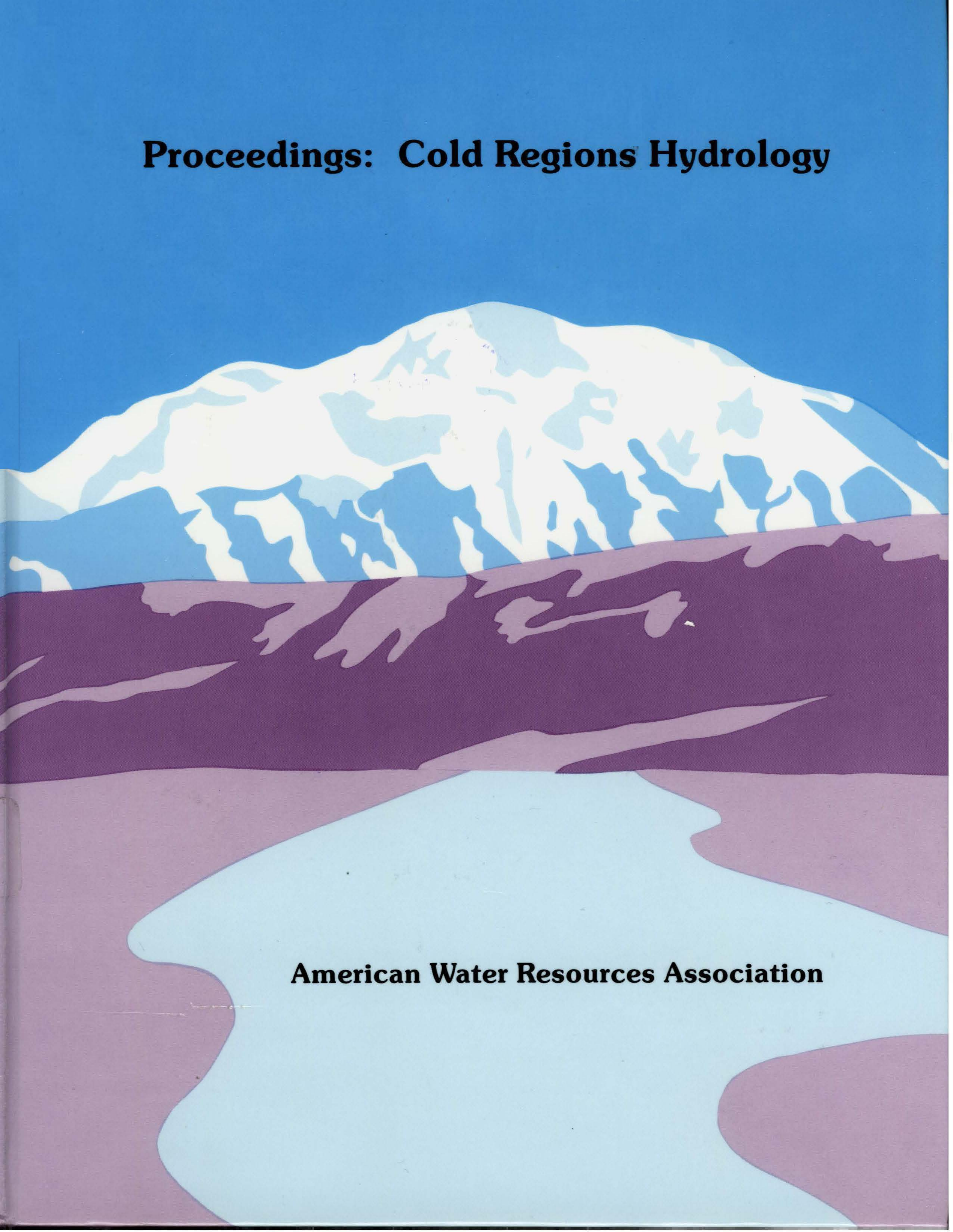
*Some aspects of glacier hydrology in the upper Susitna and Maclaren River basins, Alaska*

# Proceedings: Cold Regions Hydrology



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# SOME ASPECTS OF GLACIER HYDROLOGY IN THE UPPER SUSITNA AND MACLAREN RIVER BASINS, ALASKA

Theodore S. Clarke, Douglas Johnson and William D. Harrison[1]

ABSTRACT: Proposed hydroelectric development on the Susitna River, Alaska, has raised interest in the glaciers that form its headwaters. Three separate aspects of the hydrology of these glaciers are addressed here. First, long-term glacier shrinkage, which releases water that is not renewable in the normal sense, appears to have produced on the order of 3-4% of the total Susitna River flow above the Gold Creek gauge site since stream gauging began. Second, the major glaciers of the basin are surge-type and have the potential to produce, in a few months, up to 30 times the estimated annual sediment input into the proposed Watana Reservoir. The next surge of one of the glaciers, Susitna, is predicted in the first decade of the next century. Third, winter precipitation varies by a factor of two among the glaciers, Maclaren Glacier receiving the most.
(KEY TERMS: Glacier shrinkage, glacier surges, sediment supply, precipitation variations.)

## INTRODUCTION

This paper describes, in part, the results of a study of the glaciers that head the Susitna and Maclaren rivers (Figures 1 and 2). It addresses three separate topics: (1) whether the glaciers have changed in volume since stream gauging began on the Susitna River, (2) if and when any of the glaciers in the area may be expected to surge, and how surges might affect the Susitna River, and (3) how precipitation varies throughout the area. A previous paper provides glacier runoff and mass balances estimates (Clarke and others, 1985). Early phases of the work are described by R & M and Harrison (1981) and R & M and Harrison (1982) and summarized by Harrison and others (1983). The material presented here should be considered an update to these three early papers.

