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Sediment yields and denudation rates in Poland

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Abstract In Poland, there are many 40-year records of suspended sediment transport. These records have been used to estimate the intensity of denudation processes over the territory of Poland. The denudation index, expressed in t km^{-2} $year^{-1}$, was calculated for many river basins, using data from 50 river gauging stations. The results are presented in the form of maps of denudation rates over the territory of Poland for four decades during the period 1951-1990.

INTRODUCTION

One of the first studies of the intensity of denudation processes in the Vistula river basin was carried out by Jarocki (1957). Based on hydrological measurements at the Tczew gauge during the period 1946-1953, he concluded that the average value of the denudation index (i.e. total sediment yield/river basin area) was 8 t km^{-2} $year^{-1}$. The first maps of the spatial differentiation of the denudation index across Poland were produced indirectly, by using a map of potential soil erosion published by Reniger (1959). Two versions of such maps were produced using this approach by Dębski (1959) and Skibiński (1959). The results of Skibiński's investigation, which dealt only with suspended sediment, in contrast to Dębski's investigation which also included bed load, showed considerable spatial differentiation of the denudation index, particularly in the zone of the south Polish uplands, with values ranging from *ca* 10 to 160 t km^{-2} $year^{-1}$. Further details of the early investigations of denudation in Poland are provided by Maruszczak (1984).

In this paper, the intensity of denudation processes over the territory of Poland has been estimated using suspended sediment measurements carried out by the State Meteorological and Hydrological Service (IMiGW – Institute of Meteorology and Water Management) within a hydrological network covering the whole country since the beginning of the 1950s. The number of river gauging stations varied through time, depending on the financial situation of the Service, and during some periods there were 100 gauging stations where suspended sediment samples were collected. In the present investigation, data from 50 gauges (of which 31 are located within the Vistula river basin, 15 within the Oder river basin, one within the Pregola river basin, and three on rivers flowing direct into the Baltic Sea) were used for estimating denudation intensity. The intensity of denudation processes over the territory of Poland has been expressed in terms of the mean annual sediment yield from the river basins (t $year^{-1}$) and the denudation index or specific sediment yield (t km^{-2} $year^{-1}$).

THE METHOD OF ASSESSING DENUDATION PROCESSES

Suspended sediment sampling at a selected point in the river cross-section was carried out manually. Two 1 l samples were collected, usually using the standard PIHM-1 sampler (Pasławski, 1973). Time intervals between samples varied from a few hours to

Table 1 Mean annual suspended sediment yield and discharge of the larger rivers in Poland.

