OBSERVATIONS ON UNMEASURED RIVERS

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ABSTRACT. An analysis of data on hydraulic parameters collected during a single boat trip down a river system is presented, plotted in form of the hydraulic geometry. A dimensionless rating curve is used to estimate bankfull and average discharge for basins of various sizes. When compared with gaging station data, estimates of bankfull discharge are as consistent and possibly equal in accuracy to estimates made from gaging station data. Estimates of average discharge are less consistent; within the range of drainage areas represented by the gaging stations, errors of estimate vary from 0 to 58 percent.

Local variations of bed material size along the river are compensated mostly by changes in local channel slope and roughness and do not much affect the progressive downstream changes in width, depth, or velocity.

General statement

A large amount of manpower and money is spent on river gaging. Though for practical engineering purposes river discharge is the most important parameter, the hydraulic factors measured in conjunction with flow determination are not sufficiently inclusive for geomorphologic or even for hydrologic analysis of the river system. Two problems arise when gaging station data alone are used for analysis of the river system. There usually is an insufficient number of measuring stations to allow an analysis of downstream channel changes; also, the gaging station data do not include local measurements of sediment size, sediment load, bankfull stage, channel slope, or channel pattern. The problems of insufficient data from standard measuring techniques have previously been faced by Filip Hjulström and others who lead into new areas of study.

The question arises, then, what can be learned by simple measurements made once only along a river, as on a downstream boat trip. The present paper is a progress report on an attempt to answer that question. The data were taken on two separate boat trips down rivers. In one, no previous measurements were available but there is one gaging station downstream; the river studied is the John River, Alaska, a south-flowing tributary to the Koyukuk River, Yukon River Basin. The reach studied is within the Brooks Range at Lat. 67° N., between Crevice Creek and Beattles, a distance of about 50 miles.

The other river is the Middle Fork of the Salmon River, Idaho, Snake River system, from Dagger falls to the Salmon River, a distance of about 100 miles. In this basin there are several gaging stations, but the records from these were studied only after the field expedition was over. The same data were collected on both rivers and analysed in similar ways. The gaging stations on the Middle Fork Salmon River provide checks on some of the inferences drawn.

The authors gratefully thank all expedition members, both those in the boats and in the supporting trucks and airplanes, and especially the members of the Phoenix Research Office, U.S. Geological Survey, who made possible the measurements here reported.

Measurement program

At various points along the main stream and on nearly all entering tributaries near their mouths, a discharge measurement was made as well as certain other observations. The data collection at each such place takes about half a day, so on a boat trip traversing 50 to 500 miles an expedition can measure, on the average, not more than one location a day. Actual river travel, making and breaking camp, and other activities take the bulk of expedition time. Besides the discharge measurement, observations include: a water surface profile from which the gradient of the studied reach is obtained; a size-distribution count of debris size on a gravel bar or riffle; a measurement of height above present water surface of the bankfull stage.

The field discharge measurement

The choice of the particular cross section along the river for a discharge measurement appears to be important. Uniformity of practice gives best comparability among streams. A straight reach or segment is chosen. A cross section is selected near the downstream part of a pool or deep but upstream from the fastest and shallowest water of the riffle.

This choice, rather than an extremely deep and slow section or a shallow and fast one, results in an intermediate value of depth and velocity. At the chosen section a tape is stretched tautly across the river and an ordinary discharge measurement is made with current meter. However, we do not measure the velocity at 20 positions across the channel as would be ordinarily the practice, but about half that many. Also, the velocity at each is measured at the 0.6 point in depth; that is, the current meter is placed below the water surface at 0.6 of the distance from water surface to bed.

If the stream cannot be measured by wading the measurement is made from a boat, which is held in position by a rope stretched across the stream. When the river is too large for this technique all aspects of measurement become much more difficult and the present techniques are inapplicable. In taking measurements from the boat we usually use a metal wading rod to hold the current meter rather than a wire and weight.

Field measurement of river slope

River slope (gradient) is often the most difficult field parameter to obtain; it is subject to a large variance.