Glaciers cover about 790 square kilometers or 5.9% of the basin area above the proposed Watana dam site, 5.2% of the area above the proposed Devil Canyon site, and 4.9% of the area above the Susitna River gauge located at Gold Creek (Figure 1). Field measurements of precipitation, snow accumulation, ice melt, glacier speed, and surface elevation were made on most of the major glaciers in the basin during 1981, 1982 and 1983.

## I. LONG-TERM GLACIER VOLUME CHANGE

Long-term glacier volume change is an important part of any hydrologic feasibility or planning study because it may have a significant impact on projected water supply. In general, glaciers have decreased in size during the last half century. Consequently, water to their basins has been supplied out of ice storage. As the glaciers approach equilibrium with the present climate, the amount of water from storage approaches zero. This has led, in some instances, to an overestimation of water supply (Bezinge, 1979). It seems that before long-term water availability is predicted from stream gauge records, smoothed trends of glacier release or storage of water over the period of record should always be subtracted. This reduces the problem to a conventional one of long-term prediction for an unglacierized basin, although, of course, even the conventional approach is susceptible to errors caused by climate change. Mayo and Trabant (1986) present evidence that a definable climate change took place in the Alaska Range in the Gulkana Glacier region, starting about 1976.

Volume change estimates for the Susitna basin are based on measurements on an unnamed glacier, commonly referred to as East Fork Glacier (Figure 2), which makes up only 5% of the total glacierized surface. Previous estimates of its volume change over the period 1949 to 1980 were made from photogrammetric data (R & M and Harrison, 1981; Harrison and others, 1983). These estimates suggested an average change in thickness of -50 ± 18 m. If this were typical of the other glaciers, then 13% of the Susitna River flow at the Gold Creek gauge site would have been from glacier storage. Since this seems unreasonably large, two other methods for estimation of volume change were

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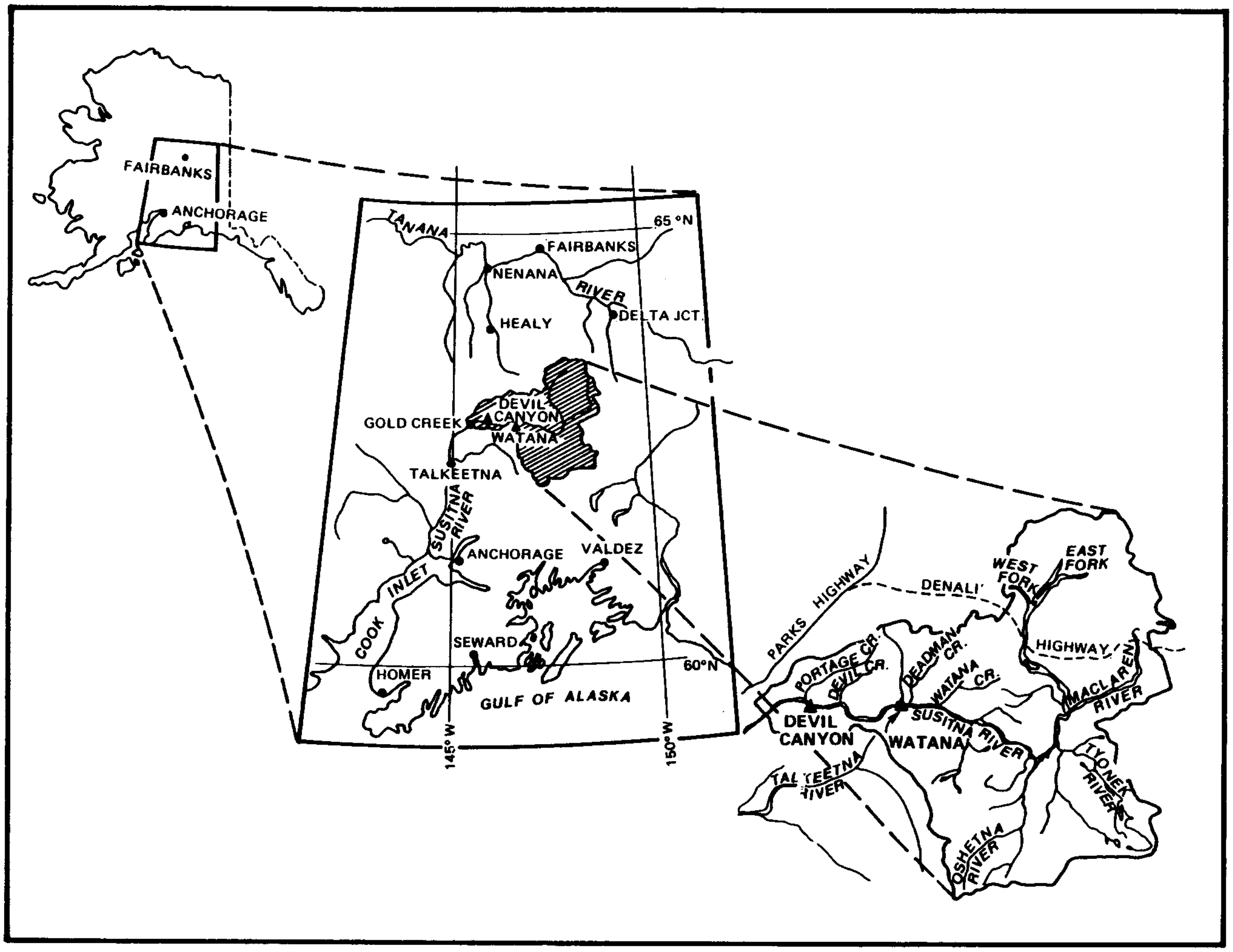


Figure 1. Location map. (From Acres American, 1982.)

applied. The first used direct measurement of glacier surface altitude; the second used the runoff precipitation model of Tangborn (1980).