River	Gauging station	Drainage area (km^2)	Sediment yield* ($\times 10^3$ t $year^{-1}$)	Discharge (m^3 s^{-1})	Period
Vistula	Skoczów	297	10.4	6.2	1956-1990
Vistula	Szczucin	23 901	1050	232	1951-1990
Vistula	Puławy	57 264	1720	459	1951-1990
Vistula	Warsaw	84 540	1300	580	1956-1990
Vistula	Włocławek	172 389	1720	934	1956-1990
Vistula	Toruń	181 033	1800	992	1951-1990
Vistula	Tczew	194 376	1760	1078	1951-1990
Przemsza	Jeleń	1 996	118	19.5	1956-1990
Soła	Żywiec	785	87.2	15.0	1951-1990
Soła	Oświęcim	1 386	109	20.1	1951-1990
Skawa	Wadowice	836	68.5	12.6	1956-1990
Raba	Proszówki	1 470	135	16.6	1951-1990
Dunajec	Krościenko	1 580	173	30.8	1951-1990
Dunajec	Nowy Sącz	4 341	305	63.0	1951-1990
Dunajec	Żabno	6 735	592	84.2	1956-1990
Biała Tarn.	Koszyce Wlk.	957	91.7	8.7	1956-1990
Wisłoka	Krajowice	2 092	236	23.0	1956-1990
Wisłoka	Mielec	3 915	324	34.4	1956-1990
San	Dynów	2 944	396	44.9	1961-1990
San	Radomyśl	16 824	600	131	1951-1990
Wisłok	Tryńcza	3 516	131	24.1	1956-1990
Kamienna	Kunów	1 106	15.7	6.2	1961-1990
Wieprz	Krasnystaw	3 001	19.1	11.9	1951-1990
Wieprz	Kośmin	10 231	33.6	36.4	1951-1990
Pilica	Przedbórz	2 536	9.5	16.1	1956-1990
Pilica	Białobrzegi	8 664	35.5	47.5	1956-1990
Narew	Ostrołeka	21 862	31.3	111	1951-1990
Bug	Włodawa	14 410	51.2	56.7	1956-1990
Bug	Frankopol	31 336	73.1	124	1956-1990
Bug	Wyszków	39 119	125	161	1951-1990
Liwiec	Łochów	2 466	9.2	10.2	1951-1971
Łyna	Sępopol	3 647	23.2	24.8	1961-1990
Oder	Chałupki	4 666	330	44.4	1961-1990
Oder	Miedonia	6 744	182	65.4	1951-1990
Oder	Scinawa	29 584	351	189	1951-1990
Oder	Słubice	53 382	307	311	1951-1990
Oder	Gozdowice	109 729	354	561	1961-1990
Nysa Kłodzka	Byczeń	2 134	40.5	19.8	1951-1974
Nysa Kłodzka	Nysa	3 276	114	34.6	1961-1980
Bóbr	Żagań	4 254	50.0	39.2	1951-1990
Nysa Łuż.	Gubin	3 974	32.8	30.3	1961-1990
Warta	Sieradz	8 140	62.4	49.1	1961-1990
Warta	Konin	13 351	32.9	59.4	1951-1975
Warta	Poznań	25 911	71.7	102	1951-1990
Warta	Gorzów Wlkp.	52 404	138	216	1951-1990
Prosna	Bogusław	4 304	17.7	17.2	1956-1990
Noteć	Nowe Drezdenko	15 970	35.9	78.4	1956-1990
Rega	Trzebiatów	2 628	16.2	21.2	1956-1990
Parsenta	Bardy	2 955	12.1	27.6	1956-1990
Słupia	Słupsk	1 450	13.4	15.9	1956-1990

* including suspended sediment deposited in 28 large reservoirs.

5 days, depending on discharge and the type of river (Pasławski, 1973). Based on simultaneous measurements of the mean suspended sediment concentration in the entire cross-section (C_m) and the concentration at the selected point in the cross-section (C_p), a relationship $C_m = f(C_p)$ was established for each gauging station. These relationships, together with the time series of C_p values and their associated discharges Q, were used to estimate the annual values of suspended sediment yield from the formula:

$$R = 0.0864 \cdot \sum_{i=1}^{d} C_{mj} \cdot Q_j \tag{1}$$

where R is the annual sediment yield (t year^{-1}), C_{mj} is the daily mean suspended sediment concentration (g m^{-3}), Q_j is the daily mean discharge (m^3 s^{-1}) and d is the number of days in the year.

To obtain representative information concerning the spatial pattern of the intensity of denudation, the amounts of sediment deposited in the 28 largest reservoirs were added to the measured sediment yields. The amounts of sediment deposited in the reservoirs were estimated using an indirect method based on discharge and suspended sediment inflow, reservoir capacity, and the trap efficiency of the reservoir. The volumes of the reservoirs ranged from 1.3 to 474 × 10^6 m^3 with a mean value of 70.5 × 10^6 m^3.

