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ANNUAL RUNOFF RATE FROM GLACIERS IN ALASKA; A MODEL USING THE ALTITUDE OF GLACIER MASS BALANCE EQUILIBRIUM

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ABSTRACT: Glaciers in Alaska occur in high precipitation areas where the runoff is difficult to measure, yet hydrologically important. The spatial variability of glacier runoff is understood poorly. The equilibrium line altitude (ELA) of glaciers is related inversely to the average precipitation rate. Therefore, information about the average runoff from individual glaciers is contained in ELA data. This newly evaluated information about runoff is available from topographic maps. An ELA runoff model proposed determines average annual runoff from basins in Alaska. As a test the runoff rate was calculated for the Knik River basin, Alaska, using the model is 2.0 m/yr which compares with the average rate of 2.03 m/yr measured from 1959 to 1985.

Applied to an ungaged site in Alaska, the Bering Glacier drainage basin, the ELA model indicates that 34 km^3 of water is produced annually from this basin which contains Alaska's largest glacier. Furthermore, Bering Glacier is the source of 76 percent of the discharge from the drainage basin and the average discharge of the Bering Glacier drainage into the Gulf of Alaska is about 1080 m^3/s.
(KEY TERMS: glaciers; runoff; Alaska; snow and ice melt; estimation technique.)

INTRODUCTION

Glaciers in Alaska occur in areas of high precipitation, most of which arrives as wind-blown snow. Measuring that precipitation is difficult. Much of the precipitation remains in storage for time periods ranging from a few hours to centuries, but eventually runs off.

Runoff from glaciers is almost as difficult to measure as is precipitation because glacier-fed rivers are shifting-bed, braided streams that are rarely stable gaging sites. Even though areas with glaciers are widespread and therefore important, relatively little is known about their runoff.

Estimates of runoff from basins with glaciers at ungaged locations are often needed. For example, most of the glacier runoff from areas such as the St. Elias Mountains, cannot be gaged because part of the water flows via innumerable short, braided rivers to the coast, and part of the water flows sub-glacially directly into the ocean. Knowledge of that runoff is important, however, to other scientific problems such as understanding the dynamics of the coastal North Pacific gyre circulation (Royer, 1982), and developing reliable weather forecasting models.

Multivariate regression analyses used to generate equations for estimating annual river discharge in Alaska have been proposed (Parks and Madison, 1985, p. 20). Their analyses obtained the highest success (r^2=0.98) for gaged basins using drainage area and precipitation as independent variables. Basin area, however, is not a truly independent variable because discharge is equal to runoff rate <u>times</u> drainage area. Furthermore, the precipitation map they used (U.S. National Weather Service, 1972) is not independent from discharge data because it was drawn by the present author to conform with the runoff data.

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Input for a runoff model must be independent from existing runoff data and must be influenced strongly by precipitation. The model results would be most useful if they could be obtained from existing, readily available information for extensive remote areas where the cost of field investigations is high. Runoff data from three research glacier basins, Wolverine, Gulkana, and McCall (Figure 1) are analysed in this paper to provide a simple model whereby glacier runoff can be estimated reliably in Alaska.

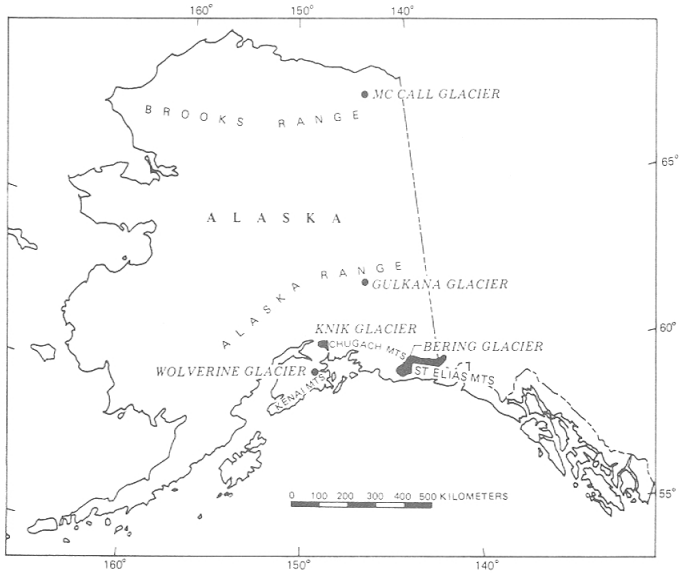


Figure 1. Locations of Glaciers used in this study.

GLACIER MASS BALANCE EQUILIBRIUM ALTITUDE

Information about spatial variations of precipitation and runoff rates is potentially contained in analyses of variations of glacier equilibrium line altitude. The equilibrium line altitude, or ELA, is the altitude at which snow accumulation is equal to snow melt. Meier and Post (1962) recognized that ELA is a function of precipitation. Increased snowfall tends to lower the ELA. Glaciers in a high precipitation climate receive considerably more snow than do glaciers in a drier, more continental climate. For a limited range of latitude, the average ELA in high precipitation areas is at relatively low altitude, and higher where drier.

