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SPATIAL PATTERNS OF STREAM ALIMENTATION IN LOWLAND AREAS OF NW POLAND A HYDROCHEMICAL AND GEOSTATISTICAL ANALYSIS

ALFRED STACH[1•)], ANDRZEJ KOSTRZEWSKI[1)], MAŁGORZATA MAZUREK[1)],
GRAŻYNA M. MICHALSKA[2)], ZBIGNIEW ZWOLIŃSKI[1)]

[1)]Institute of Quaternary Research and Geoecology, Adam Mickiewicz University, Fredry 10, 61-701 Poznań, Poland.
[2)] Adam Mickiewicz University Geoecological Station, Storkowo 32, 78-450 Grzmiąca, Poland.
[*]Corresponding author: tel: +48-61-8294675, fax: +48-61-8530234, e-mail: frdstach@amu.edu.pl

Areas of the Last Glaciation in northern Poland differ widely as to the conditions controlling the formation of river runoff and solute loads. The aim of the research was to identify chief mechanisms of stream alimentation in this area depending on the scale of a catchment. The analysis rested on data from hydrochemical profiling. Three types of systems were found to occur: in spring-head catchments with areas of the order of 10^{-2} km^2, in small catchments (10^0 km^2), and in medium-sized ones (10^1–10^2 km^2). The first is connected with the mixing of soil- and groundwater, the second, with the mixing of waters from relatively homogeneous subcatchments, and the third, with the mixing of groundwater from various water-bearing horizons. In headwater catchments, river waters reach a new physico-chemical equilibrium at a distance of 20–40 m; in small catchments, two nested autocorrelation structures (150 and 400 m) reflect the sequence of land cover changes and distances between main tributaries; in medium-sized catchments, river waters demonstrate similarity at a distance of between 300 and 450 m and 1.2 km; it is controlled by the sequence of successive valley reaches of different origins (melt-out basins & ravines).The reported analysis justifies the hypothesis that in the areas of northern Poland covered by the Last Glaciation it is possible to identify the zones and forms of channel alimentation on the basis of hydrochemical interpretation of runoff recorded in gauging profiles only in the case of small catchments no larger than $n \times 10^0$ km^2. In larger catchments, it is only possible to differentiate between 'new water' (direct fall of precipitation on the channel and the overland flow) and 'old water', composed of a mixture of soil water and the alimentation from various water-bearing horizons

KEY WORDS: Stream Alimentation, Catchment Scale, Hydrochemical Profiling, Semivariograms, NW Poland.

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V oblastiach severného Poľska ovplyvnených posledným zaľadnením existujú veľmi rozdielne podmienky tvorby odtoku a vyplavovania rozpustených látok. Cieľom nášho výskumu bolo identifikovať hlavné mechanizmy prítokov vody do povrchových tokov v tejto oblasti s ohľadom na mierku povodia. Analýza bola založená na údajoch z hydrochemického profilovania. Boli zistené tri typy systémov: pramenné oblasti s plochou rádu do 10^{-2} km^2, malé povodia (10^0 km^2)a stredné povodia (10^1–10^2 km^2). V prvom systéme pri tvorbe odtoku dominuje miešanie pôdnej a podzemnej vody, v druhom miešanie vôd z relatívne homogénnych subpovodí, v treťom miešanie podzemnej vody z rôznych vodonosných vrstiev. V pramenných oblastiach nadobúda voda v riekach novú fyzikálno-chemickú rovnováhu vo vzdialenosti 20–40 m. V malých povodiach boli zistené dve nadväzujúce autokorelačné štruktúry (150 a 400 m), ktoré odrážajú postupnosť zmien pokrytia územia a vzdialeností medzi hlavnými prítokmi. V stredne veľkých povodiach voda v riekach poukazuje na podobnosť v mierke medzi 300 a 450 m a 1,2 km. Táto podobnosť je daná postupnosťou nadväzujúcich úsekov dolín rôzneho pôvodu (povodia modelované vodou z topiaceho sa ľadovca, resp. strže). Analýzy potvrdzujú hypotézu, že v oblastiach severného Poľska zasiahnutých posledným zaľadnením možno pomocou hydrochemickej interpretácie meraného odtoku identifikovať zóny a formy prítoku vody do tokov iba v malých povodiach nie väčších ako $n \times 10^0$ km^2. Vo väčších povodiach sa dá odlíšiť iba „nová voda“ (zrážky spadnuté priamo na povrch riečnej siete a povrchový odtok) a „stará voda“ (zmes pôdnej vody a príspevku z rôznych vodonosných vrstiev).

KĽÚČOVÉ SLOVÁ: tvorba odtoku, mierka povodia, hydrochemické profilovanie, semivariogram, SZ Poľsko.

Introduction

Since 1985, an interdisciplinary research has been carried out in the upper Parsęta catchment (NW Poland, Fig. 1) concerning the processes of energy and matter flows in areas with postglacial relief and varying land-use patterns (*Kostrzewski et al.*, 1994). An element of the research has been the monitoring of hydrological and geomorphological processes in catchments of various sizes, starting with first-order ones, covering 10^{-2} km^2 (*Michalska*, 2001; *Stach*, 1993), and ending with a fifth-order one, covering 10^2 km^2 (*Kostrzewski* et al., 1994; *Mazurek*, 1999, 2000). The operation of even the smallest catchment in this area is very complex, owing to a poor organisation of the drainage system, a complicated geological structure of the Quaternary, diversified lithology, and a mosaic of land uses, including numerous water bodies and peat bogs (Tab. 1). The characteristic features of the hydrology of this northern part of the Polish Lowland are a high proportion of areas with no surface outlet, a large retaining capacity of catchments and hence big hydrological inertia of streams, and the dominance of seasonal over short-term variability connected with rainfall or snowmelt episodes. The spatial and temporal variations in the conditions controlling the channel flow are reflected in a high variation, primarily spatial, of the unit flow modulus and the physico-chemical properties of waters (Tab. 1). In small, even adjacent catchments, water mineralisation levels and solute loads can differ by more than one order of magnitude. That is why a hydrological interpretation of the channel flow in water-gauging profiles on those streams in terms of the identification of areas and ways of feeding is impossible without spatial studies and analyses. Apart from traditional hydrological mappings, a wealth of valuable data have been derived from hydrochemical profiling of the streams.

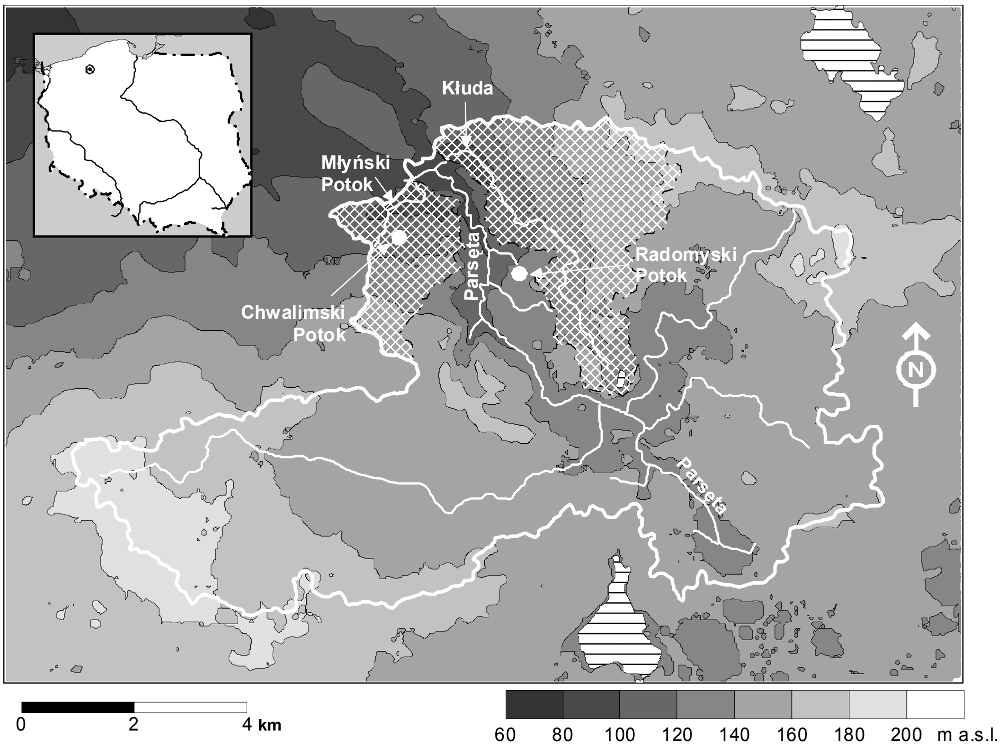

Fig. 1. Location, relief and main hydrological network of the upper Parsęta catchment. Locations of the studied catchments are marked by arrows.
Obr. 1. Lokalizácia, reliéf a hlavná hydrologická sieť hornej časti povodia rieky Parsęta; skúmané povodia sú vyznačené šípkami.

Table 1. Characteristics of analysed rivers and their catchments (morphometric indices after Zăvoianu 1985).
Tabuľka 1. Charakteristiky analyzovaných riek a ich povodí (morfometrické indexy podľa *Zăvoianu*, 1985).

Parameter/ river/ reference	The upper Parsęta (*Kostrzewski* et al., 1994)	Kłuda (*Mazurek*, 1999, 2000)	Młyński Potok	Radomyski Potok (*Stach*, 1993)	Chwalimski Potok (*Michalska*, 2001)
Catchment area [km^2]	74.00	10.69	3.94	0.109	0.051
River length [km]	13.26	6.99	2.46	0.157	0.231
River slope [m m^{-1}]	0.0041	0.0063	0.0139	0.0422	0.0156
Basin height $H_{\max}$-$H_{\min}$ [m]	119.5	96.2	79.1	26.0	10.36
Index of catchment relief $H_{\text{source}} - H_{\text{outlet}}$ [m]	137.5 – 83.4	132.0 – 88.7	117.5–83.4	116.6–110.0	114.3–110.7
Basin slope [m m^{-1}]	0.008	0.017	0.025	0.060	0.035
Drainage density [km km^{-2}]	2.24	2.97	2.35	2.12	5.71
Mean annual discharge [dm^3 s^{-1}]	$610.0^{1)}$	$94.9^{2)}$	$20.7^{3)}$	$1.33^{4)}$	$1.47^{5)}$
Mean annual unit runoff [dm^{3}s^{-1} km^{-2}]	$8.2^{1)}$	$8.9^{2)}$	$5.3^{3)}$	$12.20^{4)}$	$28.82^{5)\,6)}$
Surface lithology$^{7)}$	85%S, 13%P, 2% O	88%S, 7%P, 5%O	91.9%S, 5,4%P, 2,8%O	93%S, 3%P, 6%O	93%S, 5%P, 2%O
Landuse$^{8)}$	$^{9)}$ 43%A, 34%F, 15%M/P, 8%O	$^{9)}$ 37%A, 41%F, 18%M/P, 4% O	$^{9)}$ 40%A, 35%F, 23%M/P, 2%O	94%A, 3%F, 3%M/P, 0% O	14%A, 0%F, 26%M/P, 60%O
Water chemistry at the outlet (anions and cations concentrations are in meq dm^{-3}) Anions: $HCO_3 > SO_4 > Cl$ Cations: Ca > Mg > Na > K	388.1 µS, 7.85 pH, 10.53 mg dm^{-3} SiO_2, A: 2.86 > 0.83 > 0.38 C: 3.54 > 0.44 > 0.25 > 0.06	409.5 µS, 7.90 pH, 12.30 mg dm^{-3} SiO_2, A: 3.14 > 0.74 > 0.33 C: 3.41 > 0.43 > 0.34 > 0.05	353,3 µS, 7.10 pH, 9,61 mg dm^{-3} SiO_2, A: 2.75 > 0.78 > 0.35 C: 3.23 > 0.34 > 0.28 > 0.05	362,4 µS, 7.46 pH, 12,60 mg dm^{-3} SiO_2, A: 2.74 > 0.40 > 0.29 C: 2.90 > 0.42 > 0.29 > 0.04	382,0 µS, 7.94 pH, 8.89 mg dm^{-3} SiO_2, A: 2.51 > 0.96 > 0.29 C: 3.36 > 0.34 > 0.28 > 0.09