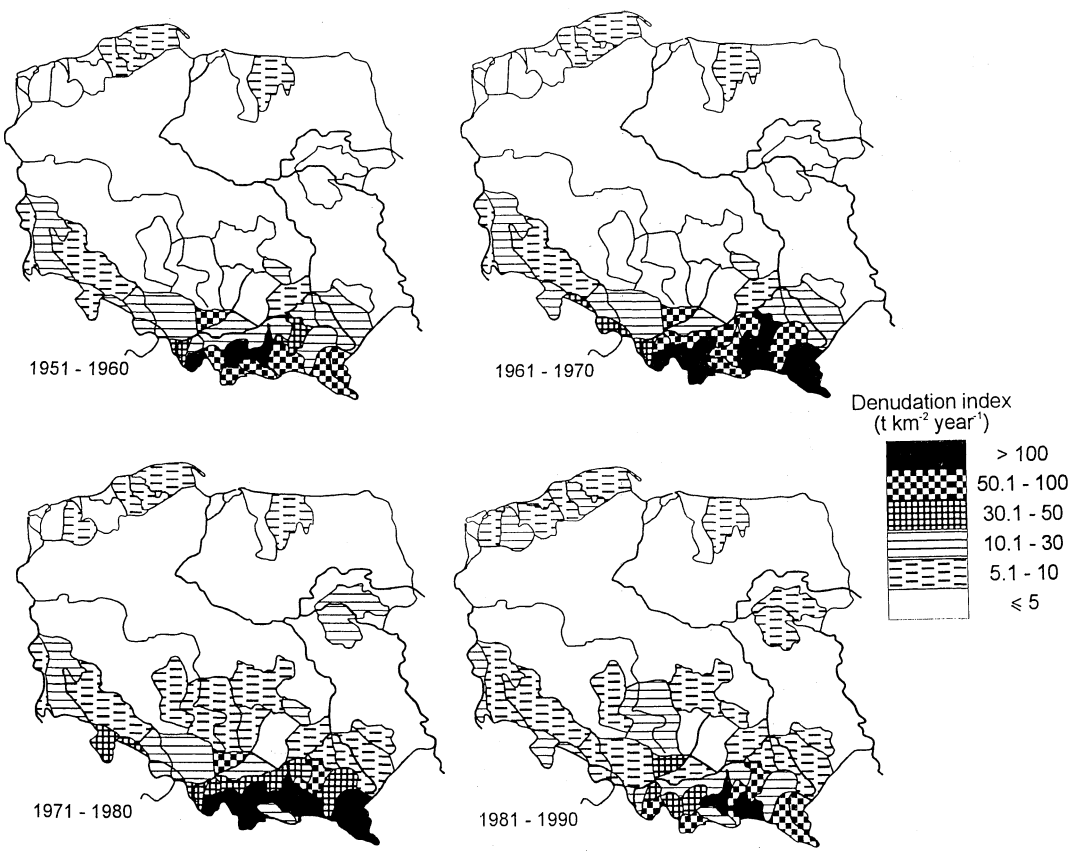

Fig. 1 Maps of the denudation index in Poland for the four decades.

Brune's (1953) method for estimating reservoir trap efficiency, which is commonly used in Poland (e.g. Brański & Dąbkowski, 1976; Wiśniewski, 1969), was also employed for this computation. By taking into account the sediment deposited in the reservoirs, denudation data for the four decades, independent of the increasing number of reservoirs, can be obtained.

The denudation index for a sub-basin bounded by two gauges was estimated from the equation:

$$\alpha = (R_k - R_{k-1})/(A_k - A_{k-1}) \quad (2)$$

where α is the denudation index (t km^{-2} year^{-1}), R_k is the mean annual sediment yield for the downstream gauge of the basin concerned and R_{k-1} is the mean annual sediment yield from the basin segment located upstream (t year^{-1}), A_k and A_{k-1} are the basin areas above the two successive river gauges (km^2). The accuracy of this approach to estimating denudation has been discussed previously by Brański (1981; 1994).

