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SEDIMENT TRANSPORT FROM THE GLACIER ZONE, CENTRAL ASIA

by

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ABSTRACT

All available data on suspended sediment concentration and sediment discharge for Central Asian rivers have been used to estimate the small-grained sediment discharge from glaciated areas. Glacial streams discharge the bulk of suspended material during the period of intensive melting (July to September). There is a good exponential relationship between the suspended sediment concentration (or sediment discharge) and air temperature over glaciers. The area of the largest glacier in the watershed is another factor influencing the silt content and sediment run-off. Its contribution is smaller than that of air temperature. Yearly sediment run-off for glacial rivers in the Pamir and Tien Shan has been computed. Highest values are from the Pamir with many rivers yielding 3 000 tonnes km^{-2} (11 200 tonnes km^{-2} for the Vukhsh river). The highest run-off in Tien Shan is 2 000 tonnes km^{-2} for the Chatkal river.

SEDIMENT DISCHARGE FROM GLACIERS

There are very few observations on sediments near the tongues of glaciers (Davydov 1967, Sadykov 1976, Krenke and Suslov 1980), but there are more measurements of suspended sediment concentration and sediment discharge at river gauges located down-river at some distance from the glacier tongues. Reduction of sediment transport in run-off down mountain rivers is not significant due to the high velocity of flow.

The washing-out of sediments from the glacier zone in Central Asia occurs mainly during the period of intensive melting, i.e. from July to September. Snow and ice on the tongues of big glaciers, such as lednik Fedchenko and lednik Zarafshan, which descend to a low altitude, can begin melting earlier, sometimes in June or even in May, but the washing-out of sediments at this time is not high because the area of melting is limited, the air temperature is not high, and sunny weather often changes into snow-falls. An example of the variation of the concentration of suspended sediment and sediment discharge during the year is shown in Figure 1. The first increase of sediment transport in spring depends on rains and on melting of snow at lower altitudes, and is not very large. The main increase of sediment concentration and solid

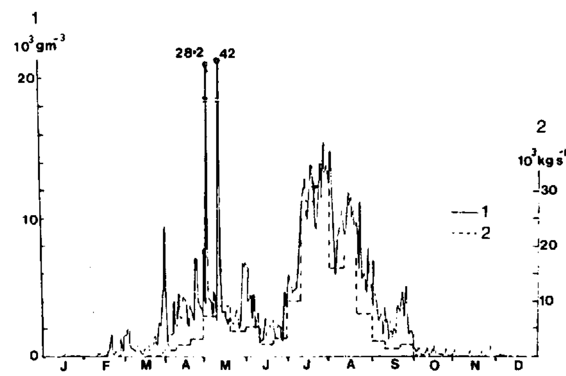

Fig.1. Variations of the daily suspended sediment concentrations (1) and the 10 days' mean sediment discharge (2) during the year. Vakhsh river, Tutkaul, 1956

discharge coincides with the intense melting of glaciers in summer.

The contribution of rain-fall floods to the flow of solid matter is normally of little importance for rivers of the Pamir and Alayskiy Khrebet; in some years, it is much more significant for the Tien Shan rivers. In calculations, when this is so, the method suggested by Shcheglova (1972) can be used to eliminate that part of the sediment run-off which is due to rain-fall floods.

SEDIMENT TRANSPORT FROM GLACIERS RELATED TO AIR TEMPERATURE

Fluctuations of suspended sediment concentration and sediment discharge are controlled by the air temperature in the glacier zone. One can obtain an exponential relationship plotting a mean sediment discharge R of a glacier river for a certain period versus a mean temperature t for the same period (Fig.2). The relationship is expressed as

$$R = a \exp\{bt\},$$

where R is the average monthly sediment discharge, t is the average monthly temperature at lednik Fedchenko meteorological station, and a and b

are parameters which differ for each river basin. They change over the range 0.66 to 256 for a and 0.36 to 0.66 for b. Their magnitudes are controlled by the areas and the topography of the watersheds and the areas of glaciers. The more glaciated the watershed the closer the relationship. The magnitudes of the parameters and correlation coefficients for the curves in Figure 2 are given in Table I.

