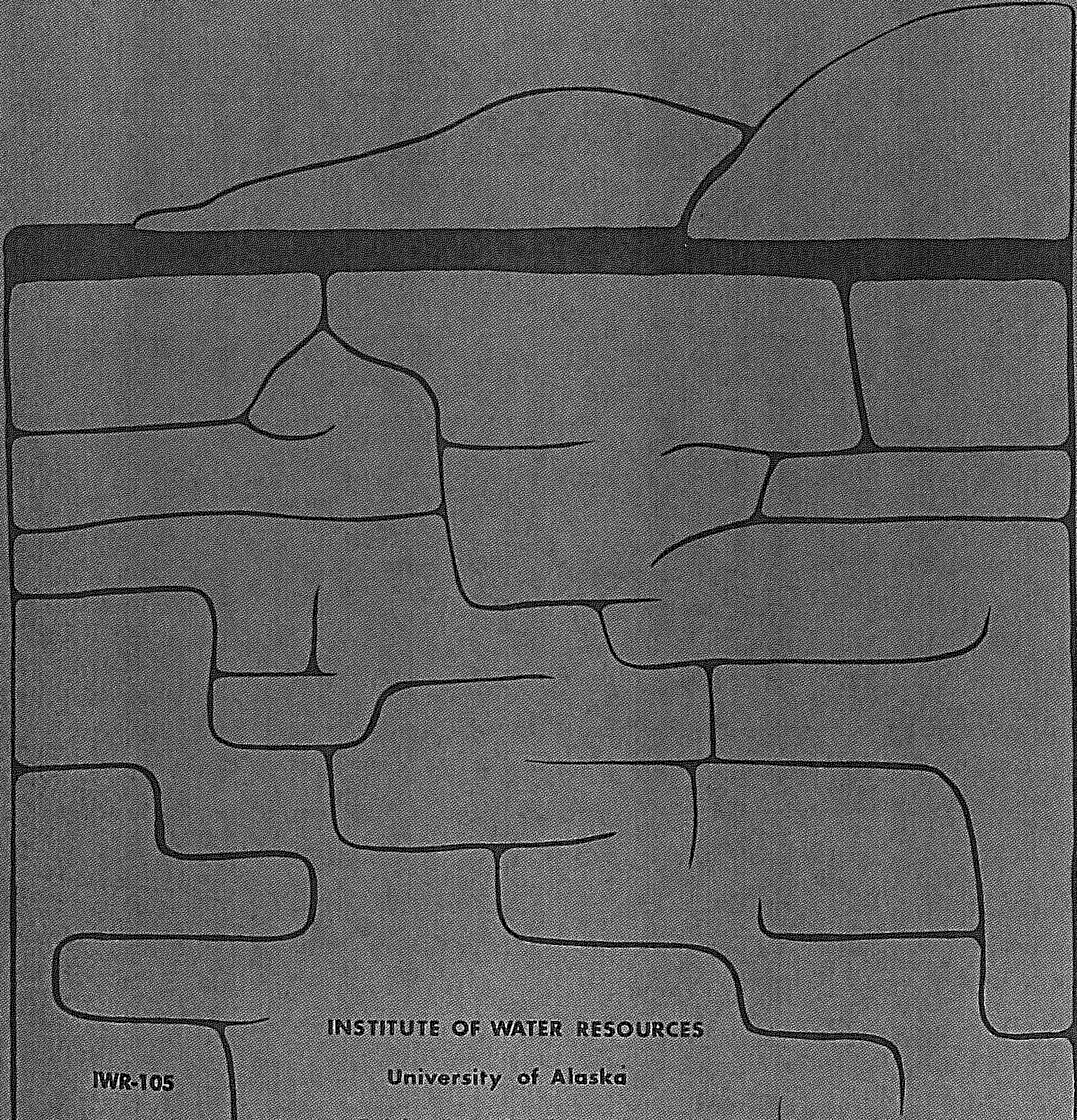
MANAGING WATER RESOURCES FOR ALASKA'S DEVELOPMENT



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INSTITUTE OF WATER RESOURCES
University of Alaska
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MANAGING WATER RESOURCES FOR ALASKA'S DEVELOPMENT

PROCEEDINGS

James W. Aldrich, Chairman
Alaska Section
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INFLUENCE OF TEMPERATE GLACIERS ON FLOOD EVENTS IN MARITIME ALASKA

by John H. Humphrey[1], Carole J. Newton[2],
and R. David Black[3]

Abstract

Many stream basins in maritime Alaska have significant glacier-covered areas. A methodology is required for determining design floods for facilities in flood plains by glaciated streams. Published techniques for estimating the magnitude of design floods for ungaged streams in maritime Alaska were not applicable if glaciers were present. Available meteorologic and hydrologic data were reviewed to select rain-flood events for analysis. The largest floods occurred in glaciated basins in late summer or fall after glacial snowpacks became melted at lower elevations and saturated at higher elevations. Stream basins studied were located in south coastal Alaska near Seward and Southeast Alaska near Juneau. Meteorologic data, when not available in the basins, were estimated by correlation of surface weather observations to upper air data. Unit hydrograph and hydraulic modeling parameters were selected which were appropriate for forest, rock slopes, snowpacks, firn, glacier ice, englacial tunnels, and stream channels. Attenuation of rain-floods was related to glacier hydrologic controls. Synthetic unit hydrograph and routing parameters were suggested for determining design floods from glaciated basins. Adjustment factors to adapt regional non-glacial peak flow regression models to glaciated terrain were derived.

Introduction

In 1980 an estimate of the 100-year recurrence annual peak flood was required for an ungaged stream near Seward which had over 50 percent glaciation. Existing regional regression methods were known to over-estimate flood peaks. Their use would have substantially increased the cost of flood protection for facilities adjacent to the stream. Efforts to estimate the attenuation of the flood discharge by the glacier pointed out the need for a justifiable methodology. This report determines techniques for

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[1] Hydrologist/Meteorologist, Ott Water Engineers, 2334 Washington Avenue, Redding, CA 96001

[2] Water Resources Specialist, Ott Water Engineers, 2334 Washington Avenue, Redding, CA 96001

[3] Water Resources Engineer, Ott Water Engineers, 4790 Business Park Blvd., Bldg. D, Suite 1, Anchorage, AK 99503

incorporating the effects of the glaciers and snowfields on the delay and attenuation of runoff.

Methodology

Annual peak flow frequency analyses of streamflow records on stream basins with significant glacier cover (defined as over 10 percent) were excluded from the regression models in the U.S. Forest Service Water Resources Atlas (Ott Water Engineers, 1979) because they were few in number and some glaciated basins were notorious for catastrophic floods known as jokulhlaups or glacier outburst floods. A review of the literature indicated that glacier stream basins subject to this type of flooding can be readily identified and treated as a separate category to which the methodology later described in this report would not apply. A report by Post and Mayo (1971) inventoried streams known in Alaska to be subject to jokulhlaups. Other papers by Richardson (1968), Young (1980), and Clarke (1982) described circumstances in which jokulhlaups have occurred and described theories regarding their origin. It is clear that nearly all jokulhlaups are caused by movement of glacier ice blocking drainage, creating a dam and backing up a lake in a valley, embankment, or sub-glacial basin. A jokulhlaup occurs periodically when hydraulic head becomes sufficient to partially float the ice dam or to enlarge existing conduits by melting. Lakes which are capable of causing jokulhlaups can be identified on aerial photography. However, most glaciers have been in a state of retreat or equilibrium in recent years. Glaciers in Alaska have been generally retreating with only minor advances since 1760, the end of the Little Ice Age (Field, 1975). Historic and geologic evidence of jokulhlaups or glacier lake damming must also be considered since a glacier can advance and renew the threat of jokulhlaups during the life of a project.

A much rarer type of jokulhlaup is associated with volcanoes. Subsurface melting due to volcanic heat can create underground lakes with no outlet until catastrophic release occurs. Glaciers on volcanoes with loose cinder and ash material also have jokulhlaups due to sub-glacial landslides which temporarily block flow before failing. This type of jokulhlaup is usually a mud or debris flow which does not travel a large distance downstream. Peak flow estimates for glaciated stream basins on volcanoes should be treated with extreme caution.

In conclusion, jokulhlaups only occur on a small minority of glaciated stream basins. Nearly all major floods in glaciated basins result from combined rain and snowmelt events occurring late in the ablation season (August-October) when snow cover on the glacier is at a minimum and ice exposure is at a maximum. Even at this time, runoff delay and attenuation due to the presence of the glacier is significant.

Criteria for selection of study stream basins were as follows:

1. Continuous stream flow records with peak flow events were available.
2. Glaciated and non-glaciated stream basins were located in closely related geographic and climatic areas to facilitate comparisons of storm events.
3. Meteorological data in the basins were available or it was likely the data could be synthesized from representative surface weather observations at nearby locations.

A review of glaciological research in Alaska, (Hubley, 1957; Marcus, 1963; Miller, 1963; Wendler and Streten, 1969; Muir et al, 1971; and Tangborn et al, 1977) indicated that extensive research appropriate to this study had been done on Wolverine Glacier near Seward and on the Juneau Ice Field. Research data from other areas, (Sharp, 1951; Field, 1975; Larson, 1978; and Alaska Geographic Society, 1982) were missing continuous flow records or meteorological data essential to runoff modeling.

All available U.S. Geological Survey streamflow records (1964, 1971, 1976, 1972-1982) were examined for stream basin records appropriate for use in this study. Stream basins selected for study are shown in Table 1. Locations of these basins are shown in Figures 1a and 1b. The base map for these figures comes from Tangborn et al (1977).

TABLE 1
STREAMFLOW RECORDS

USGS Gage Number	Name	Period of Record	Area (km^2)	Glacier Control (%)
15052000	Lemon Creek near Juneau	Aug 51-Sep 73	33.0	86
15052500	Mendenhall River near Auke Bay	May 65-Sep 82	221.4	77
15052800	Montana Creek near Auke Bay	Aug 65-Sep 75	37.2	3
15054200	Herbert River near Auke Bay	Oct 66-Sep 71	148.0	71
15101500	Greens Creek near Juneau	Oct 78-Sep 82	59.3	0
15109000	Fish Creek near Auke Bay	Oct 58-Sep 78	35.4	0
15236900	Wolverine Creek near Lawing	Oct 66-Sep 78	24.7	99
15238600	Spruce Creek near Seward	Sep 67-Sep 82	24.1	8
15238990	Upper Bradley River near Homer (Nuka Glacier)	Oct 79-Sep 82	26.0	80

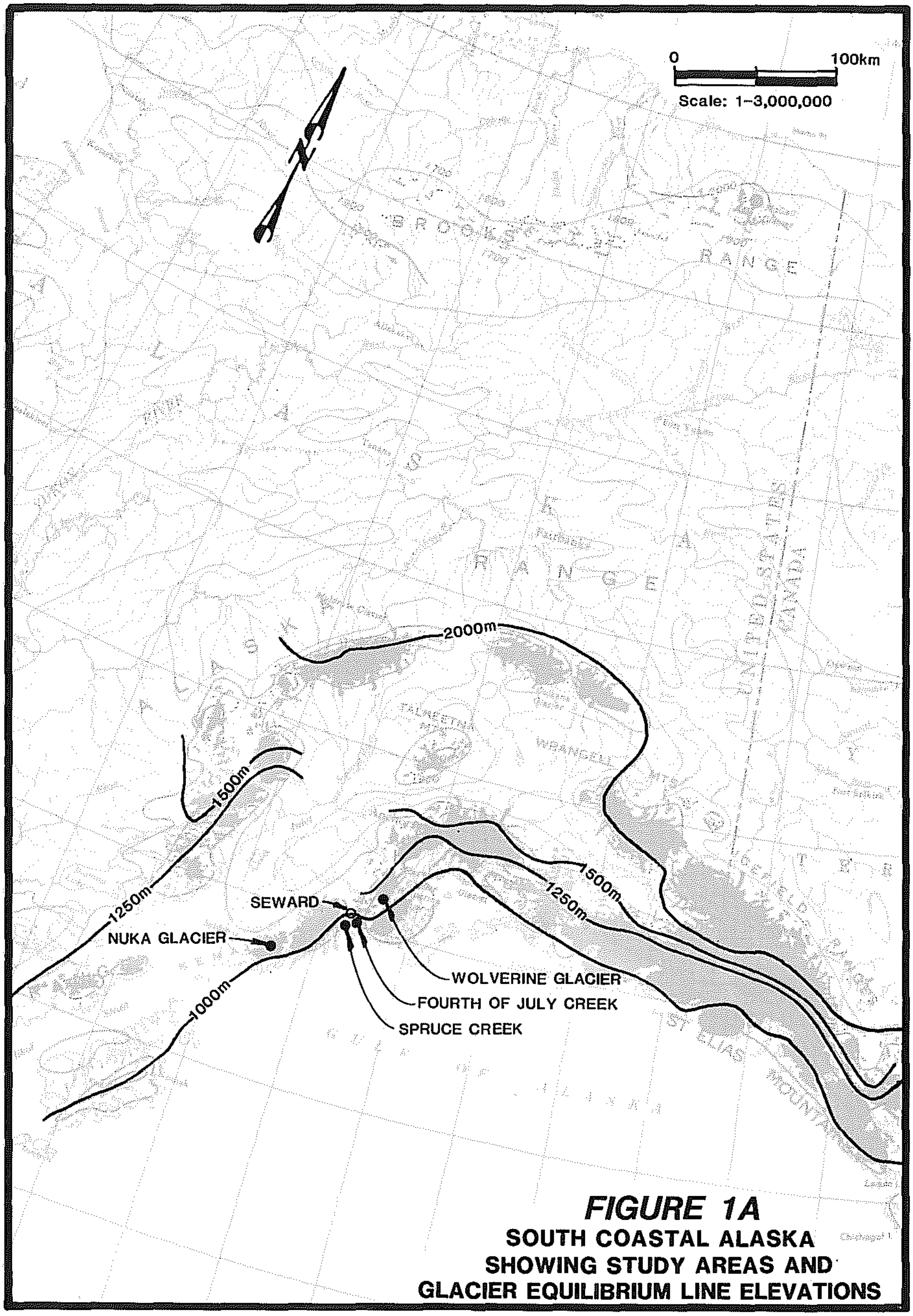

FIGURE 1A

SOUTH COASTAL ALASKA SHOWING STUDY AREAS AND GLACIER EQUILIBRIUM LINE ELEVATIONS

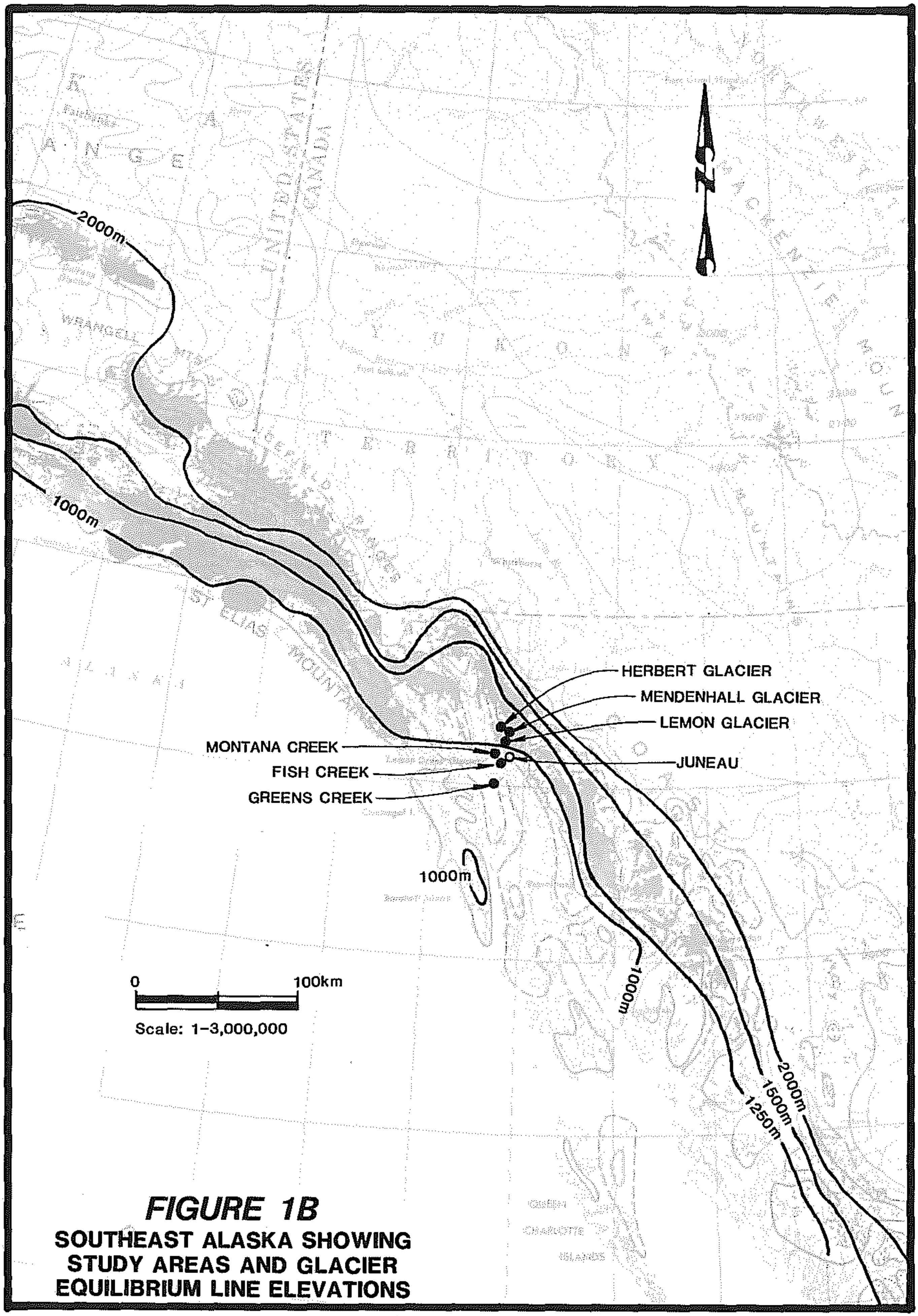

FIGURE 1B

SOUTHEAST ALASKA SHOWING STUDY AREAS AND GLACIER EQUILIBRIUM LINE ELEVATIONS

Annual peak runoff events were examined for the locations listed in Table 1. The largest flood events from the glaciated basins were selected if data for the same event was available on a nearby non-glaciated basin. The opposite procedure, selecting the largest event on non-glaciated basins, was not done since in many cases, glacier snow cover runoff attenuation or a low freezing level resulted in no corresponding significant flood event on the glaciated basin. Table 2 lists runoff events selected for analysis.

TABLE 2
FLOOD EVENTS

Basins	Aug '66	Sep '67	Oct '69	Sep '70	Sep '72	Sep '74	Sep '76	Aug '77	Sep '78	Oct '78	Oct '79	Sep '81	Sep '82
Lemon	X	X		X	X								
Mendenhall	X	X		X	X	X	X			X	X	X	
Montana	X	X		X	X	X							
Herbert		X		X									
Greens										X	X	X	
Fish	X	X		X	X	X							
Wolverine			X			X	X	X	X				
Spruce			X			X	X	X	X				
U. Bradley													X

Computer simulation models capable of converting rainfall and snowmelt to runoff incorporating suitable runoff delay and attenuation due to basin hydrologic conditions were reviewed.

Single event models suitable for this purpose were described by Feldman (1979) and Perrier et al (1977). The U.S. Army Corps of Engineers HEC-1 model was clearly superior due to its flexibility and ease of application. The description and use of the HEC-1 model were found in U.S. Army reports (1971, 1981a, 1981b, 1981c, 1982).

Application of snowmelt equations in the HEC-1 model (U.S. Army, 1960; Anderson, 1968) is simplified during storm events since cloud cover produces low solar radiation and since saturated air occurs at higher elevations on the glacier. Meteorological input data includes air temperature, wind speed, and precipitation. Relationships between sea level and upper altitude meteorologic data were available (Meier et al, 1971; Tangborn et al, 1977) for Wolverine Glacier and for the Juneau Ice Field (Miller, 1963). Information on precipitation increases with elevation were also available (Ott Water Engineers, 1979). Comparisons of sea level meteorologic data at Seward with Anchorage upper air data and of sea level meteorologic data at Juneau with Yakutat upper air data facilitated estimates of air temperature and windspeed at upper elevations on the glaciers. Details on the storm event modeling will be given in a paper which may be presented at the Third International Cold Regions Specialty Conference in April 1984 at Edmonton, Alberta.

Delay and attenuation of glacier runoff due to snow, firn, and the englacial conduit system were estimated from literature values. The effects of seasonal snow cover on runoff are well documented due to interest in this subject in non-glaciated regions. Snow cover is important to glacial runoff processes in the early part of the ablation season but becomes less important in the later part of the ablation season as the snowline retreats to the accumulation area of the glacier. The delay and attenuation of water infiltrating snowpacks were described (Denoth el al, 1978; Ebaugh and Dewalle, 1978; Wankiewicz, 1978; Anderson, 1973; Male and Gray, 1981; Jordan, 1983a, 1983b) especially in a series of papers by Colbeck (1972, 1974, 1975, 1977). Delay times for homogeneous wet snow were 1 to 2 hours per meter of depth. Typical attenuation of peak inflows was 15 percent per meter of snow, depending on inflow rates.

Snow which has been subject to the passage of meltwater for some time tends to reduce to rounded, coarse (1 to 2 mm) grains, and further metamorphism proceeds very slowly (Colbeck, 1982). By definition, firn is wetted snow that has survived one summer without being transformed to ice. Firn exhibits increasing density and grain size with age. Firn accumulations on the upper parts of glaciers can reach depths exceeding 50 meters before having such a large grain size (2 to 10 mm) and density (0.8 g/cc) as to be indistinguishable from ice. The exposed contact between firn and ice (the firn line) can be found on the glacier when seasonal snow cover has melted. But the depth of firn and the contact between firn and ice becomes increasingly hard to define as the head of the glacier is approached. As new firn is buried and compacted by additional years of snow it has increasingly higher density and lower porosity. Delay and attenuation times for water percolating firn have been found directly proportional to depth (Derikx, 1969; Stenborg, 1970; Krimmel et al, 1972; Meier, 1972; Colbeck, 1977; Ambach et al, 1981; Oerter et al, 1981; and Paterson, 1981). Water percolated firn at 0.16 to 0.31 meters per hour with an average of 0.22 meters per hour. Runoff delay and attenuation is also caused by the inability of englacial conduits to immediately convey runoff to the glacier terminus. The size of englacial conduits is adjusted to meltwater peaks or previous flood events during the ablation season. An unusual event exceeds their capacity and causes water to back up internally in glacier cavities and crevasses (Collins, 1979; Meier, 1972; and Oerter et al, 1981). Flow conduit capacity can increase under the influence of hydraulic head and can increase slowly as boundary friction dissipation of potential energy in flowing water is converted into heat for enlarging channels. This melt process is relatively slow compared to the time frame of most storm runoff events on the lower glacier (6 to 12 hours). Theoretical calculations show that enlargement rates of 50 to 100 percent in 24 hours would be typical. This slow response would also serve to further delay and attenuate runoff flowing through the glacier.

Most of the papers referenced regarding firn travel times also gave typical transit times for rain/meltwater from various parts of the glacier to its terminus. Golubev (1969) related time of travel to glacier area (lag time in days is equal to four times the log of the area in square kilometers). His paper also showed that unit hydrographs for discharge were closely related to elevation area curves since low elevations have short lag times and low attenuation and since high elevations have long lag times and high attenuation. Campbell and Rasmussen (1969) stated glacier runoff delay is probably related to glacier length.

Travel times and attenuation factors in the literature for glacier runoff were generally given for regions of the glacier defined as above the firn line (accumulation area), below the firn line (ablation area), and glacier tongue (ablation area where glacier narrows and has numerous moulins and crevasses). In some papers the term equilibrium line is given as a synonym for firn line, but the equilibrium line is actually defined as the boundary between accumulation and ablation zones where there is no net gain or loss to the glacier surface. The firn line can be located up to a few hundred meters above or below the equilibrium line depending on glacier topography and whether the glacier is advancing or retreating. The firn line can usually be determined from late ablation season aerial photographs while the equilibrium line must be determined from comprehensive field studies.

Firn lines for the study glaciers were given by Marcus (1963), Heusser and Marcus (1964), and Field (1975). Equilibrium lines for glaciers in Alaska were given by Tangborn et al (1977) and these lines are shown in Figures 1a and 1b.

Delay times, attenuation, and recession rates for glaciers were found in Behrens et al (1975), Larson (1978), Derikx (1969), Elliston (1969), Colbeck (1978), Collins (1979), Ambach et al (1981), Oerter et al (1981), and Paterson (1981). These factors are summarized as follows:

Accumulation area: Delay 4 to 10 days, recession 10 to 100 days

Ablation area: Delay 20 to 30 hours, recession 1 to 10 days

Tongue area: Delay 1 to 6 hours, recession 6 to 12 hours

Attenuation of flows from the accumulation area is so great that these flows can be considered a base flow that does not increase significantly during a storm event.

Runoff from the glacier was delayed, attenuated, and receded using unit hydrographs. Description and use of synthetic unit hydrographs was given in Linsley and Franzini (1979) and U.S. Army (1978). In the HEC-1 model assigned lag times were: accumulation area--5 days, ablation area--30 hours, and tongue area--5 hours. The time of maximum precipitation was also compared with peak flow for all events listed in Table 2 in order to estimate characteristic basin lag times. These times were consistent with the tongue and non-glaciated areas.

Glaciated stream basins were divided into sub-basins according to areas of accumulation, ablation, glacier tongues, and non-glaciated area. Non-glaciated basins were divided into upper and lower zones based upon differences in precipitation and runoff routing. Stream basins are shown in Figures 2, 3, 4, 5, and 6.

An annual peak flow probability analysis was performed for those stream gage records with sufficient length to extrapolate to 100-year recurrence. These included Lemon Creek, Mendenhall River, Montana Creek, Herbert River, Fish Creek, Wolverine Creek, and Spruce Creek. Annual peak flows were ranked, assigned a plotting position, and plotted on log- normal probability paper. A best-fit straight line (zero skew) was used to extrapolate to the 100-year recurrence.

One hundred-year-recurrence peak flows for the same stream basins were also done using the regression equations in Ott Water Engineers (1979) and Lamke (1979).

Results

Comparison of simulated and observed flood hydrographs gave strong support to the theoretical lag times and synthetic unit hydrographs assigned to the stream basin models. In glaciated stream basins, runoff contributions from the accumulation and ablation areas were not a significant component of the peak flow. In some cases recession flow from upper glacier areas from earlier storm events represented a significant base flow to the modeled storm event. For major events, base flow from preceding events was up to 10 to 20 percent of the peak runoff rate. The model was most sensitive to

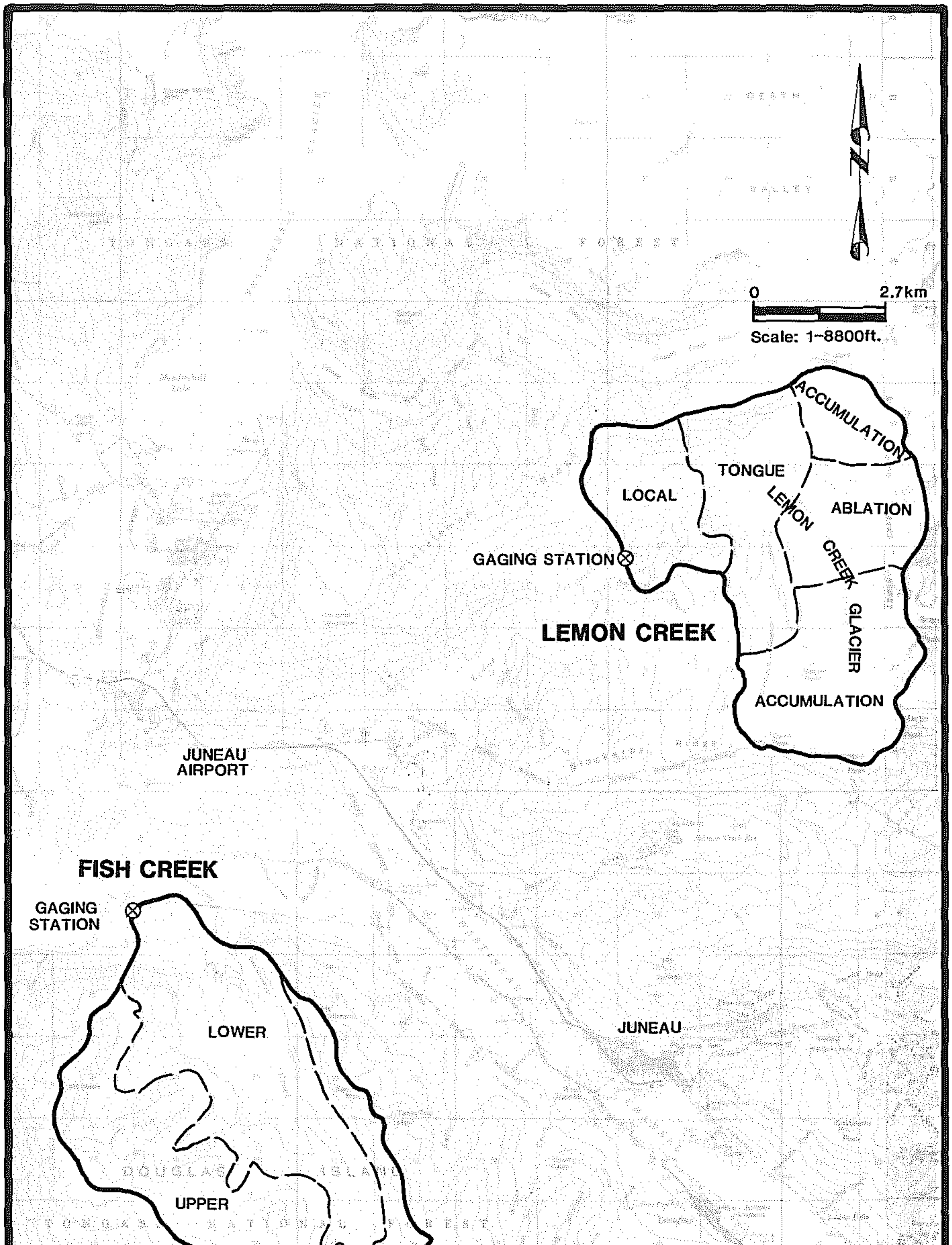

FIGURE 2
LEMON CREEK AND FISH CREEK BASINS

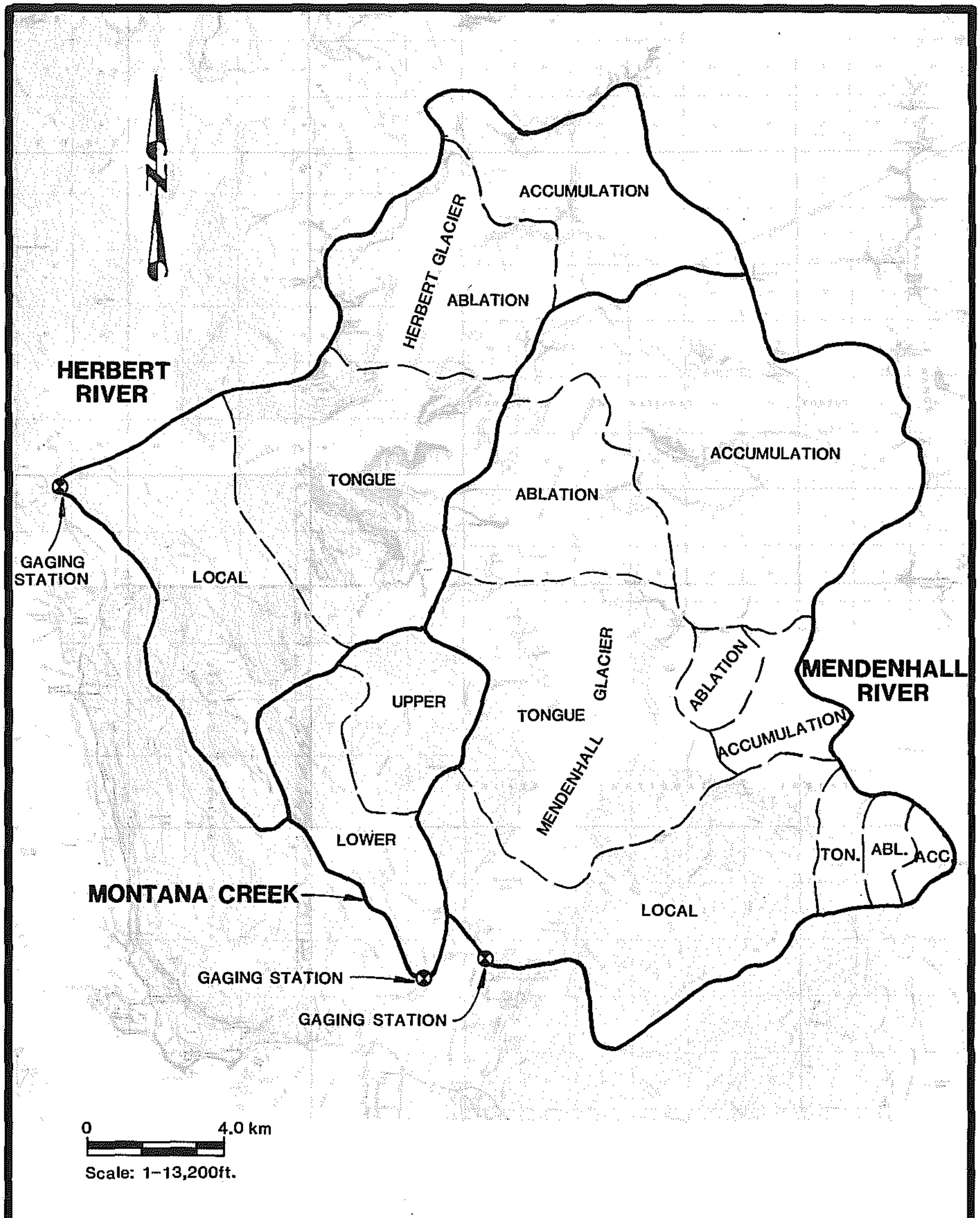

FIGURE 3
MENDENHALL RIVER, MONTANA CREEK AND HERBERT RIVER BASINS

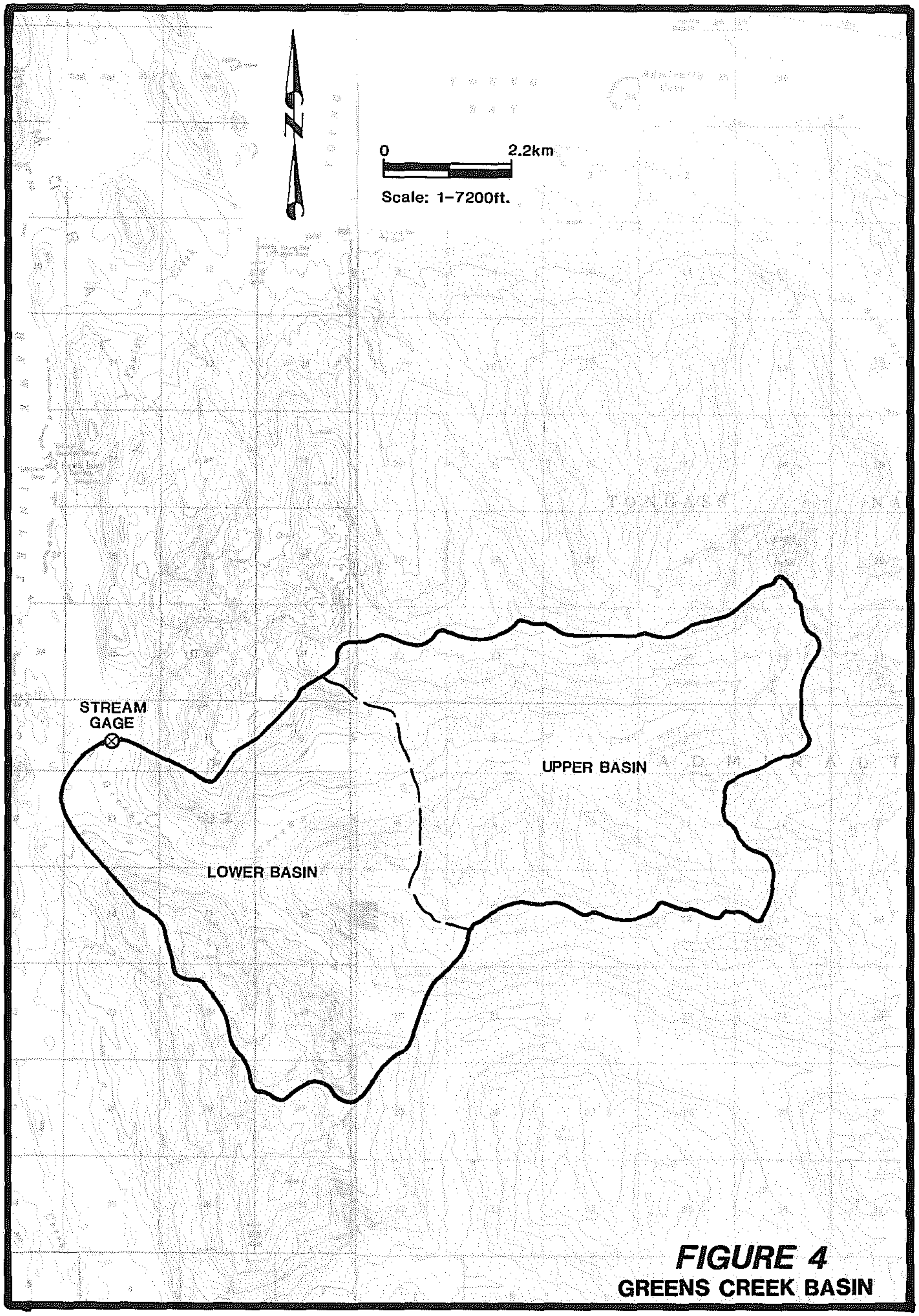

FIGURE 4
GREENS CREEK BASIN

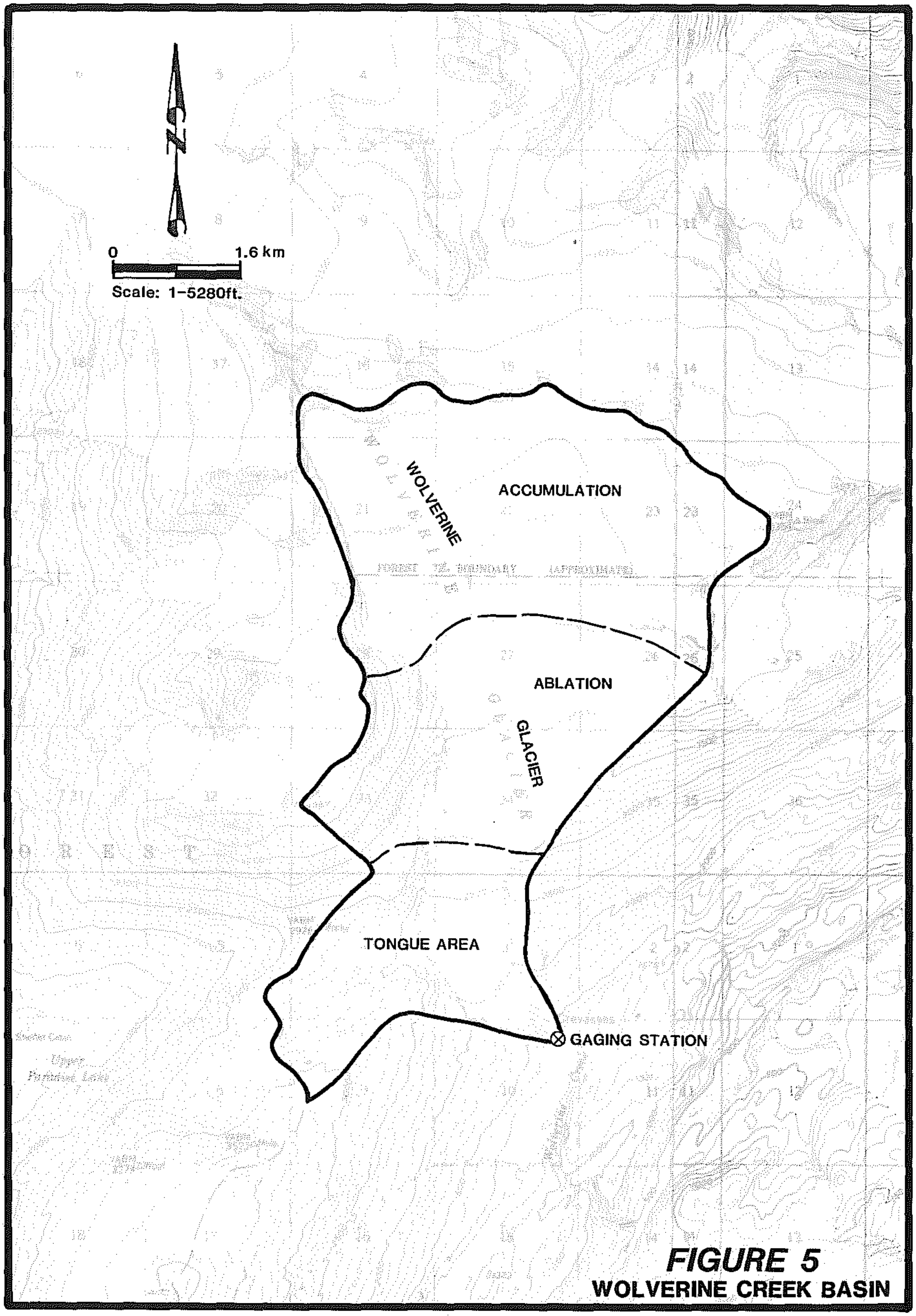

FIGURE 5
WOLVERINE CREEK BASIN

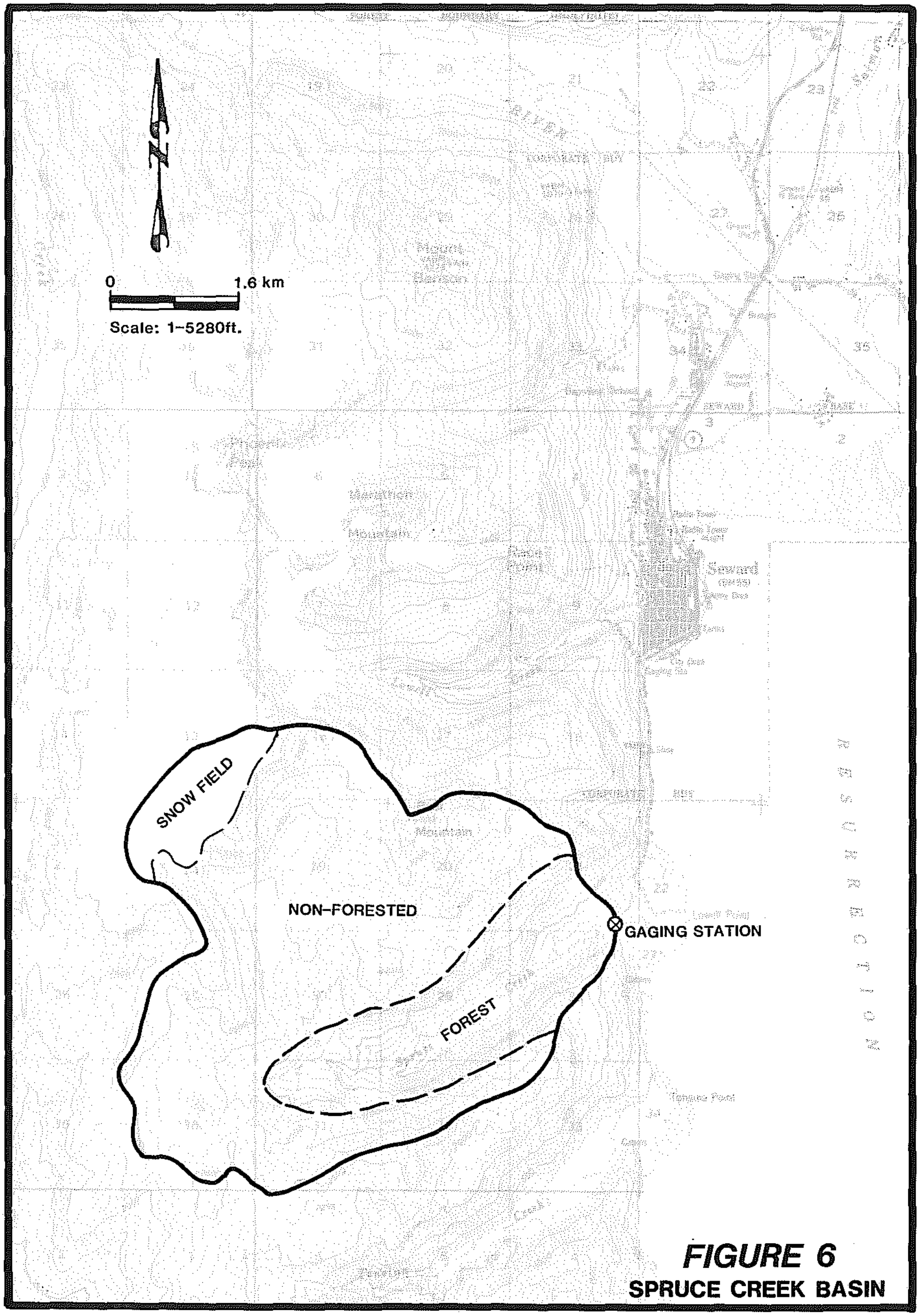

FIGURE 6
SPRUCE CREEK BASIN

the area assigned to the glacier tongue and to the precipitation multiplier used to estimate precipitation on the lower glacier from the sea level index station. Both of these values were varied within reasonable limits as part of the calibration process until consistent results were obtained from all storm events on each stream basin. Modeled peak flows and runoff volumes had errors less than 30 percent which were quite acceptable considering the lack of in-basin meteorological data and the purpose of the study.

One hundred-year-recurrence annual peak flows from a probability analysis are shown in Table 3. Average runoff and precipitation data which are derived from the average runoff data are also shown. Mean annual precipitation and basin area are the most important inputs to regional peak flow regression methods. Predicted 100-year recurrence based on regression equations from Lamke (1979) and Ott Water Engineers (1979) are shown for comparison. The final column on the table shows predicted flows using Ott Water Engineers (1979) when the accumulation and upper ablation areas are excluded.

TABLE 3
100-YEAR RECURRENCE FLOOD PEAKS

	Average Annual		100-Year Flood			
	Runoff cm/yr	Precipitation cm/yr	Observed m^3/sec	Lamke, 1979 m^3/sec	OTT, 1979 m^3/sec	Excluding Area Above Tongue
Lemon Creek	439	465	68.0	153.	126.	62.3
Mendenhall Rv.	460	483	368.	795.	745.	380.
Montana Creek	234	264	85.0	124.	85.0	--
Herbert River	356	381	234.	503.0	411.	241.
Fish Creek	198	229	85.0	111.3	79.3	--
Wolverine Ck.	315	340	59.5	98.0	90.7*	60.9
Spruce Creek	284	318	113.	89.8	80.7	--
Juneau Airport	--	140	--	--	--	--
Juneau	--	234	--	--	--	--
Seward	--	160	--	--	--	--

*120. - if based on correlation with Spruce Creek

On Table 3, note that the predicted flow for Spruce Creek was significantly lower than the observed 100-year recurrence peak flow. Using the Ott Water Engineers (1979) method gave an underprediction of 30 percent. The original regression model had 11 years of record on this creek and gave an under prediction of 17 percent. These errors are well within the 90 percent confidence limits of the regression equations.

Conclusions

The HEC-1 runoff simulation model results showed that runoff from accumulation areas of the glacier (above the firn line or equilibrium line) is not a significant contributor to annual peak flood events. A portion of the ablation zone is also non-contributing to peak events. The lower boundary of this ablation area is above the heavily crevassed ice tongue area 100 to 200 meters below the equilibrium line shown in Figures 1a and 1b. Runoff from non-glaciated or rock areas which reaches the glacier above this elevation also does not contribute to peak flows. Table 3 shows that if all runoff area above the glacier tongue is excluded from the regression model, then reasonable estimates of flood peaks from glaciated basins are obtained. The last column in Table 3 closely agrees with observed 100-year flood peaks. Suggested application of the method follows:

Step 1. Determine applicability. This method cannot be used on any basins with a jokulhlaup history or potential threat. The method may also be applied to glaciated basins with continental climate (that is, the glacier interior stays below 0°C) but will probably overestimate flows since runoff attenuation on continental glaciers whould usually be greater than on maritime temperate glaciers.

Step 2. Determine the area below accumulation and ablation areas but include area controlled by the glacier tongue. The boundary between the areas is 100 to 200 meters below the equilibrium line.

Step 3. Calculate peak flow using Lamke (1979) or Ott Water Engineers (1979) regression equations and compare to results using correlation with a representative non-glaciated basin.

Step 4. Check results against a peak flow regime which would be consistent with channel morphology, channel bank full capacity, and high water marks. Note that although glaciated basins have lower peak flows per unit area compared to non-glaciated basin, high flows have much longer duration. The relatively long duration of high flows should be considered in flood control design applications.

A comparison of methods was made for Fourth of July Creek near Seward. The stream basin is shown in Figure 7. The excluded area where runoff is controlled by snow fields and the upper zone of the glacier is shown. The elevation of this boundary is approximately 850 meters, which is 150 meters below the equilibrium line shown in Figure la. The total basin area was 66.1 km^2, the lower area was 36.7 km^2, and mean annual precipitation was 330 cm. The mean annual basin precipitation is for the entire basin including the glacier runoff controlled area.

An example of each of the six methods applied to Fourth of July Creek follows:

1. 100-year recurrence peak using Lamke (1979): 220 m^3/sec.

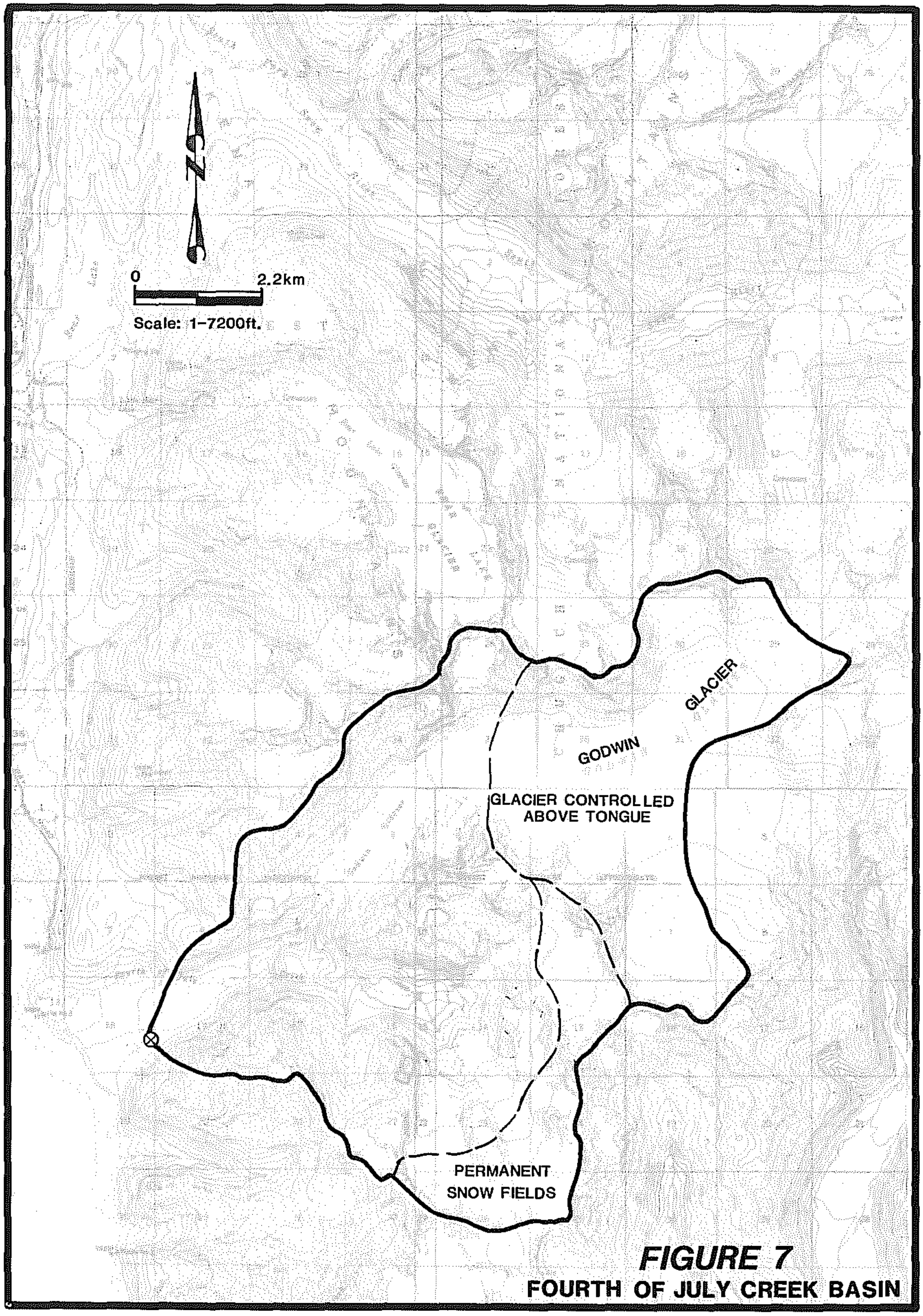

FIGURE 7
FOURTH OF JULY CREEK BASIN

2. 100-year recurrence peak using Ott Water Engineers (1979): 230 m^3/sec.
3. 100-year recurrence peak using correlation with nearby Spruce Creek: 310 m^3/sec.
4. 100-year recurrence using Lamke (1979) corrected for glaciated area: 132 m^3/sec.
5. 100-year recurrence using Ott Water Engineers (1979) corrected for glaciated area: 129 m^3/sec.
6. 100-year recurrence using Spruce Creek correlation corrected for glaciated area: 165 m^3/sec.

The result of Method 6 is recommended since a nearby representative non-glaciated stream record existed. Otherwise for other basins, Method 5 in south coastal and Southeast Alaska and Method 4 elsewhere in Alaska might be appropriate.

REFERENCES

Alaska Geographic Society, 1982, Alaska's Glaciers, Alaska Geographic, 9(1), 144 pp.

Ambach, W., M. Blumthaler, and P. Kerchlechner, 1981, Application of the Gravity Flow Theory to the Percolation of Melt Water Through Firn, Journal of Glaciology, 27(95), pp. 67-75.

Anderson, E. A., 1968, Development and Testing of Snow Pack Energy Balance Equations, Water Resources Research, 4(1), pp. 19-37.

Anderson, E. A., 1973, National Weather Service River Forecast System - Snow Accumulation and Ablation Model, NOAA Technical Memorandum NWS Hydro-17.

Behrens, H., H. Bergmann, H. Moser, 1975, On the Water Channels of the Internal Drainage System of the Hintereisferner, Otztal Alps, Austria, Journal of Glaciology, 14(72), pp. 375-382

Clarke, Garry K., 1982, "Glacier Outburst Floods from 'Hazard Lake', Yukon Territory, and the Problem of Flood Magnitude Prediction", Journal of Glaciology, 28(98), pp. 3-21.

Campbell, William J., and Lowell A. Rasmussen, 1969, The Production, Flow, and Distribution of Melt Water in A Glacier Treated as a Porous Medium, Symposium on the Hydrology of Glaciers, Cambridge, Publication No. 95, International Association of Scientific Hydrology, pp. 11-28.

Colbeck, S. C., 1972, A Theory of Water Percolation in Snow, Journal of Glaciology, 11(63), pp. 369-385.

Colbeck, S. C., 1974, On Predicting Water Runoff from a Snow Cover, Advanced Concepts and Techniques in the Study of Snow and Ice Resources, National Academy of Sciences, Washington, DC, pp. 55-66.

Colbeck, S. C., 1975, Analysis of Hydrologic Response to Rain-on-Snow, Research Report 340, Cold Regions Research and Engineering Laboratory, Hanover, NH, 9 pp.

Colbeck, S. C., 1977, Short-Term Forecasting of Water Run-Off from Snow and Ice, Journal of Glaciology, 19(81), pp. 571-588.

Colbeck, S. C., 1982, An Overview of Seasonal Snow Metamorphism, Reviews of Geophysics and Space Physics, 20(1), pp. 45-41.

Collins, David N., 1979, Quantitative Determination of the Subglacial Hydrology of Two Alpine Glaciers, Journal of Glaciology, Vol. 23, No. 89.

Denoth, A., W. Seidenbusch, M. Blumthaler, and P Kirchlectner, 1978, Some Experimental Data on Water Percolation Through Homogeneous Snow, Proceedings Modeling of Snow Cover Runoff, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, pp. 222-253.

Derikx, Leo, 1969, Glacier Discharge Simulation by Groundwater Analogue, Symposium on the Hydrology of Glaciers, Cambridge, Publication No. 95, International Association of Scientific Hydrology, pp. 29-40.

Elliston, G. R., 1969, Water Movement Through the Gonergletscher, Symposium on the Hydrology of Glaciers, Cambridge, Publication No. 95, International Association of Scientific Hydrology, pp. 79-84.

Feldman, D., 1979, Flood Hydrograph and Peak Flow Frequency Analysis, Preceedings of the Engineering Foundation Conference on Improved Hydrologic Forecasting, Why, and How, ASCE, New York, pp. 1-19.

Field, William O., ed., 1975, Mountain Glaciers of the Northern Hemisphere, Volume 2, Chapter 1, Coast Mountains: Boundary Ranges of Alaska, Volume 2, Chapter 4, Kenai Mountains, Cold Regions Research and Engineering Laboratory, Hanover, NH.

Golubev, G. N., 1969, Analysis of the Run-Off and Flow Routing for a Mountain Glacier Basin, Symposium on the Hydrology of Glaciers, Cambridge, Publication No. 95, International Association of Scientific Hydrology, pp. 41-52.

Heusser, Calvin J., and Melvin G. Marcus, 1964, Surface Movement, Hydrological Change and Equilibrium Flow on Lemon Creek Glacier, Alaska, Journal of Glaciology, 5(37), pp. 61-75.

Hubley, Richard C., 1957, An Analysis of Surface Energy During the Ablation Season on Lemon Creek Glacier, Alaska, Trans AGU 38(1).

Jordan, Peter, 1983, Meltwater Movement in a Deep Snowpack, 1; Field Observations, Water Resources Research 19(4), pp. 971-978.

Jordan, Peter, 1983, Meltwater Movement in a Deep Snowpack, 2; Simulation Model, Water Resources Research 19(4), pp. 979-985.

Krimmel, R. M., W. V. Tangborn, and M. F. Meier, 1972, "Water Flow Through a Temperate Glacier", Proceedings of the Banff Symposium on the Role of Snow and Ice in Hydrology, IAHS Publication No. 107, pp. 401-416.

Lamke, R. D., 1979, Flood Characteristics of Alaskan Streams, Water Resources Investigations 78-129, U.S. Geological Survey, Anchorage, AK, 61 pp.

Larson, Graham J., 1978, Meltwater Storage in a Temperate Glacier, Borroughs Glacier, Southeast Alaska, Institute of Polar Studies, Report No. 66, The Ohio State University, Columbus, OH, 56 pp.

Linsley, Ray K., and Joseph B. Franzini, 1979, Water Resources Engineering, McGraw-Hill Book Company, 716 pp.

Male, D. H., and D. M. Gray, 1981, Snowcover Ablation and Runoff, Handbook of Snow, Pergamon Press, Willowdale, Ontario, Canada, Chapter 9, pp. 360-436.

Marcus, Melvin G., 1963, *Climate-Glacier Studies in the Juneau Ice Field Region, Alaska*, University of Chicago, Department of Geography, Paper No. 88, 128 pp.

Mathews, W. H., 1969, Record of Two Jokulhlaups, *Symposium on the Hydrology of Glaciers*, Cambridge, September 1969, Publication No. 95, International Association of Scientific Hydrology, pp. 99-110.

Meier, Mark F., Wendell V. Tangborn, Lawrence R. Mayo, and Austin Post, 1971, *Combined Ice and Water Balances of Gulkana and Wolverine Glaciers, Alaska and South Cascade Glacier, Washington, 1965 and 1966 Hydrologic Years*, Geological Survey Professional Paper 715-A, U.S. Government Printing Office, Washington, DC, 23 pp, 6 plates.

Meier, Mark F., 1972, Hydraulics and Hydrology of Glaciers, *The Role of Snow and Ice in Hydrology*, IASH Publication No. 107, *Proceedings of the Banff Symposium*, pp. 353-370.

Miller, Maynard M., 1963, *Taku Glacier Evaluation Study for State of Alaska Department of Highways*, Alaska Dept. of Highways, Juneau, AK.

Murphy, Thomas D., and Seymour Schamach, 1960, Mountain Versus Sea Level Rainfall Measurements During Storms at Juneau, Alaska, *Journal Hydrology 4*, pp. 12-21.

Oerter, H., D. Baker, H. Moser, and O. Reinwarth, 1981, Glacial-Hydrological Investigations at the Vernagtferner Glacier as a Basis for a Discharge Model, *Nordic Hydrology*, 12, pp. 335-348.

Ott Water Engineers, 1979, *Water Resources Atlas*, U.S. Forest Service, Region 10, Juneau, AK, 90 pp.

Paterson, W.S.B., 1981, *The Physics of Glaciers*, Pergamon Press, Elmsford, NY, Second Edition, 380 pp.

Perrier, E. R., J. Harris, and W. B. Ford, 1977, *A Comparison of Deterministic Mathematical Watershed Models*, Paper No. 77-2047, American Society of Agricultural Engineers, St. Joseph, MI, 115 pp.

Post, Austin and Lawrence R. Mayo, 1971, *Glacier Dammed Lakes and Outburst Floods in Alaska*, Hydrologic Investigations Atlas HA-455, U.S. Geological Survey, Washington, DC, 10 pp, 3 maps.

Richardson, Donald, 1968, Glacier Outburst Floods in the Pacific Northwest, *Geological Survey Research 1968, Chapter D*, U.S. Geological Survey Professional Paper 600-D, U.S. Government Printing Office, Washington, DC, pp. D79-D86.

Sharp, Robert P., 1951, Accumulation and Ablation on the Seward-Malaspina Glacier System, Canada-Alaska, *Journal of Geology*, 62, pp. 725-744.

Stenborg, Thorsten, 1970, Delay of Run-Off from a Glacier Basin, *Geografiska Annaler* 52A(1), pp. 1-30.

Tangborn, Wendall V., Lawrence R. Mayo, David R. Scully, and Robert M. Krimmel, 1977, Combined Ice and Water Balances of Maclure Glacier, California, South Cascade Glacier, Washington, and Wolverine and Gulkana Glaciers, Alaska, 1967 Hydrologic Year, Geological Survey Professional Paper 715-B, U.S. Government Printing Office, Washington, DC, 20 pp, 4 plates.

U.S. Army Corps of Engineers, 1960, Runoff from Snowmelt, EM 1110-2-1406, 66 pp.

U.S. Army Corps of Engineers, 1971, Hydrologic Engineering Methods for Water Resources Development, Volume 1, Requirements and General Procedures, The Hydrologic Engineering Center, Davis, CA.

U.S. Army Corps of Engineers, 1978, HYDPAR (Hydrologic Parameters), Users Manual, Hydrologic Engineering Center, Davis, CA, 60 pp.

U.S. Army Corps of Engineers, 1981, The New HEC-1 Flood Hydrograph Package, Technical Paper No. 82, Hydrologic Engineering Center, Davis, CA, 25 pp.

U.S. Army Corps of Engineers, 1981, HEC-1 Flood Hydrograph Package, Users Manual, Hydrologic Engineering Center, Davis, CA, 192 pp.

U.S. Army Corps of Engineers, 1981, HEC-1 Flood Hydrograph Package, Users Manual, Section 16: Input Description, Hydrologic Engineering Center, Davis, CA, 110 pp.

U.S. Army Corps of Engineers, 1982, Hydrologic Analysis of Ungaged Watersheds Using HEC-1, Training Document No. 15, The Hydrologic Engineering Center, Davis, CA, 160 pp.

U.S. Geological Survey, 1964, Compilation of Records of Surface Waters of Alaska, October 1950 to September 1960, Water Supply Paper 1740, 86 pp.

U.S. Geological Survey, 1971, Surface Water Supply of the United States, 1961-65, Part 15, Alaska, Water-Supply Paper 1936, 342 pp.

U.S. Geological Survey, 1976, Surface Water Supply of the United States, 1966-70, Part 15, Alaska, 425 pp.

U.S. Geological Survey, 1972 through 1983, Water Resources Data for Alaska, Water Year 1971, 1972, 1973, 1974, 1975, 1976, 1977, 1978, 1979, 1980, 1981, 1982, Anchorage, AK.

Wankiewicz, Anthony, 1978, A Review of Water Movement in Snow, Proceedings Modeling of Snow Cover Runoff U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, pp. 222-253.

Wendler, G., and A. Streten, 1969, A Short-Term Heat Balance Study on a Coast Range Glacier, Pure and Applied Geophysics 77, pp. 68-77.

Young, G. L., 1980, Monitoring Glacier Outburst Floods, Nordic Hydrology 11(5), pp. 285-300.

SEA ICE CHARACTERISTICS IN THE NEARSHORE ENVIRONMENT

David M. Hoch[1] and Brent T. Drage[2]

Abstract

The development of large-scale marine structures in arctic waters is a relatively recent phenomenon. In the Alaskan experience, the design of such offshore and coastal structures has been predominantly associated with North Slope oil field development. Engineering design for such hostile ice environments is still in its infancy, and many unanswered questions await further analysis and testing. With these constraints in mind, contemporary design philosophy often utilizes broad generalizations regarding sea ice strength in an attempt to insure conservative estimates.

A specific case history is presented in which a generalized analysis results in an excessively high value for sea ice strength. A field sampling program and a subsequent laboratory analysis suggests that substantially lower values may, in fact, be the case. By utilizing the knowledge gained from such research, significant savings in construction costs may be realized for ice-affected structures. It is the opinion of the authors that sea ice strength is a more "site-specific" phenomenon than is commonly thought. A defense of this argument is presented, and its "real world" applicability is discussed. The economic benefits realized by this approach may be substantial when viewed in the context of the potential offshore and coastal development in the Alaskan Beaufort Sea.

Introduction

The discovery of world-class oil reserves in the North American arctic during the 1960's has spurred the development of large-scale marine structures for the arctic environment. As oil exploration efforts begin to move into the true offshore regions of the Arctic Ocean, the requirements for marine design become more and more demanding and complex. During the early days of arctic oil field development, design

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[1] Hydrologist, Peratrovich, Nottingham & Drage, Inc., 1506 West 36th Avenue, Suite 101, Anchorage, Alaska 99503

[2] Vice President, Peratrovich, Nottingham & Drage, Inc., 1506 West 36th Avenue, Suite 101, Anchorage, Alaska 99503

requirements were limited to nearshore structures such as barge offloading docks which were used to support land-based activities. Subsequent exploration, however, revealed the existence of massive oil reserves in the true offshore regions of both the Canadian and Alaskan arctic. With these discoveries came the need for sophisticated marine design techniques which could be applied to offshore drilling and production structures in such ice impacted environments.

The tremendous natural forces affecting facilities in such an environment, combined with the extreme cost of construction (and repair) in these remote regions, have led to the widespread use of conservative estimates for design parameters. Empirical data for such design situations are still relatively scarce, although data collection efforts are increasing each year. Faced with these limitations, engineers must often utilize simplistic generalizations when faced with a design problem. It is generally felt that a conservative estimate must be made until a more substantial data base is developed.

Unfortunately, the extreme cost of fabrication and construction makes "over-design" an especially expensive process in the arctic regions. In many cases, a well-executed data collection effort could provide site-specific information which would justify the relaxation of some of the accepted design criteria currently in use. The following paper describes such a data-collection effort. The engineering firm in question was faced with the task of developing ice loading criteria for a marine facility on the shores of Alaska's Beaufort Sea. It was felt that the currently utilized values for ice strength would result in a potential over-design if applied to this specific project. In order to verify this belief, a concise data-collection program was initiated to provide the necessary data. Calculations based on these results did indeed lead to the relaxation of initial design specifications. Project construction costs were reduced considerably. It is the opinion of the authors that similar situations will be encountered in many future offshore design projects. This will become a significant economic factor as arctic offshore development becomes more intensive.

Project Location

The location of the proposed design is shown in Figure 1. Of primary interest is the protective chain of barrier islands located to the north of Oliktok Point. The Jones Islands/Thetis Islands group forms a natural line of separation between the offshore environment of the Beaufort Sea and nearshore Simpson Lagoon region. The Beaufort Sea is, of course, subjected to all the large-scale ice forces commonly associated with arctic waters: massive pressure ridges, multi-year ice floes, long fetches, and generally extreme ice conditions. Such an environment can be considered typical of most of the North American arctic coast, and as such it has received most of the experimental attention during the past several decades.

The project location under discussion, however, is positioned shoreward of a chain of barrier islands, and as such is relatively protected from the large driving forces found offshore. It was felt that the commonly applied values for sea ice strength and driving forces could perhaps be reduced for a structure being placed in this area. The question, of course, is: How much of a reduction can be justified? Assuming that the project site depicted in Figure 1 is subjected to site-specific ice conditions, what sort of values can be realistically expected, and how can this be verified in the field?

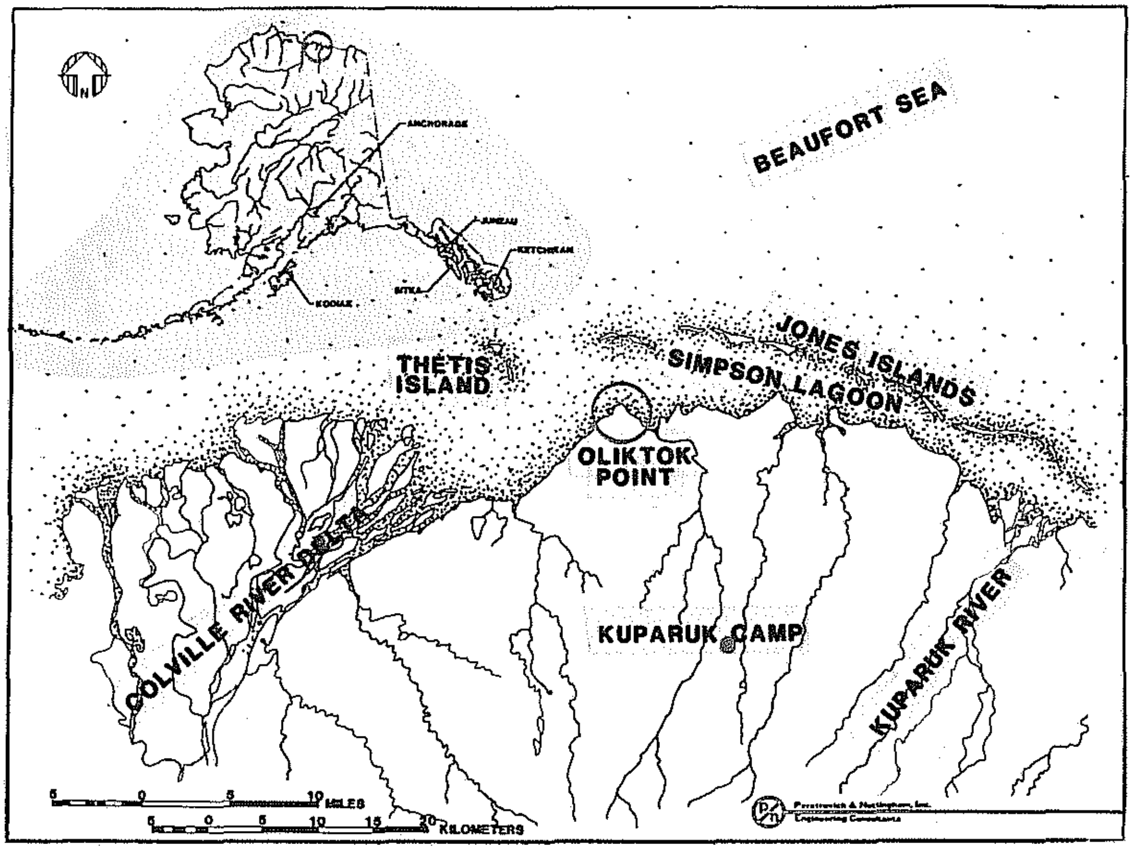


FIGURE 1 LOCATION MAP

Experimental Design

The primary site-specific value to be discussed in this paper concerns sea ice strength. It was felt that the unique geographical location of Simpson Lagoon contributes to the formation of sea ice which is quite different in character to that found offshore. If a field sampling program could be devised which would provide empirical data on this issue, a relaxation of the stringent design criteria currently in use could perhaps be justified. The overall cost savings to the project could be significant.

Fortunately, an on-going data collection project had been conducted in the Simpson Lagoon region for the two winters preceding this study. Monthly measurements of ice thickness, continuous air temperature, ice profile temperatures, sea water salinity/conductivity, and seawater temperature had been recorded for this period of record. With this data base to build upon, a sampling plan was devised in which several cores would be retrieved from the ice cover. These samples would then be examined in the laboratory, and an analysis made of the crystalline structure, salinity concentrations, and brine void ratios of the ice.

Field sampling was performed on March 15, 1983. Three cores were cut from the 5.4 ft. thick ice cover using a standard CRREL/SIPRE coring tool. The cores were cut by hand and packed in an insulated chest for shipment to the laboratory.

Parameters which were sampled, analyzed, and/or measured during this experiment consisted of:

- Ice Thickness
- Ice Crystalline Structure
- Ambient Air Temperature
- Ice Temperature Profile
- Ice Salinity
- Ice Brine Void Ratio
- Seawater Salinity and Temperature

With these site specific data, definitive ice strengths could be determined from standard relationships. For the purpose of this study, the relationships published in API Bulletin 2N "Planning, Designing, and Constructing Fixed Offshore Structures in Ice Environments," (API, 1982) were used primarily.

Ice Crystalline Structure

The three cores were retrieved in mid-March at a location approximately 200 feet offshore from Oliktok Point, Simpson Lagoon. Ice thickness at this location was recorded at 5.4 feet. Each core had about 0.2 feet of granular/snow ice on the surface; the remaining ice column consisted of columnar crystalline structure. Due to Simpson Lagoon's protection by the barrier islands and mainland, this result was to be expected. During the autumn freezeup period, frazil ice may form on the surface if a proper wind/temperature regime occurs. But after an ice cover forms and reaches a thickness of about 8 inches, calculations suggest that there will not be sufficient environmental driving force available to fracture and move the ice sheet. Ice would therefore grow with a columnar crystalline pattern throughout the winter under these stable conditions.

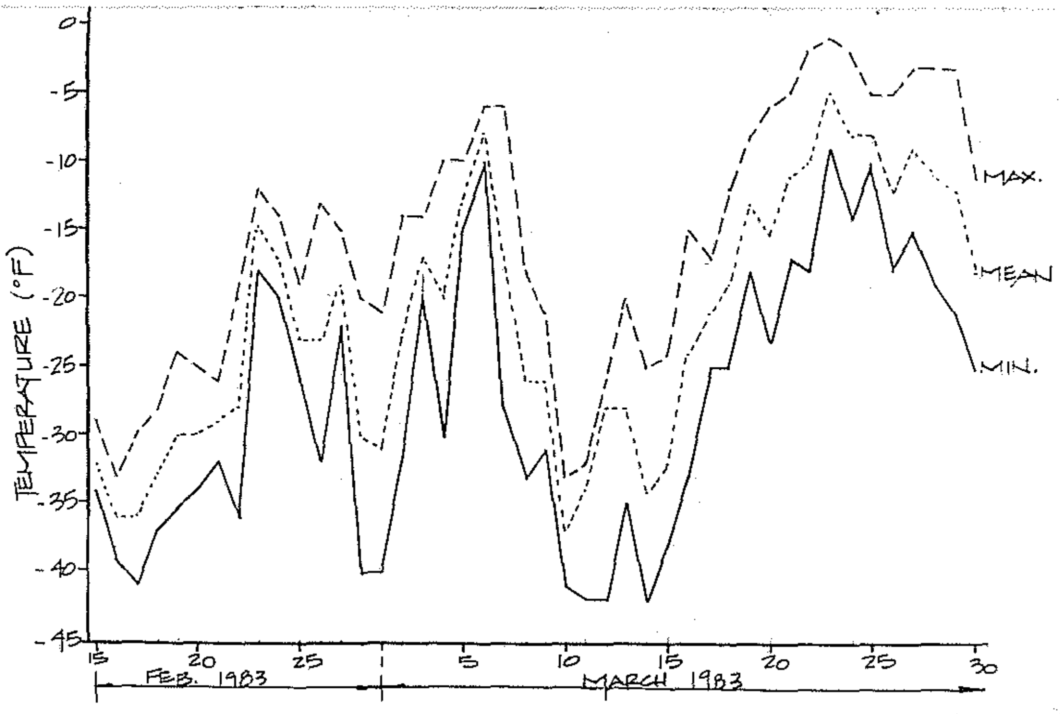


FIGURE 2 DAILY MAX/MIN/MEAN TEMPERATURES, 1983

Ambient Air Temperature

The 1982/83 winter was considered to be somewhat colder than average. Figure 2 presents recorded daily air temperatures measured at a nearby point for the preceding 30 days. The prevailing air temperature was relatively cold during the 2-week period preceding the March 15, 1983 sampling period.

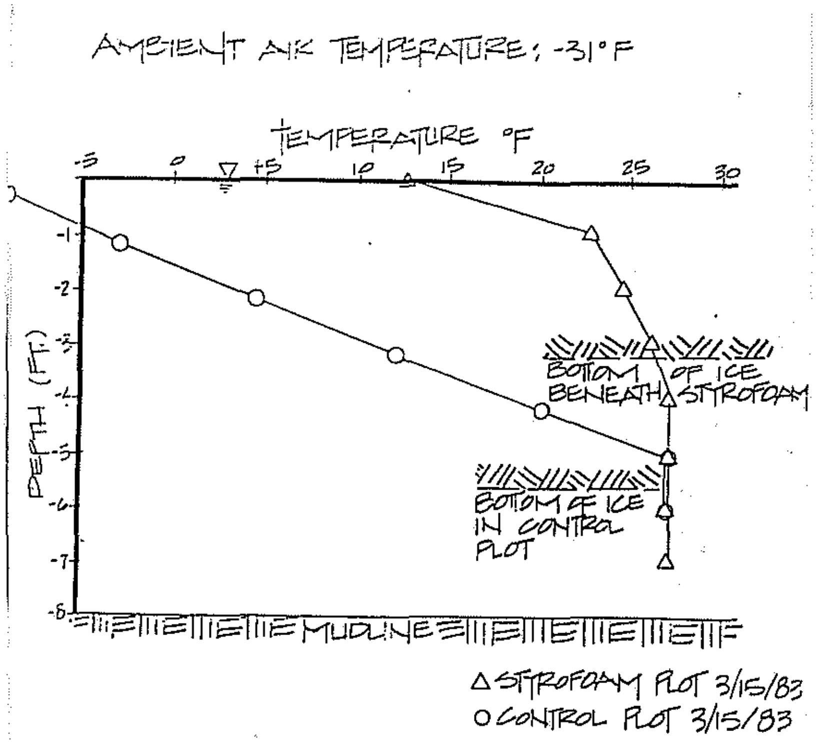


FIGURE 3 ICE TEMPERATURE PROFILE, MARCH 15, 1983

Ice Temperature Profile

Two thermistor strings were installed in the ice cover in January of 1983. One string was located in the natural ice and another was located beneath a 40 ft. x 40 ft. slab of 4 1/2 in. thick styrofoam insulation which had been in place for approximately four months. The March 15, 1983 temperature profiles are shown in Figure 3. The ice temperature on this date is considered to be cold, with an average temperature of +9°F at the time of measurement. Note the warm temperatures that exist in the bottom 0.5 to 1.0 feet of ice. The cores that were retrieved revealed a soft texture on this lower portion of ice.

Ice Salinity

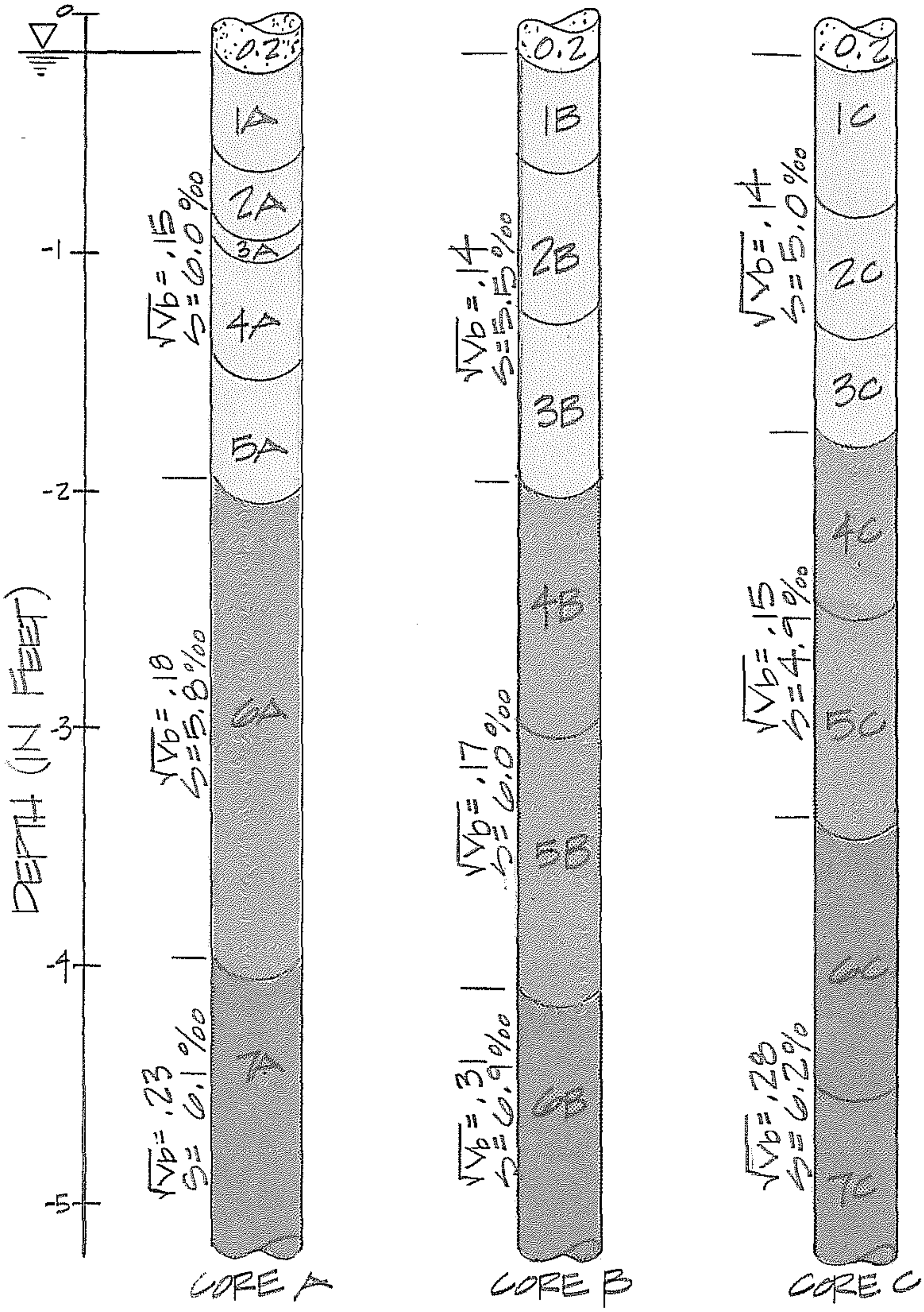
Following retrieval, each sample core was divided into thirds and the entrapped salinity was measured in the laboratory utilizing techniques recommended by CRREL (Cox & Weeks, 1975). Figure 4 summarizes the measured salinities for each core segment. Salinities averaged about 6 parts per thousand, a figure which correlates well with published findings on this topic.

