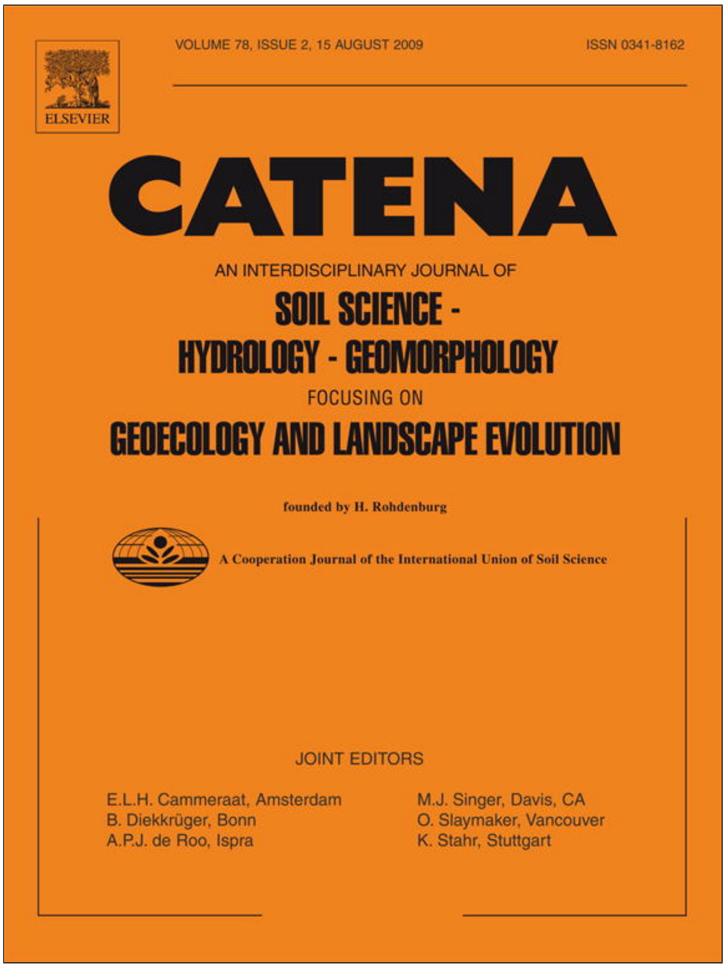
VOLUME 78, ISSUE 2, 15 AUGUST 2009
ISSN 0341-8162
ELSEVIER
CATENA
AN INTERDISCIPLINARY JOURNAL OF
SOIL SCIENCE -
HYDROLOGY - GEOMORPHOLOGY
FOCUSING ON
GEOECOLOGY AND LANDSCAPE EVOLUTION
founded by H. Rohdenburg
A Cooperation Journal of the International Union of Soil Science
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Catena 78 (2009) 122–128

Contents lists available at ScienceDirect

Catena

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Snowmelt runoff parameters and geochemical migration of elements in the dissected forest-steppe of West Siberia

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ARTICLE INFO

Article history:
Received 22 July 2008
Received in revised form 19 March 2009
Accepted 26 March 2009

Keywords:
Water erosion
Snowmelt runoff
Snow depth
Land use
Humus
Exchangeable cations

ABSTRACT

In three West Siberian geomorphological regions, the snowpack was measured and the soil frost depth, the volume of surface runoff, the humus content of the soil, and the chemical composition of meltwater were determined for each year from 1969 to 2007. The study was carried out on chernozem-type soils during different hydrological years. The water content of the snow varied in those years from 65 mm under low-snow conditions to 255 mm in very snowy winters. Both the amount of snow and the type of land use influence the surface runoff volume. Slopes covered with perennial grasses and plowland had the greatest snowmelt runoff values (>50% of the water content of snow). The removal of clay particles depletes the humus from chernozem and phaeozem soils. Moderately eroded soil is transformed into medium-humus soil, and strong erosion leads to low-humus soil. In meltwater running on the surface of phaeozems situated near a cement factory, the concentrations of calcium and magnesium were 15- to 20-fold higher and carbon concentrations were 1.5-fold higher than in soils outside the pollution zone.

In dissected areas of the West Siberia forest-steppe, the removal of soluble chemical elements by surface snowmelt runoff is considered to be ecologically safe if it does not exceed 20 kg ha^{-1}, or 5 kg ha^{-1} for carbon. The removal of 21–50 kg ha^{-1} of alkaline-earth and alkali elements (up to 30 kg ha^{-1} of carbon) is classified as slightly ecologically dangerous; 51–100 kg ha^{-1} (up to 90 kg ha^{-1} of carbon) as of moderate ecological danger; and 101–190 kg ha^{-1} (up to 150 kg ha^{-1} of carbon) as highly dangerous.

1. Introduction

Spring snowmelt runoff commonly causes water erosion in areas where below-freezing temperatures and snow cover persist for months (Dunne and Black, 1971; Johnsson and Lundin, 1991; Demidov et al., 1995; Wade and Kirkbride, 1998; Tanasienko, 2002; Ollesch et al., 2005 etc.). The intensity of this erosion depends upon a variety of factors, of which the most important are slope gradient, land use type, precipitation in autumn and winter, and frost penetration depth (Kienholz, 1940; Pierce et al., 1958; Shanley and Chalmers, 1999; Lindström et al., 2002 and others). Moving on the surface of slopes, snowmelt runoff leaches many biogenic elements from the soil. One such element is carbon (humus), an organic "glue" responsible for soil structure formation and stability against erosion that accounts for the proportion of solid compounds in the runoff (Tisdall and Oades, 1982; Elliott, 1986; Oades, 1988; Kay, 1998). Humus is known to help stabilise aggregates, as humic acids bind to highly reactive sesquioxides and contribute to soil structure formation (Tyurin, 1940; Kononova, 1963; Bogdanov, 1964). On the other hand, soils with high humus content absorb soil solution calcium, the critical element for a granular soil structure, more efficiently, making them of agricultural importance because such soil is loose and possesses good aeration and drainage qualities. According to V.R. Vilyams (1939), alkaline-earth bases, especially calcium, make humic acids into low-solubility compounds and transform the soil into a "cement," which increases the hardness of soil structural entities.