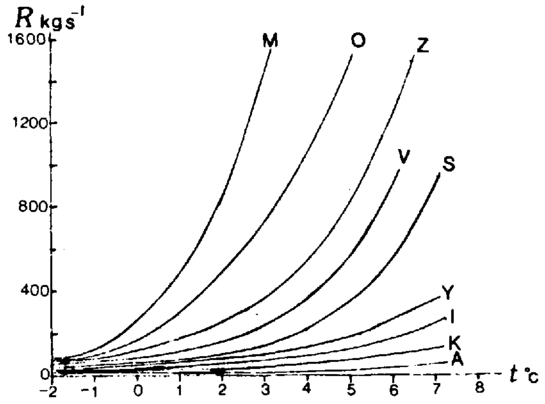

Fig.2. The monthly mean sediment discharge R for some glacier rivers versus the monthly mean temperature t at lednik Fedchenko meteorological station

M: Muksu river; O: Obikhingou river; Z: Zarafshan river; V: Vakhsh river; S: Sokh river; Y: Yazgulem river; I: Isfara river; K: Khodzhabakirgan river; A: Aravan river.

In the present study, routine measurements were performed at the river gauges by sampling the suspended sediment concentration at a fixed point twice a day (08.00 and 19.00 h).*

The air temperature over glaciers is the main factor which controls the sediment washing-out from the glaciated areas. A large or small sediment run-off usually occurs synchronously on nearly all glacial rivers in the western part of Central Asia. In 1950 and in 1973, for example, when the summers were very hot, the sediment transport of glacial rivers was 1.4 to 3.3 times larger than normal. It was especially large on rivers emerging from glaciers located at very high altitudes, e.g. the Lyangar river falling into Ozero Sarezskoye in the Pamir. The solid discharge here is usually low because of weak melting in ordinary summers; sediments accumulating on the glacier for many years can be washed off during a hot summer. In 1973 the sediment run-off of the Lyangar river was 4.2 times greater than normal. Also, the probability of strong glacial mudflows increases in very hot summers.

In years with cool summers, often preceded by heavy winter snow-falls, the sediment run-off is usually much smaller than normal. Such was the case in 1969 when some glaciers (in the Pskem river basin, for example, remained under snow for the entire summer (Shchetinnikov 1976). Summer snow-falls also decrease sediment run-off. In the Pamir they do not occur very often, but they happen more frequently in the eastern part of Central Asia, i.e. in central and eastern Tien Shan. Their influence upon intensity of melting is even greater in those mountain regions of the Soviet Union lying farther towards the east, e.g. Altayskiy Kray (Tronov 1966).

EFFECTS DUE TO SURGES AND SEISMICITY

Climatic factors controlling the flow of solid matter act synchronously. But there are also factors acting asynchronously. The main one is seismic activity. The middle of the Vakhsh river basin is a region of very high seismicity. Epicentres of many earthquakes are located there. One of the most catastrophic was the earthquake of 1949, which greatly increased the sediment run-off from glaciated areas of the watershed (Shcheglova 1974).

Glacier surges also increase sediment discharge though their influence upon sediment concentration has not been sufficiently studied so far. The sediment run-off before and after a surge was measured on the Koksu river, which runs from lednik Abramova in Alayskiy Khrebet (Akbarov and others 1979). The accelerated flow of ice was observed on the glacier in summer 1971; in April 1972, at a time of the

**Editor's note:* As has been noticed by the referees, the sampling techniques and the method of calculating monthly values of sediment discharge are not presented in this paper.

TABLE I. PARAMETERS AND CORRELATION COEFFICIENTS OF THE SEDIMENT DISCHARGE-TEMPERATURE RELATIONSHIP

River basin and outlet gauge	Parameters a	b	Correlation coefficient [a]	Date of observations
Muksu, Dovsear	256	0.66	0.971±0.010	1961-72
Obikhingou, Lyayrun	181	0.43	0.922±0.050	1966-70
Zarafzhan, Dupuli	105	0.41	0.842±0.033	1936-70
Vanch, Vanch	66.7	0.43	0.900±0.036	1950-62
Sokh, Sarykanda	36.6	0.46	0.842±0.032	1936-73
Yazgulem, Matraun	30.0	0.36	0.650±0.089	1950-55 1957-70
Isfara, Tash-Kurgan	8.17	0.49	0.786±0.042	1937-73
Khodzhabakirgan, Andarkhan	2.69	0.44	0.789±0.062	1950-67
Aravan, Iski-Naukat	0.66	0.36	0.568±0.139	1950-70

[a] Calculated for relevant straight regressions when relations are plotted in logarithmic scale.

year when glacier rivers are usually clear and have almost no suspended sediments, the water of the Koksu river became cloudy. The main phase of the surge took place in October 1972, and the largest run-off was observed in 1973. In this year, the largest suspended sediment concentration was measured. However, as stated previously, the summer of 1973 was very hot; both the run-off and the concentration of suspended sediments were much greater than normal for all the Central Asian rivers.

