

RAINFALL PATTERNS ASSOCIATED WITH RUNOFF AND EROSION LEVELS IN WEST-SIBERIAN CHERNOZEMS

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The aim of the study was to identify 1) the main regularities of surface runoff formation due to downpours and 2) the extent of erosion process on arable chernozems in areas with dissected relief and sharply continental climate. The influence of rainfall patterns and soil physical factors on soil erosion was studied in three large geomorphological regions in the South-East of West Siberia. Field observations were carried out during 1968–1979 in the Kuznetsk Depression and in 1984–1986 in the Near-Ob areas, and from 1995 until present in the Near-Salair area. The data of meteorological stations were analyzed for rainfall patterns in the same years, including inter-year variability and downpour recordings. Summer precipitation and its intensity were measured by using hydrograph unit. Water infiltration in the field was studied by the method of small flooded areas (Nesterov's method), when square or round frames with an area of 2500 (external) and 625 cm² (internal) were installed on the soil surface. To simplify and automate water supply, the PVN-00 device was used, consisting of two hermetically sealed tanks, two cylindrical frames of different diameters and a tripod. The influence of rainfall patterns and soil physical factors on the processes of soil erosion was studied. As regards climatic factors the data of meteorological stations were analyzed for historical rainfall patterns, including interannual variability and downpour recordings. Experimental data of water infiltration, runoff and soil loss were discussed for the main soils units: Greyzemic Phaeozems (Siltic), Luvic Chernozems (Siltic) and Haplic Chernozems (Siltic) with variable content of soil organic matter and erosion levels. The studied regions were characterized by the prevalence of precipitation during the warm growing season and by sporadic or cyclical precipitation patterns. Heavy rains were found to cause significant damage to agricultural land only locally, during early spring, when the soil is not protected by vegetation. The greatest erosion hazard is represented by meltwater, not only by its total amount, but also by the snow thawing rate. The significant decrease in the infiltration rates with extensive farming is the main factor of degradation of the most fertile soils in West Siberia. Soil vulnerability to erosion in the studied area was shown to decrease in the range: Kuznetsk Depression > Near-Salair > Near-Ob (no storm damage).

Key words: dissected forest-steppe; physical constraints; rainfall intensity; water infiltration; soil loss; surface runoff; Greyzemic Phaeozem; Luvic Chernozem; Haplic Chernozem; West Siberia.

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INTRODUCTION

Erosion is one of the main factors leading to the destruction of soil cover on the planet (Lal 2001; Daniel et al. 2015; Owens 2020). The accumulation and analysis of climatic and soil data describing erosion processes over long observation periods serve as good material for studying the behavior of erosional landscapes and making forecasts of erosion. In the European part of Russia, according to the generalized analysis of soil and climatic data for the period from 1963 to 2015, the decrease in annual amount of erosion losses was due to a decrease in surface runoff during the spring snowmelt. This was due to an increase in air and soil temperatures during the winter period. At the same time, summer precipitation amount increased which led to an increase in soil erosion losses (Golosoov et al., 2018). West Siberia has specific soil and climatic condition, therefore, its territory is classified as vulnerable in terms of erosion.

Most of the arable land of dissected forest steppe of West Siberia consists of chernozems which occupy almost 20·10⁶ ha, including 13·10⁶ ha of arable lands (Khmelev, Tanasienko, 2009a) that yield high-quality grain owing to its high initial fertility. The population of West Siberia increased essentially

in the 20th century with an accompanying increase in the agriculturally used area. By that time, the most fertile lands in West Siberia (chernozems) on its rather flat territory were completely developed. The further development of virgin and fallow lands was performed on sloping surfaces which are prone to soil erosion; the slope of these surfaces is sometimes greater than 5% and even 15%. The surface runoff is well known to occur already on slopes as steep as 2–4%; consequently, at present in West Siberia a total area of about $7 \cdot 10^6$ ha is exposed to different levels of erosion.

The erosion rates in West Siberia depend closely on the strong dissection of the relief, heavy snowfalls in winter and rapid snow melting, which is accompanied by the formation of an ice sheet that prevents the filtration of snow melted water into the soil profile. In consequence, during the thaw period, runoff on the slopes can affect as much as *ca.* 60% of the arable land in the region. Heavy rainfall during the summer period also significantly damages the soil cover on arable slopes. Due to the fact that profile thickness of Siberian chernozems is less than in soils of the European Russia, the soils are extremely exposed to erosion (Tanasienko, 2003).

Under these conditions and in combination with local geomorphological constraints, the analysis of extreme events has long been a major topic in environmental change research (Hudson, Inbar, 2012). Thus, this work aims to identify i) the main regularities of the surface runoff formation due to downpours and ii) the extent of erosion processes on arable chernozems under conditions of dissected relief and sharply continental climate.

MATERIALS AND METHODS

The study area is located in the basin of the upper reaches of the Ob River and is represented by structural-denudation and accumulative plains of the West Siberian lowland, denudation plains, low mountains and middle mountains of the Altai-Sayan mountain region (Orlov, 1983). The studies were carried out both in the left-bank part (Figure): the Near-Ob plateau (Preobye), and in the right-bank part, the Near-Salair hilly plain (Predsalairye) (within the limits of the Novosibirsk region) and the Kuznetsk Depression (within the limits of the Kemerovo Region). The main physical and geographical features of these geomorphological regions are given below.