With the salinity data and ice temperature profile discussed above, sea ice brine void ratios could be computed.

Ice Brine Void Ratio

Most relationships that define ice strength properties utilize the brine void ratio as a prime parameter. Brine void ratio can be defined as the square root of the brine volume. Figure 4 summarizes the brine void ratios for each segment of the three ice columns. The upper third of each core has a brine void ratio similar to those that are reported in the published literature. It can be seen, however, that the ratio increases with ice depth as the relative warmth of the seawater is approached.

Sea ice loading calculations traditionally use the brine void ratio characteristic of the upper 1/3 of the ice column to define ice strength parameters. The results of this experiment -- in particular the warm ice temperature and high brine void ratios -- lead to a theory that an



BRINE VOID RATIO & SALINITY (‰) OF ICE CORES

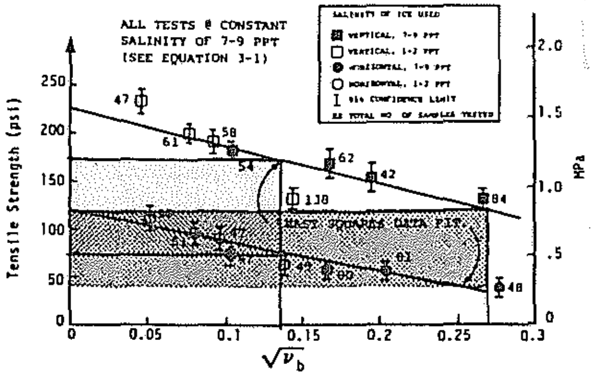
FIGURE 4

"effective ice thickness" should be considered when defining ice strengths. This "effective thickness" would be defined by a temperature threshold differentiating between good bonded crystalline ice and slushy warm ice. For this particular case, it appears that the effective ice thickness should be 0.5 to 1.0 feet thinner than the measured ice thickness.

Seawater Salinity and Temperature

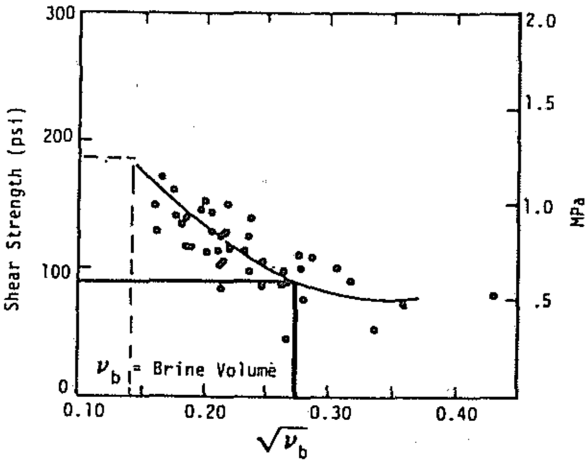
Nearshore seawater salinity increases as the ice thickness increases. As the ice cover grows, it excretes brine into the parent water. Since there is little circulation and dilution in this shallow nearshore environment, the salinity is able to increase to above normal levels. These higher salinity values, combined with the relatively warm seawater temperatures, tend to retard ice growth rates during late winter. The brine excretion process is likewise retarded, allowing higher brine void ratios, and hence, weaker ice.

As was mentioned above, most existing literature correlates ice strength properties with ice brine void ratio. Figures 5 through 8 are taken from API Bulletin 2N "Planning, Designing, and Constructing Fixed Offshore Structures in Ice Environments," (API, 1982). Based upon the work of researchers cited in these figures, various mechanical properties of sea ice have been plotted as a function of brine void ratio. We have overlain the results of the Simpson Lagoon experiment on these figures by way of comparison. The dashed lines represent properties derived from the upper one-third of the cores; the solid lines represent the lower third. In Figure 5, the darker stippling is used for the lower third of the cores.



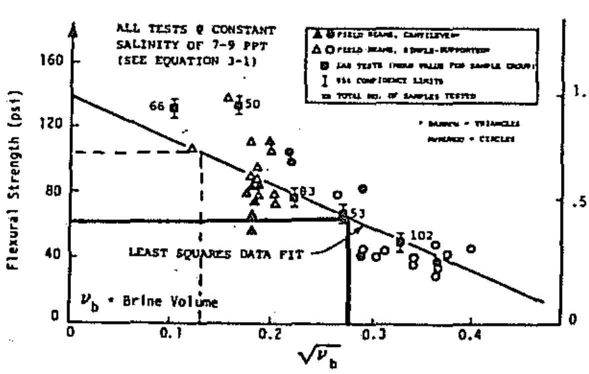
SEA ICE TENSILE STRENGTH AS A FUNCTION OF THE SQUARE ROOT OF BRINE VOLUME (DYKINS (1971))

FIGURE 5



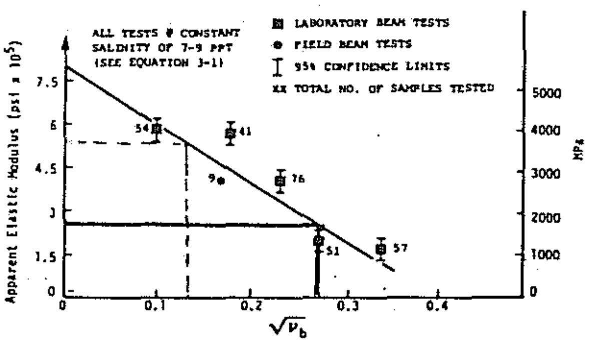
SEA ICE SHEAR STRENGTH AS A FUNCTION OF THE SQUARE ROOT OF BRINE VOLUME (PAIGE (1967))

FIGURE 6



SEA ICE FLEXURAL STRENGTH AS A FUNCTION OF THE SQUARE ROOT OF BRINE VOLUME (VAUDREY (1977))

FIGURE 7



APPARENT MODULUS OF ELASTICITY OF SEA ICE AS A FUNCTION OF THE SQUARE ROOT OF BRINE VOLUME (VAUDREY (1977))

FIGURE 8

░ $\sqrt{\nu_b}$ =.136 UPPER 1/3 OF ICE CORE

▓ $\sqrt{\nu_b}$ =.274 LOWER 1/3 OF ICE CORE

- - - $\sqrt{\nu_b}$ =.136 UPPER 1/3 OF ICE CORE

—— $\sqrt{\nu_b}$ =.274 LOWER 1/3 OF ICE CORE

From Figures 5 through 8, the following mechanical properties have been extracted utilizing the previously discussed data:

Mechanical Property	Upper 1/3 of Ice Column	Lower 1/3 of Ice Column
Tensile Strength	75-170 psi	40-120 psi
Flexural Strength	105 psi	60 psi
Shear Strength	190 psi	90 psi
Apparent Elastic Modules	5.5×10^5 psi	2.5×10^5 psi

Expected Ice Loading in the Nearshore Environment

As was stated in the Introduction to this paper, the present experiment was applied to a "real world" design problem: in particular, the calculated ice loads on a vertical wall fabricated near Oliktok Point. Calulations utilizing the traditionally recognized ice property values had already been performed for this situation by applying the following relationship (Ralston, 1979):

$$\frac{F}{W} = f_c I^G \sigma_c^G h^G + f_c I^C \sigma_c^C h^C$$

where:

F/W = Ice load per unit width of the structure,

f_c = Contact factor between ice and structure,

I^G, I^C = Indentation factors for granular and columnar ice,

σ_c^G, σ_c^C = Unconfined crushing strength of granular and columnar ice,

h^G, h^C = Thickness of granular and columnar ice.

Since our field data indicated a columnar crystalline structure throughout the ice column (with the exception of the upper 0.2 feet), we chose to eliminate the portion of the relationship pertaining to granular ice.

Accepting the effective ice thickness theory, but still utilizing a conservative value, an assigned thickness of 5 feet was applied.

All other parameters within this relationship were retained as if we were studying a location outside the barrier islands. The resultant load expected against a vertical structure was calculated to be:

$$\frac{F}{W} = f_c \, I \, \sigma_c \, h_c$$

$$\frac{F}{W} = 0.8 \times 3 \times 91 \, \frac{\text{lbs.}}{\text{sq.in.}} \times 5 \text{ ft.} \times \frac{1 \text{ kip}}{1000 \text{ lbs.}} \times 144 \, \frac{\text{sq.in.}}{\text{sq.ft.}}$$

$$\frac{F}{W} = 157 \, \frac{\text{kips}}{\text{ft.}}$$

This computed ice loading of 157 kips per unit width of structure is significantly less than the values computed using "offshore" design values.

Summary

Based upon the results of a field data collection program, revised values for sea ice strength were developed for a specific location on the shores of Alaska's Beaufort Sea. These values were significantly less than those initially calculated. A downgrading of design specifications was thus justified, resulting in substantial potential savings in construction costs. Field investigations verified that sea ice strength can often be a site-specific parameter; ice strength values applicable to the true offshore environment are not necessarily valid for the more protected nearshore regions.

The results of the salinity and brine void ratio analyses agree fairly closely with the published results of other researchers. The primary difference between Simpson Lagoon ice and the ice referenced by these authors lies in the crystalline structure of the material. Due to its protection by the barrier islands, Simpson Lagoon ice is allowed to grow in a relatively stable, calm environment. When insulated from the turbulent conditions offshore, crystalline ice dominates a majority of the ice column. Ice of this configuration maintains a significantly different strength from the more granular ice which forms under more unstable, turbulent conditions.

Much of the published literature tends to assign a single value to the entire ice-thickness column. Based upon the results of this experiment, it is suggested that the Simpson Lagoon ice profile is sufficiently stratified to modify this simplified view. For such situations, the "effective ice thickness" concept provides a more realistic view of natural conditions.

This exercise was not undertaken to provide a rationalization for reducing design specifications. Rather, it suggests that sea ice strength is a more site-specific phenomenon than is generally thought. Cost benefits in future design/construct projects may be realized by analyzing these characteristics for the specific site in question. When placed in the context of potential development in the Alaskan and Canadian arctic, the economic impact of these concepts cannot be ignored.

References

American Petroleum Institute (1982), Planning, Designing, and Constructing Fixed Offshore Structures in Ice Environments: API Bul 2N. API, Washington, D.C.

Cox, G.N.F., and W.F. Weeks (1975), Brine Drainage and Initial Salt Entrapment in Sodium Chloride Ice: Research Report 345, U.S. Army CRREL, December 1975.

Dykins, J.E. (1971), Ice Engineering - Material Properties of Saline Ice for a Limited Range of Conditions, Naval Civil Engineering Laboratory TR-720, Port Huenene, California.

Paige, R.A. and C.W. Lee (1967), Preliminary Studies of Sea Ice in McMurdo Sound, Antarctical During "Deep Freeze 65," Journal of Glaciology, Vol. 6, No. 46.

Ralston, T.D. (1979), Sea Ice Loads. In: Technical Seminar on Alaskan Beaufort Sea Gravel Island Design. Anchorage, Alaska/Houston, Texas, October 18, 1979.

Vaudrey, K.D. (1977), Ice Engineering - Study of Related Properties of Floating Sea Ice Sheets and Summary of Elastic and Viscoelastic Analyses, Civil Engineering Laboratory, TR860, Port Huenene, California.

GROUNDWATER OCCURRENCE IN EAGLE RIVER, ALASKA WITH RECOMMENDATIONS FOR WATER MANAGERS

By James A. Munter[1]

Abstract

Five distinct three-dimensional hydrogeologic terranes in Eagle River are mapped. A near-surface alluvial fan aquifer encompasses much of the area bounded by Meadow Creek, the Glenn Highway, and the Eagle River Loop Road. A two square mile area is underlain by four confined aquifers arranged tier-like (ascending from east to west) proceeding south and eastward for three miles along the Eagle River Valley Road from the Glenn Highway.

A survey of 99 private domestic wells was done that included water-level measurements in 91 wells. Comparison of 81 of these water-level measurements with levels reported by drillers at the time of well construction shows that water levels were higher in 1983 than were initially reported by drillers in 89 percent of the wells. The average water-level increase was 7.2 feet with a standard deviation of 5.8 feet. The water level increase is attributed to several recent years of above-average precipitation. An estimate 53 percent of water currently used in Eagle River is pumped from the confined aquifer system, 30 percent is withdrawn from shallow alluvial fans, and 17 percent is obtained from bedrock or miscellaneous glacial deposits. The alluvial fan aquifer at the present time is only lightly stressed. Many water-supply problems in Eagle River are directly attributable to an inadequate water storage and distribution system. Further development of groundwater in Eagle River should focus on the near-surface alluvial fan aquifer, and should proceed with caution in the confined aquifers system.

Introduction

With a rapidly increasing population and a scattered distribution of productive aquifers, the community of Eagle River, Alaska, has always had water-supply problems. Inquiries from developers, planners, water managers, and the public regarding the location and extent of developable groundwater, and the effects of existing and anticipated groundwater

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

pumpage, have never been adequately answered. In view of escalating pressures on existing resources, a detailed hydrogeologic examination of the area was undertaken in the spring of 1982. Pending formal publication of the study results, this paper discusses issues that are most pertinent to current management concerns. Data not presented in this paper are available for inspection at the offices of the Alaska Division of Geological and Geophysical Surveys (DGGS) on Fish Hatchery Road in Eagle River.

Hydrogeologic setting

The community of Eagle River is situated at the junction of the Chugach Mountains, the valleys of Meadow Creek and Eagle River, and the glaciated lowlands of Knik Arm of Cook Inlet. The close proximity of such diverse geologic features has resulted in a correspondingly diverse assemblage of aquifers. As a guide for evaluating groundwater conditions, a map of hydrogeologic terranes has been prepared for the study area (fig. 1). Hydrogeologic terranes are defined in this paper as three-dimensional geologic units with distinctive water-bearing characteristics. Detailed descriptions of the map units are presented in Table 1. A surficial geologic map (Schmoll and other, 1971) and data from approximately 420 water-well drillers logs were used to construct the map. Drillers' logs typically consist of well-construction information such as casing depths, static water levels, and well yields, and drillers descriptions of geologic materials encountered during drilling.

Test drilling was conducted at a central location in the study area (fig. 1). The results of the drilling and of the analysis of other well logs is presented in two cross sections through the area (figs. 2 and 3).

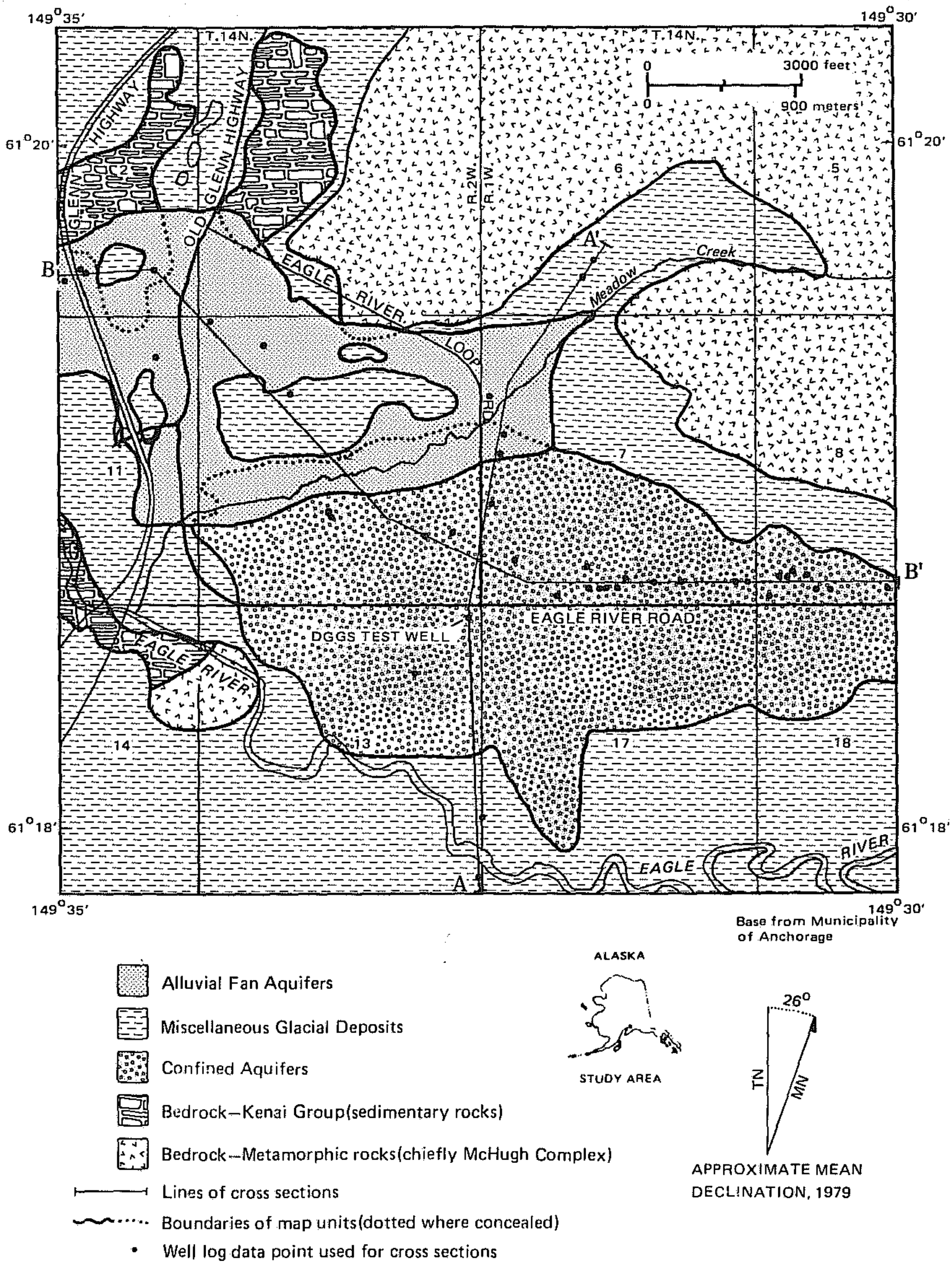


Figure 1. Hydrogeologic terranes in Eagle River (see Table 1 for further explanation of map units).

Table 1. Description of map units used in figure 1.

Map Unit	Description
Alluvial fan aquifers	Quaternary-age near-surface unit consisting of gravel and sand, with cobbles and boulders common, and minor silt. Thickness ranges from a few feet to about 70 feet. Fan sediment source areas probably include both adjacent bedrock areas and Pleistocene glaciers in Knik Arm. Most groundwater occurs under water-table conditions, although the surficial fan deposits are underlain in some areas by interbedded till and alluvial deposits, resulting in local confined or semiconfined aquifers. Yields to wells range up to 500 gpm. Unit boundaries are modified from Schmoll and others (1971).
Miscellaneous glacial deposits	Quaternary-age unit includes: till; thin alluvium overlying glacial deposits; glaciolacustrine deposits; colluvium derived from glacial deposits or interbedded with glacial deposits. Water-bearing sand and gravel deposits are typically thin, shallow, and discontinuous. Reported well yields are commonly not more than a few gallons per minute. Some wells obtain water from the underlying bedrock. Portions of map boundaries are modified from Schmoll and others (1971).
Confined aquifers	Quaternary-age unit represents an area where wells may penetrate one or more confined aquifers consisting of sand and gravel with small to moderate amounts of silt. The aquifers may be old, buried alluvial fans, or glacial outwash, or both. Thickness of aquifers ranges from a few feet to about 90 feet. Silty interbeds commonly occur in thick aquifer sections. Aquifers are confined by silty till and glaciolacustrine or glaciomarine deposits. Several wells yield about 300 gpm.
Bedrock-Kenai Group	Sedimentary rocks of the Kenai Group are within about 50 feet of the land surface. The Kenai Group rocks are of Tertiary (Oligocene or Miocene) age (Wolfe and others, 1966). The Kenai Group rocks in the study area consist of relatively flat-lying beds of siltstone, sandstone, and coal. Lithification of the clastic rocks varies from very friable to well cemented. Reported well yields in the study area are typically a few gallons per minute or less.
Bedrock-metamorphic rocks	Rocks of the McHugh Complex and another small, unnamed formation (Zenone and others, 1974) are within about 50 feet of the land surface. The McHugh Complex consists of deformed and chaotically juxtaposed sequences of metaclastic and metavolcanic rocks of Jurassic and/or Cretaceous age (Clark, 1973). Nearly all wells obtain water from fracture systems in bedrock. Reported well yields are a few gallons per minute or less.

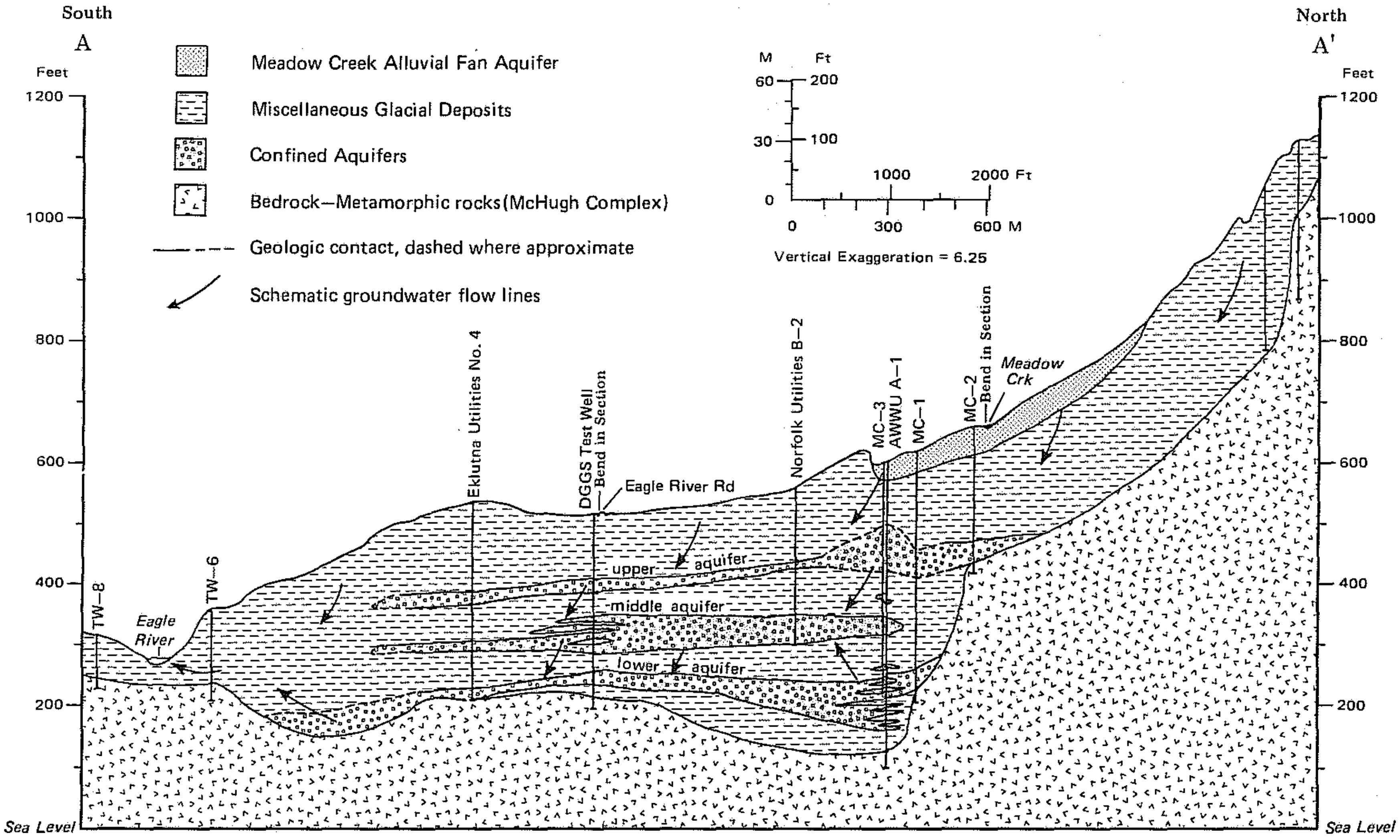


Figure 2. Hydrogeologic cross section A-A'(see Figure 1 for location of line of section).

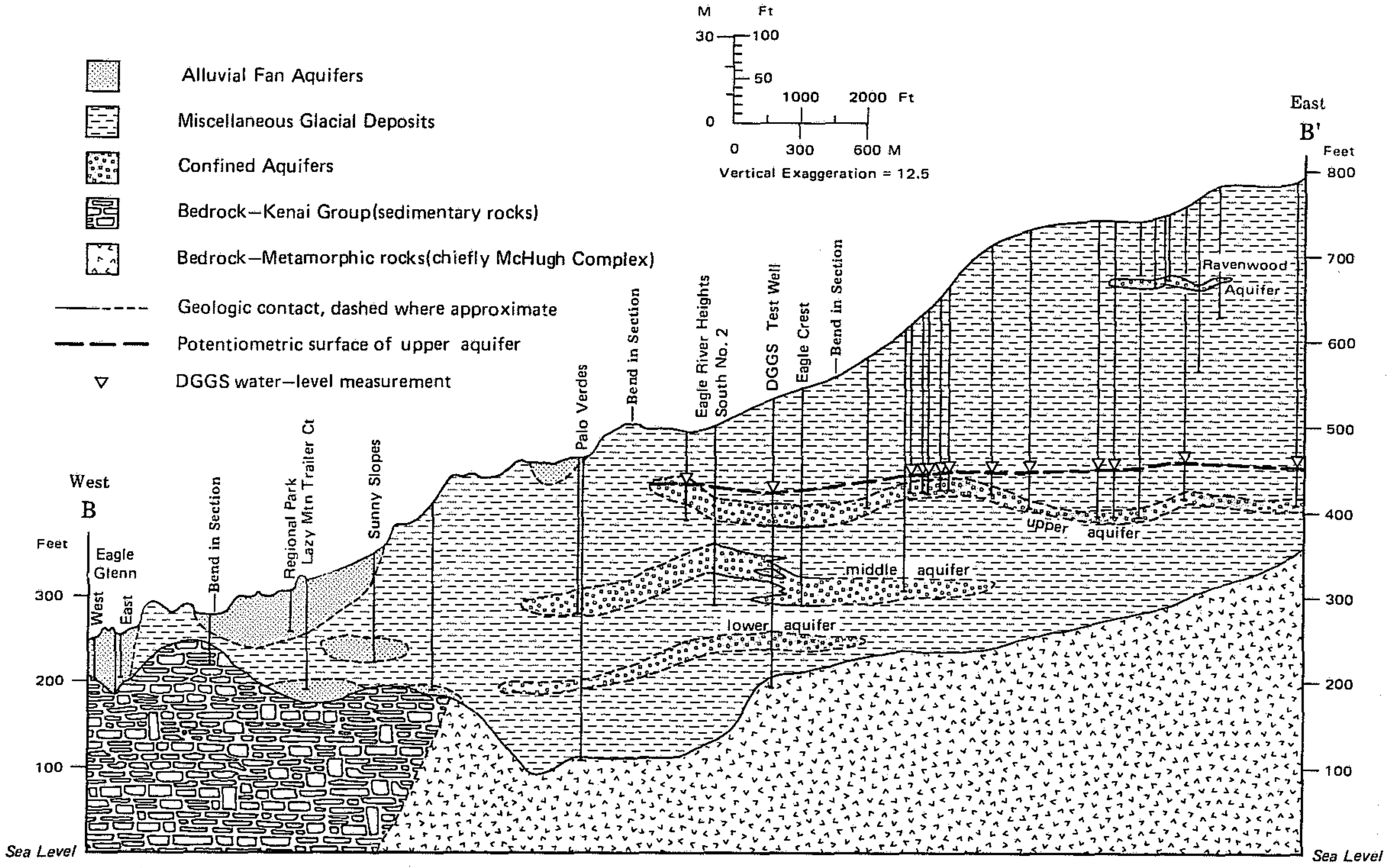


Figure 3. Hydrogeologic cross section B-B'(see Figure 1 for location of line of section).

Cross section A-A' shows the three thickest and most extensive confined aquifers identified in the area. Detailed data on the middle aquifer at the site of the DGGS test well and on the lower aquifer at the site of a well (fig. 2, AWWU well A-1) drilled by the Anchorage Water and Wastewater Utility (AWWU) shows that the aquifers, although relatively thick at these locations, consist of alternating layers of silty glacial sediments and relatively silt-free sands and gravels. The task of constructing an efficient well in the confined aquifers is significantly complicated by the depth below land surface (up to 450 feet) and the interlayered character of the fine and coarse-grained sediments.

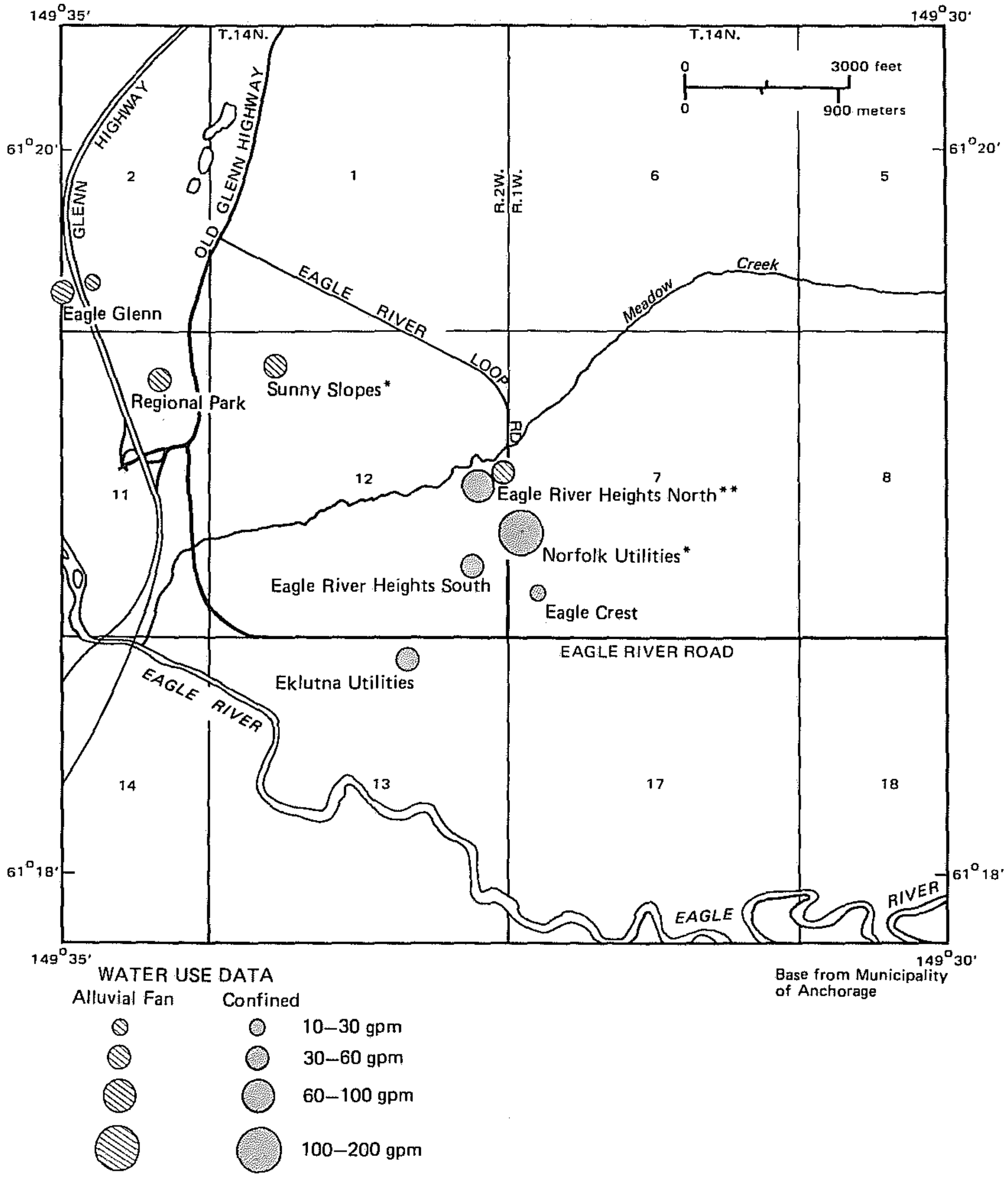
Water-level data show that the potentiometric surfaces for the three lowermost aquifers are generally within 10 to 20 feet of each other, and that groundwater gradients have a downward component of flow throughout most of the area mapped. A small upward gradient exists from the lower aquifer to the middle aquifer near well AWWU A-1, probably resulting from heavy pumping from the middle aquifer, to be discussed subsequently. The small gradients between the confined aquifers provide indirect evidence that the confining beds between aquifers are leaky, to some extent, or that the aquifers are physically connected by coarse-grained glacial sediments. Aquifer test data by a local engineering firm (F. Damron, CH2M Hill, written comm., 1983) indicates that pumping a well in the middle aquifer at 300 gpm for 24 hours results in a two-foot decline in water levels in the upper aquifer. This provides direct evidence that the confining beds separating the confined aquifers are leaky.

Cross section B-B' illustrates the fact that the potentiometric surface of the upper aquifer is approximately 20 feet or less above the top of the aquifer at some locations. Wells constructed in these areas have a low tolerance for water-level declines, whether naturally occurring or artificially induced. Ten to fifteen feet of water-level decline from current levels could significantly reduce the ability of the wells to provide water. Deepening of these wells should not be considered as a routine solution to the problem because the thickness of the upper aquifers is limited, and the extent of the deeper confined aquifers is questionable. Indications are that similar conditions exist in the western part of the study area where some wells drilled into the Ravenwood aquifer (fig. 3) have less than 20 feet of available drawdown.

The alluvial fan aquifer includes both the surficial alluvial fan deposits and older, buried alluvial sands and gravels that occur in the same area (Cross section B-B', fig. 3). The alluvial fan aquifer is surrounded by till and related glacial deposits in moraines and kames. The eastern portion of the aquifer is underlain by silty glacial sediments and the western portion is underlain by siltstones, sandstones, and lignites of the Kenai Group. Deeper sands and gravels were encountered in the Sunny Slopes well and the Lazy Mountain Trailer Court well (fig. 3). As a result of the irregular bedrock topography in the area, and the irregular distribution of glacial sediments, the deeper sands and gravels are not mappable with the existing data base. The potential for water production from these deposits, however, appears to be quite significant, probably because of their close proximity to the surficial water-table aquifer.

Water use in Eagle River

Average continuous-supply rates of estimated and metered water-use data in Eagle River for the period May - July, 1983, are presented in figure 4.



* Water use is estimated from number of households served x 400 gpd.

** Breakdown between confined and alluvial fan sources is estimated from total production data.

Figure 4. Metered and estimated water use by major community water systems in Eagle River.

Only water distribution systems delivering more than an average of 10 gallons per minute are included. Water-use data for systems for which pumping records are not available was estimated by multiplying the number of residential household consumers by 400 gallons per day per household. Based on the short period of record, 400 gpd appears to be a reasonably close approximation to annual average household water consumption in residential areas of Eagle River.

The population of the Eagle River study area is rapidly changing and is difficult to specify precisely. With dwelling unit counts for 1981 and 1982, and 1981 through 1985 population projections from the Municipality of Anchorage (A. Van Domelen, written comm. 1983), a current (August, 1983) population of approximately 9,000 people is estimated. This makes use of the 1980 U.S. Census estimate of 3.2 persons per household in the Eagle River area. Using a per capita use figure of 140 gallons per capita per day (gpcd), the total average water usage in the study area is about 900 gpm. The figure of 140 gpcd is somewhat higher than is currently used in the residential areas of Eagle River, but includes water used for commercial purposes in the town center. The per capita use figure for the AWWU in 1982 was estimated to be 140 gpcd (Mar. 24, 1983 Memorandum from J. Munter and L. Dearborn to State Rep. M. Szymanski).

The water-use data shown in figure 4 totals about 550 gpm, or about 60 per cent of the total estimated usage. The remaining 350 gpm is withdrawn from an estimated 1000 to 1500 private wells, which includes a few small neighborhood water systems. Based on the distribution of known wells in the study area and the location of major water-supply wells, an average of approximately 53 percent of the estimated water consumption in the study area, or 480 gpm, is currently withdrawn from the confined aquifer system. An average of approximately 30 percent, or 270 gpm is currently withdrawn from the alluvial fan aquifers. The remainder, or an average of approximately 17 percent (150 gpm), is withdrawn from areas mapped as shallow bedrock or miscellaneous glacial deposits. Considering only the water pumped from the confined aquifer system, it is roughly estimated that 70 percent of the water is pumped from the middle aquifer, 30 percent from the upper and Ravenwood aquifers, and 1 to 2 percent is pumped from the lower aquifer.

Potential water supply

This analysis of water-supply potential from the alluvial fan aquifers considers only the potential of several existing well systems. The limiting factor in producing water at alluvial fan aquifer well sites in Eagle River is drawdown in the individual production wells because:

1. The wells are typically shallow; with at most several tens of feet of available drawdown, and
2. The drawdown from pumping generally does not affect other wells because of the irregular aquifer geometry, the hydraulics of water-table aquifers in general, and the relatively small number of wells in the alluvial fan aquifer.

A test of the alluvial fan aquifer was performed in August, 1982, at the Eagle River Heights North well field by DGGS and AWWU. The author described the test results in a letter to the AWWU, in which he concluded that a pumping rate of 200 to 300 gpm could be sustained by the aquifer for an extended period of time. Unfortunately, severe well clogging or encrustation prevents effective utilization of the resource. Based on these results and existing water-use data, it appears that a conservative estimate of aquifer yield at this site is about 200 gpm greater than the current rate of extraction.

Another test of the alluvial fan aquifer was conducted during June, 1982, at the Eagle Glenn well field (Munter and Dearborn, in press). Although single-well pumping rates in excess of 500 gpm were attained, aquifer boundaries limit long-term aquifer yield to rates lower than 500 gpm. Data collected subsequent to the test and discussed in a memorandum from the author to the Alaska Division of Land and Water Management (Aug. 25, 1983) suggests that a conservative estimate for long-term aquifer yield at Eagle Glenn under current conditions is 150 gpm, or approximately double the current rate of withdrawal.

Two separate aquifer evaluations were conducted by local engineering firms at the Sunny Slopes Water system: one in 1970 by Dickinson, Oswald and Partners, Consulting Engineers, and the other in 1981 by Beyer Engineering. They projected sustainable yields of 350 and 500 gpm, respectively, based on low-rate (170-190 gpm) aquifer tests. The reported static water level was one foot higher in 1981 than in 1970, despite continuous supply of the Sunny Slopes subdivision in the interim. At this time, owing to the short duration and low rate of previous aquifer tests, it appears that a conservative estimate of long term aquifer yield at Sunny Slopes is about 250 gpm, or about 200 gpm in excess of current production (fig. 4).

Summarizing the preceding discussion, alluvial fan aquifers appear to be capable of producing a minimum of 475 gpm in excess of current withdrawal from existing well developments, for an estimated total yield of about 750 gpm. Additional water supplies from the alluvial fan aquifers could be obtained by developing new well sites, constructing infiltration galleries, or pumping existing wells at higher rates during wetter times of the year (May through October). The ultimate potential of the aquifer, of course, is unknown.

Methods of evaluating the potential yield of the confined aquifer system are necessarily different than methods used to evaluate the alluvial fan aquifers. The effects of large groundwater withdrawals from the confined system are propagated relatively large distances because: 1) the confined aquifers extend over larger areas, 2) the general hydraulic behavior of confined aquifers favors widespread drawdown propagation, and 3) the confining units separating individual aquifers are "leaky" enough to transmit the effects of pumping vertically from one aquifer to another. The large potential for propagation of drawdown forces consideration of the impacts of development on other users of the aquifers, or more specifically, prior water rights holders. The potential yield of the confined aquifer system is dependent on the amount of water-level decline that is deemed acceptable throughout the aquifers, rather than on drawdown limitations of individual production wells.

To determine the present hydrologic status of the confined aquifers, a water-level survey of 99 private domestic wells was conducted from February through July, 1983. Water levels were successfully measured in 91 wells, none of which were perforated, screened, or left with open ends in more than one of the confined aquifers. Of these 91 water levels, it was possible to compare 81 water levels with levels measured and reported by drillers at the time of well construction. In 89 percent of these comparisons, the water level measured during 1983 was higher. The average water-level increase was 7.2 feet, with a standard deviation of 5.8 feet.

In general, the shallowest aquifers showed the most change, and the most net increase in water level. Water-level data collected in the vicinity of the Eagle River Loop Road indicate that the non-pumping water levels of the middle aquifer may be about 10 feet lower than they were in the 1970's. This is attributed to large rates of groundwater extraction from the middle aquifer.

In determining the reason that water levels appeared to be higher in early 1983 than in the past, several factors were considered:

1. Uncertainty is commonly present as to whether the datum for a water-level measurement from a driller is ground surface, or the top of the well casing, which is commonly about 2 feet above the ground.
2. Water-level measurements taken shortly after well drilling may not reflect static conditions because of drilling, developing, and testing techniques commonly used by drillers.
3. The existing data set of drillers' logs was collected over a period of many years and during all seasons of the year.
4. The accuracy of driller's water-level measuring techniques and equipment used in the past are poorly documented.
5. Statistically the survey results may reflect an actual increase in groundwater levels caused by an increase in the rate of recharge subsequent to construction of most of the wells.

Figure 5 shows annual precipitation at Anchorage International Airport, along with a histogram of the year of well construction of the 81 wells for which comparisons were made. Although precipitation events in Eagle River are somewhat different than in Anchorage, the annual trends are probably similar. Figure 5b shows that most wells considered in this analysis were drilled between 1975 and 1977, near the end of a long period of below average precipitation in Anchorage. Figure 5a shows that the years 1979 to 1982 were abnormally wet in Anchorage.

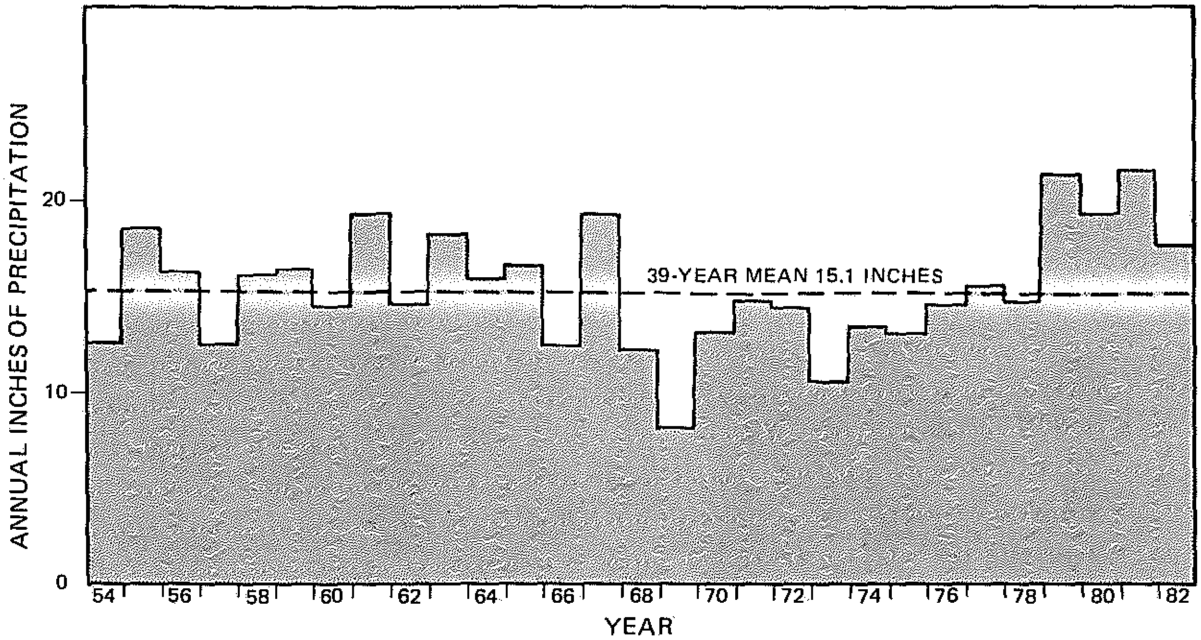


Fig. 5A Annual precipitation at Anchorage Weather Service Meteorological Office - Airport.

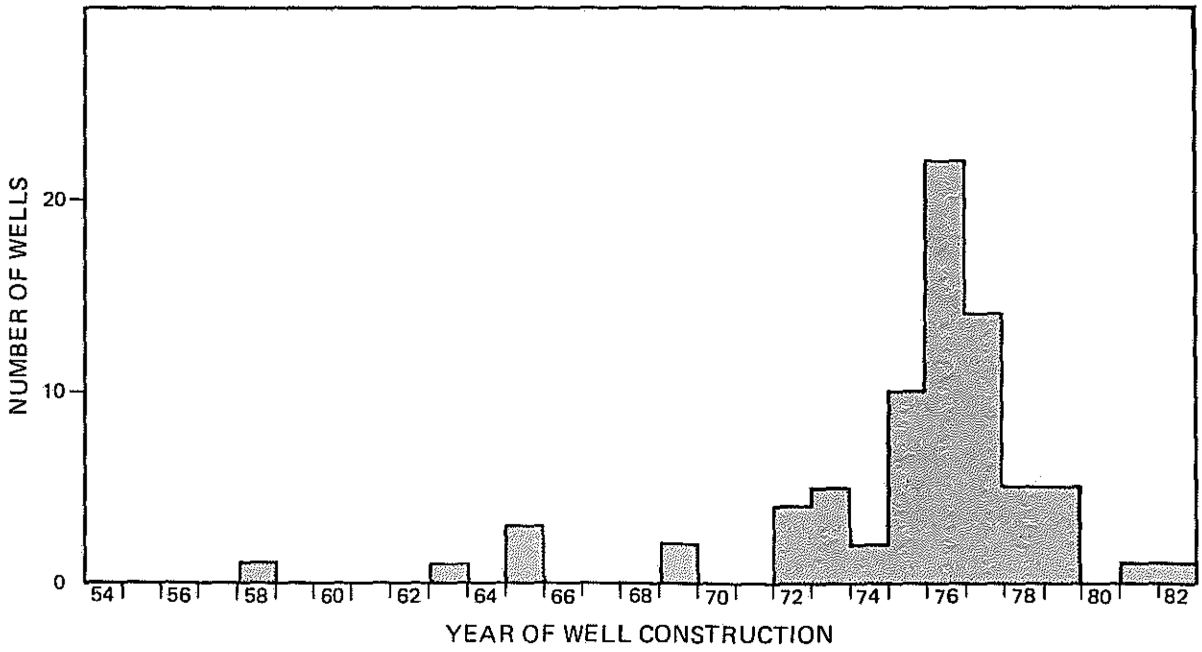


Fig. 5B Histrogram showing year of well construction of wells for which water levels were remeasured in 1983 and were compared with levels reported by drillers.

Thus, the interpretation favored in this paper is that the statistical results of the water-level survey reflect a real rise in water levels in the confined aquifers caused by an increase in precipitation subsequent to the drilling of most of the wells (option no. 5, listed above). An accompanying interpretation is that natural fluctuations in precipitation affect water levels much more so than does groundwater withdrawal from the confined aquifer system at current rates of withdrawal. The exception to this is in the local vicinity of the Eagle River Loop Road, where pumping is heaviest.

As previously discussed, several wells in the upper aquifer may be significantly impacted if water levels in the upper or Ravenwood aquifers drop 10 to 15 feet from present levels. The data suggest that natural fluctuations in water levels could be the most significant contributor to such an occurrence. Thus, a major issue facing water managers considering an expansion of existing water use from the confined aquifers is the degree to which water levels in the confined aquifer system should be maintained during droughts.

Under current conditions, approximately 10 feet of drawdown appears to have occurred near existing pumping centers, with imperceptible effects elsewhere in the aquifer system. Assuming that a simple, direct proportionality exists between pumping rate and drawdown, a doubling of existing withdrawal would result in approximately 20 feet of total drawdown near existing pumping centers, and small drawdowns elsewhere in the aquifer system. With available well construction data, it does not appear as though this would, by itself, unduly affect existing users.

Until further data are compiled and analyzed, a doubling of current use from an estimated 480 gpm to 960 gpm could be proposed as a reasonably conservative lower limit of potential aquifer supply. This assumes that future pumpage is areally distributed somewhat similarly to existing pumpage. Therefore, the sum of the potential yield of the confined aquifer system, the alluvial fan aquifers, and the current estimated pumpage from miscellaneous glacial and bedrock sources is 1860 gpm.

Future water-demand and water-supply options

Table 2 presents population projections for the study area through 2005 (A. Van Domelen, Municipality of Anchorage, written comm., 1983) and average water-demand projections. Population projections were not extrapolated beyond 2005 because the unrestricted zoning in most of the study area precludes estimation of ultimate housing densities.

Table 2. Projections of populations and water demand in Eagle River

Year	Projected population[1]	Estimated average water demand[2] (gallons per minute)
1981	7,461	720
1982	7,779	760
1983	9,251	900
1984	10,453	1000
1985	10,855	1100
1990	14,068	1400
1995	17,732	1700
2000	22,953	2200
2005	25,123	2400

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[1] Using transportation districts 46, 47, and 48, which encompass an area slightly larger than the study area shown in figure 1.

[2] Using 140 gallons per capita per day

A comparison of the average water-demand figures listed in Table 2 with the estimates of minimum available groundwater resources presented previously in this paper, reveals that groundwater resources are adequate to serve as a source of water at least until 1996. This conclusion assumes that an adequate water-distribution system and water-storage facilities are constructed. Providing water for daily or seasonal peak demands, fire protection, or emergency service does not alter projections of average water demand, which is based on an an annual time span. To meet short-term peak demand, preliminary plans call for a five million gallon (mg) water storage facility for Eagle River (R. Illian, AWWU, oral comm., 1983).

It is common belief that importation of water to Eagle River is necessary in the near future because of the lack of adequate quantities of local groundwater. Current plans by the Municipality of Anchorage under the Eklutna Water Project call for construction of a pipeline from Anchorage to Eagle River to deliver treated Ship Creek water to Eagle River as early as 1985 or 1986. Extension of the pipeline to Eklutna Lake and the construction of a treatment plant is planned to provide for delivery of water to both Eagle River (and neighboring communities) and Anchorage as early as 1988 or 1989. This study indicates that a decision to import water into Eagle River in the 1980's should be based on engineering, economic, or other considerations, and not on the lack of available groundwater in Eagle River.

Current water-supply problems

Several problems related to the water-supply situation in Eagle River have not changed since they were first recognized and reported in 1977 (Quadra, 1977). For example, some existing wells are too small to efficiently utilize available groundwater. Also, as previously mentioned, shallow wells at Eagle River Heights North are clogged. A number of existing water distribution systems, such as Sunny Slopes, have inadequately sized mains for a fully integrated water distribution system (Quadra, 1977). Another problem is that adequate storage does not exist in Eagle River for fire protection or emergency water supply. A 0.5 mg storage facility currently under construction near the AWWU well A-1 by the AWWU will be sufficient to provide only for short term variations in residential water demand, but will not be sufficient for fire protection (Bob Smith, AWWU, oral comm. Aug., 1983). Although work is progressing on integrating several existing water distribution systems by the AWWU, the task of obtaining a fully integrated water distribution system of acceptable quality in Eagle River should be viewed as a long-term project.

Conclusions

A system of alluvial fan and confined aquifers have been identified in Eagle River that, under current conditions, are lightly stressed in most areas. The impacts of further development of the alluvial fan aquifers are anticipated to be minor. The impacts of large-scale development of the confined aquifer system are likely to be significant and widespread, particularly during multi-year periods of below-average precipitation.

A minimum, long-term, average rate of potential aquifer yield of 1860 gpm (2.68 million gallons per day) of water is projected. With economic incentives, additional quantities of water could be developed. Current water-use data and population projections indicate that 1860 gpm is sufficient to supply the water requirements of the study area until at least 1996, provided adequate storage facilities and water-transmission systems are constructed. Significant problems currently exist with clogged wells, inadequate storage facilities, and substandard and unconnected water distribution systems in the Eagle River area, causing certain areas to be without adequate water service. A decision to import water into Eagle River in the late 1980's should be based on engineering, economic, or other considerations, and not on the lack of available groundwater in Eagle River.

Recommendations for water managers

1. Adequate funding should be supported and efforts should be continued to construct an adequate system of water storage and distribution in Eagle River. This would include rehabilitation or redrilling of wells and acquisition of private water-distribution systems by the AWWU.

2. Expanded development of groundwater should focus on further utilization and development of the alluvial fan aquifer.

3. Protection against water shortages resulting from seasonal or prolonged dry spells or periods of peak demand should be based on wells in the two lowermost aquifers in the confined aquifer system. Further development of the confined aquifers should be done with caution.

4. Policy should be established concerning the maintenance of water levels in the confined aquifer system. Consideration should be given to both the costs to domestic well owners of over-development of groundwater during periods of below-average precipitation, and the costs to water utilities (and ultimately to the utility customers or

the public) of over-protection of the aquifer system during periods of average or above-average precipitation.

Acknowledgements

The author would like to thank numerous employees of the Municipality of Anchorage for providing several opportunities for data collection, for allowing ready access to previously collected data, and for engaging in rewarding dialogues concerning Eagle River's water supply. Assistance from the engineering firms cited in the text is also appreciated. Significant contributions were made by Roger Allely and Larry Dearborn of DGGS. Larry Dearborn, Bill Long (DGGS), and Rick Illian (AWWU) reviewed the manuscript.

References

Clark, S.H.B., 1973, The McHugh Complex of South-central Alaska: U.S. Geological Survey Bull. 1372-D, 11p.

Munter, J.A., and Dearborn, L.D., 1983, Evaluation of a shallow sand and gravel aquifer at Eagle River, Alaska, in Short Notes on Alaskan Geology, 1982: Alaska Division of Geological and Geophysical Surveys Professional Report [in press].

Quadra Engineering, Inc., 1977, The Eagle River Community water supply and distribution plan: Unpublished report prepared for the Alaska Department of Environmental Conservation, 124 p.

Schmoll, H.R., Dobrovolny, E., and Zenone, C., 1971, Generalized geologic map of the Eagle River-Birchwood Area, Greater Anchorage Area Borough, Alaska: U.S. Geological Survey Open-file Map 71-248, 1 sheet.

Wolfe, J.A., Hopkins, D.M., and Leopold, E.B., 1966, Tertiary stratigraphy and paleobotany of the Cook Inlet region, Alaska: U.S. Geological Survey Prof. Paper 398-A, 29 p.

Zenone, C., Schmoll, H.R., and Dobrovolny, E., 1974, Geology and ground water for land use planning in the Eagle River Area, Alaska: U.S. Geological Survey Open-File report 74-57, 25 p.

ARE WE READY TO MANAGE GROUNDWATER RESOURCES IN ALASKA?

by: Larry L. Dearborn[1]

Abstract

The Alaska Department of Natural Resources is mandated the responsibility of identifying the amount of ground water that is available for development and of assuring, through a process of water appropriation, that aquifers are not overpumped to the detriment of public interests. Increasingly intense groundwater development is occurring in many Alaskan communities. Safe appropriation of withdrawals is difficult in most communities because of a lack adequate geohydrologic information for quantitative assessments. Consequently, a four-step procedure was designed to allow recognition of significantly low and significantly high groundwater-development potentials. Geologic, groundwater-level, hydrologic boundary, and climatic data are used to give a general characterization of the hydrologic environment containing the supply aquifer. Inferences drawn from the composited data may be further interpreted to provide guidelines ultimately used to make management decisions. A status review of data availability for six Alaskan communities, where keen competition for ground water seems imminent, shows that geohydrologic data for the Anchorage Bowl, Eagle River, and North Kenai are adequate for cursory-reconnaissance assessments. But, data deficiencies for the Fairbanks uplands, Chugiak-Peters Creek area, and the Mendenhall Peninsula-Auke Bay area are too great to make useful resource assessments.

INTRODUCTION

The utilization of ground water in a few densely populated areas in Alaska has increased to the point where resource management is essential. The need to be able to arrive at an elementary understanding of aquifer potential to benefit managers prior to completion of comprehensive hydraulically-oriented studies is obvious. Hydrologists and water managers should carefully consider what impacts new wells or future pumping schemes have on prior appropriators and the hydrologic environment.

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[1] Geohydrologist, Alaska Department of Natural Resources, Division of Geological and Geophysical Surveys, Water Resources Section, P.O. Box 772116, Eagle River, Alaska 99577.

Alaska's water-rights doctrine, which provides for the appropriated, beneficial use of this public resource, is the basis for governing withdrawals of ground water. In recent years state water-management officers occasionally have not issued an appropriation that would have certified a substantial increase in local pumping. In most instances, the denial resulted from projections of intolerable drawdown, which presumably would interfere with the yield of neighboring wells. In reality, an issue of equal importance -- the health of the entire aquifer -- was not given much, if any, consideration.

The purpose of this paper is to present a methodology that can be used to identify the gross supply potential of aquifers in a specified area, and thereby inform water managers and community planners early on about the assets of the resource or the possibilities for conflicting use and depletion of a low-yielding aquifer. Critical geohydrologic information that must be compiled and analyzed to accomplish the identification of aquifer potential are reviewed. Additionally, the status of geohydrologic information categories for six major development areas in Alaska are presented. The confined aquifer system in Eagle River described by Munter (1983) is given as an example of the application of the methodology.

Other authors have addressed methodologies for estimating groundwater-supply potentials where insufficient amounts of geohydrologic knowledge exists to examine the potential quantitatively. Davis (1982) proposed a "risk analysis procedure" using cumulative probability curves for making preliminary assessments in areas that are undeveloped or are poorly explored. Heath (1982) listed five "general geohydrologic criteria" as characterizing groundwater systems, and then rated 14 groundwater regions of the United States on these criteria. Peters (1972) summarized California's "experience with using the hydrologic balance as a method of determining safe yield and overdraft" by stating that "ground water is primarily a storage resource". She presented numerous criteria for designing water-level collection networks, which along with well-rounded geologic data, were considered the main inputs in preparing an early estimate of the groundwater-supply potential.

CENTRAL CONCEPTS IN MANAGEMENT OF GROUNDWATER WITHDRAWALS

The meanings of the terms "safe yield", "perennial yield", and "optimum yield" have been widely debated by many authors, yet despite the lack of universal acceptance of these or any yield expression, the basic concept must be applied whenever the use of an aquifer is planned or managed (Fetter, 1980). Although each expression has a slightly different connotation, the intent, safeguarding against over-development of the resource, is present in all definitions. In this report, 'maximum permissible pumping' will be used, as the author believes it reflects a variable limit that may be determined for any specified set of development conditions at any point in time. Development conditions of importance include well density, well distribution, depths of shallowest wells, pumping schedules, and location of major centers of pumping in relation to aquifer boundaries.

The engineering, or planning, of groundwater withdrawals is of concern on a local scale that addresses individual wells, and on a broad scale that includes entire groundwater basins that may underlie thousands of square miles. This paper focuses primarily on reconnaissance-level determinations of the supply potential of discrete aquifers or of a single confined aquifer system.

The general information requirements relating to groundwater management can be grouped into three types of input, or knowledge, as follows:

1. Management objectives must be defined that reflect permissible aquifer conditions for a specified period of time.
2. The pattern and nature of groundwater extractions (well constructions, pumping schedules, etc.) are defined, or are predictable.
3. The physical nature and behavior of the aquifer(s) are adequately understood.

Management objectives

McCleskey (1971) lists the following general management objectives:

1. to limit withdrawals to a level such that the life of aquifer utility is significantly extended;
2. to protect the basin from water-quality deterioration brought on by man's activities;
3. to provide water at a minimum cost;
4. to avoid land subsidence resulting from excessive drawdown of water levels.

Because of water-resource statutes, the most important management objective in Alaska might be the protection of the water rights of prior appropriators as resource development increases. This objective is not as well defined as the above objectives, because each water-rights case commonly requires unique technical and socioeconomic criteria for establishing the degree of protection to be afforded prior appropriators.

Pattern of groundwater extraction

To achieve the maximum yield from an aquifer, optimization in the locations and constructional features of production wells is required. Otherwise, severe artificial limitations may not allow even half the supply potential to be developed. However, rarely do the extraction facilities approach optimization; therefore, the degree of deviation is important for the resource analyst to consider. Such advantageous practices as locating the heaviest withdrawal stress in recharge areas, distributing pumpage as uniformly as possible among many wells versus a few wells, and screening of only the lower section of aquifers need to be considered. Another means of maximizing aquifer yield is to use surface-storage reservoirs to furnish ground water for periods of peak water demand, thus promoting a more constant rate of extraction from the aquifer.

CHARACTERIZATION OF AQUIFER POTENTIAL

The elements, or steps, of a simplified approach the author considers necessary to characterize the production potential of an aquifer are shown in figure 1. The term "cursory-reconnaissance assessment" (CRA) was chosen as a result of combining Peters (1972) study levels A and B. Modification of the definitions of her study levels gives an assessment scope that encompasses a rough delineation of aquifer boundaries, aquifer thickness, aquifer storage capacity, present status of storage, aquifer thru-flow, annual recharge, and sources of recharge.

The objective of the final step (4) is to assign a qualitative, and perhaps relative, rating to the maximum permissible pumping of an aquifer, such as low, moderate, or high. An underlying assumption is that if a given aquifer were thus characterized, groundwater managers can judge the sensitivity of the aquifer to existing or imminent development pressures in lieu of awaiting the outcome of many years of detailed hydrologic study.

STEP 1

collect and compile required data
(see Table 1)

STEP 2

draw hydrologic inferences for seven aquifer parameters
(see Table 2)

STEP 3

interpret favorability of five primary geohydrologic variables
(see Table 3)

STEP 4

assess combined favorability of variables
against existing development restrictions

Figure 1. Basic elements of a cursory-reconnaissance assessment of aquifer-supply potential

Data requirements

The common observable manifestations of critical geohydrologic factors are listed under three data categories in Table 1. Step 1 in initiating a CRA, is to note manifestations that apply to a given basin or aquifer, and subjectively assigned a qualifier such as low, high, pronounced, subtle, or some other suitable descriptor. The data must allow for a rudimentary understanding of the influence of the basin-wide groundwater system on the given aquifer and should be sufficient to recognize the nature of hydrologic interactions between ground water and surface waters.

TABLE 1. Data categories, associated geohydrologic factors, and their common manifestations.

Data category	Geohydrologic factor	Observable manifestations
areal geology	dominant structure	horizontal stratification
		sloped/folded stratification
		anticlinal or synclinal
		jointed, fractured
	basin/aquifer rocks	unconsolidated sediments
		mildly indurated
		strongly indurated
		crystalline
	aquifer stratigraphy	single layer
		multiple layers
		interbedded zone
		massive (non-stratified)
	aquifer size/occurrence	areally small
		areally extensive
		network of stringers
		locally patchy
	aquifer thickness	relatively thin
		individually thick
		compositely thick
areal hydraulics	aquifer water-levels	depth below ground surface
		magnitude of seasonal fluctuation
		existence of multi-year decline
		daily cyclic pattern
		sensitivity to barometric changes
		response to rainstorms
		slope of major rises in level
		slope of seasonal recession
		response to glacier-melt runoff
	system boundaries	proximity to streams
		bordered by impermeable rock
		bordered by faults
		thickness and composition of confining layers
		overlain/underlain by aquifers
basin environment	climate	amount and intensity of rainfall
		water equivalent of snowpack
		average temperatures and ranges
		wind and humidity
	physical features	basin exposure (orientation)
		topography
		vegetation types
		thermokarst terrain

The necessary data collection and compilation in each of the categories in Table 1 to achieve the above objectives is usually straightforward. Normally, well logs and geologic maps will be relied on to provide areal geologic and system boundary data, however, some assessments might be made with strong dependence on results from geophysical interpretations. Aquifers for which considerable data are available may require several months to accumulate, organize, and review enough information on the spacial variations of subsurface geology. In regards to water-level data, Peters (1972) suggests one year of data to define the annual cycle of fluctuation for a cursory study level, and about five years for an areal reconnaissance study. To satisfy the purposes of the proposed methodology, the author believes one year will normally be adequate. This time frame seems equally applicable to climatic data.

Hydrologic inferences

In step 2, seven aquifer parameters are depicted (Table 2) for which inferences as to each's magnitude must be drawn from geohydrologic information represented in Table 1. These parameters are similar to the criteria that Heath (1982) identified. The need for inferences (a) through (e) relate to determining the magnitude of aquifer thru-flow and storativity -- major technical components of the assessment step. The last two inferences are important for broader assessment of the favorability of aquifer replenishment. Characterization of recharge requires two complimentary parameters as neither inference alone is sufficient, because these parameters may represent contrasting favorability. An example is an intermittent stream that is capable of losing large amounts of water to shallow aquifers, but seldom does because its channel rarely receives runoff.

TABLE 2. Common choices for generalized inferences regarding aquifer parameters.

Aquifer Parameter	Inference Descriptors
a) confinement of aquifer	unconfined, weakly confined, tightly confined
b) typical hydraulic gradient	slight, moderate, steep, variable
c) aquifer permeability (hydraulic conductivity)	low, moderate, high highly variable
d) porosity of aquifer	low, moderate, high, fractured, solution openings
e) aquifer extent and volume	small, medium, large
f) continuity of recharge	seasonal pattern (areal infiltration), sporadic/variable (streambed perc.), vertical leakage (relatively constant)
g) availability of recharge water (topographic, geographic, and climatic considerations)	very limited, moderate, plentiful, seasonally variable

In selecting the appropriate inference descriptor for the parameters named in Table 2, choices other than the common ones shown exist and should be considered. It is also feasible for two descriptors to apply to a single parameter. Considering glacial outwash, for instance, the "aquifer extent" could be large but the "aquifer volume" may be small if the sands and gravels are compositely thin.

Assessment of aquifer potential

The third step is to weigh the pertinent inferences for each aquifer, or aquifer system, under consideration and interpret the net favorability of each primary geohydrologic variable shown in Table 3.

TABLE 3. Primary geohydrologic variables governing aquifer yield and their ranges of favorability.

Geohydrologic variable	Favorability range		
a) ground water in storage	small	→	voluminous
b) aquifer thru-flow	low	→	voluminous
c) aquifer replenishment	ineffectively slow	→	rapid filling of storage capacity
d) available drawdown	slight	→	great
e) boundary effects	total restriction of water movement	→	inexhaustible recharge

A number of techniques described extensively in the literature may be employed during in-depth groundwater studies to quantify the transmission of water through an aquifer, and to quantify the volume of water stored within an aquifer and its confining layers, if appropriate. The efforts required are too data intensive and time-consuming to justify undertaking for CRA's. Instead, the hydrologist can make judgement calls on the impacts of all the geohydrologic variables by drawing both data and inference comparisons with detailed study results for similar environments. An analogous subjective procedure was recommended to develop estimates of groundwater storage capacity (Davis, 1982). Certainly, the principles of groundwater occurrence and hydraulic behavior should be applied to guide judgement calls in the interpretation of favorability. A review of the commonly-applied principles is outside the scope of this paper.

Final assessment

In step 4, an overall assessment is made by considering the favorability of the geohydrologic variables in relation to the severity of limitations or restrictions imposed by existing water-supply development and by other land uses. The assessment should qualitatively identify the supply potential with respect to maximum permissible pumping, but also may describe the problems or limitations directly related to one or more management objectives named earlier. The artificial limitations are:

1) shallowness of uppermost well openings (screens, perforations) in relation to the depth to the bottom of the aquifer or confined aquifer system;
2) large drawdown in individual wells relative to areal drawdown, due to low specific capacity resulting from inefficient well construction;
3) excessive drawdown in one part of the aquifer caused by concentrated pumping from closely-spaced wells with pumping rates that are maintained too high;
4) location of major withdrawals unnecessarily close to non-recharge boundaries of the aquifer;
5) the placement of potential sources of pollutants, such as landfills, within areas critical to aquifer recharge;
6) appropriations of water extractions that are hydraulically inefficient or incompatible with one another; and,
7) social, economic, engineering, legal, or political restrictions preventing siting wells at favorable geologic locations.

Further explanation is required to deal properly with drawdown. The "available drawdown" variable, listed in Table 3, is that which exists without consideration of depths of wells currently in use. That is, wells are assumed to tap the lower third or half of the aquifer, and thus, the available drawdown is the distance from the current water table (or potentiometric surface) to just above the deepest practical pump setting. Therefore, the available drawdown is the maximum possible permitted by the physical limitations of the aquifer, and is not determined by existing well constructions. In step 4 the available drawdown is compared with actual well constructions for any point in time to determine the severity of this particular limitation.

Because of the number of possible combinations of favorability ratings due to seven geohydrologic variables and because of the necessity to maintain flexibility in weighing their significance, a standard scheme to arrive at the final assessment appears unworkable. Careful consideration of any extremes in favorability of the variables should allow the analyst to correctly categorize maximum permissible pumping as either low, moderate, or high. In making the assessment, a low favorability rating for any one of the five variables does not require that the overall assessed potential be rated low. But, unfavorable ratings for two or more variables would in most cases be cause to expect that less-than-abundant water supplies could be developed from the aquifer in question.

DATA STATUS OF SELECTED ALASKAN COMMUNITIES

Full-fledged evaluations that will provide managers with desired control over impacts caused by issuance of water-extraction rights require detailed technical studies lasting many years. For example, in the Raymond Basin northeast of Los Angeles, California (Mann, Jr., 1969), two 4-year studies were separated by 7 years of unacceptable groundwater allocations. Locally, the Anchorage aquifers have been investigated for three decades, and yet groundwater assessments to guide Bowl-wide aquifer management are not available.

The preceding pages outlined one methodology for gaining early insights of managerial importance. Step 1 was described as collecting and assembling certain data belonging to three basic categories. With these data, appropriately collected both temporally and spacially, a cursory-reconnaissance assessment of aquifer potential can be attained as outlined.

The intent of Table 4 is to indicate deficiencies of existing data for selected Alaskan communities. An "A" status means that the data are sufficient for a CRA. Assessments may also be possible, although not as reliable, if "M" status data are used. The tabulation, which is based on published reports and data on file at the USGS and the DGGS, shows that geohydrologic information for the Anchorage Bowl, Eagle River, and North Kenai is sufficient for CRA's. However, the Fairbanks uplands, Chugiak-Peters Creek, and the Mendenhall Peninsula-Auke Bay areas have too many data deficiencies at the present to make realistic assessments.

TABLE 4. Status of critical geohydrologic information for selected Alaskan communities for initial groundwater-supply assessments.

	COMMUNITY					
GEOHYDROLOGIC DATA CATEGORY	Anchorage Bowl	Chugiak-Peters Cr.	Eagle River	Fairbanks Uplands	Mendenhall Peninsula	North Kenai
areal geology	A	M	A	D-M	M-D	M-A
areal hydraulics	A	D	M	M-D	D	A-M
basin environment	A	M	A	M	M	M

A = adequate M = marginally deficient D = deficient in many respects

The communities listed in Table 4 are those for which important groundwater management decisions are occurring or appear imminent. Each of these rapidly developing areas have geohydrologic environments that are unique from one another, except for some similarities between the Eagle River and

Chugiak-Peters Creek areas, which lie adjacent to each other. Three communities have environments bounded by saline coastal waters. Geologic settings and climatic characteristics differ widely among the areas listed, causing groundwater occurrence and supply potential to vary markedly. As a result, water managers should expect little transfer value of resource experiences in one community to another. Therefore, a thorough evaluation of favorable groundwater conditions versus natural and man-imposed limitations to development is needed for each community to facilitate wise management of its ground water.

APPLICATION OF THE CRA METHOD

To illustrate the procedure outlined in this paper, a CRA is performed (below) for the system of confined aquifers underlying the community of Eagle River. Data collection and compilation (step 1) have been accomplished by Zenone and others (1974), Johnson (1979), and Munter (1983). These works have provided sufficient data for all geohydrologic factors listed in Table 1. The following manifestations of the aquifer system have been identified (presented in descending order as in Table 1).

- nearly horizontal stratification
- unconsolidated sediments; fine silty sand to clean sand and gravel
- multiple layers with interbedded water-yielding beds
- areally small (spanning about two square miles)
- compositely moderate system thickness
- individual aquifers thin in places
- water levels 50 to 350 feet below ground surface
- 5 ft of seasonal fluctuation; 10 ft between wet and dry years
- water levels fluctuate some with barometer
- response to rainstorms much delayed
- water-level rises are gradual
- aquifers may extend to or under Eagle River (stream)
- metaclastic or metavolcanic rock bounds system upgradient
- layers of silty glacial sediments confine individual aquifers
- confined system is overlain by a shallow, discontinuous, unconfined aquifer
- rainfall totals about 20 in. annually; few intense storms

- snowpack in recharge area contains small water equivalent
- temperature range: winter -20°to 30°F, summer 50 to 70°F
- frequent winds and generally low humidity
- southwest exposure of moderately-sloping undulating topography

The following hydrologic inferences are drawn from the geohydrologic manifestations listed above, based on the format of Table 2:

a) Aquifer system is weakly to moderately confined.

b) The general hydraulic gradient is moderately low.

c) Aquifer permeability varies from low to high.

d) Aquifer porosity is probably moderately high.

e) Aquifer is relatively small in extent and volume.

f) Most recharge occurs largely from slow, fairly-constant, downward, vertical leakage.

g) Moderate to high availability of water for vertical leakage exists.

Next, the favorability of each geohydrologic variable listed in Table 3 is interpreted from the above hydrologic inferences, with brief explanations, as follows:

a) Relatively small volume of groundwater storage is due to small volume of aquifer system, and the geologic evidence that the porosity of the confining layers are not much different than that of the aquifers. Thus, dewatering of the upper part of the system will not result in large volumes of pumpage over the long term.

b) The transmission of water through the aquifers is low to moderate, because the hydraulic gradient is naturally low and the aquifers contain appreciable quantities of silt.

c) Aquifer replenishment at relatively fixed rates of vertical leakage occurs. Recharge probably cannot be induced to increase substantially with increased pumping stress, due to low permeability and 100 ft-plus thickness of confining layers.

d) The naturally occurring (and current) available drawdown is slight; less than 20 ft above the top of the upper and confined aquifer in places. However, the deepest aquifer has over 100 ft of available drawdown. Thus, exclusive use of this aquifer would result in a high favorability for this variable.

e) The movement of ground water across an upgradient boundary is greatly restricted by the truncation of the aquifers by dense bedrock. The aquifers may also abut bedrock in their discharge areas near the stream of Eagle River. Inducing recharge from Eagle River appears unlikely because the river is much lower in elevation than the potentiometric surface.

In the final assessment of supply potential, the unfavorable interpretations made for (a), (b), and (e) above indicate that large supplies of water are not available from the confined aquifer system. In addition, small available drawdowns of the upper confined aquifer, which is tapped by many wells, present a potential for serious water-rights conflicts. The combination of these circumstances leads to a CRA rating of moderately low. Therefore, planners, water managers, and well developers should procede with considerable caution when additional large withdrawals of water from the confined system are desired.

CONCLUSIONS

Because water managers in Alaska are faced with allocations of water rights early in the groundwater exploitation of an aquifer, or basin, a rudimentary understanding of aquifer-supply potential and limitations is crucial. Groundwater experts are in general agreement that a reliable quantification of safe yield (rephrased as maximum permissible pumping in this paper) is not possible in the early stages of pumping stress.

For these reasons, a fundamental methodology for providing a cursory-reconnaissance assessment (CRA) of aquifers was presented to guide resource management decisions before substantial pumping stress occurs, or is analyzed. Using this methodology, aquifers in any stage of exploitation can be rated; thus, a historical perspective of aquifer performance is not a mandatory calibration requirement as it is for the quantitative mathematical-modeling approach.

Data requirements of the four-step procedure were classified under general categories labeled: areal geology, areal hydraulics, and basin environment. The adequacy of existing data for six Alaskan communities were subjectively rated. Data for the Anchorage Bowl, Eagle River, and North Kenai are judged to be sufficient for CRA's, whereas data for Chugiak-Peters Creek, the Fairbanks uplands, and the Mendenhall Peninsula-Auke Bay area are not sufficient. Therefore, in answer to the title question, we are not as ready as we should be to manage ground water in our state.

An example CRA made for the confined aquifer system at Eagle River indicated a moderately low development potential, due primarily to the proximity of unfavorable boundaries and a small tolerance for drawdown. A severe restriction to full development is imposed by numerous, certified water-rights granted wells that tap the upper confined aquifer.

Although this assessment method was primarily designed to allow recognition of significantly low and significantly high water-development potentials, its application to some communities will result in a qualitative determination that lies in between low and high. If so, the value to early management decisions will be an awareness to proceed with caution.

Acknowledgements

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References

Davis, G.H., 1982, Prospect risk analysis applied to ground-water reservoir evaluation: Ground Water, v. 20, no. 6, p. 657-662.

Fetter, C.W., Jr., 1980, Applied hydrogeology: Columbus, Ohio, Charles E. Merrill Co., 488 p.

Heath, R.C., 1982, Classification of ground-water systems of the United States: Ground Water, v.20, no.4, p. 393-401.

Johnson, P., 1979, Hydrogeologic data for the Eagle River-Chugiak area, Alaska: U.S. Geological Survey Water Resources Investigation 79-59, 17 p.

Mann, J.F., Jr., 1969, Ground water management in the Raymond Basin, California: Geol. Soc. Amer. Engr., geol. case studies, no. 7, p. 61-74.

McCleskey, G.W., 1972, Problems and benefits in ground-water management: Ground Water v. 10, no. 2, p. 2-5.

Munter, J.A., 1983, Groundwater occurrence in Eagle River, Alaska, with management implications: Proceedings of the 1983 annual meeting of Alaska Chapter of the American Water Resources Association, Chena Hot Springs, Alaska (this volume).

Peters, H.J., 1972, Criteria for groundwater level data networks for hydrologic and modeling purposes: Water Resour. Res., v. 8, no. 1, p. 194-200.

Zenone, C., Schmoll, H.R., and Dobrovolny, E., 1974, Geology and ground water for land-use planning in the Eagle River-Chugiak area, Alaska: U.S. Geological Survey Open-file Report 74-57, 25 p.

A WATER BALANCE FOR TWO SUBARCTIC WATERSHEDS

By Robert E. Gieck Jr.*, Douglas L. Kane** and Jean Stein***

Abstract

The hydrology of the interior Alaska uplands near Fairbanks, Alaska is not well known. Previous studies have focused on unpopulated watersheds, such as the Caribou-Poker Creeks Research Watershed and Glenn Creek. Recent water-use conflicts in the Ester Dome area have emphasized the need to study a populated area to help determine the available water resources for industrial, residential, and natural uses.

The Ester Dome area was studied to obtain a water balance for the Ester Creek and Happy Creek watersheds. Precipitation volumes were calculated from isohyetal maps that were constructed from a network of rain gages. Spring snowpack volumes were obtained from snow surveys at each 200-foot elevation zone. Evaporation during the snowmelt period was calculated using evaporation pan data. Runoff quantities were determined by stream gaging and by utilizing data collected at runoff plots. Summer evapotranspiration was estimated from evaporation pan data.

Precipitation distribution, total annual precipitation, streamflow, and evapotranspiration were calculated from these data. Groundwater recharge for the Ester Creek and Happy Creek watersheds was calculated by solving for the groundwater term in the water balance equation.

Introduction

The Ester Dome area west of Fairbanks, Alaska, is an area which has grown rapidly in recent years. Mining has historically played an important role in the area's economy and supported a small community. Recently the area has become a popular location for residential development and has also been identified as a potential site for industrial development. As this development occurs, use of the limited groundwater resources in the area may exceed the recharge capacity of the watershed, especially at higher elevations.

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* Graduate Research Assistant, Institute of Water Resources, University of Alaska, Fairbanks, Alaska 99701

** Associate Professor, Institute of Water Resources, University of Alaska, Fairbanks, Alaska 99701

*** Presently, Assistant Professor, Laval University, School of Forestry, Quebec City, Quebec, Canada G1K 7P4

To determine the groundwater recharge potential of the area a study was carried out during the 1981-1982 and 1982-1983 water years. The Ester Dome area was instrumented to provide data for a water balance in the Ester Creek and Happy Creek watersheds. Precipitation, soil moisture, runoff, and evaporation data were collected to estimate groundwater recharge by solving for the groundwater term of the water balance equation.

This paper is the first attempt at a simple water balance using data that were just collected. A more detailed analysis will be completed after the latest water year's data has been tabulated and reduced.

Related Research

Numerous watershed studies have been carried out in the Fairbanks area. Glenn Creek, a second order stream located 7 miles north of Fairbanks and 13 miles northeast of Ester Dome, has been the site of several related hydrologic studies. The Glenn Creek watershed area is 0.70 square miles. Dingman (1971) estimated a water balance for the stream based on precipitation and runoff data. Kane et al. (1981) studied snowmelt runoff generation using lysimeters. They determined premafrost-free areas of the watershed contributed little to the snowmelt runoff, while areas with permafrost contributed most to surface runoff. A study by Eaton and Wendler (1982) of the snowmelt process was done using an energy balance. They determined 78% of the solar energy was used to evaporate water from the melting snowpack. Chacho and Bredthauer (1983) studied the precipitation-runoff ratios of Glenn Creek and found the watershed had a very fast response time with long recessions and subsurface runoff before overlying organic soils were saturated. They also found little runoff was generated from nonpermafrost areas in the watershed.

In Goldstream Valley to the northeast, Slaughter and Kane (1973) studied the hydrology of a small lake in permafrost terrain. They determined the lake was recharged, at least in part, from below the lake by subpermafrost groundwater. Nearby, Hartman and Carlson (1973) studied a small thaw lake and determined it was isolated from groundwater recharge by permafrost. Stein and Kane (1983) studied groundwater recharge using runoff plots and infiltrometers. They concluded the spring snowmelt season was the principle period for groundwater recharge.

The Caribou-Poker Creeks Research Watershed has been the site of several studies including vegetation (Vogel and Slaughter 1972), precipitation-runoff characteristics (Ford 1973), geology (Koutz and Slaughter 1974), drainage network analysis (Bredthauer and Hoch 1979), and hydrology and climatology (Haugen et al 1982). Lotspeich and Slaughter (1981) studied the watershed on an ecosystem basis, relating the biotic, climatic, and physical aspects of the watershed.

In the Ester area, several hydrologic studies have been done. Barsdate (1967) studied the limnology of Ace lake, near the Lasonsky site in this paper, to determine the concentration of trace elements and aeration of the stratified waters in the lake. Hawkins et al. (1982) studied the geohydrology of the Ester area in terms of the source and distribution of dissolved arsenic in the area's waters. Presently, personnel at the Institute of Water Resources, University of Alaska, are carrying out a groundwater geochemisty study of the Ester Dome area.

Study Area

Ester Dome is located within the Yukon-Tanana Upland of interior Alaska, at latitude 64° 53' north and longitude 148° 02' west. The area lies north of the George Parks Highway and approximately seven miles west of Fairbanks within the Fairbanks Mining District. While much of the area remains undeveloped, several sections have been extensively modified by human activities.

