentrations less than 90 mg/L have any adverse effect on salmonid gill or fin tissues, or respiratory function. In one instance, an *in situ* concentration of 34 mg/L produced moderate to marked gill hypertrophy and hyperplasia in Arctic grayling in 5 days. Furthermore, suspended solids concentrations as low as 50 mg/L may be stressful to grayling, as indicated by blood glucose levels.

Algal-based productivity may begin to be reduced at turbidity levels greater than about 5 NTU in streams and lakes. Rooted aquatic plants may be absent at suspended solids concentrations greater than 200 mg/L. Benthic macroinvertebrate populations may be adversely affected by suspensions of 40 mg/L or more and zooplankton may be harmed by more than 82 mg/L suspended solids.

Lethal and sub-lethal effects of sediments have been determined for a diversity of marine organisms. Numerical data pertain primarily to

the effects of suspended solids and turbidity as opposed to sediments deposited on the bottom. Much of the work done in the marine system involves estuarine invertebrates. With few exceptions, marine invertebrates are more tolerant of high suspended solids concentrations than are anadromous fish and freshwater invertebrates, as indicated by the high concentrations reported in marine bioassay investigations.

Primary production has been reduced at turbidity levels of 41 JTU near offshore mining activity. However, mixing and dilution limited the extent to which primary production was reduced by localized or temporary sediment increases. The lethal suspended solids concentration for adult bivalves, crustaceans, tunicates, and polychaetes is in all instances greater than 400 mg/L and in most cases greater than 1500 mg/L. The survival of a variety of estuarine fish eggs and larvae is not reduced by suspended solids concentrations less than 100 mg/L. However, the feeding rate of larval herring is significantly reduced at 20 mg/L.

The sub-lethal effects of suspended solids and turbidity on mollusks are quite variable. The feeding rate of some oysters is unaffected at 100 to 700 ppm turbidity. Some clams cease feeding at 1000 NTU. The water pumping rate of the American oyster is significantly reduced at concentrations greater than 100 mg/L. The feeding rate of the mollusk Crepidula sp. is significantly reduced at 200 mg/L. Clam eggs develop normally in silt suspensions of 3000 mg/L, whereas American oyster eggs are affected by silt concentrations as low as 188 mg/L. Seed scallops exhibit elevated respiration rates at 250 mg/L or greater. The mussel Mytilus sp. is well adapted to silt concentrations up to 50 mg/L. The shell growth of certain gastropods is decreased when natural suspended solids are increased to 250 mg/L.

PROPOSED CHANGES IN EXISTING ALASKA PARTICULATES CRITERIA

The level of protection afforded by the existing Alaska particulates criteria for the designated water uses is generally supported by scientific data. However, a number of proposed modifications to the existing criteria have been suggested to attain the best criteria based on available information (Table 1).

Use categories for which turbidity criteria have been suggested to be retained include industrial water supply and contact and secondary recreation in fresh water. Under the proposed criteria, no distinction is made between lakes and streams for recreational uses. The turbidity criteria for drinking water supply, growth and propagation of aquatic organisms, and contact and secondary recreation in marine water are amended to allow variable increases in turbidity within specified ranges. It is proposed that the existing turbidity and sediment criteria for certain use categories be deleted because: (1) There is no evidence to support their validity, or (2) other criteria are judged to be more appropriate for the stated use category. It is proposed that the existing turbidity criteria be deleted for agriculture, seafood processing, industrial water supply in marine waters, harvesting for

TABLE 1. Change from existing to proposed criteria by water use category.

<u>Fresh Water</u>	<u>Turbidity</u>	<u>Sediment</u>
Drinking, culinary, and food processing	Minor Change	Minor Change
Agriculture, including irrigation and stock watering	Delete	Minor Change
Aquaculture	Delete	Major Change
Industrial	Retain	Minor Change
Contact Recreation	Minor Change	Delete
Secondary Recreation	Minor Change	Delete
Growth and propagation of fish, shellfish, and other aquatic life	Major Change	Major Change
 <u>Marine Water</u>		
Aquaculture	Delete	Major Change
Seafood processing	Delete	Minor Change
Industrial	Delete	Minor Change
Contact Recreation	Major Change	Delete
Secondary Recreation	Major Change	Delete
Growth and propagation of fish, shellfish, and other aquatic life	Minor Change	Minor Change
Harvesting for consumption of raw mollusks or other raw aquatic life	Delete	Major Change

consumption of raw mollusks or other aquatic life, and aquaculture in both fresh and marine waters.

The sediment criteria for agriculture, seafood processing, drinking water supply, and industrial supplies (fresh and marine water) are amended to include statements addressing suspended and settleable solids. The existing sediment criteria for aquaculture and growth and propagation of aquatic biota have been rewritten to include numerical suspended solids and settleable solids criteria for both fresh and marine waters. Additionally, the allowable percentage accumulation of fines in spawning gravel is recommended to be reduced for the growth and propagation of aquatic biota in fresh water. A new criterion for settleable solids is proposed for the harvesting of raw mollusks and other aquatic life. It is proposed that sediment criteria be deleted for contact and secondary recreation in both fresh and marine waters.

CONCLUSIONS OF THE REVIEW REPORT

1. Sediment is, by volume, the greatest single pollutant of surface water. The transport and deposition of natural sediments is often related to local storm events and stage of hydrograph. The fate of man-induced sediments differs from natural sediments in that the former are not necessarily associated with or dependent upon fluctuations in runoff. In some instances man-caused sediment inputs are greater in magnitude, duration, and frequency than natural inputs. Furthermore, the timing of man-caused inputs may be out of phase with natural occurrences. Consequently, the ultimate fate of man-caused sediments may be different than natural sediments. Also, the sequence of artificial sediment loading may induce abnormal behavioral responses in resident and anadromous fish.

2. Alaska currently employs particulates criteria for two categories: turbidity and sediment. The sediment category includes criteria for total suspended solids, settleable solids, and the percentage accumulation of fines in spawning bed gravel. Criteria for these four parameters are adequate for the protection of all water use categories in Alaska. It was determined that the percentage accumulation of fines in spawning gravel is a difficult parameter to measure. Hence, it is recommended that settleable solids criteria be used as the primary method to limit the accumulation of fines in spawning gravel. Actual measurement of the percentage accumulation of fines by weight can be used as a secondary method at the discretion of ADEC.

3. Because many investigators have not adhered to the definition of turbidity and instrument design specifications applied by Standard Methods for the Examination of Water and Wastewater, there is a significant amount of variability in the way turbidity is measured and reported. This factor makes it extremely difficult to assess and compare the effects of turbidity on various water uses. Common sources of error in turbidity measurements include collection of representative samples in the field, extraction of subsamples, dilution technique, and reporting data to the correct number of significant figures. Although it is

recognized that turbidity measurements may be difficult to evaluate, turbidity is the most applicable of the potential optical parameters for widespread use in Alaska.

4. Under specific conditions turbidity may be effectively used to estimate suspended solids concentrations. There is, however, no single expression which relates turbidity and suspended solids on a regional or universal basis. The development of any predictive relationship between these parameters should be on a drainage basin basis rather than a statewide basis. Any apparent correlation should be accompanied by a rigorous analysis of the data and include a statement of the error associated with the correlation. In addition to treating the data collectively, regression analyses should include calculations of coefficients of determination and confidence limits for data in the low, medium, and high ranges.

5. The standard technique for measuring total suspended solids is routine to perform under laboratory conditions and the results are relatively exact. Common sources of error include those associated with field sampling techniques and the extraction of subsamples. Alternative methods for measuring suspensions of sediment possess limitations that preclude their widespread application.

6. Gravimetric techniques represent a more accurate measure of the effects of suspended solids on aquatic biota while optical measurements may be more appropriate for photosynthesis or aesthetic purposes.

7. Settleable solids have direct and detrimental effects on aquatic biota and habitat by smothering fish eggs, alevins, and invertebrates, reducing intergravel flow, and by coating aquatic vegetation, thus reducing the potential for photosynthesis. Solids in suspension can cause invertebrate drift, cause fish to avoid previously usable habitat, prevent fish from seeing their prey, and cause physical damage such as gill irritation to fish. The lethal tolerance of salmonids and other aquatic organisms to suspended solids appears to be relatively high. In most instances, sublethal effects occur at much lower concentrations. Turbidity prevents the growth and photosynthesis of green plants and can also cause fish to avoid otherwise suitable habitat and prevent them from seeing their prey.

HYDROELECTRIC POWER DEVELOPMENT

LOWER BRADLEY RIVER FLOW REGIME AND ITS RELATION TO FISH

by Larry A. Rundquist, Jean E. Baldrige, and Michael R. Joyce^{1/}

ABSTRACT

The Alaska Power Authority has applied for a license to construct the Bradley Lake Hydroelectric Project at the head of Kachemak Bay. The Bradley River flows from the lake through a steep, narrow canyon for most of its 10-mile length before reaching the tidal flats of the bay. The lower 4-mile reach of the Bradley River crosses extensive tidal flats. The steep gradient of the Bradley River restricts anadromous fish to the lower reach; upstream movement of fish beyond mile 5.9 is prevented by a waterfall. The lower reach of the Bradley River has a single channel, moderate slope, meandering configuration, and supports spawning by anadromous fish, primarily pink salmon and Dolly Varden.

The Bradley Lake Project consists of the transfer of water from the lake through a tunnel to an above-ground powerhouse at tidewater on Kachemak Bay. A dam would be constructed at the lake outlet to increase the storage capacity of the lake.

Instream flow studies were conducted to estimate the streamflows required to maintain salmon production in the lower Bradley River. Information gained from the incremental analysis of habitat was combined with seasonal distribution and habitat utilization data, streamflow estimates for present and project conditions, and potential changes in salinity and water temperature regimes to propose a flow regime for the river. Altering streamflow in the lower Bradley River is generally expected to enhance salmon production by preventing dewatering of spawning areas during winter.

Potential changes in sediment transport and water temperature may adversely affect enhancement opportunities. Studies were conducted during the winter of 1984-85 to predict project effects on these water quality characteristics. Project effects on water temperatures and sediment transport are anticipated to be small.

INTRODUCTION

The Bradley Lake Project, as described in the Federal Energy Regulatory Commission License Application (Alaska Power Authority 1984), consists of the transfer of water from the lake through a tunnel to an above-ground powerhouse at tidewater on Kachemak Bay. A dam is proposed at the outlet of Bradley Lake to increase lake storage capacity. When completed the proposed dam would raise normal lake levels about 100 feet

^{1/} Senior Consultant, Project Scientist, Senior Consultant, respectively
Entrix, Inc., 4794 Business Park Blvd., Suite 6, Anchorage, AK 99503

to an elevation of 1,180 ft, creating a 3,820-acre reservoir. Some flow will be released to the Bradley River to maintain fish habitat in the lower reach of the river.

Construction and operation of the Bradley Lake Hydroelectric Project will alter the quantity and quality of water in the lower Bradley River. Studies were conducted by the authors to investigate the streamflow required to maintain or enhance the fish habitat in the lower Bradley River, and the effects of the recommended flow regime on selected water quality characteristics (Woodward-Clyde Consultants [WCC] 1983 and WCC and Entrix 1985). From a fisheries viewpoint, important water quality characteristics include water temperature and sediment transport.

The purpose of this paper is to summarize the results of these studies. The reader should refer to the original studies for details. The studies were conducted for Stone & Webster Engineering Corporation on behalf of the Alaska Power Authority. Studies in the Bradley River focus on habitat utilization by salmon.

GENERAL DESCRIPTION OF THE AREA

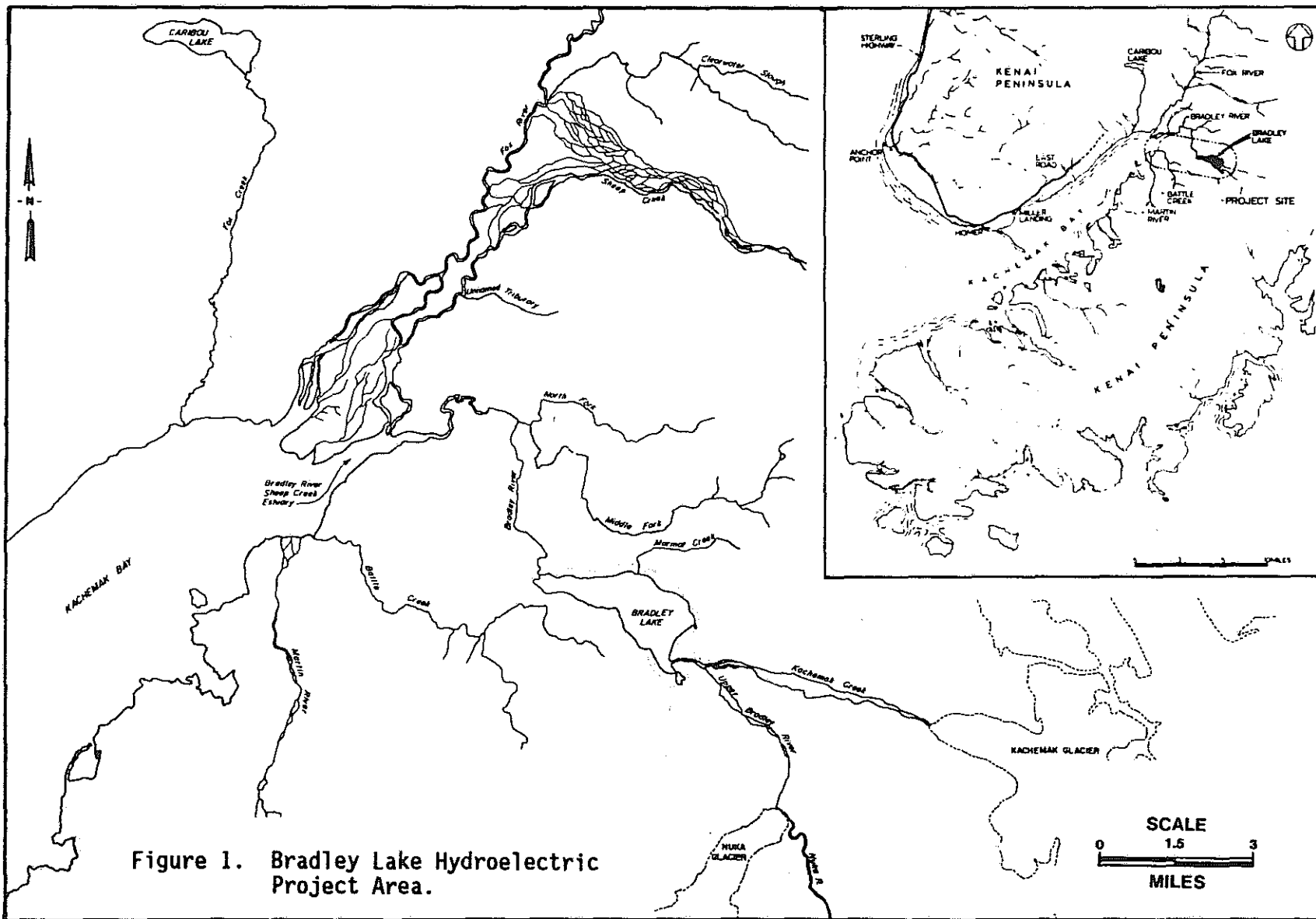
The Bradley Lake project area lies at the head of Kachemak Bay, and is about 27 air miles northeast of Homer, Alaska (Figure 1). Bradley Lake is located about five air miles east of Kachemak Bay at an elevation of about 1080 ft. The Bradley River flows from the lake through a steep, narrow canyon for most of its 10-mile length before crossing extensive tidal flats, which extend to the northwest across the head of Kachemak Bay where two major drainages, the Fox River, and Sheep Creek enter the bay.

The steep gradient of the Bradley River floodplain limits fish to the lower reach. Upstream movement of fish beyond mile 5.9 is prevented by a waterfall. In the lower reach the Bradley River is a single channel, meandering stream, with moderate slope, and supports spawning by anadromous fish, primarily pink salmon and Dolly Varden and rearing by coho salmon and Dolly Varden.

FISH RESOURCES OF THE BRADLEY RIVER

The Bradley River drainage provides habitat for five Pacific salmon. Relative to other Kachemak Bay drainages, the Bradley River is not highly productive, and supports spawning activity primarily only by pink salmon. Utilization of the Bradley River drainage by coho salmon apparently is mostly juvenile rearing of fish spawned in adjacent drainages. Minor spawning activity by chinook, chum and sockeye has occurred but is limited to few individuals.

Adult salmon return to spawn in mid-July through August and spawning activity may extend through mid-September. The embryos incubate in the streambed gravels through the fall and hatch in mid-winter. The alevins remain in the gravels until they emerge in



April or May. After emergence, fry move to nursery areas (fresh or salt water depending on species) for rearing. Pink salmon fry outmigrate from the river almost immediately upon emergence. Chum salmon fry remain briefly in fresh water (less than 2 months) and then migrate to estuarine habitats. Coho salmon juveniles remain in fresh water habitats for two years. Thus, flows must be provided throughout the year, not only to allow for spawning activity, but also for successful incubation, rearing, and outmigration of the progeny.

FLOW RECOMMENDATION

Instream flow studies were designed to estimate streamflows required to maintain salmon production in the lower Bradley River (WCC 1983). The information gained from incremental analysis of habitat was combined with seasonal distribution and habitat utilization data for targeted species, streamflow estimates for present and project conditions, and potential changes in salinity and water temperature regimes to formulate a proposed flow regime for the lower Bradley River (Table 1).

Table 1. Proposed habitat maintenance flows for project planning purposes.

Month	Activity (live stage)	Recommended ¹ Streamflow
October	Rearing	50
November	Incubation	40
December	Incubation	40
January	Incubation	40
February	Incubation	40
March	Incubation	40
April	Incubation/Outmigration	40/100
May	Outmigration	100
June	Rearing	100
July	Spawning	100
August	Spawning	100
September	Spawning/Rearing	100/50

¹ Instantaneous minimum flows to be provided at the USGS gage (15239070) at RM 5.1 on the lower Bradley River.

Source: WCC 1983

The objective is to provide habitat for anadromous fish, particularly pink, chum, and coho salmon. Habitat requirements vary with season of the year, fish species, and life history stage. The proposed flow recommendation reflects the habitat requirements of the most sensitive (or limiting) life stage in the system by month. The Bradley River presently provides limited habitat for these species; some habitat will be lost under project operation, but there is an opportunity for utilization of replacement habitat that would become available under the proposed flow regime.

The flow recommendation focused on providing habitat for pink salmon in the lower Bradley River. Pink salmon appear to have the best potential for production under project operation. A small population of pink salmon currently spawns in mainstem habitats between river mile 4.6 and 5.2. A major limiting factor appears to be the lack of incubation success due to dewatering and sedimentation. An analysis of the effectiveness of spawning habitat, as a function of spawning and incubation flows, indicates an opportunity to improve production in pink salmon spawning areas in the lower Bradley River.

Habitat requirements of chum and coho salmon were assigned a lower priority than habitat requirements of pink salmon since they were not as dependent upon mainstem habitats. Chum salmon habitat encompasses a wider range of depths and velocities than pink salmon; the values of physical habitat characteristics (depth, velocity, and substrate) used by pink salmon are also acceptable to chum salmon (Wilson et al. 1981). In the Bradley River, chum salmon spawning habitat appears to be associated with upwelling intragravel flow or strong subsurface flow. The dependence of chum salmon on upwelling may limit habitat availability under present conditions and would probably continue to limit it under project operation. Although upwelling areas have not been systematically located in the Bradley River, casual field observations of drainage patterns and present fish distribution indicate that few upwelling areas exist. There is probably little opportunity to replace upwelling habitat by regulating streamflow during project operation.

Rearing habitat for young coho salmon was also considered secondary to pink salmon spawning habitat in the proposed flow regime. Juvenile coho salmon rearing in the Bradley River are probably from adjacent drainages (USFWS 1982). Most of the coho habitat utilization is in sloughs and tributaries in the lower portion of the drainage. In many of these areas water level is controlled by tidal fluctuations and will be only slightly affected by project operation. Coho salmon did not use available rearing areas in the mainstem under present conditions. Therefore, it appears unlikely that coho salmon production would be affected by altered habitat availability in the mainstem.

In the Bradley River, as in most Alaskan glacial rivers, spawning occurs during the high-flow period. A major factor influencing production of spawning areas is the effect of low winter flows on embryo survival. As flows decrease during winter, spawning areas may become dewatered or silted. If intragravel flow is not maintained by subsurface flow, incubation would be adversely affected. The evaluation of effective spawning habitat values provided the basis for the selection of spawning and incubation flows. Table 2 presents weighted useable area (WUA) values for effective spawning habitat under the range of flows considered for project operation.

Table 2. Effective pink salmon spawning habitat in the Bradley River under project operations.

Discharge (cfs)	Spawning Habitat		Incubation Habitat		Effective Spawning Habitat	
	weighted useable area	% gross area	weighted useable area	% gross area	weighted useable area	% spawning habitat
100 30	27580	13.9	112980	69.9	26820	97.2
100 40	27580	13.9	124120	72.6	27200	98.6
100 50	27580	13.9	135840	76.8	27300	98.9
125 30	31840	14.0	112980	69.9	29820	93.7
125 40	31840	14.0	124120	72.6	30560	96.0
125 50	31840	14.0	135840	76.8	30560	96.0
150 30	35060	16.0	112980	69.9	31140	88.8
150 40	35060	16.0	124120	72.6	32220	91.9
150 50	35060	16.0	135840	76.8	32660	93.1

Source: WCC 1983

Spawning habitat at flows of 100 to 150 cfs was analyzed at incubation flows of 30 to 50 cfs. Very little difference exists between WUA values of effective spawning habitat at these flows. WUA values for effective spawning habitat under project operation are higher than those presently available in the system. Therefore, the long-term gain by the fishery would be quite similar at any of these flows.

Another consideration in selecting flows is the efficiency of the flow in providing habitat. By expressing WUA as a percentage of gross area, we can estimate the habitat efficiency of the flow. The efficiency of the flow to provide acceptable spawning and incubation habitat does not change significantly from one flow to the next. The efficiency of winter flows for incubation is high. It is apparent from a comparison of habitat values between spawning and incubation that spawning habitat is the limiting factor. Large substrates present in the thalweg will probably limit spawning habitat availability under project operation.

The percentage of original spawning habitat maintained by the incubation flow is high as indicated by the last column on Table 2. In all but one of the discharge combinations under consideration, over 90 percent of the spawning habitat would be maintained by the incubation flows.

Other physical characteristics of the basin which influence habitat conditions were also considered. Summer water temperatures may be cooler under project operations. The North Fork Bradley River will become the primary water source during project operation; additional water will be released from the reservoir during portions of the year to meet proposed minimum flow requirements. During August, the North Fork is expected to provide 53 cfs. Additional flow would come from the reservoir. Water temperatures of reservoir releases at the outlet are expected to be between 4-6°C. Water in the North Fork is expected to be warmer than the reservoir release. Water temperatures in the lower Bradley River would decrease as the quantity of water released from the reservoir increases. In order to reduce the magnitude of temperature decreases, a lower spawning flow was selected. At 100 cfs, half of the water would come from the reservoir and half would be contributed from unregulated sources, principally the North Fork. Spawning flows would be required in late July through mid-September.

From mid-September through October, juvenile fish move into overwintering habitats. Flows of about 50 cfs should provide these fish adequate passage to overwintering habitat. A flow of 50 cfs would also be sufficient to maintain incubation of salmon embryos.

From November through mid-April, the embryos developing in the gravels are in one of their more sensitive life stage. An incubation flow of 40 cfs was selected to maintain almost all (98.6%) of the spawning habitat that is available at 100 cfs. In addition, winter habitat conditions would be unchanged from natural since the incubation flow is similar to natural winter flows and would not permit further intrusion of salt water into the system.

In late April and May, a flow of 100 cfs is proposed for outmigration of young salmon. This flow must provide a stimulus for outmigration and allow passage from spawning areas. In June and early July, flow requirements for juvenile fish are the limiting factor as adults have not yet returned but juvenile fish are moving into summer feeding areas. Flow of about 100 cfs would be sufficient to accommodate this need.

WATER QUALITY

Lower Bradley River Temperature

The predicted annual temperature regime of the lower Bradley River under project conditions was estimated from mean temperatures and discharge rates from Bradley Lake and from the basin below the lake. Estimated surface water temperatures from April through August are

anticipated to be similar to, or slightly warmer than, natural temperatures. Warmer water temperatures are expected from Bradley Lake outflow during this period as the decreased volume of water is more quickly heated by warm air temperatures. From September through freezeup in November, temperatures are anticipated to be slightly cooler with a decrease of 2°C or less as smaller flows will cool more quickly in response to air temperatures. Anticipated temperatures and flows for December through March are similar to natural conditions.

Surface water temperatures measured in the lower Bradley River during the winter of 1984-1985 decreased during December to the expected lows of near 0°C. Warm (1.0-2.0°C) surface water temperatures during January resulted from unseasonably warm air temperatures, and were followed by near 0°C temperatures in February and March, and slight warmer in April.

Changes in surface water temperatures can alter intragravel water temperatures which are important to incubation of salmon embryos. The rate of incubation is directly related to water temperature. Warmer or cooler water temperatures in the intragravel environment could, respectively, accelerate or retard embryo development, thus changing emergence time. Of the salmon species using the Bradley River, pink salmon have the highest potential for changes in emergence timing under project operation. Pink salmon spawn in mainstem habitats where changes of water temperatures are expected.

Coho salmon spawning has only been documented in tributary habitats where thermal regimes are not influenced by the mainstem, and consequently are not expected to be altered by the project. Chum salmon emergence timing is not expected to be affected by an altered temperature regime in the Bradley River. Chum salmon spawn in the mainstem of the Bradley River in areas of groundwater upwelling. Small changes in the mainstem surface water temperatures under project conditions are not expected to affect intragravel temperatures in these upwelling areas. Since the selected spawning locations of these species are not expected to be influenced by small changes in mainstem temperatures, emergence timing for coho and chum salmon are expected to remain in the normal ranges for the Bradley River drainage.

Intragravel water temperatures are generally more stable and slightly warmer in Alaskan Rivers (Baldrige and Trihey 1982, Estes and Vincent-Lang 1984). There are three factors contributing to intragravel water temperatures: infiltrating surface water; groundwater or subsurface flow; and ground temperature. The relative contribution of each of these components varies on a site specific basis. However, changes in surface water temperatures are not expected to result in changes in intragravel water temperatures of the same increment. The influence of groundwater or subsurface flow and ground temperature would dampen changes in intragravel temperatures. In the lower Bradley River, intragravel temperatures are slightly warmer than surface water temperatures but they respond to changes in surface water temperatures. The data indicates that ground-water will have little influence on intragravel temperatures in the upstream portion of the spawning reach while subsurface flow and ground temperature may buffer intragravel temperatures in the downstream portion of the reach.

Pink salmon generally spawn in the Bradley River during the second half of August with fry emerging during April of the following year. Although cooler water temperatures predicted for the Bradley River during the fall months under project operation may slightly delay pink salmon emergence timing, the emergence date is not expected to exceed the natural variation in emergence and outmigration. In Kachemak Bay, the annual variation of pink salmon emergence and outmigration timing ranges from late March through May (Tom Schroeder, ADF&G Homer, pers. comm. 1985).

Experimental studies show that there is a compensation mechanism for eggs developing at colder temperatures. Development rates of embryos are expressed in temperature units (T.U. = 1°C for a 24 hour period). Total temperature units required for emergence, or complete yolk absorption, have been estimated for pink salmon populations in the Skagit River in Washington (Graybill et al. 1979).

In the Skagit River experiments, mean temperature differences of 1°C or less resulted in 2-5 days difference in incubation time to complete yolk absorption (CYA). Although the total T.U.'s required for the incubation period decreased at lower temperatures, there was a delay in the time of CYA. Comparing mean temperature of 2.9°C and 2.2°C CYA was delayed by a month for chum salmon. Coho salmon were delayed by 18 days by reducing mean temperatures from 3.0°C to 2.1°C .

Pink salmon in the Bradley River are expected to exhibit temperature compensation and delays in emergence timing if project operation results in lower intragravel water temperatures during the fall. The period of temperature data collection was not sufficient to compare TU's available for incubation during 1984-1985. Since data on water temperatures, intragravel temperatures, and incubation requirements lack sufficient resolution for a detailed analysis of temperature units, an alternative analysis was undertaken. Mean monthly surface water temperatures can be used to approximate the mean incubation temperature. Pink salmon spawn in the Bradley River primarily during the last two weeks in August, with fry emerging during April of the following year. If the predicted mean monthly temperatures for August through April are used to approximate the mean incubation temperature, the pre-project mean incubation temperature is 2.2°F , while the with-project mean incubation temperature is 1.9°F . A difference of 0.3°C probably will not have serious impacts on emergence timing or fry survival.

Sediment

Spawning areas presently utilized in the mainstem Bradley River are located along the margins of the stream as high velocities during the high flow period preclude the use of the center portion of the channel. Many of the existing spawning areas are dewatered or have low velocities during the incubation period that result in sediment accumulation. Sediment accumulation may be detrimental to salmon populations. Streambed sediments affect incubation and emergence of salmon by 1) reducing intragravel water flow (required to supply oxygen and remove metabolic waste products) and 2) trapping hatched fry within the gravel.

Numerous studies have found inverse relationships between egg to fry survival rates and the proportion of fine sediment contained within the substrate (McNeil and Ahnell 1964, Koski 1966 and 1975).

Particle sizes less than 0.84 mm in diameter can greatly decrease the rate of intragravel water flow has generally been found to be the most harmful to incubating salmon and trout eggs (McNeil and Ahnell 1964; Tagart 1976; Cederholm et al. 1981). Levels of sediment greater than 5 percent by volume have resulted in reduced fry survival or poor quality fry. High sediment levels have been found to cause early emergence of coho salmon (Koski 1966) and chinook salmon (Shelton 1953). Premature emergents are characterized by small body size and incomplete yolk absorption; factors that may reduce their subsequent ability to survive in the stream environment.

Siltation is an important consideration in evaluating spawning and incubation habitat in the lower Bradley River. Sediment transport in the lower portion of the spawning reach is complicated by tidal influence. The Bradley River transports a relatively light load of suspended sediments for a glacial system. Most of these particles appear to remain in suspension as long as velocities are greater than about 0.5 fps. An incoming tide slows the river current and increases depth and top width; silt particles are deposited over a broad expanse of the channel. As the tide recedes, discharge increases above that of the low tide discharge and velocities increase correspondingly. The increased velocities attained as the tide recedes may not be sufficient to erode the deposited silts from gravel bars before the bars become dewatered. The normal flow velocities present in the main channel without tidal influence erode much of the deposited silt from these areas and transport it downstream. The silt tends to accumulate in areas dewatered at low-tide or in other low-velocity areas. Deposition of silts up to 0.3 ft thick have been observed in dewatered areas following winter low flows.

In this lower reach of the river, sedimentation appears to have a detrimental influence on incubation. A trend of increasing fine sediment in the surface gravel samples was apparent from December 1984 to March 1985 (WCC and Entrix 1985). Temperature data collected in this reach indicates that exchange between intragravel and surface waters is not as efficient as upstream of the tidally affected reach. Pre-emergent sampling conducted in March 1984 found fewer live eggs and alevins in Riffle Reach. Since the potential spawning habitat is located more in the center portion of the channel, it experiences higher velocities (even under low flows) than the existing spawning habitat and is less likely to experience siltation problems.

Substrate samples collected upstream of the reach frequently affected by tides show little difference between percent fines in the surface layers in December 1984 and March 1985 (WCC and Entrix 1985). The samples also show little difference with depth within the 18 inch samples (WCC 1985). Water temperature data collected in this reach indicate good exchange between surface and intragravel water, thus supporting the data indicating that the substrates are relatively free of silts and sands. During the pre-emergent sampling conducted in March

of 1984, more embryos and fry were located in this section than elsewhere in the river.

SUMMARY

The flow regime proposed for the lower Bradley River under operation of the Bradley Lake Hydroelectric Project is expected to benefit pink salmon production. By reducing high spawning flows and maintaining constant incubation flows, incubation success is expected to improve. Studies indicated that dewatering and sedimentation are adversely affecting existing spawning areas. By increasing the amount of spawning area protected by winter flows, embryo mortality from dewatering and freezing should be reduced.

Although increasing habitat availability was the underlying goal of the proposed flow regime, water temperature and sediment were also considered. Lower spawning flows were selected to reduce the potential for decreased water temperatures. Tidal-influenced sediment deposition will continue to affect exposed gravel bars and low-velocity areas. However, in areas suitable for spawning, hydraulic conditions are expected to prevent substantial accumulations of fine sediment.

REFERENCES CITED

- Alaska Power Authority. 1984. Bradley Lake FERC License Application. Submitted to the Federal Energy Regulatory Commission. Anchorage, Alaska.
- Baldrige, J.E. and E.W. Trihey. 1982. Potential effects of two alternative hydroelectric developments on the fishery resource of the lower Tazimina River, Alaska. Arctic Environmental Information and Data Center. Anchorage, Alaska. Report for Alaska Power Authority.
- Cederholm, C.J., L.M. Lewis, and E.O. Salo. 1981. "Cumulative effects of logging road sediment on salmonid populations in the Clearwater River, Jefferson County, Washington." In Salmon-spawning gravel: a renewable resource in the Pacific Northwest? ed. State of Washington Water Resource Center, pp. 38-74. Report No. 39. Pullman, Washington: State of Washington Water Research Center, Washington State University.
- Estes, C.C. and D.S. Vincent-Lang, editors. 1984. Alaska Department of Fish and Game Susitna Hydro Aquatic Studies. Aquatic habitat and instream flow investigations (May-October 1983), Ch. 3: Continuous water temperature investigations. Prepared for Alaska Power Authority. Anchorage, Alaska.
- Graybill, J.P., R.L. Burgner, J.C. Gislason, P.E. Huffman, K.H. Wyman, R.G. Gibbons, K.W. Kurko, Q.J. Stober, T.W. Fagnan, A.P. Stayman, and D.M. Eggers. 1979. Assessment of the reservoir-related effects

of the Skagit Project on downstream fishery resources of the Skagit River, Washington. Final Report for City of Seattle by University of Washington Fisheries Research Institute, Seattle, Washington.

Koski, K.V. 1966. The survival of coho salmon (Oncorhynchus kisutch) from egg deposition to emergence in three Oregon coastal streams. M.S. Thesis, Oregon State Univ., Corvallis.

Koski, K.V. 1975. The survival and fitness of two stocks of chum salmon (Oncorhynchus keta) from egg deposition to emergence in a controlled stream environment at Big beef Creek. Ph.D. Dissertation, Univ. of Washington, Seattle.

McNeil, W.J. and W.H. Ahnell. 1964. Success of pink salmon spawning relative to size of spawning bed materials. U.S. Fish and Wildl. Serv. Spec. Sci. Rep. Fish. 469. 15 pp.

Shelton, J.M. 1953. "The hatching of chinook salmon eggs under simulated stream conditions." Prog. Fish-Cult. 17:20-35.

Tagart, J.V. 1976. The survival from egg deposition to emergence of coho salmon in the Clearwater River, Jefferson County, Washington. M.S. Thesis, Univ. Washington, Seattle. 101 pp.

U.S. Fish and Wildlife Service. 1982. Fish and Wildlife Coordination Act report, Bradley Lake Project. Appendix B In U.S. Corps of Engineers, Bradley Lake Hydroelectric Project, Alaska, EIS. U.S. Corps of Engineers. Alaska District. Anchorage, Alaska.

Wilson, W.J., E.W. Trihey, J.E. Baldrige, C.D. Evans, J.G. Thiele, and D.E. Trudgen. 1981. An assessment of environmental effects of construction and operation of the proposed Terror Lake Hydroelectric facility, Kodiak, Alaska. Instream flow studies. Final Report. Arctic Environmental Information and Data Center, University of Alaska, Anchorage, Alaska. 419 pp.

Woodward-Clyde Consultants. 1983. Bradley River Instream Flow Studies. Prepared for Stone & Webster Engineering Corporation, Anchorage, Alaska. 75 pp + appendices.

Woodward-Clyde Consultants. 1984. Report on Salmon Fry Sampling in the Bradley River. Prepared for Stone & Webster Engineering Corporation. Anchorage, Alaska. 13 pp.

Woodward-Clyde Consultants and Entrix, Inc. 1985. Water Quality Report. Prepared for Stone & Webster Engineering Corporation, Anchorage, Alaska. 99 pp.

APPLYING THE CONSULTATION PROCESS IN RESOLVING WATER RESOURCE ISSUES

by William A. Corbus^{1/}

and David T. Hoopes^{2/}

ABSTRACT

The recent completion of major improvements to the hydroelectric power project owned and operated by Alaska Electric Light and Power Company (AELP) on Salmon Creek just north of Juneau required amending an existing permit to appropriate water. The establishment of a minimum stream flow in the lower reach of Salmon Creek, an anadromous fish stream, and the prevention of excessive instream flows during reservoir releases were identified as major concerns by both State and Federal resource agencies. The early, good faith effort by AELP and its consulting engineer, R. W. Beck and Associates, Inc. (Beck), culminated in an agreement including both a minimum flow measured as a discharge stage and an operational plan for reservoir releases to minimize channel damage due to scouring. This agreement was reached through a continuing process of meetings, site visits and data exchanges that kept all parties updated as to the progress being made toward final settlement. The resolution of key issues depended upon maintaining contact and the open and free exchange of information and ideas. The use of an intermediary familiar with both agency and AELP requirements helped to avoid any potential communications breakdown and expedited the final agreement.

INTRODUCTION

Even in regions of apparent surface water abundance, competing water uses hold the potential for adversely impacting instream resource values, particularly those associated with anadromous and resident fishes. Several Federal and State agencies are involved with managing these fish resources and their habitats. These agencies exercise various regulatory or administrative controls over developments affecting such resources, depending upon their legislated or otherwise

^{1/} Manager, Alaska Electric Light and Power Company
134 N. Franklin Street
Juneau, Alaska, 99801

^{2/} Principal Scientist, R. W. Beck and Associates, Inc.
2121 Fourth Avenue
Seattle, Washington 98121

mandated authorities. Proponents of water-oriented projects involving fish resources are normally required to consult with such agencies during the course of project development regarding a wide variety of licensing and permitting issues.

Early and open consultation with resource agencies offers both the project proponent and the agencies several significant advantages:

- o Agencies are apprised of the proposed activity
- o Proponent becomes aware of studies or information agencies consider necessary to evaluate potential impacts
- o Proponent becomes aware of extent of existing information, thereby reducing chance of costly study duplications
- o Agencies given opportunity to identify their concerns regarding potential environmental consequences early enough to be considered while assessing project feasibility
- o Proponent can incorporate agency suggestions regarding protection, mitigation and enhancement measures during project design rather than attempting to retrofit such measures at a later date to meet agency requirements

Partial reconstruction and relicensing of the Annex Creek and Salmon Creek Hydroelectric Project (FERC Project No. 2307) presented an excellent opportunity for the project owner, Alaska Electric Light and Power Company (AELP) of Juneau and its engineering consultant, R. W. Beck and Associates, Inc. (Beck), to apply the consultation process to the resolution of issues and concerns involving water dependent resources, principally anadromous salmonids. The construction and relicensing schedule required obtaining an amended water use permit from the Department of Natural Resources (DNR) prior to applying to the Federal Energy Regulatory Commission (FERC) for a new license to operate the project.