1 – gauge of the Institute of Meteorology and Water Management at Storkowo, hydrological years 1985–2000, 2 – hydrological years 1990–1993, 3 – hydrological years 1994–2001, 4 – mean of 105 irregular measurements taken in the hydrological years 1987–1991, 5 – weekly measurements in the hydrological years 1992–1995, 6 – extraordinary high value because of big difference between surface and underground catchment, 7 – S – sands (loamy and loose sands), P – sediments of organic origin, mostly peat, O – other, 8 – A – arable land, F – woodland, M/P – meadows/pastures, O – other, 9 – data from early 1990s; there have been rapid changes in land-use pattern: drop in proportion of arable land and increase in area of wasteland and woodland.

1 – merný profil Ústavu meteorológie a vodného hospodárstva, hydrologické roky 1985–2000, 2 – hydrologické roky 1990–1993, 3 – hydrologické roky 1994–2001, 4 – priemer zo 105 nepravidelných meraní uskutočnených v hydrologických rokoch 1987–1991, 5 – týždenné merania v hydrologických rokoch 1992–1995, 6 – výnimočné vysoká hodnota spôsobená veľkým rozdielom medzi hydrologickou a hydrogeologickou rozvodnicou, 7 – S – piesky (hlinité piesky a piesky), P – sedimenty organického pôvodu, hlavne rašelina, O – iné, 8 – A – orná pôda, F – les, M/P – lúky/pasienky, O – iné, 9 – údaje zo začiatku 90-tych rokov; potom došlo k veľkým zmenám využitia krajiny: k poklesu rozsahu ornej pôdy a rastu neobrábanej pôdy a lesa.

The aim of the present work is to elucidate the mechanisms of the channel flow formation in catchments of various sizes in areas with postglacial relief on the Polish Plain. For this purpose use was made, among other things, of a geostatistical analysis (*Goovaerts*, 1997; *Gringarten* & *Deutsch*, 2001) of data from the hydrochemical profiling.

Study area

The study area embraces the upper Parsęta catchment with its diversified internal structure defined by the system of subcatchments. The catchment is situated in West Pomerania Lakeland (NW Poland, Fig. 1, Tab. 1).

The upper Parsęta catchment extends along the northern slope of the Central Pomeranian chain of end moraines within the so-called Parsęta lobe. The relief of this area is the product of deglaciation during the Pomeranian Phase of the Vistulian (*Karczewski*, 1989), and of the processes of the Holocene morphogenetic cycle. The valleys of the Parsęta and its major tributaries are characterised by narrow ravine sections which connect wedge-like basins of melt-out origin where the river acts upon a relict relief. The largest area of the upper Parsęta catchment is occupied by deposits left by the ice-sheet, namely tills, sometimes with a very high sand content. There are also high proportions of glaciofluvial and fluvial sands and gravels as well as Holocene organic deposits, mainly peats and lake gyttjas. The surface deposits of the upper Parsęta catchment display big 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. A characteristic feature of the catchment is the mosaic land-use pattern conforming to the main forms of the young-glacial relief. Because of the high proportion of arable land and woodland, which together occupy as much as 77% of the area, the upper Parsęta catchment can be classified as an agricultural-woodland one.

The catchment is exposed to polar-maritime air masses (75% of the time on average). The mean annual air temperature is 7.7 ºC, while the rainfall amounts to 670 mm (*Woś*, 1994). January is the coldest month (–0.5 ºC) and July, the warmest (17 ºC). In the annual rainfall pattern, the summer months contribute the bulk of precipitation. The area has relatively high runoff values (*Kaniecki*, 1994). The mean annual unit flow is 10.2 $dm^3s^{-1}km^{-2}$, almost twice the average for Poland. This is the result of the catchment's big storage capacity and a predominantly underground alimentation, as shown by the relatively low ratio (11.5) of maximum to minimum flow.

The Kłuda River is a fourth-order stream. Its catchment can be divided into two morphological zones. Part of it lies in the outer sub-zone of dead-ice moraine and kame moraine, while the rest is located on a morainic plateau. The land-use mosaic in the Kłuda catchment reflects the distribution of soils, its lithology, and landforms. Arable land and woodland occupy 71.8% of the area. A major characteristic of the drainage network is the presence of a single principal stream which flows along the entire length of the catchment and is disproportionately long with respect to its tributaries. Like the Parsęta valley, the Kłuda valley also exhibits reaches of different origins along its course. The valley can be described as consisting of a series of wide melt-out basins connected by ravines.

The Młyński Potok, a third-order stream, flows almost exclusively within a single type of relief: an undulating ground moraine. The central part of its catchment is under agricultural use, including arable land and meadows (on peats). In the upper and lower parts, in turn, the predominant land use is woodland with a big proportion of peat bogs.

In the postglacial lakelands of NW Poland, perennial streams rise either in big bodies of water, in peat bogs (both blanket and raised) or other wetland, or in spring-head areas where the water comes to the surface from rich, 'inter-morainic' water-bearing horizons. This last form of starting a drainage is especially common in the hilly terrain of the mid-lakeland elevation and in the marginal zones of glacial drainage channels and valleys. In the upper Parsęta catchment most perennial streams rise in spring-head areas. The areas are characterised by highly dynamic geomorphological processes in the morphogenetic system of postglacial morainic uplands.

Typical of this type of catchment is a wide disparity between the areas of the topographic and the underground catchment manifesting itself in much higher unit discharge values than the regional average. Both the first-order catchments under study display this character. Also, they are almost entirely agricultural land. What differentiates them are the morphology and the density of the stream network. The Radomyski Potok is situated in the marginal zone of a kame moraine with very high relief for a lowland area. The catchment of the Chwalimski Potok embraces a melt-out basin situated in an area of an undulating ground moraine.

Methodology

The studies were conducted in four subcatchments as well as in the entire catchment of the upper Parsęta (Tab. 1, Fig. 2). The catchment areas varied from 0.05 km^2 to 74.0 km^2, the length of streams, from 0.16 km to 13.26 km, and sampling intervals, from 2 m to 100 m. Mapping was carried out in periods of steady runoff, in a maximum of one day. The periods chosen corresponded to high water resources in the catchment, with all other forms of channel feeding beside the non-saturation (Hortonian) overland flow.

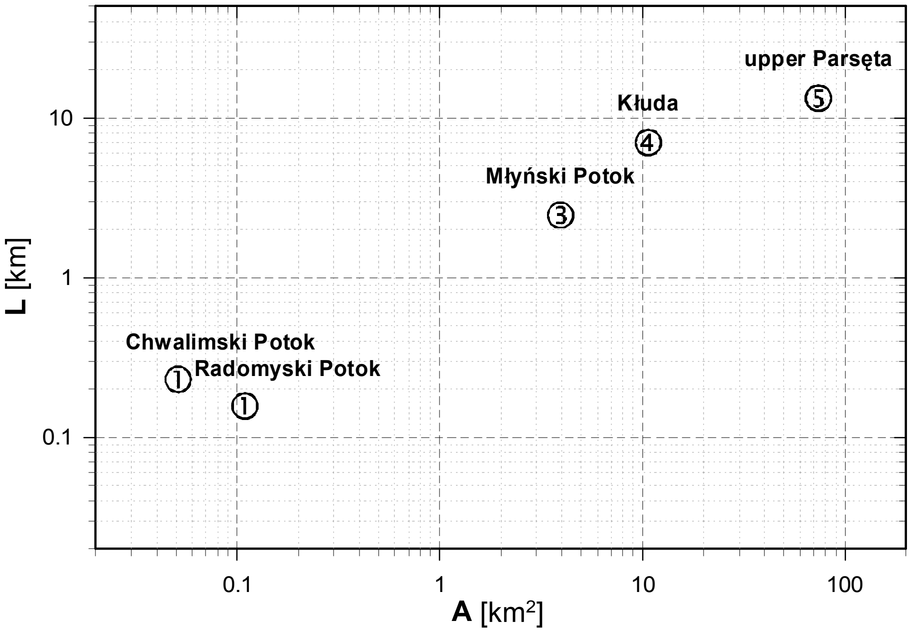

Fig. 2. Catchment area (A) – channel length (L) ratio for the studied catchments. Numbers denote catchment order according to Horton-Strahler rules.
Obr. 2. Pomer medzi plochou povodia (A) a dĺžkou koryta (L) pre študované povodia; čísla označujú rád povodia podľa Hortona a Strahlera.

At the stream sites, discharge measurements were made using the dilution gauging method (*Stach*, 1992). In addition to water sampling and discharge measurements, the water temperature, specific electrical conductance SEC (at a reference temperature of 25 °C) and pH was also measured. Laboratory analyses of filtered water samples included:

1) determination of the concentrations of calcium and chloride ions, calcium hardness and alkalinity by titration;
2) measurement of the concentrations of sodium and potassium ions by flame photometry or atomic absorption spectrophotometry (AAS);
3) spectrophotometric determination of the concentrations of sulphate and ionised silica; and,
4) calculation of the magnesium ion contents.

In all cases the values of distances used in calculations and on the graphs come from direct field measurements along the studied streams channels.

The profiling data on the physical properties of water in the streams along their courses were analysed using geostatistical methods in order to identify their underlying spatial structure. The starting point for the geostatistical analysis is the calculation of an empirical semivariogram being a measure of the mean dissimilarity between measurement data separated by a distance **h** (*Gringarten*, *Deutsch*, 2001, Fig. 3). It is half of the mean square of differences between the values of a parameter at point u_α and at point $u_\alpha + \mathbf{h}$ (1):

$$\hat{\gamma}(\mathbf{h}) = \frac{1}{2N(\mathbf{h})} \sum_{\alpha=1}^{N(\mathbf{h})} \left[z(\mathbf{u}_\alpha) - z(\mathbf{u}_\alpha + \mathbf{h}) \right]^2 , \qquad (1)$$

where

$N(\mathbf{h})$ – the number of pairs of data for the given distance interval **h** between them,

$z(\mathbf{u}_\alpha)$ for α = 1, 2, ..., *n* – denote a set *n* of measurements of the given parameter,

$\mathbf{u}_\alpha$ – a vector of the locations of measurements taken.

