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FACTORS AFFECTING NUTRIENT BUDGET IN LAKES OF THE R. JORKA WATERSHED (MASURIAN LAKELAND, POLAND)
V. NUTRIENT INPUT WITH AIR TRANSPORT*

ABSTRACT: The dust fall on drainage basins of four lakes of the r. Jorka watershed was investigated between September 1977 and August 1979. The dust fall was estimated (in g·m^{-2}) and concentrations of C org., N tot. and P tot. Spatial and seasonal differentiation of the amount of dust fall is presented, the relation between dust fall and wind erosion of soils and meteorological conditions, and also the relation between the amount of C org., N tot. and P tot. and the dust fall. The significance of allochthonous matter reaching the lake with air transport is pointed out.

KEY WORDS: Lakes, air transport, allochthonous matter, nutrient input, dust fall.

Contents

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1. INTRODUCTION

The increasing every year dustiness and dust fall are problems concerning specialists of many fields, becoming of greater interest for natural scientists (Smith et al. 1970, Jackson et al. 1973, Scriven and Fisher 1975, Reed 1976, Stern 1977). However, the studies are concentrated, especially in Poland, on highly industrialized areas or on those with great urban agglomerations Krasnokucki 1974, Michalak 1975, Pompawski et al. 1975, Rapacz and Bartosik 1976, Buszman and Kwapuliński 1978, Lewtak 1978).

The smallest particles emitted by chimneys are transported by wind very far. They fall on areas, generally considered as unpolluted, frequently with rain (Scriven and Fisher 1975), for which these molecules become nuclei condensation of aqueous vapour.

Apart from transport of air pollution sometimes very far, the wind as a common phenomenon, similarly as water, destroys the soil surface and transports soil particles to other places. Thus the wind erosion of soils is an additional source of air pollution and probably the main one on non-urban and not industrialized areas. The cutting of forests and cultivation of greater areas permit it, whereas intensive agriculture and frequent breaking of soil surface create conditions for soil deflation.

In Poland, mainly due to temperate climate, wind erosion has not caused such damages as in USA or USSR, and so-called "black dust storms" are not recorded (Bennet 1955, Gael 1965). Nevertheless, some regions of Poland are exposed to soil erosion, such as areas in the middle part of Poland, the Baltic coast, Masurian Lakeland (Uggla and Piaścik 1966, Józefaciuk and Józefaciuk 1976).

The aim of the study was to investigate the role of wind transport in matter cycling, and especially the significance of input with air transport of allochthonous, abiotic matter for water ecosystems. During the investigations all stages of wind erosion were examined, i.e., blow down, transport and deposition of the matter. Special attention was paid to the latter, mainly of phosphorus as an element stimulating the eutrophication of water bodies.

These studies were a part of complex ecological investigations on the r. Jorka watershed in Masurian Lakeland conducted by the Institute of Ecology, Polish Academy of Sciences.

2. STUDY AREA

The investigated area was a part of the r. Jorka watershed (Fig. 1), which according to physico-geographical distribution of Poland (Kondracki 1972) is in the eastern part of Mrągowo Lakeland. It covers some 30 km^2 (the r. Jorka watershed 63.3

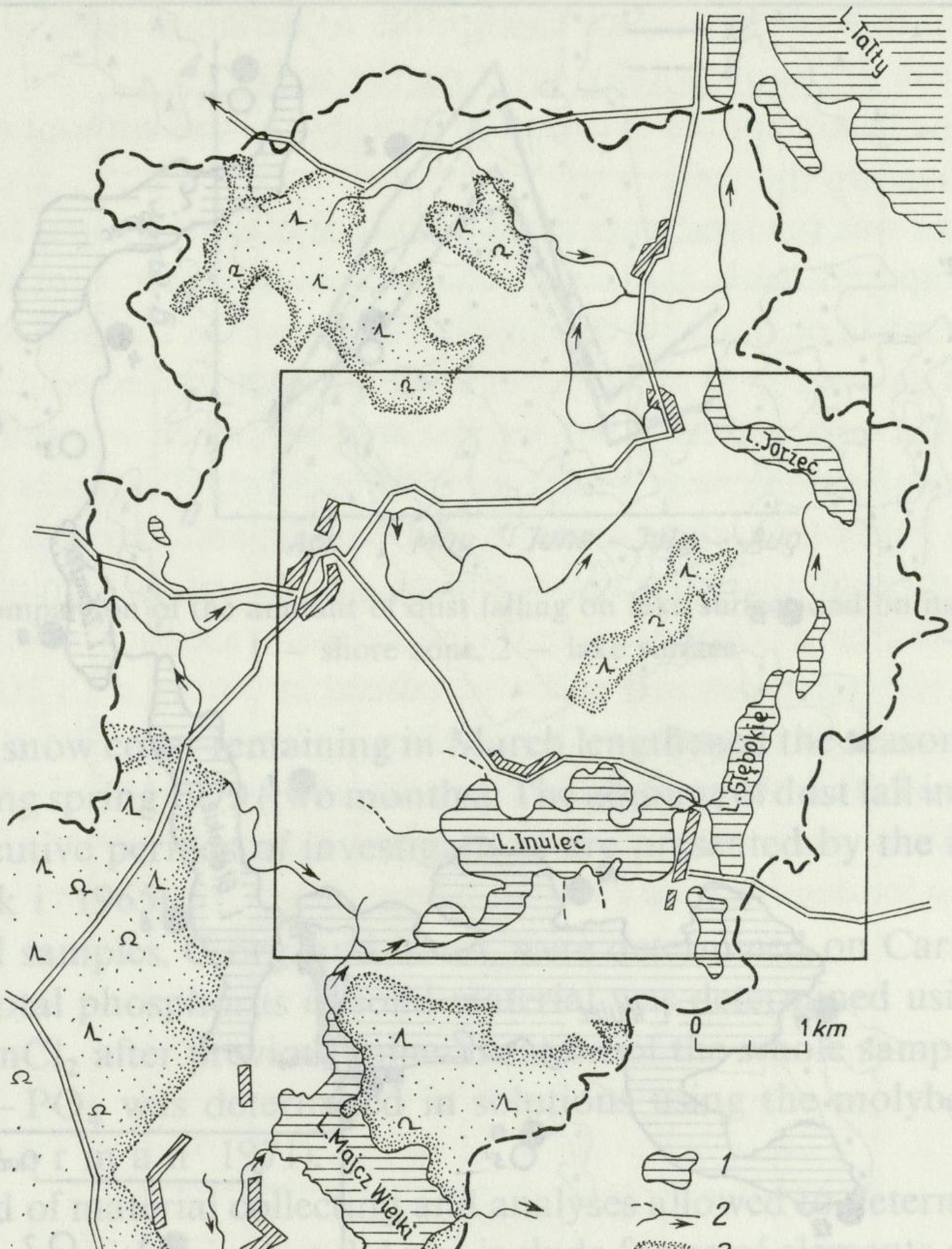

Fig. 1. The study area of dust fall against the background of all r. Jorka watershed
1 – lakes, 2 – watercourses and drains, 3 – forests, 4 – roads, 5 – compact building

km^2) of typical agricultural area: forests 8%, meadows and pastures 17%, arable land 60%, surface waters 10%, buildings and roads 5%. A detailed description of the area is given by Bajkiewicz-Grabowska (1985).

3. MATERIAL AND METHODS

The amount of dust fall was measured by the trap method (Smith et al. 1970, Krasnokucki 1974, Michalak 1975) – polyethylene traps, 40 cm in diameter, with 0.01 n HCl were placed at 15 measuring points (Fig. 2) around four lakes and also on the surface of one of these lakes (Lake Głębokie). Each measuring point

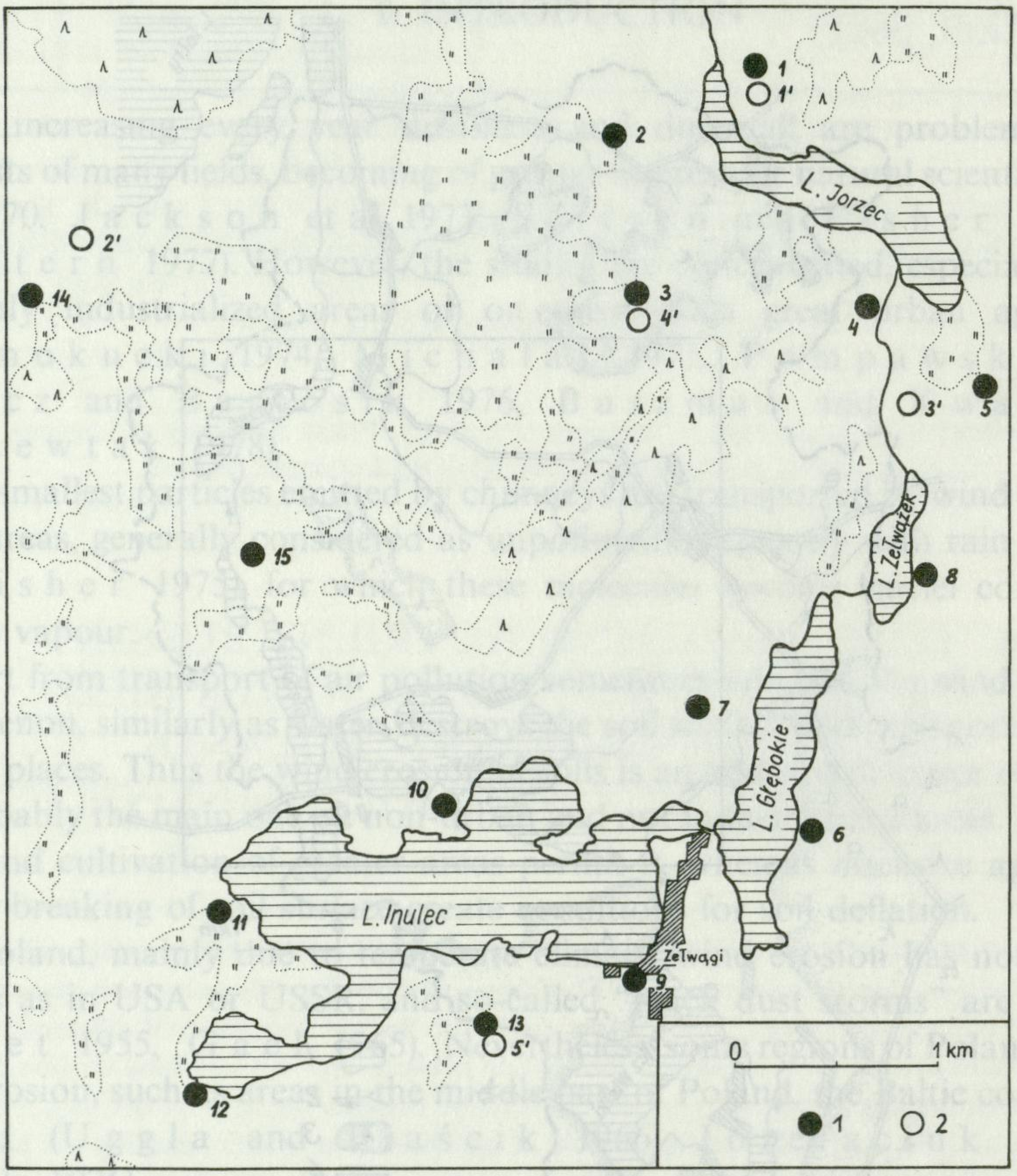

Fig. 2. Study area – distribution of measuring points
1 – dust fall measuring points, 2 – soil deflation measuring points

consisted of three traps, where the falling dust accumulated. Traps were emptied once a month, each time refilling the HCl solution. The material after being transported to the laboratory was filtered and dried at 105°C to constant weight.

No statistically significant differences were found for particular traps at each point (differences in dust fall were of the order 2–8% of mean values) thus the dust fall for each point was averaged. As the traps on the surface of Lake Głębokie were installed only for a part of the research period (5 months), the values of dust fall on lake surface were compared with points surrounding the lake. The differences among average values were small (Fig. 3) and statistically insignificant. For estimations of the dust fall on lake the data obtained at measuring points near the lake were used.