In our experience, by far the best measurement of slope as well as certain other parameters will be obtained if the following procedure can be used. A reach of river is selected which includes the cross section where the discharge measurement was made. The length of this reach should not be less than 20 times the channel width and better results are obtained if the length is equal to 30 or 40 times the channel width.

A plane table with telescopic alidade is set up on the shore, on a channel bar, or even in mid-stream. An arbitrary datum is established, marked by a nail driven into a tree, or a cross chiseled on rock, so that the survey may be repeated or extended later if necessary. The rodman moves from place to place so that shots outline the channel on both banks and the instrument-man prepares a planimetric map of the channel, including the size and position of bars, terraces, cliffs, rock outcrops, and vegetated areas. But most importantly, the rodman also gives a series of shots on the flood plain, aligned so that a longitudinal profile of the flood plain can be plotted. If possible he also wades down the center of the channel so that a longitudinal profile of the streambed near the center of the channel can be plotted.

These shots, from which the long profiles will be plotted, should be no farther apart than $^1/_2$ to 1 channel width. Thus a map is made from which downstream distances may be measured and corresponding elevations plotted for constructing profiles of the flood plain and of the water surface. If the stream is wadeable a profile of the streambed is also plotted.

A usual complication is that along a river channel there is one or more terraces as well as the flood plain related to the present stream regimen. The survey party should try to distinguish these various levels and the profiles plotted should thus help distinguish the flood plain from higher surfaces.

In the survey described distances are measured by stadia. Elevations are read to the nearest 0.1 foot, including water surface. Only if the river slope is very small is greater precision needed.

If a plane table map is impractical for some reason, the survey may be restricted merely to the profiles. Distances along the river then can be measured by pacing if the reach is longer than 300 feet, by tape (chain) along the shore, or by stadia if the instrument is set up at points near the channel.

The profiles of flood plain, water surface and bed are plotted, and average gradients of each determined while the party is still in the field because if questions arise they can often be settled by a few more observations.

One advantage of the scheme is not apparent. Experience has shown that surveying numerous cross sections usually fails to provide either a meaningful average cross section or a consistent value of down-channel slope. The longitudinal profile approximately down the channel center tends to include both deeps and shallows and thus the mean gradient is usually apparent. Despite its undulations, the bed profile generally has the same gradient as the water surface.

Sometimes the long profiles give distinctly different slope values in the upper and lower parts of the surveyed reach. No general rule is applicable, but the planimetric map will help one choose what portion of the reach is most typical.

If a topographic map is available a separate value of slope is measured from the contour lines for a zone including the surveyed reach.

Measurement of bankfull stage

When a well-developed flood plain is present its surface can be considered as the level of the bankfull stage. But along many rivers no flood plain is obvious. What then are the criteria for establishing a bankfull depth? The following seem to occur at a consistent height above the water surface and are taken to represent bankfull level:

a) Moss, and sometimes lichens, growing on shore boulders are often truncated at a particular level above low water and seem to represent the lower limit of the unusual flow.

b) Sand mixed with river boulders often extends up to a particular level. The upper limit of sand deposited in shore boulders is usually coincident with bankfull flow.

c) Vegetation tends to change progressively with elevation along the stream. The lower limit of herbs and forbs usually represents bankfull stage. Grass is ordinarily non-diagnostic. Trees and tree roots are seldom diagnostic and shrubs only occasionally.

d) Flood debris of old sticks, pine cones, and trash often occurs at several levels along a stream bank. There is often, however, a distinct break in the amount or appearance of such debris at an elevation coincident with the other features noted above.

Using these criteria, points along the stream bank are selected and surveyed to provide a longitudinal profile of the bankfull stage. Such a profile is usually less consistent than a well-developed flood plain but may be quite usable.

Bed material size

A size distribution of bed material is obtained by a sampling procedure previously described (Wolman, 1964) but summarized here with hints for expediting the measurement and with certain changes now incorporated into present practice.