Péwe and Reger (1972) and Østrem et al. (1981) used the relation of glacier ELA in Alaska to analyse precipitation patterns. However, ELA information has not been applied previously to studies of runoff.

DETERMINATION OF ELA FROM TOPOGRAPHIC MAPS

Time-averaged equilibrium line altitudes (ELA) of glaciers can be determined from topographic maps with varying degrees of precision depending on quality of the maps and the presence of mappable geomorphic indicators of glacier mass balance equilibrium. Using U.S. Geological Survey topographic maps of Alaska, the highest quality information is available at the largest scale, 1:63,360. These maps are readily available, accurate, and cover almost all glacierized areas of Alaska.

The ELA is the altitude of the boundary between a glacier's accumulation zone and its ablation zone. These two zones can be identified on high-quality topographic maps. Snow accumulation together with glacier flow in the accumulation zone cause dust and rock debris on the glacier from surrounding mountains to submerge into the glacier. The surface is therefore almost always relatively clean, smooth snow. Friction at the glacier edge retards this submergence, leaving a thin up-turned glacier edge against the adjoining mountain slope.

Ice from the accumulation zone flows into the ablation zone replacing (only approximately) the melt losses from the glacier. In this zone, the previously-deposited snow mass and rock debris emerges to the glacier surface. In late summer when the ablation zone is bare of snow and the old ice, mantled with accumulated rock debris, is exposed. This accumulation of rock is called supra-glacial till and forms medial moraines. On the air photos the topographic maps are compiled from, this rock debris usually appears black, in contrast to the white color of the ice, and is mapped with a stipple pattern. Friction at the glacier ablation zone edge retards emergence flow, leaving a narrow valley between the glacier and the adjoining mountain slope.

The rock debris and edge valleys of the ablation zone, and the upturned glacier edges in the accumulation zone are not small features; they show prominently on high-quality topographic maps. The central part of Gannett Glacier (Figure 2) near Knik Glacier illustrates these features.

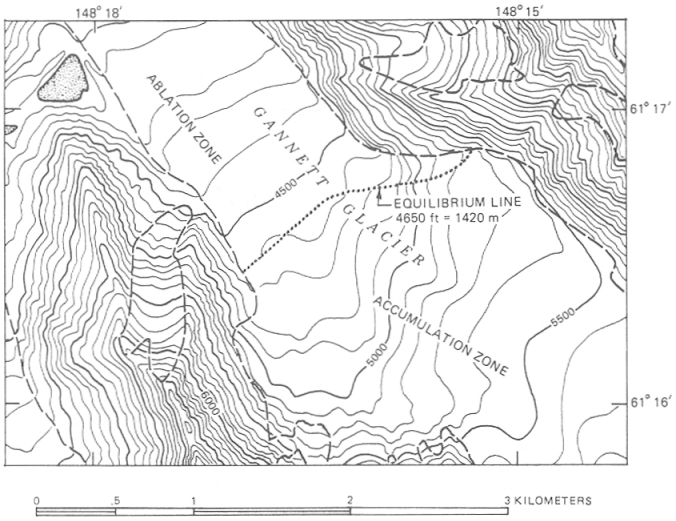


Figure 2. Central area of Gannett Glacier showing topographic features used to determine the glacier equilibrium line. Contour interval, 100 feet (30.48 meters).

The glacier zones determined from topographic maps represent the average glacier mass balance conditions over a period of many years, probably decades, because significant glacier flow responses to changing climatic conditions requires time. It is, therefore, useful for analysing only average runoff conditions.

RELATION OF ELA TO ANNUAL RUNOFF

Research by the U.S. Geological Survey at Wolverine Glacier, Kenai Peninsula, and Gulkana Glacier, Alaska Range; and by the University of Alaska at McCall Glacier, Brooks Range provide measurements of the glacier component of runoff in Alaska. Runoff from the glaciers originates from snow and ice ablation, rainfall, and condensation. Annual ablation, the dominant source of runoff, was determined from glacier mass balance measurements. Runoff from alpine (non-glacier) areas of the basins is small because part of the precipitation which falls on these areas as snow is redistributed onto the glacier by wind and avalanche action. Continuous streamflow data are available for the three glacier research basins.

In this paper, runoff rate is expressed as a vertical velocity, m/yr (meters per year) for the average over the surface considered. This is similar to the practice of reporting precipitation and glacier mass balance rates as a vertical velocity. Runoff flux rate, or discharge, is runoff rate times area, expressed here as km^3/yr (cubic kilometers of water per year) for the area specified. All runoff rates are considered to be averages in both space and time.

Runoff measurements are available for several glaciers in Alaska. The U.S. Geological Survey has monitored Gulkana and Wolverine Glaciers from 1966 to the present. Continuous streamflow information is available during the period 1967 to 1978, so this analysis is limited to that period for those glaciers.

