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Sources of material supply and nature of fluvial transport in post-glacial agricultural-forested catchment (the upper Parsęta river, Poland)

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Abstract: Understanding the character and temporal variability of fluvial transport is of fundamental importance for the qualitative and quantitative description of contemporary fluvial systems. In the present study certain features of fluvial transport are regarded as markers which indicate the way the denudation system of a catchment operates. On the basis of mapping carried out along the upper Parsęta channel, only a small part of the catchment was found to take part in the supply of suspended material to the river channel. The occurrence and intensity of processes active in the supply of sediment for transport in the Parsęta channel depends largely on lithology, channel morphology, conditions of water flow, hydrogeological conditions, and vegetation. These factors are modified by the activity of man and animals. Variations in the transport of solutes along the upper Parsęta result from differences in lithological sources, which, in turn, are associated with other environmental factors which determine the rate of water circulation.

The figures for ionic and suspended flows obtained in this research confirm the regularity with which dissolved material is overwhelmingly predominant in the fluvial transport of Pomeranian rivers. The changing meteorological conditions in the catchment, and also the seasonal development of its plant cover, are reflected in the way the river flow is sustained and, in the fluvial regime, is expressed as the amount of material leaving the catchment system. The three periods of denudational activity which have been distinguished on the basis of differences in their fluvial transport regimes, reflect the seasonal efficiency of denudation processes in the catchment. The seasonal variations in the fluvial transport in the upper Parsęta provide an insight into the development of the present-day relief of the young-glacial area of West Pomerania.

Key words: fluvial transport, source of material, solute load, sediment load, post-glacial catchment

Introduction

In the contemporary denudation system of West Pomerania, fluvial transport plays a fundamental role by carrying away material from erosion and denudation in the catchments. A detailed analysis of fluvial transport provides a good indicator of relief evolution, including soil leaching and erosion. The character of the fluvial transport is also a good indicator of change in the landscape structure of a region. In the present study, the subject of the investigation was the upper Parsęta catchment, which is regarded as representative of the post-glacial zone of West Pomerania and the Polish Plain. Systematic investigations of modern morphogenetic processes in the upper Parsęta catchment have been carried out since 1981. Since 1 November 1985, daily measurements have been taken in the profile which closes the upper Parsęta catchment (at Storkowo); this catchment is regarded as an independent denudation system.

The programme of research in the upper Parsęta catchment is based on methodological assumptions derived from Cholley's concept of a denudation system (Tricart, 1960) and Bertallanffy's (1984) systems theory. They have provided the basis for the conception of geoecosystem operation, as formulated in Kostrzewski (1986, 1993). The following, already established regularity is the basic assumption of this investigation: the kind and amount of material flowing through the measuring point reflect current geomorphological processes taking place in the river channel and catchment (Gregory & Walling, 1973; Schumm, 1977; Richards, 1982; Froehlich, 1982; Knighton, 1984; Zwoliński, 1989).

The basic objective of the research conducted in the upper Parsęta catchment is the understanding of the operation of the geo-ecosystem of a lowland river in the conditions of climatic change and various forms of human impact. The aims of the present investigations include:

1) an evaluation of the controls, pattern and intensity of fluvial transport, which are reflections of the denudation processes occurring in the upper Parsęta catchment system, i.e. mainly soil erosion and leaching,
2) an analysis of variations in the physico-chemical properties of solutes and solids in the upper Parsęta channel as factors controlling the variability of fluvial transport and determining its role in the contemporary denudation system of the catchment;

3) a comparison fluvial transport in the upper Parsęta catchment with other geomorphological regions of the post-glacial zone in Europe.

The present paper discusses the results of research into the identification of sources of material supply for fluvial transport, as well as the seasonality of river transport in the upper Parsęta channel.

Studies of fluvial transport in a post-glacial lakeland zone

A maximum impact of flowing waters and a moderate intensity of chemical weathering and mass movements are the characteristics Peltier (1950) and Leopold *et al.* (1964) ascribe to the temperate morphogenetic zone. Further, Tricart (1960) includes the woodland zone of temperate areas in which Poland is situated in the group of systems in which chemical denudation predominates. The nature of these predominant denudation processes in the temperate climatic domain is reflected in the magnitude and variability of fluvial transport in a river channel. The share of chemical denudation and fluvial processes in the present-day morphogenetic system of the temperate climatic domain is also documented in studies carried out in the young-glacial zone of the Polish Plain.

Cyberski (1984) estimated average denudation for six main rivers of Pomerania: the Rega, Parsęta, Wieprza, Łupawa, Słupia and Łeba, at 45 to 78 t km^{-2} a^{-1}, of which dissolved material took up from 71% to 88%, suspended material from 4.4% to 10.4%, and the bedload from 5.2% to 18.3%. Similar figures, 50 - 60 t km^{-2} a^{-1}, were obtained by Wilamski (1978) for the Słupia catchment. Brański (1975) states that the suspended runoff index does not exceed 3 - 4 t km^{-2} a^{-1} in the area of the North Polish lakelands. The studies of the structure of the Parsęta fluvial transport carried out by Zwoliński (1989, 1993) indicate that dissolved material constitutes 78.9% - 94.8%, suspended material 1% - 14.6%, and the bedload 0.7% - 14.7% of the total fluvial load, depending on the water stage. Smolska (1996) presented models of fluvial transport for the Szeszupa River in the Suwałki Lakeland in which the average dissolved load contributed from 85.2% to 93.5% to the total load, the suspended load, from 6.2% to 12.7%, and the bedload between 0.3% and 2.5%. In the years 1986-1988, the runoff of dissolved substances in the upper Parsęta catchment was almost 10 times higher than that of suspended material (Kostrzewski & Zwoliński, 1990, 1992a, 1992b).

On the basis of the above results, it may be concluded that the intensity of contemporary denudation-fluvial processes in the area of the North Polish lakelands is determined by:

a) physico-chemical properties of glacial, fluvioglacial and Holocene deposits affecting the availability of readily dissolved components for river transport (Pulina, 1974; Maruszczak, 1990; Kostrzewski & Zwoliński, 1992a),
b) the water cycle, which, according to Dynowska (1991), is characterised by an abundant and regular supply throughout the year, high surface and groundwater retention, and a predominance of groundwater runoff (Gutry-Korycka, 1978; Stachy, 1980; Choiński, 1988),
c) a poorly developed drainage network (Drwal, 1982; Maruszczak, 1991).

These results can be compared with those obtained in the research carried out in the post-glacial areas in Europe. Hasholt (1983) reports that the dissolved load in areas of young morainic deposits in eastern Denmark varies from 63 to 148 t km^{-2} a^{-1}. He stresses that in order to obtain the load of dissolved substances coming from weathering processes, one has to consider the load contributed by rain and throughflow amounting to 22 t km^{-2} a^{-1}. Suspended load values range between 7.8 and 1.2 t km^{-2} a^{-1}. Łajczak and Jansson (1993) estimated suspended sediment yield for the Lowland part of the Baltic Sea drainage basin between 3 and 12 t km^{-2} a^{-1}.

The amounts of dissolved substances and solid material washed out from the clay soil of the intensively cultivated Paimionjoki drainage basin in south-western Finland were studied by Mansikkaniemi (1982). He reported that the mean fluvial transport from the whole catchment was about 50 t km^{-2} a^{-1} and transport during winter season accounted for about 20% of the annual load. The amounts of solutes transported from the subcatchments close to the coast were extremely high and accounted for over 60% of the total transport. This proportion declined rapidly further up the rivers, although solutes constituted 49% of the total transport in the Paimionjoki drainage basin. Variation in the amounts of solid material could be explained, according to Mansikkaniemi, in terms of the land use and relief.

On the basis of these results, the structure of fluvial transport can be stated to be similar in areas formed during the last glaciation. The quantitative differences among of substratum deposits, the distance from the sea, the type of the climate, the occurrence of lakes in the catchment and the land-use pattern.