The studies were conducted between September 1977 and August 1979, and the whole period of observations was divided into seasons of the year: autumn (September, October, November), winter (December, January, February), spring (March, April, May) and summer (June, July, August), thus providing eight seasons. Data for each season were a sum of values for three months. An exception were: the winter of

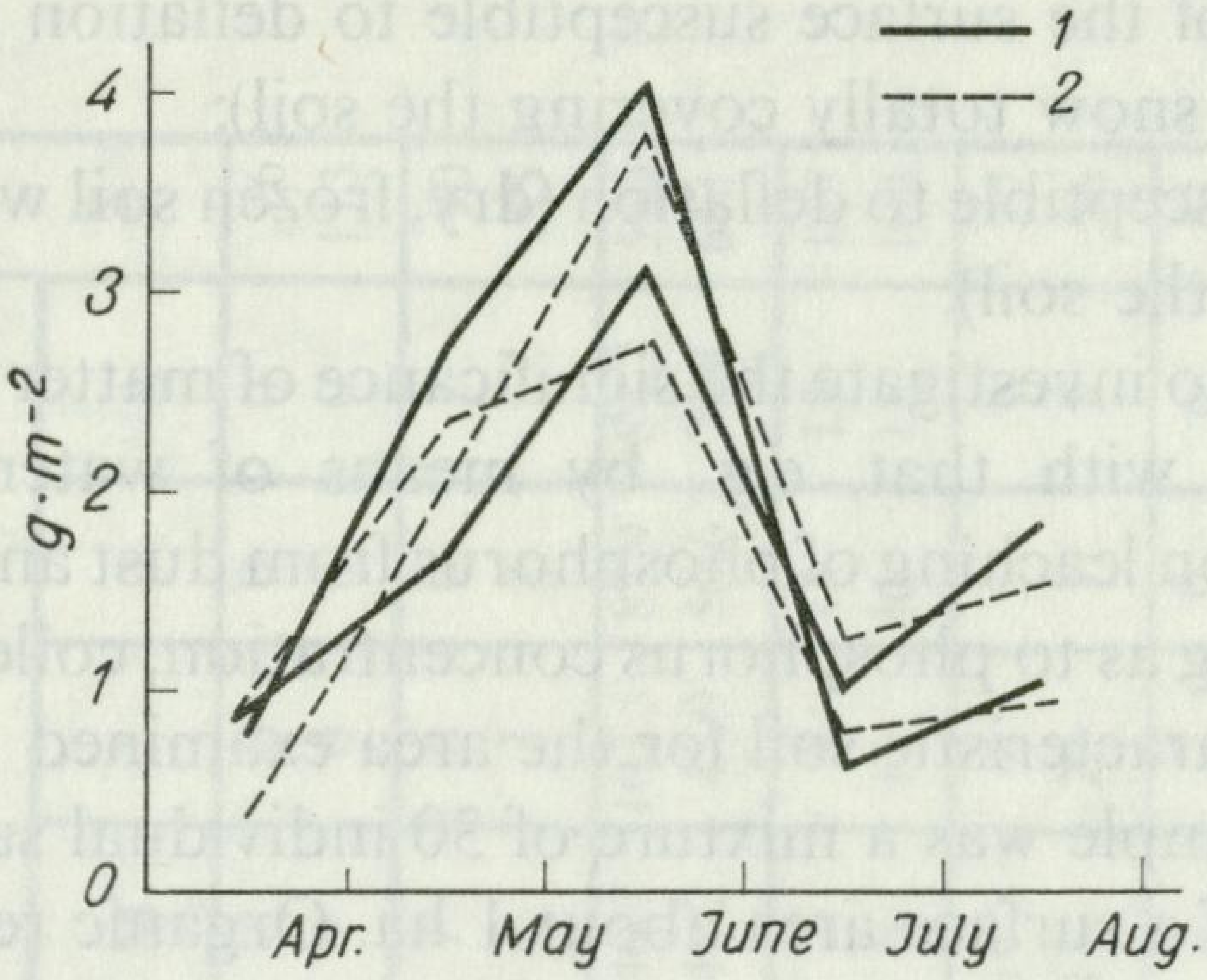

Fig. 3. Comparison of the amount of dust falling on lake surface and on its shore zone
1 – shore zone, 2 – lake surface

1978/1979 (the snow cover remaining in March lengthened the season to four months) and the following spring 1979 (two months). The amount of dust fall in each season and the two consecutive periods of investigations are presented by the isorithm method (Szaflarski 1965).

In collected samples, C org. and N tot. were determined on Carlo Erba analyser model 1102. Total phosphorus in solid material was determined using the molybdic method with $SnCl_2$ after previous mineralization of the whole sample (Jackson 1960). Also $P-PO_4$ was determined in solutions using the molybdic method with $SnCl_2$ (Golterman 1971).

The method of material collecting and analyses allowed to determine the dry dust fall and dust input with rain, but did not include forms of elements dissolved in rain. As the area examined was largely covered by arable land and was not highly industrialized, it could be assumed that the dust fall was largely conditioned by soil deflation, which in turn depended on the degree of its uncovering and on meteorological conditions. Therefore daily observations carried out by the Station of the Institute of Meteorology and Water Economy at Mikołajki[1] during the entire period of investigations (September 1977 – August 1979) were analysed. The following characteristics were taken into consideration: direction and wind velocity, dust level, number of days with fall ≥ 1.0 mm, thickness and accumulation of snow cover, soil condition. With the exception of the latter all other characteristics were estimated according to the instruction for meteorological stations of State Hydro-Meteorological Institute (1962). When determining the soil condition a 5-degree scale was used determining the susceptibility of soil surface to deflation:

0 – total unsusceptibility to deflation (wet soil with pools, total snow cover);

1 – less than half of the surface susceptible to deflation (moist soil without pools, glazed frost);

2 – half of the surface susceptible to deflation (ice and melting snow partially covering the soil);

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[1] The station is some 10 km south-east from the area examined.

3 – more than half of the surface susceptible to deflation (soil without snow or melting snow, loose dry snow totally covering the soil);

4 – soil extremely susceptible to deflation (dry, frozen soil without snow, loose dry snow partially covering the soil).

One of the aims was to investigate the significance of matter input to lakes with air transport as compared with that, e.g., by means of water erosion. Thus pilot experiments were made on leaching of phosphorus from dust and soil to lake water. In experiments, dust varying as to phosphorus concentration, collected during investigations, was used. Also characteristic soil for the area examined – sandy loam – was used. An average soil sample was a mixture of 30 individual samples taken from the arable layer on a field of a surface area about 1 ha. Organic remains were separated from soil, sieved through plankton net of a mesh size 45 μm, determining pH in H_20, organic matter and total phosphorus. In the experiment, identical samples of soil and dust were taken (100 mg). Dust and soil were placed in bottles with 100 ml of filtered lake water varying as to fertility degree and shaken up for 1 hour (Piper 1957). The experiment chart was following: (1) lake water, (2) lake water + soil, (3) lake water + dust, three repetitions each. After shaking up the samples they were filtred and 50 ml solution was taken for determining $P-PO_4$ using Golterman's (1971) method.

4. RESULTS

4.1. DUST FALL

The most differentiated spatially distribution of dustiness occurred in the autumn of 1977 (Fig. 4). The deposition of material transported with wind took place basically on two areas: northern edge of Lake Jorzec (dust fall exceeded there 60 $g \cdot m^{-2} \cdot season^{-1}$) and on fields of the north-western part of the area examined (over 26 $g \cdot m^{-2}$) and on the southern shore of Lake Inulec (over 30 $g \cdot m^{-2}$). On the remaining area the dust fall was much lower (10 – 25 $g \cdot m^{-2} \cdot season^{-1}$). In September 1977 it rained frequently, less so in the following months (Table I). Uncovering of soil surface as a result of agrotechnical treatments and occurrence of winds having high velocity, especially in November, caused probably soil deflation and transport of particles to other places. Other seasons of the year had much lower dust fall. In the winter of 1977/1978 the dust fall was 2.5 – 13 $g \cdot m^{-2} \cdot season^{-1}$ (Fig. 5) and the low values recorded were the result of almost constant accumulation of snow cover (Table I). In spring and summer (Figs. 6, 7) the dust fall was 4.5 – 15 $g \cdot m^{-2}$ and 4 – 16 $g \cdot m^{-2} \cdot season^{-1}$, respectively. In the spring of 1978 it was raining (Table I), but intensive field work and high wind velocities accelerated the drying of soils and thus the deflation. The summer as compared with spring was damper, but as the soils were less uncovered the dustiness was relatively low and almost evenly distributed.

Generally speaking, in the first period of investigations (Fig. 8), the dust fall was 23 $g \cdot m^{-2} \cdot year^{-1}$ on the eastern side of Lake Głębokie to almost 60 $g \cdot m^{-2} \cdot year^{-1}$ in

Table I. Meteorological data for the period between September 1977 and August 1979
a – I period of investigations (September 1977 – August 1978), b – II period of investigations (September 1978 – August 1979)

Parameters analysed		Months												Σ
		S	O	N	D	J	F	M	A	M	J	J	A	
Number of days with snow cover	a	0	0	0	10	29	28	9	0	0	0	0	0	76
	b	0	0	1	22	31	28	29	2	0	0	0	0	113
Number of days with moderate wind ($V \geqslant 7$ m ·sec.$^{-1}$)	a	5	1	11	22	17	9	9	7	7	0	0	2	90
	b	3	3	6	4	2	14	8	2	4	2	2	5	55
Total precipitation (mm)	a	55.4	18.5	25.1	32.4	26.9	7.4	24.2	43.6	40.7	103.5	87.9	84.3	550
	b	93.3	74.1	48.2	31.0	43.6	20.8	68.2	27.1	46.2	47.9	50.6	79.8	611
Number of days with precipitation $\geqslant$ 1.0 mm	a	18	11	8	9	9	5	12	7	5	5	13	15	117
	b	11	4	7	10	11	2	9	7	6	11	11	15	104
Number of days with soil extremely susceptible to deflation	a	6	7	2	5	0	0	2	11	19	8	5	7	72
	b	0	0	0	1	0	0	0	6	17	20	7	5	56
Number of days with soil not susceptible to deflation	a	5	2	7	9	22	8	1	6	2	7	6	6	81
	b	13	15	8	10	24	28	26	4	0	0	4	5	137

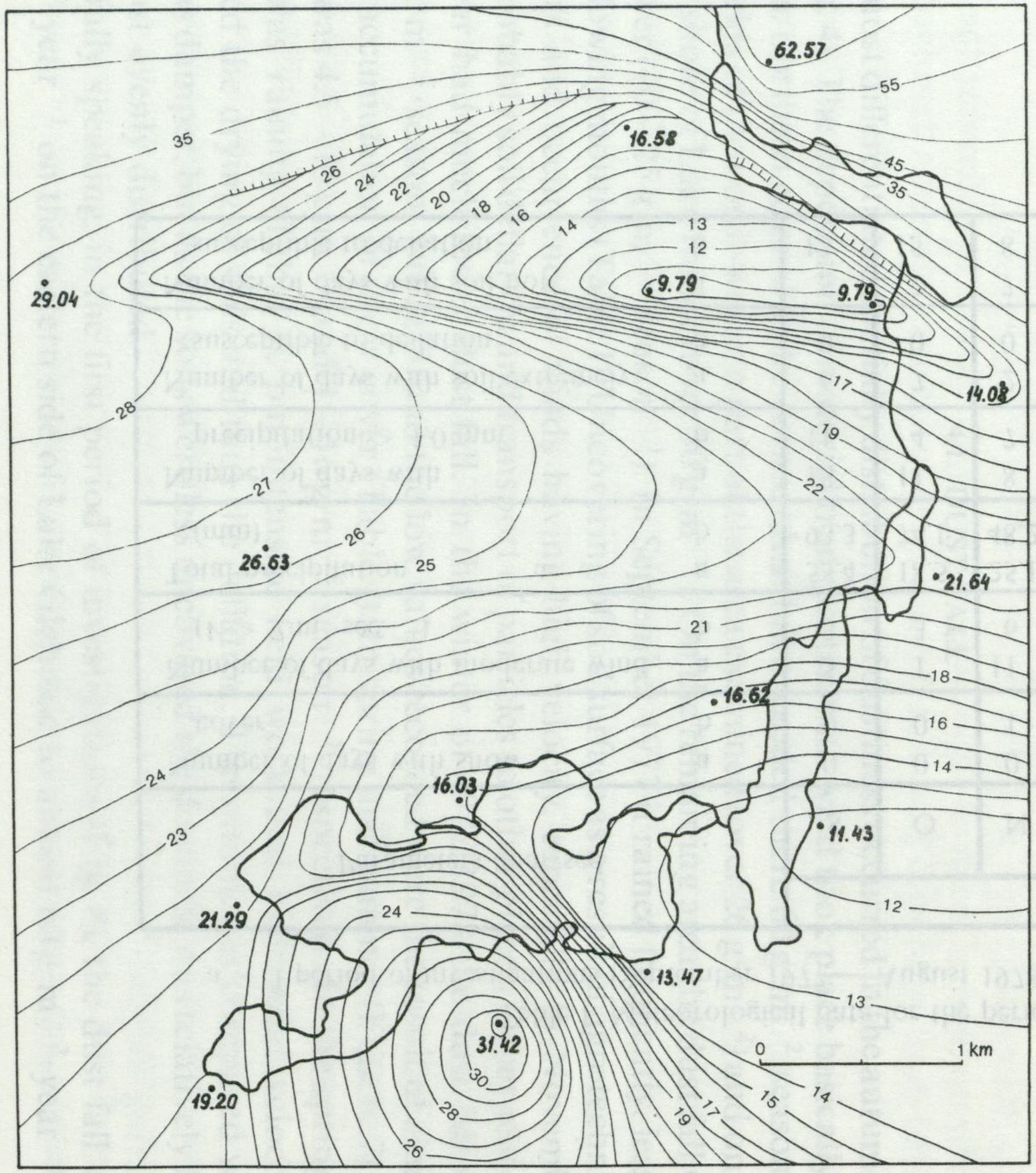

Fig. 4. Spatial distribution of dust fall (in g·m^{-2}) in autumn 1977 (names of lakes, location of study area – see Figs. 1, 2)