The geomorphological and climatic conditions in West Siberia are characterised by strong dissection of the relief, large amounts of snow in winter, the presence of an ice sheet that prevents meltwater infiltration, and rapid snowmelt. Given the lesser depth of Siberian chernozems compared to soils in the European part of Russia, these factors combine to make these soils extremely vulnerable to erosion (Tanasienko, 2003). As a result, during the snowmelt period, abundant runoff occurs on slopes, which account for approximately 60% of the arable land of the region.

Recently, the environmental load has greatly increased due to traffic and the combustion of large quantities of solid and gaseous fuel. Sulfur dioxide and nitrogen oxides are the main atmospheric pollutants generated by coal incineration (Mackenzie and El-Ashry, 1989). Considerable purification of the atmosphere occurs when snow falls. Snowflakes absorb many pollutants from the atmosphere, including acid-forming gases and aerosols (Sizuki, 1991). Addison (1989) reported that approximately 20 kg ha^{-1} of sulfates and 15 kg ha^{-1} of nitrates fall with snow. These pollutant loads can enter the soil and acidify it during the 10–15 day-long snowmelt period. They promote the leaching of many chemical elements and consequently damage the environment.

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doi:10.1016/j.catena.2009.03.008

Data on erosion losses and factors affecting erosion intensity in West Siberia are scarce and quite dispersed. This paper is an effort to summarise the results of studies conducted over 1969–2007.

The aims of the present study are to investigate:

(1) snowmelt runoff parameters on arable and virgin soils,
(2) the content of exchangeable cations in eroded soils, and
(3) the chemical composition of snowmelt runoff and the removal of elements during different hydrological years in West Siberia.

2. Materials and methods

2.1. Study area and soils

The study area is located in the south-east of West Siberia and includes three geomorphologic regions: the Bugotac Hills (called Predsalairye), the Ob' River valley within the Novosibirsk region (called Novosibirsk Preobye) and the Kuznetsk hollow (Fig. 1).

Predsalairye is a hilly plain generally inclined toward the West Siberia plain, with an absolute height of 200–300 m above sea level. Watershed areas account for approximately 20% of the Predsalairye territory. The region features long (600–800 m), complex slopes with gradients of 3–9°. The hill density of the horizontal dissection ranges from 1.0 to 1.2 km km^{-2} and the vertical dissection is approximately 75–100 m (Nikitenko, 1963).

Novosibirsk Preobye is characterised by much less dissection of the territory than in Predsalairye. According to Orlov (1971), the gully density and stabilised gully net does not exceed 0.5 km km^{-2}. However, watershed areas occupy up to 40% of the territory. Watershed side slopes are usually convex and long (800–1200 m) with a small gradient (1–5°).

The relief of the Kuznetsk hollow is strongly dissected (Orlov and Tanasienko, 1975). On the west side of the hollow, the horizontal dissection ranges from 0.6 to 0.8 km km^{-2} and is 1.0–2.6 km km^{-2} in the rest of the territory. In some agricultural areas of the hollow, the horizontal dissection reaches 3.3–3.5 km km^{-2}. The vertical dissection is the same as in Predsalairye (75–100 m). Owing to the deep, dense dissection, watershed ridges here are narrow and their axis lines are sinuous. Watershed slopes have a gradient of 3–9°, and slopes near stabilised gullies are 10–25° and steeper. Some 8–25% of the plowland is situated on slopes of up to 1°. Approximately one-third of the plowland is situated on slopes with an inclination of 1–3°, mainly on the upper parts of the slopes. More steeply sloped land (>3°) has even greater exposure to erosion. In the given geomorphologic area, land with slopes >3° accounts for 30–50% of the total and thus represents the potential for large amounts of surface runoff to develop. On average, approximately 10% of all plowland is situated on slopes with a gradient of 6–9° and 5% on slopes with a gradient of more than 9°. Because of imprudent land use on such slopes, erosion has disastrous consequences (Khmelev and Tanasienko, 1983).

The soils under study are classified as non-eroded (full profile) and eroded Luvic Phaeozems, Haplic Phaeozems and Haplic Chernozems (IUSS Working Group WRB, 2006) located in Predsalairye, Preobye and the Kuznetsk hollow (Fig. 2). The soils formed are loessial loams.

The depth of the humus horizon (A) of the Pred–Altay forest-steppe chernozem ranges from 44 to 51 cm, whereas medium-depth chernozems have a humus layer (A+AB) of 56–62 cm. The distinctive feature of the humus horizons (A and AB) is their deep tongue shade, a facial peculiarity of chernozem-type soils of West Siberia. The depth of the humus layer does not change significantly within the dissected forest-steppe ($V<10\%$). Thus, the soils of the flat watersheds or the upper parts of slopes can be used as a standard for non-eroded chernozems.