Initial development of the area occurred during the early part of this century with the discovery and subsequent placer and lode mining of gold. Mining has continued to the present time, but the level of activity has varied. More recently, the neighboring communities of College and Fairbanks have grown, and the area has become a popular location for residential development.

Ester Creek and Happy Creek watersheds lie on the south and east slopes of Ester Dome. The residential development and much of the mining development are contained in these two watersheds. The Ester Creek watershed has an area of 10.13 square miles and is adjacent to the 9.65 square mile Happy Creek watershed (see Figures 1 and 2). Both drainage areas were calculated above the location of our stream gaging stations. A large portion of the valley bottom in the Ester Creek watershed is composed of mine tailings. Residential areas lie along Old Nenana Road, in the town of Ester, and on south-facing slopes above Ester. There is little evidence of placer mining in the Happy Creek watershed, but there are several lode mines in the drainage. The residentially developed areas in the Happy Creek watershed lie along the Parks Highway, Old Nenana Road, Henderson Road, Sheep Creek Road, and St. Patrick Creek

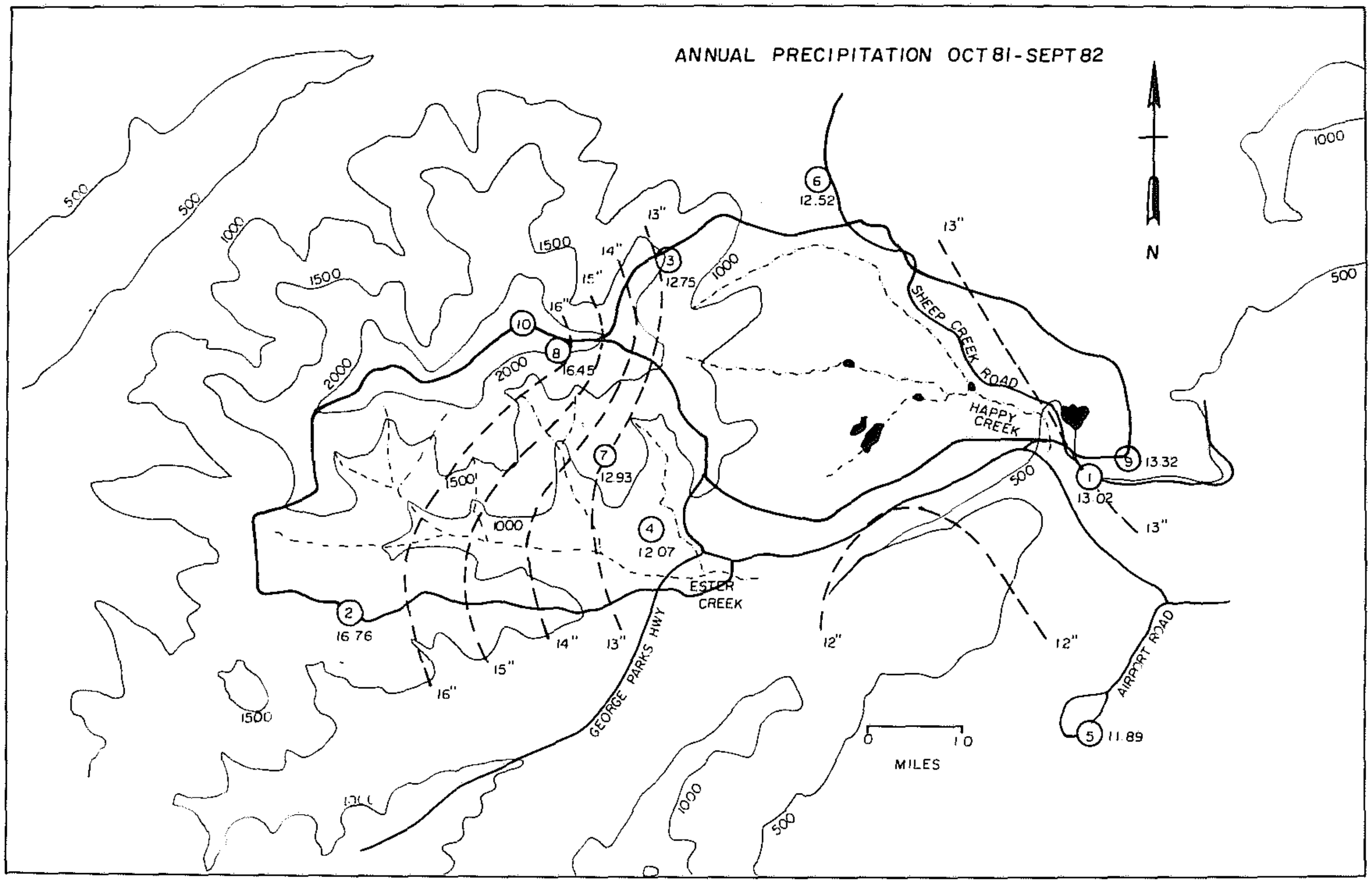

Figure 1. Isohyetal map of Ester Dome area (Oct. 1981 - Sept. 1982).

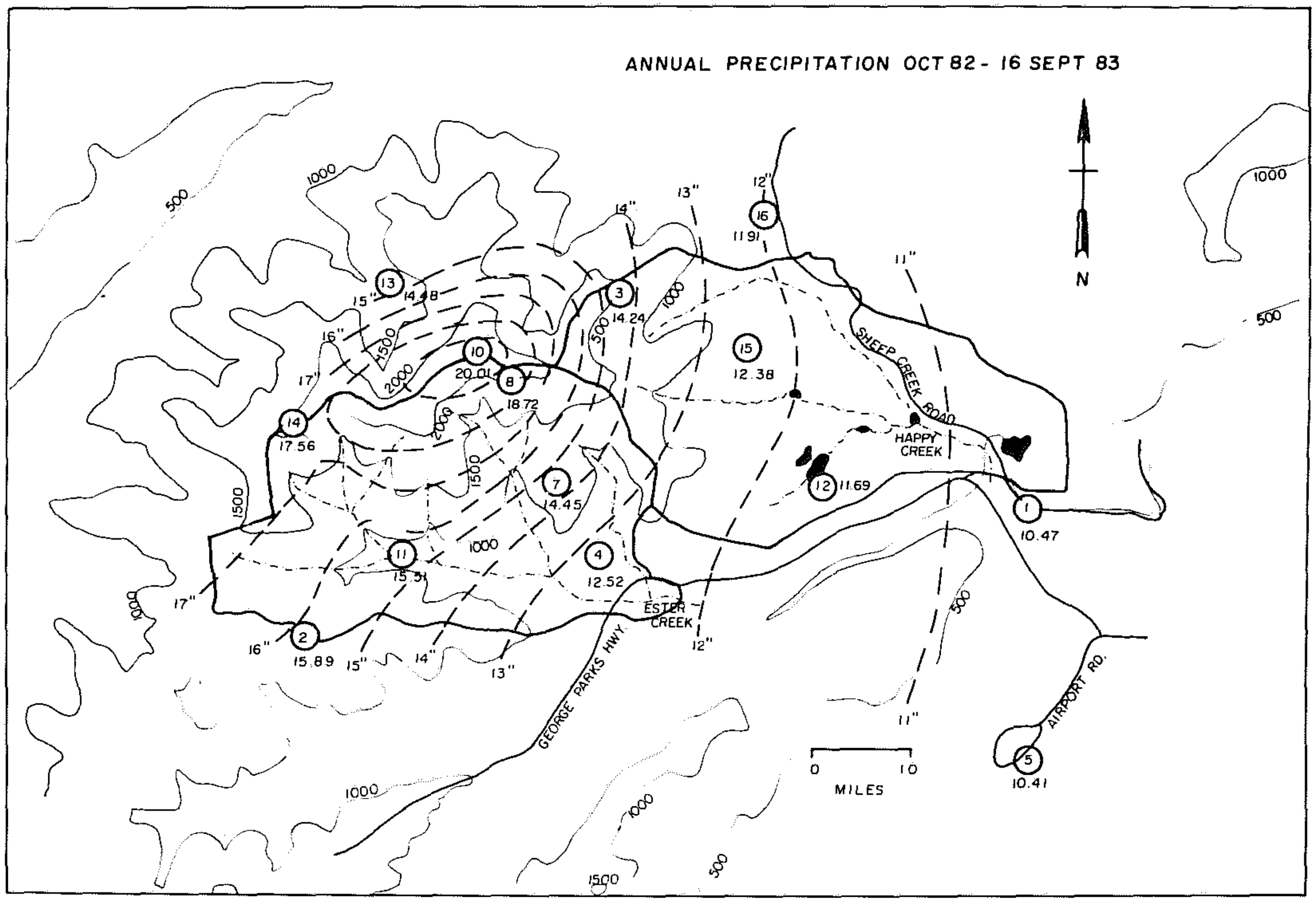

Figure 2. Isohyetal map of Ester Dome area (1Oct. 1982 - 16 Sept. 1983).

Road. There are currently 78 wells in the Happy Creek watershed and 57 wells in the Ester Creek watershed according to the records of the U.S. Geological Survey. Many more unrecorded wells may exist.

Vegetation The vegetation of the area is typical of the Yukon-Tanana Uplands. The well-drained south-facing slopes support forests of Paper Birch (*Betula papyrifera*), White Spruce (*Picea glauca*), and Quaking Aspen (*Populus tremuloides*). The relatively sparse undergrowth consists of shrubs and forbs. The valley bottoms have shallow slopes of poorly drained soils, and the north-facing slopes support forests of Black Spruce (*Picea mariana*), with occasional Paper Birch, Green Alder (*Alnus cripus*), willow (*Salix* spp.), and Larch (*Larix Larecena*). The undergrowth consists of a thick mat of mosses, lichens, tussock grasses, and shrubs.

Geology According to Forbes (1983), the bedrock of Ester Dome is primarily crystalline schists of the Yukon-Tanana metamorphic complex. These metamorphic formations are highly folded and jointed. The schists and associated quartzite lenses have experienced at least three folding events. Ester Dome is at the southwest end of a mineralized belt known as the Fairbanks Mining District. The primary economic phases (gold, lead and zinc sulfides) occur within the mineralized quartzite lenses.

Soils The mineral soils of the area are composed of layers of micaceous loess originating from the glacial outwash plains of the Tanana Valley to the south. Soil thickness varies from a few inches to over 180 feet. Typically, the organic soils of the well-drained, south-facing slopes are well developed (four-inches thick) and overlain by two inches of organic litter. The poorly drained soils of the north-facing or shallow slopes have up to 12 inches of living moss atop 10 inches of slightly decomposed moss and roots. Large areas of mine tailing consisting of coarse rock fragments remain in Ester Creek valley (USDA Soil Conservation Service 1963).

Permafrost Permafrost is absent on the steep, south-facing slopes. Discontinuous permafrost is encountered over much of the valley floor and on north-facing slopes. Well logs of the area show permafrost begins as shallow as two feet and extends to depths beyond 150 feet. Massive ice occurs in the area. Ice wedges were found beneath fields north of the University of Alaska's Agricultural Experiment Station near Smith Lake, and homes along Henderson Road have been damaged due to uneven settling (Pewe 1982).

Climate Ester Dome lies within an area of continental climate characterized by warm summers and winters of severe cold. The extremes of seasonal variation are illustrated by a record high temperature of 99°F and a record low of -66°F which were recorded at the Fairbanks International Airport several miles south of Ester Dome. The average annual temperature at the airport is 26.1°F with an average precipitation of 11.7 inches and an average annual snowfall of 66.6 inches. The duration of daylight also varies seasonally due to the high latitude of the area. There are nearly 22 hours of daylight during the summer solstice and less than four hours of daylight during the winter solstice.

Methods

The water balance equation was used to estimate the groundwater recharge of each basin:

$$P = R + E + S$$

Solving for S,

$$S = P - E - R$$

where

S = change in groundwater storage

P = precipitation

E = evapotranspiration

R = runoff.

The evapotranspiration term includes interception losses. The runoff term represents overland flow, interflow, and baseflow.

During the 1981-1982 water year, eight sites were established in the Ester Dome area to collect precipitation data, data were also obtained for three additional sites from the National Weather Service. These sites were the Agricultural Experiment Station (1), Coutts (2), Ester Dome Road (3), Gedney (4), International Airport (5), Rice (6), Stone (7), Swainbank (8), College Observatory (9), Ester Dome Observatory (10), and Nugget Creek (13) (Figure 1).

The following year four additional sites were added: Quartz (11), Lasonsky (12), Willow Creek (14), and St. Patrick Creek Road (15) (Figure 2). The College Observatory site was not included in the 1983 calculations. Summer precipitation data were obtained using standard eight-inch dipstick and tipping bucket raingages (Table 1).

Snowpack water equivalents were determined at snow courses designated by elevation along the existing road network. Snowpack water equivalents were obtained using an Adirondak sampler and averaging the amount obtained in eight to ten trails at each course. Snowmelt volumes were

TABLE 1. ESTER DOME SUMMER PRECIPITATION (in.)

Site	May	June	1982 July	Aug.	Sept	Total
1. Ag. Stat.	0.68	2.26	3.87	1.83	0.62	9.26
2. Coutts	0.94	2.49	5.05	2.48	1.07	12.03
3. E.D. Road	0.67	2.31	3.03	1.77	0.73	8.51
4. Gedney	0.68	2.25	3.02	1.90	0.78	8.63
5. Int. Arpt.	0.96	1.96	2.33	1.67	0.77	7.69
6. Rice	0.69	2.49	3.11	1.71	0.76	8.76
7. Stone	0.71	2.13	3.38	1.97	0.87	9.06
8. Swainbank	0.84	2.48	4.16	2.37	0.88	10.73
9. Coll. Obs.	0.80	2.19	3.97	1.78	0.82	9.56

Site	May	June	1983 July	Aug.	Sept. 01-16	Total
1. Ag. Stat.	0.09	1.11	0.87	2.87	0.32	5.26
2. Coutts	0.30	1.25	1.64	5.18	0.86	9.23
3. E.D. Road	0.40	1.11	0.89	6.04	1.08	8.44
4. Gedney	0.24	0.84	1.10	4.68	0.59	7.45
5. Int. Arpt.	0.14	0.57	1.71	3.33	0.71	6.46
6. Rice	0.34	1.10	0.73	4.05	0.48	6.70
7. Stone	0.29	1.34	1.02	5.24	0.76	8.65
8. Swainbank	0.48	1.38	1.31	6.44	1.17	10.78
10. E.D. Obs.	0.48	1.36	1.30	6.39	1.13	10.66
11. Quartz	0.33	1.15	1.40	6.64	0.92	10.44
12. Lasonsky	0.24	1.07	0.90	3.73	0.54	6.48
13. Nugget Crk	0.30	0.92	1.00	5.61	1.01	8.84
14. Willow Crk	0.30	1.16	1.41	5.77	0.98	9.62
15. St. Pat.	0.30	1.35	0.77	4.34	0.55	7.31

obtained by applying an average water equivalent to the area of each 200-foot elevation zone (Table 2).

Annual precipitation was obtained by adding the summer precipitation to the average snowpack water equivalent at each site. Precipitation volumes (Table 3) were obtained by plotting isohyetal maps (Figures 1 and 2) and applying the mean of the isohyets to each area within each watershed between the isohyets (Table 3). Reported areas were the mean of three calculations using a 9847A Hewlett Packard digitizer.

TABLE 2. AVERAGE SNOW WATER EQUIVALENT BY ELEVATION.

Elev. Zone (ft)	Water Eq. (in)		Watershed Area (sq mi)	
	4/22/82	4/06/83	Ester	Happy
500-700	3.76	5.21	0.80	5.78
700-900	3.44	5.07	1.45	1.64
900-1100	3.83	5.29	1.72	1.04
1100-1300	3.87	5.64	1.79	0.64
1300-1500	4.24	5.80	1.87	0.27
1500-1700	4.73	6.66	1.00	0.21
1700-1900	5.51	7.84	0.62	0.06
1900-2100	5.72	7.94	0.52	0.01
2100-2364	5.94	9.35	0.36	0.00
			10.13	9.65

TABLE 3. TOTAL PRECIPITATON DURING THE WATER YEAR

SITE	1981 - 1982	1982 - 1983*
1. Ag. Station	13.02	10.47
2. Coutts	16.76	15.89
3. E.D. Road	12.75	14.24
4. Gedney	12.07	12.52
5. Int. Arpt.	11.89	10.41
6. Rice	12.52	11.91
7. Stone	12.93	14.45
8. Swainbank	16.45	18.72
9. Coll. Obs.	13.32	
10. E.D. Obs.		20.01
11. Quartz		15.51
12. Lasonsky		11.69
13. Nugget Crk		14.48
14. Willow Crk		17.56
15. St. Pat		12.38

* Ending September 16th, 1983.

Stream gaging stations were established on Happy Creek where it crosses the Old Nenana Road and on Ester Creek approximately one mile downstream of the George Parks Highway crossing. Discharge measurements were taken using Gurley and pygmy current meters. Runoff volumes were obtained by multiplying the average discharge for each time period by the length of the time period. Additional snowmelt runoff data were collected at two

800-square-foot runoff plots in Goldstream Valley approximately five miles northeast of Ester Dome.

Soil moisture data were collected at the Stone (7) and Gedney (4) sites. Soil moisture data were obtained with tensiometers (Table 4) during the summer of 1982 and by time domain reflectometry during the summer of 1983. Due to the unavailability of an instrument, soil moistures were only obtained for April and May of 1983.

We monitored three unpumped wells on Ester Dome: the Swainbank site (8), and the upper and lower wells at the St. Joseph American Mine on Henderson Road. The depth to the piezometric surface in the wells was measured using an acoustic well probe and by a well tape. The wells were monitored during the 1981-1982 water year by Northern Testing Laboratory for the Alaska Department of Natural Resources.

Evaporation data were collected at the the Ester Dome Observatory (10) using a standard four-foot-diameter by ten-inch-deep evaporation pan. Additional evaporation data were obtained from the Agricultural Experiment Station (1).

Results and Discussion

We divided our study into two distinct intervals, the spring snowmelt period (mid-April to mid-May) and the summer-fall period (mid-May to October 1). Conditions during these periods were substantially different. Winter precipitation was temporarily stored as snow, so it did not affect the water balance until spring snowmelt. The spring snowmelt period is characterized by low evaporation rates, low interception, and high soil moisture. The summer-fall period has high rates of evapotranspiration and interception, and low soil moisture.

The interception losses are lower during the spring snowmelt period because the deciduous canopy is open, lacking its leaves.

TABLE 4. 1982 SOIL MOISTURE

	CENTIBARS OF SUCTION					
	GEDNEY			STONE		
DATE	20 cm*	40 cm*	60 cm*	20 cm*	40 cm*	60 cm*
6/25	22.0	36.0	41.5			
6/28				18.0	15.0	29.0
7/02	39.0	42.0	38.0	22.0	28.0	30.0
7/06	47.0	46.0	49.5	25.0	22.0	35.0
7/13	59.0	52.0	54.0	31.0	28.5	40.0
7/20	69.0	62.0	59.5	32.0	30.0	45.0
7/27	70.0	66.5	64.5	24.0	26.0	47.0
8/03	59.5	70.0	69.5	26.0	24.0	47.5
8/06	55.0	68.0	65.0	34.5	32.0	51.0
8/09	63.0	72.0	64.5			
8/10	66.5	73.5	66.5	42.5	40.5	55.5
8/17	72.0	74.5	57.5	39.0	46.0	59.0
8/24	74.0	76.0	70 +	47.5	48.5	62.5
8/31	74.0	74.5	70 +	40.0	58.0	66.5

* depth of tensiometer's porous cup

Spring Snowmelt Period The 1981-1982 maximum snow pack volume for the Ester Creek watershed was 2,330 acre-feet, and the average snow water equivalent for the watershed was 4.31 inches. The snowpack volume for the Happy Creek watershed was 1,940 acre-feet, and the average snow water equivalent was 3.77 inches. The runoff in Ester Creek and Happy Creek was measured once in 1982 to establish the baseflow.

The Ester Creek snowpack during the 1983 period was equivalent to 3,230 acre feet of water. The average snow water equivalent for the watershed was 6.00 inches. Evaporation following the snow survey and during the time of actual snowmelt to May 12 was 1.16 inches (626 acre-feet). The runoff volume for the snowmelt period, including the falling limb of the hydrograph, was 818 acre-feet. By placing these figures in the water balance equation, we estimated that recharge for the period was 1,790 acre feet. Snowmelt was distributed as 55.3% potential groundwater recharge, 25.3% runoff, and 19.4% as evaporation.

The Happy Creek snowmelt during the period was 2,720 acre-feet. The average snow water equivalent for the watershed was 5.28 inches. The evaporation losses were 626 acre-feet. The runoff volume was 994 acre-feet. The estimated potential groundwater recharge was 1,100 acre-feet. The melt was distributed as 40.5% groundwater recharge, 36.5% runoff, and 30.0% evaporation.

The two runoff plots that we monitored extensively during the snowmelt period are used for comparison. For 1983, the snowpack on the control plot was equivalent to 385 cubic feet of water. Runoff was 125 cubic feet (Figure 3), and evaporation was 77.3 cubic feet. The estimated groundwater recharge was 183 cubic feet. The control plot snowmelt was distributed as 47.5% potential groundwater recharge, 32.4% runoff, and

20.1% evaporation. The snowpack on the east plot was equivalent to 323 cubic feet of water. Runoff was 78.7 cubic feet (Figure 3), and evaporation was 77.3 cubic feet. The estimated groundwater recharge was 171 cubic feet. Snowmelt from the east plot was distributed as 53.3% potential groundwater recharge, 24.1% runoff, and 23.6% evaporation. The snowmelt ended on April 28 at the east plot and on April 29 at the control plot. Peak runoff occurred on April 23 at both plots (Figure 4).

The lower groundwater recharge estimate and higher runoff percentage in the Happy Creek basin may be a result of reduced infiltration rates in the watershed. The Happy Creek watershed is dominated by relatively low terrain compared to Ester Creek, and contains more permafrost which could reduce the infiltration capacity. The Ester Creek watershed is dominated by relatively steep south-facing slopes and mine tailings which are well drained and have little or no permafrost.

Note that this water balance represents a single year of data, and soil moisture conditions vary from year to year. The soils were dry in the fall of 1982. Had the soils been wet when they froze, the infiltration rates could have been much lower for the nonpermafrost soils, and the groundwater recharge could have been much less.

Summer-fall Period The summer-fall period is one of showery light precipitation and high potential evapotranspiration. Significant groundwater recharge only occurs when the surface soils have moderately high levels of soil moisture. Evapotranspiration by plants uses much of the soil water. Groundwater does move in the vadose (unsaturated) zone of soils along pressure gradients, but the volumes are small compared to saturated flow. Following a precipitation event of short duration, any

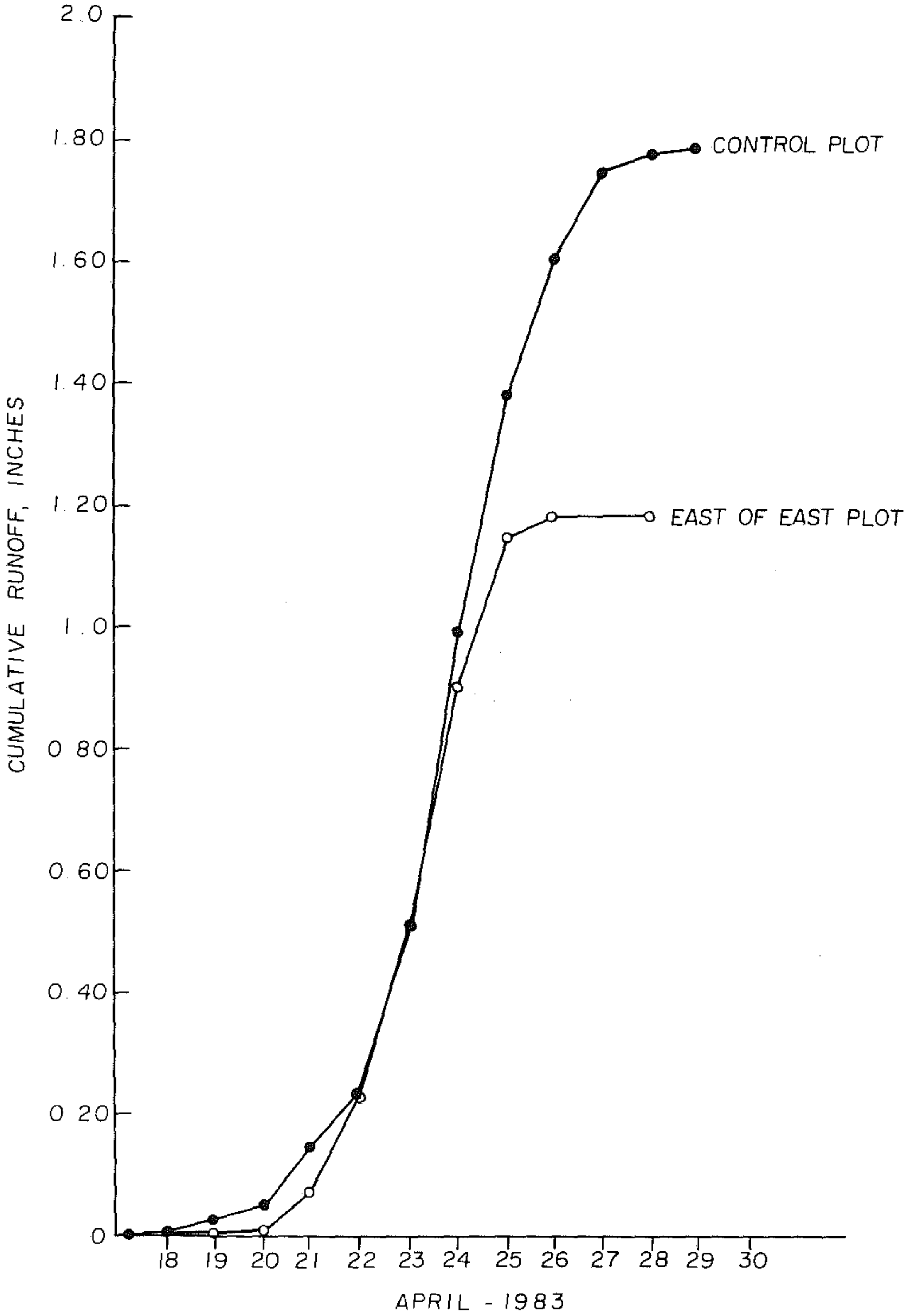

Figure 3. Cumulative runoff for the two runoff plots.

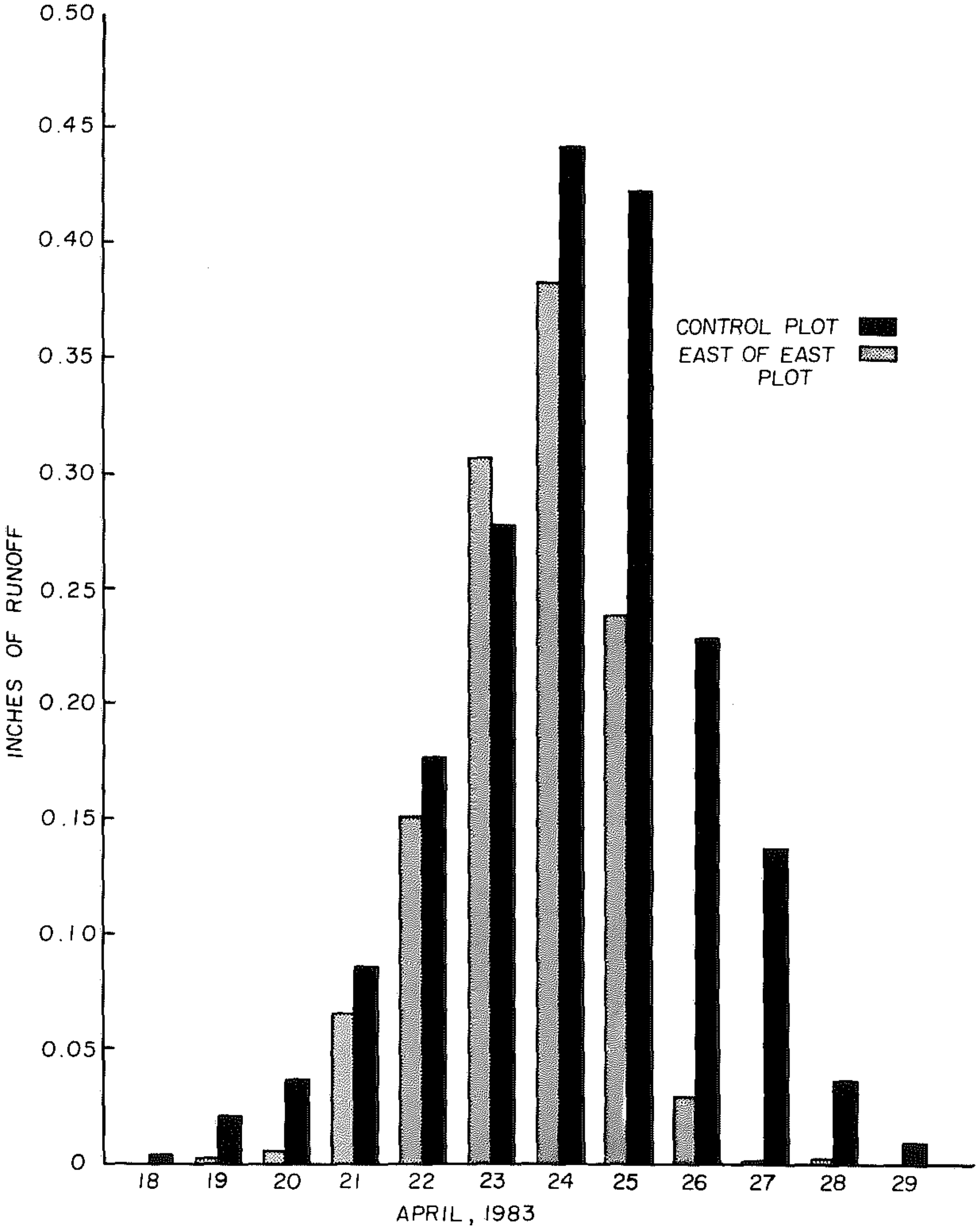

Figure 4. Daily runoff increments for the two runoff plots.

water infiltrating into the soil is quickly lost to the atmosphere (unless it migrates past the rooting zone). The soil moisture data tend to indicate that most soil water is lost by evapotranspiration (Table 4). Soil moisture levels decreased throughout the summer of 1982 as indicated by increasing soil tensions.

The pan evaporation was higher in 1983 than in 1982 at the Agricultural Experiment Station (Figure 5). The total pan evaporation for the period of June 1 to September 15 was 12.03 inches for 1982 and 14.64 inches for 1983. Precipitation in 1982 was more evenly distributed. Average ambient air temperatures in June and July of 1983 were above normal. The monthly average ambient temperatures for Fairbanks, as reported by the National Weather Service, in June and July of 1983 were 3.0°F and 2.7°F above normal respectively. During the summer of 1982, the monthly averages were 0.5°F below normal for June and 1.2°F above normal for July. During both years, less pan evaporation was recorded at the Ester Dome site (Figure 6). From July 8 to September 14, 1982, 5.55 inches were recorded at Ester Dome versus 6.09 inches at the Agricultural Experiment Station. From June 7 to September 15, 1983, 10.41 inches evaporation were recorded at Ester Dome versus 13.61 inches at the Agricultural Experiment Station. For these time periods, Ester Dome pan evaporation was 8.9% lower in 1982 and 26.0% lower in 1983.

Well data (Figures 7 and 8) showed no large responses to precipitation events, with the exception of the Swainbank well. This site showed a response to precipitation in late August 1981 and 1983; no data were available for August 1982. Evaporation rates were also lower during August of both years (Figures 5 and 6). The precipitation from August 20 to September 1, 1983, was 5.15 inches at the Swainbank site. One

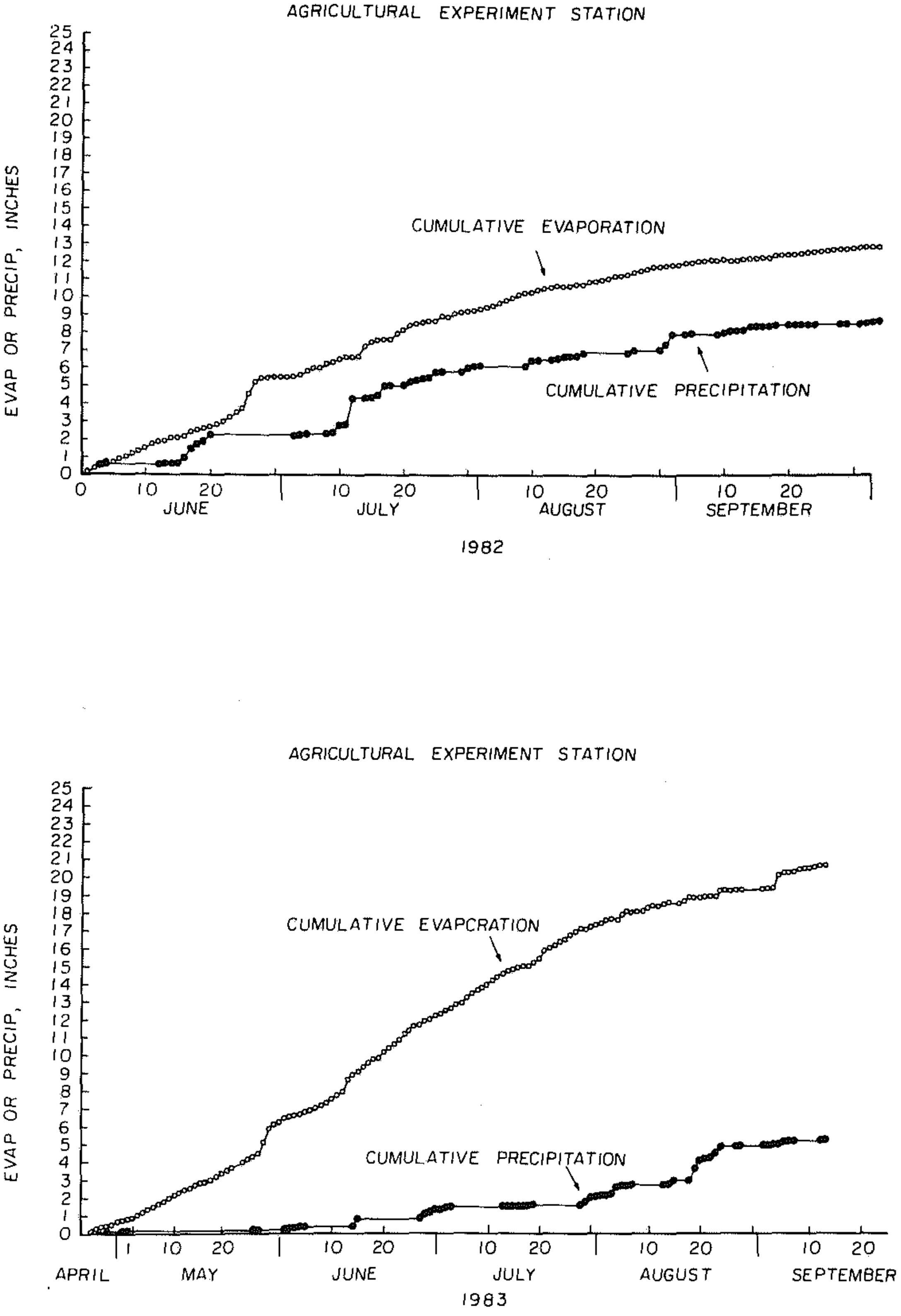

Figure 5. Cummulative evaporation and precipitation at the Agricultural Experiment Station (1982 and 1983).

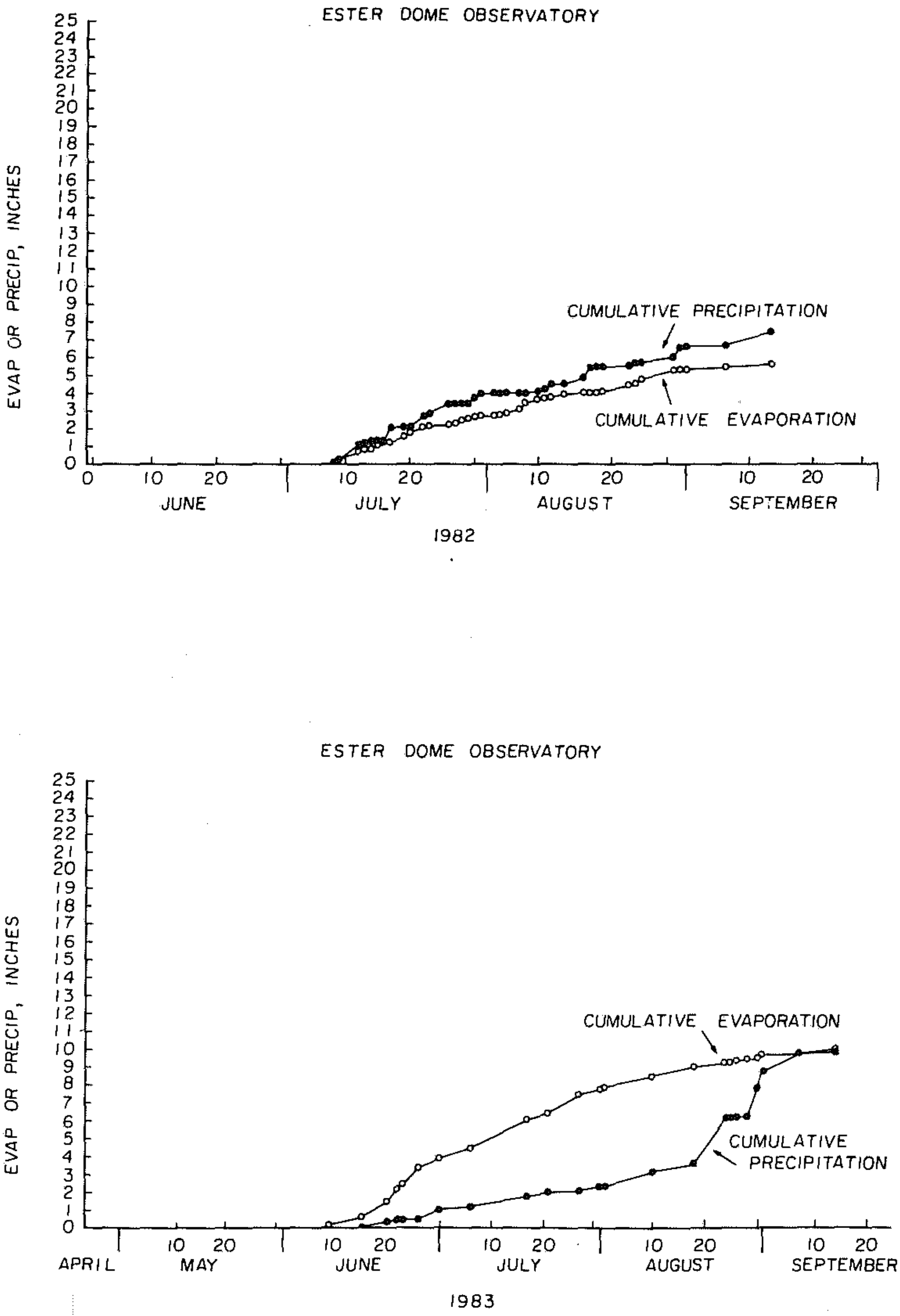

Figure 6. Cummulative evaporation and precipitation at Ester Dome Obsrvatory (1982 - 16 September 1983).

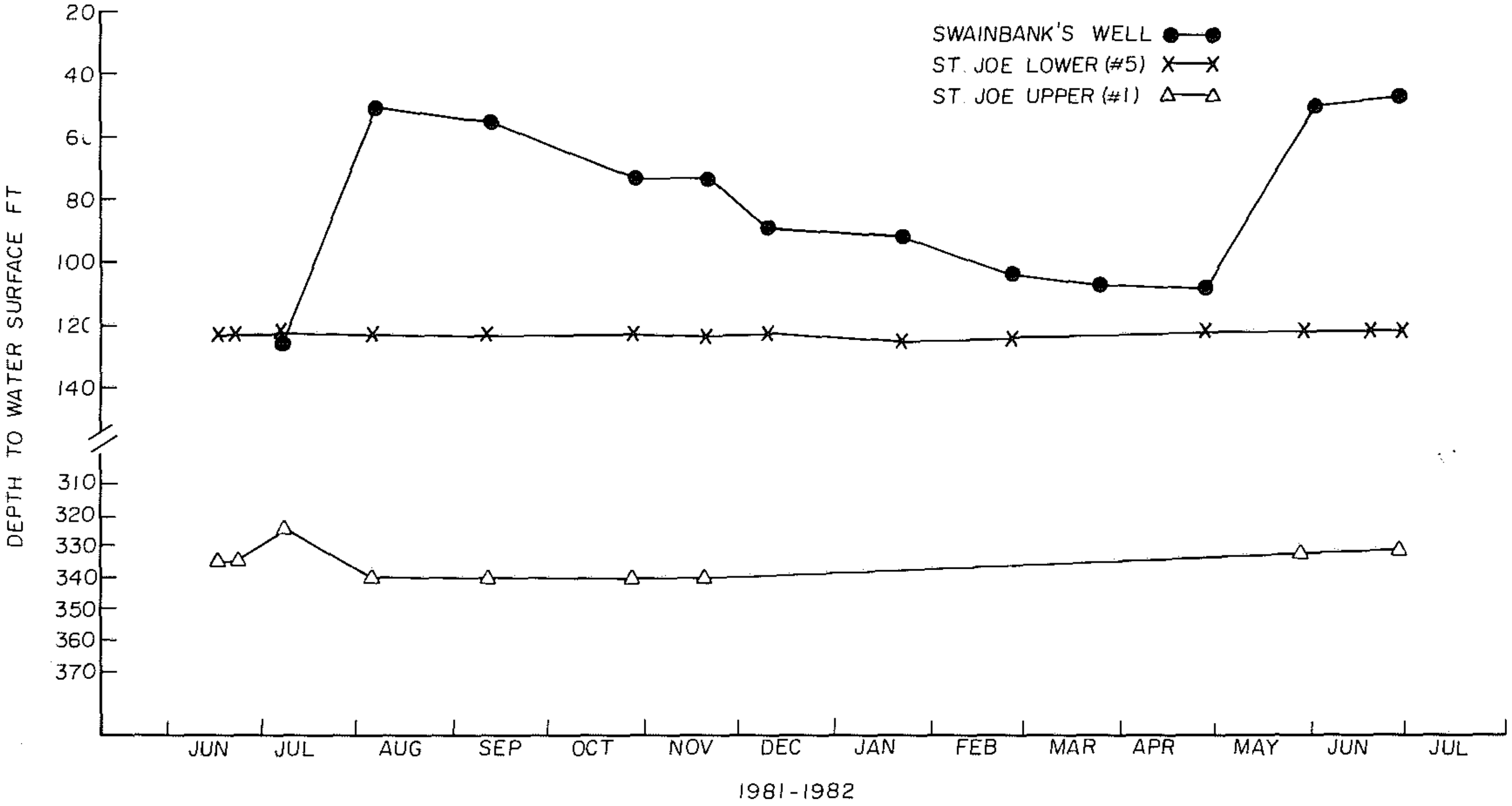

Figure 7. Well level fluctuations for 1981 and 1982 (data collected by Northern Testing Laboratories, Inc.).

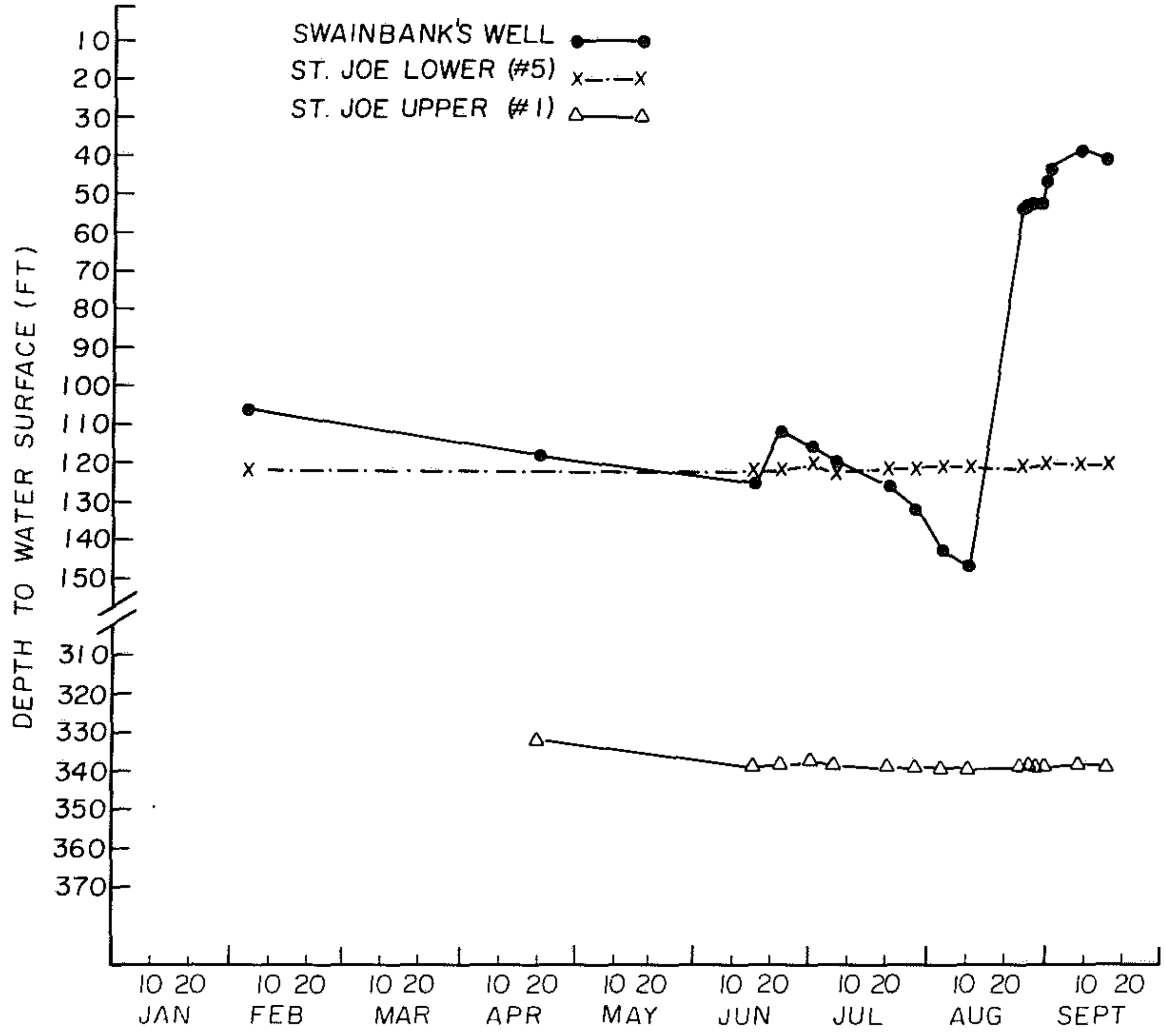

Figure 8. Well level fluctuations for 1983.

precipitation event beginning on August 20 lasted 28 hours and accounted for 1.88 inches of precipitation. This event seemed to initiate the 97-foot rise in the well between August 19 and 25. The well continued to rise slowly until September 9, when it attained a level of 39 feet. The other wells, located at lower elevations, showed little response over the period even though the precipitation amounts were similar to those at the Swainbank site. Unfortunately, there are no well logs available for these three unpumped wells.

During the period that the Swainbank well rose dramatically, increases in streamflow at both creeks were also noted (Figure 9). It should be pointed out that this was the only significant rise in the flow rates, except during the snowmelt period.

Potential groundwater recharge during this period was estimated by assuming the soils were relatively dry. Dry soil has pore space which can store water. Kane et al. (1978) reports that the porosity of a Fairbanks silt loam is 50% by volume. They also report that a dry Fairbanks silt loam is approximately 12% moisture by volume, leaving fillable porosity of 38% by volume (equal to 3.04 inches of precipitation in the eight-inch deep rooting zone). The precipitation remaining after interception and evapotranspiration losses is free to move through the soil to the water table. Water in deeper soils is not directly affected by transpiration.

The average pan evaporation for the two sites was 0.54 inches. Assuming the pan coefficient is between 0.7 and 0.85 for the Ester Dome area, the evapotranspiration was between 0.38 and 0.46 inches during this period.

Average precipitation in the Ester Creek and Happy Creek watersheds was 4.36 and 4.06 inches, respectively, during this period. Dingman (1971) estimated interception was 22% by deciduous forests and 38% by coniferous forests in the Glenn Creek watershed. We used the 22% interception factor in the Ester Creek watershed since it is dominated by deciduous forest and the 38% interception factor in the Happy Creek watershed since it is dominated by coniferous forest. After interception and evapotranspiration losses were subtracted, precipitation was between 2.9 to 3.0 inches for Ester Creek watershed, and between 2.0 to 2.1 inches for Happy Creek watershed. On the basis of average watershed infiltration, there was not sufficient precipitation to saturate the upper soils. Much of the soil water stored in the rooting zone would be lost as evapotranspiration.

These crude estimates would suggest that recharge from rainfall would be minimal. However, watershed conditions are never average. For example, higher elevation vegetation is sparse, soil cover thinner, more precipitation falls and bedrock is closer to the surface. This may account for the response of the Swainbank well, and apparent lack of response at the lower wells. The Swainbank site received more precipitation (5.15 inches).

The 1983 summer base flow for Ester Creek ranged between 1.0 and 3.0 cfs, and remained fairly constant from mid-May through late July. Our estimate of base flow for Ester Creek from mid-May to mid-September was 570.0 acre-feet. The base flow for Happy Creek declined gradually from 3.08 cfs on May 12 to a minimum of 0.028 cfs on July 14 (Figure 9), when the flow rate began to rise reaching 3.15 cfs on September 9. Our estimate of base flow for Happy Creek from mid-May to mid-September was

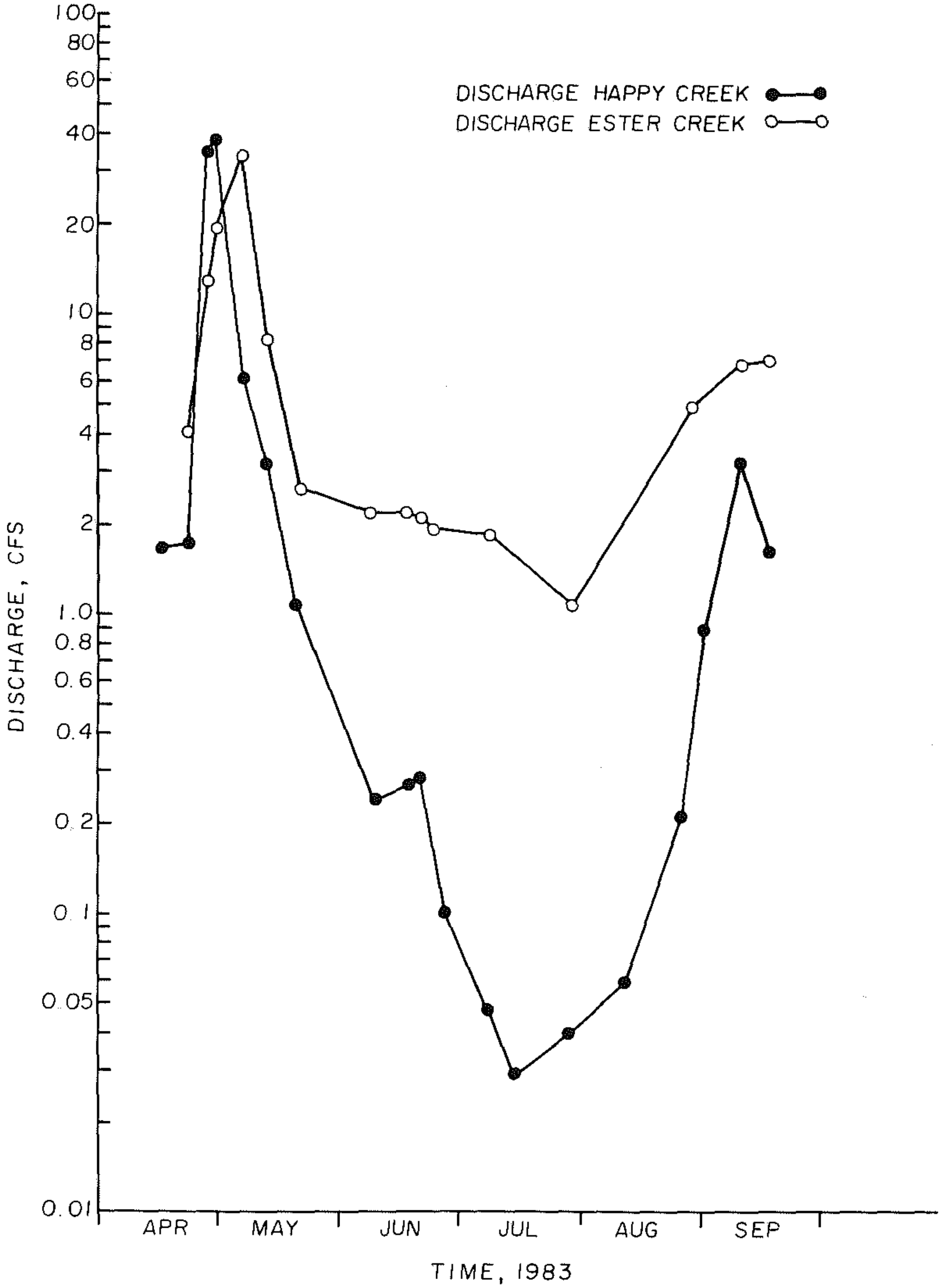

Figure 9. Variations in streamflow for Happy and Ester Creeks, 1983.

85.2 acre-feet. Precipitation from late April through mid-July was light over the entire area and extremely light at lower elevations. The extremely low flows in Happy Creek may be due to the relatively low boggy terrain and permafrost. The limnological study of Ace Lake by Barsdate (1967) discusses the anaerobic conditions of the deep water in the lake. This may be due to groundwater entering the lake from beneath the permafrost. The upper reaches of Happy Creek and its tributaries above the lakes were observed flowing only during the spring snowmelt period and after the extended August precipitation period. In a study of a similar lake in permafrost terrain, Kane and Slaughter (1973) showed water moved upward through the thawed sediments beneath the lake and into the lake. This recharge of the lake water can only occur if permafrost does not exist beneath the lake. In a small thaw lake near Ester Dome, Hartman and Carlson (1973) found that the lake was isolated from the groundwater table and recharged by spring snowmelt. Groundwater flow and subsequent recharge of Ace Lake, which is over 26-feet deep and covers 14 acres, and other similar lakes in the watershed is probably the source of the Happy Creek base flow.

Annual Relationships Average annual precipitation for Ester Creek watershed was 14.95 inches during the 1981-82 water year which is equivalent to 8,070 acre-feet. Average annual precipitation for the Happy Creek watershed was 12.67 inches equivalent to 6,520 acre-feet. The precipitation fell as 72% rain and 28% snow in the Ester Creek watershed, and as 70% rain and 30% snow in the Happy Creek watershed. Average annual precipitation for the Ester Creek watershed during the 1982-1983 water year was 17.14 inches, equivalent to 9,260 acre-feet. Average annual precipitation for the Happy Creek watershed was

12.14 inches, equivalent to 6248 acre-feet. The annual precipitation fell as 60% rain and 40% snow in the Ester Creek watershed, and as 56% rain and 44% snow in the Happy Creek watershed.

Conclusions

High evapotranspiration rates and light showery precipitation that occur in eastern interior Alaska prevent nearly all of the summer precipitation from infiltrating to the water table and providing any groundwater recharge. Only long-duration, high-volume summer precipitation events (such as the one in late August of 1983) saturate the soil to sufficient depth to provide some recharge. Therefore, the significant period for groundwater recharge is the spring snowmelt season, when a large volume of water is steadily released and evapotranspiration rates are low. During the snowmelt period of 1983, 40% to 55% of the snowpack water equivalent infiltrated to provide potential recharge to the groundwater. Some additional groundwater recharge may have occured in late August, but probably only at higher elevations.

Acknowlegments

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References

Barsdate, R. J. 1967. Pathways of Trace Elements in Arctic Lake Ecosystems. Annual Progress Report to the U.S. Atomic Energy. Contract No. AT(04-3)310PA4.

Bredthauer, S. R., and D. Hoch. 1978. Drainage network analysis of a subarctic watershed. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire. Special Report 129.

Chacho, E. F., and S. R. Bredthauer. 1983. Runoff from a small subarctic watershed, Alaska. Proceedings: Fourth International Conference on Permafrost, Fairbanks, Alaska. (in press).

Dingman, S. L. 1971. Hydrology of the Glenn Creek Watershed, Tanana River basin, central Alaska. U.S. Army Cold Regions Research and Engineering Laboratory. Research Report 297.

Eaton, F. and Wendler. 1982. The heat balance during the snow melt season for a permafrost watershed in interior Alaska. Arch. Met. Geoph. Biokl. Ser.A(31) pp 19-33.

Forbes, R. B. 1982. Bedrock geology and petrology of the Fairbanks Mining District, Alaska. Alaska Department of Natural Reources, Division of Geological and Geophysical Surveys. Open-file Report 169.

Ford, T. R. 1973. Precipitation-runoff characteristics of the Caribou Creek Research Watershed, near Fairbanks, Alaska. University of Alaska, Fairbanks. MS Thesis.

Hartman, C. W. and R. F. Carlson. 1973. Water balance of a small lake in a permafrost region. University of Alaska, Institute of Water Resoures Report 42.

Hawkins, D. B., R. B. Forbes, C. I. Hok, and D. Dinkle. 1982. Arenic in the water, soil, bedrock and plants of the Ester Dome area of Alaska. University of Alaska, Institute of Water Resources Report 103.

Haugen, R. K., C. W. Slaughter, K. E. Howe, and S. L. Dingman. 1982. Hydrolgy and climatology of the Caribou-Poker Creeks Research Watershed, Alaska. U.S. Army, Cold Regions Research and Engineering Laboratory Report 82-26.

Kane, D. L., R. D. Seifert, and G. S. Taylor. 1978. Hydrologic properties of subarctic organic soils. University of Alaska, Institute of Water Resources Report 88.

Kane, D. L., S. R. Bredthauer, and J. Stein. 1981. Subarctic snowmelt runoff generation. T. S. Vinson, ed. The Northern Community: A Search For a Quality Environment. American Society of Civil Engineers, New York. pp 591-601.

Kane, D. L., and J. Stein. 1983. Physics of snowmelt into seasonally frozen soils. Proceedings: Advances in Infiltraion, American Society of Agricultural Engineers (in press).

Koutz, F. R., and C. W. Slaughter. 1972. Geologic setting of the Caribou-Poker Creeks Reseaerch Watershed, interior Alaska. U.S. Army Cold Regions Research and Engineering Labroratory. Technical Note.

Lotspeich, F. B. and C. W. Slaughter. 1981. Preliminary results on the structure and functioning of a taiga watershed. , University of Alaska, Institute of Water Resources Report 101.

Pewe, T. L. 1982. Geologic Hazards of the Fairbanks Area, Alaska. State of Alaska Department of Natural Resources, Division of Geological and Geophysical Surveys. Special Report 15.

Slaughter, C. W.,and D. L. Kane. 1973. Recharge of a central Alaska lake by subpermafrost groundwater. Permafrost. Proceedings of the 2nd International Conference, Yakutsk, U.S.S.R., National Academy of Sciences. pP 458-462.

U.S. Department of Agriculture, Soil Conservation Service. 1963. Soil survey Fairbanks area, Alaska, Series 159, No. 25. U.S. Government Printing Office, Washington, D.C.

Vogel, T. C., and C. W. Slaughter. 1972. A preliminary vegetation map of the Caribou-Poker Creek Research Watershed, interior Alaska. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire. Technical Note.

DATA GENERATED FROM ALASKAN HYDROPOWER DEVELOPMENT

By Stephen R. Bredthauer[1], Jeffrey H. Coffin[2],
and Eric A. Marchegiani[3]

Abstract

Hydroelectric development in Alaska is usually hampered by lack of an adequate data base. This has often been the case for the numerous hydropower studies being conducted by the Alaska Power Authority. Significant efforts have been expended in each project to obtain the required information. This has led to the creation of a water resources data base previously unavailable for much of Alaska. This report summarizes the data base developed by the Power Authority.

Most hydroelectric projects have required basic data on basin hydrology, climatology and geology. Instream flow studies have required data on seasonal variation in fisheries populations and streamflow, stream temperature and sediment transport regimes. In addition, local groundwater, water quality and river and lake ice conditions have been documented. The influence of glacial melt on basin water yield, reservoir thermal regimes and sediment regimes have also been investigated. The availability of these data has contributed to the knowledge of hydrologic processes influencing hydroelectric development in Alaska.

Introduction

The Alaska Power Authority was established by the 1976 state legislature as a public corporation of the State of Alaska. The stated purpose of the Power Authority is to identify, evaluate, and develop electrical power generation facilities, using the most appropriate commercial technologies

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1. Chief, Hydrology Department, R&M Consultants, Inc., Anchorage, Alaska.
2. Senior Civil Engineer, R&M Consultants, Inc., Anchorage, Alaska.
3. Project Manager, Alaska Power Authority, Anchorage, Alaska.

(except for nuclear). With this purpose in mind, the Power Authority has identified as its goal the development of Alaska's energy resources in a manner that strengthens and diversifies the economy and improves the standard of living. This is to be accomplished by providing energy and capacity at the lowest reasonable economic, social, and environmental costs, with emphasis on energy from renewable and local resources.

The Power Authority's purpose and goal require that a variety of electrical technologies be evaluated. These include diesel or gas turbine, waste heat, wood waste, geothermal, coal, wind, and hydroelectric generation. Each type of generation requires certain data collection programs, but the successful development of hydroelectric projects is perhaps the most dependent upon an adequate water resources data base. The importance of water resources data collection for hydroelectric development has required the Power Authority to invest significant funds in the water resources field.

This emerging water resources data base is the emphasis of this paper. The paper will illustrate and describe a matrix of projects and data types. Detailed studies have been conducted at some projects to better understand the interaction of the project with the natural environment. These are briefly described in the section on special studies. The paper also describes available reports, by project, and where the reports may be located.

Description of Matrix

The location of each hydroelectric project site investigated by the Alaska Power Authority is illustrated in Figure 1. The numbers on the map relate to the numbers with the projects in the matrix in Table 1, and Table 1 shows the types of water resources field data that have been collected at each project site. Not all sites investigated by the Power Authority have been entered in the matrix. Projects which have only had reconnaissance-level studies to date (October 1983), and thus have had no or minimal field data collection efforts, have not been included. All other projects are noted, however, including a few where most of the field data were collected by agencies other than the Power Authority (such as the Army Corps of Engineers or local electric utilities).

Each of the thirteen field parameters in the matrix is briefly described below. Also discussed are the columns defining the projects' names, locations, capacity and status.

1. Project Name - The name of the project, as used by the Alaska Power Authority (though abbreviated in some cases). In the regional studies, primary emphasis was placed on a few specific sites, as follows:

    Bethel Area Power Plan Feasibility Assessment (Chikuminuk Lake)
    Bristol Bay Regional Power Plan (Newhalen River, Tazimina River)
    Cordova Power Supply (Silver Lake, Power Creek, Allison Lake)

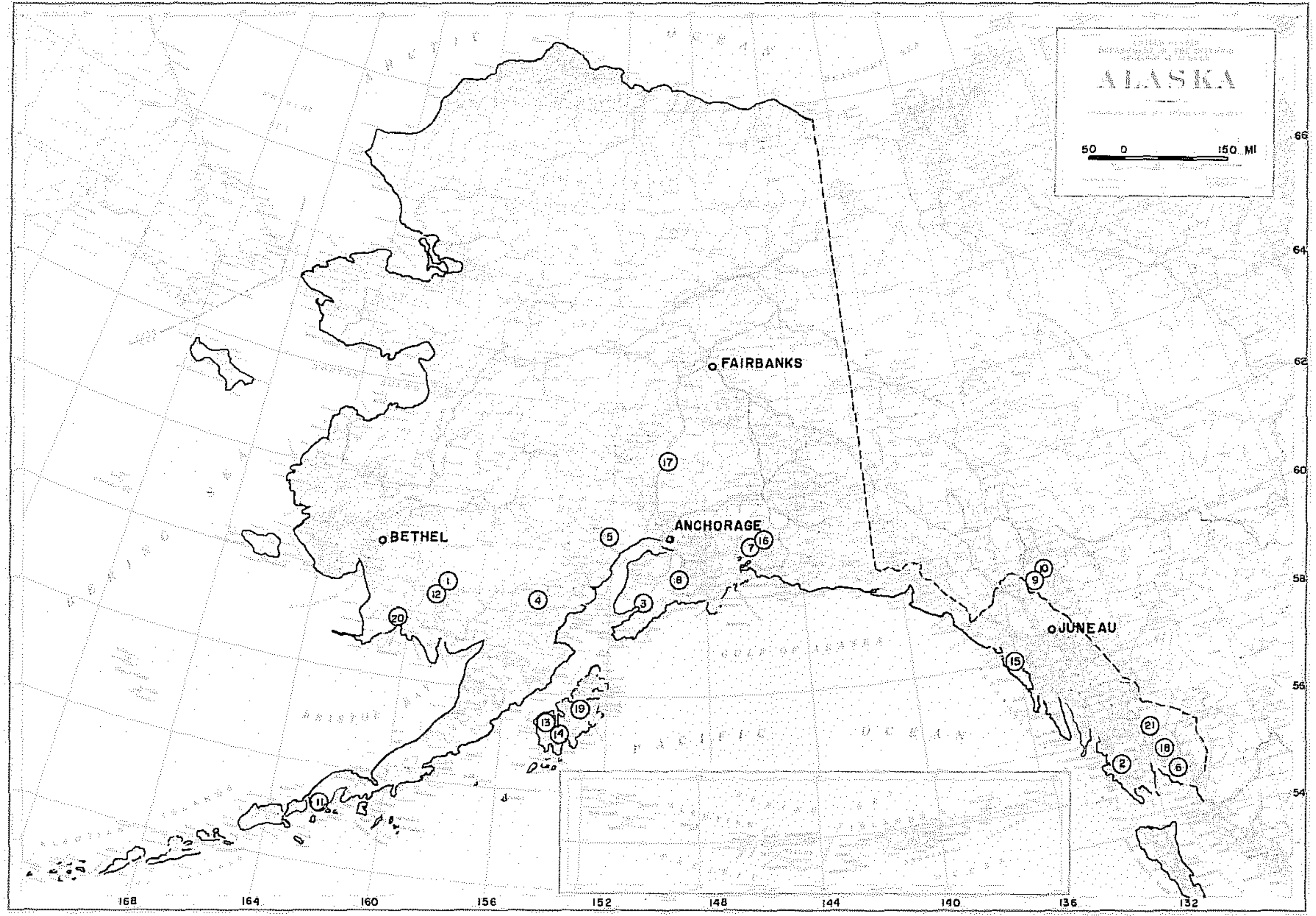

FIGURE 1

HYDROELECTRIC PROJECT LOCATION MAP

TABLE 1
WATER RESOURCES DATA COLLECTED AT ALASKA POWER AUTHORITY HYDROELECTRIC PROJECTS

PROJECT NAME	Latitude	Longitude	Power Capacity (MW)	Project Status	Glacier	Snow	Meteorological	Streamflow	Water Quality	Water Temperature	Sediment	Limnology	Bathymetric Data	River X-Sections	Ice	Fisheries	Photogrammetry
1. Bethel Region	60°13'	158°45'	9.5-24	IF					X			X				X	
2. Black Bear	55°33'	132°52'	3-6	L				X	X	X		X	X			X	
3. Bradley Lake	59°47'	150°55'	60-135	F	X	X	X	X	X	X	X	X	X	X	X	X	X
4. Bristol Bay Region	59°43'	154°53'	1.2-16	IF			X	X	X	X		X				X	
5. Chakachamna	61°12'	152°35'	330	IF	X			X	X	X		X	X			X	
6. Chester Lake	55°07'	131°31'	2.5	F									X				
7. Cordova Power Supply	60°57'	146°29'	15	IF			X	X	X	X		X	X	X		X	
8. Grant Lake	60°29'	149°18'	7	F		X	X	X	X	X		X	X		X	X	
9. Haines/Skagway-Dayebas	59°17'	135°21'	2.5	R				X								X	
10. Haines/Skagway - West Creek	59°27'	135°18'	6	F				X	X		X					X	
11. King Cove	55°03'	162°19'	0.6	F				X	X							X	
12. Lake Elva	59°38'	159°09'	1.5	F				X	X			X				X	
13. Larsen Bay	57°32'	153°58'	0.3	F				X	X							X	
14. Old Harbor	57°12'	153°18'	0.3	F				X	X							X	
15. Pelican	57°57'	136°13'	0.8	F			X										
16. Solomon Gulch	61°02'	146°17'	12	O				X	X				X				
17. Susitna	62°45'	149°41'	1620	L	X	X	X	X	X	X	X	X	X	X	X	X	X
18. Swan Lake	55°37'	131°17'	22	C				X				X	X			X	
19. Terror Lake	57°38'	153°00'	20	C		X	X	X	X	X	X	X	X	X		X	
20. Ingiak	59°04'	160°24'	0.4	R				X	X							X	
21. Tyee Lake	56°11'	131°28'	20	C				X	X	X	X	X	X			X	

NOTES:

Refer to text for explanation of parameters.
Matrix current as of October 1983.

2. Latitude - Approximate north latitude in degrees and minutes, at the primary lake or site where much of the data collection has been concentrated (e.g. Chikuminuk Lake for the Bethel Regional Study, Newhalen River for the Bristol Bay Study, Silver Lake for the Cordova Power Supply Study, and the Susitna River at Gold Creek for the Susitna Project).

3. Longitude - Approximate west longitude in degrees and minutes, at the same point as in Item 2.

4. Power Capacity (MW) - Approximate size of the project, in megawatts. Size given is the one recommended or is a range for projects proposed to be built in phases. In regional studies, the capacity for several alternatives is specified.

5. Project Status - Current status of the project. The most recent data reports may have been completed under this phase or under the prior phase. The project phases, with the codes used to identify them in the matrix, are as follows:

   R = reconnaissance study
   IF = interim feasibility assessment
   F = feasibility study
   L = license (FERC) applied for
   C = construction
   O = operation

6. Glacier - In-depth study of and data collection on glaciers in the drainage basin.

7. Snow - Systematic snow surveys of depth and water content, conducted in the basin supplying the project. Conducted on a monthly basis either by or for the U.S. Soil Conservation Service. Data are reported monthly from February to June in the "Snow Surveys and Water Supply Outlook for Alaska" series (SCS, annual).

8. Meteorological - Climatic data (air temperature, wind speed and direction, and precipitation) that have been collected specifically for the project or are unpublished, systematic data collected in the immediate vicinity (e.g. G.O. Balding report for Pelican [Balding, 1974]). NOAA data are readily available in agency publications. Since they have not been collected specifically for hydroelectric projects, they have not been considered in the matrix.

9. Streamflow - Continuous streamflow records collected for and at the project. Collected and reported by U.S. Geological Survey and/or by a private contractor. U.S.G.S. data are reported annually in the "Water Resources Data for Alaska" series (U.S.G.S., annual).

10. Water Quality - Data collected on stream water quality. Noted in matrix if one or more measurements were made of any parameters besides temperature (e.g. King Cove, Larson Bay, Old Harbor, and Togiak each have data for one date only).

11. Water Temperature - Continuous records of stream temperature, collected either by U.S.G.S., by another agency, or by a private contractor.

12. Sediment - Stream sediment data collected for analysis related to sediment deposition in the project reservoir. Bedload and suspended sediment data have also been collected for the Susitna project for analysis of downstream impacts.

10. Limnology - Data-collection and analysis of lake characteristics and processes, generally as related to project operation or environmental impacts. Data are for water quality parameters on an existing lake in the project or on an off-project lake studied as an analogy (e.g. Eklutna Lake as an analogy to Watana Reservoir in the Susitna project).

14. Bathymetric Data (Lake) - Lake-depth data collected for development of an area-capacity curve - reported in the matrix if such a curve is available. Old (1950's) U.S.G.S. plan-and-profile maps of potential project sites have also been considered.

15. River X-Sections - Cross-sections surveyed through a significant reach of river for hydraulic modeling purposes. Does not include local surveys made at damsites or other sites strictly for design purposes.

16. Ice - Collection of field data on river or lake ice conditions and processes, but only if collected systematically and if analyzed to some extent (i.e. not considered if only random measurements of ice thickness were made).

17. Fisheries - Data collection on anadromous species, resident species, and habitat characteristics in river or lake environments.

18. Photogrammetry - Aerial photography taken for water-resource studies, such as for measurement of wetted areas in sloughs or changes in glaciers. Does not include photography made strictly for topographic mapping.

Special Studies

A few of the parameters have received special attention in several Power Authority projects. These four areas of study (glaciers, limnology, ice and instream flow) and the projects which addressed them are explained in greater detail in this section.

Glacier Studies - Many of the proposed hydroelectric developments in southeast and south-central Alaska are located on glaciated basins. Glaciers significantly alter the timing of the hydrologic cycle in a basin, storing water as glacier ice during cool, wet years, and releasing water from glacial melt during dry years. This characteristic dampens the annual variations in summer streamflow.

Water resource engineers must recognize this shift in streamflow when analyzing the economic feasibility of a project.

The impact of glaciers on the water supply of a project is most evident where long-term discharge records exist. If the glaciers in the basin significantly receded during the streamflow period of record, additional flow from glacial melt is being recorded. Conversely, if the glaciers have been expanding, the gage would be recording less flow than normal. The flow frequencies estimated from streamflow records could change significantly if the glaciers' hydrologic regime were to shift due to a climate change. A project could be oversized or undersized due to these shifts.

Glaciers may have several other significant impacts on hydroelectric development. Lakes either on the glacier, or else behind a glacier blocking a tributary, may suddenly break out, causing the equivalent of a dam-break flood. Glacier surges may form lakes where none previously existed. Glaciers also contribute a large amount of sediment to the stream. The volume and size distribution of the sediment affect both the economic life of the project and the environmental conditions in the reservoir and downstream. Finally, the glaciers have a significant role in the operation of the project, providing a steady water supply under conditions which may cause drought in non-glacierized basins.

Reconnaissance-level studies have been conducted for the Susitna and Bradley Lake projects. Photogrammetric techniques were used to obtain rough estimates of long-term mass balance changes in some of the glaciers in both basins, and estimates were made of the impacts on water supply. Mass balance studies have been initiated at both projects. A reconnaissance of the Susitna basin was also conducted to determine the presence of glacial lakes with potential for significant outburst floods. In addition, investigations and observations have been made by the U.S.G.S. of the terminal zone of Barrier Glacier at the outlet of Chakachamna Lake (Giles, 1967).

Limnology Studies - As the matrix indicates, many of Alaska's hydroelectric projects have had limnological data collection and analysis. The level of effort has varied considerably from project to project. In most cases, data have been collected to identify baseline water quality conditions in existing lakes. In a few of the projects, fisheries in the lakes were also well-documented (Black Bear and Chakachamna). Numerous minnow traps were used in Terror Lake to search for resident fish, but none were found. Horizontal and vertical plankton tows were also made in Terror Lake.

An exception to the general rule of mere baseline data collection, however, was the Susitna Project. There is not an existing lake which will be part of the Susitna Project, but detailed observations were made of an off-project lake (Eklutna), in order to calibrate a numerical model of lake processes. The model (DYRESM) (Imberger and Patterson, 1981) is currently being used to analyze project effects on temperature in the reservoir and in the river downstream. Field data collected included vertical profiles of temperature, turbidity, conductivity, and light extinction at several stations on the lake. Data were collected at least monthly through the open-water season for two consecutive summers. Occasional lake samples were also analyzed for concentration and size of suspended sediment. Additional data collected on a continuous basis were meteorological conditions at the lake, streamflow into the lake from two major tributaries, and water temperature of the two tributaries.

In the studies where data were collected to document baseline conditions, measurements most commonly made were profiles of temperature. Dissolved oxygen, pH, nutrients, and other water quality parameters were also commonly measured. Spatial intensity was usually limited to one or sometimes two sites on the lake. Frequency of measurement varied widely in intensity: seasonal profiles were obtained in Black Bear Lake, Bradley Lake, and Grant Lake; monthly summer profiles were obtained in Tyee Lake; winter and summer profiles were measured in Chakachamna Lake and in Cordova (Silver Lake); and single summer profiles were observed in the Bristol Bay (Sixmile and Tazimina Lakes), Lake Elva, and Swan Lake projects.

Ice Studies - Construction of a hydroelectric power project on a northern river significantly alters the winter flow and thermal regimes of the river, subsequently modifying the rivers ice regime. Flows higher than the normal winter flows are released in winter to meet the high power demands. These flows will generally have temperatures of 2°-4°C. The combination of higher temperatures and large volumes of water creates a large heat mass which must be dissipated before ice formation can again occur downstream of a dam. In addition, the dam and reservoir block the downstream flow of ice formed in the upstream stretches of the river.

Intensive field studies have been conducted on the Susitna River to document freeze-up and breakup processes, to document the environmental impacts of these processes, and to provide data for mathematical modeling of the pre- and post-project ice conditions.

Ice formation on lakes and reservoirs is also important, both from engineering and environmental viewpoints. Forces exerted on structures during freeze-up may be significant. Frazil ice may cause blockage of intake structures. Reservoir drawdown during the winter may affect wildlife migration. Ice cover formation influences the reservoir temperature. Data are being collected at Eklutna Lake to calibrate the DYRESM reservoir temperature model in support of the Susitna studies. This model is being modified to include ice cover formation. Limited ice data have also been collected at Grant Lake and Bradley Lake.

Instream Flow Studies - The objective of completing an instream flow study is to determine the relationship between different discharges and the effects on various instream uses and resources. The natural conditions of streams fluctuate due to rainfall events and also due to seasonal effects such as snowmelt. A reservoir system has the effect of attenuating the wide fluctuations of natural flow so that a hydroelectric development could enhance certain aspects of the fishery resource, depending upon its operation. The completion of an instream flow analysis is the means of determing the options available and the ramifications of each of the options.

There are a numbers of methods (Wesche & Rechard, 1980) which might be employed to complete an insteam flow analysis. A few of the more commonly used methods are the Montana Method (Tennant, 1975 & 1976), the Oregon Method (Thompson, 1972 & 1974), and the Instream Flow Incremental Methodology (IFIM) (Bovee, 1982). Each of these methods has its own limitations and assumptions and must be applied with the appropriate judgment. The various methods are tools for evaluating the potential changes in the natural flow regime. A specific method may not always be applicable to a particular situation. Therefore, the best utilization of a method may be to either combine it with another method, or else to modify one method such that it will provide better information concerning any proposed changes to the flow regime.

The level of a particular study influences the type of instream flow methodology selected to evaluate the potential changes in flow regime. The instream flow study could be divided into two levels. Level 1 might be considered as a reconnaissance instream flow study, while Level 2 would be a comprehensive instream flow study.

The Level 1 study would determine if the project is feasible from a biological perspective. This analysis would insure that there were no unacceptable environmental conditions which would preclude development of a project. Generally, the data requirements would be seasonal flow, temperatures, and use of habitats by various species, along with some assessment of channel stability.

The Level 2 study would be a detailed instream flow analysis which would include impact evaluations and mitigation measures. The analysis would provide a biological perspective which would be utilized in the development of the project design and operation. A large amount of site-specific data would be needed in order to complete this analysis. These data would include reach-specific hydraulics, water quality, water temperature, and sediment transport, along with the necessary fishery data. A Level 2 analysis would produce a document with a delineation of pre- and post-project, reach-specific conditions which would enable one to define impacts and develop the necessary mitigation plans.

A good example of a reconnaissance level (Phase 1) study was completed in conjunction with the Bristol Bay Regional Study (Baldrige and Trihey, 1982). The analysis completed on the Terror Lake Hydroelectric Project (Wilson et al, 1981) is a good example of a Phase 2 analysis. These analyses are on two completely separate projects, which enables one to view two different local conditions and review the approaches. The Power Authority is presently pursuing a Phase 2 type analysis on the Bradley Lake Hydroelectric Project through its contractors. This study is underway, and results should be available within three months. The largest Phase 2 analysis being conducted is the one for the Susitna Project. Many of the available water resource papers listed for Susitna were written in support of the instream flow studies. These studies are in progress, and results will be available in the future.

Availability of Data

The availability of different types of data is directly related to the level of the study being conducted, as was discussed above in Instream Flow Studies. The Power Authority generally has two study levels: reconnaissance studies and detailed feasibility studies. On occasion, the Power Authority also completes an interim feasibility assessment which is an analysis between the reconnaissance study and a detailed feasibility study. At the reconnaissance level, many alternative sites are being reviewed, and it would not be cost effective to collect detailed data on all sites. Instead, office studies are conducted with a limited amount of field work being completed on the best alternatives. The detailed feasibility level involves an intensive field data collection program with detailed analysis of the data. Therefore, the level of detail for field data collection in a reconnaissance study is substantially less than that compiled for a detailed feasibility study.

Once a reconnaissance study or a detailed feasibility study has been finalized, the Power Authority submits twenty copies of the report to the state library in Juneau, Alaska. Individuals or libraries interested in borrowing Alaska State publications should contact their nearest depository library. Additional inquiries or difficulties in obtaining publications should be referred to the Alaska State Publications Distribution Center, Alaska State Library, Pouch G, Juneau, Alaska 99811 (907 465-2942).

The following is a list of the twenty depository libraries.

Alaska State Library,
Juneau, Alaska

Alaska Historical Library,
Juneau, Alaska

University of Alaska Library,
Juneau, Alaska

Sheldon Jackson College Library,
Sitka, Alaska

Ketchikan Public Library,
Ketchikan, Alaska

Z.J. Loussac Public Library,
Anchorage, Alaska

Alaska Resources Library,
Anchorage, Alaska

University of Alaska Library,
Anchorage, Alaska

Kenai Community Library,
Kenai, Alaska

A. Holmes Johnson Public Library,
Kodiak, Alaska

Noel Wien Memorial Library
Fairbanks, Alaska

University of Alaska
Rasmusson Library, Fairbanks

Kegoayah Kozga Public Library,
Nome, Alaska

Kuskokwim Consortium Library,
Bethel, Alaska

Seattle Public Library,
Seattle, Washington

University of Washington Library,
Seattle, Washington

Washington State Library,
Olympia, Washington

Center for Research Libraries,
Chicago, Illinois

Library of Congress,
Washington, D.C.

National Library of Canada,
Ottawa, Ontario

In addition to this distribution list, there are a number of other places where one can locate information generated by the Power Authority. The Power Authority deposits two copies of all final reports in its own library (334 West 5th Avenue, Anchorage). The project manager will usually deposit additional copies of reports in a local library near the project if it is not on the Alaska State Library depository list. The primary contractor for the project might also have additional data which have not been published. The Power Authority also funds data collection efforts in conjunction with hydroelectric projects through cooperative agreements with the U.S. Geological Survey (USGS). The majority of this data is published in their water supply papers on an annual basis. The same type of arrangement exists with the U.S. Soil Conservation Service (SCS). The SCS collects snowpack data which is published for the months of February through June on an annual basis.