The average measured runoff rate from all sources at Wolverine Glacier basin in southern Alaska, from 1967 to 1978, was 3.14 m/yr (meters per year) (U.S. Geological Survey, 1979). During this same period, the measured average ablation rate from snow, old firn, and ice on the glacier was 2.72 m/yr, or about 62 percent of the runoff. Rain and condensation on the glacier produce 25 percent of the basin runoff, and the alpine area contributes only 13 percent to the basin runoff. The average ELA, from yearly measurements during the period, was 1150 meters.

At Gulkana Glacier, in the Alaska Range of interior Alaska, the measured average runoff rate from 1967 to 1978 was 1.97 m/yr (U.S. Geological Survey, 1969) indicating that the climate at Gulkana is drier than at Wolverine, but still quite maritime compared with most of interior Alaska which typically has only 0.25 m/yr average runoff. The average ELA at Gulkana during the same period was 1180 meters. The total glacier area in the basin is 22.2 km^2, of which Gulkana Glacier is 19.3 km^2. Measured average ablation of Gulkana Glacier was 1.88 m/yr for the same period. This ablation with

rainfall added resulted in the glacier runoff rate of 2.38 m/yr, 85 percent of the measured runoff. Rain on the glaciers was the source of 18 percent of the runoff. The alpine area produced only 15 percent of the runoff.

Glacier ablation and runoff rates at McCall Glacier in the Brooks Range were measured in 1969 and 1970 by Wendler et al. (1973). Although the data cover only about half the ablation season for each of only two years, the information is quite useful because it indicates the magnitude of glacier runoff in a climatic setting that is different from that at either Gulkana or Wolverine Glaciers. The glacier ablation volume rate reported here (Table 1) is calculated from data presented by Wendler et al. (1973, p. 421-422). They also measured the runoff rate, which they reported was 9.1 liters per second per square kilometer, which is equivalent to 0.28 m/yr. An error in determining glacier area may have been made (Trabant, oral communication, 1986), so the glacier and basin areas reported here were determined by this author. The total area of glaciers in the basin is 10.1 km^2, of which McCall Glacier is 7.2 km^2. McCall Glacier produces only 0.62 m/yr runoff and the non-glacier area produces only 0.11 m/yr. In this relatively dry climate, the ELA of 2050 m is much higher than at either Gulkana or Wolverine Glaciers.

Table 1. Equilibrium line altitude and runoff measurements for three glaciers in Alaska. The alpine area is the non-glacier area. Measurements at Gulakana and Wolverine Glaciers by the author; at McCall Glacier by Wendler et al. (1973.

	Wolverine 1967-1978			Gulkana 1967-1978			McCall 1969-1970		
Equilibrium Line Altitude	1150 m			1780 m			2050 m		
Glacier	m/yr	km^3/yr	%	m/yr	km^3/yr	%	m/yr	km^3/yr	%
Measured Ablation	2.72	.0482	62	1.88	.0417	67	0.57	.0058	68
Estimated Rainfall	1.10	.0195	25	0.50	.0111	18	0.05	.0005	6
Calculated Runoff	3.82	.0676	87	2.38	.0528	85	0.62	.0063	74
Basin									
Est. Alpine Runoff	1.40	.0097	13	1.00	.0094	15	0.11	.0022	26
Measured Runoff	3.14	.0773	100	1.97	.0622	100	0.28	.0085	100
	km^2	%		km^2	%		km^2	%	
Glacier Area	17.7	72		22.2	70		10.1	33	
Alpine Area	6.9	28		9.4	23		20.1	67	
Basin Area	24.6	100		31.6	100		30.2	100	

The glacier and alpine components of the measured runoff were estimated (Table 1) from measurements of R, the basin runoff rate based on the equation:

$$R = (NS_n+G\ S_g)/(S_n+S_g) \qquad (1)$$

where:

N is non-glacier alpine runoff rate;
S_n is the non-glacier alpine area;
G is glacier runoff rate; and
S_g is the glacier area.

If glacier mass balance data are available, the glacier runoff,G, can be estimated as follows:

$$G = A-K+C+P_r \qquad (2)$$

where:

A is measured annual ablation;
K is freezing of water in the glacier;
C is condensation on the glacier; and
P_r is estimated annual rainfall.

Freezing of water in a glacier removes liquid from that available for runoff, and condensation adds to runoff. Both quantities are relatively small. In this analysis, condensation and internal freezing are not considered further, because they tend to cancel each other for runoff, although they can be important to glacier mass and heat balances.

The estimated quantities, N and P_r, are not uniquely determined, but the total of the two estimated quantities is known, so the estimates are constrained by the data. The estimated values of N and P_r were adjusted (Table 1) so that the calculated runoff is equal to the measured runoff. An assumption made in the process is that rain runoff from glacier and alpine areas are approximately equal because rain is not redistributed by wind to the extent that snow is. Furthermore, alpine runoff must be larger than glacier rain runoff because there is, in addition, snow melt runoff from alpine areas. The resulting uncertainty in the calculated glacier runoff is small because the snow and ice ablation from glaciers dominates the runoff from these basins.