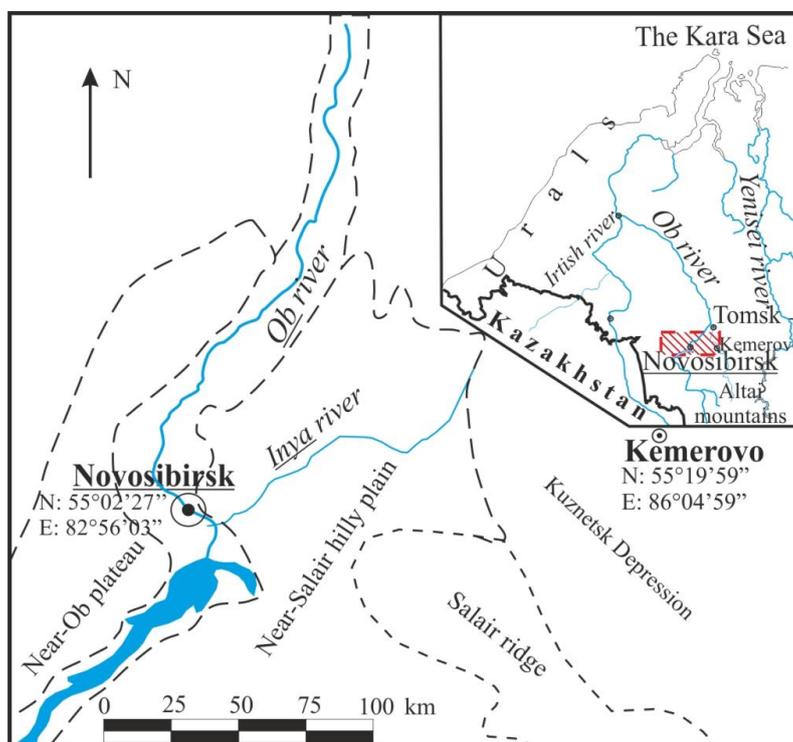


Figure. Map of the main orographic units of the South-eastern part of West Siberia, Russia (dashed lines indicate boundaries between the main units).

Near-Salair. This region refers to tabular and undulating strongly dissected flat plain with absolute heights of 200–300 m a.s.l.; in general, this territory slopes towards West-Siberian plain. Watershed spaces in this area occupy about 1/5 of the territory. The slopes are as steep as 5–15%, complicated and

rather long (600–800 m). The density of horizontal dissection ranges within the limits of $1.0\text{--}1.2\text{ km}\cdot\text{km}^{-2}$, whereas vertical dissection averages 75–100 m.

This region shows widely spread man-made degraded forest steppe landscapes under conditions in which soil cover is characterized by low complexity. Basic soil background consists of leached and podzolized chernozems. Soil-forming rocks of chernozems are loess-like loams. The following features are typical for such rocks: pale-yellow color, calcareousness, columnar structure and high porosity. Loess-like loams are homogenous in terms of their granulometric composition and most of them derive from heavy-textured rocks (Khmelev, Tanasienko, 2009a).

At present due to the general socioeconomic development of the land, the territory of Near-Salair with highly sustainable sloping soils has turned into zones of intensive denudation. In consequence, up to 1/5 part of the arable lands (i.e., about $200\cdot 10^3$ ha of $950\cdot 10^3$ ha) are eroded to weak and medium extents. Therefore, as regards erosion, this region is classified as being at the medium potential risk.

Near-Ob. This region is located in the transition belt from forest steppe to steppe. As regards soil cover, this area includes mainly leached chernozems which are medium in thickness, humus content and loamy fraction content. Total area of the arable soils amounts to $670\cdot 10^3$ ha; of which about 7.5% is subjected to serious soil loss. The most distinguishing features of the territory are the general elevation (absolute heights between 130–310 m a.s.l.), good natural drainage conditions, lack of primary salinity, and deep groundwater table (10–15 m). Soil-forming rock is loess-like, nonsaline silty clay loam, which characteristically provides high aeration. The mineral material of the deposits was subjected to syngenetic changes in response to steppe and meadow-steppe soil formation and displacements at the expenses of sheet washing during formation of the slopes in the interfluves (Shaporina, Tanasienko, 2003). This region has relatively gentle horizontal dissection, i.e., $0.6\text{--}0.8\text{ km}\cdot\text{km}^{-2}$. As a consequence, watershed flat spaces account already for 30% of total area. Really, the steepness of the near-watershed slopes ranges from 2 to 9%. The steepness of the convex near-ravine slopes approaches to 15–30%, as corresponds to significant erosion hazard of the territory, an essential part of which (15%) is eroded from weak to medium extent. Therefore, as regards erosion, this region is also classified as being at the medium potential risk.

