Mechanisms and spatial variability of erosion caused by meltwater in the USSR

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ABSTRACT Peculiarities of the mechanism and intensity of erosion processes caused by meltwater are discussed. The basic factors controlling erosion (relief, climate, soil, geological composition, land use) and their interaction within different natural zones are highlighted. The formation and distribution of solid precipitation and meltwater runoff and the character of soil erosion and its intensity were investigated at plots in the steppe zone and under forest cover where complex measures of erosion control were tested. The mechanisms of erosion were estimated on the basis of the results obtained.

Mécanismes et variabilité spatiale de l’érosion causée par les eaux de fonte en URSS

RESUME Dans cet article, on examine les particularités du mécanisme et l'intensité des processus d'érosion causés par les eaux de fonte. On met en luminère les principaux facteurs qui gouvernent l'érosion (relief, climat, sol, composition géologique, utilisation des terres) et leur interaction à l'intérieur de diverses zones naturelles. La formation et la distribution des précipitations solides et du ruissellement des eaux de fonte, ainsi que le caractère et l'intensité de l'érosion du sol ont été étudiés sur des parcelles de terrain dans la zone de steppe et sous couverture forestière, et des mesures complexes de maîtrise de l'érosion ont été testées. Les mécanismes de l'érosion ont été évalués d'après les résultats obtenus.

The territory of the USSR is mainly influenced by sheet and gully erosion caused by meltwater. Accelerated erosion is characteristic of areas of dissected relief and intensive land use. The mean meltwater runoff is 1317 mm year\(^{-1}\) for the forest-steppe zone of the European USSR. This runoff varies from 9.2 (Dniester-Azov Province) to 189.6 mm (Carpathian Province) and is dependent on the relief, climate, type of solid precipitation, meltwater runoff and erosion intensity. The water capacity of snow before melting also varies greatly. In northern non-agricultural areas meltwater runoff varies from 72 mm (Bureja-Jagdinsk Province) to 200 mm (Kamchatka, mountain area) and the snow melt intensity from 3.3 to 6 mm day\(^{-1}\), respectively. In agricultural areas these figures are 4 mm (East Georgia) and 160 mm (North Urals) and 0.3 and 0.8 mm day\(^{-1}\), respectively (Silvestrov, 1965).

Relief, geology, climate, soil and land use are known to be the basic factors controlling erosion. The combination of these factors acts universally as a generator of the erosion mechanism which
includes soil erosion, transport and accumulation, including that caused by meltwater.

Slope dissection was found to regulate the meltwater runoff concentration and erosion intensity which also varies with different types of slope (concave, positive, straight and complex). The most intensive erosion occurs on positive slopes (increasing slope towards the base) which cause accelerated increase of the meltwater runoff. On concave slopes (steepness decreased toward the base) runoff increase is not followed by an increase of the soil wash. The straight slopes are characterized by similar processes as for the concave slopes but the intensity of erosion is less. The ratio of the slope components plays the decisive role on complex slopes with various forms, slopes and length (Sobolev, 1973). Most intensive erosion occurs on slopes with south, southwest and southeast aspects.

Geology also influences the erosion processes. Investigations have revealed that "two types of slopes are distinguished by different geological composition: concave slopes are associated with alluvial fans (i.e. sediments accumulated in the lower parts of slopes as a result of soil erosion); positive slopes are mantled with colluvium (products of weathering in situ) of bedrock or Quarternary drift deposits (Sobolev, 1973).

Gully erosion in the southern European USSR occurs on loess, loess loams and clays. On these deposits erosion occurs only when the local base level of erosion is deep. If deposits are of an homogeneous nature no gully erosion is observed on the loess deposits. Gully erosion does not occur on fluvio-glacial, alluvial and eolian sands because of their high permeability. In those places where sands are underlain by loams and the base level of erosion is deep, the erosion process can be intensive.