It should be noted that the Alaska Power Authority has become involved with a number of projects which were initiated by other entities. These projects have been transferred to the Power Authority due to its ability to finance large hydroelectric projects. Specifically, these projects are Solomon Gulch, Terror Lake, Swan Lake, Susitna, and Bradley Lake. Most of the project reports containing these data are available in the Power Authority library.

Summary

The purpose of this paper has been to present a consolidated list of the types of water resources data available from hydroelectric projects undertaken by the Alaska Power Authority. Since the data, in general, are widely scattered and difficult to locate, it was felt that such a summary would be beneficial to describe the availability and locations of the data for engineers, scientists, and planners working in the water resources field.

The matrix of projects and parameters in Table 1 indicates that project data from the field have primarily been collected to determine water availability (streamflow) and conditions related to instream flow. Most projects have addressed water quality and fisheries on at least a preliminary basis to identify baseline conditions in existing streams and lakes. The number of parameters measured (and which ones) gives an indication of the level of detail of the instream flow study.

Review of the existing data base is an important part of the management process of deciding what additional data collection is required. This step is necessary, whether the concern of a project is feasibility assessment, impact assessment, project design, or project operation. It is hoped that this presentation will assist in the process of reviewing previous studies in a particular geographic area and will facilitate decision-making relative to water resources development in Alaska.

Available Reports

This section has been prepared on a project-by-project basis to compile specific reports in which hydrologic data are available. The project name is listed first, followed by the name of the prime contractor in parentheses. Reports in which field data are reported are then listed. Additional supporting references can be found in the bibliographies of these reports.

Bethel Region (Harza Engineering)

Harza Engineering. 1982. Bethel Area Power Plan Feasibility Assessment, Regional Report, App. B, D.

Black Bear Lake (Harza Engineering)

Federal Energy Regulatory Commission. 1983. Black Bear Lake, Project No. 5714, Draft Environmental Impact Statement.

Harza Engineering. 1981. Application for License before the Federal Energy Regulatory Commission, Black Bear Lake Hydroelectric Project on Prince of Wales Island, Alaska.

__________. 1979. Black Bear Lake Project, A Reconnaissance Report.

Black Bear Lake (Harza Engineering/CH_2M Hill Northwest)

Bishop, Daniel M. 1982. "Late Summer and Fall Observation in Upper Black Bear Creek and Black Bear Lake." Environaid.

Environaid. 1982. Biological-Ecological Investigations on the Black Bear Creek System near Klawock, Alaska. Environaid. Juneau, Alaska. Prepared for Alaska Power Authority.

Harza Engineering Company and CH_2M Hill Northwest. 1981. "Black Bear Lake Project Feasibility Report, Volume 2, Appendices."

Bradley Lake (Stone & Webster)

Colonell, J.M. 1980. Circulation and Dispersion of Bradley River Water in Upper Kachemak Bay. Woodward-Clyde Consultants. Prepared for U.S. Army Corps of Engineers, Alaska District.

Gatto, L.W. 1981. Ice Distribution and Winter Surface Circulation Patterns, Kachemak Bay, Alaska. U.S. Army Cold Regions Research & Engineering Laboratory, Hanover, N.H.

Gosink, J.P. and T.E. Osterkamp. 1981. A Theoretical Investigation of the Potential Modification of Ice Formation in Kachemak Bay by the Bradley Lake Hydroelectric Project. U.S. Army Cold Regions Research & Engineering Laboratory, Hanover, N.H.

Stone & Webster. 1983. Interim Report on Feasibility Evaluation for Bradley Lake Hydroelectric Project.

U.S. Army Corps of Engineers, Alaska District. 1981. Bradley Lake Hydroelectric Project, Design Memorandum. No. 1 - Hydrology.

__________. 1982. Bradley Lake Hydroelectric Project, Alaska. Final Environmental Impact Statement.

Bristol Bay Region (Stone & Webster)

Stone & Webster. 1982. Bristol Bay Regional Power Plan, Detailed Feasibility Analysis, Interim Feasibility Assessment, Volumes 1-4.

Baldrige, J.E. and E.W. Trihey. 1982. Potential Effects of Two Alternative Hydroelectric Developments on the Fishery Resources of the Lower Tazimina River, Alaska. AEIDC, in cooperation with Dames & Moore.

Chakachamna (Bechtel Civil and Minerals, Inc.)

Bechtel. 1983. Chakachamna Hydroelectric Project, Interim Feasibility Assessment Report, Volumes I-IV.

Bechtel/Woodward-Clyde Consultants. 1982. A Summary of Fish Passage Facility Design Concepts and Preliminary Results of FY 1982-83 Fish Studies.

Chester Lake (Harza Engineering)

Harza Engineering. 1982. Chester Lake Project Feasibility Report.

Cordova Power Supply (Stone & Webster)

Stone & Webster. 1982. Cordova Power Supply, Interim Feasibility Assessment, Vols. 1-2.

__________. 1982. Cordova Power Supply, Interim Feasibility Assessment, Technical Data, June 1982.

__________. 1982. Cordova Power Supply, Interim Feasibility Assessment, Addendum I.

__________. 1982. Cordova Power Supply, Silver Lake Hydroelectric Site, Field Data Collection, April - October 1982.

__________. 1982. Draft Environmental Field Study Plan. 1983-1984. Silver Lake Alternative, Cordova Power Supply Feasibility Analysis: Phase II, March 1983.

Grant Lake (Ebasco Services, Incorporated)

Alaska Department of Fish and Game. 1981. Grant Lake Survey (unpublished, on file at Alaska Department of Fish and Game, Soldotna, Alaska).

Arctic Environmental Information and Data Center. 1982. Summary of Environmental Knowledge of the Proposed Grant Lake Hydroelectric Project Area.

Ebasco Services, Inc. 1983. Grant Lake Hydroelectric Project, Detailed Feasibility Analysis, Vol. 1 & 2 - (1981). Grant Lake Hydroelectric Project, Interim Report.

R&M Consultants, Inc. 1982. Grant Lake Hydrological Data Report (unpublished).

Haines/Skagway - Dayebas (R.W. Beck & Associates)

R.W. Beck and Associates. 1981. Addendum to Reconnaissance Report on Alternatives for the Haines-Skagway Region.

Haines/Skagway - West Creek (R.W. Beck & Associates)

R.W. Beck and Associates. 1982. Haines-Skagway Region Feasibility Study, Volumes 1-3.

King Cove (DOWL Engineers)

DOWL Engineers. 1982. Volume B, Final Report, Feasibility Study for King Cove Hydroelectric Project.

__________. 1983. Feasibility Study for King Cove Hydroelectric Project, Supplemental Data Report: Hydrology.

Lake Elva (R.W. Beck & Associates)

R.W. Beck & Associates, Inc. 1981. Lake Elva Project, Detailed Feasibility Analysis, Volume 1 - Report.

__________. 1981. Lake Elva Project, Detailed Feasibility Analysis, Volume 2 - Appendices.

Lake Elva (Robert W. Retherford Associates)

Robert W. Retherford Associates. 1980. Reconnaissance Study of the Lake Elva and other Hydroelectric Power Potentials in the Dillingham Area.

Larsen Bay (DOWL Engineers)

DOWL Engineers. 1982. Volume D, Report, Feasibility Study for Larsen Bay Hydroelectric Project.

__________. 1983. Feasibility Study for Larsen Bay Hydroelectric Project, Supplemental Data Report: Hydrology.

Old Harbor (DOWL Engineers)

DOWL Engineers. 1982. Volume C, Final Report, Feasibility Study for Old Harbor Hydroelectric Project.

__________. 1983. Feasibility Study for Old Harbor Hydroelectric Project, Supplemental Data Report: Hydrology.

Pelican (USKH - Engineering Science)

Balding, G.O. 1974. Water Reconnaissance Study of Pelican, Alaska. U.S. Geological Survey.

USKH - Engineering Science. 1982. Pelican Power Alternatives, Phase I - Reconnaissance Assessment.

__________. 1983a. Pelican Power Alternatives, Phase II - Feasibility Study.

Solomon Gulch (Robert W. Retherford Associates)

Robert W. Retherford Associates. 1974 - Revised 1976. Exhibit - W, Environmental Report for Solomon Gulch Hydroelectric Project, FPC Project No. 2742. Prepared for Copper Valley Electric Association, Inc.

Federal Power Commission - Bureau of Power. 1977. Solomon Gulch Project/No. 2742 - Alaska, Draft Environmental Impact Statement.

Susitna (Acres American, 1980-1983; Harza Ebasco, 1983)

Acres American, Inc. 1982a. Susitna Hydroelectric Project, Feasibility Report. Final Draft. Volumes II, IV. Alaska Power Authority, Anchorage, Alaska.

__________. 1982b. Susitna Hydroelectric Project: Fish and Wildlife Mitigation Policy. Alaska Power Authority. Anchorage, Alaska. 11pp.

__________. 1983a. Application for License before the Federal Energy Regulatory Commission, Susitna Hydroelectric Project, Alaska.

__________. 1983b. Slough Hydrogeology Report. Draft.

Alaska Department of Fish and Game. 1972. Cook Inlet King Salmon Status Report. Alaska Department of Fish and Game. Juneau, Alaska.

__________. 1974. An Assessment of Anadromous Fish Populations in the Upper Susitna River Watershed between Devil Canyon and the Chulitna River. Alaska Department of Fish and Game. Anchorage, Alaska.

__________. 1976. Fish and Wildlife Studies Related to the Corps of Engineers Devil Canyon, Watana Reservoir Hydroelectric Project. Alaska Department of Fish and Game. Alaska.

__________. 1977. Preauthorization Assessment of the Proposed Susitna Hydroelectric Projects: Preliminary Investigations of Water Quality and Aquatic Species Composition. Alaska.

__________. 1978. Preliminary Environmental Assessment of Hydroelectric Development on the Susitna River. Alaska Department of Fish and Game. Alaska. Prepared for U.S. Fish and Wildlife Service.

__________. 1980a. Inventory and Cataloging of Sport Fish Waters of the Lower Susitna River and Central Cook Inlet Drainages. Alaska Department of Fish and Game. Anchorage, Alaska.

__________. 1980b. Inventory and Cataloging of the Sport Fish and Sport Fish Waters in the Upper Cook Inlet. Alaska Department of Fish and Game. Anchorage, Alaska.

__________. 1981a. Adult Anadromous Phase 1 Final Species/Subject Report. Susitna Hydro Aquatic Studies. Alaska Department of Fish and Game. Anchorage, Alaska.

__________. 1981b. Phase 1 Final Draft Report Adult Anadromous Fisheries Project. Susitna Hydro Aquatic Studies. 1981. Alaska Department of Fish and Game. Anchorage, Alaska. Prepared for Alaska Power Authority.

__________. 1981c. Phase 1 Final Draft Report Aquatic Habitat and Instream Flow Project. Volume I. Alaska Department of Fish and Game. Alaska. Prepared for Acres American, Incorporated.

__________. 1981d. Phase 1 Final Draft Report Juvenile Anadromous Fish Study on the Lower Susitna River. Susitna Hydro Aquatic Studies. 1981. Alaska Department of Fish and Game. Alaska. Prepared for Acres American, Incorporated.

__________. 1981e. Phase 1 Final Draft Report Resident Fish Investigation on the Lower Susitna River. Susitna Hydro Aquatic Studies. 1981. Alaska Department of Fish and Game. Alaska. Prepared for Acres American, Incorporated.

__________. 1981f. Phase 1 Final Draft Report Resident Fish Investigation on the Upper Susitna River. Susitna Hydro Aquatic Studies. Alaska Department of Fish and Game. Alaska. Prepared for Acres American, Incorporated.

__________. 1982a. Phase 1 Final Draft Report Aquatic Studies Program. Susitna Hydro Aquatic Studies. Alaska Department of Fish and Game. Alaska. Prepared for Acres American, Incorporated.

__________. 1982b. Phase 1 Final Draft Stock Separation Feasibility Report Adult Anadromous Fisheries Project. Susitna Hydro Aquatic Studies. Alaska Department of Fish and Game. Alaska. Prepared for Alaska Power Authority.

__________. 1983. Phase II Final Report, Susitna Hydro Aquatic Studies, Volumes 1-5. Prepared for Alaska Power Authority.

Arctic Environmental Information and Data Center. 1982. Periodicity Chart for the Susitna River Salmon. Blueline. Prepared for Alaska Power Authority, Anchorage, Alaska.

_________. 1983. Effects of the Proposed Susitna Hydroelectric Project on Fishery Resources in the Susitna River Basin - Demonstration Impact Analysis. Draft Report. Submitted to Harza-Ebasco Susitna Joint Venture.

Atkinson, S.C. 1982. Susitna Intergravel Temperature Report. Draft Report. University of Alaska, Arctic Environmental Information and Data Center. Anchorage, Alaska. Prepared for Acres American, Incorporated.

Barrett, Bruce M. 1974. An Assessment Study of the Anadromous Fish Populations in the Upper Susitna River Watershed between Devil Canyon and the Chulitna River: Alaska Department of Fish and Game, Division of Commercial Fisheries, 56pp.

__________. 1975a. December Investigations on the Upper Susitna River Watershed Between Devil Canyon and Chulitna River. Alaska Department of Fish and Game. Unpublished.

__________. 1975b. January Investigations in the Upper Susitna River Watershed Between Devil Canyon and Chulitna River. Alaska Department of Fish and Game. Unpublished.

__________. 1975c. February Investigations in the Upper Susitna River Watershed Between Devil Canyon and Chulitna River. Alaska Department of Fish and Game. Unpublished.

Bilello, Michael A. 1980. A Winter Environmental Data Survey of the Drainage Basin of the Upper Susitna River, Alaska: CRREL Special Report 80-19, 30 pp.

Bishop, Dan. 1974. A Hydrologic Reconnaissance of the Susitna River Below Devil's Canyon: for NOAA, U.S. Department of Commerce, 69 pp.

Cole, Terrence. 1979. The History of the Use of the Upper Susitna River: Indian River to the Headwaters. July 1979.

Friese, Nancy V. 1975. Pre-Authorization Assessment of Anadromous Fish Populations of the Upper Susitna River Watershed in the Vicinity of the Proposed Devil Canyon Hydroelectric Project: Alaska Department of Fish and Game, Division of Commercial Fisheries, 121 pp.

Gatto, L.W., C.J. Merry, H.L. McKim, and D.E. Lawson. 1980. Environmental Analysis of the Upper Susitna River Basin Using Landsat Imagery. U.S. Army Corps of Engineers CRREL, Report 80-4.

R&M Consultants, Inc., 1981a. Hydrographic Surveys. (2nd Report, 1982). Prepared for Acres American, Incorporated.

__________. 1981b. Ice Observations 1980-1981. (Subsequent Annual Reports: 1981-82, 1982-83). Prepared for Acres American, Incorporated.

__________. 1981c. Preliminary Channel Geometry, Velocity, and Water Level Data for the Susitna River at Devil Canyon. April. Prepared for Acres American, Incorporated.

__________. 1981d. Processed Climatic Data Volumes 1 - 8. Annual Reports for 6 Stations 1980-81; and for 8 Stations. 1982. Prepared for Acres American, Incorporated.

__________. 1981e. Regional Flood Studies, December. Prepared for Acres American, Incorporated.

__________. 1981f. Susitna River Mile Index: Mouth to Susitna Glacier. December. Prepared for Acres American, Incorporated.

__________. 1981g. Water Quality Annual Report 1980. (Subsequent Annual Reports 1981, 1982). Prepared for Acres American, Incorporated.

__________. 1982a. Field Data Collection and Processing Volumes 1-3. (Supplement 1, 1982. Data). Prepared for Acres American, Incorporated.

__________. 1982b. Reservoir Evaporation. January. Prepared for Acres American, Incorporated.

__________. 1982c. Reservoir Sedimentation. January. Prepared for Acres American, Incorporated.

__________. 1982d. River Morphology. January. Prepared for Acres American, Incorporated.

__________. 1982e. Tributary Stability Analysis. Prepared for Acres American, Incorporated.

__________. 1982f. Water Quality Interpretation 1981. February. Prepared for Acres American, Incorporated.

__________. 1983a. Field Data Index. (updated annually). Prepared for Acres American, Incorporated.

__________. 1983b. Glacial Lake Studies Interim Report. Prepared for Acres American, Incorporated.

R&M Consultants, Inc. and Acres American, Inc. 1982. Hydraulic and Ice Studies. March.

R&M Consultants, Inc. and W.D. Harrison, 1981. Glacier Studies. (2nd Report, 1982). Prepared for Acres American, Incorporated.

R&M Consultants, Inc. and L.A. Peterson and Associates, 1982. Water Quality Effects Resulting From Impoundment of the Susitna River. December. Prepared for Acres American, Incorporated.

Riis, James C. 1975. Pre-Authorization Assessment of the Susitna River Hydroelectric Projects: Preliminary Evaluation of Water Quality and Aquatic Species Compositions: Alaska Department of Fish & Game, Sport Fish Division, 61 pp.

__________. 1977. Pre-authorization Assessment of the Proposed Susitna River Hydroelectric Projects: Preliminary Investigations of Water Quality and Aquatic Species Composition: Alaska Department of Fish and Game, Sport Fish Division, 91 pp.

Riis, James C., and Nancy V. Friese. 1978. Fisheries and Habitat Investigations of the Susitna River - A Preliminary Study of Potential Impacts of the Devils Canyon & Watana Hydroelectric Projects, Alaska Department of Fish and Game, Sport Fish Division, 116 pp.

Trihey, E.W., 1982a. Preliminary Assessment of Access by Spawning Salmon to Side Slough Habitat above Talkeetna. Prepared for Acres American, Incorporated.

__________. 1982b. Winter Temperature Study. Open File Report. Prepared for Acres American, Incorporated.

__________. 1983. Preliminary Assessment of Access by Spawning Salmon into Portage Creek and Indian River. Prepared for Alaska Power Authority.

U.S. Army Corps of Engineers, Alaska District. 1975. Southcentral Railbelt Area, Alaska. Upper Susitna Basin. Hydropower and Related Purposes. Interim Feasibility Report 1975.

__________. 1978. Southcentral Railbelt Area, Alaska. Upper Susitna Basin. Hydropower and Related Purposes. Supplemental Feasibility Report 1978.

Swan Lake (R.W. Beck & Associates)

Federal Energy Regulatory Commission. 1980. Final Environmental Impact Statement, Swan Lake Project No. 2911 - Alaska.

R.W. Beck. 1979. Application for License for the Swan Lake Project, F.E.R.C. Project No. 2911, Ketchikan Public Utilities.

__________. Swan Lake Project, Evaluation Report, Volumes I & II. Prepared for Ketchikan Public Utilities.

Terror Lake (International Engineering Company, Inc.)

Arctic Environmental Information and Data Center. 1979. An Assessment of Environmental Effects of Construction of the Terror Lake Hydroelectric Facility, Kodiak Island, Alaska. Report for Kodiak Electric Association.

__________. 1980. An Assessment of Environmental Effects of Construction and Operation of the Proposed Terror Lake Hydroelectric Facility, Kodiak Island, Alaska; Raptor Studies, Intragravel Water Temperature Studies.

__________. 1981. An Assessment of Environmental Effects of Construction and Operation of the Proposed Terror Lake Hydroelectric Facility, Kodiak Island, Alaska, Instream Flow Studies. W.J. Wilson et al.

Baldrige, J.R. and E.W. Trihey. 1982. General Characteristics of Surface Water Temperatures in the Terror River Basin. AEIDC. Prepared for Kodiak Electric Association.

Kodiak Electric Association. 1967. Terror Lake Hydroelectric Project - Kodiak, Alaska, Definite Project Report, Vol. 1, Mapping and Engineering.

Robert W. Retherford Associates and International Engineering Company, Inc. 1978. Terror Lake Hydroelectric Project, Kodiak Island, Alaska. Definite Project Report.

Simons, Li & Associates, Inc. 1980a. Analysis of Hydraulic, Sedimentation and Morphological Changes in the Kizhuyak and Terror Rivers Associated with the Terror Lake Hydroelectric Project. Report for Kodiak Electric Association.

__________. 1980b. Analysis of Thermal Changes in the Kizhuyak and Terror Rivers Associated with Terror Lake Hydroelectric Project. Report for Kodiak Electric Association.

Simons, D.B., R.M. Li and J.R. Kinzey. 1980. Review and Extended Hydrologic Analysis for Terror River and Kizhuyak River. Report for Kodiak Electric Association.

Togiak (DOWL Engineers)

DOWL Engineers. 1982. Volume E, Final Report. Reconnaissance Study for Togiak Hydroelectric Project.

DOWL Engineers. 1983. Feasibility Study for Togiak Hydroelectric Project, Supplemental Data Report: Hydrology.

Tyee Lake (International Engineering Company, Inc.)

Arctic Environmental Information and Data Center. 1980. An Assessment of Environmental Effects of Construction and Operation of the Proposed Tyee Lake Hydroelectric Project, Petersburg and Wrangell, Alaska.

__________. 1983. Tyee Lake Hydroelectric Project, Revised Fisheries Mitigation Plan.

Federal Energy Regulatory Commission. 1981. Tyee Lake Hydroelectric Project, FERC No. 3015, Alaska. Final Environmental Impact Statement.

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References Cited

Balding, G.O. 1974. Water Reconnaissance Study of Pelican, Alaska. U.S. Geological Survey.

Baldrige, J.E. and E.W. Trihey. 1982. Potential Effects of Two Alternative Hydroelectric Developments on the Fishery Resources of the Lower Tazimina River, Alaska. AEIDC, in cooperation with Dames & Moore.

Bovee, Ken D. 1982. A guide to Stream Habitat Analysis Using the Instream Flow Incremental Methodology. Instream Flow Information Paper No. 12. Western Energy and Land Use Team, Fish and Wildlife Service, U.S. Dept. of the Interior.

Imberger, J. and J. Patterson. 1981. A Dynamic Reservoir Simulation Model: DYRESM5. In Transport Models for Inland and Coastal Waters, H.B. Fischer, ed. Academic Press, New York.

Soil Conservation Service. Annual. Snow Survey Measurements for Alaska. Anchorage, Alaska.

Tennant, D.L. 1975. Instream Flow Regimens for Fish, Wildlife, Recreation and Related Environmental Resources. U.S. Fish and Wildlife Service Report. Billings, Mont. 18 pp.

Tennant, D.L. 1976. Instream Flow Regimens for Fish, Wildlife, Recreation, and Related Environmental Resources. In Proc. Symp. and Spec. Conf. on Instream Flow Needs, ed., J.F. Orsborn and C.H. Allman. Vol. II, pp. 359-373. Amer. Fish. Soc., Bethesda, Md.

Thompson, K.E. 1972. Determining Streamflows for Fish Life. In Proc. Instream Flow Requirement Workshop, Pacific N.W. River Basins Comm., Portland, Oregon. pp. 31-50.

Thompson, K.E. 1974. Salmonids--Chap. 7. In Bayha, K. (ed.), The Anatomy of a River. Report of the Hells Canyon Task Force, Pacific N.W. River Basins Comm. pp. 85-103.

U.S. Geological Survey. Annual. Water Resources Data for Alaska. Anchorage, Alaska.

Wesche, T.A. and P.A. Rechard. 1980. A Summary of Instream Flow Methods for Fisheries and Related Research Needs. Eisenhower Consortium Bulletin.

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 Island, Alaska. Prepared by AEIDC for Kodiak Electric Association.

TROPHIC STATUS OF SUSITNA RIVER IMPOUNDMENTS

By Gary Nichols[1] and Laurence A. Peterson[2]

Abstract

Summer inflow concentrations of carbon, silica, nitrogen and phosphorus may be used to quantitatively predict the trophic status of lakes and reservoirs. Among these nutrients, biologically available nitrogen and phosphorus most often control the eutrophication process depending on which of these nutrients occurs in shortest supply. Several eutrophication models have been developed for the prediction of lake trophic status based on phosphorus and nitrogen loading values. The most widely recognized model is the Vollenweider--OECD Program model which was developed from numerous data collected in a diversity of limnological settings around the world.

The nitrogen:phosphorus (N:P) ratio calculated from water samples collected at Vee Canyon ranged between 22:1 and 46:1, indicating that phosphorus is the limiting nutrient in the Susitna River. Application of the Vollenweider--OECD Program model to the Susitna Hydroelectric Project was accomplished by incorporating measured phosphorus values with the mean depth and hydraulic residence time at each reservoir. Based solely on nutrient enrichment, Watana and Devil Canyon Reservoirs will be oligotrophic under natural conditions. Additionally, high suspended solids concentrations and turbidity levels in the Susitna River may limit the eutrophication process to a greater extent than phosphorus concentrations. Furthermore, Watana and Devil Canyon will maintain oligotrophic status if provided with a maximum additional phosphorus load equivalent to more than 100,000 permanent residents and 40,000 permanent residents, respectively. Additional loading from a 3000 person construction camp would amount to a small fraction of the maximum permissible artificial phosphorus load at each reservoir.

Introduction

The process of eutrophication is defined as the increase in nutrient enrichment that causes increased productivity in lakes (Welch, 1980). This enrichment is expressed in terms of nutrient supply or load. Nutrient supply is the concentration of a nutrient per unit volume of water received by a lake expressed in terms of mg/m^3. Nutrient load on the other hand is the concentration of a nutrient per unit of lake surface area expressed in terms of mg/m^2.

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[1] Principal, Nichols Consulting Service, 85 Pepperdine, Fairbanks, Alaska.

[2] President, L. A. Peterson & Associates, Inc., 118 Slater Drive West, Fairbanks, Alaska.

Lake trophic status is an expression of the degree to which the eutrophication process has proceeded in a particular lake of a known mean depth, hydraulic residence time, and annual inflow volume. The major characteristics used to quantify the trophic status of clearwater lakes are nutrient concentration, algal biomass, and Secchi disc transparency.

Background

The quantitative prediction of reservoir trophic status at Watana and Devil Canyon, resulting from the impoundment of the Susitna River, is based on the following rationale.

The primary nutrients controlling algal growth include carbon, silica, nitrogen, and phosphorus. Among these nutrients, nitrogen and phosphorus most often limit algal growth in freshwater systems (Shindler, 1977, Rast and Lee, 1978; Shaffner and Oglesby, 1978; Lee et al., 1978, Jones and Lee, 1982; OECD, 1982; Smith, 1982). Since algal growth occurs rapidly over a short period of time (Rast and Lee, 1978) and because certain forms of nitrogen and phosphorus are unavailable to algal uptake (Lean, 1973, Shaffner and Oglesby, 1978; Lee et al., 1978, OECD, 1982), it is more meaningful to consider the biologically available forms of these nutrients than quantities of total nitrogen and total phosphorus. The predominant form of phosphorus which is readily available for algal growth consists of the dissolved orthophosphate fraction (St. John et al., 1976; Lee et al., 1978, Welch, 1980; Lee et al., 1980; OECD, 1982). However, solubilization and mineralization reactions in a waterbody may result in the formation of dissolved orthophosphate from other phosphorus species. In many instances, the potentially bio-available phosphorus concentration in clearwater lakes is a quantity that lies between the concentrations of soluble orthophosphate and total phosphorus. It was found (Lee et al., 1978, 1980) that the bio-available fraction in these lakes could be approximated by adding the dissolved orthophosphate concentration to 0.2 times the difference between total P and PO_4. The form of nitrogen which is readily available to algae consists of the inorganic (mineral) fraction (Lee et al., 1978; Rast and Lee, 1978; OECD, 1982). The growth rate of algae in natural fresh water is regulated by the single nutrient occurring in shortest supply (OECD, 1982, Smith, 1982). A judgement on whether nitrogen or phosphorus will limit algal growth can be made from considering the nitrogen:phosphorus (N:P) ratio. However, because nutrients are required in the inorganic form for the purposes of algal growth, the use of inorganic nitrogen and dissolved orthophosphate ratios is often considered more meaningful in determining the limiting nutrient, than total N and P ratios (OECD, 1982). On the average, algal tissues contain nitrogen and phosphorus atoms in the proportion of 16N:1P and require these nutrients in this proportion for growth. When the N:P atomic ratio is greater than 16:1, phosphorus atoms are insufficient for algal growth, and algal biomass is limited by the quantity of phosphorus present. If on the other hand, the N:P atomic ratio is less than 16:1, nitrogen becomes the limiting nutrient (Lee et al., 1978, OECD, 1982). More important than the N:P ratio alone is whether nitrogen or phosphorus in a water body are reduced to growth-limiting levels during the summer period of eutrophication-related water quality concern (Rast et al., 1983). In some water bodies, inorganic suspended solids and turbidity may have a greater effect on algal growth than the N:P ratio (Smith, 1982).

Extensive eutrophication research in the last decade has resulted in the development of several models for predicting the trophic state of phosphorus limited lakes, solely on the basis of phosphorus enrichment. The phosphorus concentration in a proposed impoundment may be predicted by applying external (inflow) nutrient concentration data to the appropriate model. Through his work with the Organization for Economic Cooperation and Development (OECD), Vollenweider (1976) developed a general model which quantitatively describes the empirical relationship between the average areal load of phosphorus and inlake phosphorus concentrations, from among several lakes in North America and Europe. This relationship is expressed as:

$$[P] = \frac{L\ (Tw)}{\bar{z}\ (1 + \sqrt{Tw})}$$

where [P] = Average phosphorus concentration contained in a waterbody (Mg/m^3),

L = Areal phosphorus load (mg/m^2/time)

Tw = Hydraulic residence time (years)

$\bar{z}$ = Mean depth of a water body (meters).

The loading term (L) in this equation can be calculated by multiplying the average inflow phosphorus concentration by the total volume of water received by a lake during a specified period of time (i.e., m^3/yr), and dividing the product by the surface area of the lake or reservoir.

This equation can also be expressed in terms of the average inflow concentration of phosphorus:

$$[P] = \frac{Pi}{(1 + \sqrt{Tw})}$$

where Pi = Average inflow concentration of phosphorus (mg/m^3).

Based on the data from U.S. OECD study lakes, Lee et al. (1978) and Rast and Lee (1978) substantiated this general relationship and defined it for a number of waterbodies. Most recently, the OECD (1982) found that approximately 200 waterbodies in 22 countries around the world follow the same general relationship.

Jones and Lee (1982) concluded that this model has a wide-spread applicability to most waterbodies--those in northern latitudes as well as southern latitudes, lakes as well as impoundments. Furthermore, this model was successfully used to estimate the annual total phosphorus input at Crescent Lake in south-central Alaska (Koenings and Kyle,1982). The U.S. Environmental Protection Agency has suggested that this model be used as a basis for establishing nutrient load criteria to U.S. waterbodies (EPA, 1976)

Statistical models developed by Dillon and Rigler (1974) and Larsen and Mercier (1976) have the same technical foundation as the Vollenweider-OECD models. However, the correlations for these models were not developed from as broad a data base as those of the OECD load-response models.

Algal biomass is often a visible symptom of eutrophication, and it is usually the cause of eutrophication-related water quality problems. Chlorophyll "a" concentration is widely recognized as the best expression of algal biomass in lakes, and was selected as a principle trophic state indicator by the OECD (1982). Several equations have been developed which express the statistical relationship between phosphorus concentrations and chlorophyll "a" concentrations in clearwater lakes. The most recent of these equations are presented by Smith and Shapiro (1981), Jones and Lee (1982), OECD (1982), and Rast et al. (1983).

Lake trophic status can be generally classified on the basis of "fixed boundary" phosphorus and chlorophyll "a" concentrations. Average in-lake phosphorus concentrations of 0-10 mg/m^3 are indicative of oligotrophic conditions, 10-20 mg/m^3 are in the mesotrophic range, and levels above 20 mg/m^3 are considered eutrophic (Vollenweider, 1976). These conditions correspond to average in-lake chlorophyll "a" concentrations of 0-2 mg/m^3, 2-6 mg/m^3, and greater than 6 mg/m^3, respectively, in clearwater lakes.

Subsequently, Vollenweider determined that the critical surface load which will result in oligotrophic conditions may be calculated by using the maximum oligotrophic phosphorus concentration (10 mg/m^3) in the following equation:

$$Lc = 10 \left[\frac{\bar{z}}{Tw} \quad (1 + \sqrt{Tw}) \right]$$

where: Lc = Critical areal phosphorus load (mg/m^2/time),

10 = Maximum inlake phosphorus concentration resulting in oligotrophic status (mg/m^3),

$\bar{z}$ = Mean depth

Tw = Hydraulic residence time

Methods

Because of the wide-spread applicability of Vollenweider's (1976) model, and its successful use in south-central Alaska, this model was selected for use in the Susitna Project. At this time there are no known limitations to the application of Vollenweider's model in Alaska which are not common to all models. Average inlake concentrations of phosphorus at Watana and Devil Canyon were predicted by applying Vollenweider's equation to the average summer phosphorus concentration in river water, the maximum atmospheric phosphorus concentration at Fairbanks, Alaska, and the hydraulic residence time at each reservoir. Subsequently, the average phosphorus concentration in river water was multiplied by the average inflow volume of water at each damsite (7.0148 X 10^9 m^3/yr at Watana and 7.9965 X 10^9 m^3/yr at Devil Canyon) to derive the total phosphorus supply at each reservoir. Upon dividing the supply by the surface area of each reservoir (153,786,000 m^2 at Watana and 31,566,600 m^2 at Devil Canyon), areal phosphorus loading

(L) from the land was obtained.

Smith and Shapiro (1981) strongly recommend that the predictive use of nutrient models be based on data collected during the summer months when algal biomass is most closely related to nutrient concentrations. Accordingly, nutrient concentrations in the Susitna River were determined from samples collected during the summers of 1980 and 1981 at Vee Canyon by R & M Consultants (1981). The Susitna Project location and Vee Canyon sample station appear in Figure 1. Total nitrogen, inorganic nitrogen, total phosphorus, and dissolved orthophosphate were analyzed according to APHA (1981) methodology. The input of atmospheric phosphorus at Watana and Devil Canyon was assumed to be approximately equal to the maximum phosphorus concentration contained in rain and snow samples collected in Fairbanks, Alaska by Peterson (1973). Consequently, the total natural phosphorus load at each reservoir equals the sum of phosphorus from the land and from precipitation.

All measured summer phosphorus concentrations at Vee Canyon were below the detectable limit. However, "worst case" concentrations equal to the phosphorus detection limit were assumed because it was felt that values of zero are inappropriate for the Susitna Project area. Consequently, the total phosphorus and dissolved orthophosphate values assumed in this paper may over-estimate actual concentrations contained in the Susitna River. The biologically available fraction of nitrogen was determined by summing concentrations of ammonia, nitrate, and nitrite nitrogen contained in each sample. Dissolved orthophosphate was considered to be the biologically available phosphorus fraction in the Susitna River.

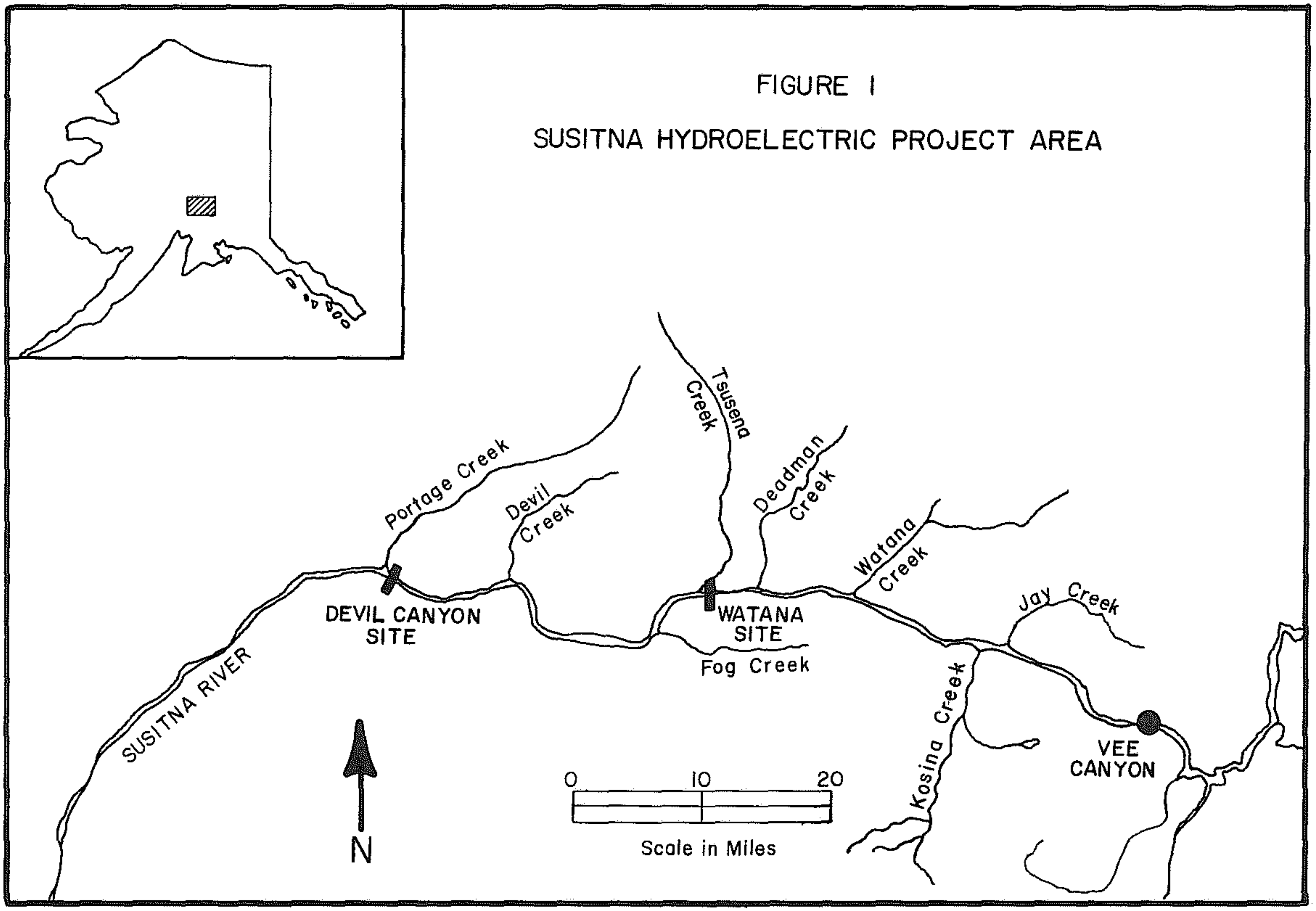

FIGURE 1

SUSITNA HYDROELECTRIC PROJECT AREA

The hydraulic residence time of a unit volume of water (Tw) represents the reservoir's water budget expressed as the total reservoir water volume (m^3), divided by the annual inflow volume (m^3/yr). Estimates of hydraulic residence time at Watana and Devil Canyon were provided by R & M Consultants (1982a).

The mean depth ($\bar{z}$) was calculated as the "full pool" volume divided by the surface area at each reservoir. This is the same method used to determine mean depth at Crescent Lake by Koenings and Kyle (1982).

Any additional phosphorus loading to Watana and Devil Canyon will cause a subsequent increase in the steady-state phosphorus concentration which may result in a change in water quality. Therefore, artificial loading in the form of domestic phosphorus inputs must be incorporated into the phosphorus model if the capacity for residential dwelling or summer cottage development is to be determined. Results from 13 studies in North America and Europe concluded that the average per capita contribution of phosphorus (excrement plus household waste) is 800,000 mg/yr from domestic sources (Dillon and Rigler, 1975). By dividing the average per capita supply by the surface area of each reservoir, average per capita surface phosphorus loading was obtained. The maximum permissible artificial load was calculated as the difference between the critical surface load and the natural surface load at each reservoir. The permissible number of permanent (year-round) residents at each reservoir was obtained by dividing the permissible artificial load at each reservoir by the corresponding average per capita surface phosphorus load. The maximum number of "permanent" dwelling unit equivalents around each reservoir was calculated by dividing the number of permissible residents by the number of residents at each dwelling unit. In the event that dwelling units will be (on the average) occupied for less than 365 days per year (i.e., summer cottages), the permissible number of "seasonal" units will equal the number of permanent dwelling units multiplied by 365 days, divided by the average number of days spent at each unit per year.

Chlorophyll "a" and Secchi disc transparency data from the Susitna River are unavailable. However, high suspended sediment and turbidity levels at Vee Canyon indicate the Chlorophyll "a" concentrations will be low in Watana and Devil Canyon. Consequently, prediction of chlorophyll "a" concentrations and Secchi depth transparencies following impoundment have been disregarded in this paper.

Results

During the summer of 1980 and 1981, the N:P atomic ratio at Vee Canyon ranged between 22:1 and 46:1. Thus, among the nutrients considered to be important to algal growth, it is apparent that phosphorus is the limiting nutrient. Average summer total phosphorus and dissolved orthophosphate concentrations measured at Vee Canyon were below the detection limit (0.05 mg/l and 0.01 mg/l, respectively) of the analytical method used. Upon conversion of these values, the "worst case" average total phosphorus concentration is 50 mg/m^3, and the worst case average dissolved orthophosphate concentration is 10 mg/m^3. The maximum phosphorus concentration measured in precipitation at Fairbanks, Alaska was 0.03 mg/l (Peterson, 1973). Conversion of this value (30 mg/m^3), in combination with the normal average precipitation at Talkeetna, Alaska, indicates that the natural phosphorus load from precipitation will be 22 mg/m^2 at both reservoirs. Reservoir mean depths were determined to be 76 meters at Watana and 43 meters at Devil Canyon (R & M Consultants, 1982b). Subsequently, the hydraulic residence time was estimated to be 1.64 years at Watana and 0.16 year at Devil Canyon (R & M Consultants, 1982a).

With respect to the bio-available phosphorus fraction (dissolved orthophosphate), the predicted summer inlake phosphorus concentration [P] equals 4.5 mg/m^3 at Watana and 6.8 mg/m^3 at Devil Canyon. These values correspond to phosphorus loading values (L) of 478 $mg/m^2/yr$ and 2555 $mg/m^2/yr$, respectively. Inlake concentrations of bio-available phosphorus [P] at Watana and Devil Canyon plot in the same area as oligotrophic waterbodies with similar areal phosphorus loads, mean depths, and hydraulic residence times (Figure 2). Thus, assuming that dissolved orthophosphate represents the only bio-available phosphorus fraction in the Susitna River, both of the proposed reservoirs will be oligotrophic.

Although both reservoirs initially will be oligotrophic, artificial loading from domestic sources could cause a shift in trophic status at one or both reservoirs at some future time. Because of this concern, an analysis of artificial loading was made. The average per capita artificial phosphorus load will be 0.005 $mg/m^2/yr$ at Watana and 0.025 $mg/m^2/yr$ at Devil Canyon. The maximum permissible artificial load was calculated to be 579 $mg/m^2/yr$ at Watana and 1208 $mg/m^2/yr$ at Devil Canyon with one dam in place. The loading at Devil Canyon could be higher if Watana is in place because Watana may act as a nutrient trap. Upon dividing the permissible artificial load by the average per capita load at each reservoir, Watana will accomodate 115,800 and Devil Canyon 48,300 permanent residents, respectively. If an average of three individuals occupy each dwelling unit for the entire year, the maximum permissible number of dwelling units will be 38,600 at Watana and 16,100 at Devil Canyon. If permanent and seasonal dwellings are constructed, the domestic load should not exceed the amount generated by 115,800 permanent residents at Watana, or 48,300 permanent residents at Devil

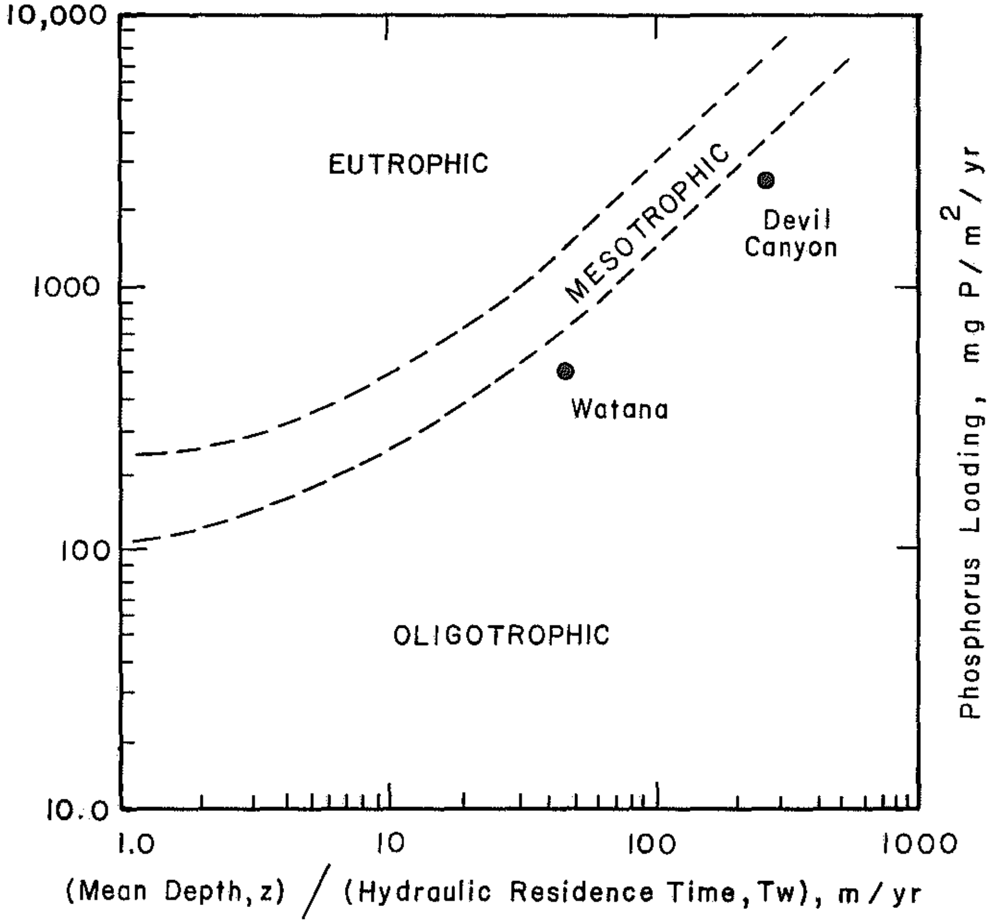

FIGURE 2

SUSITNA PROJECT DATA APPLIED TO VOLLENWEIDER'S MODEL

Canyon, if oligotrophic conditions are to be maintained.

Artificial loading from a 3000 person construction camp would amount to 15 $mg/m^2/yr$ at Watana and 75 $mg/m^2/yr$ at Devil Canyon. These loading levels represent about 3 percent (Watana) and 6 percent (Devil Canyon) of the maximum permissible artificial loading required to maintain oligotrophic conditions.

Discussion

The aforementioned trophic status predictions are dependent upon several assumptions that cannot be quantified on the basis of existing information. These assumptions include:

(1) the N:P ratio does not fluctuate in subsequent years to the extent that a nutrient other than phosphorus becomes limiting,

(2) no appreciable amount of bio-available phosphorus is released from soil upon filling of the reservoir (i.e., internal loading),

(3) estimates of land and precipitation phosphorus concentrations are accurate,

(4) phosphorus input levels are constant throughout the algal growth period (summer),

(5) phosphorus concentrations measured at Vee Canyon correspond to the time of peak algal productivity,

(6) an appreciable fraction of the total phosphorus pool is not converted to dissolved orthophosphate,

(7) hydraulic residence times are constant,

(8) phosphorus losses occur only through sedimentation and the outlet,

(9) the net loss of phosphorus to sediments is proportional to the amount of phosphorus in each reservoir, and,

(10) steady-state conditions prevail in both reservoirs.

Among the models which predict lake trophic status, the Vollenweider (1976) model appears to be the most reliable and most widely applied. However, this and other models were developed from data collected in clearwater lakes where nutrient concentrations and chlorophyll "a" concentrations are statistically related. For the proper application of the Vollenweider - OECD models, only a moderate amount of non-algal turbidity should be present (Rast et al., 1983). Waterbodies containing a high inorganic particulate load or large amounts of suspended solids should be expected to contain chlorophyll "a" concentrations lower than what these models predict (Jones and Lee, 1982). As suspended sediment concentrations increase, conversion of initially available phosphorus to unavailable forms increases (Lee et al., 1978). Koenings and Kyle (1982) report that during summer, soluble inorganic phosphorus was largely converted to particulate phosphorus in the epilimnion of Crescent Lake. They concluded that the nutrient dynamics in glacially influenced lakes having high silt inputs are different from those of clearwater lakes. Consequently, trophic status cannot be predicted solely by the nutrient concentration in a water body -- phosphorus does not adversely affect water quality unless it produces undesirable aquatic plant growth (Rast et al., 1983).

In the event that only one of the Susitna Project reservoirs is constructed, low light penetration levels owing to high concentrations of suspended glacial flour will likely limit algal biomass to a greater extent than phosphorus concentrations. Furthermore, high suspended sediment concentrations may convert available phosphorus to unavailable forms. If both reservoirs are constructed, a large fraction of the suspended sediment load entering Watana will settle to the bottom resulting in higher light penetration levels downstream at Devil Canyon. In this instance, light may not become a limiting factor to algal growth at Devil Canyon. However, a significant portion of phosphorus may also be trapped at Watana resulting in lower phosphorus concentrations downstream at Devil Canyon. Typically, 80-90 percent of the phosphorus entering lakes and impoundments is incorporated into their sediments, and will not be available for stimulation of algal growth in downstream waters (Lee et al., 1978).

Because suspended solids concentrations are high during the open-water season at Vee Canyon, and because actual phosphorus concentrations will be less than the worst case concentration used in our calculations, trophic status (oligotrophic) predictions at each reservoir probably overestimate the degree to which the eutrophication process will proceed under natural conditions. Consequently, the maximum allowable number of permanent residents at each reservoir may be greater than those determined on the basis of trophic status.

Summary

Reservoir trophic status is determined in part by relative amounts of nitrogen and phosphorus present in a system as well as the quality and quantity of light penetration. The N:P ratio indicates which nutrient limits algal productivity. The nutrient which is least abundant will be limiting. On this basis, it was concluded that phosphorus is limiting in the Susitna impoundments. Vollenweider's (1976) model was considered to be the most reliable in determining phosphorus concentrations in the Watana and Devil Canyon impoundments. However, because the validity of this model is based on phosphorus data from clearwater lakes, predicting trophic status of silt-laden waterbodies with reduced light conditions and high inorganic phosphorus levels may over-estimate actual trophic status. The summer phosphorus concentration is considered the best estimate of trophic status in phosphorus limited lakes. Bio-available phosphorus is the fraction of the total phosphorus pool which controls algae growth in a particular lake. The measured dissolved orthophosphate concentration at Vee Canyon was considered to be the best estimate of the bio-available phosphorus fraction in the Susitna River. Accordingly, average summer dissolved orthophosphate was multiplied by the average inflow at each reservoir to calculate summer phosphorus supplies from the land. These values were in turn combined with atmospheric phosphorus values and divided by the surface area of each impoundment. The resultant summer phosphorus loading values at Watana and Devil Canyon were below the maximum loading levels required for the maintenance of oligotrophic conditions. Likewise, upon incorporating summer loading values into Vollenweider's (1976) phosphorus model, the volumetric spring phosphorus concentration at both reservoirs fell into the same range as oligotrophic lakes with similar mean depths, detention times, and phosphorus loading values.

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References

APHA, 1981. Standard Methods for the Examination of Water and Wastewater. 15th Edition, American Public Health Association, Wash. D.C. 1134 pp.

Dillon, P.J., and F.H. Rigler, 1974. A test of a simple nutrient budget model predicting the phosphorus concentration in lake water. Journal Fish. Res. Board Canada, Vol. 31, No. 11, pp. 1771-1778.

_____, 1975. A simple method for predicting the capacity of a lake for development based on lake trophic status. Journal Fish. Res. Board Canada, Vol. 32, No. 9, pp. 1519-1531.

EPA, 1976. Quality criteria for Water. U.S. Environmental Protection Agency, Washington, D.C., 256 pp.

Jones, R.A., and G.F. Lee, 1982. Recent advances in assessing impact of phosphorus loads on eutrophication-related water quality. Journal Water Research, Vol. 16, pp. 503-515.

Koenings, J.P., and G.B. Kyle, 1982. Limnology and fisheries investigations at Crescent Lake (1979-1982), Part I: Crescent Lake limnology data summary. Alaska Dept. of Fish and Game, F.R.E.D. Div., Soldotna, Alaska, 54 pp.

Larsen, D.P., and H.T. Mercier, 1976. Phosphorus retention capacity in lakes. Journal Fish. Res. Board Canada, Vol. 33, pp. 1742-1750.

Lean, D.R.S., 1973. Movements of phosphorus between its biologically important forms in lake water. Journal Fish. Res. Board of Canada, Vol. 30, pp. 1525-1536.

Lee, G.F., W. Rast, R.A. Jones, 1978. Eutrophication of water bodies: insights for an age-old problem. Environmental Science and Technology, Vol. 12, pp. 900-908.

Lee, G.F., R.A. Jones, and W. Rast, 1980. Availability of phosphorus to phytoplankton and its implications for phosphorus management strategies, In: phosphorus management strategies for lakes, R.C. Loehr, C.S. Martin, and W. Rast (eds.). Ann Arbor Science Publ. Inc., pp. 259-308.

OECD, 1982. Eutrophication of waters: monitoring, assessment, and control. Organization for Economic Co-operation and Development, Paris, France, 154 pp.

Peterson, L.A., 1973. An investigation of selected physical and chemical characteristics of two subarctic streams. M.S. Thesis, University of Alaska, Fairbanks, 185 pp.

R & M Consultants, 1981. Alaska Power Authority Susitna Hydroelectric Project task 3 - hydrology subtask 3.03 - water quality 1981 annual report prepared by R & M Consultants Inc. for Acres American Inc.

_____, 1982a. Reservoir sedimentation studies. Susitna Hydroelectric Project feasibility report, Anchorage, Alaska, January.

_____, 1982b. Personal communication to Larry Peterson, L. A. Peterson & Associates, Inc., Fairbanks, Alaska.

Rast, W., and F. Lee, 1978. Summary analysis of the North American (U.S. portion) OECD eutrophication project: nutrient loading - lake response relationships and trophic state indices. Env. Research Lab., Office of Research and Development, U.S. EPA, Corvallis, Oregon, 455 pp.

Rast, W., R.A. Jones, and G.F. Lee, 1983. Predictive capability of U.S. OECD phorphorus loading - eutrophication response models. Journal WPCF, Vol. 55, No. 7, pp. 990 - 1003.

Shaffner, W.R., and R.T. Oglesby, 1978. Phosphorus loading to lakes and some of their responses. Part I. A new calculation of phosphorus loading and its application to 13 New York lakes. Limnology Oceanography, Vol. 23, No. 1, pp. 120 - 134.

Shindler, D.W., 1977. Evolution of phosphorus limitation in lakes. Science, Vol. 195, pp. 260 - 262.

Smith, V.H., 1982. The nitrogen and phosphorus dependence of algal biomass in lakes: an empirical and theoretical analysis. Limnology Oceanography, Vol. 27, No. 6, pp. 1101 - 1112.

Smith, V.H., and J. Shapiro, 1981. Chlorophyll - phosphorus relations in individual lakes. Their importance to lake restoration strategies. Environmental Science and Technology, Vol. 15, No. 4, pp. 444 - 451.

St. John, B.E., E.C. Carmack, R.J. Daley, C.B.J. Gray, and C.H. Pharo, 1976. The limnology of Kamloops Lake, B.C. Dept. of Environment, Inland Waters Directorate, Pacific and Yukon Region, Vancouver, B.C., 167 pp.

Vollenweider, R.A., 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. Mem. Ist. Ital. Idrobiol., 33, pp. 53 - 83.

Welch, E.B., 1980. Ecological effects of waste water. Cambridge University Press, New York, 337 pp.

ENVIRONMENTAL EFFECTS OF ICE PROCESSES ON THE SUSITNA RIVER

G. Carl Schoch[1], and Stephen R. Bredthauer[2]

Observations of ice processes on the Susitna River have been conducted since 1980 in conjunction with planning of the proposed Susitna Hydroelectric Project. The observations describe baseline conditions, and are providing data to better assess post-project conditions. The processes of ice generation, staging, ice jamming, and breakup on the Susitna River are presented, as well as the effect of these processes on turbidity, river morphology, aquatic habitat, wildlife, and vegetation.

Construction of the proposed Watana and Devil Canyon dams will significantly alter flow, thermal, and ice conditions on the Susitna River. Frazil ice generated in the upper basin will be trapped by the Watana Reservoir. Relatively warm water (2°C - 4°C) will be released in large volumes from the reservoirs during winter. Ice formation downstream of the project will be significantly delayed. Breakup processes will be altered by the reservoirs trapping ice from upstream, by the changes in downstream ice conditions, and by reduced flows during breakup. The projected changes and their environmental impacts are also described.

Introduction

The proposed Susitna Hydroelectric Project would be one of the largest hydroelectric projects ever located on a northern river, consisting two dams with a total capacity of 1620 MW. Watana Reservoir, the upper project, would be 48 miles long, cover 38,000 acres, and have a storage capacity of 9.5 million acre-feet. The lower reservoir, Devil Canyon, would be 26 miles long, cover 7,800 acres, and store about a 1.1 million acre-foot.

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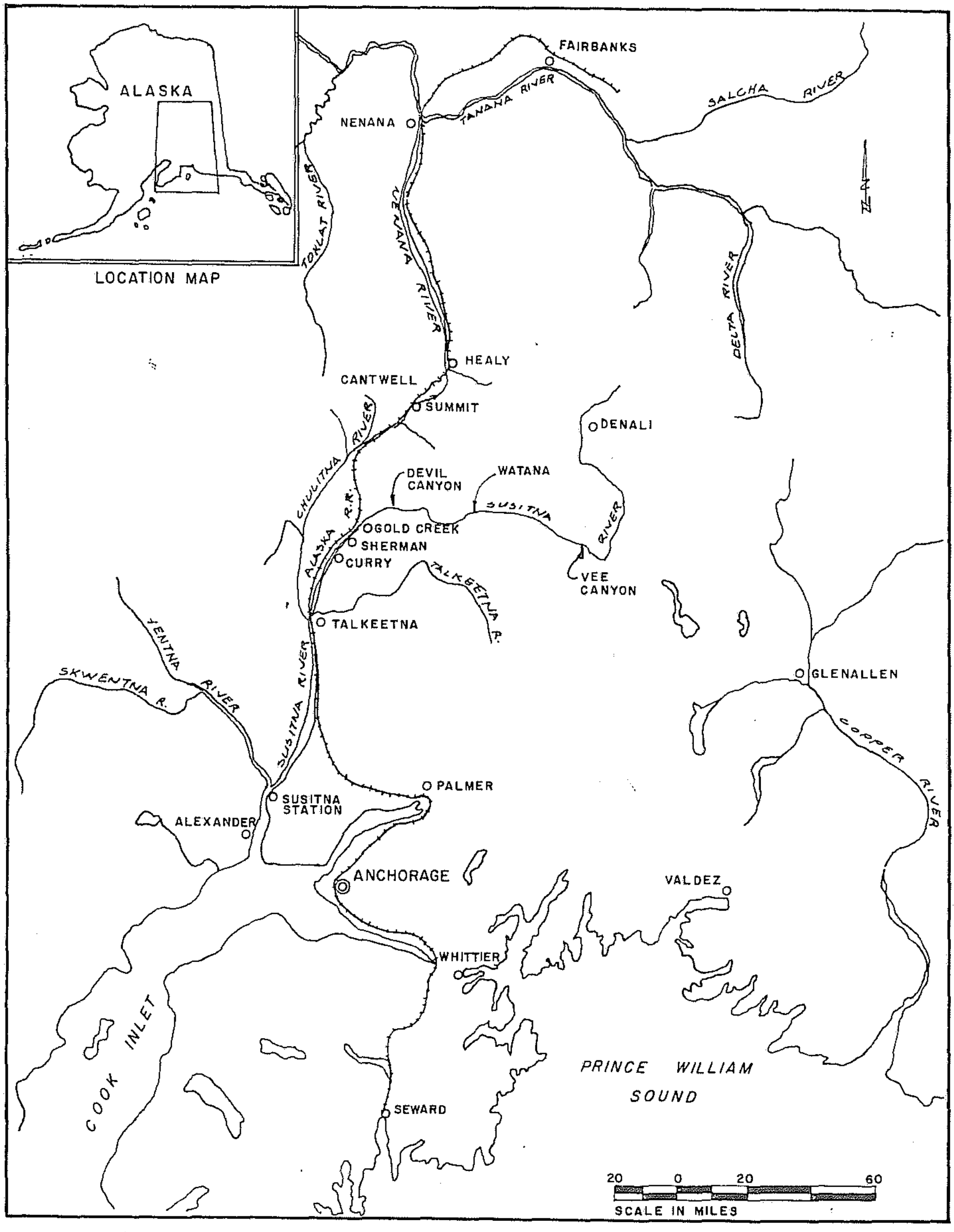
[1] Hydrologist, R&M Consultants, Inc.

[2] Chief, Hydrology Department, R&M Consultants, Inc.

Because of the proposed projects, the study of ice on the Susitna River has been ongoing since the winter of 1980. Initially, the intent was to target locations of specific ice processes such as frazil ice generation, shore ice constrictions, ice bridges, and ice jams (R&M 1981b, 1982d). Renewed emphasis by environmental concerns on potential modifications to the river ice regime by hydroelectric power development resulted in a more refined ice program for 1982-1983, directed towards answering specific problems of the Susitna River. Staging, ice cover development and ice jams, together with impacts of ice on river morphology and aquatic habitat, are among the topics discussed in this paper. General processes will be described, as will events observed in 1982-1983. Comparisons will be made to processes observed in earlier years.

Description of Basin

The Susitna River drainage basin, sixth largest in Alaska, is located in the Cook Inlet subregion of southcentral Alaska (Figure 1). The drainage basin covers 19,600 square miles. It is bordered on the west and north by the Alaska Range, on the east by the Talkeetna Mountains and the Copper River lowlands, and on the south by Cook Inlet. The river is 320 miles long from the mouth at Cook Inlet to the headwaters at Susitna Glacier. Major tributaries include the Chulitna, Talkeetna, and Yentna Rivers, all located downstream of the proposed project. Extensive glaciers in the headwaters contribute substantial suspended sediment loads during summer months. Streamflow is characterized by high flows between May and September and low flows from October to April.



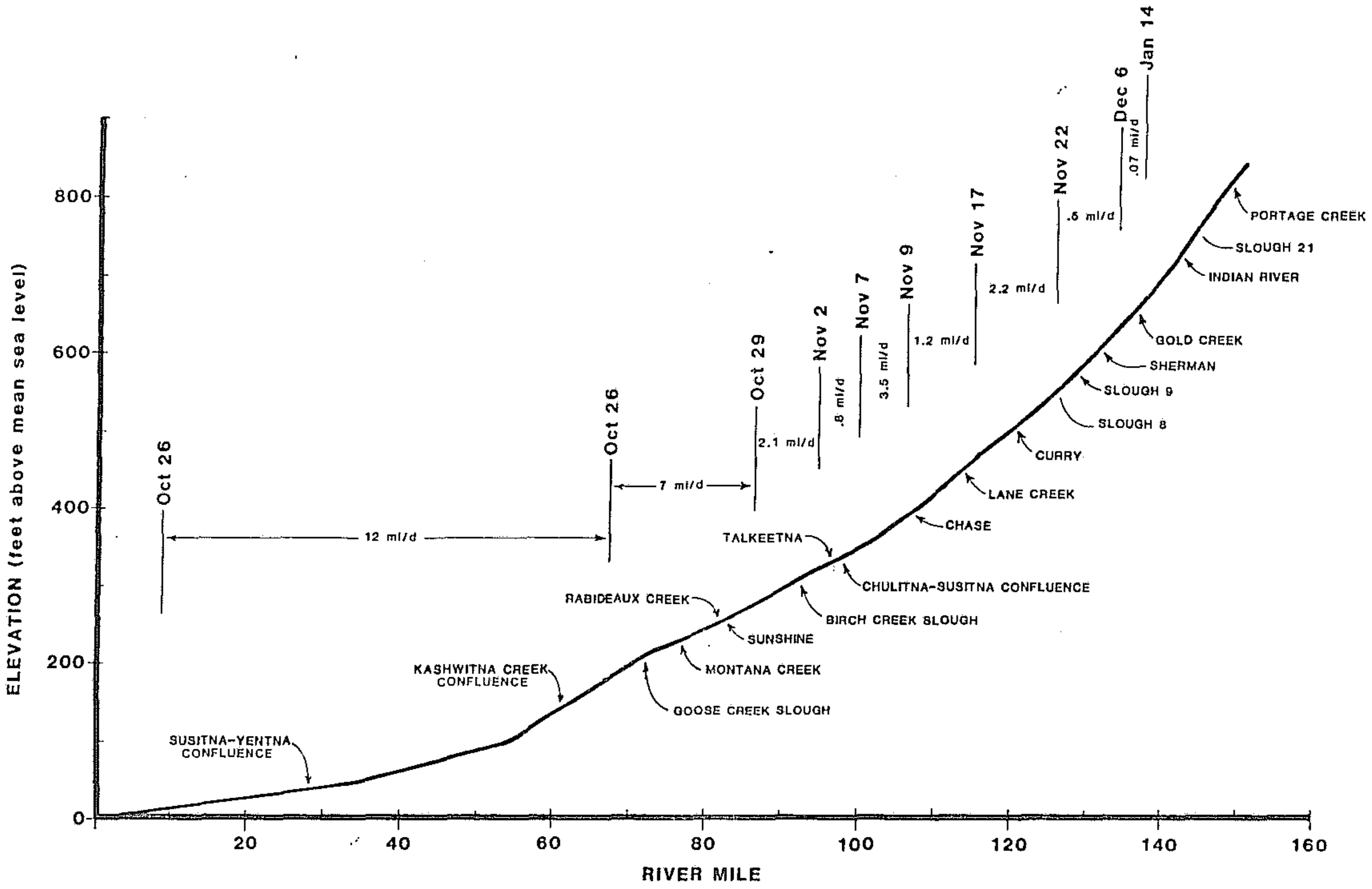
SUSITNA HYDROELECTRIC PROJECT LOCATION MAP

FIGURE 1

The headwaters of the Susitna River and the major upper basin tributaries are characterized by broad, braided, gravel floodplains below the glaciers of the Alaska Range. Below the West Fork confluence, the river develops a split-channel configuration with numerous gravel bars, flowing south between narrow bluffs for about 55 miles. Below the confluence with the Tyone River, the Susitna River flows west for 96 miles through steep-walled canyons before reaching the mouth of Devil Canyon. This reach contains the Watana and Devil Canyon damsites at River Miles (RM) 184.4 and 151.6, respectively, measured from Cook Inlet. River gradients are quite high, averaging nearly 14 feet/mile in the 54 miles above Watana damsite, 10.4 feet/mile from Watana downstream to Devil Creek, and 31 feet/mile in the 12-mile stretch between Devil Creek and Devil Canyon. Below Devil Canyon, the gradient decreases from about 14 feet/mile to 8 feet/mile above Talkeetna. The river in this reach is generally characterized by a split-channel configuration, with numerous side-channels and sloughs. About 4 miles above the confluence with the Chulitna River, the Susitna River begins to braid, and remains braided the remainder of its length to Cook Inlet. Numerous islands and side channels appear. The gradient continues to decrease, ranging from 5.5 feet/mile for the 34-mile reach below Talkeetna to 1.6 feet/mile for the last 42 miles (Figure 2).

Basin Climate

The Susitna River originates in the continental climatic zone, flowing south into the transitional climatic zone. Due to the maritime influence and the lower elevations, temperatures are more moderate in the lower basin



SUSITNA RIVER ICE LEADING EDGE PROGRESSION RATES (miles/day) RELATIVE TO THE THALWEG PROFILE FROM RIVER MILE 0 (Cook Inlet) TO RIVER MILE 155

FIGURE 2

than in the upper basin. Freezing temperatures occur in the upper basin by mid-September, with frazil ice generated in the reach from Denali through Vee Canyon by early October.

Several meteorological stations have been installed along the river since 1980. Records from these stations, located at Susitna Glacier, Denali, Kosina Creek (between Vee Canyon and Watana), Watana, Devil Canyon and Sherman, together with records from the National Weather Service at Talkeetna, illustrate the sharp difference in freezing degree-days along the length of the river (Figure 3). In general, the meteorology within the upper Susitna River basin is highly variable between weather station sites. This is due, in part, to the movement of storm systems, the topographic variance, and the change in latitude, but the major reason for the temperature variance between Denali and Talkeetna is the 2,400-foot elevation difference.

Freeze-Up Processes

Development of an ice cover on the Susitna River is a complex process influenced by many variables and mechanisms that are not fully understood. The ice on this river is primarily a continuous accumulation of frazil slush and snow slush called "hummocked ice" (Michel, 1971). It is therefore important to understand the relationship and significance of air temperature, water temperature, turbulence, snowfall and suspended sediment to frazil ice generation. These relationships will first be discussed,

AVERAGE HISTORICAL
ACCUMULATED FREEZING DEGREE DAYS
FOR SUSITNA RIVER BASIN
METEOROLOGICAL STATIONS
1980 - 1983

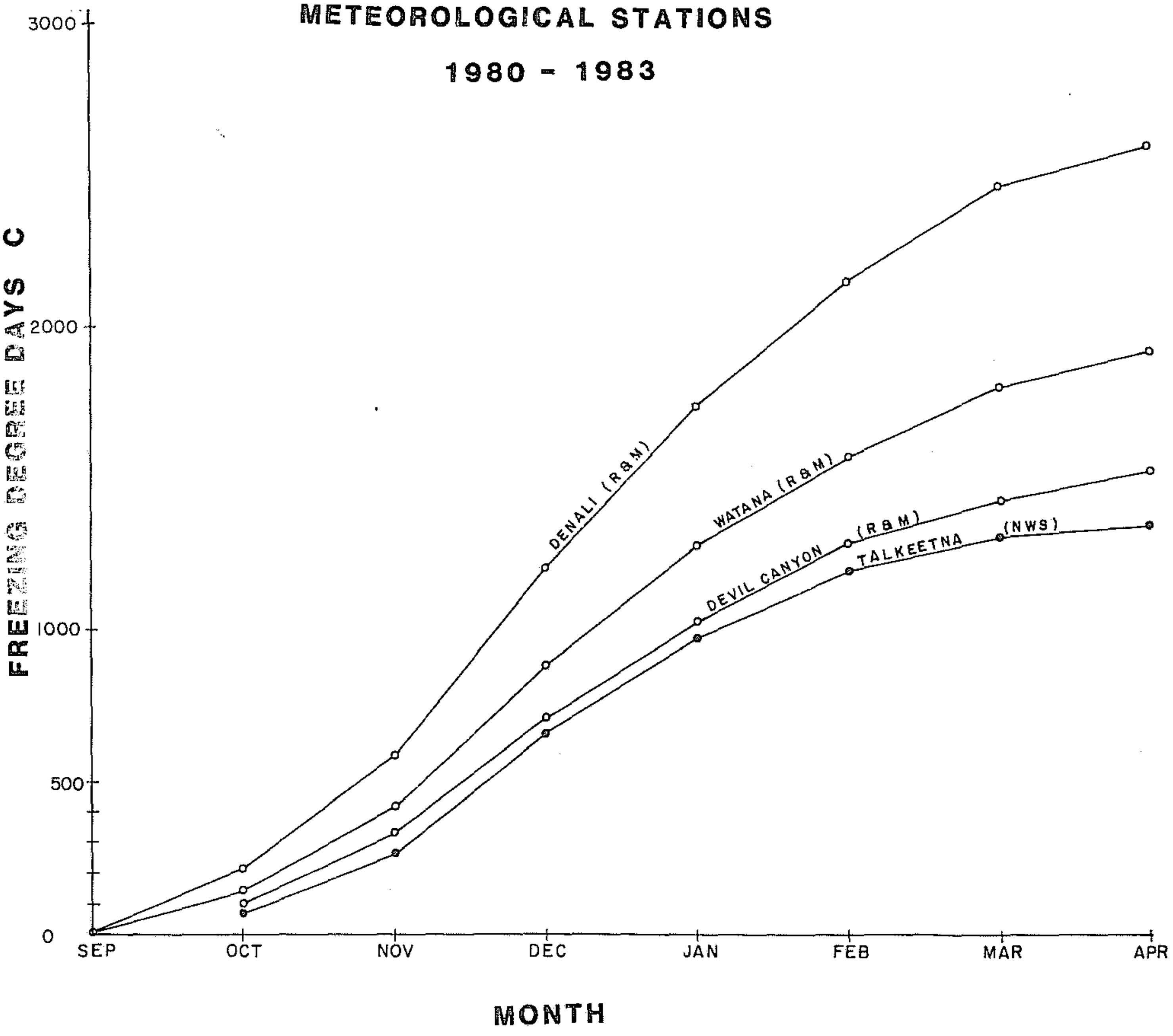


FIGURE 3

followed by a description of freeze-up characteristics of specific reaches of the river from Cook Inlet to Devil Canyon.

a. Frazil Ice Generation

Frazil ice crystals are formed when water becomes supercooled (Ashton, 1978; Michel, 1971; Newbury, 1968; Osterkamp, 1978). Supercooling is a phenomena by which water remains in a liquid state at temperatures below 0°C. Foreign particles are associated with the nucleation of ice crystals (Osterkamp, 1978). The Susitna River discharges tremendous volumes of silt and clay size particles prior to freeze-up. There is an apparent correlation between the first occurrence of frazil ice and a sudden reduction of turbidity in the river water, indicating that the fine suspended sediments may initiate the nucleation of ice (R&M, 1983). Once the river is at the freezing point, snowfall also contributes to the total slush ice discharge.

With sustained air temperatures below 0°C, a thin layer of water will be cooled to the freezing point and ice crystals will form. Under quiescent conditions, the ice crystals will form on the water surface, eventually bonding together into a sheet of black ice, and continuing to grow vertically along the thermal gradient. However, laboratory experiments have determined that flow velocities of only 0.79 ft./sec. are necessary to mix the surface layer sufficiently to produce frazil (Osterkamp, 1978). These velocities are exceeded on the Susitna mainstem through most reaches so that the water body is continually being mixed. Under these conditions, the water can be supercooled to several hundredths of a degree below $0^\circ C$ throughout the water column, and crystals of frazil ice form in suspension beneath the water's surface. Once the frazil ice forms, it has a tendency to rise to the surface. However, during the initial ice formation, frazil particles are so small that they remain entrained in the river due to turbulence.

Channel morphology can play an important role in concentrating frazil ice, as indicated by ice plumes. These plumes are an early indicator of frazil ice and have been observed at several locations between Talkeetna and Vee Canyon when otherwise no ice was seen. Most sites occur at sharp river bends caused by outcrops protruding into the channel. The rock outcrops often create a slight backwater effect on the upstream side. Suspended frazil floes are swept into these areas and swirl about, increasing in density and ice concentration until sufficient buoyancy is obtained so that the ice rises to the surface as slush. The slush floats past the outcrop in a long narrow stream which is rapidly dissipated by the river. Any subsequent turbulence can re-entrain the slush, once again making it difficult to observe. In September these ice plumes are often observed near Gold Creek and Sherman. The flow patterns are such that these sites concentrate ice throughout freeze-up.

After November, the majority of frazil ice is generated in the rapids of Devil Canyon, Watana Canyon and Vee Canyon. However, during the initial freeze-up period in October 1982, the difference in the number of freezing degree days between Denali (370) and Talkeetna (170) suggests that the majority of the slush accumulating against the leading edge downstream of Talkeetna originates either as snowfall or as frazil in the upper river from Vee Canyon on upstream. This appeared to be verified during a flight on October 21, 1982. Estimates at various locations from Talkeetna to Watana Creek showed a consistent ice discharge in this reach, indicating that no frazil ice was being generated at the rapids at Devil Canyon and Watana on this date.

b. Cook Inlet to Chulitna Confluence

Temperatures are usually not cold enough to cause significant shore ice development in this reach prior to the relatively rapid advance of the ice cover. The initiation of ice cover formation in this reach usually occurs when tremendous volumes of slush ice fail to pass through a channel constriction near the river mouth at Cook Inlet. Between October 22 and October 26, 1982, slush ice jammed and accumulated upstream for 57 miles. Daily ice discharge estimates from Talkeetna showed a sudden increase in ice concentrations during this period. The ice discharge on October 21 was estimated at 1.3×10^5 cu ft/hr and rose steadily to 5.8×10^5 cu ft/hr on October 26 following several snow storms. Assuming that the ice cover began progressing upstream on October 22, then the progression rate was 11.5 miles per day.

As the ice cover moved upstream in 1982, staging rarely exceeded 2 feet in this reach. (Staging is a process by which the ice cover thickens, restricting flow and causing increased stages upstream of the ice front. This lowers the upstream velocity so that incoming ice may accumulate against the leading edge instead of being swept under the ice cover.) Large open water areas appeared frequently in the ice pack. Surprisingly little consolidation of the ice pack had taken place by October 26, 1982. This could be due to the shallow gradient of the channel through this reach. In low velocity areas, the ice front continued to advance by juxtaposition of ice floes at a rate proportional to the ice discharge and channel configuration. Slush ice observed at the leading edge was not submerging under the existing ice cover. All of the major tributaries to the Susitna below Talkeetna were still flowing and remained ice-free during this period. The discharge from these tributaries kept large areas at their confluences free of ice. Near Talkeetna, the river remained free of shore ice even though a large volume of slush ice from the Susitna River was continually drifting downstream. No telescoping of the ice cover was evident. The ice pack remained in the narrow thalweg channel, which in most areas constitutes only 20 percent of the flat, broad river channel. Gravel islands remained above the water surface, although the staging did divert water into some side channels.

Staging effects were larger in channels near Talkeetna. On November 2 a staff gage at Talkeetna was dry, with the nearest open water more than 1 foot below the gage. After consolidation and freezing of the ice pack about November 17, the gage had a reading of 3.6 feet, a stage increase of over 4 feet at Talkeetna due to the ice cover advance.

After the initial ice cover formation, the remainder of the lower river freeze-up process requires considerably more time. Many of the side channels that are flooded by the increased stage in the mainstem gradually become narrower as shore ice layers build up along the channel banks and the flow discharge decreases. The gradual reduction of flow during winter causes the ice cover to settle. Where the sagging ice becomes stranded, it conforms to the configuration of the channel bottom and creates an undulating ice surface. Open water areas persist through March in high velocity zones. Some side-channels and sloughs may also receive a thermal influx from groundwater upwelling sufficient to keep these channels ice-free.

c. Chulitna Confluence

A slush ice bridge which forms at the confluence of the Chulitna and Susitna Rivers initiates the ice cover progression on the Susitna River above this point. This bridge has been observed each winter during the ice observation program, occurring on November 2 in 1982, but at later dates in 1980 and 1981. The processes described in this section were observed in 1982, but similar processes have occured in other years.

The Susitna River contributes approximately 80 percent of the slush ice at the confluence area near Talkeetna, while the Chulitna and Talkeetna Rivers combined produce the remaining 20 percent. The high velocities (4-5 ft/sec) of the Susitna keep the river channel open and push the slush ice downstream. After entering the confluence area, the masses of slush ice slow down and begin to pile up at the south bend of the Susitna adjacent to the entering east channel of the Chulitna. On October 18, 1982, slush was still moving easily through this area but was covering all of the open water for about 600 feet with a translucent sheet of slush ice. By October 29, the compressed slush was still moving. The ice through this area was now white instead of translucent, since the slush had consolidated sufficiently to rise higher out of the water and partially drain.

A snow storm immediately preceded the formation of the stable ice bridge at the Susitna and Chulitna confluence on November 2, 1982. This storm caused a substantial local increase in ice discharge which could not pass through the channel. The result was a sudden consolidation of the ice cover, compacting the slush which at some point became shore-fast. The cover remained stable long enough to freeze and increase in thickness. The majority of the incoming slush ice floes then accumulated against the leading edge, causing the cover to begin advancing upstream. Approximately 10-20 percent of the incoming slush ice submerged on contact with the upstream edge, either adhering under the ice cover or continuing downstream. Ice discharge estimates at Talkeetna were substantially lower after November 2. The most dramatic effect of the ice consolidation at the confluence was the flooding on the Susitna just upstream of the confluence. The flow capacity of the ice-choked main channel was greatly reduced. Water spilled from underneath the cover, flowing laterally across the river channel towards the opposite (north) bank. Water was also diverted from upstream of the ice jam, flowing into the new channel. These diverted flows combined and entered the Chulitna east channel approximately 1,500 feet upstream of the original confluence. The total estimated discharge of the diverted flow was 700-1000 cfs, about 15-20 percent of the total flow. Substantial channel erosion was caused by these diverted flows, as subsequent depth measurements through the ice located a isolated channel about 700 feet from the left bank.

After the confluence bridge formed the ice pack advanced slowly up the Susitna River. The river gradient begins to increase at this point. Slush ice can no longer accumulate by simple juxtaposition, as the high flow velocities submerge the slush on contact with the leading edge. Staging levels of 2-4 feet are necessary before ice can continue accumulating against the upstream edge.

The processes of ice cover telescoping, sagging, open lead development and secondary ice cover progression are important characteristics through this reach. Telescoping occurs during consolidation of the ice cover. When the velocity at the leading edge is subcritical for ice progression, ice floes drifting downstream will contact the edge, remain on the surface, and accumulate upstream by juxtaposition at a rate proportional to the concentration of slush ice and to the channel width. This accumulation zone can be extremely long, generally being governed by the local channel gradient, amount of staging and extent of the resulting backwater. This buildup will continue until a critical velocity is encountered, causing the leading edge to become unstable with ice floes submerging under the ice cover. The pressure on the thin initial ice cover increases as the upstream ice mass builds up and higher velocities are reached in conjunction with upstream advance. At an undetermined critical pressure, the ice cover becomes unstable and fails. This sets off a chain reaction, and within seconds the entire ice sheet is moving downstream. Several miles of ice cover below the leading edge can be affected by this consolidation. This process results in ice cover stabilization due to a shortening of the ice cover, substantial thickening as the ice is compressed, a stage increase, and telescoping. The telescoping occurs only during each consolidation. As the ice compresses downstream, tremendous pressures are exerted on the ice cover below the accumulation zone. Here the ice mass will shift to relieve the stresses exerted on it by the upstream cover, often becoming thicker in the process. This will tend to further constrict the flow, resulting in an increase in stage. As the stage increases, the entire ice cover lifts. Any additional pressures within the ice cover will then be relieved by lateral expansion of the ice across the river channel. This process can continue until the ice cover has either expanded from bank to bank or else has encountered some other obstruction (such as gravel islands) on which the ice becomes stranded.

The ice cover over water-filled channels will continue to float. Because of constant contact with the flowing water, the ice cover erodes rapidly, sagging and eventually collapsing. This process usually occurs within days after the initial ice cover formation. In some reaches these open leads can extend for several hundred yards. A secondary ice cover generally accumulates in the open leads, and completely closes the open water by the end of March. The process is similar to the initial progression except on a smaller scale. Slush ice begins accumulating against the downstream end of the leads and progresses upstream. Generally it takes several weeks to effect a complete closure.