In terms of grade structure, the soils mainly contain (Table 1) large silt (0.05–0.01 mm) and clay (<0.001 mm) fractions, with very little sand (1–0.05 mm).

2.2. Climatic characteristics

The annual precipitation in the region is 500 mm, with winter precipitation making up 20% of the annual total. The cold period of the hydrological year is from November to March, with January being the coldest month. January temperatures average −20.5 °C and may reach −50 °C. The snow cover normally begins to form in late November

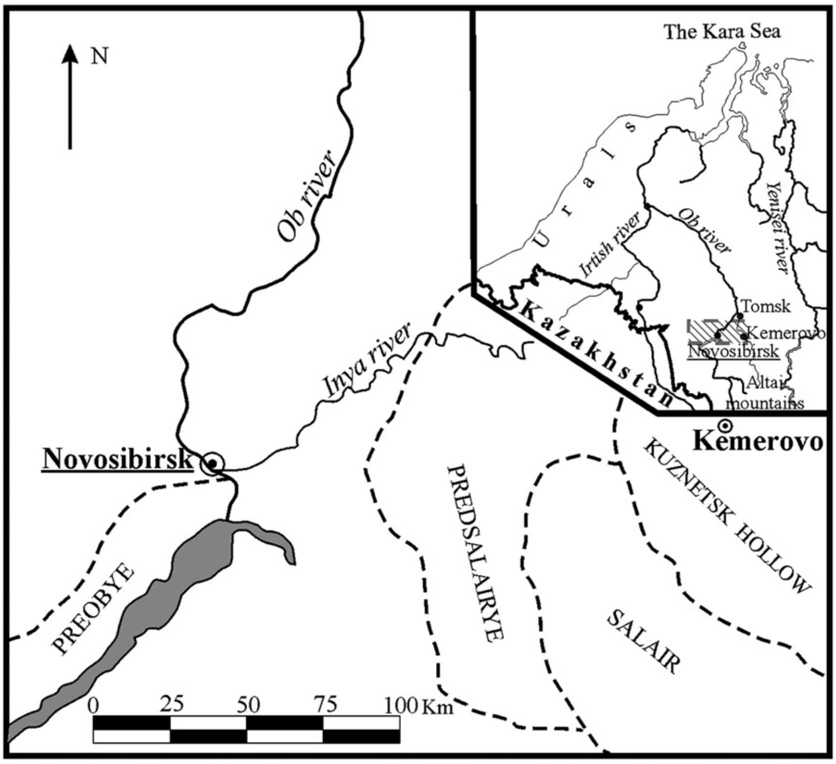

Fig. 1. Map of the main orographic units of the south-east part of West Siberia.

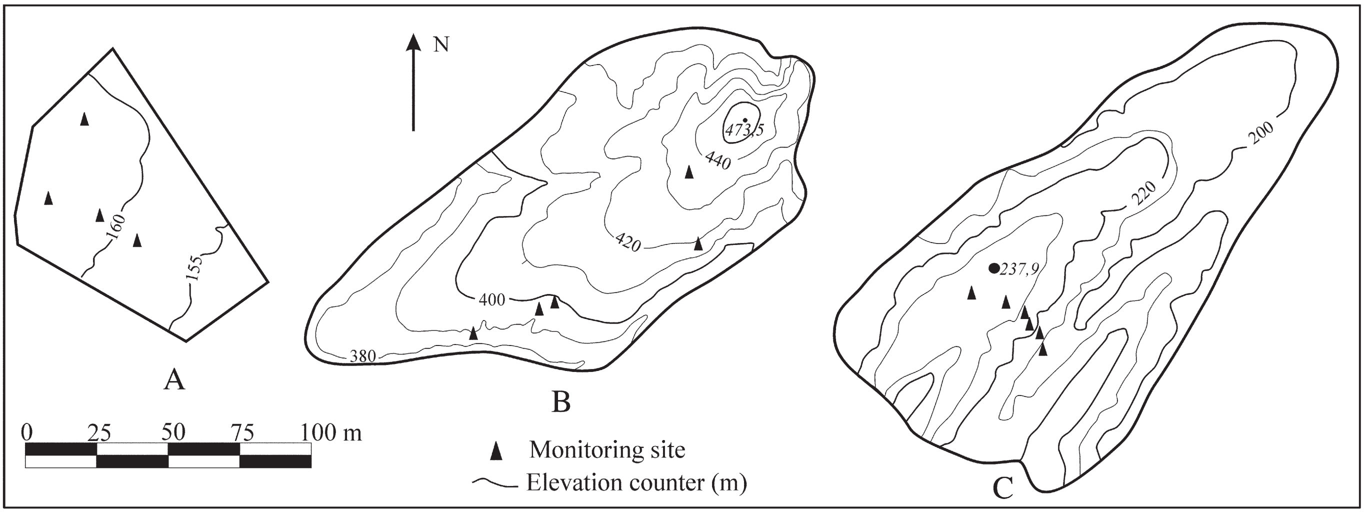

Fig. 2. Map of monitoring sites at Preobye (A), Predsalairye (B) and Kuznetsk hollow (C), West Siberia, Russia.

and is at its greatest in March, lasting 170–180 days on average (Slyadnev and Levushkina, 1968). Based on variations in the quantity of solid atmospheric precipitation during the cold period (60–320 mm), we classified hydrological years as follows: very low-snow, <75 mm; low-snow, 76–90 mm; normal, 91–105 mm; high-snow, 106–120 mm; and very high-snow, >120 mm. The occurrence of each precipitation category in the three geomorphological regions is presented in Table 2 as a percentage of the total number of years.