The investigator walks far enough along the channel in shallow water or on a gravel bar to sample both the lower end of a pool and the riffle or bar. At each step he reaches over the toe of his boot and with eyes closed, picks up the first cobble or rock his finger touches. The pebble or cobble is measured along its intermediate or B axis. The value recorded is the lower limit of the class interval within which the measurement lies, using class interval limits differing by $\sqrt{2}$. Not less than 50 pebbles are so measured, 75 to 100 being the usual number. The record is kept as a tally of number of particles within each class limit.

The number in each class is then counted and cumulated and computed in terms of percentage of total number. Cumulative percentage is plotted against mean value of size class, and the size values corresponding to the median (50 % smaller) and one standard deviation larger than median (84 % smaller) are recorded.

Analysis of data

The object of analysis is to use single measurements at various locations to construct a picture of the interaction of hydraulic factors in the basin as a whole, especially to estimate the bankfull discharge at various localities and, with less certainty, the average discharge.

The scheme of analysis as well as the choice of data to be collected is predicated on the fact that every river basin has a certain coherence in that various portions of the basin relate to each other in a reasonably consistent way. Thus a form of ergodic reasoning is involved substituting space for time.

The basic data obtained in the field and computations made from them are included in Table 1.

The Middle Fork Salmon River is a clear mountain stream flowing between steep mountain sides, is often confined within cliffs, and is neither braided nor meandering. It has a coarse gravel bed, often filled with large boulders. It is increasingly used for a wilderness boat trip because the rapids are fast and dangerous.

Data analysis begins by the construction of curves of the downstream hydraulic geometry.

Table 1. River trip and observations and data computed therefrom, Salmon River, Idaho, and John River, Alaska.

	Middle Fork Salmon River, Idaho							Brooks Range, Alaska, John River Basin						
	Middle Fk Salmon R near Velvet Falls	Deerhorn Creek	Loon Creek	Middle Salmon near Tanner Falls	Indian Creek	Sheep Creek	Big Creek	Crevice Creek	Allan River	63 Mile Creek	Timber Creek	Mamalute Fork	John R. at Departure Bar	Koyukuk River at Hughes
Observations in the field, low flow														
Discharge Q cfs	604	2.4	292	1801	135	11.3	568	20.1	77.5	50.4	113	212	891	15000 (3*)
Width w ft	64	8.4	80	120	30	17	48	23.5	46	37	53	62	118	
Depth d ft	4.4	.32	1.38	3.08	1.12	.51	2.78	.77	.84	1.22	1.04	.98	3.07	
Velocity v ft/sec	2.12	.87	2.64	4.91	3.9	1.03	4.2	1.08	2.0	1.11	2.05	3.50	2.46	
Bed grain size D50 mm (1*)	50	108	100	11.0	64	56	170	52	57	-	21	38	11	
Bed grain size D84 mm (2*)	90	180	256	204	128	112	342	108	124	95	45	74	22	
Slope s	-	.0098	.0112	.003	.0164	.027	-	.0125	.0071	.0024	.0031	.003	.00042	
Bankfull width w_{bkf} ft	70	9.5	90	130	40	20	55	115	155	-	104	260	320	1250
Bankfull depth d_{bkf} ft	6.9	1.2	2.9	7.7	2.6	1.8	5.1	3.1	3.5	3.3	4.3	3.2	9.4	12.2
Quantities computed or derived from graphs														
Drainage area DA (mi^2)	430	2	350	6500 est.	81	26	600	26	260	155	95	187	1672	18000
Slope from map, S map	.0093	.0166	.0221	.0044	-	-	.02	-	-	-	-	-	-	.0004
d/d_{bkf}	.64	.26	.48	.40	.43	.28	.54	.26	.25	.37	.24	.31	.33	
Q/Q_{bkf}	.35	.07	.24	.16	.19	.08	29	.07	.06	.13	.06	.10	.12	
Q_{ave}/Q_{bkf}	.14	.03	.13	.32	.08	.06	.15	.06	.12	.10	.09	.11	.21	
Bankfull discharge Q_{bkf} cfs	1730	34	1215	11200	710	133	1950	292	1190	390	1880	2210	7450	95000 (4*)
Average discharge Q_{ave} cfs	240	1	158	3600	57	8	290	17.5	143	39	169	243	1560	