The ice cover continues to move up the Susitna River, although at a steadily decreasing rate as the channel gradient increases. Since the gradient and the river velocities are increasing, staging levels must increase in order to create sufficient backwater to slow velocities to allow ice juxtaposition. Although flows are only in the range of 3,000-5,000 cfs at this time, the water rises to levels equivalent to open water flows of up to 45,000 cfs. This often causes breaching of upstream berms on many of the sloughs and side-channels. Significant quantities of slush ice are swept into these channels, entering the backwater area caused by the downstream staging. The slush ice then consolidates and freezes in the side-channel, resulting in ice thicknesses of up to 5-6 feet. This process occurs at different levels in different years and at different locations on the river.

Many of the sloughs have groundwater seeps which persist through the winter. This groundwater is relatively warm, with winter temperatures of 1°-3°C (R&M, 1982d). This is sufficiently warm to prevent a stable ice cover from forming in those areas not filled with slush ice. This thermal influence is evident as long, narrow, open leads extending thousands of feet down the sloughs.

d. Gold Creek to Devil Canyon

The reach from Gold Creek to Devil Canyon freezes over gradually, with complete ice cover occurring much later than on the river below it. The delay can be explained by the relatively high velocities encountered due to the steep gradient and single channel, and to the absence of a continuous ice pack progression past Gold Creek. Another factor for the slow ice cover development is that by the time the ice cover reaches this reach, there is less frazil ice from upstream, due to the upper river having already frozen over.

The most significant features of freeze-up between Gold Creek and Devil Canyon are wide border ice layers, ice build-up on rocks and formation of ice covers over eddies. Ice sills have been identified at several locations below Portage Creek. Generally, the constrictions form when the rocks to which the frazil ice adheres are located near the water surface. When air temperatures are cold (less than -10°C), the ice covered rocks will continue accumulating additional layers of frazil until they break the water surface. The ice-covered rocks effectively increase the water turbulence, stimulating frazil production and accelerating ice formation. The ice sills are often at sites constricted by border ice. This creates a backwater area by restricting the streamflow, subsequently causing extensive overflow onto the border ice. The overflow bypasses the ice sills and re-enters the channel at a point further downstream. Within the backwater area, slush ice accumulates in a thin layer from bank to bank and eventually freezes. A number of individual ice bridges form in this reach by the process of border ice growth.

Since the ice formation process in this reach is primarily due to border ice growth, the processes described for the Talkeetna to Gold Creek reach do not occur. There is only minimal staging. Sloughs and side-channels are not breached at the upper end, and remain open all winter due to groundwater inflow. Open leads exist, but are primarily in high-velocity areas between ice bridges.

e. Devil Canyon

Ice processes in Devil Canyon create the thickest ice along the Susitna River, with measured thicknesses of up to 23 feet (R&M, 1981c). The canyon has a narrow, confined channel with high flow velocities and extreme turbulence, making direct observations difficult. Consequently, in 1982 a time-lapse camera was mounted on the south rim of the canyon to document the processes causing these great ice thicknesses.

The time-lapse camera provided documentation that the ice formation through Devil Canyon is primarily a staging process. Large volumes of slush ice enter the canyon, and additional frazil ice is generated in the canyon. The slush ice jams up in the lower canyon, and the ice cover progresses up the canyon through large staging processes. However, the slush ice has little strength, and the center of the ice cover rapidly collapses after the downstream jam disappears and the water drains from beneath the ice. The slush ice bonds to the canyon walls, increasing in thickness each time the staging process occurs. The ice cover forms and erodes several times during the winter.

f. Mid-Winter

The ice cover on the Susitna River is extremely dynamic. From the moment that the initial cover forms, it is either thickening or eroding. Slush ice will adhere to the underside of an ice cover in low-velocity areas. Cold temperatures will subsequently bond this new layer to the surface ice.

If the ice cover could ever be considered stable, it would be at the height of its maturity in March. During this period, snowfalls become less frequent and very little frazil slush is generated. The only air water interfaces are at the numerous open leads which persist over turbulent reaches or groundwater seeps. These are usually of short length with insufficient heat exchange taking place to generate significant amounts of frazil ice.

Discharges in March are generally at the annual minimum, reducing the flowing water to a shallow and narrow thalweg channel, indicated by a depression in the ice cover. The depressions form shortly after ice cover formation when the compacted slush ice is flexible and porous. Water levels decrease through March, resulting in the floating ice cover grounding on the river bottom. Water gradually percolates out of the cover. Alternating layers of bonded and unconsolidated ice crystals form within the ice pack when the receding level of saturated slush freezes at extreme air temperatures. The result is the formation of rigid layers at random levels, the layers representing the frequency of critically cold periods.

Breakup Processes

Breakup processes on the Susitna River are similar to those described for other northern rivers, with a pre-breakup period, a drive, and a wash. (Michel, 1971). The general processes involved in breakup will be described, together with specific examples from the Susitna River.

The pre-breakup period occurs as snowmelt begins due to increased solar radiation in early April. This process generally begins at the lower elevations near the mouth of the Susitna River, working its way north. By late April, the snow has generally disappeared from the river south of Talkeetna and has started to melt along the river above Talkeetna. Snow on the river ice generally disappears before that along the banks, either due to overflow or because the snowpack is simply thinner on the river due to exposure to winds. As the river discharge increases, the ice cover begins to lift, causing fractures at various points. On the Susitna River, long, narrow leads begin to form. Small jams of fragmented ice form at the downstream ends against the solid ice cover. These ice jams often resemble a U- or V-shaped wedge, with the apex of the wedge corresponding to the highest velocities in the flow distribution. The constant pressure exerted by these wedge-shaped ice jams effectively lengthens and widens many open leads, reducing the potential for major jams at these points.

The drive, or the actual downstream breakup of the ice cover, occurs when the discharge is high enough to break and move the ice sheet. The intensity and duration is dependent on meteorological conditions during the pre-breakup period. Both weak and strong ice drives have been observed on the Susitna River during the last 3 years. In 1981, there was a minimal snowpack and only light precipitation during spring. Air temperatures were warmer than normal in early spring, but returned to normal in April, resulting in slow melting of what snow there was. Consequently, there was not a sufficient increase in flow to develop strong forces on the ice cover, and the ice tended to slowly disintegrate in place. Although some ice jams did occur during the drive, they did not tend to last long, and the breakup was generally mild.

Conditions were reversed in 1982. There was a significant snowpack still remaining in late April, and temperatures were slightly cooler than normal. The snowpack on the ice prevented weakening of the ice, which remained strong. The final ice push did not begin until May 10. The ice was sufficiently strong to cause jams more severe than normal. Near RM 128 below Sherman, a dry jam formed which diverted practically all the flow out of the mainstem into side channels. Closer to Talkeetna, a jam formed at RM 107 that lasted for 3 days, jamming ice for over a mile and damaging sections of the Alaska Railroad track.

Jam sites generally have similar channel configurations, consisting of a broad channel with gravel islands or bars, and a narrow, deep thalweg confined along one of the banks. Sharp bends in the river are also good jam sites. The presence of sloughs on a river reach may indicate the locations of frequently recurring ice jams. Many of the sloughs on the Susitna River between Curry and Devil Canyon were carved through terrace plains by some extreme flood. Summer floods, although frequently flowing through sloughs, do not generally result in water levels high enough to overtop the river bank. During breakup, however, ice jams commonly cause rapid, local stage increases that continue rising until either the jam releases or the sloughs are flooded. While the jam holds, channel capacity is greatly reduced, and flow is diverted into the trees and side-channels, carrying large amounts of ice. The ice has tremendous erosive force, and can rapidly remove large sections of bank. Old ice scars up to 10 feet above the bank level have been noted along side-channels near this reach. It appears that these sloughs are an indicator of frequent ice jams on the adjacent mainstem, influencing the stability and longevity of these jams by relieving the stage increases and subsequent water pressures acting against the ice.

Stable ice jams are sometimes created when massive ice sheets snap loose from shore-fast ice and pivot out into the mainstem flow. This occurred near Indian River in 1982, resulting in an ice jam that lasted for several days. The ice sheet was approximately 300 feet in diameter and probably between 3 and 4 feet thick. The upstream end pivoted around until it contacted the right bank of the mainstem. The ice sheet was then in a very stable position, jammed against the steep right bank and grounded in shallow water along a gravel island on the left bank. Several small ice jams upstream had released and were accumulating against this ice sheet, extending the jam for about one-half mile. The water level rose, with an estimated 2,000 cfs flowing around the upstream end of a gravel island into a side channel, overtopping the entrance berm to an adjacent slough. Although the estimated discharge at Gold Creek was less than 6,000 cfs, the normal summer flows required to breach this berm exceed 20,000 cfs. This illustrates the extreme water level changes caused by jams. Many ice floes also drifted through this narrow access channel and grounded in the slough as the flow dissipated over a wider area.

As drifting ice floes accumulated against the upstream edge of this jam, the floating layer became increasingly unstable. At some critical pressure within this cover, the shear resistance between floes was exceeded, resulting in a chain reaction of collisions that rapidly caused the entire cover to fail. At this point, several hundred feet of ice cover consolidated simultaneously. These consolidation phases occurred frequently during a 4 hour observation period. The frequency was dependent on the volume of incoming ice floes. With each consolidation, a surge wave resulted. During one particular consolidation of the entire half-mile ice jam, a surge wave broke loose all the shorefast ice along the left bank and pushed it onto an adjacent gravel island. These blocks of shore ice were up to 4 feet thick and 30 feet wide. The zone affected was almost 100 feet long, with the event lasting only a few seconds. This process is essentially the same as telescoping during freeze-up except that the ice is in massive rigid blocks instead of fine frazil slush, and is thus capable of eroding substantial volumes of material in a very short time. The ease with which these ice blocks were shoved over the river bank indicates the tremendous pressures that build within major ice jams.

During all of the observed consolidations, the large ice sheet forming the key of the jam never appeared to move or shift. The surge waves would occasionally overtop the ice sheet, sending smaller ice fragments rushing over the surface of the sheet. Towards the end of the day, the ice sheet began to deform. Incident solar radiation, erosion and shear stresses were rapidly deteriorating this massive ice block. Final observations showed it to have buckled in an undulating wave and fractured in places.

In general, the final destruction of the ice cover is accomplished by a series of ice jams which break in succession and are added to the next jam. This mass of ice continues building as it moves downstream. Upstream from this accumulation, the river channel is commonly ice-free except for stranded ice floes and some drifting ice coming from above Devil Canyon.

Near the Chulitna confluence the final ice release leaves accumulations of ice and debris stranded on the river banks. When ice jams on this river reach release, the ice floes piled up along the banks do not move, probably due to strong frictional forces against the boulder strewn shoreline. This creates a fracture line parallel to the flow vector where shear stresses were relieved. The main body of the ice jam flows downstream, leaving stranded ice deposits with smooth vertical walls at the edge of water. Shear walls up to 16 feet high have been measured. In this case, the extreme height of the water surface within the ice jam was demarcated by a difference in color. A dark brown layer represented the area through which water had flowed and deposited sediment in the ice pack. A white layer near the surface was free of sediment and probably was not inundated by flowing water.

Environmental Effects

Ice processes are a major environmental force on the Susitna River, affecting channel morphology, vegetation, and aquatic and terrestial habitats. The impacts vary along the length of the river. The environmental impacts of ice processes will be summarized in the following paragraphs. This will be followed by a brief discussion of potential modifications to the ice processes of the Susitna River caused by operation of the proposed hydroelectric development, and the subsequent changes in environmental processes.

Ice processes appear to be a major factor controlling morphology of the river between the Chulitna confluence and Portage Creek. Areas with frequent jams have numerous side-channels and sloughs. The size and configuration of existing sloughs appear to be dependent on the frequency of ice jamming in the adjacent mainstem.

Major ice events probably formed the sloughs when ice floes surmounted the river banks. The size and configuration of existing sloughs is dependent on the frequency of ice jamming in the adjacent mainstem. Ice floes can easily move the bed material, substantially modifying the elevation of entrance berms to the sloughs. In May, 1983, a surge wave overtopped a shallow gravel bar that isolated a side channel near Gold Creek. The surge also created enough lifting force to shift large ice floes. These floes barely floated but were carried into the side channel by the onrush of water, dragging against the bottom for several hundred feet, scouring troughs in the bed material. This same process will also enlarge the sloughs. When staging is extreme in the mainstem and a large volume of water spills over the berms, then ice floes drift into the side channel. These ice floes scour the banks and move bed material, expanding the slough perimeter. This scouring action by ice can therefore drastically alter the aquatic habitat.

Ice processes do not appear to play as important a role in the morphology of the Susitna River below the Chulitna confluence. This river reach below the confluence regularly experiences extensive flooding during summer storms. These seem to have significantly more effect on the riverine environment than processes associated with ice cover formation (R&M, 1982a, 1982c). This reach is characterized by a broad, multichannel configuration with distances between vegetated banks often exceeding 1 mile. The thalweg is represented by a relatively deep meandering channel that usually occupies less than 20 percent of the total bank to bank width. At low winter flows the thalweg is bordered by an expanse of sand and gravel (R&M, 1982c). Although ice cover progression frequently increases the stage about 1-2 feet above normal October water levels, no significant flooding takes place, although some sloughs and the mouths of some tributaries do receive some overflow. The ice cover below Talkeetna is usually confined to the thalweg, and surface profiles do not approach the vegetation trim line along the banks.

The erosive force of ice effects vegetation along the river. The frequency of major ice jam events is often indicated by the age or condition of vegetation on the upstream end of islands in the mainstem. Islands that are annually subjected to large jams usually show a stand of ice scarred mature trees ending abruptly at a steep and often undercut bank. A stand of young trees occupying the upstream end of islands probably represents second generation growth after a major ice jam event destroyed the original vegetation. Vegetation is prevented from re-establishing by ice jams that completely override these islands.

Ice processes have several impacts on aquatic habitat. The sloughs may fill with slush ice, which then forms a ice cover up to 5-6 feet thick. This would prolong colder than normal water temperatures in the slough. (It could also cause problems for any beavers with lodges in the slough by filling pools with ice). Diversion of flow and ice into the sloughs may cause large changes in channel morphology. Large amounts of silt may be deposited in the system at breakup, migrating downstream during high flows in the summer and covering good spawning habitat.

Operation of the Watana and Devil Canyon projects would significantly modify the ice regime of the river below Devil Canyon. Flow rates will be 2-4 times greater than natural winter flow rates, with water temperatures of 2°-4°C immediately below the dams. The frazil ice generated in the upper basin in early winter will be trapped by the upper reservoir. Once Devil Canyon Dam is built, the major rapids in the system will be flooded, further reducing frazil ice generation. These major changes in the physical system and in the hydrologic and thermal regimes will combine to greatly delay ice formation below the project.

Progression of the ice cover on the lower Susitna is now due to rapid juxtaposition of ice floes from the upper river, with the Susitna River contributing 70-80 percent of the ice. Much of this ice will not be available under post-project conditions. Consequently, the ice cover will not form until significantly more border ice has formed on the lower river. Full ice cover development will be delayed for several weeks.

Water temperature below the project will not decay to the freezing level for many miles. It is more likely that an ice cover will form on the river above the Chulitna confluence when Watana is the only project in operation, than when Devil Canyon is also in operation. The ice cover now progresses upstream from the confluence when slush ice bridges a narrow channel at the confluence. One question now under study is the ice formation process at this point, and whether sufficient ice will be generated under post-project conditions to cause this bridge to form. If ice cover does progress upstream of the Chulitna confluence, staging levels will likely be to a higher level, as flow levels and velocities will be greater than under natural conditions.

Breakup patterns will change on the river below the project. The warm water released from the reservoirs, combined with the increased air temperatures and solar radiation in spring, will cause the mainstem ice cover to decay earlier in the season. Flow levels will be significantly lower in May as the reservoir stores flow from upstream. No ice will reach the river above the Chulitna confluence from its upper reaches. This will result in the breakup processes now occurring above the Chulitna confluence being greatly attenuated or eliminated. Below the Chulitna confluence, breakup impacts will probably also be reduced, although ice thicknesses may be increased due to the increased winter flow levels.

Summary

Development of the Susitna Hydroelectric Project will significant change the ice processes on the Susitna River. Below Talkeetna, ice formation will be significantly delayed due to the reduction of frazil and slush ice from the Susitna River above Talkeetna. Above the Chulitna confluence, ice formation will be delayed or eliminated due to the large volumes of warm water released from the project and to the trapping of ice from the upstream reaches. Both field studies and modelling are attempting to define post-project conditions at specific sites. The results of these studies will be utilized in developing the environmental impact statement for the project.

References

Alaska Department of Fish & Game. 1982. Susitna Hydro Aquatic Studies Phase II Basic Data Report. Anchorage, Alaska. 5 vol.

Ashton, George D. 1978. River Ice. Annual Reviews on Fluid Mechanics. Vol. 10. pp. 369-392.

Benson, Carl S. 1973. A Study of the Freezing Cycle in an Alaskan Stream. Fairbanks, Alaska. Institute of Water Resources. 25 pp.

Michel, Bernard. 1971. Winter Regime of Rivers and Lakes. U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire. 130 pp.

Newbury, Robert W. 1968. The Nelson River: A Study of Subarctic River Processes. University Microfilms, Inc., Ann Arbor, Michigan. 319 pp.

Osterkamp, Tom E. 1978. Frazil Ice Formation: A Review. Journal of the Hydraulics Division. Proceedings of the American Society of Civil Engineers. September, pp. 1239-1255.

R&M Consultants, Inc. 1981a. Ice Observations 1980-1981, Anchorage, Alaska. Alaska Power Authority. Susitna Hydroelectric Project. Report for Acres American, Inc. 1 vol.

__________. 1981b. Preliminary Channel Geometry, Velocity and Water Level Data for the Susitna River at Devil Canyon. Anchorage, Alaska. Alaska Power Authority Susitna Hydroelectric Project. Report for Acres American, Inc. 1 vol.

__________. 1982a. Hydraulic and Ice Studies. Anchorage, Alaska. Alaska Power Authority. Susitna Hydroelectric Project. Report for Acres American, Inc. 1 vol.

__________. 1982b. Ice Observations 1981-82. Anchorage, Alaska. Alaska Power Authority. Susitna Hydroelectric Project. Report for Acres American, Inc. 1 vol.

__________. 1982c. River Morphology. Anchorage, Alaska. Alaska Power Authority. Susitna Hydroelectric Project. Report for Acres American, Inc. 1 vol.

__________. 1982d. Slough Hydrology. Anchorage, Alaska. Alaska Power Authority. Susitna Hydroelectric Project. Report for Acres American, Inc. 1 vol.

__________. 1983. Susitna River Ice Study 1982-1983. Anchorage, Alaska. Alaska Power Authority. Susitna Hydroelectric Project. Report for Harza/Ebasco Joint VEnture. 1 vol.

U.S. Geological Survey. 1982. Water Resources Data, Alaska, Water Year 1981. Anchorage, Alaska. Water Resources Division, U.S. Geological Survey. United States Department of the Interior.

ALASKAN HYDROPOWER: BALANCING THE LONG RUN ADVANTAGES WITH THE SHORT RUN PROBLEMS

By John S. Whitehead

Abstract

Hydroelectric facilities have been operating in Alaska since the turn of the twentieth century. Through the use of historical documents drawn from twelve hydro installations, this paper looks at the historical performance record of Alaskan hydropower. The analysis compares the advantages of hydropower with its disadvantages in terms of electric power prices, operational reliability, capital financing, power demand growth projections, and legislative intervention in the operation of the installations. The advantages and disadvantages are analyzed in terms of short run and long run time frames.

Introduction

Over the last decade the promotion of new hydroelectric power projects has been particularly strong in Alaska. Much debate has taken place in the public media both for and against this expanded use of Alaska's water resources. The debate has become particularly heated since 1981 when the Alaska legislature authorized $460 million for energy related projects including funds for the construction of seven medium-sized hydroelectric projects as well as feasibility and reconnaissance studies of a dozen potential projects ranging in size from a few thousand kilowatts to the mammoth 1.6 million KW Susitna project (SLA 1981, Chap. 90).

Advocates of hydropower often point to the use of a renewable energy source, water, which would free the state from the use of fossil fuels with ever escalating costs. Hydro is also claimed to provide stable and predictable power prices. Opponents often cite such disadvantages as runaway capital costs, environmental hazards and cheaper kilowatt hour costs coming from alternative sources such as natural gas. In the debate, as it appears in the media, there is rarely any systematic reference to Alaska's actual

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[1] Associate Professor, Department of History, University of Alaska, Fairbanks, 99701

experience with hydropower. At best, selected statistics from particular projects, sometimes from projects in other states, are brought forward.

In order to compile a systematic account of Alaska's actual experience with hydroelectric power I examined the records and operational histories of 12 hydroelectric facilities which were operational or under construction in the summer of 1981 (see Table 1). The selection covers plants built between the early 1900s and the present day and ranging in capacity from 1600 KW to 47,160 KW. It includes plants in both southeast and southcentral Alaska--the only areas of the state with major hydroelectric facilities. The survey reveals that hydropower has had definite long run advantages in terms of power price and operational reliability over periods of 30-50 years. On the other hand definite short run problems in terms of power price and operational reliability have occurred over periods of less than 10 years. Such problems have been great enough, in some cases, to jeopardize the financial viability and continued operation of certain projects. The principal tool used to balance the short run problems with the long run advantages has been legislative intervention in the operation of the projects (Whitehead, 1983).

Long Run Advantages

In general the histories reveal that in the long run (i.e. 30-50 years) hydroelectric projects have fulfilled and exceeded the expectations of their builders for three primary reasons. 1) Hydroelectric projects were responsible for bringing reasonably priced--and in some cases very low priced--electric power to Alaskan communities from the turn of the century to the early 1960s--and into the 1980s in southeastern Alaska. 2) The operation of Alaska's hydro projects has been extraordinarily reliable with examples of plants in continuous operation from 1913 to the present day.

Table 1

Hydroelectric Facilities Surveyed

	Operating Authority	Plant Name	Location	Capacity KW	Ownership	Date of Initial Operation	
1	Alaska Elec. Light and Power	Gold Creek	Juneau	1,600	Private	1904	
2	Alaska Elec. Light and Power	Annex Creek	Juneau	3,500	Private	1916	
3	Alaska Elec. Light and Power	Salmon Creek (Upper)	Juneau	2,800	Private	1913	
	Alaska Elec. Light and Power	Salmon Creek (Lower)	Juneau	2,800	Private	1914	
4	Sitka Public Utilities	Blue Lake	Sitka	6,000	Municipal	1961	
5	Sitka Public Utilities	Green Lake	Sitka	16,500	Municipal	1982	
6	Ketchikan Public Utilities	Ketchikan Lakes	Ketchikan	4,200	Municipal	1923	
7	Ketchikan Public Utilities	Beaver Falls	Ketchikan	5,000	Municipal	1947	
8	Ketchikan Public Utilities	Silvis	Ketchikan	2,100	Municipal	1968	
9	Ketchikan Public Utilities	Swan Lake	Ketchikan	22,000	Municipal	1983	(anticipated)
10	Chugach Electric Association	Cooper Lake	Cooper Landing	15,000	REA	1961	
11	Alaska Power Administration	Snettisham	Juneau	47,160	Federal	1973	
12	Alaska Power Administration	Eklutna	Anchorage	30,000	Federal	1955	

3) The long operational life of some plants has led to decreasing costs over time.

Low Priced Power.

Throughout the history of Alaska in the 20th century, the high cost of living has been a constant and recurring theme. One element in that high price has been electricity generated by imported fossil fuels--primarily diesel generation. Before the discovery of natural gas on the Kenai Peninsula and in Cook Inlet in the late 1950s and early 1960s, the lowest priced power in Alaska was hydropower.

Ketchikan was the first city in Alaska to have low priced power. Ketchikan's first developed water resource, Ketchikan Creek, was placed in service as early as 1903. By 1922 Ketchikan, with a population of approximately 2,500, had a utility capacity of 2,600 KW and a power price of a little over 2¢ per kwh (Dort, 1924). Steady growth in the capacity of the Ketchikan Lake facility from 1923 to 1957 and construction of the Beaver Falls facility in 1946-47 gave Ketchikan a system capacity of 10,000 KW in 1957 with a power price under 2¢ per kwh--less than the U.S. national average. In that year 500 kwh cost $9.88 in Ketchikan versus $10.81 in Juneau, $14.50 in Anchorage, and $27.50 in Fairbanks where there was no hydropower. Ketchikan's low prices resulted in an average annual power use of 5,800 kwh per residential customer compared to 3,780 kwh in Juneau, 3,759 kwh in Anchorage, and 2,800 kwh in Fairbanks (USFPC, 1960). Hydropower was responsible for making Ketchikan Alaska's most electrified city in the first half of the 20th century.

Juneau's experience with hydropower was similar to Ketchikan's. Several hydroelectric plants were constructed in Juneau before World War I by various private industrial corporations to power stamp mills in the gold mining industry. Surplus power was then sold to a private utility, Alaska Electric Light and Power, for distribution to utility customers (Stone, 1980). Juneau's electric rates, while not as low as Ketchikan's, were nonetheless reasonable. In 1922 AEL&P's rates varied from 3-6¢ per kwh depending on use (Dort, 1924). In 1957 Juneau still offered power at an average of 3¢ per kwh (USFPC, 1960).

Juneau and Ketchikan both had utility systems based on modern hydroelectric plants before the Second World War. Reasonably priced electricity was the norm in these cities. More dramatic illustrations of the effect of hydropower on electric prices can be seen in areas that began utility production with less efficient power systems and later switched to modern hydro facilities.

From 1912 to 1961 Sitka relied on an antiquated utility system which was composed at varying times of two 160 KW hydro generators, an inefficient steam electric plant, and diesel generators. In 1950 Sitka's system had a capacity of 2,000-3,000 KW, depending on the season, and produced power at 7-8¢ per kwh (USBR, 1954). In 1957 500 kwh sold for $26.50 (5.3¢ per kwh). But few customers could get this price for such large consumption as the average annual use was only 1750 kwh per customer or only 150 kwh a month (USFPC, 1960). In 1961 the modern Blue Lake hydro project went on line. By 1968 power prices had dropped to $19 per 500 kwh with a rise in annual customer consumption to 6,516 kwh (USFPC, 1969).

In Anchorage a similar scenario took place. The city's first hydro installation, the 1,000 KW Eklutna Creek project, began production in 1929. Unfortunately, hydro development did not keep pace with Anchorage's post World War II growth. In 1947-48 Anchorage with an estimated population of 19,000 had a system capacity of 6,800-7,700 KW, including 2,000 KW in hydro, 1,300 KW in diesel generators, and the remainder in a makeshift steam electric system salvaged from a beached naval vessel. Power was priced at $17.08 per 500 kwh (3.4¢ per kwh), but the production cost of the steam and diesel power was 1¢ per kwh above that price. The low cost of the hydropower subsidized the non-hydropower to create the relatively reasonable price of 3.4¢ per kwh (USBR, 1948). With the completion of the 30,000 KW Eklutna hydroelectric plant in 1955 prices dropped to $14.50 per 500 kwh (2.9¢ per kwh) by 1957 (USFPC, 1960).

The experiences of Ketchikan, Sitka, Juneau, and Anchorage certainly indicate that hydropower was the key to bringing the first reasonably priced electricity to Alaska.

Long Run Dependable Operation

Hydroelectric plants in Alaska have compiled a record of long term reliable operation reaching decades beyond the term in which it takes to amortize their capital costs. (Federal projects are scheduled to payout in 50 years. Municipally financed projects payout in shorter periods of approximately 30 years.) The Ketchikan Lakes facility has been operating continuously since 1923, though its capacity has been increased from 2,600 KW (1923) to 4,200 KW (1957). The 1923 facility was in fact a refurbishment of a 1912 plant. So the date of reliable continuous operation can be increased by a decade.

Two particularly striking instances of long, reliable operational lives are the Annex Creek and the Salmon Creek projects in Juneau. Constructed in 1913-14 and 1915-16 respectively, they were Juneau's basic source of electricity until 1973 (Stone, 1980). The plants were owned until 1972 by a California firm, A-J Industries, which sold wholesale power to the local utility, AEL&P, for retail distribution. A-J Industries kept the facilities in poor physical repair after the Alaska-Juneau mine closed in 1944 and also made no public disclosures of the financial aspects of its hydroelectric operations. As a result the U.S. Bureau of Reclamation as well as AEL&P considered both Annex and Salmon Creek outmoded and inefficient facilities. They both assumed that these plants would be closed after the Snettisham plant began operation. In 1972 AEL&P purchased the entire power system of A-J Industries with the expectation that it would use only the company's transmission and distribution lines, not its operating facilities (Whitehead, 1983).

In 1973 the new 47,160 KW Snettisham project went on line. Problems with its transmission system, however, led to repeated power outages in it first years of operation, thus forcing AEL&P to continue to use Annex Creek and Salmon Creek for base load power production. The utility discovered that the operation, both physical and financial, of these plants was so reliable that it has continued to run them 365 days a year after the transmission problems at Snettisham were corrected (Whitehead, 1983). In fact, the continued reliable and economical operation of these plants has caused an underconsumption of Snettisham power (see Short Run Problems--Surplus Capacity).

Rather than being junked as outdated projects, both Annex Creek and Salmon Creek are being refitted for automatic control operation which will further reduce their operating cost. The generating capacity of both plants is also being increased with loans from the Alaska Power Authority (SLA, 1981, Chap. 90).

Decreasing Costs Over Time

Hydroelectric projects have high capital costs compared to their operating costs; the price of electricity produced is thus composed of a substantial cost, from 50-90% in some cases, to amortize the capital and a smaller amount for operation and maintenance. If the capital component of the project remains operational after its initial cost has been amortized, the price of power production will obviously drop to the operation and maintenance costs--unless a large new infusion of capital is required to rehabilitate the project. Such decreasing costs over time have been acknowledged by utility operators in Juneau and Ketchikan--though reliable historic cost data in these locations is hard to come by. It appears, for example, that in 1981 the Annex Creek and Salmon Creek facilities could produce power for less than 20 mills per kwh compared to 22.5 mills per kwh charged by A-J Industries in 1962.

Possibly the most reliable data to illustrate the decreasing cost phenomenon can be found in the Eklutna plant in Anchorage, operated by the Alaska Power Administration. Eklutna went on line in 1955 and is now more than halfway into its 50 year payout schedule which will terminate in 2005. In that year the price of Eklutna power should fall dramatically. A few figures will help illustrate this. In 1979 the wholesale power rate at Eklutna was 12.5 mills per kwh. More than half of the price, however, included interest and amortization expenses. The operation and maintenance costs at Eklutna for FY 1979 were $693,928; if the allowance for plant depreciation is added the costs rise to $882,496. These costs divided by the firm annual energy generation of 153 million kwh would yield a price for Eklutna power of 5.8 mills per kwh, including depreciation, or 4.5 mills per kwh, excluding depreciation. It is possible that operation and maintenance expenses may rise over the years. In fact, APA announced a 21% price increase in January 1980. This, however, may be offset by increased production through rewinding the generators and upping their capacity by

15%. Soon after the turn of the 21st century, it is definitely possible that Eklutna will be producing power for less than 10 mills per kwh in 2005 prices. Few other known sources of power offer such possibilities (APA, 1980).

Short Run Problems

While the long run advantages cited above make a convincing case for hydropower in Alaska, the histories of the twelve facilities in my study revealed a number of short run problems which in some cases called the continued use of hydropower into question and in others produced a remarkably high price for power. The principal short run problems were 1) high power prices resulting from the debt service costs of new projects, 2) substantial variations in the annual water flow--and consequently of the annual power production--in some projects, 3) competition from natural gas, and 4) underconsumption of power.

High Power Prices Resulting From Debt Service Costs

The completion of Sitka's Blue Lake project in 1961 brought reasonably priced power to that community. By 1969 Blue Lake was beginning to reach its installed capacity, based on a low reservoir level, of 6,000 KW. To prepare for future demand the city purchased a 2,000 KW diesel generator in addition to 1,100 KW in diesel units that it already owned. Several good water years after 1969 staved off the need to generate substantial quantities of diesel power. But by 1978-79 Sitka was generating 10-15% of its powers needs through diesel production. Consequently, the price of 500 kwh of power, which had risen from only $19 in 1968 to $20.90 in 1976, rose to $25.60 in 1979. Diesel generation was eroding Sitka's reputation of low-priced electricity. (Official Statement $54,000,000, 1979).

To re-establish total hydropower generation the city embarked on plans to construct the 16,500 KW Green Lake project with a $54 million bond sale. The city was able to market the bonds at 7 5/8% interest in 1979, but under conditions which were far from ideal. The bond underwriters, Dillon Read and Co. required Sitka to refinance its outstanding utility debt as a portion of the new bond issue. Thus the city was forced to pay 7 5/8% interest on some of the Blue Lake bonds it had sold in 1961 for 4%. The utility was also required to raise its electric rates so that revenues would bring in 1.25 times the amount required for debt service. This translated into an overall 45% increase in Sitka's electric rates. That 500 kwh of power which cost $25.60 in 1979 rose to $38 in November 1980. (Official Statement $54,000,000, 1979).

The debt service requirements to build Green Lake raised Sitka's power price in the short run far beyond what it would have cost to add small annual increments of diesel generation. The city was willing to accept a substantial, though predictable, rate increase from hydropower to prevent the potentially uncontrollable rate rise which might come from ever increasing diesel generation in the long run. Sitka had to pay now for what it hoped would be cheaper power in the future.

Annual Waterflow Variation

Substantial variations in annual waterflow and a consequent variation in annual power production have occurred at two hydroelectric facilities in southcentral Alaska--Eklutna and Cooper Lake. While the average energy production over any decade has been reliable, the peaks and valleys in individual years require closer examination as potential problem areas.

Before Eklutna was constructed, the Bureau of Reclamation noted that it did not have sufficient streamflow data to make accurate predictions for

Eklutna's firm annual energy production. The Bureau set a target in 1948 of 100 million kwh of critical year firm energy and 43.6 million kwh of non-firm energy (USBR, 1948). More streamflow data was accumulated during the years of construction, and the Bureau revised the critical year estimate to 137 million kwh in 1955. Later the figure was raised to 153 million kwh.

In the first decade of Eklutna's operation water flow was sufficient to maintain a level of generating capacity substantially above the critical year estimates. The good years, however, came to an end in 1969. From 1969 to 1976 a period of poor water years severely lowered Eklutna's power production. The Alaska Power Administration, the operator of Eklutna, drew down the reservoir for a number of years to maintain capacity, but in 1973 even this option was no longer viable. In FY 1974 Eklutna produced only 86.5 million kwh of power--less than 57% of its estimated firm annual production. Low power production continued in FY 1975. Exceptionally good water years, however, came after 1976, and in FY 1980 Eklutna produced 198,864 kwh or 130% of its firm annual supply. Table 2 illustrates the power variation at Eklutna (APA, 1980).

A similar water flow problem has been encountered at the Cooper Lake hydro project, operated by the Chugach Electric Association. Cooper Lake's annual firm energy output is approximately 41 million kwh. Chugach representative Tom Kolasinski noted in 1981 that annual generation has fluctuated between 24 and 60 million kwh. As a result of this fluctuating water flow, Chugach did not deem it feasible to raise Cooper Lake's original installed capacity of 15,000 KW to the anticipated 30,000 KW (Whitehead, 1983).

Table 2

Annual Generation of Eklutna Power Project[a]

FY		Million kwh
1955		43.8[b]
1956		119.3[b]
1957		136.7[b]
1958		164.5
1959		165.8
1960		188.2
1961		198.8
1962		150.5
1963		156.5
1964		159.1
1965		135.3[c]
1966		138.9
1967		184.2
1968		164.3
1969		168.0
1970		160.8
1971		127.3
1972		159.2
1973		142.8
1974		86.6
1975		120.9
1976		160.2
1976	(Third Quarter)	24.7[d]
1977		174.4
1978		193.6
1979		153.0
1980		198.9
1981		196.3

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[a] Source: Alaska Power Administration, March 1982.

[b] Project capability exceeded demand in early years of operation.

[c] Low production mainly due to draw down of reservoir in 1964 to permit repairs to earthquake damage.

[d] After FY 1976 the federal fiscal year changed from July 1-June 30, to October 1-September 30. This entry covers July 1, 1976, to September 30, 1976.

Annual water flow variation and a resulting variation in power production are expected in all hydroelectric projects. But the variation in Anchorage seems high. At Eklutna, production has fluctuated between 199 million kwh and 87 million kwh--a drop of 57% from the high to the low. Similar figures hold for Cooper Lake. By comparison, power production in Ketchikan has fluctuated between 68 million kwh and 57 million kwh for all three plants in its municipal system--a drop of 16% from the high to the low. One may well wonder if such wide variations as those in Anchorage indicate that hydropower in certain locations is an unreliable power source. What would have happened if low water years had come 10 to 15 years earlier when Anchorage was more dependent on Eklutna's production? In 1957, for example, the energy demand in Anchorage was 154 million kwh. If Eklutna's production had dropped from 140-150 million kwh to 86.6 million kwh, Anchorage would have faced a power crisis. The two utilities with operating capacity, Chugach and the Anchorage Municipal Light and Power Department, would have been hard pressed to fill the gap from their steam and diesel plants since their combined capacity was little more than half of Eklutna's 30,000 KW.

Alaska Power Administration head Bob Cross has noted that the variation in Eklutna's production requires closer scrutiny. Before 1968 APA operated Eklutna on a "critical year" mode. Water in the reservoir was conserved in good water years so that the firm target of 137 million kwh could be met in poor water years. After 1968, when hydro was no longer the major source of power in Anchorage, APA shifted its mode of operation to "maximum annual energy production." Under this mode all the available reservoir capacity was used for energy production in good years rather than stored for poor years. According to Cross a severe drop in power production would not have occurred if poor water years had come earlier. He estimated that under critical year operation Eklutna could still have produced 130 million kwh annually under drought conditions (Whitehead, 1983).

Cross' explanation is helpful. But let us look at the figures again. Even under "critical year" operation, the variation in Eklutna's power production would have been substantial if a drought had occurred. From 1958 to 1968 Eklutna produced substantially more than 137 million kwh, except in the earthquake year of 1964. If a drought had come in the late 1950s or early 1960s, Eklutna's production could have fallen by as much as 65-70 million kwh from a high of 199 million (1961) to an estimated low of 130 million kwh--a drop of 35% between the high and the low. Chugach and AML&P would not have been as hard pressed to generate the difference with diesel and steam, but the price of electricity would certainly have risen in the days before cheap natural gas became an alternative fuel (Whitehead, 1983).

Much of my above concern is hypothetical. The poor water years came after Eklutna had acquired a reputation for good service to Anchorage and at a time when alternate energy production from natural gas was cheaper than hydropower. But what about such variations in future projects? Consumers who have enjoyed an abundance of cheap hydropower for a series of good water years may react negatively to a drop in hydro production and a consequent rise in electric rates, if power must be generated from a more expensive source. Such a short term public reaction could cause problems in Alaska where positive public opinion is often critical in securing state legislation and approving local bond proposals for a new hydro facilities. In future hydro developments it may be wise to make the potential fluctuations in production known to consumers. It might even be advisable to include an allowance for alternative fuel generation in the rate structure to smooth out any variation in power prices between good and poor water years.

Competition From Natural Gas in Southcentral Alaska

The opening of the Eklutna plant in 1955 established hydropower as the preferred form of electrical generation in the Anchorage load area. Six years later Chugach Electric Association opened its 15,000 KW Cooper Lake plant on the Kenai Peninsula. In the late 1950s and early 1960s plans were proposed by the U.S. Corps of Engineers to build the 46,000 KW Bradley Lake project; Chugach also obtained a federal license to build the 10,000 KW Grant Lake plant. Hydro advocates also pushed for federal construction of the 580,000 KW Devil Canyon (Susitna) project 150 miles north of Anchorage.

By 1964 most of the enthusiasm for new hydro construction in the state's largest load area was over. The Corps of Engineers announced that there would be no demand for Bradley Lake power, even though the project was authorized for construction in the Flood Control Act of 1962. Chugach abandoned it plans for Grant Lake. Since 1962 not one kilowatt of hydropower has been added to the Anchorage system (Whitehead, 1983). What happened?

The answer is simple. Discoveries of natural gas on the Kenai Peninsula in 1957 and later at the Beluga Field in Cook Inlet undercut the cost of hydro production by a half. Electricity from combustion turbines could be generated for less than 5 mills per kwh compared to 11 mills for Eklutna power and a projected 9-10 mills per kwh for Bradley Lake hydro. Chugach opened its first combustion turbine plant at Bernice Lake in 1963 and installed its first gas facility at the Beluga field in 1968. The price of

Chugach gas power dropped to $12.95 per 500 kwh in 1968 compared to the $14.50 per 500 kwh it charged for hydropower in 1957 (USFPC, 1960, 1968). By 1976 Chugach had installed 316,000 KW in gas power compared to 15,000 KW in hydro (USFPC, 1976). Gas turbine electricity effectively stopped the construction of new hydroelectric facilities in the Anchorage load area. What effect did it have on the existing facilities?

The purchasers of Eklutna power--Chugach, the Anchorage Municipal Light and Power Department, and the Matanuska Electric Association--were tied to 25 year contracts. Chugach also continued operation of Cooper Lake. So no immediate move to discontinue existing production developed. However, after the 1964 Anchorage earthquake concern mounted that the long-term contracts for Eklutna power might not be renewed when they expired. The cause for concern lay in the cost of reparing earthquake damage at Eklutna.

On the day of the earthquake, March 27, 1964, both Eklutna and Cooper Lake sustained little visible damage. Both facilities were able to generate power within a few hours after minor repairs. Later investigations at Eklutna in July of 1964 revealed that there had been settling at the base of the dam and a general weakening of the structure. It soon became evident that substantial rebuilding of the dam, particularly of the spillway, would have to take place (USBR, 1966).

The repairs were completed at a cost of $2,885,415. Under the terms of the original Eklutna Act of 1950, this cost would have to be fully reimbursable through power rates--an effective 1 mill per kwh increase. By the late 1960s, the increasing use of natural gas for electrical generation led the Department of Interior to be concerned over the potential effect of the 1 mill increase. In 1968 an assistant secretary in the department told

Congress that "this rate differential...will add to the problem created by current competitive natural gas prices in future contract negotiations for Eklutna Power." (U.S. Congress, 1968). In response Congress intervened in September 1968 and passed Public Law 90-523 making all but $80,000 of the repairs non-reimbursable. This legislation, coupled with the fact that Eklutna had generated more revenue in power sales prior to 1968 than had originally projected, allowed the Alaska Power Administration to lower Eklutna's prices by 10% in 1968 (APA, 1969).

When the time came to renew the power contracts in the late 1970s (the contracts would expire in 1980), the Alaska Power Administration had no problem finding purchasers for Eklutna power at 12.5 mills. The rising price of natural gas and Anchorage's ever increasing demand for power made Eklutna's electricity fully competitive. It does not appear that the legislation of 1968 was particularly important a decade later in contract negotiations. The long run stable price and availability of Eklutna power were its selling points.

The legislation of 1968 did, however, have a more important effect of the future development of hydroelectric power. It set a precedent for legislative intervention in the financial operation of a facility. Alaskans would not forget it. They would use the 1968 law as a precedent in asking the federal government to intervene in the financial operation of the Snettisham plant in 1976 for reasons much less dramatic than earthquake damage.

Surplus Capacity

The Eklutna project was built to meet an acute shortage of power for utility customers in a rapidly growing load area. Three years after going on line, Eklutna was selling more than its annual firm energy capacity (see

Table 2). In contrast, the substantially larger Snettisham plant near Juneau was built with the assumption, really the hope, that a full demand for its power would develop in 2-3 decades. If such hopes failed to materialize, or if the power growth was considerably off schedule, the project would have surplus capacity. The price of power per kwh would obviously have to rise to higher than projected levels to pay off the fixed capital costs. Depending on how much surplus capacity existed, the price rise could be minimal or it could be substantial. Surplus capacity could have the effect of making hydropower one of the most expensive forms of electricity. Why was the federal government willing to take such a risk in building Snettisham?

Snettisham was not originally planned with surplus capacity in mind. When the project was first designed in the late 1950s by the U.S. Bureau of Reclamation, it was to be a supplier of industrial power. Specifically, Snettisham would provide power for a pulp and newsprint mill to be built by the Georgia-Pacific Corporation. The hydro facility would thus promote the economic development of the timber industry in southeastern Alaska. Of the facility's projected annual energy production of 292 million kwh, 230 million kwh would go to Georgia-Pacific and only 47.4 million kwh would go for utility use. The remaining 14.6 million kwh would be absorbed in transmission losses. Based on these assumptions the Bureau recommended in 1959 that Snettisham be constructed (USBR, 1959).

The planning for Snettisham changed abruptly in June 1961 when Georgia-Pacific Corporation announced that it would not build its newsprint plant. On the surface of things, it would appear that there was no longer any justification for building Snettisham. But by 1961 Juneau residents, Alaska's new congressional delegation, and the Bureau of Reclamation itself were so committed to seeing Snettisham built that the project had almost taken on a life of its own. In November 1961 the Bureau of Reclamation revised its estimates of Juneau's potential utility growth over the next two decades and concluded that if Snettisham were built in stages, it would be feasible for utility production alone. It would take approximately a decade longer for utility demand to reach the level originally proposed for industrial demand. According to the Bureau, a rise in the price of power produced from 6.1 mills per kwh to 7.47 mills per kwh would make Snettisham feasible (USBR, 1961).

These new planning estimates assumed that the existing hydro facilities in Juneau (Annex Creek and Salmon Creek) would be retired when Snettisham came on line. The projections also assumed a certain surplus capacity or underconsumption of power in the early years of operation. But at 7.47 mills per kwh, enough revenue would be generated in later years to offset initial deficits and hence to pay out the project in the standard 50 year period for federally financed installations. In essence, Snettisham's new payout schedule resembled a "balloon mortgage" for a home. The decision to take the risk with such a forecast of initial surplus capacity was not the original plan; it was one which developed to save the project in mid-stream.

Snettisham was authorized for construction by Congress in the Flood Control Act of 1962 (P.L. 87-874). After many delays in receiving appropriations, the Long Lake stage was completed in 1972-73 at a cost roughly 50% greater than the amount authorized in 1962. As a result, the price of Snettisham power rose from the projected 7.47 mills per kwh to 15.6 mills per kwh. This was still lower than the price A-J Industries had charged for its hydropower. The price rise resulting from escalating construction costs was the least of Snettisham's problems.

During its first three years of operation (1973-76), Snettisham's transmission line was constantly problem-prone. As a result, Snettisham was out of service for months at a time. Repairs were made, but finally the Alaska Power Administration relocated the line in 1976. The total cost for repairs and relocation was $11 million--all of which was required by law to be reimbursable through increased power rates.

The failure of Snettisham's transmission line was only part of the facility's problem. By 1976 it was evident that Snettisham was simply not selling as much power as had been projected. As late as 1979 Snettisham sold only 80.45 million kwh or less than half of its 168 million kwh of firm annual energy. What caused such underconsumption? (APA, 1980)

As noted earlier, Snettisham's transmission line failures led AEL&P to depend on hydro power from its older facilities (Annex Creek and Salmon Creek) and to continue using them after Snettisham went back into service. The permanent operation of Annex Creek and Salmon Creek thus took an annual 40-50 million kwh of the market away from Snettisham. In addition, the 1961 estimates of Juneau's projected utility demand had been too optimistic. From 1960 to 1973 growth in demand had been closer to 7.6-7.8% rather than the "conservative" 9.3% estimated by the Bureau of Reclamation. (Table 3 gives the original 1959 estimate of utility growth in Juneau, the revised 1961 estimate of utility growth in Juneau, and the actual utility generation in Juneau from 1960 to 1982.)

The combination of competition from the older hydro plants and the slower than anticipated growth of the Juneau power market resulted in a surplus of power at Snettisham. If the price of electricity had to reflect

Table 3 A–C

A 1959 U.S. Bureau of Reclamation Feasibility Report of Utility Load Growth in Juneau.

	Peak (thousand KW)	Annual Generation (million kwh)
1952 (actual)	4.1	16.70
1958 (actual)	5.1	24.40
1960 (projected)	6.6	29.20
1962	7.6	33.64
1965	10.9	47.90
1970	15.3	67.61
1975	20.4	89.72

(USBR, 1959)

B 1961 U.S. Bureau of Reclamation Reappraisal of Utility Load Growth

	Peak (thousand KW)	Annual Generation (million kwh)
1958 (actual)	5.1	24.4
1960 (actual)	5.8	29.2
1962 (projected)	7.2	34.9
1965	9.4	45.5
1970	15.2	73.4
1975	24.3	116.9
1976	26.5	127.6
1977	28.9	139.1
1978	31.4	151.3
1979	34.1	164.3
1980	37.0	178.1
1981	40.0	192.7
1982	43.2	208.1
1983	46.6	224.7
1984	50.4	242.7
1985	54.4	262.1
1986	58.8	283.1
1987	63.5	305.7

(USBR, 1961)

Table 3 cont.

C Actual Generation of Power in the Juneau Area, 1960-1982

	Peak (thousand KW)	Annual Generation (million kwh)
1960 (Calendar Year)	5.8	29.2
1961	7.8	32.3
1962	7.1	34.7
1963	9.0	37.2
1964	9.4	41.5
1965	10.0	43.5
1966	10.9	48.3
1967	10.5	49.3
1968	11.1	52.8
1969	11.8	56.0
1970 (Fiscal Year)	12.4	58.3
1971	13.8	63.8
1972	14.9	70.3
1973	15.5	75.8
1974	16.2	83.1
1975	17.8	94.6
1976	19.8	106.3
1977	20.4	112.2
1978	23.4	122.2
1979	23.1	133.5
1980	26.2	143.1
1981	32.2	160.7
1982	42.2[a]	

(Alaska Power Administration, March 1982)

[a] January 1982

Note: As a rough rule of thumb, Snettisham's generation for any one year would be 50 million kwh less than the annual generation figure.

the costs involved with the transmission line as well as amortize the project's full capital costs, Snettisham's power rate would rise to a much higher level. (To my knowledge, projections of those rates have never been published.) Such potential price increases were forestalled in 1976 by federal legislation which resembled in many ways the Eklutna legislation of 1968.

In the Water Resources Development Act of 1976 (P.L. 94.-587, Sec. 201) Congress provided that the cost of relocating the transmission line ($5.6 million), though not the cost of line repairs, would be non-reimbursable. To alleviate the problem of surplus capacity the act extended the payout schedule for 10 years and froze the price of power at the rate of 15.6 mills per kwh until 1986. During this 10 year "load development period" the project would not be required to cover its full amortization costs, but would actually increase its overall capital indebtedness. In effect, the "balloon" aspects of the payout schedule were simply extended another ten years. In 1986 the price of power will rise to generate sufficient revenues to complete the 60 year payout schedule. The Alaska Power Administration predicts that the 1986 price will be 25.8 mills per kwh. What chance of success does Snettisham have to develop a full load for its power?

The current policy of the Alaska Power Administration for utilizing Snettisham's surplus capacity is the development of new markets for electricity in Juneau. The principal new market is residential electric heating. According to APA estimates made in 1980, this could provide a full demand for Snettisham power by 1983; without heating the full utility demand would not develop until 1995 or 2000. And in the event that the capital of Alaska moved from Juneau, Snettisham would never reach a full demand without residential heating (APA, 1980).

Oddly enough both the "heat" and the "no heat" strategies present problems. If the residential heating strategy is successful, Snettisham could reach capacity rather quickly. Then additional electricity may have to be generated by diesel fuel thus raising the price of power. Or new hydro facilities could be built with the potential debt servicing costs we have already noted in Sitka. If the heating strategy does not work, Snettisham will continue to have surplus capacity for at least another decade. The price of power will have to rise beyond the projected 1986 rate unless a new round of political intervention occurs. The most likely form of intervention would be a state purchase of Snettisham from the federal government. The capital costs of the project could then be absorbed by the state and an arbitrary price for power could be set.

The dilemma of surplus capacity in many ways defies a simple solution. It is particularly exaggerated in Juneau because Snettisham is not connected with another power market. Thus Snettisham's short run surplus cannot be sold to another area and saved in the long run for Juneau's potential growth. In an isolated load center surplus capacity in hydropower can cause the price of electricity to be as unstable as that generated by a fossil fuel. In such a situation, hydropower loses its advantage of stable and predictable power rates.

Conclusions

The historical survey of twelve of Alaska's hydroelectric installations provides evidence that hydropower has been successful in the long run in bringing reasonably priced electricity to Alaska. The operational lives of some of the facilities have exceeded the expectations of their builders. Hydroelectric generation has presented few operational problems. No hydro installations in the survey have declined in their ability to produce power over the long run. In fact, a number of the water power sites have had their capacity increased. Even in the Anchorage area, where water flow has varied substantially from year to year, the long run average power production has been quite reliable--even exceeding the original estimate for Eklutna.

Despite these long run advantages we have seen that in the short run communities may have to pay a substantial price for hydropower. This has come from debt servicing costs in Sitka, from earthquake damage in Anchorage, from transmission line failures and surplus capacity in Juneau. A community may also have to pay a higher price for hydropower in certain periods when an alternative fuel, natural gas in Anchorage's case, can provide a lower price. And it may be necessary to provide stand-by sources of power--and absorb the cost of power rates--in places where the annual waterflow of a project causes power production to fluctuate substantially between years.

The case histories also indicate that the Alaskan public has felt at times that the costs of the short run problems should not be borne by power consumers alone. Attempts to balance or smooth out the short run costs through legislative intervention have occurred. In the case of Eklutna the legislation was probably justified on the ground of disaster relief. In the long run the legislation has actually proved unnecessary for keeping Eklutna's price competitive.

The 1976 legislation in regard to Snettisham, however, is more problematic. It provided relief from the cost of operational failures (the transmission line problems) which had nothing to do with a natural disaster. The transmission line risks were well known. Equally risky were the planning assumptions for Juneau's electric power growth. There is an inherent risk in any project built on long-range growth projections. The Water Resources Development Act of 1976 essentially absorbed the costs of those risks to maintain reasonably priced hydropower. Thus the 1976 legislation set the precedent that consumers may not have to absorb the risks involved in constructing and operating hydro projects in their communities. If we consider the construction of a hydropower project as partially an economic enterprise and partially a political enterprise, the 1976 legislation clearly pushed Snettisham toward the political end of that scale. If future government intervention, state or federal, at Snettisham or other installations continues in this direction, the Alaskan public may well come to view the development of hydropower as a game played by politicians in which the public purse absorbs the economic risks. Such a negative public view could do serious damage to the image of hydropower and jeopardize the future development of one of the state's most valuable natural resources.

Hydropower's short run cost problems definitely pose a dilemma for its future development. The balancing act through political intervention is a delicate one which must be handled with extreme care.

References

Alaska Power Administration, 1969, First Annual Report 1968.

Alaska Power Administration, 1980a, 1979 Annual Report.

Alaska Power Administration, 1980b, Juneau Area Power Market Analysis.

Dort, J.C., 1924, Report to the Federal Power Commission on the Water Powers of Southeastern Alaska.

Official Statement $54,000,000 City and Borough of Sitka, Alaska, Municipal Utilities Revenue Bonds, 1979.

Stone, David, 1980, Hard Rock Gold.

Session Laws of Alaska 1981, Chapter 90.

U.S. Bureau of Reclamation, 1948, Eklutna Project Alaska.

U.S. Bureau of Reclamation, 1954, A Report on the Blue Lake Project.

U.S. Bureau of Reclamation, 1959, Snettisham Project Crater-Long Lakes Division Alaska.

U.S. Bureau of Reclamation, 1961, Reappraisal of the Crater-Long Lakes Division, Snettisham Project, Alaska.

U.S. Bureau of Reclamation, 1966, Eklutna and the Alaska Earthquake.

U.S. Congress, House, 1968, Providing for the Rehabilitation of the Eklutna Project Alaska, H. Report 1852, 90th Congress, 2nd Session.

U.S. Federal Power Commission, 1960, Alaska Power Market Survey 1960.

U.S. Federal Power Commission, 1969, Alaska Power Survey 1969.

U.S. Federal Power Commission, 1979, Alaska Power Survey 1976, Vol. 1.

Whitehead, John S., 1983, Hydroelectric Power in 20th Century Alaska: Anchorage, Juneau, Ketchikan, and Sitka. This paper is an adaptation and condensation of research reported in this work. Readers interested in greater detail and explanation of the issues noted in this paper should consult the above work. In citing references in this paper, I have cited (Whitehead, 1983) when the information was received through interviews or unpublished sources. When the information or data originally appeared in another published source, that source is cited.

HISTORICAL DEVELOPMENT OF ALASKA WATERLAW

By Robert E. Miller

Abstract

There are two major doctrines of water law in use in the United States. The first is the riparian doctrine which holds that private water rights exist as an incidence of ownership of land bordered or crossed by a natural water course. The second doctrine is of prior appropriation, which provides that the earliest appropriator in point of time has the exclusive right to use the water to the extent of his appropriation without diminution of quantity or deterioration of quality. Alaska's Water Use Act of 1966 provided the most recent evolution of this doctrine. The Act recognizes the unity of the hydrologic cycle by putting all water in one class. Alaska thus avoids the legal difficulties that have resulted from other states attempts to divide water into legal classes and to apply different rules of law to different types of water occurrence.

Introduction

The term "water law" refers to all those rules which have been established to resolve water use decisions toward the goal of maximizing benefits to society. Water law thus includes such topics as the allocation of supply among competing users, quality management, flood control, drainage, instream use, and wetlands management. Although these topics are functionally related, applicable law covering each topic has often developed independently. Thus, water law does not consist of an integrated body of legal principles for managing the resource and problems of coordination between different bodies of law remains a difficulty (Cox & Miller 1982).

Water Law Systems

The most developed area of water law is the allocation of supply. Two major doctrines of water law are in use in the United States. Before the

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[1] Associate Professor, Civil Engineering, University of Alaska, Anchorage, 3211 Providence Drive, Anchorage, Alaska.

settlement of the West, the right to use the water of natural streams accrued to the owners of land along the streams. This is the common law doctrine of riparian rights. Under a riparian right the owner of land adjacent to a stream is entitled to use the full natural flow, undiminished in quantity and unchanged in quality. The next downstream owner of riparian land has the same right. In applying this doctrine to groundwater a "quasi-riparian" right is based on ownership of the land overlying a water-bearing formation. Riparian rights cannot be lost by non-use; the water can be used only on riparian land; and there are no requirements as to beneficial use. With some notable exceptions, it is found that the riparian doctrine is followed by the humid East. In the humid states, as noted by Thornthwaite (1948), precipitation is generally greater than the potential evapotranspiration. Thus, precipitation is usually more than that necessary to support agriculture.

The arid and semi-arid areas of the West generally find that precipitation is less than potential evapotranspiration.[1] The climate, the topography, and an economy based primarily on agriculture and mining required a more flexible doctrine for water allocation. As more people settled in the West it became evident that a method had to be devised which would offer protection to existing water users and also conserve water. Mining law presented the precedent that the first person to stake out a mine had a claim which was superior to those that came after. Since many of the early water diversions were for mining, it followed that water claims should also adhere to the principle "first in time gives first in right." Although

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[1] The dividing line can be taken as the 97th meridian, i.e., about 200 to 400 miles west of the Mississippi River.

initially developed as a custom, this appropriation doctrine soon became formalized by constitutional and statutory enactments. The appropriation doctrine has no land ownership requirements, and water use is not restricted to riparian land.

It was customary for the early appropriators to post a notice of their water use. Later such notices were filed with the district courts, and since many streams flowed through several districts, it was necessary to make the filings statewide. The states which followed the appropriation doctrine also realized the necessity for some form of regulation. The overwhelming majority elected to adopt the permit or Wyoming system (a few Eastern states have also recently adopted permit systems - Sax, 1965). States which have initiated a permit system require as a prerequisite to taking water that an application for a permit to proceed be made with some state administrative agency, usually the State Engineer or a water control board. In Alaska the right to use water is obtained by making an application to the Commissioner of the Department of Natural Resources. Most of the permit system states have legislation empowering the administrative agency to deny the permits if there is no longer any appropriable water in the stream or if the appropriation is not in the public interest.

Of all the appropriation states, Colorado and Montana remained alone in allowing water to be appropriated without any administrative intervention. However, developments in Colorado water law suggest a trend toward a permit system. The Ground Water Management Act and the Water Right Determination and Administration Act of 1969 both provide for procedures somewhat similar to those in permit states. (Colo. Rev. Stat. Ann. 148-18-6 (Supp. 1966)

The administrative systems for water rights are often quite different depending on the nature of the water source. Although not the case in Alaska, it is quite common for a state to adhere to some variation of one doctrine for surface water and to apply the other doctrine to its groundwater. There are four basic doctrines governing the regulation of groundwater rights; Prior Appropriation Doctrine, Absolute Ownership Doctrine, Reasonable Use Doctrine, and Correlative Rights Doctrine. The Prior Appropriation Doctrine for groundwater is analogous to that of surface water. It appears that this doctrine for percolating groundwater is applicable only in those states which have adopted it by statute. The 1966 Alaska Water Use Act best illustrates the pure prior appropriation doctrine as applied to groundwater. Alaska makes no distinction between ground and surface water and provides that such waters are reserved to the people for appropriation and beneficial use. Thus, Alaska provides a pristine form of groundwater appropriation. The remaining three groundwater doctrines are all variations of general riparian concepts where by virtue of land ownership, an owner has some rights in the water under his land.

The Absolute Ownership Doctrine allows the landowner complete freedom to drain an entire groundwater source as long as the pumping takes place on his own land. This rule is based on the Latin maxim, _cujus est solum, ejus est usque ad coelum ad inferos_. There are almost no legal restrictions on the removal, even if the water is drained from beneath adjacent land. Under this doctrine the pumper is not even required to use the water on his own land.

Under the Reasonable Use Doctrine, water rights are dependent on a reasonable and non-wasteful use of water, generally, on the overlying land. This doctrine is widely followed and is quite similar to the reasonable use rule applied to riparian users of surface water. As under the absolute ownership doctrine the landowner may freely take water from under adjacent land, but his own use must be a reasonable one.

The Correlative Rights Doctrine has been developed by the California courts. This doctrine recognizes the finite limit of groundwater resources, and in time of shortage holds that the available water is to be equitably apportioned among the overlying owners.

As Sax (1968) noted these four doctrines are not rigidly followed by any one state, but rather, the individual states have developed regulations based on varying combinations of the four doctrines.

Alaska Water Supply Problems:

In an area with a seeming abundance of water, it may seem inappropriate to talk of water supply problems. However, there are periods of the year where water may become almost unavailable. The reason for the shortage varies with location. In the Southeast where stream flow is the only feasible source of water supply, a short drought can result in the drying up of streams not receiving lake outflows because there is such a lack of alluvium for natural storage. What used to be Southeastern Alaska's river valleys are now fjords.

In the interior, during the long cold winters small streams and shallow lakes freeze solid and water is made available only by melting snow or ice. Even if interior lakes do not freeze solid there is often a water quality problem due to the increase in dissolved solids in the unfrozen fraction. The long winters also cause a decline in stream flow and then at spring breakup there is a large runoff peak. Thus, seasonal variation means storage is a requisite for any power development. There are few, if any, streams in Alaska on which a run-of-river installation would be feasible.

In some areas of Alaska, there is a shortage of good quality water. In many places the groundwater is high in iron, organic matter, or both. Most of the shallow wells around Anchorage and also in other areas yield water with high iron content.

History of Alaska Law:

Alaska did not become a territory with the power to enact its own laws until 1912. The territorial law was the doctrine of prior appropriation in almost pristine form. In Alaska, as in California, miners competed for water needed to wash gold from alluvial deposits of their placer claims. The prior appropriation doctrine arrived in Alaska via Oregon whose laws relating to real estate were made applicable to the "District of Alaska" in a mining case decided in 1905.

Alaska did not adopt elaborate procedures for acquiring and recording rights like other western states. Several mining cases at the turn of the century hinted that Alaska might become a "California doctrine" jurisdiction by giving effect to both appropriative and riparian rights. However, a decision by the Circuit Court of Appeals in 1910 (Van Dyke V. Midnight Sun Mining and Ditch Co.) held that riparian rights were inapplicable to Alaska and the territory was added to the list of "Colorado doctrine" jurisdictions.

Apparently the miners of Alaska had become accustomed to having a water claim as part of a placer claim and in 1917 the territorial legislature gave the locator of any mining claim that included both banks of a stream the right to use as much water as was needed to work the claim. Riparianism in early groundwater law was evident in Trillingham v. Alaska Housing Authority. A District Judge stated that a complaint seeking to enjoin a defendant from diminishing plaintiff's supply of groundwater did not state a claim for relief "because percolating waters may be used by the owner as he sees fit." This, of course, is a statement of the common law rule of absolute ownership. To this limited extent there were early remnants of riparianism in Alaska. However, courts with the exception of the Trillingham case have had little interest in riparianism, and the mining law has been repealed.

State Constitution:

Alaska was eager for statehood and a state constitution was ratified by the people of the territory in 1956. The constitution contains 18 sections on natural resources. The constitution provides that all surface and subsurface waters except "mineral and medicinal waters" are reserved to the people for common use and are subject to appropriation. Priority of appropriation shall give prior right. Statehood came on January 3, 1959. Legislation to implement the constitutional provisions did not come until 1966.

Water Code:

In 1961, Governor William Egan called for a comprehensive water code covering all aspects of water problems, before the problem arose. The Commissioners of the Alaska Departments of Health and Welfare, Natural

Resources, Fish and Game, and Public Works employed Frank J. Trelease as a consultant to draft a water code. Trelease, at that time, was a law professor at the University of Wyoming. He apparently enjoyed his grand tour of Alaska and visited state leaders and submitted a code in January 1962.

Trelease's code was packaged as a bill and submitted to the legislature. The code had six articles:

(1) Organization
(2) Appropriation
(3) Water Pollution
(4) Conservation of Public Waters
(5) Drainage and Flood Control
(6) Water Conservancy Service Areas

The code failed to pass. Trelease believed that it failed because it was too comprehensive and addressed problems that were too distant. Repeated attempts at passage failed until a scaled down bill dealing mostly with appropriation was passed in 1966. The Water Use Act gave statutory definition to the doctrine of prior appropriation mandated by the constitution. The Act applied to all state waters, ground and surface not subject to superior federal rights.

Definition of Water Course:

The Act recognizes the unity of the hydrologic cycle by putting all water in one class. Alaska thus avoids the endless legal tangles that have resulted from other states attempts to divide water into legal classes and to apply different rules of law to different types of water occurrence. In fairness, most of these classes (water courses, diffused surface waters, springs, percolating water, underground streams, seepage, subflow) were invented a century ago and had some practical or pseudoscientific reason for their existence. Today, they are worse than useless. They require different rules of law to what is basically the same thing.

For example, in many states there is a distinction between "diffused surface water" and "water in a water course." In many states the latter can be appropriated while the former is the land owner's property. Trelease does an interesting thing with a Wyoming case, State v. Hiber, in which the court reviewed a number of defintions of a "water course" and their exceptions. When these are paralleled, the resulting definition goes something like this: A water course is a stream of water (except that the water need not always flow) in a definite channel, having a bed and banks (except that sometimes it may lack banks), usually flowing in a particular direction (but lo, a slough is a water course, though it connects two rivers and changes its direction according to which is higher) and discharging itself into some other stream or body of water (except for creeks which disappear into sand dunes). In Alaska a water source is defined simply as a "substantial quantity of water capable of being put to beneficial use."

Acquiring a Water Right:

No person can acquire a water right other than by complying with the Act and obtaining a permit. In fact, all diversions of a significant amount of water without compliance are made criminal acts. Alaskas thus will not follow Idaho's mistake of allowing a parallel system of unrecorded appropriations develop by allowing rights to develop by diversion and application to use.

The Alaska Act does not allow water rights to be obtained by adverse use or possession. Utah, Nevade, Idaho, and Montana have all had problems with adverse possession at one time or another.

Permits:

The right to appropriate water is obtained by application to the Commissioner of the Department of Natural Resources. The permit system was invented in Wyoming in 1890. It gives the state the power to protect itself from undesirable uses. It allows for underdevelopment of water resources to protect in place, non-appropriate uses such as recreation, fish habitat, or waste disposal.

The permit requires four conditions be met:

1) Rights of prior appropriators must not be unduly affected.
2) Proposed means of diversion must be adequate.
3) Proposed use is beneficial.
4) Appropriation must be in public interest.

These provisions seek to protect the public, but also to permit the development of resources for individual benefit but without undesirable detriments to society as a whole.

Different Viewpoints:

The real strength of the Act is in setting up procedures which allow all viewpoints to be brought together. Although the Department of Natural Resources (DNR) is given the authority to adjudicate water rights, the DNR must also give notice of the application to the Department of Fish and Game, the Department of Health, and at DNR discretion any agency, organization or person. Any person denied a permit may appeal to the superior court.

Problems:

After the passage of the Water Act, the Water Management Section of DNR was inundated with declarations of appropriation, some of which have still not been processed. The number of applications has continued to grow. With this large backlog it is impossible to determine how much water is being appropriated and what effect an appropriation would have on water and other resources. Oil development and the resulting population growth aggravated these problems, and the effects of limited management have begun to manifest themselves.

The DNR is seeking an amendment to the Water Use Act for the maintenance of minimum stream flows. The Act now requires that there be a diversion, withdrawal, or impounding of water before water can be appropriated.

Conclusion:

From the position of Western Water Law, the Alaska Water Use Act is the most recent stage in the evolution of prior appropriation which saw its last major mutation in 1890 in Wyoming. It would be impossible to export the Act but it may have some value as a model. Alaska was fortunate that it did not need a law to stop undesirable practices and activities. The Act was not enacted in an emergency to correct a bad situation. The State of Alaska was indeed fortunate to have expert advice in drafting a forward-looking law designed to prevent emergencies and to protect present and future water uses.

REFERENCES

Cox, W., Miller, R.E., et als, "Water Law Primer," Journal of WRP&M Division, ASCE, Vol. 108, No. WR1, March 1982, p. 107.

Curran, H. J. and Dwight, Linda Perry, Analysis of Alaska's Water Use Act and its Interaction with Federal Reserved Water Rights, Institute of Water Resources, University of Alaska, IWR 98, February, 1979.

Dewsnut, R. L., Jensen, D. W., and Swenson, R. W., A Summary Digest of State Water Laws, National Water Commission, 1973.

Sax, J. L., "Water Law Cases and Commentary," (unpublished), 1965, p. 37.

Sax, J. L., Water Law Planning and Policy, 1968, p.463.

Trelease, F.J., "A Water Code for Alaska," Report to State of Alaska, 1962.

Trelease, F. J., "Alaska's New Water Use Act," Land and Water Law Review, Vol. II, 1967, 1-49.

Trelease, F. J., Water Law: Cases and Materials, Third Edition, West Publishing Co., 1979.

ASBESTOS LEVELS IN ALASKAN DRINKING WATER: A PRELIMINARY STUDY

By Helen A. Myers[1] and Edwin S. Boatman[2]

Abstract

Thirty-five samples of water from rivers and other drinking water sources were collected for analysis of asbestos content. Water from wells or public treatment plants generally did not contain significant amounts of asbestos, even if the water source or a nearby river contained asbestos. Water content of asbestos is discussed in relation to the mineral terranes of the river watersheds. There is some likelihood that the levels of asbestos found could increase the incidence of cancer, but toxic levels of ingested asbestos are not well defined at this date.

Introduction

Since Alaska is a heavily mineralized state, it is not surprising that these minerals are found in rivers and other drinking water sources. Asbestos is one of several toxic compounds that appear, as a result of both natural erosion and mining activity.

Few measurements of asbestos levels in Alaskan rivers were found prior to the present study, all in the Yukon River. These measurements are given in Table I. Variation between amounts can reflect differences in analytical techniques, seasonal variations, or the extent of mining activity. (In 1977 the Clinton Creek Mine on the lower Forty Mile River in Canada was operational; activity has ceased by 1980). Both of the major types of asbestos, chrysotile and amphibole, were detected. Chrysotile asbestos is a long fiber; the term amphibole refers to several different subtypes of asbestos, all shorter than chrysotile. Although the length of the fiber has been postulated to contribute to the toxicity of asbestos, both types are considered to be very hazardous. Thus, the question arises whether asbestos

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[1] Assistant Professor, WAMI Program in Medical Education, University of Alaska, Fairbanks, Alaska, 99701.

[2] Professor, Department of Environmental Health SC-34, School of Public Health, University of Washington, Seattle, Washington 98195.

in the Yukon River, and possibly other Alaskan rivers, is present in amounts that would have adverse health effects.

While a link between the inhalation of asbestos fibers and the later appearance of asbestosis or various types of cancers has been well established, the link between asbestos ingestion and disease has not (Becklake, 1976; Millette, 1981). In 1979 the estimate was made that the ingestion of 0.3 million fibers per liter of water over a seventy year lifetime would result in one additional death per 100,000 people (EPA, 1979; Millette, 1981). This estimate was made from several studies of occupational exposure, largely by inhalation, making assumptions regarding the amount of asbestos that would have been cleared from the lung and subsequently swallowed. Epidemiological studies have looked at populations exposed to drinking water containing asbestos levels ranging as high as 1,800 million fibers per liter with varying results (Boatman and Polissar, 1982; Kanarek, 1980; Levy, 1976; Millette, 1981; Toft, 1981). A study of the population exposed to San Francisco area drinking water did report a statistical correlation between several types of cancer and the levels of asbestos in the drinking water. The asbestos levels in this study approximate the range of asbestos found in the Yukon both as reported in Table I and the present study.

Table I:
ASBESTOS LEVELS REPORTED IN THE YUKON RIVER
(Prior to present study)

Location, Date	Group	Amount, million fibers per liter	Reference
Eagle, 1977 5 samples	Chrysotile Amphibole	126 - 674 2150 - 6230	Metsker, 1981
U.S. border, 1977	Unspecified	200	EVS Consultants,
Mouth of Fortymile 1980	Unspecified	0.5 - 327.2	1981
Eagle, 1980	Chrysotile Amphibole	14.7 -	Justice, 1982

A survey of mining claims and the geological formations that might contain asbestos indicated that asbestos might well be present in more Alaskan drinking water than that in the region of the upper Yukon. Samples were therefore collected from several villages and rivers to provide a preliminary study of the extent of the potential for exposure to asbestos via ingestion.

Methods

Sample Collection:

The United States Fish and Wildlife Service collected samples for the study from the lower Yukon near the mouth of the Andreafsky River, from the upper Noatak River (two sites), the Kobuk River (two sites), and the Kuskokwim River.

Because of other research interests concerned with the possibility of a link between asbestos and the appearance of primary hepatocellular carcinoma (a usually rare cancer of the liver) in several western Alaskan villages, most of the drinking water sources were tested in these villages. A letter was written to the mayor and/or village health aide of several villages, explaining the project and inviting participation, at no cost to the village. Of the respondents, villages were chosen primarily for ease of access by one collector (Myers) in one trip, so that samples would be representative of the same period in time. A person specified by the village met the collector and helped collect the samples from sources identified as those from which people often obtained water.

Water Sample Preparative Procedure:

All samples were treated with one milliliter of 2% mercuric chloride to prevent bacterial growth. Samples received from Fish and Wildlife were treated when received in Fairbanks; the rest of the samples were treated at time of collection.

The preparative procedures for the analysis of asbestos fibers in water as detected by transmission electron microscopy are those described under "The Interim Method for Asbestos in Water" by Anderson and Long (1980). For asbestos fiber analyses by transmission electron microscopy the preferred preparation based upon a variety of interlaboratory comparisons is the Carbon Coated Nuclepore Jaffe Wick method modified from the original technique of Jaffe.

The sample water was well shaken and filtered as soon as possible after arrival; if this could not be accomplished the sample was refrigerated at 4°C to minimize bacterial and algal growth.

Depending upon the turbidity of the sample, a suitable aliquot from 10 to 500 ml was filtered by suction through a 0.1 μm pore size Nuclepore, 47 mm diameter membrane supported by a 2.0 μm pore size Millipore backing filter. The backing filter served to ensure a uniform deposition of the particulate material on the surface of the Nuclepore membrane. After filtration, and while the Nuclepore membrane was still wet, an equatorial strip was cut out of the membrane, attached to a glass slide, dried and coated with carbon by rotation in a vacuum evaporator (the carbon coating serves to trap and retain the particulate matter during the subsequent dissolution procedure). Random portions (~ $2mm^2$) were cut from the strip and placed individually on 200 mesh formvar coated copper rhodium electron microscopy grids. The grids were exposed to chloroform vapor in a biohazard cabinet and the filter matrix dissolved. This usually took between 18-48 hours. After dissolution of the filter, the grids were observed by a transmission electron microscope operating at 80-100 kv which had the capability of selected area electron diffraction (SAED). Up to this point, the chance errors had been associated with the manipulative skills. Sources of error could include settling of particulates in the water with time; clumping of the fibers during filtration; a non-uniform deposition of particulates on the Nuclepore membrane surface; loss of fibers during carbon coating and/or dissolution in chloroform; and fibers obscured by other organic or non-organic particulates. Beyond this point, possible sources of error involved those of counting and identification.

Counting and Identification of Asbestos Fibers:

Grids were first observed at low magnification to see if the deposited particulates were uniformly distributed. If the distribution were poor or there were either too much deposit (enough to mask fibers) or too little, then the whole procedure was repeated using a smaller or larger volume of water for filtration. In rarer circumstances, where the turbidity of the water sample was high enough to preclude immediate use, an aliquot was diluted with asbestos-free water and filtrated again. If the grids were satisfactory, 20 to 30 grid squares were randomly selected from 3 to 4 grids of each sample and observed at 21,000X for particulates suggestive of asbestos fibers.

Fibers were then rated according to aspect ratio (i.e., parallel sides and a length/width ratio of greater than or equal to 3:1), morphology and crystal structure by SAED. After these assessments, the fibers were classified as (1) chrysotile asbestos (2) amphibole asbestos (3) ambiguous or (4) non-asbestiform. Periodically throughout analyses the overall instrumentation was checked by use of preparations of reference asbestos fibers (UICC).

Results and Discussion

The levels of asbestos found in river water and other drinking water sources are given in Tables II and III. It should be emphasized that every locality visited used the rivers as a source of drinking water. Sometimes an effort was made to avoid excess silt by drawing water from mid-channel, or, as in Selawik, by travel to a clearer river (in this case the Fish River). However, some people remarked that silt "was good for you." It is likely that the asbestos fibers travel with the silt; an experiment in progress is testing this possibility.

Figure 1 provides information regarding the possibility that asbestos deposits might be present in the watershed of a river. The shaded areas indicate regions in which rock units with which asbestos is typically associated might be found. These rocks are mafic and ultramafic rocks of plutonic or mixed volcanic and sedimentary environments (AEIDC, 1979; Levine, 1978). Also included are regions in which asbestos claims are located (Sims, 1982). The areas illustrated on the map are neither all-inclusive nor, at the scale of the map, very precise. The intent of the figure is to illustrate how widespread in Alaska are the terranes which are associated with asbestos. However, the terranes illustrated do not necessarily all contain asbestos; they only indicate known geological areas in which asbestos might be found.

The map also indicates approximately the areas from which the water samples were collected.

The area to the north of the Kobuk River was an important source of asbestos in 1944-1945, particularly of tremolite, a type of amphibole asbestos (Bundtzen, 1982). It was thus surprising that the amount of asbestos in the Kobuk was so much lower than the amounts in the Yukon, and that only chrysotile was present. It is possible that tributaries from watersheds not containing asbestos had a dilution effect; the samples were taken near the mouth of the river.

The Noatak is also regarded as draining areas containing asbestos. A claim has been staked on a tributary between sample sites 1 and 2; this region may therefore be the source for the asbestos in the sample drawn at the village of Noatak.

The Kuskokwim watershed also contained a producing mine in the McGrath region. Deposits of asbestos have been sighted in the region of the lower Kuskokwim as well. However, none of the samples drawn from the Kuskokwim (just above the town of Bethel) contained asbestos.

The town of Selawik is located in a region of islands surrounded by a network of water channels. It is possible that the asbestos found in the sample taken from the Selawik River in town originated in the terrane to the east drained by the Selawik. The Fish River drains the Waring Mountains, which are separated by another valley from the mountains in the known asbestos terrane to the north. The presence of asbestos in the Fish River may indicate that the terrane is more extensive than previously thought.

The asbestos detected in the North River to the northwest of Unalakleet also cannot be related to any known asbestos related formations.

The largest amounts of asbestos were found in the Yukon River. The Yukon already contains asbestos as it leaves Canada (see Table I) both from the contribution of the Fortymile River and regions further upstream. A "world class" desposit of asbestos is located in the Slate Creek area of the Fortymile river system. It was during the operation of the Clinton Creek mine, near the mouth of the Fortymile, that the asbestos levels were recorded at the highest levels (1977) recorded in Table I; the reasons behind the differences in the values for this year are not clear.