Sheet erosion occurs mainly on deposits of boulder clays, loams and sands. Gully erosion occurs only at the river banks. In the Oka River valley and in Gorki region where Jurassic clays are exposed no deep gullies are noted and channel erosion is slight. In those places where gullies occupy Tatar stage deposits (characterized by altering firm and weak layers) their heads, banks and sometimes bottoms are step-shaped as a result of differential erodibility (Soos, 1949).

Climatic parameters (precipitation, temperature and wind regimes) also affect the mechanism of erosion. These parameters are characterized by the long-term rates of the winter solid precipitation and spring snow-melt. These parameters however cannot be used directly to estimate the erosion intensity because local rates are modified by relief, weather conditions and land use, resulting in significant deviations from the mean rates. This statement can be expanded by consideration of the Central-Chernozemic region which includes several natural zones. The mean January temperature over the Middle Russian Uplands (northern part of the forest-steppe subzone) is 9.5°C, over the Oka-Don lowland, 11°C, and in the steppe zone, -8.5°C. Winter precipitation for these areas is 155, 145 and 140 mm respectively, the snow cover 27, 32 and 20 cm and the duration of the snow cover 121, 128 and 100 days respectively. The water equivalent of the snow at the onset of melting varies from 77 mm in
the north to 57 mm in the south. The duration of the snowmelt period varies from 13 to 23 days and the intensity of melting from 3 to 5 mm day\(^{-1}\) respectively.

On leached chernozem soils (Kursk zonal-melioration station, north part of the typical forest-steppe zone) the mean water equivalent of snow in 1962-1964 was 69 mm (440, 850 and 780 mm respectively), the mean meltwater runoff - 25.8 mm (18.8, 54.3 and 4.3), the least runoff value being noted at the highest water equivalent of snow. The erosion intensity also varied greatly within the years mentioned. After 1961 with very low precipitation in 1962 the water turbidity at the runoff plots situated on an arable slope of 25\(^{\circ}\) varied from 0.72 to 3.55 kg m\(^{-3}\) depending on slope gradient (in 1983 it was 114.0 and 489.0 kg m\(^{-3}\) respectively).

On similar soils in the west region of the typical forest-steppe zone (experimental station of the Geography Institute) under similar conditions, the mean water equivalent of the snow was 111.0 mm (38.0, 43.0 174.0 mm) and the mean meltwater runoff 35.0 mm (17.0, 29.5 and 59.0). The mean water turbidity in 1962 was 3.93 kg m\(^{-3}\) in years with high precipitation, the maximum meltwater turbidity from the arable slopes of 2\(^{\circ}\) reached 56.6 kg m\(^{-3}\) (Surmach, 1976). In the Oka-Don lowland (south forest-steppe) the annual solid precipitation was 69 mm (mean of 32 years) in the open steppe and 91 mm in the forest belts (Kaulin, 1968). With a water equivalent of snow of 82 mm (mean of 24 years) the meltwater runoff from the drainage basin of the Steppnaja balka was 39.2 mm. For balka Osinovesja (partly afforestated), these parameters were 69.6 and 46.3 mm respectively. On a wind-exposed slope of southeast aspect within the forest belts (after ploughing) the mean water equivalent of snow by the onset of melt was 38.3 mm (mean of three years). Runoff was only 4.5 mm which resulted in 3.1 t ha\(^{-1}\)year\(^{-1}\) soil loss. On a similar slope of northwest aspect under steppe conditions the water capacity of solid precipitation was 48.3 mm, runoff 11.9 mm, and soil loss 9 t ha\(^{-1}\) in the year with highest precipitation.

The physical properties of snow during precipitation and the whole period of negative temperature regime also affect redistribution of the solid precipitation. We shall consider some contrasting weather situations affecting the erosion mechanism.

(a) Erosion is not seen when snow falls on dry soil under negative temperatures during the winter period (this situation is often observed in the southeast part of the Central-Chernozemic region), when runoff takes place at negative average daily air temperatures (snowmelt is observed in the day-time, but at night the water is frozen). The meltwater is fully absorbed by the soil.