A generalisation of the information included in an empirical semivariogram is a semivariance model, or a continuous function fitted to the values of empirical semivariances calculated for a finite number of distance intervals (Fig. 3). The model allows semivariance estimates for any interval and 'smoothes out' accidental fluctuations of individual values of the empirical semivariances. It is also of fundamental significance for estimating the values of a parameter at sites not sampled. The semivariance model makes it possible to determine three very important parameters of the data series under analysis:

– The range (Ao) defining the distance up to which there is an autocorrelation (similarity) between measurement results,

– The nugget variance (Co), or the theoretical estimate of the difference between measurements performed at the same time moment; it is made up of the measurement error and the short-time variability appearing along a section shorter than the distance between successive measurements.

– The structural variance (C), or the increase in semivariance from the nugget level to the range limit of correlated data (sill, Co + C). In the case of nested models, each component is characterised in terms of the type of function and the value of the structural variance. The sum of the structural variances of partial models is usually close or equal to the variance of the entire measurement series analysed.

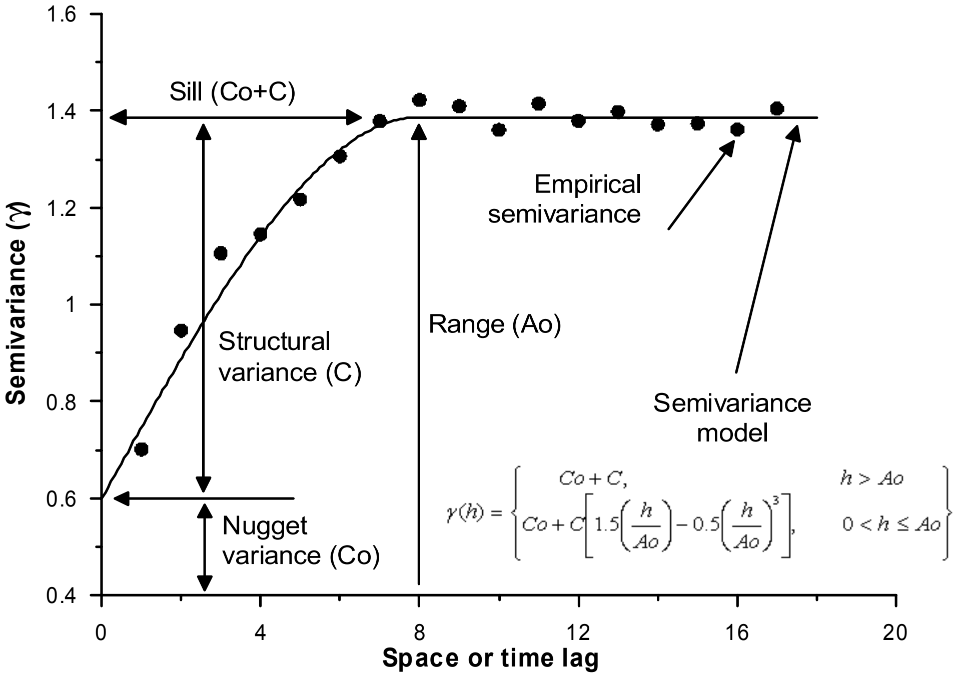

Fig. 3. The nomenclature used in semivariogram analysis.
Obr. 3. Terminológia použitá pri analýze semivariogramu.

The classical analysis of semivariance is intended for the study of series of stationary data, i.e., ones in which the deviation from the mean is random in nature (*Goovaerts*, 1997; *Gringarten & Deutsch*, 2001). The analysed measurement series are non-stationary and there is often a strong tendency for water coming from upstream to "mask" changes occurring at a given point. In most cases the actual spatial structure of the analysed data can be discerned after the elimination of the tendency or the local average (Tab. 2).

Calculations of the empirical semivariances and the fitting of models were performed using the Variowin 2.21 program (*Pannatier*, 1996).

Results

The Radomyski Potok

From its outfall from the drain pipe to the last measuring site, the stream is 156.7 m long. Its mean gradient along this reach ranges from 0.3° to 17.6°. The gradient is the biggest in the upper part (up to the 38th m) of the erosional dissection in which the stream flows, and averages 9.4° (from 7.6° to 17.6°). Lower down the slope of the channel bottom becomes much less steep, and along the final 40 metres it only amounts to 0.6° (0.3–1.0°). The cross-sectional gradient of the dissection bottom in its upper part varies between 5.5° and 7.5°, in the broad middle part, between 3° and 3.5°, and in the narrow lower part, it is about 7°. 74.8 m below the outfall from the drain pipe there is a weir, and 11.3 m farther on the stream receives a tributary from a spring-head alcove. In the lower part of the dissection there are a few other small streams, either intermittent or perennial, of which the one that joins the Radomyski Potok at the 115th metre carries much more water throughout the year than that from the spring-head alcove.

T a b l e 2. Summary results of profiling of the studied streams.
T a b u ľ k a 2. Súhrnné výsledky profilovania skúmaných tokov.

Name of river/ Sampling date	Length of section sampled/ Sampling interval	Range of parameters[1)] in sampled river section	Mean for sampled river section	Data preparation before semivariogram calculation[2)]	Nugget variance $\sqrt{C_0}$	Sill (nugget variance + structural variance) $\sqrt{C+C_0}$	Range A_0
Units	[m]	SEC - µS cm^{-1} in 25 °C, Tw - °C					[m]
Chwalimski Potok 2001-03-13	215/5	SEC: 160 – 455	419.2	none	1.0	37.9	25.2
		pH: 7.90 – 8.39	8.23	none	0.02	0.05	42
		Tw: 6.0 – 7.9	7.0	CLTR	0.1	0.18	36.4
Radomyski Potok 1992-03-05	149.5/2	SEC: 207 – 361	277.8	CLTR	2.63	6.0	17.9
		pH: 5.45 – 7.73	6.33	CLTR	0.14	0.27	23.1
		Tw: 3.8 – 6.1	5.0	LTR	0.05	0.15	17.1
Młyński Potok 2002-03-09	2460/20	SEC: 291 – 361	326.5	LMR	0.9	3.8	150/400
		Tw: 4.1 – 6.3	5.44	LMR	0.08	0.23	430
Kłuda 1992-08-20	6990/100	SEC: 352 – 419	401.8	none	0	7.5	310
		pH: 7.29 – 8.15	7.82	none	0	0.12	315
the upper Parsęta 1993-07-04	12940/100	SEC: 471 – 829	590.0	CLTR	7.21	14.5	436
		pH: 7.59 – 8.50	7.92	none	0.06	0.31	1200/2600

1 – SEC – Specific Electric Conductivity of water, pH – reaction, *Tw* – water temperature, 2 – CLTR – curvilinear trend removal, LTR – linear trend removal, LMR – local means removal.

1 – SEC – merná elektrická vodivosť vody, pH , *Tw* – teplota vody, 2 – CLTR –odstránenie krivkového trendu, LTR – odstránenie lineárneho trendu, LMR – odstránenie lokálnych priemerov.

All three parameters characterising water in physico-chemical terms measured on 5 March 1992 showed an upward tendency along the entire stream section from the outfall from the drain pipe to the last measuring site (Fig. 4). However, these changes were neither uniform nor simultaneous. In the case of temperature and reaction, undoubtedly significant were changes occurring in the channel itself; conductance responded mainly to the inflow of 'new' water. The temperature of water flowing from the drain pipe amounted to 3.9 ºC, while that of the air varied between 5 ºC and 7 ºC over the time of measurement taking and water sampling (about 2.5 hours). In turn, changes in the reaction, especially along the first 30 m, were largely connected with the release of free carbon dioxide with which the soil water is saturated in relation to the atmospheric pressure of CO_2.

The calculation of semivariances for 'crude' results of temperature and conductance measurements made in March 1992 showed there to be no distinct spatial structure (Fig. 5). Semivariance values in the distance range of up to 60 m are characterised by an unlimited, power-function increase. It is the result of the non-stationary nature of the analysed measurement series, which show a strong spatial trend: the water flowing from upstream obscures the changes occurring at the given point. The diagram of the pH semivariance shows a slump at a distance of about 50 m, which reflects a clearly tripartite shape of the curve of water pH in the stream – the changes took place roughly at the 50th and 120th metres of the stream course (Fig. 5). The local spatial structure of the data analysed can only be detected after the trend has been removed. Thus, the data obtained were fitted by the functions of a linear trend and the simplest curvilinear one, and the semivariance analysis was repeated, this time on residuals from the trend and not the original measurement data (Fig. 5). Diagrams of empirical semivariances of residuals from the trend revealed the local spatial structure of the measurement series. The conclusions from their visual analysis can be summed up as follows:

– The use of residuals from the curvilinear trend to calculate empirical semivariances produced clear advantageous effects in the case of pH and SEC. The advantage of using residuals from the curvilinear trend in the calculations consists in the fact that semivariance curves do not show any upward ten dency after the first inflection and oscillate within the variance range for the entire sample. This indicates a successful elimination of the principal deterministic component of the variance of the parameter under analysis. The remaining part of the variance is mainly determined by autocorrelation and a random element (noise).

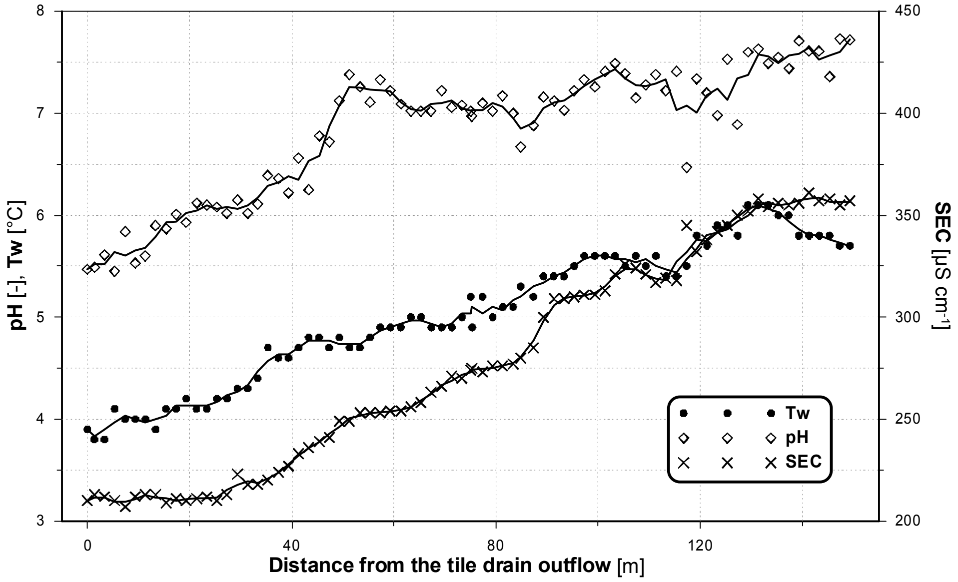

Fig. 4. Variations in water temperature (*Tw*), reaction (pH), and specific electric conductance (SEC) of river waters along the Radomyski Potok channel on March 5th, 1992. Lines denote a three-element moving average.