Table 1
Particle-size distribution in chernozems of West Siberia.

Soil depth, cm	Loss from treatment HCl, %	Particle quantity (%) diameter, mm					
		1–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001	<0.01
Predsalairye							
Haplic Phaeozem, average humus depth, virgin land							
0–10	2.0	9.8	41.4	10.0	15.0	21.8	46.8
10–20	1.1	10.0	42.5	13.4	12.5	20.5	46.4
Haplic Phaeozem, average humus depth, non-eroded, plowland							
0–20	3.6	7.3	41.6	10.4	15.4	21.7	47.5
Haplic Phaeozem, average humus depth, slightly eroded, plowland							
0–20	2.0	9.4	42.4	11.0	10.6	24.6	46.2
Haplic Phaeozem, short humus depth, moderately eroded, plowland							
0–20	2.2	10.2	35.7	9.5	13.5	28.9	51.9
Colluvic Regosol, deep humus depth, slightly drift, plowland							
0–20	3.3	13.2	33.7	3.8	11.8	34.2	49.8
Kuznetsk hollow							
Haplic Chernozem, average humus depth, virgin land							
0–10	3.0	9.8	34.4	15.5	19.8	17.5	52.8
10–20	3.2	7.8	38.8	16.3	16.8	17.1	50.2
Haplic Chernozem, average humus depth, non-eroded, plowland							
0–20	3.6	4.3	35.2	15.5	20.6	20.8	55.9
Haplic Chernozem, average humus depth, slightly eroded, plowland							
0–20	3.6	7.7	35.2	12.2	16.3	25.0	53.3
Haplic Chernozem, short humus depth, moderately eroded, plowland							
0–20	3.4	3.3	38.9	8.7	18.9	26.8	54.4
Haplic Chernozem, short humus depth, strongly eroded, plowland							
0–20	4.0	4.0	37.2	11.7	11.7	31.4	54.8
Preobye							
Haplic Chernozem, average humus depth, virgin land							
0–10	3.0	10.2	47.9	6.0	8.8	24.1	38.9
10–20	3.4	10.7	46.0	6.7	9.0	24.2	39.9
Haplic Chernozem, average humus depth, non-eroded, virgin land							
0–20	2.4	9.4	46.4	5.0	11.5	25.3	41.8
Haplic Chernozem, average humus depth, slightly eroded, plowland							
0–20	3.7	8.6	46.9	6.7	9.6	24.5	40.8
Haplic Chernozem, short humus depth, moderately eroded, plowland							
0–20	3.1	8.2	48.6	7.5	7.8	24.8	40.1

Soil freeze begins in late October–early November and lasts throughout the winter. Frost penetration depth (Table 3) depends primarily on how much snow has fallen and varies from 220 mm in very high-snow years to 0 mm in very low-snow years.

The snow melts over a period of 2 weeks, with the majority (~80%) melting within 5–7 days. During the winter, an ice sheet of 20–30 cm in depth forms that is impenetrable to melting water. With the soil frozen and at a temperature of ~10 °C at a depth of 10–20 cm for up to 100 days, snow melts over frozen soil. On the last days of snowmelt, the depth of the thawing layer is no more than 30 cm, leading to thixotropy. The water content in this layer reaches 60%. Under the thawing layer, the water quantity does not exceed 30–40%, and at a depth of 50 cm the water content is only 20–25%.

2.3. Plot characteristics, sampling and analysis

Studies were carried out on catenas oriented mainly in a south-east direction. The snow was measured with a special depth stick and a BC-1 snow-measuring instrument. These observations were generally carried out during 25–30 March, prior to snow compression caused by high solar activity and positive daytime air temperatures.

Surface snowmelt runoff was studied using short- and long-term runoff plots of 30–60 m in length and 5–10 m in width in ordinary water catchments 2–10 ha in area. The runoff plots were set up prior to the winter (the third ten-day period in October–the first ten-day period in November), when the upper part of the soil (0–20 cm) was still warm. The runoff plots were normally oriented from North to South. One runoff plot each was established on slightly, moderately, and strongly eroded soil. Each runoff plot was bordered with 20–25-cm high walls made of the upper part of the soil. A gutter made of galvanised sheet metal was attached at the lower end of each short-term runoff plot. A small hole was dug under the gutter to accommodate a 1-L measuring flask with which to measure, using a stopwatch, the amount of meltwater running off per time unit. Runoff water was collected manually at 1-h intervals in

Table 2
Number of years (% of sum total) experiencing varying amounts of solid atmospheric precipitation during 1969–2007.

Characteristics of the hydrological year	Predsalairye	Preobye	Kuznetsk hollow
Very low-snow	21	29	16
Low-snow	19	11	16
Normal	22	22	24
High-snow	15	23	24
Very high-snow	23	15	20

Table 3
Characteristics of soil frost depths in years with different amounts of snow (average value ± standard deviation).