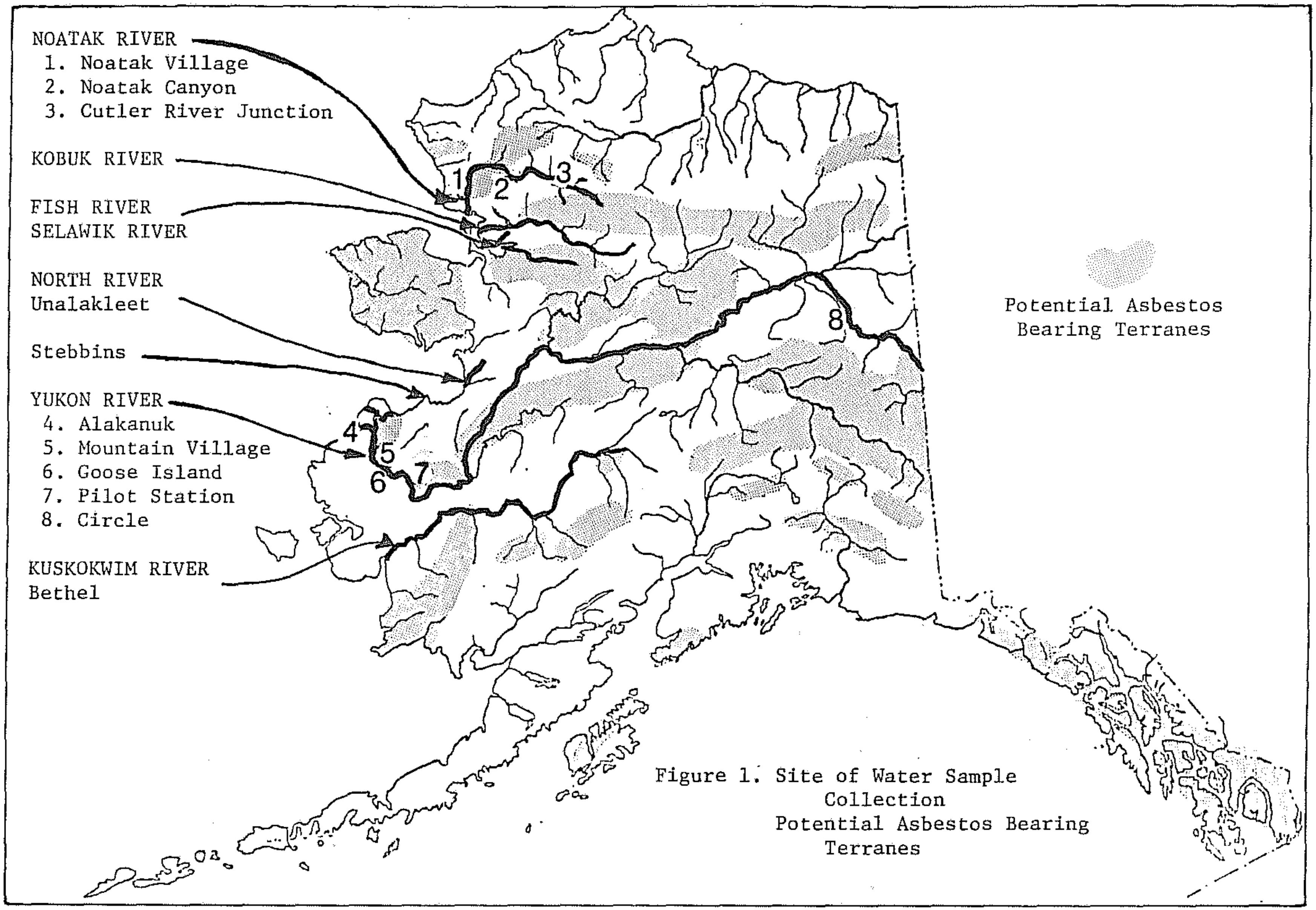

Figure 1. Site of Water Sample Collection
Potential Asbestos Bearing Terranes

Table II

ASBESTOS LEVELS IN DRINKING WATER SOURCES
(Excluding rivers, see Table III)

Source, Date	ASBESTOS CONTENT Million fibers per liter Chrysotile	Amphibole
Noatak, 6 August, 1982		
PHS hose; well in Noatak River	-	-
Health Clinic tap, another well in river	-	-
Unalakleet, 9, 10 August 1982		
City Hall tap, public water from well	-	-
Me Too Creek, culvert between Musk Ox Farm and White Alice Station	-	-
Stebbins, 10 August 1982		
Elementary school, own well	-	0.1
Public water supply in laundry, source in volcanic lake	-	-
Rain Water, off metal roof into metal can	1.3	-
Alakanuk, 12 August 1982		
Clear Lake, at end of path from Yukon channel	1.0	0.1
Safe water plant, source in another channel passing village	-	-
Mountain Village, 12 August 1982		
Health Clinic tap, main well	1.2	-
High School tap, different well	-	5.3
Elementary school tap, different well	0.5	-
Spring on bank of Yukon, downstream from village	-	-
Pilot Station, 13 August 1982		
Spring on side of hill	0.3	-
Pump house tank, public water from well	-	-
Bethel, 20 August 1982		
Yukon Health Clinic tap, own well	-	-
Hospital tap, own well	-	-
Circle, 29 August 1982		
McDonald's well, on bank of Yukon	-	-

Table III
ASBESTOS CONTENT OF SELECTED ALASKAN RIVERS

Source, Date	ASBESTOS CONTENT Million fibers per liter Chrysotile	Amphibole
Selawik River, in Selawik, 5 August 1982	16.4	-
Fish River, near Selawik, 5 August 1982	2.0	-
North River, at bridge near Unalakleet	2.6	-
Noatak River, 19 July, 6 August 1982		
Above Noatak Canyon, at game warden cabin	-	-
1000 ft. Noatak, where drinking water collected	1.9	-
Kobuk River, 16 July 1982		
Above junction of Riley Channel	1.9	-
At mouth of Riley Channel	1.2	-
Kuskokwim River, upstream from Bethel		
11 November 1981 (three samples)	-	-
20 August 1982	-	-
Yukon River		
Circle, 29 August 1982		
Slough where drinking water collected	32.7	6.1
Bank below slough, main channel	42.9	22.5
Goose Island (off Pitka's Point)		
11 November, 1981 (two samples)	33.2	13.5
	41.8	8.4
3 June 1982 (three samples just after breakup)	5.7	1.4
	3.7	1.0
	8.9	-
Delta, main channel near Alakanuk		
12 August 1982	22.5	21.0

Samples taken in 1982 (Table III) did not show much difference between the amounts of asbestos in the upper Yukon (Circle) and the lower Yukon (delta, near Alakanuk). While several large and many small tributaries between the border and the delta might be expected to dilute the asbestos from the upper region deposits, it can be seen from Figure 1 that these tributaries may, for the most part, also contain asbestos.

If the asbestos in the rivers comes from natural erosion of the watershed, a seasonal variation might be expected. Such a variation is seen in Table I: the high value of 327 million fibers per liter was obtained in July, while only 0.5 million fibers were detected in November. The variation seen at Goose Island in the lower Yukon did not follow the same time pattern, however. It is possible that the lower Yukon contains asbestos eroded by the Yukon itself, and that in winter this asbestos is not diluted by rainwater or water from tributaries. More data regarding seasonal variation is needed. To estimate the total exposure of the population to ingested asbestos it is necessary to know this variation. The differences between the variation in the upper and lower Yukon point out the need for data rather than assumptions in accessing year-round exposure.

It would appear that knowledge of the geology of river watersheds at the level presented in Figure 1 is not enough to predict the presence or the amount of asbestos in the water of major rivers draining a large area. However, in most instances the presence of asbestos in the water could be related to presence of appropriate geological formations. The presence of asbestos in the Fish and North Rivers could represent a sampling error or indicate the presence of as yet undetected sources of asbestos.

In two locations, Circle and Noatak, water from wells either in the river (Noatak) or nearby on the bank (Circle) contained considerably less asbestos than did the river water. It seems quite probable that the ground filters out the asbestos before the river water percolates through to the well.

The safe water plant in Alakanuk drew its water supply directly from the Yukon. The treatment system seemed quite effective in removing asbestos, since the level dropped from about 20 million fibers each of chrysotile and amphibole forms in raw river water to levels that were undetectable in treated water.

It should be kept in mind that the asbestos levels reported in this study cannot be taken as the representative asbestos level for the sources, since generally only one sample was taken from each source. Experimental variability due to the factors of sampling and measuring are thus not assessable. In addition, it is clear that the levels could have a seasonal variation.

It is difficult at this point to make a statement regarding the possible health effects of the asbestos found in Alaskan drinking water. Firstly, the results just reported are preliminary and do not adequately define the exposure level, which must consider year-round variation. Secondly, neither animal nor epidemiological studies have produced conclusive results clarifying the question of what levels of asbestos in water are definitely toxic. The estimation of 0.3 million fibers per liter by the Environmental Protection Agency has not been adequately supported by animal and epidemiological studies. The San Francisco study, which did report a correlation between asbestos ingestion (at levels found in the Yukon and Selawik Rivers) and cancer development has been criticized for its statistical methods. The lack of a statistical correlation in other studies can be due to the long latency (decades) between exposure and appearance of cancer, to the impossibility of maintaining a stable population to study, and/or to the difficulty in establishing the actual exposure of individual cases. A more definite statement regarding the toxicity of ingested asbestos must await replication by other studies of the studies to date, in a time frame that satisfies concerns that the expected cancers had enough time to develop.

Conclusions

The preliminary data presented indicate that asbestos is present in varying amounts in rivers as well as other drinking water sources. Seasonal variations may not be qualitatively similar from site to site. Research to date has not provided a firm figure for levels of asbestos ingestion that would be toxic. However, the amounts of asbestos measured in the drinking water would, according to some of the current experiments and estimates, present some risk for the development of cancer.

References

Anderson, C.H. and Long, J.M., 1980, Interim Method for Determining Asbestos in Water. EPA-ORD Research Report #EPA 600/4-80-005, p.34.

Arctic Environmental Information and Data Center, 1979, Mineral Terranes of Alaska (a map series). Anchorage, Alaska.

Becklake, M.R., 1976, Asbestos Related Diseases of the Lung and Other Organs: Their Epidemiology and Implications for Clinical Practice. American Review of Respiratory Disease 114:187-227.

Boatman, E.S. and Polissar, L. 1983, Unpublished research.

Bundtzen, T.K. and Smith, T.E., 1982, Alaska's Industrial Minerals. Alaska Geographic 9:64-73.

EVS Consultants, 1981, Assessment of the Effects of the Clinton Creek Mine Waste Dump and Trailings, Yukon Territory. For Cassiar Resources Ltd., Vancouver, B.C. Canada.

Environmental Protection Agency (U.S.), 1979, Water Quality Criteria: Asbestos. Federal Register 44:56632-56635.

Justice, S. (Alaska Department of Environmental Conservation, Fairbanks, Alaska) 1982. Personal communication regarding analysis by E.S. Boatman.

Kanarek, M.S. et al, 1980, Asbestos in Drinking Water and Cancer Incidence in the San Francisco Bay Area. American Journal of Epidemiology 112:54-72.

Levine, R.J., ed., 1978, Asbestos: An Information Resource. DHEW Publication Number (NIH) 79-1681.

Levy, B.S., et all, 1976, Investigating Possible Effects of Asbestos in City Water: Surveillance of Gastrointestinal Cancer Incidence in Duluth, Minnesota. American Journal of Epidemiology 103:362-368.

Metsker, H., (United States Fish and Wildlife Service, Anchorage, Alaska), 1981, Personal communication.

Millette, J.R., 1981, The Need to Control Asbestos Fibers in Potable Water Supply Systems. Science of the Total Environment 18:91-102.

Sims, J. (Office of Mineral Development, State of Alaska, Fairbanks), 1982, Personal communication of computerized search of U.S. Bureau of Mines records for status of asbestos claims.

Toft, P. et al, 1981, Asbestos and Drinking Water in Canada. Science of the Total Environment 18:77-89.

EFFECTS OF GOLD PLACER MINING ON INTERIOR ALASKAN STREAM ECOSYSTEMS

Jacqueline D. LaPerriere[1], David M. Bjerklie[2], Rodney C. Simmons[3], Erwin Van Nieuwenhuyse[4], S. Mitchell Wagener[5], and James B. Reynolds[6]

Abstract

During the summers of 1982 and 1983, we evaluated the effects of placer mining for gold on the water quality and ecology of streams in interior Alaska, northeast of Fairbanks. Our field studies involved two sets of paired watersheds, each having one with placer mines and one without. Increased suspended sediments that settled out downstream cemented the streambed, causing the surface flow and the groundwater flow to be hydraulically isolated from each other. As a result the water chemistry of the mined streams was different than that of their unmined partners. The mined streams were often lower in hardness, alkalinity, and specific conductance. Due to mining activity, the mined streams were higher in settleable solids and turbidity. Total heavy metals were also elevated in the mined streams.

Benthic algae, the base of the food chain, were severely reduced in heavily mined streams. Whether this was due to increased turbidity cutting off light for photosynthesis, scouring, or toxic heavy metals was not determined. Benthic macroinvertebrates, mostly aquatic insects, were also reduced in numbers and species; these animals are the critical link between algae and fish in the food chain. Although the unmined streams contained many Arctic grayling (Thymallus arcticus), no grayling were found in the mined streams when mining produced heavy loads of suspended materials. The only exception occurred during fall out-migration, when grayling were running to overwintering grounds in the large glacial rivers. Cage bioassays demonstrated that if grayling could not

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[1] Assistant Leader, Alaska Cooperative Fishery Research Unit, U of Ak., Fairbanks 99701 (The Unit is jointly sponsored by the U.S. Fish and Wildlife Service, Alaska Department of Fish and Game, and University of Alaska, Fairbanks.)

[2] Research Assistant, Institute of Water Resources, U of Ak., Fairbanks 99701

[3], [4], [5] Research Assistant, ACFRU

[6] Leader, ACFRU

escape from streams carrying mining sediments, they would suffer physiological harm including reduced feeding, slowed maturation, and gill damage. We conclude that placer mining sedimentation severely reduces the aquatic life in heavily mined interior streams, and results in reduced biological carrying capacity of the affected watersheds.

Introduction

In 1980 the U.S. Environmental Protection Agency published a request for proposals, soliciting responses to study the effects of placer mining in Alaska on salmonid fishes. This request was issued from a new program called "Partners in Research" which funds academic institutions to conduct some of the research needed by the EPA to address its mission. The University of Alaska-Fairbanks, through the Institute of Water Resources, and the Alaska Cooperative Fishery Research Unit, proposed a comprehensive study of the stream-ecosystem effects of placer mining.

We proposed an ecosystem approach because we felt that important effects of mining on fishes might be not only direct (e.g. gill damage), but indirect (e.g. through reductions along their food chain). Fish are mobile enough to avoid localized increases of stream sedimentation, but their food organisms, the benthic invertebrates, are less mobile. The algae on which the macroinvertebrates feed are mostly benthic and sessile in streams (only large rivers have true phytoplankton), and thus are very vulnerable to increased suspended sediment.

Our proposal was funded in August, 1981. Because of limitations on available funds, some of the work we originally proposed could not be conducted. Detailed engineering studies of mining practices and water use could not be included. Studies of the mobilization of heavy metals associated with this activity also had to be cut from this project. However, those mobilization studies have been conducted by Dr. Edward Brown of the Institute of Water Resources with other funding. The data presented in this paper should be considered preliminary at this time, since data analysis for the 1983 field season has just begun. We hope that the dialogue generated by this manuscript at the meetings will improve our analysis and subsequent journal publications.

Study site description

This study was carried out at two major sites accessed from the Steese Highway northeast of Fairbanks (Figure 1). The first site surrounded the confluence of McManus Creek with Faith Creek to form the Chatanika River, which then flows southward, ultimately entering the Yukon River after joining the Tolovana. This site is near milepost 69 on the Steese Highway (69 miles from Fairbanks). At least four mines are located on Faith Creek and its tributaries while the McManus Creek watershed has no mines.

Our second site was located around the confluence of Twelvemile Creek with Birch Creek near milepost 94 of the Steese Highway. Twelvemile Creek has no active mines while Birch Creek above the confluence has on the order of ten mines. Below the confluence, Birch Creek is classified as a Wild and Scenic River under the Alaska Native Interest Land

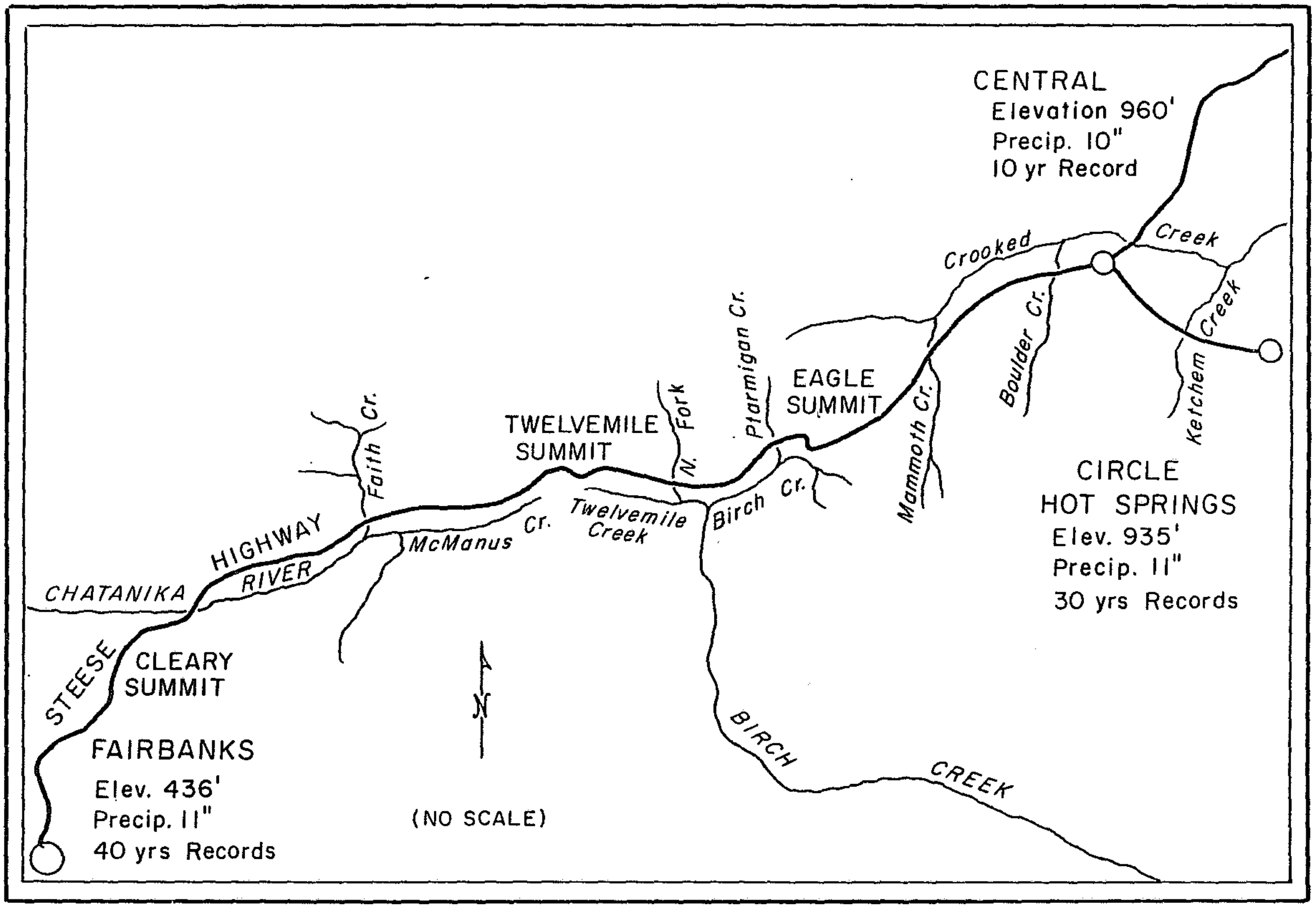

Figure 1. The Study Area with Annual Precipitation Data for Three Stations.

Claims Act for approximately 160 river miles until it passes under the Steese Highway at milepost 138.

A secondary study site was established at Ptarmigan Creek, a clearwater tributary of the Eagle Fork of Birch Creek, where some algal productivity work was conducted in 1982. In August of 1983 mining was started for the first time on this creek, and algal productivity above and below mining was measured for a three day period. Secondary sites were also established in 1983 for invertebrate sampling at Ptarmigan, Mammoth, Boulder and Ketchem Creeks. The latter three streams are tributaries of Crooked Creek which flows into Birch Creek before it enters the Yukon River.

Methods

The description of methods which follows is somewhat detailed. We have presented this detail in anticipation of questions about our methodology. The reader may prefer to refer to this section only as necessary.

Precipitation

Twelve rain gauges were placed along the Steese Highway. Terrain along the highway includes low valleys with forest vegetation (birch, white spruce, and black spruce) and higher elevations with muskeg and tundra vegetation. The network of gauges was designed to provide a representation of surface distribution of rainfall. In order to obtain a representative elevational distribution, some gauges were placed off the highway at higher elevations. The rain gauges used were nonstandard. In order to obtain a check on the accuracy of the measurements, two brass standard Weather Bureau gauges were placed alongside one of our gauges. Our gauges were constructed with graduated cylinders and funnels, and calibrated to be read with a dipstick. Volume measurements were also taken to check the dipstick readings. The standard gauges not only helped to verify the results obtained from the homemade gauges, but also allowed for catching an overflow which our gauges do not. Oil was placed in each gauge to reduce evaporation. They were read and emptied weekly.

Stream flow measurement

Stream flow was measured using a Marsh-McBirney meter to determine velocities across a section of each river. Seven to ten flow measurements were taken over the period of the summer and correlated with staff-gauge heights in order to develop a stage-discharge relationship for each stream. Gauge heights were read daily while at each camp and periodically at the other sites when visited. Flows not measured directly were calculated from the rating curves.

Groundwater

Well points were driven in the stream beds in pools at Birch, Twelvemile, Faith and McManus Creeks to obtain weekly water levels and water samples. The chemistry of the groundwater just beneath the streams and the peizometric surface of the groundwater were determined. Each well point was driven into the streambed at least 6 inches past the screening. The wells were hand pumped to obtain samples for measuring water quality constituents other than dissolved oxygen. Dissolved oxygen samples were pulled under hand-pump-generated vacuum through 1/4 inch tubing into a 1000 ml Erlenmeyer flask, after the well had "rested" for at least 24 hours. Samples were then siphoned to the bottom of 300 ml BOD bottles, overflowing the bottle at least twice before obtaining the sample. Samples were fixed with dry chemicals (Hach Chemical Company) and titrated with phenylarsine oxide which had been standardized against an iodate-iodide standard. Percent saturation was calculated according to Mortimer (1981).

Water Quality

Stream water samples were collected by grab sampling. Groundwater samples were collected by pumping the wells for several minutes, to replace the water standing in the well several times, before sampling. Both types of samples were collected weekly. Rain water samples were collected on tent canvas to obtain adequate surface area to collect large enough samples. The canvas material was checked for possible contamination, and none was found. In addition, rain was collected with funnels for comparison and no differences in water chemistry were found.

Accepted procedures for measuring pH, temperature, conductivity, alkalinity, total and calcium hardnesses, iron, copper, silica, manganese, ammonia-N, nitrate-N, nitrite-N and color were used. Our primary tool for water quality measurements was a Hach field test kit containing a spectrophotometer, conductivity meter and pH meter. The method of standard additions was used periodically to check the accuracy of quantitative analyses. Turbidity was measured using a Hach portable turbidity meter. Suspended sediment samples were taken with a hand-held suspended-sediment sampler, and residues were determined in the lab using procedures from Standard Methods (A.P.H.A. 1980). Settleable solids were determined in the field using Imhoff cones. Chemical oxygen demand was measured by the reactor digestion method (Jirka and Carter 1975). All constituents were reported as mg/l except temperature (°C), pH, conductivity (µmhos), turbidity (NTU) and settleable solids (ml/l).

Algae

In this two-year study, stream algal productivity was estimated using the now standard Odum diel oxygen curve method (Odum 1956). Two YSI Model 56 dissolved oxygen (D.O.) monitors, calibrated against five Winkler titrations prior to each measurement period, continuously recorded D.O. concentration and temperature. These data were digitized, computerized, then subjected to a FORTRAN program which calculates values for change in D.O. concentration (corrected for diffusion), plots them against time, and then solves for gross daily production and respiration using the trapezoid rule. Daytime respiration was accounted for by connecting the predawn and post-sunset minimums as suggested by Hall and Moll (1975). We used the tables of Mortimer (1981) to calculate oxygen saturation and the formula of O'Connor and Dobbins (1956) to derive the reaeration coefficient. Wilcock (1982) showed that the O'Connor-Dobbins formula is best suited for use in relatively small headwater streams. The reaeration coefficient was corrected for temperature according to Elmore & West (1961). All calculations were based on mean temperature and D.O. values of the appropriate time interval (either 1 hr or 0.5 hr). The single station method was used during the 1982 field season, but was verified as being equivalent to the dual station method during the 1983 season when two D.O. monitors became available. The amount of photosynthetically active radiation (PAR) reaching a study site was recorded continuously during each study period using a LI-COR 190SB deck sensor and a LI-COR 550B printing integrator. The deck sensor remained in an unshaded area throughout the study period.

Data used to calculate the light extinction coefficient were collected with a LI-COR 188B integrating quantum radiometer photometer and two sensors; one 190SB sensor for surface readings and one 192SB sensor for underwater readings. A LI-COR SS-3 sensor selector permitted readings to be taken alternately at the surface and at depth. This was done at 20 second intervals using an integration time of 10 seconds and repeated at least six times for each depth. The entire process required an average of one hour. The deck sensor was positioned in an unshaded area on shore, while the underwater sensor was mounted on a #5 rebar section with a clamp. Measurements were taken at 5 cm intervals beginning at 5 cm beneath the surface. The three key plant nutrients we measured were inorganic carbon (from alkalinity, pH and temperature), nitrogen (as ammonia, nitrite and nitrate), and phosphorus (as total phosphorous). Total phosphorus samples were stored frozen and analyzed within three months according to the method presented in Eisenreich, et al (1975).

Invertebrates

Stream benthic invertebrates were sampled over the course of two summers. In 1982, four streams, Faith Creek, McManus Creek, Birch Creek, and Twelvemile Creek were sampled using a $0.1m^2$ box sampler. Twenty five non-random benthos samples each were taken from Faith Creek and McManus Creek. Fifty non-random benthos samples each were taken from Twelvemile and Birch Creeks. All the sampling done in 1982 occurred in July and August.

In 1983, nine streams were sampled for benthic invertebrates. These streams were the four above and, Ptarmigan Creek, Ketchem Creek, Boulder Creek, Mammoth Creek, and the Chatanika River downstream from the confluence of Faith and McManus Creeks. Ketchem, Mammoth, Birch, and Faith Creek were mined. Ptarmigan Creek was clear and unmined until the middle of August when mining on this creek began. The Chatanika River is formed from the confluence of a mined creek and an unmined creek. The remaining sampled creeks were unmined. These streams were sampled randomly during each of six sampling periods evenly spaced from mid-June through September. Five box samples were taken from each stream during each sampling period for a total of thirty random samples from each stream for the year. Substrate particle size composition and percent embeddedness were estimated at the point at which each sample was taken. Concurrently with benthos sampling, turbidity, settleable solids, suspended solids, alkalinity, calcium and total hardnesses, pH, water temperature, conductivity, color, and chemical oxygen demand were measured once for each stream during each of the six sampling periods. Heavy metals were sampled once for each stream.

Since all of the 1982 samples were taken non-randomly within the streams, the tests for significant differences in numbers of benthic organisms between streams were done using non-parametric statistics. The 1983 samples were taken randomly and the date will be analyzed using parametric methods.

Fish

Mined and unmined streams were seined occasionally using fine-meshed seines to attempt to capture grayling residing in them. Approximately 150 seine-hauls were made in each of the four major streams.

To assess the impacts of mining sediment on grayling, two life stages of these fish were used for experimentation: young-of-the-year (YOY) fish from the Twelvemile Creek, and juvenile fish (Age II) transported from Pile Driver Slough, a backwater of the Tanana River near Fairbanks. These year classes were chosen for testing because they could be captured in sufficient numbers and would likely be more sensitive to sediment exposure than adult grayling.

YOY grayling were held in 18 x 8 inch cylindrical cages with 1/8-inch mesh size screening, 10 fish per cage. Cages were placed in the mined streams and exposed to the existing sediment levels. Exposure periods varied from 24 hours to 10 days. Control cages were kept in the clearwater unmined streams for equal durations. The fish were monitored for mortalities and later sacrificed for examination of gill tissue, stomach contents, and external and internal appearance after exposure. Gill-tissue samples were fixed in Bouin's solution, paraffin embedded, sectioned at 0.7 micron thickness, and stained with hematoxylin-eosin solution. Stomach contents were examined using a low power (15x) compound dissecting scope and analyzed by percent volume and number of individual organisms in each taxonomic order.

To study stress responses in grayling, Age II fish captured from Pile Driver Slough were anesthetized with MS-222 at a dosage of 10 ppm; transported to the two study sites; and held in a 10 x 30 foot pen in the control streams to acclimate for 48 hours. These fish were then held in 2 x 4 foot cylindrical cages with 1/4 inch mesh size screening, with 10 fish per cage. Exposure periods varied from 6-96 hours. After each exposure period, each fish was weighed to the nearest 0.01 gm, measured (± 1 mm), and two blood samples taken in heprinized microhematocrit tubes (0.5± 0.05 mm I.D.) from the severed caudal peduncle. Leucocrit and hematocrit values were determined using the method of Wedemeyer and McLeay (1981).

During all caged bioassay experiments four turbidity and settleable solid samples, and one suspended sediment sample were taken daily.

Results and Discussion

Precipitation

There are no long term precipitation records for the immediate vicinity of the study area. However, records from Fairbanks, Gilmore Creek, Central and Circle Hot Springs are available. The more detailed study of precipitation made for the study area during the summer of 1983 has revealed distinct patterns (Figure 2). Ten rain gauges, distributed along a 35 mile stretch of the Steese Highway, from Faith Creek to Eagle Summit showed that rainfall is concentrated on Twelvemile Summit, dropping off to the east and west; and that, over the summer greater precipitation occurred at greater elevations, but on a weekly basis elevational trends were much less apparent (Table 1).

Observations taken over the course of the summer showed storms moving from the north, west and south, and that frontal storms produced longer duration rains and were more prone to be affected by elevation, whereas thunder storms often produced heavy rain but occurred more randomly.

In addition to the rain gauge depths, pH, conductivity, alkalinity and hardness measurements were taken on the rain water, occasionally. It was interesting to find that pH's were often below 5.00, and on several occasions below 4.00 (Table 2). With consecutive storms, the pH increased,

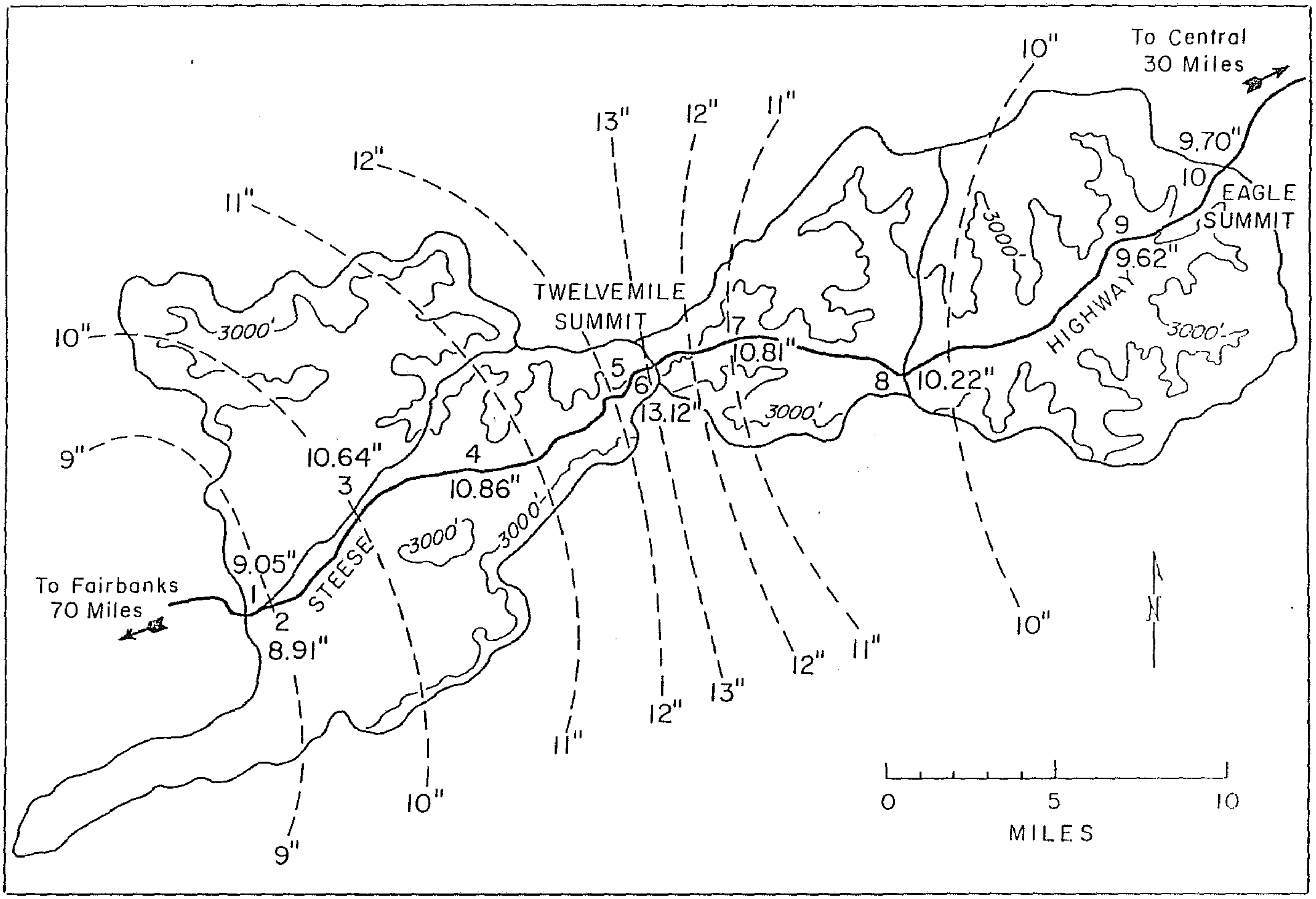

Figure 2. Summer Precipitation - 1983

TABLE 1. Precipitation

Dates	Faith Creek	Mc Manus	Faith Rd	Idaho	Twelve-mile Left	Twelve-mile Right	Reed	Birch	Ptar-migan	Eagle
5/23-6/1	0.15"	0.12	0.08	-	0.13	0.06	0.12	-	0.07	0.09
6/1-6/6	0.42"	0.44	0.56	0.62	0.62	0.47	0.37	0.21	0.13	0.15
6/6-6/14	0.10"	0.13	0.04	0.28	0.17	0.19	0.14	0.29	0.36	0.48
6/14-6/19	0.09	0.10	0.18	0.14	0.18	0.21	0.19	0.15	0.14	0.18
6/19-6/29	0.78"	0.63	~1.50	1.05	~1.50	~1.50	~1.50	~1.50	1.35	~1.50
6/29-7/3	0.40"	0.38	0.27	0.22	0.43	0.45	0.52	0.68	0.40	0.45
7/3-7/13	1.39"	1.17	1.33	~1.50	~1.50	1.85	~1.50	1.28	1.31	1.08
7/13-7/18	1.25"	1.32	~1.50	~1.50	~1.50	1.82	1.40	0.96	~1.50	1.26
7/18-7/28	0.12"	0.15	0.12	0.49	0.61	0.42	0.34	0.34	0.31	0.28
7/28-8/1	0.03"	0.02	0.01	0.00	0.02	0.03	0.02	0.11	0.03	0.06
8/1-8/10	0.98"	1.00	0.60	0.67	1.12	1.02	0.71	0.47	0.52	0.31
8/10-8/15	0.57"	0.60	0.85	1.27	1.04	1.05	-	1.07	1.29	1.28
8/15-8/24	1.27"	1.35	~1.50	~1.50	~1.50	1.55	~1.50	1.69	1.08	1.08
8/24-9/2	~I.50"	~1.50	~1.50	~1.50	~1.50	2.00	~1.50	1.37	1.13	~1.50
TOTAL:	9.05"	8.91"	10.04"	10.86"*	11.82"	13.12"	10.86"*	10.04"*	9.62"	9.70"

~ - rain gauge was full.
* - adding average of two nearest rain gauges to make up missing data.

TABLE 2. Rainfall Chemistry

	pH	Conductivity (µmhos)	Alkalinity (mg/l)	Hardness (mg/l)	Comments
7/2	3.60	14	0.0	4.0	1st storm; complete overcast
7/2	4.95	9			2nd storm
7/3	4.02			2.0	1st thunder storm
7/3	4.50				2nd storm, light rain
7/13	4.43	20			2:00 pm storm; overcast
7/13	5.03	16			4:00 pm storm
7/14	4.03	8.5			frontal system, drizzle
7/15	3.70	5.0			frontal system, showers
7/29	4.5				short thunder showers
8/2	3.78				heavy, brief
8/2	4.76				2nd storm, drizzle
8/14	5.02				9:00 am, night before
8/14	4.72				8:00 pm day-long light rain
8/15	4.88				all night rain
8/15	4.80				5:00 pm
8/16	6.11				intermittent showers
8/16	4.87				from 2 directions
8/16	5.70				
8/24	5.45				snowing on summits
8/24	6.02				frontal storms
8/25	5.85				frontal storms
8/26	5.14				frontal systems
8/26	5.19	3			showers from west

indicating a washing-out of acidic constituents in the atmosphere.

Hydrology

Streamflow measurements were taken and rating curves developed for 5 streams in the study area: Birch Creek, Twelvemile Creek, Faith Creek, McManus Creek and Ptarmigan Creek. Watershed areas, discharge per unit areas and high and low flows for the summer of 1983 are recorded in Table 3. The highest flows for all streams were recorded early, and were the result of intense thunder storms. The lowest flows for all streams occurred in the beginning of August. The end of August showed high flows again, similar to the early highs, but were the result of an extended period of rain. Flows for the summer of 1982 were high in spring and low in August. High rainfalls and subsequent high flows were not as dramatic in 1982 as in 1983. Birch Creek, in both summers, exhibited rapid changes in discharge because of draining of settling ponds. Stage changes of several tenths of a foot were observed on Birch Creek over a half-hour period.

The streambeds of the mined streams were heavily embedded and compacted with silt, Birch more so than Faith. Ptarmigan became noticeably embedded and compacted within weeks of the start of mining on that stream. The impact of the embeddedness on groundwater was investigated by driving in well points in each stream bed except Ptarmigan. We found that over the entire summer, 1983, the peizometric surface of the groundwater at the unmined streams was essentially at the

TABLE 3. Hydrology

Stream	High Flow (cfs)	Date	Flow per Area (cfs/sq. mi.)	Low Flow (cfs)	Date	Flow per Area (cfs/sq. mi.)	Watershed Area (sq. mi.)
Birch	490.30	6/27	5.50	45.40	8/11	0.51	89.1
Twelvemile	338.80	6/27	7.18	20.13	8/12	0.43	47.2
Ptarmigan	89.08	7/18	4.57	11.36	8/10	0.58	19.5
Faith	332.74	7/17	5.51	39.83	8/11	0.66	60.3
McManus	465.51	7/17	5.98	38.71	8/13	0.50	77.8

same level as the stream. The peizometric surface below the mined streams was lower compared with the unmined streams. The increased siltation and subsequent embeddedness in the mined streams acts to partially seal the streambed and thereby decrease recharge to the groundwaters. This hypothesis is supported by the lack of any artesian conditions in the wells at the mined streams and the different chemistry of their water as compared to their stream water. The groundwater of unmined streams was chemically similar to their surface waters. In August, three well points were placed at the Birch Creek site and at the Twelvemile site to investigate the water level differences at different locations in the streams and to profile the peizometric surfaces downstream and across (Figure 3 and 4). It is clear that the siltation has acted to depress groundwater levels beneath the mined streams and surrounding them, and reduced the hydraulic contact between the groundwater and surface water.

Water Chemistry

Two streams, Ptarmigan and Faith, showed low levels of alkalinity, (20 to 30 mg/l), total hardness (30 to 40 mg/l), calcium hardness (20 to 30 mg/l), and conductivity (50-80 µmhos). It was felt that these values reflected less groundwater contribution to the flows, Ptarmigan due to its high elevation and Faith for this reason as well as a partially sealed streambed. Birch, Twelvemile and McManus all showed higher levels of these constituents. Alkalinity ranged from 40 to 60 mg/l, total hardness 50 to 70 mg/l, calciuim

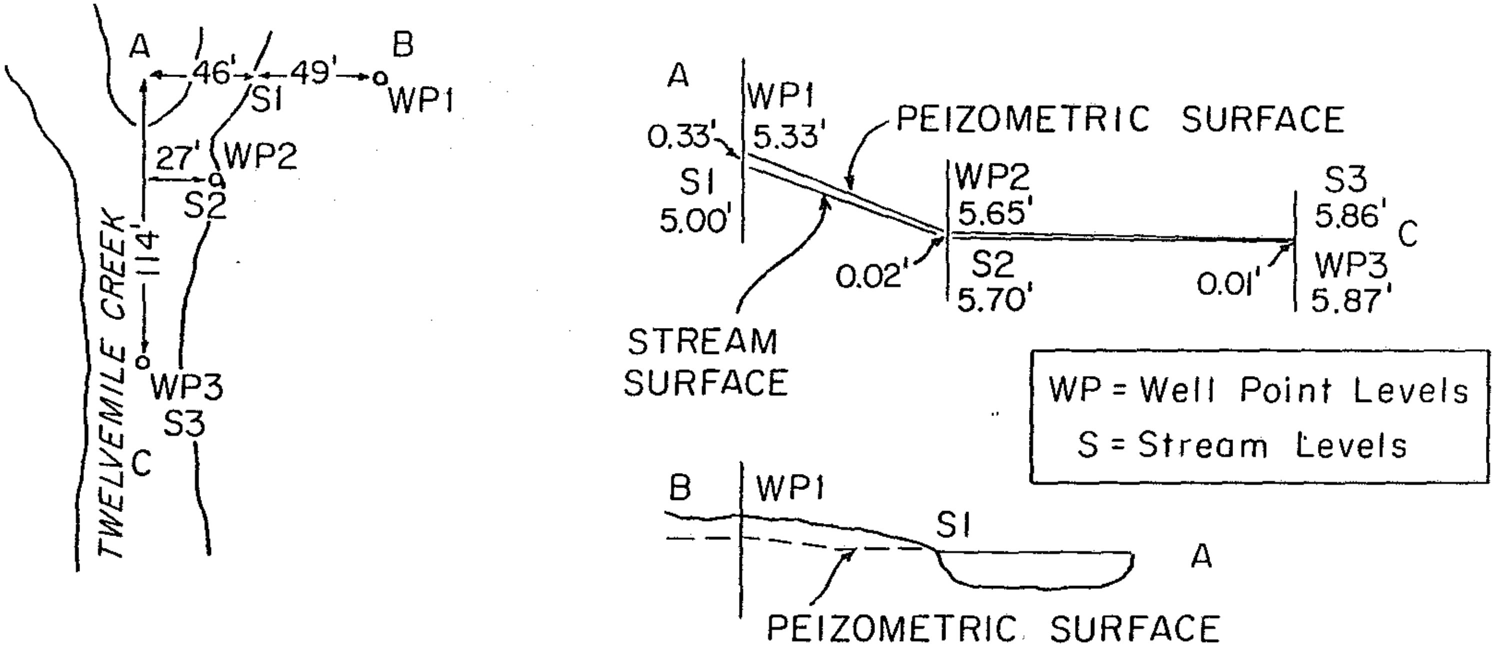

Figure 3. Well Positions (left) and Downstream (right upper) and Across-stream (right lower) Profiles of Groundwater and Surface Water Levels, Twelvemile Creek, September, 1983.

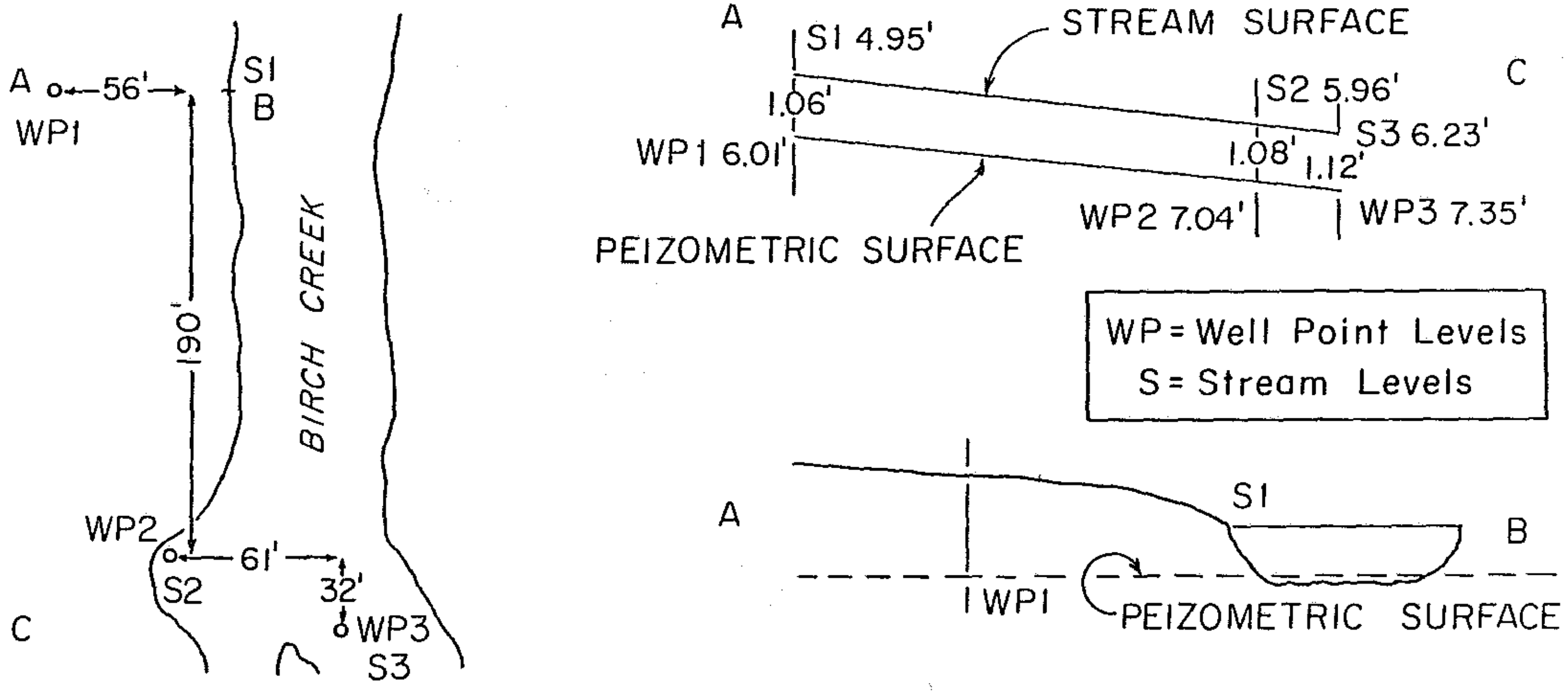

Figure 4. Well Positions (left) and Downstream (right upper) and Across Stream (right lower) Profiles of Groundwater and Surface Water Levels, Birch Creek, September, 1983.

hardness 35 to 50 mg/l and conductivity 110 to 180 umhos. Recent rains caused concentrations to be lower in Birch than Twelvemile, but the reverse was true during dry periods. All the streams showed high silicia (6 to 10 mg/l) and low ammonia and nitrate (less than 1 mg/l as nitrogen), low copper, manganese and nitrite (as nitrogen)(all less than 0.5 mg/l). The pH ranged from 6.00 to 7.50 over the summer for all streams and the groundwater. Temperatures in the streams ranged from 2 to 3 C in May and early June to highs of 10 to 12 C in August. The temperatures dropped off quickly at the end of August into September.

Iron was found to be much higher in the mined streams than in the unmined streams. Iron ranged from less than 0.10 mg/l for the unmined streams to 1.5 mg/l for the mined streams. When Ptarmigan began to be mined on August 15th, iron went from less than 0.1 mg/l to 0.35 mg/l.

Settleable solids were higher in Birch than the other streams due to the mining and values ran between trace amounts and 2.0 ml/l. Faith showed values that were, on occasion, as high as 0.2 ml/l, but were substantially lower than those at Birch. Twelvemile and McManus showed no detectable settleable solids. Ptarmigan showed no settleables until after mining, when they rose as high as 3.5 ml/l. Turbidities were higher in the mined streams, as would have been expected. Suspended sediments in Birch Creek were an order of magnitude higher than the other streams in 1982. However, during 1983, the suspended sediment loads in Birch dropped considerably to average several times that of Twelvemile. This change may have been brought about by a change in mining practices or the wetter weather. Total residues in Ptarmigan Creek increased an order of magnitude with mining (from less than 100 to the 1000's mg/l). The total residues in Faith were never as high as the other mined streams and often totals were no higher than in McManus (less than 100 mg/l). Total residues, however, include all dissolved solids as well as suspended sediment.

Groundwater temperatures were lower than stream temperatures over the summer until September, when the situation reversed. The groundwater chemistry was similar to the surface water for McManus and Twelvemile, the unmined streams, and was significantly different than the surface water at the mined streams. Comparisons of chemistry between the different groundwater sites reveals similar levels of all constituents in Twelvemile, McManus and Faith with the exception of iron, which was higher in Faith. Birch Creek groundwater was higher in conductivity, alkalinity, total hardness, calcium hardness and iron than any of the other groundwaters. The concentrations of iron in the groundwaters of Birch and Faith were both lower than their respective surface waters, however. The dissolved oxygen conditions of the groundwaters under the streams also indicated that the groundwaters of the mined streams are isolated from the surface waters. Table 4 displays data obtained from wells under pools of five streams in 1983. Unmined streams are seen to be near saturation and

TABLE 4. Temporal Distribition of Dissolved Oxygen (mg/l and % saturation) in Groundwater under Pools of Selected Streams

	Stream Type		
Date	Clearwater	Mined	Glacial
8/12/83	Twelvemile Creek $5.90^{+}0.30$(n=3) 54%	Eagle Fork-Birch Creek $0.25^{+}0.05$ (n=3) 2%	
8/13/83	McManus Creek $3.76^{+}0.13$ (n=3) 33%	Faith Creek $2.90^{+}0.27$ (n=3) 25%	
8/31/83			Phelan Creek $9.31^{+}0.29$ (n=5) 82%
9/7/83	McManus Creek $10.95^{+}0.07$ (n=4) 86%	Faith Creek $2.99^{+}0.83$ (n=5) 25%	
9/14/83	Twelvemile Creek $7.75^{+}0.99$ (n=3) 63%	Eagle Fork-Birch Creek $0.41^{+}0.04$ (n=5) 3%	

mined streams depleted. Comparing the August and September percent saturation for the two unmined streams, there appears little change over time for Twelvemile Creek, but considerable increase in McManus Creek. We believe that this increase in dissolved oxygen is associated with high flows. Surface flow is known to correlate with dissolved oxygen conditions in the groundwater, probably because of increased recharge (McNeil 1962). One glacial stream was also successfully sampled, and it is interesting to note that the dissolved oxygen is near saturation. We will be examining the size distribution of the substrate to determine if glacial flour has different characteristics than the clays that are sealing Birch and Faith Creeks.

Table 5 presents D.O. data obtained from wells placed one each in a pool, riffle and on the bank of each Birch Creek and Twelvemile Creek. This table shows that the low D.O. conditions in the mined streams are not localized. It is interesting to note that even under the banks, which in ordinary streams provide recharge head, Birch Creek groundwaters have low D.O. content as well as low elevation. These low dissolved oxygen conditions have important ecological implications. Salmon eggs that are buried in nests called redds could be suffocated if the streambed becomes sealed after they are laid, as could benthic macroinvertebrates

Algae

In both systems we studied, undisturbed streams displayed

TABLE 5. Spatial Distribution of Dissolved Oxygen (mg/l and % saturation), of Groundwater under a Steam-pair (unmined and mined) in early September, 1983.

Location	Twelvemile Creek (unmined)	Eagle Fork of Birch Creek (mined)
Pool	7.75^{+}0.99 (n=3) 63%	0.41^{+}0.04 (n=5) 3%
Riffle	10.13^{+}1.47 (n=3) 82%	1.15^{+}0.26 (n=5) 9%
Bank	4.43^{+}0.11 (n=3) 36%	1.99^{+}0.01 (n=3) 15%

higher productivity than mined streams. Birch Creek, which supports intensive mining throughout the summer, averaged only 0.1 g-$O_2/m^2/d$ with a summer peak of 0.49, while unmined Twelvemile averaged 1.09 with a peak in July of 2.57. Ptarmigan Creek, which was unmined throughout the 1982 field season and most of the 1983 season, displayed an average daily gross production rate of 0.65. For three days in August 1983, productivity was measured simultaneously both above and below a mining operation. During this period, which was mostly cloudy or raining, productivity above the mine averaged 0.38, while below the mining it averaged 0.13.

Faith Creek, which supports only four operations, faired slightly better than Birch with a mean daily gross production rate of 0.39 for the two field seasons, but the unmined stream receiving it (McManus Creek) displayed a seasonal average of 0.87.

Daily gross production rates for both mined and unmined streams apparently increased with the amount of available light as defined by incident PAR levels, mean depth, and turbidity. This relationship has yet to be defined pending further analysis. However, the relationship between turbidity and its effect on the ability of water to transmit PAR to the substrate has been defined on a regionl basis as: $n(t) = 0.00022(T) + 0.011$ ($r^2 = 0.98$) where n(t) is the total extinction coefficient and T is turbidity (NTU's).

Total phosphorus concentrations averaged 598 ug/l in Birch

Creek., 34.4 in Twelvemile, and 36.8 in Ptarmigan before mining. Faith Creek averaged 225 and McManus 23.4 µg/l. The considerably higher levels found in mined streams probably results from the organic matter they carry (from removal of over burden) and/or the adhesion of P-containing molecules to the sediment particles. This is likely since the total P concentrations recorded tended to increase with suspended sediment concentrations. Another contributing factor could be the scouring effect of suspended sediment which would tend to increase the amount of algae found in the water column.

Macroinvertebrates

The differences in invertebrate densities between streams is summarized in Table 6. Mann-Whitney tests for significant differences in medians between streams showed that each stream was significantly different from every other stream. The unmined streams showed significantly higher invertebrate densities than did mined streams.

From the data analyzed so far it appeared that mining in Birch and Faith Creeks significantly lowered the density of benthic invertebrates with some alteration of community structure. As the degree of mining impact increased, certain taxa, such as stoneflies, mayflies, caddisflies, and blackflies, made up a decreasing proportion of the invertebrates found, while other taxa, such as chironomid midges occupied a larger percentage of the invertebrate community. With a high degree of mining activity, like that found at Birch Creek, most taxa became very rare or disappeared completely. It has been hypothesized that sediment input like that associated with placer mining eliminates those invertebrates that make a living by filter-feeding and has a relatively less effect on collector-gatherer organisms. This hypothesis will be tested using the 1983 data.

It seemed apparent from examination of the relatively scant data of 1982 that those factors that did the most to determine invertebrate densities in mined streams were settleable solids and substrate embeddedness. Analysis of the 1983 data will attempt to relate these factors and others to invertebrate density, biomass, and community structure.

Table 6. Invertebrate densities in sampled creeks.

	Mean no./m^2	Std. Dev.	Median no./m^2
Faith (mined)	206	140	210
McManus (unmined)	460	296	365
Birch (mined)	8	11	0
Twelvemile (unmined)	693	285	680

Fish

Periodic beach seining of mined and unmined streams resulted in many fish being caught in unmined streams, but none in mined ones. The only exception to this was during the spring spawning migration of adults and fall out-migration of juvenile and adult grayling. Apparently, adult and juvenile grayling avoided the mined streams in preference for the clearwater tributaries. Mined streams supported neither reproductive nor feeding areas.

From the caged YOY grayling experiments we concluded that the sediment levels of Birch Creek were not of sufficient concentration to cause any mortalities (up to ten days exposure periods). Although there were no deaths caused by sedimentation, the external appearance of the fish caged in Birch Creek was noticeably different from normal healthy individuals. Spots and parr marks were nearly absent in the Birch Creek fish as well as their having a more pale brown coloration on the dorsal surface. Examination of internal organs showed that the fat bodies surrounding viscera in the Birch Creek caged fish were nearly absent which is a likely sign of starvation. Stomach analysis supported this idea in that the Birch Creek fish were not capable of locating many food items. Fish caged in Twelvemile Creek were able to locate aquatic insects and looked normal in appearance when compared to free-living grayling in Twelvemile Creek.

Gross microscopic examination of gill tissue of Birch Creek YOY grayling showed mucus secretions with embedded sediment particles in as short a time period as 12 hours when suspended solids were $>$ 800 mg/l.

Short-term exposure of mining sediments on Age II grayling did not cause a consistent acute stress response (Table 7). The mean leucocrit and hematocrit values of tested individuals did not differ significantly (p=0.5) from control groups. It appears that Arctic grayling in interior Alaska are more tolerant to short-term exposure to sediment than other salmonids such as rainbow trout (Herbert and Merkens, 1961).

A recent study completed by McLeay (1983) on the effects of sediment on grayling in the Yukon showed a decrease in mean leucocrit value and/or more variable glucose levels, but no difference in hematocrit values. It would be difficult to determine why leucocrit values were significantly lower in test fish in the Yukon study, but not in ours. Several possibilities exist: there may be a difference in the tolerance to stress of Yukon and interior Alaska grayling; this study conducted on-site field testing while the Yukon study was mostly laboratory research; or, there is of course, the chance of differences in experimental techniques. It seems evident that further investigations are in order to obtain more baseline data.

Although individual Arctic grayling were tolerant to short term exposure to sediment, they were likely affected at the population level. Heavily mined streams degraded the spawning and rearing habitat of grayling by the filling-in of interstitial gravel spaces, forming a cement-like substrate.

Also, highly turbid waters made slight-feeding impossible for grayling. As a result of these disturbances, grayling were forced into clearwater tributaries for the majority of the summer.

TABLE 7. Acute Stress Bioassay. Leucocrit and hematocrit values of grayling held in Birch Creek and Twelvemile Creek (control)

Stream	Exposure Period (hr)	Suspended Solids (mg/l)		Settleable Solids (mg/l)		Turbidity (NTU)		Leucocrit value (%)		Hematocrit value (%)	
		x	S.D.	x	S.D.	x	S.D.	x	S.D.	x	S.D.
N. Fork	6	124	-	N.D	-	0.4	-	1.16	0.38	42.7	2.7
Birch		624	-	0.5	-	2250.	-	1.06	0.19	41.9	3.7
N. Fork	24	110	14.1	N.D	-	0.6	0.23	1.12	0.24	38.1	4.4
Birch		1388	212.1	0.8	0.53	1855.	490.6	1.12	0.34	43.5	2.7
N. Fork	24	152	5.7	N.D	-	1.1	0.31	1.00	0.14	37.8	2.0
Birch		462	93.3	0.4	0.55	813.	927.0	1.18	0.31	39.9	3.8
N. Fork	36	113	67.1	N.D	-	1.1	0.29	1.37	0.25	39.7	3.3
Birch		527	130.0	0.4	0.43	721.	7332.0	1.20	0.16	40.8	3.5
N. Fork	48	114	9.5	N.D	-	0.6	0.18	1.23	0.20	38.2	4.0
Birch		1205	219.5	0.8	0.54	2121.	1058.2	*0.96	0.17	40.9	2.3
N. Fork	96	115	8.7	N.D	-	0.6	0.16	1.13	0.31	36.9	3.6
Birch		1158	216.7	0.4	0.55	1931.	1024.0	1.18	0.45	**41.8	3.2

* Leucocrit value significantly (p=0.5) lower than control

** Hematocrit value significantly (p=0.5) lower than control

N.D Not Detectable

The ultimate effect, then, of mining on streams in a watershed is to render some of them--the mined ones--partially or wholly incapable of supporting fish and their food base. In other words, the biological carrying capacity for aquatic life in the watershed is reduced in direct proportion to the number and length of streams that receive sediment from placer mines.

References

American Public Health Association. 1980. Standard Methods for the Examination of Water and Wastewater. 15th Edition. 1134pp.

Eisenreich, S.J., R.T. Bannerman, and D.E. Armstrong. 1975. A simplified phosphorous analysis technique. Environmental Letters 9(1): 43-53.

Elmore, H.L., and W.F. West. 1961. Effect of water temperature on stream reaeration. Journal of the Sanitary Engineering Division ASCE, 87 (No. SA6):59-71.

Hall, C.A., and R. Moll. 1975. Methods of assessing aquatic primary productivity. In Primary Productivity of the Biosphere. H. Lieth, and R.H. Whittaker (eds.) Springer-Verlag. New York.

Herbert, D.W.M., and J.C. Merkens. 1961. The effect of suspended mineral solids on the survival of trout. Int. J. Air. Wat. Poll. 5(1):46-55.

Jirka, A.M., and M.J. Carter. 1975. Anal. Chem. 47(8):1397.

McLeay, D.J. 1983. Effect on Arctic grayling of short-term exposure to Yukon placer mining sediments: laboratory and field studies. Can. Tech. Rpt. Fish. Aq. Sci. No. 1171.

McNeil, W.J. 1962. Variations in the dissolved oxygen content of intragravel water in four spawning streams of Southeastern Alaska. United States Fish and Wildlife Service. Special Scientific Report--Fisheries No. 402. Washington, D.C. 15pp.

Mortimer, C.H. 1981. The oxygen content of air-saturated fresh waters over ranges of temperature and atmospheric pressure of limnological interest. Mitt. Internal. Verein. Limnol. 22:23pp.

O'Connor, D.J., and W. Dobbins. 1956. The mechanisms of reaeration in natural streams. J. Sanit. Eng. Div., Proc.

ASCE, 82, SA6.

Odum, H.T. 1956. Primary production in flowing waters. Limnol. and Oceanogr. 1:102-117.

Wedemeyeer, G.A., and D.J. McLeay. 1981. Methods for determining the tolerance of fishes to environmental stressors. pp. 247-275. In Stress and Fish. A.D. Pickering, ed. Academic Press. London.

Wilcock, R.J. 1982. Simple predictive equations for calculating stream reaeration rate coefficients. New Zealand Journal of Science 25:53-56.

NON-SOLAR INFLUENCES ON TEMPERATURES OF SOUTH COASTAL ALASKAN STREAMS

Abstract

Solar radiation plays a key role in the temperature regime of south coastal Alaskan streams, but is less dominating than in sunnier climes. Other factors - wind, precipitation, lakes, glaciers,falls and rapids, soils and aquifer routings - also have important effects, and are the subject of this work.

Conduction and evaporation-condensation processes of heat exchange both proceed at rates linearly responsive to wind speed. These processes may be more dramatic in cooling exposed waters in fall-winter than in warming during summer. Wind produces important heat losses and mixing action in lake waters. Freeze-up is likely to occur in clear, quiet weather following wind chill conditions. Rainfall seldom provides heat to surface waters, but snowfall can be a significant cooling agent.In addition to the role of lakes as solar heat sinks, mechanisms of wind mixing, wind chilling, and protective ice cover produce temperature effects in the outlet flows of lakes. Glacial streams, though cold in spring to fall months, often produce sustained, relatively warm spring-fed flows in winter. Falls and rapids act like wind in producing changes as large as 4° C. through extended falls. Groundwater aquifer routes are important temperature moderators, cooling in summer and warming in winter. Deeper soils probably also moderate temperature, while muskeg dominated watersheds favor warm stream temperatures.

The sequence or combination of these influencing factors produce the temperature character of a stream, which may be variable from head to mouth or may be dominated by only few factors according to the conditions of local climate and physiography.

Introduction

The most prominent variable influence on stream temperatures in mid-latitude drainages is generally recognized as sunshine. Presence or absence of shade along a stream is often a critical habitat feature in plans for logging or other activities which may affect streamside margins. While solar radiation remains an important influence on south-coastal Alaskan streams, other factors can also have major, even dominating, effects on stream temperatures and are associated with varied specific climatic and physiographic conditions within watersheds. These factors -- wind, precipitation, lakes, glaciers, falls and rapids, soils and aquifer conditions -- are the subject of this discussion.

The process or mechanism by which factors affect temperature is described, and the magnitude of effects are illustrated when information is available. Examples of the effect of specific factors upon fishery habitats are described. Finally, a discussion is provided of how the several temperature influences of a drainage may be integrated into patterns of variable complexity.

Wind alters temperatures of streams and tributary lakes and ponds by influencing the rates of transfer of sensible heat by conduction, or of evaporation-condensation. The conduction or transfer of sensible heat is linearly dependent upon (a) wind speed, and, (b) difference between air and water temperatures. In a study of the heat and water balance of Lynn Canal, southeast Alaska, oceanographer D.R. Mclain (1969) notes that transfer of sensible heat "was greatest during the winter (November to March) at Eldred Rock, due again to the strong cold winds blowing over relatively warmer water." The rate of evaporation or condensation is linearly dependent upon (a) wind speed, and upon (b) difference between saturation vapor pressure of water at surface water temperature and the vapor pressure at dewpoint temperature condition.Mclain's analysis(1969) indicates that evaporation is a significant factor in heat loss from Lynn Canal during winter. This, he notes, is particularly true in upper Lynn Canal, where strong winds are common. His work further suggests that heat gain in a southeast Alaskan water body due to condensation is only likely in summer, and then only when the water body is quite cold compared to the air temperature. He found little or no heat gain by condensation in his investigation of Lynn Canal.

Measurements of water temperatures at two locations in Black Bear Creek near Klawock, Alaska on Prince of Wales Island, were examined for the possible role of wind on lake outlet water temperature. Figure 1 shows average water temperatures at the mouth of Black Bear Lake, elevation 1685 ft., and at the base of the falls and rapids at elevation about 200 ft., about a half mile below the lake mouth.

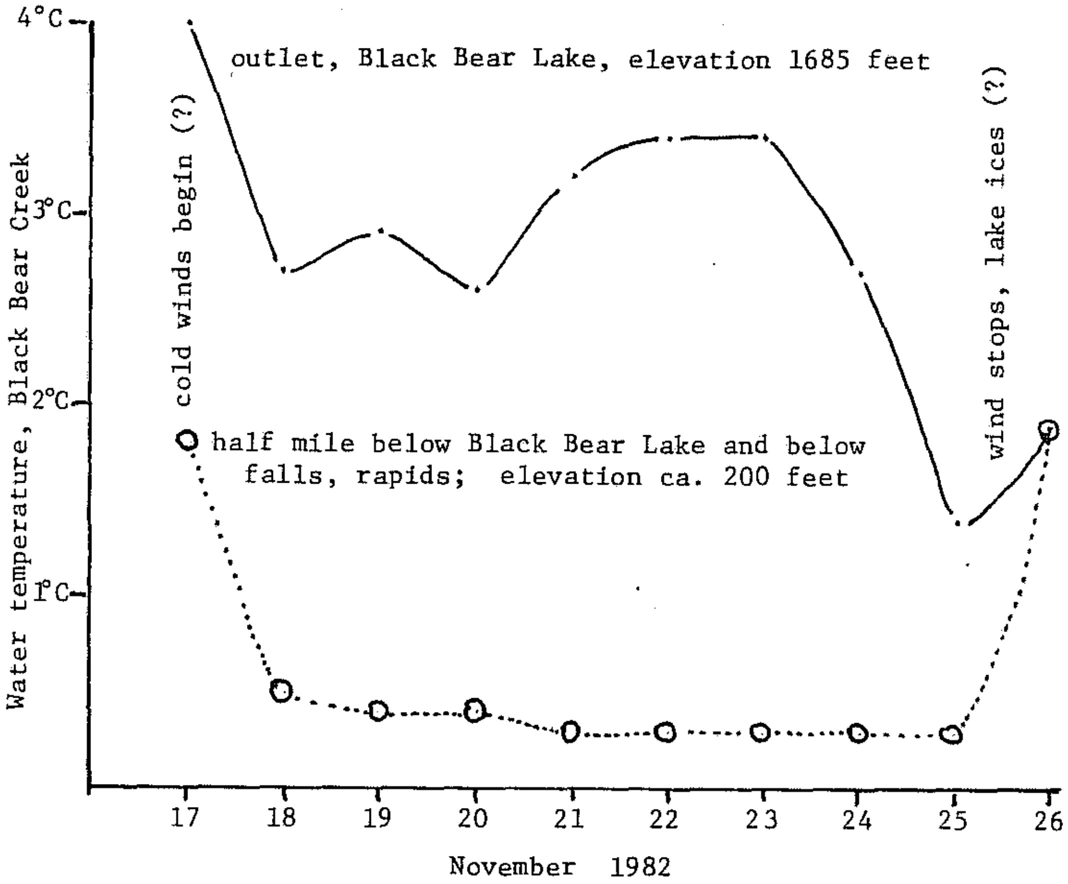

Figure 1: Comparison of Black Bear Lake outlet temperatures with temperatures a half-mile below lake outlet and falls-rapids, used to illustrate fall wind-chill, lake mixing and freeze-up behavior.

This figure is believed to show: (a) initial brief period of conductive cooling;(b)mixing of lake surface and sub-surface waters; and,(c)probable freeze-up of lake surface as winds and mixing cease under clear weather.

The role of exposed versus ice-free lake conditions is further indicated in Figure 2. The effect of wind on lake surface temperatures is probably an important temperature-related factor when lake ice is not present, disappearing when the lake freezes over.

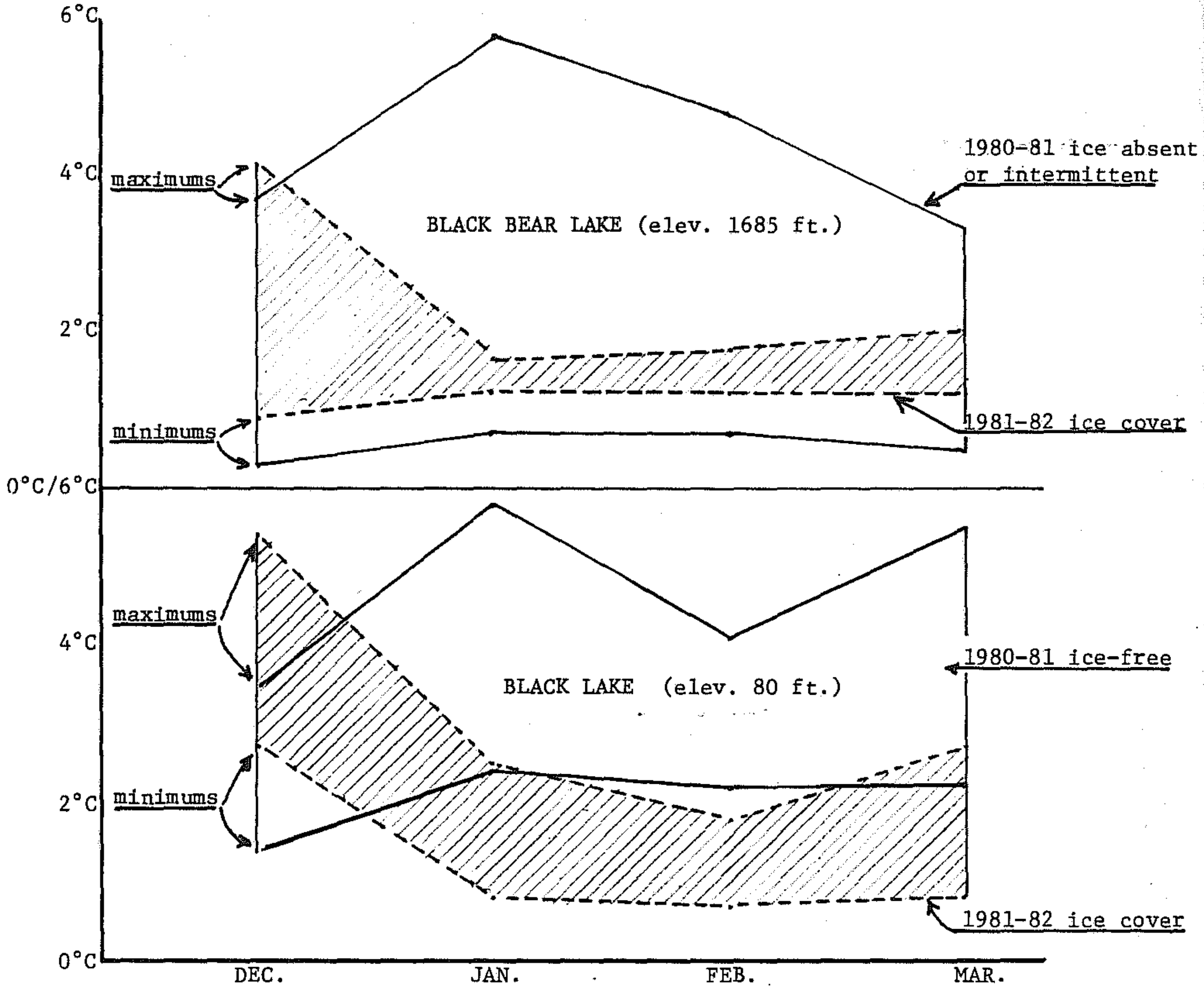

Figure 2: Monthly extremes of daily temperature, winters 1980-81 and 1981-82, for Black Bear Lake and Black Lake outlets. Data from Bishop, et.al.,1982.

As shown in Figure 2, Black Bear Lake was never fully ice-covered in winter, 1980-81, and Black Lake (at elevation 80 ft. about a mile and a half downstream) remained ice-free. In the winter of 1981-82 both lakes were ice covered. Strong, local mountain winds are common in the vicinity of these lakes, with evident potential for mixing . The access of wind to the water surfaces is believed to have been an important factor in producing the differences in water temperature ranges seen in Figure 2.

Wind can also directly cool water within a stream channel. Bishop (1974) made the following observation of wind cooling of a stream tributary to Becharof Lake, Alaska Peninsula. "A graphic example of cooling was seen on (stream) E-130.0. At the mouth on Sept. 30 this stream measured 6.0°C. with air temperature of 7.4°C, while 20 minutes later and 1/3 mile upstream above the falls (about 20-30 ft. high) the stream was 6.4°C. The strong wind (10-20 mph at the surface) provided a powerful cooling agent as it struck the turbulent water at the falls."

In summary, the effects of wind on water temperature are to:

a. increase rates of sensible heat transfer or evaporation-condensation in proportion to wind velocity, and to,

b. induce mixing in water bodies.

Wind on shallow lakes or exposed streams can produce rapid temperature change. Even on deeper lakes it appears that surface water temperature change, particularly from winter chilling, can occur rapidly in addition to mixing action.

Precipitation effects: In Mclain's (1969) heat balance study of Lynn Canal, he concluded that rainfall is likely to have a relatively small impact upon water temperatures. He states, " The transfer of heat by precipitation, Q_p , between the atmosphere and the water of Lynn Canal was primarily by the mechanism of melting of the winter snowfall. Thus the heat transfer was predominantly a negative heat exchange -- a heat loss by the water. The only times when the heat exchange might be positive would be when warm rainwater fell on cooler water. This would only occur during summer months when snowmelt is zero. If positive heat exchange by precipitation ever occurred, it would be of small magnitude since during summer the air temperature (and hence the rainwater temperature) is almost equal to the sea surface temperature."

The validity of Mclain's conclusion, as it might be extended in application to fresh waters, was briefly examined using observations made in the Black Lake basin of Black Bear Creek, near Klawock. Figure 3 compares mean daily temperatures taken at the mouth of Black Lake with rainfall measurements made at the lake.These plots, for spring and for late summer suggest that rainy periods are associated with dropping water temperatures through these seasons. Exceptions to this behavior seem to occur in the late March and mid-September plot relations.

There are occasions when precipitation plays an important water temperature role. In August of 1971 the author observed sockeye salmon holding at the saltwater mouth of Shrode Creek in Prince William Sound. Biologists attributed this delay of salmon migration to the exceptionally low temperatures in Shrode Creek - about 4°C. The low stream temperatures during that August were caused by the very heavy winter snowpack and the late

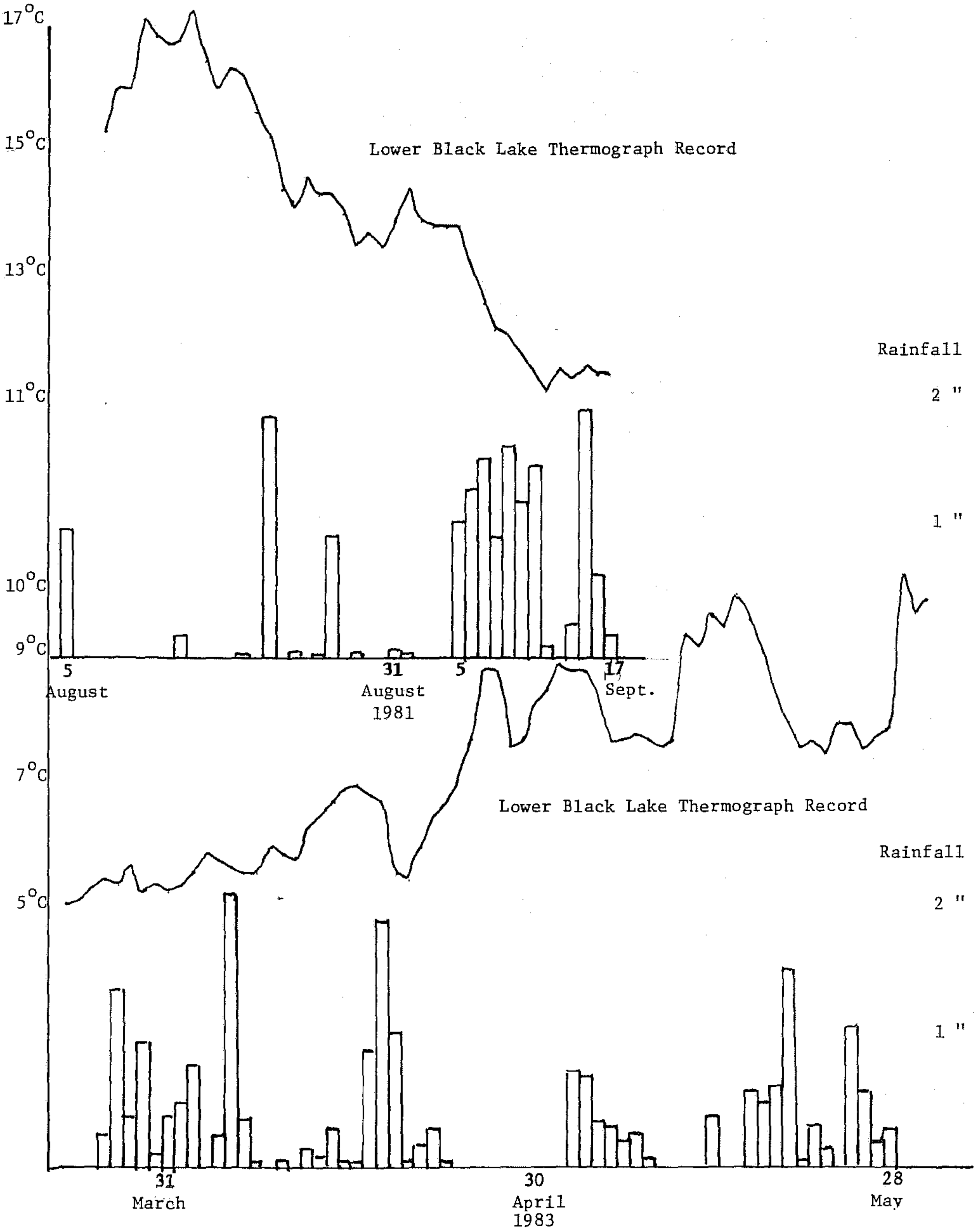

Figure 3: Simultaneous plottings of Black Lake outlet temperatures and of rainfall measurements taken at Black Lake.

spring-summer melt, even at tidewater. Such depression of stream temperature is not uncommon in areas which may receive heavy snowfall. Noerenberg (1957) also reported depressed temperatures in Prince William Sound during the summer of 1956, after a winter with heavy snow followed by a slow melt season.

Rain on snow accelerates melt both because of the rain's heat content and because the action of rain on snow reduces the snow-surface albedo and thereby increases absorption of solar radiation. These effects have been observed by the author to produce increased runoff with low water temperatures in streams having sizeable sub-alpine areas.

Lakes are widely recognized to profoundly influence temperatures of the associated stream system. Lakes provide the most important of physiographic influences upon water temperatures in many drainages and exert control not only on means and extremes of water temperature, but also upon the timing and the duration of temperature conditions.

The climatic elements of air temperature, solar radiation, back radiation, wind, precipitation, act individually or together on lake surface waters to affect temperatures. The physical characteristics of a lake including water quality, area, shape, depth, elevation, orientation with regard to surrounding terrain, and exposure to wind, control the degree of temperature response to climatic elements.

Bishop (1974) performed a small experiment on the rate of solar heating of four kinds of water held in respective containers on a sunny day. The respective waters were Chulitna River(glacial sediment), Talkeetna River (glacial sediment), Auke Lake(stained with iron-organics), and tapwater (clear).An electronic thermometer with a highly sensitive probe was used to measure the changes in profiles of temperatures for the respective containers of water. The following conclusions were reached:

a. In sunny conditions, with air temperatures greater than water temperatures, sedimented waters warmed fastest. Iron-organic stained water warmed faster than tap water.
b. Under conditions when air temperatures were less than water temperatures, heat loss of sedimented water evidently exceeded that of stained or tap water.
c. the more heavily sedimented Chulitna River water developed a stronger temperature stratification than Talkeetna River water. Both sedimented waters stratified more than the clearer waters.

These water quality characteristics undoubtedly affect lake heating. Further information describing this effect is not available.

The most important lake characteristic is area, since each of the climatic elements act in proportion to the area, though the respective roles of direct solar radiation or effective back radiation will be diminished according to the lake's shading or to lakeside obstructions which influence the intensity of back radiation heat loss.

Shape and depth of lake act together to influence rates of shoreline versus offshore heating, development of lake temperature stratification, and impacts of winds.

Lake elevation affects potential solar radiation with significant increases developing above 3,000 ft. elevation. Mean air temperature drops with increasing elevation, while wind speed effects on temperature will be larger as elevation increases.

The compass orientation of a lake and its relation to surrounding terrain may influence the solar radiation it receives. In some cases a lake's orienttation or position will strongly influence its exposure to wind, as for example, mainland lakes which may be exposed to strong gradient winds moving off mountains. Island lakes are sometimes located in positions exposed to williwaw winds, while other lakes are not vulnerable to these frontal disturbances.

Wind action also has strong effects upon the thermal regime of a lake and its outlet stream's temperature, as discussed earlier. Differences in extremes of lake outlet water temperatures under ice-covered versus open winter contions were shown earlier in Figure 2.

The timing of weather events acting on a lake can have strong influence on its thermal characteristics. In the fall and winter of 1981-82,Black Bear Lake near Klawock froze over about December 25. In the fall and winter of 1982-83, the lake froze over about November 18-25. 1/ This difference of a month in the time of freezing may be the cause of the range of values shown in lake temperature profiles, January 1982 versus January 1983 (see Figure 4).

The reduced amount of heat stored in Black Bear lake in January, 1982 as compared with heat remaining in January, 1983 (Figure4) is believed to be due to the cooling action of the wind on the lake surface throughout December, 1981, compared with the early freeze-up in November, 1982. The comparative spring responses have not been evaluated, but there is, no doubt, a basis

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1/Dates were derived from interpreting lake outlet temperature records.

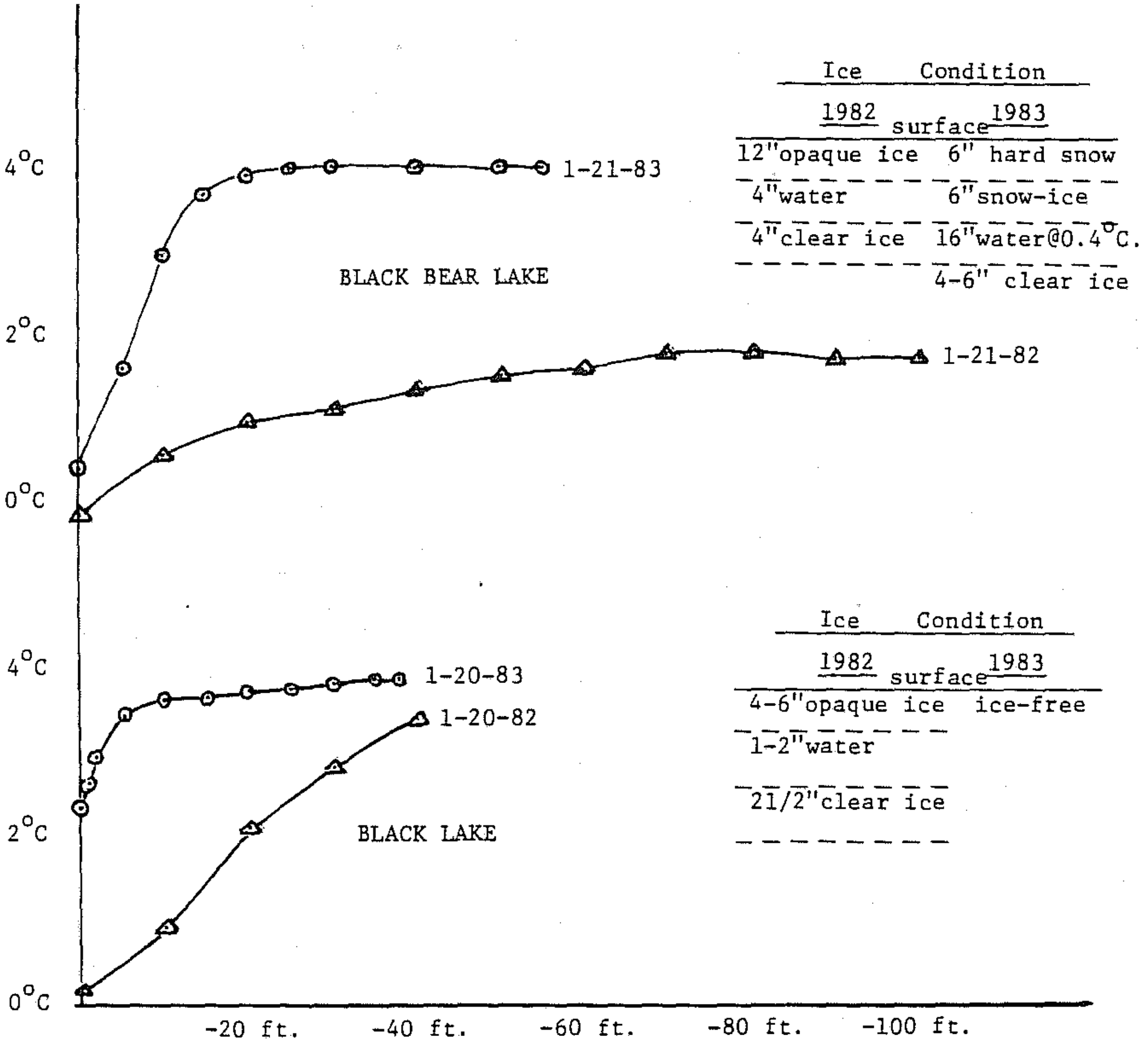


Figure 4:Temperature profiles for Black Bear Lake and Black Lake, near Klawock; January 1982 and January 1983. Lake conditions are also shown.

for a significantly different temperature regime below Black Bear Lake in spring 1983, as compared with the previous year. The most notable feature of this comparative set of observations is that differences in heat-temperature regime appear to have resulted primarily from differences in timing and pattern of freezing of the lake during the two years.