## Direct Measurement of Glacier Surface Elevation

In 1982 surface elevations were measured at several points on East Fork Glacier as a check of those estimated photogrammetrically from 1980 photos in the earlier work. Elevations were measured with a helicopter and its altimeter. Measurement points were located either by Brunton compass bearings to map identifiable features or by theodolite and established control points. The altimeter was calibrated periodically on rock points of known elevation. The results are shown in Table 1.

The results agree with those from the 1980 photos except at the highest point. According to the altimeter data, this point has remained at roughly the same elevation since 1949 when the U.S. Geological Survey maps were made, but the data provided by the photogrammetric method show this point to have lost 40 m of elevation. This discrepancy might be explained by the fact that the 1980 aerial photographs of East Fork Glacier show almost no contrast in its accumulation area. This makes it difficult to identify the surface accurately in these smooth snowy areas. Also, one might expect the accumulation area of a "normal" (non surge-type) glacier in retreat to remain at roughly the same elevation because a decrease in annual balance over the surface of a glacier affects the volume of ice transported by the glacier in a way that accumulates down-glacier.

The change in volume of the glacier was obtained by comparing the altimetry data with elevations obtained from 1949 photos. Unlike the 1980 photos, the 1949 photos are of very good quality. The elevations obtained from these early photos agree with published map elevations and are therefore probably accurate. In practice, the volume change was computed by determining a thickness change versus elevation relationship, multiplying it by the area per elevation interval determined from the map, and finally, by integrating over the elevation interval spanned by the glacier.

Taking the altimetry data as the more reliable, the average thickness change of East Fork Glacier comes out to -13 m water equivalent for the 1949 to