Study area

The study area embraces the upper Parsęta catchment which has a diversified internal structure defined by a system of subcatchments (Fig. 1). The catchment is situated in the West Pomerania Lakeland. It covers 74 km^2 and its circumference is 58.3 km. The average gradient of its surface is 8.4‰. The main river, closed by the hydrometric profile at Storkowo (the location of the Adam Mickiewicz University Geoecological Station), is 13.26 km long. Within the upper Parsęta catchment, ten subcatchments have been distinguished; these differ in size, morphology, lithology, soil and land-use pattern.

The upper Parsęta catchment extends along the northern slope of the Central Pomeranian end-moraine hummocks within the so-called Parsęta lobe (Karczewski, 1989). The relief of this area is the product of deglaciation during the Pomeranian Phase of the Vistulian, and of the processes of the Holocene morphogenetic cycle. The relief of the particular subcatchments is diversified. Their morphological character determines the flow of surface and ground water. The largest area of the upper Parsęta catchment is occupied by glacigenic deposits, which sometimes have a very high sand content (Fig. 2). Sands and gravels of fluvioglacial origin represent an important source supplying the Parsęta with its bedload and suspended load.

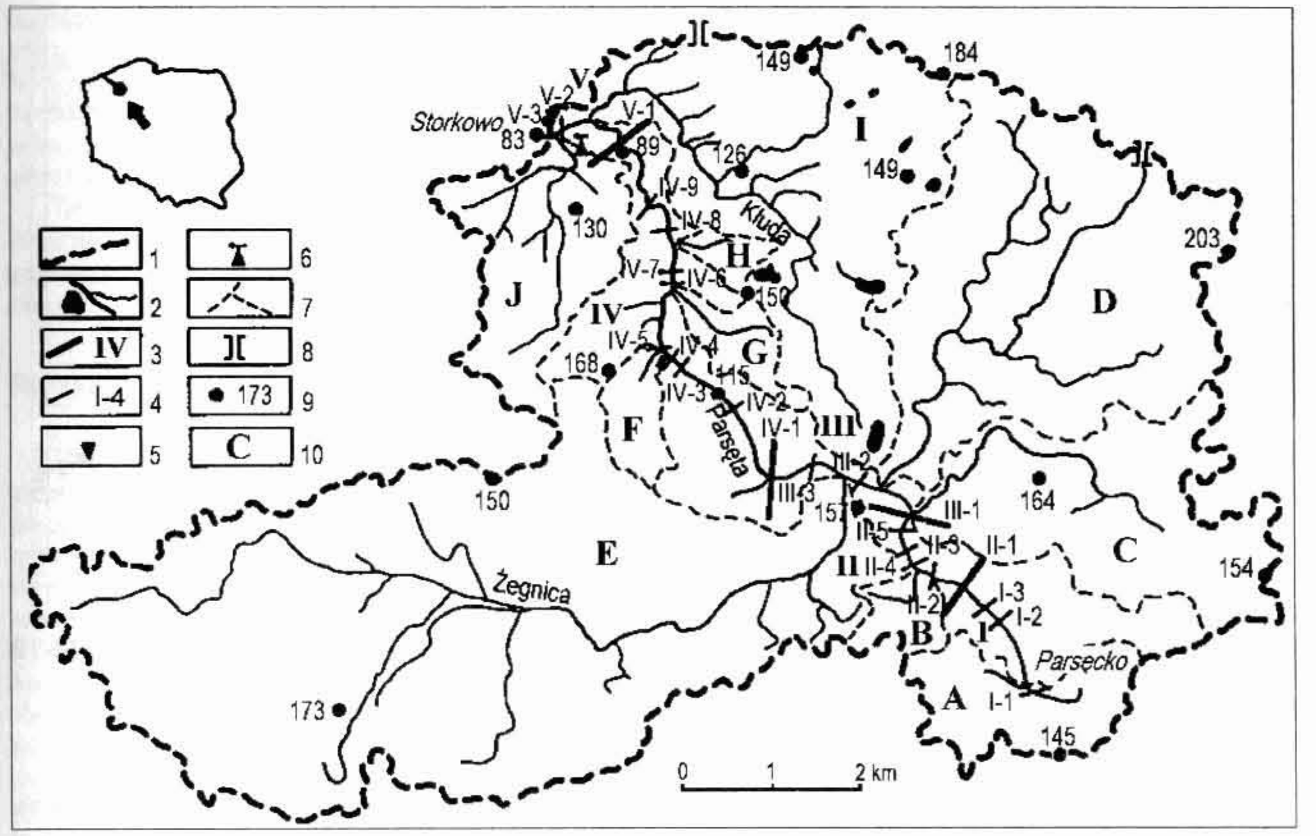

Fig. 1. Location of the upper Parsęta catchment and study sites.
1 - watershed of upper Parsęta catchment, 2 - river network, lakes, 3 - measurement cross-sections on limits of segments of upper Parsęta channel, 4 - measurement cross-sections on limits of reaches of upper Parsęta channel, 5 - water-gauging station, 6 - meteorological station, 7 - watersheds of subcatchments, 8 - gate in watershed, 9 - spot heights, 10 - subcatchments: A - Parsęta Springs, B - Ditch, C - Dalęciński Stream, D - Skalneński Stream, E - Żegnica, F - Leśny Stream, G - Suchy Stream, H - Krętacz, I - Kłuda, J - Młyński Stream.

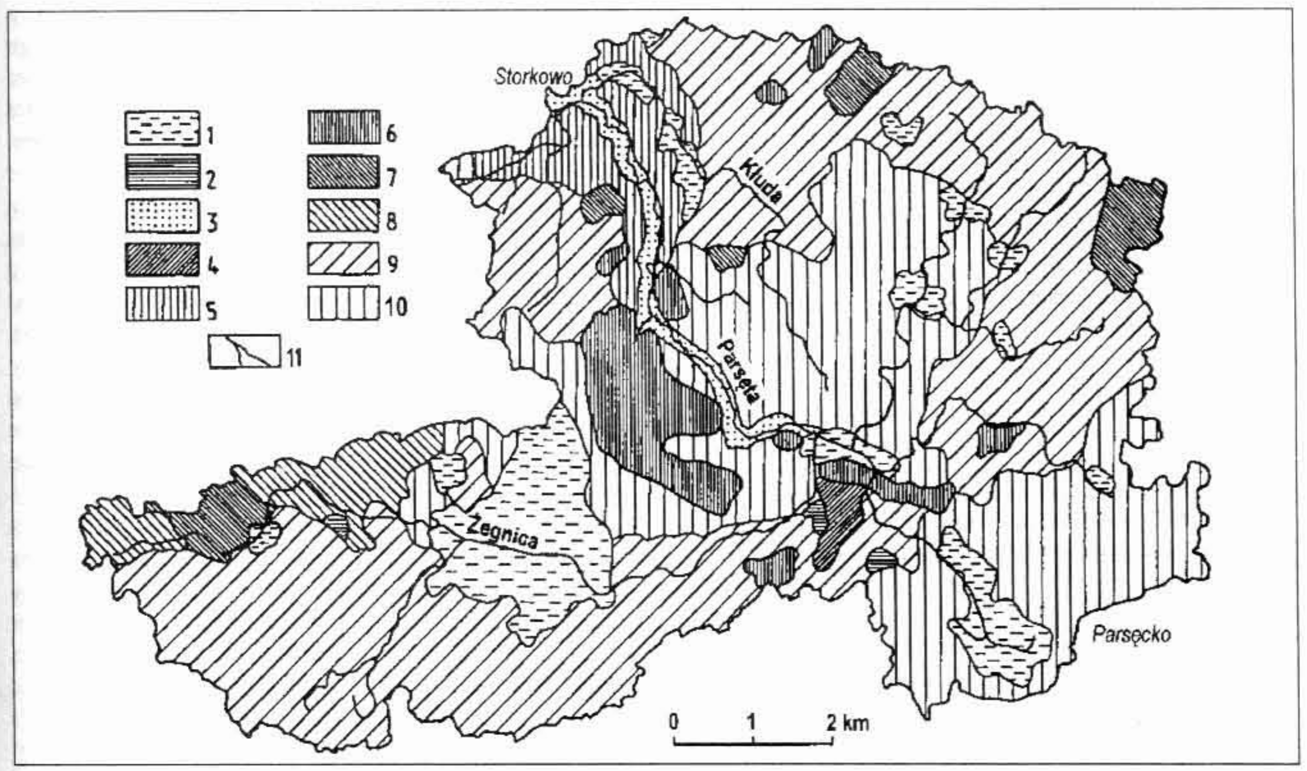

Fig. 2. Lithology of the upper Parsęta catchment (based on Detailed Geological Map).
Holocene deposits: 1 - peats, 2 - loams, 3 - alluvial sands and gravels.Pleistocene deposits: 4 - till eluvium, 5 - alluvial sands, gravels and muds, 6 - clays, silts, sands and gravels of kames, 7 - sands, gravels and boulders of terminal moraines, 8 - glacial and fluvioglacial sands, gravels and boulders, 9 - tills, 10 - fluvioglacial sands nad gravels. Other: 11 - river network.