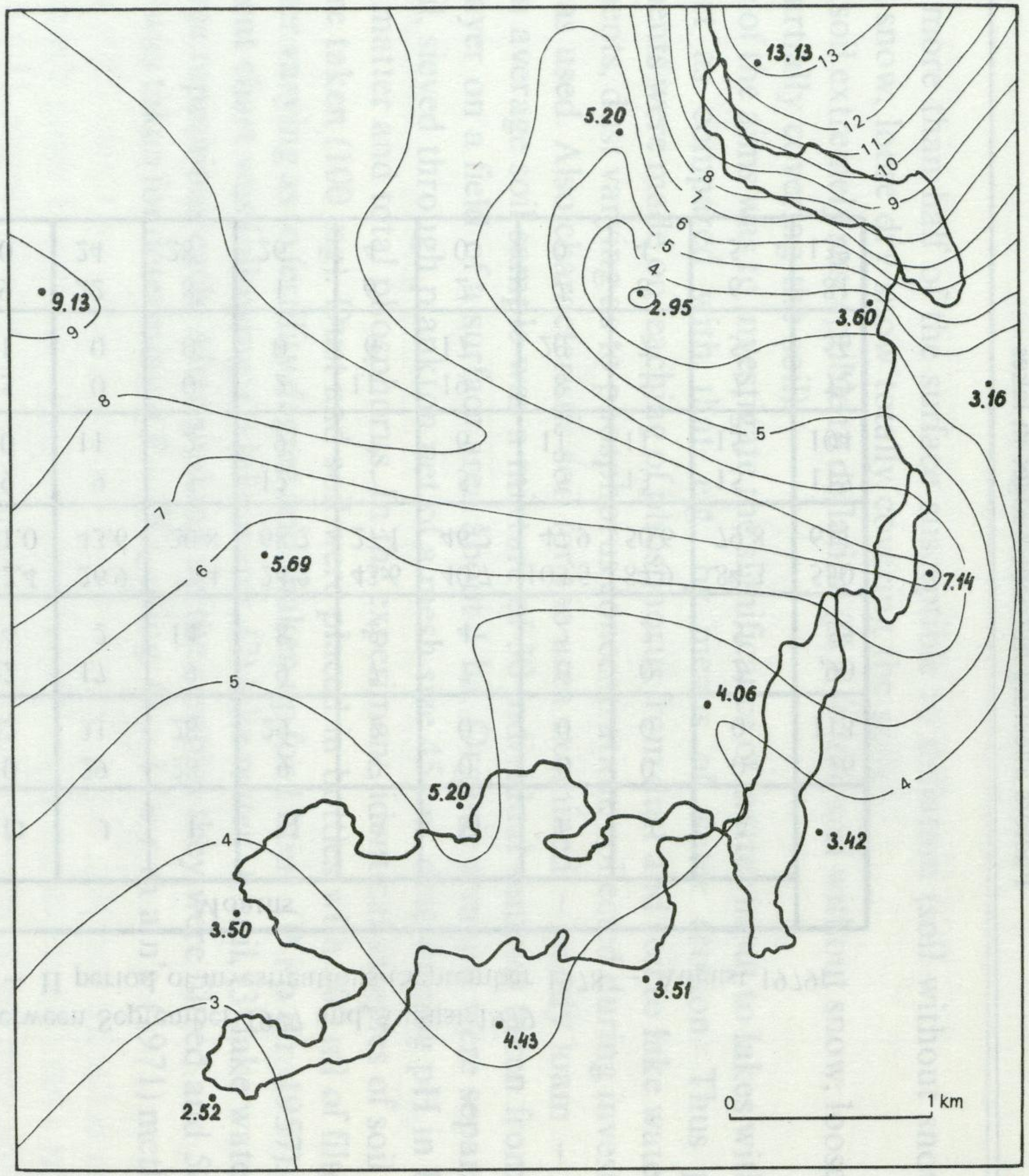

Fig. 5. Spatial distribution of dust fall (in g·m^{-2}) in winter 1977/1978 (names of lakes, location of study area – see Figs. 1, 2)

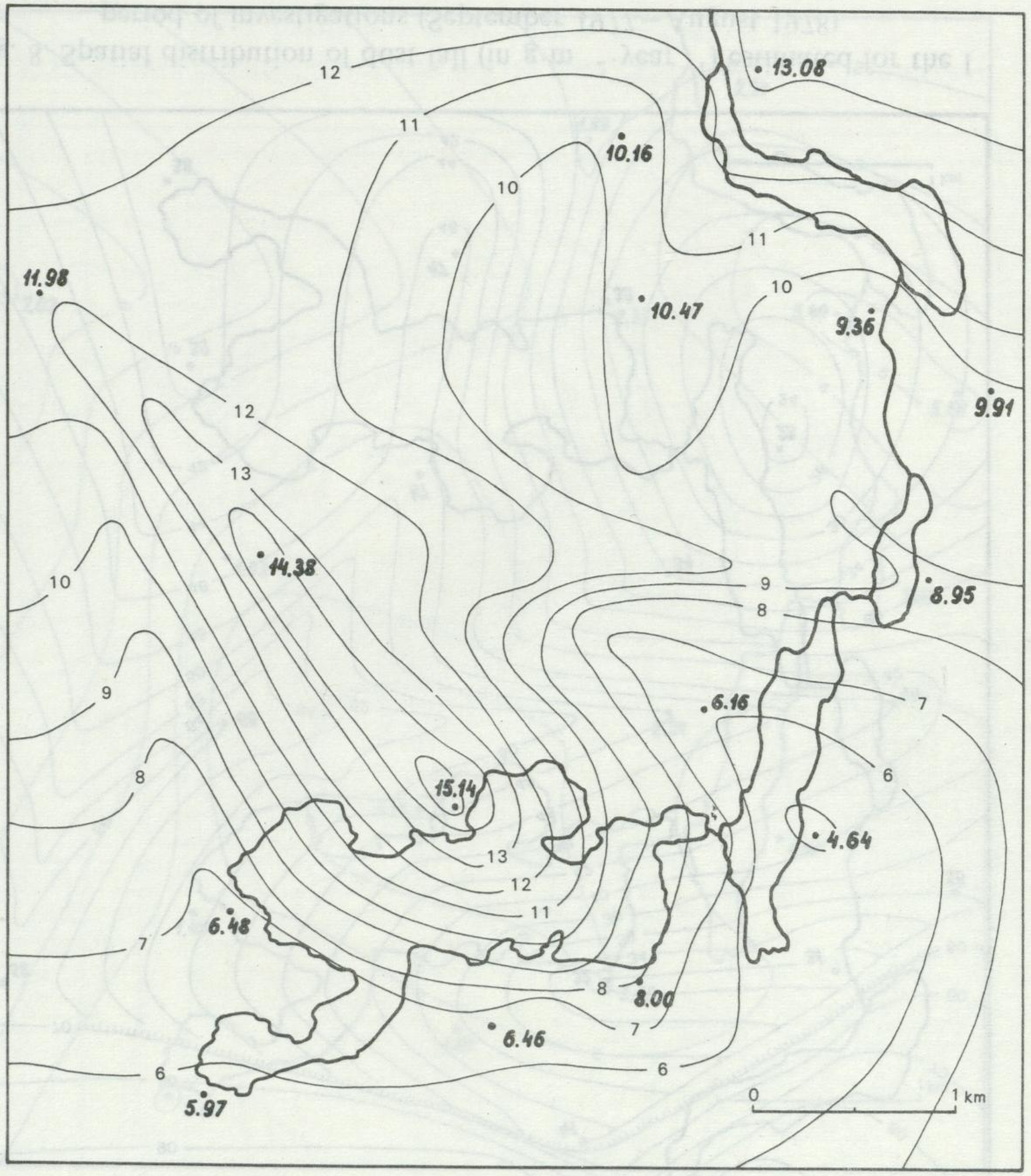

Fig. 6. Spatial distribution of dust fall (in $g \cdot m^{-2}$) in spring 1978 (names of lakes, location of study area – see Figs. 1, 2)

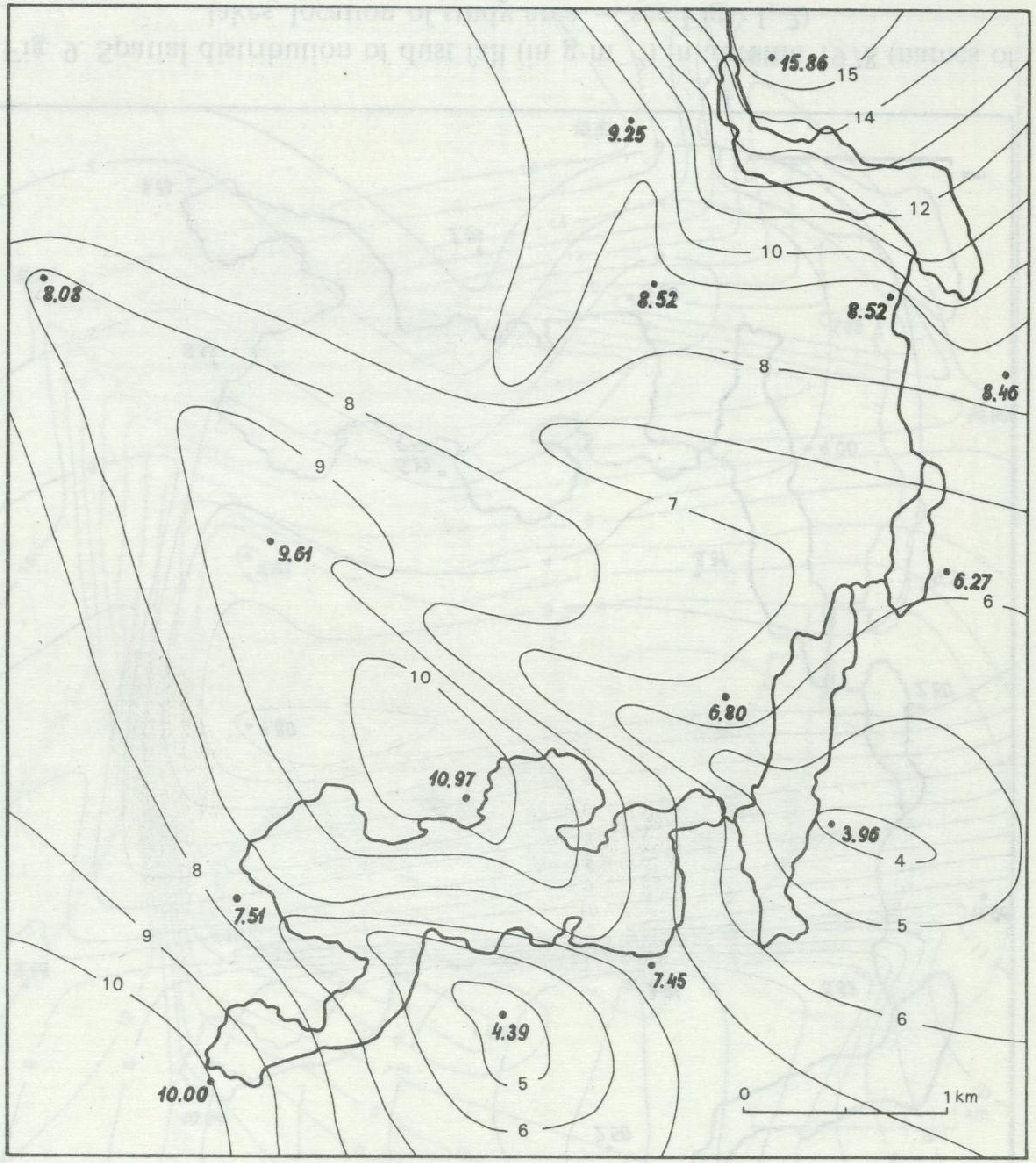

Fig. 7. Spatial distribution of dust fall (in $g \cdot m^{-2}$) in summer 1978 (names of lakes, location of study area – see Figs. 1, 2)

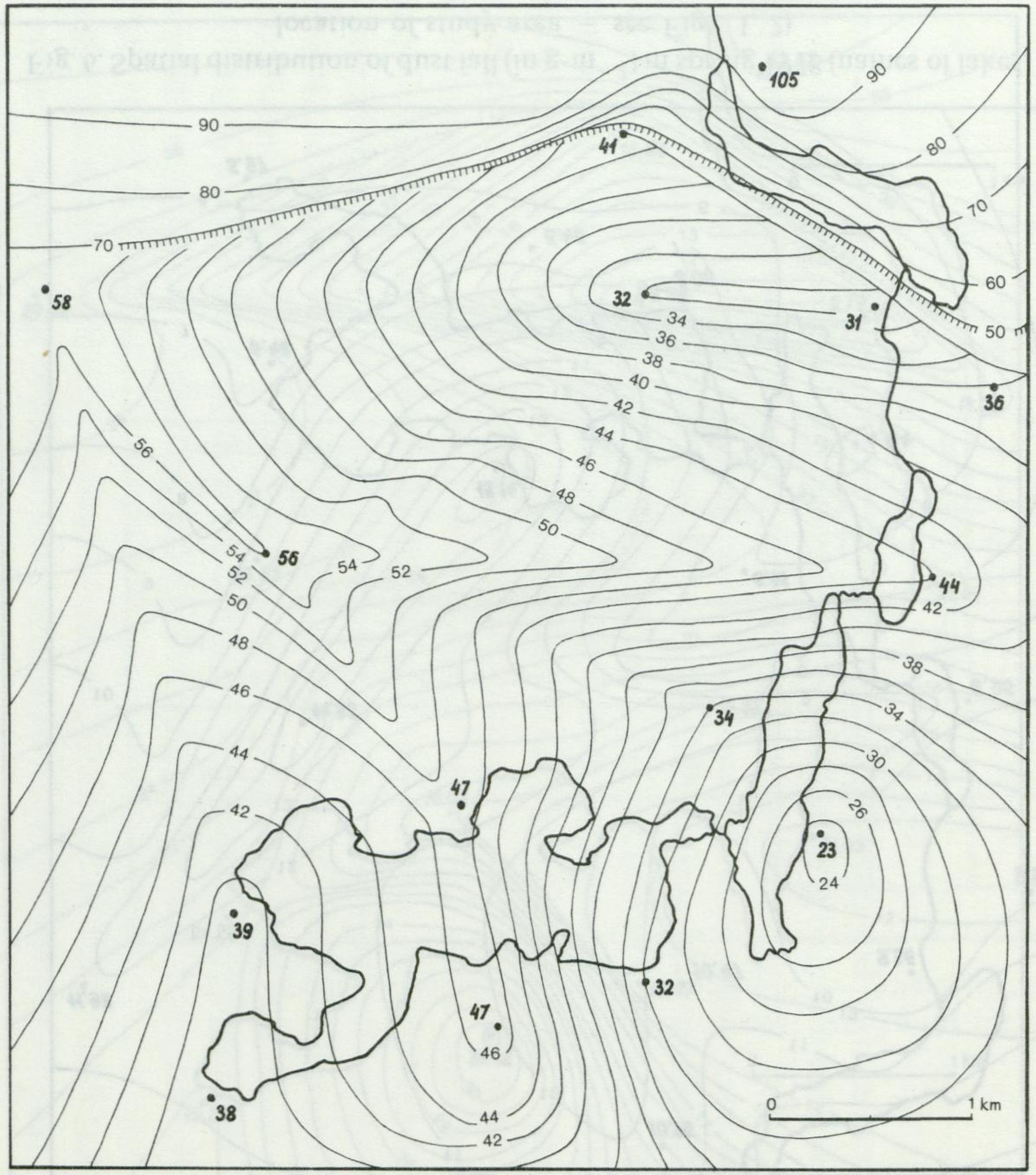

Fig. 8. Spatial distribution of dust fall (in g·m^{-2}·year^{-1}) estimated for the 1 period of investigations (September 1977 – August 1978)