The interpreted runoff and ELA data (Table 1) from the research glaciers indicates a well-defined inverse relationship of runoff rate to ELA exists in Alaska, as shown in Figure 3.

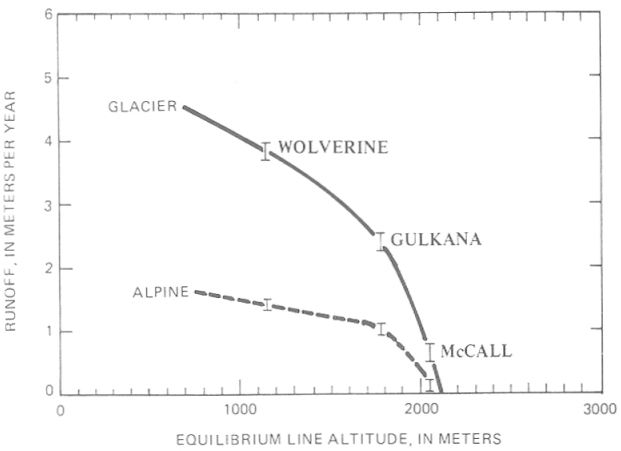


Figure 3. Relationship of average glacier equilibrium line altitude to the average runoff rate. Dashed line is the runoff from the alpine part of the basin adjacent to the glacier.

PROPOSED ELA RUNOFF ESTIMATION MODEL

It is proposed here that the relationship of runoff rate to ELA shown by Figure 3 is a general relationship over much of Alaska and it is, therefore, useful for calculating glacier runoff. The ELA Runoff Model proposed is the application of the measured relationship between ELA and runoff to other basins in Alaska.

The ELA Runoff Model is developed as follows:

The basin average runoff rate, R, is calculated by first determining the glacier and alpine runoff rate from the graph (Figure 1) for each hydrologically different area in the basin; determining the area of each unit from the map; multiplying runoff rate by area to obtain runoff volume rate; and then dividing by the total basin area. If a basin has forested lowlands, the runoff of that part of the basin must be estimated from other studies.

Thus, for a basin with glaciers, equation (1) stated previously here applies, that:

$$R = (NS_n+G\ S_g)/(S_n+S_g) \qquad (1)$$

For a single glacier or a set of glaciers with a representative ELA, the annual glacier and alpine runoff rates, G and A, are determined from Figure 3.

ELA variations within a drainage basin are so large in some cases that no single ELA is representative. In this situation, the basin can be sub-divided into zones where representative ELA values can be obtained. The basin average runoff rate is calculated by first determining the runoff volume rate for each subdivision; then the total runoff volume rate is accumulated before dividing by basin area. If a basin has forested lowland areas, the runoff from those areas must be estimated from other studies.

The ELA runoff model provides time- and area-average runoff rates, which is new hydrologic information for vast ungaged areas of Alaska. It should be recognized, however, that the is quite limited. In this model, for example, annual variations of glacier runoff have not been demonstrated to be related to annual variations in ELA. Furthermore, runoff calculated using the ELA model cannot be used directly to construct contour maps of runoff rate because glacier runoff varies inversely with altitude on individual glaciers. Snow and ice melt is the primary source of glacier runoff and the melt rate generally decreases with altitude. Additional techniques must be developed before glacier runoff contours over large areas of Alaska can be drawn using ELA as part of the argument. The estimated accuracy of the model is not known, but cannot be more accurate than about0.2 m/y

ELA RUNOFF MODEL TEST AT A GAGED BASIN

As a test of the ELA runoff model, runoff was calculated for the Knik River basin near Palmer, Alaska. Water flowing from the Knik River Basin has been gaged continuously since 1959 (U.S. Geological Survey, 1959-1985). In the Knik basin, glacier equilibrium altitudes range widely from 670 m in the southern part of the basin to 2100 m in the northern part of the basin (Figure 4). This large variation of ELA indicates that a strong