Obr. 4. Priebeh teploty (*Tw*), pH, a mernej elektrickej vodivosti (SEC) vody v rieke pozdĺž toku Radomyského potoka 5. 3. 1992; čiary označujú kĺzavý priemer.

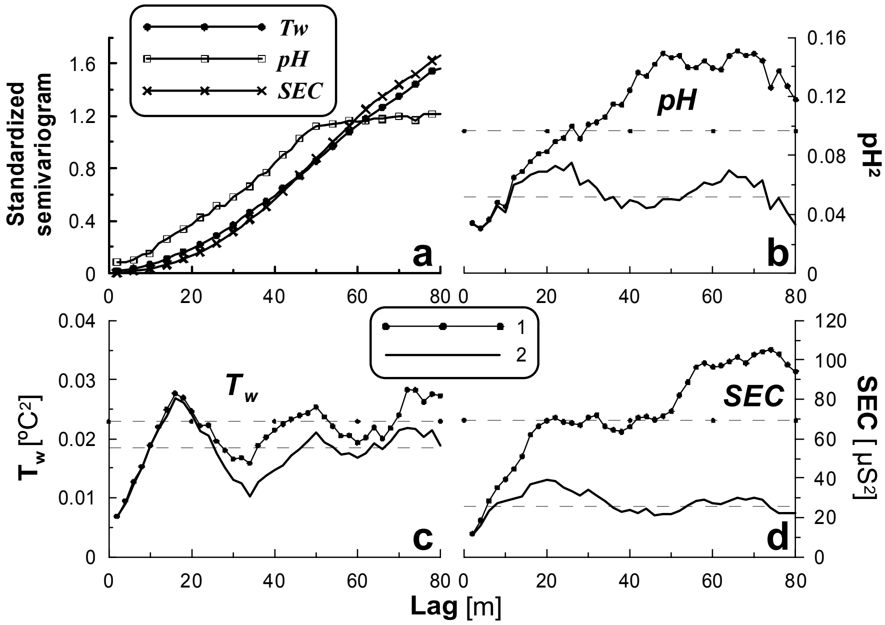

Fig. 5. Empirical semivariances of reaction (pH), water temperature (Tw) and specific electric conductance (SEC) for river waters along the Radomyski Potok channel on March 5th, 1992; plot a) standardised (sample variance = 1) empirical semi-variance of crude measurements, plot b), c), and d) empirical semi-variance of residuals from the trend of measurements; 1 – residuals from linear trend, 2 – residuals from curvilinear trend; dashed line – sample variance.

Obr. 5. Empirické semivariancie pH, teploty vody (*Tw*) a mernej elektrickej vodivosti (SEC) vody v rieke pozdĺž toku Radomyského potoka 5. 3. 1992; a) normalizované (variancia výberu sa rovná 1) empirické semivariancie nespracovaných údajov, b), c), d) empirické semivariancie reziduálnych hodnôt od trendovej čiary meraní; 1 – reziduálne hodnoty od lineárneho trendu, 2 – reziduálne hodnoty od krivkového trendu; čiarkovaná čiara – variancia výberu.

– All the three curves display a marked inflection when the distance between samples equals 17÷21 m. This is the point at which the semivariance value stops growing. Hence, it is the maximum range of autocorrelation, i.e., a local similarity among the samples.

– The removal of the trend, however, failed to make the obtained series of residuals strictly stationary. After the first inflection mentioned, the semivariance curves show, apart from random, variously directed swings (the 'teeth' of a curve), a marked cyclic variability over an interval of 40–50 m. As has been mentioned above, the principal factor of non-stationarity was the 'cumulation' of water from upstream (both its volume and physico-chemical properties). But the channel is also fed by new water 'from outside', differing in volume and properties. The removal of the trend caused a total reduction of the first factor of deterministic variability and only a partial one of the other. 40–50 m is the length of the chief streams feeding the principal one with water and substances dissolved in it.

The further part of the geostatistical analysis consisted in expressing in quantitative terms some of the qualitative observations described above. In order to minimise the effect of the cyclic variability, the fitting of the semivariance model was limited to a 0–30 m section in the case of SEC and pH, and to a 0–25 m section for water temperature (*Tw*). Each time a spherical model of the semivariance proved to be the best (by visual evaluation and the Indicative Goodness of Fit index in *Variowin*, *Pannatier*, 1996). The results of model calculations are presented in Tab. 2.

The absolute values of the nugget variance were very low: 0.05 °C, 0.14 pH, and 2.63 μS cm^{-1}, when compared with either the accuracy of reading or the actual accuracy of measurement: ±0.1 °C, ±0.01 pH, ±1 μS and ±0.1°C, ±0.1 pH, and 0.5% of the parameter measured, respectively. It can be assumed, therefore, that the value of the nugget variance is almost exclusively measurement error. With a sampling distance of 2 m, short-distance variability seems to be negligibly small.

The structural variance was equal to 0.15 °C, 0.27 pH, and 6.0 μS respectively, which means that the 'nugget' constituted 33, 52 and 44% of it. An average difference between samples which no longer showed any similarity in terms of the parameters under analysis was very small, taking into consideration the accuracy of measurements mentioned above. Still, the values of the coefficients of determination of the models show them to be highly significant statistically.

The autocorrelation ranges of temperature and conductance are practically identical: between 17 m and 18 m. The water reaction displays a slightly greater spatial 'continuity'– 23.1 m.

The analysis carried out on the basis of hydrochemical data is summed up in Fig. 6 (*Stach*, 1992). An interpretation of the profiling data allows the following sources supplying water to the stream channel to be distinguished:

1. Drainage water, or shallow soil nourishment from the aeration zone. The water comes from the water-logged colluvial soils of the upper part of the catchment. A large proportion of the supply is water stored in the muck and peat filling a small kettle-hole. The relatively short runoff time and the range of penetration limited to a 1-m soil layer are responsible for the low general mineralisation level, specific ionic composition, and still high aggressiveness of this water (Fig. 6).
2. The throughflow from the organic-mineral soils in the upper part of the bottom of the erosional dissection – zone 1. Along the section between the 30th/40th and 80th/90th metres of the stream course, a slight, uniform increase in the discharge volume was recorded, as well as synchronic changes in the mineralisation level and proportions of the ionic composition. Because height differences along this short section are about 4–5 m, the most reasonable conclusion is that this water still does not come from the saturation zone. A characteristic chemical feature of the water flowing into the stream channel in the upper part of the dissection was the biggest disequilibrium of the ionic balance – there was probably a high proportion of nitrates, which were not determined, produced by the decomposition of organic matter.
3. Shallow groundwater nourishment. This is water flowing into the main stream from a spring-head alcove. Its low level of saturation with carbonates as well as lower concentrations of SiO_2 than at the last measuring site and in the remaining tributaries indicate a shorter time of its circulation. A significant disequilibrium of the ionic balance is probably due to a small proportion of throughflow from the water-saturated area of the spring-head alcove.
4. Throughflow – zone 2. Along the section between the 84th and 92nd metres of the stream course, a stepwise change in a lot of physico-chemical parameters of water and a noticeably big increase in the discharge volume were recorded during map-

ping. The mineralisation level is similar to those recorded in the spring-head alcove and the last measuring site (351 – 360 – 358 μS cm^{-1}), but the ionic composition is unique among all other sites. Its most characteristic features are high concentrations of magnesium, sulphates, and sodium. The water is also high in chlorides. The concentration of calcium is low, even lower than in the throughflow water of zone 1. The disequilibrium of the ionic balance is slight, a mere 0.247 meq dm^{-3}.

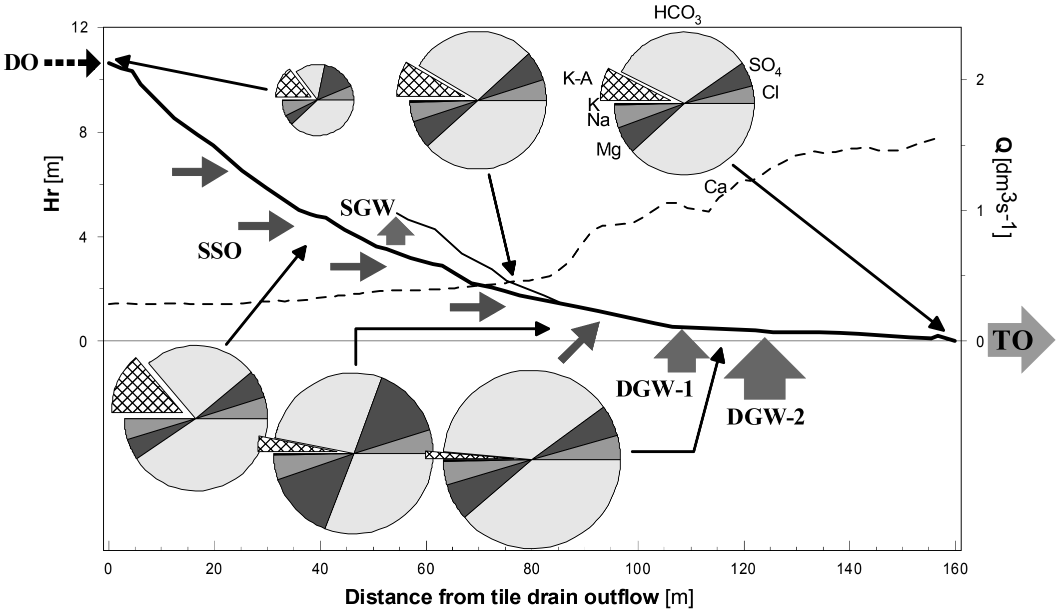

Fig. 6. Chemical composition of waters from the main sources feeding the Radomyski Potok channel on March 5th, 1992. The long profile of the channel (Hr – continuous line) and estimated variation in the discharge (*Q* – dashed line) are indicated. Pie-charts present the chemical composition of tile-drain water (DO), throughflow (SSO), three zones of groundwater nourishment (SGW, DGW-1, DGW-2), and water leaving the catchment (TO).

Obr. 6. Chemické zloženie vody pochádzajúcej z rôdnych zdrojov dotujúcich Radomyský potok 5. 3. 1992; pozdĺž koryta (Hr– súvislá čiara) a odhadnutá variabilita prietoku (*Q* – čiarkovaná čiara); kruhové grafy predstavujú chemické zloženie drenážnej vody (DO), hypodermického odtoku (SSO), príspevku z troch zón podzemnej vody (SGW, DGW-1, DGW-2) a vody v záverečnom profile povodia (TO).