Glacial streams found along the mainland and in some instances on larger islands with glacial headwaters, have special water temperature regimes. In the vicinity of Lituya Bay, meltwaters immediately below glacial sources were found to be in the range of 0°C to 4 or 5°C during May through October (Bishop,1977). In larger glacial rivers with considerable distance of flow below the glacial origin of flow, downstream surface water temperatures may reach or exceed 10°C. Glacial lakes act to elevate temperatures, and glacial sediment probably affects the nature of this process.

A somewhat unexpected feature of glacial streams is their winter flow regime. L.R. May, USGS Glaciologist, notes that glaciers provide good winter low flows (personal communication, 1981) These flows may derive from relatively large groundwater aquifers common in glacial vallies. The effect of sustained winter low flows on river water temperatures just downstream of the glacial origin , is to elevate temperatures above near-0°C levels, in some cases even during the coldest periods of winter. Thus, Bishop (1981,1982) found that glacially-fed West Creek, near Skagway, Alaska, seldom fell below 1°C, while the receiving water of the nearby Taiya River, flowing from more distant glacial and other sources,dropped to near 0°C.

The role of groundwater flows in glacial streams during fall to spring months is a key factor in late runs of chum and coho salmon into many large and small glacial rivers of Alaska. These runs of salmon have adapted timing suitable for the temperature regime found in groundwater upwelling areas, and locate these areas by using temperature sensors on their skin.

Waterfalls and rapids favor extremes of temperature and associated flow conditions. In summer, south-facing falls and rapids are particularly favorable conditions for rapid warming. Even the north-facing falls below Black Bear Lake (vertical fall about 1500 ft.) produced a temperature increase on June 20, 1982, from $1^{o}C$ above the falls to $5.5^{o}C$ immediately below the falls.(Bishop, et.al.,1982)

In fall and winter, falls and rapids may lose heat rapidly and when streamflows are already at or very near freezing may produce heavy volumes of needle or frazil ice. Figure 5 provides a record of stream temperatures of upper Black Bear Creek, at the outlet of Black Bear Lake, at the base of the falls - also the location of entry of much flow into groundwater, and, downstream 1500 to 2000 ft., where much of the stream re-appears as springflow. Comparison of the temperatures above and below the falls demonstrates fall-winter temperature losses of up to $4\ ^{1}/2^{o}C$. along the course of the falls.

An important result of falls or rapids demonstrated in Figure 5 is the fluctuating character of temperature immediately below the falls as compared with the entry temperatures found above the falls at the outlet of the lake. The loss of thermal stability in a system due to falls or rapids is apt to work against the quality of fishery habitats.

Soil and groundwater aquifer routes exert strong influence on water temperatures. As a general rule, deeper mineral soils provide greater flow

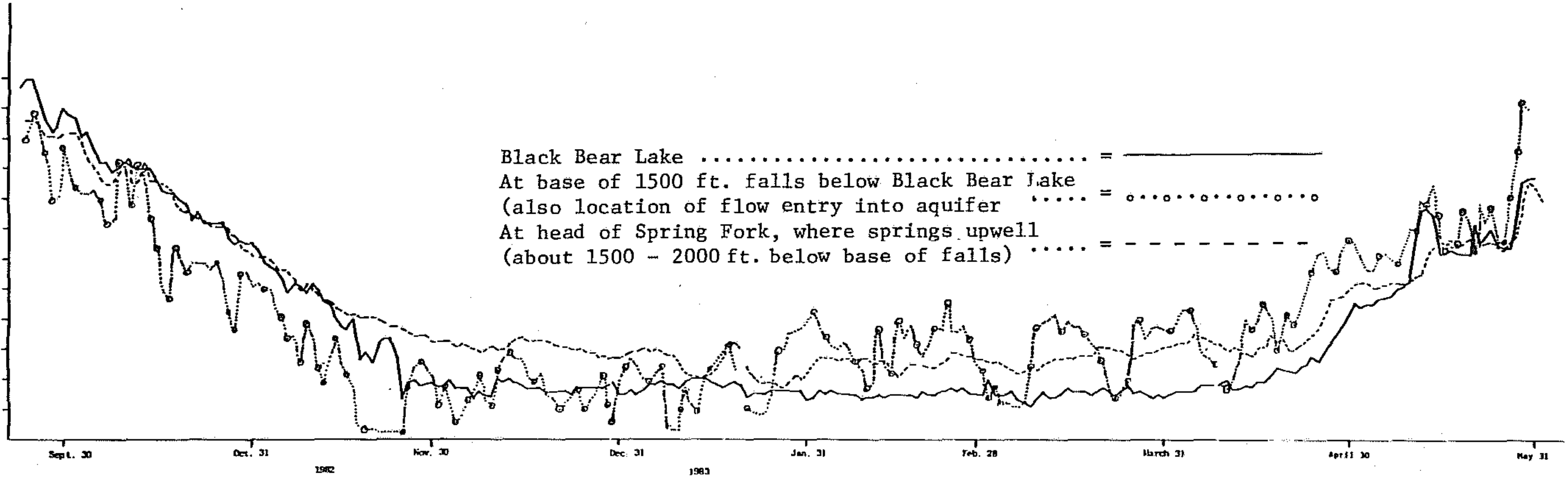


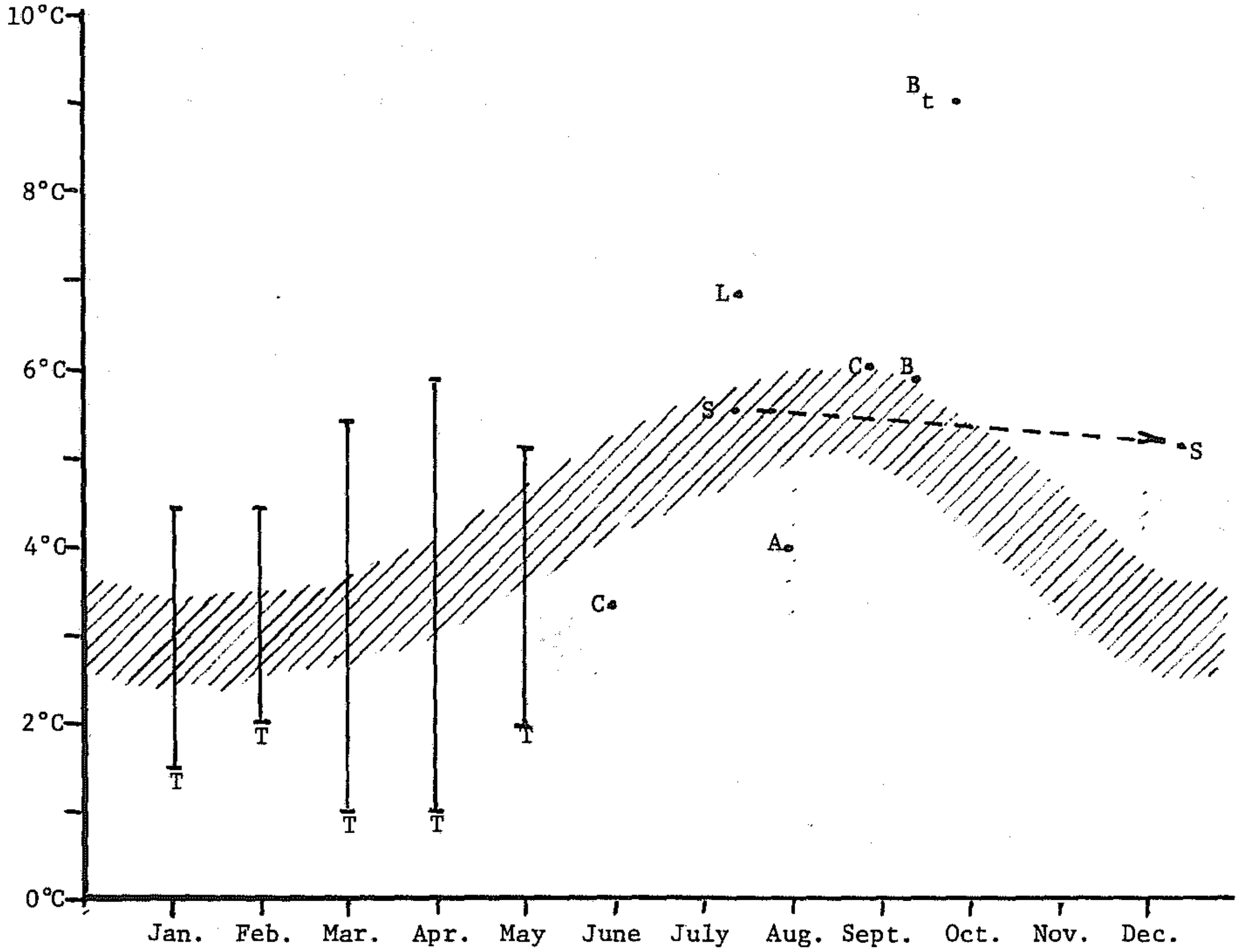
Figure 5: Average daily temperatures for three sites below Black Bear Lake, September 1982 through May 1983.

regulation and less surface heating of tributary water sources than soils which are shallow to bedrock. Deeper soils are also highly correlated with better forest growing conditions, indicating that heavily timbered watersheds are likely to have well regulated water temperatures in their natural state.

In contrast, open muskeg soils provide direct access of solar radiation to the soil-groundwater profile. Thus, although the albedos of wet muskegs and northern conifer forests are probably similar, the energy actually received at the soil level in a muskeg is likely to be higher, since a significant part of a forest's incoming radiation is absorbed by the forest canopy and only part of this direct radiation received by the forest canopy is retransmitted as long-wave radiation reaching the soil surface. In effect, such open, wet muskegs may be strong heat sinks, once the winter's snows are melted, producing dramatic reduction in heat (radiation) reflected up from the surface. Sheridan and Bloom (1975) reported maximum expected temperatures for muskeg-forest tributaries at 55-60^{O}F. and muskeg tributaries at 65-70^{O}F.

Groundwater entry into surface waters may dominate temperature conditions prevailing at specific locations on a drainage. In some smaller systems, and during periods of either summer or winter low flow, the groundwaater contribution may control stream temperatures. The temperature of emergent groundwater is conditioned by the depth of its flow path, the time spent in groundwater flow, and by the mean annual temperature of the geographic region.Examples of groundwater temperatures at various locations along the Gulf of Alaska, shown in Figure 6, suggest the likely annual range of temperatures of waters emerging after a significant period of groundwater flow.

Figure 6: Plotting of miscellaneous groundwater temperature measurements made by D.M. Bishop at varied locations and times on fresh waters along the Gulf of Alaska. A speculative curve of likely groundwater temperatures is shown.



A = Aleutians, Umnak Island, Sheep Creek drainage, 1977.
B = spring near Becharof Lake, Alaska Peninsula, 1974.
B_t = upwelling near Becharof Lake, Alaska Peninsula, 1974; water temperature may be geothermally influenced.
C = Clear Creek, near Chilkat Lake near Klukwan, 1981.
K = groundwater from Klehini River near Klukwan, 1981.
L = groundwater in dug pit, 1/4 mile from ocean near Lituya Bay, 1977.
S = groundwater headwaters of Switzer Creek near Juneau, 1971 - 72.
T = six groundwater observation wells at confluence of Tsirku River with Chilkat River, near Klukwan, 1981.

Bishop, et.al.(1982) measured inflow and outflow water temperatures associated with a very fast flowing groundwater route, estimated by dye tracing work to flow at a rate of 100 ft per hour through an aquifer about 1500 to 2000 ft. in length. In summer, when water flowing into the groundwater route was 12°C.,the temperature of the outflow springs ranged from 9.5 to 12°C. Thermographs installed in early fall, 1982 immediately above and below this groundwater route yielded the results also shown in Figure 5. Fall-winter observations of water temperature show increases of as much as $3^{1}/2$°C. through the groundwater route.Volume of this flow was in the magnitude of 12 to 25 c.f.s.

In general, the entry of water into groundwater flow produces modulated temperatures at the springs below. The direction of heat flow varies seasonally. This process is likely to be strongest when largest temperature differences occur between inflowing water and aquifer materials. In the fall-winter period larger differences between inflow and outflow temperatures may be expected than in the winter-spring period, because the heat reserve and temperature differential required to produce change in temperature may be reduced or depleted. This reduction in magnitude of change is suggested upon careful examination of Figure 5.

Groundwater flows are critical to the spawning habitat of chum and coho salmon, as noted earlier in the discussion of glacial waters.Springflow temperatures are in a useful range and are dependable; stable flows are also highly beneficial. In Japan, only springfed streams are selected as sites suitable for establishment of chum salmon hatcheries.

Important geologic and landform situations producing springflows include glacial and alluvial gravel formations,limestone areas, uplifted beaches, Landslide deposits, fault zones, and volcanic ash deposits. All of these occur along south coastal Alaska.

In conclusion, the immediate function of this work is to assist the field ecologist or hydrologist in identifying likely stream temperature regimes within a drainage. An expansion of the work is in the recognition that many streams contain several distinct, linked temperature regimes. The nature of these respective regimes and the sequence of their occurrence is vital to a stream's character. Some examples of linked regimes are:

a. a lake in the headwaters of a stream has more impact on stream temperature downstream if the lake does not have a waterfall or rapids at its mouth;

b. the fluctuating temperature effect of rapids or falls is rapidly mitigated by a groundwater flow route downstream and conversely, the temperature stabilizing quality of groundwater flow may be largely eliminated by a waterfall downstream and,

c. lakes with little exposure to wind are likely to have different outlet temperature regime than those exposed to winds.

An understanding of these relationships between streams and their associated terrain and climatic conditions may help to enlarge our background of knowledge and improve our ability to predict or to understand the hydrologic and biologic performance of coastal Alaskan streams.

CITATIONS

Bishop, D.M. 1974. A Hydrologic Reconnaissance of the Susitna River Below Devil's Canyon. A report for the National Marine Fisheries Service, Juneau, Alaska. Environaid Juneau, Alaska.

__________ 1974. Investigation of Selected Streams of Becharof and Ugashik Lakes. Environaid. October 1974 in The Bristol Bay Rehabilitation and Enhancement Opportunity Program, A Progress Report. Dec. 17, 1974. Alaska Dept. of Fish & Game, Div. of Comm. Fish, Anchorage, Alaska.

__________ 1977. Hydrology of Coastal Streams Near Lituya Bay. Environaid. Dec. 1, 1977, A report for U.S. Park Service, Juneau Alaska.

__________ 1982. Letter to R.W. Beck & Associates, Seattle, summarizing a year's water temperature records on West Creek & Taiya River near Skagway, Alaska. Environaid, Oct. 21, 1982.

Bishop, D.M., A. Milner & L. Smith 1982. Biological-Ecological Investigations on the Black Bear Creek System Near Klawock, Alaska. A report to Harza Engineering Company for Alaska Power Authority, Anchorage, Alaska. August, 1982.

Bishop, D.M., O.C. Wallmo, & T. Moore. Environmental Investigation of the West Creek Hydroelectric Project. A report to R.W. Beck & Associates for Alaska Power Authority, Anchorage, Alaska. December 15, 1981.

Mc. Lain, D.R. 1969. Heat and Water Balance of Lynn Canal, Alaska. Doctoral dissertation, University of Michigan, 1969. 143 pp.

Mayo, L.R., 1981. Personal Communication with D.M. Bishop re Bishop & Havrilak's work (1981) cited earlier.

Noerenberg, W. 1957. In Fisheries Research Institute Archives, University of Washington, Seattle, Washington.

Sheridan, W.L. & A.M. Bloom, 1975. Effects of Canopy Removal on Temperatures of Some Small Streams in Southeast Alaska. USDA Forest Service Administration Report, R-10 Juneau, Alaska, June, 1975.

A COMPARISON OF VELOCITY MEASUREMENTS BETWEEN CUP-TYPE AND ELECTROMAGNETIC CURRENT METERS

By Paula M. Wellen* and Douglas L. Kane**

Abstract

Several methods for determining the velocity in an open channel stream are in use today, two of which are the cup-type current meter (such as the Price AA, Gurley, or pygmy) and the electromagnetic flowmeter. The cup-type current meter is the most widely accepted and is used as a standard by the U.S. Geological Survey. Use of the electromagnetic flowmeter by field workers is increasing due to its ease of use and the direct readout of the velocity measurement.

Velocity measurements were taken with a Price AA current meter, a pygmy current meter, and two Marsh McBirney Model 201 flowmeters. Velocity profiles were made in numerous streams with a wide range of water velocities; measurements were also taken in metal culverts.

Differences were detected in the velocity measurements from the different current meters. A strong linear relationship was found between the readings from the electromagnetic flowmeters and the cup-type current meters at lower velocities. For water velocities greater than 5.0 fps (152.4 cm/sec), the electromagnetic meter registered a lower velocity than the Price AA, but no quantifiable relationship was found.

Introduction

Velocity determination in open channels is an important design parameter used by a variety of engineers and scientists. Biologists, foresters, agricultural engineers, hydrologists, environmental engineers and civil engineers all gather and use stream velocity data. Because of the diversity of people and possible end uses, the data must be accurate, precise and independent of the method by which they were gathered. Several methods for determining open channel stream velocities are presently used: cup-type current meters; pitot tubes; floats;

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* Graduate Research Assistant, Institute of Water Resources, University of Alaska, Fairbanks, Alaska 99701

** Associate Professor, Institute of Water Resources, University of Alaska, Fairbanks, Alaska 99701

propeller-type current meters; and electromagnetic flowmeters. The cup-type current meter is the most widely accepted method and is used by the U.S. Geological Survey as a standard. The mechanical simplicity, ease of checking proper functioning and relatively low initial and maintenance costs of this device contribute to its acceptance. The electromagnetic flowmeter is becoming popular due to its ease of use in the field and the direct readout of the velocity measurement. This paper compares velocity measurements using these two types of instruments in a range of field conditions.

Cup-type current meters are manufactured under several different names and come in two different sizes (for example, Gurley and Price AA, pygmy and mini-current meter). All of these instruments work on the same principle. A set of six conical cups revolve about a vertical axis; when placed in the current, the water impinges on the cups causing them to rotate. Tail vanes or fins are used to keep the current meter facing directly into the current. A small cam inside the current meter driven by the rotating cups closes an electrical circuit with each revolution (or each fifth revolution) producing a click in the headphones worn by the operator. The clicks are counted and timed, and are directly proportional to the water velocity (Brater and King, 1976).

The electromagnetic flowmeter is based on Faraday's law of induction (Grzenda, 1981). This law states that a conductor moving through a magnetic field (at right angles to that field) produces a voltage that is proportional to the velocity of the conductor (see Figure 1). In 1832 Faraday performed an experiment to measure the discharge of the river Thames. By placing two large metal electrodes in the river, he

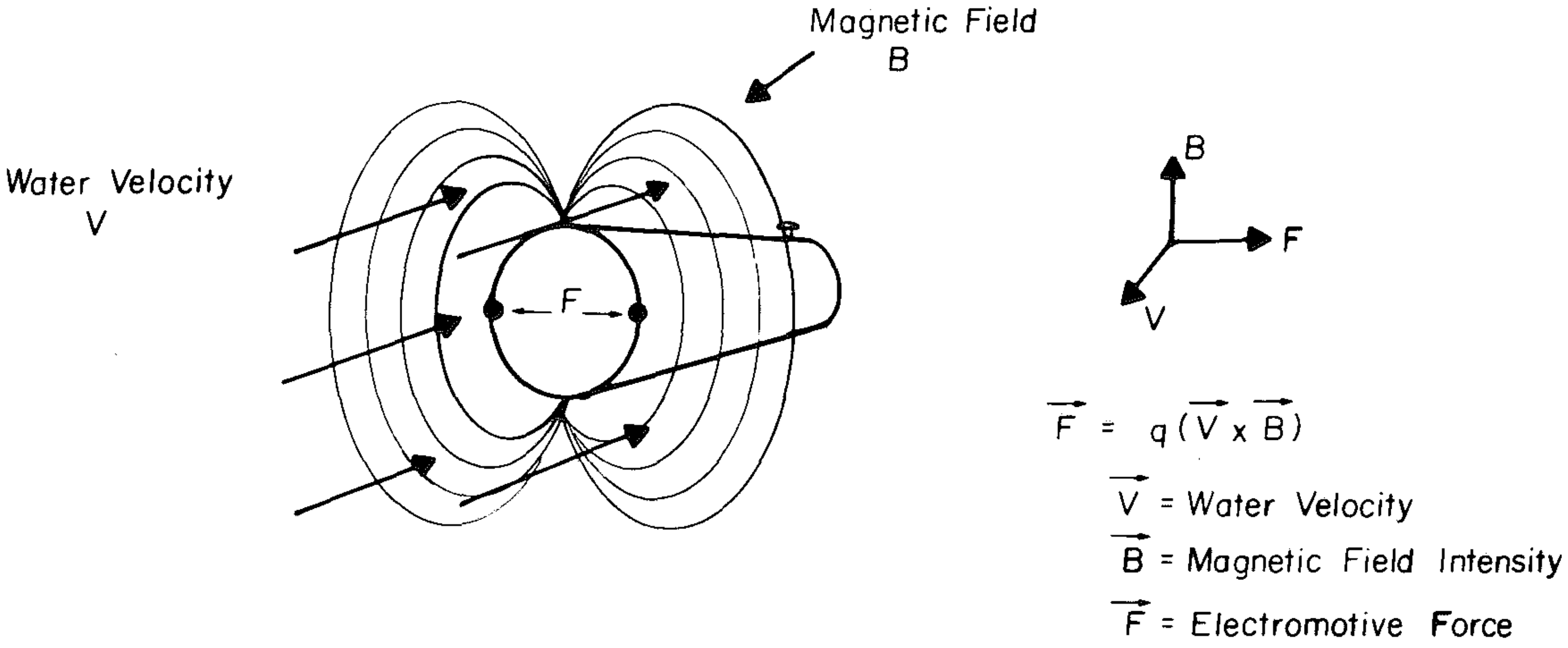

Figure 1. A schematic drawing of the Marsh McBirney electromagentic current meter probe.

tried to measure the induced voltage produced by the water flowing through the earth's magnetic field. Although Faraday's original experiment failed, the principle behind his experiment set the stage for the development of the electromagnetic flowmeter (Springer, 1980).

Water is the conductor when using the electromagnetic current meter to measure stream velocities. A probe containing an electromagnet and two electrodes is lowered into the stream. Tail vanes or fins are used to keep the probe facing directly into the current, ensuring the conductor and the magnetic field are at right angles. The water flowing through the magnetic field produced by the electromagnet creates a voltage drop between the two electrodes and the voltage drop is linearly proportional to the water velocity. Direct readout of this velocity is available in English (feet per second) or SI (centimeters per second) units.

Field Methods

Twenty stream sites were visited resulting in 145 comparisons of velocity measurements using both electromagnetic and Price AA meters. Velocity profile measurements were taken with a Price AA cup-type current meter and two Marsh McBirney Model 201 electromagnetic flowmeters. At streams with low water velocities, a pygmy current meter was used. A Marsh McBirney (in English units) was used for most of the electromagnetic flowmeter work. At selected field sites, the accuracy of this unit was confirmed by comparing it with a second Marsh McBirney (in SI units). In all cases, the electromagnetic probe and the rotating cups were affixed to a top setting rod.

Velocity measurements were started 0.10 ft (3.0 cm) or 0.15 ft (4.6 cm) from the streambed. Near the stream bottom, readings were taken at 0.10

ft (3.0 cm) increments. This spacing was maintained to the stream surface in relatively shallow streams. For deeper streams the readings were spaced progressively further apart as the depth of the reading approached the surface of the stream. This variable spacing was used to better define the velocity profile close to the streambed where the greatest velocity change occurs, while economically reducing the number of readings required in deeper streams.

Measurements were performed over a wide range of water velocities, ranging from 0.40 to 12.09 fps (12.3 to 368.5 cm/sec). The Marsh McBirney was calibrated to read velocities from 0 to 10 fps (0 to 305 cm/sec). The Price AA meter had rating limits of 0.25 to 8.0 fps (7.6 to 243.8 cm/sec). The pygmy current meter was rated for velocities ranging from 0.25 to 3.0 fps (7.6 to 91.4 cm/sec). Profiles were taken in natural stream channels, near bridges and in culverts to cover the widest possible range of velocities.

Results

Ideally, the velocities measured by cup-type and electromagnetic current meters should be the same. A plot of the Price AA velocities versus the Marsh McBirney velocities indicates a high correlation between the readings from the two instruments at lower velocities (see Figure 2). At higher velocities the relationship (if any exists) is not readily apparent.

Figure 2 clearly illustrates the linear relationship between measurements from the two meters at lower velocities. A linear regression of the Marsh McBirney velocity readings on the Price AA velocity readings through the origin for velocities less than 5.0 fps

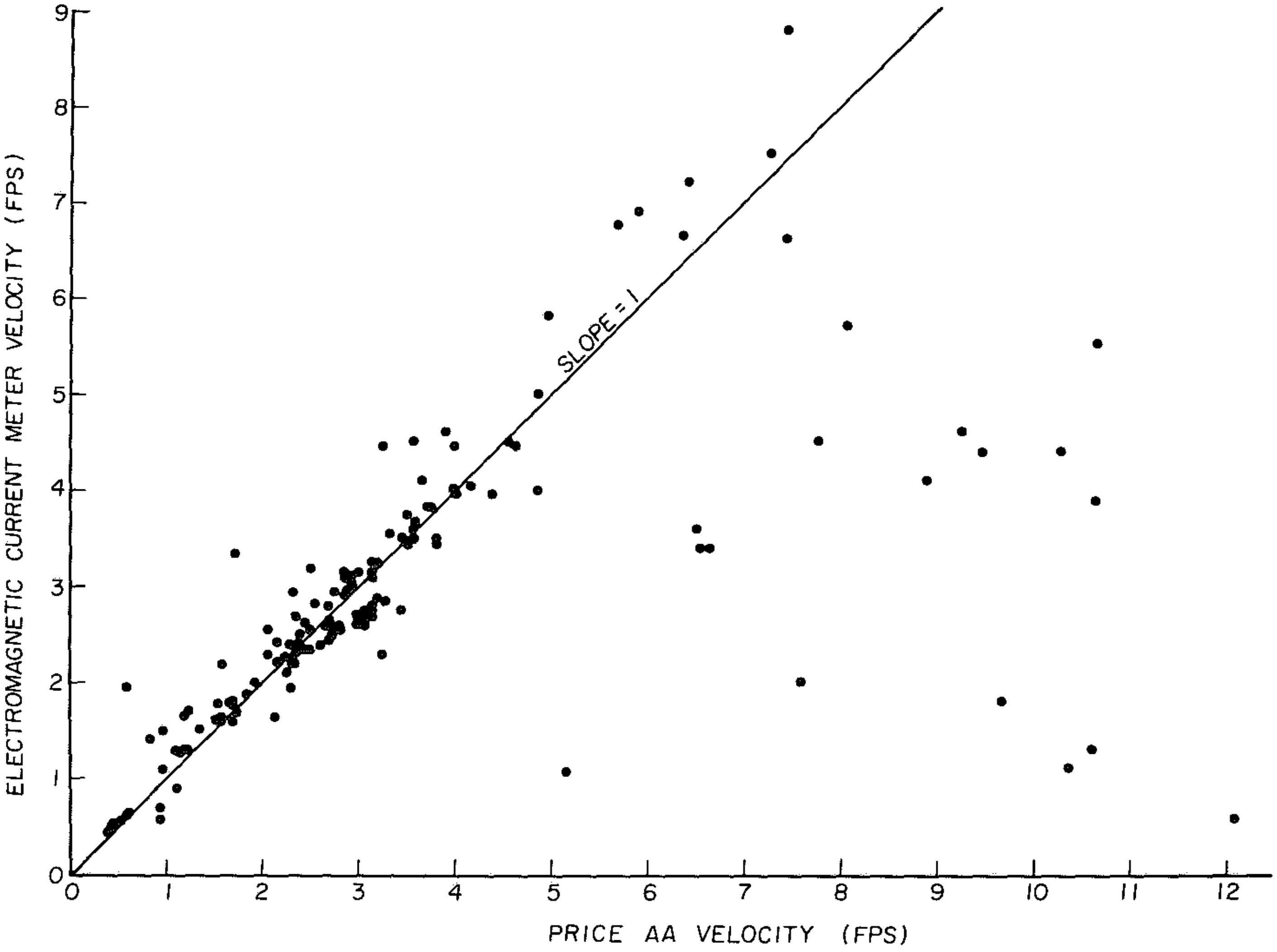

Figure 2. Comparison of measured velocities from Price AA and electromagnetic current meters.

(152.4 cm/sec) results in a straight line with a slope of 1.006. The results of a standard t-test ($t = 0.4736$, $\alpha = 0.05$, $n = 121$, degrees of freedom = 120, P-value = 0.637) show there is no statistical difference between this line and a line through the origin with a slope of 1. The close agreement in readings between the two types of instruments is exemplified in Figure 3: velocity profiles are illustrated for two sites in this study. The water velocity (as measured by the Price AA meter) never exceeds 5.0 fps (152.4 cm/sec) at these two sites. The Marsh McBirney velocity readings are within ten percent of the Price AA velocity readings for all but four measurements at these two locations and are within twenty percent for all but one measurement.

The linear relationship in Figure 2 does not hold true at higher velocities. In fact, the readings from the two meters are negatively correlated ($r = -0.435$, $n = 24$) for velocities greater than 5.0 fps (152.4 cm/sec). Sites 009 and 020 both have water velocities in excess of 5.0 fps (152.4 cm/sec). The velocity profiles for these two locations are illustrated in Figure 4. Even with the compressed velocity axis (as opposed to Figure 3), the difference in readings from the two types of meters is apparent. Two Marsh McBirney instruments were used at site 020, producing comparable readings to each other as opposed to the Price AA meter.

Discussion

One plausible explanation for the erroneous velocity readings given by the electromagnetic current meter lies in the design shape of the probe (see Figure 1). At higher velocities, separation of water from the

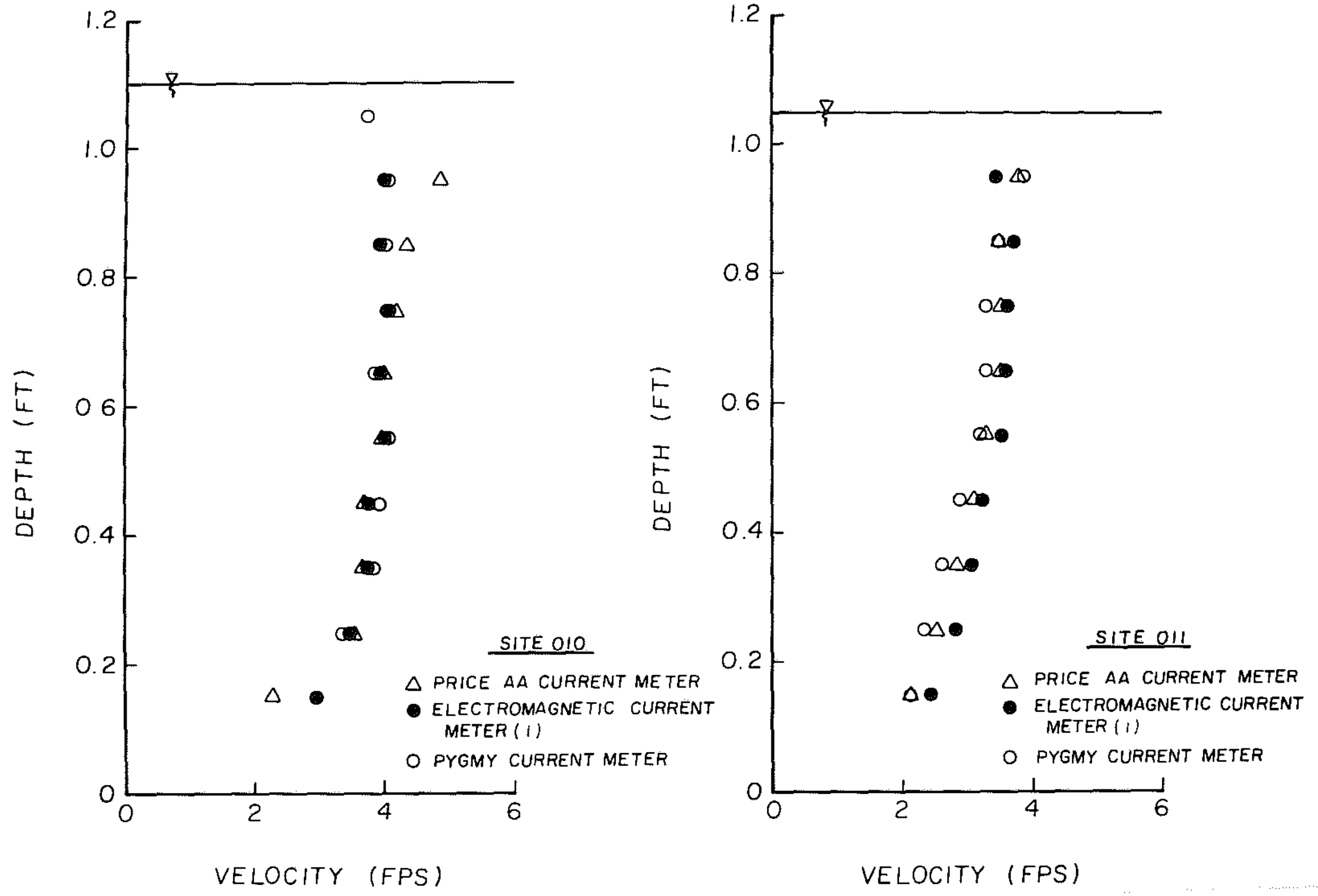

Figure 3. Velocity profiles for two sites showing close agreement of current meter readings for water velocities less than 5.0 fps (152.4 cm/sec).

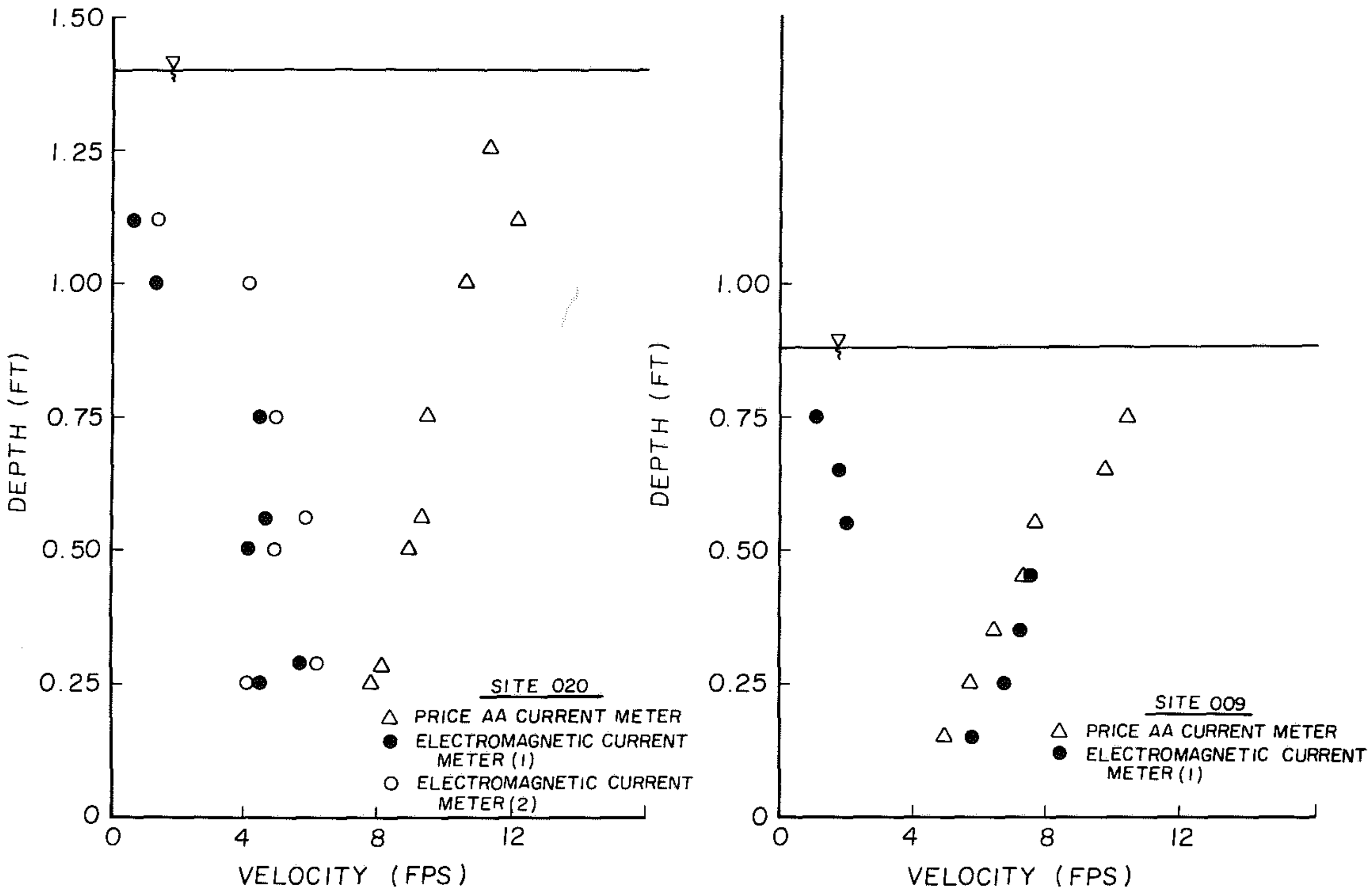

Figure 4. Velocity profiles for two sites showing variations in current meter readings for water velocities greater than 5.0 fps (152.4 cm/sec).

probe was noticed during several measurements. Separation was more readily apparent at depths closer to the water surface. In some cases, readings were not obtainable because of pronounced separation and wake. Improved streamlining of the probe might eliminate the separation or move it further back along the probe (behind the sensing electrodes), thus decreasing its interference with the velocity reading. Roughening the leading edge of the probe might also move the separation point further back, possibly behind the sensing electrodes. The effect of inducing a turbulent boundary layer on the sensing electrodes is unknown.

Electromagnetic current meters are increasingly being used by field workers. Without a backup velocity reading by another method, the field worker does not know if the Marsh McBirney velocity reading is correct. For example, the Marsh McBirney current meter might incorrectly read 4 fps (122 cm/sec) at a given stream flowing 6 fps (183 cm/sec). Yet a stream actually flowing at 4 fps (122 cm/sec) might result in a correct Marsh McBirney reading of 4 fps (122 cm/sec). Thus the Marsh McBirney current meter should not be used indiscriminately without knowing the expected range of velocities.

The cutoff velocity of 5.0 fps (152.4 cm/sec) at which the Marsh McBirney starts giving erroneous readings is rather arbitrary. This value was selected by an iterative process, finding the maximum velocity where the slope of the line in Figure 2 was closest to 1 with the highest coefficient of correlation (r). Thus, the cutoff velocity is defined by this particular data set. The reported P-value (0.637) is subject to the iterative value obtained for the cutoff velocity. Further study may result in a slight adjustment of the cutoff velocity.

Conclusions

The Marsh McBirney current meter can be used by field workers with confidence where expected velocities are less than 5.0 fps (152.4 cm/sec). Results of this study show the Marsh McBirney electromagnetic current meter gives erroneously low velocity readings above this cutoff velocity. Published electromagnetic velocity readings should be used with caution unless additional velocity measurements have been made by another method.

Three areas need further study to better define the relationship between the velocity readings from the two instruments. First, the cutoff velocity at which the Marsh McBirney no longer gives accurate results needs to be better defined. Second, the relationship for velocities above 5.0 fps (152.4 cm/sec), or some other specified cutoff velocity, needs to be examined and quantified. Finally, the shape of the probe needs to be experimentally altered to see if separation is the major cause of the erroneous readings and, if so, to eliminate the separation.

Acknowledgements

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References

Brater, E.F., and H.W. King. 1976. Handbook of Hydraulics. McGraw Hill, Inc. New York, N.Y.

Grzenda, J.H. 1981. Understanding Magnetic Flowmeters. Plant Engineering. Vol. 35, April. pp. 67-70.

Springer, E.K. 1980. The Electromagnetic Flowmeter - its Theory and Applications. The South African Mechanical Engineer. Vol. 30, March. pp. 66-83.

DEVELOPMENT AND USE OF A RESOURCES ATLAS FOR THE CHUGACH NATIONAL FOREST

By David Blanchet

Abstract

The Chugach National Forest encompasses the eastern half of the Kenai Peninsula, Prince William Sound, and the Copper River Delta Region. The Forest is managed for recreation use, fish and wildlife habitat, potential wilderness, timber, minerals, and power development. The "Chugach National Forest Environmental Atlas" was developed to aid in planning for Forest management activities. The Atlas focuses on climate, water resources, geology, and available maps and aerial photography for the Forest. The intended audience is land managers and resource planners from a variety of disciplines.

Development of the Atlas involved inventorying climatic, hydrologic and geologic data and information collected from the Forest and presenting it in map form with accompanying text. Several of the maps were created through new interpretations of existing data. The Atlas can accommodate additions of new maps or changes in the existing maps.

Introduction

Purpose and Scope. Throughout the last 80 years, a great deal of environmental data and information has been collected on the Chugach National Forest by numerous agencies and individuals. The "Chugach National Forest Environmental Atlas" was published in an attempt to compile much of this information into one document. The Atlas provides a reference to a large variety of climatic, hydrologic, geologic, and aerial photographic information. Its intended audience is both resource specialists and land managers, and its intended use is for long-range Forest resource planning and for project-level work. Information from the Atlas has been used by the author in evaluating a wide variety of Forest Service projects. The Atlas can aid also resource specialists

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[1] Forest Hydrologist, Chugach National Forest, 2221 E. Northern Lights Blvd. Suite 238, Anchorage, Alaska.

investigating other parts of Alaska by identifying types of available information and by demonstrating a possible presentation format.

The Atlas is comprised of maps, figures, and text which interpret data collected on the Forest. It does not display an actual listing of data records (for example: daily stream discharge records), but does list where the data can be found and in some cases how it can be best used.

Information in the Environmental Atlas is divided into four primary catagories: climate, water resources, geology, and map and aerial photography resources. This paper focuses on the climate and water resources sections of the Atlas, and explains the processes used in developing these section.

Setting. The Chugach National Forest presently covers approximately 5.9 million acres of the Kenai Peninsula, Prince William Sound, and the Copper River Delta east to Cape Suckling. There are numerous non-National Forest land tracts within the Forest boundary owned by private individuals, Native corporations, and the State of Alaska. Thirty-five percent of the Forest land lies within the Greater Municipality of Anchorage and the Kenai and Matanuska-Susitna Boroughs. The remaining 65% is not within any specific governmental unit other than the State of Alaska. Communities lying within or adjacent to the Forest boundaries include Cordova, Valdez, Whittier, Girdwood, Seward, Moose Pass, and Cooper Landing. Anchorage, Alaska's largest city (population 230,000), lies approximately 35 miles west of the Forest boundary.

The Forest is contained within the Kenai-Chugach Mountain System. The majority of the landscape is rugged mountainous terrain which arcs the

Gulf of Alaska. Mountain peaks on the Forest range in elevation from 1,000 to 13,000 feet. All areas on the Forest (excepting some mountain peaks and ridges) have been glaciated within the last 200,000 years, and most areas within the last 10-15,000 years. Approximately one third of the Forest is still ice covered. The entire region is also very seismically active and has experienced episodes of both uplifting and subsidence in recent geologic time.

The Forest is an area of sharp contrasts in climate, runoff, vegetation, landscapes, land use, and access. Annual precipitation ranges from very high along the Gulf of Alaska to quite low at some inland sites. Topographies vary from the vast, level plains of the Copper River Delta to the rugged, glaciated mountains of the Chugach Range. These contrasts, along with a limited data base, add together to make forecasting of climatic and hydrologic events on the Forest a complex and often inexact science.

Applying the Atlas for Agency Goals. The USDA Forest Service is a multiple-use land management agency. Management on the Chugach is directed primarily towards recreation (dispersed and non-dispersed), fish and wildlife habitat improvements, timber production, proposed wilderness, mineral extraction, and power development. Typical projects on the Forest include: campground, trail and winter sports developments; salmon steeppass construction and channel enhancements; moose habitat improvement through prescribed burns; long-range Forest planning; timber sale layout; and review of mining plans of operations. Environmental information provided in the Atlas is intended for use in project preplanning, site evaluation and selection, and project design, and monitoring.

Methods and Discussion

Maps were used as the primary tool for displaying information in the "Chugach Environmental Atlas". Text was added to further explain the purpose and use of the maps. A brown, 1:500,000 (approximately 8 miles to the inch) Forest map was used as the base for the majority of the maps in the Atlas. Environmental information was overlayed onto these maps in black. The 1:500,000 scale proved very satisfactory for displaying information on most of the maps in the Atlas. For several maps the density of information was too great for resolution at a this scale and base maps at a 1:250,000 and 1:63,360 scale became neccessary.

The Atlas also displays information using figures and graphs with explanatory text. Many of the figures have been taken from other resource documents and modified to the specific informational needs on the Chugach National Forest.

Maps and figures presented in these sections include both original presentations and reformatting of existing maps and figures. Development of the "Chugach National Forest Environmental Atlas" has relied heavily on information and formatting used in other resource atlases on Alaska. The "Alaska Regional Profiles, Southcentral Region" (Selkregg, 1974) has been particularly useful in terms of providing information, and for guidence in searching for more specific information concerning the Chugach National Forest.

Most of the meteorologic and hydrologic data stations referenced in the Atlas are located at elevations of 1,500 feet and below (where the majority of Forest activities and developments take place.) The Atlas presents information for both low and high elevation areas, however, higher elevation information has frequently been extrapolated from data taken at lower elevation sites. Following is a discussion of information displayed in the climate and water resources sections and how that information was derived.

Climate

Introduction. The Chugach National Forest has extremes of both precipitation and temperature. Changes in the weather can occur rapidly and may be difficult to predict. Several locations on the Forest have annual precipitation and/or snowfall values which are among the highest in the world, while other areas have very moderate (semi-arid) annual precipitation. Temperatures vary from moderate and steady in coastal regions, to cooler and more highly fluctuating in inland areas, to continuously cold in high altitude, mountainous regions. The extreme variation in daylight hours and the low sun angles (as compared to the continental United States) adds another degree of variability to the Forest climate. In the conventional climate zone system (temperate, subarctic, and arctic), most of the Forest lies within the subarctic zone (one to four months with mean monthly temperatures greater than 50°F and at least one month with a mean temperature 32°F or colder.) Forest areas above 3,000 feet in elevation fit the classification for arctic climate (no months with mean monthly temperatures greater than 50°F and at least one month with a mean temperature 32°F or colder.)

This section of the Atlas displays a variety of maps and figures compiled from climate data collected on the Forest. This data can be used as a working tool for project design, analysis, and implementation.

1. Hydrometeorologic Stations Map. This map displays the location, station number, and dates of operation for meteorologic and hydrologic data stations on the Chugach National Forest and surrounding areas for which published data is available. Data collected from these stations is of three different types: 1.) weather records (primarily temperature and precipitation) collected by the Environmental Data Service of the National Oceanic and Atmospheric Administration (NOAA), 2.) depth and water content of the seasonal snowpack collected by the U.S. Soil Conservation Service (SCS) and, 3.) surface water quantity and quality records collected by the U.S. Geological Survey, Water Resourses Division (USGS).

Weather records for a few sites on the Forest date back as far as the early 1920's, and USGS stream data to 1910. Collection of snowpack data on and near the Forest first started in the early 1950's. Most data records for stations on and adjacent to the Forest are relatively short in duration and are sometimes only intermittent over the period of record. Data gaps exists for many parts of the Forest. Nonetheless, a remarkable amount of data is available and can prove very usely for project analysis and development.

Accurate identification of data sources is often the first step in project analysis and may involve digging through a variety of records to locate and date the stations. This map can be very useful for quickly assessing what climatic and hydrologic data sources are available and in turn, how they may be used.

2. Mean Annual Temperature Map. This map displays the average yearly temperature at sites throughout the Forest. This value is useful for

gaining initial insights into: predictable annual heating costs and energy needs, likelihood for development of permafrost soils, type of climate, wildlife habitat areas, ground and groundwater temperatures, and environmental stresses to vegetation and/or structures. The map displays a series of isotherms or contour lines of equal mean annual temperature for the Forest. Also displayed are the mean annual temperatures from the NOAA weather stations on and near the Forest. Isotherms for the map were extrapolated from the existing NOAA weather stations. The primary consideration used in developing the isotherms was that of elevation. Using an average lapse rate of -3.5°F per 1000 feet gain in elevation, isotherms were drawn along elevation contour lines using existing weather stations as base points. Factors such as sun exposure, wind patterns, and topography, which in some cases can significantly effect mean annual temperatures, were not used in developing this map.

3. Mean January and July Temperatures Map. For most areas on the Forest, January is the coldest month of the year and July is the warmest. This map lists four temperatures at each NOAA weather station on and near the Forest. These temperatures are as follows: January mean monthly temperature, January mean daily minimum temperature, July mean monthly temperature, and July mean daily maximum temperature. These temperature values are helpful for project design, for energy costing, and for understanding access problems and winter icing potentials.

4. Map of Primary Storm Tracks by Month. Most storm tracks reaching the Forest come from the west southwest out of the Gulf of Alaska or more infrequently out of the west from the Bering Sea. A map is presented for each month of the year showing the generalized pattern of storm track

movements across southern Alaska. These maps were taken from "Climatic Altas of the Outer Continental Shelf Waters and Coastal Regions of Alaska, Vol. 1 - Gulf of Alaska" (Brower, 1977). They help to explain weather system behavior on the Forest.

5. Mean Annual Precipitation Map. This map displays mean annual precipitation values across the Forest. This information can be used in determining flood flows, mean annual flow, and low flows for a given stream. Mean annual precipitation is a useful design criteria for numerous developments on the Forest such as roads, bridges, campgrounds, timber sales, fish passes, and ski areas.

The mean annual precipitation map was taken from the "Region 10, Water Resources Atlas" (Ott Water Engineers, 1979). Mean annual precipitation includes both inches of rainfall and water equivalent inches of snow. The contour lines on the map (isohyets) show mean annual precipitation throughout the Forest. These isohyetal lines were developed from: 1.) weather station data, 2.) runoff values of USGS gaged watersheds minus evapotranspiration, and 3.) elevation contours (increased precipitation at higher elevations.)

6. Mean Annual Maximum Snowpack (By Lawrence R. Mayo and David Blanchet). This map shows the average maximum depth of snow on the ground during the winter. Displayed are contours of equal snow depth (isopleths) and the actual measurement sites used in development of the map. This information has a variety of applications including determination of: structural loading on buildings and bridges, river runoff and flood potentials, mode of surface travel, winter range limitations for wildlife, and avalanche potential.

Relative to the large size and complex terrain of the Forest, only few measurements of snow depth have been made. However, these measurements are widely scattered and sample forests, mountains, and glaciers to as high as 8,400 feet. The following elements were used in developing the mean annual maximum snowpack map:

a. Snow course data (U.S. Soil Conservation Service)
b. Weather station data (National Oceanic and Atmospheric Administration).
c. Snow data on glaciers (U.S. Geological Survey).
d. Snow data from Turnagain Pass (USDA Forest Service).
e. Mean annual precipitation map of the Forest (Ott Water Engineers).
f. Location and size of existing glaciers (U.S. Geological Survey).
g. Terrain altitude (U.S. Geological Survey).
h. Major storm patterns (National Oceanic and Atmospheric Administration).
i. Major snow redistribution by wind at higher altitudes (authors).
j. Slope steepness and avalanching. Steeper slopes usually have less snowpack than nearby flat areas due to wind redistribution and snow sliding (authors).

The measurements reported on the map are relatively accurate. The contours on the map are extrapolated using the criteria mentioned above and are less accurate. The snow depths reported on the map are a generalization of the real situation. An accurate map of snow depths measured in any small area would reveal details of the complexity of snow depth variability that cannot be shown at the scale of this map.

7. Selected Diagrams Relating to Meteorological Data. This page of the Atlas reproduces a series of diagrams from other publications and tailors

them to the Chugach National Forest. These diagrams are as follows:

a. Sun Path Diagram For 60° North Latitude. This diagram was taken from "A Solar Design Manual for Alaska" (Seifert, 1981) and plots the path of the sun across the sky (solar elliptic) throughout the year. Using the diagram, the location of the sun in the sky can be determined for any time of the day and year. This information is valuable for locating sites or structures which depend on solar input. Heating costs for many structures can be significantly reduced by optimizing solar input. The diagram displayed is for 60° north latitude. This is the latitude of Seward, Alaska, however, the diagram may be applied to the entire Forest with only a small margin of error.

b Sunlight and Twilight Hours. This diagram, taken from "Alaska Regional Profiles, Southcentral Region" (Selkregg, 1974), displays the number of lighted hours per day throughout the year. The lighted hours of the day include both sunlight and twilight hours. The diagram can be read for different northern latitudes. This information is valuable for both schedule planning and design.

c. Growing Degree Days. This chart was compiled by using both the "Alaska Regional Profiles, Southcentral Region" (Selkregg, 1974) and additional NOAA weather data for other selected locations on the Forest. The chart lists the average growing degree days and length of growing season for seven communities located within or near the Forest. This chart is useful for planning revegetation or planting projects.

d. Heating Degree Days. This chart was developed using the "Alaska Regional Profiles, Southcentral Region" (Selkregg, 1974) and additional NOAA weather data. It displays heating days by month for nine communities within or near the Forest. Heating degree day values are useful in determining energy needs for different areas and for different times of the year.

e. Ground Temperature. This chart (Selkregg, 1974) shows average monthly soil temperatures by depths for a site located in Anchorage, Alaska. The chart gives an indication of: what kind of temperature fluctuations may be seen at various depths, how deep and how long-lasting the frost level is, and how temperature fluctuations decrease with depth. These concepts may be applied (along with additional weather and soils data) to most lower elevation areas on the Forest.

f. Freeze-up and Break-up Data for Selected Lakes and Rivers. This chart (Selkregg, 1974) shows the average annual dates for freezing and breaking up of several lakes and rivers on or near the Forest. The chart indicates the average date when the ice first becomes safe for walking and vehicular travel, and then when it becomes unsafe in the spring. Lake freeze-up and break-up dates may be extrapolated to other lakes on the Forest using caution and additional temperature and wind data. Extrapolation of freeze-up and break-up to other rivers is difficult because of the number of variables involved (ie. gradient, elevation, local climate, and drainage characteristics.)

g. Spring and Fall Freeze Dates for Selected Locations. This chart was compiled using "Alaska Regional Profiles, Southcentral Region" (Selkregg, 1974) and additional NOAA weather data. It shows the average date of both the last spring frost and the first fall frost for seven communities within or near the Chugach National Forest. These dates are useful for planning revegetation or planting projects.

Water Resources.

Introduction. The Chugach National Forest has an abundant water supply resulting from the heavy precipitation it receives. Fresh water lakes and streams on the Forest were used in the past by Native cultures for locating settlements, water supply, and transportation routes. Within the last century, new uses of water on the Forest have included metal separation in lode and placer mining operations, domestic water supply, industrial water supply (such as canneries), hydropower, and small scale agriculture. Water plays a role in almost all Forest projects. This section of the Atlas explains water resource characteristics on the Forest from a variety of perspectives.

Surface runoff, groundwater, and water quality (physical, chemical, and biological) are discussed in a narrative in the "Chugach National Forest Environmental Atlas". A series of maps and figures are used in this section to display different aspects of the water resource. Also, a bibliography of water resources reports concerning the Forest is given. Development of the maps displayed in this section and their use is discussed below.

1. Map of Mean Annual Runoff per Square Mile. This map delineates the mean annual runoff of Forest watersheds in cubic feet per second per square mile of drainage area. Mean annual runoff can be a useful tool in determining watershed storage capabilities for such uses as hydropower, drinking water, flood control, and hatcheries. Mean annual runoff may also be used for water rights determinations and a variety of other land management applications.

The mean annual runoff displayed on the map was derived by using an equation from the "R-10 Water Resources Atlas" (Ott Water Engineers, 1979). The equation was developed by regressing a variety of drainage basin characteristics against the actual mean annual runoff of USGS gaged watersheds on and near the Forest. For this particular regression equation, mean annual precipitation and drainage basin area turned out to be the only significant parameters in estimating mean annual runoff. The equation (for the Forest) is as follows:

$$\text{Mean annual runoff} = .0283\ P^{1.16}\ A^{1.02}$$

Where P = mean annual precipitation and A = the drainage area in square miles. For determining mean annual flow per square mile, A = 1.0, and $A^{1.02}$ is dropped from the equation. This yields:

$$\text{Mean annual runoff per square mile} = .0283\ P^{1.16}$$

Thus, the contour lines of equal annual runoff on the map become a close reflection of the mean annual precipitation map (discussed in the climate section of this paper.) By determining the drainage area of a basin and taking it times the mean annual flow per square mile value from the map, an estimate of mean annual flow for the basin may be derived. The ninety percent confidence interval for mean annual runoff may be determined from a graph in the "R-10 Water Resources Atlas" (Ott Water Engineers, 1979).

2. Fifty-Year Peak Flows Map. This map shows flow values in cubic feet per second per square mile for a fifty-year recurrence interval flood. The fifty-year flood value is useful for designing any instream structure and in determining what areas along a stream are endangered during a flood. It is a neccessary design criteria for determining what forces must be withstood during a flood. This map was again produced by using a regression equation from the "R-10 Water Resources Atlas" (Ott Water

Engineers, 1979). This equation for Chugach streams is as follows:

$$\text{Fifty-year peak flow} = .632\ P^{1.26}\ A^{.984}\ L^{-.344}$$

Where P = precipitation in inches, A = drainage area in square miles, and L = 1 + the percent of the drainage basin area which is lake surface. (L = 1 when there is no lake area). Thus, for a one square mile drainage with no lakes:

$$\text{Fifty-year peak flow} = .632\ P^{1.26}$$

The flood value contour lines on the map were developed from this equation, and are again a reflection of the mean annual precipitation map. By multiplying the drainage area of a basin times the 50-year flow per square mile value from the map, an estimate of the 50-year flow value is derived for the given basin (assuming there is not significant lake area within the drainage). If there are lakes of any significant size located within a drainage, the values displayed on the map will be anomalously high. The ninety percent confidence interval for the fifty-year peak flow may be determined from a graph in the "R-10 Water Resources Atlas" (Ott Water Engineers, 1979).

3. Glaciers and Glacial Streams Map. This map shows the location of glaciers and glacial streams on the Forest and surrounding areas. From this map it may be seen that approximately 30 percent of the Forest area is covered by glacial ice. USGS contour maps (1:63,360) were used as a reference for mapping onto the base map for the Atlas. The map gives a strong visual display of the extent of present glaciation on and near the Forest.

4. Mean and Extreme Tides Map. This map shows mean and extreme tides for a number of coastal locations around the Forest for the year 1982. "Tide

Tables for 1982, West Coast of North and South America" (NOAA, 1981) served as the data source for this map. Average daily tidal fluctuations on the Forest vary from about ten feet for exposed areas along the Gulf of Alaska to over 33 feet along portions of Turnagain Arm. The extreme highs and lows are the maximum and minimum levels of the tide reached in 1982 and will differ slightly in other years. The tidal fluctuations displayed are useful for determining access problems for a given stretch of coastline, and for consideration in designing coastal structures (such as boat ramps, docks, and cabins.)

Water Resource Reports Concerning the Forest. The Atlas lists a bibliography of water resource reports (1904-1981) relating to the Forest which have been published in a variety of formats by the U.S. Geological Survey, and the Alaska Division of Geological and Geophysical Surveys. These reports were accessed through several bibliographies published by the USGS (Cobb 1974-82).

Summary

This paper has only focused on the development of the climate and water resources section of the "Chugach National Forest Environmental Atlas". Data and information for this document were taken entirely from existing sources with no new data being collected specifically for the Atlas. Information displayed in the Atlas involves both original presentations and replications from existing documents.

The Atlas also covers a variety of geological and map and aerial photographic data and information concerning the Forest, but these sections are not discussed in thus paper. The information displayed in the Atlas is used by the author in planning and investigation of Forest projects. The Atlas is designed in a loose leaf format so that it may accommodate additional maps or revisions to the existing maps. This format also allows for maps and figures to be removed for copying.

The Atlas may be used in application to both Forest projects and projects on State, Native, community, and private lands within the Forest. Land management agencies interested in developing similar map displays for other parts of Alaska may wish to reference the Atlas for information sources.

References

Blanchet, David. "Chugach National Forest Environmental Atlas", Anchorage, AK: USDA-Forest Service, Region 10, 1983.

Brower, William A., Jr., Diaz, Henry F., Prechtel, Anton S., Searby, Harold W., Wise, James L., "Climatic Altas of the Outer Continental Shelf Waters and Coastal Regions of Alaska, Vol. I - Gulf of Alaska". Anchorage, AK: Arctic Environmental Information and Data Center, 1977.

Cobb, E.H., "Reports of the Alaska Division of Geological and Geophysical Surveys and Predecessor Agencies, 1913-1973, Indexed by Quadrangle". Anchorage, AK: U.S. Geological Survey Open File Report 74-209, 1974.

Cobb, E.H., "Geological Survey and Selected U.S. Bureau of Mines and Alaska Division of Geological and Geophysical Surveys Reports and Maps on Alaska Released during 1974". Anchorage, AK: U.S. Geological Survey Open File Reports, 1975 through 1982.

Environmental Data and Information Service, National Oceanic and Atmospheric Administration, "Climatological Data". Ashville, N.C.: U.S. Dept. of Commerce, 1900-1981.

Hartman, Charles W., Johnson, Philip R., "Environmental Atlas of Alaska". Fairbanks, AK: University of Alaska, 1978.

Ott Water Engineers, Inc.,"Water Resources Atlas". Juneau, AK: USDA-Forest Service, Region 10, 1979.

National Oceanic and Atmospheric Administration, U.S. Department of Commerce, "Tide Tables for 1982, West Coast of North and South America". Rockville, MD: 1981.

Searby, H.W., "Climates of the States: Alaska". Climatology of the United States No. 60-49, Environmental Data Service, ESSA, 1968.

Seifert, Richard D., "A Solar Design Manual for Alaska". Fairbanks, AK: University of Alaska, 1981.

Selkregg, Lydia L., "Alaska Regional Profiles, Southcentral Region". Anchorage, AK: Environmental Information and Data Center, University of Alaska, 1974.

Soil Conservation Service, "Snow Surveys and Water Supply Outlook for Alaska". Anchorage, AK: U.S. Department of Agriculture, 1951-1982.

Still, Patsy J., "Index of Streamflow and Water Quality Records". Open-File Report 80-600, Anchorage, AK: U.S. Geological Survey, 1978.

U.S. Geological Survey, "List of Geological Survey Geologic and Water-Supply Reports and Maps for Alaska". Washington, D.C.: U.S. Government Printing Office: 1981.

U.S. Geological Survey, "Water Resources Data for Alaska". Anchorage, AK: 1966-80.

U.S. Geological Survey, "Surface Water Supply of the United States 1961-65, Part 15. Alaska". Water-Supply Paper 1936, Washington, D.C.: U.S. Government Printing Office, 1971.

U.S. Geological Survey, "Compilation of Records of Surface Waters of Alaska, October 1950 to September 1960". Water-Supply Paper 1740, Washington, D.C.: U.S. Government Printing Office, 1964.

U.S. Geological Survey, "Compilation of Records of Quantity and Quality of Surface Waters of Alaska through September 1950". Water-Supply Paper 1372, Washington, D.C.: U.S. Government Printing Office, 1957.

U.S. Geological Survey, "List of Geological Survey Geologic and Water-Supply Reports and Maps for Alaska". Washington, D.C.: U.S. Government Printing Office: 1981.

U.S. Geological Survey, 1:63,360 and 1:250,000 quadrangle maps, (various).

THE AQUATIC PORTION OF THE INTEGRATED RESOURCE INVENTORY, TONGASS NATIONAL FOREST - CHATHAM AREA

by Daniel A. Marion[1] and Steven J. Paustian[2]

Abstract

The development, implementation, and applications of the Aquatic portion of the Integrated Resource Inventory (A-IRI) for the Tongass National Forest- Chatham Area are described in this paper. The A-IRI is a characterization of water and fisheries habitat designed to provide aquatic resource information and evaluation techniques for use in forest planning and management. Essential to A-IRI applications is the use of a channel type classification system. Watershed drainage networks are stratified into stream segments with homogeneous aquatic resource characteristics. These characteristics are then used to determine aquatic resource conditions and sensitivity. Use of the channel type classification system promotes resource discipline integration while dividing the drainage network complex into a workable number of resource management areas. In addition, it provides an efficient resource accounting and data extrapolation system. Other notable developments during A-IRI implementation have been a channel type mapping procedure and computer data base.

The A-IRI is designed so that aquatic resource information and evaluations can be applied at several planning levels. Recent A-IRI applications have clearly demonstrated its utility and value in making multiple use resource management decisions.

A hydrologic and fish habitat resource inventory is currently being conducted on the Tongass National Forest - Chatham Area (TNF-CA) which is noteworthy for several reasons. It is the first complete, systematic inventory of those resources within the intensively managed areas of the TNF-CA. Fisheries and hydrology disciplines are combined in this inventory to produce one, integrated effort driven by identified resource information needs. A hierarchial stream classification system is

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[1] Hydrologist, Tongass National Forest - Chatham Area, P.O. Box 1980, Sitka, Alaska 99835.

[2] Supervisory Hydrologist, Tongass National Forest - Chatham Area, P.O. Box 1980, Sitka, Alaska 99835

employed to delineate meaningful resource management areas and provide a tool for data stratification and extrapolation. The development, implementation, and applications of this inventory are described in this paper.

Background

The legal direction to collect and interpret resource information is contained in several national laws. The Forest and Rangelands Renewable Resources Planning Act of 1974 as amended by the National Forest Management Act of 1976 requires the Forest Service to supply basic distribution, capability, limitation, and condition information on soil, water, and geologic materials on all National Forest System lands. In addition, the Soil and Water Resources Conservation Act of 1977 and the Federal Land Policy and Management Act of 1976 both require that soil, water, and related resource inventories be conducted periodically.

Federal laws also strongly encourage the integration of these natural resource inventories and information. The Multiple Use - Sustained Yield Act of 1960 requires a joint consideration of all major outputs from the national forests. The interdisciplinary planning process stipulated within the National Environmental Policy Act of 1969 would be greatly facilitated by an existing integrated information base. The Forest and Rangelands Renewable Resources Planning Act of 1974 as amended by the National Forest Management Act of 1976 directs that all Forest Service planning activities recognize and consider the interrelationships which exist between resources.

Hamilton (1978) offers several reasons for integrating separate resource inventory efforts. Among others he lists increased data collection efficiency, providing for data compatibility, improving resource assessment precision, and providing a single, best estimate of the resource situation. However, he concludes that the most direct reason for integration is that because resources are interrelated and interdependent in nature, our inventory approach must allow us to describe these interactions or interaction products in a particular time and place. Dixon (1981) supports these reasons, adding that separate resource inventories cannot meet current multiresource information needs because of the high costs involved and the difficulty in assessing resource interrelationships.

Integration is also necessary to produce a resource classification system in which all concerned disciplines relate their information and evaluations to common geographic areas. This system would incorporate the principle of resource interrelationships while providing a means for delineating resource management areas in which environmental conditions and potential responses to development activities are similar. Most importantly, it would reduce the natural complexity of the biosphere to a manageable number of different situations that can be communicated to and understood by land managers, planners, and technical specialists (Bailey et al., 1978).

The TNF-CA Integrated Resource Inventory project is being implemented as a means of collecting and evaluating multiresource information within a framework of integrated land and stream classification systems. The project is divided into two parts based on an aquatic versus a land emphasis. Timber, soils, and wildlife specialists have adopted a

Land Systems Classification approach (Wertz and Arnold, 1973) to integrate land based resource data collection and interpretation. In the aquatic portion of the Integrated Resource Inventory[3] (A-IRI) hydrologists and fisheries biologists are using a Channel Type Classification System for integrating stream based resource data collection and interpretation. The two systems are designed to be complementary in that each fills a void inherent in the other. They are linked through the use of a common landform classification legend. In the Landsystems approach landforms are subdivided using geology, vegetation cover, slope class, and soil type to produce landtypes. These landtypes satisfy the needs of timber, soils, and wildlife specialists but are inadequate for characterizing and evaluating aquatic resources. In the Channel Type Classification System landforms are subdivided using channel morphologic features to produce channel types. These channel types suit the needs of hydrologists and fisheries biologists but are insufficient for timber, soils, and wildlife specialist needs. Either system alone is inadequate to address all potential natural resource concerns for a given landform. However, used together they provide a comprehensive means for addressing both the land and aquatic resource situation for all TNF-CA landforms.

The A-IRI is designed to provide water and fish habitat resource information and evaluation techniques for forest management and planning. The Channel Type Classification System is employed to stratify drainage networks into stream areas with different hydrologic and fish

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[3] Formerly called the Aquatic Resource Inventory (e.g., Paustian et al., in preparation).

habitat conditions and responses. This system provides the common stream based geographic area in which fisheries biologists and hydrologists collect resource data and make evaluations. Using this integrated approach the A-IRI accomplishes the objectives of separate Level IV Forest Service Fisheries Survey (USDA Forest Service Alaska Region, 1981) and Order 2 Water Resource Inventory (USDA Forest Service Intermountain Region, 1979) projects while avoiding the redundant data collection and potential incompatibility of separate inventory efforts.

Geographic Setting

The TNF-CA covers almost 28,000km^2 of the northern Southeast Alaska panhandle. Approximately 39% or 11,000km^2, of this area is allocated for intensive, multiple use management under the Tongass Land Management Plan (USDA Forest Service Alaska Region, 1979). The A-IRI effort is currently focused on this latter area, with the remaining TNF-CA area to be considered later (see Figure 1).

The inventory area falls within the Sitka Spruce - Cedar - Hemlock forest section of the Pacific Forest Province as defined by Bailey (1980). The area climate is maritime with mean annual temperatures ranging between 2°C and 10°C, and annual precipitation ranging between 1500mm and 6600mm. Vegetation is predominantly coniferous forest types with interspersed moss sedge marshes (after Viereck and Dyrness, 1980). Alpine tundra and shrub types occur at elevations above 500m.

Major streams draining this area occur within glaciated valleys of varying width. Watershed size typically varies between 25km^2 to 200km^2 for these streams. Runoff commonly originates within alpine

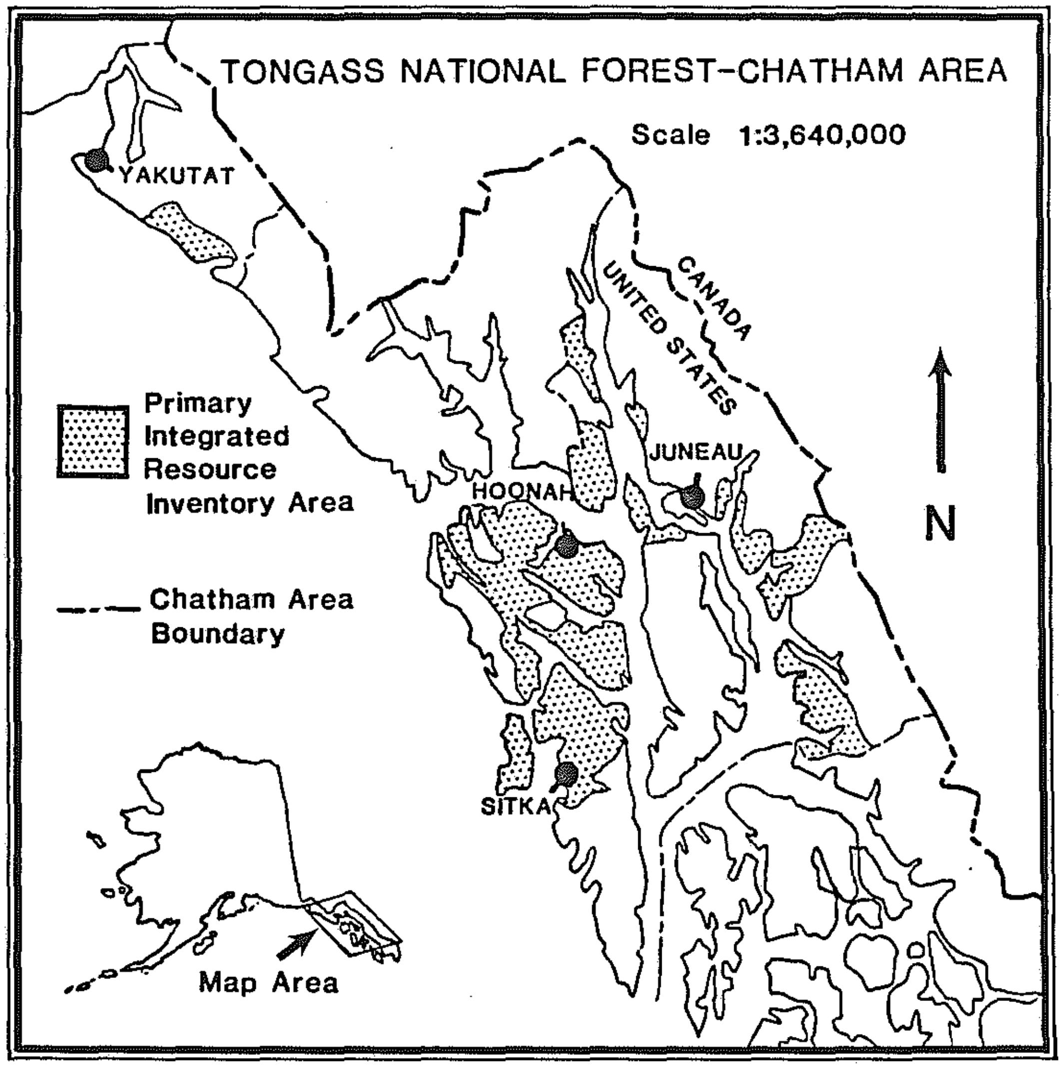

Figure 1. Area covered by the aquatic portion of the Integrated Resource Inventory.

snowfields or cirque basins on the islands, or from alpine glaciers on the mainland. High unit runoff volumes coupled with rapid elevation drops over short distances result in high energy streamflows occurring within the inventory area.

Five commercially important anadromous fish species utilize TNF-CA streams for spawning and rearing. The majority of this activity occurs within watersheds which are mostly undeveloped. Existing development is

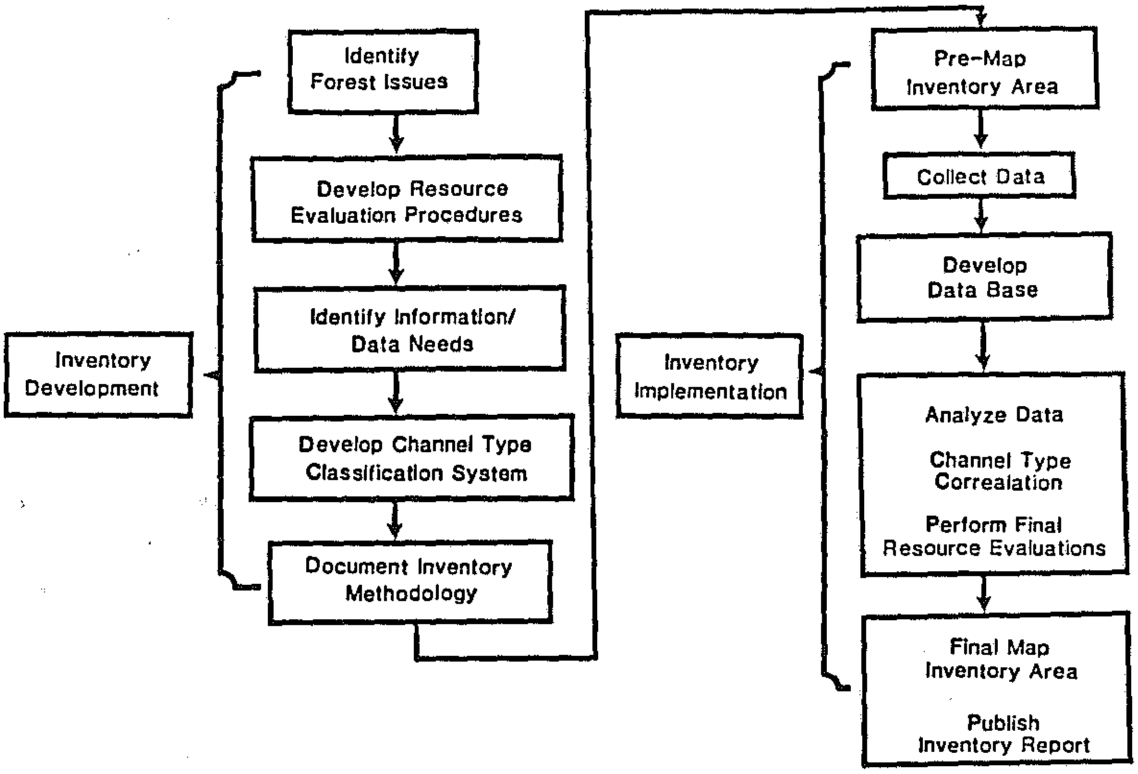

Figure 2. Flow chart of the process used for the aquatic portion of the Integrated Resource Inventory.

largely restricted to forest road systems, timber harvest activities, and small scattered fishing villages and logging camps.

Inventory Development

The A-IRI process discussed below is illustrated in the flow chart in Figure 2. This process can be divided into a development phase and an implementation phase. During the development phase information needs are determined and procedures are developed to satisfy these needs. In the latter phase these procedures are implemented to obtain the required data, information, and map products. The A-IRI process began in 1981 and is scheduled to be completed by 1985.

Forest resource issues are addressed by information and evaluation techniques developed from the A-IRI. They were compiled from previously identified TNF-CA management issues (USDA Forest Service Alaska Region, 1979, 1980, and 1983a) and from consultation with regional, forest, and research specialists. An information needs assessment was then performed to identify what evaluation techniques, information, and data were required to address these issues, and what information was currently available. The assessment results are summarized in Table 1. They indicated that very little was currently available to address these issues. Several resource evaluation procedures (often called management interpretations) were recognized as being needed to meet the A-IRI objective. In order to use these procedures successfully it was necessary to control the variation in environmental characteristics within each area they were applied. Therefore, a stream classification system for stratifying drainage networks into discrete channel areas with consistent physical characteristics was also identified as being essential.

Management interpretations are systematic methods for assessing resource conditions (e.g., fish habitat quality) and resource sensitivity to disruption by forest development activities. They are designed to answer the questions posed by forest resource issues. The management interpretations developed for the A-IRI are listed as column headings in Table 2. They are generally qualitative rating procedures due to the lack of quantified cause-and-effect knowledge. Each procedure is based on measurements or evaluations of physical channel characterisitcs determined as being important in interpreting natural resource conditions or resource sensitivities. These determinations are based on resource

Table 1. Tongass National Forest-Chatham Area Aquatic Resource Data Needs Assessment Summary.

Forest Planning Issue	Activities Involved	Information/Resource Interpretation Required	Factors of Concern	Existing Information/Data Sources	Additional Data Needs
Potential impacts to anadromous or resident fish habitat.	Timber harvesting Road construction and maintenance Fisheries enhancement projects	Location, quantity, quality, and sensitivity of existing and potential fish habitat.	Sediment Temperature Debris Riparian Vegetation Channel stability	ADF&G escapement records and anadromous fish stream maps.	Channel type classification Sediment input, storage, and transport characteristics Debris loading characteristics Stream temperature characteristics Channel stability characteristics Habitat quality Passage barrier locations
Potential changes in water quality.	Timber harvesting Road construction and maintenance Fisheries enhancement projects	Natural and post-treatment water quality characteristics.	Sediment Temperature All chemical parameters regulated by Alaska State Water Quality Standards	USGS water quality data for SE Alaska streams Various research publications	Channel type classification Water quality characteristics Potential for post-treatment water quality changes Subsection classification
Potential failure of in-channel structures (nonconsumptive water uses).	Stream crossing construction and maintenance Fish pass construction and maintenance	Discharge variation Site stability Typical end area	Discharge variation Flow containment Channel migration	<u>R-10 Water Resources Atlas</u> (Ott Water Engineers, 1979)	Channel type classification Bank and bed composition Bank and bed stability Stream power Channel morphology characteristics
Potential consumptive water uses for water supply, aquaculture, recreation, minerals, or energy development.	Timber harvest Road construction and maintenance Inchannel structure construction and maintenance Water withdrawls	Discharge variation Site stability Instream flow needs	Discharge variation Flow containment Channel migration	Existing instream flow determination methods <u>R-10 Water Resources Atlas</u> Water Use Permits	Channel type classification Channel stability characteristics Stream power Channel morphology characteristics
Potential impacts to wetlands and flood plains.	Timber harvest Road construction and maintenance	Quantity, location, and sensitivity of existing wetlands and flood plains	Vegetation Water quality Soil erosion Channel erosion		Landtype classification Channel type classification Vegetation characteristics Channel stability characteristics Soil characteristics Sediment input, storage, and transport characteristics Stream temperature characteristics

Table 2. Management Interpretations for Selected Tongass National Forest-Chatham Area Channel Types (revised 9-15-83).