(1*) Diameter of bed grain B (intermediate) axis 50% finer than
(2*) Diameter of bed grain B (intermediate) axis 84% finer than
(3*) Average flow for September 10
(4*) 1.5 yr. recurrence interval

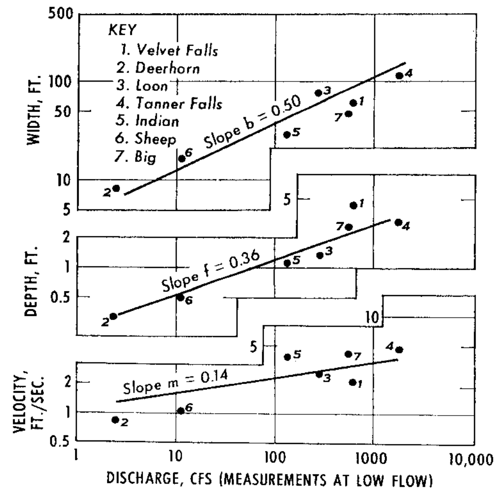

Fig. 1. River trip measurements at low flow, Middle Fork Salmon River, Idaho, and tributaries, plotted as width, depth, and velocity as they change downstream with discharge.

The measured width, depth and velocity at each river section observed are plotted against the accompanying discharge, figure 1. The condition represented is for a low flow (condition of observation) of unknown frequency. Nor is it known that all tributaries measured had a discharge of constant frequency value.

The bankfull discharge is estimated by using the dimensionless rating curve (figure 7–10, p. 219, Leopold, Wolman and Miller, 1964), which relates the ratio of observed depth/bankfull depth (ordinate) to the ratio of observed discharge/bankfull discharge. In the field three of these were measured and thus the fourth can be computed. Data for the computations are shown in Table 1.

In the field the width of channel at bankfull level was measured when the bankfull elevation was determined. Thus one can plot channel width bankfull vs bankfull discharge, as shown on figure 2. Similarly, bankfull depth is plotted against corresponding discharge.

Bankfull velocity is obtained by reading values of bankfull discharge, width, and depth from the previously plotted curves and computing velocity as the ratio of bankfull discharge to cross sectional area. In this manner the downstream curves of bankfull w, d, and v are plotted against bankfull discharge, figure 2.

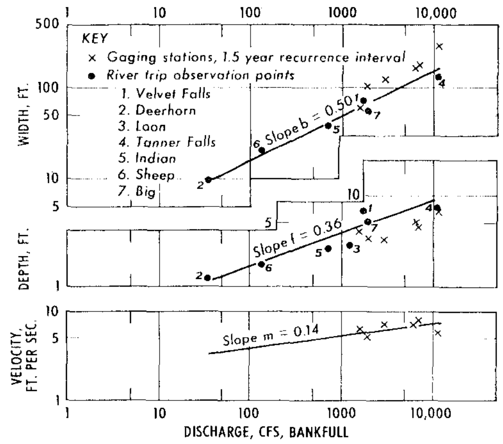

Fig. 2. Downstream changes of bankfull width, depth, velocity with discharge, from river-trip data, Middle Fork Salmon River, Idaho, and tributaries; compared with values derived from gaging station record.

To obtain further information as well as to provide a rough check on the three downstream graphs already drawn, a plot is made of water surface (river) slope against discharge for each measuring point, and of the grain size (bed particle size) 84 % finer than. These two graphs are shown in figure 3.