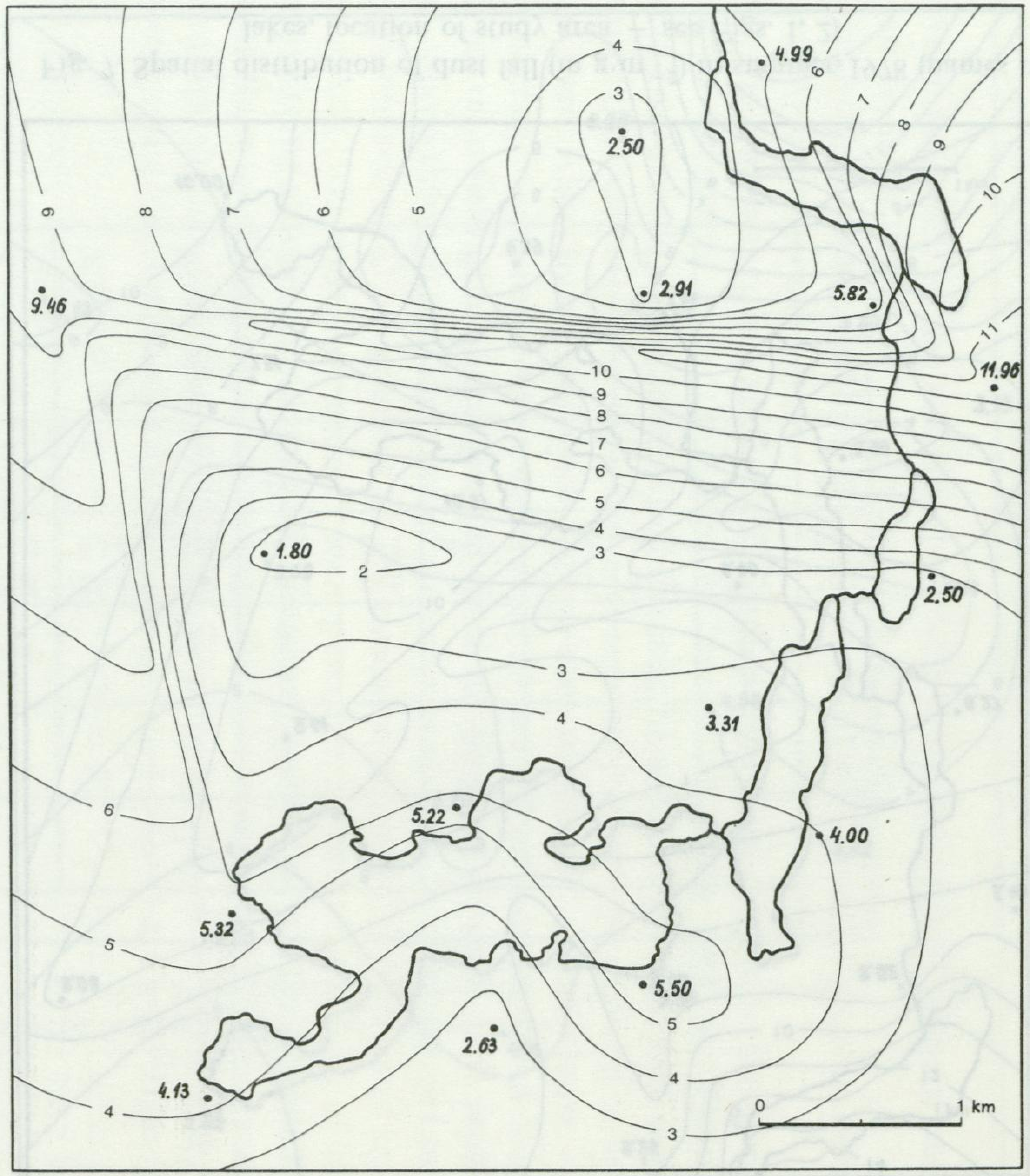

Fig. 9. Spatial distribution of dust fall (in g·m^{-2}) in autumn 1978 (names of lakes, location of study area – see Figs. 1, 2)

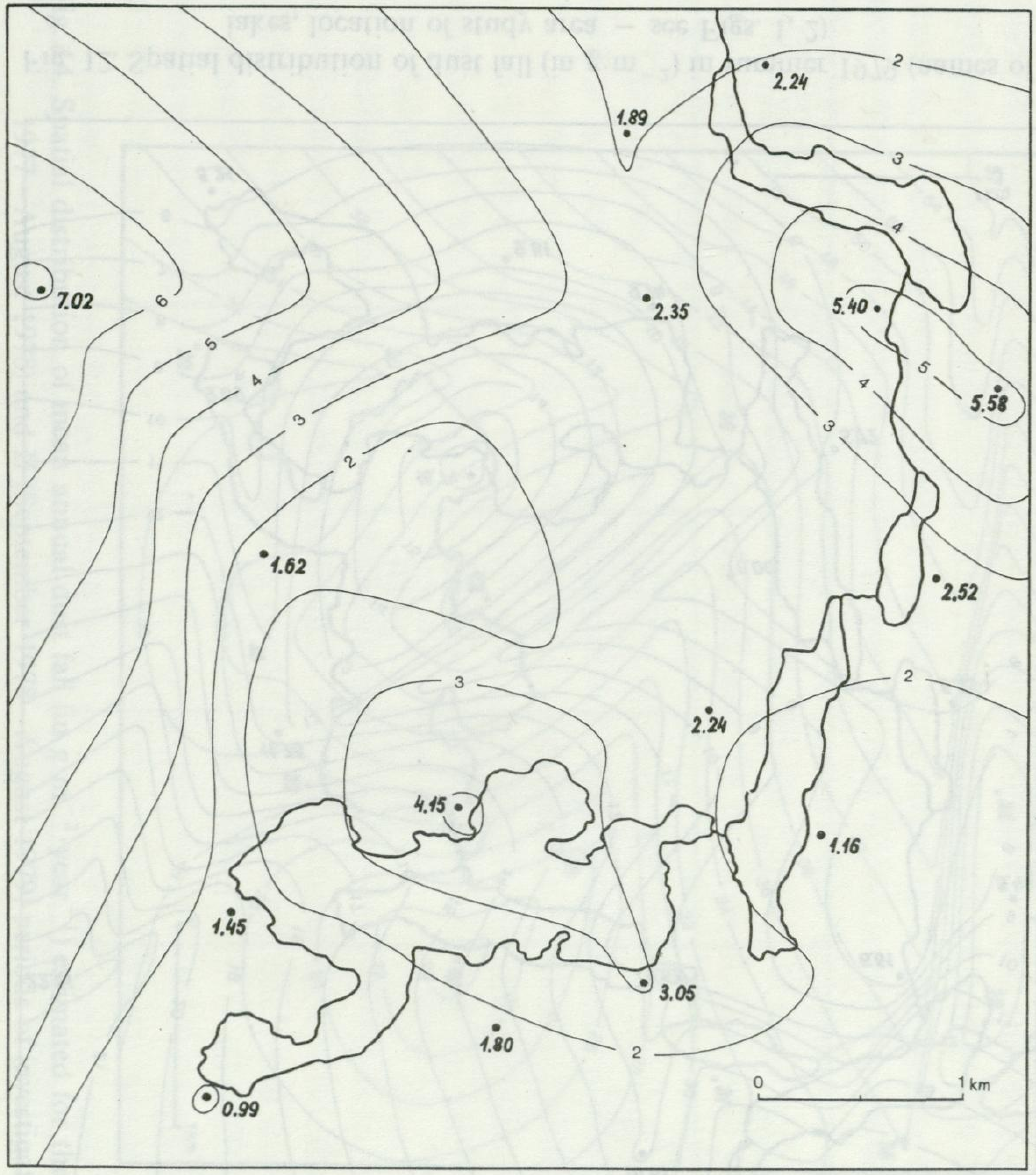

Fig. 10. Spatial distribution of dust fall (in g·m^{-2}) in winter 1978/1979 (names of lakes, location of study area – see Figs. 1, 2)

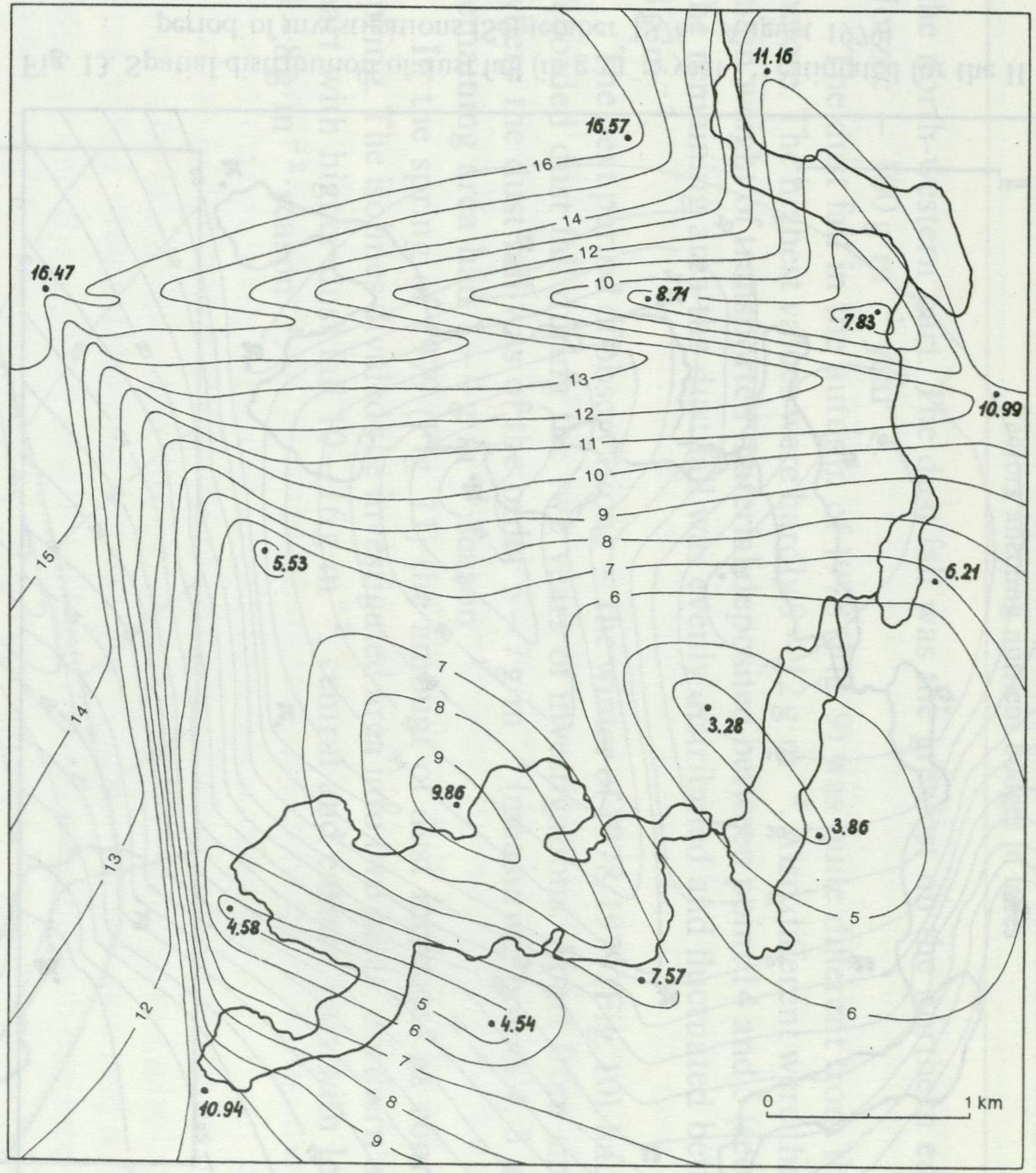

Fig. 11. Spatial distribution of dust fall (in g·m^{-2}) in spring 1979 (names of lakes, location of study area – see Figs. 1, 2)