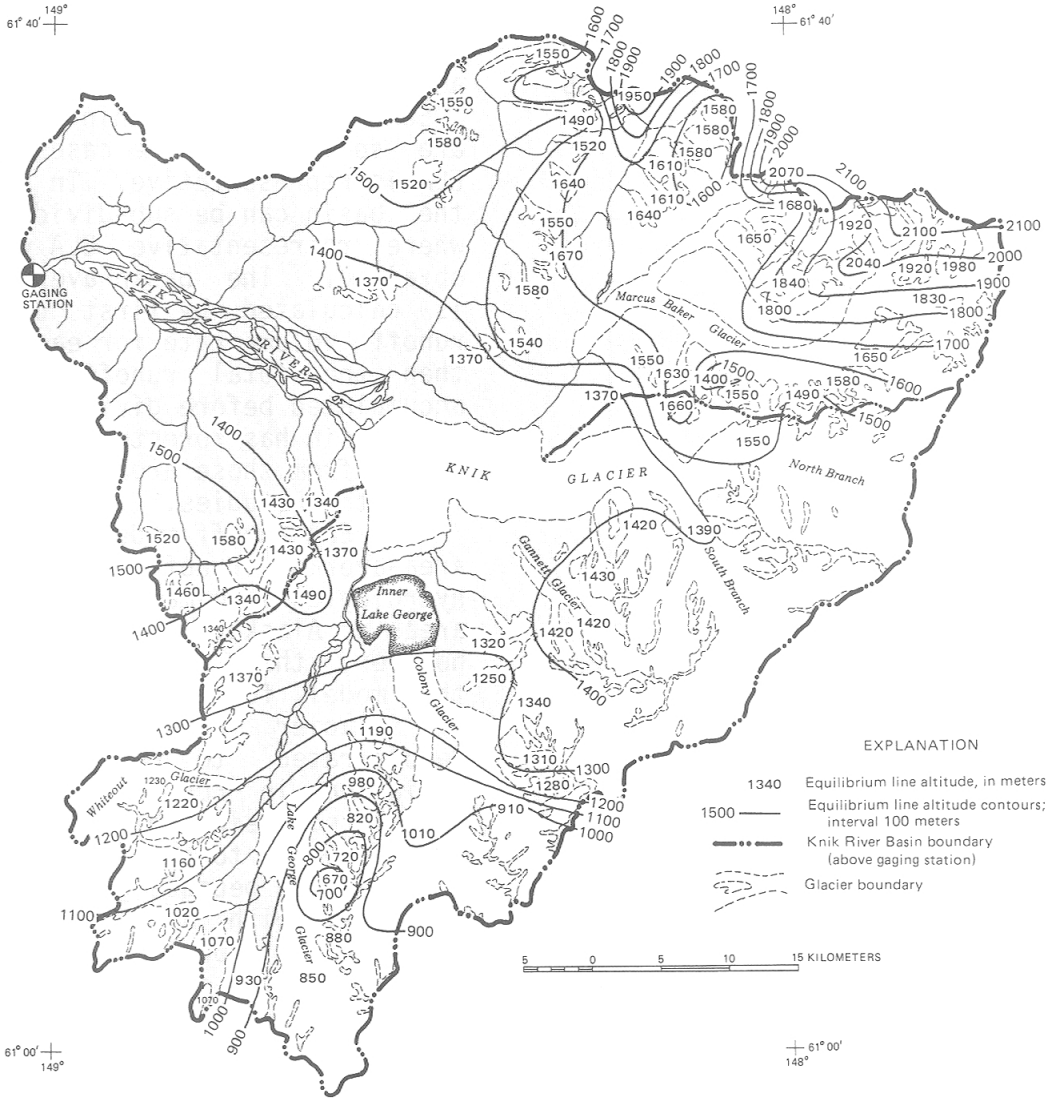
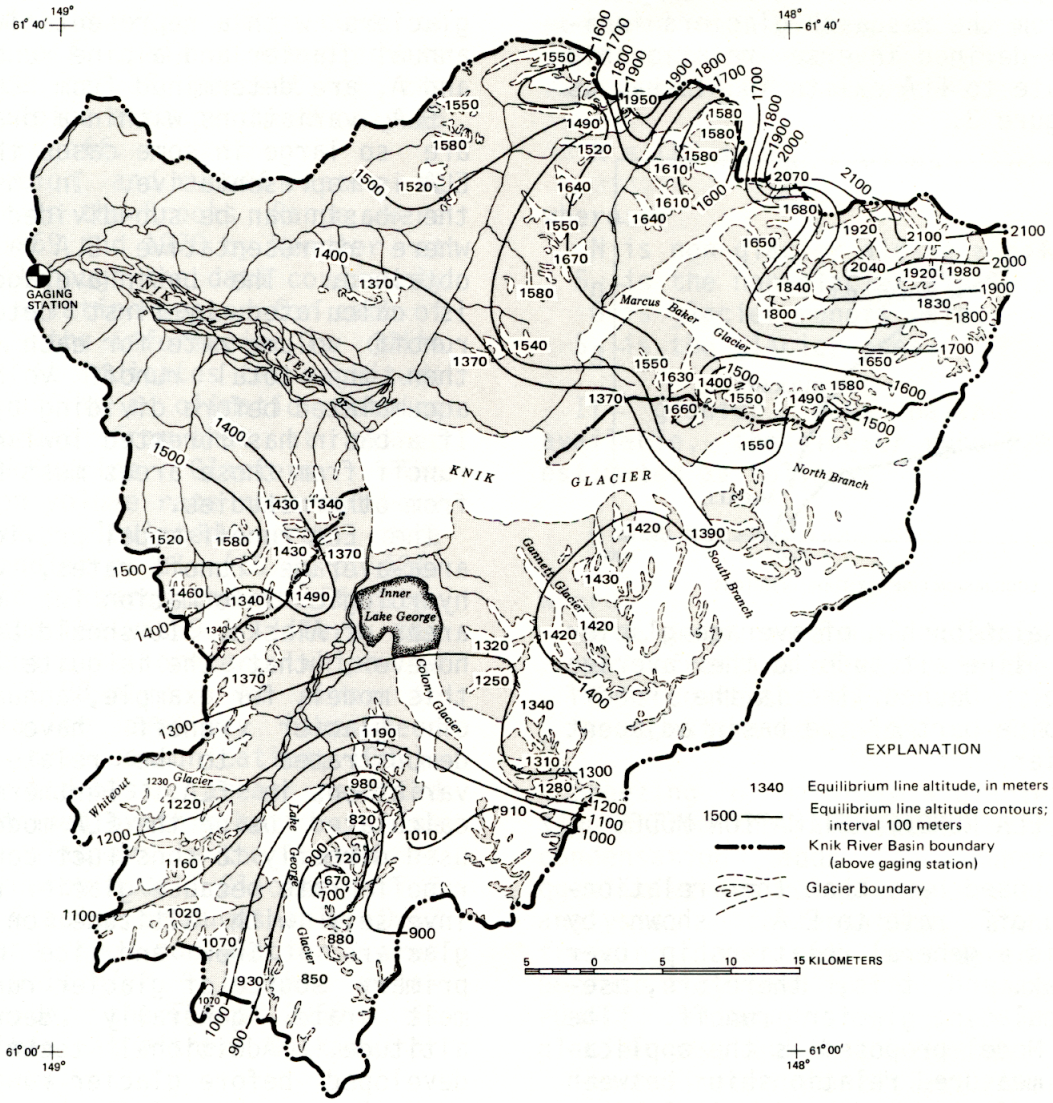