Clearly there is a much wider variance in river slope and grain size as discharge increases than there is in width, depth or even velocity. Through such scattered points a mean line is not easy to draw, but some guidance can be ob-

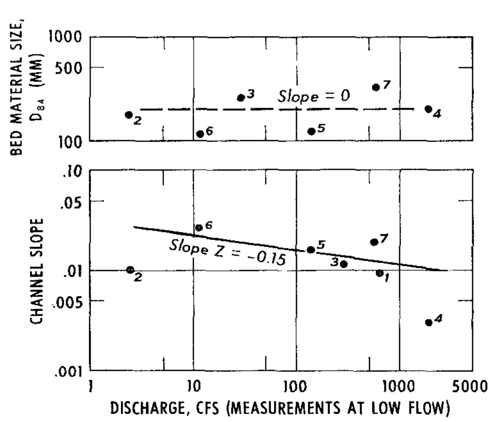

Fig. 3. Downstream changes of bed-material size (84% finer), and of channel slope as function of discharge, Middle Fork Salmon River, Idaho, and tributaries.

tained by considering a hydraulic roughness formula, say the Manning equation

$$v \propto \frac{d^{2/3}\ S^{1/2}}{n} \quad (1)$$

in which v is velocity, S is river slope, and n is Manning's roughness coefficient. Because each of these can be thought of as a function of discharge downstream, the formula can be written

$$Q^f \propto \frac{(Q^m)^{2/3}\ (Q^Z)^{1/2}}{Q^y} \quad (2)$$

$$f = (2/3)m + (1/2)Z - y \quad (3)$$

Substituting the values of these exponents read from the slope of the graphs already plotted, and solving for the exponent of roughness, y, we get

$$y = 2/3(0.36) - 1/2(0.15) - 0.14 = 0.03 \quad (4)$$

This value agrees with the usual condition that roughness decreases downstream only slightly with increasing discharge, or remains about constant. This value of y is also in general agreement with the data on bed material size which appears to be about constant downstream.

The data presented emphasize a general characteristic of rivers which is usually overlooked. Width, depth, and velocity are relatively very stable and consistent despite the fact that rivers flow from one lithology to another, from open valley to canyon. These changes along a river caused by change in hardness or erodibility are absorbed in the hydraulic parameters through values of roughness and slope, and only to very minor degree through values of width, depth, or velocity. Thus when a tributary puts coarse material into a channel which upstream is carrying finer debris, the coarse sediment causes an increase in roughness which results in a local increase in river slope, with but minor adjustments of width, depth, or velocity.

Estimates of mean annual discharge, Q_{ave}, are made for each measuring point. Analysis of some river data suggest the following tentative relation of the ratio bankfull discharge/average discharge as a function of drainage area.

More data will be needed to improve this tentative relation.

Drainage Area (sq/mi.)	Ratio $\frac{Q_{ave}}{Q_{bkf}}$
100	.09
500	.15
750	.17
1000	.18
5000	.30
7500	.33
10000	.37

Multiplying the value for Q_{bkf} by the appropriate ratio given above an estimate of mean annual flow is obtained. The values of Q_{ave} and of Q_{bkf} are plotted against drainage area on figure 4. Usually the plot of Q_{bkf} vs area has a slope of about 0.7 on log paper and the plot Q_{ave} vs area, a slope of 1.0. In the present data the slopes are respectively 0.74 and 0.90.

The above computations were all made without reference to available streamflow records from recording stations. The estimates will now be compared with actual record, summarized in Table 2. On the Middle Fork Salmon River and immediately adjacent areas there are 6 gaging stations totalling 140 station years of record. For none of them is there a field measurement of bankfull discharge so that this quantity was assumed to be the discharge ($Q_{1.5}$) having a recurrence interval of 1.5 years. In other words, even for recording stations unless a special field investigation were to be made the bankfull discharge is an estimate.