Kuznetsk Depression. This region is an elevated denudational plain where leached, high humus content and medium in thickness heavy-textured chernozems present the greatest agricultural significance, the latter being determined not only by their wide spreading but also by the fact that these soils are the most fertile in West Siberia. The area of arable soils of the Depression makes up to $900\cdot 10^3$ ha. It is important to emphasize that $150\cdot 10^3$ ha is eroded to various extents. Soil-forming rocks consist of loess-like loams which occupy almost all the ecosystems of erosion catena. The thickness of loess-like loams varies: high values occur in the depressions of the interfluves (up to 20–25 m) and minimum values (often less than 1 m) at the exposures of Paleozoic and other bedrocks (Khmelev, Tanasienko, 1983). The relief of the Depression is strongly dissected. Horizontal dissection varies from $0.6\text{--}0.8\text{ km}\cdot\text{km}^{-2}$ in its western border to $1.0\text{--}2.6\text{ km}\cdot\text{km}^{-2}$ in the remaining area. Vertical dissection is the same as in Near-Salair (75–100 m). In view of such essential dissection the watershed spaces make up to 20 % of the total area. It is necessary to emphasize that 15% of the arable land in the dissected part of the Depression is eroded from slight to moderate extent. Therefore, this geomorphological region, as well as the regions described above, should be classified as prone to a medium erosion hazard. Thus, undulating relief of the Near-Salair and Near-Ob areas as well as the Kuznetsk Depression in addition to sufficient supply with solid and liquid precipitation favors considerable surface runoff of thawing and downpour waters on the arable land; this leads to substantial losses of the soil solid phase and hence decreased chernozems' fertility.

In Near-Salair and the Kuznetsk Depression the main arable lands are represented by medium- and heavy-textured humus-rich leached chernozems (Luvic Chernozems (Siltic)) (Khmelev, Tanasienko, 2009a, 2013; IUSS Working Group WRB, 2014), in Near-Ob by medium-textured, medium in thickness ordinary chernozems (Haplic Chernozems (Siltic)) (Panfilov et al. 1976; IUSS Working Group WRB, 2014). Total area of the arable lands amounts to $2.5\cdot 10^6$ ha, the most part of which (on the average 80%) representing the non-eroded land. Non-eroded chernozems of the Near-Altai soil province perform two very important functions: a) environmental because they are the main constituent of the soil cover in the most populated area of West Siberia; b) high agronomical production as they are fundamental for grain crop production (Khmelev, Tanasienko, 1983).

A specific feature of humus horizons (A+B) is the tonguing, which is a specific feature of chernozems in West Siberia (Karetin, 1982). The thickness of humus horizons varies within the limits of 50–60 cm. The most specific and stable feature of the chernozems subjected to erosion processes is the

decrease of the thickness of humus horizons. Slightly eroded chernozems occupy the upper third of the slope; they are characterized by a reduced thickness (up to 30%) of humus horizon. Moderately eroded chernozems can be found in the middle part of the slope. The thickness of their humus horizons is reduced by 50%. Strongly eroded chernozems are found in the lowest and steepest part of the slope and do not have separate horizons (A, AB and B).

Humus content in humus-rich non-eroded chernozems which are widely spread in the Kuznetsk Depression and partly in Near-Salair amounts to 8–10%, in some cases being as high as 12–13%. Haplic Chernozems (Siltic) of Near-Ob are classified as medium in humus content. It is known that the heavier the chernozem texture is, the richer in humus their upper part of the profile is. Main “carriers” of humus in chernozems are finely dispersed particles (Tanasienko et al. 2019). Annual loss of considerable part of silty particles (no more than 200 kg · ha⁻¹ in very low-snow hydrological year and up to 330–4200 kg · ha⁻¹ in very high-snow year) led to the fact that only slightly eroded chernozems of the West Siberia in the Kuznetsk Depression are explicitly included in the group of high-humus chernozems (more than 5% C), moderately eroded to medium-humus (4.0–4.5% C) and strongly eroded transformed to low-humus chernozems (2–4% C). Sedimentation of highly dispersed particles in the lower parts of the slope caused by slow velocity of thawing and downpour water leads to the formation of slightly drift meadow chernozemic soils in ploughed layer where humus content is the same or even higher than in the non-eroded chernozems (5.8–6.8% C).

In order to assess the role of the climatic factor in the development of erosion processes in West Siberia, long-term data on precipitation including downpours were acquired and processed by variation statistics. At the same time, the lack of general consensus among specialists in soil erosion was taken into account concerning the controversy about which kind of precipitation (solid or liquid) plays a more crucial role in removing the soil cover of arable slopes. Most researchers consider that solid precipitation should be taken into account as the main factor, especially in West Siberia. The duration of a cold season is about half a year, and for this time interval a quarter of precipitation is accumulated. Apart from this, in West Siberia downpours are frequent, repeating every 5 or 6 years. For instance, in the Kuznetsk Depression during cold and warm periods (hydrological year) the total amount of liquid precipitation is *ca.* 430 mm in the very wet years, and from 450 to 500 mm during extremely wet years. The minimum amount of liquid precipitation sometimes falls to 50 mm (i.e., during the cold period, i.e. November–March). Therefore, taking into account such variation in the amount of liquid atmospheric precipitation we analyzed moisture gradations during the warm time interval for each geomorphological region under study. The gradations were also studied in detail regarding the inputs of solid precipitation on the territories during the cold time interval (Table 1). This is the case with the Kuznetsk Depression and Near-Salair areas where during the warm time interval a “very dry year” is considered to be such a year when precipitation is no more than 360 mm. In this scenario, the total amount of liquid atmospheric precipitation sometimes exceeds 450 mm. Consequently, we have to distinguish an extremely wet warm period. At the same time, extremely moist warm period was not observed in the course of almost 50 years of meteorological records in the Near-Ob area which is located in the transitional belt from forest steppe to steppe.

SPECIFIC FEATURES OF CLIMATE AS A SOIL-FORMING FACTOR

The climate of the three geomorphological regions under study, similar to the entire West Siberia, is sharply continental. Its specific features consist of different duration of the cold and warm periods of the year and uneven distribution of atmospheric precipitation (Slyadnev, 1965; <http://aisori.meteo.ru/ClimateR>). The largest duration occurs in the cold period (about six months) and the shortest in spring.