Figure 4. Distribution of the equilibrium line altitude in the Knik River Basin. Altitudes in meters.

precipitation shadow occurs in the Marcus Baker Glacier area and that precipitation and runoff are probably quite high in the southern part of the basin.

The Knik basin can be divided into three parts (Figure 4), the North sub-basin with the highest ELAs, the Knik Glacier sub-basin dominated by Knik Glacier, and the south sub-basin which has low ELAs. Each sub-basin contains a major glacier, other small glaciers, rock with alpine tundra vegetation, and forested lowland.

To apply the ELA model, the areas of glacier, alpine, and forested terrain in each sub-basin were measured from the map and shown in Table 2. The average ELA's of glaciers in each sub-basin were determined from the ELA graph (Figure 4); then used to determine runoff rates (Figure 5). ELA contours represent an imaginary surface above which glaciers form only where the land or glacier surface is higher. Runoff from the forested lowlands was estimated to be approximately half that from alpine areas because the annual precipitation measured nearby at Palmer is only 0.35 m/yr. The accuracy of this estimate is relatively unimportant, however, because the runoff from the forested lowlands is only 6 percent of the basin total.



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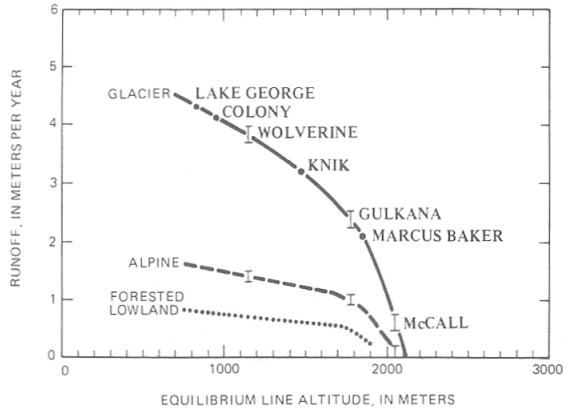

Figure 5. ELA model interpretation of runoff rate for Knik River Basin using glacier equilibrium line altitude information (see Figure 4).

During the calculation process (Table 2) high accuracy is shown only to avoid committing rounding errors during the calculation. Reportable results should be rounded. The ELA model calculation (Table 2) indicates that the basin average runoff rate is 2.0 m/yr. The measured 24-year average runoff rate for the Knik River from 1960 to present is 2.03 m/yr. This remarkable agreement, at least for this one case, indicates that the technique potentially can produce valid results.

Other interesting results, such as the percentage of runoff from each identified source, also come from the ELA model at Knik River basin. Glaciers occupy 47 percent of the basin area yet contribute 77 percent of the runoff. Glaciers occupy high local precipitation areas and also serve as effective precipitation traps in the windy climate. Furthermore, the south sub-basin, which is closer to the coast, contributes more water than the larger north sub-basin. Knik Glacier (14 percent of the basin) is the source of 23 percent of the river flow.

ESTIMATION OF GLACIER RUNOFF FROM AN UNGAGED BASIN

The ELA runoff model can be applied to other hydrologically important areas in Alaska, such as the St. Elias Mountains, where runoff measurements are sparse yet considerable runoff occurs. The basin chosen for an application example is the Bering Glacier basin. Runoff from the basin would be particularly difficult if not impossible to gage because the glacier runoff forms 12 rivers that flow into the Gulf of Alaska along 100 km of shoreline before they can gather into a single large river.