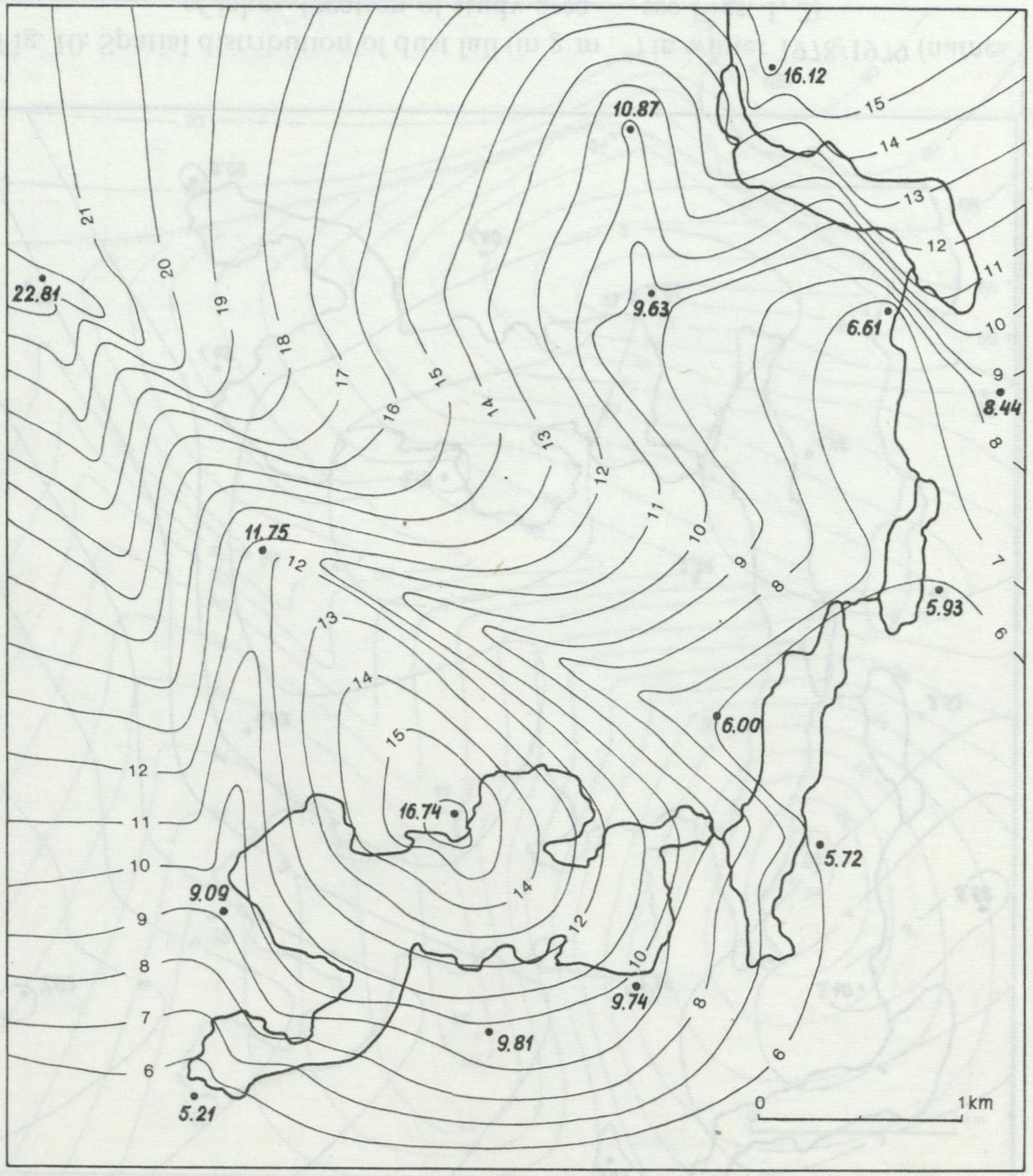

Fig. 12. Spatial distribution of dust fall (in g·m^{-2}) in summer 1979 (names of lakes, location of study area – see Figs. 1, 2)

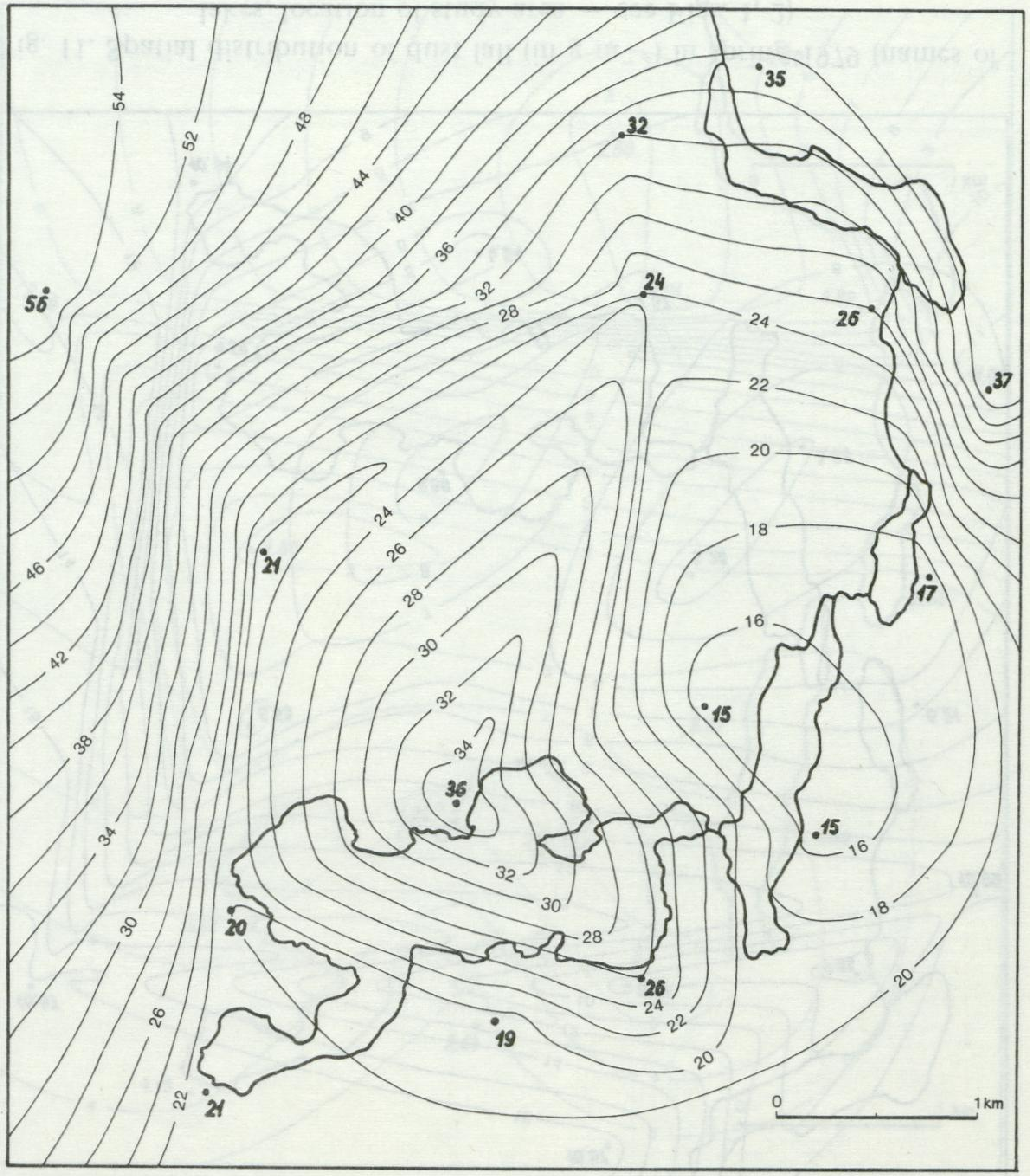

Fig. 13. Spatial distribution of dust fall (in g·m^{-2}·year^{-1}) estimated for the II period of investigations (September 1978 – August 1979)

the north-western part. The dust fall was the greatest on the northern edge of Lake Jorzec — 100 $g \cdot m^{-2} \cdot year^{-1}$.

The dust fall in the autumn of 1978 (Fig. 9) was quite different from that the year before. The highest values were hardly $9-12\ g \cdot m^{-2}$. Also different were the isolines — main weight of transported material deposited between point 14 and 5 (see Fig. 2). On the remaining area the dust fall was evenly distributed and fluctuated between 4 and $8\ g \cdot m^{-2}$.

The next period of observations — the winter of 1978/1979 (Fig. 10), had the lowest recorded dust fall during the two years of investigations. Apart from small islands, where the dust fall was of the order $5-7\ g \cdot m^{-2}$ (measuring points 4, 5 and 14), the remaining area had $1-4\ g \cdot m^{-2} \cdot season^{-1}$.

In the spring of 1979 (Fig. 11) the amount of dust increased as compared with spring. The isolines divided the investigated area into two parts: northern and western part with higher dust fall $10-16\ g \cdot m^{-2}$, central and eastern part with low dust fall $4-8\ g \cdot m^{-2} \cdot season^{-1}$.

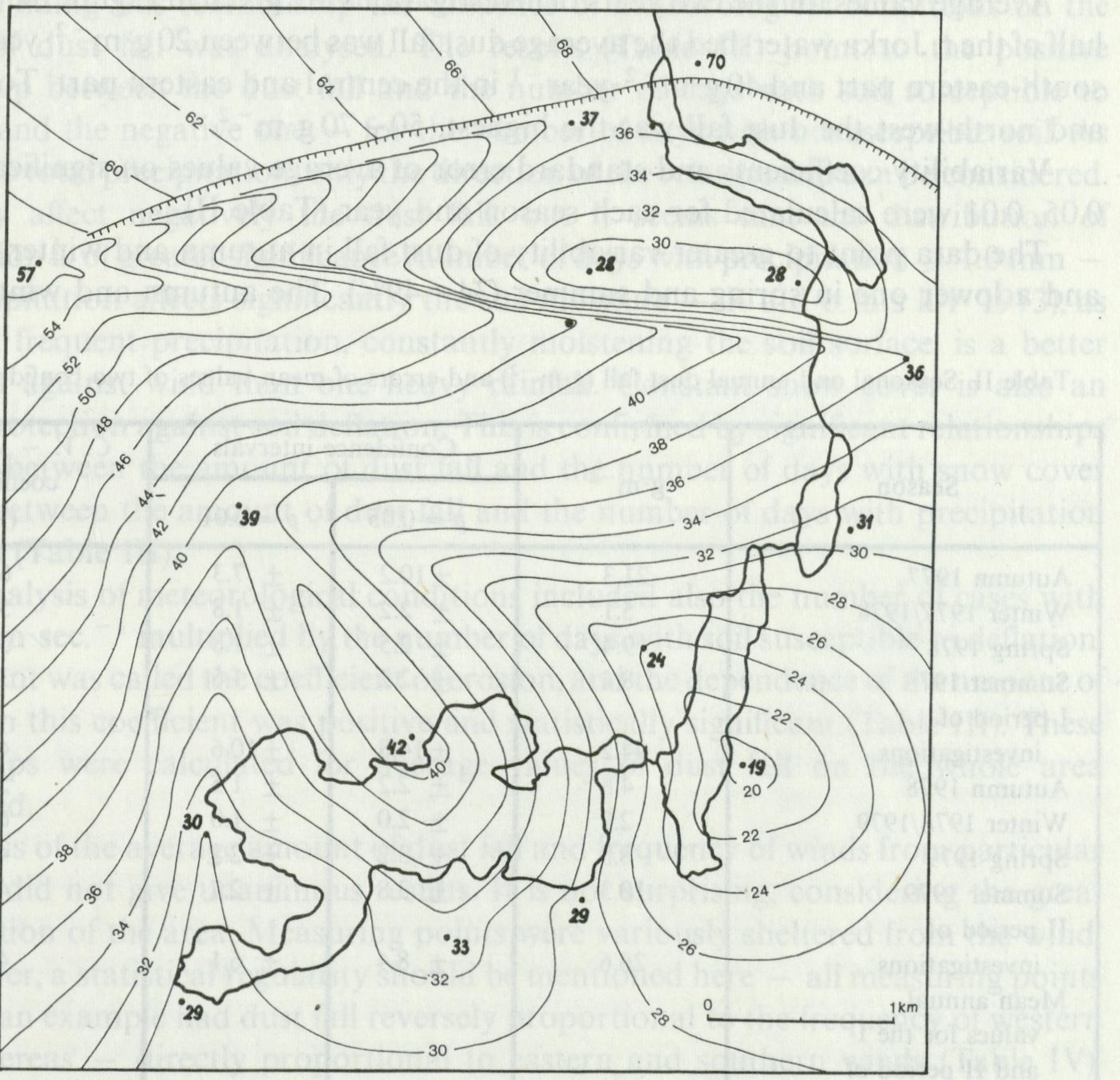

Fig. 14. Spatial distribution of mean annual dust fall (in $g \cdot m^{-2} \cdot year^{-1}$) estimated for the I (September 1977 – August 1978) and II (September 1978 – August 1979) periods of investigations

In the summer of 1979 the dust fall increased as compared with spring. On almost 2/3 of the area this fall ranged between 10 and 23 $g \cdot m^{-2}$. Only in the surroundings of lakes Zełwążek and Głębokie and southwards from Lake Inulec these values were much lower, 5 – 8 $g \cdot m^{-2} \cdot season^{-1}$ (Fig. 12).

The results of the second period of investigations confirmed also the influence of meteorological conditions and the degree of soil uncovering on dustiness.

The autumn of 1978 was much damper than the previous one (twice higher precipitation in September and November, four times higher in October – cf. Table I). In that season on not day was the soil susceptible to deflation. The winter of 1978/1979 differed also from the previous one. Much thicker and twice longer remaining snow cover protected the soil efficiently against deflation. But the shorter spring in 1979 could have been the reason of lower dustiness than in summer.

In the second period of investigations (Fig. 13) the dust fall on the whole area was between 15 $g \cdot m^{-2}$ per year in the surroundings of Lake Głębokie and 56 $g \cdot m^{-2}$ on the north-western part of the area. It increased distinctly from the south-east towards the north-west.

Average values for the two years of investigations are given in Figure 14. On almost half of the r. Jorka watershed the average dust fall was between 20 $g \cdot m^{-2} \cdot year^{-1}$ in the south-eastern part and 40 $g \cdot m^{-2} \cdot year^{-1}$ in the central and eastern part. To the north and north-west the dust fall was the highest, 50 – 70 $g \cdot m^{-2}$.

Variability coefficients and standard error of average values on significance levels 0.05, 0.01 were calculated for each season and year (Table II).

The data point to greater variability of dust fall in autumn and winter (55 – 62%) and a lower one in spring and summer (34 – 49%). The autumn and winter in both

Table II. Seasonal and annual dust fall ($g \cdot m^{-2}$) and errors of mean values of two confidence intervals

Season	$g \cdot m^{-2}$	Confidence intervals		*C. V.* – variability coefficient (%)
		$p = 0.05$	$p = 0.01$	
Autumn 1977	21.3	± 10.2	± 7.3	62
Winter 1977/1978	5.1	± 2.2	± 1.8	55
Spring 1978	9.4	± 2.5	± 1.8	34
Summer 1978	8.4	± 2.2	± 1.6	34
I period of investigations	44.2	± 14.8	± 10.6	44
Autumn 1978	4.8	± 2.2	± 1.5	57
Winter 1978/1979	2.9	± 2.0	± 1.0	63
Spring 1979	8.5	± 3.2	± 2.3	49
Summer 1979	10.3	± 3.8	± 2.7	48
II period of investigations	26.6	± 8.4	± 6.1	41
Mean annual values for the I and II period of investigations	35.4	± 9.9	± 7.1	36

periods varied in precipitation, thickness of snow cover and sometimes in the time of its occurrence. Springs and summers were climatically similar (cf. Table I). Therefore, it seems, that the variability of dust fall is determined by meteorological conditions.