The proportion of winter precipitation with respect to the annual amount is comparatively low (Table 1) and represents about 25 %, whereas in spring it represents only 10 %. Thus most of the precipitation falls during the warm season (from April to October). During the cold time interval (from November to March) the Kuznetsk Depression on average receives 100 mm of solid atmospheric precipitation, Near-Ob receives less than 90 mm and Near-Salair area receives more than 130 mm. Snow cover usually forms on the frozen soil. The duration of the preliminary winter period varies from two to three weeks.

Table 1

Precipitation in the cold (XI–III), warm (IV–X) periods and hydrological year in the forest steppe of West Siberia (Tanasienko, 2003)

Period	Description of the year	Statistical parameters				
		<i>n</i>	lim, mm	M±m, mm	δ, mm	V, %
Near–Salair, Toguchin weather station (1936–1997)						
Cold	Very low–snow	12	61–72	66±2	4.6	7
	Low–snow	10	81–90	85±1	3.6	4
	Normal–snow	11	98–105	101±1	3.0	3
	High–snow	9	108–119	114±2	4.6	4
	Very high–snow	17	122–190	148±5	17.5	12
Warm	Very dry	18	233–296	262±5	20.0	8
	Dry	14	307–330	319±2	8.3	3
	Normal	3	339–345	342±5	6.6	2
	Moist	7	361–390	369±5	11.0	3
	Very moist	15	394–450	430±8	30.1	7
	Extremely moist	4	451–490	476±4	7.4	2
Hydrological year	Very droughty	11	303–374	338	–	–
	Droughty	10	380–415	396	–	–
	Normal	18	427–462	446	–	–
	Moist	8	466–508	483	–	–
	Very moist	13	512–606	560	–	–
Near–Ob, weather station of Ordynskoye (1936–1990)						
Cold	Very low–snow	14	51–75	64±2	5.2	8
	Low–snow	4	78–88	82±3	6.2	7
	Normal–snow	10	93–105	100±2	5.2	5
	High–snow	10	106–115	111±2	4.9	4
	Very high–snow	6	129–159	141±5	13.1	10
Warm	Very dry	15	160–243	213±7	28.0	13
	Dry	9	276–300	287±3	13.0	5
	Normal	7	301–319	308±6	20.5	6
	Moist	6	332–349	344±3	8.5	3
	Very moist	9	370–497	419±12	26.3	6
Hydrological year	Very droughty	9	215–341	297	–	–
	Droughty	14	349–389	369	–	–
	Normal	5	412–435	420	–	–
	Moist	9	443–477	456	–	–
	Very moist	5	489–570	538	–	–
Kuznetsk Depression, weather station of Kolchugino (1936–1990)						
Cold	Very low–snow	8	49–75	68±3	8.4	12
	Low–snow	8	77–90	81±2	5.4	7
	Normal–snow	12	93–105	99±2	5.4	6
	High– snow	12	106–117	113±1	4.1	4
	Very high–snow	9	121–153	131±4	11.3	8
Warm	Very dry	9	67–300	287±4	12.2	4
	Dry	9	307–330	318±3	8.7	3
	Normal	7	338–360	350±4	9.7	3
	Moist	9	361–381	370±3	10.0	3
	Very moist	12	393–443	436±10	41.3	9
	Extremely moist	4	459–493	484±5	8.8	2
Hydrological year	Very droughty	5	342–379	358±8	18.9	5
	Droughty	10	389–429	405±4	12.8	3
	Normal	10	433–479	461±6	17.6	4
	Moist	4	495–428	513±7	13.9	3
	Very moist	5	533–641	569±23	50.3	9

Footnotes for Tables 1–3. Compiled from: Climatologic Reference Book of the USSR (1956); Reference Book of Climate of the USSR (1977); Meteorological Reference Book (1961–1988).

n – sampling years; lim – fluctuation of data; M – mean; m – standard error of the mean; δ – mean-square deviation; V – coefficient of variation. Dashes indicate not available data.

Precipitation is the most important factor which determines the erosive role of climate. Not all the climatic indices to the same extent influence the intensity of erosion processes. The most important indices are annual precipitation and snowfall regime. In any location the amount of precipitation varies with time and is rhythmic by its nature (Rode, 1978). Therefore, annual precipitation gives a general idea of the moisture on the territory but is associated with the fact that the higher the precipitation is, the stronger the erosion is. At the same time, it was established that the correlation between total precipitation and erosion intensity was not significant as the same precipitation amount could result in different extents of erosion (Gudzon, 1974). Considerable variation of the precipitation in the cold and warm seasons and its annual amount was related to its rhythmic falling (Table 1). While studying meteorological data for the 40–60 years long period we succeeded in observing conspicuous regularity patterns. As it was noted earlier (Slyadnev, 1965), droughty seasons are known to be repeated in cycles of ca 10–11 years. In fact, no more than half of the annual amount of precipitation falls in these years during a warm weather interval. Nevertheless, as a rule, precipitation in the cold weather interval proved to be extremely high over the course of these years (Khmelev and Tanasienko, 1983; 2009 a,b). As for the three geomorphological regions under study, erosion losses were greatly different that is why it is interesting to follow how the total amount of precipitation and slope exposure determined the erosion intensity and how solid atmospheric precipitation and radiation regime influenced snow thawing. Based on the precipitation data, it is possible to forecast yearly erosion losses due to downpour and thawing water runoff, in order to implement appropriate strategies to reduce erosion processes to admissible levels.