Bering Glacier, 6540 km^2 area, is a complex system of ice streams (see Figure 6) that includes the Bagley Icefield and the Stellar Glacier as a tributary. Even without considering the Stellar tributary, 830 km^2, the Bering is still the largest glacier in North America. The ELA rises dramatically with increasing distance from the ocean (Figure 6), indicating that precipitation decreases significantly over a relatively short distance.

A small, low altitude basin, Dick Creek, at the west edge of the basin, gaged from 1970-1981, had an average of 5.9 m/yr

Table 2.-- Average annual runoff from Knik River Basin, Alaska, calculated by the ELA runoff model. ELA and area data from Figure 4 (map); estimated runoff (one decimal) from Figure 5 (graph); calculated runoff (two decimals). All calculations carried out to full accuracy. Apparent errors in totals are not real, but are due to rounding.

	Data from map AREA km^2	%	ELA m	Model predicted RUNOFF RATE m/yr	km^3/yr	%
NORTH SUB-BASIN						
Marcus Baker Glacier	270	9	1830	2.1	0.57	9
Other Glaciers	160	5	1500	3.2	0.51	8
Alpine	760	25		0.9	0.68	11
Forested lowland	500	17		0.45	0.23	4
Subtotal	1690	56		1.18	1.99	33
KNIK GLACIER SUB-BASIN						
Knik Glacier	430	14	1470	3.2	1.38	23
Other Glaciers	20	1	1450	3.3	0.07	1
Alpine	60	2		1.2	0.07	1
Subtotal	510	17		2.97	1.51	25
SOUTH SUB-BASIN						
Colony Glacier	160	5	950	4.1	0.66	11
Lake George Glacier	200	7	830	4.3	0.86	14
Other Glaciers	180	6	1170	3.7	0.67	11
Alpine	140	5		1.6	0.22	4
Forested lowland	140	5		0.8	0.11	2
Subtotal	820	27		3.07	2.52	41
KNIK RIVER BASIN SUMMARY						
Glaciers	1420	47		3.31	4.70	78
Alpine	960	32		1.02	0.98	16
Forested lowland	640	21		0.53	0.34	6
TOTAL	3020	100		1.99	6.02	100
	Measured runoff			2.03 m/yr		

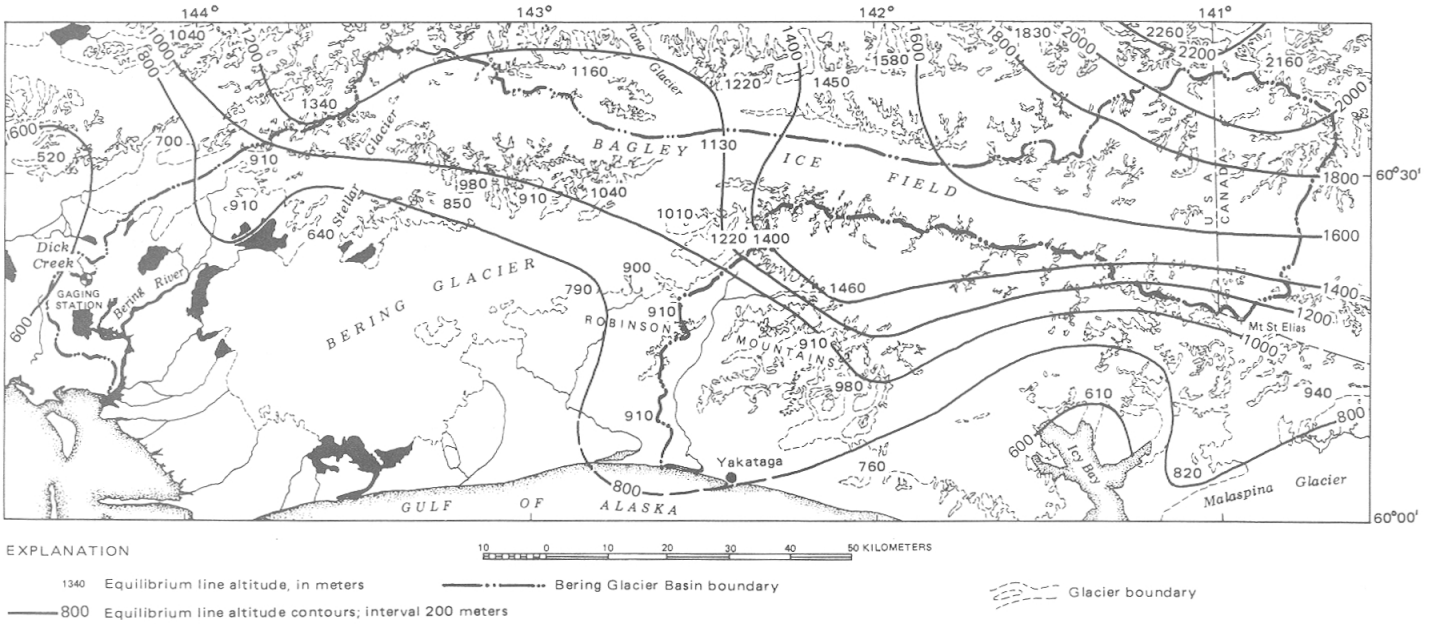

Figure 6. Equilibrium line altitude in the Bering Glacier basin. Contour interval, 200 m.

runoff (U.S. Geological Survey, 1982). Precipitation at nearby Yakutat (2.1 m/yr) and Yakataga (3.1 m/yr) average 2.6 m/yr. The sparse precipitation and runoff measurements indicate that the average runoff rate from the forested lowlands in this region is probably very high, between 3 and 4 m/yr.