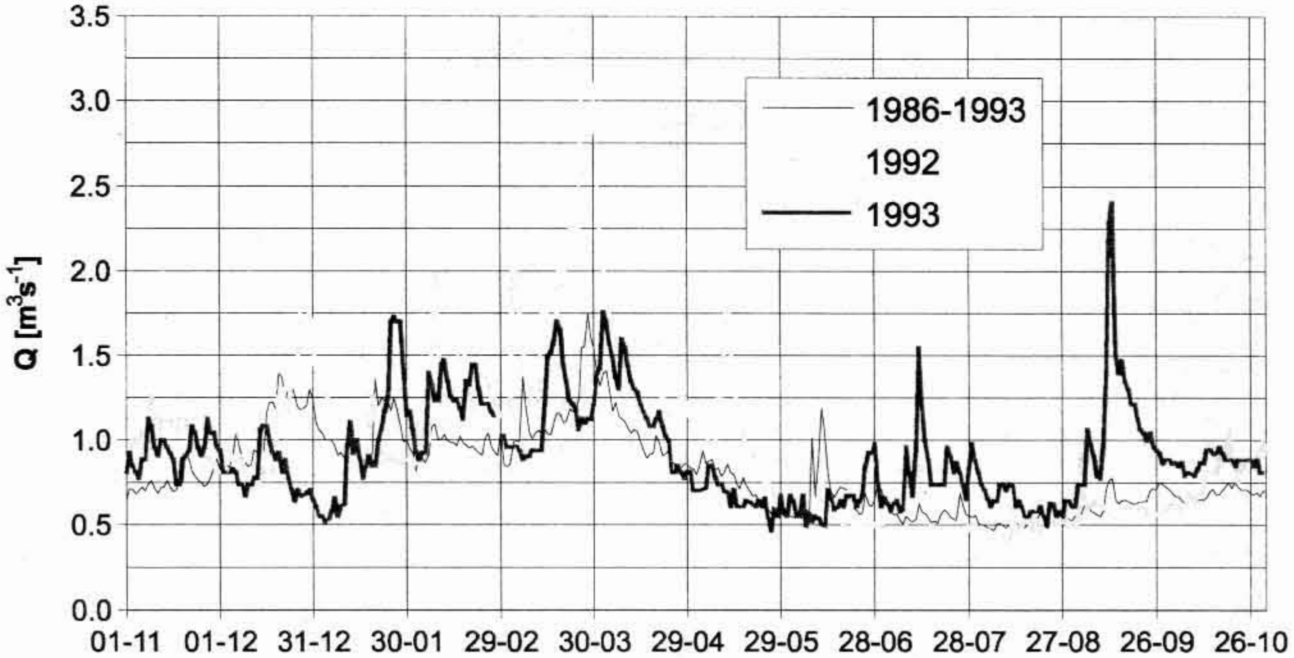

Fig. 3. Daily discharge of the upper Parsęta river at Storkowo in hydrological years 1992 and 1993 compared with mean daily discharge for years 1986-1993 at Storkowo.

Table 1. List of sources which suppy the Parsęta River with dissolved material and solid particles (cf. Table 2).

Code	Delivery sources
	1. Hydrographic network
	Surface water:
A	Upstream part of channel
B	Tributaries
C	Ditches
	Ground water:
D	Drains
E	Sepages and springs
F	Saturated areas
	2. Floodplain
	3. Channel perimeter
G	Erosional bottom of channel
H	Subaquatic accumulation forms
I	Exposed part of channel bed
J	Bank edges
	4. Biogenic elements
K	*Dead plants:*
Ka	in channel
Kb	on banks
L	*Living plants:*
La	in channel
Lb	on banks
M	Animal action in water
N	Animal trails to channel
	5. Man-made delivery
O	Sewage discharge
P	Refuse
R	Cart-roads
S	Paths
T	Fords
U	*Hydraulic-engineering facilities:*
Ua	Bridges
Ub	Weirs
Uc	*Bank consolidation:*
Uca	Fascine
Ucb	Stone
Ucc	Concrete

The physico-chemical properties of the river water are directly influenced by zones of organic deposits. Surface deposits of the upper Parsęta catchment display wide variations in their mechanical composition. The dominant soils in the catchment are brown earths, which occupy 46.1% of its area. Next are black earths, which occupy 2.62% of the area. In river valleys there are patches of alluvial soils proper (0.4%), while podzols can be found in the woodland. The mosaic land-use pattern conforming to the main forms of the post-glacial relief is a characteristic feature of the catchment. Because of the high proportion of arable land (33%) and woodland, which together occupy as much as 70% of the area, the upper Parsęta catchment can be classified as an agricultural-woodland type.

West Pomerania displays certain distinctive climatic characteristics, especially in respect of precipitation. Due to exposure to the oceanic influence, it receives larger amounts of precipitation. As opposed to Poland's other regions, heavy and driving rains are less frequent there (Karwowski, 1963).

The two hydrological years studied, 1992 and 1993, can be regarded as average climatic years in relation to the 1951-1993 period. In 1992, the mean annual air temperature was 8.3°C, while in 1993 it was 7.6°C. The annual precipitation totals were 543.6 mm and 699.9 mm, respectively. The predominant diurnal rainfall was below 5 mm, while figures in excess of 15 mm were recorded during 10 days only.

As in the case of other rivers in the coastal region, the Parsęta has an even hydrological regime, being fed by groundwater, rain and snow, as well as spring floods. The upper Parsęta discharge varied between 0.3 $m^3 s^{-1}$ and 11 $m^3 s^{-1}$ in the period 1986-1995, and averaged 0.9 $m^3 s^{-1}$. In 1992 and 1993, the upper Parsęta discharges varied between 0.3 m^3s^{-1} and 3.1 m^3s^{-1}, and averaged 0.94 m^3s^{-1} (Fig. 3). The mean annual specific runoff was 12.7 $dm^3 s^{-1} km^{-2}$. The dominance of higher discharge in the winter half-year over the summer one in this respect results not only from the distribution and intensity of precipitation, but also, to a large extent, from the specific

operation of the upper Parsęta geoecosystem. Over the two years, there were 38 discharges that can be treated as floods. In only 11 of them the increment of discharge from the start of the flood to the peak exceeded 0.5 m^3s^{-1}. The most frequent causes of flood discharges are falls of rain and snow, as well as mid-winter and spring thaws.

Taking into consideration all the physiographic properties of the upper Parsęta catchment, it may be considered to be a geoecosystem typical of a post-glacial zone in a temperate climate.

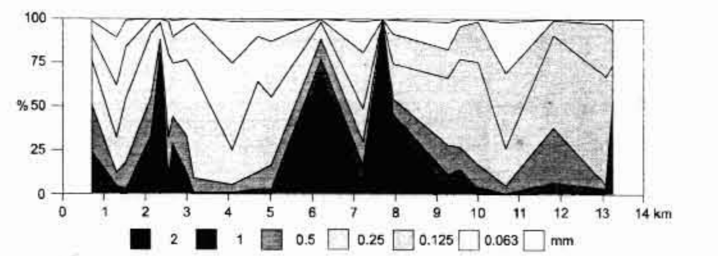

Fig. 4. Grain-size composition of bed material (current facies) along the upper Parsęta channel.