	Natural Condition Interpretations			Resource Sensitivity Interpretations				
Channel Type	Natural Sediment Potential	Sediment Conveyance	Flood Frequency (%)	Stream crossing Approach Hazard	Stream Crossing Site Stability Hazard	End Area Recomendation (m^2)	Riparian Zone Sensitivity	Aquatic Value Rating
A1	High	High	---	High	High	---	Mod	---
A2	High	High	10	High	Low	15-20	Low	Low
A4	Low	High	---	Mod-High	Low	---	Low	---
A5	High	High	---	Low	Low	---	Low	---
B1A	Mod	Low	10	Low-Mod	Mod	15-20	High	High
B1B	Low	Low	10	Low	Mod	15-20	Low	Mod
B2	Mod	Mod	18	Mod-High	Mod	30	High	Mod
B3A	High	Mod	---	Mod-High	High	---	High	High
B3B	High	High	---	Mod	High	---	Mod	Low
B4	Low	Mod	10	Low	Mod	15-20	Low	Mod
C1A	High	Low	35	Mod	High	60	High	High
C1B	Mod	Mod	18	Low-Mod	Low	30	Low	Mod
C2A	Mod	Low	35	Mod	High	100	Mod	Mod
C2B	High	Mod	35	High	High	100	Mod	Low
C3A	Mod	Mod	35	V. High	Low	60	Mod	Low
C3B	High	Mod	35	V. High	Low	60	Mod	Low
D1	Mod	Mod	---	Low	Mod	---	Low	---
E	Mod	Mod	---	High	Mod	---	Low	Mod

NOTES: Channel types and management interpretations for the Tongass National Forest-Chatham Area are described in the Aquatic Portion of the Integrated Resource Inventory Handbook (USDA Forest Service Alaska Region, 1983b).
The symbol "---" indicates that the interpretation is not applicable to that particular channel type.

interrelationships recognized in the literature, successful procedures used elsewhere, and the professional judgment of TNF-CA resource specialists. Each qualitative interpretation procedure produces an index number that is then assigned a relative ranking. For resource condition interpretations these rankings are based on the range of values found for all TNF-CA channel types. For resource sensitivity interpretations these rankings indicate the probability of severe limitations to forest development activities being present. The current management interpretation rankings for selected TNF-CA channel types are also shown in Table 2.

The Channel Type Classification System (CTCS) is the means by which drainage networks are divided into channel areas having relatively homogeneous management interpretations. It satisfies the need for a manageable framework, reducing natural complexity (Bailey et al., 1978) while strengthening the ecological foundation of land management (Nelson et al., 1978). In addition:

1. It provides a framework for an aquatic resource accounting system.
2. It serves as the initial stratification step in a data sampling design method.
3. It provides a means of data extrapolation to unsampled areas.

A review of existing stream classification methodologies found that no previously documented system suited the A-IRI requirements. The stream reach pre-typing methods of Aquatic Biophysical Inventory of British Columbia (Chamberlain, 1980) are poorly defined and seem intended for single issue interpretation rather than several issues as required by the A-IRI. Subdivisions by landform alone as done in Cole (1972), Collotzi (1974), and Harding (1981) produce too general a stratification for intended A-IRI uses. In contrast, habitat type classification schemes such as Bisson et al. (1981) or methods using first order watersheds (Lotspeich and Platts, 1981) are too site specific or large in scale to be appropriate. Therefore, the CTCS is largely a unique product, although it makes use of many concepts put forward in these earlier works.

Three concepts form the basis of the CTCS (Paustian et al., in preparation). First, geomorphic processes that are independent of in-channel processes affect stream channel characteristics. Second, in-channel fluvial processes affect channel characteristics and fish habitat quality. Third, abiotic processes within the streamside riparian zone affect in-channel fish habitat quality. Implicit in all three of these concepts is the assumption that physical channel characteristics determine aquatic resource conditions and sensitivity.

Based on these assumptions then, physical characteristics which distinguish areas of differing out-channel geomorphic processes, in-channel fluvial processes, and riparian processes can be used to produce the CTCS. The physical characteristics used to distinguish selected TNF-CA channel types are shown in Table 3. Figure 3 is included to show the relative size and landscape positions of these channel types. At present 27 channel types have been defined for the TNF-CA although this number may change before the A-IRI completion.

Completing the A-IRI development phase is the preparation of the A-IRI Handbook (USDA Forest Service Alaska Region, 1983b). Documentation of all concepts, techniques, and procedures used for classifying and mapping channel types, making management interpretations, collecting data, and using the A-IRI computer data base are contained within this report. It is a working draft at present, being revised as preliminary data analyses and increasing experience result in procedural modifications. It will be in final form at the A-IRI completion in 1985.

Inventory Implementation

As shown in Figure 2, the A-IRI implementation phase consists of five steps: channel type pre-mapping; data collection; preliminary data base development; final data analysis and channel type correlation; and final report publication. Highlights of each of these steps are discussed below.

The channel type pre-mapping procedure is a technique for locating and

Table 3. Physical Characteristics used to Distinguish Selected Tongass National Forest - Chatham Area Channel Types.

Channel Type	Adjacent Landform(s)[1]	Channel Morphology[2]	Basin Area[3]	Canopy Cover[4]
A1 (Steep, mountain slope, forest channel)	Subalpine sideslopes Mountain slopes Hillslopes	Very high gradient Deep incision Narrow width Single channel	Small	Moderate to high
A2 (High gradient, upper valley, forest channel)	Subalpine sideslopes Mountain slopes Hillslopes	High gradient Moderate to deep incision Narrow width Single channel	Moderate	Moderate to high
B1A (Low gradient, lowland, forest channel)	Undissected footslopes Flood plains Sloping plateaus	Low gradient Shallow incision Narrow width Single channel	Small to moderate	Moderate to high
B2 (Moderate gradient, middle valley, forest channel)	Mountain slopes Hillslopes Undissected footslopes Alluvial fans	Moderate gradient Shallow to moderate incision Moderate width Single channel	Moderate to large	Moderate
C1A (Low gradient, valley bottom, forest channel)	Flood plains	Low gradient Shallow incision Moderate width Multiple channels	Moderate to large	Low to moderate
C3A (Moderate gradient, narrow valley, forest channel)	Mountain slopes Hillslopes Undissected footslopes	Low to moderate gradient Moderate incision Moderate width Single channel	Large to very large	Moderate
D1 (Moderate gradient, upper valley, glacial outwash channel)	Subalpine sideslopes Mountain slopes Cirque basins	Low to moderate gradient Shallow incision Moderate width Braided channel	Small to moderate	Low
E (Low gradient, estuarine channel)	Estuaries	Low gradient Shallow incision Moderate to broad width Multiple channels	Large to very large	Low

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NOTE: All feature interpretations are made using 1977 1:15,840 color aerial photographs.

[1] Landforms are defined according to the Landform Descriptive Legend of the Chatham Area (USDA Forest Service Alaska Region 1982).

[2] Channel incision ranks: Shallow = less than 3m; moderate = 3m to 10m; deep = 10m to 30m; very deep = greater than 30m. Channel gradient ranks: Low = less than 3%; moderate = 3% to 6%; high = 6% to 10%; very high = greater than 10%. Channel pattern classes: Single channels have one continuous main channel bed; multiple channels have a main channel bed that is frequently broken by overflow channels or islands; braided channels have numerous, interlaced channels and extensive gravel bar development. Channel width ranks: Narrow = less than 10m; moderate = 10m to 30m; broad = greater than 30m.

[3] Basin area classes: Small = less than 3.2 km^2; moderate = 3.2 km^2 to 8.0 km^2; large = 8.0 km^2 to 24 km^2; very large = greater than 24 km^2.

[4] Canopy cover classes: Low = less than 25%; moderate = 25% to 50%; high = greater than 50%.

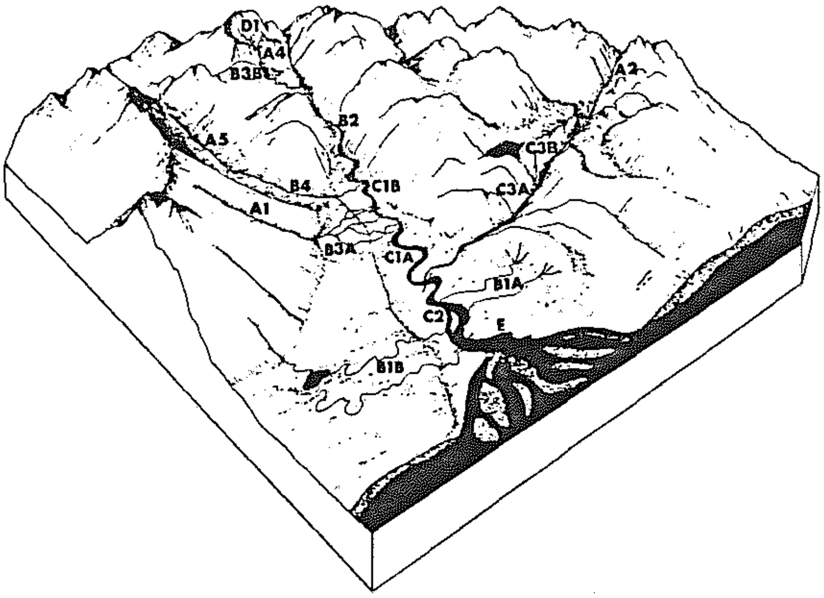

Figure 3. Typical channel type distribution in Tongass National Forest - Chatham Area watersheds.

delineating channel types on 1:15840 color aerial photographs. It was developed by TNF-CA hydrologists and fisheries biologists using standard aerial photograph interpretation techniques (Paustian et al., in preparation) found to be effective in consistently differentiating channel types. In addition to aerial photograph interpretation techniques, methods were also developed for delineating the extent of the drainage network to be mapped, and for assigning each stream order segment a unique identification number. We have found this pre-mapping procedure to be most accurate and precise when interpreters visit several of the areas they have mapped. This allows them to calibrate their aerial photograph perceptions with the actual channel features.

Field data acquisition is accomplished using a representative sampling design method based on channel types. Channel areas representative of the channel types within a watershed are identified during pre-mapping and visited by field crews. Emphasis is given to sampling within those channel types with expected high fisheries value because management interpretation accuracy is most important there. Field crews composed of one hydrologist and one to two fisheries biologists are able to accurately and efficiently accomplish this data collection thus minimizing personnel needs.

A computer data base is used to facilitate A-IRI data storage, analysis, and retrieval. At present, it is a two dimensional data array stored on the USDA Fort Collins Computer Center system. This arrangement facilitates preliminary data analysis using the extensive software statistical programs available at Fort Collins. Such a computer data base has proved essential for the efficient handling and analysis of a data file that already exceeds 2500 eighty column lines, and will probably be twice this size when field work is completed. A-IRI data will be converted to a more flexible, multidimensional data base system in the near future to facilitate future data storage, updates, and ad-hoc retrievals.

Once all data are accumulated and analyzed, final channel type correlation will occur. The correlation process will eliminate those channel types covering insufficient area to be significant. New channel types may be created where the data indicate substantial variation exists within a single channel type, and such variation can be discriminated in a systematic manner. Data analysis completion will also permit the final management interpretations to be determined for all channel types retained after the correlation.

A final A-IRI report will be published along with the channel type maps by 1985. The final map product will be published on a 1:31680 scale topographic map base. This report will contain the final channel type descriptions and management interpretations. A User's Manual for non-resource specialists will be included to explain the CTCS, the interpretations, and their applications. This will insure understanding and the appropriate usage of the A-IRI information by administrators, planners, and project engineers and foresters.

Inventory Applications

The A-IRI is primarily intended to supply resource information and interpretations for forest project planning. Individual channel types are designed to be of a size most applicable for this purpose. However, the CTCS is also designed to be a hierarchial classification system in which channel types can be aggregated into larger hydrologic groupings (Paustian et al., in preparation). This hierarchy and possible interpretations associated with each level are shown in Table 4. A-IRI information can be generalized through successive hierarchy divisions to produce management interpretations at several organizational or information resolution levels. This CTCS feature provides for coordination between different Forest Service management levels and maximizes A-IRI information usage. Both of these attributes are highly important in deciding the adequacy and value of a classification system (Frayer et al., 1978).

Although it is still not completed, the A-IRI information and interpretations have been used recently in developing the Alaska Lumber and Pulp Co. 1986-90 Operating Plan (USDA Forest Service Alaska Region,

Table 4. Possible Management Interpretations for Different Hierarchy Levels of the Tongass National Forest-Chatham Area Channel Type Classification System.

Classification Level	Size	Primary Interpretation Value
Subsection	50,000 - 250,000ha	Regional fish habitat amount and value patterns Regional/Forest chemical water quality patterns
Watershed	1,000 - 10,000ha	Forest fish habitat value patterns Land use allocations
Channel type association	1,000 - 5,000m	Reconnaissance level projects (e.g., wilderness plans)
Channel type	500 - 1000m	Project planning (e.g., timber sales)

1983a). Inventory information was used as the basis for the hydrologic and fisheries resource reports prepared for each of the 48 affected watersheds on the TNF-CA. The availability of A-IRI data collected prior to the project proposal eliminated much of the need for additional field work. In addition, use of the preliminary channel type maps and descriptions maximized resource specialist field time efficiency by directing them to those channel areas most requiring onsite inspections. Areas indicated as having highly sensitive or valuable stream resources could be thoroughly checked to avoid or reduce impacts. Resistent or less valuable areas could be visited briefly or, in certain cases, safely ignored.

An A-IRI management interpretation procedure called the Aquatic Value Rating (Paustian et al., this volume) was also used in the project plan proposal. Using this procedure stream value classes were developed based on fish habitat quality and sensitivity to adverse impacts from timber harvest activities. The relative impacts of each operating plan alternative were then evaluated based on the amount each stream value class would be affected by each alternative. This approach proved an efficient, rational, and defensible means of judging the potential resource impacts between the plan alternatives.

A-IRI utility has also been demonstrated recently in resolving two site specific resource problems. In each case, knowledge of typical channel type characteristics and processes gained through the A-IRI, and extrapolation of this knowledge to other areas using the CTCS, greatly aided specialist ability to evaluate specific resource questions.

The first situation involved a proposed municipal water intake development for the city of Hoonah on Chichagof Island. Available anadromous and resident fish habitat possibily affected by this project were quickly identified without field work using the channel type pre-mapping. Potential resource impacts were efficiently analyzed using the appropriate channel type management interpretations and verifying their accuracy during a brief field visit. In addition, the assessment of potential in-channel structure stability problems did not have to rely on site observations alone. Knowledge gained from numerous observations of streamflow, channel migration, and bank and bed stability characteristics made on the same channel types in different areas could also be drawn upon for this evaluation. Therefore, the confidence placed in the accuracy of this assessment was greatly increased.

The second case involved a boundary dispute between the TNF-CA and a private land owner. A change in the stream course used as the legal boundary between these two parties resulted in the private owner claiming the additional land which now lay on his side of the boundary stream. Once again, A-IRI information on the channel types in question, plus onsite hydrologic observations, lended very strong support to the TNF-CA position that the stream course change was an avulsive action, and therefore the original boundary location was still enforce, regardless of the present stream location. The case was settled out-of-court in favor of the TNF-CA.

Summary and Conclusions

Managing Alaskan water resources is a complex task due to the diversity and high value of the resource, and the numerous development interests involved. It is a task made more difficult by the lack of basic aquatic resource information and evaluation techniques for Alaskan streams. The aquatic portion of the Integrated Resource Inventory is a particularly useful means of gaining this information on the Tongass National Forest - Chatham Area. To date, approximately 8000km^2 have been mapped and inventoried. Information and resource evaluation methods developed through this inventory have already proved valuable in assessing forest management related problems. Two key features make this inventory a sucessful tool. First, all data collection is driven by identified management interpretation needs. Second, use of the Channel Type Classification System allows for the delineation of integrated aquatic resource management areas; systematic resource accounting and data extrapolation; and a hierarchial structure for applying resource information and evaluations at several management levels.

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References

Bailey, Robert G. 1980. Description of the Ecoregions of the United States. USDA Forest Service Intermountain Region Misc. Publication No. 1391, Ogden, Utah, 77 pp.

Bailey, Robert G., Robert D. Pfister, and Jan A. Henderson. 1978. Nature of Land and Resource Classification - A Review. Journal of Forestry, vol, 76, no. 10, pp. 650-655.

Bisson, Peter A., Jenifer L. Nielsen, Ray A. Palmason, and Larry E. Grove. 1981. A System of Naming Habitat Types in Small Streams, with Examples of Habitat Utilization by Salmonids during Low Streamflow. In: Acquisition and Utilization of Aquatic Habitat Inventory Information: Proceedings of the Symposium, Oct. 28-30, Portland, Oregon, pp. 62-73.

Chamberlin, T. W. 1980. Aquatic System Inventory (Biophysical Stream Surveys). APD Technical Paper 1, B.C. Ministry of Environment, Victoria, British Columbia, 33 pp.

Cole, Gene F. 1972. Valley Types, an Extension of the Landsystems Inventory to Valleys. Unpublished report on file at the Boise National Forest, Boise, Idaho.

Collotzi, Albert W. 1974. A Systematic Approach to the Stratification of the Valley Bottom and the Relationship to Land Use Planning. Unpublished report on file at the Bridger - Teton National Forest, Jackson, Wyoming.

Dixon, Gary E. 1981. Multiresource Inventories: Meeting Challenging New Information Needs. In: In-Place Resource Inventories: Principles and Practices, Society of American Foresters National Workshop, Univ. of Maine, Orono, Maine, Aug. 9-14, 1981, pp. 383-388.

Frayer, W. E., L. S. Davis, and Paul G. Risser. 1978. Uses of Land Classification. Journal of Forestry, vol. 76, no. 10, pp. 647-649.

Hamilton, Thomas E. 1978. National Integrated Inventories - Is What You Need What You Do? In: Integrated Inventories of Renewable Natural Resources: Proceedings of the Workshop, Tucson, Arizona, Jan. 8-12, 1978. USDA Forest Service Rocky Mountain Forest and Range Experiment Station General Technical Report RM-55, Fort Collins, Colorado, pp. 136-139.

Harris, Arland S., O. Keith Hutchison, William R. Meehan, Douglas N. Swanston, Austin E. Helmers, John C. Hendee, and Thomas M. Collins. 1974. The Forest Ecosystem of Southeast Alaska: The Setting. USDA Forest Service Pacific Northwest Forest and Range Experiment Station General Technical Report PNW-12, Portland, Oregon, 40 pp.

Lotspeich, Frederick B., and William S. Platts. 1981. An Integrated Land - Aquatic Classification. In: Acquisition and Utilization of Aquatic Habitat Inventory Information: Proceedings of the Symposium, Oct. 28-30, Portland, Oregon, pp. 103-108.

Nelson, DeVon, Grant A. Harris, and Thomas E. Hamilton. 1978. Land and Resource Classification - Who Cares? Journal of Forestry, vol. 76, no. 10, pp. 644-646.

Ott Water Engineers, Inc. 1979. Water Resources Atlas for USDA Forest Service Region X[10]. USDA Forest Service Alaska Region, Juneau, Alaska, 7 pp.

Paustian, Steven J., Daniel A. Marion, And Daniel F. Kelliher. In preparation. Stream Classification using Large Scale Aerial Photography for Southeast Alaska Watershed Management. In: Proceedings of the RNRF Symposium on the Application of Remote Sensing to Resource Management, May 22-27, 1983, Seattle, Washington.

Paustian, Steven J., Douglas Perkinson, Daniel A. Marion, and Philip Hunsicker. In preparation. An Aquatic Value Rating Procedure for Fisheries and Water Resource Management in Southeast Alaska. In: Managing Water Resources for Alaska's Development: Proceedings of the Meeting, Nov. 10-11, 1983, Chena Hot Springs, Alaska.

USDA Forest Service Alaska Region. 1979. Tongass Land Management Plan: Final Environmental Impact Statement, Part 1. USDA Forest Service Alaska Region, Juneau, Alaska, 312 pp.

_______________. 1980. The ALP 1981-86 Timber Sale Operating Plan: Final Environmental Impact Statement for the Chatham and Stikine Areas, Part 1. USDA Forest Service Alaska Region Report No. 100, Sitka, Alaska, 311 pp.

_______________. 1982. Integrated Resource Inventory: Legends Handbook II. Unpublished report on file at Tongass National Forest-Chatham Area Supervisor's Office, Sitka, Alaska.

_______________. 1983a. Planning Update for the ALP 1986-90 Operating Plan. USDA Forest Service Tongass National Forest - Chatham and -Stikine Areas, Sitka, Alaska, 25pp.

_______________. 1983b. Aquatic Portion of the Integrated Resource Inventory: Draft. Unpublished report on file at Tongass National Forest-Chatham Area Supervisor's Office, Sitka, Alaska.

USDA Forest Service Intermountain Region. 1979. Guidelines for Water

Resources Inventory. USDA Forest Service Intermountain Region, Ogden, Utah, 9 pp.

Viereck, Leslie. A., and C. T. Dyrness. 1980. A Preliminary Classification System for Vegetation of Alaska. USDA Forest Service Pacific Northwest Forest and Range Experiment Station General Technical Report PNW-106, Portland, Oregon, 38 pp.

Wertz, W. A., and J. A. Arnold. 1973. Land Systems Inventory. USDA Forest Service Intermountain Region, Ogden, Utah, 12 pp.

AN AQUATIC VALUE RATING PROCEDURE FOR FISHERIES AND WATER RESOURCE MANAGEMENT IN SOUTHEAST ALASKA

By Steven J. Paustian[1], Douglas Perkinson[2], Daniel A. Marion[3], and Philip Hunsicker[4]

Abstract

The Aquatic Value Rating (AVR) is a tool for evaluating forest management alternatives on the Tongass National Forest-Chatham Area (TNF-CA). The AVR is a qualitative rating method designed to assess stream ecosystem suitability for streamside timber harvesting activities. Stream ecosystems that have significantly different characteristics are identified using the TNF-CA channel type classification system. Channel types are readily discernible stream segments with relatively homogeneous physical, biological, and resource management properties.

An AVR is developed for each channel type from fish habitat, channel stability, and morphology data. The fish habitat component is derived from empirical relationships between measured habitat features and fish utilization estimates. These values are used as a relative index of habitat quality. The channel stability and morphology component is determined from quantitative and qualitative estimates of channel conditions. It is assumed that the channel stability parameters are useful indices for assessing stream ecosystem sensitivity to management activities. The channel type AVR procedure provides resource managers and planners with an efficient, flexible, rational, and defensible methodology for planning management activities affecting fisheries and water resources.

Introduction

The Aquatic Value Rating (AVR) is an outgrowth of the Tongass National Forest-Chatham Area (TNF-CA) Integrated Resource Inventory effort. The AVR approach was developed in response to a need for better assimilation of fisheries and water resource concerns and opportunities into the

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[1] Supervisory Hydrologist, Tongass National Forest-Chatham Area, P. O. Box 1980, Sitka, AK 99835.
[2] District Fisheries Biologist, Hoonah Ranger District, P. O. Box 135, Hoonah, AK 99829.
[3] Hydrologist, Tongass National Forest-Chatham Area, P. O. Box 1980, Sitka, AK 99835.
[4] Fish Culturist, Alaska Department of Fish and Game, P. O. Box 499, Sitka, AK 99835.

Forest Service land management planning process. The concepts and applications discussed in this paper have been used successfully in evaluating resource management alternatives for the proposed Alaska Lumber and Pulp Co. 1986-90 Operating Plan (USDA Forest Service Alaska Region, 1983b).

The AVR is an initial attempt to depict stream or watershed fish production capability, and to account for relative fish habitat sensitivity to timber harvest induced impacts. Important attributes of the AVR approach include:

1. The AVR is based on distinct stream channel mapping units called channel types, that allow for the efficient compilation, verification, and extrapolation of resource inventory and research data.
2. The AVR incorporates biotic and abiotic factors that are known to influence fish habitat quality and sensitivity to management induced perturbations.
3. The AVR model provides a foundation for a more precise quantitative approach to assess fish production and management induced habitat changes and recovery trends.

Aquatic Value Rating.

The AVR approach is a fish habitat classification scheme with sufficient precision to address site specific stream and fish habitat management issues. It also has sufficient generality to expand data applications to large watershed or land use planning units. The AVR incorporates quantifiable aquatic and riparian habitat features that correlate with fish habitat quality and sensitivity as evidenced by fish production and observations of timber harvest responses.

The TNF-CA AVR has three fundamental components: Channel Type mapping units (CT); a Habitat Quality Index (HQI); and a Riparian Sensitivity Index (RSI). Channel type measurements provide the spatial framework for quantification of fish habitat characteristics. The habitat quality index is a relative measure of fish production potential. The riparian sensitivity index is a qualitative measure of stream dependence on streamside characteristics for regulating inchannel structure and functional processes. These three AVR components are combined algebraically to form the following expression:

$$CT \times HQI \times RSI = AVR$$

The product of these three parameters (AVR) is a dimensionless, qualitative value rating of aquatic resource potential. The following discussion will examine each AVR component in detail and present some examples for AVR applications in forest land use planning problems.

Channel Type Mapping Units. Channel types are discernable stream channel mapping units having relatively homogeneous morphological, biological, and resource management characteristics (Paustian et al., in preparation). Channel types are delineated on aerial photographs using differentiating criteria that include: adjacent landforms, channel incision depth, channel gradient, riparian vegetation, and contributing drainage area. This channel type classification provides a framework within which fish habitat and channel stability features can be measured and quantified in a systematic manner. Limited field samples of representative channel type segments can be efficiently compiled and extrapolated to unsurveyed areas using channel types. A limited fish habitat quality and sensitivity data base can thus be extended over relatively large geographic land use planning areas with some degree of confidence.

Habitat Quality Index. Numerous fish habitat studies have focused on geologic and morphologic characteristics of watersheds, but few have had land and water management value (Platts, 1974). These habitat classifications typically correlate fish habitat, stream channel, and watershed characteristics with wome measure or index of fish distribution or production potential. Dunham and Collotzi's (1975) transect survey used stream channel morphologic variables to rate channel reaches by a percentage of "optimum" habitat. Heller, Maxwell, and Parsons (1983) developed a relative index for watershed habitat quality using fluvial geomorphic parameters. Platts (1974, 1979) examined geomorphic and aquatic variables as to how they relate to fish distribution and abundance, but restricted his classification to large landform units.

Four basic objectives: realism, generality, efficiency, and precision were set for the TNF-CA Habitat Quality Index (HQI). The goal of realism demands that the HQI should portray stream habitat values in a way that allows for easy comparison with other resource values. A relative measure of fish production potential was chosen that with further refinement could be used to put a dollar value on the fish habitat resource. The HQI also had to be applicable to a wide range of geomorphic and fluvial conditions, and account for the varied life phases of most of the important fish species found in SE Alaska. The actual inventory methodology for collecting HQI data needed to be efficient and reliable in measuring habitat variables amenable to modeling fish production. Finally, index variables had to be precise enough to have information value for land and water management decisions.

Barber et al. (1981) examined two inventory methods in use by fisheries biologists in Southeast Alaska. The two methods were a subjective estimate of quality (transect method), and an objective measurement of quantity (area method)(USDA Forest Service Alaska Region, 1981). Barber et al. evaluated the statistical abilities of the two methods to predict fish populations residing in the inventoried stream sections. Examination of their multivariate predictive equations suggested that the area method could be adapted to meet our criteria for a habitat quality index.

The area method requires objective measurements of stream features and construction of diagramatic maps of 30m segments of active stream channels. Prior to our field work, 300m long representative stream reaches were selected on 1:15840 aerial photographs. Within the representative reach 30m samples segments were selected and mapped. Samples were either single or matched pairs stratified by channel type. Seventeen habitat variables: gradient, available spawning area, water types, and three cover classes among others, were measured and mapped to scale.

Calculations from the Barber et al. equations resulted in a population estimate for a 30m sample station. For data comparison purposes we reduced that value to an estimate for a meter long channel segment. As an index of habitat quality for stream rearing anadromous species we chose the authors' equations for coho (Onchorhynchus kisutch) age 0 and

1+. The index for stream rearing resident species used the Dolly Varden (*Salvelinus malma*) equation. Because the majority of fish production comes from pink (*Onchorhynchus gorbuscha*) and chum (*Onchorhynchus keta*) salmon that rear in saltwater, we felt it necessary to develop and use an index to rate habitat quality for saltwater rearing species. Standard Alaska Region (USDA Forest Service Alaska Region, 1981) values for production (harvestable adults produced per square meter of spawning habitat) of pink and chum were averaged ($1.51/m^2$ [pink] + $1.12/m^2$ [chum] / 2 = $1.31/m^2$) and multiplied by the amount of spawning habitat measured in the surveys. This better accounts for situations in which one or the other species dominates watershed production. Table 1 illustrates the multivariate regression equations used in the indices, and their respective correlation coefficients (R and R^2). Also included is the index for saltwater rearing species.

The final form of the three HQI indices were:

$$\text{Freshwater Rearing HQI} = 0.033(\log^{-1}\text{coho } 0 + \log^{-1}\text{coho } 1+)$$

$$\text{Saltwater Rearing HQI} = 0.033)\text{pink/chum})$$

$$\text{Resident HQI} = 0.033(\log^{-1}\text{Dolly Varden})$$

The mean HQI scores and standard error of the estimates are listed for selected channel types in Table 2. Scores are the mean of HQI's for all sample sites stratified by channel type.

The HQI is a realistic index of fish habitat quality. After sampling nearly 200 major watersheds, participants in this inventory are confident that it tracks observed habitat use. Generality is maintained due to

Table 1. Barber et al. Multivariate Regression Equations used in the Tongass National Forest - Chatham Area Habitat Quality Index.

Fish	R	R2	Predictive Equation[1]
coho 0	0.87	0.76	$\log Y = 0.871 + 1.011 \log ASA + 0.010 RV - 0.009 S$ (1)
coho 1+	0.70	0.49	$\log Y = 0.249 - 0.073 G + 0.416 \log SS + 0.006 RV + 0.260 \log UB$ (1)
Dolly Varden	0.70	0.49	$\log Y = 3.223 - 1.110 \log IA + 0.344 \log FDR$ (1)
pink/chum	---	---	$Y = (1.36/m^2) ASA/1000$ (2)

SOURCES: (1)Barber et al., 1981, p. 19; (2)USDA Forest Service Alaska Region production estimate used in cost/benefit analyses, multiplied by available spawning area of the 30m sample. Production equals mean of pink (1.51 adults/m^2) and chum (1.12 adults/m^2).

[1] Equation abbreviations: ASA = available spawning area; RV = riparian vegetation; S = season; G = gradient; SS = shallow slow water type; UB = undercut banks; IA = intensive area; FDR = forest debris riffle.

use of explicit and consistent channel type and inventory standards over broad geographic areas. This confirms the wisdom of stratifying watersheds into channel types based on aquatic and riparian structure and function. However, confidence limits frequently overlap between two or more channel type HQI's. This is probably attributable to variability in habitat characteristics and inventory sample design. Narrower confidence bands are anticipated after stratification of the HQI data within land units (TNF-CA physiographic sections) having relatively homogeneous climatic, lithologic, and geomorphic characteristics. Channel type delineations are not based solely on fish habitat considerations but also account for timber harvesting and road design concerns. A certain degree of precision is sacrificed by this multifunctional stream mapping approach. It should be noted that at present the HQI rates fish habitat capability in relative terms and not in numbers of fish. We have applied

Table 2. Habitat Quality Index Mean Scores and Standard Error of the Estimates for Selected Tongass National Forest - Chatham Area Channel Types.

Channel Type	Sample Size	Freshwater Rearing	Saltwater Rearing	Resident
E (Low gradient, esturarine channel	23	5.12 (1.32)	13.96	0.02 (0.005)
C1A (Low gradient, valley bottom, forest channel)	54	2.14* (0.47)	5.03	0.08 (0.02)
C1B (Low gradient, incised valley bottom, forest/muskeg channel)	35	1.56 (0.36)	5.36	0.16 (0.13)
B1A (Low gradient, lowland, forest channel)	23	1.58* (0.25)	3.03	0.80 (0.26)
B2 (Moderate gradient, middle valley, forest channel)	43	0.36 (0.09)	0.97	0.77 (0.56)
B4 (Moderate gradient, incised lowland, muskeg'forest channel)	26	0.24 (0.04)	0.84	0.27 (0.10)

NOTE: Values are mean Habitat Quality Index per meter length of channel type. Standard error estimated by taking square root of standard error of the mean for a 30m sample.

*Freshwater rearing scores were adjusted upward by 50% to account for large amounts of off-channel flood plain rearing sites typically found in association with these channel types.

the Barber et al. equations in a broader spectrum of stream channels than the orginal population samples used to develop the multivariate equations, thus reducing statistical accuracy. In addition, fish production rates are generally lower in northern panhandle streams versus streams in the southern panhandle due to lower water temperatures.

Furthermore, important habitat influences such as upwelling ground water, lakes, and off-channel flood plain rearing areas were not taken into account in the orginal validation. Therefore, in our judgement there is presently insufficient validation of the Barber et al. equations on the TNF-CA to permit their use for precise estimates of fish populations. However, we feel strongly that use of these equations as a relative index of habitat quality is justifiable.

Riparian Zone Sensitivity

A major problem facing aquatic resource managers is not only defining a means of assessing aquatic habitat quality. In addition, they must make predictions about how activities such as timber harvesting will affect or impact aquatic habitat. In the AVR approach we apply the term riparian zone sensitivity to describe the probability for timber harvesting induced impacts to aquatic habitats.

The interactions between fluvial processes, stream channel morphology, and riparian factors directly shape aquatic habitat conditions (Swanson et al., 1982, 1983; Trisca el al., 1983). A riparian or stream sensitivity index must adequately describe the balance between these biotic and abiotic factors as they affect the stability and quality of aquatic habitats. Most attempts at such a classification are necessarily qualitative. The Stream Reach Stability Classification by Pfankuch (1975) is a widely used approach to predicting stream sensitivity. Platts, Megahan, and Minshall (1983) identify several important parameters including: stream bank soil stability, stream bank vegetation stability, stream bank undercut, stream bank slope, channel elevation, channel gradient, channel sinuosity, substate size, substrate embeddedness, channel debris and sediment storage, vegetation cover, that have proven useful in evaluating stream channel and riparian zone conditions. We have incorporated many of these qualitative and quantitative channel assessment procedures (USDA Forest Service Alaska Region 1983) into developing the riparian sensitivity index of the AVR.

Various aquatic ecosystems functions of riparian zone vegetation that may be influenced by timber harvesting activities are displayed in Figure 1. For the AVR model these riparian zone functions have been combined into three categories referred to as: sediment, LOD, and energy factors. Each of these three factors are combined to form the riparian zone sensitivity index (RSI). The RSI is a qualitative means of assessing the positive or negative influences of streamside timber harvesting on fish habitat in TNF-CA.

In developing this approach we recognized the futility of attempting to quantify all the many complex interrelationships between riparian factors and instream processes. These include fluvial and biotic processes such as: sediment input and routing; stream temperature regimes; the processing and flushing of organic detritus; photosynthesis and nutrient uptake; and stream bank cutting, channel scouring, or sediment deposition. Instead, two major assumptions are made in the determining riparian sensitivity factors:

1. Riparian functional relationships can be adequately described for TNF-CA streams using three simple functional categories (sediment, LOD, and energy) and that these factors reflect stream dependence on riparian vegetation for long term aquatic environment stability.
2. The relative importance of each of these functional components is

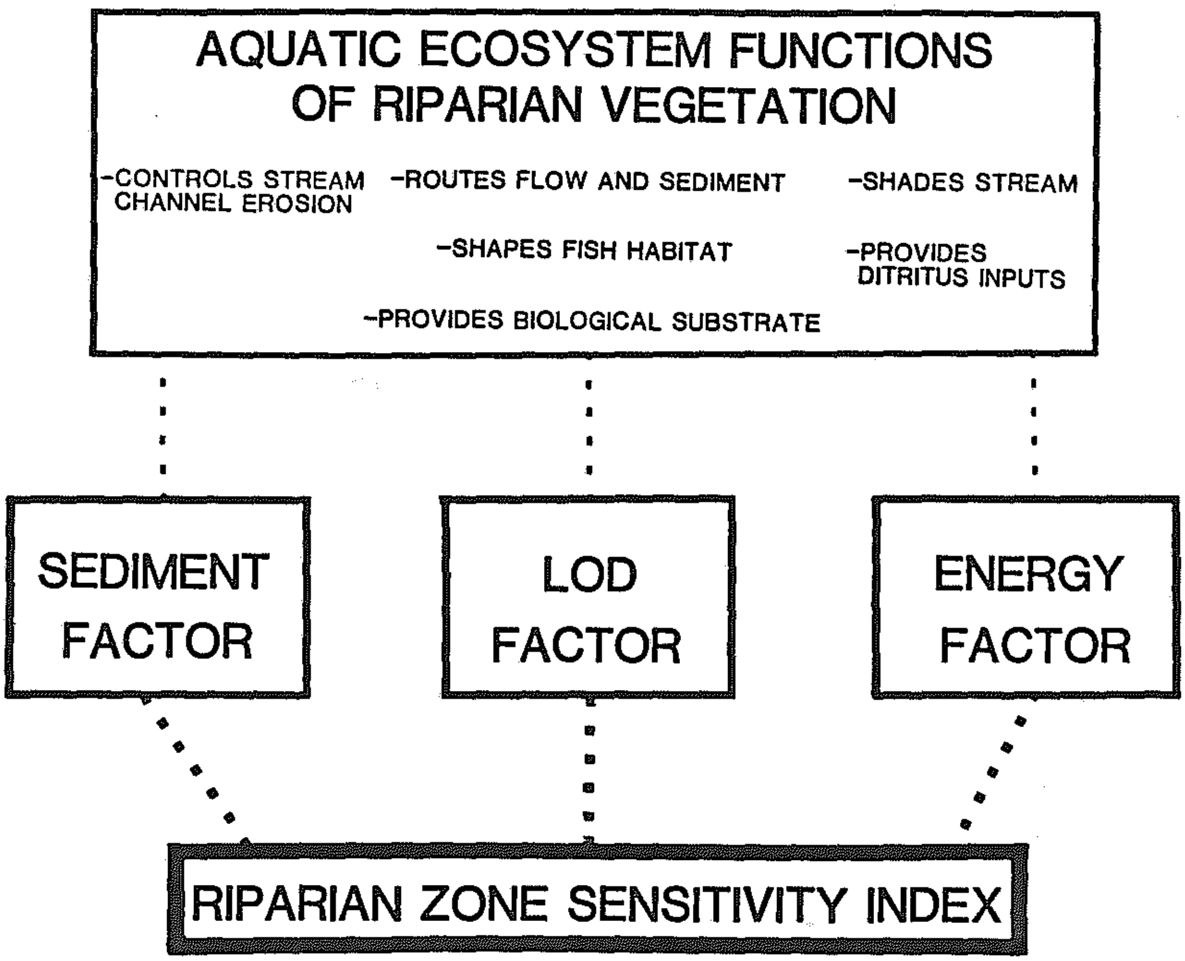

Figure 1. The relationships between qualitative sensitivity factors (Sediment, LOD, Energy) used to derive the Tongass National Forest - Chatham Area Riparian Zone Sensitivity Index, and the functional roles of riparian vegetation that influence aquatic ecosystem stability and responses to timber harvesting activity.

equal and is therefore given equal weight in qualitative assessments of riparian zone sensitivity.

Sediment Factor. The sediment factor in the riparian zone sensitivity index reflects the role of riparian vegetation in controlling the process of stream channel erosion (Figure 1). Timber harvesting can exacerbate natural channel erosion through the breakdown and destruction of stream banks by falling and yarding operations, and through loss of root binding strength due to decay of conifer root mats after cutting (Chamberlin, 1982). A number of important fish habitat features can be affected by such alterations to stream channel erosion processes (Reiser and Bjornn, 1979). For example, the quality of spawning gravel can be altered through shifts in substrate particle size distribution or reduced intergravel permeability. Mechanical disturbance to the stream channel can reduce available cover associated with undercut banks and shallow pools. Filling of substrate voids with fine sediments eroded from channel banks can eliminate important habitat for bentic organizms.

Sediment sensitivity factors are determined from a combination of sediment input and sediment conveyance ratings for TNF-CA channel types. Sediment input potential is determined from channel stability ratings for: upper bank stability, lower bank stability, and streambed stability. Sediment conveyance is based upon bankfull unit stream power which is used as a relative predictor of stream sediment load transport ability (USDA Forest Service Alaska Region, 1983a). Bull (1979) has demonstrated that channel sensitivity to sediment induced impacts can be expressed in terms of the balance between sediment input and conveyance. A qualitative comparison between sediment input and conveyance potentials

Table 3.

Riparian Zone Sensitivity Ratings for Selected Tongass National Forest - Chatham Area Channel Types.

Channel Type	Sediment Factor	LOD Factor	Energy Factor	Riparian Sensitivity Index
B1A (Low gradient, lowland, forest channel)	Mod	Mod	Mod	1.98
B2 (Moderate gradient, middle valley, forest channel)	Low	High	High	2.31
B4 (Moderate gradient, incised lowland muskeg/forest channel)	Low	Low	Low	0.99
C1A (Low gradient, valley bottom, forest channel)	High	High	Mod	2.64
C1B (Low gradient, incised valley bottom, forest channel)	Low	Low	Low	0.99
E (Low gradient, estuarine channel)	Low	Low	Low	0.99

NOTE: Sediment, LOD, and energy ratings: Low = 0.33; Moderate(Mod) = 0.66; and High = 0.99.

was therefore used to derive the overall sensitivity ranking for the sediment factor in column one of Table 3.

Rating classes of high, moderate, and low were determined for the sediment input and sediment conveyance potentials. If the sediment input class is the same rank or lower than the conveyance class (e.g., low versus moderate), than the sediment sensitivity is rated low (see Table 3). In this situation it is assumed that increases in sediment due to timber harvesting activities will not significantly exceed the ability of the stream to cope with the new sediment load. However, if the sediment input class is greater than the conveyance class rating, increased sediment loads will likely change channel conditions. In the latter situation sediment sensitivity is moderate if input exceeds conveyance by one class (e.g., high versus moderate), and high if input exceeds conveyance by two classes (e.g., high versus low).

This sediment rating approach addresses only potential onsite impacts from streamside timber harvesting. The effects of hillslope erosion and sediment transported from upstream channels are not accounted for by the sediment factor of the riparian zone sensitivity index.

LOD Factor. LOD input potential is the second major factor used in rating riparian zone sensitivity. LOD is one of the more important links between terrestrial and aquatic components of northern coniferous forest streams (Swanson et al., 1982). The primary functions of LOD in stream ecosystems are: controlling the routing of streamflow and sediment; shaping fish habitat; and providing a substrate for biological activity (Figure 1). These functions are highly time dependent in nature and are a result of balances between input and output that occurs over decades (Swanson et al., 1982)

Logging can shift this equilibrium between the rate of processing or breakdown of LOD and the rate of LOD input causing changes in stream habitat and fish populations (Everest and Meehan 1981). The cumulative effects of LOD inputs from natural or management related causes may be both positive and negative. Positive aspects of LOD are that it contributes cover and enhances habitat diversity for stream biota. Once encorporated into streambed and banks LOD improves channel stability. Organic debris dams slow the movement of sediment and fine particulate organic matter and thus contribute to the availability of allocthonous food sources and spawning gravels. However, large scale debris inputs such as those resulting from hillslope debris torrents or major blowdown certainly have negative short term impacts on fish habitat. These large scale debris jams commonly impede fish migration and are closely associated with large sediment inputs and channel migration. Heavy accumulations of needles and branches also associated with massive debris inputs may completely clog small streams and may significantly reduce intergravel dissolved oxygen concentrations in larger channels (Everest and Meehan, 1981; Chamberlin, 1982).

Although judicious inputs of organic debris and slash during logging activities will likely improve fish habitat on some stream reaches, the long term effects of logging on the stability of LOD related habitat is a concern. Rapid liquidation of old growth conifer stands along extensive reaches of channel prevents an even flow of LOD inputs to the channel. Intensively managed second growth stands will be denser and more wind firm resulting in fewer natural debris input events. The smaller stems and rootwads of second growth trees will also be smaller providing less fish cover, and will be less stable features in larger channels.

The LOD sensitivity factor (Table 3, column 2) for TNF-CA channel types was determined from field observations of LOD loading in stream channels. LOD includes all woody debris greater than 10cm in diameter (Swanson et al., 1982). The class ranks of high, moderate, and low sensitivity corresponds to the relative channel area typically affected by LOD accumulations: less than 10%, 10% to 20%, and greater than 20%, respectively. The area or zone of LOD influence was defined by the percentage of sample stream segment within which LOD controlled the development or maintenance of habitat features such as bank and bebris cover, scour pools, and gravel bars.

In assessing LOD influences on riparian zone sensitivity it was assumed that those stream habitats typically having the highest natural debris loading are also the most dependent on LOD for maintenance of habitat integrity. Therefore, in Table 3 C1A and B2 channel types are assumed to have a high LOD sensitivity because frequent organic debris accumulations are consistently associated with them and the removal of streamside conifers can limit the long term supply of LOD. It should also be recognized that LOD input rates are controlled by a large number of environmental factors including: riparian canopy successional stages, local wind patterns; and stream channel dynamics. Therefore, a high degree of natural spatial variability in LOD accumulations can be expected to occur within a given channel type segment.

Energy Factor. The energy factor is the last major component of the riparian sensitivity index. The functions of riparian vegetation in stream shading and fine organic detritus input are accounted for by this parameter (Figure 1). The quantity and quality of stream detrital food sources are major factors in controlling the distribution of various functional groups of aquatic invertebrates (Cummins, 1974). The diversity and abundance of these aquatic invertebrates in turn directly affects the productivity of anadromous and resident fisheries (Swanson et al., 1982). The effects of clearcutting on stream energy budgets are twofold. First, the rate of fine particulate organic matter inputs to the stream are altered. Second, the rate of aquatic photosynthetic activity can increase significantly following riparian canopy removal (Chamberlin, 1982). This potential increase in autotrophic food supplies may counteract the loss of the stable allocthonous food supply provided by the undisturbed riparian canopy. However, this may be only a temporary enhancement of stream productivity, and may result in long term reductions in overall biological production due to intense shading by second growth stands (Trisca et al., 1982).

Riparian canopies also regulate stream temperature, a second major factor influencing the growth and survival of aquatic biota. The effects of canopy removal in elevating summer stream temperatures can be substantial in forest streams (Brown and Krygier, 1967). However, the moderating influence of riparian forest canopies on winter stream temperature could potentially be a more important management consideration in TNF-CA (Sheridan and Bloom, 1975).

Management implications relating to maintenance of a stable stream energy regime are somewhat ill-defined in TNF-CA. Canopy openings in some low gradient floodplain channels (C1A, B1A) will likely enhance summertime aquatic productivity by elevating stream temperatures and increasing photosynthesis. However, these benefits may be totally negated by increased winter mortality of incubating eggs or rearing juveniles with the removal of temperature moderation effects by the canopy. Data are not presently available to indicate the long term responses of the various functional groups of aquatic invertebrates to manipulation of riparian vegetation. Therefore, potential impacts to anadromous fisheries from riparian clearcutting is not clear (Swanson et al., 1982). However, a general riparian management criteria for the long term maintenance of a stable and productive stream energy base would suggest that manageable portions of important channel types should have a variety of canopy successional stages associated with them.

Energy factor ratings in Table 3 are based upon the size, composition, and structure of riparian canopy types generally associated with a given channel type (USDA Forest Service Alaska Region, 1983a). The high, moderate, and low energy sensitivity ratings correspond to the following riparian canopy closure classes determined from aerial photographs: greater than 50%, 25% to 50%, and less than 25%. This rating criteria assumes that stream ecosystems associated with dense riparian canopies must rely on sources of fine particulate organic matter for a significant portion of their aquatic food base. Aquatic production in these streams may also be sensitive to changes in water temperature resulting from canopy removal. An example is the B2 channel type in Table 3. Streams typically having a greater range in canopy closure (e.g., C1A and B1A channel types) are rated as moderately sensitive to energy factors because a better natural balance between primary production and detrital processing would tend to buffer the effects of canopy removal. Temperature sensitivity may still be a concern for channels in this category. Streams with sparse or no forest canopies recieve a low energy sensitivity rating.

The summation of ratings for the sediment, LOD, and energy factors yields the overall riparian sensitivity index (RSI) in Table 3. The RSI represents a qualitative measure of channel type response to timber harvesting. It should be reiterated that this numerical index is conceptually sound but the rating classes were not derived from quantitative analyses. This approach is undoubtebly an oversimplification of the complex interactions between biotic and abiotic factors of riparian and aquatic ecosystems. However, the RSI is useful in comparing the relative sensitivity of distinct channels to timber harvesting. Hopefully with this preliminary foundation the RSI will evolve into a more precise predictor of aquatic ecosystem response to timber harvesting.

Assumptions/limitations

1. The correlations between habitat and fish utilization that Barber et al. (1981) found are generally applicable throughout the TNF-CA, and it is only the magnitude of the population estimate that varies due to local conditions.
2. Pink and chum habitat quality can be adequately measured and modeled using available spawning area.
3. Sediment, LOD, and energy factors are the riparian habitat characteristics most likely to be impacted.
4. In the development of riparian sensitivity ratings the use of standard timber harvesting practices are assumed. These are clearcutting of all merchantable streamside timber within defined unit boundaries using high-lead cable yarding with partial log suspension.

5. In its present form, channel typing and the A.R.V. model applies only to the geomorphic zone thus far incorporated into the inventory.

AVR Applications

The AVR approach was developed specifically to facilitate forest resource planning efforts and management decisions pertaining to fisheries and watershed management on the TNF-CA. The AVR information base can be applied to several levels or types of Forest resource planning. Examples for two levels of forest land management planning (general allocative resource planning and area specific project planning) are presented in the following discussion.

Allocative planning in the Forest Service multiple resource management scheme determines management emphasis for large management units. This allocation may shift management objectives in favor of intrinsic wilderness values on one extreme or intensive management of commodity resources such as timber products at the other end of the spectrum. At this point, the AVR does not display fisheries habitat as a dollar commodity but can be useful in displaying and comparing the relative value of fisheries resource between two or more management units. Two watershed planning units, "Finger Creek" and "Bent Prop Creek," on Chicagof Island are shown in Figure 2. They have many similarities including drainage area, elevation, drainage pattern, total channel length and length of useable anadromous fish habitat. However, the watershed aquatic value rating for "Bent Prop" Creek is 2.5 times greater than the total for "Finger Creek" (see Table 4). This difference is due primarily to the occurrence of a long segment of potentially very high quality ClA habitat on "Bent Prop Creek." This example illustrates that

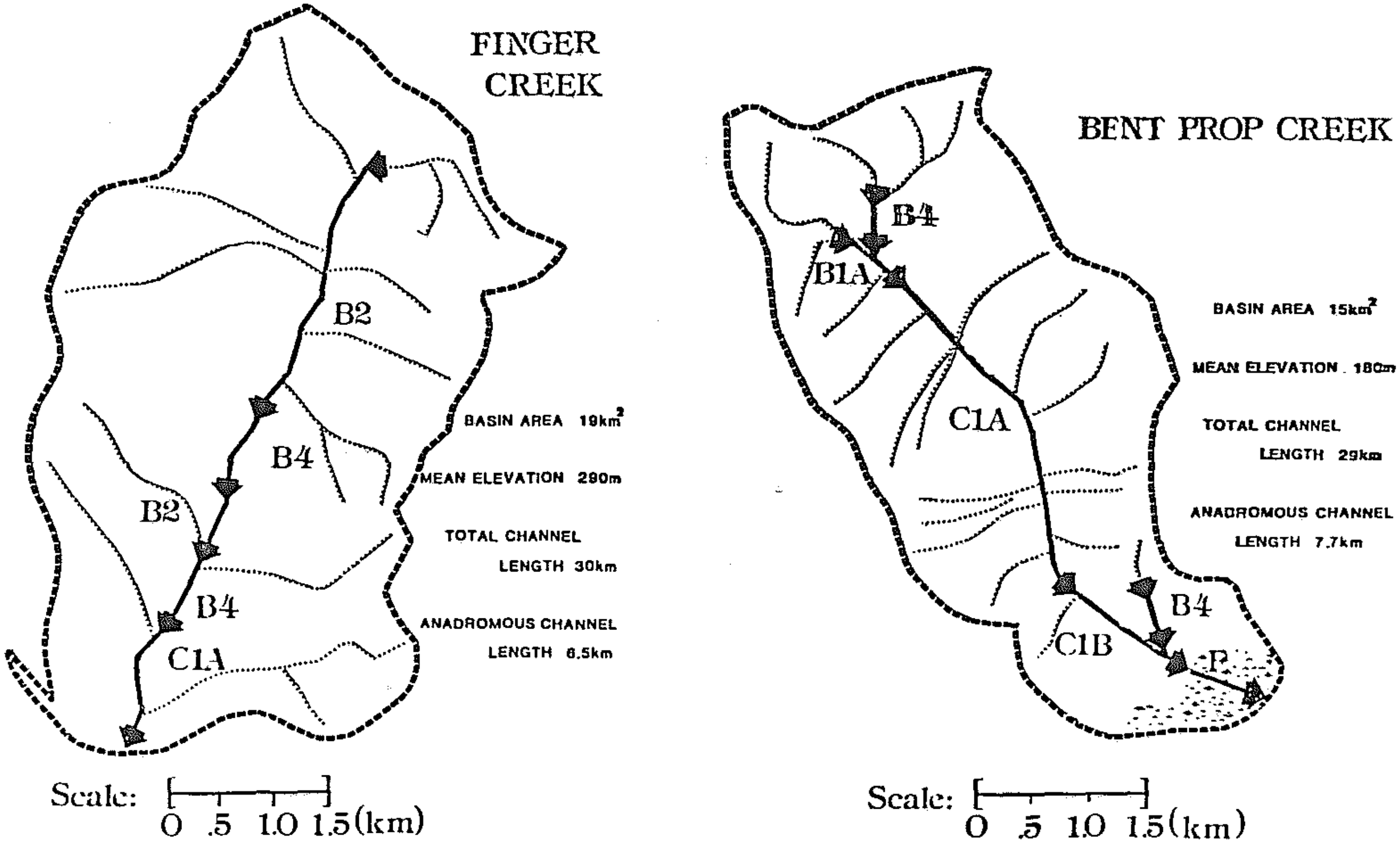

Figure 2. Distribution of channel types having anadromous fish habitat in two typical Tongass National Forest - Chatham Area 3rd order watersheds.

fish habitat management opportunities between two apparently similar watersheds can be differentiated in a simple, straight forward manner. The AVR approach has not been applied in allocative planning efforts to date. It is hoped that in future allocation planning a version of the AVR will aid in developing improved land management allocations compatable with fisheries, water, timber and recreation management goals.

The AVR can also be used to assist project planning efforts by identifying site specific management issues, concerns, and opportunities that will result from various resource development alternatives. The AVR-channel type information base allows for consistent, reproducible and efficient assessment of the potential effects of individual management alternatives on fish habitat and stream stability. These assets are particularly important for scheduling multiple entries for timber harvesting where the long term impacts of management activities are a concern. An examination of a proposed project timber harvest plan for "Finger Creek" illustrates the utility of AVR data in this type of application (Figure 3). In this timber harvesting and road construction alternative (treatment 1 and 2), four cutting units are proposed immediately adjacent to the upper valley B2 channel type, impacting about 60% of the riparian zone. Although this channel type is rated as having only moderate fish habitat quality, it has a high riparian sensitivity (Tables 2 and 3). Fisheries management and water quality objectives for this watershed may require that special stream management prescriptions be considered, or another cutting unit alternative be implemented. These prescriptions may include a number of options: deferring harvest of a

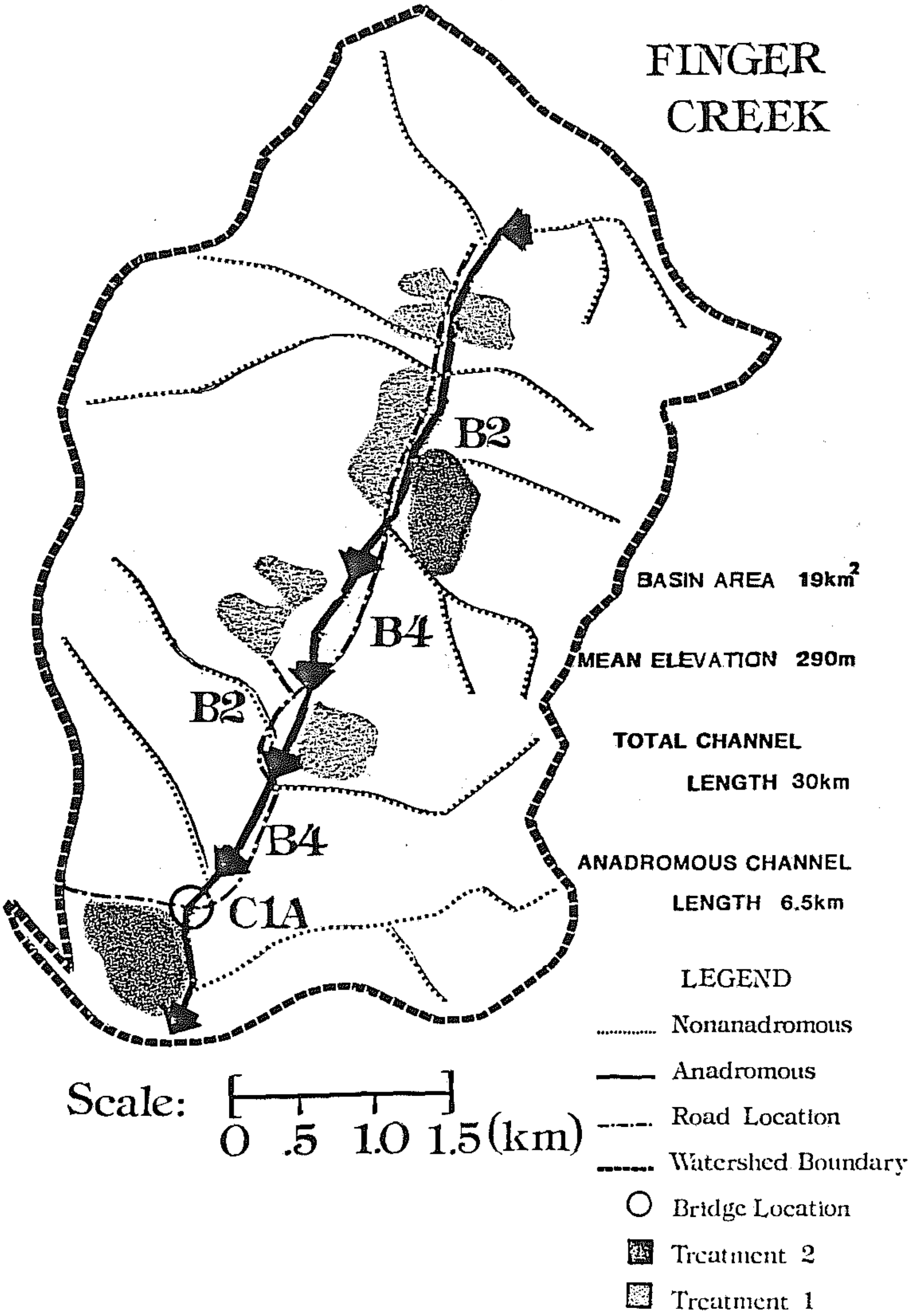

Figure 3. Example of a timber harvest and road construction planning alternative for a Tongass National Forest - Chatham Area watershed.

unit until the second entry (treatment 2, Figure 3); partial retention of a narrow strip of riparian timber; or a selective cutting treatment

Table 4. Aquatic Value Ratings for Two Watersheds on Chichagof Island, Southeast Alaska.

"Bent Prop Creek"

Channel Type	C1A	E	C1B	B1A	B4
Habitat Quality Index	25,892	16.304	11,050	3,776	1,090
Riparian Sensitivity Index	2.64	0.99	0.99	1.98	0.99
Aquatic Value Rating	68,354	16,141	10,939	7,476	1,079

Watershed Aquatic Value Rating = 103,989

"Finger Creek"

Channel Type	C1A	B2	B4
Habitat Quality Index	9,877	4,662	1,831
Riparian Sensitivity Index	2.64	2.31	0.99
Aquatic Value Rating	26,075	10,769	1,813

Watershed Aquatic Value Rating = 38,657

rather than clearcutting. Through proper distribution of cutting units and timing of entries habitat maintenance and possibly enhancement of fish productivity can be achieved. Canopy openings can be spaced out along high value stream segments with some short term retention of old growth riparian zones. This approach to managing riparian vegetation would provide a stable detrital energy base. It would also provide a stable source for LOD inputs.

AVR information can also be useful to in indicating the need for impact mitigation measures by identifying potential problem areas. In Figure 3, potential conflicts exist between habitat protection objectives and timber harvesting and road construction plans associated with the C1A floodplain channel segment near the mouth of "Finger Creek." The nature of the proposed flood plain bridge crossing (circled) is such that stabilization of bridge abuttments and channel banks and special provisions for passing flood flows will require careful onsite investigation by hydrology and fisheries resource specialists prior to project implementation. The clearcut unit (treatment 2, Figure 3) adjacent to this C1A channel segment may also pose a hazard to fish habitat and stream channel integrity. Practices to help mitigate potential timber harvesting impacts might also be considered here.

The final outgrowth of the AVR is that it improves the efficiency of future resource inventory, monitoring, and research efforts. The AVR allows for prioritization of these studies to specific streams based upon the relative project importance to fish production and the potential project sensitivity to natural or management induced perturbations.

Opportunities

We have already realized the utility of channel typing and the AVR model as tools appropriate for large scale land and water management planning. Channel type field data were extrapolated to unsurveyed areas with a reasonable degree of confidence, and facilitated a cost efficient interdisciplinary decision in the Alaska Lumber and Pulp 1986-1990 Operating Plan Draft Environmental Impact Statement (USDA Forest Service Alaska Region, 1983b).

Future developments and data base management goals we have identified are:

1. Further data stratification for identified geomorphic zones.
2. Area-specific validation of the Barber et al. regression equations.
3. Development of regression equations specific to channel types.
4. Replace the RSI with quantifiable values.
5. Refine the static AVR with dynamic model components that track land management activities through time.
6. Develop area method validation procedures to account for the influence of the following habitat features: lakes, springs, beaver ponds, upwelling groundwater, water quality, and the presence of unmappable first order floodplain streams.
7. Examine the potential for incorporating species and life-phase habitat preferences and seasonal use for all fish species encountered.
8. Encourage the application of the indices, AVR, and data to guide site-specific research, inventory, and project implementation.

Summary.

Numerous management and resource planning applications for the Aquatic

Value Rating exist. The Aquatic Value Rating is a communication tool that succinctly describes fisheries habitat conditions in terms of a habitat quality index; sensitivity to streamside timber harvesting in terms of a riparian sensitivity index; and habitat distribution in terms of channel type mapping units. As an approach to presenting aquatic resource information, the Aquatic Value Rating allows for greater flexibility in applications requiring varying levels of planning. This permits relative value comparisons between watersheds, watershed subunits, or individual stream channel segments.

The Aquatic Value Rating rates the potential for stream and riparian zone multiple resource management conflicts and opportunities. It aids in developing management plans that optimize prescription, mitigation, and enhancement strategies. It can also aid in optimization of aquatic resource inventory, monitoring, and research efforts by focusing attention on critical habitat areas.

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References

Barber, W.E., M.W. Oswood, and S. Deschermeir. 1981. Validation of Two Habitat Fish Stream Survey Techniques: The Area and Transect Methods. Unpublished Final Report to USDA Forest Service, Contract 53-0109-0-00054, Juneau, Alaska, 64 pp.

Bull, W. B. 1979. Threshold of Critical Power in Streams. Geol. Soc. of

Amer. Bull. Part I, vol. 90, pp. 453-464.

Chamberlin, T. W. 1982. Influence of Forest and Rangeland Management on Anadromous Fish Habitat in Western North America: Timber Harvest. USDA Forest Service, General Technical Report PNW-136, 30 pp.

Cummins, D. W. 1974. Structure and Function in Stream Ecosystems. Bio Science vol. 24, pp. 631-641.

Dunham, D. K., and A. Collotzi. 1975. The Transect Method of Stream Habitat Inventory: Guidelines and Applications. USDA Forest Service Intermountain Region, Ogden, Utah, 98 pp.

Everest, Fred H., William R. Meehan. 1981. Forest Management and Anadromous Fish Habitat Productivity. In: Transactions of the 46th North American Wildlife and Natural Resources Conference, Wildlife Management Institute Publication, Washington D.C., pp. 521-530.

Heller, D. A., J. R. Maxwell, and M. Parsons. 1983. Modeling the Effects of Forest Management on Salmonid Habitat. USDA Forest Service, Siuslaw National Forest, 38 pp.

Paustian, Steven J., Daniel A. Marion, and Daniel F. Kelliher. In: preparation. Stream Classification using Large Scale Aerial Photography for Southeast Alaska Watershed Management. In: Proceedings of the RNRF Symposium of the Application of Remote Sensing to Resource Management, May 22-27, 1983, Seattle, Washington.

Pfankuch, D. J. 1975. Stream Reach Inventory and Channel Stability Evaluation: A Watershed Management Procedure of the U.S. Forest Service, USDA Forest Service Northern Region, 26 pp.

Platts, W. S. 1974. Geomorphic and Aquatic Conditions Influencing Salmonids and Stream Classification with Application to Ecosystem Management. USDA Forest Service, SEAM Program, Billings, Montana, 199 pp.

_______________. 1979. Relationships Among Stream Order, Fish Populations, and Aquatic Geomorphology in an Idaho River Drainage. Fsiheries, vol. 4, No. 2, pp. 5-9.

Platts, W. S., Walter F. Megahan, G. Wayne Minshall. 1983. Methods for Evaluating Stream, Riparian, and Biotic Conditions. USDA Forest Service, General Technical Report INT-138, 70 pp.

Reiser, D W., and T. C. Bjornn. 1979. Habitat Requirements of Anadromous Salmonids. USDA Forest Service General Technical Report PNW-96.

Sheridan, W. L., and A. M. Bloom. 1975. Effects of Canopy Removal on Temperatures of Some Small Streams in Southeast Alaska. USDA Forest Service Alaska Region, 13 pp.

Swanson, F. J., S. V. Gregory, J. R. Sedell, and A. G. Campbell. 1982. Land - Water Interaction: The Riparian Zone. US/IBP Synthesis Series 14, Hutchinson Ross Publishers, pp. 267-291.

Trisca, F. J., J. R. Sedell, and S. V. Gregory. 1982. Coniferous Forest Streams. US/IBP Synthesis Series 14, Hutchison Ross Publishers, pp. 292-331.

USDA Forest Service Alaska Region. 1981. Fisheries Survey Handbook - FSH 2609.23. Region 10 Amendment No. 1, Jan. 1981.

______________. 1983a. Aquatic Portion of the Integrated Resource Inventory: Draft. Unpublished report on file at Tongass National Forest - Chatham Area Supervisor's Office, Sitka, Alaska.

______________. 1983b. Alaska Lumber and Pulp 1986-90 Operating Plan Draft Environmental Impact Statement.

WATER QUALITY PROTECTION PROGRAM FOR AGRICULTURE IN ALASKA

Bruce W Rummel and William C Leitch[1]

Abstract

A water quality protection program for agriculture contains four major elements: 1) technical information, including a set of agricultural best management practices, 2) a set of institutional mechanisms to deliver the technical information and implement the program, 3) agriculturalists, including farmers and ranchers, and 4) an assessment activity to monitor, verify, and evaluate program operations. In Alaska, technical information is available in published literature and is delivered to farmers by the Alaska Soil Conservation District. Institutional mechanisms to implement the program are being established by the Alaska Department of Environmental Conservation. ADEC is developing a cooperative relationship with ASCD to provide for mutual assistance in meeting the goal of water quality protection with agricultural development. In addition, ADEC is seeking participation of other resource and regulatory agencies to promote an effective and efficient program and where advantageous, to coordinate activities.

Introduction

Water quality protection for agricultural development in Alaska has evolved in two steps: 1) preparation of a background report and recommendations and 2) implementation. In addition to being a program designed in the preventive, rather than remedial mode, this program exemplifies a smooth and effective transition from a consultant's report to an institutional program.

BACKGROUND REPORT

Summary

1) Water Quality Protection Program. A water quality protection program should maintain Alaska Water Quality Standards (18AAC70) without having to

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[1] Principal, Great Water Associates, Box A-475H, Anchorage AK 99507, and Ecologist, Alaska Department of Environmental Conservation, Pouch O, Juneau AK 99811.

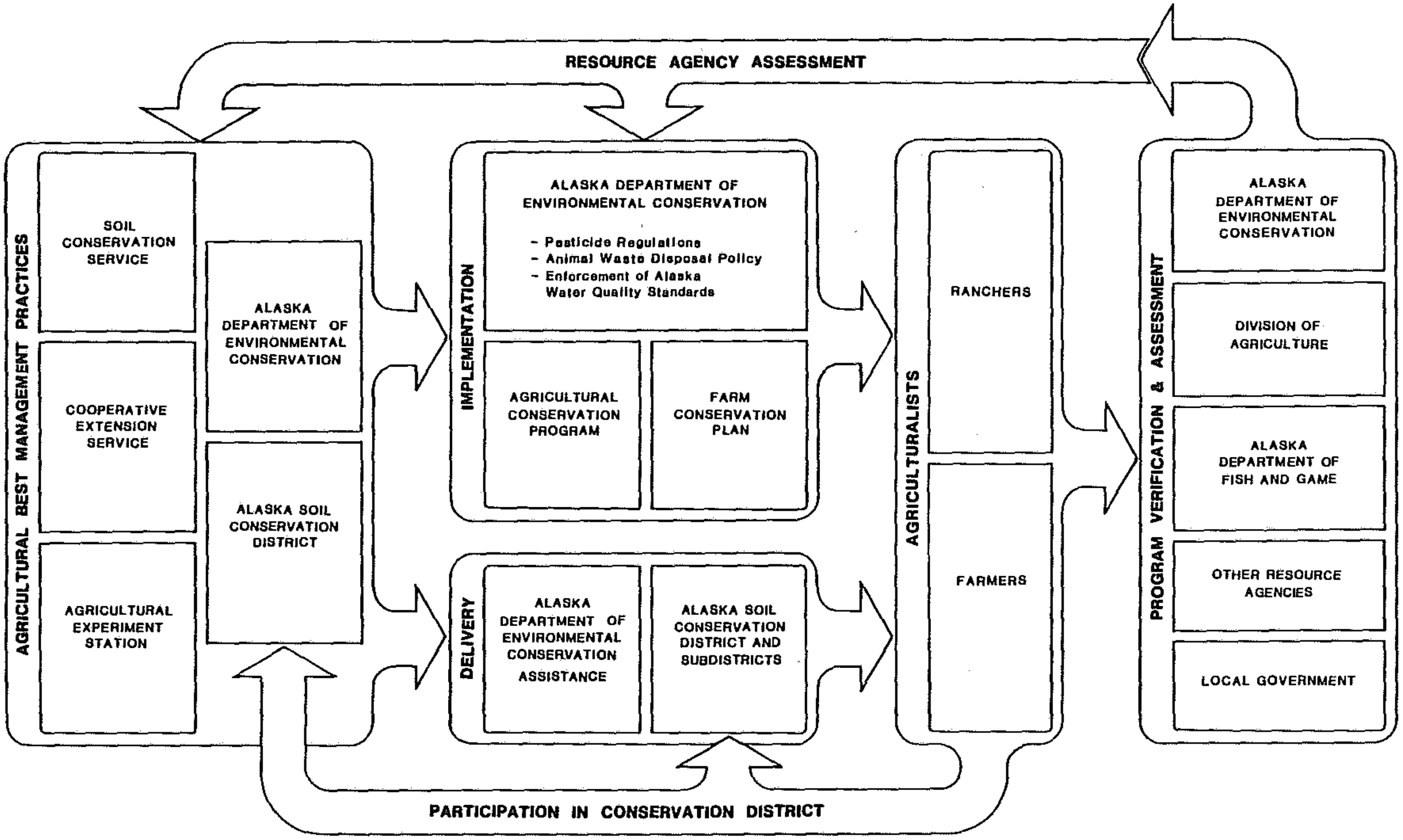
enforce those standards directly. The program should respond to identified needs and should be flexible. The program recommended in the background report has four basic elements related to agricultural activities: 1) recommended practices: agricultural best management practices, 2) means of disseminating and implementing those practices: delivery and implementation, 3) agriculturalists who use those practices: farmers and ranchers, and 4) means of verifying and evaluating applied practices: program verification and assessment (see Figure 1).

2) History of Agriculture in Alaska. Agriculture in Alaska probably began in 1784 with the introduction of livestock on Kodiak Island. Throughout most of its history, agriculture has been a subsistence activity, sometimes undertaken to support development of other natural resources or commercial activities. In this century, commercial agriculture in Alaska developed first in the Tanana Valley around Fairbanks, then around Palmer, and most recently in the area near Delta Junction as a result of State agricultural disposals.

3) Location of Future Agricultural Development. Based on agricultural potential, land ownership, and proposed development schedules, future agricultural development will most likely occur in areas with existing agricultural activities, on Pt. MacKenzie, or in the Nenana or Yukon Flats areas.

4) Water Quality Effects. The water quality effects of agricultural development in Alaska are similar to those of other activities that cause large- scale changes in vegetation and land use, e.g. timber harvest and

FIGURE 1. WATER QUALITY PROTECTION PROGRAM FOR GENERAL AGRICULTURAL ACTIVITIES



Source: Rummel 1982

residential development; in fact, only a few water quality effects are expected to be unique to agriculture. Most of the effects occur as a result of soil erosion: the transport, processing, and relocation of soil particles. Agricultural chemicals and wastes may also alter natural water quality.

5) Alaska Environmental Information. Very generally, the environmental factors that contribute to high agricultural potential, e.g. adequate soil depth and drainage, low slope, high number of degree days, tend to promote processes beneficial to protecting water quality, e.g. infiltration, low soil erosion, high rate of pesticide weathering.

6) Agricultural Best Management Practices. Agricultural best management practices (BMPs) consist of three kinds of practices: 1) practices designed to protect water quality directly and inherently; 2) practices that are components of general agricultural operations but are conducted in ways to minimize adverse water quality effects; and 3) agricultural practices that combine 1) and 2). BMPs that have been adapted to Alaskan conditions are available from the Soil Conservation Service of the U.S. Department of Agriculture and from the Cooperative Extension Service of the University of Alaska and USDA. BMPs can be incorporated into field activities on cropland, pasture and hay land, and rangeland, and can provide guidance for proper animal waste disposal (see Table 1 for examples).

7) Institutional Mechanisms. Existing institutional mechanisms for water quality protection form a patchwork of individual programs aimed at specific agricultural activities. Nonetheless, existing statutory and regulatory

Table 1. Examples of Agricultural Best Management Practices (BMPs)

Practice Code Number	Name of Practice (Units)	Definition	General Agricultural Purpose	Potential Primary Water Quality Effects	Water Quality Protection Measures
I. BMP's for Field Activities					
A. CROPLAND					
560	ACCESS ROAD (Ft.)	A travelway constructed as part of a conservation plan.	Provides a route for travel for moving equipment and supplies and provides access for proper operation and maintenance of conservation enterprises.	erosional effects	Stabilize cut and fill slopes and install cross drains for road ditches; treat surface if required to limit erosion.
310	BEDDING (Ac.)	Plowing, blading, or otherwise elevating the surface of flat land into a series of broad, low ridges separated by shallow, parallel dead furrows.	Provides improved surface drainage at relatively low cost by establishing adjoining parallel beds or lands running in the direction of available natural slope. This purpose is accomplished by moving soil toward centers of beds to form a series of ridges and dead furrows (troughs) which will accomplish one or more of the following: minimize water pondage, provide gradients for moving runoff, and permit efficient operation of tillage and harvesting equipment, or eliminate sources for mosquito production.	erosional effects	Limit slope (combination of natural land slope and cross slope); assure adequate root zone.
324	CHISELING AND SUBSOILING	Loosening the soil, without inverting and with a minimum of mixing of the surface soil, to shatter restrictive layers below normal plow depth that inhibit water movement or root development.	Improves water and root penetration and aeration and breaks up subsurface compaction to improve internal soil drainage.	erosional effects	Avoid inversion and minimize mixing; chisel along contour on lands subject to water erosion.
328	CONSERVATION CROPPING SYSTEM (Ac.)	Growing crops in combination with needed cultural and management measures. Cropping systems include the use of rotations that contain grasses and legumes, as well as rotations in which the desired benefits are achieved without the use of such crops.	Improves or maintains good physical condition of the soil; protects the soil during periods when erosion usually occurs; helps control weeds, insects, and diseases; and meets the needs and desires of the farmer for an economic return.	--	This practice generally protects water quality (see Table 7 for examples of cropping system alternatives).

Source: Rummel 1982

authorities are probably sufficient to implement a comprehensive water quality protection program. Institutional mechanisms for soil conservation are extremely well developed, as are state regulations governing activities in the agricultural land disposal program. Pesticide application is governed by explicit regulations. Less well developed are institutional mechanisms for management of fertilizer use or animal wastes.

8) Monitoring Activities. Four types of programs for field collection of water quality data can be identified: 1) programs for collecting baseline and follow-up data, 2) experimental programs, 3) programs for monitoring compliance, and 4) programs for monitoring trends. Baseline and follow-up studies seek to measure pre- and post-project conditions to assess changes in water quality. Experimental studies seek to assess water quality effects of agricultural practices in controlled conditions for eventual broader application. Compliance monitoring checks for maintenance of Alaska water quality standards, and trend monitoring assesses long-term, large-scale changes in water quality conditions.

9) Environmental Assessment. The program should produce environmental benefits.

Recommendations

To institute a water quality protection program for agriculture, the Alaska Department of Environmental Conservation should:

- Adopt the program structure described in the background report

- Establish a working relationship with the Alaska Soil Conservation District and subdistricts

- Formulate a policy on animal waste disposal

- Participate in the land use planning process of the Alaska Department of Natural Resources at all three planning levels: 1) statewide, 2) area, and 3) management

- Establish an interagency review group for program verification and assessment

- Establish a field program to extend existing baseline studies and to incorporate field data acquisition in the disposal process for agricultural lands

- Encourage the Agricultural Experiment Station, the Institute of Water Resources, and other research institutions to study the water quality effects of agricultural practices (Rummel 1982).

IMPLEMENTATION

The current program, also called the Agricultural Phase of the State Water Quality Management Plan, has been developed from the information and recommendations of the background report. In particular, a number of milestone accomplishments can be identified: 1) Memorandum of Understanding between ADEC and the soil conservation district, 2) Checklist of Agricultural Best Management Practices, 3) Senate Bill 120, 4) 205(j) proposal.

Memorandum of Understanding

After a series of preliminary meetings between staff of the Alaska Department of Environmental Conservation and the Alaska Soil Conservation District, the two organizations decided to draft a Memorandum of Understanding (MOU) that would formalize their relationship and establish a written basis for cooperation on activities related to water quality and agriculture. The MOU provided for increased contact between staff of the two organizations, provided for a policy and procedures document that spelled out how ADEC field staff would cooperate with subdistricts in resolving water quality problems, and authorized ADEC to grant $10,000 to ASCD to assist that organization in undertaking activities related to water quality concerns associated with agricultural operations. In addition, the MOU established the use of "Checklist of Agricultural Best Management Practices" in reviewing farm conservation plans submitted during applications for agricultural leases and required that subdistricts provide DEC with summary reviews of the checklists.

The MOU, signed in April 1983, set two important precedents with respect to the farming community, ADEC, and water quality problems:

1) it established a formal cooperative relationship between ADEC--a regulatory agency--and an organization representing the Alaskan farming community, and

2) it cast ADEC field staff into the role of cooperators rather than enforcers with respect to farmers and water quality problems.

Checklist

The Checklist of Agricultural Best Management Practices (ADEC 1983) was developed for three purposes:

1) to bring pertinent agricultural BMPs to the attention of officers and cooperators of the Alaska Soil Conservation District and Subdistricts,

2) to facilitate the efforts of Subdistricts to include water quality considerations in their reviews of farm conservation plans, and

3) to assist the Department of Environmental Conservation to identify potential water quality problems associated with agricultural development.

The BMPs described in the checklist identify specific water quality conservation practices, as well as methods for conducting general agricultural operations so as to minimize adverse water quality effects (see Table 2 for example). To keep the checklist brief, the BMPs were

Table 2. Example of Checklist

CHECKLIST OF AGRICULTURAL BEST MANAGEMENT PRACTICE

Agricultural Activity	Yes	No	N/A	Water Quality Protection Measures
A. CROPLAND				
Access Road(34)	☐	☐	☐	Stabilize slopes
	☐	☐	☐	Install cross drains
	☐	☐	☐	Treat surface, if required
Bedding(34)	☐	☐	☐	Limit slope
	☐	☐	☐	Preserve adequate root zone
Chiseling and Subsoiling(34)	☐	☐	☐	Avoid inversion of soil
	☐	☐	☐	Minimize mixing
	☐	☐	☐	Chisel along topographic contour
Conservation Cropping System(34)	☐	☐	☐	This practice protects water quality
Cover and Green Manure Crop(35)	☐	☐	☐	This practice protects water quality
Critical Area Planting (35)	☐	☐	☐	This practice protects water quality

Source: ADEC 1983

summarized; detailed descriptions of each BMP are found in the background report and in publications of the Soil Conservation Service and the Cooperative Extension Service. The BMPs in these publications are specifically adapted for application in Alaska.

Like the MOU, the Checklist, distributed to Subdistricts in August 1983, also set important precedents:

1) in effect, the checklist puts a significant share of responsibility for protection of water quality into the hands of the farming community itself,

2) designed for repeated use, and referenced by page to the original report, the checklist serves as an ongoing educational tool for farmers.

Senate Bill 120

This act of the Alaskan Legislature, "An Act relating to soil and water conservation," (committee substitute for Senate Bill 120) modifies the structure and purposes of the state soil conservation district. Effective July 1, 1983:

1) the number of Governor-appointed members of the District Board is increased from three to five, providing for broader geographic representation,

2) the organization's name is changed from Alaska Soil Conservation District to Alaska Soil and Water Conservation District, a subtle, but important change, and

3) the jurisdiction of the District is increased so as to include land areas rather than farming areas, and users of land rather than occupiers of land.

These changes broaden the conservation district program in Alaska.

205(j) Proposal

In June 1983, staff of four organizations--(Department of Environmental Conservation, U.S. Environmental Protection Agency, Alaska Soil and Water Conservation District, and Soil Conservation Service)--met to discuss Idaho's water quality program related to agriculture, a program widely acknowledged as the model of such projects. Their program is distinguished by careful identification of priority problem areas and maintenance of close contact with the Idaho Legislature in order to secure implementation funds from the state for studies completed with funds made available through Section 208 of the Clean Water Act.

It was clear that many of the successful features of the Idaho program could be applied in Alaska, although on a much reduced scale. As a result, staff of ASWCD and SCS applied for federal funding to identify priority problem areas in the state and carry out programs to ensure that adverse water quality effects associated with agriculture would be prevented or minimized in those areas.

The final result of the June 1983 meeting was a 2-year proposal to complete both a comprehensive drainage and erosion control plan for the Delta Project, and a dairy waste management plan for the Point MacKenzie Project. The plan, submitted in August 1983, was drafted by the ASWCD, and will be a cooperative effort with the SCS. The proposal is still under study, but is likely to be accepted and funded.

References

Rummel, B.W. 1982. Agricultural Practices and Water Quality Effects. Prepared for Alaska Department of Environmental Conservation, Juneau. 82pp+vi, 2 Appendixes.

Alaska Department of Environmental Conservation 1983. Checklist of Agricultural Best Management Practices. MS 12pp.