4.2. INFLUENCE OF METEOROLOGICAL CONDITIONS AND SOIL EROSION ON THE AMOUNT OF DUST FALL

As already mentioned, the investigated area has been ranked among areas exposed greatly to wind erosion. Also the area is not highly industrialized. According to Fett (1961) from 2/3 to 3/4 of dust on non-urban areas are soil particles reaching the atmosphere as a result of wind erosion.

Six-month observations of soil deflation and dust fall at 5 points of the area examined (Fig. 2), carried out simultaneously, allowed to compare these data. Monthly data were used in calculations. The relationship was very high ($r = 0.95$, $N = 30$, $Y = 5.09X + 1.94$, where Y – dust fall) and statistically significant ($p < 0.01$). It also showed that dust fall depended largely on wind erosion.

After finding this relationship the influence of meteorological conditions on the amount of dust fall was analysed. The results (Table III) point to the positive relationship between the dust fall and the number of days with soil susceptible to deflation and the negative one – for the number of days with unsusceptible soil. As regards the total precipitation, only the direction of the relationship can be considered. Rain may affect negatively the dust fall, but it seems that the distribution of precipitation is of greater significance (number of days with precipitation $\geqslant 1.0$ mm – such precipitation affects significantly the soil moisture – Radomski 1973), as small and frequent precipitation, constantly moistening the soil surface, is a better protection against wind than one heavy rainfall. Constant snow cover is also an efficient protection against soil deflation. This is confirmed by significant relationships (negative) between the amount of dust fall and the number of days with snow cover and also between the amount of dust fall and the number of days with precipitation $\geqslant 1.0$ mm (Table III).

The analysis of meteorological conditions included also the number of cases with wind $\geqslant 7\ \mathrm{m \cdot sec.^{-1}}$ multiplied by the number of days with soil susceptible to deflation. The quotient was called the coefficient of erosion, and the dependence of the amount of dust fall on this coefficient was positive and statistically significant (Table III). These relationships were calculated for average values of dust fall on the whole area investigated.

Analysis of the average amount of dust fall and frequency of winds from particular directions did not give unanimous results. It is not surprising, considering the great differentiation of the area. Measuring points were variously sheltered from the wind.

However, a statistical regularity should be mentioned here – all measuring points chosen as an example had dust fall reversely proportional to the frequency of western winds, whereas – directly proportional to eastern and southern winds (Table IV). Negative relationships between western winds and dust fall can be explained by the fact that these winds carry moist masses of air, which are frequently the cause of

Table III. Relationships between the dust fall (Y)

Number of days with soil susceptible to deflation	Number of days with soil not susceptible to deflation	Total precipitation	
		rain*	snow*
$r = 0.58$ $N = 24$ $Y = 0.20\,X + 1.87$ $p < 0.01$	$r = -0.58$ $N = 24$ $Y = 4.31 - 0.15X$ $p < 0.01$	$r = -0.38$ $N = 18$	$r = 0.20$ $N = 6$

*Statistically insignificant relation.

rainfalls. A decade analysis of cases of western wind and the number of days with precipitation $\geqslant$ 1.0 mm shows a positive and significant relationship ($r = 0.46$, $N = 18$, $Y = 0.2X + 1.95$, $p = 0.05$, where X – number of cases with western wind). This relationship is calculated for the period when soil deflation is calculated simultaneously with dust fall. Precipitation connected with western winds by frequent sprinkling of soil surface decreases its susceptibility to erosion and also decreases the dustiness.

These data prove the strong relationship of these two stages of erosion and confirm the assumption that dustiness on agricultural areas depends largely on wind erosion of soils.

4.3. DUST AS THE SOURCE OF NUTRIENTS FOR LAKES

In order to find whether there are differences in the amount of dust fall, including nutrients, for watersheds of particular lakes, the measuring points were grouped (Fig. 1) as follows:

Lake Jorzec – measuring points 1, 2, 4, 5
Lake Zelwążek – measuring point 8
Lake Głębokie – measuring points 6, 7
Lake Inulec – measuring points 9, 10, 11, 12, 13
fields – measuring points 3, 14, 15

For these areas the seasonal variability of dust fall is presented and also the concentration and content of particular elements in the dust.

The data in Table V on the amount of dust fall on particular areas are consistent with those previously analysed for the whole area in consecutive seasons.

The character of changes in C org. concentration (in per cents of dry dust weight) was almost the same for all distinguished areas and ranged between 10 and 19% (Fig. 15). The concentration increased in winter (on the average by 16%) and in summer (on the average by 14%), whereas C content decreased in dust in autumn and spring (on the average by 13%) (Fig. 15). The differences in content of C org. for particular areas were not statistically significant.

and meteorological parameters analysed (X)

Number of days with snow cover	Number of days with precipitation $\geqslant$ 1.0 mm	Erosion coefficient (number of days with soil susceptible to deflation·number of cases of wind velocity $V \geqslant 7\ \mathrm{m \cdot sec^{-1}}$)
$r = -0.63$ $N = 10$ $Y = 2.12 - 0.035X$ $p = 0.05$	$r = -0.46$ $N = 18$ $Y = 5.95 - 0.25X$ $p = 0.05$	$r = 0.46$ $N = 24$ $Y = 0.011X + 2.085$ $0.02 < p < 0.05$

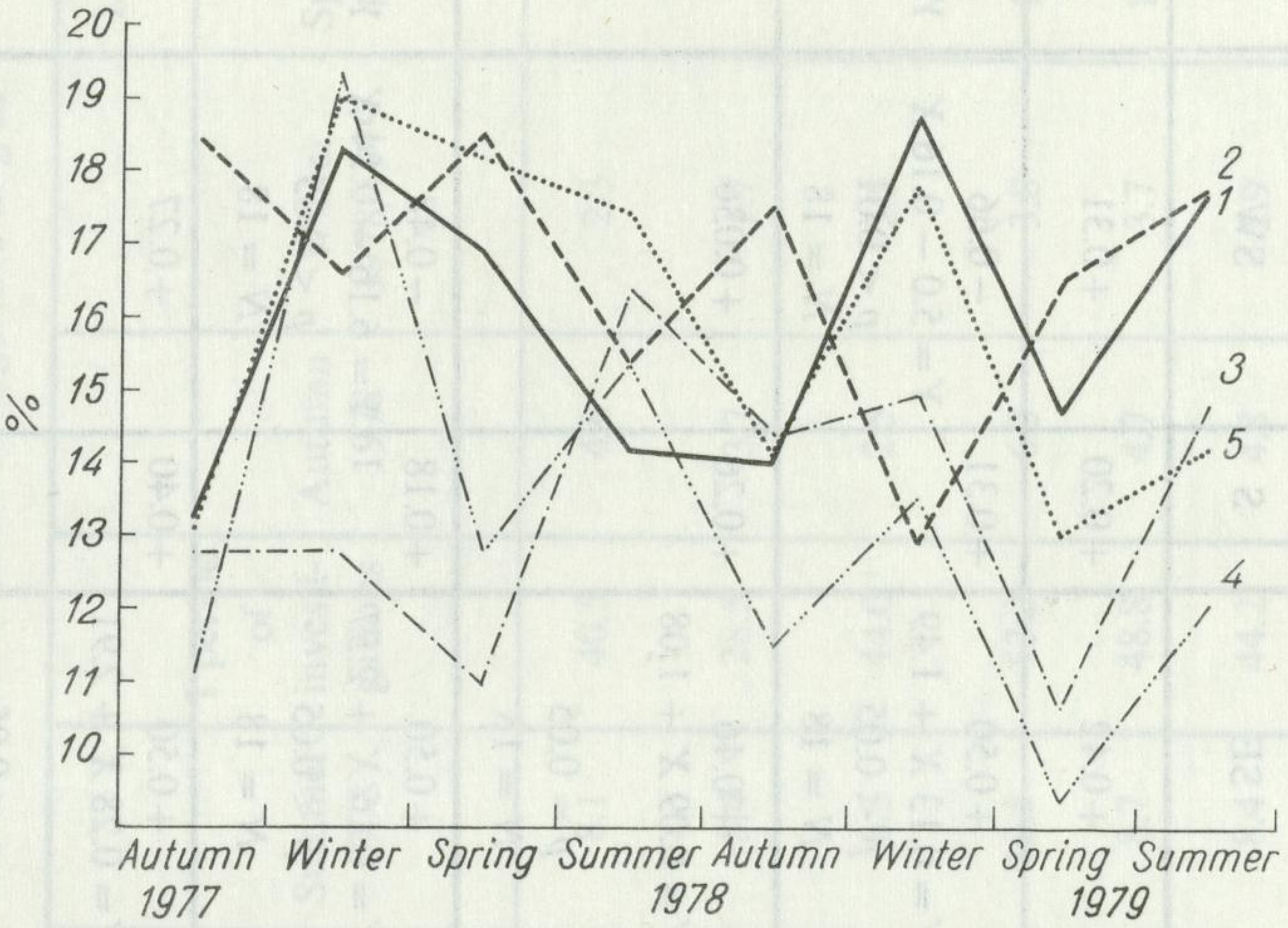

Fig. 15. Seasonal variability of C org. content (in per cents of d.wt.) in dust fall on distinguished areas 1 – Lake Inulec, 2 – Lake Głębokie, 3 – Lake Zelwążek, 4 – Lake Jorzec, 5 – fields

Concentrations of total nitrogen in dust fall ranged between 0.8 and 3% and decreased during the winter to 1.1% on the average. The concentrations increased mainly in autumn (on the average to 1.5%) (Fig. 16). Despite the considerable fluctuations of N concentration no statistically significant differences were observed between particular areas. The changes in concentrations of P tot. were also different. In the first period of investigations the lowest values were recorded in winter (on the average to 0.08%) and the highest – in autumn and summer (on the average to 0.18%). In the second period of investigations a decrease was observed between autumn and spring (in spring to 0.07%) and an increase of P content in dust fall in summer (on the average to 0.13%) (Fig. 17). In the first period of investigations significant differences in P content for particular lakes were observed in Lake Głębokie (higher concentration, $p < 0.01$) and in the second period for Lake Jorzec (lower concentration, $p = 0.01$).

Table IV. Relationship between the amount of dust fall (Y) and frequency of winds from particular directions (X), for chosen measuring points
Regression equations were calculated for significant relations

No. of point (shelter)	N	NE	E	SE	S	SW	W	NW
1. totally exposed	+0.28	+0.30	+0.30	+0.42	+0.20	+0.31	−0.40	−0.16
3. sheltered from SW	+0.34	+0.23	+0.32	+0.50 $Y = 0.13X + 1.49$ $p < 0.05$ $N = 18$	+0.31	−0.66 $Y = 5.0 - 0.16X$ $p < 0.01$ $N = 18$	−0.65 $Y = 4.75 - 0.11X$ $p < 0.01$ $N = 18$	+0.14
6. sheltered from the S and W	−0.22	−0.18	+0.30	+0.46 $Y = 0.09X + 1.08$ $p = 0.05$ $N = 18$	+0.26	+0.036	−0.21	−0.50 $Y = 3.44 - 0.12X$ $p < 0.05$ $N = 18$
10. sheltered from SW	+0.40	+0.12	+0.46 $Y = 0.16X + 3.14$ $p = 0.05$ $N = 18$	+0.50 $Y = 0.16X + 2.57$ $p < 0.05$ $N = 18$	+0.18	−0.48 $Y = 6.16 - 0.14X$ $p < 0.05$ $N = 18$	−0.67 $Y = 6.64 - 0.14X$ $p < 0.01$ $N = 18$	−0.43
14. sheltered from the N	−0.14	+0.25	+0.33	+0.50 $Y = 0.28X + 2.91$ $p < 0.05$ $N = 18$	+0.40	+0.27	−0.47 $Y = 8.53 - 0.17X$ $p = 0.05$ $N = 18$	−0.39

Table V. Dust fall on areas distinguished in g·m^{-2}

Area	Autumn 1977	Winter 1977/1978	Spring 1978	Summer 1978	I period of investigations	Autumn 1978	Winter 1978/1979	Spring 1979	Summer 1979	II period of investigations	Mean annual for the I and II period of investigations
Lake Inulec	20.3	3.8	8.4	8.1	40.5	4.6	2.3	7.5	10.1	24.5	32.5
Lake Głębokie	14.0	3.7	5.4	5.4	28.5	3.7	1.7	3.6	5.9	14.8	21.7
Lake Zełwążek	21.6	7.1	9.0	6.3	44.0	2.5	2.5	6.2	5.9	17.2	30.6
Lake Jorzec	25.8	6.3	10.6	10.5	53.2	6.3	3.8	11.6	10.5	32.2	42.7
Fields	21.8	5.9	12.3	8.7	48.8	4.7	3.7	10.2	14.7	33.4	41.0
Area – average	21.3	5.1	9.4	8.4	44.2	4.8	2.9	8.5	10.3	26.6	35.4