The geological effect of surging glaciers is much greater than that of ordinary ones. This fact depends on several causes. Dolgushin and Osipova, who studied the surging lednik Medvezhiy (1975, 1978), described six of them: (i) the glacier cuts up its rock sides, especially stone screes while it surges; (ii) the glacier slides over its bed as a whole body while it surges; (iii) weathering and mechanical destruction of rocks also increase because of the changing regime of a surging glacier; (iv) moraine material is carried down the glacier much more quickly during a surge; (v) debris accumulates at the lower part of a glacier after a surge during the degradation period and then is washed away by melt water; (vi) the largest sediment run-off takes place when the lake created by an ice dam bursts out, which is usual during a glacier surge.

The quantity of sediment in the ice of a surging glacier was also estimated for lednik Medvezhiy. In July 1968, after the 1963 surge, samples were taken from the dirty lower layers of ice, where the glacier was 82 m thick near its tongue. The content of small-grained sediments less than 2 mm in diameter in the whole 82 m layer was 8 690 g m^{-3} of ice (Dolgushin, personal communication). It is quite possible that such a quantity could be washed out and carried down the Vanch river as suspended sediments. However, the significance of glacier surges for sediment run-off is not so great as it is often believed to be. This can be confirmed by available data.

The surge of lednik Medvezhiy in 1963 and the burst of the glacier-dammed lake created a great flood down the Vanch river, resulting in the destruction of the river gauge. A new gauge was established some distance down-stream from the original one and observations were renewed in 1965. Data obtained here in 1973, when a new surge of lednik Medvezhiy took place, showed that the sediment run-off in the Vanch river was as great as that in neighbouring glacial rivers in that hot summer. Thus the influence of glacier surges on sediment run-off is of special interest.

From recent studies, it is known that there are many surging glaciers in nearly all Pamir watersheds. Surges happen everywhere in the Pamir and this is one of the factors influencing the flow of solid matter and making it very large.

MULTIPLE CORRELATION CONCERNED WITH DIFFERENT PARAMETERS RELEVANT TO SEDIMENT DISCHARGE

The analysis of factors which control the sediment transport from the glacier zone has shown that, as well as the climatic factors, the glacio-morphometric characteristics of the watersheds should be considered. The most important of these is the area of the largest glacier in a watershed (Shcheglova and Lebedeva 1978). Such a conclusion has been drawn using the method of multiple correlation (Alekseyev 1971). Relationships between the specific suspended sediment run-off from the glacier zone M and factors which control it were obtained. Data concerning the sediment run-off of many glacial rivers were used, namely from 37 basins with areas varying up to 31 000 km^2 in the Caucasus, Polar Urals, Alps, and Kamchatka, as well as in Central Asia. The climatic characteristic chosen was the mean summer temperature t (July to September) at the lower limit of the glaciers in the watershed. The study shows that the contribution of the temperature amounts to 52%, the remaining 48% is given by the area of the biggest glacier F. The contribution of the area of the small glaciers in the watershed has been statistically proved to be insignificant. The final relation is shown in Figure 3. The coefficient of multiple correlation is 0.752 ± 0.073.

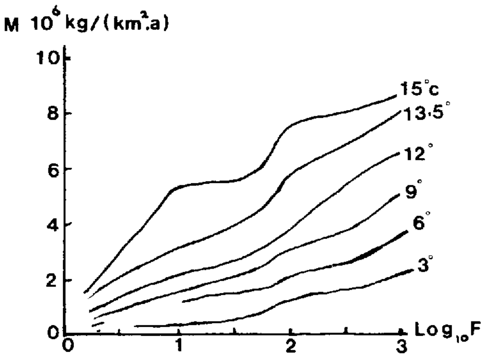

Fig.3. The specific suspended sediment run-off M plotted against the area F in km^2 of the largest glacier in the watershed for different levels of the mean summer temperature t (July-September) at the lower limit of glaciers in the watershed.