5. Deep groundwater nourishment. The groundwater nourishment zone (an increase in the discharge volume of about 28%) is situated between the 115th and the 135th metres of the stream course. It is associated with the inflow of water from a few streams some dozen metres long rather than with direct channel alimentation. The most salient features of water in this zone include: the highest electrical conductance (425 μS cm^{-1}) as well as concentrations of calcium, bicarbonates and silica, and the smallest difference between the sums of cations and anions (0.124 meq dm^{-3}). This is evidence of a long time of circulation. It is justified to conclude that the nourishment of this water-bearing horizon is not restricted to the area of the topographic catchment.

The above analysis indicates that the headwater section of the Radomyski Potok is nourished by four, if not five, different types of water (Fig. 6), and the observed big changes in the physico-chemical properties of its water are the result of the mixing of all these waters and striking a balance under the subaerial conditions of temperature and pressure.

The Chwalimski Potok

The Chwalimski Potok rises in an arcuate spring-head alcove some 5 m in diameter. After a few metres the scattered flow is gathered into a small channel. At the 25th metre of its course it is joined by the only tributary along the stream section under study which drains a small kettle-hole with a seasonal pond. Below it the stream's course is regularly rectilinear, which is indicative of improvements made to it some time ago. At present the channel itself is natural in character. Between the 150th and 180th metres the stream passes through a dense willow thicket. The gradient is small here and the water spills widely. Vegetation exerts a very big influence on the dynamics of fluvial processes in the Chwalimski Potok. During the growing season the channel is overgrown along its entire length with a compact cover of green hygrophilous plants which mask it completely. The plants act like a mechanical filter sifting very fine suspended matter, and probably like a chemical one as well changing the water's ionic composition.

In morphometric terms, the channel of the Chwalimski Potok can be divided into three distinct sections. From the spring-head alcove where it rises to the 30th metre it has the steepest gradient (2.27 ± 1.00°), narrowest width, and average depth. The next section stretching to the 110th metre of the course has a gentle and fairly stable gradient (0.73 ± 0.40°). The width and depth of the channel are markedly bigger. Farther on the gradient of the bottom starts to grow noticeably (1.32 ± 0.52°).

The picture obtained from measurements made in the smallest of the catchments under study, that of the Chwalimski Potok, was relatively simple. The most significant changes occurred along the first 25 – 30 m of the course of the stream, which rises in a small spring-head alcove. They included a steady increase in SEC from 160 to 449 µS cm^{-1}, and variations in the temperature and reaction of water in the respective ranges of 7.2–7.9 °C and 7.90–8.39 pH. Along a further 180 metres the changes were only slight. The specific electrical conductance of water gradually diminished from nearly 450 µS to about 415 µS, and its temperature from 7.9 °C to 6.0 °C. The reaction along the entire section kept at 8.2–8.3 pH. There was a change in all the three parameters between the 110th and 120th metres. There was also a sharp drop in water temperature between the 150th and 175th metres. The former phenomenon is probably the effect of the aforementioned morphometric changes in the channel, and the latter, of its being overshadowed by a thicket of shrubs.

Because of the small scale of variability of the parameters under study and the lack of strong, clear-cut tendencies, the semivariance analysis was carried out on crude data (Tab. 2). Semivariograms of water temperature and reaction were rather chaotic. This was a result of the small size of the sample (a mere 44 measurements) and the range of variation of these parameters hardly greater than measurement error. A distinct structure was obtained from the analysis of the SEC data – a spherical semivariogram of 20–25 m in range, i.e., very similar to the one obtained in the Radomyski Potok catchment (Tab. 2). In the Chwalimski Potok catchment there are three alimentation sources: (1) poorly mineralised (ca. 150 µS) throughflow (soil) water flowing from the steeply inclined margins of the spring-head alcove, (2) highly mineralised (> 500 µS) groundwater flowing out in the central part of the spring-head, and (3) soil water again, relatively poorly mineralised and flowing into the channel along the section from the spring-head alcove to the site closing the catchment under analysis. The autocorrelation distance is interpreted again as a section where a hydrochemical balance is being achieved.

The Młyński Potok

The pattern of changes in the physico-chemical properties of water along the course of the Młyński Potok was clearly different from those in the two headwater catchments. Although the difference in the electrical conductance of water in the spring and the mouth was slight – a mere 13 µS, the range of change along the entire course of the stream was much bigger – 70 µS. The most characteristic feature of this variability was stepwise increases or drops in SEC below the stream's chief tributaries, with minimum differences among them (Fig. 7). Along hundreds of metres of reaches between the tributaries, changes in the conductance ranged from 0.7% to a maximum of 5.2% (with a weighted mean of 2.6%), while the tributary effect varied between 4.8% and 10.4% (with a weighted mean of 8.9%). Such a structure reflects changes in the discharge volume. Between the tributaries they ranged from 6.4% to 30.4% (16.8% on average), whereas the tributaries supplied the stream with 14.7% to 135.7% of water (74.6% on average). A very characteristic feature of discharge variability along the course of the Młyński Potok can be observed in the section between the 257th and 847th metres, where the volume of flowing water decreases by about 15% (Fig. 7). The final part of this section embraces a small alluvial cone accumulated on the margin of a kettle-hole which is a drained blanket bog. At times of high-water flows the water escapes from the stream channel to deposits of the fan and the peats. This development is typical of small streams in the lakelands of northern Poland. During lows the direction of water flow is reversed – it is the peat bog that nourishes the stream.

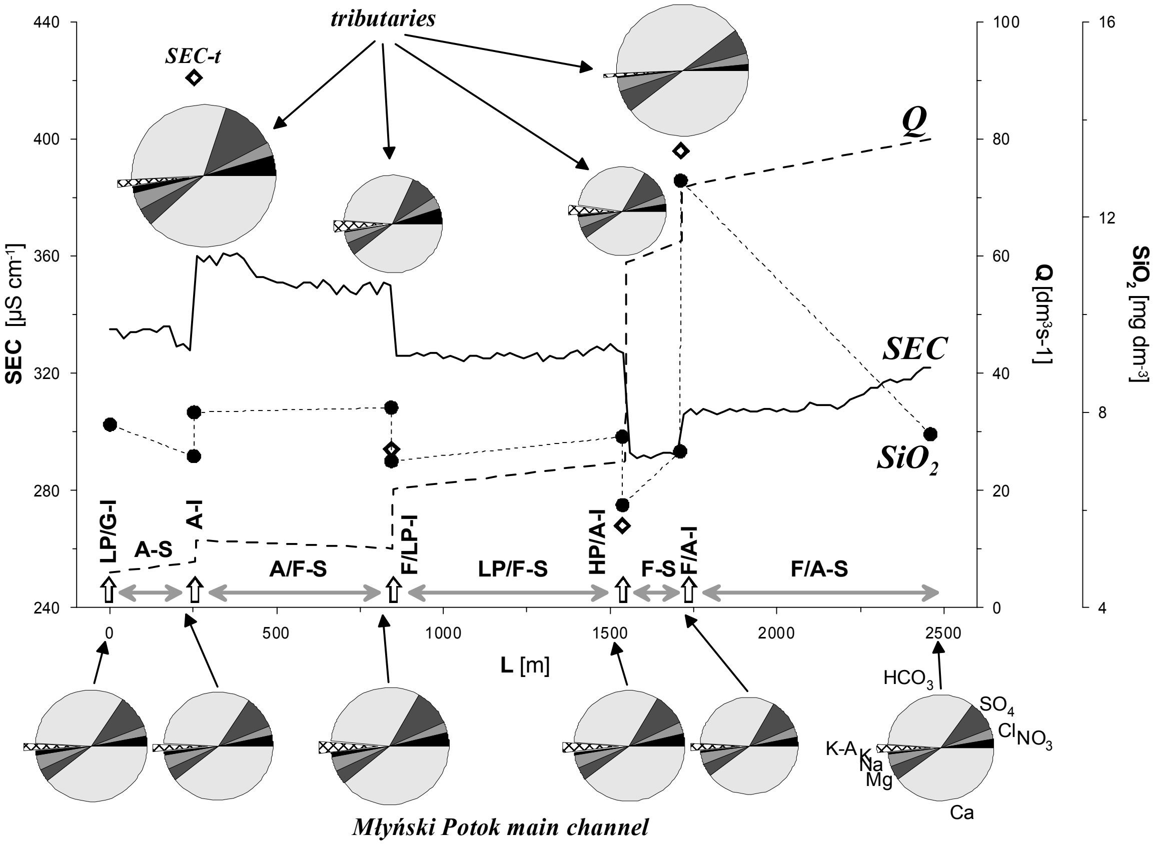

Fig. 7. Hydrochemical variations along the Młyński Potok channel on March 9th, 2002. Pie-charts present the chemical composition of tributary waters (above diagram) and waters of the main channel above tributary mouths (below diagram). SEC – specific electrical conductance, SEC-t, ◊ – specific electric conductance in tributary mouths, Q – water discharge, SiO_2 – concentration of ionised silica. Sources of channel feeding: ⇧ (I) – from tributary catchment, 1 (S) – from differential catchments. Types of land covers/use: A – arable land, F – forest, LP – blanket bog, HP – raised bog, G – meadow/pasture.

Obr. 7. Hydrochemická variabilita pozdĺž toku Mlynského potoka 9. 3. 2002; kruhové grafy predstavujú chemické zloženie vôd z prítokov (horné grafy) a vody v hlavnom toku nad prítokmi (dolné grafy); SEC–merná elektrická vodivosť, SEC-t, ◊ – merná elektrická vodivosť v ústí prítokov, Q – prietok, SiO_2 – koncentrácia SiO_2; zdroje dotácie koryta: ⇧ (I) – z povodia prítoku, (S) – z medzipovodia; využitie územia: A–orná pôda, F–les, LP a HP– močiar, G–lúka/pastvina.

The empirical semivariograms of SEC and Tw for the Młyński Potok showed an unlimited decline in the similarity of data with the distance growing to 600 metres. Hence, it was decided to eliminate the 'tributary' effect from the data by subtracting the difference between the results of measurements directly above and below a tributary from the values measured below it. This operation corrected the non-stationarity of the analysed data and made it possible to detect the underlying spatial structure. The pattern of the SEC semivariance is best described by a complex spherical model 150 m and 400 m in range (Tab. 2, Fig. 14), and that of Tw, a 'simple' spherical model about 430 m in range.

We see the above-described changes in the physico-chemical properties of water along the course of the Młyński Potok as stemming mainly from the land-use pattern and ground cover. Almost its entire catchment is situated within a single geomorphological unit - an undulating ground moraine. While the lithology and soils are highly variable here, within the particular subcatchments their proportion is comparatively constant. Fig. 7 presents the dominant types of land use/ground cover for the catchments of the tributaries and the differential catchments between them. Agricultural land use clearly raises the water mineralisation level, while woodland and especially peat bogs tend to lower it. Particularly low in minerals is water from the subcatchment draining a raised peat bog. An exception to this rule is water flowing from the lowest situated tributary whose catchment is largely wooded. It is hard to explain this oddity because the proportions of the principal solution components are similar due to the abundance of relatively easily dissolved carbonates in all types of glacial and glaciofluvial deposits; what varies is only the level of mineralisation. Ionised silica turned out to be the indicator best differentiating the waters in the area under study. In all the samples from the principal stream and its tributaries except the lowest, its concentrations ranged in a narrow interval of 6.1 to 8.1 mg dm^{-3}. In this untypical woodland brook its concentration exceeds 12.7 mg dm^{-3}. We suppose this may indicate that it is nourished from a different water-bearing horizon than the rest of the Młyński Potok catchment.