RESULTS

The mean annual suspended sediment yields estimated for 50 river gauging stations are listed in Table 1 and the spatial pattern of the denudation index over the territory of Poland for the four decades of the period 1951-1990 is shown in Fig. 1. Figure 1 indicates that for each of the decades the highest, but at the same time the most variable values of the denudation index, ranging from *ca* 10 to over 100 t km^{-2} year^{-1}, are found in the zone of the south Polish uplands. Over a large part of the lowland territory of

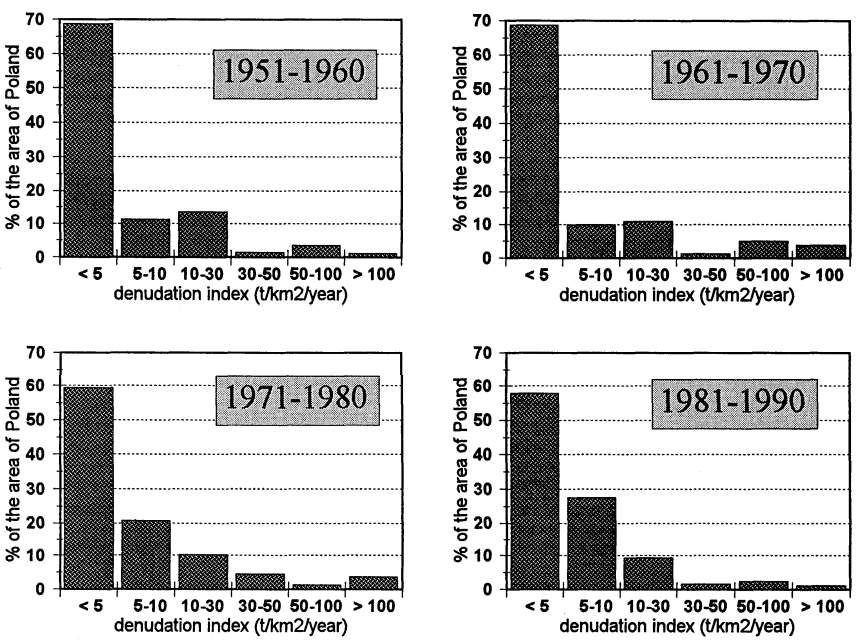

Fig. 2 The distribution of denudation intensity in the four decades.

Table 2 Distribution of denudation indices for the four decades during the period 1951-1990.

Period	Range of denudation index (t km^{-2} year^{-1})	Percentage of the territory of Poland	Mean value of denudation index (t km^{-2} year^{-1})
1951-1960	> 100	1.2	144.0
	50.1-100	3.6	80.7
	30.1-50	1.6	40.6
	10.1-30	13.6	17.2
	5.1-10	11.2	6.6
	≤ 5	68.8	2.7
	Σ	100.0	10.2
1961-1970	> 100	3.9	115.7
	50.1-100	5.1	62.5
	30.1-50	1.3	43.0
	10.1-30	10.9	20.3
	5.1-10	10.0	7.6
	≤ 5	68.8	2.5
	Σ	100.0	13.0
1971-1980	> 100	3.7	145.0
	50.1-100	1.3	66.2
	30.1-50	4.6	39.3
	10.1-30	10.3	13.7
	5.1-10	20.7	6.8
	≤ 5	59.4	2.7
	Σ	100.0	12.5
1981-1990	> 100	1.1	131.3
	50.1-100	2.5	78.3
	30.1-50	1.6	38.8
	10.1-30	9.4	18.1
	5.1-10	27.5	7.3
	≤ 5	57.9	2.6
	Σ	100.0	9.3

Poland, the denudation index is no greater than 5 t km^{-2} year^{-1}. Figure 1 also demonstrates that the denudation process was more intense during the decades 1961-1970 and 1971-1980 than in the decades 1951-1960 and 1981-1990. The distributions of the denudation index values for the four decades are presented in Fig. 2 and in Table 2. The data listed in Table 2 show that the estimated denudation index was greater than 100 t km^{-2} year^{-1} over 3.9% of the territory of Poland in the decade 1961-1970 and over 3.7% of the territory in 1971-1980, i.e. over an area about three times larger than that associated with the decades 1951-1960 and 1981-1990. In addition, the mean denudation index for the whole territory of Poland was higher in the decades 1961-1970 and 1971-1980, at 13.0 and 12.5 t km^{-2} year^{-1} respectively, than in the decades 1951-1960 and 1981-1990 for which the estimated denudation index was 10.2 and 9.3 t km^{-2} year^{-1} respectively.

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