Months	Characteristics of the hydrological year (the water content of snow)									
	Very low-snow		Low-snow		Normal		High-snow		Very high-snow	
	n	Depth, cm	*n*	Depth, cm	*n*	Depth, cm	*n*	Depth, cm	*n*	Depth, cm
Haplic Phaeozem, Predsalairye										
XI	4	33 ± 14.5	10	17 ± 4.1	7	17 ± 4.2	7	30 ± 7.6	11	25 ± 6.2
XII		92 ± 16.4		72 ± 5.6		67 ± 7.9		83 ± 10.1		47 ± 7.1
I		129 ± 10.9		100 ± 4.3		105 ± 8.1		119 ± 7.6		86 ± 10.7
II		143 ± 3.7		125 ± 6.1		130 ± 6.9		141 ± 4.6		108 ± 12.0
III		150 ± 7.9		139 ± 6.2		143 ± 5.6		149 ± 5.8		130 ± 13.1
IY		150 ± 11.7		141 ± 6.3		144 ± 5.5		133 ± 11.7		130 ± 14.3
Haplic Chernozem, Kuznetsk hollow										
XI	10	55 ± 5.0	6	39 ± 7.7	3	77 ± 5.7	5	25 ± 2.0	13	20 ± 2.1
XII		113 ± 7.3		57 ± 8.6		82 ± 7.9		50 ± 2.9		37 ± 2.2
I		151 ± 7.0		82 ± 19.4		113 ± 12.7		100 ± 8.9		55 ± 6.5
II		190 ± 14.8		90 ± 14.3		115 ± 8.6		110 ± 11.9		68 ± 5.7
III		219 ± 11.9		120 ± 21.2		117 ± 6.2		140 ± 7.9		75 ± 6.6
IY		219 ± 13.2		88 ± 8.8		120 ± 11.6		120 ± 12.0		56 ± 8.5
Haplic Chernozem, Preobye										
XI	5	7 ± 2.1	4	10 ± 3.4	6	8 ± 1.0	10	9 ± 1.5	5	0
XII		35 ± 3.2		51 ± 9.0		39 ± 9.7		68 ± 7.1		36 ± 9.2
I		78 ± 5.3		74 ± 13.9		70 ± 19.2		121 ± 8.1		97 ± 9.7
II		100 ± 11.1		96 ± 20.0		134 ± 10.8		158 ± 6.8		132 ± 9.8
III		115 ± 15.1		115 ± 11.6		154 ± 9.7		177 ± 10.4		160 ± 14.8
IY		137 ± 16.8		124 ± 13.9		183 ± 20.3		187 ± 14.3		180 ± 17.9

1-L plastic jars for analysis of turbidity and chemical composition. Meltwater runoff measurements were performed every hour after the initiation of snowmelt.

Because the short-term runoff plots had a limited length (30–60 m), the kinetic energy the meltwater could gain was lower than it would have been if the meltwater had travelled down the entire slope. Although short-term runoff plots are quite good at accurately measuring surface meltwater runoff, they are not as good at measuring solid runoff. Consequently, we measured the liquid and solid components of surface meltwater runoff in the outlet below a small area (8–10 ha) on the same slope where the short-term runoff plots were established. To determine meltwater runoff intensity, the water flow velocity and the depth and width of the runoff rill were monitored hourly along a 5-m section. Simultaneously, meltwater samples were collected in triplicate in 1-L jars for further analysis for turbidity. These observations were made in 1969–1979 on the Haplic Chernozems in Kuznetsk hollow, in 1980–1981 on the Haplic Phaeozems in Predsalairye, and 1984–1992 on the Haplic Chernozems in Preobye. Since 1993, observations have been confined to the Haplic Chernozems in Predsalairye.

Soil samples were collected in duplicate at four positions (upper, middle, bottom and train) on the slope of plots according to the degree of soil erosion.

A number of elements were analyzed in each runoff sample. The carbon concentration in the soils was measured according to Tyurin and exchangeable calcium was determined according to the Gedroyc procedure (Sokolov, 1975). The carbon concentration in the meltwater samples was determined according to Tyurin, and potassium, calcium, magnesium, sodium by atomic adsorption spectrometry (Sokolov, 1975).

The mathematical statistics methods of Dospekhov (1979) have been used for data processing.

3. Results and discussion

3.1. Snowmelt runoff characteristics

Surface snowmelt runoff was observed in all hydrological years studied, and the runoff volume increased as the water content of snow rose (Table 4). An important parameter describing the erosion intensity is the snowmelt runoff coefficient, which is the ratio of snowmelt volume to the volume of the water contained in the snow. Normally, large surface runoff volumes and a high runoff coefficient were observed in very high-snow winters, whereas minimal surface runoff was observed in low-snow winters. Overall, there were no significant

Table 4
Characteristics of snowmelt runoff on soils with various land uses in years with different amounts of snow.

Characteristics of hydrological year	*n*	Water content of snow (mm)	Runoff volume (mm)	Runoff coefficient
Luvic Phaeozem, forest. Predsalairye (Kovaleva et al., 1998)				
Low-snow	1	101	22	0.22
Normal	1	109	27	0.25
Very high-snow	3	135	31	0.23
Luvic Phaeozem, plowland. Predsalairye (Kovaleva et al., 1998)				
Very low-snow	2	65	8	0.12
Low-snow	1	85	22	0.26
Normal	1	101	72	0.71
High-snow	2	111	82	0.74
Very high-snow	3	142	99	0.70
Haplic Chernozem, virgin land. Predsalairye (Orlov, 1983)				
Very low-snow	2	69	28	0.4
High-snow	1	120	19	0.16
Very high-snow	6	255	119	0.47
Haplic Chernozem, perennial grasses. Predsalairye				
Very low-snow	2	59	35	0.59
Normal	1	96	64	0.66
High-snow	1	107	82	0.76
Very high-snow	5	156	105	0.67
Haplic Chernozem, plowland. Kuznetsk hollow				
Very low-snow	1	69	0	0
Low-snow	1	90	30	0.33
Normal	1	99	59	0.60
High-snow	1	113	73	0.65
Very high-snow	1	234	153	0.65
Haplic Chernozem, plowland. Preobye				
Very low-snow	1	65	24	0.37
Low-snow	2	84	40	0.48
Normal	3	97	60	0.62
High-snow	1	120	61	0.51
Very high-snow	3	136	73	0.52

Table 5
Content of humus and exchangeable calcium in the 0–20 cm layer of West Siberia soils.