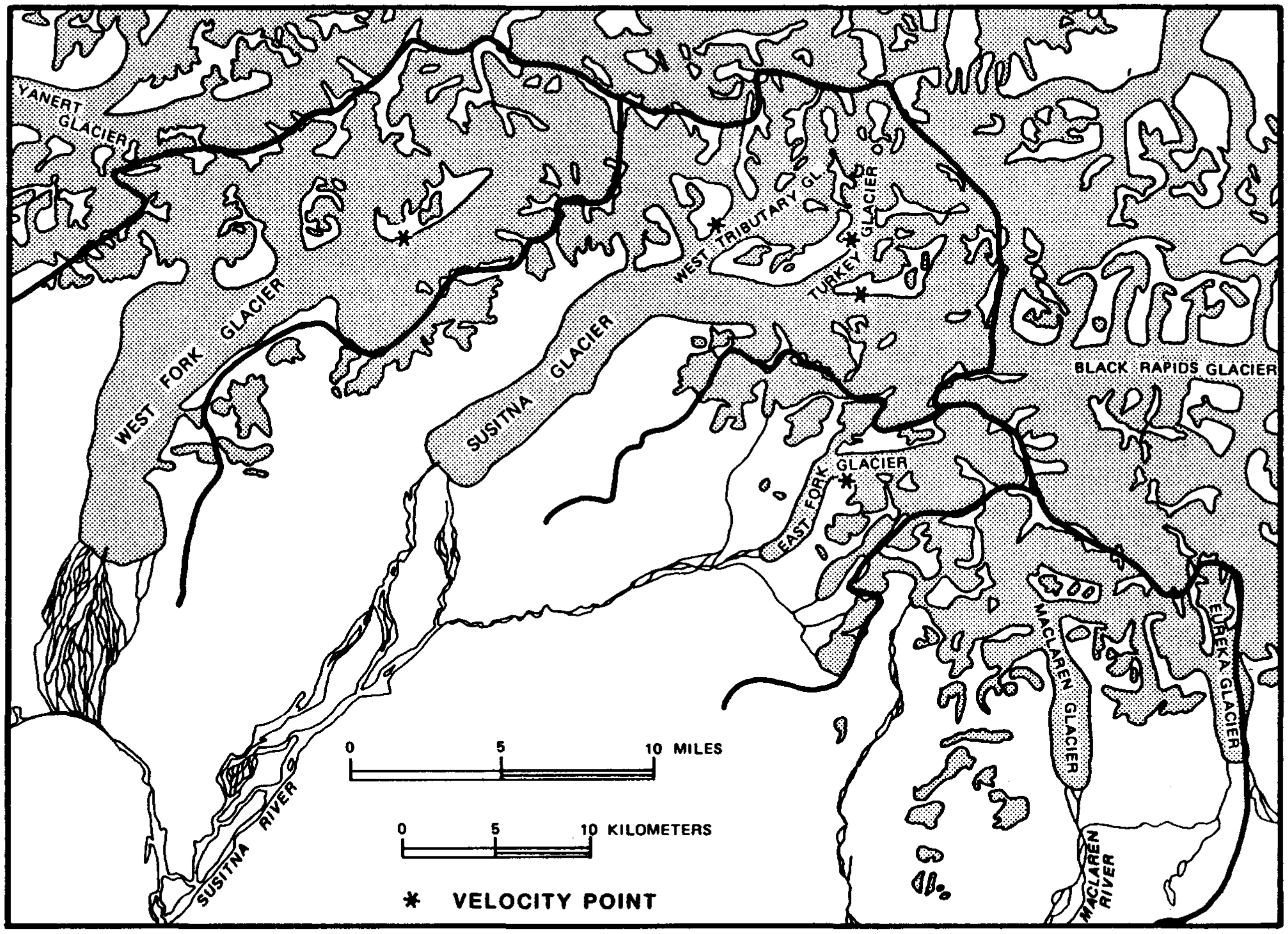


Figure 2. Glacier names, locations and drainage divides. Glacier center line velocity was measured where indicated. The points on the figure were placed next to the glaciers for clarity. (Modified from Harrison and others, 1983.)

1982 period, rather than the -50 m for the 1949 to 1980 period estimated by the previous work. If this 13 m of water equivalent loss is again extrapolated over the remaining 95% of the ice in the basin (with suitable caution) then, on the average, about 3 or 4% of the Susitna River flow at Gold Creek has been due to glacier recession as opposed to the 13% of the earlier estimates. This estimate has very large errors associated with it since it is based on four points on a glacier that makes up only 5% of the ice in the basin. However, it does seem more reasonable considering that the glacier runoff over the 1981 to 1983 period, when the glaciers were in approximate equilibrium, totaled only about 13% of the flow at the Gold Creek gauge site (Clarke and others, 1985).

## Tangborn Runoff-Precipitation Model

Tangborn (1980) has suggested a model for determining long-term historical glacier balances by comparison of adjacent glacierized and unglacierized basins. The model works by determining differences in runoff that do not correspond to precipitation changes, and these differences are assumed to be caused by changes in storage of water as glacier ice. The annual precipitation in each basin is determined by using a representative precipitation station and determining a coefficient that corrects for precipitation differences between the basins and the precipitation station. The sum of evaporation, transpiration and condensation, per unit area, is assumed to be the same for both basins. The coefficient can be determined if runoff from both basins and glacier volume change are known for a period of at least 1 year and if a suitable precipitation station exists.

The model was tested against published mass balances of nearby Gulkana Glacier for the period from 1967 to 1977 (Meier and others, 1980). Six different precipitation stations and three different unglacierized basins were checked for the best possible fit of the model. Phelan Creek was used as the glacierized runoff station since this drains Gulkana Glacier. The best correlation between calculated and measured balance occurred when Talkeetna precipitation station was used with the unglacierized basin Ship Creek near Anchorage ($r^2$ = 0.77). Further details are given by Clarke (1986).

Table 1. Comparison of photogrammetric data (R & M and Harrison, 1981; Harrison and others, 1983) to helicopter altimetry data on East Fork Glacier. The surface elevation changes for the altimetry data are for the period from 1949 to 1982; the surface elevation changes for the photogrammetric data are for the period from 1949 to 1980. A loss of elevation is indicated by a negative sign.

East Fork Glacier

| Location on Glacier Center Line (1949 Map Elevation) (m) | Elevation Change Altimeter (m) (1949 to 1982) | Elevation Change Photogrammetry (m) (1949 to 1980) |
|---|---|---|
| 1080 | -74 ± 18 | -67 ± 18 |
| 1390 | -43 ± 18 | -32 ± 18 |
| 1590 | -51 ± 18 | -78 ± 18 |
| 2050 | +16 ± 18 | -40 ± 18 |

In applying the model to the Susitna basin, there was a considerable uncertainty in what the actual balance was for the period from 1981 to 1983. The measurements, for all ice in the basin, came out to +0.06 m water equivalent when summed over the 3-year period, but the cumulative uncertainty for the 3-year period was 0.6 m (Clarke, 1986). In Tangborn's model this uncertainty plays a large role in the resulting change in glacier mass for the period from 1950 to 1983. These dates were chosen because 1950 is the first year from which complete runoff data are available for the Susitna River at Gold Creek. If it is assumed that balance for the period from 1981 to 1983 was +0.06 m, then the average loss from the glaciers above the Susitna River at Gold Creek gauge site for the period from 1950 to 1983 was -16 m water equivalent. If the balance was +0.66 m, then the average loss comes out to -9 m, and if the balance was -0.54 m, then a calculated balance of -22 m water equivalent results.

The results of the two methods of volume loss estimation are summarized in Table 2. They are uncertain, but not inconsistent. They imply that 3 to 4% of the water flow at Gold Creek between 1949 and 1980 came from ice storage. This amount is within the stream gauging error and would therefore probably not be significant in terms of projected water supply.

## II. GLACIER SURGES

The major glaciers of the Susitna basin are West Fork, Susitna, "East Fork", Maclaren, and Eureka (Figure 2). All except East Fork are listed by Post (1969) as being surge-type. Surges are sudden episodes of rapid glacier speed triggered by some internal instability, during which ice movement may be hundreds or thousands of meters within a few months. The effects on sediment and water supply, particularly the former, may be substantial.