The same precipitation pattern was found to be peculiar to Near-Salair and Near-Ob areas for the same years. Therefore, the rhythm of precipitation which we observed in the dissected forest steppe of West Siberia confirms and supplements the observations of researches in different regions of Russia (Bazykina, Boiko, 2010; Komissarov, Gabbasova, 2014; Bazykina et al. 2015; Bazykina, Ovechkin, 2016; Gusarov et al. 2018). As for the West Siberia, purposeful soil studies on the changeability of atmospheric moistening have not been practically carried out (Tanasienko et al., 2019).

FIELD STUDIES: DATA COLLECTION AND SAMPLING

Summer precipitation and its intensity were measured by using Hydrograph unit. Water infiltration in the field was studied by the method of small flooded areas (Nesterov's method), when square or round frames with an area of 2500 cm² (external) and 625 cm² (internal) are installed on the soil surface. The outer frame is protective and the inner one is measuring. The essence of the method is to take into account the amount of water poured into the measuring frame (known area) per unit of time. To simplify and automate the water supply, the PVN-00 device is used which consists of two hermetically sealed tanks (Marriott vessels), two frames (cylindrical) of different diameters and a tripod. The calculation of water permeability is carried out in the same way as in the Nesterov method. The snow survey stage was measured using a BC-1 snow-gauge and a special metal snow scale (Mueller et al., 2016).

Descriptive statistics (Dospikhov, 1979), Microsoft Office Excel 2007 were used for the data processing.

RESULTS AND DISCUSSION

It should be pointed out that a specific feature of farming in the three geomorphological regions under study is represented by the lack of winter crops. Fallows and perennial sown pastures account for no more than 20% among agricultural lands. The sowing of spring crops begins, as a rule, in the first decade of May. During the entire May soil surface is not protected by plant cover. Therefore, the highest erosion risk in the strongly dissected forest steppe of West Siberia is in May. In May, during all the years regardless of moisture, except the dry years, precipitation varied within very narrow limits, such as 46–53 mm (Table 2). The characteristic property of the very dry vegetative season was found to be represented by a small and approximately equal precipitation, i.e. 44–54 mm, whereas in the remaining years (dry → very wet) the maximum precipitation falls in June and July. During these months the precipitation was half of that in May. However, by the end of June soil surface is closely covered by spring crops and the erosion hazard becomes essentially weaker.

It is known that total precipitation data are routinely used to assess the potential soil erosion, although the increase in summer precipitation is not always accompanied by appropriate increase in the surface runoff and the loss of solid soil phase (Cheremisinov, 1955; Zaslavsky, 1979). The value of surface runoff depends mainly on rainfalls intensity, their duration and frequency as well as on soil infiltration capacity (Livovich, 1974). It should be taken into account that about 70% of the precipitation

at the territory under study falls during the months of extreme erosion risk, i.e. May–August. At a given time, the daily maximum precipitation ranged widely (from 15 to 83 mm) in the Kuznetsk Depression and the Near-Ob area during the years with normal moistening. On the other side, daily maximum precipitation was not high in the very dry and dry warm erosion risk periods, with the exception of Near-Salair.

Table 2

Monthly precipitation during vegetational season in the years with various moistening. Kuznetsk Depression, Kolchugino weather station (1948–1988)

Month	Statistical parameters			
	lim, mm	M±m, mm	δ, mm	V, %
Very dry, <i>n</i> = 9				
May	21.4–77.9	46.2±7.9	23.9	52
June	25.1–76.8	43.9±4.8	14.3	32
July	10.1–82.9	53.7±31.0	93.0	173
August	20.3–59.0	45.1±7.5	22.5	50
Total	–	130.7	–	–
Dry, <i>n</i> = 10				
May	13.5–49.9	23.5±3.5	11.1	47
June	31.4–85.8	49.1±5.8	18.5	37
July	18.7–112.6	64.1±8.8	28.0	44
August	10.9–107.2	73.1±26.6	94.0	128
Total	–	209.8	–	–
Normal, <i>n</i> = 7				
May	23.8–98.6	53.1±10.7	28.3	55
June	35.4–120.3	74.4±12.4	32.8	44
July	23.5–100.8	68.3±12.6	33.8	49
August	18.9–70.1	45.7±9.2	24.6	54
Total	–	222.1	–	–
Moist, <i>n</i> = 6				
May	30.7–62.8	48.3±5.2	12.8	26
June	35.5–73.0	51.3±5.7	14.1	27
July	65.9–113.7	93.7±8.2	20.2	22
August	18.9–121.8	65.5±15.0	36.8	56
Total	–	258.8	–	–
Very moist, <i>n</i> = 9				
May	27.7–90.5	55.0±6.5	19.4	35
June	70.8–125.6	90.4±6.8	20.3	22
July	27.8–144.2	80.6±14.8	44.4	55
August	48.5–109.4	81.0±5.6	16.8	21
Total	–	307.0	–	–

Footnotes: *n* – sampling years; lim – fluctuation of data; M – mean; m – standard error of the mean; δ – mean-square deviation; V – coefficient of variation. Dashes indicate not available data.