Erosion degree of soil, type of land use	Humus content			Exchangeable calcium content	
	Statistical parameters				
	n	Lim, %	$M \pm m$,%	Lim, mg-eq 100 g^{-1}	$M \pm m$, mg-eq 100 g^{-1}
Haplic Phaeozem, Predsalairye					
Non-eroded, virgin land	10	9.3–13.8	10.5 ± 0.68	36.2–43.5	40.1 ± 1.2
Non-eroded, plowland	63	9.1–10.8	9.8 ± 0.19	30.3–51.0	38.3 ± 0.7
Slightly eroded, plowland	46	6.6–9.7	7.9 ± 0.11	27.2–38.0	32.0 ± 0.5
Moderately eroded, plowland	13	4.1–5.1	4.6 ± 0.16	20.4–27.6	24.0 ± 0.8
Slightly drift, plowland	13	8.0–16.9	11.5 ± 0.66	30.9–40.6	35.5 ± 1.1
Haplic Chernozem, Kuznetsk hollow					
Non-eroded, virgin land	7	11.6–14.8	12.6 ± 0.39	47.8–59.2	53.3 ± 2.1
Non-eroded, plowland	18	10.3–14.6	11.1 ± 0.57	44.2–55.9	51.3 ± 1.2
Slightly eroded, plowland	16	9.1–13.4	9.6 ± 0.47	37.5–46.4	41.5 ± 1.3
Moderately eroded, plowland	14	5.2–10.3	7.8 ± 0.34	30.3–42.6	39.0 ± 1.3
Strongly-eroded, plowland	9	4.0–8.0	5.7 ± 0.50	26.8–38.1	33.0 ± 1.3
Slightly drift, plowland	5	10.2–13.5	11.7 ± 0.59	37.6–46.6	41.0 ± 2.2
Haplic Chernozem, Preobye					
Non-eroded, virgin land	5	6.9–11.2	8.6 ± 0.40	30.1–40.2	35.5 ± 0.9
Non-eroded, plowland	31	6.8–10.8	8.2 ± 0.17	25.1–39.2	32.0 ± 0.8
Slightly eroded, plowland	20	4.4–6.7	5.9 ± 0.17	23.0–30.6	27.7 ± 0.7
Moderately eroded, plowland	5	3.3–4.8	3.8 ± 0.26	16.2–20.3	19.1 ± 1.0

Lim (range); $M \pm m$, (average value ± standard deviation).

differences in runoff figures among the three geomorphological regions reported. For instance, the runoff values for plowland in Preobye, Predsalairye, and Kuznetsk hollow were very similar to each other. On the other hand, considerable differences were observed within regions on land with different usage types. It has been proposed that runoff volume develops more extensively in open land than in forest because open land experiences deeper soil frost (Sartz, 1957; Pierce et al., 1958; Shanley and Chalmers, 1999). According to our studies, lesser runoff volumes were generated over the entire study period in the forest than in the open land. Importantly, the water content of snow and the runoff volume in the forest displayed little dependence on the amount of snow fallen, while on the open land, these parameters depended strongly on the quantity of snowfall. On virgin soils, plowland, and land covered with perennial grasses, the runoff volume during very high-snow years was 3–4-fold higher than in low-snow years, and soil frost depth does not appear to have been a critical factor. Data reported for areas in Scotland and northern Sweden (Wade and Kirkbride, 1998; Lindström et al., 2002) further challenge the view that there is a significant association between soil frost depth and runoff volume. Consistently high values of runoff volumes and runoff coefficients were obtained for soils covered with perennial grasses, no matter how snowy the year. Runoff volumes were high on plowland during normal and high-snow years, while in low-snow years, there was little difference between the runoff volume in forest and virgin soils.

3.2. Humus and exchangeable calcium content in eroded soils

The most typical characteristic of eroded soils is a decrease in humus horizons (Palis et al., 1990; Kashtanov and Yavtushenko, 1997; Lal et al., 1999; Olson et al., 1999). Slightly eroded chernozems in Siberia occupy the upper parts of slopes and are characterised by a low-depth humus horizon (approx. 30%). Soil profile consists of a whole set of genetic horizons typical for non-eroded soils. For moderately eroded soils, located on the middle parts of slopes, the depth of the humus horizon (A) is less than 50%. Therefore, the plowing layer of these soils corresponds to the humus horizon (A) and part of the sub-horizon (AB). Strongly-eroded soils occur on the lower, steepest parts of slopes and have no isolated horizons (A, AB and B). The plowing layer of these soils is a mixture of the above-mentioned horizons and often includes the alluvial-calcareous horizon (Bca).

In areas of dissected relief, the solid phase of soils moves during snowmelt from a trans-alluvial to a trans-accumulative landscape position. The main mass of sediments that is washed away from plowland by flowing water accumulates at the bottom of the slopes, in shallow gullies or in the river valley. Only 10% of the solid sediment phase reaches the river system from slopes. Approximately 60% of the washed soil accumulates on the lower parts of slopes, forming semi-terrestrial drift soils. The depth of the humus horizon of drift soils is 25–60% greater than that depth of a given horizon in non-eroded (full profile) chernozems.