Strictly speaking, the FERC and Federal resource agencies do not become involved in water rights issues, leaving the regulation of appropriated waters and establishment of instream flows up to each state. In this case, however, the Federal agencies, Fish and Wildlife Service (FWS) and National Marine Fisheries Service (NMFS) would be involved in reviewing any instream flow agreement reached between AELP and DNR because the flows established under the water use permit would, hopefully, receive Federal agency approval when they appeared as part of the forthcoming FERC license application. Other issues, principally those involved with regulating downstream releases from Salmon Creek Dam, the site of diversion for AELP's Upper and Lower Salmon Creek powerhouses, also pertained to both the water appropriation permit and the license application.

In view of these closely related issues, AELP and Beck decided to include Federal agencies in the consultation required to establish instream flows as part of AELP's State water appropriation permitting

process. This decision was strongly supported by the Alaska Department of Fish and Game (ADFG) to whom the DNR looks for recommendations regarding permit stipulations to protect fish and wildlife resources. The Alaska Department of Environmental Conservation (ADEC) must also provide a water quality certification, pursuant to Section 401 of the Clean Water Act of 1977 for the existing developments at both Salmon and Annex creeks. The ADEC also considers the recommendations of the ADFG when making its evaluation of the proposed action's impact on water quality. As ADFG's Regional Habitat Protection Supervisor, Rick Reed, pointed out, there would be nothing gained by reaching agreement with the State over a flow regime during water appropriation negotiations only to turn around and have the Federal agencies require a different regime that would then have to be renegotiated with the State agencies. Clearly, early and open consultation with all involved parties was essential if the water permit amendment was to be approved and a timely license application filed with the FERC.

PROJECT HISTORY

The Annex Creek and Salmon Creek Hydroelectric Project was constructed in 1914-1915 and first licensed by a Joint Power Permit issued to the Alaska-Gastineau Mining Company on January 24, 1918. In 1963 the continued operation of the system was authorized in a license issued to A-J Industries, a descendent of the old Alaska-Gastineau Company, by the Federal Power Commission, the immediate precursor of the FERC. This license was transferred to AELP on March 23, 1973 after the purchase of the system by AELP. On December 20, 1974 AELP terminated operation at the lower Salmon Creek powerhouse. The decision to close down operations at the lower powerhouse was predicated upon high maintenance and operating costs not being offset by the low system capacity. The resulting cost of energy proved uneconomical for AELP ratepayers when compared to other energy sources. The lower powerhouse remained inoperative for over ten years.

On May 16, 1983 the FERC granted AELP a license amendment to rehabilitate the lower Salmon Creek component of the system. A further amendment issued on July 23, 1984 authorized the construction of a new powerhouse and alteration of the existing penstock arrangement. It was this proposed construction that prompted AELP's request for an amended water permit from DNR and the subsequent considerations outlined above. The new lower Salmon Creek powerhouse went on-line December 17, 1984. The water permit authorizing changes in AELP's existing Certificate of Appropriation was executed by DNR on June 13, 1985. The permit includes conditions establishing a low flow in lower Salmon Creek and measures for ensuring the agreed-to flow of ± 9 cfs can be related to a water level of 1.4 feet as measured on an established staging staff gage.

CONSULTATION PROCESS

Many states, including Alaska, offer some type of clearinghouse process whereby a single office coordinates project review by all

agencies having some type of jurisdictional or administrative authority. The office then provides the project proponent with a composite review of agency concerns and recommendations for evaluation and inclusion in any required license or permit application. In Alaska this coordinating service is located in the Governor's Office, Office of Management and Budget, Division of Governmental Coordination. Our contact in this office has been Ms. Lorraine Marshall, the Project Coordinator. In this particular instance, the relicensing action must also be reviewed in light of the Alaska Coastal Management Plan to verify our consistency determination pursuant to Section 307(c)(1) of the Federal Coastal Zone Management Act as per 15 CRF 930, Subpart D.

In addition to interacting with the Governor's Coordination Office, we approached each involved agency, both State and Federal, on an individual basis. Our first step was to prepare an informational packet describing in general terms the project as it currently existed, any proposed changes in project configuration or operation (in this case none), existing environmental conditions and an estimation of the impacts continued operation would have on environmental resources, especially fishes in Salmon Creek. This informational packet was sent to the agencies prior to a scoping meeting held in Juneau on January 17, 1985. This was the first general meeting at which all agencies concerned with environmental issues were present. Earlier meetings had been held with representatives from DNR and ADFG in October and December, 1984 to specifically discuss DNR requirements for the amended water permit.

Several issues were surfaced at this scoping meeting that served to lay the groundwork for future studies and negotiations. These were:

- o The need to establish a mutually acceptable low flow for that portion of lower Salmon Creek accessible to anadromous fish.
- o The need to establish a mutually acceptable plan for releasing water from Salmon Creek Reservoir through the low-level outlet works downstream into Salmon Creek to meet FERC safety requirements by not exceeding a reservoir level of E1 1140 feet without causing excessive downstream flushing.
- o The need to acquire additional data on the frequency of low flows and the extent to which available spawning and rearing habitat in lower Salmon Creek is affected by various discharges.

With these goals in mind, AELP, Beck and the agencies agreed to a monitoring plan to continue throughout the remainder of the winter to verify flow conditions at various discharges. Monitoring included several field trips to the site during which ADFG, AELP and Beck biologists and engineers engaged in streamside discussions of the relevant issues and conditions. Available hydrologic data were reviewed to arrive at a best estimate of the long-term low flow regime in Salmon Creek and these data were provided to the agencies by AELP.

Because the water appropriation issue remained a State responsibility, ADFG took the lead in helping establish an acceptable low flow while DNR, ADEC and ADFG reviewed AELP's proposed operating plan to minimize adverse impacts from releases through the low-level outlet works. Throughout the winter both Federal agencies were kept apprised of the results of joint field trips and discussions with State agencies as well as further analyses of hydrologic data.

By the end of the potential winter low flow season, observations indicated that a flow represented by a staff gage reading of 1.4 feet would provide the minimum water level necessary to maintain fish and other aquatic resources in lower Salmon Creek. This water level equates to a discharge of approximately 9 cfs as measured by the U.S. Geological Survey streamflow gage located just upstream of the impassable falls that confine anadromous fishes to the lower 1,250 feet of Salmon Creek.

On April 5, 1985 we presented our proposed minimum stream flow to ADFG. Immediately after this meeting the junior author met informally with both FWS and NMFS to describe our proposal and the current status of the instream flow negotiations with the State. Both agencies were also provided copies of the most recent synthetic flow data describing the hydraulic regime of Salmon Creek. Later the same day, Rick Reed advised AELP that ADFG agreed to our minimum flow proposal. As a result of that agreement, DNR included the 1.4-foot water level and flow of 9 cfs in the revised water permit and both the FWS and NMFS accepted the negotiated settlement during their subsequent review of a draft version of the forthcoming FERC license application.

We are pleased to be able to report that comments received during draft review of our application for relicensing support our feeling that negotiations remained positive and open at all times. DNR's response to our application review included the following statement in a letter from Paula Burgess, DNR Regional Manager, to Bill Corbus, AELP Manager, dated August 26, 1985:

ADNR contacted AELP following the FERC notice of March 1984 and informed AELP of the necessity to make changes to their existing Salmon Creek Water Rights, to allow the water use described in the 'Amendment of License.' Since that initial contact ADNR staff has experienced an excellent working relationship with the management of AELP who have demonstrated a very cooperative approach toward the resolving of State Water Management concerns involving minimum flows as well as emergency releases within the Salmon Creek watershed.

CONCLUSIONS

The Salmon Creek instream low flow negotiation was the first such negotiation for AELP. Although the principal Beck representative had been involved in a number of similar consultations prior to the Salmon

Creek water appropriation case, the unique situation of obtaining a State water appropriation that would become subject to Federal scrutiny as to effects on fish resources had never arisen before. Normally, the licensee either already possesses the necessary water rights or applies for a water appropriation in conjunction with a license application. In the case of Salmon Creek, however, the agreement reached with DNR and ADFG had to satisfy the Federal agencies at the time they received the FERC license application. If not, AELP ran the risk of having to negotiate an entirely new low flow agreement with FWS and NMFS with no guarantee that ADFG and DNR would agree. Taking this approach early in the process enabled us to circumvent any problems by involving all concerned parties, both present and future, from the outset. Our success in this particular instance speaks for itself but, in addition, we have arrived at several caveats and recommendations we believe have general applicability when negotiating any natural resource issue with the agencies administering those resources and regulating their use(s).

- o Inform agencies of your proposed action at the earliest practicable date. Provide each agency with information describing the proposed action. Go through a central clearing house system if one exists, but do not let the clearinghouse serve as a substitute for direct agency contact.
- o Hold a scoping meeting as soon as possible after agencies have been informed of your plans. Be certain everyone with any interest in the project is invited to attend. One means of identifying agencies with potential interest in your project is to review the Directory of Permits prepared by the Alaska Department of Environmental Conservation.
- o Once a dialog has been established, make certain it is maintained. Informal contact, even by phone, to keep agencies apprised of study progress, preliminary results and schedules for draft reviews and meetings creates an air of openness that encourages agency cooperation and support. More formal contact through correspondence should involve sending copies to all concerned parties. In this way you can prevent any feeling among agencies that you are "cutting" a deal with someone.
- o Never hold a closed meeting. If you plan to meet with only certain people to accomplish some specific objective, either report the results of such meetings or field trips to all parties or, if practicable, invite them to participate and let them make the decision whether to attend or not.
- o Always come to any meeting with agency representatives prepared with a plan of action or specific agenda if you have called the meeting or know in advance the purpose for which it is being held. Solicit agency concerns regarding your project, but never ask agencies what to do to measure, as-

sess or mitigate impacts. Always have a well-conceived proposal for agency personnel to review and respond to.

We believe that if you follow the five simple steps suggested above during consultations with resource agencies, you will find that the problem-solving process will become simpler, require less time, and culminate in solutions more acceptable to all parties involved.

HYDROLOGY AND HYDRAULICS

GLACIER RUNOFF IN THE UPPER SUSITNA AND MACLAREN RIVER BASINS, ALASKA

by Theodore S. Clarke¹, Douglas Johnson¹, and William D. Harrison²

ABSTRACT

Mass balance measurements were made on the major glaciers at the headwaters of the Susitna and MacLaren Rivers during 1981, 1982 and 1983. The primary purpose of the work has been to estimate the amount of water originating from this 790 km² glacierized area, in connection with the development of water forecast models for the proposed Susitna hydroelectric project (Figure 1). The study has been at the reconnaissance level since only one stake per 50 km² has been monitored. Average runoff from glaciers due to the melting of ice, firn and snow was about 1.35 m/yr, as estimated by monitoring melt on the glacier surfaces. Average runoff from rain on glaciers was about 0.25 m/yr, as estimated from rain gauge data. Overall, the glaciers produced about 1.6 m/yr of water. This is compared to 0.95 m/yr for the unglacierized portion of the Susitna River basin above the Denali Highway and 0.59 m/yr from the basin as a whole above the Susitna River gauge at Gold Creek for the same period. Glacier balances, when summed over the three year measurement period, were estimated at +0.1 + 0.6 m water equivalent. Since water was not being withdrawn from glacier storage, the data suggest that runoff rate from the glacierized portion of the basin is about 2.7 times greater than that of the basin as a whole above Gold Creek. Glacier runoff accounted for 18% of the flow at the Watana dam site during the study period, but probably accounts for about 30% during drought years such as 1969 even though glaciers cover only 5.9% of the area above the dam site. It is estimated that nearly 75% of the melt water originating on the glaciers ran off in July and August, while the remaining 25% was distributed between May, June, September and October.

INTRODUCTION

This paper summarizes the glacier balance data obtained for the Susitna basin in 1981, 1982 and 1983, and estimates the amount and timing of runoff produced by those glaciers (Clarke and others, 1985). Glaciers were singled out for special study primarily because they produce very large quantities of water when compared to surrounding unglacierized areas, and they have a decided moderating effect on year-to-year stream flow variations (Fountain, 1985). Three other reports describe early phases of the work, including thermal and flow regimes of the glaciers, the effect of glacier surges on sediment and water supplies, the effect of long term glacier volume change, glacier outburst floods and possible effects of climate change on glacier runoff (R & M and Harrison, 1981; R & M and Harrison, 1982; Harrison and others, 1983).

¹ Research Assistant, Geophysical Institute, Univ. of AK, Fairbanks, 99775

² Prof. of Physics, Geophysical Institute, Univ. of AK, Fairbanks, 99775

With the exception of Eureka Glacier, which straddles the eastern boundary of the basin, and the small glaciers of the Talkeetna Mountains to the south, all major glaciers of the basin were studied. (Figure 2). The total area of glacierization is about 790 km², or 5.9% of the total basin area above the proposed Watana dam site. Limitations on interpretation of the data are imposed by the sparse coverage (3 measurement points per major glacier, Figure 2), and perhaps more important, by the short time span (1981 to 1983) of the data.

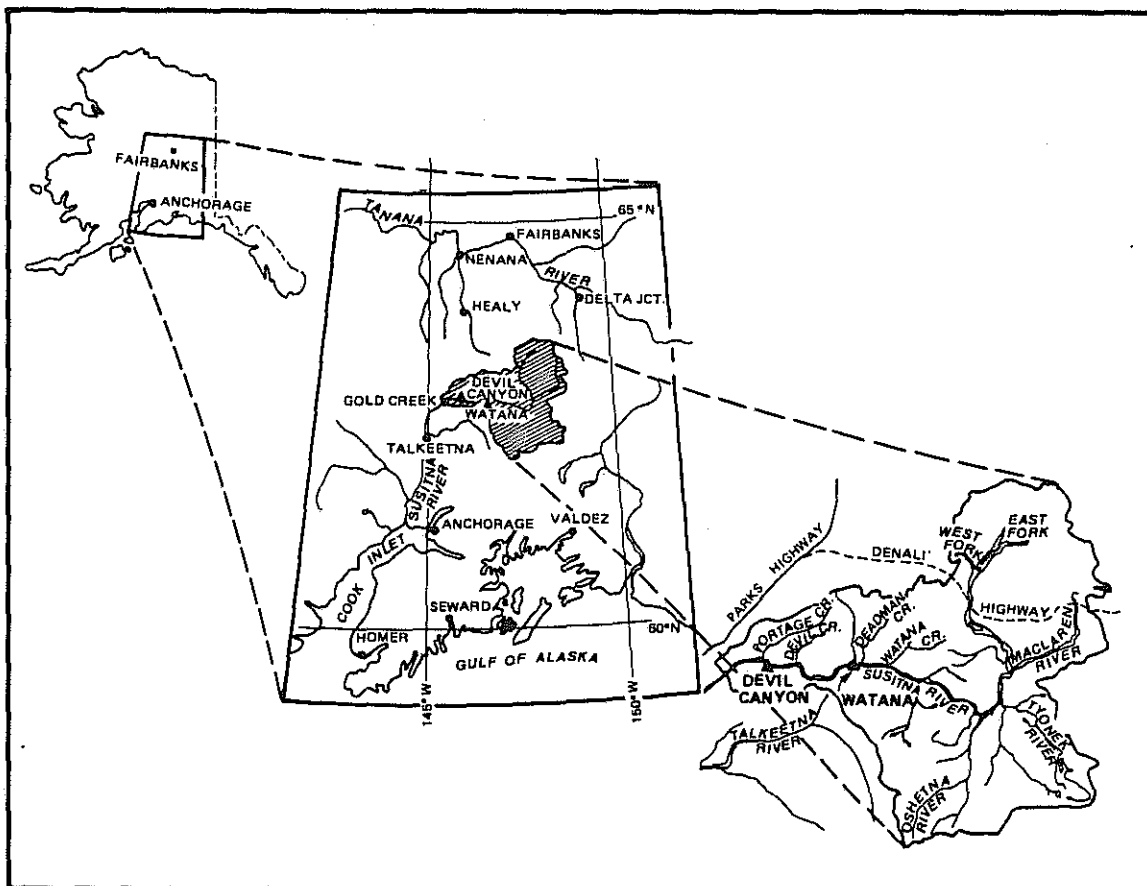


Figure 1. Location map. (From Acres American, 1982)

METHODS AND RESULTS

Melt runoff from the Susitna basin glaciers was estimated from measurements of melting and accumulation at a network of stakes drilled into the glacier surfaces. Total melt and accumulation quantities over the glacier surfaces were determined by integrating these (point) measurements over the glacier surfaces. The smaller glaciers in each basin were assumed to behave in a manner similar to the major glacier in their respective basins. In the case of Eureka Glacier, which straddles the drainage divide, it was assumed that 60% (24 km²) of its area contributed runoff to the Maclaren-Susitna River basin, and that its accumulation and melt characteristics were similar to those of Maclaren Glacier.

A certain amount of glaciologic terminology will be useful for what follows. More complete terminology can be found in Anonymous (1969) and Mayo and others (1972).

Ablation: Melt of snow, firn or ice.

Annual balance: The change in thickness of a glacier at a point from 1 October to 30 September. Water equivalent depth is used throughout.

Average annual balance: The integrated annual balance over the glacier surface divided by the glacier area.

Equilibrium line: The line on a glacier that divides the area of positive annual balance (high elevation) from the area of negative annual balance (low elevation). This is usually 1800 ± 150 m in the upper Susitna and Maclaren River basins.

Firn: Snow that has survived at least one summer.

Internal accumulation: The process of liquid water freezing within a glacier. This happens in two ways. First, water left as capillary water at the end of summer freezes during winter. Second, the first water to penetrate the glacier during spring freezes in the underlying cold snow and firn (Trabant and Mayo, 1985).

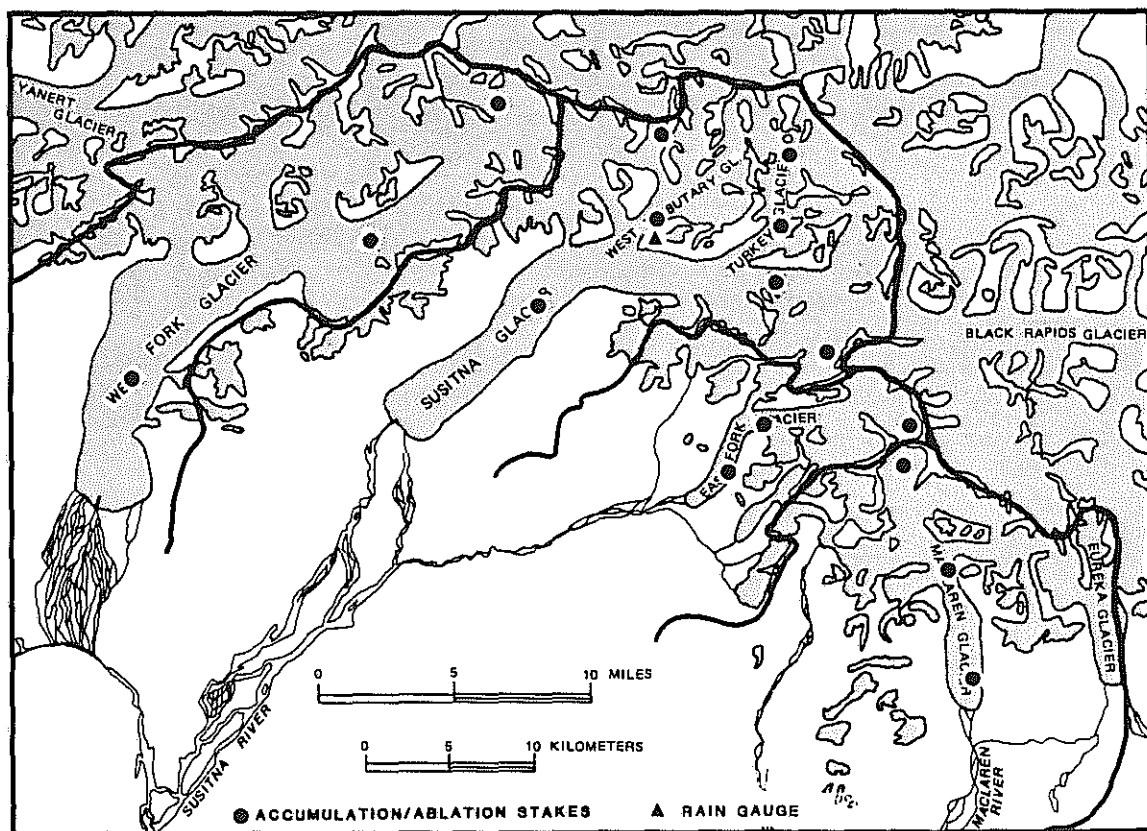


Figure 2. Glacier names and locations, drainage divides, stake locations and rain gauge site. (Modified from Harrison and others, 1983.)

Snow Melt

Snow melt on the glaciers below their equilibrium lines could be estimated directly from summer precipitation data and winter snowpack data taken in spring. However, since snow melt is often obscured at higher elevations by a net gain of snow during the summer months, an ablation-elevation curve had to be developed to estimate melt at these elevations. Melt rate on glaciers decreases with increasing elevation to the point where all melt is absorbed by the glacier as internal accumulation, above which no runoff occurs. Trabant and Mayo (1984) place this melt/internal accumulation equality at roughly 2100 m in the central Alaska Range. Assuming the glacier area above 2100 m produces no runoff, the net ablation rate (in excess of that needed for internal accumulation) versus elevation plot of Figure 3 was developed. All low and mid-elevation ablation data were used as a guide in drawing this ablation-elevation curve. The total snow melt at high elevation, even though these areas showed a net gain of snow during summer, was then approximated by integrating this ablation-elevation relation over the area between the equilibrium line and 2100 m. The total snow melt is the sum of the water contained in the snow that fell below the equilibrium line in both summer and winter, and the calculated amount of melt from above (Table 1).

TABLE 1. Annual runoff from snow melt, firn and ice melt, and rain from the Susitna basin glaciers during 1981, 1982 and 1983. These data are averaged over the glacier area above the indicated stream gauges, not the basin area.

<u>Year</u>	<u>Stream Gauge</u>	<u>Glacier Snow Melt m/yr</u>	<u>Firn and Ice Melt m/yr</u>	<u>Glacier Rain Runoff m/yr</u>	<u>Total Glacier Runoff m/yr</u>
1981	Maclaren R. near Paxson	0.57	0.42	0.33	1.3
	Susitna R. at Denali	0.54	0.93	0.33	1.8
	Susitna R. at Gold Creek	0.54	0.83	0.33	1.7
1982	Maclaren R. near Paxson	0.68	0.51	0.25	1.4
	Susitna R. at Denali	0.55	0.95	0.25	1.8
	Susitna R. at Gold Creek	0.57	0.86	0.25	1.7
1983	Maclaren R. near Paxson	0.71	0.36	0.17	1.2
	Susitna R. at Denali	0.53	0.77	0.17	1.5
	Susitna R. at Gold Creek	0.56	0.69	0.17	1.4
Average	Maclaren R. near Paxson	0.65	0.43	0.25	1.3
	Susitna R. at Denali	0.54	0.88	0.25	1.7
	Susitna R. at Gold Creek	0.56	0.79	0.25	1.6

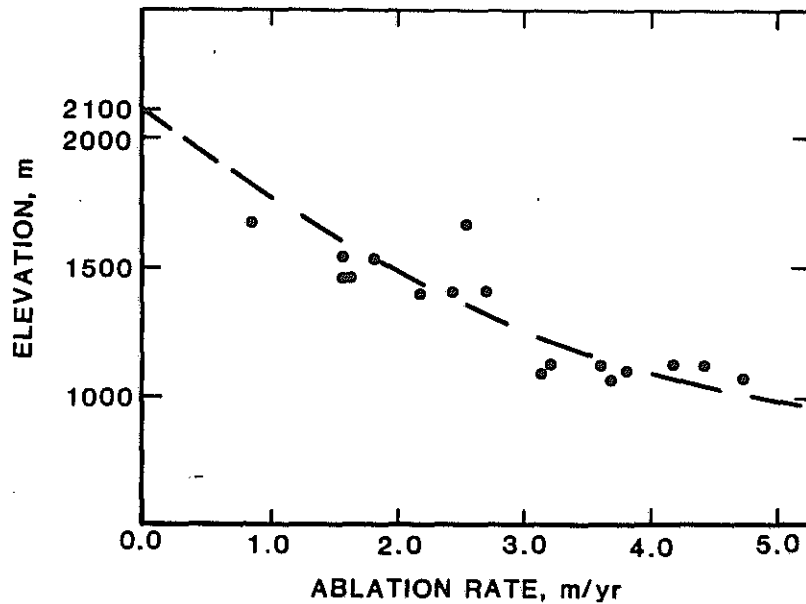


Figure 3. Ablation per year, in excess of that refrozen by internal accumulation, versus elevation for 1981-1983 in the Susitna basin, Alaska. Ablation is given in meters of water equivalent.

Firn and Ice Melt

The firn and ice melt is the amount of summer melt produced below the equilibrium line in excess of the past winter's snowpack. Firn and ice melt for each year and stream gauge are listed in Table 1. It is this melt water that makes glacierized basins different from unglacierized basins. It provides a very large reservoir of solid water available for melt, the amount of which depends almost entirely upon summer, rather than winter meteorological conditions.

Rain

A shielded rain gauge has been maintained by R & M Consultants on a west facing slope above the confluence of the Northwest tributary and the main Susitna Glacier at 1430 m elevation since 20 July 1981 (Figure 2; R & M, 1984). The data obtained by this gauge are listed in Table 2a. The data in Table 2a were supplemented by linear regression using precipitation data from Talkeetna Airport. Any month that had only a partial record as well as April and October of 1983 were excluded from the regression analysis. April and October of 1983 were excluded because it is believed that precipitation generally falls as snow during those months on the Susitna glaciers. The resulting regression equation is:

$$P_s = 1.65 P_t - 36.5 \text{ mm} \quad (r^2 = 0.86)$$

where: P_s = precipitation on Susitna Glacier(s) in mm
 P_t = precipitation measured at Talketna Airport in mm

The supplemented data set appears in Table 2b. Mayo (Pers. comm., 1985) has found that summer precipitation almost invariably falls as snow above 1600 m and is mixed as rain and snow below 1600 m on nearby Gulkana Glacier. Assuming, for the case of the Susitna Glaciers, that all summer precipitation below 1600 m falls as rain, and all summer precipitation above 1600 m falls as snow, and assuming the catch efficiency of the R & M rain gauge to be 100%, and ignoring precipitation-elevation gradients, the average liquid precipitation on the glaciers could be determined by multiplying the rainfall in Table 2b by 0.37 since only 37% of the basin's glacier area lies below 1600 m. It was further assumed that 100% of the precipitation that fell as rain left the glacier as surface runoff, and that the water left the glaciers the same month it fell. This assumption is probably reasonable since glaciers are essentially impermeable at these lower elevations where glacier ice forms the substrate. The results of this calculation are shown in Table 1 and graphically in Figure 4. It should be pointed out that this is probably a lower limit on rainfall runoff since the catch efficiency of the gauge is likely less than 100%.

Evaporation

It is known from energy balance studies that "net" condensation, the difference between condensation and evaporation, plays a significant role in the surface energy budget of a glacier (Paterson, 1969; Sharp, 1960). Data from a number of glaciers indicate that the energy input from "net" condensation varies from near zero to about 30% of the total energy used for summer melt. However, because the ratio of the heat of vaporization to the heat of fusion is about 7.5, the upper limit of 30% in energy converts to one of 4% in mass. In other words, the ratio of condensed water to total melt water is usually less than 4%, which was considered negligible.

Table 2a. Rainfall collected by an R & M rain gauge during 1981, 1982 and 1983 at 1430 m elevation next to Susitna Glacier. Data are listed in mm. (Data courtesy of R & M Consultants.)

	<u>1981</u>	<u>1982</u>	<u>1983</u>
April	--	16.6*	13.0
May	--	26.0	2.6***
June	--	103.8	18.8****
July	--	194.2	50.8
August	300.2	78.6	242.0
September	66.7	0.4**	108.0
October	--	--	3.4
TOTAL	366.9 mm	419.6 mm	438.6 mm

*14-30 April **1-2 September ***1-10 May ****14-30 June

Table 2b. Summer precipitation on the Susitna Glaciers during 1981, 1982 and 1983. In general, summer precipitation above 1600 m elevation falls as snow (Mayo, pers. comm., 1985) and, since only 37% of the glacier area lies below 1600 m, these precipitation quantities must be multiplied by 0.37 to get approximate rainfall runoff. (N/S = Not Significant)

	<u>1981</u>	<u>1982</u>	<u>1983</u>
April	N/S	N/S	N/S
May	11*	26	16*
June	183*	104	38*
July	330*	194	51
August	300	79	242
September	67	279*	108
October	N/S	N/S	N/S
TOTAL	891 mm	682 mm	455mm

* Precipitation approximated by linear regression with Talkeetna Airport data ($r^2 = 0.86$).

Timing of Melt Runoff

Like other glacierized basins in Alaska, runoff from the upper Susitna basin, on the average, peaks in late July or early August (Chapman, 1982). This is when the air is warm, most precipitation falls as liquid, insolation is still relatively high, and a large amount of low-albedo glacier ice is exposed. If storage of early summer melt water by the glacier is ignored, the proportional monthly melt runoff can be approximated by adding the water equivalent of melt at all stakes for a given month and dividing by the melt at all stakes for the summer as a whole. This could not be done for each year owing to lack of mid-summer data, especially in 1983. All high elevation (2000 m) stakes were omitted from this analysis since summer snow accumulation obscures melt quantities.

The glacier melt distribution as calculated by this method comes out to 4%, 20%, 42%, 30% and 4% for May, June, July, August and September respectively. For comparison, the average monthly total flows at Phelan Creek, a 70% glacierized basin 40 km east of Susitna basin, were 1%, 15%, 40%, 33%, 9%, and 2% for May, June, July, August, September and October during the 1967-1978 period of record (Chapman, 1982). These percentages, although very similar, show a larger Susitna spring melt than Phelan Creek runoff, which is probably at least partly due to spring melt storage in the Phelan Creek glaciers. Since such storage is a well-known and documented phenomenon from other glaciers (Paterson, 1981; Tangborn and others, 1975; Stenborg, 1970), the average monthly Phelan Creek data were used to distribute the Susitna glaciers' melt water, even though it is a different basin and the data are for different years. The results are shown in Figure 4.

GLACIER WATER AND TOTAL WATER AT STREAM GAUGES

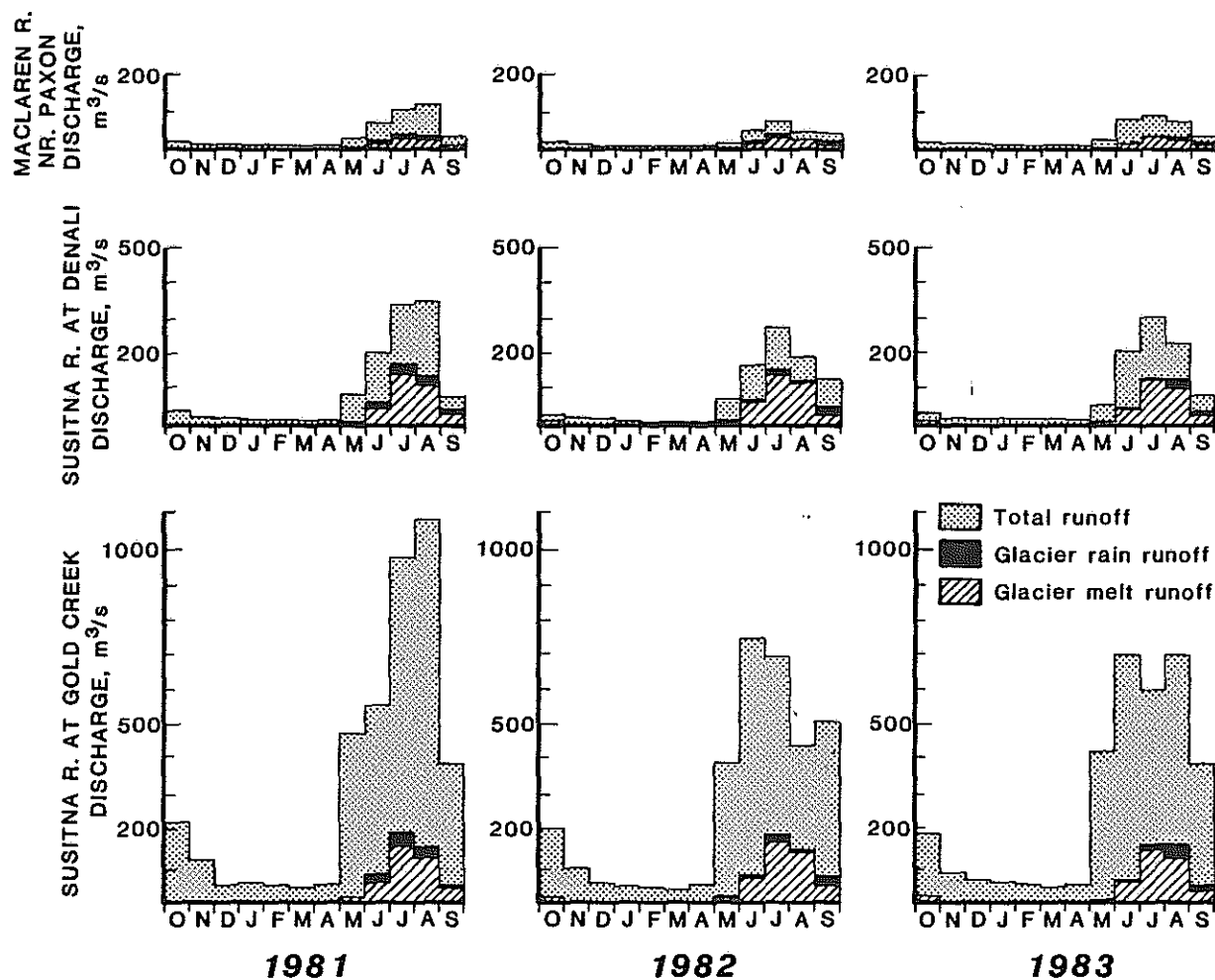


Figure 4. Runoff from glaciers compared to total runoff at stream gauges on the Susitna and Maclaren Rivers. The ice above the Maclaren River near Paxon gauge contributed a proportionally lower quantity of water because Maclaren Glacier had positive average annual balances during all three years of the study.

Glacier Mass Balance

Glacier mass balance is a measure of the gain or loss of glacier mass, and its distribution over the glacier and over time. The average mass balances of the Susitna basin glaciers during 1981, 1982 and 1983 were estimated by integrating the point balance measurements over the glacier surface, and dividing by the total glacier surface area. The results of these integrations can be found in Table 3. The average annual balance indicates the "health" of a glacier, as it represents the mass gain or loss in a given year. For ease of calculation, the dates chosen to divide one year from the next coincide with the hydrologic year, 1 October to 30 September.

The 1983 average annual balance shown in Table 3 for Susitna Glacier is probably an upper limit. In 1981 and 1982 three high elevation stakes were monitored at various points in the basin (Figure 2), but in 1983 only one high elevation stake was monitored and this stake had shown higher accumulation rates than the other two stakes. No adjustment was made to account for this possible overestimation. For comparison, if the one 1983 high elevation stake is used to calculate 1981 average annual balance, the result is -0.09 m rather than -0.30 m, or 0.21 m greater.

Table 3. Average Annual* Balances (meters water equivalent)

<u>Glacier</u>	<u>1981</u>	<u>1982</u>	<u>1983</u>
West Fork**	-0.01	-0.24	+0.12
Susitna**	-0.30	-0.22	+0.40 [#]
East Fork**	-	-0.20	+0.09
MacLaren**	+0.31	+0.14	+0.37
Weighted Average:	-0.05 ^{##}	-0.15	+0.26
Total change over period of study:	+0.06 ± 0.60 m		

* 1 October-30 September

** Error on individual balances is estimated to be ± 0.40 m (Clarke and others, 1985).

The 1983 average annual balance for Susitna Glacier is probably an upper limit. See text for explanation.

Assumes East Fork Glacier's balance was -0.30 m

DISCUSSION AND CONCLUSIONS

The primary objective of the work described here has been to assess the impact of high-elevation glacierized areas on the flow of the Susitna River above Gold Creek. Melt and accumulation data obtained on the glacier surfaces in 1981, 1982, 1983 were used for the analysis. The

interpretation of the data serves three purposes: first, to provide an estimate of the amount of water produced by different sources on the glaciers; second, to provide an estimate of the timing of this runoff; third, at least in principle, to assess glacier volume change over the 1981-1983 period as an indication of whether the glaciers are, at present, growing or shrinking.

The conclusions are as follows:

- (1) Averaged over 1981, 1982 and 1983, roughly 36% of the water flow from above the Denali Highway originated on the 25% (790 km²) glacier cover, and about 13% of the Susitna River flow at Gold Creek originated on the 4.9% glacier cover above that gauge (exclusive of the glaciers in the Talkeetna Mountains) (Table 4). Of the roughly 1.6 m/yr (40.1 m³/s) discharge from the glaciers, 0.56 m/yr came from snow melt, 0.79 m/yr came from ice and firn melt and about 0.25 m/yr came from rain (Table 1). Flow from the unglacierized portion of the basin above the Denali Highway averaged about 0.95 m/yr; flow from the basin above the Denali Highway as a whole was 1.1 m/yr; flows through the Susitna River at Denali, MacLaren River near Paxon and Susitna River at Gold Creek gauges were 1.1 m/yr, 1.2 m/yr and 0.59 m/yr (Table 4), respectively. For comparison, the smaller Phelan Creek drainage, 70% glacierized and 40 km to the east, produced about 2.02 m/yr from 1967 to 1979 (Mayo, 1984), which indicates the 1.6 m/yr for the Susitna basin glaciers is probably a conservative estimate.
- (2) If the average monthly measured runoff from 1967-1978 for Phelan Creek (Gulkana Glacier) is taken as representative for the 1981-1983 melt runoff from the Susitna Glaciers, the resulting flow distribution is 1%, 15%, 40%, 33%, 9% and 2% for May, June, July, August, September and October (Figure 4).
- (3) For 1981, 1982 and 1983 the average annual glacier balances (in m water equivalent, weighted according to glacier area) were $-0.05 + 0.40$ m, $-0.15 + 0.40$ m and $+0.26 + 0.40$ m, respectively (Table 3). Based on these data, which add to a net gain of $+0.06 + 0.6$ m for the three year period, it appears that the glaciers were in approximate equilibrium for these years, but the error is so large that this cannot be said with much confidence.