There are some descriptive reports of high sediment production during glacier surges (Uskov and Kvachev, 1979; Shcheglova and Chizhov, 1981) and two direct measurements. Humphrey (1986) reported that the 1982-1983 surge of Variegated Glacier, Alaska, released as suspended sediment the equivalent of about 0.3 m of eroded rock from the bed of that glacier. Björnsson (1979) reported an erosion rate of 0.014 m/yr from the surge of Bruarjökull Glacier

Table 2. Summary of glacier shrinkage estimates by two different methods.

| Method | Time Span | Area Covered | % Total Glacierized Area | Thickness Loss | Error |
|---|---|---|---|---|---|
| Altimetry | 1949-1982 | East Fork Glacier | 5 | 13 (m) | large, see text |
| Runoff Precipitation Model | 1950-1983 | all glaciers in basin | 100 | 16 | +6, -7 if model applicable |

in Iceland. The two measurements differ by more than an order of magnitude, but both are extremely high when compared to sediment production in non-surge years. Although Variegated Glacier is considerably smaller than Susitna Glacier, both are narrow valley glaciers underlain by faults. If Variegated Glacier is representative of the Susitna basin, then a surge of the 250 $km^2$ Susitna Glacier could release as much as 200 x $10^9$ kg of suspended sediment into the Susitna River, assuming a rock density of 2.7 x $10^3$ kg/$m^3$. This is 30 times the estimated annual sediment influx, including bed load, of 6.8 x $10^9$ kg (5.8 x $10^6$ $m^3$) into the proposed Watana Reservoir (R & M, 1982).

There is little direct evidence about the effect of surges on water supply. However, there are three potential effects. First, there should be a temporary increase in melt water because of the increase in ablation area that accompanies some surges. Second, the extreme crevassing that occurs during a surge temporarily increases effective surface area, and therefore ablation. Third, surges release stored water (Kamb and others, 1985), although it is not clear whether this water comes from long-term storage or merely from the most recent summer season.

Given these effects of surges on sediment and water supply, it seems worthwhile to review the past history of surges in the Susitna basin, and what it may imply for the future, particularly since surges tend to be periodic (Meier and Post, 1969). West Fork Glacier is known to have surged sometime shortly before 1940 when Bradford Washburn photographed it. Susitna Glacier underwent a strong surge between 1949 and 1954 (Post, 1960); photos that we recently examined indicate that the surge was complete by July, 1952. Maclaren Glacier underwent a weak surge or strong "pulse" in 1971 (Mayo, 1978).

Surface speed measurements on West Fork, Susitna, and East Fork glaciers indicate flow regimes that reflect the surge behavior of the first two. For both of these glaciers the rate of ice flow from the accumulation area is considerably less than the rate of snow accumulation there (Table 3). This indicates a thickening of the accumulation area that will probably be terminated by another surge. The velocity data and details of how accumulation and outflow were calculated are given by Clarke (1986).

## West Fork Glacier

The disequilibrium of West Fork Glacier evident in Table 3 is consistent with its past behavior. Oblique aerial photographs of the terminus, taken by Bradford Washburn in 1940, show it to be extremely broken up and chaotic (see Clarke, 1986). This information, along with the looped moraine pattern, is conclusive evidence that a surge took place. Post (written comm. to Steven Wilbur, 1984) places the surge in 1937. Close inspection of 1981 NASA color infrared aerial photographs shows at least three successive terminal moraines, each of which was very likely caused by a successively weaker surge. Unfortunately, the periodicity of the surges cannot be estimated quantitatively because little

Table 3. Comparison of annual ice flow through several cross sections to the annual accumulation above the sections. The location of each cross section is shown as a velocity point on Figure 2. Surface center line velocity is assumed to be caused by 50% internal deformation and 50% basal sliding. All quantities are given in water equivalents. The cross sections are slightly below the accumulation areas and are shown as velocity points on Figure 2.

| Glacier Name | Average Annual Ice Flow May 1981–June 1983 ($m^3$/yr x $10^6$) | Annual Accumulation Above the Cross Section ($m^3$/yr x $10^6$) 1981 | 1982 | 1983 | Volume Change Above Cross Section (1981–1983 average) ($m^3$/yr x $10^6$) |
|---|---|---|---|---|---|
| West Fork | 54 ± 21 | 98 ± 33 | 82 ± 33 | 113 ± 33 | +44 ± 39 |
| Susitna, Main Branch | 14 ± 6 | 50 ± 19 | 34 ± 19 | 71 ± 19 | +38 ± 20 |
| Susitna NW Trib. | 36 ± 14 | 21 ± 15 | -- | -- | -- |
| Susitna Turkey Trib. | 72 ± 28 | 89 ± 15 | 70 ± 15 | -- | -- |
| East Fork | 31 ± 12 | -- | 20 ± 13 | 25 ± 13 | -- |

information exists for West Fork Glacier prior to the Washburn photographs. Moffit (1915) gives a brief description of the glacier as it was in 1913 but nothing to indicate a surge had occurred recently. If its recurrence period is similar to the 50 or so years for Susitna Glacier, discussed below, a surge may be expected fairly soon.