In all three geomorphological regions the precipitation usually varied during the warm period within 15–46 mm, significantly increasing as the temperature rose. For instance, in the Kuznetsk Depression, the maximum daily precipitation reached 36, 67 and 49 mm in May, June and July respectively, in the very wet and warm period. It was supposed that all daily rains—as heavy as 20 mm and more—were associated with significant erosion hazards (Kaufluss, 1980). However, it should be noted that rains with comparatively smaller daily precipitation can also lead to substantial erosion risks. In West Siberia and in the Kuznetsk Depression in particular considerable part of liquid precipitation falls as downpours. Maximum precipitation during a downpour varied 50–54 mm in the Kuznetsk Depression.

In May downpours were infrequent and poor, precipitating 10–16 mm (Table 3). However, they fall on the soil unprotected by plant cover, and hence significant erosion loss of soil solid phase in arable lands occurred on the slopes. The most frequent downpours occurred in June and July, especially in the normal and extremely wet years. For instance, 5–8 downpours fall in June and July, whereas in the normal and extremely wet years such downpours were twice as frequent. Of course, the risk of erosion

by rains in June and July was much lower than in May, but in the course of these two months it was 2–3 times higher than in May.

Table 3

Description of downpours in the years with different moistening (Kolchugino weather station). Roman numbers indicate months of the year

Description of the years	Months				Total downpours, V–VIII, mm*	Total precipitation, V–VIII, mm	Downpours, % of total sum for V–VIII
	V	VI	VII	VIII			
Very dry, n= 3	–	14.1/1	62.9/4	68.0/5	145.0/10	318.8	45
Dry, n= 3	27.0/2	40.5/3	84.9/6	18.5/2	170.9/13	729.3	23
Normal, n= 3	13.3/1	93.2/6	111.3/7	62.3/4	280.1/18	769.5	36
Moist, n= 3	16.5/1	38.8/3	93.6/4	71.8/5	219.7/13	839.3	26
Very moist, n= 1	–	41.6/3	77.4/3	12.2/1	131.2/7	384.3/1	34
Extremely moist, n=3	10.1/1	104.7/7	84.8/7	41.2/3	240.8/18	1312.5	18

Footnotes: *Left-hand value refers to total precipitation, mm; right-hand value refers to number of downpours.

Comparing regions under study, one should note that the most prolonged and intensive downpours were recorded in the Kuznetsk Depression. For instance, in June 1977 the downpour delivered a total of 39 mm, being extremely intensive (2.7 mm per min) for 10 minutes, and in July 1983 the precipitation amounted to 22.4 mm in 7 minutes. The same territory obtained 48 mm of rain that was highly intensive during the first hour (1.9 mm per min for 5 minutes and 0.43 mm per min for the first hour) and low over 12 hours with intensity of 0.04 mm per min (Meteorological Reference Book, 1961–1988). Rather intensive and prolonged downpours were recorded in the Near-Salair area, in particular on July 10, 1963, when there was a downpour totalling 84 mm, its temporal intensity being as follows: 5 min: 1.6; 10 min: 1.4; 20 min: 1.0; 1 h: 0.30; 12 h: 0.07 (Orlov, 1971). As for the Near-Ob area, we never succeeded in finding there in 1984–1993 period the downpours of intensity and amount exceeding 0.5 mm · min⁻¹ and 10 mm, respectively. These observations confirm that downpours were not associated with erosive risks, and eroded soils began to form due to surface runoff from the thawing water. In fact, the only intrinsic effect of downpours did not represent severe hazard to soil cover of the sloping surfaces if their intensity is smaller than water infiltration, which is of special importance in the dissected regions. First, infiltration values inform about the degree “absorption” of atmospheric precipitation, downpours in particular, and possible formation of surface runoff. Second, according to our results infiltration rate changes in soils displaying different degrees of erosion. Since the eroded and non-eroded chernozems and drift meadow chernozemic soils are located on different positions of the drainage basin, it can be confirmed that water infiltration varies greatly throughout the whole drainage basin as well as in the individual plots of the slope; this fact adversely affects the accumulation of warm period precipitation and the water balance of the territory as a whole and leads to the increase both surface runoff and erosion processes. Nevertheless, in the case of the water infiltration throughout the whole drainage basin (even though such a case can hardly occur) erosion resilience of soils will depend to a certain degree on their slope location: the lower positions of the slope where water enters from the top are exposed to the greater water absorption load as compared with the overlying plots (Burykin, 1972). Therefore, the water infiltration of all slightly drift meadow chernozemic soils without an exception was considerably higher even in comparison with the non-eroded chernozems which occupy slightly sloping watershed areas. The high infiltration of slightly drift meadow chernozemic soils can be explained by the fact that the drift layer of these soils consists of sorted water-stable aggregates of more than 1 mm in diameter. During its flow along the slope, the downpour water causes a loss of the solid phase; this phase sediment on the surface of meadow chernozemic soils as a consequence of the decreased velocity of the water flow. Characteristically, the biggest infiltration rate (judging by the third hour of observation) was recorded for the podzolized non-eroded and slightly eroded chernozems of the Kuznetsk Depression (more than 1 mm · min⁻¹). Infiltration rate of moderately eroded chernozems is two times less than that of non-eroded and slightly eroded soils.