(b) If several thaws occur during the winter period, the last of which being longer and accompanied by a sharp and long temperature drop, an ice crust is formed on the soil surface. In this situation erosion does not occur even during intensive snowmelt. Only established runoff routes such as hollows and depressions can be destroyed.

(c) The most intensive meltwater runoff and erosion occur when soil is saturated in autumn, slightly frozen in winter, the snow cover is deep and an intensive melt takes place at positive average air temperatures, with liquid precipitation. The prolonged period of snowmelt (15-20 days longer than usual) usually promotes
considerable destruction and loss of soil.

Besides the natural factors mentioned above the erosion intensity is also affected by the soil type, its chemical and physical properties. Chernozems with their aggregation due to the high amount of humus and calcium and homogeneous texture are the least erodible. They are also characterized by the best water permeability and capacity.

Grey forest and podzolic soils as well as the non-structured alkaline chernozem occupy second place from the point of view of resistance to erosion. Sand soils are easily eroded. Surface runoff does not occur on them, but if they are underlain by deposits with low water permeability, erosion is very intensive.

All soils of the loam and clay types on slopes are easily eroded due to poor water permeability and siltation. Resistance to erosion is also greatly dependent on strength, particle density and infiltration capacity especially at the beginning of the meltwater runoff. Deterioration of these properties results in increased runoff and erosion. Sodium saturation of the soil complex and decreases in calcium content and pH result in less resistance to erosion. Loss of the upper soil layers highly enriched by humus causes similar consequences.

According to the classification adopted in the USSR there are three levels of soil erodibility: slight, moderate and severe. This evaluation enables us to make a proper diagnosis of soils taking into account their type and subtype.

We shall consider two types of soils under arable agriculture and exposed to meltwater erosion.

**TYPE I**

(a) Typical chernozem with humus layer up to 50 cm, a third of the A + B_I horizon washed out, part of the dark B_I horizon ploughed - slightly erodible soil.

(b) Half of A + B_I horizon is washed out, considerable part of B_I horizon underlain by transition horizon B(B_2) is ploughed - moderately erodible soil.

(c) Most of the humus layer is washed out, the soil colour is that of the parent rocks - severely erodible soil.

**TYPE II**

(a) Grey forest soil with an arable layer of 20-22 cm (original thickness of humus layer was 30-40 cm), a third of the humus layer is washed out, A_2B_I horizon is not ploughed or only the upper horizon is ploughed - slightly erodible soil.

(b) More than a third of the humus horizon is washed out, part of A_2B_I horizon is ploughed, arable layer is of brown colour - moderately erodible soil.

(c) Humus layer is completely washed out, B horizon is ploughed, its colour is brown, it is impossible to determine the soil subtype - severely erodible soil.

Measures to control the meltwater erosion and soil loss were investigated at a number of drainage basins (Table 1) located in the area of the experimental station (V.V.Dokuchaev Agricultural Research Institute of the Central-Chernozemic Zone, Voronezh region).

In the Steppnaja, Travopolnaja and Selektrevorskaja balkas
Erosion caused by meltwater

TABLE 1  Parameters of balkas and drainage basins investigated

<table>
<thead>
<tr>
<th>Name of balka</th>
<th>Drainage basin area (km²)</th>
<th>Length of talweg (km)</th>
<th>Mean width of drainage basin (km)</th>
<th>Mean slope: talweg drainage basin</th>
<th>Beginning of observation (month-year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vysokaja</td>
<td>0.66</td>
<td>0.74</td>
<td>0.55</td>
<td>0.5</td>
<td>III-1950</td>
</tr>
<tr>
<td>Travopolnaja</td>
<td>0.93</td>
<td>1.2</td>
<td>0.50</td>
<td>0.8</td>
<td>III-1950</td>
</tr>
<tr>
<td>Steppnaja</td>
<td>1.92</td>
<td>1.9</td>
<td>1.20</td>
<td>1.5</td>
<td>III-1950</td>
</tr>
<tr>
<td>Selektrovskaja</td>
<td>1.02</td>
<td>0.74</td>
<td>0.57</td>
<td>0.3</td>
<td>III-1950</td>
</tr>
<tr>
<td>Khorolskaja</td>
<td>0.83</td>
<td>0.93</td>
<td>0.69</td>
<td>0.5</td>
<td>III-1952</td>
</tr>
</tbody>
</table>

runoff was estimated by means of thin-plate triangular weirs, in Vysokaja and Khorol'skaja by means of flumes and triangular weirs. All gauging sites were equipped with "Valdai" water-stage recorders.