Research scope and methods

The measurement system adopted, its spatial distribution, and investigation periods are sympathetic to the concept of a geoecosystem and its operation. Selected meteorological, hydrological and hydrochemical parameters are monitored at various time intervals which have been established in accordance with the nature of geomorphological processes, and which follow generally accepted measuring standards. Apart from daily standard hydrological and meteorological observations, the special observations necessary for geomorphological and hydrochemical mapping were also carried out. The data presented in this paper are based mainly on observations carried out in the hydrological years 1992 and 1993.

In organising the measurement system, much attention was devoted to observations of material supply to the catchment's geo-ecosystem. Therefore, geomorphological mapping was carried out along the upper Parsęta course which was intended to define:

1) the variability of the morphological parameters of the river channel,
2) the morphological-lithological characteristics of the river bank zone and channel bed, and
3) the supply sources of dissolved material and solid particles to the river channel.

Before the mapping started, the river was divided in accordance with the principles of Gordon *et al.* (1992), who distinguished segments, reaches, transects, and point measurement sites. It was assumed that the 13-km long section of the upper Parsęta was diversified in terms of the morphology of its valley and that of the neighbouring areas, and also the land-use pattern. On the basis of these two criteria, five channel segments (I- V) were distinguished (Fig. 1). Within the segments, the same two criteria were adopted, although at a local spatial scale. Also, in order to obtain fairly homogeneous reaches of the Parsęta channel, the criterion of the channel morphology and pattern was applied. As a result, the following numbers of reaches were obtained for the successive Parsęta segments: 3, 6, 3, 9, and 2, or a total of 23 reaches, all homogeneous as regards morphology and land use.

Within successive reaches, bank forms and supply sources of dissolved material and solid particles were recorded, the mean Manning roughness coefficient for the entire reach was determined, and the nature of the channel bank zone was recorded. In observations of the latter, elements were incorporated which were taken from the cartographic symbols proposed for morphological maps of river banks by Kostrzewski and Zwoliński (1985) and Zwoliński (1988). As regards the supply of dissolved material and solid particles to the channel, five recorded groups of sources are shown in Table 1.

At the borders of the successive reaches, measured cross-sections of the river channel were set up (Fig. 1). These were sites of:

1) morphometric measurements depicting the channel morphological profile; vertical measurements were taken evenly every 10 cm starting at the left bank, and if the channel width exceeded 4 m, every 20 cm,
2) sampling of bed material from the current facies for chemical analysis.

In any channel cross-section, a measuring point was chosen at which to determine the amount of suspended material flowing through it and the physico-chemical properties of the water. Taking into consideration the available studies of the distribution of dissolved and suspended material in a channel cross-section which disprove any significant spatial connections within such a cross-section (Gregory & Walling, 1973; Froehlich, 1975; Zwoliński, 1989), in the present research, the measuring point was situated in the middle part of the channel width and depth. At this point:

1) physico-chemical properties of the water were measured, viz. its temperature, specific conductivity, and concentration of hydrogen ions, and
2) the water was sampled using a water bottle in order to determine the amount of suspended particles and ionic macrocomposition of river water.

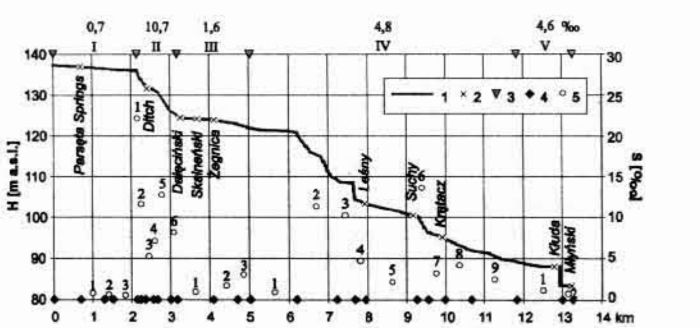

Fig. 5. Changes of river channel slope in the long profile of the upper Parsęta channel.
1 - long profile of river, 2 - mouths of subcatchment tributaries, 3 - limits of channel segments with slope gradient , 4 - limits of channel reaches, location of channel cross-sections, 5 - slopes of river channel reaches.

Table 2. Sources of supply of solutes and solids into river channel *(for the explanation of symbols from A to Ucc see Table 1).*

Segment	I			II						III			IV									V	
Reach	1	2	3	1	2	3	4	5	6	1	2	3	1	2	3	4	5	6	7	8	9	1	2
Supply sources:	**1. Hydrographic network**																						
	a) surface water																						
A	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#
B						#		#		#		#	#			#	#	#	#	#	#	#	#
C	-	-				-				+		+				#	=			#		=	
	b) groundwater																						
D	-	-				-				#		+											
E	-	-							-	=			+	+	-	+	+		=	+	+	+	+
F	-				+				-				+	+	-		=			+	+	+	
	2. Floodplain																						
					#									#		#	#	#	#	#	#	#	
	3. Channel perimeter																						
G			+	+	+	+	+	+	+	+	+	+	+	+		+	+	+	+	+	+	-	=
H		-			-	=										+		=	=	=	=	=	=
I	=	-		=	=	-		-		-	=				-		+		-	-	-	-	=
J	-	-	-		+			=		+			+	+	-	+	+	-	-	+	+	+	+
	4. Biogenic elements																						
K	a) dead plants																						
Ka	-	-					-					-		=	+		=	+		-	=		=
Kb	-	-		+	-		-			-	-	-			+	+		+	=	+	+	+	=
L	b) living plants																						
La											-	-			+		+	-			-		-
Lb	+	+	+	+	=	=	+	=	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
M											-	-										-	
N		#	#			#	#	+	-	+	+	+	+	=		+	+	+	+	-	=	=	-
	5. Man-made delivery																						
O			-	-														+	=				-
P	-		=	=	-	-								=		=		+	+	=	=		-
R	#		#					#															
S																		+	-	-		=	-
T																	#						
U	a) hydraulic-engineering facilities																						
Ua	#							#								#	#						#
Ub	#		#				#	#		#					#							#	
Uc	b) bank consolidation																						
Uca	+	-	=			+	+	+	+	+	+	+	+										
Ucb					+									-				+		-			
Ucc	#		#				#	#		#					#	#	#					#	

Intensity: "+" - high, "=" - average, "-" - low, "#" - occurrence observed, " " - lack

Also, measurements of the specific conductivity and reaction of its water in the long profile of the upper Parsęta channel were made every 100 m.

Sources of material for fluvial transport

Supply of solids

Like river runoff, the movement of solid particles is controlled by spatially and temporarily variable sources of supply. The character and rhythm of the post-glacial relief, lithological diversification, drainage density, shape of the valley and channel, and the land-use pattern are the factors which determine the magnitude of supply of material to the upper Parsęta and the distribution of its sources. In the yearly climatic cycle, these factors combine to form specific systems of material supply for fluvial transport, thus determining the character of the present-day denudation system of the upper Parsęta catchment. On completing the geomorphological mapping of the area, five principal sources of solid particles (mineral and organic) have been distinguished in the analysed fluvial system. They are (Table 2):

- the drainage system (supply through streams and groundwater),
- the wetted perimeter of the river channel (supply from the channel bed and banks),
- the floodplain (surface and underground supply),
- biogenic supply, and
- humanly-made supply.

The occurrence and intensity of the processes responsible for supplying sediment for transport in the Parsęta channel depend largely on lithology, channel morphology and conditions of river flow, hydrogeological conditions, and vegetation. In lowland rivers, bed and bank erosion are thought to be the processes primarily responsible for the supply of material transported in the river channel. The particle-size distribution of the upper Parsęta bed deposits indicates three basic lithofacies in the long profile of the river, viz. one with an even particle-size distribution in which fine sands predominate, one with a predominance of gravels, and one with a predominance of medium sand.

The channel bed deposit facies (Fig. 4) are clearly related to variations in the slope gradient in the long profile (Fig. 5). An important source of bedload is washed-away features of channel accumulation such as channel bars and point-bars.