With only one measurement point per 50 km², this can, at best, be considered a reconnaissance level study. An even more serious problem may be its short (3 year) duration, which has given but little perspective into the year-to-year variability of the water supply from glaciers. If it is assumed that glacier runoff during 1969, a drought year, was similar to that of the 1.6 m/yr 1981-1983 average, then 30% of the flow in the Susitna River at the Watana dam site and 26% at the Devil Canyon site was glacier runoff. These percentages are based on flows calculated by Acres American (1982) at the respective dam sites. The assumption that 1.6 m of water came from the glaciers in 1969 is probably reasonable because, while there was less snow melt and rain runoff from the

Table 4. Comparison of glacier runoff and total runoff. The years in parentheses below each stream gauge refer to the time period over which river flow averages were taken. All glacier runoff data are the average of 1981-1983 data. Runoff at the two dam sites, (3) and (4), do not strictly compare because streamflow data are for a different time period than glacier data.

Gauge Site	Basin Area above Stream Gauge (km ²)	Average Gauged Flow (m ³ /s)	Glacier Area (km ² /%)	Glacier Melt Runoff (m ³ /s) (%)	Glacier Melt plus Glacier Rain Runoff (m/yr) (m ³ /s) (%)
(1) Maclaren River at Denali Highway (1981-1983)	730	28.3	160*/22	5.48 19	1.33 6.7 24
(2) Susitna River at Denali Highway (1981-1983)	2460	83.6	628/25	28.3 34	1.67 33.4 40
Sum of (1) and (2)	3190	112	790*/25	33.8 30	1.60 40.1 36
(3) Susitna River at Watana Dam Site (1949-1981 calculated flow***)	13,420	224	790*/5.9	33.8 15	0.09 40.1 18
(4) Susitna River at Devil Canyon Dam Site (1949-1981 calculated flow***)	15,050	258	790*/5.2	33.8 13	0.08 40.1 15
(5) Susitna River at Gold Creek** (1981-1983)	15,950	299	790*/4.9	33.8 11	0.08 40.1 13

* Area is not known accurately because Eureka Glacier straddles the drainage divide.

** Numbers do not include glaciers in the Talkeetna Mountains.

*** From Acres American, 1982.

glaciers, the lower albedo glacier ice and firn must have provided considerably more runoff. And finally, the problem of long term (30 year) glacier volume change and its effects on runoff in the Susitna River Basin has not been addressed. This problem is addressed by R & M and Harrison (1981), Harrison and others (1983) and Clarke (1985). The most recent estimates by Clarke (1985) indicate that on the order of 3-4% of the Susitna River discharge at Gold Creek has been from long term decrease of glacier volume rather than the 13% originally estimated by R & M and Harrison (1981) and Harrison and others (1983) in an earlier reconnaissance level study.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge that this work is the result of many people's efforts. For the field efforts, credit is especially due to Carl Schoch of R & M Consultants and Clifton Moore of the University of Alaska, as well as Steven and Randy Bergt and Elizabeth Senear also of the University of Alaska. We are grateful to Steven Bredthauer of R & M Consultants for his advice and perspective and for providing rain gauge data. Lawrence Mayo, Dennis Trabant and Rod March of the U.S. Geological Survey and Carl Benson of the University of Alaska all helped with ideas concerning snow accumulation and metamorphism, and mass balance in general. We wish to thank Eugene Gemperline of Harza Engineering and Lawrence Mayo for their critical reviews of the manuscript. Cooperating companies and or agencies have been R & M Consultants, Acres American Inc., Harza-Ebasco Susitna Joint Venture, North Pacific Aerial Surveys, the Alaska Power Authority and the State of Alaska Division of Geological and Geophysical Surveys. Helicopter support was supplied by Air Logistics. Finally, financial support has been from the Alaska Power Authority, the State of Alaska Division of Geological and Geophysical Surveys, and the University of Alaska.

REFERENCES

- Acres American Inc. 1982. Susitna hydroelectric project; feasibility report. Final draft report for the Alaska Power Authority, Anchorage, AK. 8 vols.
- Anonymous. 1969. Mass balance terms. Journal of Glaciology. 8(52):3-7
- Chapman, D. L. 1982. Daily flow statistics of Alaskan streams. NOAA Technical Memorandum NWS AR-35. 57 pp.
- Clarke, T. S. 1985. Glacier Runoff, Balance and Dynamics in the Upper Susitna River Basin, Alaska. M. S. Thesis. University of Alaska, Fairbanks. In preparation.
- Clarke, T. S., D. Johnson and W. D. Harrison. 1985. Glacier mass balances and runoff in the upper Susitna and Maclaren River basins, 1981-1983. Final Report to Harza-Ebasco Susitna Joint Venture. 51 pp.

- Fountain, A. G., and W. V. Tangborn. 1985. The effect of glaciers on stream flow variations. *Water Resources Research*. 21(4):579-586.
- Harrison, W. D., B. T. Drage, S. Bredthauer, D. Johnson, C. Schoch and A. B. Follett, 1983. Reconnaissance of the glaciers of the Susitna basin in connection with proposed hydroelectric development. *Annals of Glaciology*. 4:99-104.
- Mayo, L. R. 1984. Glacier mass balance and runoff research in the U.S.A. *Geografiska Annalar*. 66A(3):215-227.
- Mayo, L. R. 1985. Personal communication. U. S. Geological Survey, Cold Regions Hydrology Project Office, 101 12th Ave., Fairbanks, Alaska, 99701.
- Mayo, L. R., M. F. Meier, and W. V. Tangborn. 1972. A system to combine stratigraphic and annual mass-balance systems: a contribution to the International Hydrological Decade. *Journal of Glaciology*. 11(61):2-14.
- Paterson, W. S. B. 1969. *The Physics of Glaciers*. Pergamon Press, New York, N.Y. 250 pp.
- Paterson, W. S. B. 1981. *The Physics of Glaciers*, 2nd ed. Pergamon Press, New York, N.Y. 380 pp.
- R & M Consultants. 1984. Field data index; Susitna hydroelectric project. Final report to the Alaska Power Authority. Document no. 1660. 90 pp.
- R & M Consultants and W. D. Harrison. 1981. Alaska Power Authority Susitna Hydroelectric Project; task 3 - hydrology; glacier studies. Report for Acres American, Inc., Buffalo, N.Y. 30 pp.
- R & M Consultants and W. D. Harrison. 1982. Alaska Power Authority Susitna Hydroelectric Project; task 3 - hydrology; glacier studies. Report for Acres American, Inc., Buffalo, N.Y. 22 pp.
- Sharp, R. P. 1960. *Glaciers*. University of Oregon Press, Eugene, Oregon. 78 pp.
- Stenborg, T. 1970. Delay of runoff from a glacier basin. *Geografiska Annalar*. 52A:1-30.
- Tangborn, W. V., R. M. Krimmel and M. F. Meier. 1975. A comparison of glacier mass balance by glaciological, hydrological and mapping methods, South Cascade Glacier, Washington. *IAHS*. 104:185-196.
- Trabant, D. C. and L. R. Mayo. 1984. Effects of internal accumulation on five glaciers in Alaska. *Annals of Glaciology*. 6: in press.
- U.S.G.S., U.S. Geological Survey Water Data Reports, 1949-1983.

GROWTH OF WOLVERINE GLACIER, ALASKA;
DETERMINED FROM SURFACE ALTITUDE MEASUREMENTS, 1974 AND 1985

by Lawrence R. Mayo, Rod S. March, and Dennis C. Trabant (1)

ABSTRACT

Precision surveys of the glacier surface altitude in 1974 at 73 locations along a longitudinal and three transverse profiles of 18.1 square kilometer Wolverine Glacier were made to provide baseline data to help understand the present regime of glaciers in Alaska. In 1985, 66 of these sites were remeasured to determine glacier thickening and thinning during the 11-year interval.

The accumulation zone and the upper part of the ablation zone of the glacier thickened about 5 meters with a net gain of 70×10^6 cubic meters. The lower part of the ablation zone thinned with more than 30 meters of loss at the terminus and with a net loss of 15×10^6 cubic meters. The glacier thus gained 55×10^6 cubic meters or an average thickness increase of 3.0 ± 0.7 meter at an average rate of 0.28 meters per year. This verifies an earlier measurement of glacier growth at Wolverine Glacier caused by recent increases in precipitation (Mayo and Trabant, 1984).

The different responses in the two zones of the glacier indicate that a hydrologically significant climate shift has occurred and that the glacier flow is not in equilibrium with present conditions. Runoff has been less than precipitation during this period of glacier growth.

INTRODUCTION

Glacier recession during this century in Alaska has been common, but not universal. It is important to know whether glaciers are growing or shrinking at the present time because that bears significantly on hydrological interpretations of precipitation and river runoff. Furthermore, some predictive value can be gained about future glacier conditions if the current glacier regime is known. The present health of glaciers cannot be determined from measurements of glacier terminus position or thickness change because of the time delay effects of glacier flow. However, glacier terminus position changes may have information about climatic events in the past and direct measurements on the glaciers are required to assess present conditions.

Wolverine Glacier (60.4°N , 148.9°W) on the Kenai Peninsula, Alaska, is studied by the U.S. Geological Survey to investigate climate, glaciers, and glacier-fed rivers. The glacier terminus is receding, but mass balance measurements at three sites indicate that glacier growth is occurring, and the growth is related surprisingly to climatic warming with associated increases in mountain precipitation, especially snow fall (Mayo and Trabant, 1984). Mass balance measurements have the

(1) U.S. Geological Survey, 101 12 th Ave., Fairbanks AK 99701

problem, however, that numerous measurements are made over time and eventually becomes much larger than the measurement. Also, the three measurement sites at Wolverine Glacier may not adequately represent the entire glacier. Thus, direct measurements of glacier volume change are desirable to verify estimates based on mass balance data.

GLACIER SURFACE SURVEYS

Precision surveys of the glacier surface altitude at 73 locations along a longitudinal and three transverse profiles of Wolverine Glac. (fig. 1)

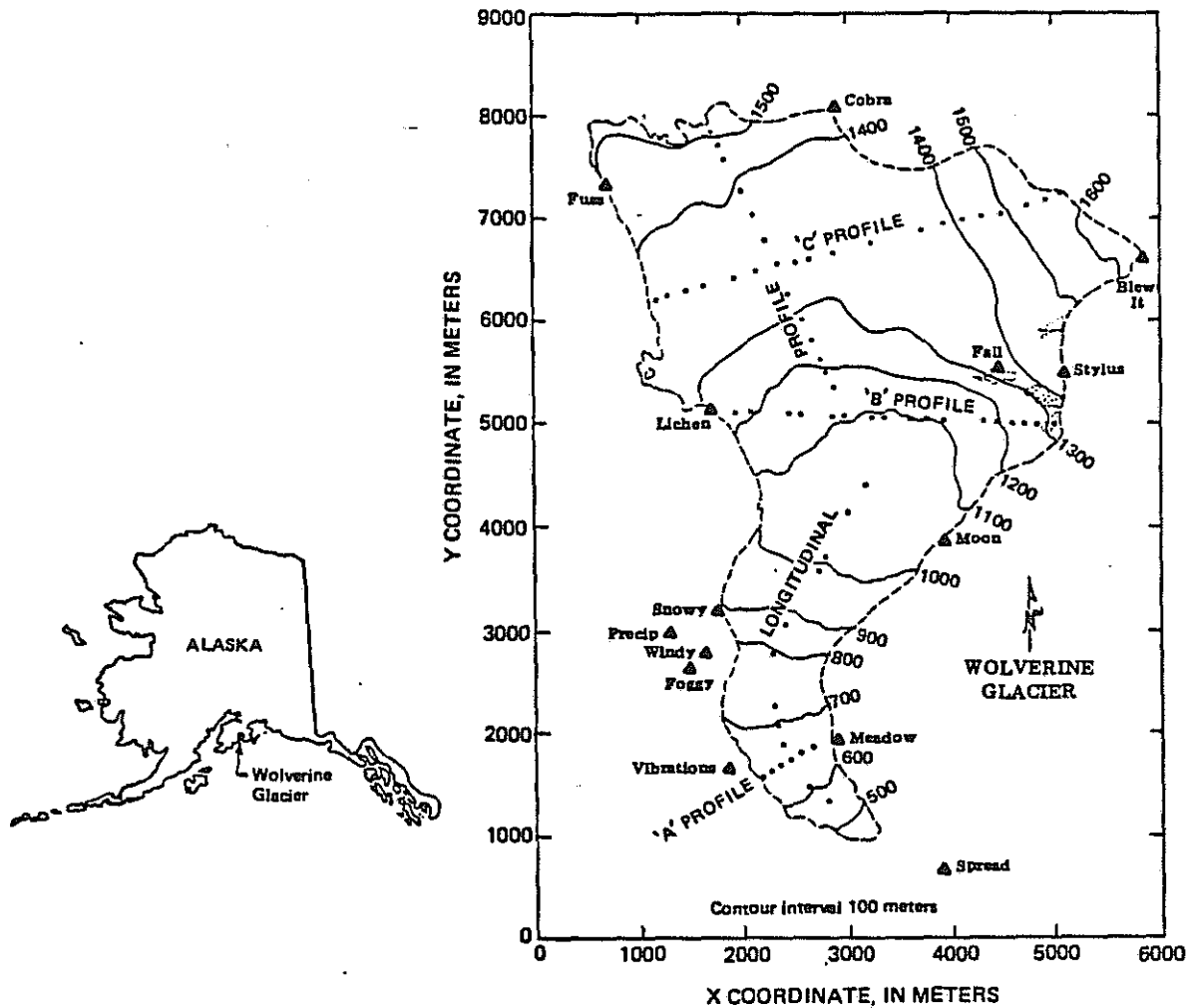


FIGURE 1. Map showing location of altitude measurement sites on Wolverine Glacier, Alaska. Survey monument locations shown by triangles. Altitude contours on glacier surface in meters. Horizontal position coordinate grid is based on the Universal Mercator Projection.

were made on March 10-12, 1974 as baseline data for subsequent volume change surveys. In 1985, 66 of these sites were remeasured successfully on June 8-15 to determine the amount and location of glacier thickening

and thinning that had occurred during the 11-year interval (fig 1). Several sites that were not remeasured in 1985 were not visible from survey monuments due to glacier surface changes. A few other sites lacked valid comparisons due to unknown errors in surveying in 1974 or 1985.

Relocation in 1985 of the 1974 measurement sites was accomplished by pre-calculating the horizontal angle, vertical angle, and slope distance from several geodetic control monuments to each glacier site. Corrections for instrument errors such as horizontal angle drift and air density errors on microwave distance measurement equipment were made in the field. All but 6 relocations were within 1.0 m (meter) of the 1974 sites. The average position error between the 1974 and 1985 surveys was 0.56 m. The average slope of the glacier is 0.14 so the average vertical error due to position error is only 0.04 m. The horizontal coordinate system used (fig. 1) is arbitrarily located parallel with the Universal Transverse Mercator Zone 6 and originating at 392,000mE, 6,693,000mN.

Geodetic surveys in both 1974 and 1985 included measurements of atmospheric refraction by techniques explained by Mayo and others (1979, p. 9-13) and were corrected for observed variations. Briefly, atmospheric refraction is detected by observing precisely the apparent height between two monuments whose coordinates are known with high accuracy, and then comparing the observation with the actual height. The difference between the actual and observed height differences is due to light refraction and earth curvature. The accuracy of the vertical measurements was within 0.03 m, but local variations in surface height due to glacier roughness at each measurement site caused a further uncertainty of .01 to .10 m. Thus the overall uncertainty of each altitude measurement is 0.10 m or less. The uncertainty of the calculated altitude change at each site is within 0.2 m.

OBSERVED CHANGES IN GLACIER SURFACE ALTITUDE

The surveys of 1974 and 1985 were not made during the same month, so part of the difference in measured glacier surface altitude is due to the seasonal effects of different snow depth and glacier flow. To correct for these factors, the seasonal variations of thickness change (fig. 2) was measured at the three sites where the profiles intersect. To obtain altitude comparisons on the same date, either the 1974 baseline altitude data must be raised or the 1985 measurements reduced, both producing the same results. The uncertainty of estimating the altitude in March 1985 (fig. 2) to obtain the seasonal correction is approximately 0.5 m.

The longitudinal profile resurvey (fig. 3) shows that a long reach of the glacier thickened. All of the normal accumulation zone (average rather than for a specific year) and the upper part of the normal ablation zone of the glacier thickened about 5 m (fig. 3). In contrast, the lower part of the ablation zone thinned progressively toward the terminus with more than 30 m of thinning occurring near the terminus. In detail, changes from point to point are more variable in the accumu-

lation zone than in the ablation zone of the glacier. The reason for this is unclear, but may be due to wind effects on the distribution of snow. There is much more wind and snow high on Wolverine Glacier than at low altitudes. The single point of measured thinning in the accumulation zone is at a location that was on top of a large serac between crevasses in 1974 but was in a snow-filled crevasse between seracs in 1985. Thus, this measurement is not to be interpreted as indicating glacier thinning.

Along transverse profile "C" there is a striking uniformity of glacier thickening (fig. 4). The lack of thickening 2200 m east of the centerline is caused by the fact that the height of the glacier surface is controlled by wind deposition of snow behind the crest of a rock ridge. Snow does not accumulate higher than the ridge top. The snowy part of the ridge on the lee (glacier) side of the rock ridge is much broader in 1985 than it was in 1974.

Transverse profile "A" shows strong thinning averaging about 11 m. The western-most point, originally near the glacier margin, is now off the glacier, so the thinning is less than average because it simply ran out of ice to melt. The adjacent point is in a gully at the glacier margin where the melt rate may be unusual due to radiation from adjacent land and the ice replacement rate by glacier flow is probably diminishing to produce a rapid thinning rate. These "edge effects" are not important for glacier volume change calculations.

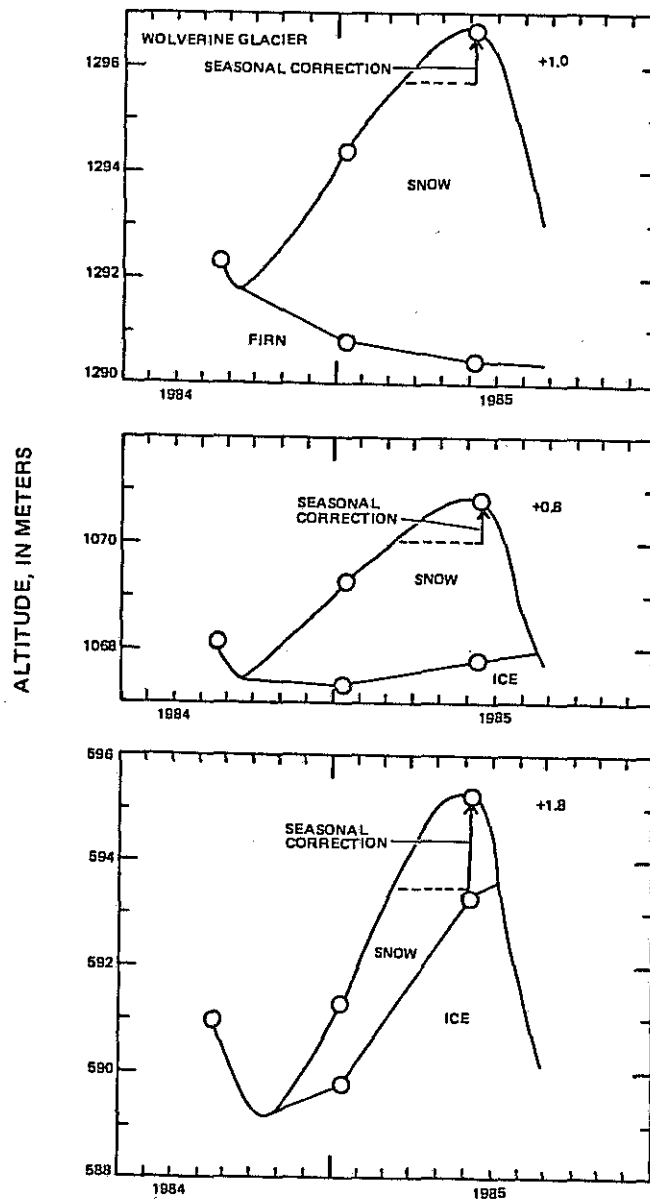


FIGURE 2. Measured altitude change during 1985 at points on Wolverine Glacier where the profiles intersect. The seasonal altitude correction is for the period March 11 to June 12, 1985.

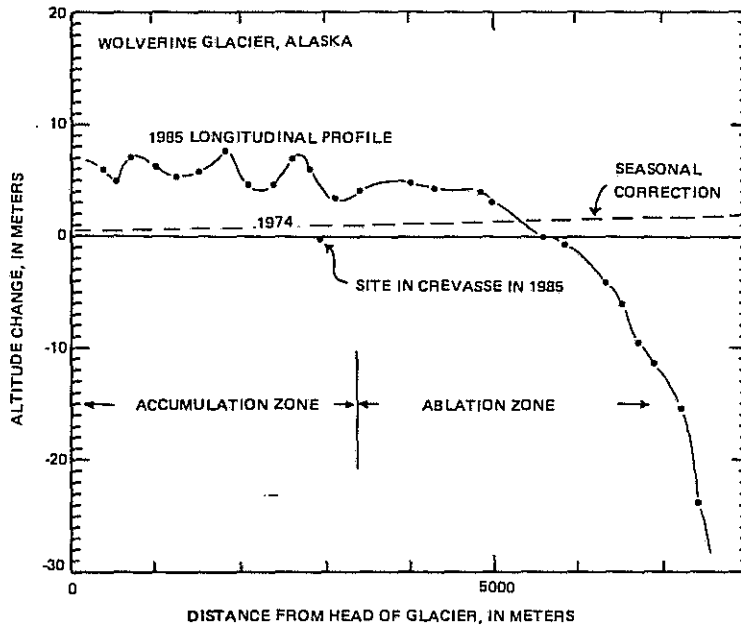


FIGURE 3. Measured changes in altitude of the glacier surface along the longitudinal profile of Wolverine Glacier. The seasonal correction of the 1974 base line is needed because the survey dates in 1974 and 1985 were not identical.

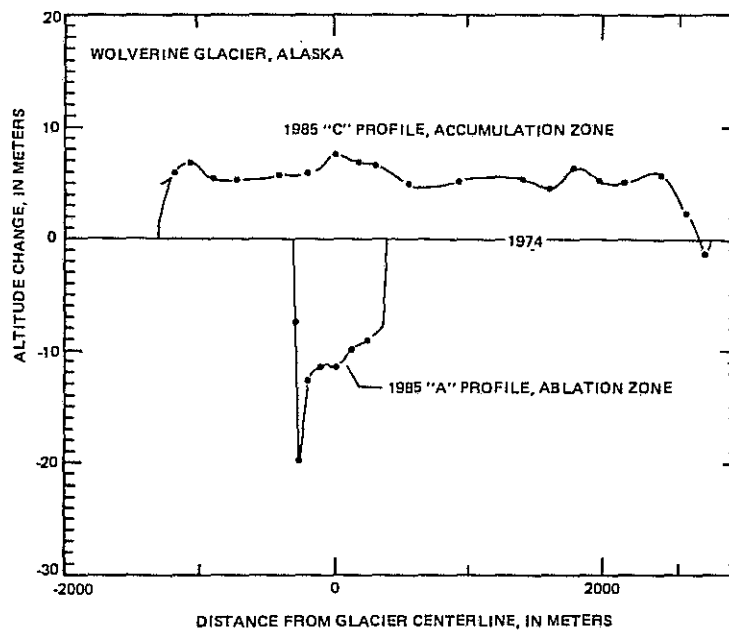


FIGURE 4. Measured changes in altitude of the glacier surface along transverse profiles "C" and "A" of Wolverine Glacier. The positive horizontal direction along each profile is east, zero is at the point where the longitudinal profile intersects.

Large thickness change variations occurred on the eastern section of transverse profile "B" (fig. 5). One area of thickening of more than 10 m corresponds with an area that receives ice block avalanches from a precipitous ice fall. The other area with a measured thickening of 17.4 m is where rocks from a cliff roll onto the snow in the accumulation zone. There, part of the accumulation is rock and part is snow. A recent rock fall was exposed at the surface in June 1985. On the down-wind side of both of these areas of anomalously great thickening are zones of less than average thickening. It is judged that both rocks and ice blocks on the glacier intercepted wind-blown snow.

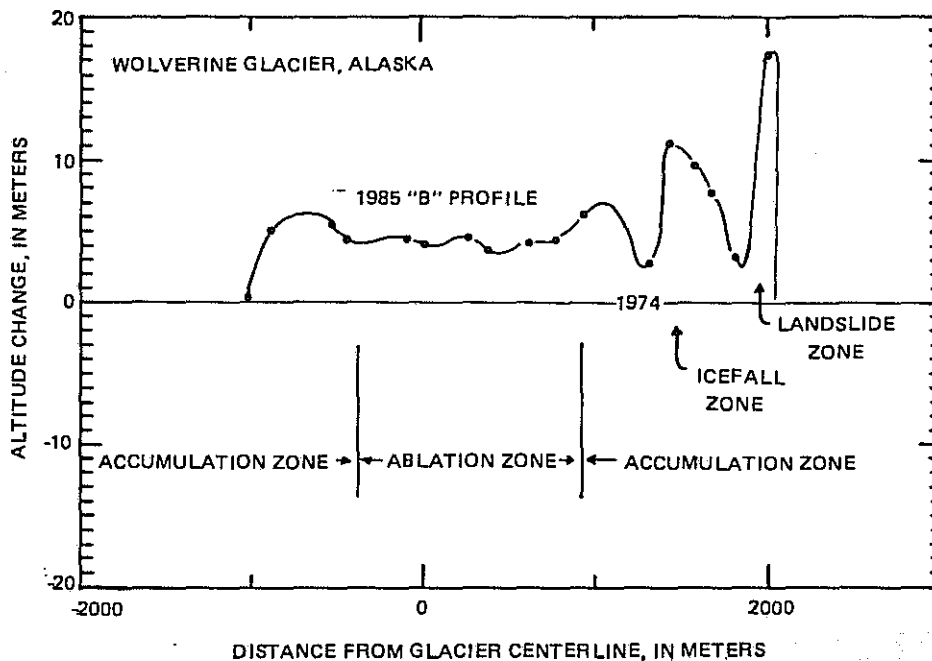


FIGURE 5. Measured changes in altitude of the glacier surface along transverse profile "B" of Wolverine Glacier. The positive distance along the profile is east from the longitudinal profile.

VOLUME CHANGE OF THE GLACIER

Two methods can be used to calculate the total volume change of the glacier from the point measurements. Either the thickness change can be contoured, or the average thickness change with altitude can be integrated with the area/altitude distribution. The latter is easier if there is a reasonably uniform distribution of change in thickness with altitude.

All altitude change measurements were plotted on one graph (fig. 6). Significant outliers from the central group have been explained already and all are on the glacier's edge except one caused locally by a crevasse. All the data define well a general change of glacier surface altitude as a function of altitude, so integration of this relationship with the area/altitude distribution is judged to be adequate to calculate glacier volume changes.

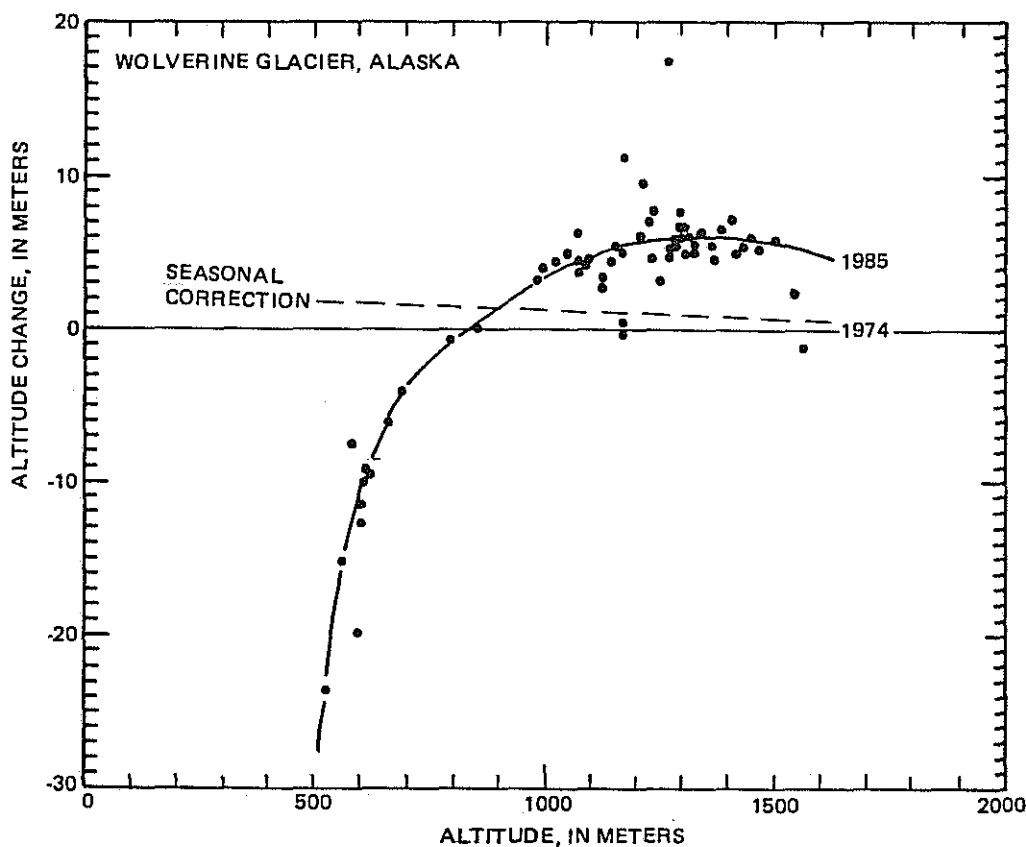


FIGURE 6. Change in surface altitude of Wolverine Glacier as a function of altitude. Data from all profiles are shown.

Even though the ice thinned more than 30 m near the terminus, only 2.0 km² (square kilometers) of area was involved, so a volume loss of only 15×10^6 m³ (cubic meters) occurred. The area of Wolverine Glacier that thickened, the upper ablation zone, and accumulation zone is much larger, 16.1 km². This area gained 70×10^6 m³ in volume.

The average thickness change of the glacier (fig. 7) is the volume change (55×10^6 m³) divided by the glacier area (18.1 km²). This calculation yields an average increase of 3.0 ± 0.7 m. This is an average thickening rate of 0.28 m per year from 1974 to 1985. For comparison, the average measured runoff rate from the basin is 3.14 m/yr.

Three sources of error must be combined. The surveying error already reported was 0.2 m. A larger uncertainty is the seasonal correction, already estimated to be 0.5 m. In addition, the uncertainty of generalizing the altitude distribution of altitude change is about 0.5 m also. Using the rule that the error of the sum of errors is the square root of the sum of the squares of the individual errors, the total error is 0.7 m.

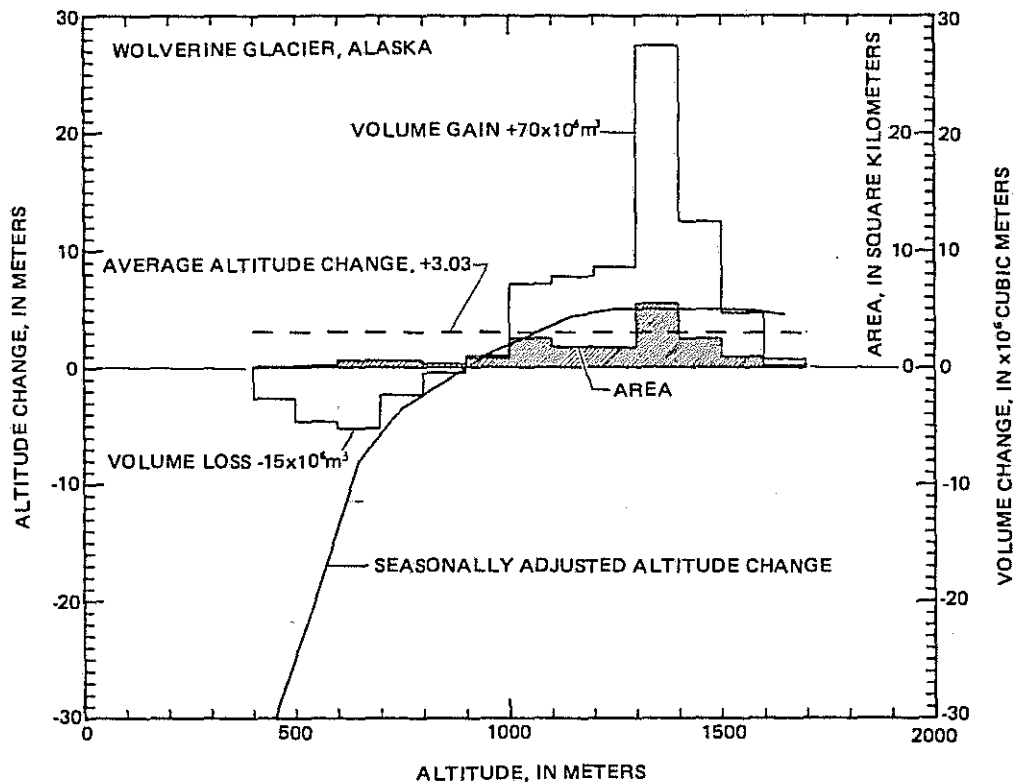


FIGURE 7. Variations of seasonally-corrected altitude change, surface area, and volume change of Wolverine Glacier as a function of altitude.

CONCLUSIONS

Earlier work (Mayo and Trabant, 1984) concluded that for much of this period (1977-1981) temperatures were warmer and that ablation, accumulation, and runoff rates were greater than in the preceding 9-year interval (1968-76). The observed thinning of the ablation zone and thickening of the accumulation zone reported here for the period 1974-1985 tend to agree with these conclusions and substantiate the notion that the glacier grew during a relatively warm period due to an increase in accumulation which exceeded the simultaneous increase in ablation.

The rapid thinning near the terminus is probably due also to the delayed effects of a previous period of negative glacier mass balance (overall glacier thinning) that propagated to the terminus by glacier flow. Because these effects are not sustained by the current positive regime of the glacier, the wave of glacier thickening will travel to the terminus. This will eventually halt the current recession and the glacier will then advance. Of course, the climate could shift again, and this simple prediction would be in need of modification.

An important hydrological consequence of these measurements is that the average precipitation regime in the mountains is increasing more rapidly than runoff since storage is increasing.

It is assumed by many glaciologists, that the gradient of glacier mass balance with altitude remains constant while the overall mass balance and equilibrium altitude varies from year to year due to shifts in the position of the balance gradient. Simultaneous increase of accumulation high on Wolverine Glacier and increase of ablation low on the glacier is evidence for a steepening of the mass balance gradient. Thus, the assumption of constant gradient may not always be correct and it may be necessary to measure the variability of glacier mass balance gradients for a particular glacier or region rather than to assume the variability to be zero.

It is likely that other glaciers of the region are growing at present and are likewise subject to eventual advances. An average thickness increase of 4.3 ± 5.5 m was measured at Nuka Glacier, also on the Kenai Peninsula (Bredthauer and Harrison, 1984). Gulkana Glacier, Alaska Range, also recently began to grow (Mayo and Trabant, in press). Thus, the extent of this recent shift to glacier growth is probably large.

ACKNOWLEDGEMENTS

Critical reviews including many helpful suggestions were given by Chet Zenone, U.S. Geological Survey, Anchorage, and by W.D. Harrison, University of Alaska, Fairbanks. We thank these colleagues for their valuable comments.

REFERENCES

- Bredthauer, S.R. and Harrison, W.D., 1984, Impact of glaciers on long-term basin water yield, in Alaska's water, a critical resource: Fairbanks, Univ. Alaska, Inst. Water Resources Report IWR-106, p. 51-59.
- Mayo, L.R. and Trabant, D.C., 1984, Observed and predicted effects of climate change on Wolverine Glacier, southern Alaska, in McBeath, J.H., Juday, G.P., Weller, Gunter, and Murray, Mayo, eds., The potential effects of carbon dioxide-induced climate change in Alaska: Fairbanks, Univ. Alaska Misc. Pub. 83-1, p. 114-123.
- Mayo, L.R. and Trabant, in press, Recent growth of Gulkana Glacier, Alaska Range, and its relation to glacier-fed river runoff, in Subitzky, Seymour, ed. Selected Papers in the Hydrologic Sciences, 1985: U.S. Geological Survey Water-Supply Paper.
- Mayo, L.R., Trabant, D.C., March, Rod, and Haerberli, Wilfried, 1979, Columbia Glacier stake location, mass balance, glacier surface altitude, and ice radar data, 1978 Measurement Year: U.S. Geological Survey Open-File Report 79-1168, 72 p.

FISH PASSAGE DESIGN CRITERIA FOR CULVERTS

by Douglas L. Kane¹ and Paula M. Wellen²

ABSTRACT

Ideally, culverts are designed to pass an instantaneous peak flow of a specified return period. This design should not prevent fish from migrating upstream through the culvert. When fish are delayed, it is desirable to keep this delay to a minimum to prevent harmful effects to the fish population. The present design criterion assumes that fish can withstand some delays, but they must eventually be able to swim upstream through a culvert against the mean velocity that results from the mean annual flood. Theoretically, the return period for a mean annual flood is slightly greater than two years, while the design flow for a culvert may be 5, 10, 25 or even 50 years depending upon the type of structure. We discuss the limitations of the above design criterion, particularly the methodology of using mean velocity. We propose a more realistic approach using the velocity that exists in the occupied zone (the area of the culvert where fish generally swim when migrating upstream). This zone is located along the outside boundary where the lowest velocities in the cross section are found.

INTRODUCTION

Fish passage through culverts in Alaska is a very real and important problem. In the design of a culvert, one is interested in passing the required quantity of the design flow and, at the same time, not significantly retarding the passage of fish. It is much easier to make this general statement on design criteria than it is to actually develop the specific criteria that lead to both successful passage of the fish and an economical structure.

During the summers of 1982 and 1983, an extensive field program to study the performance of in-place culverts with emphasis on fish passage and hydraulic design criteria was performed. Two objectives of this project that were intended to complement the field program were:

- a) review and assess the current knowledge and design practices of fish passage through drainage structures with regard to conditions in Alaska; and

1 Associate Professor, Institute of Water Resources/Engineering Experiment Station, University of Alaska-Fairbanks, Fairbanks, AK 99775-1760.

2 Staff Engineer, CH2M Hill, 2550 Denali Street, Anchorage, AK 99503, formerly graduate student at University of Alaska-Fairbanks.

- b) develop conceptual improvements and/or recommend design modifications of culverts for improved fish passage.