Table 2 shows that the highest amount of solid precipitation was retained at 16% afforestation, but 3% afforestation is considered to be the most profitable. Our investigation revealed that to control erosion and to decrease the meltwater runoff from the arable lands, optimum results are obtained by land treatments to decrease water movement along the slope and to speed up infiltration into the soil. These treatments produce a thicker arable layer which promotes increased infiltration and water permeability.

TABLE 2  The meltwater runoff as affected by the drainage basin afforestation

<table>
<thead>
<tr>
<th>Name of balka</th>
<th>Drainage basin afforestation (%)</th>
<th>Mean data for 1950-1961</th>
<th>Surface detention: (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Water equivalent runoff of snow (mm)</td>
<td>Meltwater runoff index (%)</td>
</tr>
<tr>
<td>Vysokaja</td>
<td>3</td>
<td>93.3 122</td>
<td>26.6 83</td>
</tr>
<tr>
<td>Travopolnaja</td>
<td>1</td>
<td>78.8 100</td>
<td>32.2 100</td>
</tr>
<tr>
<td>Steppnaja</td>
<td></td>
<td>121.7 154</td>
<td>27.0 84</td>
</tr>
<tr>
<td>Selektrovskaja</td>
<td>16</td>
<td>98.1 124</td>
<td>4.0 12</td>
</tr>
<tr>
<td>Khorol'skaja</td>
<td>11</td>
<td>101.7 129</td>
<td>13.4 42</td>
</tr>
</tbody>
</table>

NOTE: Percentages are calculated with respect to the parameters of the 2d balka.
The effect of different measures of soil cultivation was tested at the forest site of the Dokuchaev Soil Institute. The experimental plot of 64 ha was surrounded by a forest belt of 15 m width. It was situated on a 3° southeast facing, wind-exposed slope of the Talovaja balka.

Investigations were carried out for three years. The area of the runoff plots was 0.5 and 0.32 ha with the length along the slope equal to 100 m. Meltwater runoff was estimated by means of thin-plate triangular weirs. Data before and during runoff are presented for several years to give the better representation on interaction of the basic erosion agents, such as relief (form, steepness, length and aspect of the slope), climate and weather conditions, soil type and measures to control erosion.

The year 1957-1958 was characterized by a dry autumn (76% of the mean long-term rate), frequent long thaws and a wet winter (142% of the mean rate). Due to thaws, however, the snow cover was rather irregular and ice crusts were noted on the soil surface and within the snow cover. Snowmelt started on 2 March 1958. Warm weather with positive temperatures promoted runoff. On 4 March meltwater runoff was observed at the second, third and fifth plots with different treatment (Table 3), and on 9 March at the other plots (the control plot and the fourth plot). With falling temperature on 7 and 8 March the runoff stopped. It resumed on 8 March at the second and third plots, and on 9 March at the control and fourth plots. The new temperature fall on 11 March interrupted the runoff at the second and fourth plots, and the following day it stopped at the other plots. On 5 April it resumed at the third and fifth plots but at the others the snow had already melted by that time.

The soil loss values for the plots with the various treatments were 4.0, 0.0, 19.6, 0.0 and 2.3 respectively. The autumn-winter period of 1958-1959 was unfavourable for runoff. In the autumn the precipitation was 26% less than usual, and the winter was 35 days shorter than normal with little precipitation. There were 10 thaws in December-January destroying the snow cover. By the beginning of snowmelt the water capacity of snow at the fifth plot was twice as much as at the control, at the second plot it was 27.7 mm, at the third - 4.5 mm and at the fourth - 21.9 mm higher than at the control plot. These data show the last treatment (non-ploughed, stubble) to be the most effective measure for snow detention even on wind-exposed slopes.