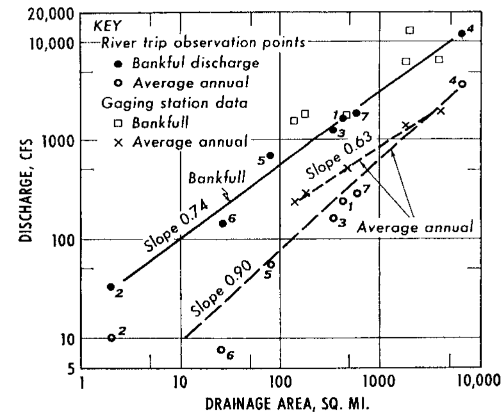

Fig. 4. Discharge related to basin drainage area, for bankfull and average annual discharge; data estimated from river-trip data and from gaging station records; Middle Fork Salmon River, Idaho, and tributaries.

The values of $Q_{1.5}$ are plotted against drainage area on figure 4. It can be seen that our estimates extend over a larger range of drainage area than the gaging records do and are as internally consistent. It appears that an estimate of bankfull discharge from our simple measurements is as good as one made from the usual gaging station data.

The values of width, depth, and velocity corresponding to bankfull discharge can be read off at-a-station curves plotted from current me-

Table 2. Data from records at gaging stations, Middle Fork Salmon River, Idaho.

	Middle Fork Salmon nr Cape Horn	Bear Valley Creek nr Cape Horn	Middle Fork Salmon nr Meyers Cove	Big Creek near Big Creek	Salmon R. at Salmon	Salmon R. at Challis
Drainage area DA mi^2	138	180	2020	470	3670	1800
Average discharge Qave cfs	236	290	-	509	1918	1450
Discharge at 1.5 yr recur $Q_{1.5}$ (1*)	1580	1900	11200	2930	6750	6230
Mean Annual flood $Q_{2.33}$	2020	2370	14100	3660	9000	8340
Basin mean altitude, ft	7370	7040	7180	7000	7380	7820
Ratio $Q_{1.5}/Q_{2.33}$	.78	.8	.8	.8	.75	.75
Ratio Q_{ave}/Q_{bkf}	.15	.15	-	.172	.284	.233
At a station exponents						
(width) b	.16	.06	.04	.08	.27	.10
(depth) m	.30	.43	.36	.41	.20	.42
(velocity) f	.52	.51	.61	.52	.53	.49
At bankfull						
width w_{bkf}	61	102	290	125	178	161
depth d_{bkf}	4.1	3.4	7.0	3.2	4.7	5.2
velocity v_{bkf}	6.3	5.4	5.7	7.4	7.9	7.4
At average discharge						
width w_{ave}	44	90	-	109	128	140
depth d_{ave}	2.2	1.5	-	1.5	3.7	2.8
velocity v_{ave}	2.3	2.1	-	3.0	4.0	3.6
Number of years of record (2*)	32	32	7	14	31	31

(1*) Used 1.5 yr recurrence interval discharge as equivalent to bankfull discharge
(2*) To 1960; record averages used here are from beginning of record to 1960

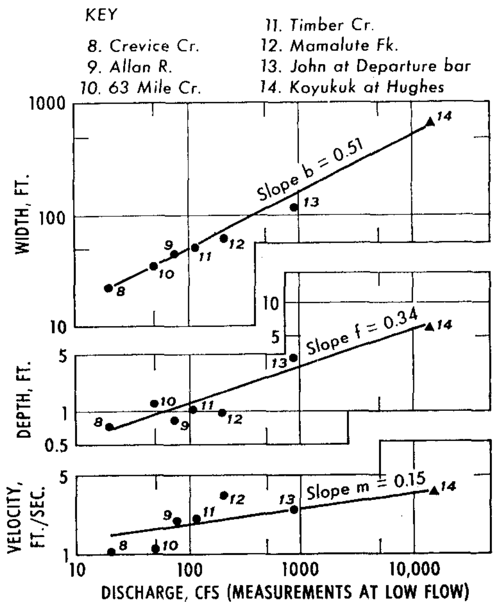

Fig. 5. River trip measurements, John River system, Alaska, plotted as downstream changes of width, depth, and velocity with discharge; included are values for gaging station on Koyukuk River at Hughes.