One of the recommendations to come out of this study was that the use of the mean velocity, as the design velocity, should be discontinued. The rationale for this conclusion is that when fish are migrating upstream, they take the path of least resistance. The path of least resistance exists where the velocities are the lowest, and this occurs along the boundary. In addition, if a design engineer wants to alter the velocity in the culvert, he can increase the boundary roughness or install baffles. These modifications reduce the local velocity around the boundary more significantly than the mean velocity for the entire structure. This paper presents a case for using the velocity in the occupied zone rather than the mean velocity when designing for fish passage.

EXISTING CULVERT DESIGN CRITERIA

The selection of the flood design frequency for culverts depends upon the type of structure, as well as economic and safety considerations. The design flow can have a return period from 5 to 50 years. The procedure for the determination of design flows of a given return period is quite simple and numerous techniques exist. However, the accuracy of these techniques is questionable. Ideally, one would use data collected at the proposed stream crossing and analyze the data using either the Log Pearson III method or some other probability distribution. Unfortunately, very few gaging stations exist in the state; if they did exist, they would most likely not be located at the crossing site. Two other problems are that the record length of most gaging stations in Alaska is relatively short and most of the gaging stations are located on larger drainages where bridges are generally installed. Because of these limitations, other methods have been developed to estimate design flows. Lamke (1979) used multiple regression techniques to derive equations of flow for a specified return period. His regression equations are based on both physical and climatic characteristics: surface storage in lakes and ponds, drainage area, quantity of forested land, annual precipitation and mean minimum January temperature. Kane and Janowicz (1985) divided the state into three hydrologic regions and developed equations to predict flows of various return periods for each region.

When designing a culvert in Alaska, the design discharge used to determine design velocities for fish is not the same as that used to size the culvert. Instead, the mean annual flood is determined for the drainage area, and the mean velocity resulting from this design flood is used to determine whether the culvert is acceptable for fish passage. If the design velocity is near what is now considered to be the ultimate swimming capability of the design fish, the design fish will be delayed in its migration any time the actual flow exceeds the peak of the mean annual flood. The length of the delay will depend upon the duration and magnitude of the resulting flow.

The magnitude of the mean annual flood can be determined in a manner similar to design flow used in sizing the culvert. Mean annual flood has a return period of approximately 2.33 years; this is physically equivalent to bank full conditions.

Acceptable velocities for fish passage through culverts are derived from relatively few field studies. Although numerous reports are available relative to fish swimming performance, a review of these papers reveals that a small core of papers are repeatedly cited. Most of the earlier work had been directed at anadromous fish with commercial value such as salmon (Johnson, 1960; Becker, 1962; Brett, 1965a, b; Ellis, 1966; and Brett and Glass, 1973). More recently with accelerated resource development in cold regions, the swimming performance of sport fish found in northwest Canada and Alaska have been studied (Jones, 1973; Jones et al., 1974; and MacPhee and Watts, 1976). These last three publications have the most relevance to this study, because they examined fish that would represent design fish in the culverts we examined. Here we are speaking of the design fish as being the weakest swimmer present in the stream of interest.

The swimming capability of Arctic grayling as found by Jones et al. (1974) and MacPhee and Watts (1976) is shown in Figure 1. Both of these excellent studies provide an enormous amount of data and knowledge about fish swimming performance, but they also raise several questions. When one compares the data of MacPhee and Watts to Jones et al. for the same fish, Arctic grayling, substantially different conclusions are reached.

First, a plot of swimming performance versus fork length (Figure 1) shows that a large discrepancy exists in the swimming performance of Arctic grayling. Part of this difference can be explained by the research methods. Jones et al. (1974) were interested in establishing the critical velocity (a velocity that fish could maintain for 10 minutes). Their procedure was to allow the fish to swim at 10 cm/sec for one hour to acclimate themselves; thereafter, the velocity was increased by 10 cm/s for a period of 10 minutes. The velocity was continually increased by the same velocity increments for each subsequent 10-minute period until the fish could no longer maintain this velocity.

MacPhee and Watts (1976) monitored the passage of spawning fish through two culverts (18.3 and 30.5 m long). Knowing the velocity through the culvert, they measured the percent success rate as a function of fork length.

Both of the previous research groups followed their field study with laboratory studies. The major differences in the results were that Jones et al. (1974) could not verify any relationship between swimming performance and water temperature (for Arctic grayling), whereas MacPhee and Watts (1976) felt there was a very significant effect.

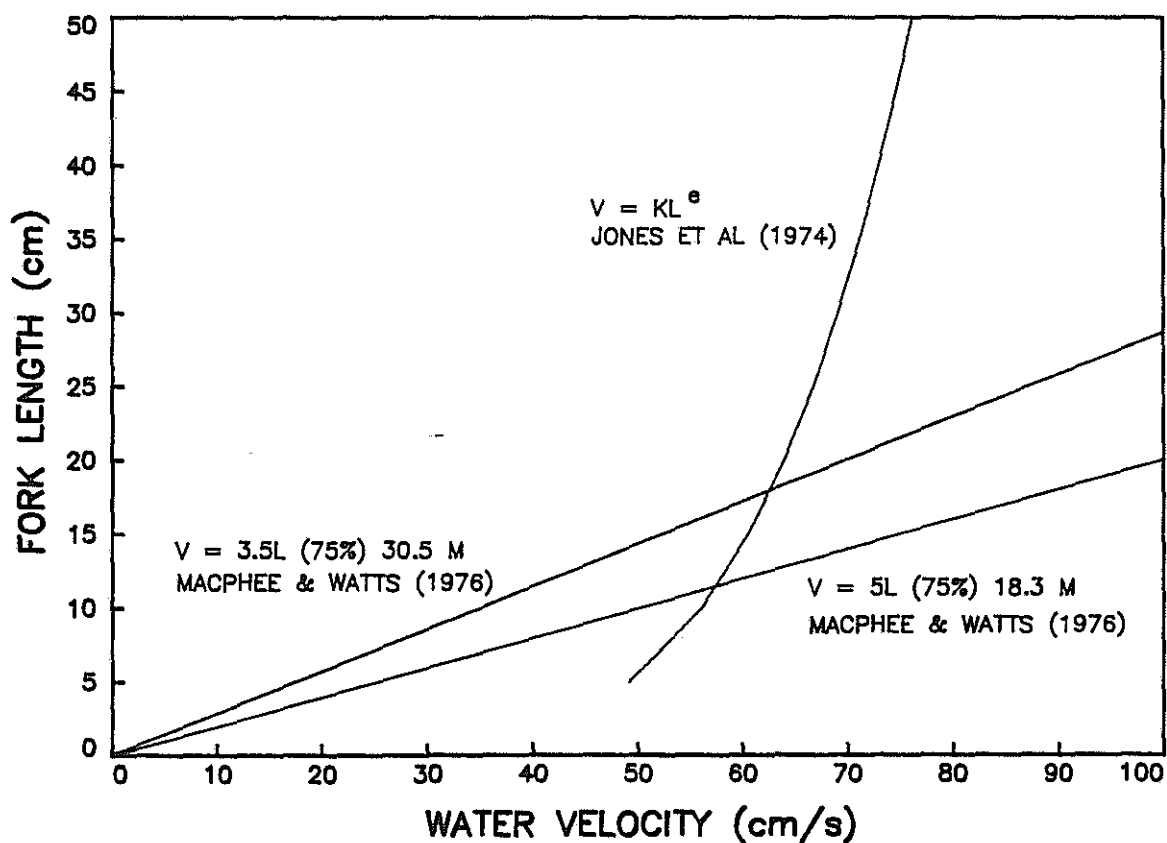


Figure 1. Results of swimming capability of Arctic grayling versus fork length from two different studies.

Jones et al. came up with a relationship for the critical swimming velocity of

$$V_{cr} = KL^x \quad (1)$$

where

- V_{cr} = critical velocity, cm/s
- K^{cr} = constant
- L = fork length, cm
- x = exponent

The curve in Figure 1 was plotted using the constant and exponent that they developed for Arctic grayling.

MacPhee and Watts came up with a linear equation, relating the water velocity with 75% success of passing for two culvert lengths

$$V_w = 3.5L \quad (30.5 \text{ m culvert}) \quad (2)$$

$$V_w = 5.0L \quad (18.3 \text{ m culvert}) \quad (3)$$

where

V_w = water velocity for a particular culvert length, cm/s
 L^w = fork length, cm

It is readily obvious from the results that if one is willing to accept 75% passing as acceptable, much higher allowable velocities would be predicted by MacPhee and Watts than by Jones et al. (1974). It should be noted for MacPhee and Watts' study that the fish were able to rest before attempting to pass through the culvert. In the Jones et al. study, the fish were not resting prior to the critical velocity, but had been swimming at increasingly higher velocities for 10 minutes at 10 cm/s-velocity increments before attaining the critical velocity.

Some questions can be raised relative to upstream fish migration. In these two major studies, the fish were handled. What effect does this handling have on the fish? Other related questions follow.

- a) How important is the motivational factor on fish swimming performance?
- b) Many immature fishes were observed moving upstream with the spawners in MacPhee and Watts' study. Is it necessary that the culvert be designed to pass these weaker swimming fish?
- c) How critical is the timing of fish relative to the timing of the floods, and how long can fish be delayed in their migration for purposes of spawning?

MacPhee and Watts (1976) implied in their report that spawning fish tended to show higher swimming performance than nonspawning fish. Also, during one year of their field study, they noted that many immature grayling migrated upstream with the adult spawners and returned downstream shortly thereafter. No explanation was given for this behavior; possibly this rapid return downstream (within three weeks) was in response to decreasing flows. Another observation of MacPhee and Watts was that at their site, Arctic grayling arrived on the receding portion of the spring streamflow. This would indicate that at some point along the river system they encountered the peak flow. Fish arriving at a culvert during peak flow may be delayed longer than they would if they were moving up a natural stream. The effect of a delay on spawning fish does not appear to have been studied or documented, although some guidelines have been suggested. Dryden and Stein (1975) state that three days is the maximum amount of time that annual spawning migrations should be delayed. They also state that delays are more critical as fish approach the spawning area. Lastly, they point out that delays of seven days would be tolerable once in 50 years when the floods coincide with fish migration.

VELOCITY DISTRIBUTION WITHIN CULVERTS

Present design criteria for culverts in Alaska make use of the mean velocity in the cross-section for the mean annual flood. However, it is common knowledge that fish do not seek areas where the mean velocities exist when migrating, but instead they seek the path of least resistance. This is where the velocities are the lowest, which is near the banks and bottoms of natural streams and along culvert boundaries.

In this study, we wanted to examine in detail the velocity profiles in culverts for various field conditions and also propose the concept for fish passage design, that velocities near the boundary be used instead of the mean velocity. The rationale for this approach is that (1) this is where fish swim and (2) by altering the roughness of the culvert, the velocity can be modified near the boundary.

The concept of using some measure of the velocity near the boundary is not new. Morsell et al. (1981) proposed the concept of the velocity in what they call the occupied zone (Figure 2). We will continue to use their notation. The size of the occupied zone should be defined for each type of fish, and then some technique developed to predict what the velocity is in this zone.

Morsell et al. (1981) defined the velocity in the occupied zone as

$$V_{occ} = V_{skin} + 0.25(V_{ave} - V_{skin}) \quad (4)$$

where

$$\begin{aligned} V_{occ} &= \text{water velocity in occupied zone [L/T]} \\ V_{skin} &= \text{water velocity adjacent to sides of culvert [L/T]} \\ V_{ave} &= \text{average water velocity within culvert [L/T]} \end{aligned}$$

They arbitrarily define

$$V_{skin} = 0.4 V_{max} \quad (5)$$

$$V_{ave} = 0.8 V_{max} \quad (6)$$

This means that

$$V_{skin} = 0.5 V_{ave} \quad (7)$$

Substituting these equations back into Equation 4 yields

$$V_{occ} = 1.25 V_{skin} = 0.625 V_{ave} = 0.5 V_{max} \quad (8)$$

This is a simpler expression than they present in their paper. Generally, the average velocity is determined from Manning's equation, and the velocity in the occupied zone can be determined using Equation

8. There is no need to determine the skin velocity before determining the velocity in the occupied zone.

We have some reservations about the equations used to determine the velocity in the occupied zone, but we do strongly support the concept of using the velocity in the occupied zone when designing culverts.

Our suggestion is that first the size of the occupied zone be defined by the type and size of the design fish in the stream, and then the velocity in this zone be determined by using established equations. Chow (1964) presents an equation to predict velocity profiles incorporating three variables: average velocity, relative depth and a roughness coefficient.

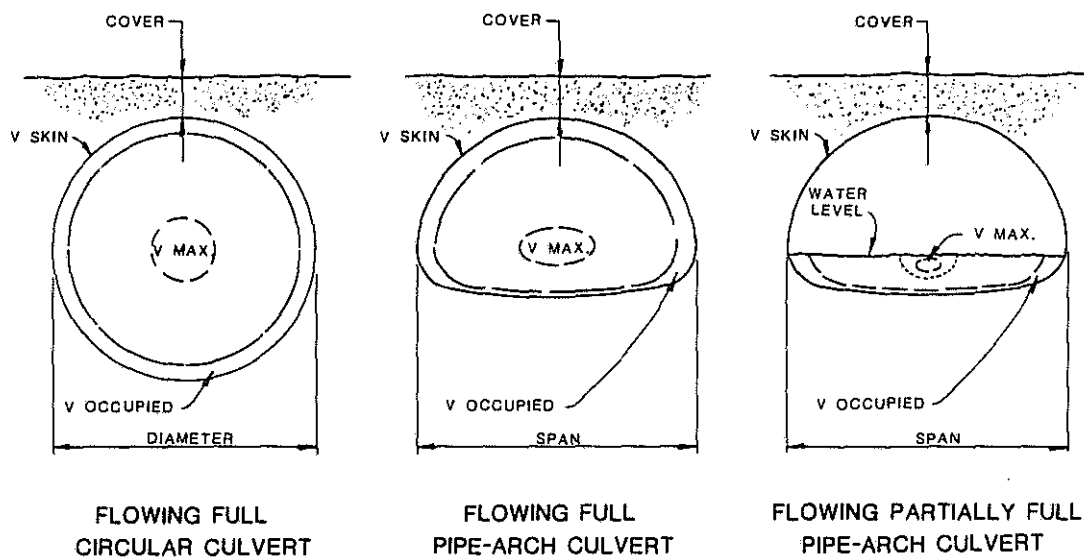


Figure 2. Schematic of the occupied area in a culvert.

$$\frac{(V - V_{ave})C}{V_{ave}(8g)^{1/2}} = 2 \log_{10} Y/Y_0 + 0.88 \quad (9)$$

where

- V = velocity at any point, fps
- V_{ave} = average velocity in cross-section, fps
- Y_{ave} = depth at any point, ft
- Y₀ = total depth, ft
- C⁰ = Chezy's roughness coefficient²
- g = gravitational constant, ft/sec²

Earlier we used Manning's roughness coefficient (n), and this can be equated to Chezy's roughness coefficient

$$C = \frac{1.49}{n} R^{1/6} \quad (10)$$

where

R = mean hydraulic radius (or wetted cross sectional area divided by wetted perimeter), ft.

If Equation 10 is substituted into Equation 9 and rearranged, then

$$V = \frac{(32g)^{1/2}}{1.49} V_{ave} n R^{-1/6} \log_{10}(Y/Y_0) + \frac{0.88(8g)^{1/2}}{1.49} V_{ave} n R^{-1/6} + V_{ave} \quad (11)$$

Predictions of velocity were made for many (47) of the culverts where velocity profile measurements were taken. In 34 cases the predicted velocity profiles conform quite well with the measured ones, while in 13 cases the comparison is not very good.

Substantial variation exists in Manning's roughness coefficient for the culverts observed. The main reason for this is that sediment and large riprap were found in the bottom of the culverts -- for the entire length in some cases and only in part of the culvert for other cases. This could often be observed in the measured velocity profiles. Instead of the velocity profile being uniform as depicted in many publications, it was often irregularly shaped. It must be recalled that many of these culverts have been in place for a considerable time, so flow conditions have changed. Changes in velocity regime could be due to debris within the culvert barrel, but also the culvert could have been deformed, slope changed, or culvert perched. Perched culverts typically allow the flowing water to accelerate at the outlet of the culvert, and many of the measured profiles were taken here.

Our estimate of the average Manning's n over the entire length of the culvert was determined by the slope (from elevation measurements at each end of culvert), discharge measurement (made in the stream), and hydraulic radius and area determinations (made at point of velocity profile measurements). Because it was often difficult to make water surface measurements inside the culvert, entrance and exit losses are also reflected in our estimate of n.

We used an average Manning's n for the entire culvert length in our predictions for the velocity profiles; technically, we should have used a value for that section of the culvert where the velocity measurement was made. But since we did not have water surface elevations throughout the culvert, we could not generate an n value for just a section of the culvert.

Using equation 11, the velocity profile in a 12 ft diameter culvert is determined as a function of roughness (Figure 3). First,

the maximum depth of flow is calculated from Manning's equation for a slope of 0.01, $Q = 50$ cfs and a selected value of n ; from this, the average velocity is calculated. It can be seen how much an increase in roughness increases the maximum depth of flow and also reduces the velocity.

CONCLUSIONS

In designing a culvert, the engineer has the option to modify the boundary roughness. This could be accomplished by using larger corrugations, oversizing the culvert and placing rip-rap or some other similar material in the culvert bottom, or by placing baffles of various configurations in the culvert. The effect of these changes is to influence the local velocity near the boundary. Since this is the same region where fish swim when migrating upstream, the question is whether the velocity in this region exceeds the swimming ability of the design fish used. The point of this paper is that the engineer can significantly reduce the velocity near the boundary by altering

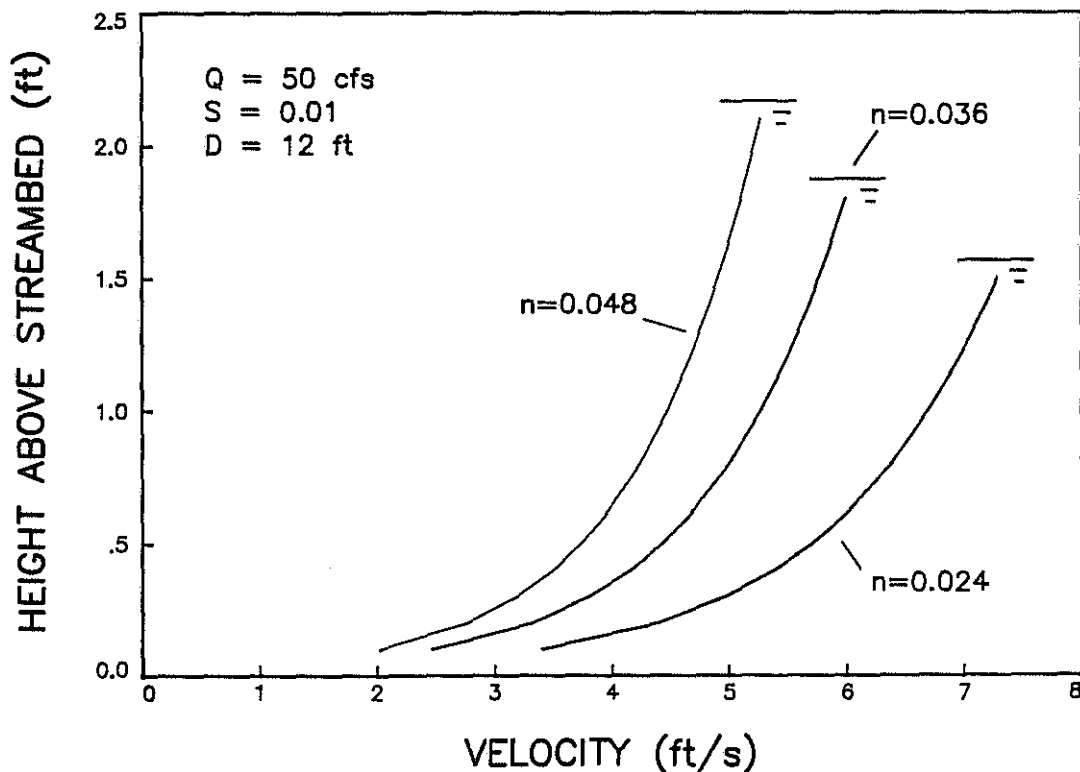


Figure 3. Velocity profiles and maximum depths of flow for varying boundary roughness.

the roughness -- but for the entire wetted area of the culvert, this may only slightly reduce the mean velocity. So the design engineer should base his fish passage design on the velocity in the occupied

zone. If these velocities are too high, the designer has some options available to reduce these velocities so that a culvert can still be used at a crossing.

ACKNOWLEDGMENTS

This project was funded by a research agreement from the Federal Highway Administration through the Alaska Department of Transportation and Public Facilities. The contents of this paper reflect the views of the authors and do not necessarily represent the views or policies of the funding agency. The authors would like to thank several people who helped collect field data on this project: Cathy Egan, Cynthia Little, Jean Stein, Robert Gieck, Michael McCrum and William Ashton.

REFERENCES

- Becker, C.D. 1962. Estimating red salmon escapements by sample counts from observation towers. U.S. Fish. Bull. 192: 16:355-369.
- Brett, J.R. 1965a. The relation of size to the rate of oxygen consumption and sustained swimming speeds of sockeye salmon (*Oncorhynchus nerka*). Journal Fish. Res. Board, Canada. 22:1491-1500.
- Brett, J.R. 1965b. The swimming energetics of salmon. Scientific Amer. 213:80-85.
- Brett, J.R., and N.R. Glass. 1973. Metabolic rates and critical swimming speeds of sockeye salmon (*Oncorhynchus nerka*) in relation to size and temperature. Journal Fish. Res. Board, Canada. 30:379-387.
- Chow, V.T. 1964. Handbook of applied hydrology, a compendium of water resources technology. McGraw-Hill Book Co., New York.
- Dryden, R.L., and J.N. Stein. 1975. Guidelines for the protection of the fish resources of the Northwest Territories during highway construction and operation. Dept. of the Environment, Fisheries and Marine Service, Technical Report Series No. CEN/T-75-1.
- Ellis, D.V. 1966. Swimming speed of sockeye and coho salmon on spawning migration. Journal Fish. Res. Board, Canada. 23:181-189.
- Johnson, J.H. 1960. Sonic tracking of adult salmon at Bonneville Dam, 1957. U.S. Fish. Bull. 60:471-485.
- Jones, D.R. 1973. An evaluation of swimming performance of several fish species from the MacKenzie River. Department of the Environment, Fisheries and Marine Service, Winnipeg, Manitoba.

- Jones, D.R., O.S. Bamford and V.W. Kiceniuk. 1974. An evaluation of the swimming performance of several fish species from the Mackenzie River. University of British Columbia, Zoology Department.
- Kane, D.L., and J.R. Janowicz. 1985. Flood frequency estimation for Alaska. University of Alaska-Fairbanks, Institute of Water Resources. In press.
- Lamke, R.D. 1979. Flood characteristics of Alaskan streams. U.S. Geological Survey, Water Resources Investigations 78-129.
- MacPhee, C., and F.J. Watts. 1976. Swimming performance of Arctic grayling in highway culverts. Bulletin No. 13, College of Forestry, Wildlife and Range Science, University of Idaho, Moscow, ID.
- Morsell, J., J. Houghton, M. Bell and R. Costello. 1981. Fish protection strategies for the design and construction of the Alaska segment of the natural gas transportation system. Report prepared by Dames and Moore for Northwest Alaskan Pipeline Company, Anchorage, AK.

COMMUNITY AND REGIONAL WATER CONFLICTS

FROM DATA TO DECISIONS

by Elizabeth A. Baron^{1/}

ABSTRACT

The Department of Natural Resources' Water Management Section has developed a conflict resolution process which provides resource managers with pertinent data for the purpose of improving water resource management decision making. The conflict resolution process is a vehicle which integrates resource data throughout all levels of decision making and policy formulation. The critical factor linking resource data into the decision making process is collecting, organizing, and presenting data in a format suitable for meeting user needs. The initial step in the process is defining the issues and data needed by the user to adequately address water resource issues and conflicts. Secondly, the way in which the data is collected, analyzed, and presented will determine the extent to which the data will assist decision makers in policy formulation and resource management. The Division's goal is to manage efficiently the state's water resources in the public's greatest interest. The provision and utilization of adequate resource data in the decision making process will greatly contribute towards achieving optimum resource management.

INTRODUCTION

Water resources within Alaska often have been perceived as being plentiful and of acceptable quality for many water related uses. However, recent shortages of water supplies and quality degradation have brought light to many existing and potential water resource issues. In an attempt to resolve or minimize water resource conflicts, the Department of Natural Resources' Water Management Section has developed a conflict resolution process designed specifically for assessing water resource problems and recommending management solutions.

The ultimate purpose of the conflict resolution process is to provide a mechanism promoting efficient water management in the public's greatest interest. Efficient water management historically has been dependent upon the success of the resource management agency's ability to provide: 1) an adequate database, and 2) a means of incorporating data throughout all levels of policy formulation and decision making. The process employed by the Water Management Section for resolving water resource conflicts provides a way of establishing an adequate database and incorporating it into the decision making process.

^{1/} Resource Officer, Alaska Department of Natural Resources
Pouch 7-005
Anchorage, AK 99510

The following two-part paper briefly outlines the conflict resolution process and presents a case example implementing the process. The conflict resolution process is presented in four sections: 1) identification of management issues and agency objectives, 2) determination of data needs, collection and format, 3) documentation and management of a flexible database, and 4) integration of data into the water resource management decision making process.

PART I: CONFLICT RESOLUTION PROCESS

Identifying Management Issues And Agency Objectives

Identifying resource problems or management issues is the first and perhaps most critical step of the conflict resolution process. Issue identification greatly influences the success or failure of a data collection project in providing appropriate data for the decision making process. Similar to the essential role of a hypothesis in guiding and structuring the methods of an experiment, defining the management issues provides all project participants with a common and precise description of the problem being investigated. In turn, the nature of the issues warranting investigation will determine the data needs and appropriate data format, interpretation, and application.

Although the importance of defining management issues as the initial step in the conflict resolution process may appear obvious, many resource management agencies have been unsuccessful in coordinating all staff divisions--from technicians through decision makers--in clearly defining the issues. Consequently, this often results in decisions made without appropriate data. Uncoordinated data collection efforts and disorganized data formatting and management produce an inconsistent and seemingly random database which may be useless to the decision maker. A recent national survey has revealed that policy makers within resource management agencies were unable to incorporate resource data into their policy formulation 81% of the time due to inappropriate or unavailable data! (National Council of State Governments, 1978.)

Management issue identification serves two major purposes: 1) it coordinates project participants, identifies the data needed for water management formulation, and shapes the format in which to collect the data; and 2) it provides socio-economic and political justification for project funding. For instance, assuming public monies available for research are limited, a legislator may favor funding a project addressing critical water shortages or other specific resource management issues in a populated area over a general resource investigation in a remote, low resource value area. A clear definition and purpose justifying a data collection project will more likely receive funding than a non-specific, uncoordinated project.

Determining Data Needs, Collection And Format

Determining the user's data needs requires that the elements in the database represent information needed to address water resource management issues and agency objectives. After identifying the management issues and agency responsibilities, the types of information essential to making well informed decisions or fulfilling those responsibilities must be determined, and a database built.

Establishing a database is typically done in three stages:

1. Identifying specific data elements and formats necessary in addressing management issues (i.e., maps, statistical summaries, status plats, well logs, etc.)
2. Prioritizing data collection efforts based on user needs and available resources (staff, funding, automated support, etc.)
3. Coordinating data collection efforts of both existing and new data from field investigations, existing references, etc.

Once data needs are assessed and collection efforts complete, a database must be designed to enable users to extract pertinent data in an efficient and versatile fashion. The design should format the data in a way that provides users with a variety of retrieval, analytical, and dissemination options. The particular format will depend upon the mechanism employed to store the database--such as a literature reference document or a computer support system. In either case, fast and easy retrieval from discrete data storages will provide the user with access to an array of information specific to user needs.

Flexible Database Management And Documentation

Database management. The Water Section's ultimate goal for data collection is to maintain and manage data for the purpose of satisfying immediate and long term water resource manager needs. To fulfill this goal, two objectives were incorporated into the conflict resolution process: 1) to maintain and manage data to be readily and easily available to assist users in current resource management decisions and policy formulation; and 2) establish a data base which can be applied in addressing future undetermined management issues. In sum, the goal of the early design phase of a data collection project is to produce a flexible database structure adaptable to a changing user environment.

Additionally, data design structures must be adaptable to technological changes. The database should be structured so it may be modified and updated in response to technological changes to guarantee optimal performance of ever-changing processing requirements. Ultimately, a flexible data base structure will provide resource managers with a database sensitive to changing user and technological needs while also providing a variety of retrieval and analysis options applicable to the resolution of immediate and future water resources conflicts.

Documentation. Complete documentation describing how the database was established and formatted is essential in managing and maintaining a dynamic database. Thorough documentation should include a clear description of the data elements, the level of detail and techniques used in collecting the data, and how the data was formatted and stored in a databank. Equally important, documentation should include an explanation of why the data was collected, the purpose it was intended to serve, and its appropriate application.

Documentation describing the limitations and applicability of the data elements will help prevent future users from misusing or overextending the data which may result in erroneous resource management conclusions. For instance, it may not be appropriate to apply a database initially developed for a large scale regional water resources planning study to a detailed site design of a water impoundment project. The intent of establishing the original database, therefore, must be fully explained to assist future users in determining the applicability and reliability of the data for assessing various water resource problems.

Integrating Data Into the Decision Making Process

Although the early stages of the conflict resolution process provide for the creation of a database tailored towards addressing management issues in an efficient and flexible fashion, the actual transfer of data into the decision making process is often obstructed. Elevating data from the technicians and resource specialists up to planners and policy makers for decision making often fails when the data is incomprehensibly organized and presented. The user seldom has time to interpret and summarize many pieces of data. Rather, the data should be sorted, summarized, organized, and presented so the user can easily draw conclusions and recommend appropriate management solutions.

Part II: A CASE EXAMPLE

The conflict resolution process outlined in Part I is a tool utilized by the Water Section in responding to water management issues, such as: site specific water resource problems; local, regional, and statewide planning concerns; policies guiding future water management; and adequate water rights appropriation standards.

Part II presents a case example of incorporating the conflict resolution process into the Department of Natural Resources' land use planning process. The Department's land use planning process is outlined below and followed by descriptions of how the database was compiled, the method used in formatting and managing the database, and how data is directly used in the decision making process.

The Department of Natural Resources' Land Use Planning Process

The Department of Natural Resources' land use planning process guides the assessment of natural resources and management issues in geographically defined areas. The process provides a means for reviewing resource information and public concerns before making long range decisions on the use of state lands. Ultimately, the process is a way of resolving conflicting ideas on land use and presenting several land use and resource management options to decision makers and the public supported by reasons for those options. The process involves participation from individuals, citizen groups, private organizations and state, federal, and local governments in the steps listed below:

1. An interagency planning team is formed with state and local government members representing each of the important resources in the area: forestry, settlement, agriculture, fish and wildlife, transportation, recreation, minerals and energy, and water.
2. The planning team identifies land and water resource issues during public workshops, and review existing resource information.
3. Databases describing land and water resources are compiled, and existing and potential resource conflicts identified.
4. Alternative land use plans showing possible resolutions to land and water use issues are developed by the planning team and reviewed by the public.
5. Based on the public and agency response to land and water use alternatives, a draft plan is prepared by the planning team and reviewed by affected agencies and the public.
6. Final revisions are made following public hearings, and the plan is approved by the Commissioner of the Alaska Department of Natural Resources and local governments. Land and water management policies described in the plan will then guide land management decisions on public lands in geographically defined areas.

The conflict resolution process defined by the Water Management Section is directly incorporated into an ongoing land and water use planning effort in the Copper River Basin. The Copper River Area Plan is a land use planning effort in which water related data is collected, formatted, and managed for the purpose of assisting resource managers, decision makers, and the public in resolving existing and potential water resource conflicts.

Determining Data Needs

As outlined by the conflict resolution process, the initial steps in establishing a database are the identification of water resource issues and agency objectives, and determination of data needs (step 2 of the land use planning process).

A major water related issue identified within the Copper River Basin is the limited availability of ground water supplies due to the occurrence of permafrost. Permafrost decreases the quantity of available groundwater and often causes those supplies which are available below permafrost to be saline. The data needed to address the water resource issues in the Copper River Basin must address 1) existing supplies and quality of groundwater of existing wells, 2) the percentage of water consumed from groundwater sources and 3) the availability of surface water as an alternative source. Other factors, such as accessibility to water sources and land uses which may impact water supplies, must also be considered.

Data Collection

The data necessary to address water resource issues were compiled from a variety of sources--past interagency research conclusions, water rights and water use data extracted from the Department's automated Land Administrated System, data collected through the Alaska Water Resources Evaluation program, and information collected specifically for the Copper River Area Plan.

Conclusions drawn from past research efforts which were most applicable in addressing the water resource issues in the Copper River Basin were furnished by the U.S. Geological Survey, Water Resources Division. The USGS's recently published Hydrologic Investigations Atlas (Emery, Jones and Glass, 1983) provided an overview of water resources, surface and ground water, water quality, hydrogeology, precipitation, runoff and streamflow sediment. After reviewing the study's conclusions, more specific data needs were identified and collected from a variety of sources described below.

In assessing the quantity of water used or appropriated from ground water and surface water supplies, data were extracted from the Water Subsystem of the Department's automated Land Administration System. This subsystem tracks and coordinates the issuance of water rights appropriations from ground water and surface water sources, and water quantities appropriated for various uses. Water appropriation quantities specified in individual water rights case files were sorted and summarized by water source. These figures provided useful information on the amount of water claimed from surface and groundwater supplies, and will assist in determining available surpluses.

The Department's Division of Geophysical and Geological Surveys supplied information on water well depths through their well log program, as well as data on surface water flow and availability through the Alaska Water Resources Evaluation program. Much of this data were incorporated into several maps created for the Copper River Area Plan, and presented information on potential water supplies.

A data collection project was designed and conducted specifically for the Copper River Area Planning effort to compile and supplement additional land use and resource information. The data elements extracted from the database provided by the Copper River resource mapping project and used to assess water availability and accessibility included: surface hydrology, infrastructure such as roads, hydroelectric sites, pumping stations, thermal springs, and land use patterns.

The Surface Hydrology maps depict stream network, stream order, water color, and watershed boundaries (Christy, 1984). Map sources consist of U.S.G.S. 1:250,000 quadrangle maps, rectified topographic maps, and LANDSAT imagery and color infrared photography to update and refine dynamic boundaries of shifting rivers and stream course extensions resulting from glacial retreats.

Infrastructure mapping is a composite of published and unpublished information which was rescaled and mapped at 1:250,000. Information was extracted from maps, books, and aerial photography provided by the Alaska Departments of Transportation, Natural Resources, Fish and Game, and U.S. Bureau of Land Management, U.S. Park Service, and Ahtna Native Corporation. Infrastructure elements include federal, state, and local roads, USGS and DGGs stream gaging stations, existing and proposed hydroelectric sites, water pumping stations, and thermal springs.

Elements extracted from land use maps represent the pattern of man's activities which impact water use such as settlement and recreation. Information pertaining to settlement activities include maps of federal homestead lands, state land sales, and statistics provided by the Alaska Departments of Labor and Economic Development on population and demographics. Information on recreational water access points was supplied by the Alaska Department of Fish and Game.

Formatting And Flexible Database Management

The complexity and volume of data collected from numerous sources for the Copper River Area Plan made data format and management a critical factor in the accurate and timely assessment of water resource information. The first step in successful management of such a sizeable database was to assemble the various pieces of data and store them in a single databank in a format capable of multiple retrieval and analysis options. The mechanism employed was the Department's geoprocessor.

5989157

5960000

5940000

5920000

5900000

5874202

499399

520000

540000

560000

580000

600000

620000

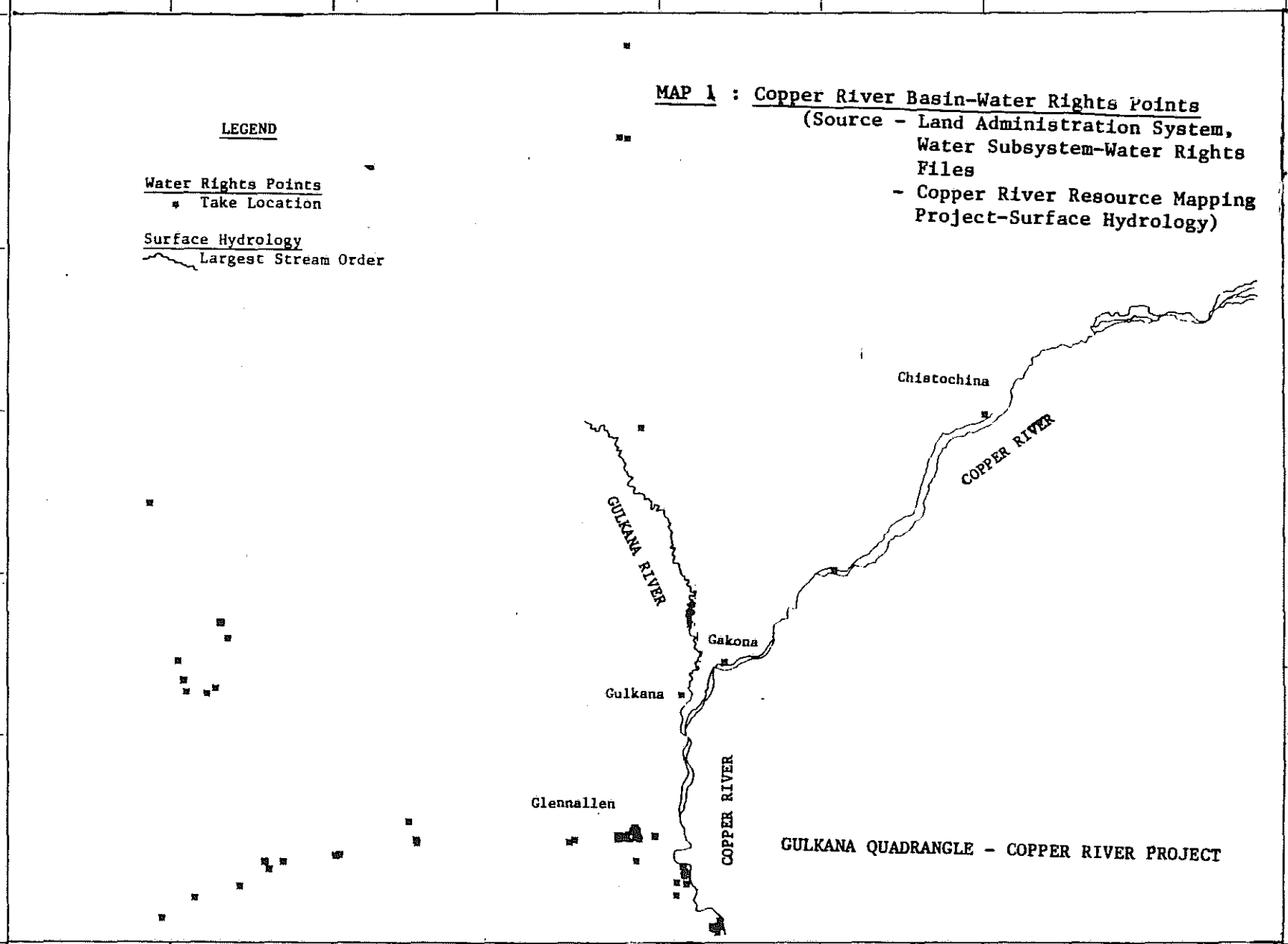
647000

LEGEND

Water Rights Points
* Take Location

Surface Hydrology
- Largest Stream Order

MAP 1 : Copper River Basin-Water Rights Points
(Source - Land Administration System,
Water Subsystem-Water Rights
Files
- Copper River Resource Mapping
Project-Surface Hydrology)



This document has not received official D.G.G.S. review & publication status, and should not be quoted as such. It is intended for regional planning purposes, site specific planning will require ground verification of

The geoprocessor provides centralized computing support for the Division of Geophysical and Geological Surveys (DGGS) to conduct analytical modeling of raw data commonly used in resource planning. The geoprocessor, a versatile system, has the capability of processing and displaying data which can be described by geographic location. A large amount of descriptive or attribute information can be stored and manipulated. In addition to working with digitized or electronically mapped geographic data, the system is capable of statistical analysis and 3-D surface manipulation which serves as an interactive graphics system.