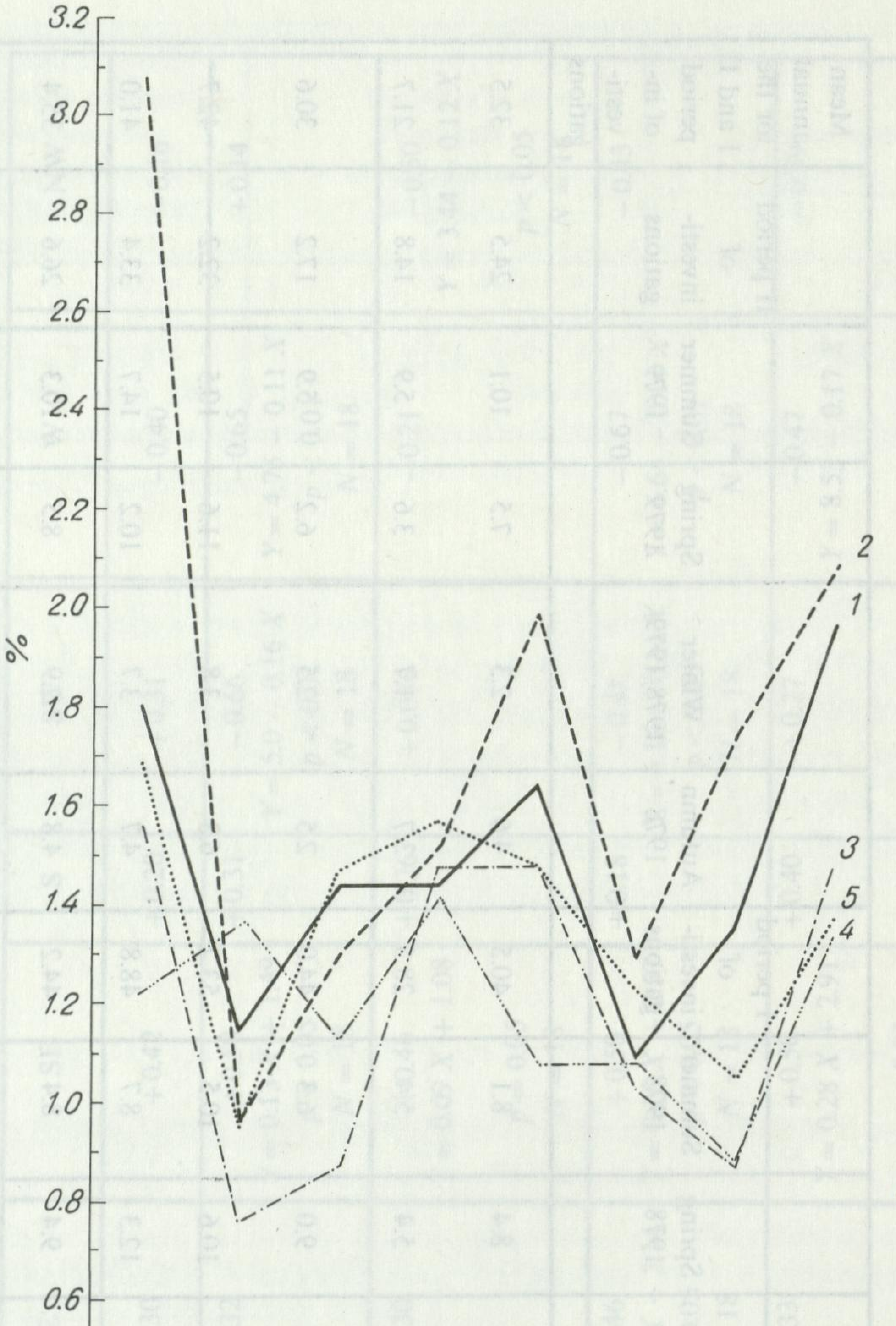

Fig. 16. Seasonal variability of N tot. content (in per cents of d. wt.) in dust fall on distinguished areas
1 – Lake Inulec, 2 – Lake Głębokie, 3 – Lake Zełwążek, 4 – Lake Jorzec, 5 – fields

On the whole, no statistically significant differences between the concentrations of elements mentioned on various sites during the same season were observed. An exception were the winter periods, when the differentiation in concentration of elements examined was the greatest, but the differences were at the significance level ($p = 0.05$, $t_{0.05} = 2.048$, $t_{\text{I period}} = 1.98$, $t_{\text{II period}} = 2.01$).

Detailed analysis of changes in concentrations of these elements showed that C org. content (14%) decreased the least. N concentration (18%) varied more, whereas P concentration (34%) varied the most (Table VI). C concentration varied the most in the

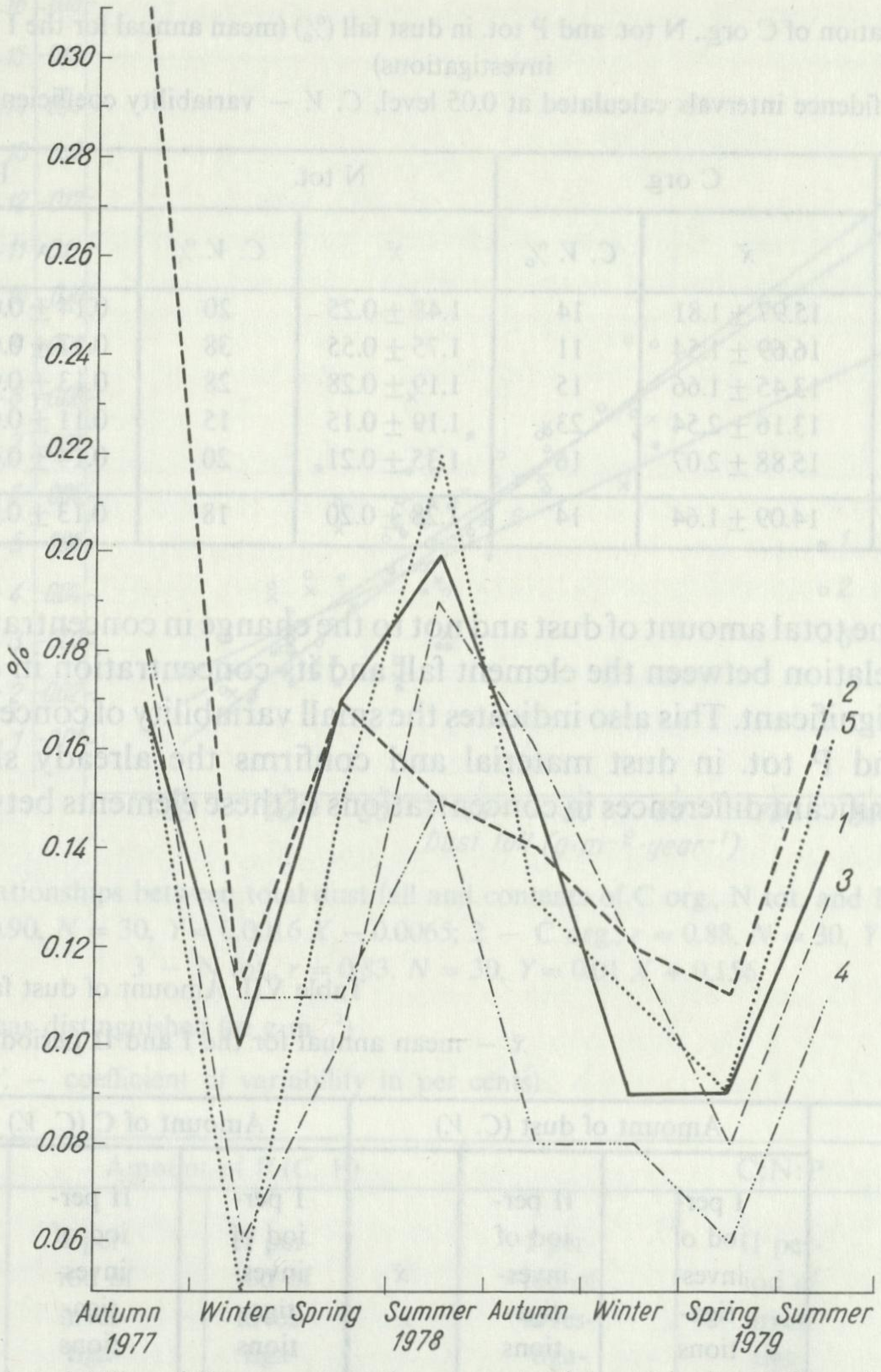

Fig. 17. Seasonal variability of P tot. content (in per cents of d. wt.) in dust fall on distinguished areas
1 – Lake Inulec, 2 – Lake Głębokie, 3 – Lake Zełwążek, 4 – Lake Jorzec, 5 – fields

surroundings of Lake Jorzec. Concentration of N and P changed the most in the surroundings of Lake Głębokie (Table VI).

Comparison of the C, N and P input of watersheds of particular lakes and fields showed that the average annual ratio of these three elements was 100 : 10 : 1 being similar for all areas distinguished (Table VII) and both periods of investigations.

The average dust fall for the whole area examined was 35 $g \cdot m^{-2} \cdot year^{-1}$, including 5 $g \cdot m^{-2}$ of C org., 0.5 $g \cdot m^{-2}$ of N and 0.05 $g \cdot m^{-2}$ of P (Table VII). These average values were used by Hillbricht-Ilkowska and Ławacz (1983) for preliminary estimations of total P loading of lakes of the r. Jorka watershed. Variability coefficients in Table VII characterize the variability of parameters presented in successive months. They are high, both in time and space, and are 60 – 130%. This is

Table VI. Concentration of C org., N tot. and P tot. in dust fall (%) (mean annual for the I and II period of investigations)
Confidence intervals calculated at 0.05 level, *C. V.* – variability coefficient

Area	C org.		N tot.		P tot.	
	$\bar{x}$	*C. V.* %	$\bar{x}$	*C. V.* %	$\bar{x}$	*C. V.* %
Lake Inulec	15.97 ± 1.81	14	1.48 ± 0.25	20	0.14 ± 0.03	30
Lake Głębokie	16.69 ± 1.54	11	1.75 ± 0.55	38	0.17 ± 0.07	49
Lake Zełwążek	13.45 ± 1.66	15	1.19 ± 0.28	28	0.13 ± 0.04	36
Lake Jorzec	13.16 ± 2.54	23	1.19 ± 0.15	15	0.11 ± 0.03	34
Fields	15.88 ± 2.07	16	1.35 ± 0.21	20	0.14 ± 0.04	39
Area – average	14.09 ± 1.64	14	1.28 ± 0.20	18	0.13 ± 0.04	34

mostly due to the total amount of dust and not to the change in concentration of a given element. The relation between the element fall and its concentration in dust has been statistically insignificant. This also indicates the small variability of concentrations of C org., N tot. and P tot. in dust material and confirms the already shown lack of statistically significant differences in concentrations of these elements between points of

Table VII. Amount of dust fall, C org., N tot.
$\bar{x}$ – mean annual for the I and II period of investigations

Area	Amount of dust (*C. V.*)			Amount of C (*C. V.*)			Amount
	I period of investigations	II period of investigations	$\bar{x}$	I period of investigations	II period of investigations	$\bar{x}$	I period of investigations
Lake Inulec	40.6 (75)	24.5 (90)	32.5	5.9 (66)	4.0 (99)	5.0	0.6 (95)
Lake Głębokie	28.5 (63)	14.8 (77)	21.7	5.0 (83)	2.5 (84)	3.8	0.6 (127)
Lake Zełwążek	44.0 (61)	17.2 (86)	30.6	5.7 (61)	2.3 (75)	4.0	0.6 (89)
Lake Jorzec	53.2 (59)	32.2 (79)	42.7	7.1 (56)	3.6 (75)	5.3	0.7 (73)
Fields	48.8 (64)	33.4 (98)	41.1	7.7 (53)	4.8 (92)	6.3	0.7 (81)
Area – average	44.2 (63)	26.6 (78)	35.4	6.3 (50)	3.4 (81)	4.8	0.7 (85)

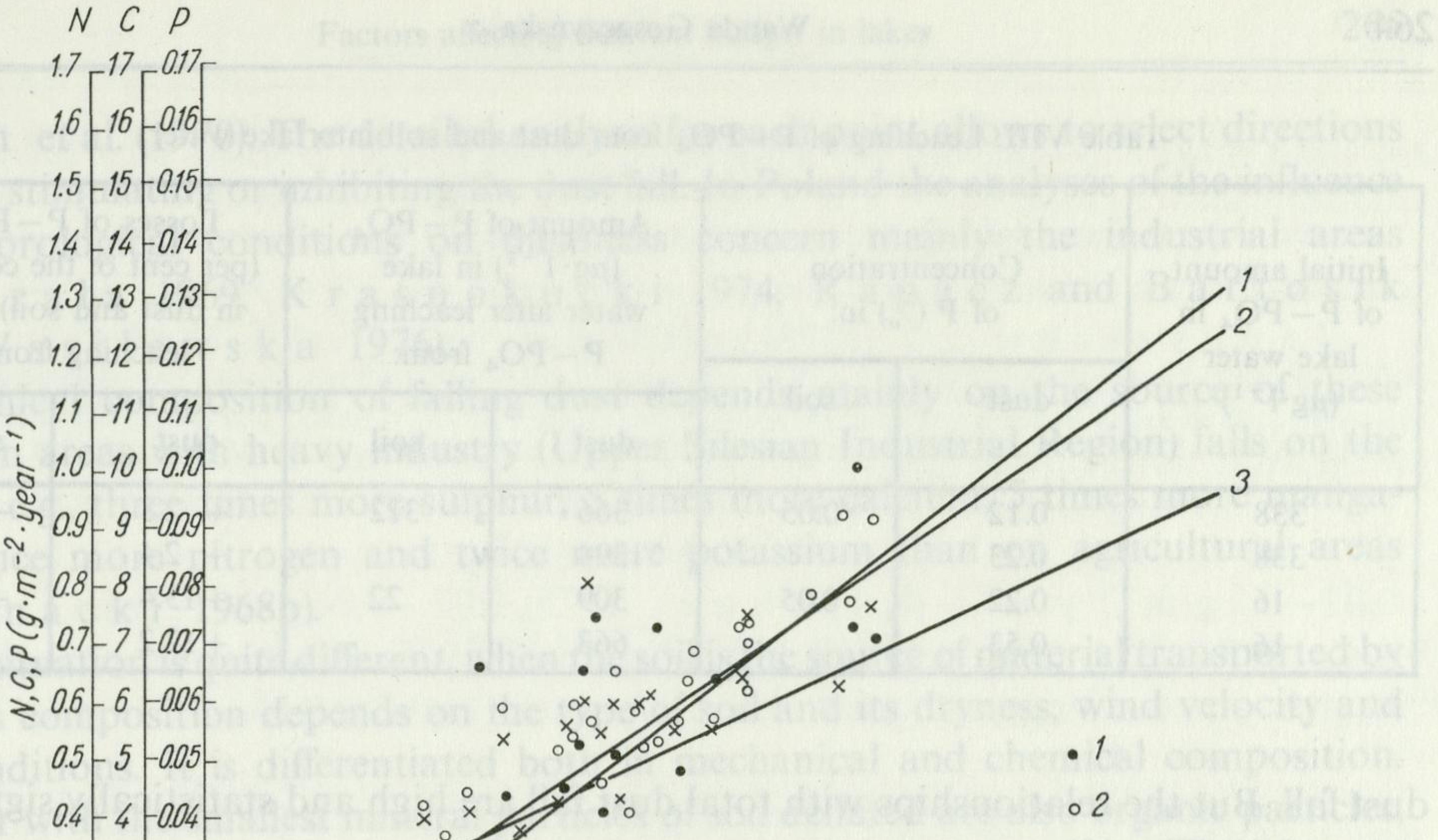

Fig. 18. Relationships between total dust fall and contents of C org., N tot. and P tot. in dust
1 − P tot., $r = 0.90$, $N = 30$, $Y = 0.0016\,X - 0.0065$; 2 − C org., $r = 0.88$, $N = 30$, $Y = 0.138\,X + 0.35$; 3 − N tot., $r = 0.83$, $N = 30$, $Y = 0.01\,X + 0.156$

and P tot. for areas distinguished (in g·m^{-2})