## Susitna Glacier

Susitna Glacier, unlike West Fork, has a complex set of tributaries that were studied individually, as summarized in Table 3. It can be seen that the main branch of Susitna Glacier is transporting only a fraction of the accumulated snow down-glacier. This would indicate that either this branch of the glacier is the one causing the surges, or it is at least a reservoir that depletes during a surge. Altimetry data collected in the accumulation area of Susitna Glacier also show this branch to be accumulating mass. A gain of 56 ± 18 m of elevation from 1956 to 1982 was measured by comparing 1982 altimetry data to 1956 map elevation data (Clarke, 1986). This translates to a gain of $93 \pm 30 \times 10^6\ m^3/yr$, which is reasonably consistent with the average rate of gain of $38 \pm 20 \times 10^6\ m^3/yr$ for the 1981 to 1983 period (Table 3). Examination of moraine patterns confirms that this basin did indeed contribute a large quantity of ice to the last surge. Figure 3 depicts the moraine patterns on Susitna Glacier before and after the early 1950's surge. Before the surge, ice motion in the main trunk above Turkey tributary appeared to be very small, with relatively vigorous flow from Turkey pinching it off. After the surge, a large volume of ice had clearly advanced from the basin of the main branch. A large volume of ice appears to have come from Turkey tributary also, and Northwest tributary appears to have contributed very little ice, if any, to the surge. These observations indicate that flow and accumulation in Northwest tributary were probably in equilibrium before the surge, the main branch was far out of equilibrium, and Turkey tributary was somewhere in between.

There are two reasonably quantitative approaches to determining Susitna Glacier's surge period. First, the lobe created in the moraines of the main glacier by Northwest tributary had an area of about $4.0\ km^2$ in 1949. A surge of the main glacier took place about 1951, as already noted. By 1980 the new lobe had grown to an area of about $2.0\ km^2$ (Figure 3). Assuming the surge occurred in 1951, and assuming the present glacier speeds to be similar to those in the past, a period of roughly 60 years is indicated. Second, close inspection of the same lobe in 1949 aerial photographs shows about 47 ogives to have passed from Northwest tributary into the main glacier trunk (see Clarke, 1986). Ogives, or Forbes bands, are known to form on an annual basis (Nye, 1958). Again assuming the surge occurred in 1951, a surge return period of 49 years is indicated. It could be argued that Northwest tributary surges independently, but the slow growth

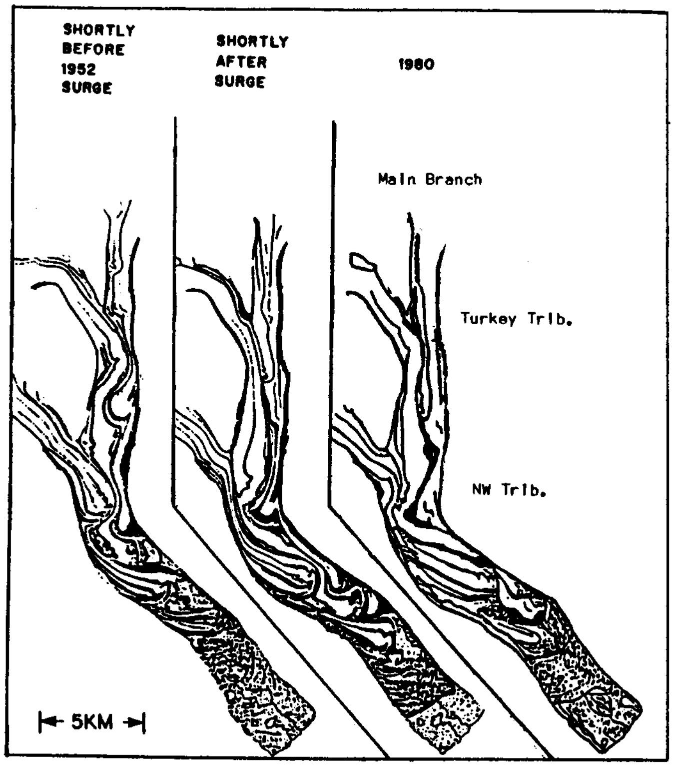


Figure 3. Evolution of moraine patterns on Susitna Glacier. Left and center diagrams are from Meier and Post (1969). Right diagram is sketched from National Aeronautics and Space Administration photographs. (Modified from Harrison and others, 1983.)

of its new lobe and the balance between accumulation and flow makes this seem unlikely (Table 3). The next surge would therefore be expected within the first decade of the next century.

## East Fork, Maclaren and Eureka Glaciers

East Fork Glacier is probably not a surge-type glacier, as suggested by the approximate balance in Table 3, and by evidence from the displacement of surface features that the speed has not changed much since 1949 (R & M and Harrison, 1982).

Both Maclaren and Eureka glaciers are thought to be weak surge-type glaciers; they do not surge on the order of kilometers like Susitna and West Fork. As noted previously, Maclaren Glacier underwent a "pulse" in 1971 (Mayo, 1978). No speed measurements were made on these glaciers.

## III. PRECIPITATION VARIATIONS

Another interesting aspect of glacier hydrology in this basin is the large difference in winter precipitation among the different glaciers. In the late winter of 1981, 1982 and 1983, snowpack thick-