The data collected and compiled for the Copper River Area Plan were mapped, digitized and loaded onto the geoprocessor. All mapped information, hence, was geographically referenced and associated with descriptive or attribute information and readily available for assessment and manipulation.

Although the Department's Land Administration System stores record information and not spatial data as the geoprocessor, both water rights and water use records contain legal descriptions. The legal descriptions expressed in these files were read into the geoprocessor and geographically calculated--thereby producing mapped representations of the water use and water rights files. (See Map 1.) Each geographically referenced water right and use point also carried a string of attribute information which was transferred from the Land Administration System to the geoprocessor.

The final product of loading extract data from all sources onto the geoprocessor resulted in a single database compiled and formatted onto one databank which could now be employed in a wide variety of statistical and graphical manipulations for the purpose of addressing pertinent water resources issues. (See Map 2.)

Integration into the Land Use Planning Process

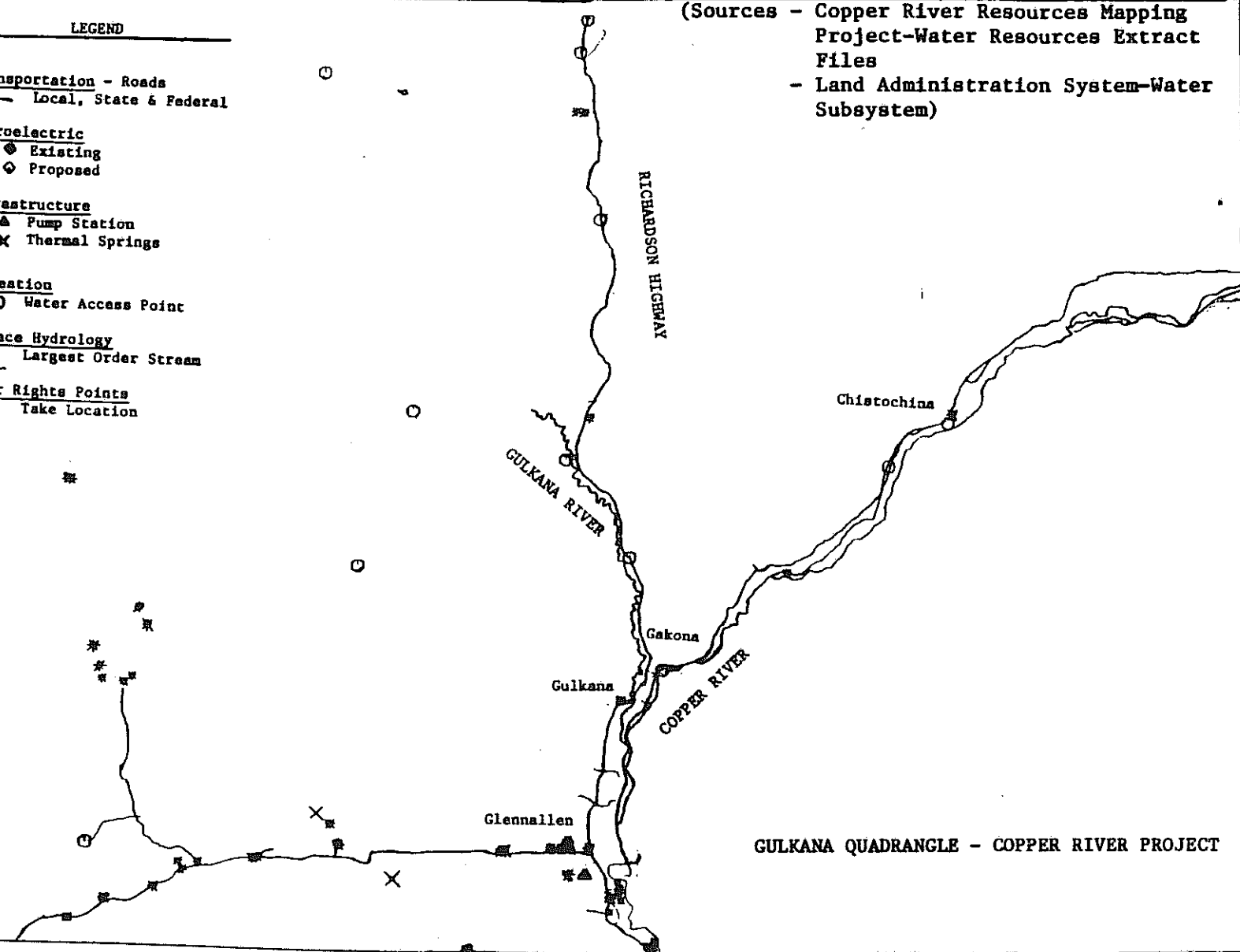
Once the technicians and resource specialists compiled and formatted the Copper River database onto one computer support system, the user or resource manager determined what data was to be extracted, summarized, and presented in a report which will be available for agency and public review. Similar reports describing the various natural resource characteristics and development potential will be produced and used to guide the formulation of alternative land use plans (step 4 of the land use planning process).

MAP 2 : Copper River Basin-Composite Water Resources Map

(Sources - Copper River Resources Mapping Project-Water Resources Extract Files

- Land Administration System-Water Subsystem)

- LEGEND**
- Transportation - Roads**
 - Local, State & Federal
 - Hydroelectric**
 - ◆ Existing
 - ◇ Proposed
 - Infrastructure**
 - ▲ Pump Station
 - X Thermal Springs
 - Recreation**
 - Water Access Point
 - Surface Hydrology**
 - Largest Order Stream
 - Water Rights Points**
 - Take Location



GULKANA QUADRANGLE - COPPER RIVER PROJECT

This document has not received official D G S S review & publication status, and should not be quoted as such. It is intended for regional planning purposes, site specific planning will require ground verification of map data.

Conclusion

The Department of Natural Resources' Division of Land and Water Management specializes in resource management and policy formulation. The Division's ability to recommend sound resource management practices and policies is largely dependent upon the availability and useability of pertinent resource data. Subsequently, databases containing information needed by resource managers must be established and made available for use in various decision making processes. In order to ensure the useability of data in the decision making process, the collected data and the format in which it is stored must be tailored towards meeting the user's needs. Once data needs are determined in response to specific resource management issues, the data must be collected, compiled, and stored in a format conducive to providing a variety of retrieval, analytical, and dissemination options. The utilization of data throughout all levels of decision making is most likely to occur if databases are designed to meet user needs, and if data interpretations are summarized, organized, and clearly presented.

REFERENCES

- Christy, Scott. 1983. User's guide to the Copper River Mapping Project. Division of Geological and Geophysical Surveys, Alaska Department of Natural Resources, 78 pp.
- Emery, P.A., S. H. Jones, and R. L. Glass. 1983. Water resources of the Copper River Basin, Alaska. Preliminary Report, Water Resources Division, U.S. Geological Survey, 58 pp.
- National Council of State Governments. 1978. Natural resources data use survey results. 13 pp.

WATER-QUALITY CHARACTERISTICS OF THE CHESTER CREEK BASIN
ANCHORAGE, ALASKA

by Timothy P. Brabets¹

ABSTRACT

Chester Creek flows primarily through urbanized areas of Anchorage. Water quality was evaluated for different flow conditions (low or baseflow, rainfall runoff, and snowmelt runoff) and for different land-use classifications (natural or 'undisturbed', residential, and commercial).

During baseflow periods, differences in water quality could not be related to different land uses, and only fecal coliform bacteria levels exceeded State of Alaska drinking water standards. Rainfall-runoff periods showed increases in suspended sediment, certain trace metals, nutrients, and fecal coliform bacteria; lead and fecal coliform bacteria exceeded State standards. During these periods, the highest concentrations of coliform and nutrients originate from residential areas while the highest concentrations of trace-metals originate from commercial areas. Snowmelt periods were characterized by concentrations of chloride greater than State standards, and trace metal and suspended-sediment concentrations higher than rainfall-runoff periods. Trace metals were found to be adsorbed to suspended-sediment particles. These metals are also being deposited in the streambed.

¹ Hydrologist, U.S. Geological Survey, WRD, 1209 Orca Street, Anchorage, AK 99501.

PREFERENTIAL SALTWATER INTRUSION INTO THE METAMORPHIC ROCK AQUIFER AT INDIAN COVE, SOUTHEAST ALASKA

by Larry L. Dearborn ¹

ABSTRACT

Pumping stress on a basalt-greenstone aquifer at the small community of Indian Cove has resulted in unique spatial relationships between water levels in wells and the chemical characteristics of well water. Large negative heads with respect to sea level occur in some wells, and some wells produce brackish water. Several bedrock wells that extend uncased to over 300 ft below sea level have non-pumping water levels varying between -68 and -92 ft. However, these wells supply water having only half the salinity as that of much shallower wells with water levels varying between 5 and -40 ft. The depth of wells, the amount of water each pumps, and their distances from the nearest saltwater beach appear not to control the level of salinity in pumped waters. Instead, a combined effect of inferred faults, favorably oriented joint sets, and a clayey aquifer cap seem to be largely responsible for preferential flow path of sea water into the aquifer. The result is that wells located between the salt-water recharge locality and the major drawdown area are more contaminated than wells located near the drawdown center.

INTRODUCTION AND SETTING

Residents of the small community of Indian Cove, largely occupying a small isthmus leading to Auke Cape (fig. 1), have had well yield and salinity problems for many years. Recently collected data indicate that six of the 18 wells now in use (Table 1) produce brackish water, defined by total dissolved solids (TDS) concentration exceeding 1000 mg/L (Todd, 1980, p. 310). All wells draw water from fractured rock of the Douglas Island volcanic group (Barker, 1957) at depths up to 350 below sea level. Driller's logs available for 10 of these wells do not document at what depths in the uncased bedrock water enters the drillhole. Some well owners contend that their water quality varies considerably, and occasionally during long dry periods they run out of potable water.

Upon receiving a water-rights application for 6,000 gallons per day by a condominium developer in 1984, the Alaska Department of Natural Resources embarked on a ground-water study of the Indian Cove area. The purpose of this report is to describe some important physical characteristics of the bedrock aquifer and relate these to field measurements of water quality to explain saltwater intrusion.

¹ Hydrologist, State of Alaska, Department of Natural Resources, Division of Geological & Geophysical Surveys, P.O. Box 772116, Eagle River, Alaska 99577

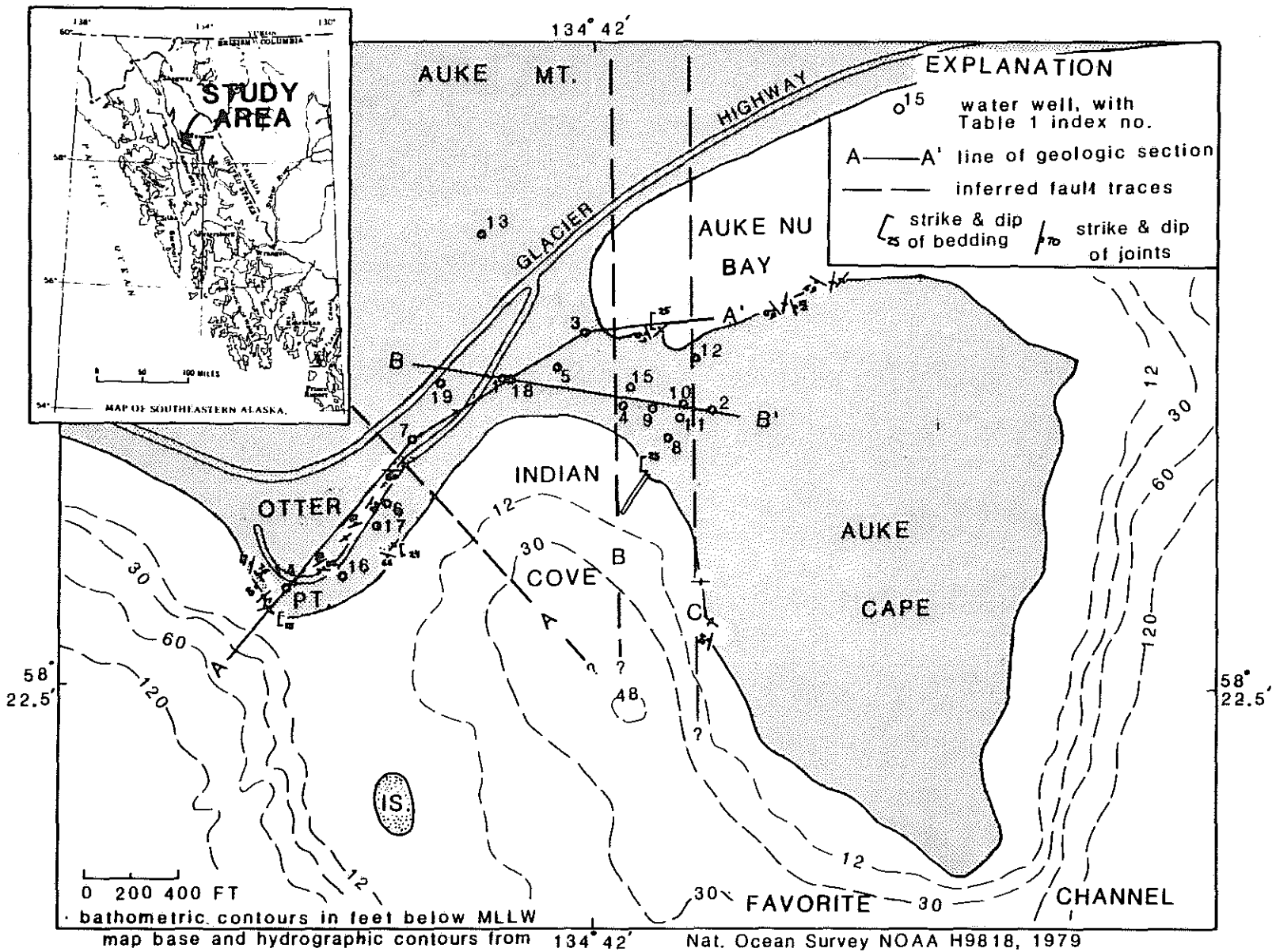


FIGURE 1 Hydrogeologic setting of Indian Cove and location of water wells

Table 1. Well construction and water-level fluctuation data.

Well No.	Well owner	Well depth (ft)	Depth to bedrock (ft)	Date drilled	Observed water levels [ft above (+) or below (-) MLLW ¹]			
					When drilled	Nov. 14, 1984 ²	June 18-20, 1985 ²	Sept. 14, 1985 ²
1	Indian Cove Water Co.	142	30	10/61	+33 ³		-89.49/-89.63/29	
2	National Park Service	95	14	4/60	+18			+17.40/+17.38/5
3	Auke Nu Condominium	378	75	3/84	-95	-71.40/-80.00/426	-92.24/-92.30/10	
4	Kack, G.	254	50	9/78		-24.90/-25.27/24	-33.32/-33.50/9	-40.36/-41.14/34
5	Schoenmann, J.	250	66	5/78			-82.94/-84.94/60	-92.02/-92.04/3
6	Bertholl, B.	-	-					
7	Hurley, L.	370	19	9/78	+42 ³			+10.70/+10.69/5
8	Robinson, C.	135	22	4/81		-4.51/-5.55/18	-5.53/-4.70/20	-23.10/-24.83/122
9	Mercer, H.	130?	-					
10	Carlson, C.	151	10	7/77			+14.46/+14.18/8	
11	"abandoned & plugged"	300?	-					
12	Wilkerson, G.	177	17	4/82		+5.79/+5.72/24		
13	Verrelli, L.	400	-		+72 ³			
14	Darnell, F.	143	-	7/57 ⁴	+29		+17.60/+17.39/10	
15	Cartmill, R.	300	38	4/81			-25.58/-25.76/7	
16	Ciccolo, E.	82	-				+4.68/+4.65/10	
17	Clark, R.	130?	-	?78				
18	Indian Cove Water Co.	300	-			-69.97/-75.51/254		
19	Hurley, L.	148	-					

¹ MLLW = mean lower low water sea-level datum

² highest/lowest/minutes monitored

³ flowing

⁴ deepened from 108 ft in late 1950's

GEOLOGY OF BEDROCK AQUIFER

The bedrock geology of the area, based on Barker's map (1957) and recent unpublished work by David Brew and James Smith (U.S.G.S., written commun., Sept. 18, 1985), consists of metamorphic rock composed primarily of augite-rich basalt, in places mixed with graywacke and occasionally containing thick units of slate or volcanic conglomerates.

About 85 percent of all rock drilled during well construction in the community was logged as "greenstone" -- undoubtedly the augite-bearing basalt Barker (1957) and Ford and Brew (1973) describe. Shale and slate comprise the bulk of the other rock types logged by drillers. At the isthmus, well logs indicate that 20 ft to as much as 70 ft of glaciomarine diamicton (Miller, 1975), called stoney clay by drillers, overlies bedrock.

In general, bedding has a northerly strike and dips about 25° east at Indian Cove. Barker attributed these attitudes to the existence of a northeastern limb of the regional overturned syncline now referred to as the Barker-Shelter Island syncline (Brew, written commun., Sept. 18, 1985). The axis of the syncline supposedly lies about two miles to the southwest and plunges about 14 degrees to the southeast. The study area is located stratigraphically about the middle of the Douglas Island volcanic group (Jurassic to early Cretaceous in age), which is estimated to be roughly 10,000 ft thick (Barker, 1957).

Three primary sets of joints are recognized from field measurements (fig. 1) by DGGGS personnel and from Barker's geologic map. Perhaps the most recognizable set has a vertical or near vertical dip and strikes between 20 and 50° east of north. They probably represent vertical dip-jointing during the orogeny that produced the Shelter Island syncline. Another area-wide joint set has a northwesterly strike and dips about 67° to the west. These joints might be termed release or tension joints (Billings, 1962), and may also have been created by synclinal folding.

On the land point served by Otter Way (hereafter called Otter Point in this report) "feather" jointing may explain strikes of 60 to 80° east of north and high-angle dips of about 75° north. Breakage planes of this type commonly accompany movement of fault blocks, and in this case may be associated with fault A.

Three faults (A, B, and C on figure 1) are inferred to extend from the mainland to beneath the water of Indian Cove. The existence of the faults is evidenced by well-log lithology, rock outcrops, and relationships involving ground-water chemistry and water levels at various wells. Fault A trends northwest and intersects the fault trace mapped by Barker (1957), according to Brew (written commun., Sept. 18, 1985). Section A-A' (fig. 2), which parallels the mainland shoreline, indicates graywacke west of the fault and greenstone to the east.

The existence of faults B and C are supported by a U-2 photo showing indications of faulting on Auke Mountain in line with

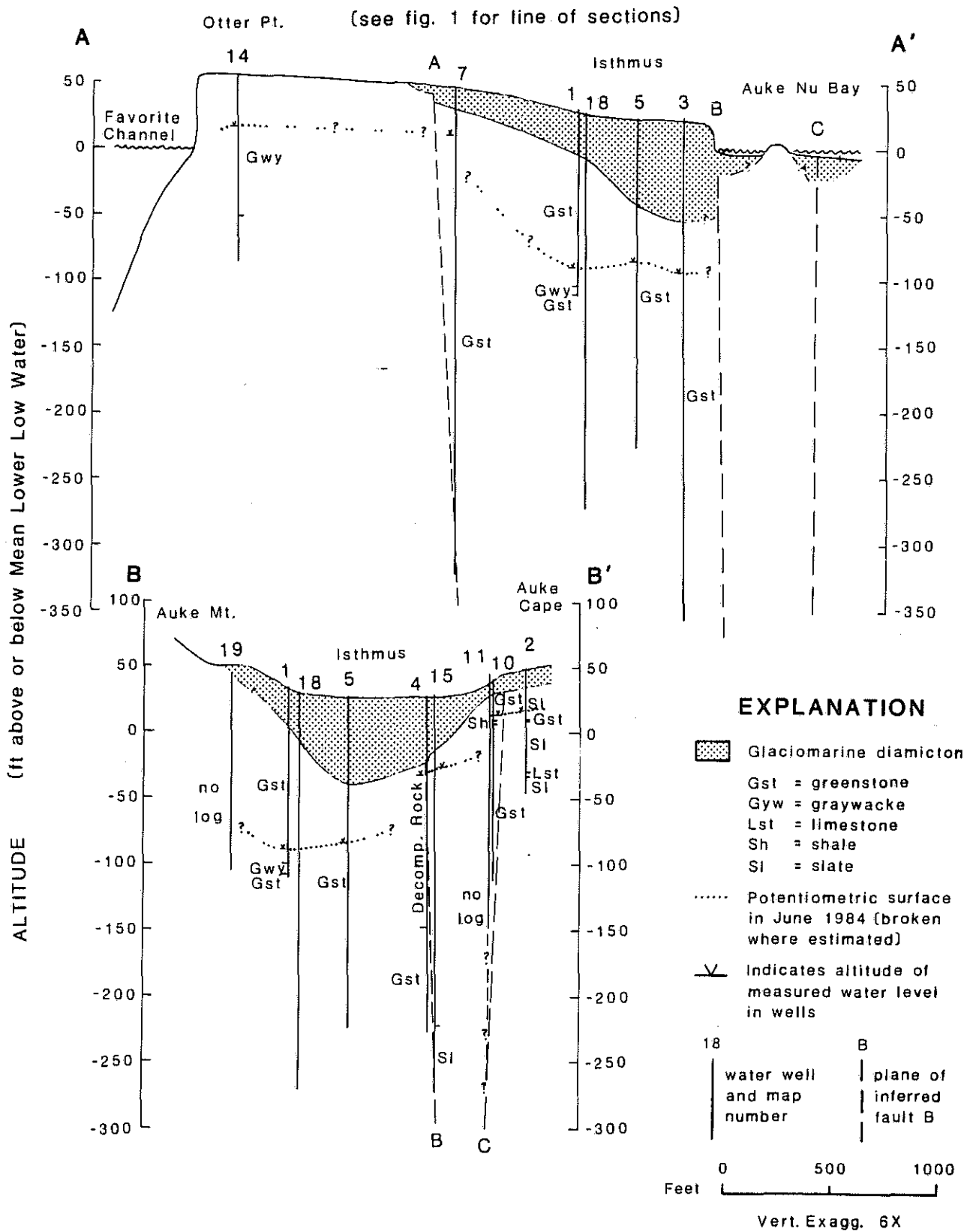


FIGURE 2 Hydrologic sections through the Indian Cove area

projections of the faults. Down-dropping between faults B and C may have occurred, creating a structural block that could be closely related to fault A, a probable through-going dominant fault (Brew, written commun. Sept. 18, 1985). The bedrock lithology east of fault C (fig. 2, B-B') differs enough from that to the west to suspect vertical and/or horizontal displacement, but geologic data are too sparse to portray movement. Section B-B' shows 50+ ft of slate between faults B and C below -220 ft that was not logged in four deep wells west of fault B, also suggesting fault displacement.

GROUND-WATER EXTRACTIONS

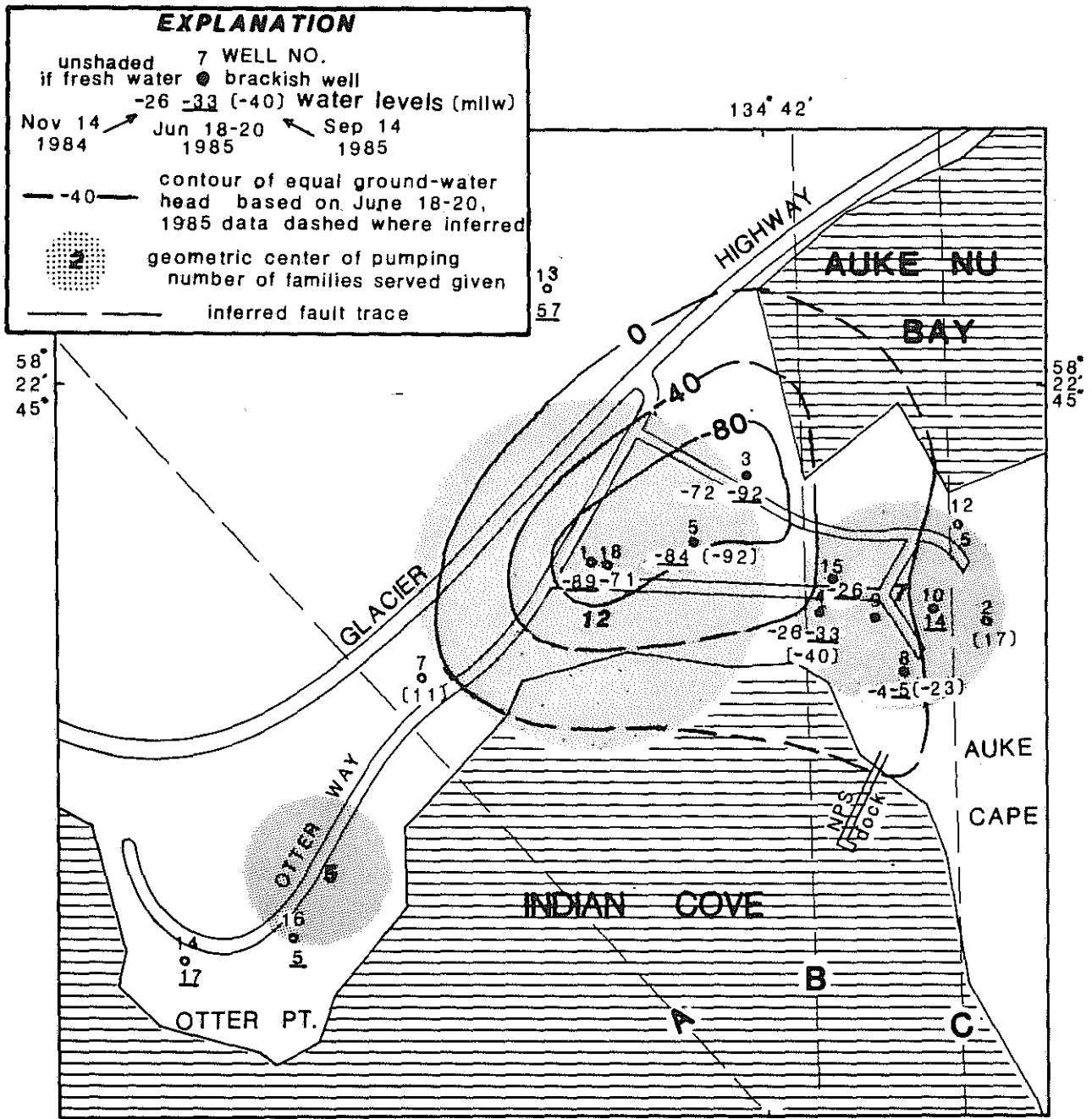
Three areas of concentrated pumping, indicated on figure 3, appear significant in relation to the inferred faults. Based on the number of families served, pumpage centered at the Indian Cove Water Company wells between faults A and B should be about twice that occurring between faults B and C, and that occurring southwest of fault A near Otter Point. Actual pumpage figures are non-existent, and estimates are not considered dependable in this water-conscious community.

AQUIFER WATER LEVELS

Water levels were measured in 13 of the wells in the community (see Table 1) at times when their pumps had not run for at least 3 to 4 hours. The maximum and minimum measured water levels, referenced to mean lower low water (MLLW), are given for wells in which several measurements were made during the period from November 1984 to September 1985. Three wells in which artesian flow occurred when drilled are noted. The variability of measured "static" water-level fluctuations appears unusually large at most wells, but only at well 3 (new condominium well) is a range of 25 ft (fig. 4) known to approximate the actual maximum and minimum for the above period.

A float-driven digital water-level recorder installed at the condo well in November 1985, shows daily water-level recoveries lasting about 1 to 6 hours (fig. 5). Also, water-level measurements made on November 14, 1984, in four other wells (fig. 6) show that between 9:30 am and 2:55 pm levels were rising throughout the area, but at different rates. The fact that the level in the deep water company well rose 5.6 ft suggests that neither it nor the adjacent supply well was pumped during this period.

Observations of water levels at the condo well and well 5, and of pump cycling of the water company's deep well, on two different days (January 4 and June 20, 1985) substantiate a close correlation between water extraction and ground-water-level fluctuations. From these data data it seems reasonable to conclude that most, if not all wells on the isthmus, fluctuate through several rise-and-decline cycles daily as a result of local well pumping. Thus, the bedrock aquifer must be sufficiently fractured so that it behaves like a porous media continuum.



map base from Triad North Technical, Juneau, 4-B31-0, 134° 42' Feb 1985 revision

FIGURE 3 Ground-water extraction and drawdown at Indian Cove

AUKE NU CONDO WELL

DGGS DATAPOD RECORDER
WELL DEPTH=378 FT

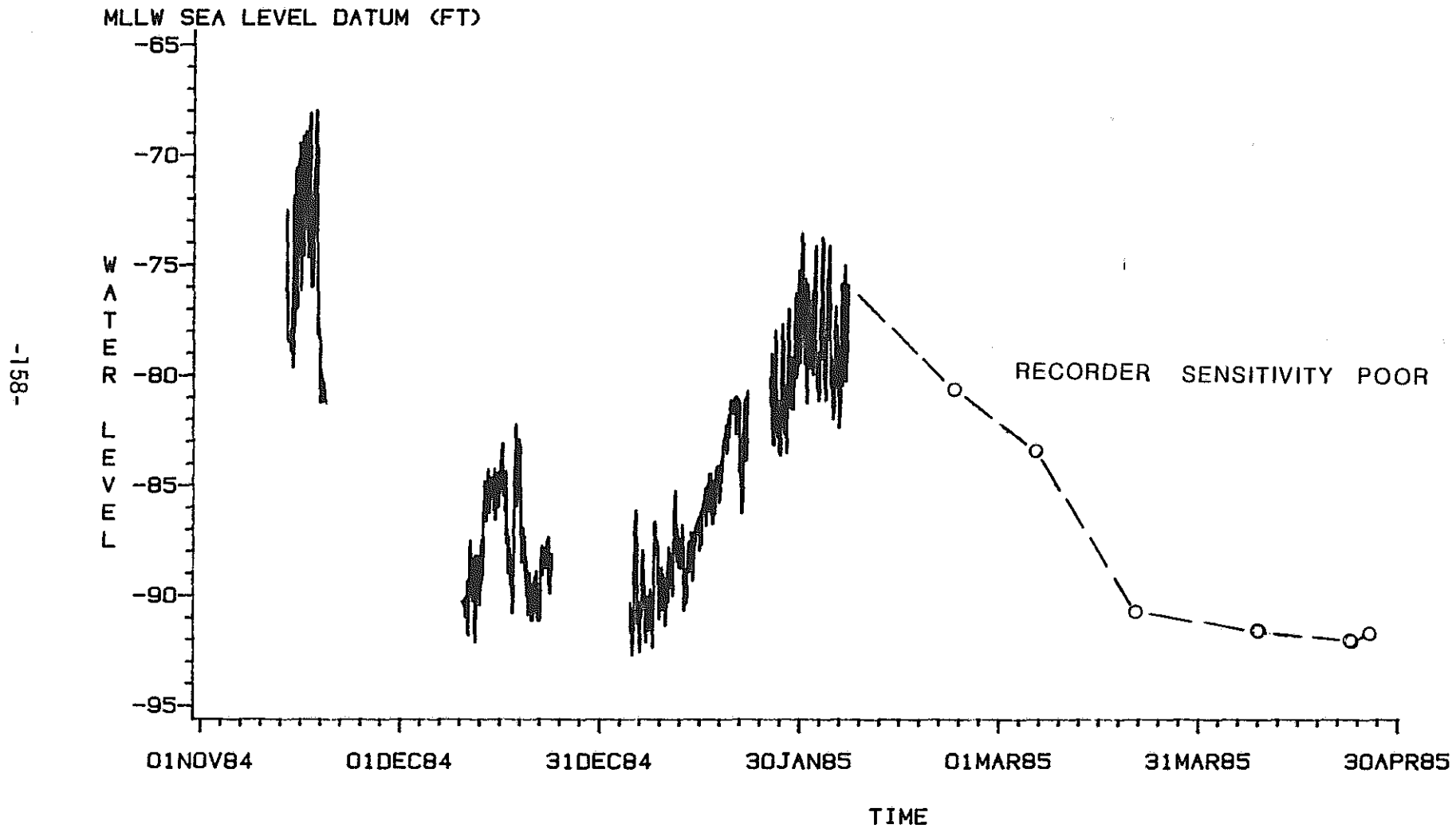


FIGURE 4 Water-level fluctuations intermittently recorded in unpumped well 3

AUKE NU CONDO WELL

DGGS DATAPOD RECORDER

WELL DEPTH=378 FT

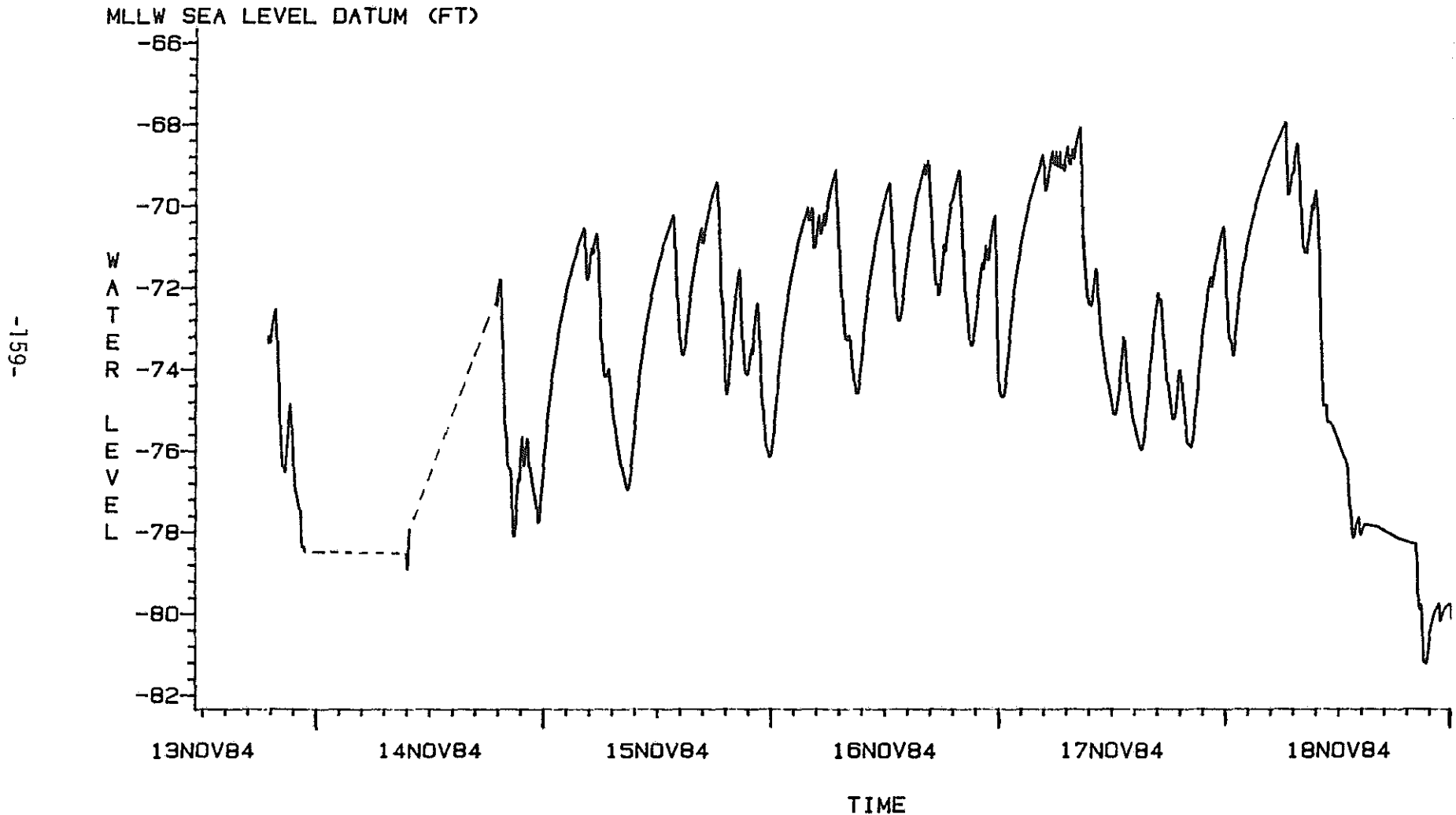


FIGURE 5 Typical daily water-level fluctuations in unpumped well 3

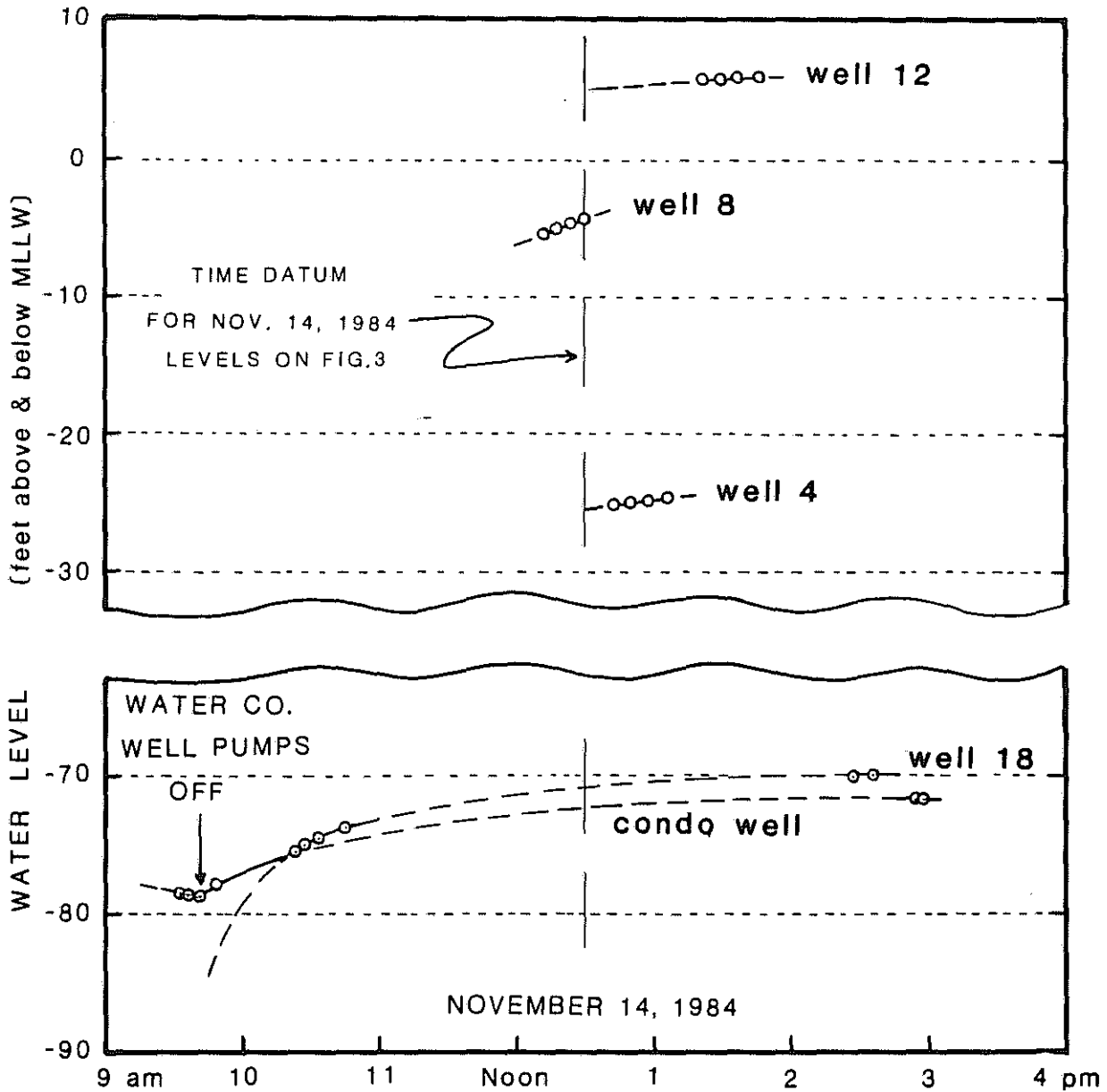


FIGURE 6 Ground-water levels in wells at Indian Cove, indicating areal recovery from local pumping.