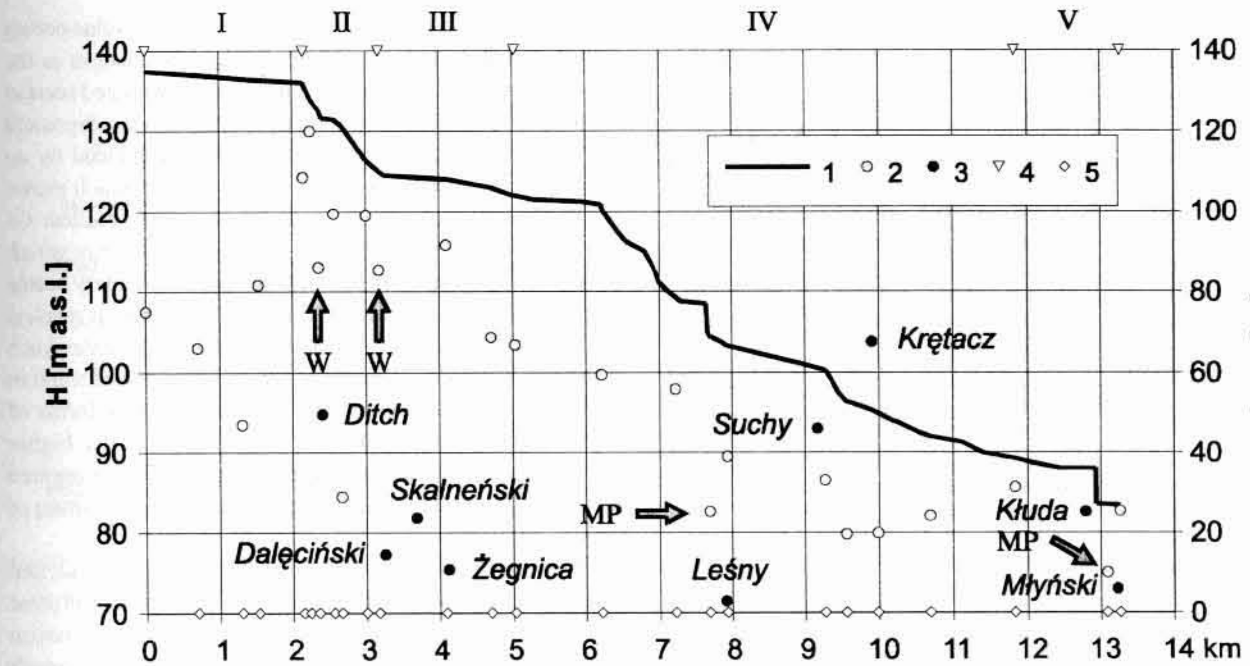

Fig. 6. Differences in suspended sediment concentration along the upper Parsęta river.
1 - long profile of upper Parsęta channel, 2 - suspended material concentrations, 3 - suspended sediment concentrations in mouth sections of subcatchments, 4 - limits of segments, 5 - limits of reaches; W - weirs, MP - mill ponds.

During heavy rains, the area supplying the material expands to include terrain adjacent to the river channel.

The wetted channel perimeter is the most important zone of suspended load supply. The material from this zone comes from lateral erosion, mass movements, overland flow and rainsplash. The supply of suspended material from other sources is basically unrelated to water stages. Worth noting are man-made sources, which are abundant but of episodic nature.

The magnitude of the suspension load is markedly diversified downstream. Generally, however, it tends to decrease from the headwaters to the gauging station at Storkowo (Fig. 6). This tendency reflects the episodic and pulsed character of suspended material transport, with the resultant frequent periodic deposition of this material with variable spatial and temporal intensity in the channel subsystem (Zwoliński, 1989). The highest concentrations of suspended material (Cs) are recorded in ravine reaches where channel slope gradients are high (cf. Figs. 5 and 6). The principal source of supply there is the channel bed, primarily its exposed fragments, especially those which temporarily

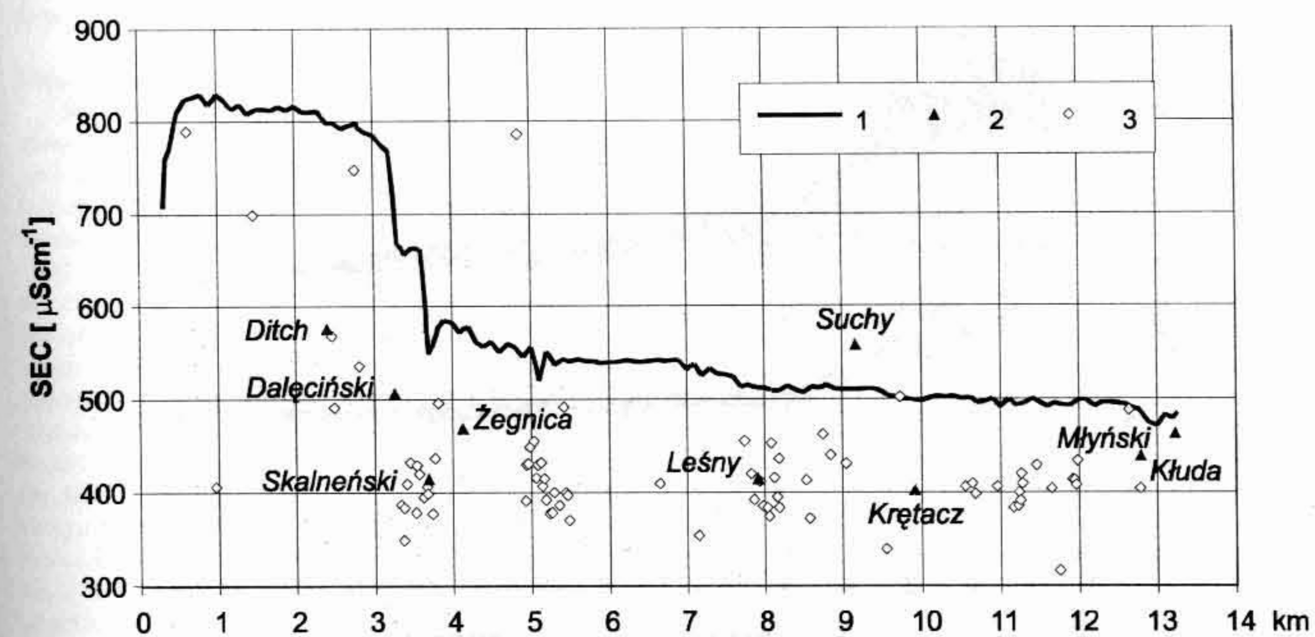

Fig. 7. Variations in specific conductance SEC along the upper Parsęta River.
1 - specific conductance of upper Parsęta water, 2 - specific conductance of mouth sections of main tributaries, 3 - specific conductance of other water flowing into upper Parsęta channel.

Table 3. Physico-chemical properties of bulk precipitation at Storkowo, stemflow and throughfall in a pine wood, and of the upper Parsęta waters at Storkowo.

Parameter	*Unit*	min	max	$\bar{x}$	x^	SD
bulk precipitation (in hydrological years 1992 and 1993)						
pH	[-]	3,45	6,93	4,35	4,34	0,063
SEC_m	μScm^{-1}	7,75	117,00	37,10	31,50	24,01
SEC_c	μScm^{-1}	2,09	106,14	27,13	20,00	20,96
Na^+	$mgdm^{-3}$	0,12	4,58	1,16	0,92	0,87
K^+	$mgdm^{-3}$	-	2,20	0,25	0,20	0,31
Cl^-	$mgdm^{-3}$	1,99	5,40	3,38	3,05	0,95
SO_4^{2-}	$mgdm^{-3}$	1,13	15,90	5,64	5,43	3,58
SiO_2	$mgdm^{-3}$	-	1,52	0,30	0,33	0,38
pine stemflow (in hydrological year 1992)						
pH	[-]	2,39	5,40	3.12	3,09	0,063
SEC_m	μScm^{-1}	119,00	1141,00	563,3	568,02	236,63
SEC_c	μScm^{-1}	87,04	671,00	316,00	300,9	133,38
Na^+	$mgdm^{-3}$	2.00	23,40	11,26	11,44	6,36
K^+	$mgdm^{-3}$	1,50	24,80	7,99	6,78	5,42
SO_4^{2-}	$mgdm^{-3}$	30,41	142,56	71,23	64,4	30,37
SiO_2	$mgdm^{-3}$	0,03	1,47	0,68	0,69	0,36
pine throughfall (in hydrological year 1992)						
pH	[-]	2,80	7,88	4,35	4,34	0,71
SEC_m	μScm^{-1}	53,00	802,00	138,80	149,40	93,75
SEC_c	μScm^{-1}	29,80	289,70	110,60	103,70	49,31
Na^+	$mgdm^{-3}$	1,70	16,8	5,26	4,67	3,07
K^+	$mgdm^{-3}$	1,10	63,9	4,39	3,46	8,48
SO_4^{2-}	$mgdm^{-3}$	10,20	47,85	24,66	24,36	8,69
SiO_2	$mgdm^{-3}$	-	3,30	0,31	0,26	0,54
upper Parseta water at Storkowo (in hydrological years 1992 and 1993)						
pH	[-]	7,65	8,66	8,04	7,64	0,23
SEC_m	μScm^{-1}	345,00	549,00	471,28	465,94	28,28
Na^+	$mgdm^{-3}$	6,45	11,40	8,81	8,67	1,07
K^+	$mgdm^{-3}$	1,76	3,58	2,51	2,64	0,44
SO_4^{2-}	$mgdm^{-3}$	23,50	66,40	44,52	48,03	11,05
SiO_2	$mgdm^{-3}$	6,98	15,62	11,71	11,20	1,79