The lowest infiltration rate ($0.4 \text{ mm} \cdot \text{min}^{-1}$) was characteristic for strongly eroded chernozems. Due to the low content of humus and organic colloids (mainly humic acids) that contribute to soil structure formation, water permeability of the non-eroded chernozems of the Near-Salair and Near-Ob areas was approximately half of that in the similar soils of the Kuznetsk Depression. In particular, humus depletion is a major driver of soil degradation after soil structure destruction, soil compaction and soil biodiversity loss, i.e. conditions which make soils prone to accelerated erosion (Lal, 2004). As for the eroded chernozems of the Near-Salair and Near-Ob areas, the infiltration rate there was found to be extremely low, ranging $0.23\text{--}0.6 \text{ mm} \cdot \text{min}^{-1}$. In those areas the downpours with intensity exceeding $5 \text{ mm} \cdot \text{min}^{-1}$ should cause surface runoff on chernozem at the sloping surfaces. Previous observations (Surmach, 1955) reported that surface runoff occurred already due to 5 min of downpour. As a rule, in most cases the downpours last for 5–7 minutes, resulting in 10–15 mm of precipitation (sometimes 30–50 mm over more prolonged time intervals), so that the high kinetic energy of the surface runoff of downpour water becomes obvious.

Many authors noted that because of intensive rains, the slope runoff, especially from the steep slopes, is greater on arable lands than on virgin or lay lands (Konovalov, Pyzhov, 1969; Spomer et al., 1973), resulting in high removal of soil material on arable slopes. Furthermore, due to downpours the amount of water per unit area of soil surface is several times higher than due to the intensive snow thawing (Makkaveev, 1975). Moreover, the amount of removed soil can average from 100–160 up to 500 $\text{mg} \cdot \text{ha}^{-1}$, which is equivalent to 10–50 mm of soil profile (Luca, 1963; Gorbunov, Ryabov, 1972; Lal, 1976; Zaslavsky, 1979; Schwertmann, 1981). The chernozems under study are heavy-textured but downpours prove to be extremely destructive in light-textured soils as compared with chernozems. For instance, under subtropical conditions of the Mediterranean region (e.g., Spain) where luvisols are mainly characterized by loamy sand texture, the August downpour was as intensive as 70 mm for 45 minutes. As a result, the loss of soil mineral part ranged from 200 to 700 $\text{Mg} \cdot \text{ha}^{-1}$ and more, as measured in runoff plots (10 m wide and 50 m long). It is noted that the least loss was found to occur under minimum (zero) soil tillage practices (De Alba et al. 2003). In this line, the analyses by Nunes et al. (2016) of the spatial variability of annual precipitation and erosion in southern Portugal suggested that their decrease was partly counterbalanced by an increase in their intensity i.e., that the recorded decrease in precipitation should not be interpreted as a decline in the potential risk of soil erosion. This is in line with the studies by Strohmeier et al. (2016) in plot locations in Austria who also found that the magnitudes of the large extreme events may overcome the effect of its low occurrence probabilities, and therefore, the large extreme events effectively contribute to the long-term soil loss.

The processes of soil erosion caused by downpours essentially differ from the thawing water erosion (Kalianov, 1974). During the warm time interval the surface water runoff occurs only on the moist and sometimes on the dry sloping surface, rather than on extremely moist surface which is in the “fluidity stage” like during snow thawing. The slope exposure is of low importance during downpour precipitation, whereas during snow thawing its importance is very high. In the warm time interval the steepness of the slope and soil-protective capacity of plants play a substantial role in mitigating the downpour effects.

The largest soil loss due to erosion occurs during downpours in fallow fields (Hairston et al., 1984) with tilled and close-growing crops, but in early stages of development of plants when their soil-protective capacity is still low (beginning or middle of June). During heavy showers the erosion loss of solid phase of slightly eroded leached chernozems averaged $4.6 \text{ mg} \cdot \text{ha}^{-1}$ when the slope inclination was up to 5% (Table 4). With increasing slope inclination, and consequently the flow kinetic energy, the removed mass sharply increases (Wischmeier et al. 1958). This is the case with Kuznetsk Depression, where the soil loss already reached $16 \text{ mg} \cdot \text{ha}^{-1}$ at slopes of 5–9% and $22 \text{ mg} \cdot \text{ha}^{-1}$ at slopes of 9–15%, as estimated by Khmelev and Tanasienko (1983).

The most abundant and intensive downpour during the study was observed on July 24, 1970. For the first 10 min the downpour intensity was $2 \text{ mm} \cdot \text{min}^{-1}$, then for 21 min it was $1 \text{ mm} \cdot \text{min}^{-1}$. As the surface of the leached, medium thickness, heavy-textured chernozems was protected by the well-developed wheat plants, downpours did not seriously destroy the soils of 3–5% slopes, where soil loss was not more than $2 \text{ Mg} \cdot \text{ha}^{-1}$. Nevertheless, on steeper slopes (5–15%) the soil loss was considerable and ranged from 23 to $48 \text{ Mg} \cdot \text{ha}^{-1}$. In the lower near-narrow part of the slope, at the lower altitude than the wheat field, the fallow plot was prepared for the forest belt as wide as 15–20 m. In some places of this plot the downpour washed off completely the ploughed layer as wide as 30 cm; the depth and width of the rain channels was