Potentiometric contours of the bedrock aquifer (fig. 3), based primarily on the June 1985 water-level measurements given, shows a somewhat triangular-shaped depression of drawdown. Drawdown of up to 123+ ft at well 1 is evident from a comparison of driller's levels (table 1) and the recent water-level measurements. Water levels in wells between faults A and B have fluctuated as much as 25 ft during the study period. The hydrograph (fig. 4) and subsequent individual measurements made in the condo well also indicate that here levels have remained below -68 ft for months. Water levels in five wells east of fault B were measured in the range of -40 to +17 ft. In general, heads show poor correlation with horizontal distances from centers of pumping or with depth of drilling. Static levels in two accessible wells west of fault A were measured only once and were found to be 5 and 17 ft above sea level (MLLW).

AQUIFER WATER QUALITY

Field water-quality testing was performed on discrete samples of water from all wells, except wells 6 and 11. The parameters measured were specific conductance, water temperature, pH, and bicarbonate alkalinity. These data are presented in Table 2.

Historic water-quality data for wells at Indian Cove are sparse. Some local residents reportedly have experienced saltiness, sometimes intermittently, in their well water during the past 3 to 5 years. Water from the Indian Cove community wells (1, 18) had a sodium-ion concentration of 80 mg/L, 190 mg/L, and 370 mg/L at samplings prior to 1968, 1968, and 1984, respectively (Al Kegler, Alaska Department of Environmental Conservation [DEC], oral commun., 1984). The U.S. Environmental Protection Agency's (EPA) maximum recommended concentration of sodium in drinking water is 250 mg/L (EPA, 1976). Values of TDS shown in Table 2 indicate that at the times when sampling occurred, six wells produced brackish water (TDS > 1000 mg/L) and four others had TDS values over 500 mg/L. The EPA's and Alaska DEC's (Statute 18 AAC 70, 1984) recommended maximum TDS concentration for drinking water is 500 mg/L. The TDS values shown in Table 2 were calculated by multiplying field values of specific conductance by 0.55, a value considered conservative (American Public Health Association, 1980, p. 71).

DISCUSSION OF AQUIFER BEHAVIOR

Upon assembling the physical and chemical data just presented, several paradoxes suggest that the ground-water system behaves in an unusual manner. Of paramount significance is the fact that heads in the bedrock aquifer underlying the isthmus have been well below sea level (20 to 90 ft below MLLW) at least since October 1984, when this study began, and probably since the late-1970's, after most wells were in use for a few years.

Table 2. Field water-quality measurements of well water.

Well No.	Well owner	Well depth (ft)	Sample date	Specific conductance (siemens @ 25°C)	TDS calculated ¹ (mg/L)	pH	HCO ₃ alkalinity (mg/L)	Prior Data	
								Sample date	Specific conductance (siemens @ 25°C)
1	Indian Cove Water Co.	142	7/20/85	1430	790	8.0	214	6/19/85	1510
2	National Park Service	95	9/12/85	467	260	8.3	240		
3	Auke Nu Condominium	378	8/10/84	2030	1120				
4	Kack, G.	254	7/20/85	5640	3100	7.6	146	6/18/85	5300
5	Schoenmann, J.	250	7/22/85	2080	1140	6.4	187	4/18/85	1480
7	Hurley, L.	370	9/14/85	715	390	8.6	303		
8	Robinson, C.	135	7/22/85	3370	1850	7.6	335	6/18/85	3300
9	Mercer, H.	130?	11/14/84	2020	1110				
10	Carlson, C.	151	7/19/85	567	310	8.9	264	6/18/85	575
12	Wilkerson, G.	177	7/19/85	1710	940	8.4	347	4/18/85	1280
13	Verrelli, L.	400	7/23/85	700	390	8.6	319	4/18/85	460
14	Darnell, F.	143	7/22/85	582	320	5.7	245	6/17/85	580
15	Cartmill, R.	300	6/18/85	4490	2470				
16	Ciccolo, E.	82	7/21/85	1220	670	6.8	206	6/20/85	1290
18	Indian Cove Water Co.	300	7/20/85	1450	800	8.2	263		
19	Hurley, L.	148	9/14/85	478	260	8.7±	236		

¹ Specific conductance X 0.55

This study reveals that the narrow strip of land bounded on two sides by sea water contains an aquifer that is not as brackish as head levels would suggest, and that some freshwater wells have survived. Furthermore, the disassociation of the most brackish wells and the area of lowest aquifer head requires an explanation. Also, ground-water-level fluctuations up to 12 ft daily in the unused condo well, located 190 ft from the nearest pumped well, suggests good fracture permeability that should have promoted severe contamination of the aquifer underlying the isthmus. This is contradictory to actual findings.

The proposed explanation of these data centers on a combined unique effect caused by geologic features present at Indian Cove. These features are:

1. a network of open joints within a bedrock aquifer underlying an isthmus adequate to create a hydraulic continuum,
2. a fault and/or favorably oriented and inclined joints occurring between the major pumping center and beach outcroppings of fractured bedrock some distance away,
3. a relatively impermeable cap over the bedrock aquifer in the extraction area, and
4. a very steep fresh-water gradient from an adjacent mountain front.

Because the wells having the lowest non-pumping water levels (nos. 1, 3, 5, and 18) are less brackish than shallower wells with higher water levels (nos. 4, 8, 9, and 12), sea-water intrusion must originate as horizontal inflow rather than from vertical upconing of a natural saltwater-intrusion wedge. Although the depths of water-yielding fractures are poorly documented in well records, it is believed that the deeper wells receive their inflow from fractures near their bottoms.

The gravelly beach and/or the bedrock outcrop near the National Park Service (NPS) dock (see fig. 3) seem to be the most logical place for sea water to move horizontally into bedrock. Elsewhere along the isthmus' shorelines, clayey glaciomarine diamicton appears sufficiently thick so as to prevent significant sea-water intrusion (see B-B', fig. 2).

The strongest evidence that sea-water contamination of the aquifer originates near the NPS locality is the alinement of domestic wells pumping brackish water (fig. 3). If sea water were entering bedrock to the west of fault B, wells 1, 5, and 18, which extract considerably more water and have created a deep drawdown depression, should produce the most brackish water. Instead, fault B may function as a primary conduit for introduction of sea water into the aquifer. Support for this premise is the head difference of 66 ft measured on June 18, 1985, between well 3 located west of the fault, and well 15 located east of

the fault although only slightly farther from the major center of pumping. But, a possibility exists that wells 3 and 5 are rather directly connected to well 1 or 18 by unusually permeable fractures, whereas other wells are not as interconnected.

Rock outcroppings along the southern Auke Cape shoreline between faults B and C also may transmit bay water towards the residential wells via joint-fracture intersections serving as effective conduits (Kohut and others, 1983). On the north side of the isthmus, Auke Nu Bay is not considered a prime recharge area due to the extensive tidal mud, which can be seen at low tide.

Contours of equal head (fig. 3) show that the shape of the deep drawdown depression is somewhat triangular towards the NPS dock, a suspected recharge area. In fractured rock aquifers, Kohut and others (1983) found that a "trough" of drawdown over $\frac{1}{2}$ mile in length extended preferentially away from the pumping well in the general direction of a local recharge area. They observed that the trough's alignment coincided with a direction that bisected the obtuse angle between major joint sets. At Indian Cove, vertically dipping joint sets along the neck of Auke Cape have both westerly and northerly strikes. Therefore, the northwest bisector might explain the development of a weak trough-like tongue of drawdown oriented approximately northwest-southeast.

The thick diamicton over bedrock along the coast at Indian Cove suggests that fresh-water recharge enters the Indian Cove aquifer on the nearby southeast-facing slope of Auke Mountain. Precipitation amounting to about 60 inches annually falls on bedrock as low as 150 ft altitude, where a large bedrock exposure has been mapped (Miller, 1975). Some portion of water that infiltrates re-appears as seeps and small springs in the vicinity of the Glacier Highway and Otter Drive. Consequently, standing water is continually present immediately north of the water company wells. But because of 30 ft of diamicton (clay and rock or muskeg on the drillers' logs), this water may be unable to move downward and effectively recharge the bedrock aquifer even under the large vertical gradients present.

Along Otter Drive and southwest to Otter Point the ground-water system is not nearly as stressed by pumping as at the isthmus. Values of TDS are generally well below that of brackish water. The reason for only small effect from the large drawdown under the isthmus may be that fault A acts as a recharge line-source from Auke Mountain. In fact, the excellent yield of well 7, reportedly 25 gal/min, probably is a result of its interception of this fault. Relatively high alkalinity and pH values of water from this well also suggests that a different geologic environment is tapped by the drill hole.

CONCLUSIONS

The domestic use of ground water during the past 10 to 20 years by about 25 families at Indian Cove has severely stressed the fractured rock aquifer. Six of 18 total wells in use now produce water that may be termed brackish, but a few wells yield water of acceptable quality that has not changed substantially with time. Apparently, well depth, amount of water pumped, and distance to nearby beaches are not the primary factors controlling the salinity of well water.

This study indicates that the influence of suspected faults and of the observed proliferation of joints cause preferential directions of drawdown and subsequent sea-water intrusion. An extensive 20 to 70 ft thick cap of clayey glaciomarine deposits is believed to effectively seal the underlying aquifer from sea-water intrusion except at one limited shoreline reach in the vicinity of the NPS rock outcrops. These outcrops apparently are located on the opposite side of the fault(s) of the deep drawdown locality. Also, crossing joint sets with moderate to steep dips create fracture intersections that trend northward, and which might serve as conduits from the Cove to the brackish wells.

The normal relationship of maximum sea-water contamination occurring at wells in maximum drawdown localities in coastline settings does not occur here. Instead, the brackish wells are believed to draw water upward from a diffuse zone of salt-water contamination that receives sea water via faults and joints from primarily one beach locality. It is proposed that these features preferentially conduct a large part of the sea water that disperses into the area of deep drawdown 200 to 400 ft inland. Thus, horizontal intrusion as well as vertical upconing under the drawdown depression are important mechanisms here.

It is hypothesized that the daily large-magnitude fluctuation of aquifer head measured during this study is a manifestation of the sensitivity of the balance between available fresh-water recharge and extraction of ground water by wells. The interconnectiveness of fractures (joints) and faults allows the ground-water system to adjust head levels rapidly, as storage within rock openings is small and cannot sustain well pumpage. Very steep hydraulic gradients created at the mountain front, particularly during rainless periods, maximize fresh-water recharge. When total well pumpage exceeds this recharge rate, the inland-sloping head gradient at the isthmus increases so as to induce more recharge, and thus, greater contamination by salt water occurs. Apparently, the hydraulic conductivity of limited fracture systems leading to the sea is low enough to prevent massive salt-water intrusion, while aquifer heads persist well below sea level.

ACKNOWLEDGEMENT

The author wishes to acknowledge the helpful review of this manuscript rendered by James Munter of DGGS.

REFERENCES CITED

- American Public Health Association, American Water Works Association, and Water Pollution Control Federation, 1980, Standard methods for the examination of water and wastewater (15th ed.): Washington, D.C., American Public Health Association, 134 p.
- Barker, Fred, 1957, Geology of the Juneau (B-3) quadrangle, Alaska: U.S. Geological Survey Quadrangle Map GQ-100, 1 sheet.
- Billings, Marland P., 1962, Structural geology; second edition: Prentice-Hall, Inc., New Jersey, 514 p.
- Ford, A.B., and Brew, David A., Preliminary geologic and metamorphic-isograd map of the Juneau B-2 quadrangle, Alaska: U.S. Geological Survey Misc. Field Studies Map MF-527, 1 sheet.
- Kohut, A.P., Foweraker, J.C., Johanson, D.A., Tradewell, E.H., and Hodge, W.S., 1983, Pumping effects of wells in fractured granitic terrain: in Ground Water, Vol. 21, No. 5, Sept-Oct 1983, p. 564-572.
- Miller, Robert D., 1975, Surficial geologic map of the Juneau urban area and vicinity, Alaska: U.S. Geological Survey Misc. Investigation Series, Map I-885, 1 sheet.
- Todd, David K., 1980, Groundwater hydrology: John Wiley and Sons, New York, 535 p.
- U.S. Environmental Protection Agency, 1976, Quality criteria for water: U.S. Government Printing Office, Washington, D.C., 256 p.

RECOGNITION AND RESOLUTION OF EAGLE RIVER'S GROUND-WATER CONFLICTS:
ROLES OF DATA AND WATER RIGHTS

by James A. Munter¹ and Gary J. Prokosch²

ABSTRACT

Controversy intensified during the summer of 1984 concerning the use of Eagle River's confined aquifer system described by Munter (1984). Water levels were declining at a rate of 4 ft/yr because of pumping of private and public water-supply wells in the area. A proposal for a new extraction of 0.076 million gallons per day (mgd) was being considered by the state in the context of a total potential extraction of 1.64 mgd by major water users with prior water rights in the immediate vicinity. Average 1984 water use by major users was about 0.46 mgd.

Analysis utilizing a three-dimensional ground-water flow model indicated that excessive drawdown would prevent realization of the total potential extraction rate, and that if development of such magnitude could occur, numerous wells, with and without water rights, would fail. It was concluded that the system had been technically over-appropriated with the issuance of several permits to appropriate water to major water users, and that additional water rights had been applied-for and granted until recognition in 1984 that conflicts existed.

Temporary resolution of conflicts was achieved by Municipal acquisition of a private water-distribution system, changes in pumping patterns, issuance of temporary water-use permits, and promise of Municipal water from Anchorage's Ship Creek through the Eklutna Water Project, phase I pipeline in August, 1985. More timely data collection would have resulted in earlier recognition of the over-appropriation. Alaska's data-collection program, water rights statutes and regulations, and Anchorage's Municipal water system were all important contributors to resolving water-use conflicts in a rapidly growing community.

INTRODUCTION

A detailed hydrogeologic study of the most populated portion of Eagle River (fig. 1) was initiated in 1982 by the Alaska Division of Geological and Geophysical Surveys (DGGs). Rapid population growth in the study area, combined with complete reliance on local ground water

¹ Hydrogeologist, Alaska Department of Natural Resources, Division of Geological and Geophysical Surveys, P.O. Box 772116, Eagle River, AK 99577

² Regional Water Officer, Alaska Department of Natural Resources, Division of Land and Water Management, Pouch 7-005, Anchorage, AK 99510

for water supply, had resulted in elevated concerns regarding the adequacy of local supplies for continued growth.

The increase in the amount of ground water granted for appropriation by the Alaska Division of Land and Water Management (DLWM) through December 31, 1983 (fig. 2), illustrates the exponential rate of growth. This paper examines the origin and resolution of a conflict associated with the rapid growth in Eagle River.

Setting

The greatest concentration of ground-water extraction in Eagle River occurs from the Eagle River confined aquifer system described by Munter (1984). Figure 3 shows that major community water systems and areas of residential well development occur in close proximity to each other within the boundaries of the aquifer system. Ground water is obtained from one of several confined sand and gravel aquifers within the 200 to 500 ft thick accumulation of Quaternary deposits. Confining units consist of till and silty lacustrine or marine sediments. During 1984, an estimated 500 to 600 domestic wells tapping the confined aquifer system were in use.

Statement of Problem

Water-level data collected at a DGGs observation well since April, 1983 show that water levels were declining at a rate of about 4 ft/yr through mid-1984 (fig. 4). Other data suggested that 10-15 ft of water-level decline had occurred prior to 1983 near the geographic center of the confined aquifer system (Munter, 1984). During 1984, several residential wells were reported to have problems related to low water levels, and an areal analysis indicated that numerous wells in the vicinity had less than 20 ft of water standing freely in them at the time of drilling or during a 1983 DGGs water level survey (Munter, 1984). It was concluded that a significant decline in water levels from 1984 levels would have had adverse effects on private wells in the area.

Cursory analysis suggested that the cause of the declining water levels in the area was an increase in pumping by the major water systems listed in Table 1. Although historic water-use data for the major systems are sparse, construction histories for the systems document rapid growth in the early 1980's. Water rights applied-for or granted through December 31, 1983, for the confined aquifer system totalled 1.64 mgd, including 1.39 mgd for the major water users (Table 1). Potential growth of water use, as indicated by the amount of water rights applied-for or granted, represented a major potential threat of causing water levels to decline rapidly, and thus increase the number of well failures.

On January 11, 1984, application was made to DLWM for a proposed additional extraction of 76,000 gpd of water from the Eagle Crest wells for delivery to Heritage Estates subdivision located 1 mi east of the Eagle Crest wells. Construction of the subdivision began in the spring

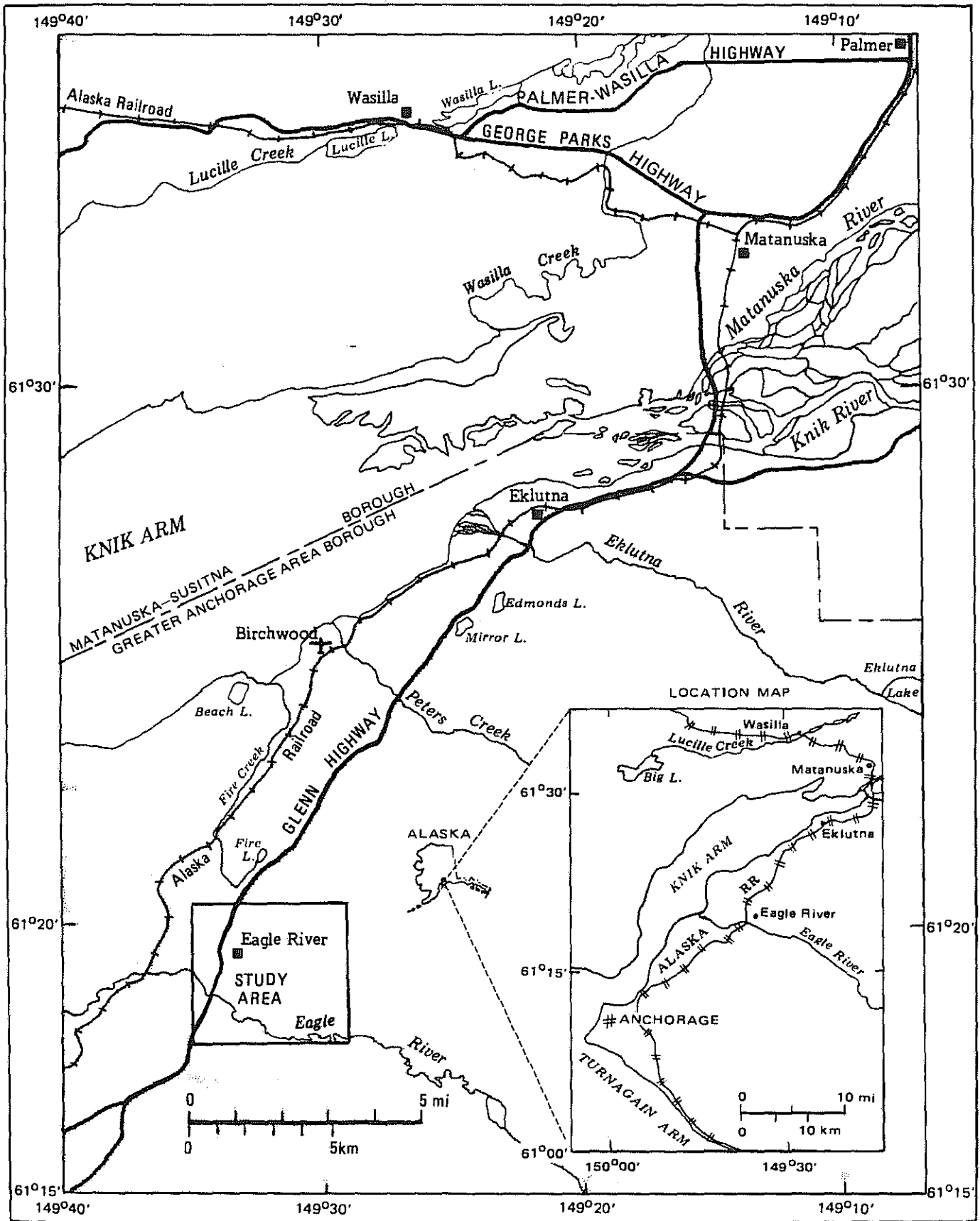


Figure 1. Location map of study area.

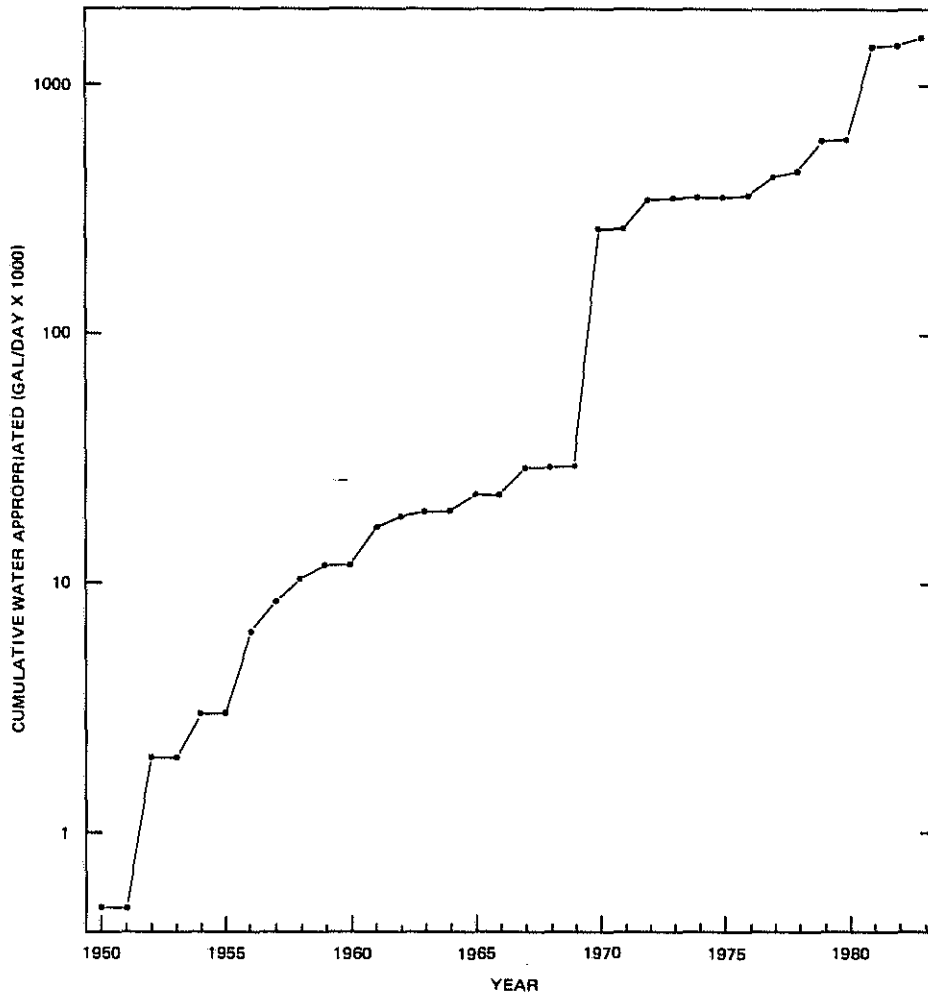


Figure 2. Cumulative ground-water appropriations from the Eagle River confined aquifer system. Plotted values are year-end totals.

of 1984. DLWM requested that DGGs assess the effects of the proposed extraction, taking into account the possibility that the total appropriation to major water users (Table 1) could also be pumped and put to use by March, 1987.

METHODS AND RESULTS

A three-dimensional finite-difference ground-water flow model (McDonald and Harbough, 1984) was constructed to simulate the flow system and the development history of the Eagle River confined aquifer system. The model consisted of 11 layers, 12 rows, and 24 columns, treating each of 6 aquifers and 5 confining units explicitly. Grid blocks in most of the area modeled were 40 acres in area. The boundaries of the modeled region were treated as impermeable, except the water table (including the Eagle River) which was treated as a specified

DGGS WELL SB14-2-13AAAA3-3

WELL DEPTH=268 FT, LAND SURFACE ALTITUDE=516 FT
PERIOD OF RECORD

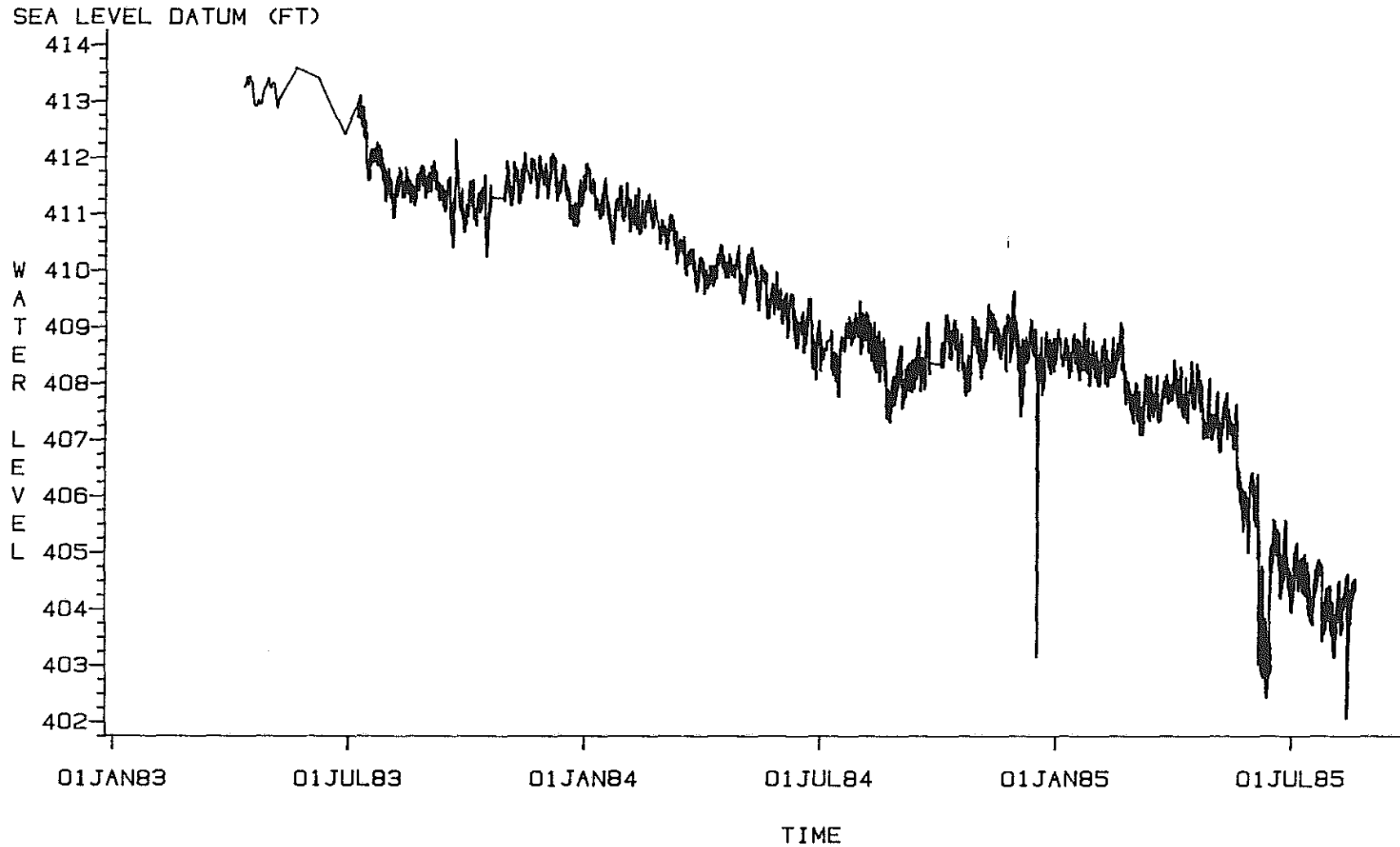


Figure 4. Water-level data from DGGS observation well shown in figure 3.

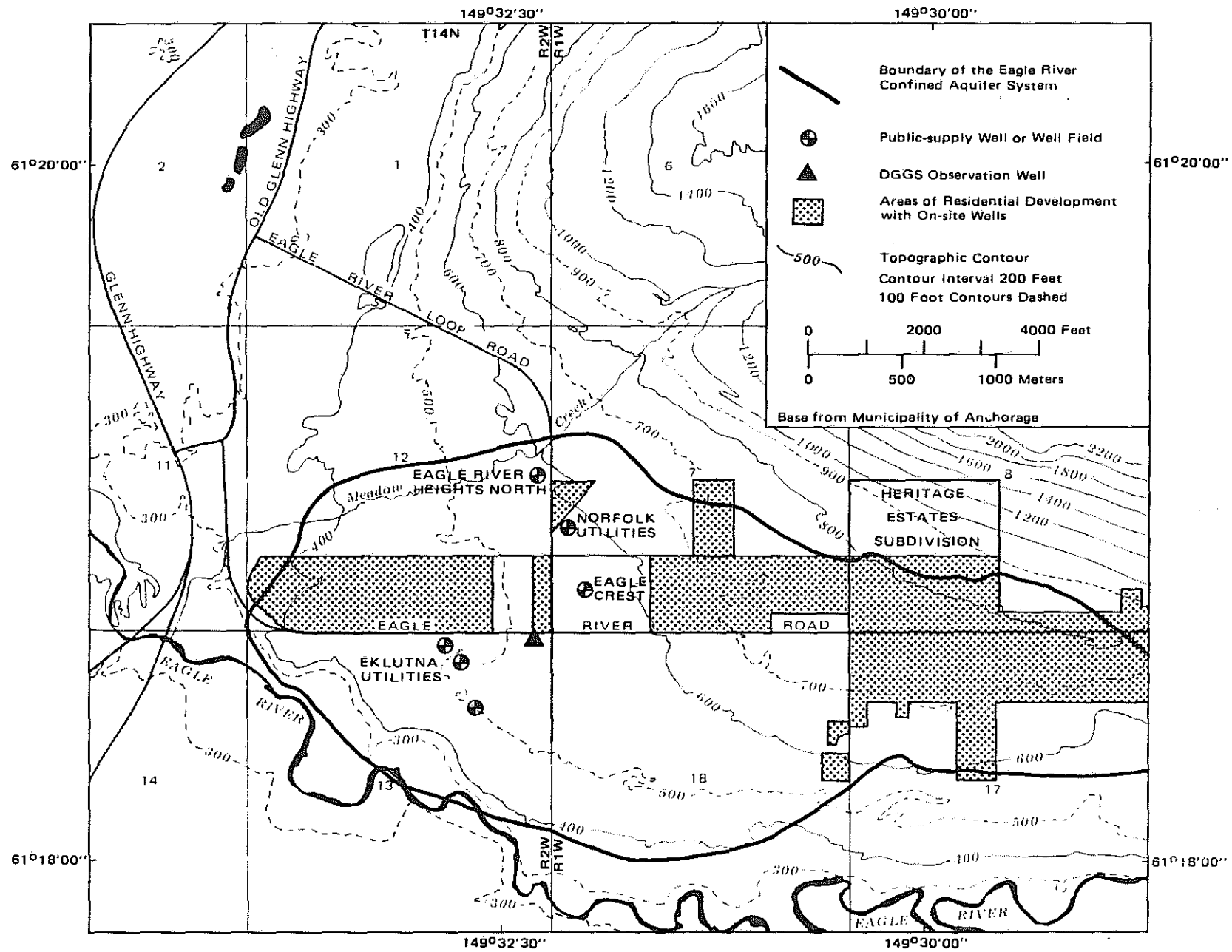


Figure 3. Location of the Eagle River confined aquifer system, with locations of wells.

Table 1. Water-use and water-rights data for major users of the Eagle River confined aquifer system.

<u>Major user</u>	<u>Average 1984 water use (gpd)</u>	<u>Total State appropriation as of 12-31-83</u>	<u>Owner as of 12-31-83</u>
Eagle River Heights North	194,000 ^a	260,000	Anchorage Water & Wastewater Utility
Norfolk Utilities	135,000	569,111	Norfolk Utilities & Development, Inc.
Eagle Ridge	86,000	487,880	Eklutna Utilities, Inc.
Eagle Crest	44,000	77,500	Alaska USA Federal Credit Union
TOTAL	459,000	1,394,491	

^a Includes an unknown amount of water pumped from a shallow water-table aquifer.

head boundary. For transient simulations, the water-table boundary was converted to a specified flux boundary. Hydraulic conductivity and storativity values for the model were initially estimated from aquifer test data and a literature review, and were adjusted by trial-and-error matching of simulated heads with observed heads, using the strong horizontal and vertical gradients that were found to occur in the area, and measured and estimated historic drawdown and pumping data.

Simulations were performed projecting potential growth in total water extraction to 1.48 mgd through 1988. The model indicated that 30 to 80 ft of drawdown would occur over most of the confined aquifer system, except for aquifers less than about 280 ft deep in sections 8 and 17, which would incur less than 10 ft of drawdown. Comparison of model-projected drawdown with specific capacity and available drawdown data from local wells resulted in several conclusions. First, the analysis indicated that it would be physically impossible for all major users except Eagle Crest to extract water at the levels indicated by their water appropriations because projected water levels would be near or below the bottoms of the production wells. Also, if pumping would occur at proposed rates, 34 wells protected by water right and tapping the confined aquifer system would probably fail, as well as many other wells in the area. In view of these results, the Eagle River confined aquifer system is concluded to have been overappropriated by December 31, 1983, and probably as early as 1981, when several large water-use permits were issued.

Conflict: Water Permit Issuance or Non-issuance?

DLWM faced a dilemma. To issue a permit to extract 76,000 gpd of water at Eagle Crest would constitute a significant deviation from water-rights statutes and regulations that prohibit issuance of water permits if prior appropriators would be significantly affected. On the other hand, an area-wide water shortage did not occur in Eagle River in 1984, and the developers of Heritage Estates subdivision required a permit to extract water to continue development during the 1984 construction season.

Resolution of Conflict

None of the owners of the four major water systems in the area (Table 1) were receptive to voluntarily reducing their own water appropriation and thereby reduce the total potential stress on the aquifer system. The Anchorage Water and Wastewater Utility (AWWU), however, took the lead in formulating a plan that resulted in at least a temporary and partial resolution to immediate problems. Under the plan, AWWU would: (1) acquire ownership of the Eagle Crest system; (2) begin pumping (through newly-installed transmission mains) more water from wells with excess capacity located outside of the confined aquifer system; and (3) reduce pumpage from Eagle River Heights North wells. In return for reducing pumpage at Eagle River Heights North, DLWM would issue a temporary permit to extract 15,000 gpd of water from the Eagle Crest wells for Heritage Estates subdivision. The temporary permit would expire on August 31, 1985, when water from Ship Creek in Anchorage was promised to be available to Eagle River through phase 1 of AWWU's Eklutna Water Project. The Eklutna Water Project is designed to provide water for the Municipality (including Eagle River) from Eklutna Lake (fig. 1).

In late summer of 1984, the initial aspects of the plan described above were implemented, temporarily resolving all immediate controversies. A significant reduction in pumping at the Eagle River Heights North well field has occurred since mid-1984 (fig. 5). A long-term solution for the overappropriated state of the confined aquifer system had not been achieved as of August 31, 1985. Adjudication of pending water-rights applications and expired permits within the area was resumed during September, 1985.