When the mean summer temperature at the lower limit of glaciers is not high, the washing-out of sediments is small and nearly independent of the area of the biggest glacier in the watershed. Such conditions are typical for high-altitude glaciers of the central Tien Shan. But when the temperature there is high (as is the case for such glaciers as lednik Fedchenko and lednik Zaravshanskiy), the influence of the morphological factor greatly increases. The specific quantity of suspended sediment washed out from the glacier zone M for watersheds having large glaciers reaches 8×10^6 kg km^{-2}a^{-1} as shown by Figure 3. Observations show that the magnitude of M for some watersheds can be even greater than this, e.g. for the Vakhsh river basin, $M=14.9\times10^6$ kg km^{-2} a^{-1}. This deflection from the relationship is due to the seismic activity of the region. The quantity of sediments added to the usual value because of seismicity can, however, be eliminated (Shcheglova 1974). Then $M = 8.81\times10^6$ kg km^{-2}a^{-1}, which is close to the relationship of Figure 3.

It seems evident that the geological structure of a watershed is of little significance for the value of sediment run-off because the glacier river basins used for the relationship of Figure 3 are of quite different geological character.

GEOGRAPHICAL DISTRIBUTION OF THE WASHING-OUT OF SEDIMENTS FROM THE GLACIER ZONE

The quantities of small-grained sediment washed out from the glacier zone for some watersheds of Central Asia (Fig.4) are given in

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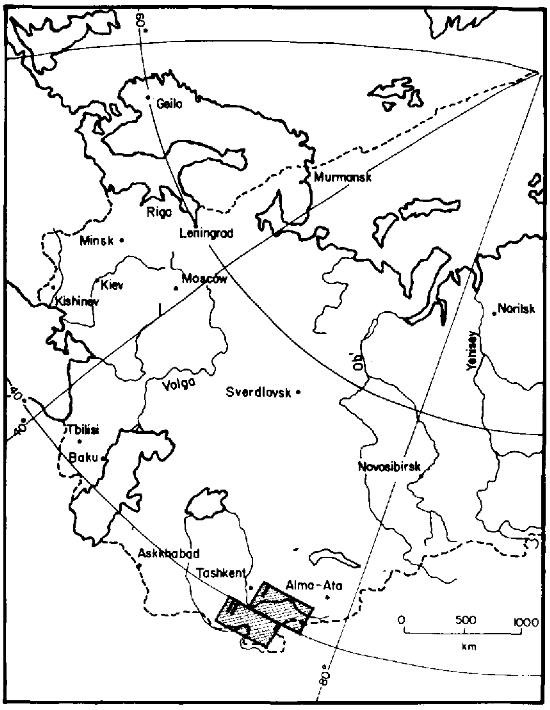
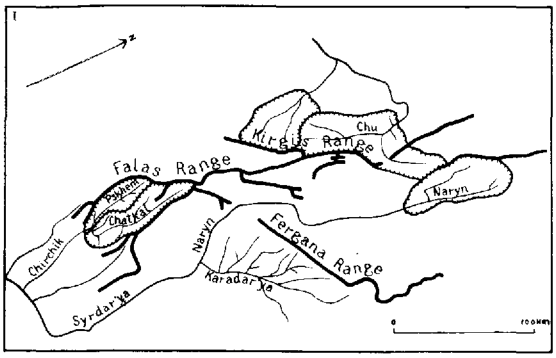
TABLE II. MORPHOLOGICAL AND GLACIO-CLIMATOLOGICAL CHARACTERISTICS OF GLACIER RIVER BASINS