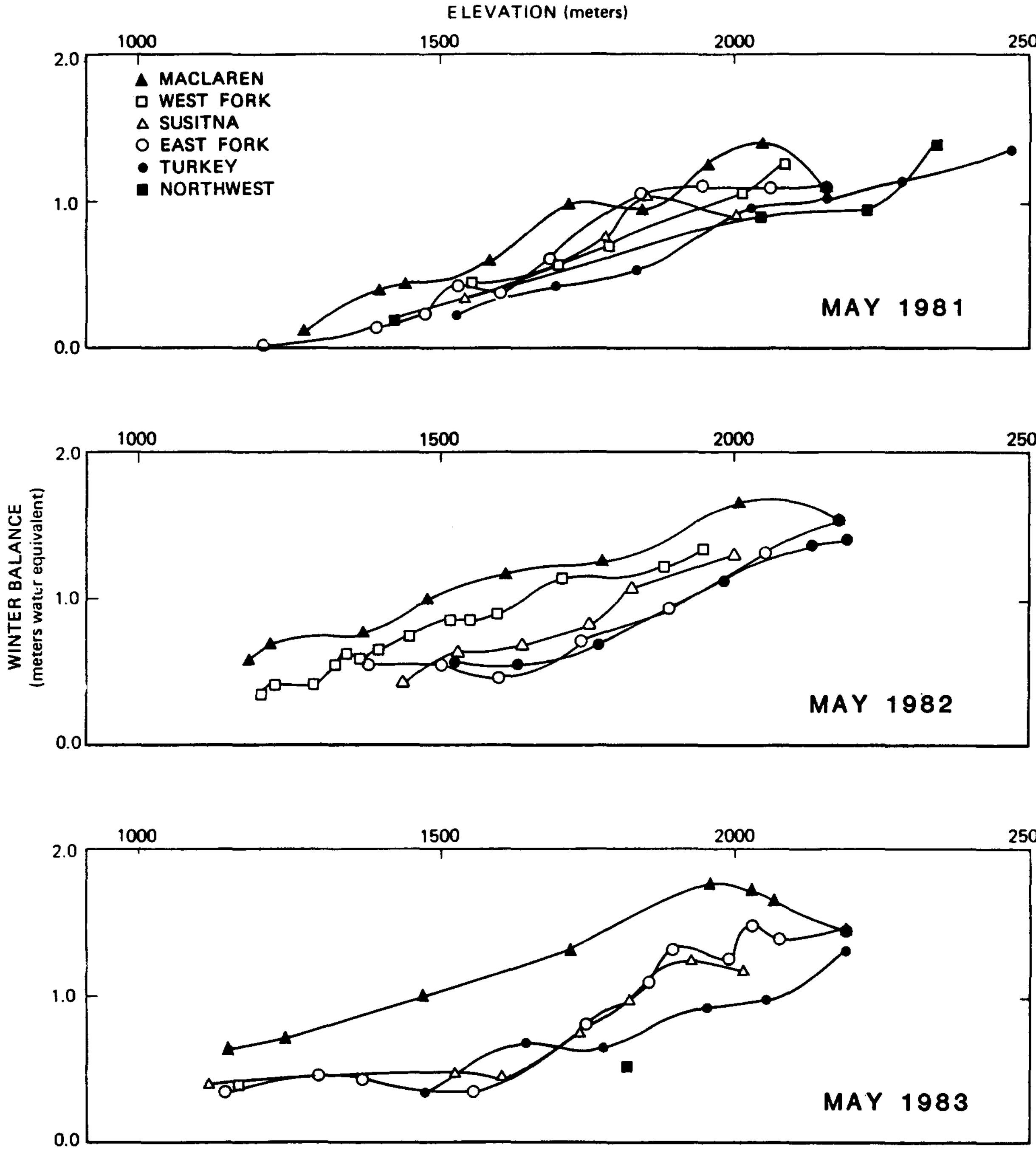


Figure 4. Winter accumulation versus elevation as determined from snow probe data. (Top figure is modified from R & M and Harrison, 1981; middle figure is from R & M and Harrison, 1982.)

ness was measured by probing at several points along the center line of each glacier, and snowpack density was measured at representative points on each glacier. The water equivalent thickness at each point is plotted in Figure 4. These data are reasonably consistent with more accurate snow depths measured at a few sites where stakes were maintained.

Generally the winter precipitation gradients are the same from glacier to glacier, about 1.2 mm water equivalent per meter of elevation, but the absolute amount of water varies considerably from glacier to glacier. Maclaren Glacier consistently received the most precipitation, and the two steep south-facing tributaries of Susitna Glacier consistently received the least. An orographic effect created by the Clearwater Mountains, which divide the tributary Maclaren River basin from the Susitna River basin, may direct moisture toward Maclaren Glacier and reduce precipitation in the Susitna basin to the west. It is worthwhile to note that because Maclaren Glacier had a positive mass balance of nearly 0.3 m/yr and the others had generally negative balances, it produced less runoff over the study period even though it received considerably more precipitaton (Clarke and others, 1985).

## IV. DISCUSSION AND CONCLUSIONS

An attempt has been made here to (1) determine whether the glaciers that head the Susitna and Maclaren rivers have changed in volume since stream gauging began on the Susitna River, (2) determine when these surge-type glaciers may surge again, and what the effects of surges are likely to be, and (3) describe variation in winter precipitation throughout the area. The conclusions are as follows:

1. The elevation change due to glacier wasting seems to be on the order of -10 to -15 m water equivalent for the 1949 to 1983 period for East Fork Glacier rather than the -50 m estimated by R & M and Harrison (1981) and Harrison and others (1983) for the 1949 to 1980 period. This amounts to 3 or 4% of the total flow of the Susitna River at Gold Creek rather than 13%. This quantity seems more consistent with the fact that during 1981, 1982, and 1983, when the glaciers were in approximate equilibrium, the average runoff from the Susitna basin glaciers was about 13% of the total Susitna River flow at Gold Creek (Clarke and others, 1985).
2. West Fork and Susitna are surge-type glaciers. If sediment output during a surge of Susitna Glacier, for example, is similar to that of Variegated Glacier, a single surge may produce about 30 times the estimated average annual sediment influx into the proposed Watana reservoir. The rates of transport and dispersion of such a large sediment influx are unknown. A surge of Susitna seems likely because about two-thirds of the snow accumulating in the basin of its main branch is not being transported out (Table 3), and the accumulation area of this same branch has gained approximately 56 m of elevation since the last surge. If past history is any indication, it appears that Susitna Glacier has a surge period of 50 to 60 years, which places the next surge sometime between the years 2000 and 2010. It is also likely that West Fork Glacier will surge in the future, but no quantitatively determined period can be placed on it since no data are available for the period prior to its 1937(?) surge.
3. Accumulation varies considerably from glacier to glacier, with Maclaren Glacier receiving more winter precipitation than any of the other glaciers. Generally, the winter precipitation gradients are the same throughout the basins, about $1.2 \pm 0.1$ mm water equivalent/m elevation, but each glacier's accumulation versus elevation curve is shifted vertically with respect to the accumulation axis. The shift ranges over about 0.5 m water equivalent (Figure 4).