SUMMARY AND CONCLUSIONS

Prior to 1984, ground-water data collection and analysis were not sufficiently detailed to allow effective management of Eagle River's confined aquifer system. More water was technically appropriated through Alaska's water-rights system by December 31, 1983, and probably as early as 1981, than was available. Conflicting proposed water extractions in 1984 were temporarily resolved through cooperative arrangements between DLWM and AWWU that made use of AWWU's newly-acquired integrated water-distribution system in Eagle River. In

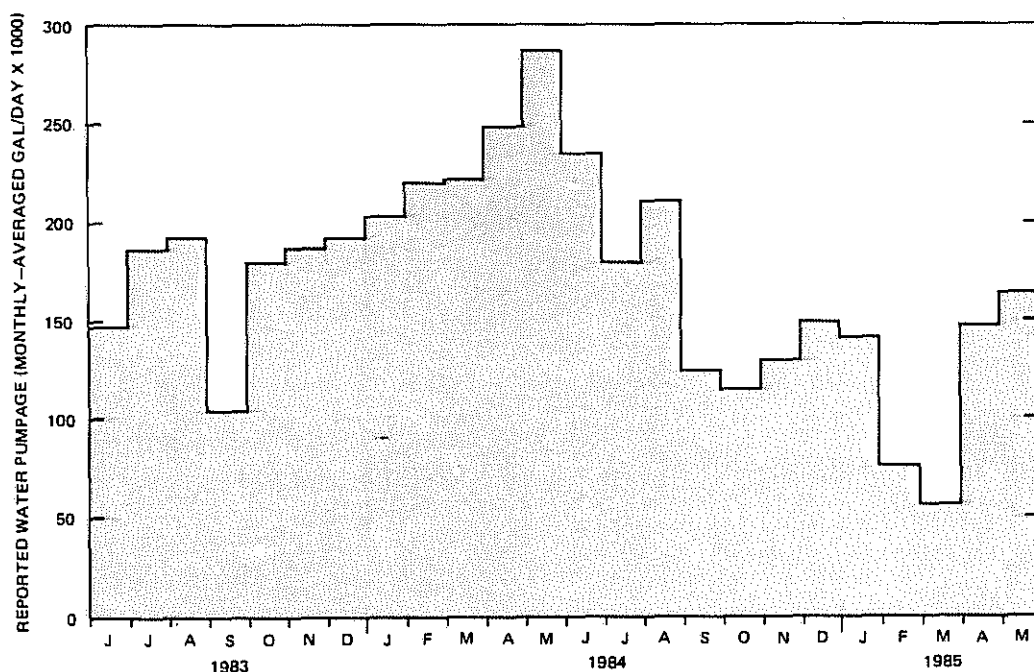


Figure 5. Reported pumpage by AWWU at the Eagle River Heights North well field.

1984, detailed hydrogeologic data collection and analysis provided the foundation that allowed Alaska's water-rights statutes and regulations to function as a framework for resolving current water-use conflicts in Eagle River. The critical factor in resolving conflicts has been, and will likely continue to be, the ability of AWWU to provide public water to key areas in Eagle River with a water source from outside of the confined aquifer system.

ACKNOWLEDGEMENT

The authors thank Larry Dearborn of DGGs for his thoughtful review of the manuscript.

REFERENCES CITED

- McDonald, M.G., and A.W. Harbough. 1984. A modular three-dimensional finite-difference ground-water flow model. U.S. Geological Survey. Open-File Report 83-875. 528 pp.
- Munter, J.A.. 1984. Ground-water occurrence in Eagle River, Alaska. Div. of Geological and Geophysical Surveys, Alaska Dept. of Natural Resources. Report of Investigations 84-21. 15 pp.

APPENDIX
PAPERS PRESENTED AT THE 1984 ANNUAL MEETING

HYDROLOGY OF TSIRKU RIVER ALLUVIAL FAN NEAR HAINES, ALASKA

by Edward F. Bugliosi¹

ABSTRACT

Ground-water discharge at the toe of Tsirku River alluvial fan, 20 miles north of Haines, Alaska, maintains open reaches in the Chilkat River throughout the winter low-flow period. A late fall/early winter run of chum salmon spawn in these open reaches. The spawned-out salmon attract the largest known concentration of bald eagles (more than 3,000) to the area by providing an easily obtainable food source.

Analysis of hydrologic data from the Tsirku fan area, including seismic refraction, water-level, water-quality, and isotopic data, indicated that:

1. Depth to bedrock at the axis of the Chilkat Valley is at least 850 feet.
2. The principal source of recharge to the ground-water system of the fan is water lost from stream channels crossing the fan surface.
3. Seventy-five percent of the winter flow of the Tsirku River at the head of the fan was derived from ground water discharge.
4. Oxygen and hydrogen isotope data suggest that water at a depth of 260 feet is derived from precipitation deposited at relatively high altitude, continental areas.
5. Although areas of visible ground-water discharge at the toe of the Tsirku Fan appear to be randomly distributed, their locations are probably controlled by differences in hydraulic conductivity in the alluvium.

INTRODUCTION

The Tsirku fan is located west of the village of Klukwan, about 20 mi northwest of the city of Haines, Alaska (fig. 1). The area around the toe of the fan, which is bordered by the Chilkat River, is the site of the largest known concentration of bald eagles in the world (Boeker et al., 1980). More than 3,000 birds are attracted to this area by late fall/early winter runs of chum and coho (silver) salmon. Open leads in the Chilkat River during the winter provide spawning habitat, and the spawned-out salmon are an abundant food source for the eagles.

In 1979, the Alaska Chapter of the National Audubon Society asked the U.S. Geological Survey to become involved in hydrologic investigations of the Tsirku fan area. In 1980, a formal request for such a

¹Hydrologist, U.S. Geological Survey, Water Resources Division, Juneau, Alaska 99802

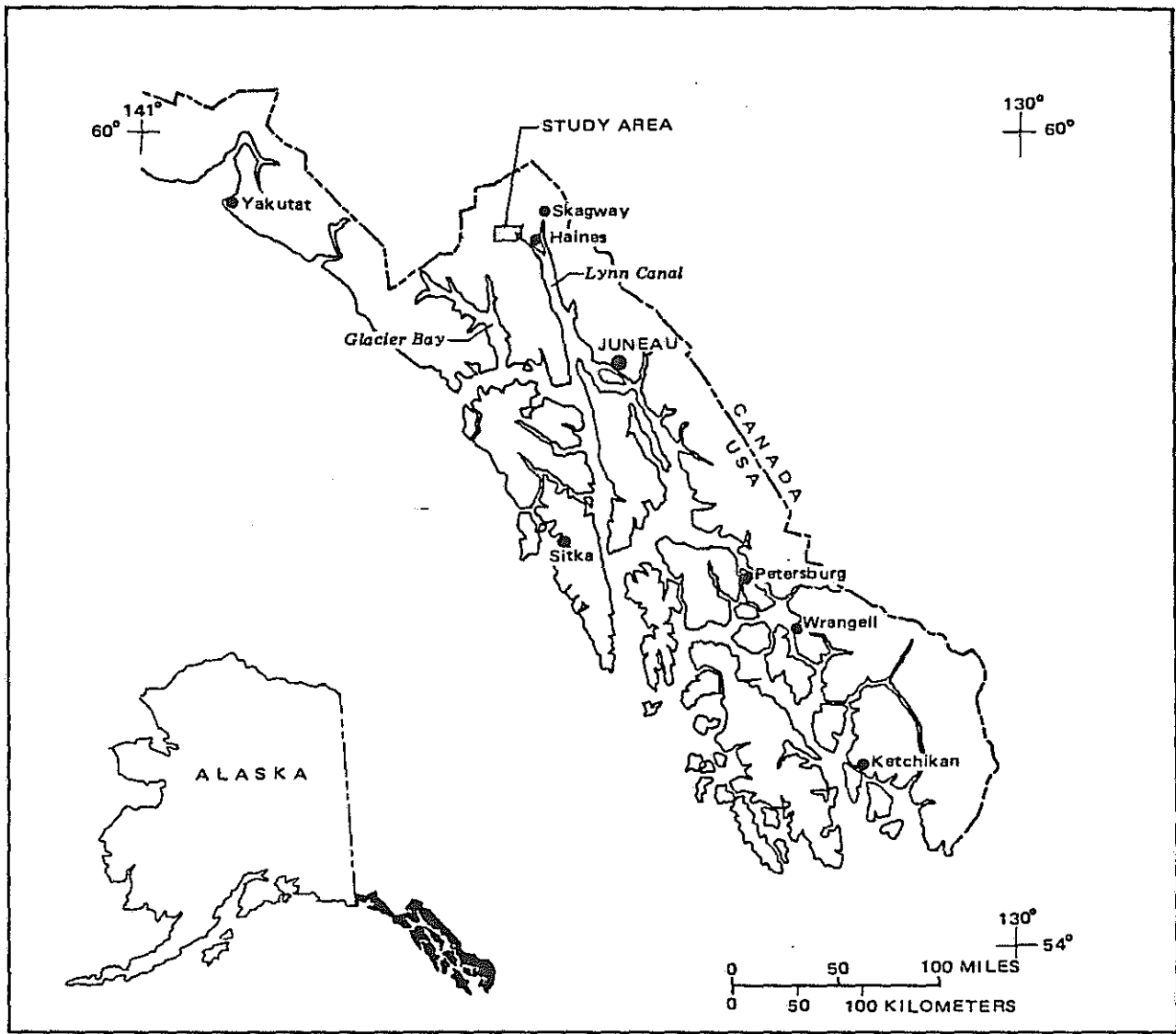


Figure 1.--Location of study area.

study was made by the Alaska Department of Natural Resources, Division of Geological and Geophysical Surveys (ADNR-DGGS). The objectives of the study were to describe (1) the general hydrology of the Chilkat River basin, and (2) more specifically, the relation between surface water and ground water in the vicinity of the Tsirku River alluvial fan. The study began in May 1981, and field work was completed in July 1983. This paper will deal only with the findings of investigations of hydrology of the Tsirku fan area.

The Chilkat River basin, which has an area of about 1,000 mi², is characterized by rugged, highly dissected mountains with steep-gradient streams; braided rivers in broad, glaciated valleys; and numerous glaciers. Altitudes range from sea level at the mouth of the Chilkat River to 7,434 ft at the summit of Mt. Henry Clay. Areas below timberline (about 2,000 ft) support dense brush and forests of spruce and hemlock.

The Chilkat River basin has moderate summer and winter temperatures, heavy precipitation in late summer/early fall, and heavy snowfall in winter. Local orographic effects cause differences in weather conditions over short distances. It is not uncommon for simultaneous temperatures at Haines and Klukwan to differ by as much as 10° F. Average yearly precipitation ranges from about 55 in. at Haines to 20 in. at Klukwan.

GEOLOGY

The Chilkat River basin is divided into two distinct geologic provinces by the Chilkat River fault (which roughly underlies the Chilkat River), an extension of the Chatham Strait fault system to the south (Brew et al., 1966; Ovenshine and Brew, 1972). East of the fault and Chilkat River, the structural trends are predominately northwest, as in much of southeast Alaska; west of the fault and river the structural trends are complex and include west-trending faults and lineaments.

The rocks east of the Chilkat River consist of intrusives and meta-volcanics that range in age from Cretaceous to early Tertiary (100-50 million years). Lithologically diverse, metamorphosed Paleozoic, Cretaceous, and Tertiary rocks (500-50 million years) are present west of the river.

GLACIAL HISTORY

The principal land-shaping process during recent geologic time has been glaciation, and this process continues to modify the landscape. About 25 percent of the Chilkat basin is ice covered. Most types of glacial features can be found in the basin, and ground moraine covers most of the bedrock at lower altitudes. The complex glacial history includes multiple, basin-wide glaciations as well as local fluctuations of individual glaciers. The latest ice advance into the Tsirku fan area may have been as recent as 1,700 years ago or as early as 11,000 years ago (McKenzie and Goldthwait, 1971).

DATA COLLECTION

In the fall of 1982, the Alaska DGGS contracted for 1,000 ft of air rotary drilling. Eleven 6-inch diameter wells were drilled and cased -- eight are 40 ft deep and three others are 100, 220, and 260 ft deep, respectively (fig. 2). Three 2-inch diameter observation wells were also drilled using a vibrating-coring device.

Seismic refraction surveys were made on the Tsirku fan, lower Tsirku River valley, lower Klehini River valley, and an area between the Klehini and Tsirku Rivers within the Little Salmon River drainage (fig. 2). The primary purpose of the seismic survey was to delineate the bedrock floor in the respective valleys, and thus determine the possibility of hydrologic connection between the Klehini and Tsirku Valleys. A Nimbus ES1210F^{2/} multichannel signal-enhancement seismograph was used with 12 geophones. Data were analyzed and plotted by computer.

On April 6, 1982, during low-flow conditions, a seepage run (a series of discharge measurements to determine gaining and losing reaches of a stream) was conducted on streams of the Tsirku fan and adjacent areas (fig. 3).

Water samples were collected from both deep (260 ft) and shallow (40 ft) wells and from the Tsirku, Klehini, and Chilkat Rivers. The samples were analyzed for concentrations of major cations and anions, nutrients, heavy metals, and oxygen and hydrogen isotopes.

DISCUSSION OF RESULTS

Drilling Data

Almost all drill cuttings were glaciofluvial materials derived from rocks in the basin, except for those from well AR-1 at the head of the fan. Well AR-1 encountered lacustrine deposits from depths of 150 to 200 ft, and bedrock from 200 to 220 ft. Grain sizes of material in all wells ranged from silt to 2-inch fragments of broken gravel, cobbles, and boulders. Geophysical well logs indicated distinct layers of fine-grained material between coarser grained sediments, a reflection of the complex depositional environment of glaciated valleys.

Seismic Survey

Seismic traverses were made perpendicular to the axes of the Chilkat, Tsirku, and Klehini Valleys, and also across a remnant outwash terrace between the Klehini and Tsirku Valleys, in the area of the Little Salmon River drainage (fig. 2). Data from the Chilkat Valley correlated well both with observation wells drilled on the Tsirku fan

^{2/} Use of brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

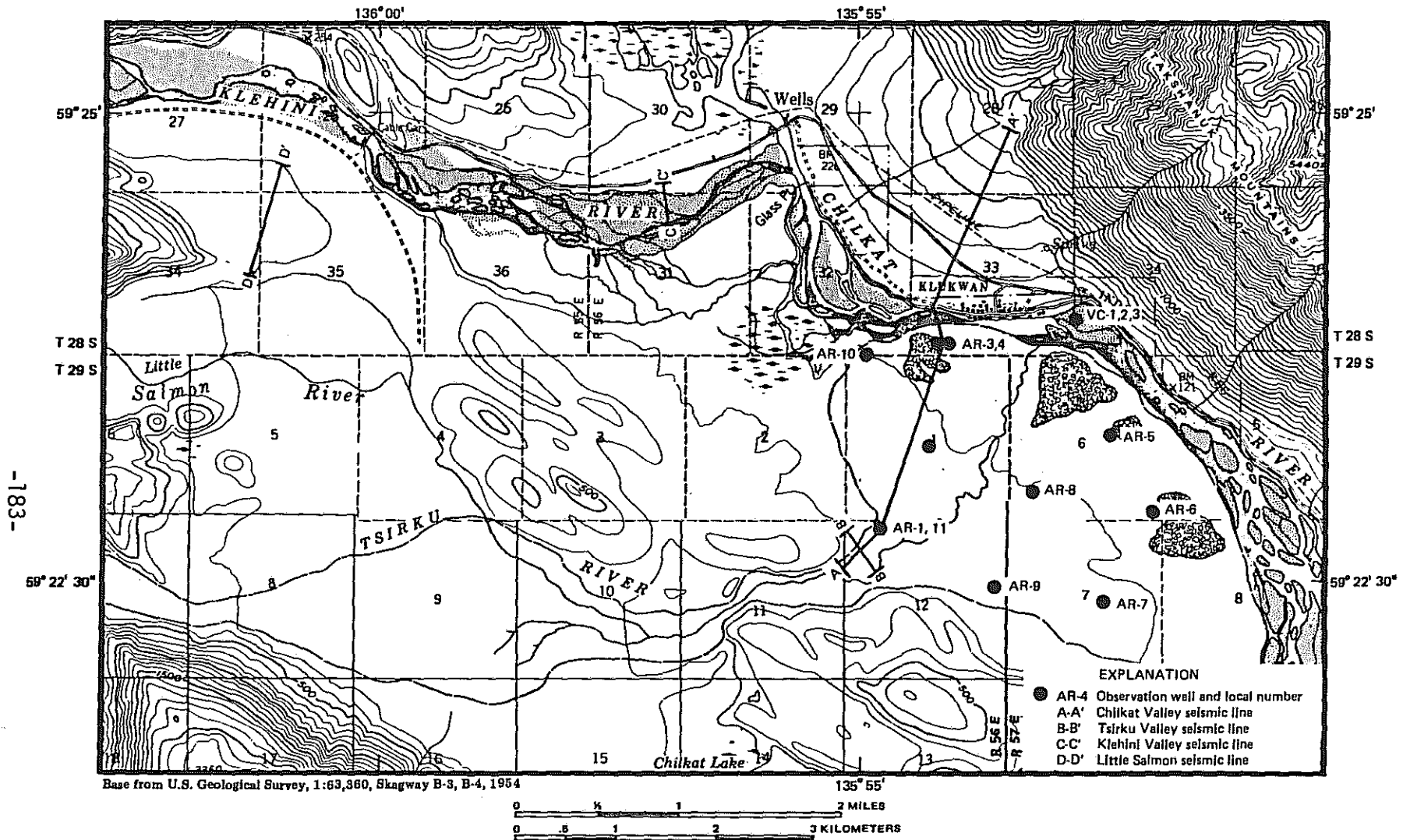


Figure 2.--Tsirku Fan, Klukwan Fan and vicinity, showing locations of observation wells and seismic survey lines for the Chilkat, Tsirku, Klehini, and Little Salmon valleys (for cross section of Chilkat Valley see figure 4).

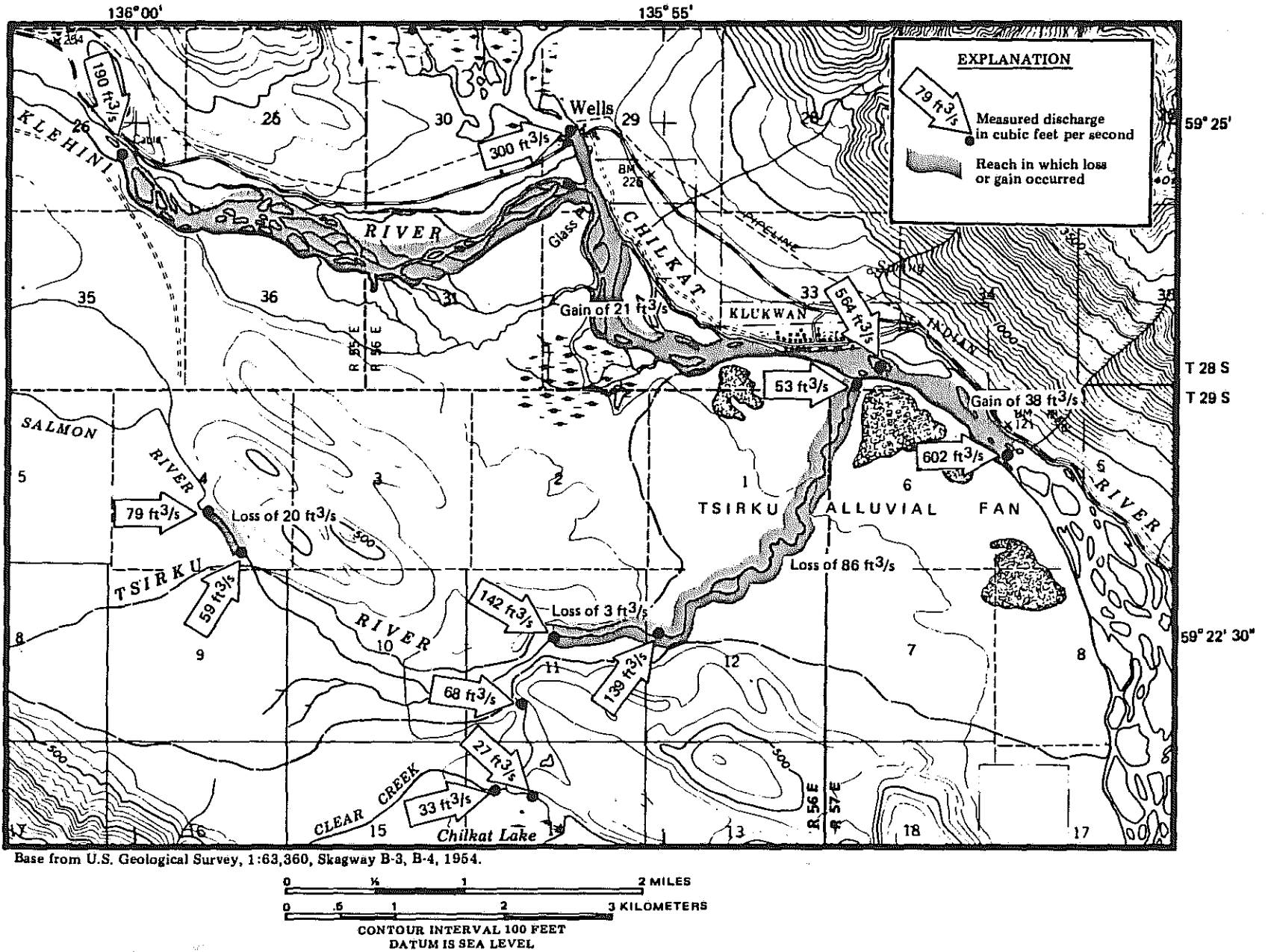


Figure 3.--Losses and gains in streamflow in the Tsirku River Fan area, April 6, 1982.

and with a 1972 gravimetric survey of the Klukwan fan on the east side of the valley made by the H.J. Kaiser Co. (M.M. Holmes, Klukwan Iron Ore Co., written communication, 1983).

Seismic data indicated a depth to bedrock of about 200 ft at the head of the Tsirku fan. The gravity profile of the bedrock surface beneath the Klukwan fan matched well with the projection of the seismic trace of the bedrock profile beneath the Tsirku fan (fig. 4). The greatest depth to bedrock indicated by the seismic survey was about 750 ft, about 1.25 mi from the west edge of the Chilkat Valley. The gravimetric survey indicated almost 900 ft as the deepest bedrock, at a point about 0.8 mi from the east side of the Chilkat Valley. Average seismic velocities were 7,000 ft/s for the saturated, unconsolidated glaciofluvial sediments, and 12,000 ft/s for the bedrock, a fractured schist and phyllite.

Seismic data from the Klehini Valley indicated a depth to bedrock of about 100 ft at a point 1,000 ft south of the Haines Highway at mile 25. Data from Little Salmon River drainage area indicated a depth to bedrock of more than 150 ft. These results indicate the presence of a continuous alluvial layer between Klehini, Tsirku, and Chilkat Valleys and thus probable hydraulic connection among them.

TSIRKU FAN AQUIFER

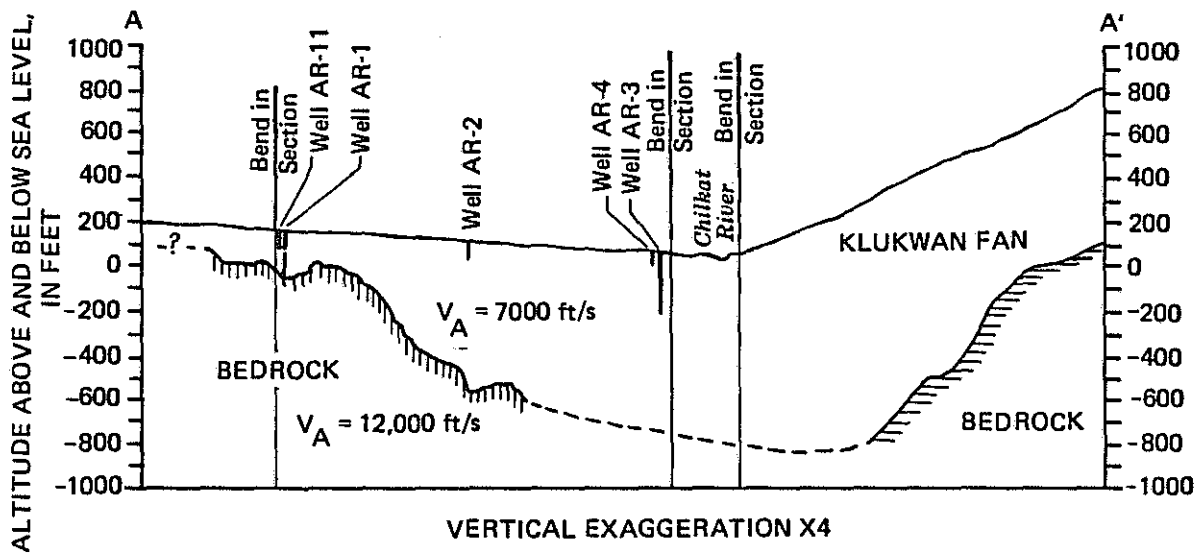
The Tsirku fan aquifer is bounded by the bedrock valley floor and the east and west bedrock walls of the Chilkat Valley, and is continuous with sediments, both up- and downvalley. The potentiometric surface of the aquifer, drawn on the basis of water-level measurements in observation wells on the fan, approximates the shape of the fan, becoming slightly skewed down the Chilkat Valley at about mid-valley (fig. 5). The altitude of the potentiometric surface fluctuates seasonally, declining during winter to about 50 ft below land surface and rising during summer and fall to about 10 ft below land surface at the head of the fan. Water levels at the toe of the fan fluctuate seasonally from about 15 to 5 ft below land surface.

Ground-water flow rates can be estimated using Darcy's law:

$$V = (K/O)(i)$$

where V is average linear velocity, in feet per day;
K is hydraulic conductivity, in feet per day;
i is hydraulic gradient, a dimensionless variable;
O is porosity of the aquifer, expressed as a decimal.

The hydraulic conductivity and porosity have not been directly determined for the Tsirku fan sediments. However, coarse, sandy gravel typically has a hydraulic conductivity ranging from 200 to 2,000 ft/d and the porosity of such material is commonly about 0.25. The gradient of the potentiometric surface is 0.0052. Thus the rate of ground-water movement would range from 4 to 40 ft/d, and travel time from apex to the toe of the fan from 0.5 to 5 years.



EXPLANATION




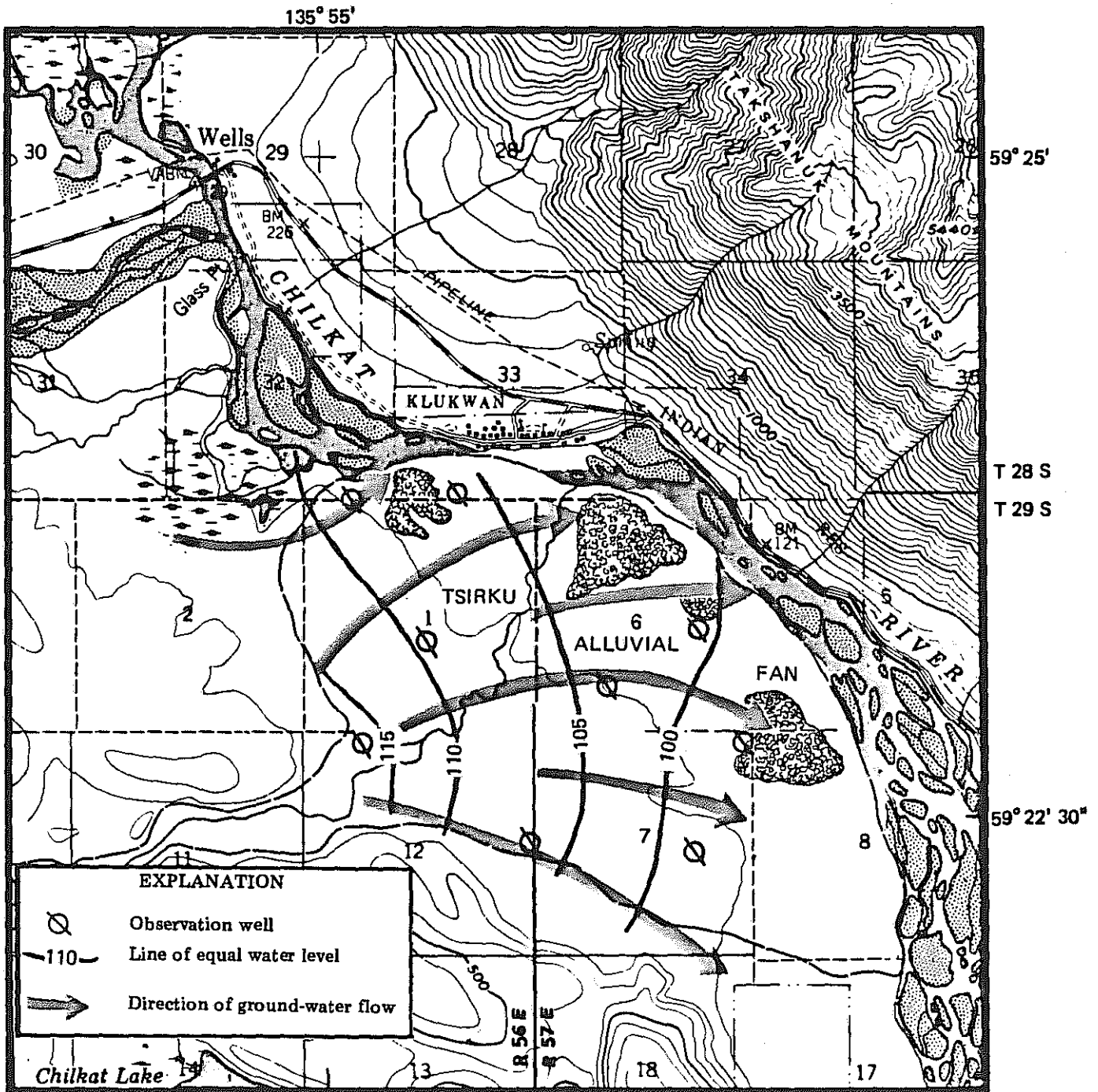
-  Bedrock surface by seismic-refraction survey
 -  Bedrock surface by gravimetric survey
 -  Bedrock surface inferred
- V_A = Acoustic velocity

Figure 4.--Section across Chilkat Valley and Tsirku Fan showing bedrock depth from seismic refraction and gravimetric data. See figure 2 for location of line A-A'. (Gravimetric data from M. M. Holmes, Klukwan Iron Ore Co., 1972, written permission.)



Base from U.S. Geological Survey, 1:63,360, Skagway B-3, B-4, 1954.

Figure 5.--Potentiometric surface map of Tsirku Fan shallow ground-water system, March 11-16, 1983.

Recharge

A seepage run conducted on April 6, 1982 indicated that 63 percent of the water entering the head of the Tsirku fan as streamflow was lost to the aquifer along the channels across the fan--streamflow decreased from 142 to 53 ft³/s (fig. 3). Of the water in the Tsirku River entering at the head of the fan on April 6, 1982, about 70 percent was from the combined ground-water discharge to the surface in the Little Salmon River drainage, and from the area between Chilkat Lake and the Tsirku River. The remaining 30 percent of Tsirku River flow was outflow from Chilkat Lake.

Analysis of oxygen 18/16 and hydrogen 2/1 isotope data indicates that the water in observation well AR-3 (260 ft deep) was derived from an interior, high altitude source, whereas water from observation well AR-4 (40 ft deep), only 10 ft west of AR-3, was derived from a near-coast, lower altitude source. This suggests that there may be two zones of flow.

Discharge

Ground-water discharge from the Tsirku fan aquifer is concentrated in the Chilkat River at the toe of the Tsirku fan. The discharge zones are easily identified during the winter as ice-free channels where warmer (4-6 °C) water keeps the channels open at the toe of the fan and in a 10-mile reach downstream. Observation wells VC-1, 2, and 3 were drilled 30, 15, and 25 ft deep respectively, in exposed gravel bars in the Chilkat River. Water levels in the wells were higher than in the adjacent river channel during the winter low-flow period, which indicates movement of ground water toward the river. During summer high flows, these ground-water discharge areas are inundated and the discharge zones concealed.

Several possibilities exist for the cause of these ground-water discharge zones. A downstream decrease in hydraulic conductivity due to a general downstream decrease in sediment size could cause a damming effect, inducing the potentiometric surface to rise above the altitude of the land surface at the toe of the fan, resulting in discharge at the surface.

Another reason for the occurrence of discharge zones at the toe of the fan may be the interlayering of sediments from the Tsirku fan, Klukwan fan, and Chilkat River, which could cause local changes in hydraulic conductivity. Depositional modes may have ranged from catastrophic, colluvial/fluvial deposition on the Klukwan fan, to primarily fluvial on the Tsirku fan. The Klukwan fan appears to be built by a series of mud flows and slides with poorly sorted sediments in a fine-grained matrix (H.J. Kaiser Co., written communication, 1983). This mode of deposition is dominant along the flanks of the eastern Chilkat Valley, where there is a series of steep colluvial/fluvial fans.

In contrast, the Tsirku fan is built entirely by fluvial transport of sediment. Consequently, the sediments are better sorted than on the Klukwan fan, and have a greater hydraulic conductivity. Sediment in the

Chilkat River sampled upvalley from the Tsirku and Klukwan fans is finer grained than Tsirku fan sediments. This condition may add to the variation in sediment size and complex structure of the alluvial aquifer in the Tsirku fan area.

The cause of the discharge zones is most likely a combination of the above factors. No geochemical, isotopic, or physical evidence was found to indicate that the Chilkat River fault has any influence on ground-water flow paths or discharge at the toe of the Tsirku fan.

SUMMARY

Ground-water discharging to the Chilkat River at the toe of the Tsirku fan is derived from the Tsirku fan aquifer. The major source of recharge to the aquifer is stream loss on the fan. During winter low-flow periods, most of the water in the Tsirku River at the head of the fan is from ground-water discharge to the surface in both the Little Salmon River drainage and in the area between Chilkat Lake and the Tsirku River.

The potentiometric surface in the Tsirku fan is deltaic in plan view, and is skewed slightly downvalley as it flows toward the center of the Chilkat River valley. Ground-water levels in the Tsirku fan fluctuate seasonally, rising in the summer and fall and declining in the winter and early spring. The greatest seasonal fluctuations in water level occur at the head of the fan.

The depth to bedrock in the Chilkat Valley in the vicinity of the Tsirku fan is more than 850 ft. Ground water sampled at 260 ft in the Tsirku fan aquifer is probably derived from high altitude, interior precipitation. Shallower ground water is probably derived from precipitation originating in lower altitude, coastal areas.

The locations of ground-water discharge areas at the toe of the Tsirku fan are probably controlled by the distribution of zones of varying hydraulic conductivity in the alluvium.

REFERENCES

- Boeker, E.L., A.J. Hansen, and R.A. Meredith. 1980. Progress report: Chilkat River cooperative bald eagle study. National Audubon Society. 53 pp.
- Brew, D.A., R.A. Loney, and L.J.P. Muffler. 1966. Tectonic history of South-eastern Alaska. Pages 149-170 in Canadian Institute of Mining and Metallurgy Special Volume No. 8.
- McKenzie, G.D., and R.P. Goldthwait. 1971. Glacial history of the last eleven thousand years in Adams Inlet, Southeastern Alaska. Geological Society of American Bulletin 82: 1767-1782.
- Ovenshine, A.J., and D.A. Brew. 1972. Separation and history of the Chatham Strait fault, southeast Alaska, North America. Pages 245-254 in Proceedings of the 24th International Geological Congress, Montreal, 1972.

SEDIMENT TRANSPORT IN THE SUSITNA RIVER BASIN, 1982-1983

by Stephen W. Lipscomb¹ and James M. Knott²

ABSTRACT

Large seasonal variations in sediment transport rates occurred in the Susitna River basin in 1982 and 1983. More than 80 percent of the total annual water and sediment discharge of the basin took place during the icefree periods between May and September, so that data were separated into summer and winter periods to develop the sediment transport curves used to estimate annual yields. A sediment "budget" for the middle reach of the Susitna River and its major tributaries, the Chulitna and Talkeetna Rivers, was determined by comparing the amount of sediment entering and leaving the reach. During 1982, 11.3 million tons of fine sediment (clay-fine sand) entered the reach and 12.6 million tons were transported out of it. In 1983, the input was 13.0 million tons and output 13.6 million tons. Thus, the input of fine sediment is about equal to the outputs; this material is transported through the reach with little or no deposition. There is a large deficiency, however, in the budget for coarse sand and gravel -- input of these materials to the reach was greater than output in both 1982 and 1983.

INTRODUCTION

The Susitna River is a major river in Alaska, ranking fifth in the state in drainage area. Its importance as a fishery, coupled with the proposed construction of two dams in its upper reaches, has made the river the subject of much concern. The potential environmental effects of hydropower development on the Susitna River system has spurred interest in the hydrologic processes within the basin. Changes in streamflow characteristics associated with reservoir operations will likely result in altered sediment transport rates. The U.S. Geological Survey, in cooperation with the Alaska Power Authority, has implemented a study to determine the amount and distribution of sediment transported by the Susitna River and its major tributaries between Gold Creek and Sunshine (fig. 1.) This paper provides information on seasonal characteristics of sediment transport and on the sediment budget for selected monitoring sites in the Susitna River basin.