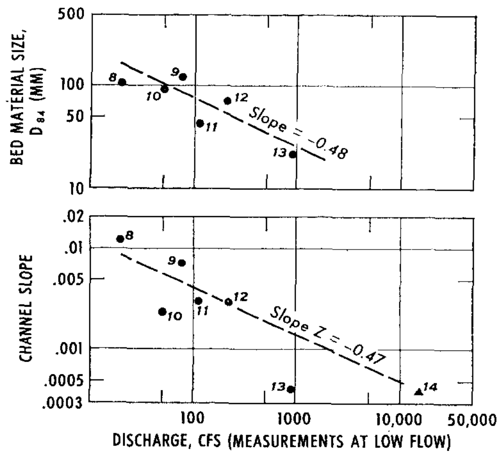

Fig. 6. Downstream changes of bed-material size (84% finer) and of channel slope as function of discharge, John River and tributaries, Alaska.

ter measurements at a gaging station. These values are plotted as crosses on figure 2. Our river trip estimates give slightly lower values of width, larger values of depth and comparable values of velocity at bankfull discharge than shown in gaging station data. In general the results are comparable.

With regard to average annual discharge, the gaging records are more consistent than our estimates and our method failed to discern that in the Salmon River the average discharge per square mile decreases with increased drainage area, resulting in a line on figure 4 with a slope of 0.63 rather than the usual value near unity. Thus our estimates are close to the gaging record for drainage areas greater than 1000 sq. mi. but too low by 58 percent at 100 sq. mi.

However, because the gaging records do not measure areas smaller than 138 sq. mi. the error for small basins is unknown.

Application to a wilderness river

A boat trip was run down the John River, a south-flowing tributary to the Yukon River in Alaska. The river is fast, wide, and clear with a bed of very uniform rounded gravel. The riffles are of very uniform depth across the channel. The river is meandering and braided at the same time. No previous records of flow are available so estimates made here are not possible of verification. One gaging station exists in the area but it is on the Koyukuk River into which the John River flows.

On Figure 5 actual observations are plotted as downstream curves of width, depth, and velocity, and on Figure 6 slope and grain size vs discharge. The measurements were made during

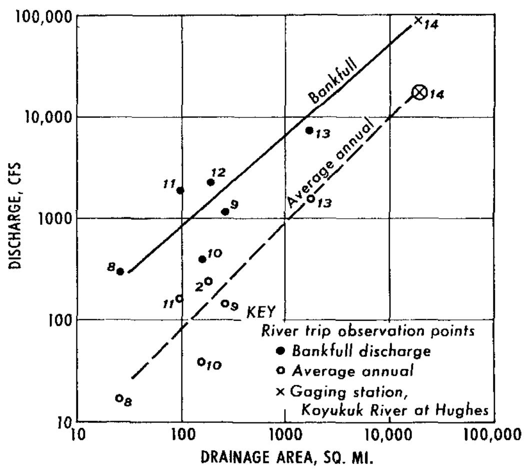

Fig. 7. Discharge related to basin drainage area, for bankfull and average annual discharge; data estimated from river-trip data and one gaging station, John River, Alaska.