The quantity of humus in higher part of the full profile virgin Haplic Phaeozems and Haplic Chernozems of Kuznetsk hollow and Predsalairye ranges between 8% and 16% (Trofimov and Bomber, 1968; Gradoboev, 1972; Khmelev and Tanasienko, 1983; Khmelev, 1989). Therefore, the silty clay loam Haplic Phaeozems and Haplic Chernozems that are widespread in the Kuznetsk hollow, the foothills of Altay and in parts of Predsalairye are termed “fat.” The clay loam Haplic Phaeozems and Haplic Chernozems of Predsalairye and Haplic Chernozems of Preobye are denoted medium-humus soils.

The humus content depends on the texture of the soil. Small-sized soil particles contain more organic matter (humus) than do larger aggregates (Wan and El-Swaify, 1977; Rodríguez Rodríguez et al., 2004; Rumpel et al., 2006). The main bearers of humus are clay particles. In Siberian phaeozems and chernozems (Table 1) they accumulate for half to three-quarters of the total humus quantity (Ponomareva and Plotnikova, 1980; Tanasienko, 1992). Removal of considerable quantities of clay particles from the plow layer of soils on slopes each year results in the transformation of soils from one grade to another (Table 5). Only the slightly eroded soils of Kuznetsk hollow remained as fat soils, whereas moderately eroded soils were transformed to moderate-humus soils and strongly eroded soils to low-humus soils. In comparison to non-eroded soils, humus loss is 25% for slightly eroded soils, 40% for moderately eroded soils and >50% for strongly eroded soils. Sedimentation of clay particles at the bottom of slopes, where drift soils formed, led to an increase in humus content. In the plow layer in these areas, the humus quantity is equal to or even greater than that in virgin soil.

The Haplic Chernozems of Kuznetsk hollow and Haplic Phaeozems in Predsalairye are considered to be fat not only because they have considerable humus content in the upper horizons, but also because they have the highest content of exchangeable calcium (40–60 mg-eq

Table 6
Chemical composition of meltwaters on slightly eroded soils.

Characteristics of the hydrological year	n	Content (mg l^{-1}, average value ± standard deviation)				
		C	Ca	Mg	K	Na
Predsalairye. Luvic Phaeozem						
Normal	15	7.33 ± 0.4	11.4 ± 1.2	1.9 ± 0.14	5.7 ± 0.42	1.2 ± 0.08
Very high-snow	10	19.9 ± 0.07	12.8 ± 0.4	3.1 ± 0.18	10.9 ± 0.58	6.5 ± 0.20
Predsalairye. Haplic Phaeozem						
Low-snow	16	138.0 ± 7.2	267.0 ± 12.0	25.3 ± 1.56	ND*	ND*
Normal	11	125.0 ± 9.8	231.0 ± 7.3	20.6 ± 0.65	ND*	ND*
Predsalairye. Haplic Chernozem						
Very high-snow	131	91.0 ± 2.6	10.0 ± 0.3	1.7 ± 0.07	5.0 ± 0.08	1.0 ± 0.06
Kuznetsk hollow. Haplic Chernozem						
Low-snow	15	91.0 ± 3.6	5.4 ± 0.3	2.5 ± 0.13	ND*	ND*
Normal	11	86.0 ± 5.3	4.1 ± 0.2	2.0 ± 0.12	ND*	ND*
High-snow	21	76.0 ± 2.9	8.4 ± 0.4	2.5 ± 0.15	ND*	ND*
Very high-snow	15	98.0 ± 5.3	11.9 ± 0.7	4.3 ± 0.28	ND*	ND*
Preobye. Haplic Chernozem						
Very low-snow	31	90.0 ± 2.3	6.4 ± 0.3	1.1 ± 0.05	2.4 ± 0.11	3.0 ± 0.12
Low-snow	17	83.0 ± 1.8	6.8 ± 0.03	1.1 ± 0.07	1.5 ± 0.07	2.3 ± 0.14
Normal	19	84.0 ± 2.6	3.6 ± 0.2	0.8 ± 0.03	3.6 ± 0.17	ND*
High-snow	95	102.0 ± 2.3	6.3 ± 0.2	1.1 ± 0.03	2.2 ± 0.09	1.2 ± 0.07
Very high-snow	40	64.0 ± 3.2	9.2 ± 0.3	1.6 ± 0.04	3.0 ± 0.12	5.1 ± 0.11

*Not determined.

100 g^{-1}), accumulated largely from biogenic processes. There is a direct association between humus content and exchangeable calcium in the humus horizon: the higher the humus content, the higher the content of exchangeable calcium (Tanasienko, 1974; Khmelev, Tanasienko, 1983).

3.3. Runoff chemical composition and removal of chemical elements

The prolonged presence of snowmelt water on slightly eroded soils rich in humus and biogenic elements leads to significant leaching. The data (Table 6) show that meltwaters on the surface of the Haplic Phaeozems of Predsalairye are characterised by the highest carbon concentrations compared to the other measurement sites. The higher carbon, calcium and magnesium contents in this meltwater may be explained by a nearby cement factory, dust from which accumulates in the snow cover. Surface water in this area is alkaline (pH 8.5–9.1), while the pH of pure snow is 5.56. The solubility of soil organic matter under alkaline conditions is known to be rather high (Ponomareva and Plotnikova, 1968). Moreover, Haplic Phaeozems are characterised by a moderate loamy texture and relatively small contents of exchangeable calcium (see Tables 1 and 5). All of these factors affect soil erosion stability and the quantity of leached carbon.