Table 4

Downpour loss of solid phase of chernozems of different erosion degree

Month	Crop	Degree of soil erosion	Steepness of slope, %	Precipitation, mm	Downpour intensity, mm·min ⁻¹	Runoff, mm	Soil loss, mg·ha ⁻¹
Kuznetsk Basin							
May	Wheat	Slight	3–5	25.0	1.2	13.8	5.3
June				36.0	1.5	18.0	6.2
July				38.5	1.1	17.3	5.1
July				41.0	1.5	18.0	6.2
June	Corn	Moderate	5–9	25.6	1.5	15.3	2.0
June				36.0	1.0	19.5	1.5
July				17.0	1.3	9.0	1.2
August				19.0	1.2	10.0	1.2
August				38.5	1.1	16.0	1.7
August				30.0	1.0	18.5	2.9
May	No corn	Moderate	5–9	25.0	1.2	15.0	2.2
July				41.0	1.3	28.7	23.5
July				36.0	1.3	19.8	12.5
July		Strong	9–13	25.0	1.2	18.7	15.6
July				36.0	1.3	17.3	12.5
July				41.0	1.3	19.8	46.7
Near–Salair							
June	Wheat	Slight	1.5	40.0	2.0	32.0	12.5
June	Wheat	Moderate	1.5–5	40.0	2.0	32.0	50.0

measured as 44 and 220 cm, respectively. Therefore, general soil mass loss amounted to ca. 24 m³ from every rain channel. Podzolized loamy chernozems of Near-Salair are characterized by very high erosion loss. As compared to non-eroded chernozems, their insignificant erosion-preventive resilience can be explained by the reduced content of clay and humus, i.e. the mineral and organic glues, combined with not high cation exchange capacity; therefore, these soils are washed off intensively. It is remarkable that in these soils at the same slopes the thawing waters remove 3–4 times less solid phase than during downpours. According to our calculations it takes 53–110 m³ of thawing water to wash off 1 Mg of chernozem in West Siberia, whereas during downpours the respective amount is estimated as 8–50 m³. Such difference in erosion losses due to the snow-thawing runoff or the downpour waters can be explained by the fact that during snow melting in low-snow hydrological years the thawing waters are in contact with the surface of thawed soil for 4–6 hours during 3–5 days, averaging 12–30 hours. In high and very high-snow hydrological years the duration of contact of thawing water with the surface of slope chernozems increases up to 6–10 days, making up to 30–50 hours. As for the downpour water, its contact with the surface of chernozems lasts for 10–40 min. It is necessary to keep in mind that downpour water is partly absorbed by a warm soil profile, and during snowmelt the depth of the maximum soil defrosting is 5–20 cm. Beyond the thawed layer the soil is in a frozen state and practically does not absorb thawing water.

CONCLUSIONS

In West Siberia heavy rains cause significant damage to agricultural land only locally, during early spring, when the soil is not protected by vegetation. The greatest erosion hazard is represented by meltwater, and not only by its total amount, but also by the thawing rate. In both cases, soil permeability plays an important role in the resulting runoff amounts. The vulnerability to soil erosion in the studied area was found to be as follows: the Kuznetsk Depression > Near-Salair > Near-Ob (no storm damage). These studied regions were characterized by i) the prevalence of precipitation during the warm growing season; ii) sporadic or cyclical precipitation patterns; and iii) a significant decrease in the infiltration rate during extensive agriculture as the important factor determining the degradation of the main fertile soils in West Siberia.

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ЛИВНЕВАЯ ЭРОЗИЯ ЧЕРНОЗЕМОВ ЗАПАДНОЙ СИБИРИ

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Целью исследования было 1) установить основные закономерности формирования поверхностного ливневого стока и 2) оценить масштабы эрозионных процессов на пахотных черноземах в условиях расчлененного рельефа и резко континентального климата. Влияние ливней и почвенно-физических факторов на эрозию почв изучали в пределах трех больших геоморфологических районов на юго-юго-востоке Западной Сибири. Полевые наблюдения проводили в Кузнецкой котловине и Приобье в 1968–1979 и 1984–1986 гг. соответственно, в Присалаирье – с 1995 года по настоящее время. Полевые замеры водопроницаемости проводили методом Нестерова на небольших закладываемых водой участках, где установленные на поверхности почвы квадратные или круглые рамки ограничивали площадь 2500 см² (внешняя) и 625 см² (внутренняя). Количество и интенсивность осадков измеряли с помощью гидрографа. На основании собственных наблюдений и многолетних данных метеорологических станций (1936–1997 гг.) изучены пределы варьирования количества и интенсивности ливневых осадков, их пиковые значения. Исследованы и обобщены данные по водопроницаемости почв, объемам жидкого и твердого стоков на основных типах почв данной территории – серых лесных почвах, выщелоченных и оподзоленных черноземах, различающихся по степени эродированности и содержанию органического вещества. Исследованные территории по степени уязвимости к эрозии располагаются в следующем порядке: Кузнецкая котловина > Присалаирье > Приобье. Продолжительность и интенсивность твердых и жидких осадков играют ключевую роль в развитии поверхностного стока. Сильные дожди наносят значительный ущерб сельскохозяйственным угодьям только локально, ранней весной, когда почва не защищена растительностью. С крутых склонов ежегодно теряется порядка 10–20 т/га твердой фазы почвы. Проницаемость почв играет важную роль в формировании объемов стока, как в случае ливней, так и талых вод.

Ключевые слова: расчлененная лесостепь; водопроницаемость; интенсивность стока; поверхностный сток; потери почвы; серая лесная почва; выщелоченный чернозем; оподзоленный чернозем; Западная Сибирь.

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