Intensive snowmelt in the forest belts started only on 23 March whereas in the open steppe the snow had already melted. At the fifth plot (with stubble) meltwater runoff took place during the seven days up to 30 March. At the second plot it lasted only one day (23 March) and its volume was insignificant. At the fourth plot a runoff of 0.5 mm was observed over 24-25 March. There was no meltwater runoff at the other plots. The water balance investigation at the runoff plots in 1958-1959 revealed that the significant part (almost half of the water) at the fifth plot was lost by runoff in spite of the high winter precipitation and snow accumulation by the stubble. No runoff at the other plots was noted.

Weather conditions during 1959-1960 were characterized by a rainy September and October. There were 14 days in September with 93.9 mm precipitation and 19 days in October with 40.4 mm. From the start
<table>
<thead>
<tr>
<th>Plot No.</th>
<th>Treatment</th>
<th>Area (m²)</th>
<th>Gradient</th>
<th>Water equivalent of snow before melting (mm)</th>
<th>Water equivalent of ice crust (mm)</th>
<th>Liquid and solid precipitation (mm)</th>
<th>Total income (mm)</th>
<th>Meltwater runoff (mm)</th>
<th>Infiltration loss (mm)</th>
<th>Runoff index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mouldboard ploughing to 20-22 cm (control)</td>
<td>3788</td>
<td>0.053</td>
<td>62.4</td>
<td>15.2</td>
<td>12.1</td>
<td>89.7</td>
<td>5.6</td>
<td>84.1</td>
<td>0.06</td>
</tr>
<tr>
<td>2</td>
<td>Mouldboard ploughing to 20-22 cm ridges and dikes</td>
<td>3462</td>
<td>0.047</td>
<td>86.7</td>
<td>21.0</td>
<td>10.8</td>
<td>118.5</td>
<td>16.2</td>
<td>102.3</td>
<td>0.14</td>
</tr>
<tr>
<td>3</td>
<td>Mouldboard ploughing to 20-22 cm 15 cm soil deepening</td>
<td>3850</td>
<td>0.048</td>
<td>30.1</td>
<td>40.5</td>
<td>27.9</td>
<td>98.5</td>
<td>22.6</td>
<td>75.9</td>
<td>0.23</td>
</tr>
<tr>
<td>4</td>
<td>Disking to 35-40 cm (stubble of 10-15 cm)</td>
<td>3367</td>
<td>0.049</td>
<td>88.2</td>
<td>2.7</td>
<td>10.8</td>
<td>101.7</td>
<td>6.5</td>
<td>95.2</td>
<td>0.06</td>
</tr>
<tr>
<td>5</td>
<td>Unploughed plots (stubble of 10-15 cm)</td>
<td>3678</td>
<td>0.053</td>
<td>61.6</td>
<td>16.0</td>
<td>27.9</td>
<td>105.5</td>
<td>74.5</td>
<td>31.0</td>
<td>0.71</td>
</tr>
</tbody>
</table>
of the first 10-day period there were 23 days with frosts, in the last 10-day period the average temperature was -7°C. Temperature variations resulted in considerable destruction of the soil aggregates. Stable soil freezing occurred in the first 10-day period, in the second it was frozen to 25 cm. In the first and second 10-day periods the temperature reached -20 to 25°C, the solid precipitation being only 3.9 mm. Lack of snow cover and over-wetting of the upper soil layer resulted in frost crack formation at the third plot.

The heavily frozen soil layer and the ice crust promoted intensive meltwater runoff from the plots. It started on 16-17 February and was repeated in March. The highest runoff index in February (0.144) was noted at the fifth plot. At the control plot the runoff index was 0.043 (twice as much as at the third and fourth plots). At the fourth plot (non-mouldboard disking) runoff started on the first day of the third 10-day period and lasted (with intervals) up to 25 March, at the fifth plot - up to 29 March. Meltwater runoff took place over the frozen soil even at the end of the spring flood. The highest runoff index in March (0.482) was observed at the fifth plot. At the control plot the runoff index was 0.378, 2.6 and 2.3 times higher than that at the second and third plots respectively.