(in brackets *C. V.* − coefficient of variability in per cents)

of N (*C. V.*)		Amount of P (*C. V.*)			C:N:P		
II period of investigations	$\bar{x}$	I period of investigations	II period of investigations	$\bar{x}$	I period of investigations	II period of investigations	annual mean
0.4 (126)	0.5	0.07 (81)	0.03 (102)	0.05	97: 9:1	100:13:1	100:10:1
0.3 (93)	0.5	0.07 (133)	0.02 (87)	0.05	83: 9:1	83:15:1	76:10:1
0.2 (92)	0.4	0.06 (95)	0.02 (89)	0.04	95:10:1	115:10:1	100:10:1
0.4 (89)	0.5	0.08 (77)	0.03 (96)	0.05	101: 9:1	90:13:1	106:10:1
0.4 (106)	0.6	0.08 (82)	0.04 (115)	0.06	110: 9:1	120:10:1	105:10:1
0.3 (103)	0.5	0.07 (82)	0.03 (92)	0.05	90:10:1	113:10:1	96:10:1

Table VIII. Leaching of $P-PO_4$ from dust and soil into lake water

Initial amount of $P-PO_4$ in lake water ($\mu g \cdot l^{-1}$)	Concentration of P (%) in:		Amount of $P-PO_4$ ($\mu g \cdot l^{-1}$) in lake water after leaching $P-PO_4$ from:		Losses of $P-PO_4$ (per cent of the content in dust and soil) after leaching from:	
	dust	soil	dust	soil	dust	soil
338	0.12	0.05	366	312	+ 2.3	− 5.2
338	0.23		394		+ 2.4	
16	0.22	0.05	309	22	+ 13.4	+ 1.2
16	0.53		663		+ 12.2	

dust fall. But the relationships with total dust fall are high and statistically significant ($r \approx +0.9$) (Fig. 18).

The laboratory experiments have shown that regardless of the concentration of phosphates in water, some amounts of phosphates are always leached from dusts: more (>10%) at lower $P-PO_4$ concentration and less (about 2%) at high concentration (Table VIII). In the case of soil the situation is different. At low $P-PO_4$ concentration in water only 1% of this phosphorus form is leached from soil, whereas at a high concentration the soil absorbs phosphates from water. The estimated "losses" were 5% (Table VIII).

5. DISCUSSION

The dust fall on the area examined remains within the Polish Standard (Law Gazette No 42, September 13, 1966) for areas under special protection and are lower than unpublished data recorded by the Station of the Institute of Meteorology and Water Economy at Mikołajki between 1968 and 1976 (over 60 $g \cdot m^{-2} \cdot year^{-1}$). They are also lower than data for the Olsztyn province obtained between 1977 and 1978 (163 $g \cdot m^{-2} \cdot year^{-1}$, Lewtak 1978). The slightly higher values in Mikołajki and Olsztyn province are perhaps due to placing the measuring points near the town or in the town (Lewtak 1978). Similar differences have been observed when studying the dustiness in Kołobrzeg (Brodniewicz and Korzeniowski 1969). Results of statistical analysis of the amount of dust fall and meteorological conditions are consistent with results of investigations conducted on other areas. For example, Smith et al. (1970), have stated that in USA there are no significant relations between dust fall and average wind velocity, number of days with strong wind, very strong wind and total precipitation. Still, significant relations have been observed with the number of rainy days. Smith et al. (1970) have also pointed out, that as far as shelter is concerned, each dust fall measuring point should be treated individually. Similarly as on the area of the r. Jorka watershed no significant relations are observed for the dust fall and winds from particular directions on all points examined by

Smith et al. (1970). The detailed analysis for each point allows to select directions of winds stimulating or inhibiting the dust fall. In Poland the analyses of the influence of meteorological conditions on dustiness concern mainly the industrial areas (Kruczała 1969, Krasnokucki 1974, Rapacz and Bartosik 1976, Wasilewska 1976).

Chemical composition of falling dust depends mainly on the source of these dusts. On areas with heavy industry (Upper Silesian Industrial Region) falls on the average, e.g., three times more sulphur, 5 times more calcium, 5 times more manganese, twice more nitrogen and twice more potassium than on agricultural areas (Chojnacki 1968b).

The situation is quite different, when the soil is the source of material transported by wind. Its composition depends on the type of soil and its dryness, wind velocity and field conditions. It is differentiated both in mechanical and chemical composition. Together with the smallest mineral particles of soil deflated are also organic particles, especially humus. According to Uggla and Piaścik (1966) the material eroded and then deposited is 2–4 times more abundant in humus than the surrounding soil. According to my own investigations the dust fall is 10 times more abundant in humus than soils of the area examined.

C org. content, which is more than half of the humus content, is several times higher in dust material than in surrounding soils (Čakvetadze and Jakubov 1967) and depends on the size of particles transported (Zenchelsky, Delany and Pickett 1976).

The losses of C org. from soil are closely connected with those of N tot., and the ratio C : N is lower in dust material than in eroded soils (Čakvetadze and Jakubov 1967, Gryzlov, Mirončenko and Poluektov 1975).

The ways of nutrient input and output in the landscape are different in various types of ecosystems. Generally, this transport can be divided into biotic and abiotic.

As regards the abiotic transport, attention should be paid to water and air transport. Nutrient input and output with water transport is well known, but that with air transport, because of difficulties when conducting the investigations and because of less visible effects than, e.g., at sewage run-off, is neglected or minimized during investigations. The results presented here are an attempt to determine the role of air transport in matter cycling.

In terrestrial ecosystems the nutrient air transport is practically perpetual. In a microscale this is a transport from hill tops and deposition in hollows or on slopes (Uggla, Piaścik and Róg 1971). Air transport of particles within terrestrial ecosystems enriches some parts of it and exhausts others. Whereas transport of particles from terrestrial to aquatic ecosystems exhausts the former in favour of the latter. Greater dust fall may contribute to the eutrophication of lakes. This concerns first of all phosphorus in the dust fall. On the area examined the phosphorus in dust fall is on the average 0.05 $g \cdot m^{-2} \cdot year^{-1}$ (without distinguishing between "dry" fall and dust fall with rain). The values approximate those given for Poland by Chojnacki (1968b), i.e., 0.02–0.07 $g \cdot m^{-2} \cdot year^{-1}$ of phosphorus reaching soil surface on agricultural areas with rain. But the definition "with rain" is a matter of discussion, as in Chojnacki's (1968a) method pluviometers were without covers. Apart from phosphorus with rain probably the phosphorus in dust fall is recorded.

Januszkiewicz (1976) has also given similar values of phosphorus fall to those obtained in present investigations: 0.02 – 0.1 g·m^{-2}·year^{-1}. Available literature data show similar amounts of phosphorus falling with rain and dust on areas not exposed to industrial pollution, both in America and in Europe: 0.01 g·m^{-2}·year^{-1} (Hobbie and Likens 1973), 0.004 – 0.04 g·m^{-2}·year^{-1} (Likens 1975), 0.07 – 0.1 g·m^{-2}·year^{-1} (Kirchner 1975), 0.02 – 0.04 g·m^{-2}·year^{-1} (Landner 1976), 0.1 – 1.0 g·m^{-2}·year^{-1} (Wetzel 1975). Whereas the phosphorus fall in the surroundings of great cities is much higher: 0.16 – 0.21 g·m^{-2}·year^{-1} (Frissel 1977).

Air transport is only one of the ways of phosphorus input to lakes. Thus, about its significance may decide the ease with which the phosphorus passes from solid forms into dissolved ones, as mentioned earlier by Barica and Armstrong (1971) and confirmed by present investigations.

Concluding, it can be said, that phosphorus input with air transport to lakes should be given more attention because:

(a) Dust fall with nutrients is a continuous phenomenon, occurring all year round with smaller (winter) or greater (spring, autumn) intensity, thus being considerably different from inflow by watercourses providing the greatest load to water, mainly in spring (Ławacz et al. 1985).

(b) Phosphorus input with air transport covers the whole surface area of water body, otherwise than watercourses and run-offs supplying determined points or lake zones, usually within the littoral.

(c) Phosphorus concentration and its facility of dissolving are much higher in the case of dust material. Although in relation to water or shore erosion the amounts of dust fall are much smaller, its quality may significantly enrich the water bodies.

6. SUMMARY

On an agricultural area covering half (this including 4 out of 5 lakes – Fig. 1) of the r. Jorka watershed (Masurian Lakeland) the dust fall was investigated between September 1977 and August 1979 using polyethylene traps, 40 cm in diameter, distributed at 15 points (Fig. 2).

The highest dust fall was recorded during dry and windy periods, when the soil surface was maximally uncovered – autumn, spring (10 – 20 g·m^{-2}·season^{-1}), whereas the lowest one was recorded in winter at a permanent snow cover (2 – 5 g·m^{-2}·season^{-1}) (Tables I, II).

Spatial differentiation of the amount of dust fall was observed (Figs. 4 – 14, Table V). Relationships were recorded between the amount of dust and soil drifting, susceptibility of soils to deflation and also the frequency of eastern and southern winds. Negative relationships were found for a number of days with precipitation ⩾ 1.0 mm, number of days with snow cover, soil condition defined as not susceptible to deflation, and frequency of western winds (Tables III, IV).

Contents of C org., N tot. and P tot. were determined in the dust fall (Table VI). No significant differences were observed in concentrations of elements examined in particular seasons (Figs. 15 – 17). Also no spatial

differentiation in the content of elements analysed was observed. The amounts of C, N and P, falling with dust, depend largely on the amount of dust (Fig. 18). The ratio C : N : P – average for the whole investigated area – was 100:10:1 and was similar during the whole time of investigations (Table VII).

The average dust fall on the area examined was 35 g·m^{-2}·year^{-1}, including 5 g·m^{-2} of C org., 0.5 g·m^{-2} of N and 0.05 g·m^{-2}·year^{-1} of P (Table VII).

According to laboratory investigations the passing of P–PO_4 to water was higher in the case of dust material than that from soil (Table VIII) as it could reach water bodies by means of water or shore erosion.

Thus, the significance of load reaching the lakes depends not only on the amount of transported material, its nutrient content, but also on the ability to produce forms easily joining the cycling.

7. POLISH SUMMARY

W okresie od września 1977 do sierpnia 1979 r. prowadzono badania opadu pyłu na terenie rolniczym obejmującym połowę (w tym 4 z 5 jezior – rys. 1) dorzecza rzeki Jorki (Pojezierze Mazurskie), stosując pułapki polietylenowe o średnicy 40 cm, rozmieszczone w 15 punktach (rys. 2).

Największe opady pyłu notowano w okresach suchych i wietrznych, przy maksymalnie odkrytej powierzchni gleb – jesień, wiosna – 10–20 g·m^{-2}·sezon^{-1}, najmniejsze w okresach zimowych, przy stale zalegającej pokrywie śnieżnej – 2–5 g·m^{-2}·sezon^{-1} (tab. I, II).

Stwierdzono zróżnicowanie przestrzenne ilości opadającego pyłu (rys. 4–14, tab. V). Stwierdzono zależności między ilością pyłu a erozją wietrzną gleb, podatnością gleb na wywiewanie, a także częstotliwością wiatrów z kierunków wschodnich i południowych. Zależności ujemne znaleziono dla liczby dni z opadem $\geqslant$ 1.0 mm, liczbą dni z pokrywą śnieżną, stanem gruntu określonym jako niepodatny na wywiewanie i częstotliwością wiatrów z kierunków zachodnich (tab. III, IV).

W opadającym pyle oceniano zawartość C organicznego, N ogólnego i P ogólnego (tab. VI). Istotnych różnic koncentracji badanych pierwiastków w ramach poszczególnych sezonów nie stwierdzono (rys. 15–17). Nie stwierdzono także zróżnicowania przestrzennego zawartości analizowanych pierwiastków. Ilości opadającego z pyłem C, N i P zależą w głównej mierze od ilości pyłu (rys. 18). Stosunek C : N : P, średnio dla całego terenu badań, wynosił jak 100:10:1 i był podobny przez cały okres badań (tab. VII).

Średni opad pyłu na badanym terenie wynosił 35 g·m^{-2}·rok^{-1}, w tym C organicznego było 5 g·m^{-2}, N – 0.5 g·m^{-2} i P – 0.05 g·m^{-2}·rok^{-1} (tab. VII).

Badania laboratoryjne wykazały, że przechodzenie P–PO_4 do wody jest znacznie wyższe w przypadku materiału pyłowego niż z gleby (tab. VIII), która może dostawać się do zbiorników wodnych poprzez erozję wodną czy brzegową.

O ważności dostających się do jezior ładunków decydować więc może nie tylko ilość materiału wnoszonego, nie tylko zawartość w nim substancji odżywczych, ale także zdolność do tworzenia form łatwo włączanych do obiegu.

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