The heavy, loamy, fat Haplic Chernozems of Kuznetsk hollow contain high amounts of humus and exchangeable bases. Because of the considerable quantity of clay and exchangeable calcium responsible for soil stability, carbon leaching was not as extensive here as for Preobye and Predsalairye. Surface water on the Haplic Chernozems of Kuznetsk hollow leached significant quantities of absorbed bases. The high content of exchangeable calcium and magnesium in the plow layer saturates meltwaters in these ions. The higher carbon concentration in meltwater on the surface of Haplic Chernozems in Preobye may be explained by the presence of sodium ions (up to 3% of the exchange capacity) in the soil absorbing complex. As a result, the meltwaters are slightly alkaline.

The volume of surface runoff increased with the amount of snow. Therefore, the intensity of geochemical erosion depends on meltwater volume on one hand and on the content of a particular element in the plow layer on the other hand.

It was determined that no surface snowmelt runoff occurred after very low-snow winters in Kuznetsk hollow (Table 7). However, in those same years, approximately 20 kg ha^{-1} of carbon was removed in Preobye. We consider this quantity to be ecologically acceptable and use it as a standard. Carbon losses in meltwaters were 1.5-fold higher than this standard after low-snow winters in Preobye and two-fold higher in Kuznetsk hollow. In such years, Predsalair Haplic Phaeozems lost three times as much water-soluble carbon as Preobye because of the proximity of the cement factory. In Preobye and in Kuznetsk hollow, carbon loss was 50 kg ha^{-1} in normal hydrological years. In Kuznetsk hollow, carbon removal by meltwater after high-snow winters was practically the same as in normal hydrological years, whereas in Preobye, it was more than 70 kg ha^{-1}. In Kuznetsk hollow, maximum carbon removal by meltwater occurs during very high-snow years and was almost seven-fold higher than standard removal.

Geochemical migration of carbon in meltwater on the surface of Predsalair Luvic Phaeozems near the cement factory was always lower than the standard after both normal and very high-snow winters because of the relatively low-humus content in the plow layer of these soils. Removal of calcium, magnesium, potassium and sodium in snowmelt runoff followed identical trends to carbon removal. It should be noted that approximately 14–24% of the total losses of calcium and 30–55% of magnesium were discharged with liquid runoff.

Table 7
Removal of chemical elements by meltwaters in years with different amounts of snow.

Characteristics of the hydrological year	Elements (kg ha^{-1})				
	C	Ca	Mg	K	Na
Predsalairye, slightly eroded Luvic Phaeozem					
Normal	5.2	8.2	1.4	4.1	1.0
Very high-snow	19.2	12.7	3.1	10.8	6.4
Predsalairye, slightly eroded Haplic Phaeozem					
Low-snow	57.9	115.9	10.6	ND*	ND*
Normal	75.0	138.6	12.4	ND*	ND*
Predsalairye, slightly eroded Haplic Chernozem					
Very high-snow	95.6	10.5	1.8	5.3	1.1
Kuznetsk hollow, slightly eroded Haplic Chernozem					
Very low-snow	0	0	0	ND*	ND*
Low-snow	40.4	2.4	1.1	ND*	ND*
Normal	50.7	2.4	1.2	ND*	ND*
High-snow	55.5	6.1	1.8	ND*	ND*
Very high-snow	149.9	18.2	6.6	ND*	ND*
Preobye, slightly eroded Haplic Chernozem					
Very low-snow	21.6	1.5	0.2	0.6	0.5
Low-snow	33.2	2.7	0.4	0.6	0.9
Normal	50.4	2.2	0.5	2.2	ND*
High-snow	70.4	4.3	0.7	1.5	0.8
Very high-snow	46.7	6.7	1.2	2.2	3.7

*Not determined.

4. Conclusions

1. The water content of snow on the soils of the West Siberia forest-steppe at the beginning of snowmelt varied from 65 mm in low-snow conditions to 255 mm in very snowy winters. Snowmelt runoff in very low-snow winters was practically absent and in others winters reached 60% of the total precipitation volume for the cold period.
2. Land-use type affects the level of surface runoff. Slopes occupied by perennial grasses and plowland exhibited the highest levels of snowmelt runoff (>50% of the water content of snow).
3. In dissected areas of the West Siberia forest-steppe, removal of soluble chemical elements by surface snowmelt runoff is considered ecologically safe if it is not more than 20 kg ha^{-1}, or 5 kg ha^{-1} for carbon. The removal of alkaline-earth and alkali elements in the range 21–50 kg ha^{-1} (up to 30 kg ha^{-1} of carbon) is classified as slightly ecologically dangerous; 51–100 kg ha^{-1} (up to 90 kg ha^{-1} of carbon) as of moderate ecological danger; and 101–190 kg ha^{-1} (up to 150 kg ha^{-1} of carbon) as highly dangerous.
4. Pollution greatly influences the removal of chemical elements by meltwater. In the relatively ecologically unthreatened region of Preobye, the removal of soluble chemical elements depended on the water content of snow and varied from 25 to 75 kg ha^{-1}. Removal of elements from chernozem by meltwater in Kuznetsk hollow increased to 170 kg ha^{-1}. In Predsalairye, near the cement factory, where the plow layer has an alkaline pH and the snow cover accumulates a great quantity of cement dust, removal of biogenic elements increased to 225 kg ha^{-1}, which is four-fold greater than the removal in Preobye.

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