x^ - *volume-weighted mean*
SD - *standard deviation, for pH in μ eqdm^{-3} H$^+$*
SEC_m - *measured specific conductance for T = 25 °C*
SEC_c - *specific conductance after allowing for hydrogen ions*
"-" - *outside detection limits*

accumulated there (Table 2). A decrease in the Cs value occurs in those reaches of the river where its energy changes as the channel slope gradient changes on entering a widened section of the valley; these are places where sediments are deposited in the channel. This periodic deposition is enhanced by an increase in roughness caused by the vegetation which grows in the channel bed and along its banks. The smallest Cs concentrations were recorded in reaches below weirs which separate mill ponds; these function as local sedimentary basins (Fig. 6). Thus, the material for suspension in the next reach is largely contributed by the wetted perimeter. The meander reach of the upper Parsęta is characterised by a downward trend in the concentration of suspended material, whereas forms of river accumulation become more diversified. Locally, higher Cs concentrations can result from the supply from saturated areas located along the channel, and from the undercutting of banks.

The transport of suspended material displays marked differences in the long profile of the Parsęta; these correspond to the channel segments distinguished. Suspension concentrations in the channel hydrometric cross-sections result from transformation of the load transported downstream. Analysis shows that the very location of a hydrometric cross-section in a catchment determines the figures obtained for fluvial transport intensity. Froehlich (1982, 1992) emphasises that this knowledge is especially relevant when attempting to extrapolate the entire area of a catchment from the results of only one hydrometric cross-section.

The patterns of suspended material concentration as established down the upper Parsęta's long profile were confirmed by mapping along the streams of the subcatchments (Fig. 6). The amount of material transported in the channel of the principal river is augmented or reduced by its tributaries, which are important supply routes from areas outside the channel and river valley (Tab. 2). Small streams in agricultural catchments (the drainage ditch, Suchy Potok and Krętacz)

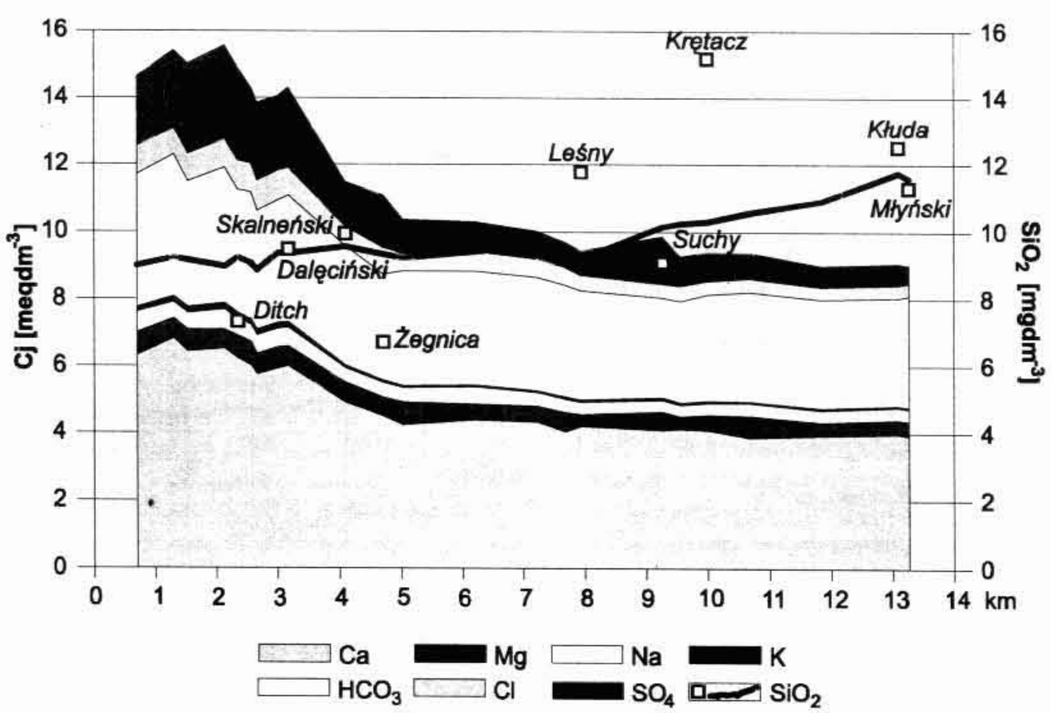

Fig. 8. Variations in the concentration of ion macrocomponents Cj and silica SiO_2 along the upper Parsęta river.

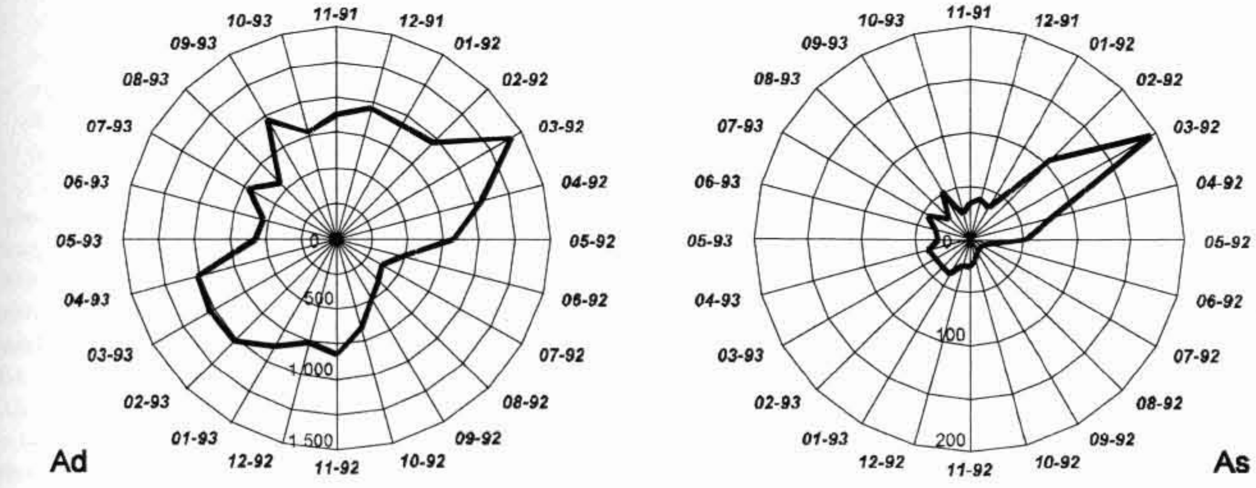

Fig. 9. Monthly sums [t] of ionic outflow Ad and suspended outflow As from the upper Parsęta catchment in the hydrometric cross-section at Storkowo in the hydrological years 1992-1993.

have high Cs concentrations (Fig. 6). The lowest Cs values are recorded in the Leśny Potok, which drains a catchment which is 90% woodland. Here, a system of drainage ditches contributes to the supply of transported suspended material - mostly organic-derived from meadow reaches.