To apply the ELA Runoff Model to the Bering Glacier basin, the area was subdivided into 3 glacier and 2 non-glacier areas. The Bering Glacier and Stellar Glacier tributary were separated because the ELA of the Bering is 1100 m, whereas it is only 640 for the Stellar. Other small glaciers (210 km^2), alpine, and forested lowland areas were also considered separately. ELA model calculations (Table 3) indicate that the Bering Glacier basin produces a considerable amount of water, 34 km^3/yr (1080 m^3/s, or 38,000 ft^3/s), 79 percent of which comes from the glaciers.

The average runoff rate indicated by the ELA model for the Bering basin is 3.8 m/yr. Royer (1982, p. 2018) estimated the average runoff rate to be 2.4 m/yr for the same region based on sparse precipitation and oceanographic data, but concluded that this was probably an underestimate of the actual amount.

Table 3. Average annual runoff calculated for the Bering Glacier drainage area. The equivalent average river discharge rates are also given in units of cubic meters per second, m^3/s, and cubic feet per second, ft^3/s, for comparison.

	AREA km^2	AREA %	ELA m	RUNOFF RATE m/yr	RUNOFF RATE km^3/yr	RUNOFF RATE %	RUNOFF RATE m^3/s	RUNOFF RATE ft^3/s
GLACIER SYSTEM								
Bering tributary	5710	63	1100	3.9	22.3	65	707	25000
Stellar tributary	830	9	640	4.5	3.7	11	117	4100
Bering/Stellar	6540	72		4.0	26.0	76	824	29100
Other glaciers	210	2	910	4.1	0.9	3	29	1000
TOTAL	6750	74		4.0	26.9	79	852	30100
NON-GLACIER AREAS								
Alpine	550	6	900	1.6	0.9	3	29	1000
Forested lowland	1770	20		3.5	6.2	18	196	6900
TOTAL	2320	26		3.1	7.1	21	225	7900
BASIN TOTAL	9070	100		3.8	34.0	100	1078	38000

DISCUSSION

The relationship of runoff to ELA, Figure 3, suggests that the highest expected ELA in Alaska is about 2100 m. No glaciers in Alaska have ELA's higher than 2200 m. In a study of the refreezing of water in glaciers, Trabant and Mayo (1985) showed that almost all glacier meltwater above 2100 m altitude refreezes in cold, permeable glacier firn where it remains as glacier accumulation, which

explains the altitude limit. Rock areas above about 2100 m altitude shed most precipitation by avalanching rather than by liquid runoff. Thus, little liquid runoff occurs from glaciers or alpine areas above that altitude. Most precipitation above 2100 m flows by avalanching and glacier ice motion.

Precipitation in mountainous areas tends to increase with altitude. This generalization does not, however, apply well to Bering Glacier. The ELA runoff model of the Bering area indicates that precipitation and runoff from this large glacier are less than the runoff measured at Dick Creek, the small, lower altitude subbasin. Thus, the zone of maximum precipitation adjacent the Pacific Ocean in this part of Alaska may be as low as only 500 m altitude.

The ELA runoff model for Alaska can be expected to give good estimates of runoff from ungaged basins that contain glaciers. The model as calibrated in this paper is restricted to the latitude band from 60° to 70° North in northwestern North America, and can be expected to overestimate runoff north of this band and underestimate runoff to the south. Where glacier ablation and runoff data are available for other areas, the ELA runoff model could be recalibrated.

Among the five basins studied in Alaska, snow and ice melt produced substantially more runoff than did rainfall, and glaciers produced from 74 to 87 percent of the total runoff.

The ELA model provides a means of estimating the runoff from all glaciers in Alaska, which can be compared to the total runoff of the nation. Glaciers occupy 73,000 km^2, or about 5 percent of Alaska. The average ELA of these is not known precisely, but is between that of Gulkana and Wolverine Glaciers. Thus, the average runoff rate from Alaskan glaciers is approximately 3 m/yr, or 220 km^3/yr. Average runoff from the conterminous states has been estimated to be 1,230 billion gallons per day (U.S. Geological Survey, 1984), or 1550 km^3/yr. R.D. Lamke (oral comm., 1986) estimated the average runoff from Alaska to be 620 km^3/yr.

Bering Glacier produces 4.2 percent of Alaska's runoff and 1.2 percent of the national runoff including Alaska. Glaciers in Alaska produce approximately 35 percent of Alaska's runoff; an amount equal to 14 percent of that from the conterminous states; and 10 percent of the total runoff from the nation.

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