River basin and outlet river gauge	Area of water-shed, km²	Mean weighted altitude m a.s.l.	Glaciated area: Total km²	Glaciated area: Total %	Glaciated area: Largest glacier km²	Mean summer (July-September) temperature °C: at the firn line	Mean summer temperature °C: at the end of the lowest glacier	Annual water discharge: total 10^6kg	Annual water discharge: glacial 10^6kg	Annual water discharge: glacial %	Specific suspended sediment discharge: total† 10^3kg km^{-2}a^{-1}	Specific suspended sediment discharge: glacial[x] 10^3kg km^{-2}a^{-1}	Dates of observa-tions
PAMIR													
Vakhsh, Turkaul	31 200	3 300	3 790	12.1	652	-1.3	13.4	89 500	56 500	63	2 870	14 900	1942-44, 1948-66
Vanch, Vanch	1 920*	3 780	354	18.4	64.4	3.5	15.3	2 360	1 990	84	1 230	5 630	1947-48, 1950-54, 1957, 1959-62, 1965-76
Yazgulem, Matraun	1 940	3 920	313	10.2	47.2	2.5	14.0	1 080	951	88	559	3 040	1950-55, 1957, 1959-76
Muksu, Dovsear	6 550	4 540	2 020	30.8	652	-2.5	13.4	12 500	11 500	92	1 910	5 660	1961-75
Obikhingou, Lyayrun	4 130	3 750	712	19.0	115	2.2	11.1	6 560	5 370	82	1 590	5 740	1966-73, 1975-76
Lyangar, mouth	335	4 670	52.8	15.8	9.5	0.0	7.7	21.1	17.1	81	63.0	323	1944-45, 1950-76
ALAYSKIY KHREBET													
Zarafshan, Dupuli	10 200	3 100	557	5.4	107	2.8	12.2	4 130	2 970	72	405	5 540	1940-43, 1946-76
Sokh, Sarykanda	2 480	3 480	158	10.4	25.4	1.0	12.3	1 740	1 530	88	704	5 930	1940-48, 1950-76
Isfara, Tash-Kurgan	1 560	3 170	170	10.9	13.0	0.3	9.0	391	329	84	250	1 940	1940-42, 1946-47, 1952-76
Khodzhabakirgan Andarkhan	1 740	2 420	51.8	3.0	6.5	1.8	8.0	249	113	45	64.0	2 180	1948-50, 1952-67
Aravansay, Iski-Naukat	1 680	3 290	87.8	5.2	9.8	0.5	6.8	90.8	229	25	54.0	261	1952-70
TIEN SHAN													
Pskem, Charvak	2 830	2 690	121	4.3	3.8	2.8	4.3	917	56.9	6.2	324	470	1950-64
Chatkal, Charvak	7 110	2 610	51.1	0.7	2.3	2.0	3.2	1 140	73.0	6.4	160	1 430	1950-64
Naryn, Naryn	10 500	3 570	964	9.2	69.8	-2.8	5.9	1 890	816	43	180	840	1954-62
Chu, Kochkorka	5 370	2 840	107	2.0	5.0	-1.5	2.0	118	14.2	12	22	133	1948-64
Issykata, Yur'yevskoye	546	3 030	54.6	10.0	5.2	-0.5	4.1	108	25.3	23	198	463	1950-64

*The gauge was removed down the river in 1965. The new area of the watershed is 2 010 km². Its mean altitude was not changed.
†The quotient of the total annual washing off (column 8) divided by the area of the watershed (column 2).
[x]The quotient of the glacial annual run-off (column 9) divided by the glaciated area (column 4).





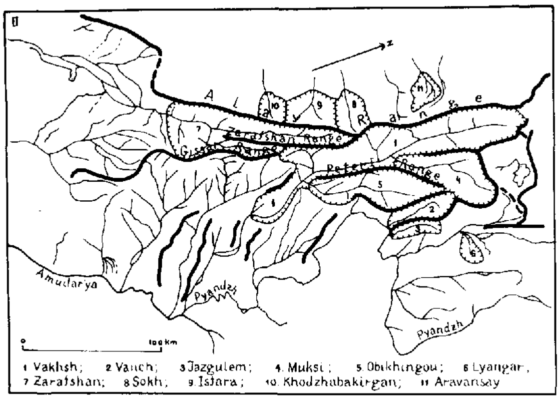


Fig.4. Key map.

I: Western Tien Shan watersheds. II: Pamir and Alayskiy Khrebet watersheds.

Table II. There is a great difference between values obtained from the two main mountain regions of Central Asia: the Pamir (including Alayskiy Khrebet) and Tien Shan. A typical value in the Pamir is about 5x10^6 kg km^{-2} a^{-1}. In Tien Shan these values are much lower, a typical value being about 5x10^5 kg $km^{-2}a^{-1}$. The geological activity of the glaciers and rivers of the Pamir is very marked. This conclusion is supported by the visual impression of the mountains with their abrupt slopes and fresh, morphologically young forms. These features are explained, at least partly, by taking into account the current uplift of the land, the rate being about 10 to 30 mm a^{-1} or more, which is also accompanied by great seismic activity in the region.

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