Only a small part of the catchment was found to take part in the supply of suspended material to river channels. The wide, flat valley floor effectively reduces the direct supply of material from the slopes, which can come only from the active undercutting of valley slopes. Along meadow reaches, grasses with dense root systems play an important role in reinforcing the banks and reducing the magnitude of supply. The limitations of farming and the practice of letting arable land lie fallow since 1990 have greatly reduced the effects of overland flow in the sloping areas of the catchment. The vegetation of woodland areas performs this function to a lesser degree, although, by contrast, trees can affect the conditions of water flow and lateral erosion by forming biogenic spurs.

Supply of solutes

Substances dissolved in river water may come from the atmosphere and the biological cycle, but primarily from the processes of chemical weathering and leaching taking place in the soil and deeper levels in the substratum (Dethier, 1986; Swank, 1986; Harriman *et al.*, 1990; Kostrzewski & Zwoliński, 1992a). The transformation of precipitation into runoff is associated with a constant change in the physico-chemical parameters of water supplying the river channel. The results of the investigation of the chemistry of precipitation water registered by the meteorological post at the Geoecological Station at Storkowo, as well as of throughfall and stemflow water on a pine-wood test plot, indicate significant changes in the physico-chemical properties of rainwater. Its chemical composition is first altered through contact with the vegetation cover, and then through infiltration into the soil profile and the water cycle in the saturation zone, it acquires the properties noted in the Parsęta channel (Table 3).

The chemistry of river water at the gauging station is the resultant of all the supply sources and routes of circulation of water and solutes in the catchment system. However, it is hard to apportion the spatial diversification of the sources supplying these substances on the basis of at-a-station measurements. The concentrations of dissolved material observed downstream display various tendencies and differences in dynamics (Froehlich, 1975, 1982; Webb, 1976; Krzemień, 1976, 1982, 1991; Wilamski, 1978; Dethier, 1986; Kostrzewski & Zwoliński, 1986; Webb & Walling, 1983; Ternan & Murgatroyd, 1984; Zwoliński, 1989). Hydrochemical profiles of the main stream of the catchment make it possible to establish the proportion of each of the various zones supplies the river water. They also allow an assessment of the relative importance of the tributaries to be made and the recognition of local sources of human pollution.

When analysing the physico-chemical properties of water down the long profile of the upper Parsęta, three zones of dissolved material supply may be distinguished. These basically reflect the morphological differences observed in the river's long profile (Figs. 7, 8).

1) The first covers the initial 3 kilometres of the river course and is characterised by the highest total ionic concentration and a low SiO_2 concentration. The high concentrations of dissolved materials result from the supply coming from areas rich in calcium carbonate, and from the supply of readily soluble compounds in water which drains from organic and mineral soil horizons.
2) The water flowing along the next 5 kilometres of the Parsęta course is made up, in varying proportions, of water from subcatchments supplied by different groundwater aquifers, each with its own duration of the hydrological cycle.
3) The third zone, again 5 kilometres long, displays the least variability of dissolved components except for silica concentrations, which show an increasing tendency. This is indicative of the supply by groundwater of fairly stable physico-chemical parameters determined by the properties of the discharge from the glaciofluvial and alluvial deposits which line the valley floor. The floodplain area also plays a significant part in regulating the flow of dissolved salts between the catchment and the channel bed.

Hydrochemical mapping along the upper Parsęta showed that the various lithological zones there have significantly

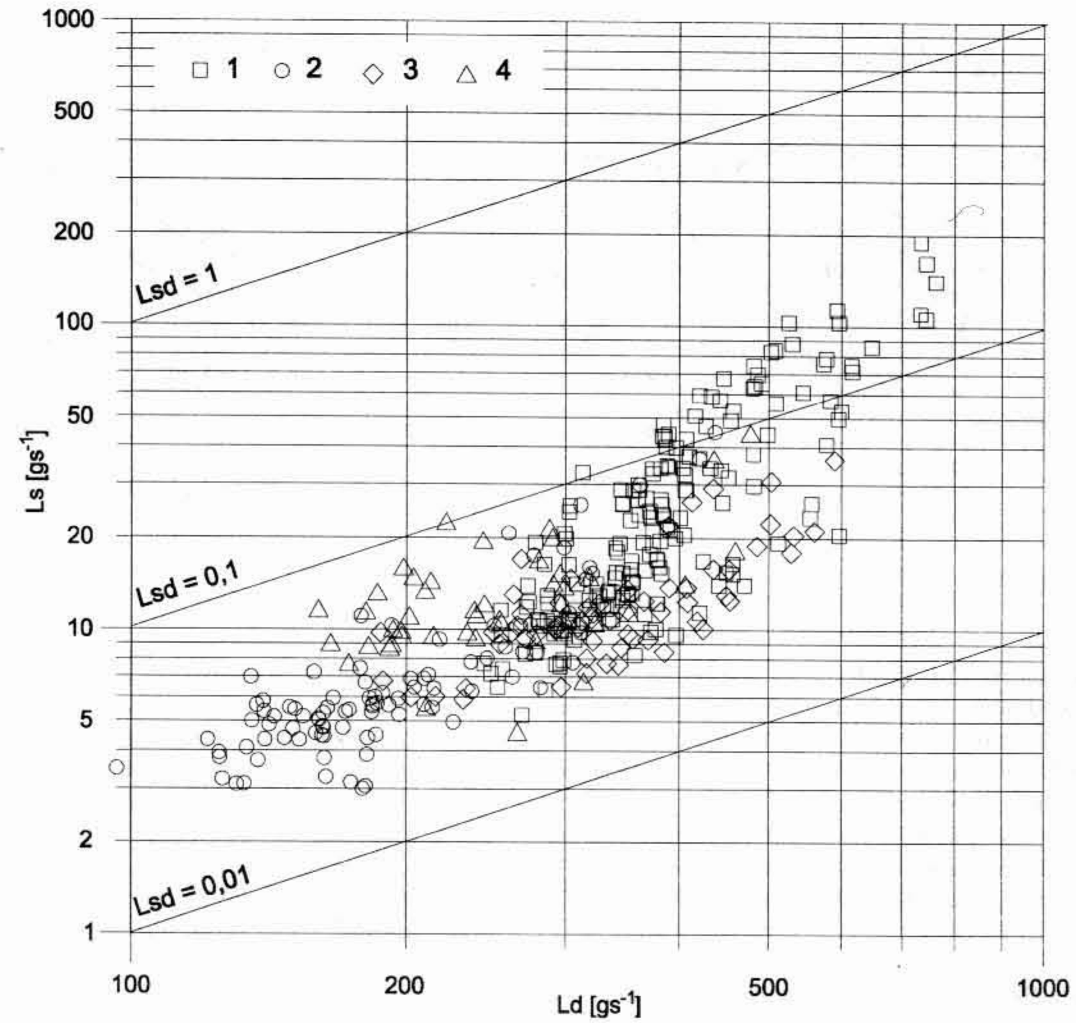

Fig. 10. The ratio of suspended load Ls to dissolved load Ld in the upper Parsęta River at Storkowo in the hydrological years 1992-1993.
Hydrological year 1992: 1 - winter half-year, 2 - summer half-year; Hydrological year 1993: 3 - winter half-year, 4 - summer half-year

affected the nature of the solutes. Lithological differences are related to other features of the environment which control the duration of the water cycle in the catchment. Variations in the concentration of Ca^{2+}, K^{+}, SO_4^{2-}, and SiO_2 ions are useful as natural indicators in the examination of spatial differences in the sources of supply and their geochemical properties.

Character of fluvial transport

To understand the operation of a contemporary geo-ecosystem in a post-glacial area, it is necessary not only to define the quality and amount of transported material, but also their variation in space and time. The variability of the fluvial load reflects the dynamics of the processes of soil leaching and erosion in the catchment. This results mainly from the distribution and type of precipitation, because it is the principal factor which controls the amount of water flowing in the catchment. This, in turn, determines the dynamics of supply and the quantity of material carried away from the catchment system.