The Kłuda River

The long profile of the Kłuda valley features much higher gradients in the middle and outlet parts than in the headwater section (Fig. 8). The Kłuda rises in a seasonal wetland situated on a small outwash plain. In its upper reaches the valley is a flat-bottomed melt-out basin with a small gradient (about 0.06°) and low flow velocity in an overgrown channel. This area, which is filled with organic-mineral deposits (silt, calcareous gyttja, lacustrine chalk, peat), is occupied by a waterlogged meadow cut by drainage ditches. Below the melt-out basin the wooded Kłuda valley cuts across a series of morainic hills. Fragments of the middle course of the valley display the greatest morphological variety, which is reflected in gradients increasing to 1.2°. The valley floor narrows to a few metres and attains a depth of more than 10 m in the lower part of the ravine segment. In the lower course of the river the valley spreads wider and embraces two extensive melt-out basins up to 400 m in width that are drained by a dense system of drainage ditches. In its mouth section the valley gradient drops to 0.19°. Here the Kłuda channel dissects sand-gravel deposits with intercalations of peat and carbonate gyttjas.

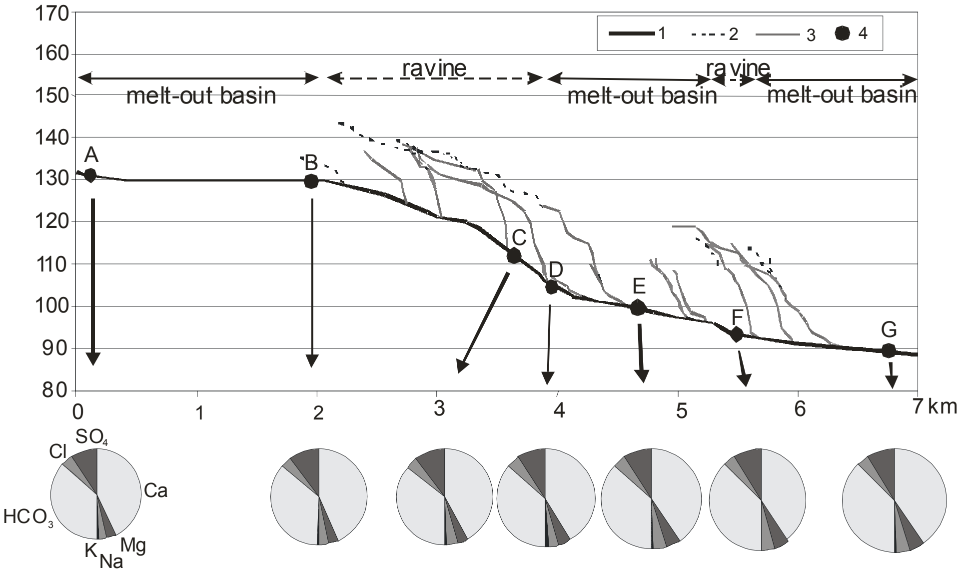

Fig. 8. Chemical composition of water along the Kłuda channel. 1 – long profile of the Kłuda, 2 – intermittent streams, 3 – perennial streams, 4 – sampling sites along the Kłuda (ion composition in meq dm^{-3}).
Obr. 8. Chemické zloženie vody pozdĺž toku Kłuda. 1 – pozdĺž Kłuda, 2 – občasné toky, 3 – trvalé toky, miesta odberu vzoriek pozdĺž Kłuda (iónové zloženie v meq dm^{-3}).

The hydrochemical profiling carried out along an almost 7-km long section of the Kłuda revealed little variability of the pH, electrical conductance (Fig. 9) and chemical composition of its waters, which represent a single, calcium-bicarbonate, type of water along the entire long profile (Fig. 8). The only parameter displaying significant variations down the whole length of the river was ionised silica (Fig. 10). The lowest pH values, between 7.3 and 7.9, were recorded in the headwater section and meadows. The reaction exceeded 8 in the ravine section of the Kłuda valley where the river channel is nourished 'directly' by groundwater from a morainic upland area. Also in the headwater section, the lowest SEC values were recorded (about 350 µS cm^{-1}) which increased by about 50 µS cm^{-1} after the first 200 m. This change in the concentration of dissolved material is certainly associated with the river's alimentation by waters draining the melt-out basin filled with organic-mineral deposits. Along the entire remaining length of the river variations in SEC do not exceed 20 μS cm^{-1}. The effect of the lithology and water cycle conditions in the kettle-hole sections of the Kłuda valley on water chemistry makes it difficult to determine the contribution of the particular sources of dissolved material in the catchment to the total ionic outflow. A comparison of the chemical compositions of river water and groundwater examined on the morainic plateau reveals a change in the properties of water in the valley zone. The alimentation of the river channel occurs through shallow groundwater whose characteristics are probably the effect of the mixing of waters coming to the valley zone from all over the catchment, and their chemical composition also undergoes a transformation under the influence of calcium carbonate contained in the mineral-organic deposits filling the kettle-hole sections of the Kłuda valley and in the vegetation.

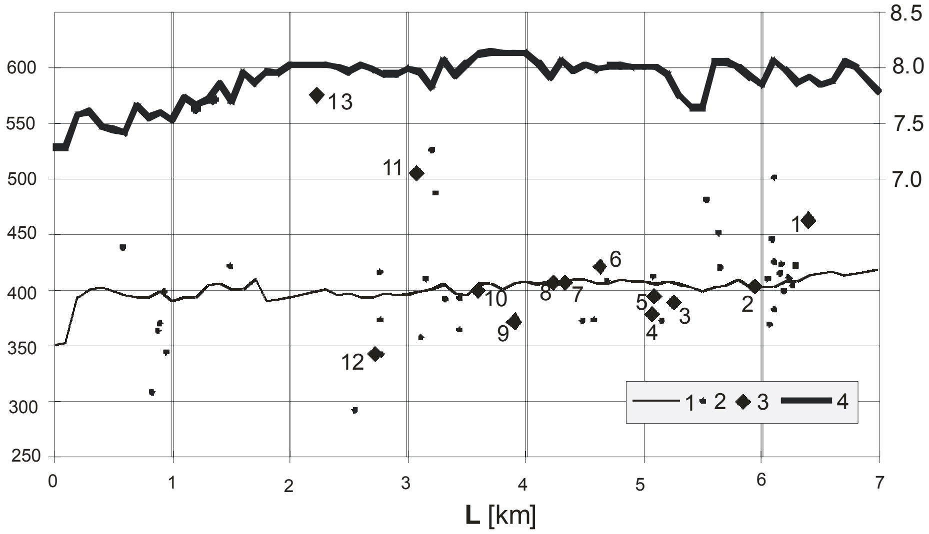

Fig. 9. Variations in the specific electric conductance (SEC) of main river waters (1), waters flowing into the main channel (2), waters of the main tributaries: 1 – 13 (3) and reaction pH (4) along the Kłuda channel.
Obr. 9. Merná elektrická vodivosť (SEC) v hlavnom toku (1), vo vodách pritekajúcich do hlavného toku (2), vo vode hlavných prítokov 1–13 (3) a pH (4) pozdĺž koryta Kłuda.

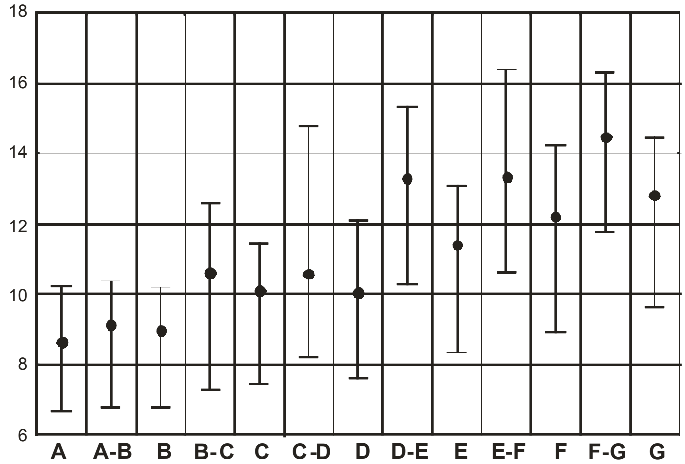

Fig. 10. Range of variation in concentrations of ionised silica (SiO2) along the Kłuda channel, hydrological years 1990–1993; A, B, C, D, E, F and G – sampling sites, A-B, B-C, C-D, D-E, E-F and F-G – sections between sites from which concentrations are calculated on the basis of the mixing model.
Obr. 10. Rozsah variability koncentrácií SiO_2 pozdĺž toku Kłuda, hydrologické roky 1990–1993; A, B, C, D, E, F, G – miesta odberu vzoriek, A-B, B-C, C-D, D-E, E-F, F-G – úseky medzi miestami, z ktorých sú koncentrácie vypočítané podľa zmiešavacieho modelu.

As to the significant variability in the concentrations of ionised silica shown to occur in the Kłuda's long profile, it is indicative of the integration in the Kłuda channel of waters from at least two alimentation zones differing in the circulation time and/or ability to leach silica. Its concentrations start to grow downstream, and values in excess of 11 mg dm^{-3} are recorded beginning with the 4th km of the river course, below the ravine section (Fig. 10). The lower concentrations of ionised silica that can be found along the first kilometres (up to site D) indicate a short time of water circulation in highly permeable deposits, which prevents a rapid increase in its content owing to the low solubility of crystalline silica and the slow pace of the reaction. The high silica content in the river water below the ravine section (Fig. 10) may suggest the contribution of water with a longer circulation time in channel alimentation. Flowing in a valley deeply incised in the morainic plateau, the Kłuda starts to drain a productive inter-morainic water-bearing horizon, which is also indicated by an almost threefold increase in water discharge in the ravine section of the Kłuda valley.

As in the case of the Chwalimski Potok, the low variability of the parameters measured along the river course and the absence of distinct trends made it unnecessary to transform the data in order to calculate semivariances. The picture they produced is also the least complex among the catchments under investigation. The pattern of empirical semivariances of the electrical conductance of water is best described by a spherical model with a zero nugget variance and a range of about 300 m. The water reaction curve shows an unlimited decline in similarity along a section up to 2.5 km with, however, a marked flattening between the 300th and 500th m.

The hydrochemical profiling carried out along the Kłuda course shows the water in the river channel to be much less diversified than the water circulating in the catchment. In the case of streams flowing through several morpholithological units, it is hard to tell the effect of these units from the properties of river water. Despite the different derivation of chemical substances, during water migration they change their physico-chemical parameters and as a result the chemistry of river water rather reflects the pathways of supply and biochemical processes taking place in the river channel.