The soil losses at the plots were: 5.5, 4.0, 0.4, 0.0 and 8.5 kg ha⁻¹ respectively.

Observation of the runoff and wash formation showed that in the case of meltwater runoff occurring under negative air temperatures, the first stages of the process of soil destruction takes place mainly in rills on the surface of the arable plots. In places where the soil is characterized by micro-elevations and cracks or is of cloddy structure, microflows dissolve the melting clods and crumbs. On their way along the slopes such microrills transport or deposit the soil material. In field ditches and ravines large flows wash away the banks and bottoms. The highest soil and ground wash occurs during runoff peaks when water discharge is high and the surface soil layer is melting.

Data obtained have revealed the complex nature of the erosion mechanism. Long-term observations of erosion and measures to control it are necessary for a proper evaluation of the mechanism of erosion processes.

REFERENCES


The IAHS International Commission on Snow and Ice (ICSI) designed and encouraged the snow and ice programmes of the UNESCO sponsored International Hydrological Decade (IHD) and International Hydrological Programme (IHP). As a result of the IHD and the IHP very considerable advances have been made in our understanding of hydrological processes in high mountain areas, and several good integrated data sets are now available for further research analysis.

This new IAHS publication has been produced by the ICSI Working Group on Prediction of Runoff from Glacierized Areas and edited by Gordon J. Young, the working group chairman. The publication opens with an overview by Gordon Young (Ottawa, Canada) which discusses the worldwide distribution of glacierized areas; how predictive techniques for runoff serve water supply and flood control; and climate and hydrological response. An overview of contemporary techniques then follows by Andrew G. Fountain (Tacoma, USA) & Wendell Tangborn (Seattle, USA). This second overview summarizes current techniques for predicting runoff from glacierized basins with emphasis on techniques for estimating the drainage of water from glaciers. The next section presents case studies as illustrations in an attempt to bring together the current knowledge and practices in hydrological predictive techniques. The wide-ranging case studies include studies of river basins of various sizes and having substantially different climatic regimes, and are separated into case studies for water supply (from Switzerland, Canada, Greenland, USSR, China and Pakistan) and case studies of catastrophic floods (USSR, Nepal, Pakistan and Canada).

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The International Symposium on Sea Level, Ice Sheets, and Climatic Change was held at Canberra, Australia, on 7 and 8 December 1979 as part of the 17th General Assembly of IUGG. The symposium was sponsored by IAHS, IAMAP and IAPSO and was organized by the International Commission on Snow and Ice of IAHS, with support from the Local Organizing Committee for the IUGG General Assembly.

The major objective of the symposium was to review current ideas and recent results on the processes and the effects of interactions between sea level, ice, and climatic change on time scales of 100 to 10,000,000 years. While the cryosphere has been the subject of considerable speculation regarding the climatic past and future, the exact causal relationships between cryosphere phenomena and sea level in the past remain uncertain. Description of those changes in sea level and ice sheets which had causes and effects other than climatic, would hopefully define a residue of features with direct climatic implications, and help to identify interconnections between the three phenomena.

As might be expected with a symposium theme of such general scope, the contributed papers cover a very wide range of topics, and it is hoped that this will highlight the complexity and multidisciplinary nature of the study of relationships between sea level, ice, and climatic change. The papers have been grouped into two major sections, each divided into sub-sections.

ICE AND SNOW AS ELEMENTS IN THE WEATHER AND CLIMATE SYSTEM AND AS INDICATORS OF CHANGE
- The record of climate change in glaciers
- The climatic role and environmental effects of snow
- Sea ice as a climatic element
- Evidence of the past climatic change from large ice sheets

FEATURES AND INTERACTIONS OF SEA LEVEL, ICE AND CLIMATE IN THE QUATERNARY
- The global record of the late Quaternary changes of sea level, ice and climate
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