¹Hydrologist, U.S. Geological Survey, Water Resources Division, 1209 Orca St., Anchorage, Alaska 99501

²Hydrologist, U.S. Geological Survey, Water Resources Division, 4230 University Drive, Suite 201, Anchorage, Alaska 99508-4664

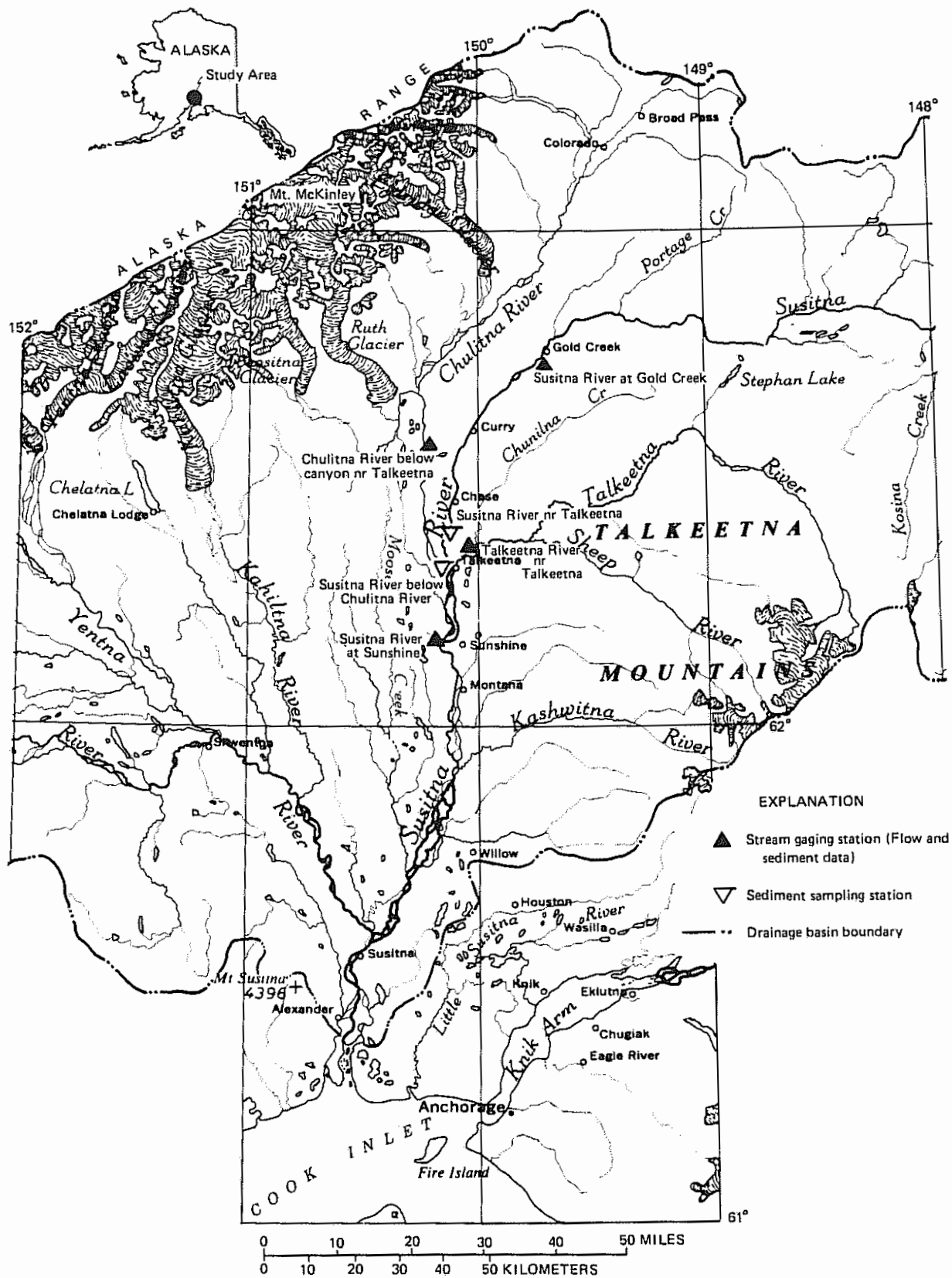


Figure 1.--Location of sediment sampling sites on the Susitna River and its major tributaries between Gold Creek and Sunshine.

DESCRIPTION OF AREA

The Susitna River, which drains an area of 19,500 mi², originates from the glaciers on the southern flank of the Alaska Range and empties into Cook Inlet west of Anchorage (fig. 1). The major tributaries included in the study are the Chulitna and Talkeetna Rivers. These two rivers originate from glaciers as well and both enter the Susitna River near the town of Talkeetna. All the rivers in the study area have alluvial channels which adjust their shape to changes in streamflow.

DATA COLLECTION

The study was initiated in 1981. Four sampling sites were selected within the basin: two on the Susitna River (at Gold Creek, and at the Parks Highway crossing near Sunshine-Creek) and one site each on the Chulitna and Talkeetna Rivers (fig. 1). Data were collected monthly between July and September; during 1982, weekly field trips were scheduled. The sampling site at Gold Creek was relocated 30 mi downstream and designated "Susitna River near Talkeetna." Data collection was continued in 1983 and a fifth site was added to the program. This site, designated "Susitna River below Chulitna River near Talkeetna" is located immediately downstream from the confluence of the Susitna and Chulitna Rivers.

The sampling program was designed to define the amount, distribution, and characteristics of sediment transported by the Susitna River and its major tributaries between Gold Creek and Sunshine (fig. 1). To provide this information the following were required for each site:

- 1) Suspended sediment samples
- 2) Bedload samples
- 3) Bed material samples
- 4) Water-discharge measurements
- 5) Measurements of channel geometry

The methods used for the collection of these data are described in an earlier data report (Knott and Lipscomb, 1983).

SEDIMENT TRANSPORT CHARACTERISTICS

Fluvial sediment, which is defined as sediment that is transported by, or suspended in water, or that has been deposited in beds by water, is composed of suspended load and bedload (Colby, 1963). Suspended load consists of the finer particles that are transported in a stream while being held in suspension by the turbulent force of the flowing water. Bedload includes the coarser particles that are transported by rolling, bouncing, and sliding along the streambed. Fluvial sediment is categorized by particle size. Clay particles are those less than 0.004 mm, whereas silt ranges in size from 0.004 to 0.062 mm. This paper will treat the silt and clay size particles as one class. The sand size particles range in size from 0.062 to 2.0 mm. Finer sand particles, much like the silt-clay particles, are transported in suspension at virtually

all flows. Medium and coarse sand particles, however, tend to move as suspended load at higher flows, as bedload at medium flows, and to settle out as part of the bed material at low flows. Gravel particles, which range in size from 2.0 to 64.0 mm, are usually transported as bedload at high flows but are immobile at low flows.

A high concentration of silt and clay is characteristic of glacier-fed rivers during the summer months. This accounts for the milky appearance associated with these streams. The finely pulverized rock flour in suspension is commonly transported the entire length of the river without settling out. Under quiescent conditions it sometimes takes several weeks for the very fine clay particles to settle. Therefore, the silt-clay fraction of the sediment load at a given location is usually equivalent to the total input upstream from that sampling site. Total monthly yields may have large fluctuations depending on variations in storm runoff and glacial melt. This characteristic of the silt-clay component is demonstrated by the suspended-sediment data for 1982 and 1983 (table 1). The silt-clay particles are referred to as the wash load because of their tendency to remain in suspension at all flows.

Coarse sand and gravel are transported intermittently near the bed, depending upon the flow velocity. As the flow declines, resulting in reduced velocities, these coarser materials settle to the bed in order of decreasing size. In many instances the velocity is sufficient to transport sand and fine gravel but lacks the power to move the coarse gravel and cobble size materials. The finer materials are gradually washed away leaving the coarse material exposed and resulting in an armoring of the bed. This serves to protect the underlying finer grained sand particles from transport since they are not exposed to the force of the flow. If the velocity increases to a rate sufficient to dislodge the armored layer, the underlying material is exposed resulting in an increase in the amount of sand-sized material available for transport.

SEASONAL CHARACTERISTICS

Many streams in Alaska, including the Susitna River, display seasonal characteristics which affect the transport of sediment. From about the end of October until April or early May, flows steadily decline and the streams are usually ice covered. The open-water period generally occurs between May and September. During May, rising temperatures cause snowmelt runoff to increase throughout the basin until the flow cannot be contained by the ice-covered channel. At this point breakup occurs and the ice is flushed from the river by increasingly greater flows. During June, nonglacial snowmelt runoff peaks and begins to decline. During July and August, glacial melt runoff increases to a maximum and annual peaks in streamflow occur when glacial melt and storm runoff coincide. During September and extending into October, as air temperatures cool and the rate of snow and icemelt decreases, streamflow declines except for occasional peaks due to storm events. These summer and winter trends in streamflow are easily recognized when presented graphically as an annual hydrograph or in the form of a bar graph (fig. 2). Most of the flow occurs during the May to September period, while the winter period, from October to April, contributes much less.

TABLE 1. Water discharge and sediment yields at selected sites in the Susitna River basin, May - September, 1982, and 1983.

Month	1982				1983					
	Input			Output	Input			Output		
	Chulitna River	Susitna River	Talkeetna River	Total	Susitna River at Sunshine	Chulitna River	Susitna River	Talkeetna River	Total	Susitna River at Sunshine
Silt/clay (tons)										
May	90,000	200,000	30,000	320,000	400,000	120,000	140,000	13,000	273,000	370,000
June	880,000	450,000	150,000	1,480,000	1,500,000	1,100,000	480,000	110,000	1,690,000	2,100,000
July	1,900,000	670,000	310,000	2,880,000	2,800,000	2,000,000	750,000	260,000	3,010,000	2,900,000
Aug.	1,000,000	310,000	56,000	1,366,000	1,800,000	1,800,000	570,000	240,000	2,610,000	2,700,000
Sept.	1,200,000	330,000	82,000	1,612,000	1,900,000	240,000	35,000	7,800	283,000	280,000
May-Sept.	5,070,000	1,960,000	628,000	7,658,000	8,400,000	5,260,000	1,970,000	631,000	7,861,000	8,350,000
Total sand (tons)										
May	70,000	100,000	32,000	202,000	210,000	185,000	217,000	37,200	439,000	583,000
June	610,000	360,000	290,000	1,260,000	1,200,000	670,000	460,000	125,000	1,255,000	1,374,000
July	890,000	220,000	230,000	1,340,000	1,500,000	890,000	344,000	189,000	1,423,000	1,037,000
Aug.	510,000	53,000	140,000	703,000	660,000	1,500,000	426,000	130,000	2,056,000	2,044,000
Sept.	550,000	140,000	180,000	870,000	870,000	478,000	89,400	19,600	587,000	465,000
May-Sept.	2,630,000	873,000	872,000	4,375,000	4,400,000	3,718,000	1,541,000	501,000	5,760,000	5,521,000
Bedload sand (tons)										
May	30,000	3,000	2,000	35,000	6,000	55,000	73,000	4,200	66,500	23,000
June	210,000	12,000	36,000	258,000	45,000	110,000	20,000	15,000	145,000	74,000
July	140,000	11,000	29,000	180,000	78,000	130,000	140,000	19,000	163,000	37,000
Aug.	110,000	3,900	54,000	168,000	60,000	95,000	16,000	20,000	131,000	44,000
Sept.	57,000	4,400	18,000	79,400	52,000	88,000	3,400	3,600	95,000	73,000
May-Sept.	547,000	34,300	139,000	720,000	241,000	478,000	60,700	61,800	600,000	251,000

TABLE 1. Continued

Month	1982				1983					
	Input			Output	Input			Output		
	Chulitna River	Susitna River	Talkeetna River	Total	Susitna River at Sunshine	Chulitna River	Susitna River	Talkeetna River	Total	Susitna River at Sunshine
	Bedload gravel (tons)									
May	50,000	900	2,000	52,900	10,000	32,000	1,100	430	33,500	23,000
June	220,000	5,400	45,000	270,000	130,000	80,000	7,200	4,100	91,300	110,000
July	190,000	1,900	11,000	203,000	74,000	100,000	1,600	5,000	107,000	64,000
Aug.	150,000	90	4,700	155,000	14,000	84,000	930	6,300	91,200	38,000
Sept.	20,000	1,000	21,000	92,000	43,000	60,000	400	120	60,500	55,000
May-Sept.	680,000	9,290	83,700	773,000	271,000	356,000	11,200	15,900	383,000	290,000
	Water discharge (acre-ft)									
May	386,700	920,000	203,700	1,500,000	1,633,000	551,000	1,002,000	280,000	1,833,000	1,930,000
June	1,092,000	1,700,000	770,200	3,562,000	3,738,000	1,124,000	1,604,000	536,000	3,264,000	3,457,000
July	1,575,000	1,500,000	680,900	3,756,000	3,876,000	1,372,000	1,391,000	535,000	3,298,000	3,405,000
Aug.	1,252,000	1,000,000	447,100	2,699,000	2,083,000	1,364,000	1,642,000	541,000	3,574,000	3,725,000
Sept.	1,085,000	1,100,100	568,000	2,754,000	2,906,000	652,000	849,000	235,000	1,736,000	1,786,000
May-Sept.	5,391,000	6,200,000	2,670,000	14,261,000	14,236,000	5,063,000	6,488,000	2,127,000	13,678,000	14,303,000
	Total sediment (tons)									
May	210,000	301,000	64,000	575,000	620,000	337,000	358,000	506,000	746,000	976,000
June	1,710,000	815,000	485,000	3,010,000	2,830,000	1,850,000	947,000	239,000	3,036,000	3,584,000
July	2,980,000	892,000	551,000	4,423,000	4,370,000	2,990,000	1,096,000	454,000	4,540,000	4,001,000
Aug.	1,660,000	363,000	201,000	2,224,000	2,470,000	3,384,000	997,000	376,000	4,757,000	4,782,000
Sept.	1,820,000	471,000	283,000	2,574,000	2,810,000	778,000	125,000	27,500	930,000	800,000
May-Sept.	8,380,000	2,840,000	1,580,000	12,800,000	13,100,000	9,334,000	3,522,000	1,148,000	14,004,000	14,169,000

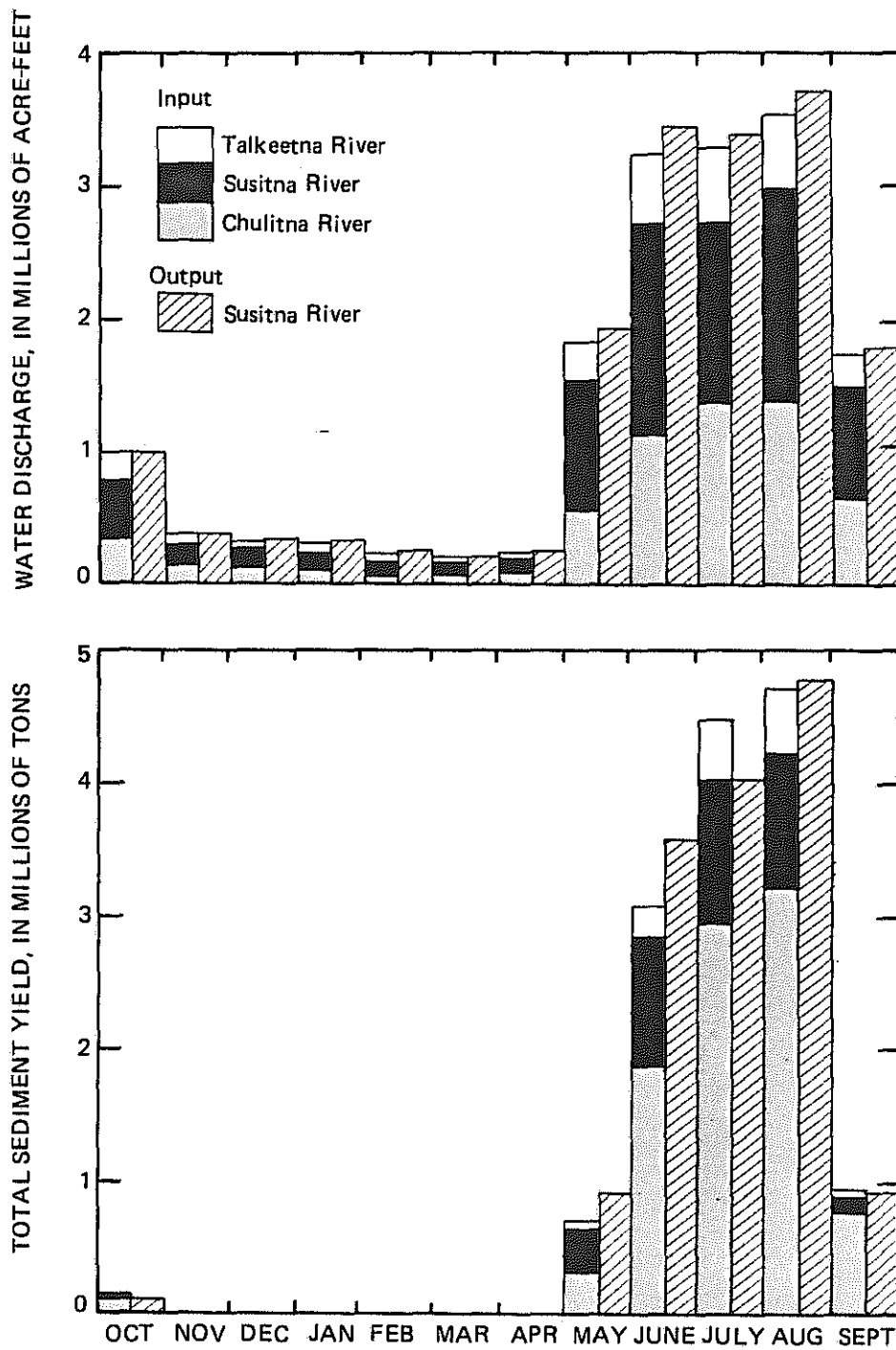


Figure 2.--Sediment and water budgets for the Susitna River and major tributaries, 1983.

Sediment discharge follows the same trend as streamflow but its fluctuations are more pronounced. Virtually all of the sediment transported through the study reach during the 1983 water year was accounted for during the May to September period (fig. 2). With exception of a small discharge in October before freezeup, the winter period produced only negligible amounts of sediment. By late May, as air temperatures begin to rise above freezing at higher elevations, glacial meltwater begins to contribute to the streamflow and a corresponding increase in silt-clay concentration is observed. This causes the stream to take on the turbid, milky appearance that is characteristic of glacier-fed streams.

As the end of the summer approaches, air temperatures begin to decrease and streamflows decline. The peak flows that were capable of transporting gravel, cobbles, and even small boulders have diminished. These particles then settle to the bed or onto bars where they will remain throughout the winter, to be overlain with finer grained particles deposited as the flows decline. During September, the stream slowly becomes less turbid until, just prior to freezeup, the bed is easily visible from the water surface.

Due to the pronounced differences in hydrologic characteristics from summer to winter, any analysis that spans both periods should take these seasonal trends into account. For the purposes of this study, we found it necessary to develop separate sediment transport curves for the summer and winter periods.

BUDGET

This paper is concerned with the movement of sediment at selected sites in the Susitna River basin. Although emphasis is on the summer period, during which most material is transported, sediment transport during the winter season cannot be overlooked. Transport rates during the winter are small compared to the summer but are nevertheless significant to the total sediment-transport system. Sediment transport through a river system may be described in terms of a "budget." The sediment that passes upstream stations eventually either passes the stations downstream or is deposited between them. In the study reach, the Chulitna and Talkeetna Rivers, and the Susitna River above the confluence of these two, are the input stations. The Susitna River near Sunshine is the output station. It has been noted that the silt-clay fraction of the sediment load is accounted for by summing the monthly input values and comparing the total with the output value at Sunshine. On a monthly basis, silt-clay input ranges from 10 to 20 percent of silt-clay output (fig. 3). Total silt-clay yields for the entire summer (both 1982 and 1983) indicate that these particles remained in suspension throughout the reach (table 1). Thus, the input yield was approximately equal to the output yield, after minor adjustments were made.

The finer sand particles (lower end of the 0.062 - 2.0 mm range) were usually transported as wash load, similar to the silt-clay particles, and remained in suspension at very low flows. These fine sands accounted for a large percentage of the total sand load. The coarser sand particles were transported intermittently and deposited as the flows were reduced. A com-

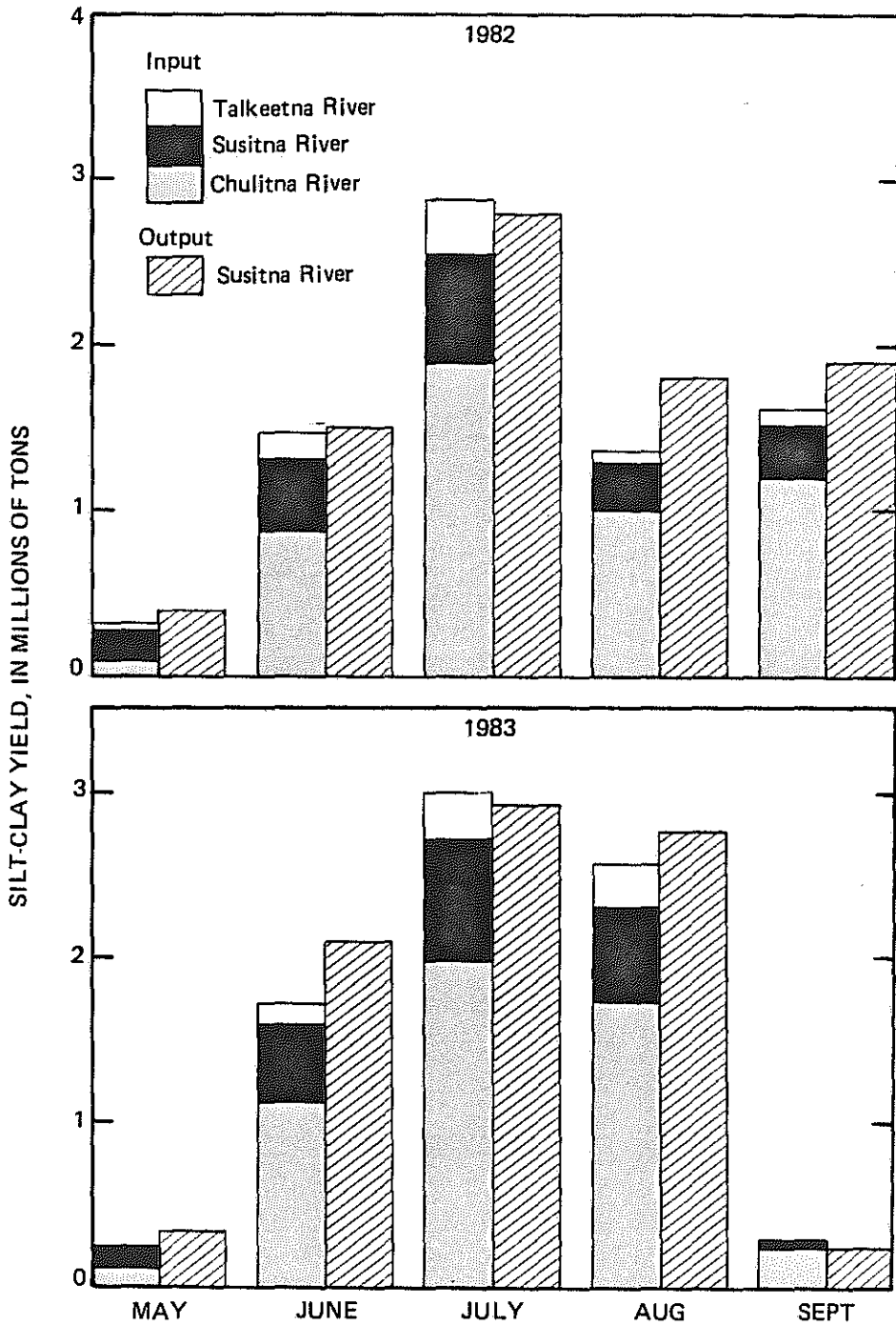


Figure 3.--Silt-clay budgets for the Susitna River and major tributaries, 1982 and 1983.

parison of total sand input with output indicates that the budget is similar to the silt-clay budget (fig. 4); that is, the monthly input and output totals were nearly equal. Figure 5 illustrates the budget for coarse sand particles that were sampled as bedload. This graph demonstrates a net deficit of output during both the 1982 and 1983 summer periods. The total input of bedload sand in 1982 was 720,000 tons whereas the output was only 241,000 tons. In 1983 the proportions were similar -- 600,000 tons input and 251,000 tons output.

Bedload gravel is another component of the sediment load. The net deficit of gravel between the input and output stations is similar to that of the coarse sand load (fig. 6). In 1982 the total input of gravel material was 773,000 tons and output was 271,000 tons. In 1983 the deficit was less pronounced with 383,000 tons input and 290,000 tons output.

Figure 2 illustrates the relative contribution that each river makes to the total sediment load. The Chulitna River, which has a watershed one-third the size of the Susitna and Talkeetna Rivers, by far surpasses both as a sediment producer. This is evident in all size categories from silt-clay to gravel and is probably due to the availability of material and hydraulic characteristics of the stream such as slope, velocity, and channel dimensions. The Talkeetna River transports a large amount of coarse sand at times, but its overall contribution is minor relative to the Chulitna River. The Susitna River near Talkeetna also makes a relatively small contribution to the total input load and though it produces a significant amount of suspended load, its bedload yield is generally even less than that of the Talkeetna River. Although coarse sediment discharge is minor in the upper Susitna River, its total water discharge accounted for nearly half of the total input discharge in 1982 and 1983. As a result, much of the coarse material that is moved into the confluence area and deposited by the Chulitna River is available for transport by the Susitna River.

During the 1983 sampling period, an additional station was added immediately downstream from the confluence of the Susitna and Chulitna Rivers. The objective of data collection at this site was to determine where the deficits of coarse sand and gravel were being deposited. To date, data collected at this site are insufficient to adequately answer this question. Preliminary findings indicate that less bedload is being transported below the confluence of the Susitna and Chulitna Rivers than the sum of that transported by the individual streams above their confluence. The summation of the bedload discharge at the confluence area and in the Talkeetna River also gives a net deficit when compared with Sunshine. This indicates that aggradation was also occurring between the confluence area and Sunshine. The data, however, were collected during a period characterized by medium flows with few storms events. More data are needed during peak flows to provide a firm basis for analyzing the sediment transport above and below the confluence area.

Winter measurements during 1983 and 1984 water years indicate that more coarse sand is transported at the confluence area and at Sunshine than for the sum of the input stations during this period. This is possibly due to a lack of transportable material above the upper input station and/or to the circumstance that the individual flows at these sites are not sufficient to move the material that is available. Below the confluence it is possible that

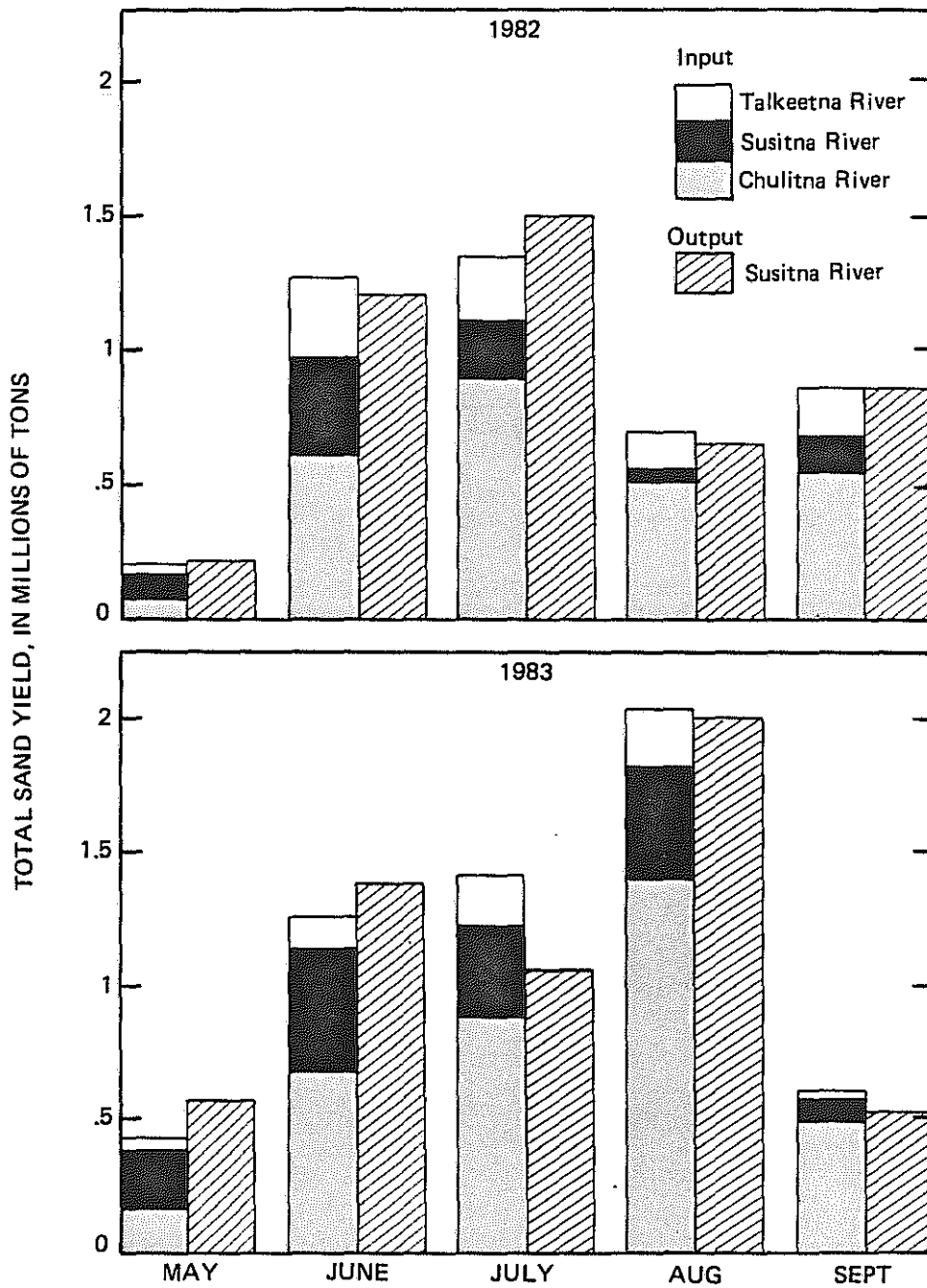


Figure 4.--Total sand budgets for the Susitna River and major tributaries, 1982 and 1983.

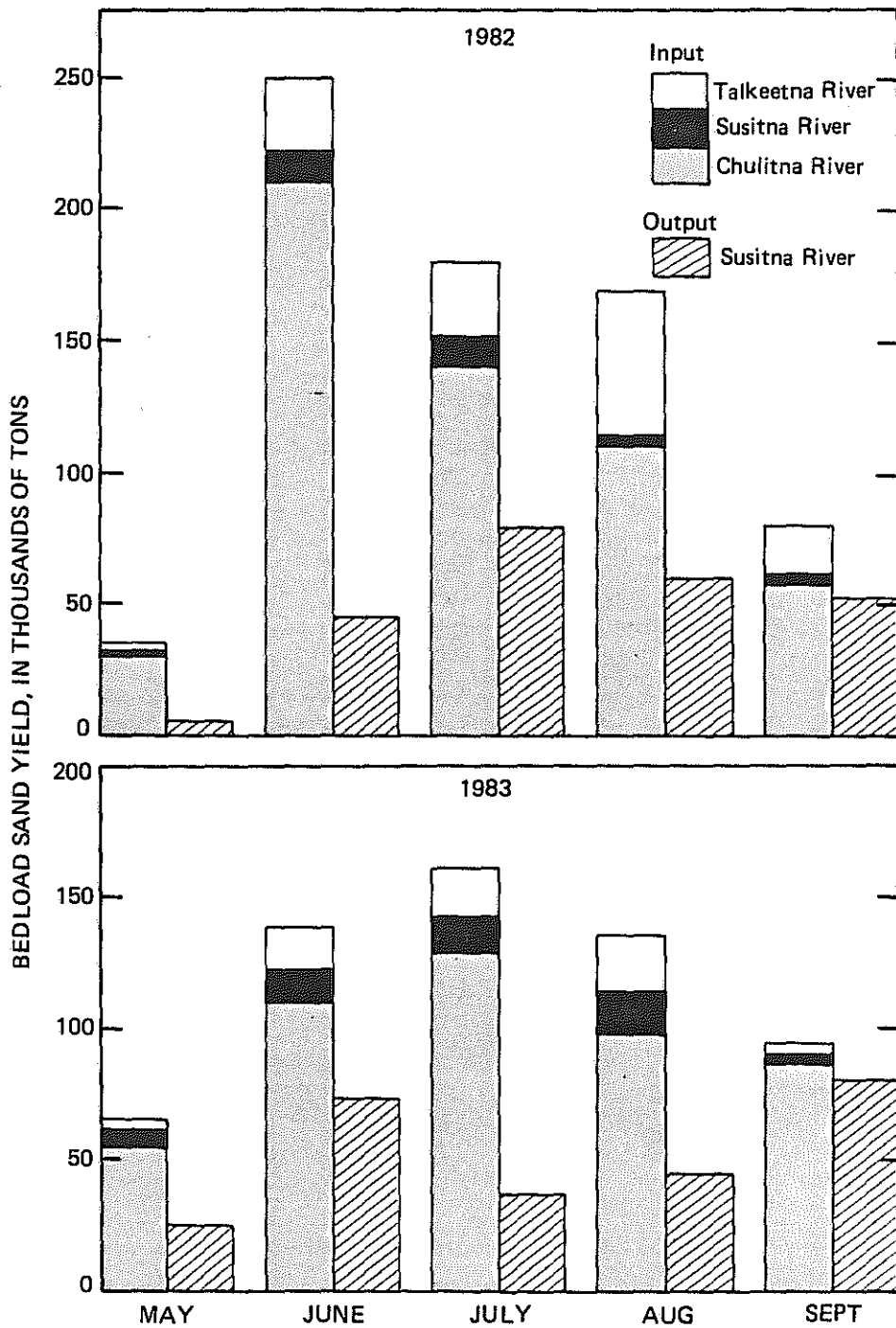


Figure 5.--Bedload sand budgets for the Susitna River and major tributaries, 1982 and 1983.

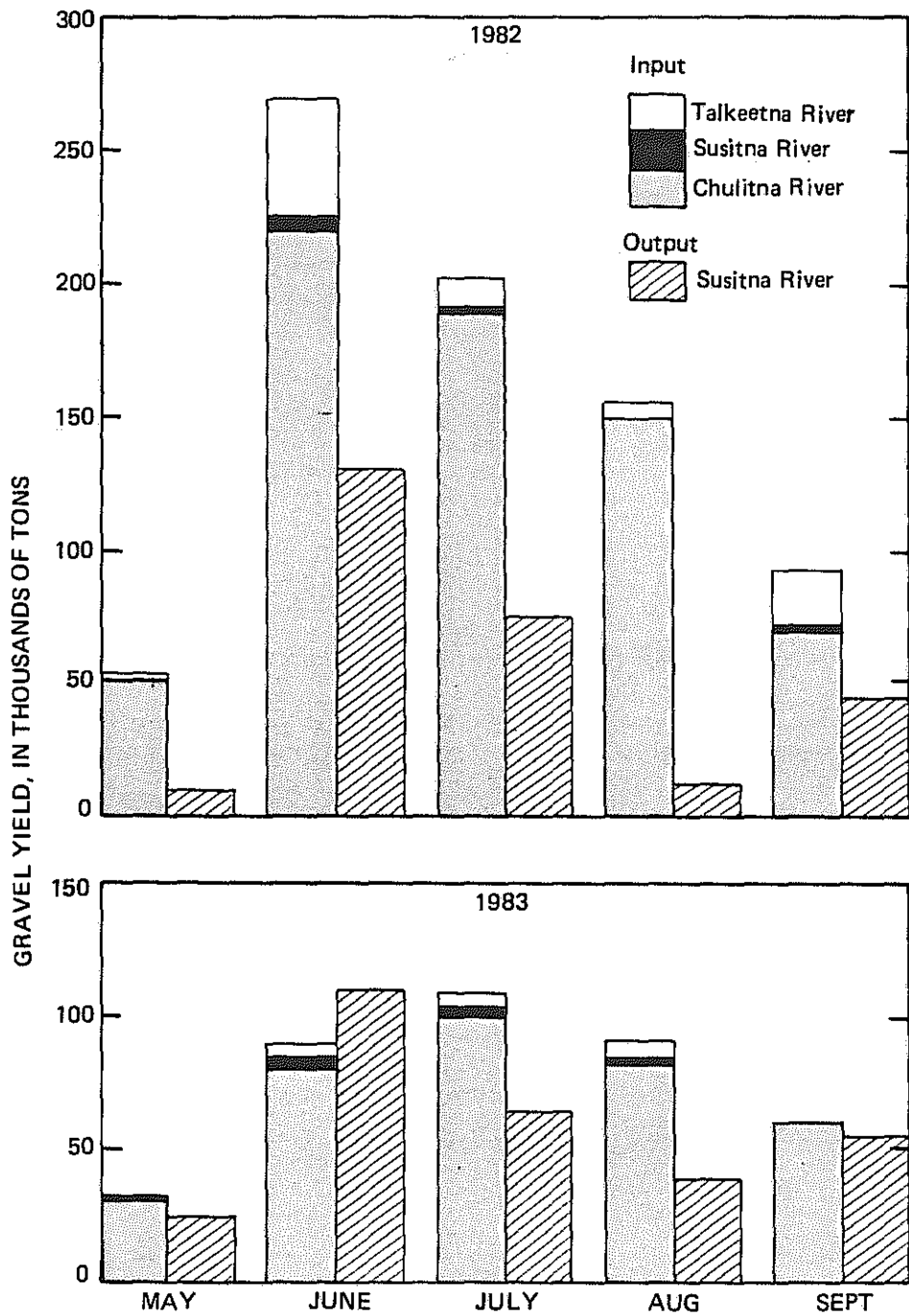


Figure 6.--Gravel budgets for the Susitna River and major tributaries, 1982 and 1983.

the combined flows of the three rivers can provide sufficient energy to gradually transport much of the coarse sand that accumulates toward the end of the summer. Although an increase in the transport of coarse sand has been observed in the reach below the confluence area, the total amount of material transported throughout the entire winter is negligible compared with the total of the summer months.

CONCLUSION

The Susitna River is typical of Alaskan glacier-fed streams. Its origin is from the glaciers of the Alaska Range, where it becomes highly charged with fine-grained sediment. More than 80 percent of the total annual water discharge occurs during the ice-free period between May and September. This is equally true of sediment discharge, as the two are closely related. The use of separate transport curves for summer and winter periods was found to be useful in determining accurate annual yields. Data collected in 1982 and 1983 indicate that total sediment discharge during an average May to September period for the Susitna River near Sunshine is approximately 14 million tons. Of this amount about 24 percent is contributed by the Susitna River, 10 percent by the Talkeetna River, and 65 percent by the Chulitna River. Of approximately 14 million acre-feet of water passing Sunshine during the same period, roughly 44 percent is contributed by the Susitna River above the mouth of the Chulitna and Talkeetna Rivers, 17 percent by the Talkeetna River, and 35 percent by the Chulitna River.

Separating the sediment load into its individual components yields additional information. The silt-clay and fine sand fractions pass through the study reach with little or no intermediate deposition. The total discharge of these fine-grained materials measured at the upper sites generally equals what is sampled at Sunshine. The coarse sand and gravel portions of the sediment load, however, are subject to continual deposition and erosion. The rate of transport for these materials depends on available supply and on stream velocity. During 1982 and 1983 there was a net deficit of coarse sand and gravel between the upstream input stations and the output at Sunshine. During 1982 an estimated 1.5 million tons of bedload (sand and gravel) were input to the system and only 512,000 tons were output. In 1983 the input was 983,000 tons while the output was 541,000 tons. This deficit might explain the presence of sand and gravel bars that extend upstream and downstream from the confluence area of the Susitna, Chulitna, and Talkeetna Rivers. As additional data become available, especially from the confluence area, it should be possible to determine whether the deficit is a long-term trend or merely the result of two average water years with peak flows of insufficient capacity to transport the deposited material.

REFERENCES

- Colby, B.R. 1963. Fluvial sediment -- a summary of source, transportation, deposition and measurement of sediment discharge. U.S. Geological Survey Bulletin 1181-A. 47 pp.
- Knott, J.M., and S.W. Lipscomb. 1983. Sediment discharge data for selected sites in the Susitna River basin, Alaska, 1981-82. U.S. Geological Survey Open File Report 83-870. 45 pp.
- U.S. Geological Survey. 1977. National handbook of recommended methods for water-data acquisition.