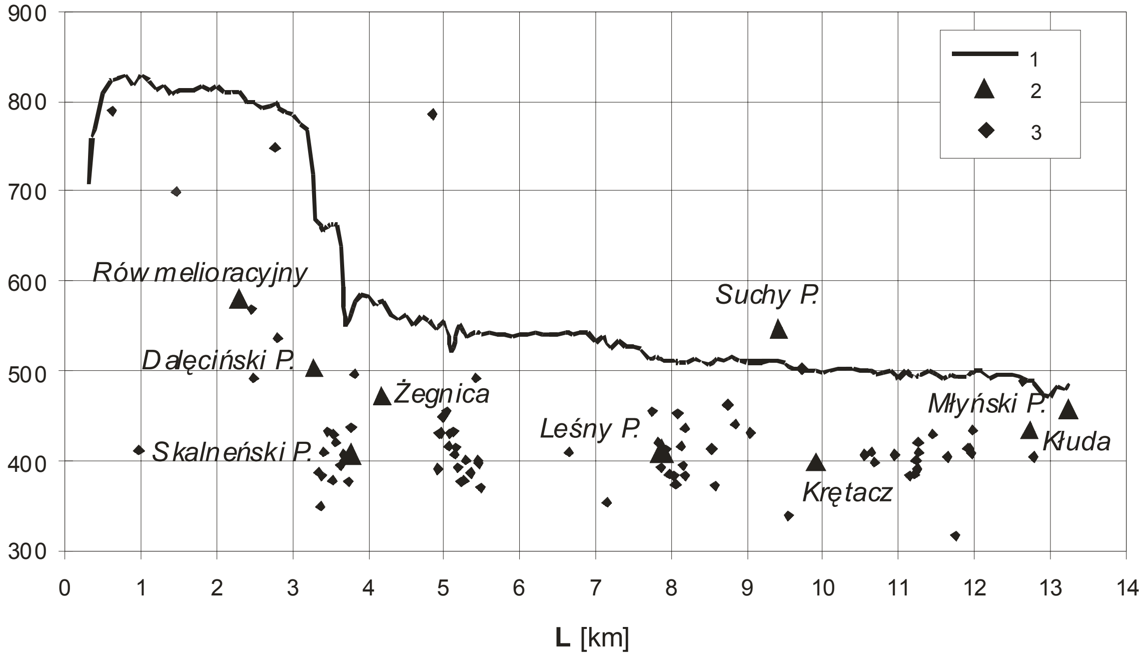

Fig. 11. Variations in specific electric conductivity SEC along the upper Parsęta River. 1 – SEC in Parsęta River main channel, 2 – SEC in mouth sections of main tributaries, 3 – SEC in other waters feeding main river (small tributaries, drainage ditches, tile drains, etc.).

Obr. 11. Variabilita mernej elektrickej vodivosti SEC pozdĺž horného toku rieky Parsęta; 1 – v hlavnom toku rieky Parsęta, 2 – v úsekoch ústí hlavných prítokov, v iných vodách dotujúcich hlavný tok (malé prítoky, drenážna priekopa, atď.)

The Parsęta River

When analysing the physico-chemical properties of water down the long profile of the upper Parsęta, three zones of dissolved material supply can be distinguished. The first covers the 3 initial kilometres of the river course and is characterized by the highest ion concentration and a low SiO_2 concentration. The high concentrations of dissolved material result from supplying from areas rich in calcium carbonate, and from the supply of readily soluble compounds in water drained from organic and mineral soil horizons. The water flowing along the next 5 kilometres of the Parsęta course is made up, in varying proportions, of water from sub-catchments supplied by different water-bearing horizons, each with its own duration of the hydrological cycle. The third zone, again 5 kilometres long, displays the least variability of dissolved components except for silica concentrations, which show an upward tendency (Fig. 12). This is indicative of feeding by groundwater of fairly stable physico-chemical parameters. The hydrochemical profiles along the upper Parsęta course have shown variations in the concentration of Ca^{+2}, K^{+}, SO_4^{-2}, and SiO_2 ions to be useful as natural indicators when studying the mechanism through which precipitation is transformed into river runoff. They may also be used in the examination of spatial differences in the sources of supply and their geochemical properties.

The SEC and pH data from the profiling of the upper Parsęta showed different patterns of variability, hence their preparation for geostatistical calculations was different. In the case of the former parameter, use was made of residuals from the curvilinear trend, and the latter, of crude data. SEC displays a strong autocorrelation up to about 450 m. Readily visible is also a distinct structure 1.2 km in range. The water reaction also varies in a complex way showing two ranges of similarity: 1.2 km and 2.6 km (Tab. 2).

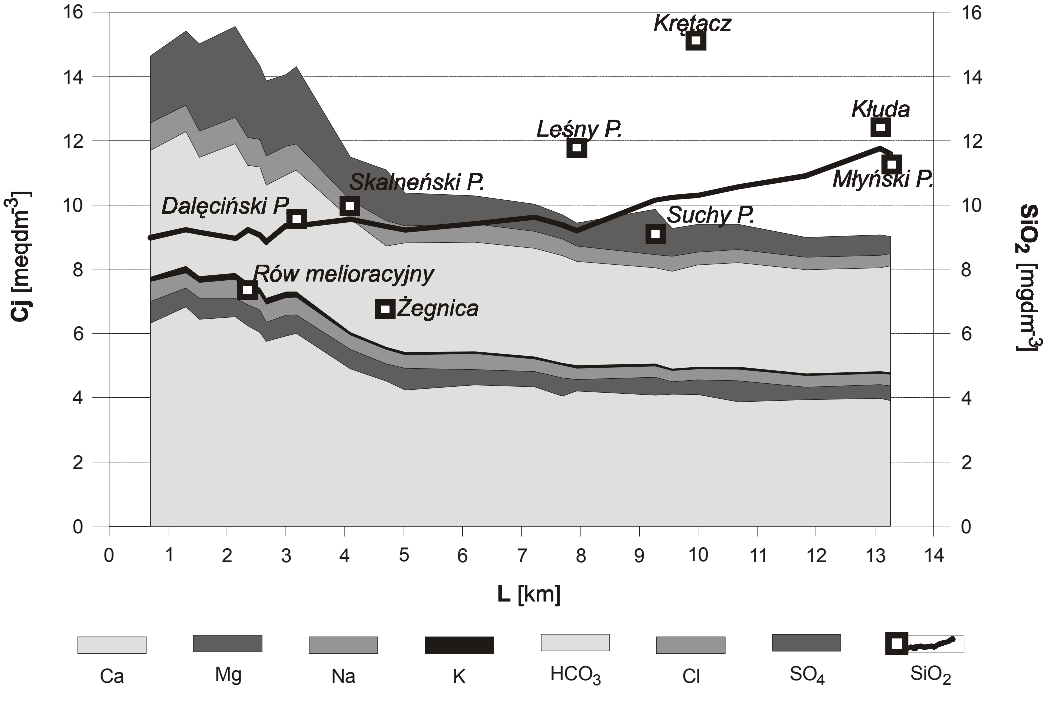

Fig. 12. Variations in the concentration of ion macrocomponents Cj and ionised silica SiO_2 along the upper Parsęta River.
Obr. 12. Priebeh koncentrácií iónov makrokomponentov Cj a SiO_2 na hornom toku rieky Parsęta.

Conclusions

Each investigated stream turned out to have its own, unique features. However, there were noticeable differences at three spatial catchment scales (Figs 13 and 14).

In spring-head catchments covering 0.05-0.10 km^2 and stream lengths of 0.16–0.23 km, variations in the measured physico-chemical properties of waters were relatively big, but nonetheless gradual (Fig. 13C). The range of autocorrelation roughly equalled 20 m (Fig. 14C, Tab. 2). The basic processes responsible for this pattern were:

- the gradual attaining of a physico-chemical equilibrium by water reaching the ground surface under current conditions of temperature and atmospheric pressure; mainly the establishment of a new carbonate equilibrium and a new pH of water,
- the mixing of soil- and groundwater differing significantly in total mineralisation levels and ionic composition.

In the third-order catchment big changes were recorded in the parameters downstream of the tributaries, while they were negligibly small between them (Fig. 13B). Hence, in this case the crucial factor is the spatial variability of the feeding sources. The tributary catchments are relatively homogeneous in terms of lithology/soils and land-use patterns, and at this spatial scale they differ significantly. Because the discharge in the tributaries is comparable with the amount of water flowing in the principal stream, changes in the physico-chemical parameters of water are stepwise. To some extent, the storm/melting runoff-related and seasonal changes in solute concentrations recorded in a gauging profile can be interpreted in terms of changes in the relative contributions of water flowing from the individual subcatchments. The analysis of semivariance, after the mean 'tributary effect' has been eliminated, indicates the presence of two ranges of data autocorrelation: 0.15 km and 0.40 km (Fig. 14, Tab. 2), which reflects the sequence of land cover changes and distances between the main tributaries.

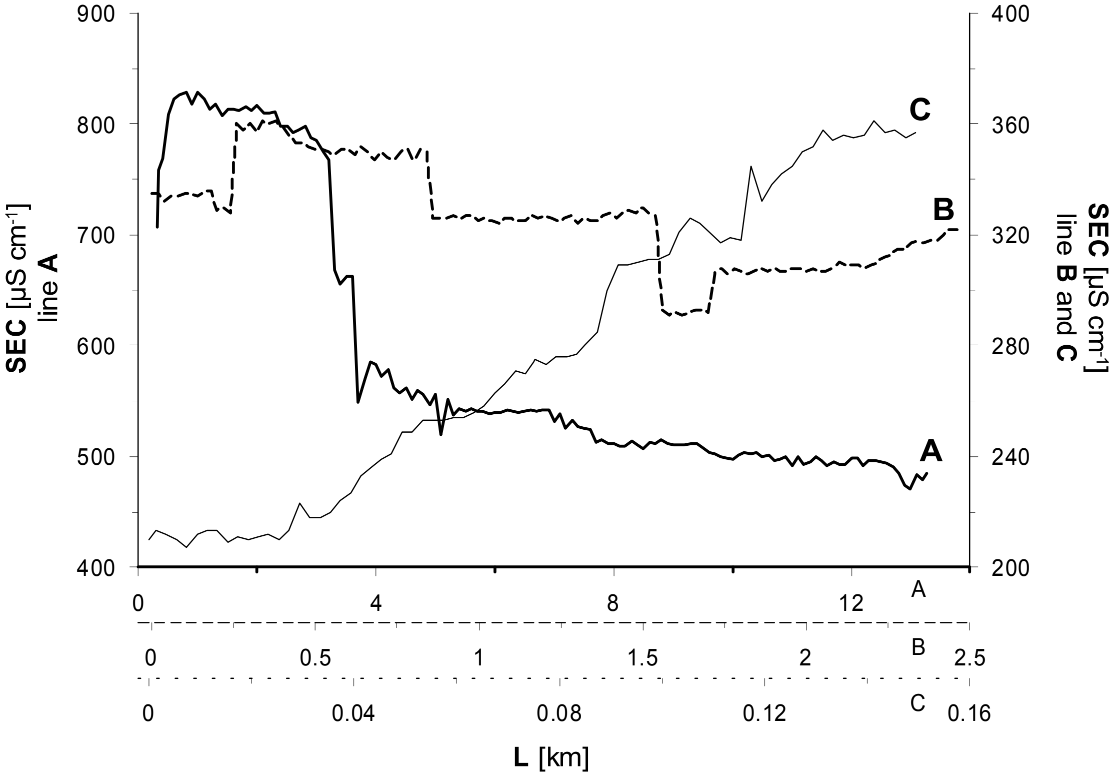

Fig. 13. Variations in the specific electrical conductance of river waters in the upper Parsęta (line A), Młyński Potok (line B), and Radomyski Potok (line C).