## REFERENCES


Acres American Inc., 1982. Susitna hydroelectric project; feasibility report. Final draft report for the Alaska Power Authority, Anchorage, Alaska. 8 vols.

Bezing, A., 1979. Grande Dixence et son hydrologie, la collection de donnees hydrologiques de base en Suisse, Association Suisse l'amenagement des eaux. Service Hydrologique National, 19 pp.

Bjornsson, H., 1979. Nine glaciers in Iceland. Jokull 29:74-80.

Clarke, T. S., 1986. Glacier runoff, balance and dynamics in the upper Susitna River basin, Alaska. M.S. Thesis. University of Alaska, Fairbanks, 98 pp.

Clarke, T. S., D. Johnson and W. D. Harrison, 1985. Glacier runoff in the upper Susitna and Maclaren River basins, Alaska. In: L. P. Dwight, 1985. Resolving Alaska's Water Resources Conflicts. Proceedings. Alaska Section, American Water Resources Association. Institute of Water Resources/ Engineering Experiment Station, University of Alaska, Fairbanks. Report IWR 108. 212 pp.

Harrison, W. D., B. T. Drage, S. Bredthauer, D. Johnson, C. Schoch and A. B. Follett, 1983. Reconnaissance of the glaciers of the Susitna basin in connection with proposed hydroelectric development. Annals of Glaciology 4:99-104.

Humphrey, N. F., 1985. Suspended sediment discharge from Variegated Glacier during its surge and pre-surge phases of motion. A contribution to the workshop on Alaska hydrology, 10-13 April, 1985. In preparation.

Kamb, B., C. F. Raymond, W. D. Harrison, H. Engelhardt, K. A. Echelmeyer, N. Humphrey, M. M. Brugman and T. Pfeffer, 1985. Glacier surge mechanism: 1982-1983 surge of Variegated Glacier, Alaska. Science 227(4686):469-479.

Mayo, L. R., 1978. Identification of unstable glaciers intermediate between normal and surging glaciers. Academy of Science, USSR, Section of Glaciology, Proceedings of the International Workshop on Mechanism of Glacier Variations, Pub. 33, p. 47-55 and 133-135.

Mayo, L. R. and D. C. Trabant, 1986. Recent growth of Gulkana Glacier, Alaska Range, and its relation to glacier-fed river runoff. Short paper for U.S. Geological Survey Water Supply Series. In press.

Meier, M. F. and A. S. Post, 1969. What are glacier surges? Canadian Journal of Earth Science 6:807-817.

Meier, M. F., L. R. Mayo, D. C. Trabant and R. M. Krimmel, 1980. Comparison of mass balance and runoff at four glaciers in the United States, 1966 to 1977. Academy of Science, USSR, Section of Glaciology, Report of the International Symposium on the Computation and Prediction of Runoff from Glaciers and Glacial Areas, Pub. 38, p. 138-143 and 214-216.

Moffit, F. H., 1915. The Broad Pass Region, Alaska. U.S. Geological Survey Bull. 608. 80 pp.

Nye, J. F., 1958. A theory of wave formation on glaciers. IASH 47:139-154.

Post, A. S., 1960. The exceptional advances of the Muldrow, Black Rapids and Susitna glaciers. Journal of Geophysical Research 65:3703-3712.

Post, A. S., 1969. Distribution of surging glaciers in western North America. Journal of Glaciology 8(53):229-240.

R & M Consultants, 1982. Alaska Power Authority, Susitna Hydroelectric Project; Appendix B.8, Reservoir Sedimentation. Report for Acres American, Inc., Buffalo, NY, 49 pp.

R & M Consultants and W. D. Harrison, 1981. Alaska Power Authority Susitna Hydroelectric Project; task 3 - hydrology; glacier studies. Report for Acres American, Inc., Buffalo, NY, 30 pp.

R & M Consultants and W. D. Harrison, 1982. Alaska Power Authority Susitna Hydroelectric Project; task 3 - hydrology; glacier studies. Report for Acres American, Inc., Buffalo, NY, 22 pp.

Shcheglova, O. P. and O. P. Chizhov, 1981. Sediment transport from the glacier zone, central Asia. Annals of Glaciology 2:103-108.

Tangborn, W. V., 1980. Two models for estimating climate-glacier relationships in the North Cascades, Washington, USA, Journal of Glaciology 25(91):3-21.

Uskov, Ju. S. and V. I. Kvachev, 1979. The didal surging glacier. Data of Glaciological Studies, Chronicle, Discussion. Academy of Sciences of the USSR, Section of Glaciology of the Soviet Geophysical Committee and Institute of Geography, Pub. 36, p. 170-175.