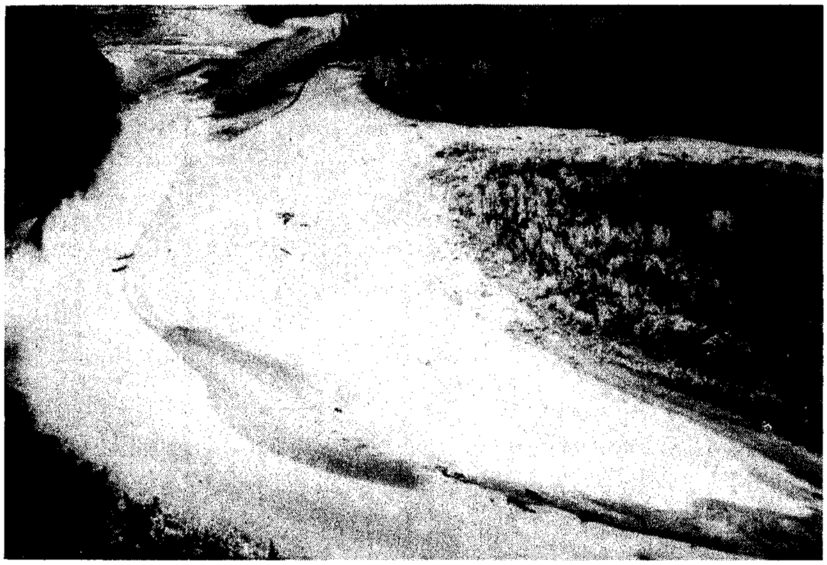

Fig. 8. Air view of John R., Alaska, at Departure Bar. Note boats at water's edge, left center in photo. Width of river at boats 120 ft.

a one-week river trip at time of low flow, September 1966. The gaging station record for the Koyukuk River at Hughes is included.

The bankfull condition of the gaging station is approximated by the discharge of 1.5 year interval. Figure 7 is a plot of Q_{bkf} and Q_{ave} vs drainage area. It can be seen that the river trip estimates fit consistently with Koyukuk gaging station record.

Estimates of average annual flow of an unmeasured river such as the John River could be made from consideration of all the gaging station records of north-central Alaska. The river trip data, however, add certain information that is not available even from gaging station records. For example, the downstream rate of change of particle size is large (exponent $-.48$) and of roughness about average ($y = -.17$). For the latter, Langbein's theoretical value (in Leopold, Wolman, Miller, 1964, p. 271) is $y = -0.22$.

The concavity of the profile of the John

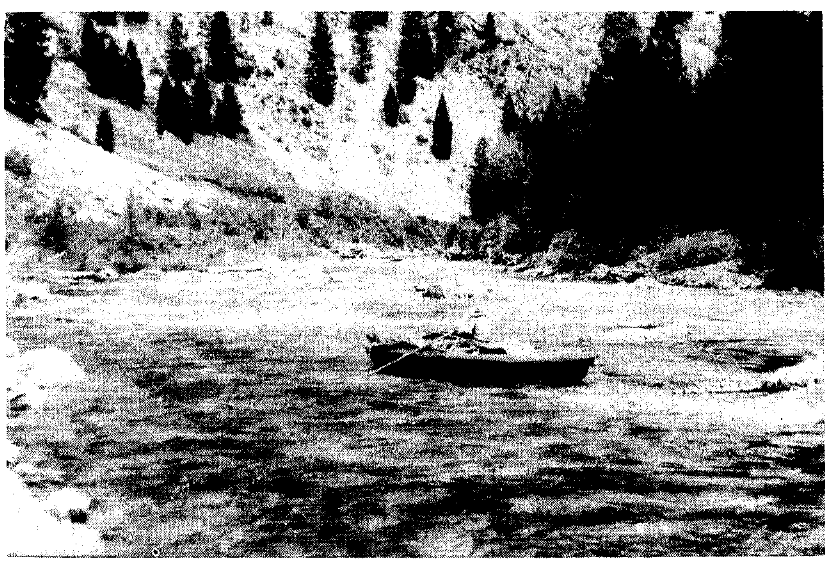

Fig. 9. A typical view of Middle Fork Salmon R., Idaho.

River is slightly less than average. Our value of exponent Z is –0.50 whereas Langbein's theoretical value for rivers is $Z = -0.73$. The concavity is in agreement with the decrease of bed material size.

For the John River as for the Salmon River local river slope varies greatly, apparently in response to variation in bed-material size, but the adjustment between these factors does not much affect downstream rates of change of width, depth, or velocity.

Concluding statement

A few simple observations made during a river boat trip yield a general picture of the hydraulic morphology of the rivers in the basin quickly and cheaply. The resulting estimates of significant flow parameters are useful for geomorphic description and are more complete for that purpose than even long records at a series of instrumented stations.

The purpose of the paper is to stimulate extension of these types of measurements in the hope of improving the estimates which can be made by simple procedures.

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