A deep understanding of precipitation and of the role of heavy rainfall is fundamental for determining the variability of sources supplying material for fluvial transport. The relatively low coefficients of determination for the relationships Cd = f(Q) and Cs = f(Q) prove that variations in the concentration of dissolved and suspended material in the upper Parsęta have a more complex character and depend on more factors than merely the discharge, which is controlled primarily by precipitation. Relief, permeability of the substratum, and high storage capacity of the upper Parsęta catchment are all responsible for the lack of direct links between the magnitude of precipitation and water chemistry, except for the condition of heavy rainfall.

The ionic outflow in the upper Parsęta catchment amounted to 9 440 t and 9 664 t in the hydrological years 1992 and 1993, respectively, while the respective figures for the outflow of suspended material were 614 t and 413 t. Such a large disproportion in the two kinds of outflow is a characteristic of the catchment (Kostrzewski & Zwoliński, 1990, 1992a; Kostrzewski *et al.*, 1992); not only this catchment, were we to accept the opinion of Maruszczak (1990) concerning the area of North Polish Lakelands. The charts in Figure 9 clearly illustrate the following features of fluvial transport over the two years under analysis:

- the most effective flood discharges occurred in the spring of 1992,
- negligible amounts of dissolved and suspended material were transported during the summer base-flow period of 1992,
- increased amounts of chemical substances and suspended material were recorded in the winter of 1993, and
- during the rainy summer of 1993 the two most conspicuous periods of flood discharge were in July and September.

The magnitude of the ionic and suspended outflows is closely associated with the pattern and intensity of the morphogenetic processes involved in the operation of the denudation system of the upper Parsęta catchment. These parameters allow an estimate of the rates of chemical and mechanical denudation in the catchment to be made. Thus, the rates of chemical denudation can be estimated at 127 $tkm^{-2} a^{-1}$ in the hydrological year 1992 and at 131 $t km^{-2} a^{-1}$ in the hydrological year 1993, while the rates of mechanical denudation are 8.3 $t km^{-2} a^{-1}$ and 5.6 $t km^{-2} a^{-1}$, respectively.

The above indices once again corroborate the view that chemical denudation dominates over mechanical denudation in the upper Parsęta catchment, as proved by the research carried out there in previous hydrological years (Kostrzewski & Zwoliński, 1990, 1992a) and by studies relating to the entire Parsęta drainage basin (Zwoliński, 1989). In the opinion of Walling and Webb (1981), the relationship between these two kinds of denudation is best illustrated by a bi-logarithmic Lsd diagram (Fig. 10). The distribution of points in the diagram shows that the majority of Ls/Ld ratios are in the 0.1 - 0.01 interval, which means that chemical denudation is from 10 to 100 times greater than mechanical denudation. The points located above the Lsd = 0.1 straight line represent the days of the spring 1992 flood. Their shift in relation to the remaining points in the Lsd diagram indicates an increasing role of suspended material during flood discharges.

Also, it is noteworthy that the Lsd diagram (Fig. 10) reveals significant differences in fluvial transport in the upper Parsęta catchment in the winter and summer half-years. Certainly, the Ls/Ld ratios were somewhat higher for the summer half-year of 1993 than 1992. By contrast, the winter half-year Ls/Ld ratio was higher in 1992. Thus, the period of a more intensive rate of fluvial transport in the winter half-year may be concluded to be a regular occurrence in the river channel under analysis, and implies more effective denudation processes. While the dynamics of fluvial transport are very clearly associated with the changing discharge of river waters, it must be stressed that its seasonal rhythm is also dependent on the type of weather, the duration of the vegetation season, the density of vegetation cover, the pattern of precipitation, changes in the land-use pattern (especially in recent years), the composition of fertilizers and the time of their spreading, the introduction of human pollution, and other factors. Those mentioned appreciably control the magnitude and character of supply of solutes and solids to the channel system, hence they also control their leaching and removal from the upper Parsęta catchment.

As mentioned above, the fluvial regime of the upper Parsęta is clearly different in the winter and summer half-years. The seasonal variation in the leaching of the catchment substratum and in the supply of material to the river channel produces a characteristic concentration and load patterns of the fluvial parameters under study. It has been possible to distinguish two morphogenetic seasons:

1) a season of reduced denudation activity, from May to September/ October,
2) a season of heightened denudation activity, connected with winter and early spring, especially from February to April.

It is possible to make a more precise division which changes with hydro-meteorological conditions. Denudation processes are most active in winter and spring. This corresponds to the dynamics of water discharge and is related to weather types.

Geomorphic role of fluvial transport in the upper Parsęta - summary

Fluvial transport is one of the basic processes of a contemporary denudation system of the temperate morphoclimatic zone and is a good indicator of the operation of a catchment system. A detailed knowledge of its character and variability in a yearly cycle is fundamental for a quantitative and qualitative description of modern fluvial systems.

Denudation processes in the upper Parsęta catchment are highly seasonal in character, with variable rates of chemical and mechanical denudation in the successive seasons distinguished. The result is the variability of the upper Parsęta river regime reflected in variations in the ionic flow and suspension flow over the hydrological year. The alternating intensity of denudation processes in the river catchment system should be recognised as a morphogenetic regularity in the temperate morphoclimatic zone. The data presented in this paper document the dominance of chemical denudation processes over those of mechanical denudation. The obtained figures presenting the structure of the fluvial transport are comparable with those quoted by other authors for post-glacial catchments (see chapter 3) and are compatible with opinions about the dominance of dissolved material transport in the temperate zone. Maruszczak's (1991) findings indicate the dominance of the solute flow over the suspension flow in the majority of Poland's morphogenetic regions, and the differences among individual regions stem from mutual relations between these two types of river load.

It should be kept in mind, however, that the structure of material transported in the river channel can change during catastrophic events. In the two hydrological years 1992-1993, 68% of dissolved material and 76% of suspended material left the catchment with floods. It should be emphasised, however, that the solute and solid loads were calculated on the basis of the concentration of fluvial transport measured once a day. Taking into consideration the high temporal and spatial variability of material transport in the river channel, there may be errors in the results. Extreme weather conditions, such as lasting droughts or flash-floods, cause fluctuations in the supply of matter to the river channel at various time scales, which makes it hard to obtain reliable figures. The question of the frequency of sampling is not new, taking into consideration earlier statements by Walling (1974).

One can express the opinion that the good preservation of glacial relief in the study area is the result of the dominance of chemical denudation, which is reflected in the high figures for dissolved transport. The present-day denudation-erosional system has been forced by the relief and lithology, while its seasonal variability depends on meteo-hydrological conditions typical for a temperate zone. Contemporary fluvial processes concentrate primarily along the old routes of glaciofluvial runoff, emphasising and modifying the polygenetic character of river valleys. It is only extreme processes that can produce immediate visible effects in the present-day evolution of the fluvial system.

It can also be concluded that human activities make it difficult to obtain accurate values of denudation rates. There are non-denudation components contributing material to be transported in the river channel, viz. precipitation, dry deposition, fertilisers, and household waste. Considering the concentrations of dissolved substances reaching the surface of the upper Parsęta catchment through precipitation, the calculated indices of chemical denudation can be regarded as overestimated from 5 to 10%. The denudation rate is also affected by the activity of the organic world, owing to which some products of chemical weathering are introduced into the biological cycle and kept temporarily in the organisms of plants and animals (Dethier 1986). This is reflected in seasonal variations in the concentrations of the studied ions in river water that correspond to the vegetative rhythm.

The period of increasing morphogenetic activity in the upper Parsęta catchment embraced the cycle of thaws and spring and summer floods, i.e. the periods of increasing denudation activity. The high efficiency of denudation processes is associated with certain types of weather and this influences the dynamics of the river regime. Thus, a knowledge of the distribution of the hydrochemical and fluvial transport seasons allows an assessment of morphogenetic activity in the present-day denudation system of the catchment to be made. A temporal analysis of the various hydrochemical and fluvial seasons, on their basis of the seasons of denudation activity, leads to the conclusion that the evolution of the denudation system of the upper Parsęta catchment is a continuous process with periods of reduced, average and heightened denudation activity, dependent on the weather rhythm of the temperate zone. The temporal variability of those periods is responsible for differences in the development of the morphosystem of the upper Parsęta catchment.

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