Obr. 13. Priebeh mernej elektrickej vodivosti vody na hornom toku rieky Parsęta (čiara A), v Mlynskom potoku (čiara B) a v Radomyskom potoku (čiara C).

In the two larger catchments two types of structure can be observed. Relatively small changes in the channel of the principal stream downstream of the biggest tributaries overlap with trends embracing longer channel sections and characterised by different gradients, and sometimes also directions of change (Fig. 13A). Of basic importance in this case is a belt pattern of the main geomorphological-lithological zones forming distinct hypsometric levels within the catchments of the two streams. On cutting them, the streams are fed from a few levels of groundwater with different circulation times, and hence also mineralisation and ionic composition. However, owing to the abundance of readily soluble carbonates in various types of glacial and fluvioglacial deposits, the proportions of chief solution components are similar. The best hydrochemical indicator differentiating groundwater with respect to the circulation time has been found to be ionised silica. In these catchments, therefore, the crucial factor controlling the runoff is the 'vertical' variability of feeding sources, i.e. groundwater levels at a variety of depths and with a variety of alimentation areas. Also in those streams, after the trend has been eliminated, one can observe an autocorrelation of measurement results at a distance of 300–450 m and 1.2 km (Fig. 14, Tab. 2). It is controlled by the sequence of successive valley reaches of different origins (melt-out basins & ravines).

A significant role in controlling the flow of dissolved salts between the catchment area and the stream channel is played by the valley zone, which is filled with mineral-organic sediments (with a large proportion of silt, calcareous gyttja, lacustrine chalk and peat). A comparison of the chemical composition of river water and groundwater examined on the morainic plateau shows that the alimentation of the stream channel occurs through the shallow groundwater of the valley zone. The properties of this shallow groundwater result from the mixing of waters flowing from the catchment to valley floors. The chemical composition of the inflowing water also undergoes a transformation under the influence of calcium carbonate contained in the mineral-organic sediments characteristic especially of melt-out basin sections of the valleys.

The reported analysis confirms the hypothesis that in the areas of northern Poland covered by the Last Glaciation it is possible to identify zones and forms of channel alimentation on the basis of hydrochemical interpretation of runoff recorded in gauging profiles only in the case of small catchments no larger than $n \times 10^0$ km^2. In larger catchments, it is only possible to differentiate between "new water" (direct fall of precipitation on the channel and the overland flow) and "old water", composed of a mixture of soil water and the alimentation from various water-bearing horizons. The hypothesis is being verified by studying a bigger catchment sample in diversified hydrological conditions. An examination of the stable isotope content of the water might shed a new light on this issue.

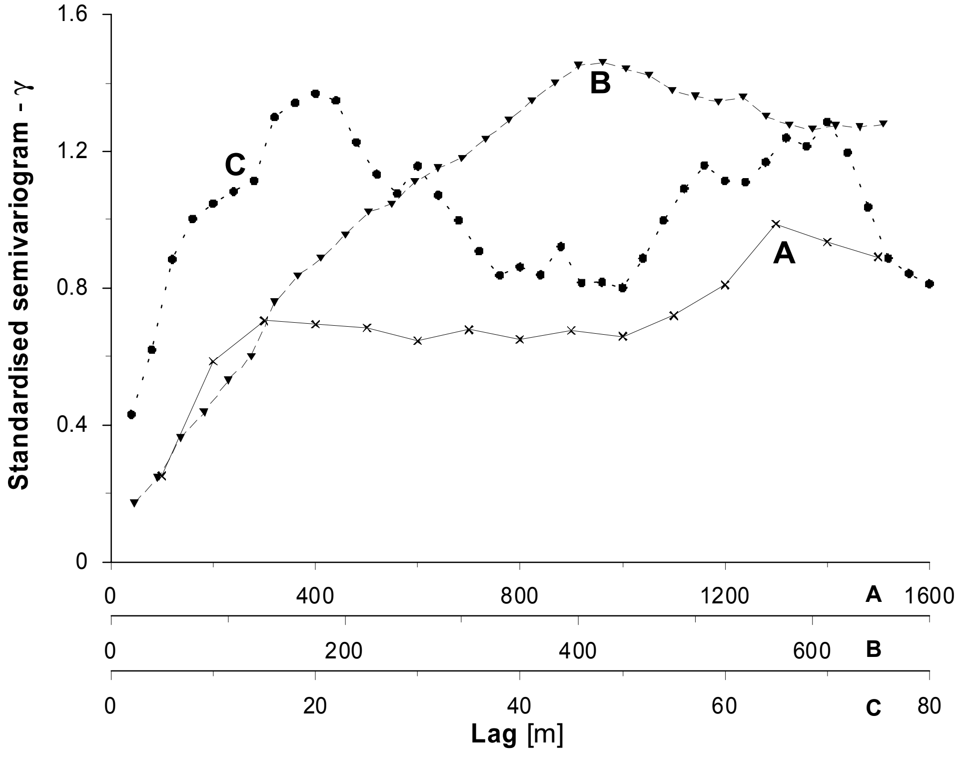

Fig. 14. Standardised semivariograms of the specific electrical conductance of river waters for channels of the Kłuda (line A), Młyński Potok (line B), and Radomyski Potok (line C).

Obr. 14. Variogramy mernej elektrickej vodivosti vody v tokoch Kłuda (čiara A), Młyński Potok (čiara B), a Radomyski Potok (čiara C).

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PRIESTOROVÉ ROZLOŽENIE TVORBY ODTOKU V NÍŽINNÝCH OBLASTIACH SEVEROZÁPADNÉHO POĽSKA. HYDROCHEMICKÁ A GEOŠTATISTICKÁ ANALÝZA

Alfred Stach, Andrzej Kostrzewski, Małgorzata Mazurek,
Grażyna M. Michalska, Zbigniew Zwoliński

Jedným z prvkov interdisciplinárneho výskumu v hornej časti povodia rieky Parsęta (obr. 1), zameraného na procesy toku energie a hmoty v oblastiach s postglaciálnym reliéfom a rôznym využitím krajiny, bol monitoring hydrolologických a geomorfologických procesov v povodiach rôznej veľkosti. Charakteristickými črtami hydrologických pomerov v tomto území je vysoké zastúpenie oblastí bez odtoku vody z povodia v povrchových tokov, veľká záchytná kapacita povodí, a teda aj vysoká hydrologická zotrvačnosť tokov a dominancia sezónnej variability nad krátkodobou variabilitou spôsobenou dažďom alebo topením snehu. Priestorová a časová variabilita podmienok určujúcich tvorbu odtoku sa prejavuje veľkou variabilitou (najmä priestorovou) jednotkového odtoku a chemických vlastností vody. Cieľom tejto práce bolo objasnenie mechanizmov tvorby odtoku v riečnej sieti v povodiach rôznej veľkosti. Okrem iného bola pritom použitá geoštatistická analýza údajov z hydrochemického profilovania (odberu a vyhodnocovania charakteristík pozdĺž tokov).

Výskum bol vykonávaný v štyroch subpovodiach (Radomyský potok, Chwalimský potok, Mlynský potok, rieka Kłuda) aj v celom povodí horného toku rieky Parsęta (tab. 1, obr. 2). Plochy povodí sa menili od 0,05 km^2 do 74,0 km^2, dĺžka tokov od 0,16 do 13,26 km, vzdialenosti medzi vzorkovanými lokalitami od 2 do 100 m. Mapovanie bolo uskutočnené v období ustáleného prietoku a trvalo vždy maximálne jeden deň. Obdobie merania zodpovedalo vysokému stavu zásob vody v povodí. Pri tvorbe odtoku sa v tomto období uplatňovali všetky mechanizmy okrem povrchového (Hortonovského) odtoku. Na meracích lokalitách boli vykonávané merania prietoku, teploty, pH a mernej elektrickej vodivosti vody a odoberali sa vzorky na chemickú analýzu. Pri chemickej analýze v laboratóriu boli následne analyzované koncentrácie sodíka, draslíka, vápnika, chloridov, síranov, SiO_2 a horčíka. Výsledky boli analyzované geoštatistickými metódami (obr. 3).

Hoci každý zo skúmaných tokov vykazoval vlastné jedinečné charakteristiky, boli zistené zjavné rozdiely v troch priestorových mierkach (obr. 13 a 14):

- V pramenných oblastiach s plochou 0,05–0,1 km^2 a dĺžkou tokov 0,16–0,23 km, bola relatívne vysoká variabilita meraných fyzikálno-chemických vlastností, ale zmeny boli postupné. Rozsah autokorelácie sa rovnal približne hodnote 20 m.
- V povodiach tretieho rádu boli pozdĺž toku namerané veľké rozdiely pod prítokmi, kým v úsekoch medzi nimi boli rozdiely zanedbateľné.
- Vo väčších povodiach boli zistené dve štruktúry. Relatívne malé zmeny v koryte hlavného toku pod najvýznamnejšími prítokmi sa prelínali s trendami zahŕňajúcimi dlhšie úseky koryta charakterizované rôznymi gradientmi

SiO_2 sa ukázalo byť najlepším hydrochemickým indikátorom odlíšenia podzemnej vody s rôznou dobou obehu. Ddôležitú úlohu pri určovaní toku rozpustených solí medzi povodím a korytom hrá príbrežná zóna. Prítok vody do povrchového toku prechádza cez oblasť plytkej zvodnenej vrstvy v údolí. Kvalitatívne vlastnosti vody v tejto zvodnenej vrstve sú výsledkom miešania vody prúdiacej z povodia smerom k údoliu, aj transformácie vplyvom uhličitanu vápenatého nachádzajúceho sa v minerálno-organických sedimentoch v údolí.

Zoznam symbolov (rov. (1))

$N(\mathbf{h})$ – počet dvojíc pre daný interval vzdialenosti $\mathbf{h}$ medzi nimi,
$z(\mathbf{u}_\alpha)$ – $\alpha = 1, 2, ..., n$ – súbor n meraní daného parametra,
$\mathbf{u}_\alpha$ – vektor lokalít s meraniami daného prametra.